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LHCb detector momentum calibration with the first year data and a performance study of CP violation measurement with the $B_s^0 \rightarrow J/\psi\phi$ decays

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Abstract

A new area in particle physics has begun with the start of the Large Hadron Collider (LHC) at CERN at the end of 2009, which collides protons at energies never reached before. To detect the products of the collisions, four main experiments are located around the LHC, among which the LHCb experiment. LHCb has been designed as a single-arm forward spectrometer and is dedicated to measurements of CP violation and rare decays of B hadrons. These searches could also potentially lead to the discovery of phenomena that cannot be described by the model used to date, called the Standard Model. The physics beyond the Standard Model is referred to as New Physics.

A measurement of the phase of the $B_s^0 - \bar{B}_s^0$ oscillation amplitude with respect to that of the $b \rightarrow c^+ W^-$ tree decay amplitude, called $\phi_s^{J/\psi\phi}$, is one of the key goals of the LHCb experiment with first data. In the Standard Model, this phase equals $-2\beta_s$, with β_s the smallest angle of the unitary triangle of the CKM matrix relevant to B_s^0 . The $\phi_s^{J/\psi\phi}$ phase is hence predicted to be small, $\phi_s^{J/\psi\phi} \equiv -2\beta_s = -0.0360^{+0.0020}_{-0.0016}$ rad. However, possible contributions of New Physics to the $B_s^0 - \bar{B}_s^0$ box diagram, such as new particles entering into it, could modify the $\phi_s^{J/\psi\phi}$ value from its Standard Model expectation. Due to its very small theoretical uncertainty in the Standard Model, $\phi_s^{J/\psi\phi}$ is therefore a very sensitive probe to detect the presence of New Physics.

The $\phi_s^{J/\psi\phi}$ phase will be measured from a time-dependent angular analysis to $B_s^0 \rightarrow J/\psi\phi$ events with tagging the initial flavor of the B_s^0 mesons. Due to the pseudo-scalar to vector-vector particle nature of the decay, an angular analysis is required to disentangle statistically the CP-even and CP-odd components present in the final state. Already with 2 fb^{-1} of data taken at the nominal luminosity $\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^2 \text{ s}^{-1}$, corresponding to $\sim 117,000$ $B_s^0 \rightarrow J/\psi\phi$ signal events, the LHCb experiment is expected to achieve a statistical uncertainty $\sigma(\phi_s^{J/\psi\phi}) \simeq 0.03$ rad, similar to the value predicted by the Standard Model.

On the way to this measurement, we present prospects for the time-dependent angular analysis to $B_s^0 \rightarrow J/\psi\phi$ events without tagging the initial flavor of the B_s^0 mesons. This analysis is less sensitive to $\phi_s^{J/\psi\phi}$, but it has the advantages of being independent of the tagging calibration and less stringent about the proper time resolution, as it does not have to resolve the fast $B_s^0 - \bar{B}_s^0$ oscillations. Consequently, it can be applied on first data. Sensitivity results for $\phi_s^{J/\psi\phi}$, but also for the other parameters entering in

the analysis are given. In particular, the amplitudes of the CP-even and CP-odd components and the B_s^0 meson lifetime can already be measured with a better precision than the latest CDF results (June 2010) with only 0.2 fb^{-1} of data at nominal luminosity with the untagged analysis.

To perform this analysis, the trajectories through the spectrometer of the particles coming from the $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay, the muons and kaons, need to be reconstructed very precisely. Indeed, from the curvature of their trajectory in the magnetic field, the momentum of the particles is obtained, which is then used in the calculation of the angles forming the basis for the angular analysis to $B_s^0 \rightarrow J/\psi\phi$ events. For particles flying in the innermost part of LHCb, the Inner Tracker is the detector that provides information about the tracks. It consists of twelve detector boxes fixed on three tracking stations located downstream of the magnet in a cross-shaped configuration around the beam pipe. They are each filled with four layers of silicon microstrip sensors. We have assembled the twelve Inner Tracker detector boxes in a clean environment at CERN. By summer 2008, they were all assembled and installed in the LHCb cavern.

To reconstruct track trajectories very accurately, two ingredients are essential: a good alignment description of the detectors used for tracking and an accurate description of the magnetic field. Before closing the Inner Tracker detector boxes, we organized with the survey team at CERN measurements of the silicon sensor positions. Once installed in the LHCb cavern, the Inner Tracker detector boxes were aligned as close to their nominal position as possible on the tracking stations previously adjusted. From the final measurements, we provided to the LHCb software a first realistic geometry description of the Inner Tracker, which was validated using particles coming from LHC injection tests of September 2008 and June 2009.

The magnetic field map used initially in the LHCb software had been generated with a model based on finite element calculation. To obtain a better magnetic field map description, we developed a method for parameterizing magnetic field measurements that were recorded in December 2005 in the LHCb cavern using Hall probes. This new map replaced the former field map in the LHCb software. However, the magnetic field measurements showed some different features compared to the simulated magnetic field values, which needed to be validated with real data. As an example, an asymmetry of the magnetic field between the lower and upper parts of the magnet is observed in the measurements, while simulated values do not have this by design of the dipole magnet. Using reconstructed masses of $K_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p^+\pi^-$ and $\bar{\Lambda} \rightarrow p^-\pi^+$ decays coming from 2009 and early 2010 real data, we validated the magnetic field map based on the measurements against the one based on simulated values according to several criteria, one of which being the confirmation of the up-down asymmetry in the field. From the same studies, we calculated a factor to correct globally for the momentum scale. As this factor should be universal, it can be calculated for one resonance and validated using the results for other resonances.

Keywords :

CERN, LHCb, Silicon Tracker, Survey Measurements, Magnetic Field Map, Momentum Calibration, K_s and Λ Resonances, $B_s^0 \rightarrow J/\psi\phi$, CP-Violating Weak Phase $\phi_s^{J/\psi\phi}$, New Physics, Time Dependence, Angular Dependence, Trigger Selection, Angular Acceptances, Untagged Analysis.



Résumé

Une nouvelle ère de la physique des particules a commencé, avec le démarrage du Grand Collisionneur de Hadrons (LHC) au CERN à fin 2009, qui collisionne des protons à des énergies jamais atteintes auparavant. Pour détecter les produits des collisions, quatre expériences principales sont situées autour du LHC, dont l'expérience LHCb. LHCb a été conçue en tant que spectromètre à un seul bras et est dédiée à des mesures de violation CP et de désintégrations rares de hadrons B. Ces recherches pourraient aussi potentiellement mener à la découverte de phénomènes qui ne peuvent pas être décrits par le modèle en date, le Modèle Standard. La physique au-delà du Modèle Standard est appelée Nouvelle Physique.

Une mesure de la phase de l'amplitude d'oscillation $B_s^0 - \bar{B}_s^0$ par rapport à celle de l'amplitude de la désintégration en arbre $b \rightarrow c^+ W^-$, appelée $\phi_s^{J/\psi\phi}$, est l'une des mesures clé de l'expérience LHCb avec les premières données. Dans le Modèle Standard, cette phase est égale à $-2\beta_s$, où β_s est le plus petit angle du triangle unitaire de la matrice CKM en rapport avec B_s^0 . La phase $\phi_s^{J/\psi\phi}$ est donc petite par prédiction, $\phi_s^{J/\psi\phi} \equiv -2\beta_s = -0.0360^{+0.0020}_{-0.0016}$ rad. Cependant, de possibles contributions de Nouvelle Physique au diagramme en boîte de $B_s^0 - \bar{B}_s^0$, telles que de nouvelles particules, pourraient modifier la valeur de $\phi_s^{J/\psi\phi}$ de la prédiction faite par le Modèle Standard. Au vu de sa très petite incertitude théorique dans le Modèle Standard, $\phi_s^{J/\psi\phi}$ est donc une sonde très sensible pour détecter la présence de Nouvelle Physique.

La phase $\phi_s^{J/\psi\phi}$ sera mesurée à partir d'une analyse angulaire dépendante du temps appliquée à des événements $B_s^0 \rightarrow J/\psi\phi$ pour lesquels la saveur initiale des mésons B_s^0 est étiquetée. A cause de la nature de la désintégration (particule pseudoscalaire se désintégrant en deux particules vecteur), une analyse angulaire est requise pour séparer statistiquement les composantes paires et impaires de CP présentes dans l'état final. Avec seulement 2 fb^{-1} de données prises à la luminosité nominale de $\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^2 \text{ s}^{-1}$, ce qui correspond à $\sim 117,000$ événements de signal $B_s^0 \rightarrow J/\psi\phi$, l'expérience LHCb devrait atteindre une incertitude statistique de $\sigma(\phi_s^{J/\psi\phi}) \simeq 0.03$ rad, qui est de l'ordre de grandeur de la valeur prédite par le Modèle Standard.

En vue de cette mesure, nous présentons les prévisions pour l'analyse angulaire dépendante du temps appliquée à des événements $B_s^0 \rightarrow J/\psi\phi$ pour lesquels la saveur initiale des mésons B_s^0 n'est pas éti-

quetée. Cette analyse est moins sensible à $\phi_s^{J/\psi\phi}$, mais elle a l'avantage d'être indépendante de la calibration de l'étiquetage et est moins exigeante en ce qui concerne la résolution du temps propre, comme elle ne doit pas résoudre les oscillations rapides de $B_s^0-\bar{B}_s^0$. Par conséquent, elle peut être appliquée aux premières données. Des résultats de sensibilité pour $\phi_s^{J/\psi\phi}$ sont présentés, ainsi que pour d'autres paramètres entrant dans l'analyse. En particulier, les amplitudes des composantes paires et impaires de CP et le temps de vie du méson B_s^0 peuvent être mesurés avec une meilleure précision que les derniers résultats de CDF (Juin 2010) en utilisant seulement 0.2 fb^{-1} de données enregistrées à la luminosité nominale avec l'analyse n'étiquetant pas la saveur initiale des mésons B_s^0 .

Pour faire cette analyse, les trajectoires à travers le spectromètre des particules provenant de la désintégration de $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$, les muons et kaons, doivent être reconstruites très précisément. En effet, la quantité de mouvement des particules est obtenue à partir de la courbure de leur trajectoire dans le champ magnétique, qui est ensuite utilisée dans le calcul des angles formant la base dans laquelle l'analyse angulaire pour les événements $B_s^0 \rightarrow J/\psi\phi$ est faite. Pour les particules volant dans la région centrale de LHCb, le Trajectographe Interne est le détecteur qui fournit de l'information au sujet des traces. Il est composé de douze boîtes, qui entourent le tube dans lequel circulent les faisceaux dans une configuration en croix sur trois stations derrière l'aimant depuis le point d'interaction. Les boîtes sont chacune remplies de quatre couches de senseurs au silicium. Nous avons assemblé les douze boîtes du Trajectographe Interne dans une chambre blanche au CERN. En été 2008, elles étaient toutes assemblées et installées dans la caverne de LHCb.

Pour reconstruire les trajectoires des traces de manière très précise, deux ingrédients sont essentiels: une bonne description de l'alignement des détecteurs utilisés pour tracer la trajectoire des particules chargées et une description précise du champ magnétique. Avant de fermer les boîtes composant le Trajectographe Interne, nous avons organisé avec l'équipe de géomètres du CERN des mesures des positions des senseurs au silicium. Une fois installées dans la caverne de LHCb, les boîtes elles-mêmes ont été alignées aussi près que possible de leur position nominale sur les stations préalablement alignées. A partir des mesures de position finales, nous avons fourni au logiciel utilisé à LHCb une première description réaliste de la géométrie du Trajectographe Interne, qui a été validée en utilisant des particules provenant de tests d'injections du LHC en septembre 2008 et juin 2009.

La carte du champ magnétique utilisée initialement dans le logiciel de LHCb avait été générée avec un modèle basé sur des calculs d'éléments finis. Pour obtenir une meilleure description du champ magnétique, nous avons développé une méthode pour paramétrer les mesures de champ magnétique qui avaient été enregistrées en décembre 2005 dans la caverne LHCb par des sondes Hall. Cette nouvelle carte a remplacé l'ancienne carte dans le logiciel de LHCb. Cependant, les mesures de champ magnétique ont montré quelques caractéristiques différentes comparé aux valeurs de champ magnétique simulées, qui doivent être validées avec des données réelles. Par exemple, une asymétrie du champ magnétique entre la partie inférieure et supérieure de l'aimant est observée dans les mesures, alors que les valeurs simulées n'ont pas cela vu la géométrie prévue de l'aimant dipolaire. En reconstruisant des masses provenant de désintégrations telles que $K_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p^+\pi^-$ et $\bar{\Lambda} \rightarrow p^-\pi^+$, provenant des données enregistrées à fin 2009 et début 2010, nous avons validé la carte du champ magnétique

basée sur les mesures aux dépens de la carte basée sur les valeurs simulées. Pour ce faire, nous avons utilisé plusieurs critères, comme la confirmation de l'asymétrie du champ magnétique entre les parties supérieure et inférieure de l'aimant. A partir des mêmes études, nous avons calculé un facteur pour corriger globalement l'échelle de la quantité de mouvement. Comme ce facteur devrait être universel, il est calculé pour une résonance et validé en utilisant les résultats d'autres résonances.

Mots-Clés :

CERN, LHCb, détecteur de traces au silicium, mesures de position, carte de champ magnétique, calibration de la quantité de mouvement, résonances K_s et Λ , $B_s^0 \rightarrow J/\psi\phi$, phase faible de violation CP $\phi_s^{J/\psi\phi}$, Nouvelle Physique, dépendance temporelle, dépendance angulaire, sélection de déclenchement, acceptances angulaires, analyse sans étiquetage.

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Introduction

The *Standard Model (SM)* [1] is a relativistic quantum field theory that describes the elementary particles composing all the matter, the quarks and leptons, and their interaction through the exchange of gauge bosons introduced by the principle of gauge symmetries. So far, the SM has been extremely successful, not only in describing experimental observations, but also in making predictions that have been confirmed by experimental results. However, the SM still leaves room for open questions. For instance, the gravitational force is not included. Its number of parameters is large (19) and it does not explain the mass hierarchy. In the SM, the origin of mass is explained by the Higgs mechanism. It has left the Higgs boson as the single missing piece yet to be discovered. An experimental evidence for physics beyond the Standard Model already exists and comes from the observation of neutrino oscillations. These enforce that at least two neutrinos are massive, whereas they are described as massless in the SM. Therefore, physicists believe that the SM is an effective low-energy model of a more fundamental theory called *Grand Unified Theory (GUT)* [2]. In this model, the coupling constants associated to the three gauge groups, which evolve with energy, converge approximately to an energy $\sim 10^{16}$ GeV, suggesting a unification of the strong and electroweak interactions.

Three discrete symmetries, the *charge conjugation (C)*, the *parity (P)* and the *time reversal (T)* are particularly relevant in particle physics (Figure 1) [4]. The C operator interchanges a particle with its antiparticle without changing its spin nor momentum. The P operator inverses space, such that the momentum of a particle is reversed, but it leaves its angular momentum and spin unchanged, hence transforming a left-handed particle into a right-handed one. The T operator interchanges the direction of the time. The combination of the three operators, CPT, is an exact symmetry in any relativistic quantum field theory with local interactions, while C, P, T nor CP, CP, PT are not. As a result of the CPT conservation, the mass and the lifetime of an elementary particle and its antiparticle must be equal. All the experimental results obtained up to now agree with this statement.

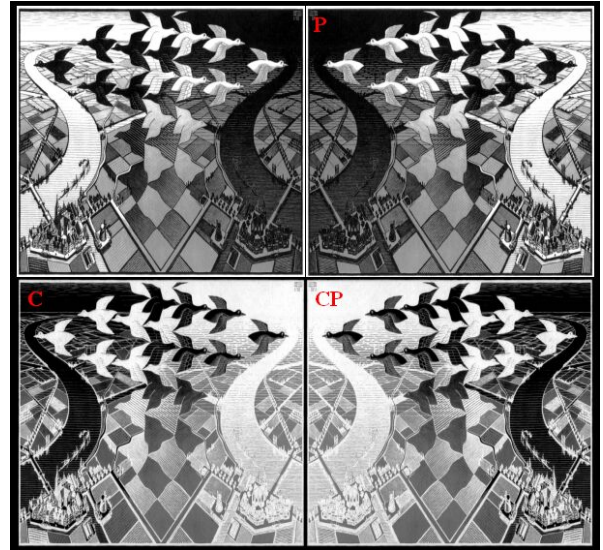


Figure 1: C, P and CP discrete symmetries [3].

While the strong and electromagnetic interactions are invariant under C, P and T transformations, the weak interaction violates C and P. The violation of CP was discovered in 1964 by studying rare decays of neutral kaons [4]. Since then, it has been observed in the neutral B^0 decays by the B-factories (Babar, Belle) and is under study in the B_s^0 system at Fermilab. The LHCb experiment at CERN will perform the most precise measurements of the CP symmetry violation in the B_s^0 system. This will allow to test even more stringent the Standard Model, and also potentially lead to the discovery in an indirect way of New Physics beyond the Standard Model.

At the birth of the universe, the so-called *Big-Bang*, large quantities of matter and antimatter were produced in equal amounts. When matter and antimatter annihilated and become photons, there was some tiny asymmetry in the universe between matter and antimatter, with a 10,000,000,001 : 10,000,000,000 ratio, which produced our universe entirely made of matter (Figure 2). According to Andrei Sakharov [5], this matter-antimatter asymmetry would have not been possible if the three following conditions had not been fulfilled:

1. Baryon number non-conservation.
2. Presence of CP violation.
3. Lack of thermal equilibrium to ensure that the reactions creating more baryons are not compensated by the reverse reactions.

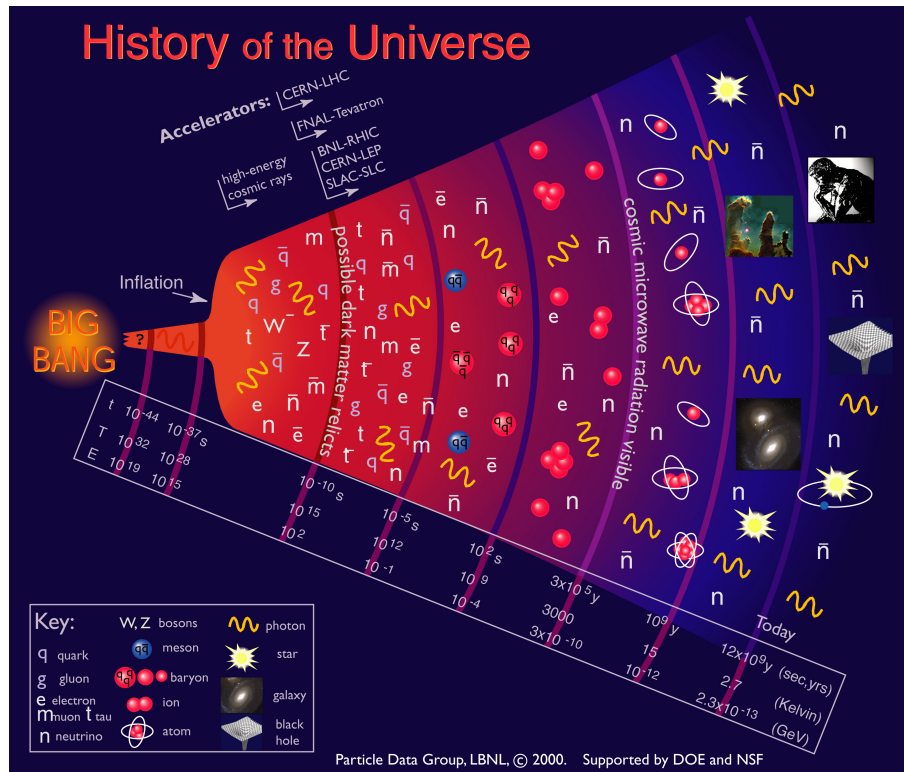


Figure 2: Evolution of the universe, from its creation at the Big-Bang (left) to the universe of today (right) [6].

The Standard Model conserves baryon number classically, but there is a global anomaly under which this conservation could be violated. Even though they have never been observed, baryon number violating processes are possible in the SM. There is a also natural setting for interactions outside of thermal equilibrium in the SM. However, with the current lower limit on the Higgs mass, this process would not have taken place. As for CP violation, the SM includes it, however in quantities that are much too small for explaining the observed asymmetries. Therefore, New Physics is searched for, which also generate CP violation. The LHCb experiment at CERN will have a leading role in this quest.



1

The LHC Accelerator and Experiments at CERN

Out of the embers of World War II sprang the positive wish of establishing international organizations that would unite European citizens across several domains. In this context, the idea emerged of creating a European collaboration dedicated to atomic physics research with aim of unifying the European scientists, but also of coping with the rising costs of nuclear physics instrumentation. The first proposal was made by the French Nobel prize Louis de Broglie at the European Cultural Conference held in Lausanne in 1949. This led in 1954 to the birth of the *European Council for Nuclear Research (CERN)* with the ratification of the Convention by the twelve founding member states. Meyrin, which is located close to Geneva at the French-Swiss border on the Swiss side, is chosen as the site that will host CERN. Nowadays, CERN is the biggest particle physics laboratory in the World, counting twenty European member states, but also six observer states and several non-member states collaborating from all other the World.

1.1 The LHC Accelerator

The *Large Hadron Collider (LHC)* [7] is a high luminosity proton-proton ring collider housed in the 27 km tunnel previously used for the LEP accelerator at 100 m underground (Figure 1.2). The protons are created from hydrogen atoms from which the electrons are extracted. The acceleration chain is composed of a series of particle accelerators allowing progressively higher energies to be reached (Figure 1.1). The proton bunches are first accelerated up to 50 MeV using a linear accelerator located at the Meyrin site, called *LINAC 2*. They are then boosted in two circular accelerators up to 1 GeV in the *BOOSTER*, before the *Proton Synchrotron (PS)* accelerates the beam up to 26 GeV. From the PS, the proton bunches enter into the *Super Proton Synchrotron (SPS)* where they reach energies of 450

GeV before entering into the LHC via two tunnels (TI2 and TI8). The LHC will also provide during dedicated runs heavy ion collisions (Pb – Pb) starting from the *LINAC 3* accelerator.

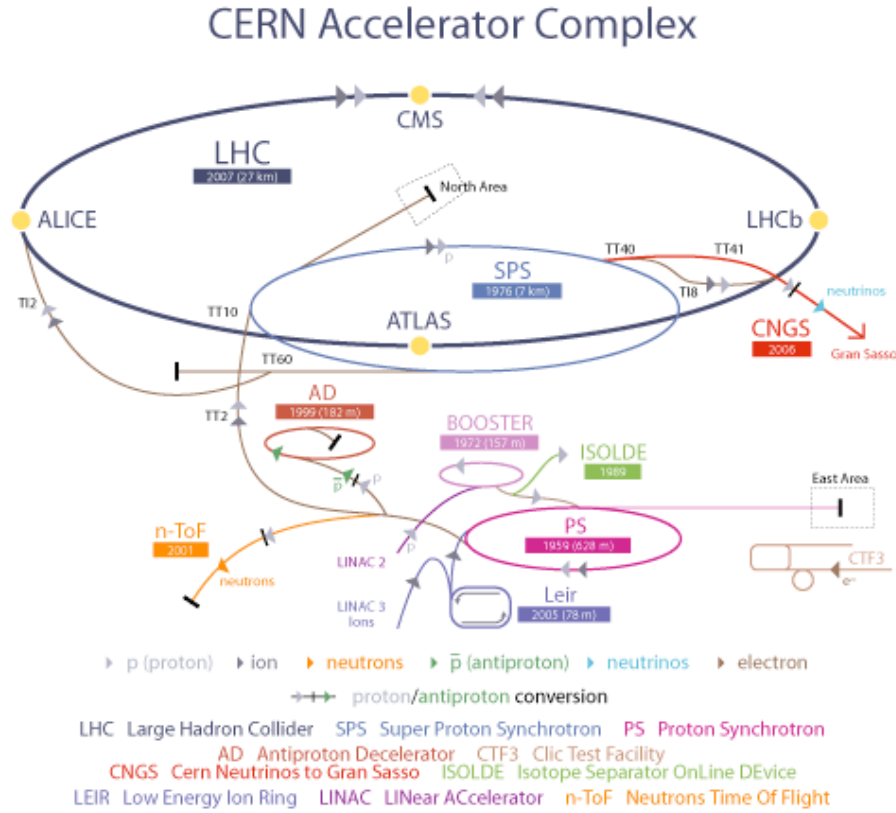


Figure 1.1: The CERN accelerator complex, comprising the LINAC 2, the BOOSTER, the PS, the SPS and finally the LHC, used to reach energies per beam of 7 TeV [8].

The LHC has been designed to reach an energy per beam of 7 TeV, which is limited by the magnetic field in the super-conducting dipole magnets. A magnetic field of 8.34 T is chosen to bend the 7 TeV bunches given the radius of the LHC tunnel. With such a magnetic field, the dipole magnets deflect the beam by 0.6 mm per meter. They are cooled down at 1.9 K ($-271.3\text{ }^{\circ}\text{C}$) using super-fluid Helium.

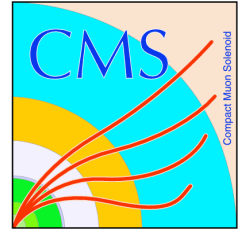
In a LHC nominal beam, 3564 RF buckets are equally spaced by 7.5 m along the circumference of 27 km. The corresponding LHC frequency is 40.079 MHz, with a 24.95 ns time spacing between two consecutive buckets. Of these, 2808 are filled with $1.1 \cdot 10^{11}$ protons, which are called *proton bunches*. The others are empty, which allow to dump the beams on beam stoppers.

The LHC started to deliver proton-proton collisions on November 23rd 2009 at the injection energy of 450 GeV. Not more than one week later, it became the most powerful collider in the world by reaching beam energies of 1.18 TeV; the previous record being held by the Tevatron at 0.98 TeV. Collisions at 2.36 TeV were registered mid-December 2009. After the winter shutdown, the LHC broke a new record on March 19th 2010 by raising the beam energy to 3.5 TeV, before the first collisions of two beams at this energy were recorded on March 30th 2010.

1.2 The LHC Experiments

Seven experiments are located around the LHC machine (Figure 1.2), six of which are described below. The LHCb experiment [9] is detailed in Chapter 2.

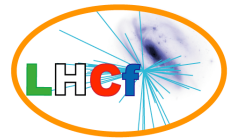
ATLAS [10] and CMS [11] are general-purpose experiments. They will look for direct creation of unknowns, which could arise as extra dimensions of space or microscopic black holes. They will investigate why the matter of the universe is dominated by an unknown type of matter, called *Dark Matter*. If it is made of new particles, ATLAS and CMS could discover them. The origin of mass will be studied by hunting for the Higgs boson, which is predicted by the SM to be responsible for it. They will search for new forces through the discovery of new force carrier particles (W or Z). ATLAS and CMS have similar barrel-shaped designs. ATLAS, located at Meyrin, is 45 m-long with a 25 m-diameter and weighs ~ 7000 tons. CMS, located at Cessy (France), is 21 m-long, with a 15 m-diameter and weighs 12,500 tons.



ALICE [12] is dedicated to the physics of strongly interacting matter at extreme energy densities, where the formation of quark-gluon plasma is expected. This new phase of matter probably existed just after the Big-Bang, when the universe was still extremely hot, in which the protons and neutrons would have formed. For this, the LHC accelerator will deliver heavy ion collisions. ALICE is at St Genis-Pouilly (France) and is 26 m-long, with a 16 m-diameter and a weight of 10,000 tons.



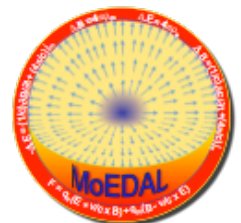
LHCf [13] aims at simulating cosmic rays from LHC collisions by detecting particles produced at the extremely forward direction. This will help in calibrating the huge detectors dedicated to cosmic rays and interpreting their results. LHCf is composed of two 30 cm-long, 10 cm-wide and 80 cm-high detectors with a total weight of 80 kg. It is located close to ATLAS, at Meyrin.



TOTEM [14] goal is the determination of the size of the protons by measuring the elastic and total cross sections. This will also enable the precise evaluation of the LHC luminosity. For this, it detects particles produced close to the LHC beams. TOTEM is 440 m-long, 5 m-large and 5 m-high, with a weight of 20 tons. It is located close to CMS, at Cessy.



MoEDAL [15] is the latest experiment to date that has joined the LHC. It is dedicated to the direct search for the magnetic monopole and other highly ionizing (pseudo-) stable massive particles. MoEDAL is not yet fully installed in the LHCb cavern, where it is foreseen to cover the walls and ceiling of the cavern that house the vertex locator detector in Ferney-Voltaire (France).





20 **Figure 1.2:** The LHC collider, its injection chain (PS + SPS) and the major experiments located around it, ALICE, ATLAS, CMS and LHCb.



2

The Large Hadron Collider beauty Experiment

The *Large Hadron Collider beauty experiment (LHCb)* is one of the seven experiments hosted around the LHC at CERN. The experiment consists of a spectrometer located in France at the interaction point P8, 100 m underground (Figure 1.2). This is the place where the DELPHI experiment was located during the years of the collider prior to LHC, the LEP.

The LHCb experiment [16] is dedicated to precise measurements of CP violating processes and rare decays, mainly through the study of B mesons. These studies will help understand open questions in cosmology about the matter/antimatter asymmetry.

LHCb was approved in September 1998 as the last of the four big experiments at CERN (after ALICE, ATLAS and CMS). The magnet was the first part assembled and fully installed in the cavern, reaching its nominal magnetic field at the end of 2004. In summer 2005, the electromagnetic and hadronic calorimeter walls were erected, followed at the end of the year by the descent of the big Cherenkov detector assembled beforehand at the surface. In October 2007, the delicate installation of the vertex locator detector was completed. By summer 2008, all the LHCb spectrometer parts were installed in the cavern, except the first muon station, which was installed in the first half of 2009.



My thesis director (right) and LHCb spokesman celebrating the approval of the LHCb project.

The LHCb detector design is described in Section 2.1. Section 2.2 is dedicated to the beam pipe. The detection principle explained in Section 2.3 is an introduction to the tracking and particle identification systems. These are detailed in Sections 2.5 and 2.6 respectively, after the definition of the LHCb coordinate system in Section 2.4. Section 2.7 gives an overview of the LHCb triggering system and Section 2.8 of the LHCb software.

2.1 The Design of the LHCb Detector

In proton-proton collisions at the LHC high energies, two partons of the colliding protons interact at small distances with large momentum transfer during hard scattering processes. From this interaction, $b\bar{b}$ pairs are created through different processes explained in Subsection 7.3.1. The produced $b\bar{b}$ pairs are boosted along the beam direction, in the direction of the parton of higher momentum. The b and $\bar{b}$ hadrons originating from these $b\bar{b}$ pairs are hence predominantly produced at very small angles with respect to the beam axis, in the same forward or backward cone (Figure 2.1, left). As a consequence, the LHCb detector is designed as a forward spectrometer covering one of the two peaks (Figure 2.2).

The acceptance of the spectrometer in terms of the polar angle θ with respect to the beam line is 10–300 mrad in the horizontal plane and 10–250 mrad in the vertical plane. Equivalently, this acceptance covers pseudorapidities η of $2.0 < \eta < 5.3$, where $\eta = -\ln(\tan(\theta/2))$. This was optimized for the gain in the $b\bar{b}$ pair acceptance against the cost of the detector. The design of the spectrometer was also limited by the size of the existing cavern, leading to a 6 m-wide, 5 m-high and 20 m-long detector.

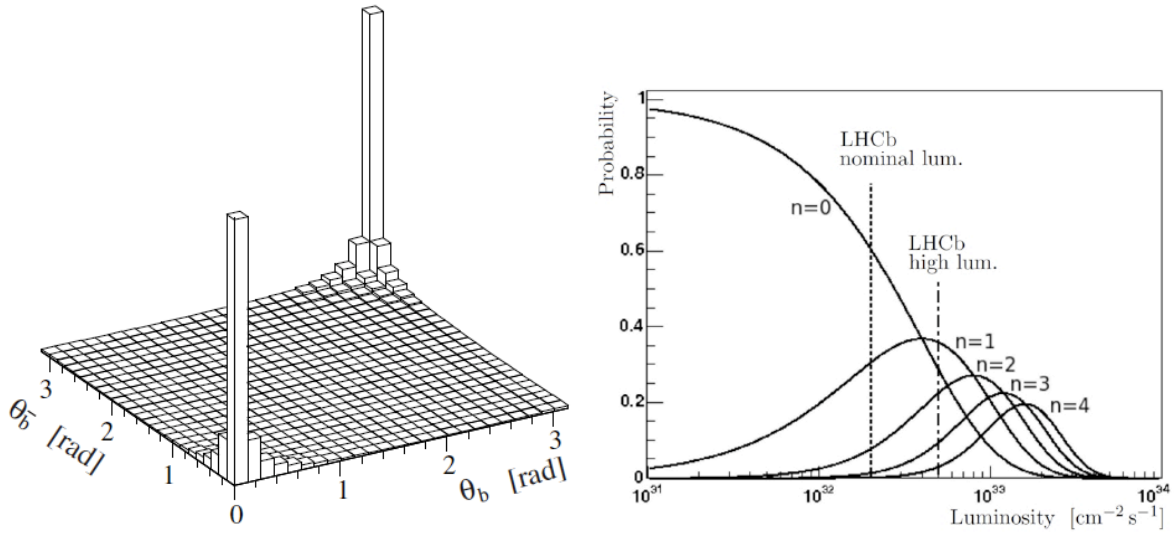


Figure 2.1: Correlation of the polar angles of the b and $\bar{b}$ hadrons produced in proton-proton collisions at $\sqrt{s} = 14$ TeV (PYTHIA) (left). Probability for having $n=0,1,2,3$ or 4 inelastic proton-proton interactions as a function of the luminosity $\mathcal{L}$ (right).

To perform precise measurements, the average number of inelastic proton-proton interactions per bunch crossing, $\langle n_{pp} \rangle$, has to be limited and should ideally equal one. This number is given by:

$$\langle n_{pp} \rangle = \frac{\mathcal{L} \cdot \sigma_{pp}^{\text{inel}}}{v_{bx}} \quad (2.1)$$

where $\mathcal{L}$ is the luminosity and $\sigma_{pp}^{\text{inel}}$ the inelastic cross-section. The parameter v_{bx} is the average crossing frequency. From the 2808 bunches filled with protons in a LHC beam, 2622 collide at the LHCb interaction point. This leads to an average non-empty bunch crossing frequency $v_{bx} = 29.49$ MHz.

To limit $\langle n_{pp} \rangle$ at LHCb, the luminosity is decreased from $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ used at ATLAS and CMS to $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ by defocusing the beams with the help of magnets. With this value of $\mathcal{L}$, collisions with one interaction happen in 30% of the bunch crossings (Figure 2.1, right).

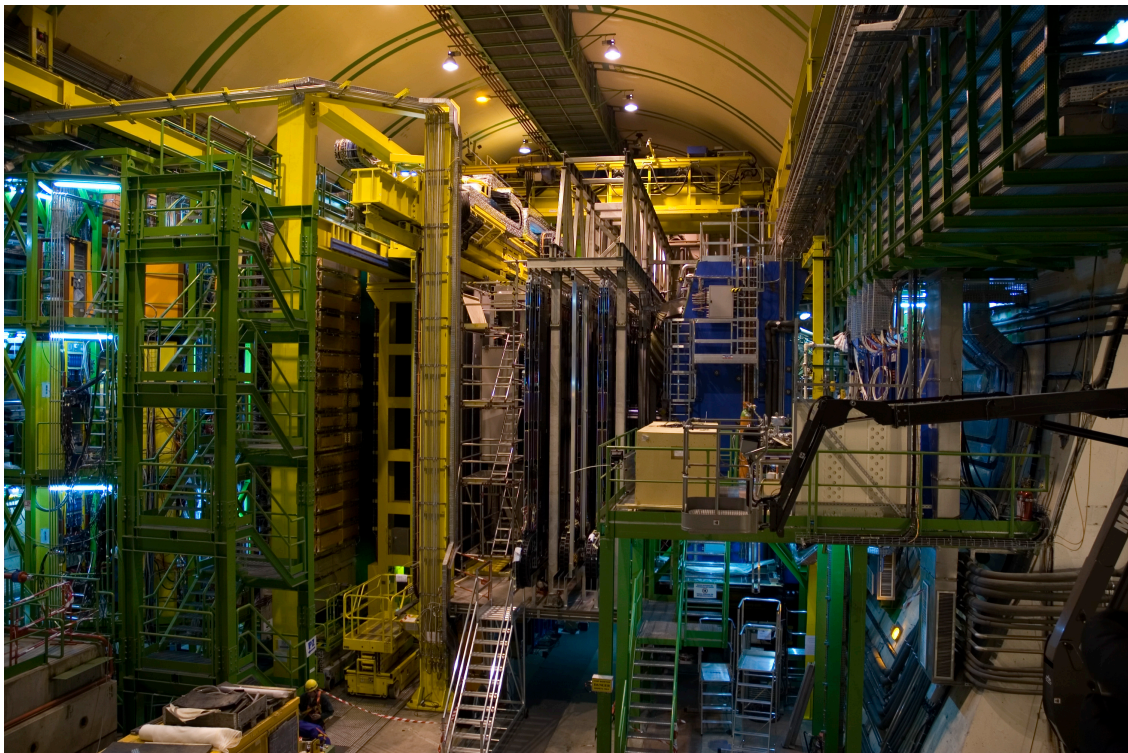
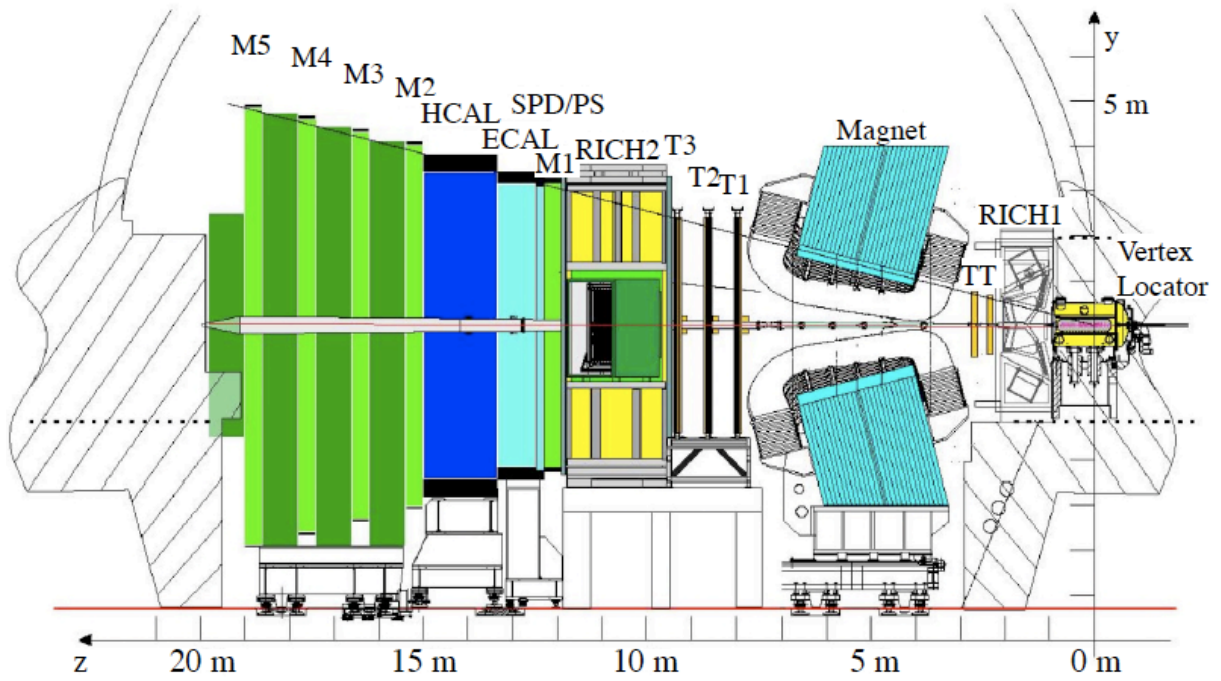


Figure 2.2: Schematic of the LHCb spectrometer (top) and corresponding view in the LHCb cavern (bottom).

2.2 The Beam Pipe

The 19 m-long beam pipe [17] traverses the center of all the detectors (Figure 2.3, left), except for the detector surrounding the interaction point, which is directly connected to it inside a vacuum vessel. Its forward window, covering the LHCb acceptance, is visible in Figure 2.3 (right).

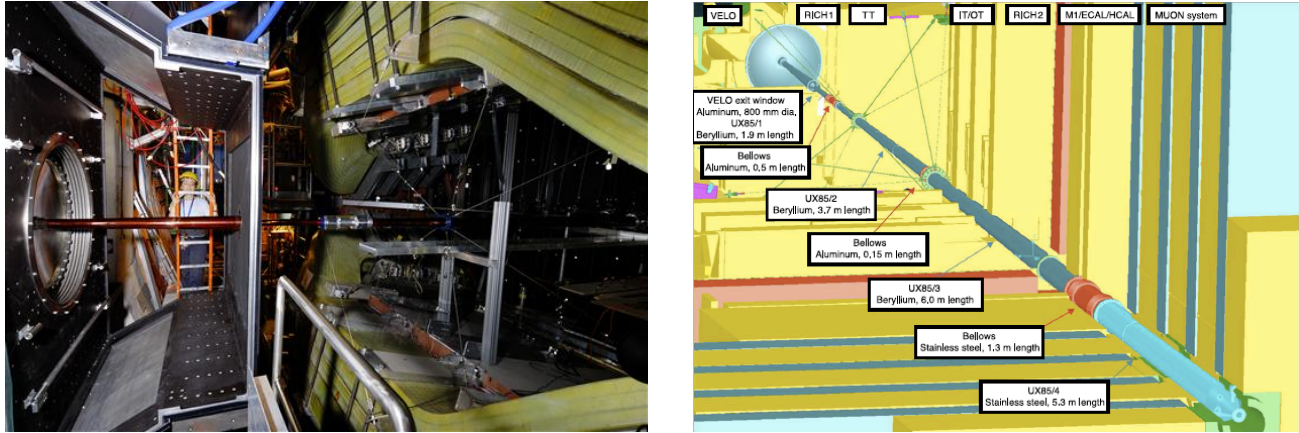


Figure 2.3: View of the beam pipe inside the first Cherenkov detector and at the entrance of the dipole magnet (left) and four-part structure of the beam pipe (right).

The beam pipe design is crucial for the LHCb experiment that is focused on the high rapidity region where the particle density is high. The number of secondary particles has to be limited as much as possible to reduce the occupancy in the tracking stations and in the Cherenkov detectors. These secondary particles are due to interactions of the proton-proton interaction primary particles with the beam pipe they encounter in their paths or the material of the detectors.

The choice of the material used for the four beam pipe conical sections (Figure 2.3, right) is hence of high importance. Beryllium (1 mm- to 2.4 mm-thick) is used for the first three sections (up to 12 m from the interaction point), since it is virtually transparent to the particles coming from the collisions. The conical parts are interconnected through aluminum bellows (Figure 2.3, right).

After the tracking system, stainless steel is used for the fourth conical section and for the bellows connecting it to the third section (Figure 2.3, right), as beryllium is expensive and toxic. Interactions with the material of this part of the beam pipe do not play a crucial role anymore, since particles are stopped in this region by the calorimeter system and the muon chambers.

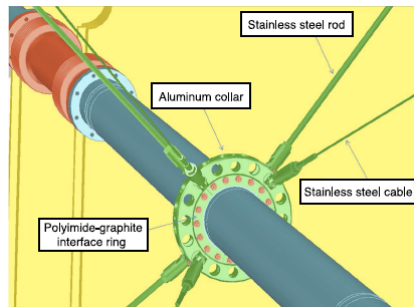


Figure 2.4: Beam pipe support system.

The support system of the beam pipe has also been designed with great care, as it is mostly inside the LHCb acceptance. It could be an important source of background. For instance, the beam pipe is supported in the middle of the dipole magnet by a polyimide-graphite ring surrounded by an aluminum collar. From it, eight stainless steel cables or rods are mounted under tension, pulling in both upstream and downstream directions (Figure 2.4).

2.3 The Detection Principle in a Nutshell

The B mesons of interest, due to their small mean lives $\tau \sim 1.5 \cdot 10^{-12}$ s [18], are reconstructed from their long-lived (grand-)daughter particles flying through the LHCb spectrometer. The detectable (grand-)daughter particles are usually electrons $e^\pm$, muons $\mu^\pm$, protons p, kaons $K^\pm$, charged pions $\pi^\pm$, as well as photons γ . Neutral pions π^0 are not directly detectable, since they decay instantaneously, most of the time into two photons. Neutrinos ν are not detectable.

It is essential to identify the daughter particles correctly and measure their momenta precisely to determine the flavor of the mother B meson and to distinguish between topologically similar decay modes. Due to their charged/neutral hadronic/leptonic nature, particles interact differently with matter (Figure 2.5). This explains why the LHCb spectrometer is composed of several detectors based on different technologies. Each of them brings information about the trajectory or the identification of the different particles, which is essential for subsequent physics analyses.

The detectors used for reconstructing the particle trajectories form together with the magnet what is called the *tracking system* of the experiment. The *particle identification system* includes electromagnetic and hadronic calorimeters, muon chambers and also devices based on the detection of Cherenkov light (not shown in Figure 2.5).

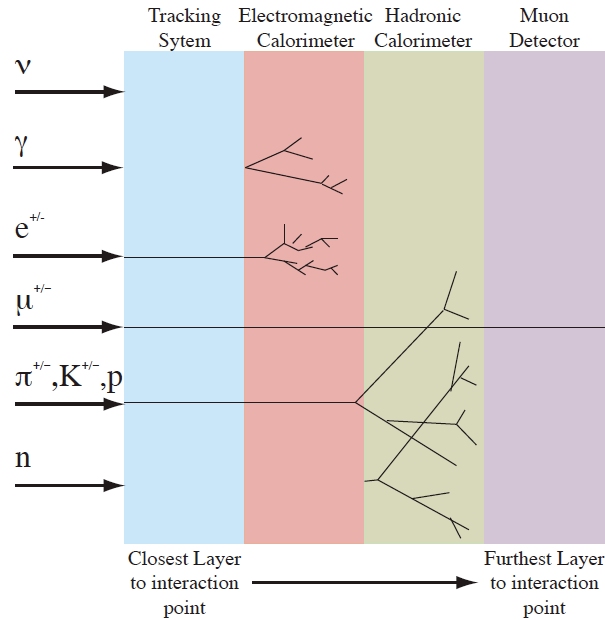


Figure 2.5: Interactions (black lines) of the detectable particles with different parts of the detector. The ν do not interact with matter. The γ give a signal in the electromagnetic calorimeter only. The $e^\pm$ are detected in the tracking system and in the electromagnetic calorimeter. The $\mu^\pm$ leave some information in all the detector parts. Due to their large matter penetration power, they need a dedicated device at the end of the spectrometer to detect them. The $\pi^\pm$, $K^\pm$ and p are observed in the tracking system, in the electromagnetic calorimeter and leave most of their energy in the hadronic calorimeter. The neutrons n leave information only in the hadronic calorimeter, as they are neutral hadrons. The π^0 are not depicted as they decay instantaneously into two γ >98% of the time. Their detection is therefore performed via the search for two γ in the electromagnetic calorimeter, given specific selection criteria.

2.4 The LHCb Coordinate System

The origin of the LHCb coordinate system is the interaction point. The z axis follows the beam line tilted by 3.601 mrad with respect to the LHCb cavern floor¹ in the direction of the LHCb spectrometer. Perpendicular to it, the y axis is defined as pointing towards the ceiling of the cavern, which is inclined by 3.601 mrad from the vertical. The x axis results from the right-handed Cartesian rule, pointing towards the side providing access to the LHCb experimental cavern, called *A-side* [19].

2.5 The Tracking System

The determination of the trajectory of charged particles is of fundamental importance. Hits identified as belonging to the same particle trajectory recorded by different detectors are connected, taking into account magnetic field effects. The track reconstruction at LHCb is explained in Section 6.1.

To illustrate the pieces of information that can be provided by the tracking system, let's assume a constant magnetic field B (T)². The tracking system allows the measurement of the radius of curvature r (m) of a charged particle trajectory, which is bent by the magnetic field. For a given magnetic field polarity, the electric charge q can be determined by the direction in which the particle trajectories are bent. The momentum p (GeV/ c) can then be calculated using:

$$p = 0.3 \cdot B \cdot r \quad (2.2)$$

The flight distance f_d between the interaction point where the B mesons are produced, called *Primary Vertex (PV)*, and the position where the B mesons decay, called *Secondary or Decay Vertex (SV)*, is also determined. Knowing p , the lifetime τ of the B mesons can be deduced, with c the speed of light:

$$\tau = \frac{f_d}{c} \frac{m}{p} \quad (2.3)$$

The tracking system represents the first layers of the LHCb spectrometer to limit as much as possible multiple scattering occurring when the particles pass through matter. For the same reason, the detectors composing the tracking system are by design made of light and low-interacting materials.

The tracking system uses (Figure 2.2):

- The VERtex LOCator (Subsection 2.5.1).
- The Tracker TURicensis (Subsection 2.5.2).
- The Dipole Magnet (Subsection 2.5.3).
- The Tracking Stations T1-T3, also named *T-stations*, use two detectors: The Inner Tracker (Subsection 2.5.4) covers the innermost area and around it is the Outer Tracker (Subsection 2.5.5).

¹The detectors located upstream the magnet (included) follow the beam line, the ones downstream are vertical.

²At LHCb, the magnetic field is not homogeneous. Hence, the calculation of the momentum is performed using a Runge-Kutta 5th-order method to propagate the tracks through the magnetic field.

2.5.1 The Vertex Locator

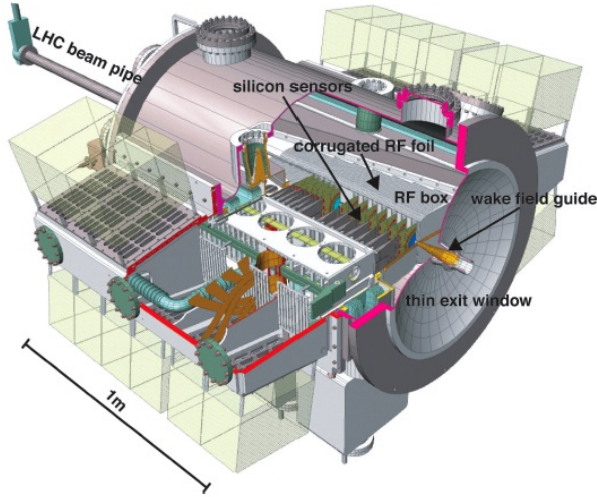


Figure 2.6: Schematic of the VELO detector.

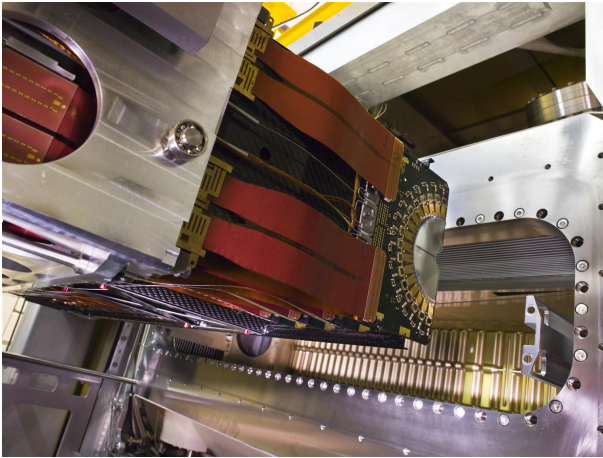


Figure 2.7: VELO half with its half-disk sensors.

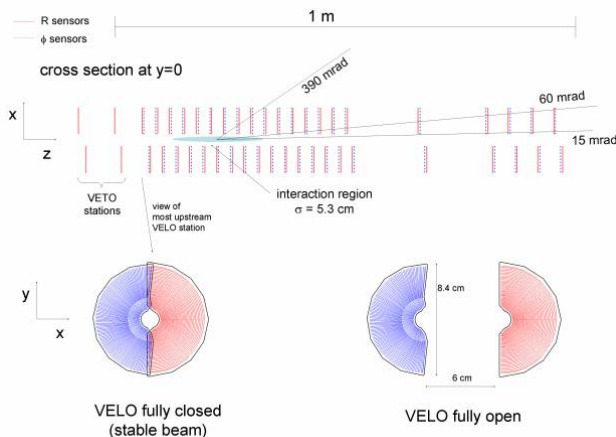


Figure 2.8: Position of the 21 stations along z .

The *Vertex Locator (VELO)* (Figure 2.6) [20, 17] is used to reconstruct primary and secondary vertices from tracks going in the forward or backward directions. Straight track segments reconstructed in the VELO from charged particle trajectories are matched to hits recorded in the tracking stations during track reconstruction (Section 6.1). Two special modules of the VELO, the so-called *Pile-Up detector*, participate in the first level of trigger (Section 2.7).

The VELO is located around the region where the proton-proton collisions occur, from $z = -50$ cm to $z = 100$ cm, and covers the full LHCb acceptance. It uses a single-sided n^+ -on- n silicon strip sensor technology, with the exception of one module manufactured in n^+ -on- p . The sensors are located inside a vacuum vessel (Figure 2.6), which is separated from the machine vacuum by an aluminum foil. This foil is made as thin as possible, and corrugated, to limit the amount of material crossed by charged particles before they traverse the sensors. The foil also preserves the LHC vacuum, shields the VELO electronics against the radio-frequency pickup from proton bunches and guides the beam wake-fields.

The VELO is divided into two halves that can be retracted by 3 cm, as a bigger aperture is needed during beam injection (Figure 2.7). In each half, 21 half-stations of sensors are spread along the beam line (Figure 2.8), with two additional upstream sensors used for the detection of pile-up events. In closed position, the half-stations are staggered in z by gaps of 1.5 cm, to provide overlapping regions between the sensors placed in both VELO halves (Figure 2.9).

Two types of half-disk sensors, r - and ϕ -sensors, are placed back-to-back. In data taking position, the first silicon strips are at 8 mm from the beam and the silicon edges at 7 mm.

The r-sensors contain 512 circular strips centered around the beam axis that measure the radial coordinate r (Figure 2.10). To lower the occupancy and strip capacitance, the strips are divided into four regions of 45° inside the half-disk. The distance between the nominal beam axis and the closest strip is 8.2 mm, the last strip being at 41.9 mm. Between these two extremes, the strip pitch varies linearly from $\sim 38 \mu\text{m}$ to $\sim 102 \mu\text{m}$.

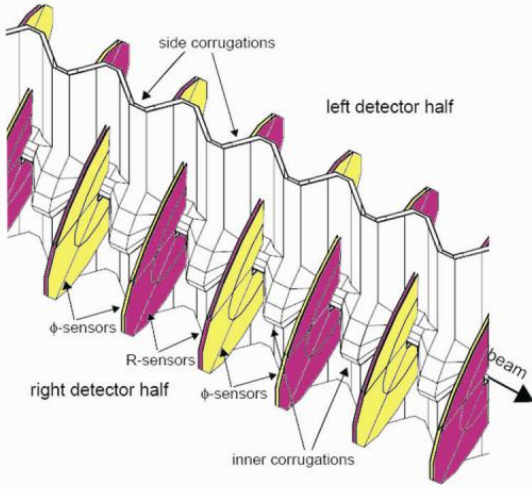


Figure 2.9: Staggering in z of the two VELO halves.

The ϕ -sensors have radial strips which determine the azimuthal coordinate ϕ (Figure 2.10). The strips are divided into two regions, the inner ones with radii ranging from 8 mm to 17.25 mm and the outer ones with radii from 17.25 mm to 41.9 mm. The 683 strips of the inner region make an angle of $\pm 20^\circ$ with respect to the radial direction. They have pitches between $35.5 \mu\text{m}$ and $78.3 \mu\text{m}$. The 1365 strips of the outer region make an angle of $\pm 10^\circ$. They have pitches between $39.3 \mu\text{m}$ and $97 \mu\text{m}$. Inside the VELO, two consecutive ϕ -sensors have opposite skew orientation.

The VELO technical specifications are summarized in Table 2.1.

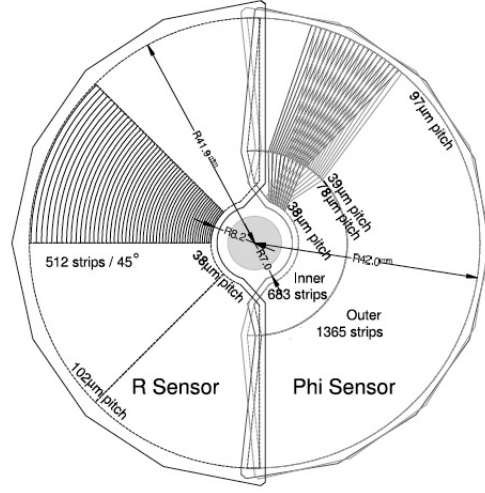


Figure 2.10: Two VELO half-disk sensors in closed position. For the ϕ -sensor, the strips on two adjacent modules are drawn, which allow stereoscopic reconstruction.

Depending on the strip pitch and track angle, the hit resolution varies between 4 and $25 \mu\text{m}$. The vertex reconstruction resolution is expected to be $\sigma(x, y, z) = (12, 11, 57) \mu\text{m}$ by design in the offline environment.

Table 2.1: VERteX LOcator technical specifications.

Properties	Vertex Locator
Geometry and Location	
Location	$z = [-50, 100] \text{ cm}$
Diameter	$\sim 1 \text{ m}$ (full LHCb acceptance)
Active area	$\sim 0.27 \text{ m}^2$
Cooling system [21]	
Coolant	evaporative CO_2
Cooling Temperature	-25°C
Silicon technology	
Technology	n^+ -on-n
Strip Pitch	from ~ 40 to $\sim 100 \mu\text{m}$
Silicon Thickness	$300 \mu\text{m}$
Sensor Radius	from 8.2 to 42 mm
Stereo Angle (ϕ -sensors)	from 10 to 20°
Number of Sensors	84 (+4 for Pile-Up)
Readout	
Readout Channels/Sensor	2048
Total Readout Channels	172,032
Signal Shaping Time	25 ns
Readout Chip Technology	$0.25 \mu\text{m}$ CMOS

2.5.2 The Tracker Turicensis

Apart from providing additional information to tracks recorded in the VELO that traverse also the tracking stations, the *Tracker Turicensis* (TT) (Figure 2.11) [22, 17] is used in the following two cases. Firstly, it allows the reconstruction of the trajectory of low momentum particles which, bent out of the detector acceptance by the magnetic field, never reach the tracking stations. Secondly, trajectories of long-lived neutral particles decaying outside of the VELO, such as K_s^0 , also benefit from TT information.

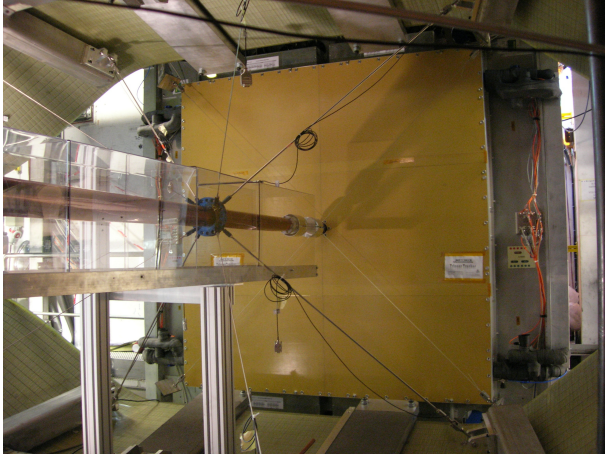


Figure 2.11: TTb station from the magnet region.

The TT is located in the upstream region between the RICH1 and the entrance of the magnet, at $z \sim 2.5$ m, covering the full LHCb acceptance. It uses a single-sided p^+ -on-n silicon strip sensor technology.

TT consists of four detection layers (Figure 2.12) grouped in two stations, TTa and TTb, with two layers each. The two stations are separated by 27 cm. The first and fourth layers have vertical detection strips, while the second and third layers have strips rotated by stereo angles of $\pm 5^\circ$ to allow spatial reconstruction.

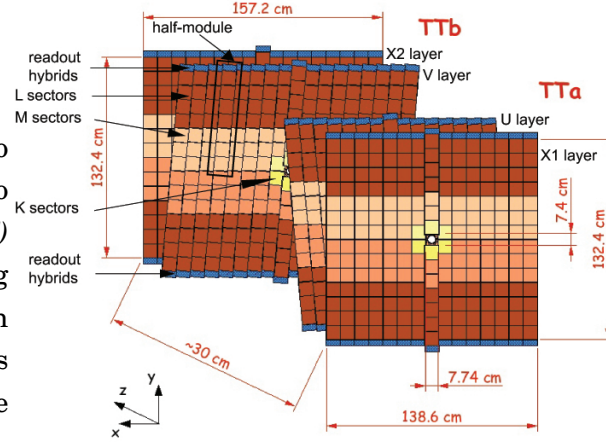


Figure 2.12: The four TT detection layers.

Seven silicon sensors are fixed on each module, for a total of 128 modules. The sensors are grouped into two or three readout sectors depending on proximity to the beam pipe.

The TT has a design spatial resolution $\sim 50 \mu\text{m}$ with a maximal strip occupancy of a few percents. Its technical specifications are given in Table 2.2.

Table 2.2: Tracker Turicensis technical specifications.

Properties	Tracker Turicensis
Geometry and Location	
Location of the Stations	TTa: $z = [233.2, 236.8]$ cm TTb: $z = [260.2, 263.8]$ cm
Station Size	150 cm-wide, 130 cm-high (full LHCb acceptance)
Active area	8.4 m ²
Cooling system [21]	
Coolant	C ₆ F ₁₄
Cooling Temperature	-15°C
Silicon technology	
Technology	p^+ -on-n
Strip Pitch	183 μm
Strip Implant Width	46 μm
Silicon Thickness	500 μm
Sensor Dimensions	94.4 mm $\times$ 96.4 mm
Number of Modules	128 with 7 sensors each
Readout	
Readout Channels/Sensor	512
Total Readout Channels	143,360
Signal Shaping Time	25 ns
Readout Chip Technology	0.25 μm CMOS

2.5.3 The Dipole Magnet

The *dipole magnet* is described in Section 5.1.

2.5.4 The Inner Tracker

The *Inner Tracker (IT)* is detailed in Chapter 3.

2.5.5 The Outer Tracker



Figure 2.13: View of OT modules.

The *Outer Tracker (OT)* (Figure 2.13) [23, 17] is used to reconstruct the trajectory of charged particles. Their momenta are measured from the curvature of their trajectories in the magnetic field.

The OT uses straw tubes filled with a gas mixture containing 70% Ar, 28.5% CO₂ and 1.5% O₂. This technology choice was driven by the low cost, the large area to be covered ($\sim 29 \text{ m}^2$ per station) and the need for a good spatial resolution.

The layout of the OT is similar to that of the Inner Tracker explained in Chapter 3. Each of the three stations illustrated in Figure 2.14 contains four detection layers. The first and fourth layers have vertical detection modules and the second and third layers modules rotated by stereo angles

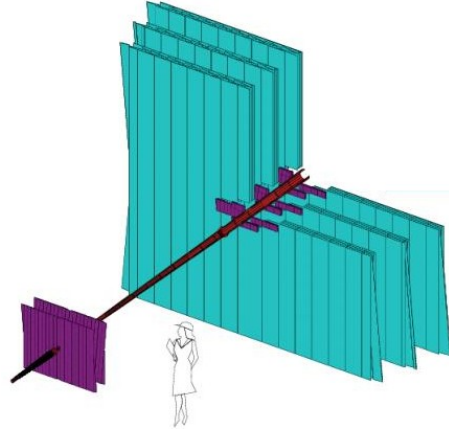


Figure 2.14: The three OT stations (blue). of $\pm 5^\circ$. The modules are composed of two staggered layers of 64 drift tubes each with inner diameters of 4.9 mm.

The OT design occupancy is $\sim 5\%$ on average, going up to a maximum of 10% at nominal luminosity. The gas mixture chosen allows for a maximum drift time of $\sim 40 \text{ ns}$, within the time of two LHC bunch crossings ($2 \cdot 25 \text{ ns}$), while manufacturing a good intrinsic position resolution of $\sim 190 \mu\text{m}$. The OT technical specifications are summarized in Table 2.3.

Table 2.3: Outer Tracker technical specifications.

Properties	Outer Tracker
Geometry and Location	
Location of the Stations	OT1: $z = [783.8, 803.8] \text{ cm}$ OT2: $z = [852.5, 872.5] \text{ cm}$ OT3: $z = [921.5, 941.5] \text{ cm}$
Station Size	$\sim 29 \text{ m}^2$ (full acceptance)
Active area per station	$5.97 \times 4.85 \text{ m}^2$
Cooling system [21]	
Coolant	demineralised water
Cooling Temperature	19°C (in) / 21°C (out)
Drift-time technology	
Gas Mixture	70% Ar, 28.5% CO ₂ , 1.5% O ₂
Drift Time	$< 50 \text{ ns}$
Tubes Inner Diameter	4.9 mm
Readout	
Total Readout Channels	55,000
Signal Shaping Time	25 ns
Readout Chip Technology	$0.25 \mu\text{m}$ CMOS

2.6 The Particle Identification System

All the detectable particles ($e^\pm$, $\mu^\pm$, p , $K^\pm$, $\pi^\pm$ and γ) need to be disentangled from one another. For this, the calorimetry system is used to distinguish electrons, photons and hadrons by recording their electromagnetic or hadronic showers. To distinguish hadrons with similar signatures in the hadronic calorimeter, devices based on the detection of Cherenkov light rings are employed.

To detect muons that do not interact much with the material of the calorimeters, dedicated stations are placed at the end of the LHCb spectrometer. Neutrinos interact with matter only very weakly. The only way to measure them is to have the interaction point totally surrounded by detector parts, such as for the ATLAS or CMS detectors at CERN, and measure the missing transverse energy E_T . As such measurements are not part of the LHCb physics program, LHCb does not need to fulfill this coverage requirement.

Electromagnetic and Hadronic Showers

When high-energy particles interact with dense matter, they create cascades of secondary particles, called *showers* [24]. By interacting, the incoming particle produces multiple new particles with lesser energy, which at their turn interact to create other particles, and so on. Two types of showers exist, *electromagnetic* and *hadronic* showers, which are detected in the *Electromagnetic CALorimeter (ECAL)* and the *Hadronic CALorimeter (HCAL)* respectively (Figure 2.5).

Electromagnetic showers are produced by a particle interacting via the electromagnetic force, usually an electron or photon. At energies above a few MeV, electrons and positrons primarily emit photons, a process called *Bremsstrahlung*, while photons interact with matter predominantly via e^+e^- *pair production*. The shower stops when the remaining particles have energies low enough to stop further multiplication. From this point, the shower decays slowly through *ionization* losses for electrons or by *Compton scattering* for photons. This change is characterized by the critical energy E_c in the absorber material. For an incoming particle of energy E_0 , the *average shower depth* X equals:

$$X \sim X_0 \ln(E_0/E_c) \quad (2.4)$$

where X_0 is the *radiation length* of the material.

Hadronic showers are produced by hadrons and proceed mostly via the strong nuclear force. The process is dominated by a succession of inelastic hadronic interactions. At high energy, multiple particles are produced or emitted from nuclear decays of excited nuclei. Due to the large amount of π^0 created, hadronic showers also possess an electromagnetic component. They can be parameterized by a nuclear *interaction length*, which is equivalent to the radiation length for electromagnetic showers. However, nuclear interaction lengths in the detector material are typically much larger than interaction lengths. Therefore larger amounts of absorber are required to stop the hadronic showers.

The detection of different types of particles is explained in the following.

Neutral pions are detected through their decay products, which are two γ more than 98% of the time, due to their very short mean life, $\tau \sim 8.4 \cdot 10^{-17}$ s [18]. In the ECAL, two neutral clusters or only one are searched for [25]. Neutral clusters are selected by extrapolating all reconstructed tracks of the event to the calorimeter and observe that no matching is possible between the clusters and the tracks. Neutral pions reconstructed from two neutral clusters are called *resolved* π^0 . If the two clusters are merged, only one cluster is effectively observed in the ECAL. In this case, the cluster is divided into two sub-clusters. Each of the two sub-clusters is reconstructed as a single photon hypothesis cluster, from which a π^0 is reconstructed. Criteria based on the π^0 energy, the neutral origin of the cluster and a mass window are applied to select the neutral pions, which are in this case called *merged* π^0 .

Photon clusters in the ECAL must not be associated with any tracks of the event reconstructed by the tracking system.

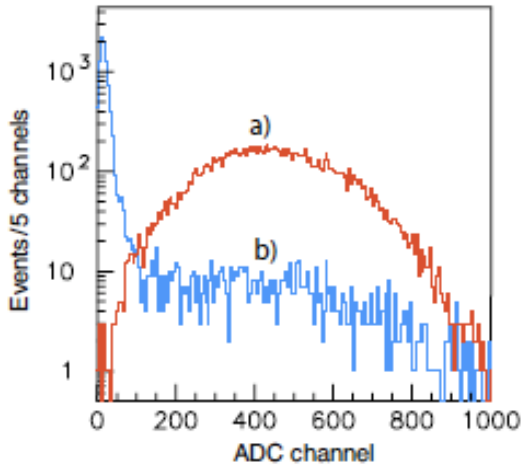


Figure 2.15: Energy deposition of 50 GeV $e^\pm$ a) and $\pi^\pm$ b) in the Pre-Shower.

Two layers placed in front of the ECAL, the Scintillating Pad Detector and the Pre-Shower, bring additional information to separate different particles with close signatures in the ECAL calorimeter.

As an example, electrons are distinguished from photons using the Scintillating Pad Detector information, where only charged particles leave a signal through ionization.

Charged pions are distinguished from electrons using the PS information, where electrons produce showers while pions do not. This is illustrated in Figure 2.15 showing the energy depositions of 50 GeV electrons a) and charged pions b) in the Pre-Shower.

Cherenkov Effect

When a dielectric medium is locally polarized by the passage of a charged particle, it emits photons when it returns to equilibrium. This polarization is symmetric as long as the speed v of the particle is smaller than the speed of light c/n in the medium of refractive index n (Figure 2.16, left). In this case, the emitted photons interfere destructively with each other. If the particle speed v is bigger than the speed of light in that medium, the emitted photons interfere coherently and form a wavefront at a fixed angle θ_C with respect to the charged particle direction, resulting in a cone of light emission (Figure 2.16, right) [26].



Figure 2.16: Medium polarization for $v < c/n$ (left) and $v > c/n$ (right) [26].

By measuring the angle θ_C , the speed v of the charged particle is deduced using Equation 2.5. Knowing the momentum, its mass can then be determined, allowing for particle identification. The choice of the medium, called *radiator*, depends on the required momentum range for the particle identification. A smaller refractive index n is used to cover larger momenta values.

$$\cos(\theta_C) = \frac{1}{n\beta} \quad \text{with} \quad \beta = \frac{v}{c} \quad (2.5)$$

Charged pions, kaons and protons have the same types of signature in the tracking system and the hadronic calorimeter. To distinguish them, their masses are calculated. The mass is given as a function of the momentum p as $m = p/(\gamma v)$ with $\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$ the Lorentz factor. The speed v is determined by the emission of Cherenkov light in RICH1 or RICH2 and the momentum is measured by the tracking stations.

The detectors of the LHCb spectrometer contributing to particle identification are:

- The Ring-Imaging Cherenkov Detectors (Subsection 2.6.1)
- The Calorimeter System (Subsection 2.6.2)
- The Muon Chambers (Subsection 2.6.3)

2.6.1 The Ring-Imaging Cherenkov Detectors

Two *Ring-Imaging Cherenkov* detectors (*RICH1* and *RICH2*) [27, 17] are used to discriminate between decay channels with equal topology, such as in $B_q \rightarrow hh$ (h =pions, kaons, protons). A good π -K separation is also required for flavor tagging.

RICH1 is located just behind the VELO at $z = [99, 216.5]$ cm. RICH2 is placed after the last tracking station at $z = [950, 1183.2]$ cm. As shown in Figure 2.17, the Cherenkov light is focused using a combination of spherical and flat mirrors (top) and is projected as a ring image (bottom) onto a plane of pixel *Hybrid Photon Detectors* (HPDs) located outside of the LHCb acceptance (Figure 2.18). The opening angle θ_C is deduced from the ring radius.

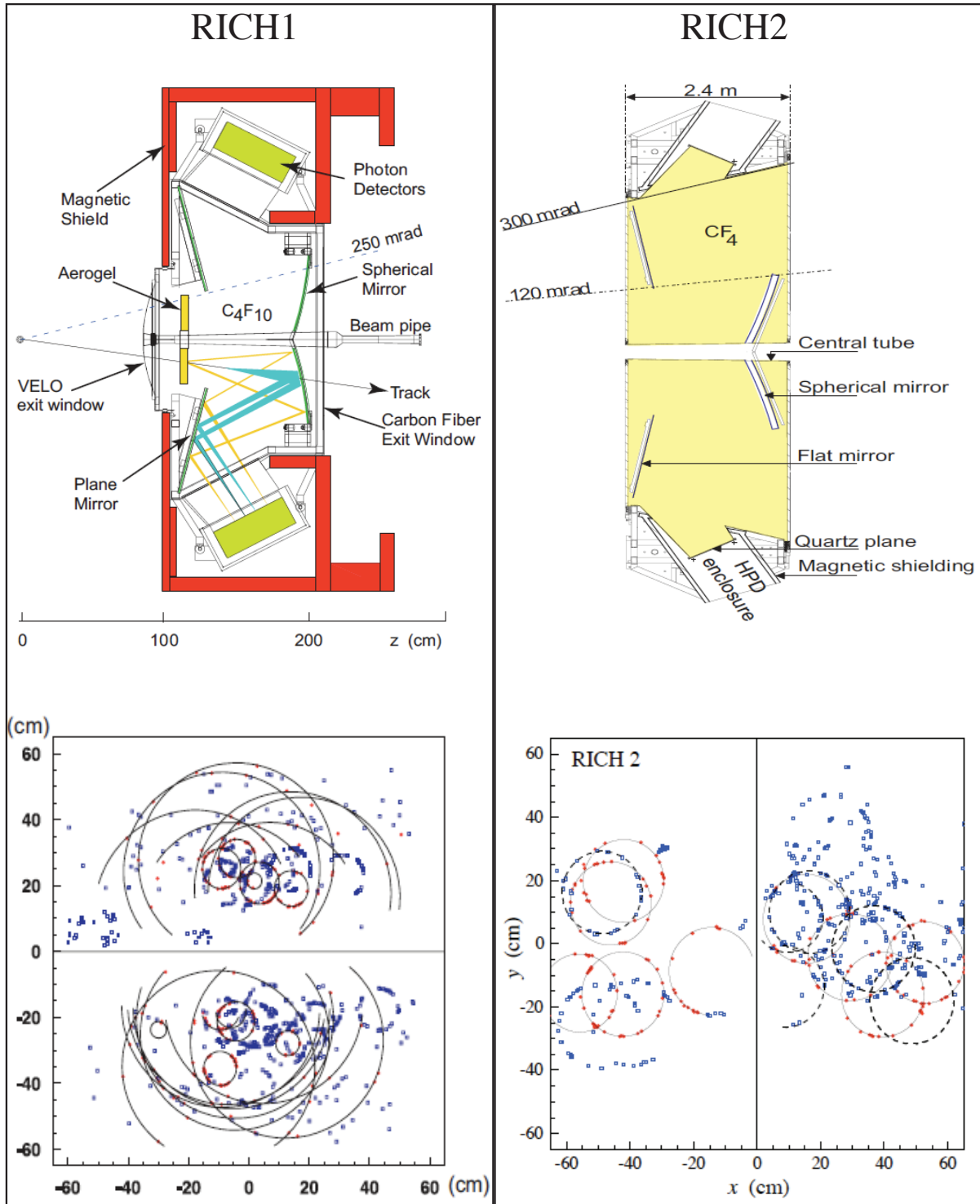


Figure 2.17: RICH1 (left) and RICH2 (right) detection principles (top) and typical simulated events (bottom).

The HPDs (Figure 2.18) contain 1204 pixels each, corresponding to a granularity of $2.5 \times 2.5 \text{ mm}^2$, with a time resolution of 25 ns. As the HPD performance is degraded by the magnetic field, they are shielded from the fringe field of the dipole magnet using iron plates. The design of the shields was optimized to reduce the magnetic field as much as possible in the HPDs, while not degrading it elsewhere in the LHCb acceptance, especially in the VELO and TT for the RICH1 case.

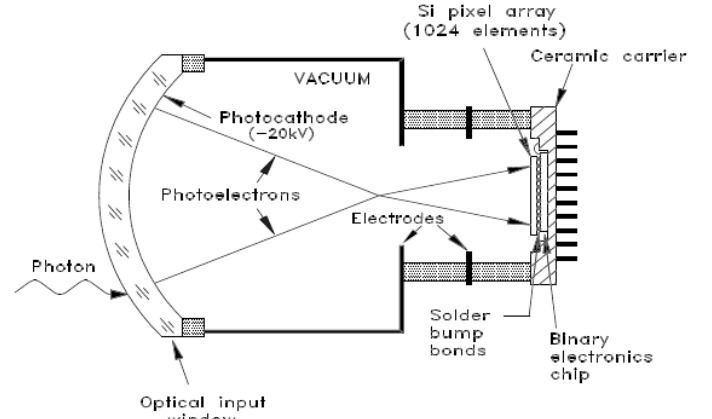


Figure 2.18: Detection principle of a pixel HPD.

RICH1 uses two radiators, the silicon aerogel ($n = 1.03$) for the identification of low momentum particles up to $10 \text{ GeV}/c$ and C_4F_{10} ($n = 1.0014$) for momenta between 10 and $60 \text{ GeV}/c$. It covers the whole LHCb acceptance. RICH2 uses CF_4 ($n = 1.0005$) for high momentum particles from 15 to $100 \text{ GeV}/c$, hence covering only a limited angular acceptance where high momentum particles are produced ($\pm 15 - 120 \text{ mrad}$ horizontally, $\pm 100 \text{ mrad}$ vertically). The design separation power of the different radiators is depicted in Figure 2.19.

The resolution expected on θ_C receives four different contributions. First, it depends on the assumption made about the photon emission point, $\sigma_\theta^{\text{emission}}$. Another source of imperfect resolution is the chromatic dispersion in the refractive index of the radiator, $\sigma_\theta^{\text{chromatic}}$. The finite pixel size and the point spread function of the HPDs gives also a contribution, $\sigma_\theta^{\text{HPD}}$. Finally, an additional uncertainty comes from the reconstruction of the track direction, $\sigma_\theta^{\text{track}}$.

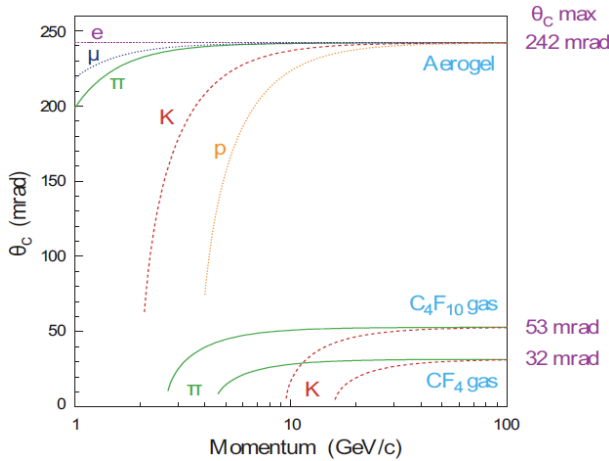


Figure 2.19: θ_C versus momentum for the three RICH radiators and associated particles that can be distinguished.

The different contributions are given in Table 2.4 for the three radiators. The resolution expected on θ_C is 2.6 mrad for the aerogel, which is dominated by chromatic dispersion. It is 1.5 mrad and 0.7 mrad for the C_4F_{10} and CF_4 radiators respectively.

Table 2.4: Different contributions to the single design resolution $\sigma_\theta^{\text{total}}$ for the three RICH radiators. The numbers are given in mrad.

	Aerogel	C_4F_{10}	CF_4
$\sigma_\theta^{\text{emission}}$	0.4	0.8	0.2
$\sigma_\theta^{\text{chromatic}}$	2.1	0.9	0.5
$\sigma_\theta^{\text{HPD}}$	0.5	0.6	0.2
$\sigma_\theta^{\text{track}}$	0.4	0.4	0.4
$\sigma_\theta^{\text{total}}$	2.6	1.5	0.7

2.6.2 The Calorimeter System

The calorimetry system [28, 17] is used to distinguish electrons, photons and hadrons by measuring their energies and positions. The reconstruction of neutral particles, such as photons and pions, is also important for the LHCb physics program. Moreover, the calorimeter system provides information about the transverse energy of hadron, electron and photon candidates to the first-level trigger.

The calorimetry system consists of four detector parts, the *Scintillating Pad Detector (SPD)*, the *Pre-Shower (PS)*, the *Electromagnetic CALorimeter (ECAL)* and the *Hadronic CALorimeter (HCAL)*. The whole system is located between the first muon station M1 and the second one M2. They absorb almost all the particles, except for the weakly interacting muons, which will be detected in the downward muon stations, and neutrinos that escape detection.

The four parts of the calorimeter system are based on the same detection technology. High energy particles going through the calorimeter system will interact with different parts depending on their nature and charge. These interactions generate in scintillating plates photons that are collected using *WaveLength-Shifting fibers (WLS)* and transmitted to multi-anode *PhotoMultiplier Tubes (PMT)* located at the periphery of the detector.

The Scintillating Pad Detector

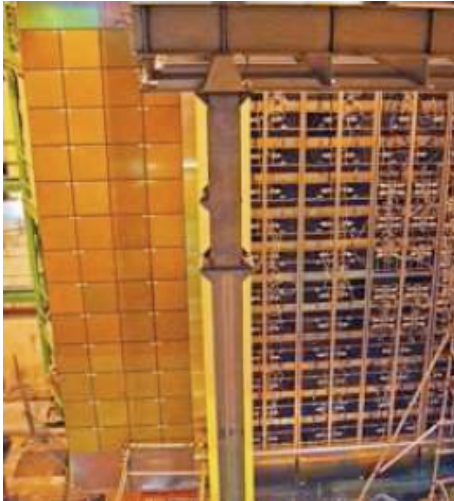


Figure 2.20: SPD/PS system.

The SPD (Figure 2.20) is used to distinguish charged particles from neutral ones. In the trigger, it is used to reject high- E_T π^0 background. It is located just after M1 and is made of 6000 15 mm-thick squared scintillator pads (Figure 2.21), in which four turns of WLS fiber are inserted in a centered round groove. Both ends of the fiber are used to transmit the light to the PMTs via clear fibers.

The main background of the SPD comes from photons that have converted into pairs before the SPD. Consequently, they are identified as charged particles.

The Pre-Shower

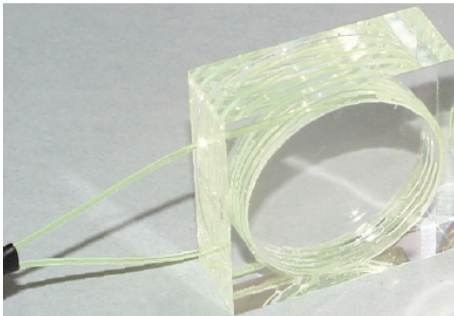


Figure 2.21: SPD/PS scintillator pad.

A 12 mm-thick layer of lead separates the SPD from the PS (Figure 2.20). A signal in the PS indicates the electromagnetic character of charged or neutral particles. For instance, electrons can be distinguished from charged pions, as illustrated in Figure 2.15. The PS is composed of 6000 scintillators similar to the ones used for the SPD (Figure 2.21). For particle momenta from 10 to 50 GeV/c, the pion rejection factor is $\sim 99.6\%$.

The Electromagnetic and Hadronic Calorimeters

The ECAL is used to detect electrons and photons and measure their transverse energy E_T in the first-level trigger. For an optimal E_T resolution, it is important that the showers are entirely contained in the ECAL volume, which corresponds to a depth of $25 X_0$ [29].

The ECAL (Figure 2.22, left) is located between the PS and the hadron calorimeter. It employs a Shashlik technology and consists of 3312 modules of alternating 4 mm-thick scintillating tiles with 2 mm-thick lead absorber slices (Figure 2.22, right). The scintillating photons result from electromagnetic showers created in the lead absorber by the passage of electromagnetic particles ($e^\pm, \gamma$). As particle density variations depend on the distance to the beam pipe, three types of modules are used, containing 3×3 , 2×2 or 1 readout cells for the inner, middle and outer modules (Figure 2.22, right). The size of the cells is the same for the SPD, PS and ECAL, allowing for a combined use in $e^\pm/\gamma$ separation.

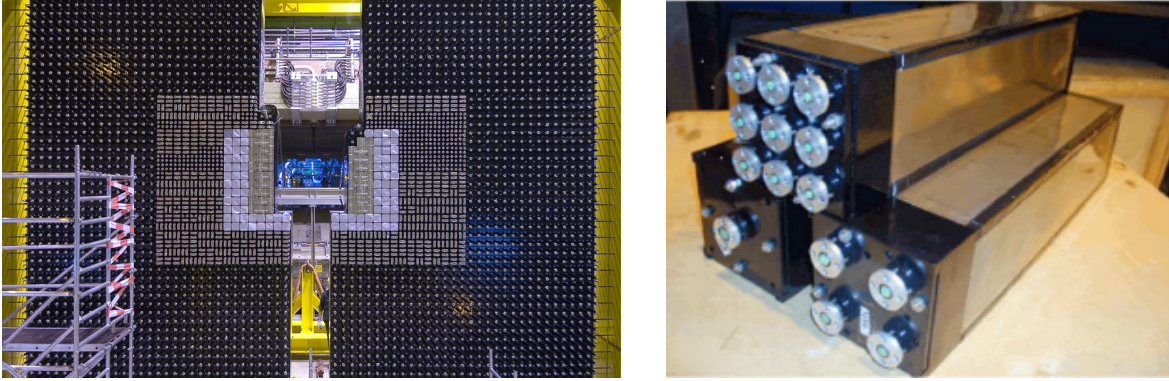


Figure 2.22: Electromagnetic calorimeter (left) composed by three different readout cells (right).

Just after the ECAL is the HCAL, which detects hadrons and estimates their energy. It consists of 6 mm-thick and 1232 mm-long master iron plates, which are interlaced by six 4 mm-thick spacer iron plates (Figure 2.23). The scintillator tiles are placed between the absorbers. This structure is repeated 208 times in each module. A special characteristic of the sampling structure is that the scintillating tiles are parallel to the beam axis. Along the beam axis, it represents six 202 mm-long rows with interchanging order of spacers and scintillator tiles. As the lateral extension is wider for hadronic showers than for electromagnetic ones, larger cells are used. The scintillating photons are produced in showers created in the iron absorber by hadron particles.

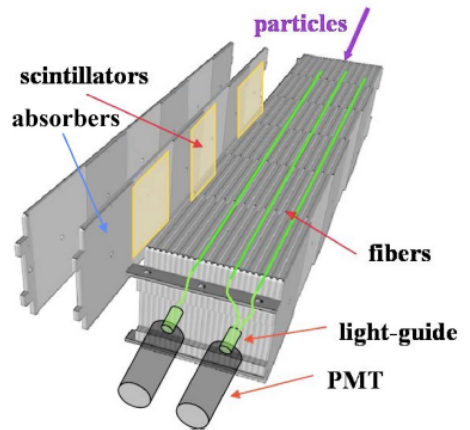


Figure 2.23: HCAL readout cell.

The total depth, chosen by space limitations in the LHCb cavern, does not provide a full shower containment. However, it was shown to be sufficient for the trigger operation [30].

The design energy resolution of the ECAL (left) and HCAL (right) is given by (E in GeV):

$$\sigma(E)/E = 10\%/\sqrt{E} \oplus 1\% \quad \sigma(E)/E = 80\%/\sqrt{E} \oplus 10\% \quad (2.6)$$

where the first term corresponds to the statistical fluctuations in the showers and the second one represents the systematics induced by the inter-calibration of the cells.

2.6.3 The Muon Chambers

The muon system [31, 17] provides information about the transverse momentum p_T of muon candidates in the first-level trigger (Section 2.7). It is also used in the high-level trigger and offline reconstruction to confirm muon candidates, by extrapolating tracks from the T-stations to the muon stations.

The muon stations (Figure 2.24, left) are mainly located at the end of the LHCb spectrometer, after the calorimeters, due to the large matter penetration power of the muons. They are equipped with *multi-wire proportional Chambers (MWPC)* [32], except the innermost part of M1 where *Gaseous Electron Multiplier (GEM)* detectors are used [33]. In this region, the fluence³ is too high to achieve the required efficiency using MWPCs.

To select the muons, three layers of 80 cm-thick iron walls are interleaved between the stations M2 to M5. Another iron wall is located after M5 to shield LHCb from potential LHC machine induced background. The M1 station has been added in front of the SPD to improve transverse momentum information in the first-level trigger. The whole system, including the iron filters, represents $\sim 20X_0$. Only muons with momenta higher than 6 GeV/c will cross all five stations.

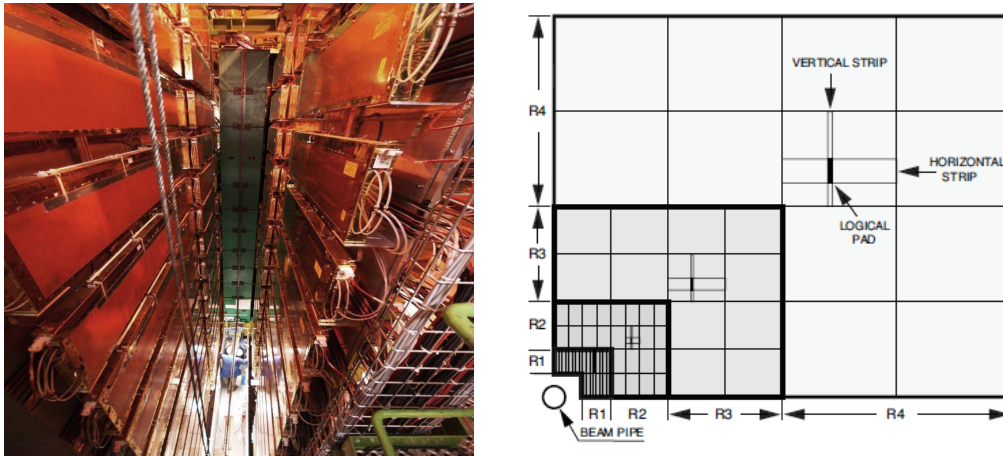


Figure 2.24: The muon chamber MWPCs (left) are divided in four regions of similar particle fluxes (right).

The stations are divided in four regions with approximately the same particle flux, and their granularity decreases from the centre to the outer regions (Figure 2.24, right). This is due to the fact that multiple scattering is higher in the outer regions, hence relaxing spatial resolution requirements.

A resolution of 20% is achieved on the muon candidate p_T using the stations M1-M3, which have a higher spatial resolution along the x coordinate than M4-M5.

³Fluence is the flux (particle or radiative) integrated over time. The potential radiation damage for detector systems is expressed in *1 MeV neutron equivalent fluence*. It corresponds to the fluence of 1 MeV neutrons producing the same damage in a detector material as induced by an arbitrary particle fluence with a specific energy distribution.

2.7 The LHCb Triggering System

At the LHCb nominal luminosity of $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, inelastic proton-proton collisions take place at a rate $\sigma_{\text{pp}}^{\text{inel}} \mathcal{L} = 16 \text{ MHz}$, where $\sigma_{\text{pp}}^{\text{inel}}$ is the inelastic proton-proton cross section⁴.

Visible proton-proton interactions are defined at LHCb as collisions producing at least two charged particles with enough information in the VELO and T-stations to be reconstructible. They account for $\sim 79\%$ of $\sigma_{\text{pp}}^{\text{inel}} \mathcal{L}$ (12.7 MHz). Out of them, only 100 kHz contain a $b\bar{b}$ pair, which are reduced to a few Hz when requesting at least one B meson with all its decay products inside the LHCb acceptance.

The initial number of visible interactions therefore has to be sizeably reduced, to remove as early as possible in the data acquisition process events uninteresting for physics analyses and to satisfy the $\sim 2 \text{ kHz}$ maximum rate for writing the events to permanent storage⁵. The reduction is achieved by the LHCb *trigger system* [34]. The trigger system is optimized to be efficient at quickly rejecting background events while preserving signal.

2.7.1 Structure of the LHCb Triggering System

The LHCb triggering is performed at two levels: A hardware *first level trigger (L0)* and a software *High Level Trigger (HLT)* (Figure 2.25).

The first-level trigger L0 is implemented in custom made electronics and reduces the visible bunch crossing rate from 10 MHz to $\sim 1 \text{ MHz}$, which is the maximal DAQ readout rate allowed by the TELL1 boards (Section 3.2.3). At the L0 level, only single objects are triggered (except for $\mu\mu$) (Figure 2.26). The global trigger decision is taken for each bunch crossing by the *L0 decision unit (L0DU)* collecting the information of three sub-systems: the *VELO Pile-Up system*, the *calorimeter trigger* and the *muon trigger*. The time separating a proton-proton interaction and the arrival of the corresponding L0 trigger decision at the front-end electronics is $4 \mu\text{s}$, covering exactly 160 bunch crossings. $2 \mu\text{s}$ are taken up by the time-of-flight of the particles and the readout and cable delays, leaving the other $2 \mu\text{s}$ for processing the information and reaching the decision.

The HLT software trigger is a C++ application executed on an event filter farm. It reduces the rate of 1 MHz further down to 2 kHz using the full event data. It contains two sub-levels, *HLT1* and *HLT2*.

The HLT1 trigger confirms objects selected by the L0 trigger by reconstructing them partially in regions of interest using information from the VELO and/or T-stations, or confirms the absence of charged particles in the case of L0-triggered γ and π^0 candidates. To minimize the time spent per event, reconstruction and filtering phases alternate in HLT1. The HLT1 is divided in *alleys*, which are streams

⁴The average number of interactions per bunch crossing is $\nu \sim 0.54$. This value is obtained as follows. From the 2808 bunches filled with protons in a LHC beam, 2622 collide at the LHCb interaction point. This leads to an average non-empty bunch crossing frequency of 29.49 MHz. The ν value is obtained by dividing the 16 MHz rate of inelastic proton-proton collisions by 29.49 MHz.

⁵The events have a size of 35 kB. The rate for writing the events to permanent storage is $\sim 2 \text{ kHz} \cdot 35 \text{ kB} = 70 \text{ MB/s}$.

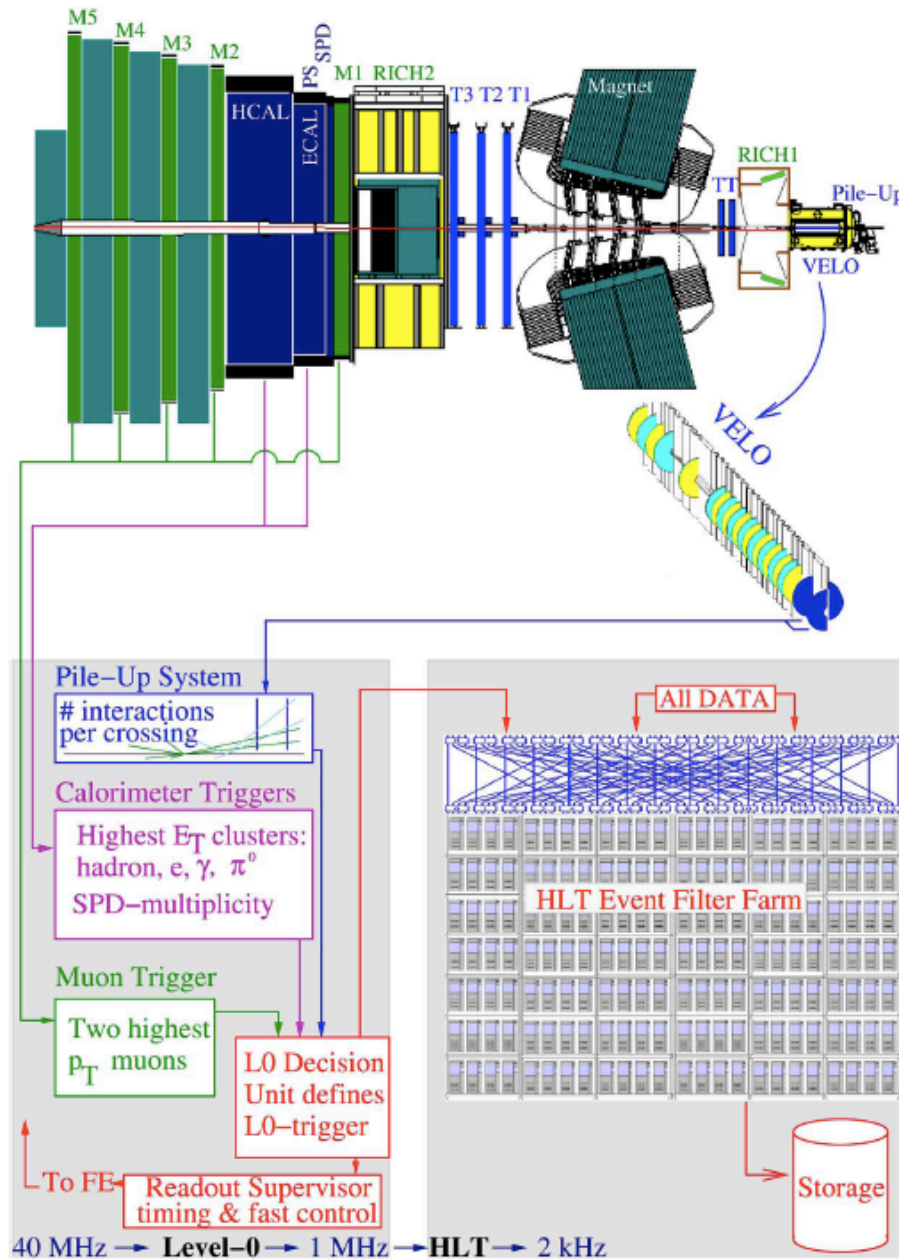


Figure 2.25: LHCb trigger structure with the L0 hardware level and the HLT software level [16]

refining the L0 trigger decision (Figure 2.26). The alleys are logically independent, such that the decision of one alley does not affect the decision of the other alleys. As the alleys run in a sequence, some algorithms are designed to run the common tasks only once per event⁶. For instance, the transverse momentum p_T and the impact parameter IP of the tracks are calculated with respect to the primary vertex by such algorithms. Inside an alley, several *lines* allow for a more refined classification of the L0 objects once confirmed. The HLT1 reduces the event rate to ~ 30 kHz. The bandwidth division between the different alleys is flexible and is still being tuned with real data.

After HLT1, the event rate becomes low enough to allow for a full reconstruction of B-hadron final states, which is performed within the HLT2 trigger framework. All the events are tested by every available HLT2 trigger algorithm, hence no confirmation of a previous trigger is required in HLT2 (Figure 2.26). Common composite particles, such as $J/\psi \rightarrow \mu^- \mu^+$, $K^{*0} \rightarrow K^+ \pi^-$, $\phi \rightarrow K^+ K^-$, $D^0 \rightarrow hh$ or $D_s \rightarrow K^+ K^- \pi^-$, are reconstructed from a set of tracks selected with very loose cuts, which are subsequently used by the selection algorithms to avoid multiple reconstructions of the same object. The algorithms can be *inclusive* or *exclusive*. Inclusive algorithms select partial B decays to ϕX , $J/\psi X$, $D_s h$, $\mu^\pm X$, $\mu(h)X$, $hh(h)$,... Exclusive algorithms are developed for all physics analyses separately and are close to the corresponding offline selections. For a given event, if the decision of at least one inclusive or exclusive selection is positive, the event is kept. The HLT2 results in a final output rate of 2 kHz.

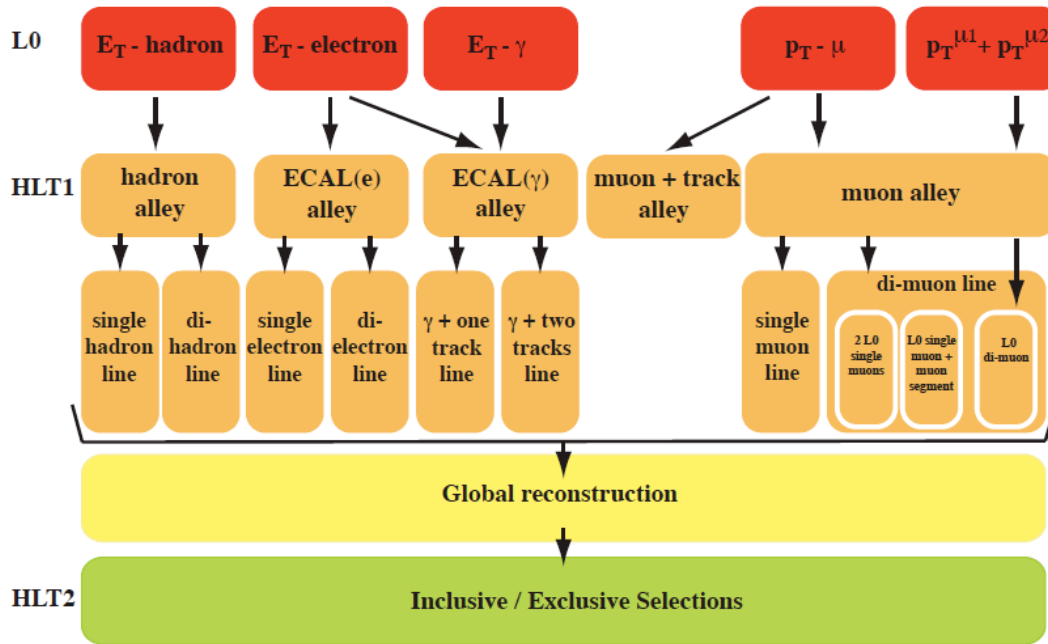


Figure 2.26: The confirmed L0 objects are directed to independent HLT1 alleys, which contain different lines. Once the candidates have passed the different lines, a global reconstruction is performed. Inclusive and exclusive selections are then applied at HLT2 level. [16]

In the following, the different L0 objects and HLT1 alleys of Figure 2.26 are described⁷.

⁶About 15% of the L0-triggered events pass through more than one HLT1 alley.

⁷The scheme presented here is applicable to the datasets used for the Monte Carlo studies of Chapter 7, but considerable changes are now being implemented at HLT level.

2.7.2 The First-Level Trigger and the L0 Objects

The VELO Pile-Up System. Bunch crossings with multiple visible primary interactions result in trigger decisions that are more likely to be based on combinatorics than real B decays. Moreover, they require disproportional amounts of bandwidth and processing during event building. They can be vetoed using the VELO Pile-Up system, which is located upstream of the interaction point and consequently only detects backward tracks. It is composed of two r-sensitive Silicon-planes located perpendicular to the beam axis (Figure 2.8). The planes have special cabling and operate the front end chip in a comparator mode, allowing full readout of the silicon at 40 MHz. The system can distinguish single from multiple primary interactions, which allows the rejection of bunch crossings with multiple interactions. The total multiplicity of the backward charged tracks is also determined using the Pile-Up counter.

The Calorimeter Trigger. The clusters are formed from 2×2 sensitive cells, which are sufficient to contain most of the energy of the narrow showers, while small enough to prevent shower overlaps. Due to their relatively large mass, B mesons often decay in particles with large transverse energy E_T . Consequently, the calorimeter trigger accepts events with at least one cluster in the HCAL with a large E_T^{hadron} (L0-hadron line), or in the ECAL with large E_T^e and/or E_T^γ (L0- $e^\pm$ and L0- γ lines).

The Global Event Cuts (GEC). These can be used to remove specific bunch crossings. To remove bunch crossings with multiple interactions, the total track Pile-Up multiplicity, $m_{\text{track}}^{\text{PU}}$, and the number of tracks used to reconstruct a second vertex, $n_{\text{tracks}}^{\text{vtx}}$, are requested to be low. To remove bunch crossings without visible interactions, the total transverse energy, E_T^{tot} , collected by the two calorimeters has to be large. This requirement also acts as veto on triggering on muons coming from the beam halo. Too complex events with high multiplicities in the Scintillating Pad Detector, $m_{\text{track}}^{\text{SPD}}$, are also rejected.

The Muon Trigger. Hits aligned in the muon stations are searched for by a track finding algorithm. The transverse momentum p_T of a muon candidate is then calculated with a resolution of 20% from the hits in the first two stations and under the hypothesis that the muon originates from the interaction point. The muon trigger accepts single muons with a large p_T regardless of whether the GEC is fired or not (L0- μ , no GEC line) or satisfying the GEC (L0- μ , GEC line). It can also accept two muons with large $(|p_T^{\mu_1}| + |p_T^{\mu_2}|)$ regardless of the GEC decision (L0-di μ line, no GEC line). Up to eight candidates per event are sent to the L0DU, with a maximum of two per quadrant with the highest p_T .

2.7.3 The HLT1 Alleys

Five different alleys are implemented at HLT1 level:

1. **The Muon Alley** [35]. L0-triggered muons are confirmed by extrapolating the muon tracks to the T-stations. Windows are opened around these extrapolations, in which clusters are collected to reconstruct the T tracks. The T-tracks are then matched to VELO tracks, which improves the momentum resolution from $\sim 20\%$ to $\sim 2\%$. The muon objects confirmed with a long track (see

Section 6.1 for the definition) are then directed through the lines of the muon alley, requiring one L0-triggered muon candidate (single muon line), two muon candidates triggered together by the L0 (di-muon from L0 di-muon line) or two muons triggered separately by the L0 (di-muon from 2 L0 single muon line). Cuts on the p_T for the single muon line or on the invariant mass and Distance Of Closest Approach (DOCA) for the two-muon lines, and potentially on the impact parameter IP, are used to lower the output rate.

To improve the two-muon event efficiency, in case a L0-triggered candidate is confirmed, a search for an extra muon in the muon stations is performed. If one is found and satisfies the cuts of the two-muon lines, this extra track is included at this stage, allowing for a partial recovery of low momentum muons (di-muon from 1 L0 single muon + 1 muon segment line).

2. **The Muon+Track Alley** [36]. A L0-triggered muon is confirmed as in the muon alley case, but the output rate is reduced in another way. Additional information from the decay is required, which are tracks forming good vertices with the L0 muon candidate. In the process, these additional tracks are not identified. They could be muons, electrons or hadrons.
3. **The Hadron Alley** [37]. A L0-triggered hadronic cluster is confirmed as follows. A rough momentum estimate obtained from the cluster energy is used together with the kick caused by the magnetic field to correct the slope between the LHCb origin and the cluster position. The L0 candidate is then matched with VELO tracks by comparing their slopes. At this stage, a reduction of the rate and number of candidates is obtained by cutting on a minimum impact parameter value with respect to any primary vertex. Using the matched VELO tracks and clusters in the calorimeter, regions of interests are reconstructed in the tracking stations. If tracks are found, then the L0 object is confirmed and is directed to one of the two lines of the hadron alley. The first line requests a single hadron (single hadron line). The second line requires that there is an extra track in the event, called companion track, forming a secondary vertex with the L0 confirmed track (di-hadron line). Cuts on p_T , IP and track quality are used to reduce the rate, and additionally on the distance of the displaced secondary vertex from the primary vertex for the di-hadron line.
4. **The ECAL (γ) Alley** [38]. As photons can convert in material before reaching the ECAL, signal photons are sometimes classified as L0 electron objects. Therefore, L0 photon and electron objects are used as input for this alley. The photon nature of a candidate is confirmed if its cluster cannot be associated with any track segments in the T-stations. VELO tracks filtered by IP cuts are used along with the photon as input for two lines in which one (γ +one track line) or two tracks (γ +two tracks line) with high IP and p_T are selected.
5. **The ECAL (e) Alley** [38]. The L0-triggered electron is confirmed by track segments in the T-station regions of interest pointing to the candidate. The candidate track is matched with VELO tracks. Lines requesting a single electron (single electron line) or an electron with an additional track (di-electron line) are filtered with cuts on IP and p_T , and additionally on the goodness of a displaced vertex for the second line.

2.8 The LHCb Software

2.8.1 The GRID Computing

The huge amount of collision data expected to be collected by the LHC experiments, ~ 15 petabytes per year corresponding to more than 1.7 million dual-layer DVDs, exceeds by far that of any previous high energy experiment. Consequently, it was not possible anymore to count only on the computing resources of CERN to access and analyze the data. Therefore, a model of shared computing resources between distant computers has been developed, called the *GRID*. The LHC experiment data are distributed around the globe, with a primary backup recorded on tape at CERN, known as the *Tier-0* center. After a first processing, they are distributed to eleven computing centers, the *Tier-1*, where a large fraction of the data are stored. The data are accessible for specific analysis tasks through 160 *Tier-2* centres linked to the Tier-1 centres. The user submits his jobs on the GRID, which are then allocated to processing centers that have a spare capacity at that time.



2.8.2 The Monte Carlo Simulation and the LHCb Software

In order to quantify the detector performance, to test the software and develop analyses, the use of Monte Carlo simulations is very important. A *Monte Carlo method (MC)* is a numerical technique that uses random draws to calculate a statistical quantity. The generation of the random numbers is performed by a generator. Their values are uniformly distributed in the $[0, 1]$ interval. These numbers are then used to generate another sequence of numbers representing the observable, whose distribution is described by a *Probability Density Function (PDF)*. The created values are called *Monte Carlo data*.

The LHCb software chain is depicted in Figure 2.27. Monte Carlo simulations require several steps [39].

First, proton-proton collisions and successive decays are generated by GAUSS. The simulation phase emulates the passage of particles inside the spectrometer and the detector response. The simulated data are then digitized by BOOLE and given as input for the reconstruction performed by BRUNEL. It is at this stage that real data can also enter

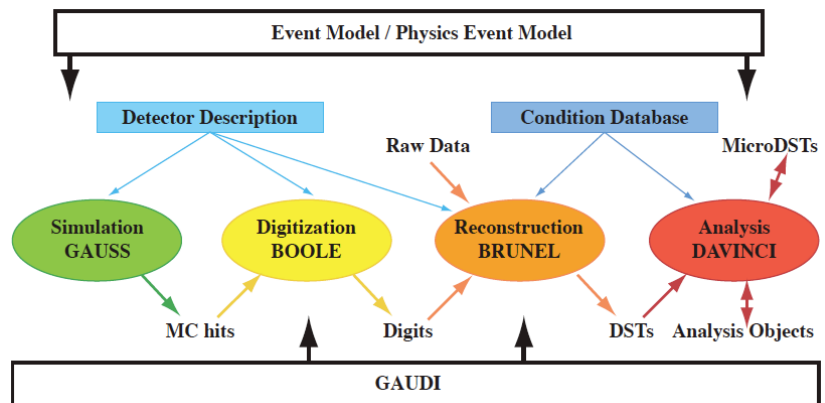


Figure 2.27: The LHCb data processing applications and data flow. The event model describes the data expected by the applications.

into the reconstruction process. From the reconstructed clusters and tracks, objects are made available to the physics analyses using DAVINCI. The different applications are detailed in the following.



GAUDI [40] is the framework on which the LHCb offline software is based. All the LHCb applications are embedded in it, where they perform their tasks. These are event generation, detector simulation, digitization, reconstruction, trigger, physics analysis, and event and detector visualization. Initially developed for the LHCb experiment, GAUDI has been adopted and extended by the ATLAS, GLAST and HARP experiments.



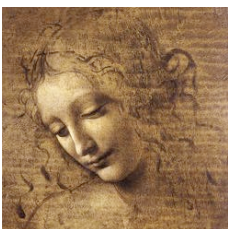
GAUSS [41] is the simulation program of the LHCb experiment. A first generator phase generates the proton-proton collisions using PYTHIA [42] and the decay of the particles produced using the EVTGEN package [43]. It is followed by a detector simulation phase, during which the particles are tracked in the detector, including magnetic field effects and the physics processes occurring in the experimental setup. These are simulated using the GEANT4 toolkit [44].



BOOLE [45] is the LHCb digitization application, the final stage of the detector simulation. It applies the detector response to MC hits previously generated with GAUSS. Additional hits are added from the spill over events and the LHC background. The digitization step includes the simulation of the detector response, the readout electronics and the L0 trigger hardware.



BRUNEL [46] is the LHCb event reconstruction application. After a positive trigger decision, it creates tracks, RICH Cherenkov rings and clusters from digitized output data provided by the BOOLE application or from raw data recorded at LHCb from collision events. BRUNEL contains the full pattern recognition and tracking software. As output, it provides *Data Summary Tape (DST)* files, which are used as input for further physics analyses.



DAVINCI [47] is the physics analysis software of the LHCb experiment. The tracks and clusters reconstructed by BRUNEL are assigned to particle identification hypotheses before the reconstruction of primary vertices. A series of algorithms is then applied to combine the particles to reconstruct the decays of interest. The selection of particles can be eased by using the available user-friendly toolkit LOKI [48].



PANORAMIX [49] is the visualization application used at LHCb. It offers graphical displays of the detector geometry and of the event data objects. As it is based on the GAUDI framework, it can be run with any of the LHCb applications.



The Inner Tracker Assembly

At LHCb, the Inner Tracker [22] is part of the tracking stations located downstream of the magnet. It consists of twelve detector boxes, four on each station, which cover a cross-shaped region around the beam pipe. To provide information about the trajectories of charged particles and their momenta, it uses a p^+ -on-n single-sided silicon microstrip sensor technology. The Inner Tracker detector boxes contain each four detection layers of seven silicon sensor modules. The two external layers have vertical modules, while the two internal layers have modules rotated by a stereo angle of $\pm 5^\circ$ to provide three-dimensional spatial information.

The assembly of the Inner Tracker detector boxes was performed in a clean environment at CERN [50]. All individual pieces of the assembly were checked beforehand. Once this was achieved, the delicate detector box assembly process could start.

An introduction to semiconductor detectors and their properties is given in Section 3.1. The Inner Tracker is described in Section 3.2, with an overview of the technical requirements and design challenges. The steps for assembling an IT detector box are detailed in Section 3.3.

3.1 Semiconductor Detectors

The most commonly used material in semiconductor detectors is *Silicon (Si)*. Silicon is the second most abundant element in the Earth's crust, representing 25.7% in weight [51]. The silicon-based technology for tracking is relatively young, with the first silicon strip detector used in the NA11 experiment at CERN in the 1980's [52]. Since then, the technology has developed a lot, also with the introduction of more complex designs such as pixel detectors.

Silicon detectors present nice features that make them ideal for tracking purposes. The average energy needed for the generation of an electron-hole pair in the silicon is low. The radiation energy is directly converted into an electrical signal. The signal generation and readout is performed at high speed, with a response time less than 25 ns. Silicon detectors have a high efficiency and a low dead time. The high granularity allows the reconstruction of complex events, hence a high spatial resolution.

In the future, an alternative to silicon detectors could be diamond or GaAs detectors [53, 54]. Due to their larger band gap compared to silicon, they offer a higher radiation hardness. At present, they are to date still much more expensive and more difficult to manufacture. They also give less signal than silicon for the same material thickness.

3.1.1 Semiconductor Properties

The energy band structure of a semiconductor is composed of a valence and a conduction band, separated by a forbidden band gap. The electrical conductivity of a semiconductor depends on [55]:

- *The number of charge carriers.* The charge carriers responsible for the electrical conductivity are electrons and holes. Electrons acting as carriers are located in the conduction band. Holes are unoccupied states in the valence band. These do not propagate by themselves, but can be filled by neighboring electrons of the valence band and thus change position. The number of carriers increases with temperature. The more carriers in a semiconductor, the bigger is the electrical conductivity.
- *The band gap energy E_g .* It is the energy required for charges of a semiconductor to overcome its band gap. The smaller E_g , the bigger is the electrical conductivity. At room temperature, the value of E_g for silicon is ~ 1.2 eV¹. The average energy needed to generate an electron-hole pair is however 3.62 eV due to additional momentum transfer [56].

The probability that an electronic state is occupied by an electron of energy E at a temperature T is given by the Fermi-Dirac function

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_f}{k_B T}\right)} \quad (3.1)$$

where k_B is the Boltzmann constant and E_f the Fermi energy at which $F(E) = 0.5$.

¹The band gap energy E_g is 5.5 eV for diamond and 1.43 eV for GaAs.

At room temperature, only one in every 10^{12} atoms in a silicon crystal is ionized [55]. To increase the electrical conductivity for a given temperature, the number of carriers of a pure semiconductor can be raised by adding impurities to its crystal lattice through a *doping process*.

The silicon possesses four valence electrons. If a silicon atom is substituted by an element of the group V of the Mendeleev table (e.g., phosphorus), four of the valence electrons form covalent bonds with the neighboring silicon atoms. The fifth valence electron remains weakly bonded and can move around the silicon crystal, acting as charge carrier. This kind of doped silicon is of *n-type* (Figure 3.1, (a)).

If the doping atoms are from group III (e.g. boron), the three valence electrons form covalent bonds with three of the silicon neighbors. The bond with the fourth neighbor remains unsatisfied and attracts electrons from the neighboring bonds. This kind of doped silicon is of *p-type* (Figure 3.1, (b)).

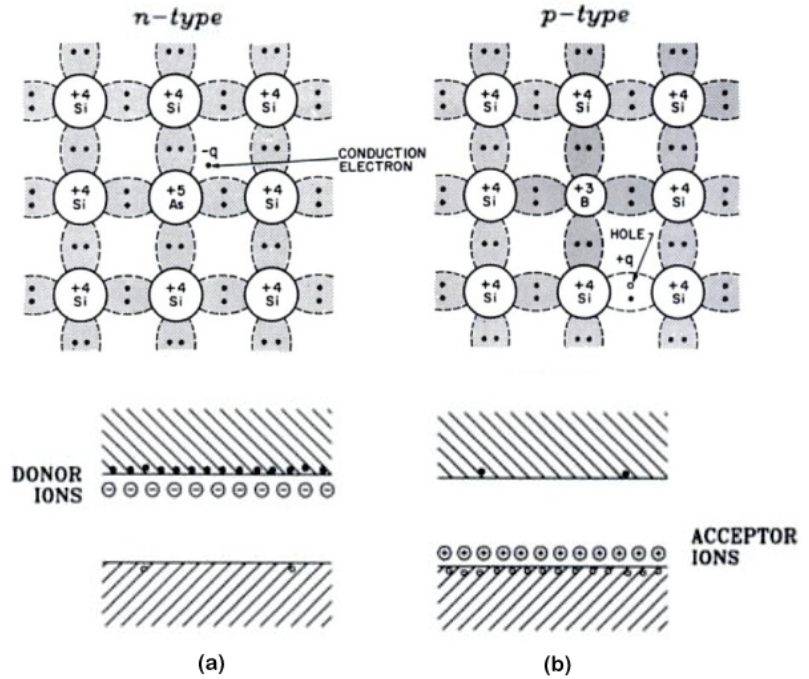


Figure 3.1: Bond representation of n-type (a) and p-type (b) semiconductors [56, 54].

The loosely bound electron or hole states as a result of the dopants appear as additional energy levels in the band gap region (Figure 3.1, bottom). At room temperature, they are almost all excited in the corresponding conduction band.

3.1.2 Principle of Particle Detection in Silicon

A *p-n junction* is created by placing a semiconductive layer of n-type next to a layer of p-type (Figure 3.2, (a)) [56]. The Fermi energy E_f is equalized at the junction, resulting in a shift of the valence (E_v) and conduction (E_c) bands (Figure 3.2, (b)). At the junction, a diffusive process is caused by the difference in carrier concentration. The electrons diffuse into the p-region and holes into the n-region, resulting in the recombination of opposite carriers and the apparition of a new zone at the junction, called *depletion zone*. Because of the very small fraction of the carriers inside the depletion zone, the electrical conductivity is strongly suppressed, making the zone non-conductive.

Inside the very thin depletion zone, space-charge zones are created from the surplus of negative charges in the p-region and of positive charges in the n-region. These produce an electric field counteracting the diffusion process (Figure 3.2, (b)). It is responsible for the drift of the electrons towards the n-region

and the holes towards the p-region created in the depletion zone by the ionization of a passing charged particle.

In practice, p^+-n junctions with a highly doped p-type layer, p^+ , and a n-doped bulk are used instead of p-n junctions (Figure 3.3). They offer an enlarged depletion zone matching the bulk width, which allows better charge collection.

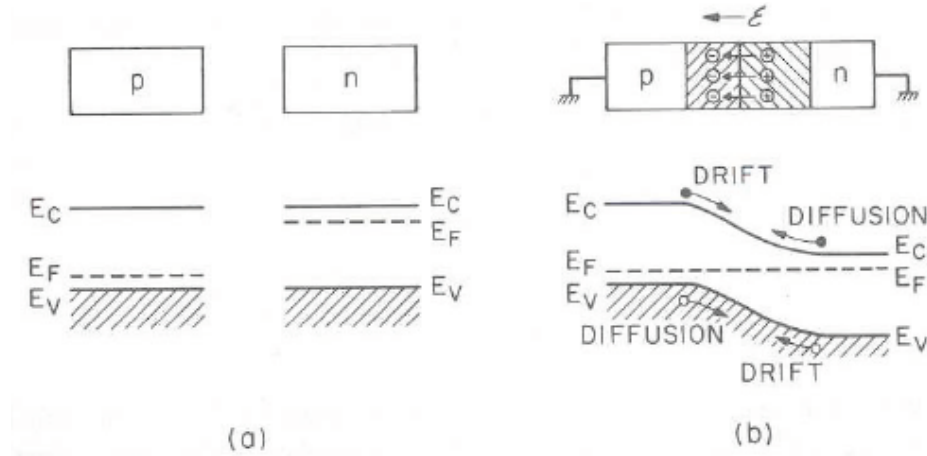


Figure 3.2: A p-n diode junction in thermal equilibrium, with its parts separated (a) and brought together (b) [56].

The electric field produced by the space charges is not strong enough for good charge collection and for depleting the whole n-bulk from its free charge carriers. Therefore, an external voltage, called *Reverse Bias*, is applied. It is positive on the n-bulk with respect to the p^+ -side. The holes are pulled away towards the p^+ -region and the electrons towards a highly n-doped layer (n^+) (Figure 3.3).

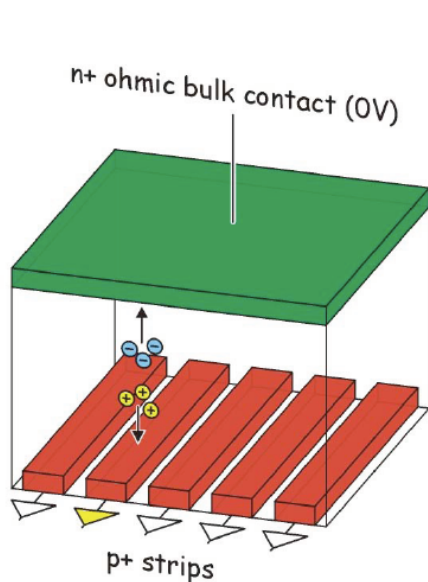


Figure 3.3: Stripped p^+ layer (right) [55]

To achieve position resolution of the passing ionizing particle, the p^+ -layer is segmented. The segmentation can be strips, as shown in Figure 3.3 [57]. The distance between two readout channels, called *pitch*, is typically of 20 to 200 μm . Each strip is linked to one electronic readout channel.

The charges are created by the ionization of a passing charged particle in the depletion zone². The movement of the electrons and holes induces a charge on the electrodes through a capacitive effect. Indeed, the movement corresponds to an elementary work, which is provided by the variation of the potential energy of the electrodes. Due to energy conservation, the charge of the electrodes increases during the movement proportionally to the charge of the carrier. The final charge induced on each electrode is therefore proportional to the number of charge carriers, hence to the energy of the incoming particle, as well as the current I_{in} induced in the external circuit is (Figure 3.4). The current pulse

²About 80 electron-hole pairs are created per micrometer of silicon.

is collected at the front-end electronics, where a pre-amplifier reads the number of charges integrated on the feedback capacitor C_f and provides an output voltage V_{out} proportional to the total integrated input charge. To discharge C_f and thus avoid pile-up, a feed-back resistor R_f is put in parallel to the capacitor. The output voltage is reshaped by a shaper, which acts also as a band pass filter to reduce the noise. The analog output signal is then redirected to a digitizer delivering a logic signal.

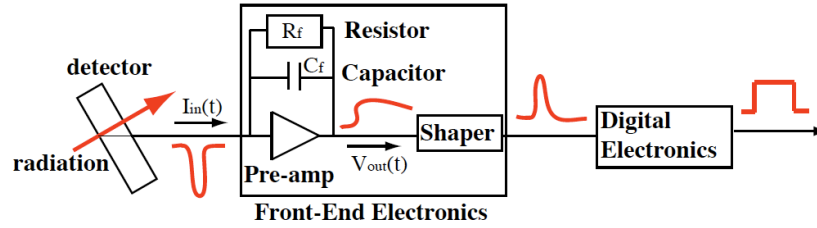


Figure 3.4: The current pulse is sent to the front-end electronics, where it is amplified and shaped. The voltage output signal is then directed to the digital electronics.

3.2 The Inner Tracker

The Inner Tracker is used to reconstruct the trajectories of charged particles. From their curvature in the magnetic field, the momenta of the charged particles can be measured.

The IT uses a silicon strip sensor technology and consists of four detector boxes in each of the three IT1, IT2 and IT3 tracking stations in the downstream region (Figure 3.5). The boxes are located in the innermost area around the beam pipe, where the track density is expected to be the highest. In each tracking station, the detector boxes cover a cross-shaped area of 1.3% of the total acceptance around the beam pipe. About 20% of charged particles produced at the interaction point passing through the tracking stations are expected to go through the IT area.

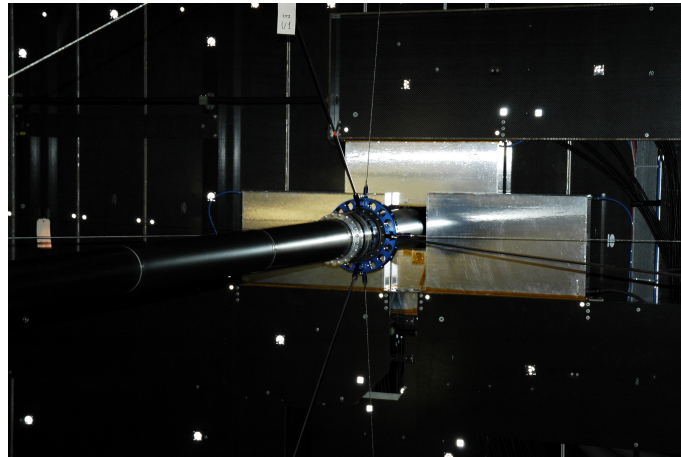


Figure 3.5: View of an IT station and beam pipe in the LHCb experimental cavern.

3.2.1 Design Requirements and Challenges

In addition to the production costs, the challenges and technical requirements in the design of the Inner Tracker detector are listed in the following.

- *Dimensions.* The silicon sensor dimensions are determined by the fabrication process, which is the float zone [58] for the Inner Tracker. The overall area covered by the Inner Tracker should be minimal, as silicon sensors are expensive, while ensuring an average occupancy of the Outer Tracker modules below 10% at the nominal luminosity. An overlap between the Inner Tracker and the Outer Tracker areas is needed to prevent gaps in the LHCb acceptance. The overall geometry of the Inner Tracker is explained in Subsection 3.2.2.
- *Spatial resolution.* A spatial resolution $\sigma_{\text{hit}}=70 \mu\text{m}$ of the Inner Tracker is adequate for the LHCb experiment. The momentum resolution of the spectrometer is then dominated by multiple scattering over almost the full range of particle momenta. A readout strip pitch of $\sim 200 \mu\text{m}$ meets this requirement.
- *Active/Dead Material.* At LHCb, multiple scattering dominates the momentum resolution up to $\sim 80 \text{ GeV}/c$. Therefore, the material budget of the Inner Tracker has to be minimized as much as possible, while keeping sufficient rigidity and precision.

The amount of material of the Inner Tracker includes the mechanical supports, the electronics, the cooling system and the silicon sensors. It is important to minimize the amount of material of the mechanical supports, cables and cooling of the front-end electronics, as they cover the active region of the Outer Tracker. The thickness of the silicon sensors is optimized to lower the amount of material while keeping a good signal-to-noise ratio requested to get a good hit efficiency.

- *Readout.* The electronics used in the front-end should fulfill the following requirements. At the LHC, proton-proton collisions are expected to happen with a frequency of 40 MHz. The readout chips responsible for the amplification and shaping of the signal have to work at this frequency, to avoid pile-up of events coming from consecutive bunch crossings³. The front-end electronics should consume little power to limit the cooling required in a confined space and support high levels of radiation. It must provide clear hit information, hence a low noise. As there is no charge multiplication in silicon detectors, the amplitude of the signal is determined by the thickness of the active material. As the thickness needs to be thin, the signal-to-noise ratio is a critical issue. There is a huge number of electronic channels to be read out in a silicon detector. As the readout electronics contributes considerably to the overall cost of a detector, the number of readout strips is reduced as much as possible, while keeping the strip occupancy at a maximum of a few percent. The readout chain is explained in Subsection 3.2.3.

³Track reconstruction is only possible if the remaining fraction of the signal amplitude at the sampling time of the next bunch crossing is less than 30%.

- *Hit occupancy.* Charged particle densities for minimum bias events of $1.5 \times 10^{-2} \text{ cm}^{-2}$ are expected in the innermost region of the Inner Tracker and $2 \times 10^{-3} \text{ cm}^{-2}$ in the outermost region [16]. The chosen strip geometry, pitch and strip length, results in a maximum strip occupancy that does not exceed a few percent. As for the spatial resolution, this is met by $200 \mu\text{m}$ pitch and $\sim 20 \text{ cm}$ -long strips.
- *Cooling.* Leakage currents can appear from radiation damage. They tend to increase the temperature of the silicon sensors. As the leakage currents increases with temperature, a thermal runaway process takes place, at which point the sensors could not be biased anymore. To limit the increase of temperature of the sensors and the front-end electronics, active cooling is hence required. However, three resulting effects have to be considered. The operation at low temperatures requires flushing with dry gas in order to avoid condensation. The material used in the detector required to be stable in terms of thermal expansion. Finally, a very good insulation of the detector is required. The cooling chain of the Inner Tracker is explained in Subsection 3.2.4.
- *Radiation damage.* At the LHC, radiation damage in silicon detectors has become an important factor to be studied. For ten years of operation, the innermost part of the Inner Tracker is expected to have a 1 MeV neutron equivalent fluence of $9 \times 10^{12} \text{ cm}^{-2}$. Damages are classified into two types, *cumulative* and *single event effects*. In cumulative effects, the damage gets progressively worse with the radiation dose. Single event effects have a discrete character, and the effect is either reversible or permanent. The radiation damage appear at two levels, in the electronics and in the active material. As the sensitive components of the electronics are located close to the surface, their damage from radiation is mostly a surface damage. The $0.25 \mu\text{m}$ CMOS technology produced with specific process rules is radiation hard [59].

Silicon sensors mainly suffer from bulk damage [60]. The displaced atoms create a distribution of vacancies and interstices in the crystal lattice. This results in two effects :

1. *Increase of leakage currents.* As explained above, cooling is a good prevention against this effect (a factor two is gained per seven degree drop).
 2. *Variation of the depletion voltage with fluence.* The behavior of the material changes from n-type to p-type. After inversion, the depletion grows from the n^+ layer instead of the p^+ -n junction. If the depletion voltage becomes too high, the bulk cannot be fully depleted anymore, resulting in a charge spread and loss. To limit this effect, the sensors are cooled down, as the depletion voltage tends to increase if the detector is kept warm (reverse annealing), which is illustrated in Figure 3.21.
- *Single hit efficiency.* For each single detection layer, a detection efficiency for a *Minimum Ionising Particle (MIP)* close to 100% is expected, while maintaining an acceptably low noise hit rate. The critical parameter is the signal-to-noise ratio. The Inner Tracker is designed to have a signal-to-noise ratio of 12, taking into account the expected deterioration from radiation damage of ten years of operation at nominal luminosity.

3.2.2 The Inner Tracker Geometry

The Tracking Stations

The IT1, IT2 and IT3 stations (Figure 3.6) are placed at equidistant positions along the beam line, between the end of the magnet and the entrance window of the RICH2 Cherenkov detector. Their positions are $z = [767.3, 782.8]$ cm, $z = [836.0, 851.5]$ cm and $z = [905.0, 920.5]$ cm, respectively.

The stations are made of 76×76 mm² and 3.2 mm-thick glass-carbon fiber pillars and very light 8 mm-thick honeycomb-carbon plates covered by 0.5 mm carbon fiber skins.

Each IT station consists of two vertical half-stations, one on each side of the beam pipe. The half-frames on the cryogenic side are called *IT{1,2,3}C*, whereas the half-frames on the access side are called *IT{1,2,3}A*. The half-frames allow an easy access to the IT detector components, in case of maintenance or repair during LHC shutdown times.

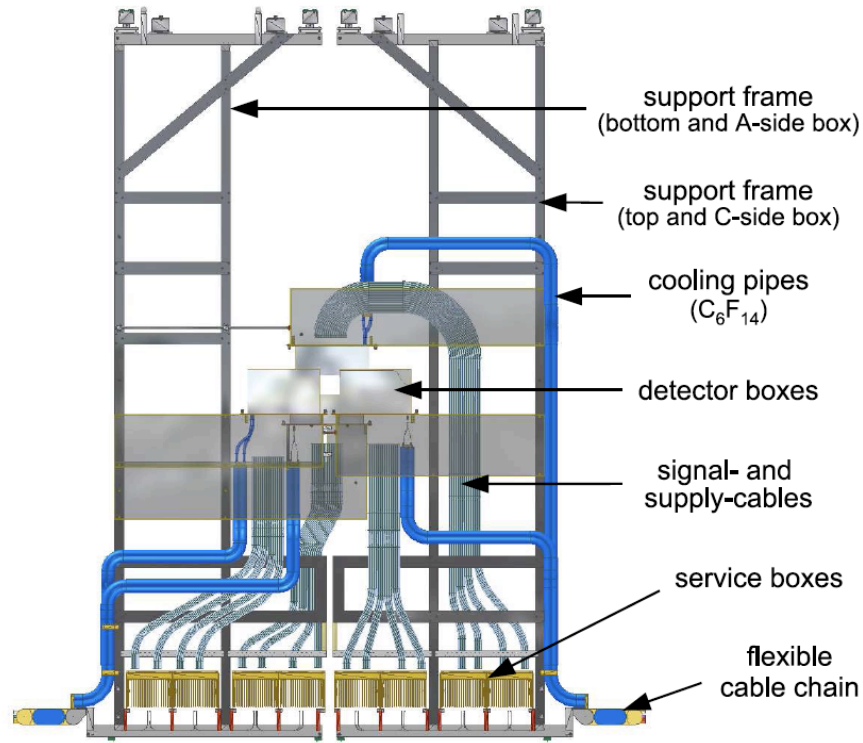


Figure 3.6: IT station with the four detector boxes surrounding the beam pipe.

The half-frames are hung on the rails of a bridge (Figure 4.14) and are guided on rails at the bottom. As the length of the rails does not allow precise guiding of the frames, four precise guiding rails have been added on each rail near the end position of the half-frames. When approaching their end positions, the left and right top trolleys of each half-frame get engaged on these precision rails. The location is then known better than $200 \mu\text{m}$ in the z direction.

Each half-station carries two detector boxes (Figure 3.7, left) on each of its plates. The cross-shaped area covered by the four detector boxes in a tracking station is 120 cm-wide and 40 cm-high (Figure 3.7, right).

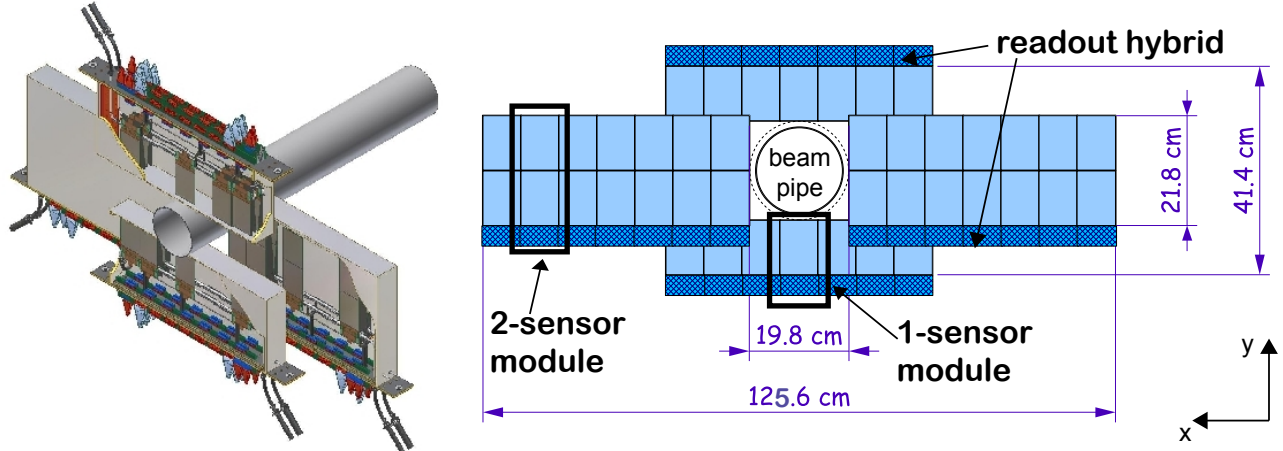


Figure 3.7: Cross-shaped area around the beam pipe covered by four IT detector boxes of a tracking station.

The boxes above and below the beam pipe are called *Top* and *Bottom central boxes* respectively. The boxes on the sides are called *Access* and *Cryo side boxes*, following the LHCb naming convention. Top boxes are mounted on the frames upside down compared to the other boxes, such that readout hybrids, cooling plate and box mechanics face away from the beam pipe (Figure 3.7).

To ensure that the IT half-stations do not touch the beam pipe during closure or operation, an alarm system called *BEam pipe Approach Monitoring System (BEAMS)* is used. It consists of two gold plated metallic fingers glued on the detector box sides facing the beam pipe, which are in contact with each other in their nominal position (Figure 3.8). The touching fingers are part of an electric circuit that is closed in nominal position. If the outermost finger touches the beam pipe, the fingers separate from each other. This opens the circuit and raises an alarm. The detector box nominal distance to the beam pipe is 7 mm. The fingers will trigger an alarm when the detector box is closer than 5 mm.

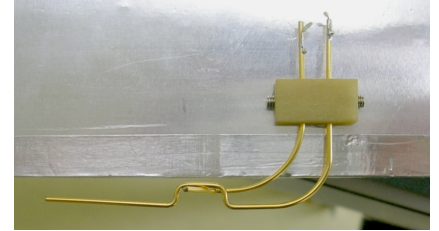


Figure 3.8: BEAMS system. An alarm is triggered by the opening of the circuit in case the lower finger get into contact with something.

To measure the total amount of radiation absorbed by the Inner Tracker, the *Radiation Monitoring System (RMS)* is used [61]. It consists of four boxes with seven 75 mm-wide and 110 mm-high sensors employing the *Metal Foil Detector (MFD)* technology [62]. These boxes are fixed on the upstream surface of the four detector boxes of station IT2. The MFD sensors of the central boxes are displaced by 14 mm away from the beam pipe due to space constraints, while covering almost entirely the silicon sensors. The MFD sensors of the side boxes cover only half the height on the silicon sensors.

The Detector Boxes

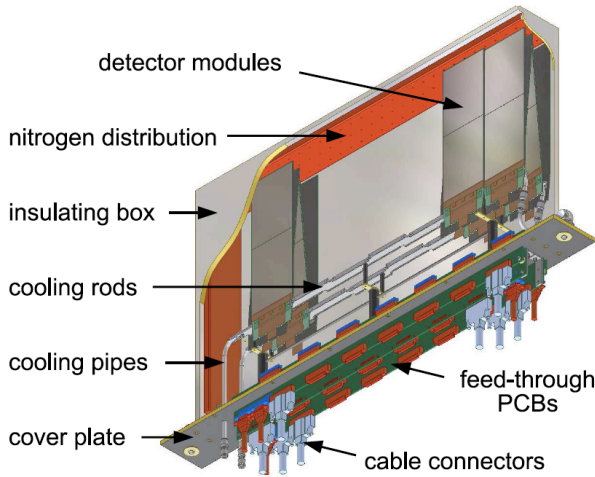


Figure 3.9: Schematic of an IT Detector Box.

A detector box consists of four layers of seven silicon sensor modules, for a total of 28 modules. To measure the three-dimensional trajectory of a particle, the IT layers are placed in a typical stereo layout. The two external layers possess vertical readout strips and are called *X1* and *X2*. Modules rotated by a stereo angle of -5° and $+5^\circ$ are used in the internal layers, called *U* and *V* (Figure 3.9).

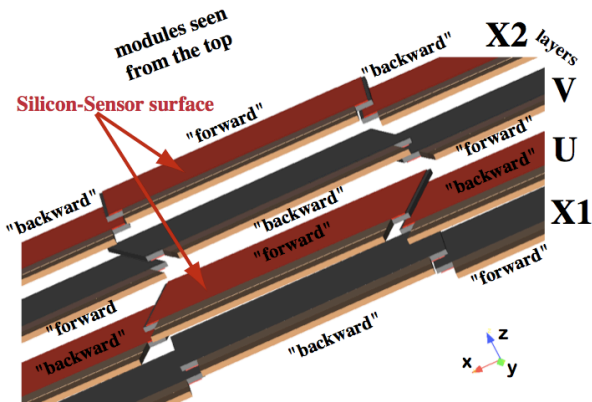


Figure 3.10: Forward and backward positions of the modules inside the X1, U, V and X2 detection layers.

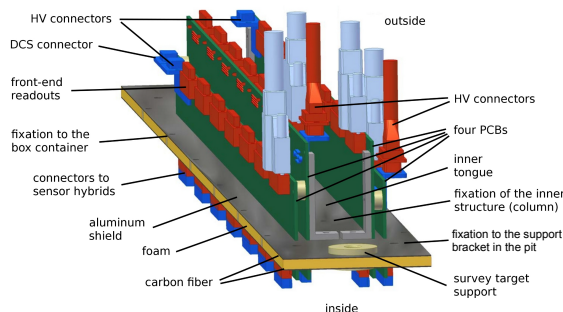


Figure 3.11: Schematic view of a cover.

The detector boxes consist of a box and a cover forming a thermally and electrically insulated system.

The box is made of a glass fiber and PIR-foam sandwich covered with aluminum shielding on the inside and outside. The foam part of the walls is 8 mm-thick, except for the walls close to the beam pipe that are 3 mm-thick.

The cover is made of foam sandwiched between carbon-fiber sheets (Figure 3.11). The sandwich is covered on both sides with 81 μm -thick aluminum foils. The cover acts as a mechanical interface between the IT support frame (Figure 3.6) and the detector module support structure inside the box (Figure 3.9).

The silicon sensor modules are fixed on the complex staggered structure of the cooling rod, which induces a 4 mm-staggering in z between adjacent modules and overlaps of the sensitive areas in the x direction. These overlaps ensure full acceptance coverage. The modules are hence placed in an alternative "forward" (completely visible inside a layer) or "backward" (partially hidden by the "forward" modules) positions (Figure 3.10). The X1 and V layers have "forward" modules at their two extremities, while the X2 and U layers have "backward" modules at their two extremities.

The precise positioning of the sensor modules in the detector boxes is achieved by precision pins on the cooling rod onto which the modules with the according positioning holes are placed (Figure 3.9).

Four *Printed Circuit Boards (PCB)* are embedded in the cover (Figure 3.11). They act as a stiff skeleton for the part of the cover between the inner PCBs.

The Silicon Sensor Modules

Single-sided p^+ -on-n silicon sensors are used. They have a length of 11 cm and a width of 7.8 cm and their strip pitch is $198 \mu\text{m}$. The dimensions are limited by the size of the wafer from which the sensors are extracted. The total active material of the IT represents an area of 4.2 m^2 . The technical specifications of the silicon sensors are summarized in Table 3.1. Thicknesses of $320 \mu\text{m}$ are used for one-sensor modules and of $410 \mu\text{m}$ for two-sensor modules⁴.

As shown in Figure 3.12, the silicon sensors are glued on modules made of a layer of foam sandwiched between two sheets of high thermal conductivity carbon fiber ($k=1100 \text{ W/mK}$) [63]. A Kapton sheet is glued on top of this structure for insulating electrically the sensor backplane carrying the bias voltage from the sandwich support. To protect the sensors mechanically, the supports extend by 1 mm over the edges of all sides. The dead area between the sensors in the two-sensor modules is about 0.2 mm.

The charged particle density in the region the closest to the beam pipe covered by the IT is $1.5 \cdot 10^{-2} \text{ cm}^{-2}$ and $2 \cdot 10^{-3} \text{ cm}^{-2}$ in the outer regions [22]. These densities are still low enough to allow the use of longer strips in the IT side boxes. Therefore, the modules for side boxes are designed with two-sensors bonded together (Figure 3.12), while modules for central boxes contain only one sensor. The total number of readout strips is hence reduced from 193'536 to 129'024 (384 readout strips per module).

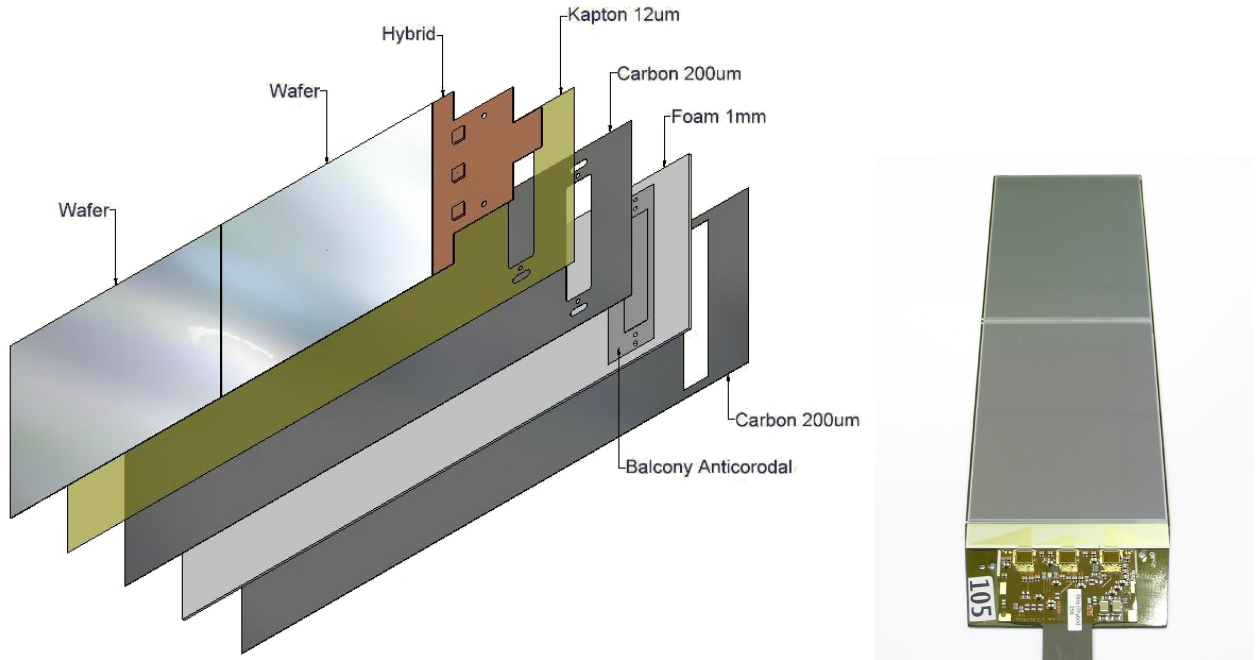


Figure 3.12: Layers composing the silicon sensor modules (left) and module for side boxes (right).

⁴These thicknesses ensure a high signal over background ratio. For the two-sensor modules, the load capacitance is larger, which induces a larger noise. In order to get the same S/B ratio as for one-sensor modules, more signal is needed, hence thicker silicon sensors.

3.2.3 The Readout Chain

When a charged particle goes through the silicon sensors, it creates charges in the depleted zone by ionization, as explained in Subsection 3.1.1. The holes drift towards the strips (negative side) and the electrons towards the backplane (positive side). The consecutive readout chain is explained below.

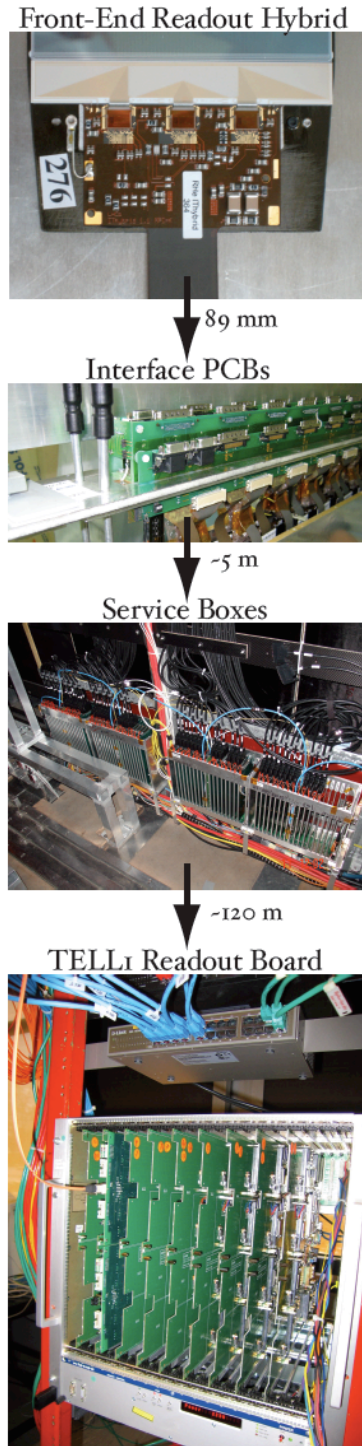


Figure 3.13: IT readout chain and distances between the elements.

The Front-end readout Hybrid. The silicon sensors are bonded via a ceramic pitch adaptor to the front-end hybrid [64]. It consists of a PCB with three readout chips, called *Beetle chips* (Figure 3.13, top) [65]. The role of the pitch adaptor is to match the readout sensors pitch to the pitch of the Beetle input pads ($\sim 40.25 \mu\text{m}$).

Each Beetle receives as input 128 readout channels. The readout chips amplify, shape and sample the detector signals (Subsection 3.1.2). Inside them, the sampled data are stored in an analog pipeline for a maximum duration of $4 \mu\text{s}$, until the first-level trigger decision is received (Section 2.7). In the case of a positive response, the analog signal is transmitted further through the four output ports of the Beetles. Four ports are used to cope with the 1.1 MHz output rate of the first-level trigger (900 nanoseconds).

The Interface PCBs. The end of the front-end readout hybrid is connected through a 89 mm-long readout tail to the interface PCBs, which act as interface between the inside and the outside of the detector boxes (Figure 3.13, middle up). Four of them are inserted vertically in each cover plate, one per detection layer.

The Service Boxes. These are located outside of the LHCb acceptance (Figure 3.13, middle down). In the service boxes, there is for each detector module a so-called *Digitizer Board*, on which the analog output signals coming from the front-end electronics are digitized, multiplexed and converted to optical signals [66].

One control board per service box provides the *Time, Trigger and Control (TTC)* signals and slow control interface for the digitizer boards and readout chips. The control board also monitors the temperature and humidity in the detector boxes and service boxes.

The TELL1 readout Boards. The optical signals are transmitted via 120 m-long twelve-fiber optical ribbon cables from the service boxes to readout boards, called *TELL1* [67] (Figure 3.13, bottom), located in a counting house shielded from radiation. Each TELL1 receives data from two optical cables, which corresponds to eight modules.

3.2.4 The Cooling Chain

The cooling is performed by liquid C_6F_{14} at -15°C flowing through the cooling pipes [21], which keeps the sensors below 5°C (Figure 3.14). The cooling pipes are made of aluminum, with an external diameter of 6 mm and a wall thickness of 0.3 mm.

An 70 mm-wide, 15 mm-high and 1.5 mm-thick aluminum insert, called *minibalcony*, is embedded into the module support at the location of the readout hybrid. It provides a direct heat path between the front-end chips and the cooling rod to evacuate the waste heat.

The box is continuously flushed with N_2 to prevent condensation. The humidity has to be such that the dew point remains below the temperature of the coldest element in the box. A humidity sensor is fixed to one PCB inside the boxes to monitor the humidity.

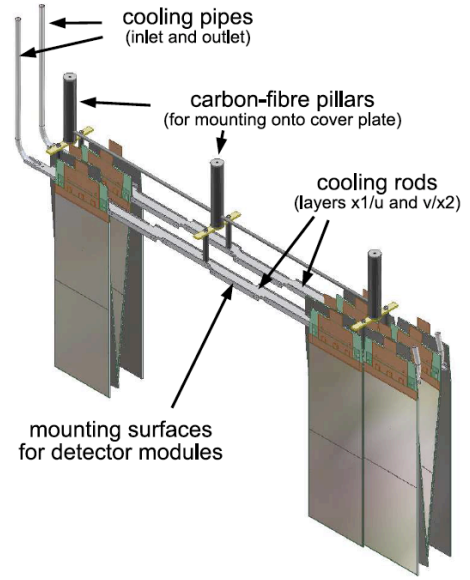


Figure 3.14: C_6F_{14} flows in the cooling pipes to cool down the sensors fixed to the cooling rods.

Four temperature probes are placed inside the detector box in addition to the probes on each readout hybrid. A thermo switch required by the *Detector Safety System (DSS)* [68] is glued to the bottom side of each cover. Its purpose is to trigger an alarm if any over-temperature is recorded inside the boxes.

A summary of the Inner Tracker technical specifications is given in Table 3.1.

Table 3.1: Inner Tracker Technical Specifications.

Properties	Inner Tracker
Geometry and Location	
Location of the Stations	IT1: $z = [767.3, 782.8]$ cm IT2: $z = [836.0, 851.5]$ cm IT3: $z = [905.0, 920.5]$ cm
Station Size	120 cm-wide and 40 cm-high
Active area	4.2 m^2
Operating system	
Temperature	$< 5^\circ\text{C}$
Cooling Liquid	C_6F_{14} at -15°C
Power Consumption	0.86 W per Beetle (72 W per box)
Silicon technology	
Technology	p ⁺ -on-n
Strip Pitch	$198 \mu\text{m}$
Strip Implant Width	$50 \mu\text{m}$
Silicon Thickness	$320 \mu\text{m}$ for 1-sensor modules $410 \mu\text{m}$ for 2-sensor modules
Si-Sensor Dimensions	$110 \text{ mm} \times 78 \text{ mm}$
Readout	
readout Strips Number/Sensor	384
Signal Shaping Time	25 ns
readout Chip Technology	$0.25 \mu\text{m}$ CMOS

3.3 Inner Tracker Assembly

The assembly process is described by the following procedure:

1. Checks of the Main Components

Before using the detector box in the assembly, depth and verticality controls are performed. The depth of the detector box is measured. The six measurement locations are defined by the position of the screw holes on the detector box lip. Conservatively, the minimal depth is considered when assessing whether the detector modules will fit the box. This is especially important for central boxes, as the detectors modules are by design very close to the bottom of the box, at only ~ 0.5 mm.

As the boxes stand vertically during the sensor modules insertion, their verticality is therefore checked. If needed, corrections are brought by applying 100 μm -thick layers of Kapton tape on the appropriate side of the detector box bottom.

The cooling rods are individually tested for leaks. The procedure consists in blocking one end of the cooling tube and connecting the other end to a manometer. The cooling rod is filled with Argon up to 4.8 bars and the circuit is closed (Figure 3.15). After two days, the pressure is checked again. If any significant variation of pressure corresponding to more than a few tenths of bars is noted, the test is redone. A cooling rod is rejected if the second test fails as well. All cooling rods were accepted.

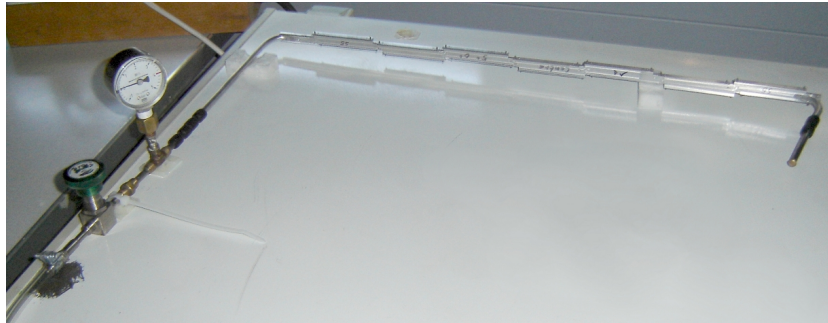


Figure 3.15: A cooling rod under pressure test.

For each detector module, the bond wires are checked visually with a magnifying glass for possible handling damage and dust.

The positioning of the silicon sensors on their module support is determined by metrology measurements. A first calibration step consists in measuring the position of positioning pins located on a controlled $x - y$ table using a microscope. The modules are then fixed through their positioning holes. Metrology measurements of targets located on the silicon sensors (Figure 4.5) are performed with respect to the positioning pins positions measured during the calibration.

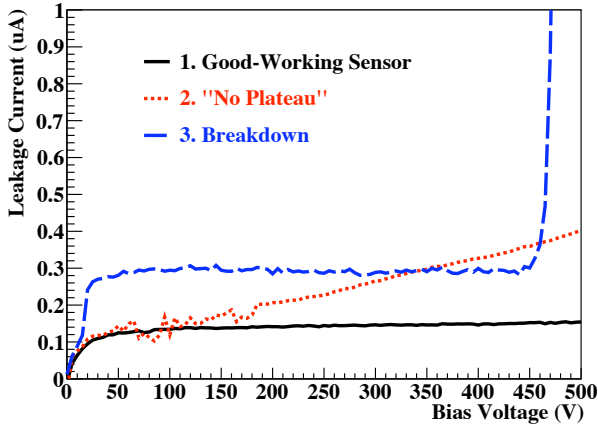


Figure 3.16: I-V curves for well-working and badly-working IT silicon sensor modules. Breakdown (blue dashed line) or continuous increase of the bias voltage (red dotted line) are usually signs of problems. The I-V curve of the well-working modules looks like that of a reverse biased diode, i.e. a quick increase converging to a "plateau" (black continuous line).

When a bias voltage V is applied on silicon sensors, even without signal, leakage currents I appear. The increase of the leakage current with the bias voltage is expected to behave as a reverse biased diode: a rapid increase at low bias voltage values converging to a plateau at higher values (Figure 3.16, black line). No continuous increase (red dotted line) nor breakdown (blue dashed line) should be observed for any bias value up to 500 V⁵. Plotting the $I - V$ curves of the silicon sensors is therefore an important quality check to perform. At a bias voltage of 500 V, the leakage current for typical well-working IT silicon sensors is $\sim 0.4 \mu\text{A}$ for two-sensor modules and $\sim 0.2 \mu\text{A}$ for one-sensor modules. The leakage currents have rarely exceeded $1.5 \mu\text{A}$.

A SiO_2 oxide layer located between the p^+ -implant and the aluminum readout strips has as purpose to get rid of all direct current components before they reach the pre-amplifier, as leakage currents. If shorts are present in the SiO_2 layer, called *Pinholes*, then leakage currents flow to the readout chips. For non-irradiated sensors, where leakage currents are small, this is not a problem. However, after irradiation, the leakage current rises and eventually saturates the readout channel. To detect the presence of pinholes, high currents are produced by illuminating a silicon sensor with a 25 Watt light bulb (HV off). The noise distribution registered in the sensor is then observed. In case of leakage currents, the noise is expected to be very small, as the leakage currents saturate the pre-amplifier.

The detection of *shorted* or *open channels* is also important as module quality check and as information for the hit reconstruction. For this, a test-pulse is sent to the channels of a silicon sensor. The pulses are alternately negative and positive for neighboring channels. The response of all the channels together is observed. In the case of two shorted channels, the observed signal is hence approximately zero, as the two signal components with different signs cancel. Open channels are identified by larger readout signals, caused by smaller input load capacitance of the respective input channel.

The resistance of the silicon sensor modules through time is also tested by exposing them to temperature cycling, which causes an artificial ageing. The temperature varies from -5 to $+40^\circ\text{C}$ thirty times in two days [69]. Once the test is achieved, the good functionality of the modules is checked.

⁵In practice, however, silicon sensors with a continuous increase but with leakage currents below $1 \mu\text{A}$ at 500 V were classified as well-working sensors.

2. Preparation of the Cover

The cover is mounted on a support, called *sliding setup*, which allows the cover to be moved up and down. It is carefully cleaned with compressed air and alcohol to remove residual dust. Three columns (Figure 3.17, (a)) are screwed to the cover together with hard-paper collars preventing damages to the thin aluminum film, which makes the cover a Faraday cage.

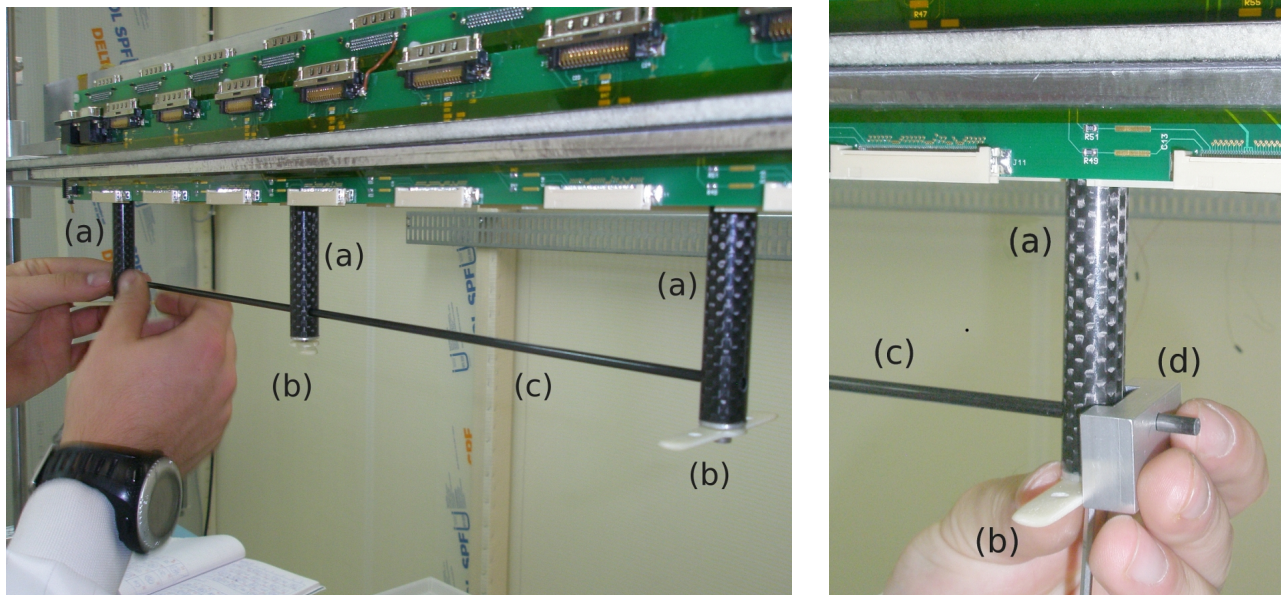


Figure 3.17: (a) columns, (b) fork, (c) bar, (d) special piece to control the position of the fork while it is screwed tight.

A stesalite transverse piece (b), called fork, is screwed to each column. The fork connects the columns to two colonnettes (Figure 3.18), onto which the two cooling rods will be fixed. The forks are larger than the distance between the two sensor module support structures and their extremities are 0.5 mm away from the detector box wall. In case of shock to the box, the extremities of the forks will therefore stop the movement before the sensors can touch the detector box wall.

A thin carbon fiber bar (Figure 3.17) (c) is inserted through the holes located at the bottom of the three columns (a) to align the three forks while they are mounted. For this, a special piece (d) is used to align the forks perpendicularly to the carbon fiber bar, which is removed once the mounting procedure is completed.

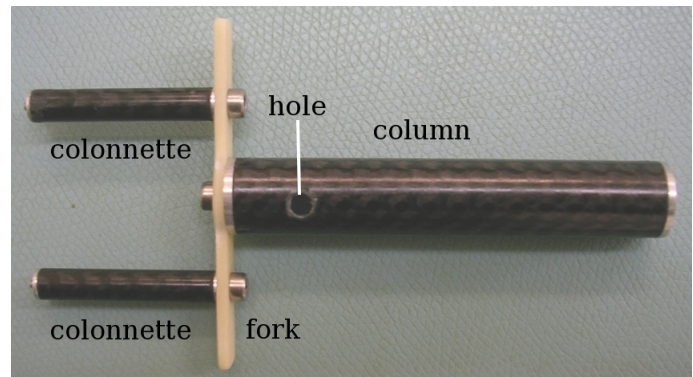


Figure 3.18: Detail of the assembly of a column, a fork, and two colonnettes. The hole in the column tube through which the carbon fiber bar is inserted when the fork is aligned can be seen. On this picture, the alignment was not done, thus the hole is not centered with respect to the fork.

3. Preparation of the Detector Box

To ensure that the cover populated with modules will be aligned with the detector box during the final insertion, the position of the empty box is first adjusted. This is done by placing the empty detector box on the base plate of the sliding setup, on which the cover is fixed. The cover is moved down and stops on the base plate are adjusted to maintain the detector box at the correct location⁶. Once the stops are adjusted, the cover is moved up and the box is removed.

4. Preparation of the Cooling Rod

A grounding wire is screwed on each cooling rod (Figure 3.19, left). Three 35 mm-long carbon fiber colonnettes are then screwed and secured with glue to the cooling rod (Figure 3.19, right). These allow the cooling rod to be fixed on a dedicated setup⁷, which can rotate along the vertical axis to ease the mounting of the modules on both sides of the cooling rod. A cleaning of the cooling rods is performed using alcohol, especially on the surfaces that will be in contact with the modules.

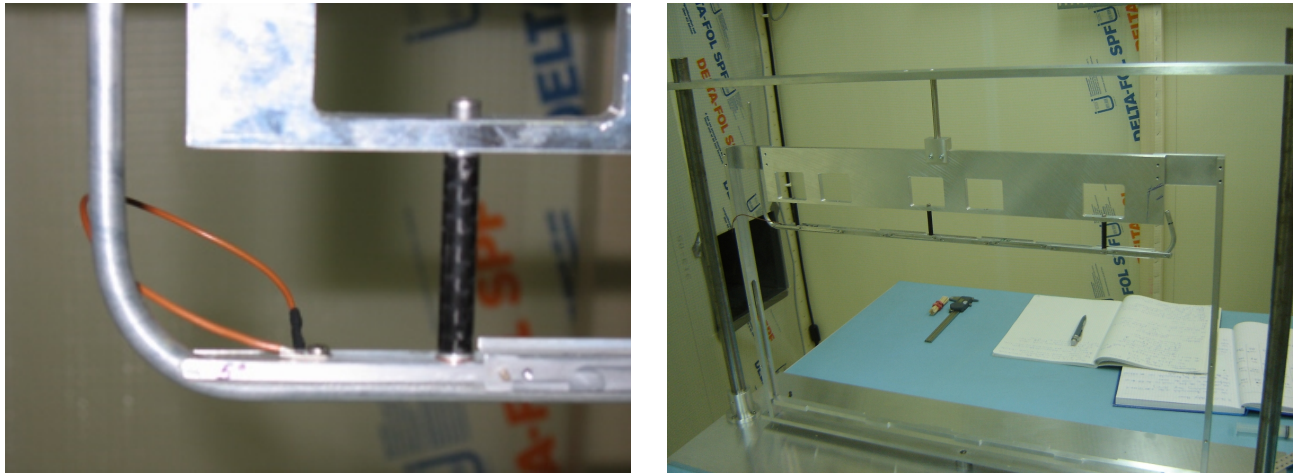


Figure 3.19: Grounding wire (left) on the cooling rod, which is mounted on its setup (right) via the three colonnettes.

5. Preparation of the silicon sensor Modules

The modules are cleaned with air to remove residual dust on the sensors. For the X1 and X2 external layers, there is a risk that the sensors, or the bonds, will touch the inner walls of the detector boxes. To prevent this, 55 mm-long and 27 mm-large foam buffers are centrally glued with double-sided adhesive tape on top of the forward sensors, at about 15 mm from the bottom of the modules (Figure 3.20, left). To have complete spatial coverage, the modules within a layer are staggered in the z direction by 4 mm. To prevent the back of one module from touching the sensor behind, 80 mm-long and 10 mm-large foam buffers are glued at the rear of the forward modules at about 20 mm from the bottom of the modules (Figure 3.20, right).

⁶For the side boxes, the position of the right-hand stop is set in order to have about 1 cm between the stop and the box wall. This precaution is needed because the distance between the edge of the module and the box inner wall is only 0.5 mm on this side. Thus, during the module insertion, this distance is increased for safety reasons.

⁷At the final stage of the assembly, they will be fixed to the forks of the cover.

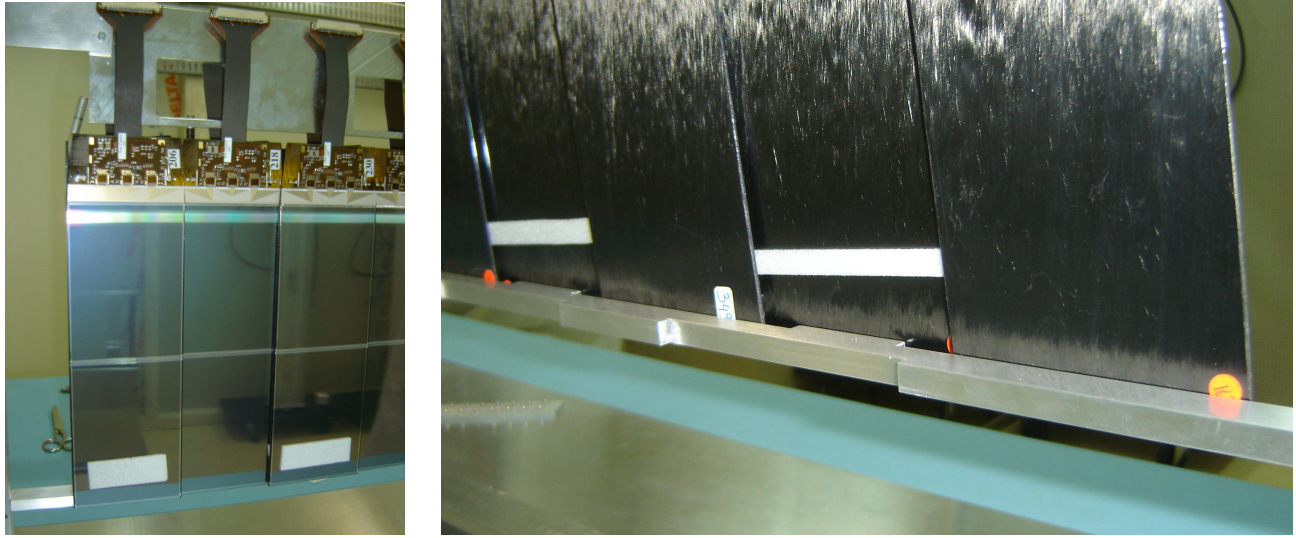


Figure 3.20: Foam protections glued on forward sensors of the external layers to prevent them from touching the walls of the boxes (left) and at the rear of all the forward modules to protect the backward sensors to be touched by those (right).

Inside a box, two criteria have led to the actual distribution of the individual silicon sensor modules.

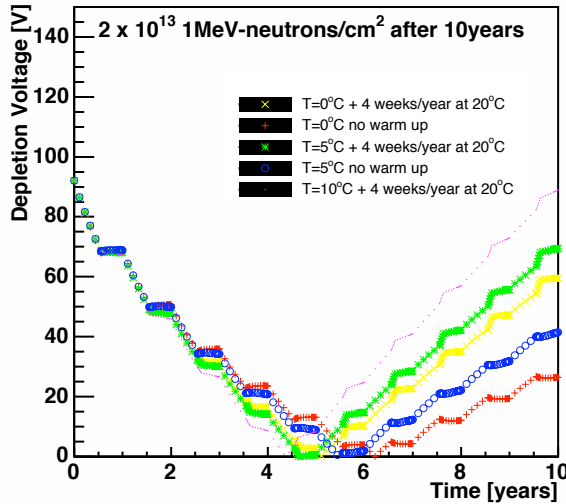


Figure 3.21: Depletion voltage variation as a function of time for different temperatures. After type inversion, the depletion voltage increases with time.

quality of the sensor in terms of shorted, open or pinholed channels⁹. The sensor specifications demand $\leq 1\%$ of faulty channels. Most of the modules installed are 100% working. The number of faulty strips is found to be 111 out of 129,000. The modules with faults, but still meeting the specifications, are placed where the particle density is expected to be the least.

The first criterion is based on the depletion voltage values of the modules. In an IT detector box, the bias voltage comes from a single HV channel for groups of four modules. Therefore, modules with similar depletion voltage values are grouped together⁸. As the depletion voltage varies with time due to the radiation dose (Figure 3.21), it will be possible to partition in a different way the high voltage, such that the depletion voltage needed is properly provided at any time to all the modules.

The second criterion is about the overall quality of the sensor in terms of shorted, open or pinholed channels⁹. The sensor specifications demand $\leq 1\%$ of faulty channels. Most of the modules installed are 100% working. The number of faulty strips is found to be 111 out of 129,000. The modules with faults, but still meeting the specifications, are placed where the particle density is expected to be the least.

⁸Depletion voltages ranging from 40 V to 160 V are found.

⁹As a remainder, shorted channels are two strips connected together, which is typically due to a fault on the pitch adapter. Open channels are readout strips that are not connected to the Beetle chip, which is typically due to traces on the pitch adapter that were interrupted or to a failed bond. Pinholed channels are shorts in the SiO_2 layer between the aluminum readout strip placed above the implanted p^+ doped strip.

6. Mounting of two layers of modules on each side of the first cooling rod

To maximize the heat transfer between the cooling rod and the back of the detector modules, a layer of thermally and electrically conductive grease is spread on the contact surfaces on each side of the cooling rod (Figure 3.22, left), as well as at the rear of each module (Figure 3.22, right).

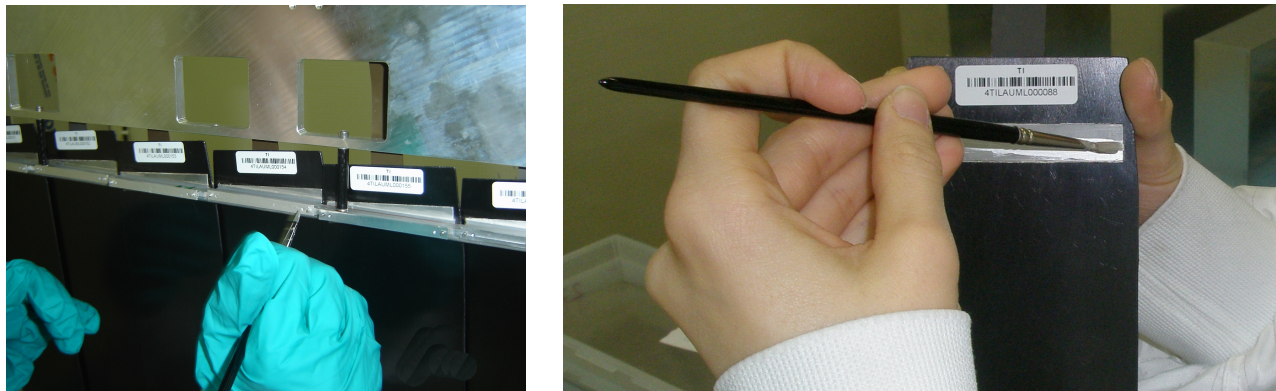


Figure 3.22: Application of thermally and electrically conductive grease on the cooling rod where the modules will be fixed (left) and on the module balconies (right).

The modules are placed starting with the ones located behind and then with the ones located in front (Figure 3.23). They are fixed with screws at each side of the alignment pins (Figure 3.24). An aluminum bar with specially designed crenelated shapes on both sides can be inserted in the support setup (Figure 3.20, right). The bar acts as a stop, preventing the back of forward modules from touching the sensors or the bonds of the backward modules during the assembly.

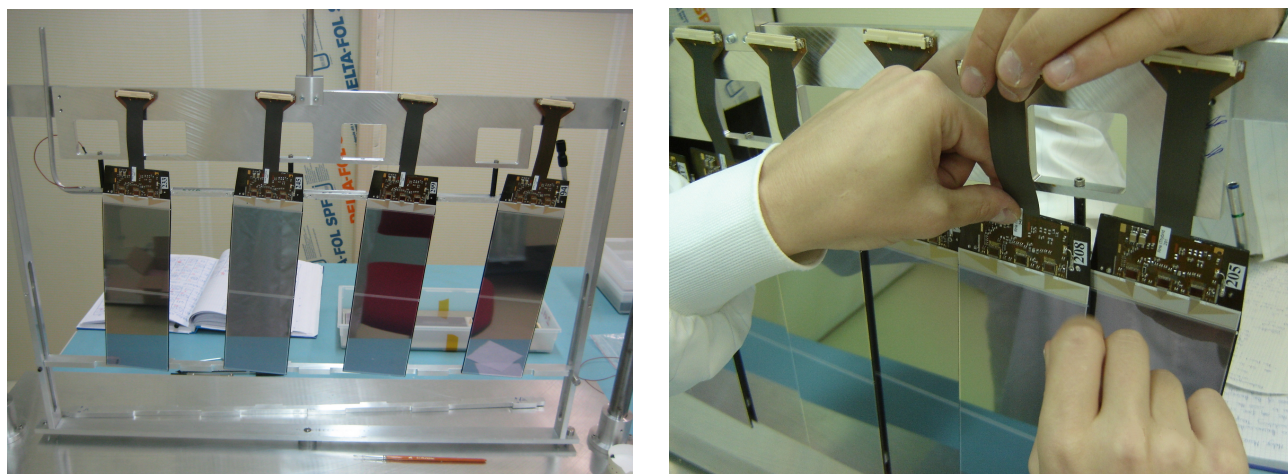


Figure 3.23: Fixation of the modules on the cooling rod, starting with the backward modules (left) and following with the forward modules (right).

The bonds of each module are re-inspected with the help of a magnifying glass after the assembly procedure.



Figure 3.24: Fixation of a silicon sensor module using two screws located besides the alignment pins.

7. Mounting of the first cooling rod under the cover

The cooling rod, populated with modules is brought to the cover plate prepared on the sliding setup. The long pipe extremity of the cooling rod is carefully inserted into a hole in the cover and is slid until the three colonnettes of the cooling rod are in place to be screwed to the forks of the cover (Figure 3.25, left).

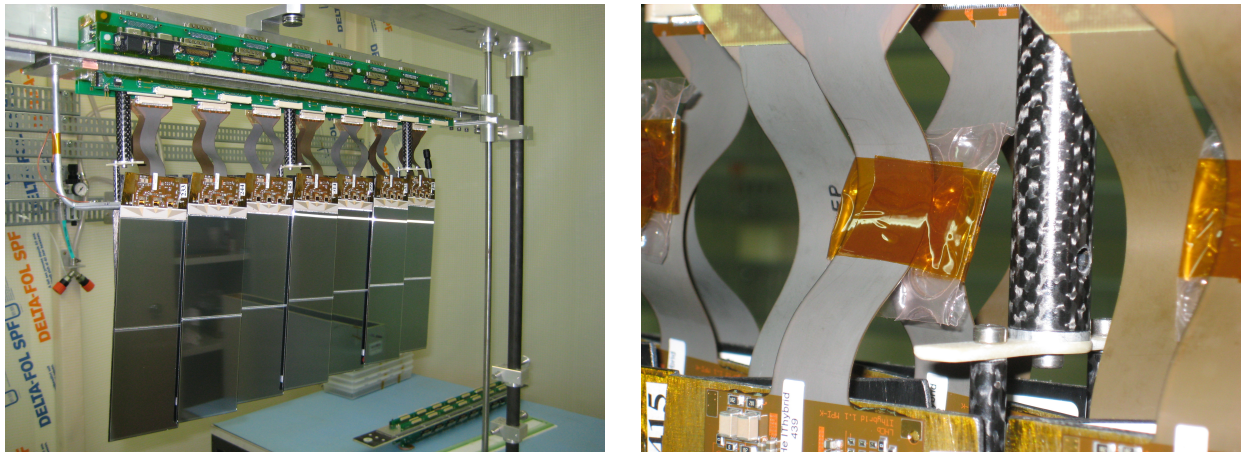


Figure 3.25: First cooling rod mounted on the detector box cover located on the sliding setup.

8. Mounting of the second cooling rod

The second cooling rod is furnished with sensors and is fixed to the cover, as detailed for the first one. At the end of the step, the two cooling rods are therefore fixed on their cover support. The detector modules are then connected to the inside connectors on the interface PCBs. The ground thread of each cooling rod is also connected to the cover and is secured to the vertical cooling pipe with Kapton tape. Bubble wrap is inserted to prevent the Kapton tails from touching one another, which is potentially a source of noise (Figure 3.25, right). Before closing the cooling circuit, which is a delicate procedure, High Voltage tests are first performed, to detect possible faulty modules.

9. HV Test of the Modules

HV problems are the ones most frequently observed during module production. In addition, the HV-bond wires are located very close to the edges of the modules. Hence, they are prone to accidental damage during the box assembly. For these reasons, additional HV tests are performed once the box is assembled. The test is done by inserting the assembly into a large aluminum test box, which provides light shielding for the modules. The HV-connectors are connected to the HV-modules as described in the full module test (Item 13. of this Subsection). The modules are slowly (~ 3 min) ramped to 500 V and the test is passed if none of the modules show signs of a breakdown, in the form of a sudden increase of leakage current, as previously done before the assembly (Item 1. of this Subsection).

10. Closing of the Cooling Circuit

The cooling circuit is completed by connecting the two cooling rods. The missing piece of the circuit is a steel tube bent in a U-shape (Figure 3.26).

11. Cooling Circuit Leak Test

The test setup consists of a bottle of argon (Ar), a pressure probe, a valve on one side, a brass plug on the other side and an electronic device, which has been designed to read out a pressure probe and to display the measured pressure (Figure 3.27). The Ar bottle, pressure probe and valve are connected to one end of the cooling circuit with a Legris connector. The air inside the circuit is flushed away with some Ar. Then, the other end of the circuit is blocked with the brass plug via another Legris connector. The circuit is pressurized up to about 5 bars, the valve is closed, isolating the cooling circuit, and the Ar bottle is disconnected. Any pressure drop is then recorded¹⁰.

The current pressure in the circuit, the temperature and pressure of the room, and the time are recorded to compute the leak rate. After about two days, the same physical quantities are measured again. These data allow the computation of the leak rate of C_6F_{14} in cubic centimeters per year. This computation and the conversion from Ar leak rate to C_6F_{14} leak rate is based on the method documented in [70].

If leak rates are found, several actions are taken. The connectors of the pressure setup are tightened, the setup itself is retested and the four Legris connectors composing the cooling circuit are changed for new ones. Eventually, all twelve detectors boxes have passed the cooling circuit leak test. Once the cooling circuit is validated, it is possible to circulate the coolant, which is necessary to power up the Beetles for full electric tests.



Figure 3.26: U-shaped tube.



Figure 3.27: The cooling circuit leak test setup.

¹⁰This test is similar to the test of the individual cooling rods described in Item 1. of this Subsection.

12. Survey of the Visible External Layers X1 and X2

The goal of the survey is to provide estimates of the position of the sensors. The survey procedure is detailed in Chapter 4.

13. Full electrical tests

A full readout test of a cooling rod assembly with 28 modules is carried out before the assembly is placed in the final detector box. This is done in the large aluminum box used for the HV test (Item 9. of this Subsection). The test uses all the final parts of the detector readout (Subsection 3.2.3). One detector box is read out by two service boxes, each containing one control board together with 28 digitizer boards for each module inside one detector box. The service boxes are powered by low voltage supplies. The digitizer boards are connected to the readout hybrids of the modules via 28 data readout cables. During the test, the service box backplanes are cooled. The box is also cooled and connected to the N₂ supply to lower the humidity. High voltage power supplies are used to provide the 500 V bias voltage to the silicon sensors. One ODIN board [71] provides the *Clock and Timing and Fast Control (TFC)* signals, which are dispatched by an optical splitter to the TELL1 boards. The data collection is done using the TELL1 boards, which are connected via an ethernet switch to a computer where the data are recorded.

Additional leakage current tests are performed and raw data are recorded for all the modules, with or without (pedestal) testpulse injection into the Beetle readout chip. The readout of the temperature probes and the humidity sensors inside the detector box has also been checked during these tests.

14. Height of the Modules

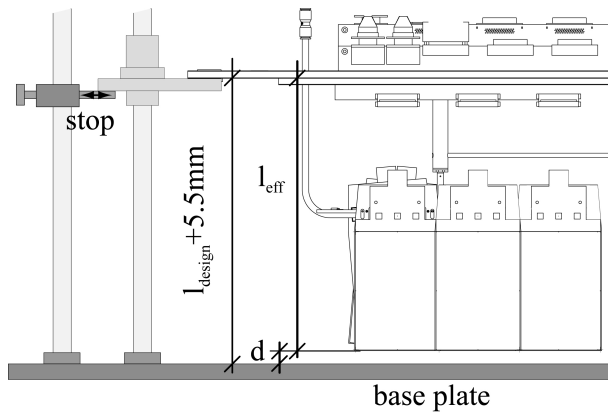


Figure 3.28: Measurement of the distance between the cover and the tip of the sensor modules.

The height of the sensor modules is checked to ensure that they will fit in the box without touching the bottom of the box. The distance between the lower edge of the modules and the lip of the cover l_{eff} is measured and compared to the depth measurement of the detector box explained previously (Item 1. of this Subsection). For central boxes, the nominal space between the bottom edge of the modules and the bottom of the detector box is 0.5 mm. For side boxes, the space underneath the tip of the modules is not critical in term of acceptance and hence the space is much larger, ~ 5 mm.

To measure l_{eff} (Figure 3.28), the cover supporting the modules is maintained at a distance $l_{\text{design}} + 5.5$ mm using stops of the sliding setup (Figure 3.29, left). The distance d is then estimated using calibrated wedges and precision blades (Figure 3.29, right), from which l_{eff} is deducted ($l_{\text{eff}} = l_{\text{design}} + 5.5 \text{ mm} - d$). Conservatively, the minimal depth measurement of the detector box is kept, from which the maximal l_{eff} value is subtracted to assess whether the modules fit into the detector box.

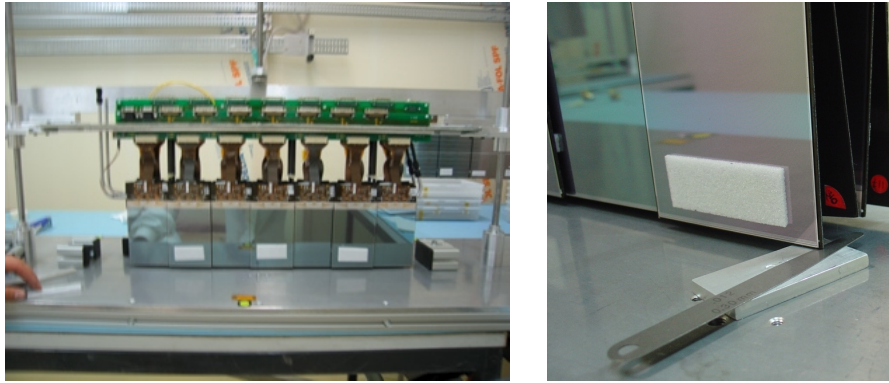


Figure 3.29: Test of the height of the sensor modules, with the cover resting on the stops of the sliding setup (left). The distance d is measured between the base plate and the bottom of the module supports using a calibrated wedge and precision blades (right).

In case it is found that the modules will not fit into the detector box, an appropriate number of 0.2 mm-thick glass fiber frames is added between the cover and the top of the detector box to increase artificially the depth of the detector box.

15. Final Insertion of the Silicon Sensors into the Detector Box

The detector box is placed under the cover according to the stops set on the base plate (Item 3. of this Subsection). The cover with the detector modules is slowly lowered into the box manually using a vertical screw on top of the setup (Figure 3.30). At the entry of the modules inside the box, a visual inspection is done to ensure that bonds do not touch the walls of the detector box.

For side boxes, one lateral wall of the box is only at 0.5 mm from the edge of the modules. For the delicate insertion operation, the detector box is shifted laterally so that this distance is increased to a safe value of 1 – 2 cm.

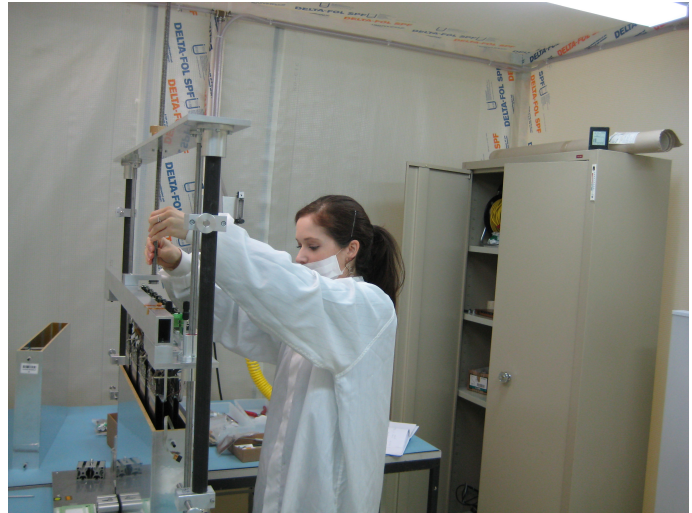


Figure 3.30: Closure of a detector box.

A few centimeters before the completion of the insertion process, the temperature probes and the inner shield ground thread are connected to one PCB. The bundle of wire is secured to one of the cooling pipes to prevent any constraint on the connector, which could lead to a disconnection.

Just before the inside of the cover reaches the lip of the box, its position can be readjusted to allow a smooth entry of the cover inside the detector box. For side boxes, the detector box is shifted back to its nominal position. To maximize the air tightness of the detector boxes, a large band of Kapton tape is glued on the cover before it is screwed to the box. The air tightness is crucial to minimize the transfer of humidity to the inside of the box. By Summer 2008, all the IT detector boxes were assembled and installed in the LHCb cavern.



4

Inner Tracker Survey Strategy and Implementation in the LHCb Software

Since a very good momentum resolution is expected at LHCb, the alignment of the tracking system is of prime importance. The first step in the alignment procedure consists in adjusting the position of the tracking system components as close by as possible to the nominal design values using survey measurements. Once the adjustments are achieved, their final positions are measured very precisely and a first realistic description of the geometry can be derived from the results. For the Inner Tracker, survey measurements have been performed at different levels: the survey of the IT silicon sensor modules in a clean environment gives the position of targets printed on the silicon sensors with respect to a target located on the detector box cover. The same target is also visualized during the IT frame and detector box survey in the LHCb experimental cavern. The first realistic Inner Tracker geometry description obtained from the final survey measurements has been used as the starting point in the Inner Tracker detector alignment procedure using particles coming from LHC synchronization tests.

The methods used for the Inner Tracker survey are explained in Section 4.1. The strategy for the silicon sensor survey in a clean environment is detailed in Section 4.2 and in Section 4.3 for the frame and detector box survey in the LHCb experimental cavern. Section 4.4 summarizes the implementation of the survey results in the LHCb software to provide a first realistic Inner Tracker geometry description. This description was tested during the software alignment of the Inner Tracker using secondary particles coming from LHC injection tests (September 2008 and June 2009). Results from the LHC injection test Inner Tracker alignment are given in Section 4.5, together with the performance of the Inner Tracker estimated from the same data.

4.1 Survey Measurement Methods

Theodolite Measurements



Figure 4.1: Theodolite (top) and survey target (bottom).

A theodolite (Figure 4.1, top) measures horizontal and vertical angles from the station where it is placed to the observed target (Figure 4.1, bottom) [72]. Some theodolites, called *total stations*, are additionally equipped with a distancemeter, which enables them to measure distances between the station and the target. The 3D coordinates of the observed target are determined:

1. By *polar coordinates* (Figure 4.2, left) from the station using horizontal angle H , vertical angle V and distance D observations. In this case, there is no redundancy.
2. By *triangulation* (Figure 4.2, right) using only the horizontal $H1$ and $H2$ and vertical angles $V1$ and $V2$ observed from different stations, a condition being that at minimum one distance between two points is known in the model to fix the scale. This measurement is slightly redundant as four angles (two horizontal and two vertical angles) are observed for three unknown variables (x , y and z).

The triangulation is used in the case of the silicon sensor survey in a clean environment (Section 4.2) and the polar coordinates for the positioning of the IT detector boxes in the cavern (Section 4.3).

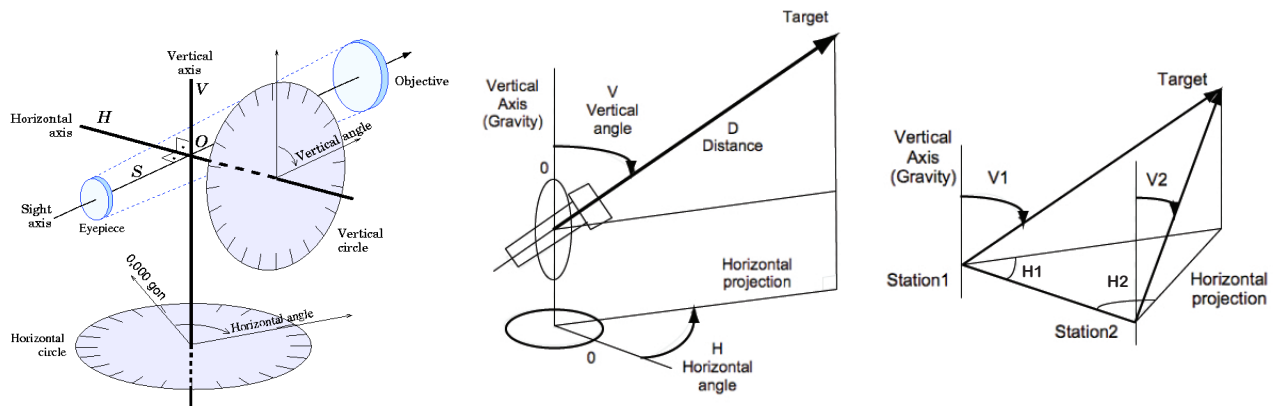


Figure 4.2: Basic principle of theodolite measurements [72].

Typically, accuracies of 0.2 to 0.5 mm are obtained for the measured point coordinates. However, the accuracy can be improved depending on the way the theodolite is used to minimize the instrumental errors, the quality of the targeting, the configuration and the environmental conditions. As an example, the stability of the theodolite station and the surveyed object is very important, as the measurements are made point by point and take time.

Photogrammetry Measurements

Close-range photogrammetry relies on the reconstruction of an object simultaneously from at least several images (Figure 4.3). Different and best possible perspectives ensure a suitable geometry of intersecting rays. The photogrammetric network is reconstructed from the bundle of rays. The internal parameters of the camera, the object coordinates and the orientation parameters of the network are estimated simultaneously in a common process called *bundle adjustment* [73].

This method is applied in the LHCb cavern to map the half-frames and determine the IT detector boxes positions on them. The reconstructed objects are retroreflective targets. The 3D coordinates of the targets are determined from a hundred pictures taken from different points of view by a Nikon D2X digital camera (Figure 4.4, left) connected via WiFi to a portable PC. Some targets are coded (ring-shaped sectors on Figure 4.4, middle). This coding provides to the targets a unique number and enables the software to find them automatically on different pictures. The coordinates of the central disks (Figure 4.4, middle) are calculated. Some other non-coded targets only contain the central reference point (Figure 4.4, right). From the coded targets, the external parameters of the camera (position, rotations, translations) in the object space are determined. This allows the matching between the uncoded points on the different pictures and therefore their numbering. A final bundle adjustment is then performed.

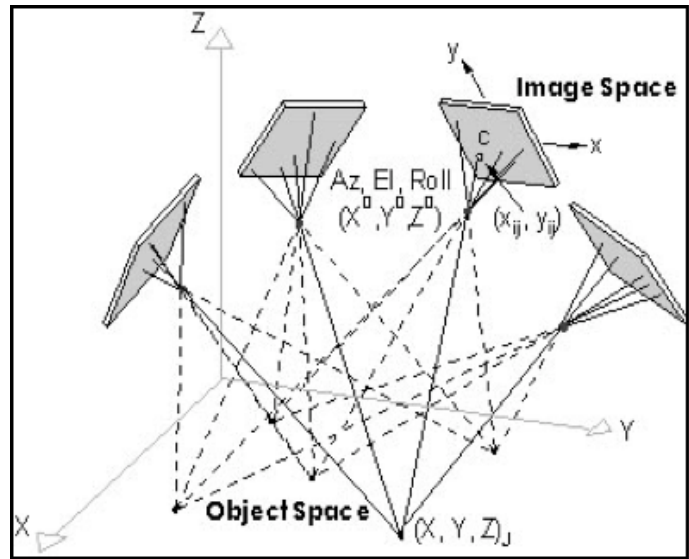


Figure 4.3: Basic principle of photogrammetry [73].

Accuracies of 0.03 mm to 0.5 mm are expected depending on the working conditions and on the object size, which can be from some decimeters up to more than 20 m.

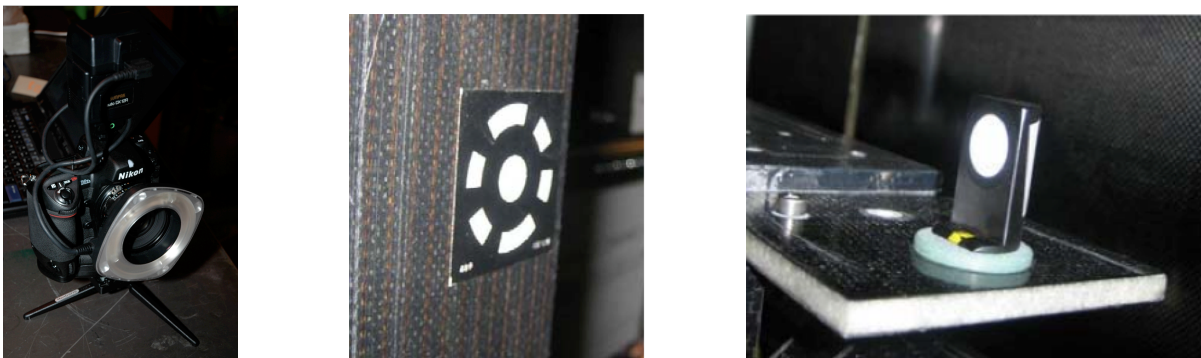


Figure 4.4: Camera (left), coded (middle) and non-coded (right) targets used for the photogrammetry measurements.

4.2 IT Silicon Sensor Survey in a Clean Environment

Eight fiducial marks are etched on each sensor (Figure 4.5), which are crosses of 0.2 mm long branches.

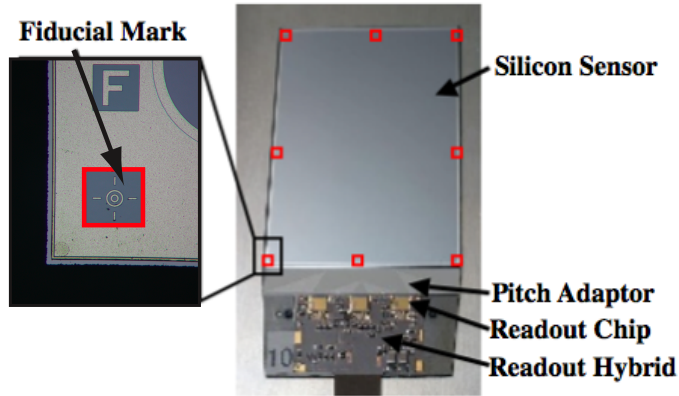


Figure 4.5: Cross-shaped fiducial marks locations (red).

of high precision (LEICA T3000) equipped with a panfocal telescope. The instruments are installed on tripods fixed to the floor and work simultaneously (Figure 4.6). Neon lights are used to ease the detection of the fiducial marks without heating locally the room air to avoid pointing errors due to air turbulences. Before surveying, the horizontality of the cover is checked with a bubble level of precision of 0.3 mm/m (Figure 4.7).

For forward modules (Figure 3.10), all the targets are visible, but only the ones at the four corners are measured, as they are sufficient to obtain a very good accuracy on the sensor position. For backward modules, only the two targets in the middle of the sensor short edges are visible, except for the modules placed at the extremities of the X2 layers, where two more targets at one edge are visible. All the fiducial marks are measured with respect to a target located on the box cover (Figure 4.7).

The silicon sensor survey is performed in a clean environment by two electronic theodolites

To get the reference direction, the theodolites point at each other in order to align their optical axes. Each fiducial mark is then observed from both theodolites and coordinates are calculated using triangulation. As triangulation consists of angle measurements only, at least one distance has to be added in the process to fix the scale, as explained in Subsection 4.1. These additional distances are given by measurements of targets installed on four invar or carbon fiber scale bars observed simultaneously to the sensors (Figure 4.7). The distances between the scale bar targets have been calibrated with an accuracy better than 20 μm .

Due to the small size of the clean room, the two external layers X1 and X2 are measured independently. A rotating frame has been designed in order to improve the accuracy of the relationship between the two sets of measurements. This relationship is obtained after a 3D best fit transformation using six common targets visible in the two positions of the rotating frame, which are placed on the sides of the rotating frame (Figure 4.7). No measurement is performed on the U and V internal layers, as they are by design hidden by the external X1 and X2 layers. The survey results can be found in [74].

As the silicon sensor survey has been performed in excellent conditions (clean room, stable temperature, good lightning), the measurement accuracy is reduced to ± 0.05 mm. The target position accuracy on the box cover is ± 0.1 mm and ± 0.2 mm for the geometrical link between the two sides.

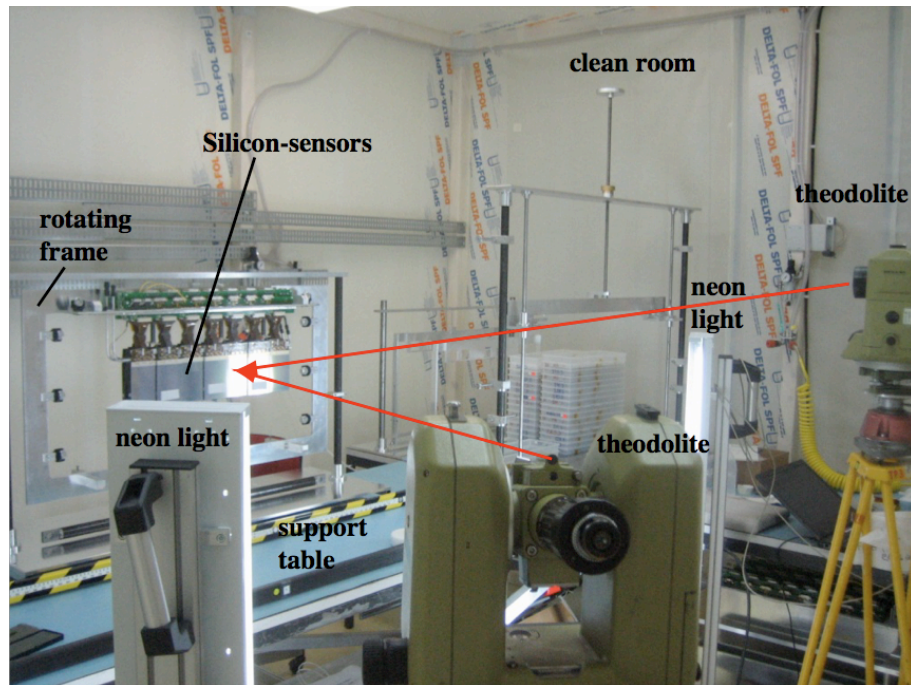


Figure 4.6: Survey measurements with two theodolites in a clean environment. Neon lights are used to ease the detection of the fiducial marks on the sensors.

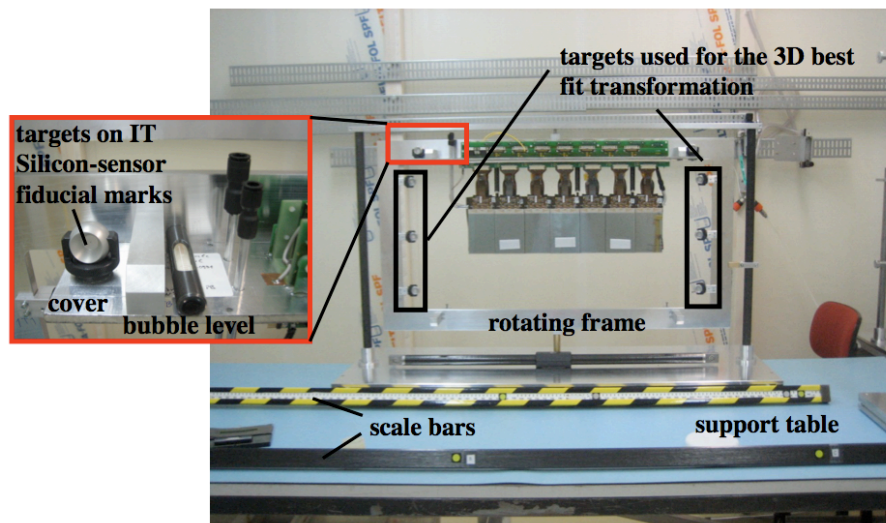


Figure 4.7: Six targets are placed on the rotating frame to get a redundant relationship between the measurements of the layers X1 and X2. Scale bars are used to provide the global scale of the system. Before the survey measurements, the cover is checked to be horizontal with a bubble level. The survey results are given with respect to a target located on the cover.

Metrology measurements have also been performed in a clean environment on each individual module. In the case of two-sensor modules, these measurements give the relative position of one sensor with respect to the other, with a precision of a few micrometers.

4.2.1 Silicon Sensor Survey Results

The residual distributions (δx , δy , δz) between the silicon sensor survey measurements (x_{meas} , y_{meas} , z_{meas}) of the fiducial marks and the corresponding nominal values (x_{nom} , y_{nom} , z_{nom}) are shown in Figure 4.8 for central boxes (left) and side boxes (right), separately for the x (top), y (middle) and z (bottom) coordinates.

The δx and δy values are smaller than ± 1.5 mm. The largest values are often related to modules located at the extremity of the cooling rods where these start to bend to connect to each other. Indeed, for these modules, the position of the last pin is not constrained by the cooling rod.

Some δz values reach ± 4 mm. These are caused by the "freedom" of the modules to rotate around the x axis, as these are attached to their support by only one side. Hence, measurements of targets located the furthest away from the cooling rods show worse agreement with the expected values than the ones located the closest to the cooling rod.

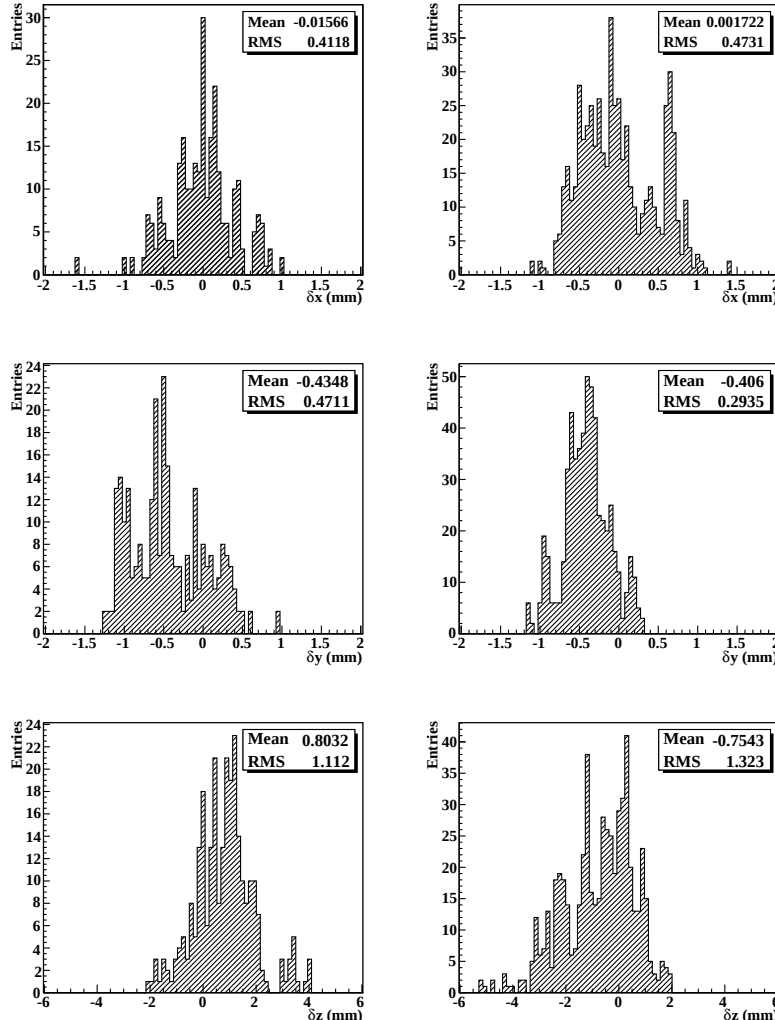


Figure 4.8: δx , δy and δz ($\delta_p = p_{\text{meas}} - p_{\text{nom}}$) residuals for central boxes (left) and side boxes (right).

4.3 IT Frame and Box Survey in the LHCb Cavern

A first survey of the IT frames was performed by theodolite from the magnet region to check their verticality and vertical position. The frames were rolled in the precision rails and adjusted for their positions along the z axis and their orientation in the $x-y$ plane. These operations led to the discovery of a mis-mounting of the rolling carts which had, as a consequence, an inclination of the IT3 half-frame plane with respect to the vertical plane. Once fixed, the measurements also allowed the adjustment of the position along z of the frames by tuning their attachment onto the upper rolling carts.

Once the beam pipe and its protection box were installed in February 2007, it became unsafe to set up the theodolite in the magnet region. Moreover, a sub-set of the reference points became not visible nor accessible anymore. Therefore, to obtain a complete mapping of the half-frames including IT dummy boxes¹, the frames needed to be in an open position.

To perform these measurements, the photogrammetry method (accuracy of 0.1 mm) is chosen (Figure 4.9), as no stable position can be found to install theodolite stations at different levels in front of the opened half-frames. However, when fully opened, the rolling carts of the half-frames are not engaged on the precision rails, resulting in possible imprecision in the measurements, mainly in the z direction. Therefore, a theodolite measurement of the targets that remain visible when the half-frames are in an almost closed position is performed in addition. To get the mapping of the half-frames in closed position, a best fit 3D transformation is calculated using the full set of point coordinates measured in opened position. The transformation parameters are calculated using two best fits of the common points measured in both open and almost closed positions by photogrammetry and theodolite.

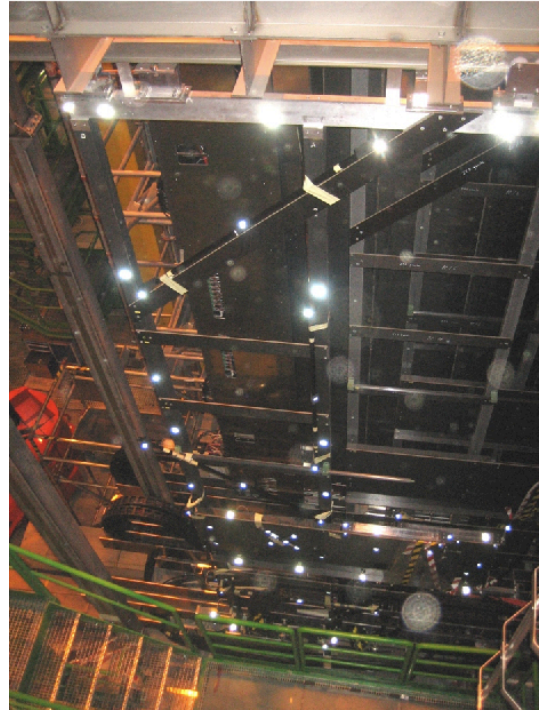


Figure 4.9: Photogrammetry measurements of the IT1A half-frame.

The photogrammetric measurements led to the discovery of a weak positioning element of the half-frames, as their positioning was not accurately reproducible (~ 3 mm difference in x of the target positions on the side box cover before/after closing IT1C) [75]. By the time this element was replaced, the working conditions for photogrammetry became not optimal in the LHCb cavern.

At this time, it was decided to continue the survey measurements on the IT detector boxes themselves, instead of the IT frames, which was possible using theodolite. The final determination of the IT detector box positions could hence start.

¹As the IT detector boxes were not finished at the time when these measurements were performed, they were substituted with dummy boxes consisting of box covers.

4.3.1 Final Determination of the IT Detector Box Positions

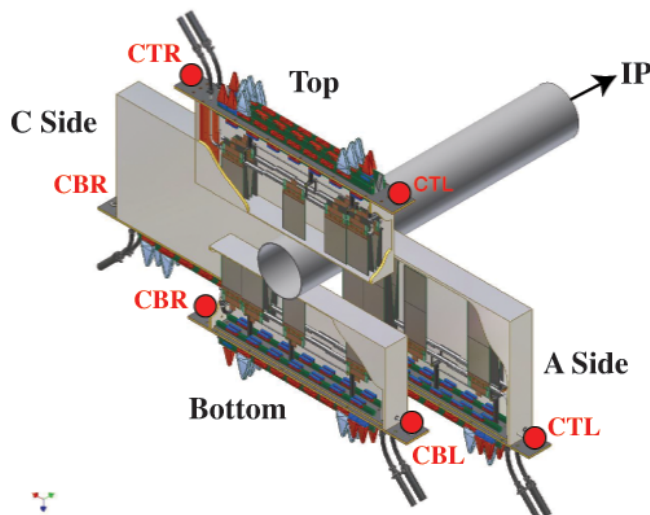


Figure 4.10: CT/R and CBL/R survey targets (red circles).

to lack of visibility in the LHCb cavern. Therefore, multipoint target bars have been designed to replace these single targets. They have also the advantage of bringing some redundancy to the results. The original target of 20 mm is only used for one side of the Top boxes (Cryo side) (Figure 4.11).

The multipoint target bars used are equipped with retroreflective stickers, even though the precision of distance measurement is worsened from 0.2 mm for a standard glass reflector to 0.5 mm. This was accepted mainly for safety reasons. In fact, the use of standard glass reflectors means that an access is needed to put and remove the target for each individual point measurement. This is not allowed because the frames are closed around an unprotected region of the beam pipe. In addition, due to the IT survey configuration, this change in precision influences mostly the coordinate in the beam direction, for which the demanded accuracy is relaxed. The retro-reflective target choice makes also the multipoint bar design easier and cheaper. The target centers are aligned on the supports. The distances between the targets are known with an accuracy better than 0.1 mm.

Three types of bars are designed (Figure 4.11):

1. 150 mm-bars containing three retroreflecting targets at 30, 100 and 140 mm. This type of target bar is used for the Top Boxes (placed on the Access side of the box), for the A-Side Boxes (Cryo side), for the C-Side Boxes (Access side) and the Bottom Boxes (Cryo side).
2. 500 mm-bars containing four targets at 30, 270, 400 and 490 mm. Such targets are employed for the A-side Boxes (Access side) and the C-side Boxes (Cryo side).
3. 600 mm-bar containing three targets at 510, 560 and 590 mm. Only one target of this design has been used for the Bottom Boxes (Access side).

²A new beam pipe protection was designed with new supports and sliding protection covers. It was optimized to allow IT survey from the wall in RICH1 region, in order to minimize the access inside the magnet.

The whole station is surveyed for the first time in the final closed position (Figure 4.11). From the method of calculation of Euler angles and offsets developed for the analysis of the survey measurements (Subsection 4.4.2), corrections to be applied at the level of the brackets supporting the boxes are calculated. The final survey measurement of the station is performed and the accuracy of the survey measurements is ± 0.5 mm for the x and y coordinates, and ± 1 mm for the z component. The survey results can be found in [74].

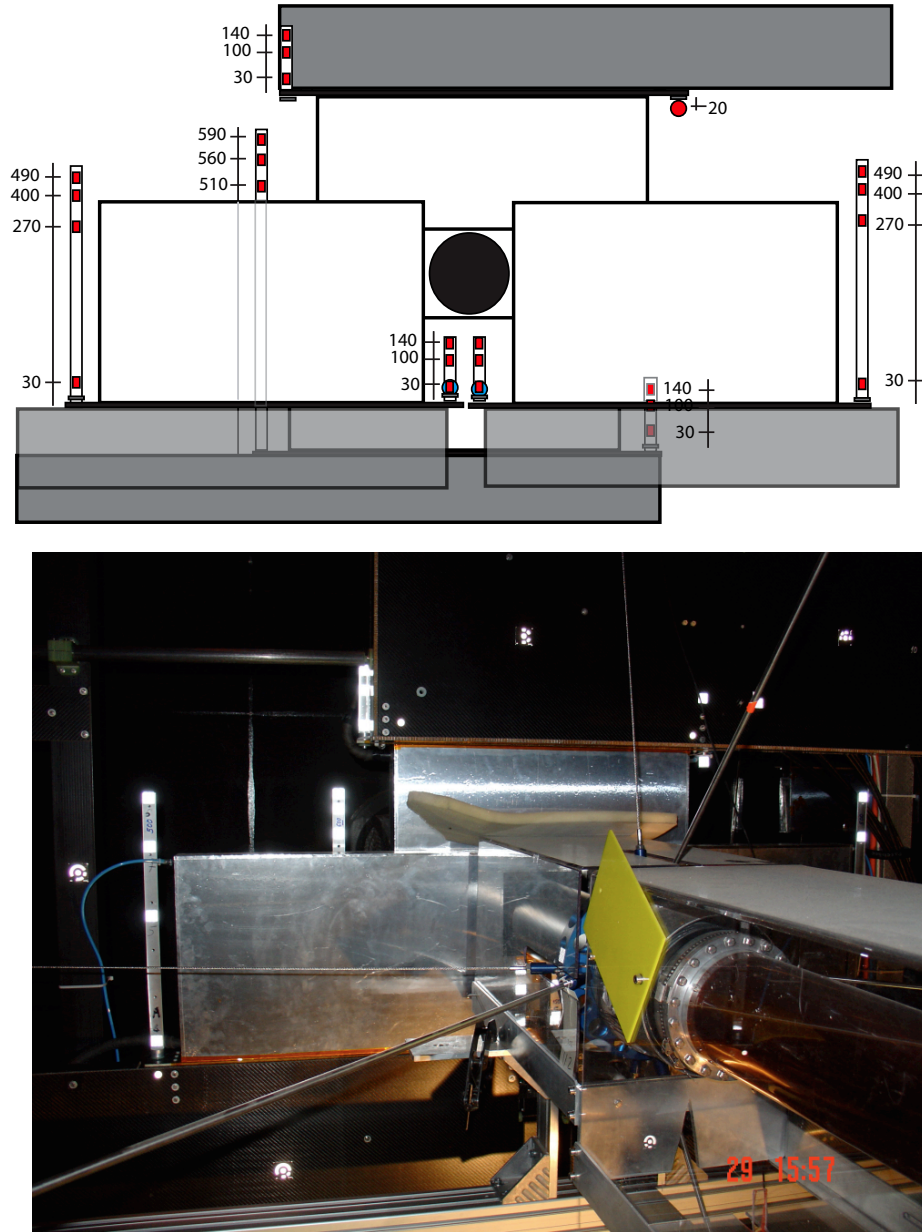


Figure 4.11: Multipoint target bars used for the survey of a station in the final closed position from the RICH1 region.

4.3.2 Detector Box Survey Results

The residual distributions (δx , δy , δz) between the IT detector box survey measurements (x_{meas} , y_{meas} , z_{meas}) and the corresponding nominal positions (x_{nom} , y_{nom} , z_{nom}) are shown in Figure 4.12 for the x (left), y (middle) and z (right) coordinates. The distributions of residuals for each component show a non-negligible dispersion. This could be explained by the fact that the bars supporting the retroreflecting target stickers could have been tilted by a small angle relative to their nominal position during the survey measurements in the LHCb cavern, as illustrated in Figure 4.13. In this case, the further the targets are located from the covers, the most affected their position determination is.

To ensure the most accurate estimate of the box position, a straight line passing through the measured targets is determined (Figure 4.13) each time no target at 20 mm or 30 mm from the cover has been measured. Then, the position of a virtual target, placed at a nominal position of 20 mm or 30 mm, is computed (Figure 4.13, green star) and used together with the target measurement placed at 20 mm or 30 mm on the other bar at the other side of the box to obtain the rotation angles and offsets of the box (Figure 4.12).

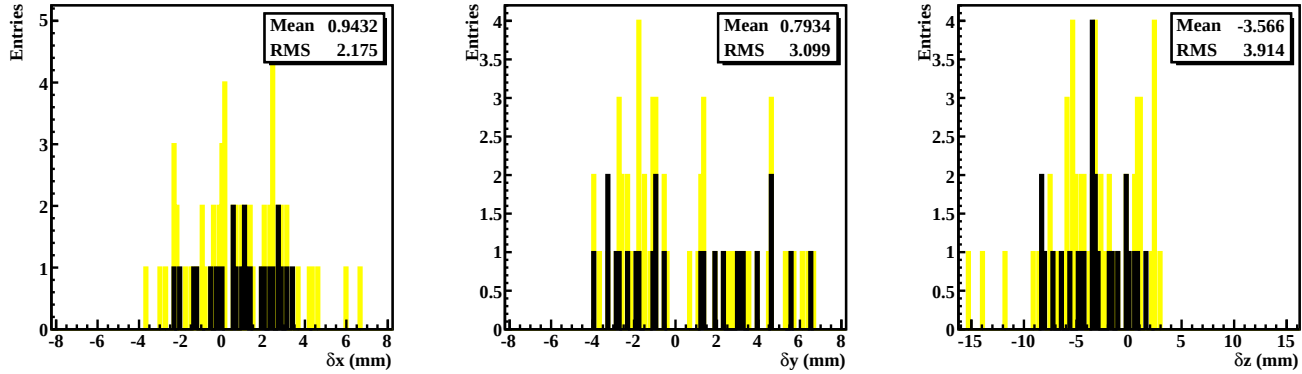
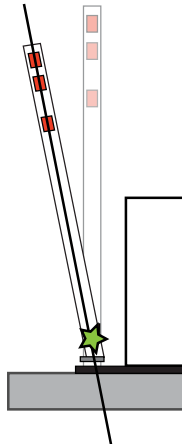


Figure 4.12: δx , δy and δz ($\delta_p = p_{\text{meas}} - p_{\text{nom}}$) residuals for real and virtual targets used in the calculation (black area) and the targets not used (yellow area).



The precision of the measurements is ± 0.5 mm for the x and y coordinates and ± 1 mm for the z component.

However, this does not include the uncertainties due to the fact that the survey measurements had to be performed with the Outer Tracker detector in the open position (Subsection 4.3.3). The uncertainties rising from constraints due to the cabling and cooling are also not taken into account. For these reasons, the final uncertainties on the survey measurements in the LHCb cavern are estimated to be within 1 – 2 mm.

Figure 4.13: Bending of a survey multipoint target bar.

4.3.3 External Constraints on the IT Frames

Measurements of the Magnetic Forces applied on the Bridge

During the LHC runs, the magnet will not be kept always at full field, but the field will be reduced to some intermediate values after each fill of the accelerator with protons and then ramp up to full field. As the LHCb magnet is brought up to full field, some detectors close to the magnet could possibly shift slightly [76]. It is also not excluded that some of the joints of the stainless steel bridge supporting the IT stations (Figure 4.14) have been magnetized during assembly procedure. Moreover, in order to give to the bridge more rigidity along the beam direction, it has been fixed to the magnet by means of two stiffening bars. The attachment points were selected as points where the magnet structure was measured not to move by more than 1 mm, but this has to be checked again. Survey results show that the bridge does not move more than 1 mm, which is the survey measurement accuracy, due to magnetic forces applied on it. Moreover, the yoke of the magnet does not move when the magnet is on.

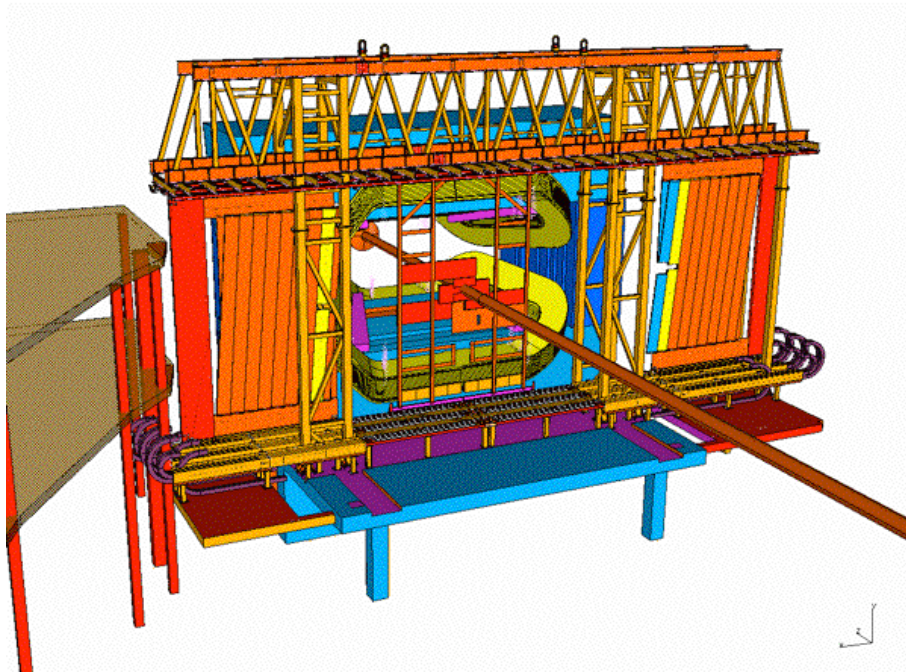


Figure 4.14: Bridge holding the IT and OT frames.

Forces applied on the Bridge by the Outer Tracker Detector

During the final survey measurements of the IT detector boxes, the stations of the Outer Tracker were in an open position. Once closed, it has been observed that the IT1 station went down by 0.4 – 0.5 mm and the IT3 station by 1 mm. This is certainly related to the weight of the OT detector.

4.4 Corrected IT Geometry Implementation in the Software

4.4.1 Geometry Description in the LHCb Software

In the GAUDI framework [40], two hierarchy trees are defined: the *geometry tree* and the *structure tree*. The geometry tree is constructed from *logical* and *physical volumes*. Logical volumes have information about shapes (box, sphere,...), dimensions (width x , height y , thickness z), material content and children nodes, represented by physical volumes. Each physical volume has information about its position inside the mother logical volume.

In the structure tree, all the logical volumes, called *detector elements*, are positioned relatively to their logical volume mother. The absolute coordinate reference system is defined by the top-level logical volume, the whole LHCb detector, and the origin (0,0,0) is located at its center. Apart from the top-level logical volume, no logical or physical volumes have any information about their absolute position in space [77].

The misalignments deduced from the survey measurements can be implemented either in the *Condition DataBase (CondDB)*, which acts on the detector element positions in the structure tree or by changing the ideal geometry database (*DDDB for Detector Description DataBase*). A combination of both is also possible: including gross misalignments in the DDDB and finer in the CondDB.

The DDDB [78] stores persistent information about the description of the detector. The advantage of using it is that it is common for real data and simulation and is applicable to any volume in the IT detector. However, it requires that the parents of the volumes being aligned are unique.

The CondDB [79] stores time-dependent elements of the DDDB in XML files. In it, the requirements about the IT module positions are expressed in the *321 Euler representation* in terms of a rotation of the system (ϕ, θ, ψ) around the z , y' and x'' axes about a pivot point, followed by an offset (dx, dy, dz) with respect to the nominal position. Its advantage is that it does not require that the parents of the volumes to align are unique. Its disadvantages are that it is not common for real data and simulation and that it works only for detector elements.

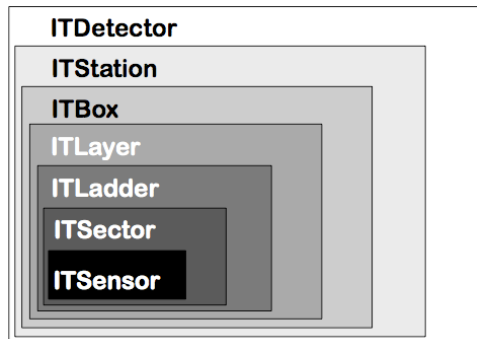


Figure 4.15: IT detector element tree starting with the whole IT detector, that has the IT stations, IT detector boxes, IT layers, IT modules (ITLadder), IT sectors and the IT silicon sensors as descendants.

As the IT silicon sensors survey results have not shown a common offset behavior between the IT boxes corresponding to the same logical volume, for all central boxes for example, and as the two internal layers were not surveyed, the offsets and rotation angles are introduced in the CondDB.

The detector element tree of the IT detector in the *eXtensible Markup Language representation (XML)* (Figure 4.15) starts with the whole IT detector (ITDetector), and has as descendants the stations (ITStation), the detector boxes (ITBox), the layers (ITLayer), the modules (ITLadder), the one-/two-sensor systems (ITSector) and the sensors (ITSensor) [80].

4.4.2 321 Euler Angles and Offsets Calculations

The nominal values of the silicon sensors are corrected at four levels (Figure 4.16):

1. the Detector Box level (ITBox)
2. the Layer level (ITLayer)
3. the Module level (ITLadder)
4. the Sensor level (ITSensor)

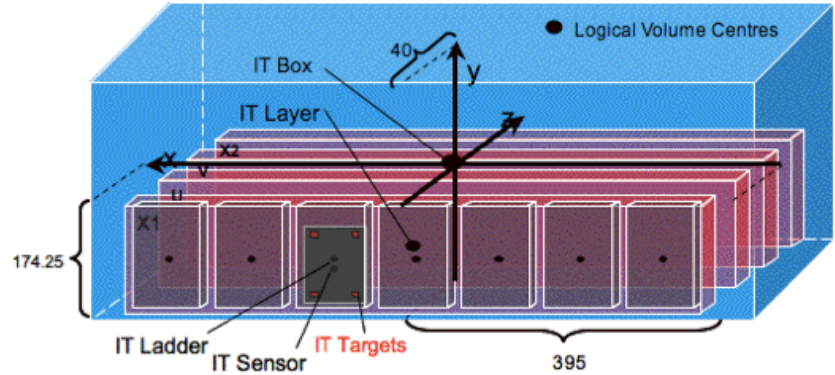


Figure 4.16: Logical volumes of the IT detector at the box level.

Although the IT Stations were surveyed, as explained in Section 4.3, it has been decided not to apply any corrections at this level. It has been observed that the relative position of the Carbon fibre plates supporting the IT detector boxes with respect to the pillars sustaining the IT stations is not so precise. Moreover, the final adjustments of the IT detectors boxes have been performed locally and individually for each box, adjusting the brackets positions supporting the detector boxes.

Euler angles characterize three successive rotations into which a general rotation in the 3D Euclidean space can be decomposed. The convention chosen by LHCb is the *xyz convention*, also called *Tait-Bryan angles*, for which the global rotation is a composition of a rotation around the z axis (ϕ angle) followed by a rotation around the y' axis (θ angle) and a rotation around the x'' axis (ψ angle) (Figure 4.17).

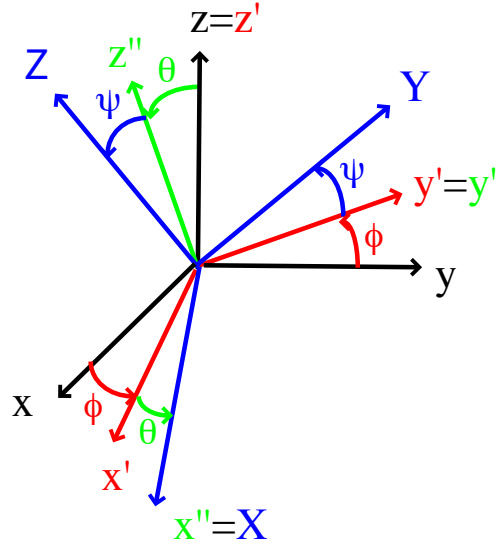


Figure 4.17: 321 Euler angle representation. The original system (x, y, z) is transformed into the final coordinate system (X, Y, Z) , passing through (x', y', z') and (x'', y'', z'') .

The 321 Euler angles and offsets of a logical volume are calculated with respect to its center.

In the case of the Inner Tracker, the (x, y, z) coordinates are given by the nominal coordinate system and the X, Y and Z vectors are determined as followed:

1. *At layer level.* Only sensors placed in a forward position in a layer are taken into account. The four targets placed at the extremities of the sensor modules are used only (Figure 4.5), for a total of 16 targets in the case of X1 layers and 12 for X2 layers. The sums in absolute value of the x and y coordinates of these targets are calculated and normalized. This provides two vectors, namely X and Y . The Z vector is derived by inner product of X and Y . To ensure orthogonality, the X vector is recalculated by inner product between the Y and Z .
2. *At module level.* The same calculation as for layer level is applied to modules in the forward position. For modules in the backward position, only two (or four for two-sensor modules) points positioned on a line are available. To derive a set of orthogonal vectors describing the system, a new point, non-aligned with the measured points, has to be inserted. The measured point the closest to the cooling rod is taken as a reference point. The z coordinate of the new point is set at the coordinate value of the reference point, z_{ref} . The x coordinate of the new point is defined by the sum of the coordinate of the reference point x_{ref} and the x component of the vector perpendicular to the vector passing through the measured points in the $z = z_{\text{ref}}$ plane. The y component of the new point is calculated in a similar way.

3. *At sensor level.* Metrology measurements are used for two-sensor modules (Figure 4.18). They give the relative position of one sensor with respect to the other. Metrology results have shown a systematic shift and rotation of the sensor the furthest away from the readout hybrid (Figure 4.18, red).

As only the four fiducial marks located at the extremities of the two-sensor modules were used for the calculations at layer and module levels, the position of the two-sensor system after rotation lies in between the true position of each sensor separately (Figure 4.18, blue). The corrections at sensor level are therefore half the shifts and rotations measured by metrology. Opposite values are used for the second sensor (Figure 4.18, green).

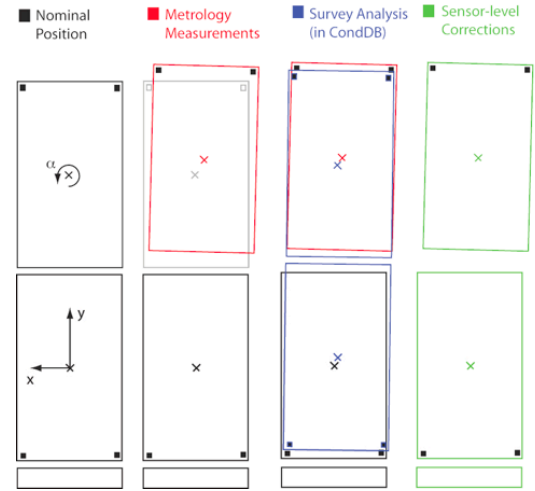


Figure 4.18: The average positions of the two sensors after layer and module rotation (blue) are corrected to bring the sensors to their relative positions measured by metrology (green).

4. *At box level.* Only two targets are used for the calculation of the X vector. As explained in Subsection 4.3.2, these can either be real targets located at 20 mm or 30 mm from the cover or virtual targets. For the bars containing multiple targets, vectors are obtained by subtracting the coordinates of the target with the smallest y to the target with the largest y coordinate. If two multiple bars are used for a given box, an average vector is computed. The Y vector is obtained by projecting the resulting vector on the plane defined by X as the normal vector. The Z vector is obtained by inner product of X and Y .

The final rotation matrix of the 321 Euler representation to pass from the nominal system to the corrected one is given by:

$$R = \begin{pmatrix} \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ \sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \cos\theta\sin\psi \\ \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi & \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\theta\cos\psi \end{pmatrix}$$

with:

$$\begin{pmatrix} x_{\text{corr}} \\ y_{\text{corr}} \\ z_{\text{corr}} \end{pmatrix} = R \cdot \begin{pmatrix} x_{\text{nom}} \\ y_{\text{nom}} \\ z_{\text{nom}} \end{pmatrix}$$

The offsets and 321 Euler angle values can be found in [81]. In a detector box, the X1 and U layers are attached to the same cooling rod, while the X2 and V layers are fixed on the other one. As it is assumed that the rotation at layer level mainly comes from the rotation of the support cooling rods, it is decided to apply the same offsets and rotation angles than X1 for the U layer, and than X2 for the V layer. No correction is applied at the module level for the silicon sensors of the U and V layers.

In Figure 4.19, the δx , δy and δz residuals between the survey measurements and the nominal values (hatched area) are shown together with the residuals between the survey measurements and the values obtained after the rotation and translation of the layer (double hatched area), and the residuals between the survey measurements and the values obtained after layer and module corrections (filled area). The mean μ and σ values of the distributions of the residuals after layer and module corrections are given in Table 4.1. This table and Figure 4.19 show that the calculation of the rotation angles and offsets for the layers and modules is precise, because the reconstructed values are located within the window of ± 0.05 mm (red dashed lines) corresponding to the survey measurements precision.

In Figure 4.20, the δx , δy and δz residuals between the survey measurements and the nominal values corrected by box rotation and translation are shown, both for the targets used (filled area) and the targets not used in the calculation (hatched area). The mean μ and σ values of the distributions for the target used are given in Table 4.1. The final offsets for the used targets are in good agreement with the survey measurement precision of ± 0.5 mm in x and y and ± 1 mm in z (red dashed lines). The determination of the position in x of the detector box was overconstrained because two measurements were available, but the constraint arising from the length of the covers was applied at the same time. This explains the bigger dispersion of the δx distribution centered to zero.

Table 4.1: Mean μ and σ of the residual distributions of the silicon sensors targets after layer and module corrections (left), and of the LHCb cavern targets used after box correction (right).

	residual distributions after layer layer and module correction (filled area, Figure 4.19)		residual distributions of the targets used in the calculation after box correction (filled area, Figure 4.20)	
	μ (mm)	σ (mm)	μ (mm)	σ (mm)
δ_x	-0.0003 $\pm$ 0.0067	0.008 $\pm$ 0.006	-0.0264 $\pm$ 0.0747	0.309 $\pm$ 0.091
δ_y	-0.0004 $\pm$ 0.0110	0.013 $\pm$ 0.009	-0.0000 $\pm$ 0.0006	0.001 $\pm$ 0.001
δ_z	-0.0005 $\pm$ 0.0205	0.034 $\pm$ 0.024	-0.0000 $\pm$ 0.0009	0.001 $\pm$ 0.001

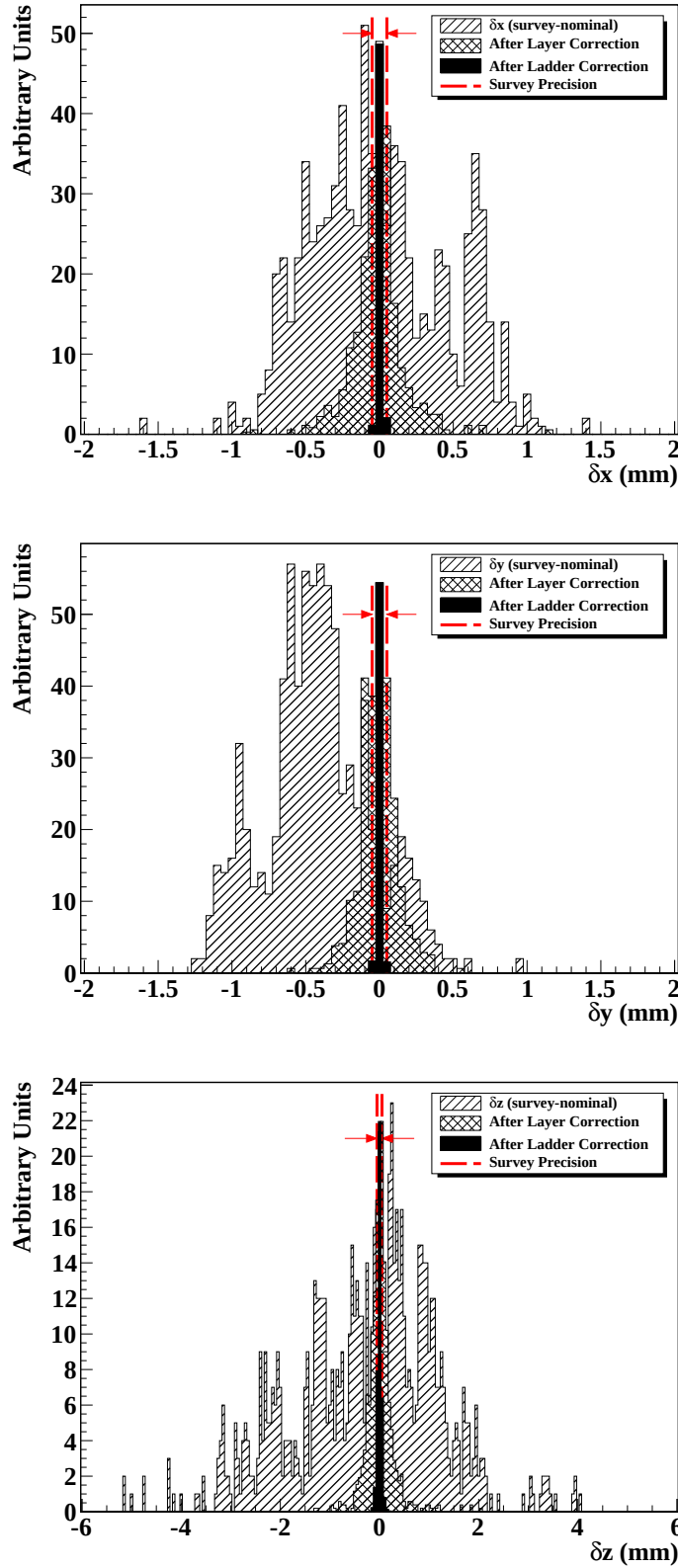


Figure 4.19: δx (top), δy (middle) and δz (bottom) residuals between survey measurements and nominal positions (hatched area), nominal positions corrected by layer rotation and translation (double-hatched area) and nominal positions corrected by layer and module rotations and translations (filled area). The fits to a Gaussian of mean μ and width σ of the final residuals (filled area) give ($\mu = -0.0003 \pm 0.0067$ mm, $\sigma = 0.008 \pm 0.006$ mm) for δx , ($\mu = -0.0004 \pm 0.0110$ mm, $\sigma = 0.013 \pm 0.009$ mm) for δy and ($\mu = -0.0005 \pm 0.0205$ mm, $\sigma = 0.034 \pm 0.024$ mm) for δz . In all cases, the final residuals are in good agreement with the survey measurement precision of ± 0.05 mm (dashed lines).

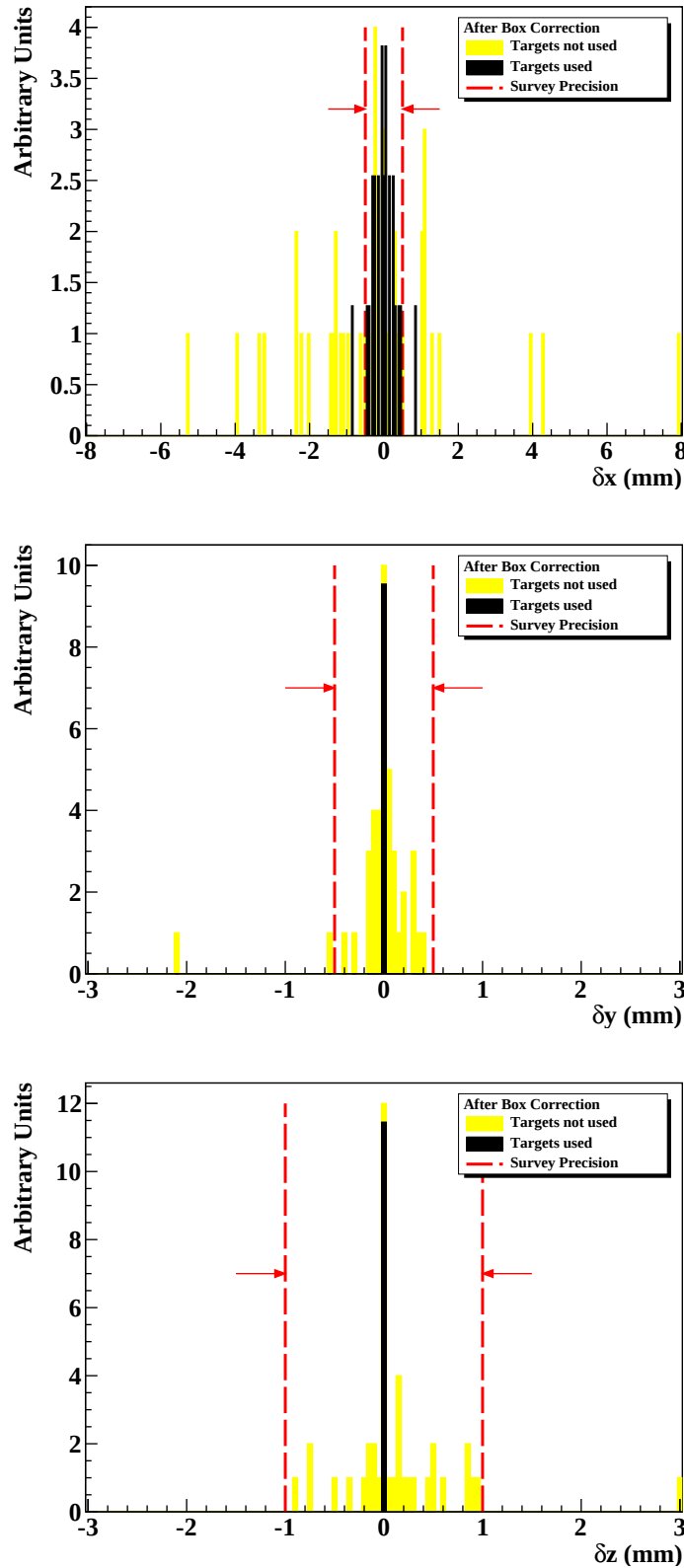


Figure 4.20: δx (top), δy (middle) and δz (bottom) residuals between survey measurements and nominal positions corrected by box rotation and translation for the targets not used in the calculation (yellow) and the targets used in the calculation (black). The fits to a Gaussian of mean μ and width σ of the final residuals (black) give ($\mu = -0.0264 \pm 0.0747$ mm, $\sigma = 0.309 \pm 0.091$ mm) for δx , ($\mu = -0.0000 \pm 0.0006$ mm, $\sigma = 0.001 \pm 0.001$ mm) for δy and ($\mu = -0.0000 \pm 0.0009$ mm, $\sigma = 0.001 \pm 0.001$ mm) for δz . In all cases, the final residuals of the targets used are in good agreement with the survey measurements precisions of ± 0.5 mm in x and y and ± 1 mm in z (dashed lines).

4.4.3 Validation of the Corrected IT Geometry Implementation

The introduction of the misalignments in the CondDB or GeomDB can lead to *overlaps*. These are the result of a volume extending beyond the boundaries of its mother volume or the intersection of volumes positioned within the mother volume [44]. A check for overlaps is performed using PANORAMIX [49] (Figure 4.21, left). No overlap has been detected using this method.

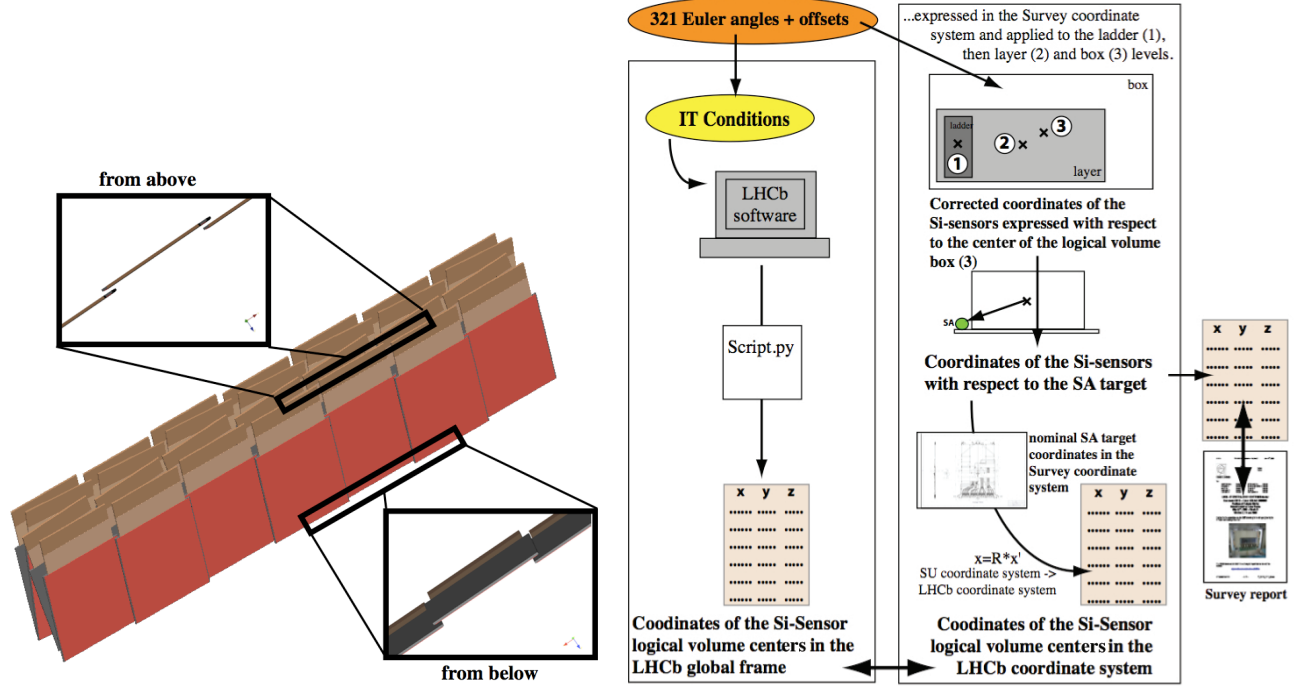


Figure 4.21: Zooming on the top and bottom of PANORAMIX views of the layers allows a check for overlaps between adjacent modules inside the layers (left). Method for checking the computed Euler angles and offsets at the module, layer and box levels using the LHCb software (right). The positions of the sensor logical volumes are obtained in the LHCb coordinate system from the software by applying the survey database. They are compared with the values obtained by applying the rotation angles and offsets to the nominal positions of the sensor logical volumes in the survey coordinate system, which are then expressed in the LHCb coordinate system. The results can also be compared with the results of the survey measurements performed in the clean room.

Since the IT detector geometry is a complex multi-level structure, the following procedure is used to ensure that each rotation and translation is correctly applied at all levels (Figure 4.21, right).

The (x, y, z) coordinates of the sensor volume logical centers expressed in the LHCb coordinate system are computed by a python script in the LHCb software, applying the IT survey conditions. A second list of coordinates is obtained by applying the module, layer and box corrections to the sensor logical volume centers expressed in the survey coordinate system, with as origin the survey target located on the cover. The position of this target in the LHCb cavern is obtained from the design plans. Once this value is added, the coordinates are transformed by rotation into the LHCb coordinate system³.

The two lists are compared and the δ_x , δ_y and δ_z residual distributions are checked. The coordinates of the second list, before adding the position of the box cover target in the cavern, are also compared to the values quoted in the silicon sensor survey reports (Figure 4.21, right).

³The survey coordinate system is rotated with respect to the LHCb coordinate system [74]

4.5 Inner Tracker Commissioning and Performance

4.5.1 Alignment Strategy at LHCb

The alignment strategy is defined in four steps. As the LHCb coordinate system is defined by the VELO (Subsection 2.4), the first step naturally consists of a VELO internal alignment. It is followed by a standalone alignment of the T-stations. The T-stations and the TT are then aligned with respect to the VELO [82], before the RICHs, calorimeters and muon chambers are aligned with respect to the T-stations.

A standalone alignment of the Inner Tracker is possible using tracks going through its three stations. The alignment procedure starts with the biggest elements to align, usually the detector boxes, down to the smallest elements, usually the modules. The IT system possesses 2016 degrees of freedom (3 stations x 4 boxes x 4 layers x 7 silicon-strip modules x 6 degrees of freedom) [82].

Alignment Procedure in the LHCb software

The software alignment method is based on a χ^2 minimization [83]. The model contains parameters for tracking (x) and for alignment (α). The alignment procedure is performed in four steps:

1. *Track Reconstruction.* Alignment parameters are global, as they are common to all the tracks in the sample. As track parameters are local, they are first determined using an initial estimate α_0 for the alignment parameters. Tracks are reconstructed using pattern recognition and track fit algorithms (Section 6.1). Optionally, track selection criteria on the track quality χ^2 , the momentum, the number of hits per detector or the number of missed hits on the tracks are applied to obtain a cleaner sample of tracks.
2. *Track Processing.* A C++ algorithm allows the alignment for any of the six degrees of freedom coming from translations T and rotations R , (T_x , T_y , T_z , R_x , R_y , R_z), for any combination of detector elements. This algorithm takes as input the selected tracks and the detector elements chosen by the user to be aligned. It assigns the hits on tracks. The alignment parameters α are calculated by minimizing the sum of the track quality χ_t^2 , χ^2 , with respect to α [83]:

$$\frac{d\chi^2}{d\alpha} = 0 \quad \text{with} \quad \chi^2 = \sum_t \chi_t^2 \quad \text{and} \quad \chi_t^2 = r_t^T V_t^{-1} r_t \quad (4.1)$$

with $r = m - h(x, \alpha)$ a first order linearization of the residuals between the measurements m and the function h describing the measurements in terms of x and α , and V^{-1} the measurement covariance matrix.

3. *Solving Phase.* After processing all the tracks of the calibration sample, the corrections to the alignment parameters, $\Delta\alpha = \alpha - \alpha_0$, are determined by a solver tool.
4. *Update Phase.* The alignment parameters are updated in the LHCb geometry database.

4.5.2 First IT Software Alignment from LHC Injection Tests

In Summer 2008, the IT detector boxes of Chapter 3 were installed in the experimental cavern and commissioning began. Due to the LHCb spectrometer geometry, a commissioning procedure using secondary particle showers from cosmic rays was not ideal. However, thanks to LHC injection tests performed in September 2008 and June 2009, a source of horizontal particles became available.

These tests consisted in transferring bunches of $2 - 5 \times 10^9$ protons at 450 GeV from the SPS towards the LHC ring and dumping them onto a beam stopper, called *TED*, just before the LHC tunnel (Figure 4.22). The LHCb experiment located 350 m downstream received huge amounts of secondary particles. Simulation studies indicate that most of the particles reaching LHCb were 10 GeV muons coming from decays of pions produced in the TED.

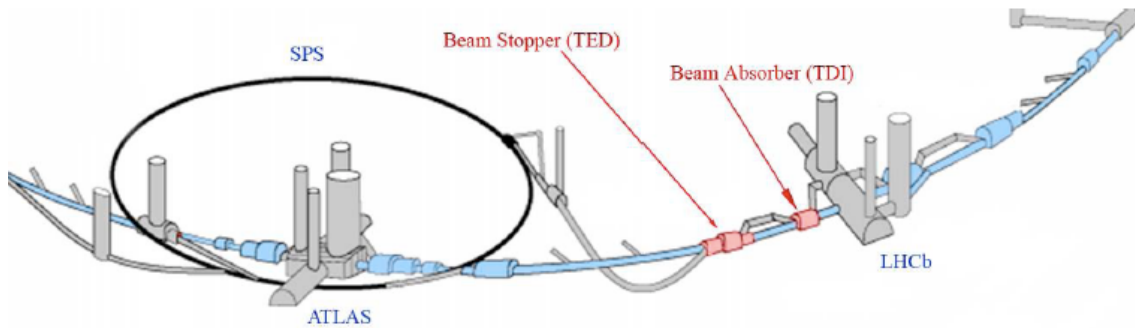


Figure 4.22: LHC and SPS rings with the LHCb cavern and the beam stopper (TED) located at 350 m to it.

The particles allowed a standalone alignment of the Inner Tracker in the x direction at software level [84]. The alignment was challenging, as the particle fluxes reached ten times the flux expected in a $b\bar{b}$ event. The occupancy was high, up to 8%, as was the number of ghost tracks (Section 6.1).

The algorithm used for the standalone IT alignment required a pair of hits in the same type of detector box, one being in the first module layer of the IT1 station, one in the last layer of IT3. The alignment of the other layers relative to those two layers was then extracted from residual distributions⁴.

Using the nominal geometry (Figure 4.23, top), only a clear peak is observed for the Top Boxes, which corresponds to the correct combination of hits. With the survey corrections (Figure 4.23, bottom), clear peaks are observed for each type of detector box, which validates the IT survey measurements and their implementation in the LHCb software.

After alignment, the overall precision of the module position is on average $19 \mu\text{m}$ along the x direction, compared to a single-hit resolution of $57 \mu\text{m}$.

These particles also allowed a test of the full readout chain. For the Inner Tracker, 99.26% of the channels were found to be operational [84].

⁴The residuals are calculated as the distance between the measured hit and the point of intersection of the track on the sensitive plane. Unbiased residuals of a hit are obtained by removing the information of this particular hit when refitting the track.

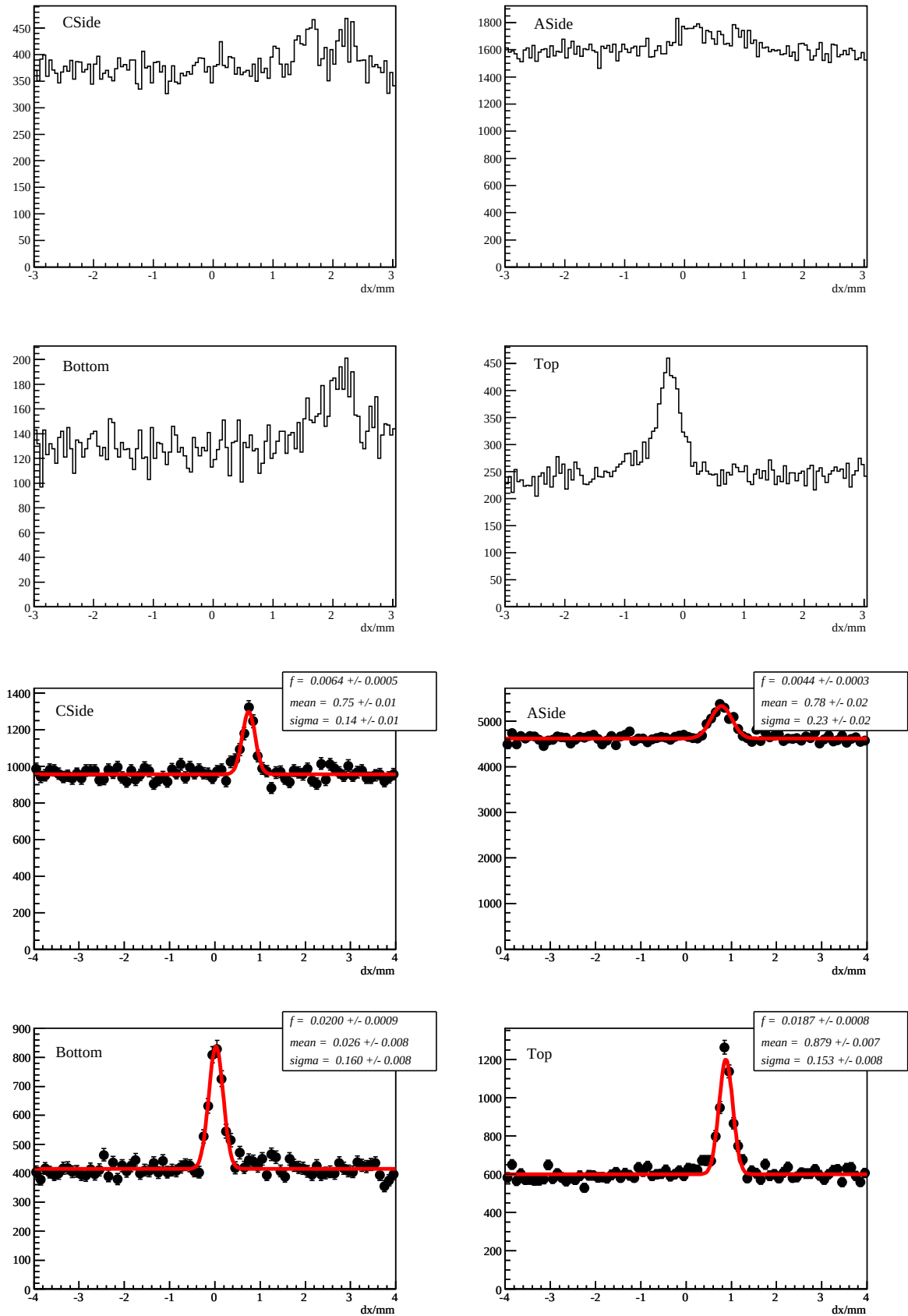
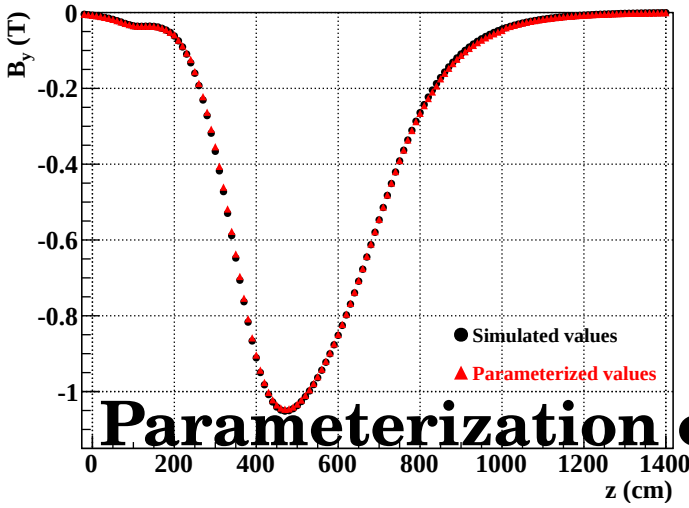


Figure 4.23: Residuals in station IT2 using the nominal geometry (top) and the survey geometry (bottom) [84].



Parameterization of the LHCb Measured Magnetic Field Map

From a magnetic field measurement campaign performed in the LHCb experimental cavern in 2005, a three-dimensional description of the magnetic field is obtained [85, 86, 87, 88]. An accurate description of the magnetic field is necessary to ensure a good momentum resolution of particles traversing the detector. In the LHCb software, the description previously used was a linear interpolation of simulated values positioned on 10 cm-cubic cells of a field map generated by the TOSCA model based on finite element calculation. To prepare for real data, the method could be improved by employing the measurements. Strategies to eliminate systematically the measurements of unphysical values arising from some defective or wrongly positioned Hall probes during the 2005 campaign have been developed. As the measurements do not cover the whole LHCb acceptance, extrapolating techniques have been explored to obtain a complete magnetic field map. The final magnetic field parameterization reaches a precision of $\sim 10^{-3}$ T for the measurements taken with the down polarity of the dipole magnet. From the parameterization, a new magnetic field map is obtained, which has been used as the default map in the LHCb software since 2008.

The LHCb dipole magnet is introduced in Section 5.1 and the TOSCA Magnetic Field Map in Section 5.2. The 2005 measurement campaign is described in Section 5.3, together with the cleaning strategies and comparisons between the cleaned data and the simulated values. The parameterization method is explained theoretically in Section 5.4 and is validated on simulated values in Section 5.5. This method is then applied in Section 5.6 to the magnetic field measurements obtained with the down polarity of the dipole magnet, resulting in the LHCb Measured Magnetic Field Map. A recent update of this map is explained in Section 5.7.

5.1 The LHCb Dipole Magnet

The LHCb dipole magnet is used for the separation of charged particles [89]. From the curvature of their trajectories in the magnetic field, momenta can be determined. The LHCb magnet allows a momentum resolution $\delta p/p \sim 0.4\%$ for momenta up to 200 GeV/c. To achieve this precision, the bending power, characterized by the total integrated field, is $\int B \cdot dl \sim 4 \text{ Tm}$ for 10 m-long tracks originating near the primary interaction point. The magnetic field needs to fulfill other requirements:

- It must be as high as possible in all the regions except inside the RICH envelopes, where a magnetic field smaller than 5 mT is required for the photosensitive detectors (Subsection 2.6.1).
- It needs a good lateral field uniformity to achieve a trigger performance independent of the position in the muon chambers.

The precision required on the total magnetic field is a few 10^{-4} T , corresponding to a precision on the magnetic field components of $\sim 10^{-3} \text{ T}$ due to the anticorrelation between the components. Moreover, the magnetic field peak position must be known as a function of z within a few millimeters to determine precisely the trajectory of the charged particles through the magnet.

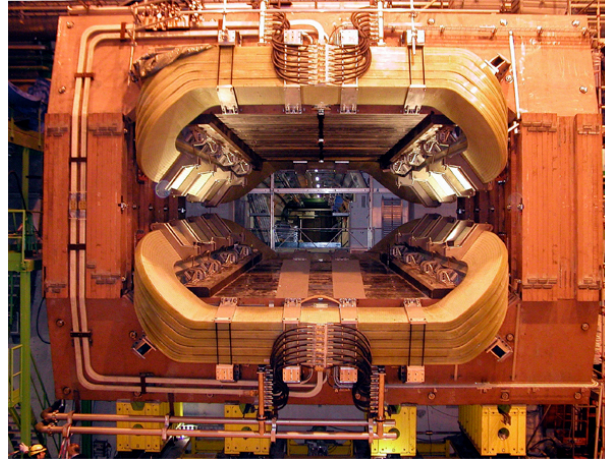


Figure 5.1: The LHCb warm dipole magnet.

The LHCb dipole magnet (Figure 5.1) is an electromagnet using two warm saddle-shaped identical coils. The coils are mounted mirror-symmetrically to each other at the top and bottom of a window-frame yoke, whose sloping poles follow the LHCb acceptance. The magnet is located between $z = 270 \text{ cm}$ and $z = 770 \text{ cm}$ and covers the LHCb acceptance. The main magnetic field component is oriented along the y axis, with a maximal value $|B_y| \sim 1.1 \text{ T}$ at $z = 470 \text{ cm}$. Consequently, the particles are mostly bent in the LHCb $x - z$ plane.

The warm coils permit a rapid ramping-up of the magnetic field as well as regular field inversions by reversing the current going through the coils. These inversions are needed to study systematic effects induced by possible left-right asymmetries of the detector, which are important to control the measurements of CP asymmetries. The *down polarity* is defined as the one with the B_y component pointing down (Figure 5.19, bottom) and the *up polarity* with the B_y component pointing up.

Technical Description

The Yoke. The window-frame iron yoke is assembled from 100 mm-thick rolled low carbon steel plates, with a total weight of 1500 tons and outer dimensions of $11\text{ m} \times 8.01\text{ m} \times 2.7\text{ m}$ (x, y, z) (Figure 5.2). The lateral field quality is enhanced by pole pieces located on the upper and lower parts of the yoke. The side parts are used to close the flux return. The pole gap is 2.6 m to 4.2 m for the horizontal aperture and 2.2 m to 3.5 m for the vertical one. As the magnetic field is stronger on the upstream side of the aperture than on the one downstream, it requires a larger amount of steel. This is provided by the horizontal and vertical yoke parts, whose inner side-walls follows the wedge-shape aperture while the outer walls are rectangular and parallel to the beam. From survey measurements, the yoke is aligned to the LHCb coordinate system within a few millimeters [89].

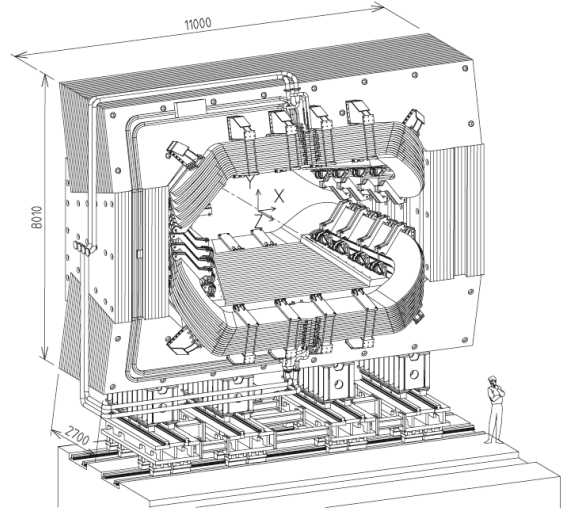


Figure 5.2: Schematic of the LHCb magnet: The two coils are fixed to the iron yoke by aluminum clamps.

The Coils. Each coil consists of fifteen mono-layer pancakes made of hollow aluminum conductor organized in five sub-coils, called *triplets*. In each pancake, the conductor is a 290 m-long piece, corresponding to 15 turns. To keep the power dissipation reasonably low, a large conductor cross-section is used, hence $50 \times 50\text{ mm}^2$. The coils follow the trapezoidal shape of the pole pieces (Figure 5.2). They are bent by 45° towards the gap region along the horizontal aperture to reach good field quality. The cooling of the pancakes is done in parallel with demineralized water going through 24 mm-diameter channels located at the centre of the conductor, with a total water flow $\phi \sim 125\text{ m}^3/\text{h}$. To reach the nominal field integral of $\int B dl = 4\text{ Tm}$ for tracks of the length of 10 m, the current through the conductor is set to 5.85 kA, with a maximal current of 6.6 kA^1 . The total electrical power dissipation in the aluminum is $P_e = 4.2\text{ MW}$. The weight of each coil is 27 tons.

The Clamps. Cast aluminum clamps fixed on the iron yoke are used to hold the triplets together and support the coils. During magnet operation, the coils are slightly displaced due to thermal stress and magnetic forces on the conductor. To lower these constraints, the pancakes of the coils have some freedom to slide upon their supports. The coil is kept fixed against the iron yoke only around $x=0$.

Protections Against the Magnetic Field. Due to the large magnet gap, stray fields occur in the neighboring detectors. Local magnetic shieldings have been designed to protect the photosensitive detectors of the Cherenkov counters located upstream (RICH1) and downstream (RICH2) of the magnet. These consist of large steel boxes around the RICH systems and additionally for RICH1 of mu-metal tubes around the hybrid photon detectors, attenuating the field further. Measurements have shown that the residual field inside these shields is below the acceptable limit of 5 mT.

¹The value of the current is $\sim 8\%$ higher than that is required for a $\int B \cdot dl = 4\text{ Tm}$, to allow a safety factor for uncertainties due to deviations from flatness of the steel plates.

5.2 The TOSCA Magnetic Field Map

The *Vector Fields TOSCA* program is an analysis package based on finite element methods [90]. At LHCb, TOSCA has been used to generate the initial LHCb magnetic field map, called *TOSCA Magnetic Field Map*. This map contains a 3D-modeling of the dipole magnet, of the iron shielding plates of the RICH1 and of the iron of the hadron calorimeter and of the muon system (Figure 5.3) [89].

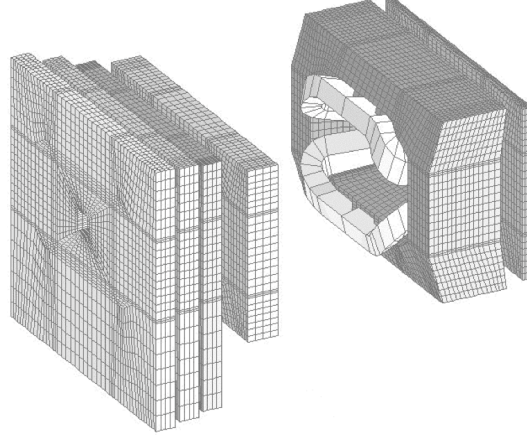


Figure 5.3: TOSCA model of the dipole magnet, the iron of RICH1 shields, the calorimeter and muon systems [89].

The points used for the generation are located on a 10 cm-grid inside a $4\text{ m} \times 4\text{ m} \times 21.5\text{ m}$ volume (x, y, z) starting at the beginning of the VELO detector ($z = -50\text{ cm}$). This volume covers only one quadrant of LHCb ($x \geq 0, y \geq 0$) cm, called Q1, as the magnetic field components are by design (anti-)symmetric between the different quadrants. The other quadrants are called Q2 ($x < 0, y > 0$) cm, Q3 ($x > 0, y < 0$) cm and Q4 ($x < 0, y < 0$) cm. The vertical B_y component is symmetric in all the quadrants, while B_z is anti-symmetric between $y > 0\text{ cm}$ and $y < 0\text{ cm}$ and B_x has diagonal symmetries (Table 5.1).

The number of values of the TOSCA Magnetic Field Map (only Q1) in the $4\text{ m} \times 4\text{ m} \times 14.5\text{ m}$ volume starting from the VELO² is given in Table 5.2 for different regions, and additionally by requesting that they belong to the LHCb detector acceptance.

Table 5.1: Symmetries of the magnetic field components in each quadrant.

Quadrants	B_x	B_y	B_z
Q1 ($x \geq 0, y \geq 0$) cm	+1	+1	+1
Q2 ($x < 0, y > 0$) cm	-1	+1	+1
Q3 ($x > 0, y < 0$) cm	-1	+1	-1
Q4 ($x < 0, y < 0$) cm	+1	+1	-1

Table 5.2: Total number of values in the TOSCA magnetic field map and number inside the LHCb acceptance for different regions.

Regions	$z_{\min}$ (cm)	$z_{\max}$ (cm)	Total	Inside acceptance
negative z	-50	-10	8,405	11
upstream	0	290	50,430	811
magnet	300	790	84,050	13,346
downstream	800	1400	102,541	61,166

At a given point in the LHCb space, the magnetic field components are calculated using a linear interpolation of the eight values located on the corners of the cube surrounding it.

²This volume is considered to be sufficient for the following magnetic field studies.

5.3 Magnetic Field Measurements

A magnetic field measurement campaign was performed in December 2005 in the LHCb cavern [91]. Measurements were obtained for the two magnet polarities using a demagnetization cycle. The machine used for the measurements consists of two parallel planes distant by 6.4 cm oriented towards two different directions: the *Downstream* and the *Upstream planes*. Each plane supports 30 sensor cards (Figure 5.4) arranged in a 3×10 fixed grid configuration with a 8 cm-spacing (Figure 5.5, left). The sensor cards contain three Hall probes for the independent calculation of each magnetic field component. On each card, the probes are mounted orthogonally on a 4 mm-width glass cube (Figure 5.4, right). The sensor cards are calibrated to a precision of 10^{-4} T on the total magnetic field.

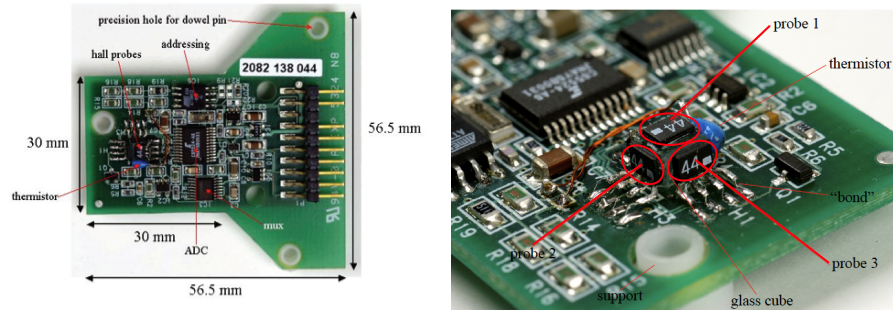


Figure 5.4: Hall probe cards used during the 2005 magnetic field measurement campaign [92].

The planes are positioned perpendicularly to the z axis (Figure 5.5). To map different regions, the device can take four positions: above, below or on both sides of the beam pipe. The machine is moved along the z axis in steps of 10 cm in a motor-controlled way and along the x and y axes in steps of 8 cm in a manually adjusted way. The measuring device is aligned with respect to the experiment reference frame within ± 1 mm [16]. Due to possible rotations of the probes in their supports, the precision on the magnetic field components is estimated to be 10^{-3} T. The total number of measurements taken with the down polarity of the dipole magnet is $\sim 212,600$.

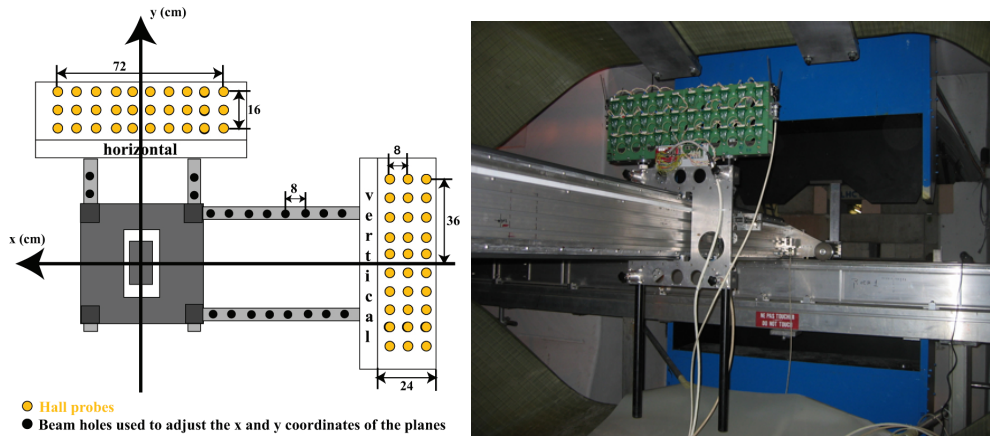


Figure 5.5: Horizontal and vertical configurations of the measurements planes (left). The x and y coordinates of the Hall probes are adjusted manually by moving the planes fixation points inside the beam holes. Picture of the device during the 2005 measurement campaign (right). The machine is moved along z in a motor-controlled way.

5.3.1 The LHCb Simulated Magnetic Field Map

After the 2005 campaign, a first comparison between the TOSCA values and the measurements³ showed differences at the percent level in the RICH1 region ($100 \text{ cm} < z < 250 \text{ cm}$), as shown in Figure 5.6. Calculating the numerical integration of the bending vector $\int \vec{B} \times d\vec{l}$ between the origin and $z = 250 \text{ cm}$, the measurements gave $116.1 \text{ kG}\cdot\text{cm}$ instead of the $148.9 \text{ kG}\cdot\text{cm}$ predicted by simulation [91].

At that time, this sizeable difference ($O(30\%)$) affected the trigger strategy that depended critically on the field in that region. For this reason, the TOSCA map was corrected for this discrepancy by applying

an overall scale factor in the $0 < z < 250 \text{ cm}$ region. This corrected description is called *Simulated Magnetic Field Map*, as it still remains largely based on the TOSCA simulated values, given that the corrected area is small compared to the LHCb acceptance.

One explanation for these differences could be that the iron embedded in the concrete of the reinforced foundation in the upstream region is not included in the model. Simulations have indeed shown that iron located close to the RICH1 lower shield and around it can modify the field shape on the z axis ($x=0 \text{ cm}$, $y=0 \text{ cm}$) by deviating the magnetic flux. However, adding it in the simulation only explains part of the discrepancy. No explanation has been found for the remaining part.

The B_x , B_y and B_z components of the simulated magnetic field map⁴ are shown in Figure 5.7 requiring that they are inside the LHCb acceptance. The distributions for different z regions are stacked onto each other. The distribution of the total magnetic field, $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$, is also shown.

The B_x component is almost always positive. For each region in z , the peak around zero corresponds to small x or y coordinates, resulting from its diagonal symmetries (Table 5.1). The tails on the right of Figure 5.7 (top, left) are due to x and y coordinates that are simultaneously large. The B_x component is the weakest magnetic field component with values less than $\sim 0.1 \text{ T}$.

The B_y component is almost always negative. It is smaller in the upstream region than in the magnet region, where it reaches its peak at around $z = 470 \text{ cm}$. It decreases at the end of the magnet region and in the downstream region. The B_y component can reach values up to $\sim -1.5 \text{ T}$, making it the most important magnetic field component.

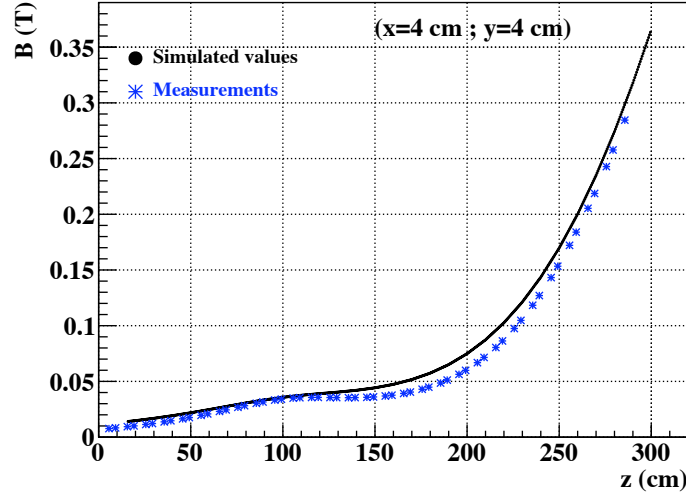


Figure 5.6: Measured (blue stars) and simulated (black dots) B field values as a function of z for $x=4 \text{ cm}$ and $y=4 \text{ cm}$.

³The measurements have been expressed in the LHCb coordinate system.

⁴The simulated magnetic field map values correspond to coordinates inside quadrant Q1 only.

The B_z component is negative in the upstream and beginning of the magnet region and becomes positive at around $z = 470$ cm. The largest B_z values are always obtained at large y values for all possible z coordinates, reaching maximal values at the end of the magnet region, at around $z=700$ cm.

The total magnetic field B is dominated by the description given for the B_y component (neglecting the sign difference), as it is the predominant component. Its maximal value ~ 1.6 T is reached in the first half of the magnet region.

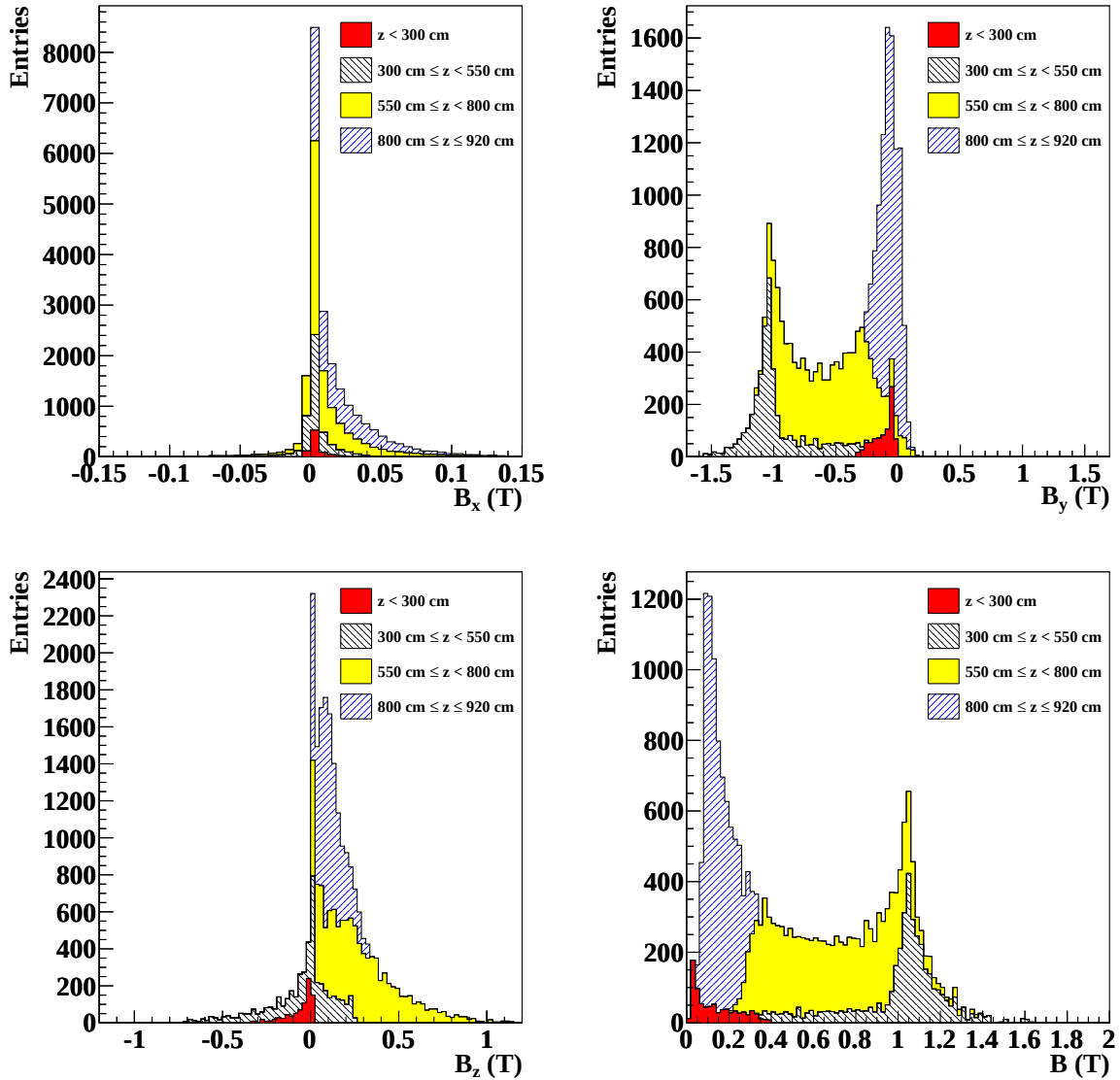


Figure 5.7: B_x , B_y and B_z simulated magnetic field components and total B field for different regions in z .

5.3.2 Cleaning Strategy

Before using the measurements, unphysical values, arising from defective or wrongly positioned Hall probes during the 2005 magnetic field campaign, must be removed. This cleaning strategy is defined in three steps with increased refinement of the data quality control. The first step consists in removing obvious peaks. Secondly, offsets are identified in some Hall probe measurements. Correlations between disagreeing measurements and the corresponding Hall probe *IDentification numbers (IDs)* are searched for in the last cleaning procedure. Results are presented for measurements obtained with the down polarity of the magnet.

1. Peak Removal

Scans of the field components values as a function of x and y for different z slices show some unphysical measurements arising as peaks. These are especially visible in the B_x component due to its small magnetic field values (Figure 5.8).

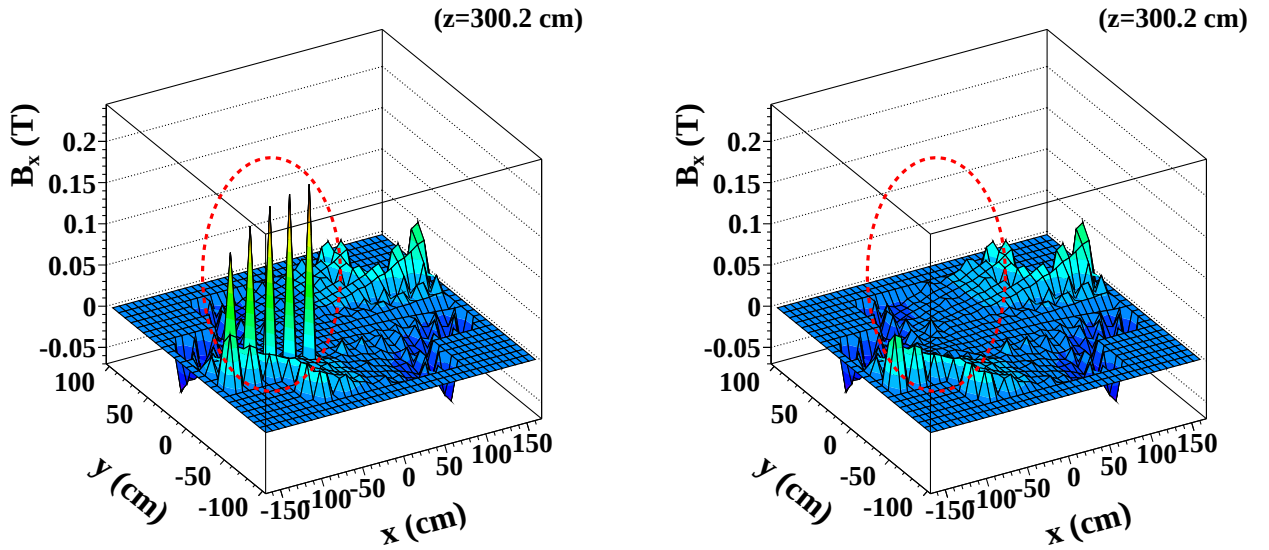


Figure 5.8: B_x as a function of x and y before (left) and after (right) the measurement clean-up at $z=300.2$ cm.

During the measurement campaign, some of the Hall probes had been listed as suspicious because of their loose fixing to the board⁵. Part of them are indeed found responsible for unphysical peaks.

Histogramming the probe IDs correlated with the problematic probes reveals that not only the suspicious probes, but most of the probes have a small fraction ($\propto 1\%$) of wrong measurements. Detailed studies on these measurements show that they are seen in (almost) all the Hall probes at the same time. They could therefore be the result of interaction problems between the cable providing the high voltage to the two planes and the magnet. More details about the results of this cleaning step can be found in [85].

⁵They correspond to probes with IDs 50, 110, 190 and 181 in the Downstream plane and IDs 66, 69, 74, 76, 101, 145, 163 and 185 in the Upstream plane.

Figure 5.9 depicts the results of the peak removal cleaning step, where the measurements (blue stars) are compared with the interpolated values (black dots), before (left) and after (right) data cleaning for the three magnetic field components.

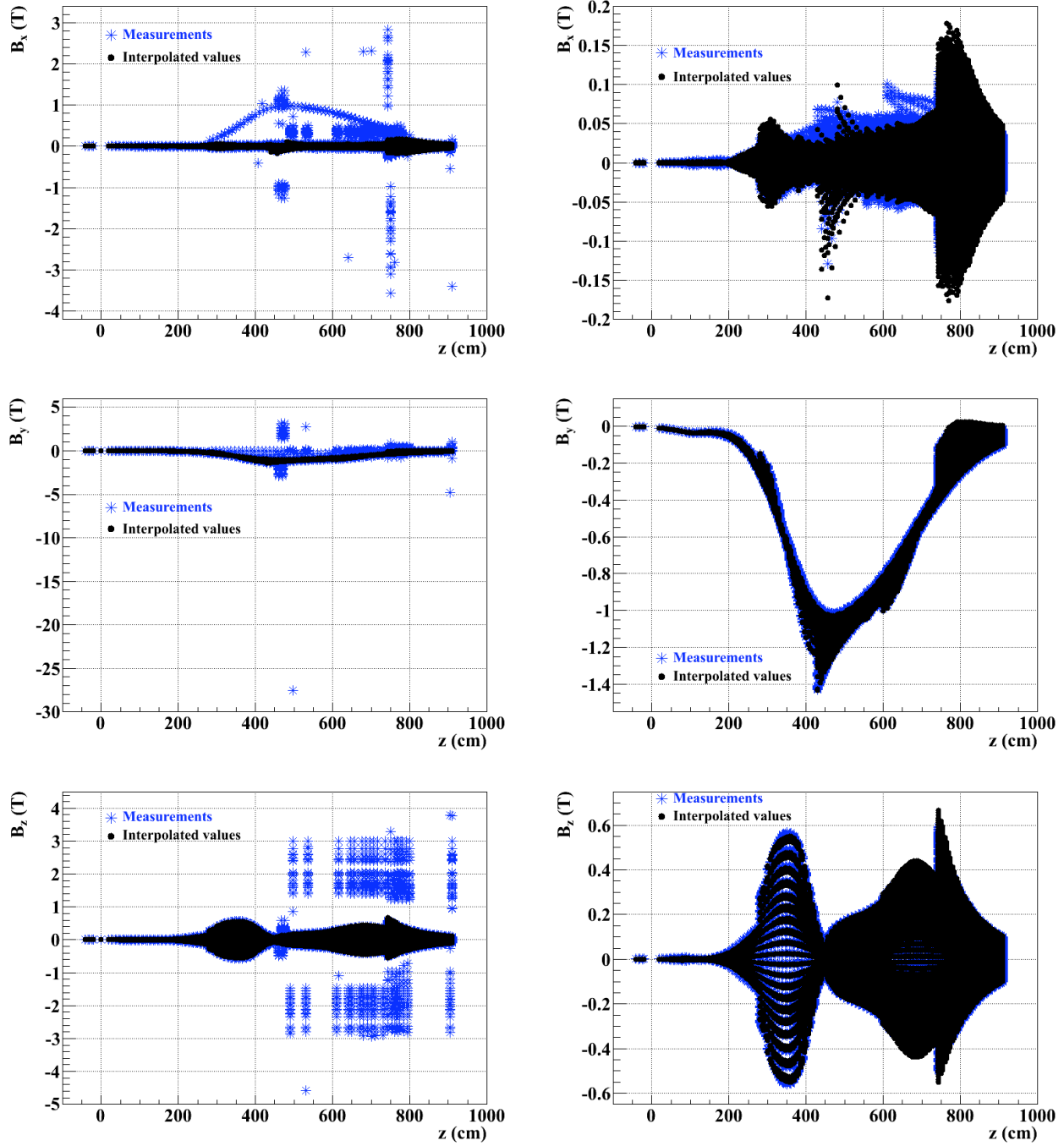


Figure 5.9: Magnetic field components as a function of z , before the peak removal cleaning step (left) and after (right). Measurements and TOSCA values are represented by blue stars and black dots, respectively.

2. Offset Identification

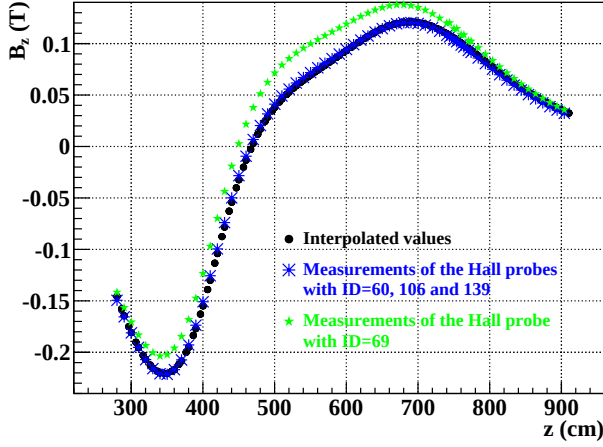


Figure 5.10: B_z as a function of z for $x=36$ cm and $y=36$ cm. The probe ID 69 is responsible for offset values (green stars).

Most of these mismatches are due to the remaining suspicious Hall probes that did not show up in the first cleaning step⁶. The corresponding shifted measurements are all associated to data taken in the vertical configuration of the measurement planes.

3. Disagreeing Measurement - Probe ID Correlation

After the second cleaning, the δB_x and δB_y residual between the measurements of different probes at same space coordinates are within ± 0.0025 T, where the residuals are computed as the differences of each measurement to the average value of the measurements. For δB_z residuals in the magnet region, tails extend up to ± 0.006 T (Figure 5.11, left). To study these tails, the probe IDs of the two disagreeing measurements are plotted as a function of each other. As shown in Figure 5.11 (right), some ID numbers appear more often than others. The measurements of these probes are therefore considered invalid and discarded⁷. After this cleaning, the δB_z residuals are within ± 0.0025 T.

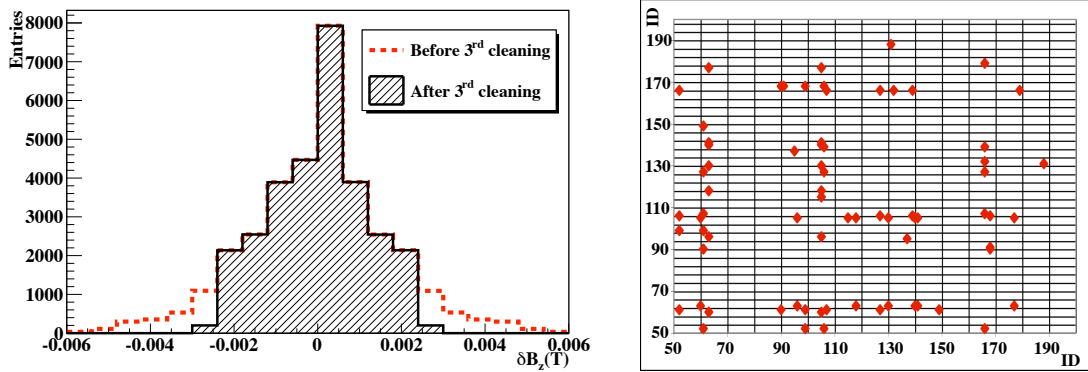


Figure 5.11: δB_z (magnet region) before and after 3rd cleaning (left) and correlation between disagreeing probe IDs of the tails (right).

⁶They have IDs 110, 181 and 190 for the Downstream plane and IDs 69, 76 and 185 for the Upstream plane

⁷Seven probes are concerned, with IDs 52, 63, 61, 105, 106, 166 and 168. The number of removed values is ~ 2200 .

5.3.3 Space Coverage of the Measurements

The measurements have been taken from the origin to the RICH2 detector region ($z \sim 920$ cm). As shown in Figure 5.12 (left), the measurements (black dots) do not cover the whole tracking volume inside the LHCb acceptance (red dashed line), especially in the regions close to the acceptance borders.

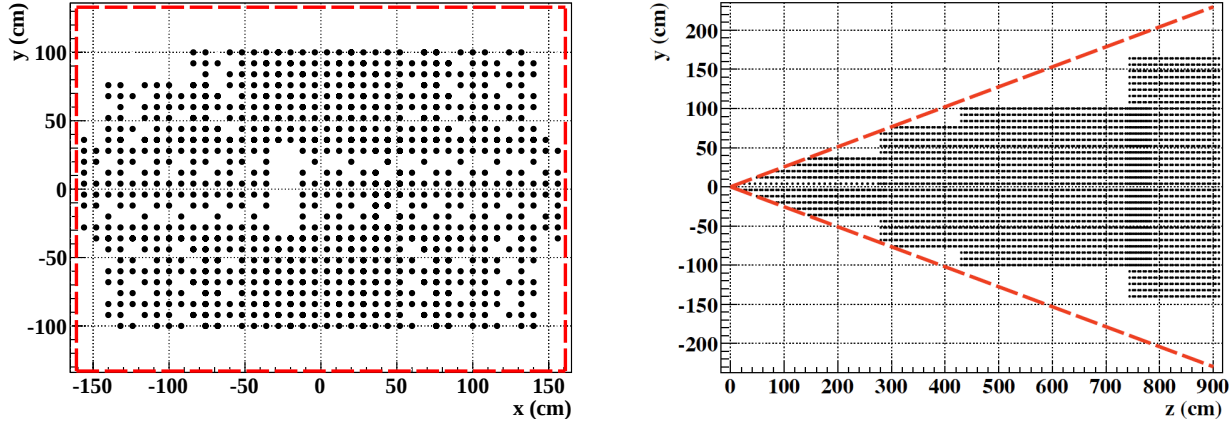


Figure 5.12: Measurements (black dots) taken at $z=520$ cm (before cleaning) and LHCb acceptance (dashed red line) (left). The y coordinates covered in the LHCb acceptance by measurements after cleaning as a function of z (right).

The y coordinates covered by the measurements inside the LHCb acceptance after cleaning are shown as a function of z in Figure 5.12 (right). The lack of measurements for y values close to the acceptance borders is clearly visible.

Several measurements have been taken at the same spatial position by different sensor cards after successive repositionings of the device. This redundancy allows an estimation of the measurement precision, which is described in Subsection 5.3.4.

The number of different coordinates covered in the LHCb acceptance, and from which the number of coordinates with redundant measurements are given in Table 5.3, before and after cleaning for the three regions in z . An estimation of the number of coordinates expected to be covered in the LHCb acceptance by the measurements is obtained by considering a grid of $8 \text{ cm} \times 8 \text{ cm}$ moving every 5 cm in z (as two planes were moved by 10 cm in z during the measurement campaign).

Table 5.3: Numbers of space coordinates expected and covered by the measurements for different regions in z , before and after cleaning. The number of coordinates where redundant measurements exist is also given.

	Expectation	Before Cleaning		After Cleaning	
	Space Coverage	Space Coverage	Redundant Measurements	Space Coverage	Redundant Measurements
Upstream	8,688	5,589	548	4,814	353
Magnet	158,338	105,604	32,246	90,727	21,311
Downstream	74,999	49,963	18,649	49,374	18,273

5.3.4 Measurement Accuracy After Cleaning Procedure

Once the cleaning procedure is completed, the measurement accuracy is determined by comparing measurements taken at same space coordinates by different Hall probes ($\sim 40,000$ space coordinates). At a given point, the residuals equal the difference of each measurement to their average value:

$$\delta B_i = B_{\text{meas},i} - \mu \quad \text{with} \quad \mu = \frac{B_{\text{meas},i,1} + B_{\text{meas},i,2}}{2} \quad (5.1)$$

The distributions of the residuals are shown in Figure 5.13 for each magnetic field component and for the total field. The resolutions obtained from (double-)Gaussian fits are of a few 10^{-4} T. The tails still present in the B_z distribution could be explained by a contribution of the B_y component from an inaccurate orthogonal alignment of the Hall probes.

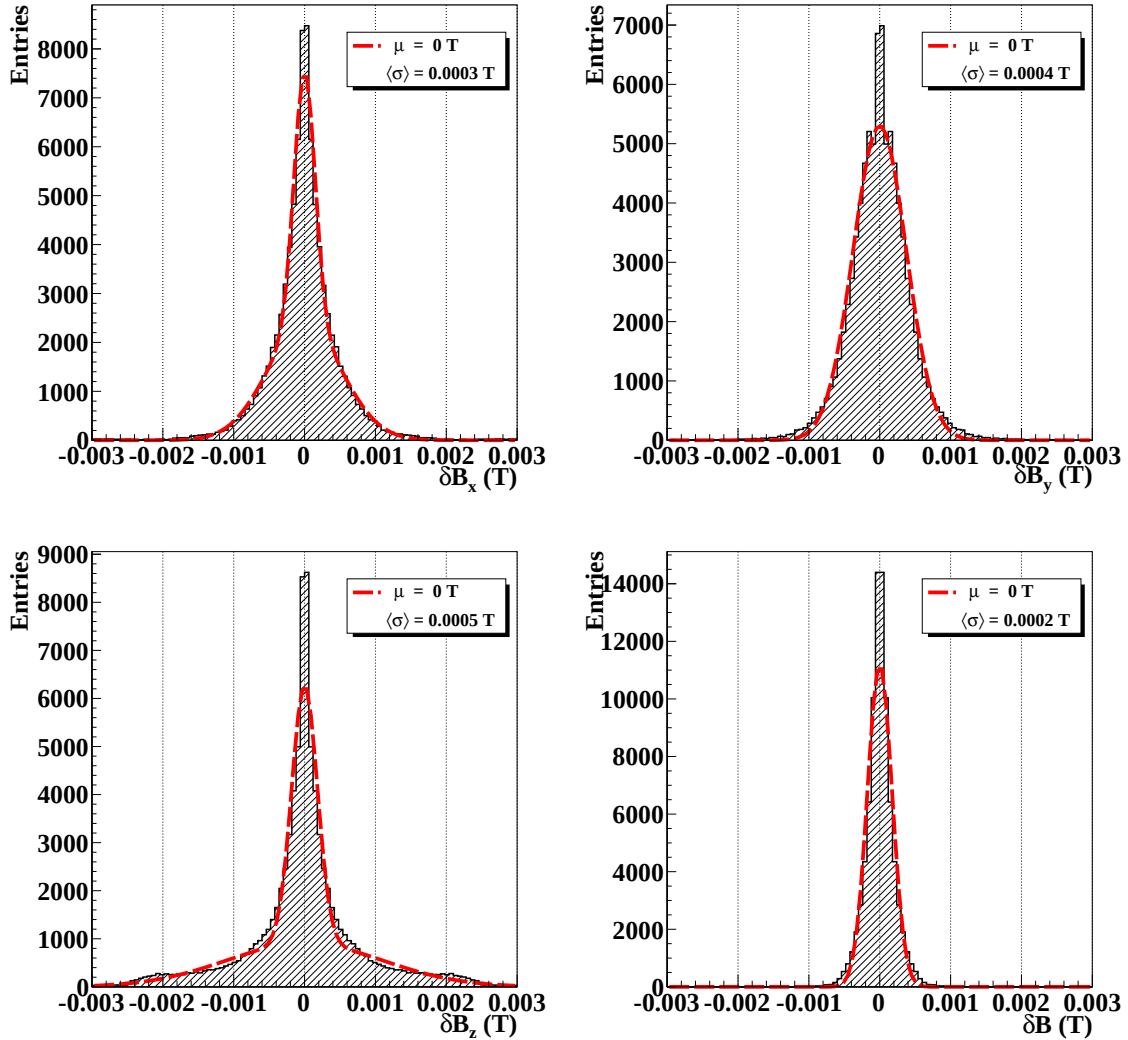


Figure 5.13: Distributions of the field component differences between probes at the same measurement points. The resolutions are $3 \times 10^{-4} \text{ T}$, $4 \times 10^{-4} \text{ T}$, $5 \times 10^{-4} \text{ T}$ and $2 \times 10^{-4} \text{ T}$ for δB_x , δB_y , δB_z and δB respectively.

5.3.5 Agreement between Measurements and Simulated Values

The simulated values are interpolated onto the measurement space coordinates. The residuals are calculated as the difference between the absolute values of the measurements and interpolation:

$$\delta B_i = |B_{\text{meas},i}| - |B_{\text{sim},i}| \quad (5.2)$$

The residuals are studied as a function of x , y and z separately. For the x and y cases, the residuals are divided into two categories, the coordinate being positive or negative. As the simulated values are (anti-)symmetric between the quadrants, this provides a check if there is any left-right or up-down asymmetry in the measurements. For the z case, the residuals are separated as a function of the upstream ($z < 300$ cm), magnet ($300 \text{ cm} \leq z < 800$ cm) and downstream ($z \geq 800$ cm) regions.

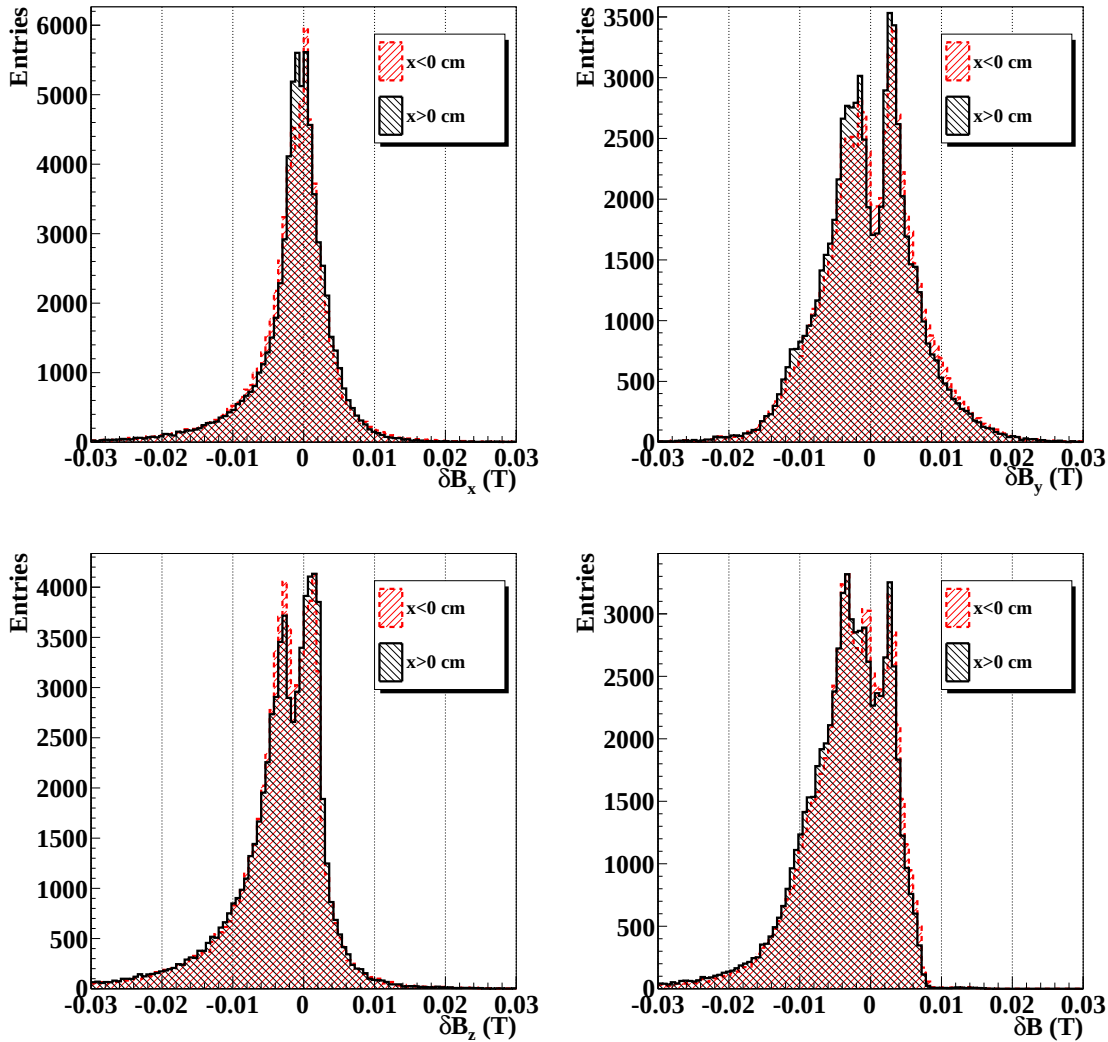


Figure 5.14: Residuals between the measurements and interpolated values for $x > 0$ cm and $x < 0$ cm.

Results of Figure 5.14 show no left-right asymmetry. However, when plotting the residuals per quadrant instead, a left-right asymmetry is observed in the B_x component only, the quadrants Q1 and Q4

having similar distributions that slightly differ from the ones of quadrants Q2 and Q3. In Figure 5.14, this asymmetry is compensated by the fact that quadrants Q1-Q3 ($x > 0$) and Q2-Q4 ($x < 0$) are combined. No left-right asymmetry is observed for the B_y nor B_z components.

The average value of the total B field residuals is negative, which means that the measurements are globally smaller than the simulated values. When the coils are switched on, they open by ~ 8 mm at the end of the magnet region. The reduction of the magnetic field values in the measurements compared to the simulation could therefore be explained by this coil opening, which is not taken into account in the Simulated Magnetic Field Map.

Figure 5.15 shows an up-down asymmetry for the B_y and B_z components, and consequently for the total field. The B_x component does not show any significant up-down asymmetry. Measurements coming from the lower part of the magnet have smaller discrepancies with the simulated values than the ones coming from the upper part of the magnet.

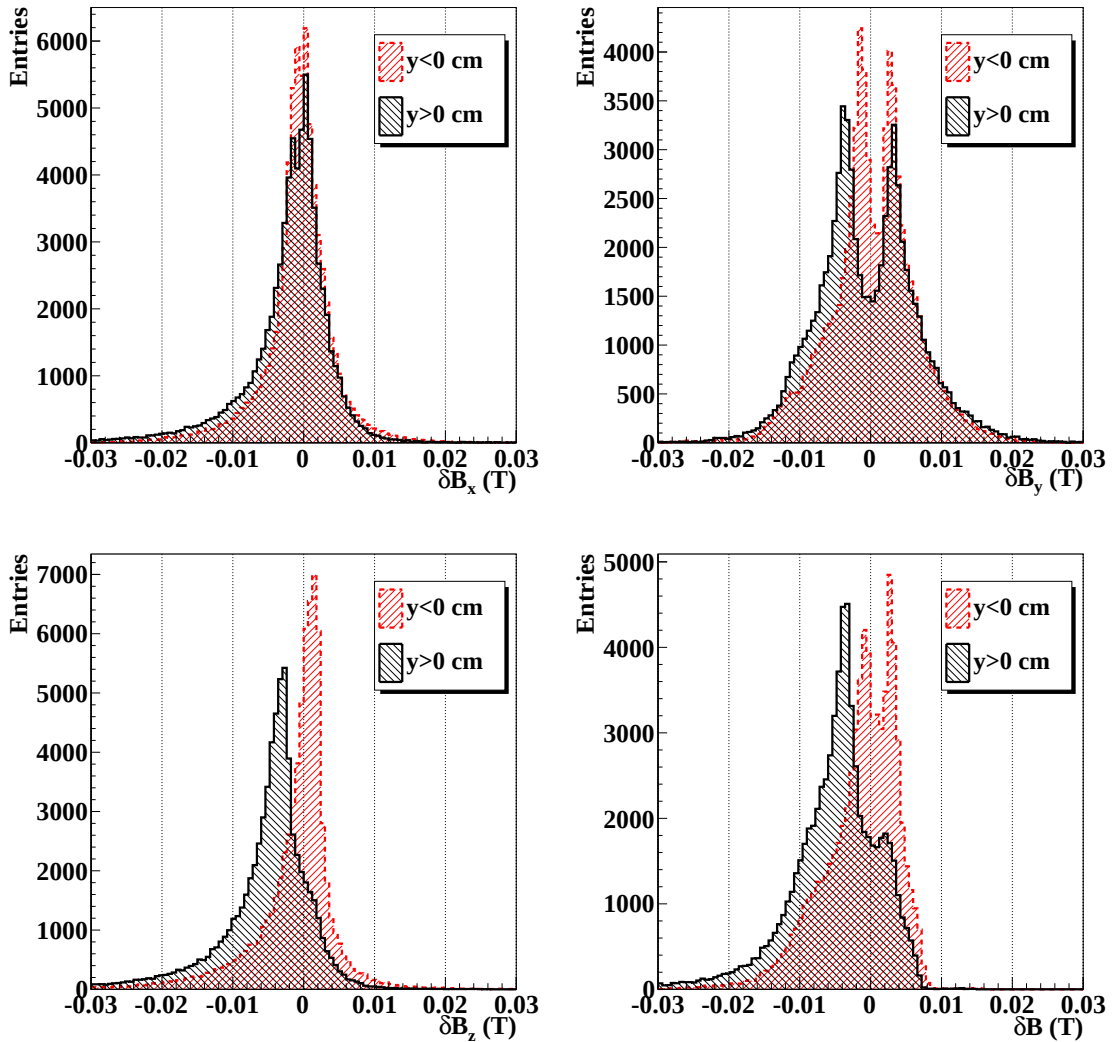


Figure 5.15: Residuals between the measurements and interpolated values for $y > 0$ cm and $y < 0$ cm.

The residuals for all the magnetic field components are of a few 10^{-2} T. This highlights the necessity for correcting the Simulated Magnetic Field Map using the measurements, as the precision required on the components is $\sim 10^{-3}$ T (Subsection 5.1). The discrepancies become larger as approaching the LHCb acceptance borders for both x and y coordinates.

Contrary to the x and y coordinates where (anti-)symmetries are expected, no symmetry in the magnetic field components is expected as a function of z due to the LHCb dipole magnet design. For a better comparison, the residual distributions are stacked onto each other for the three regions in z . From Figure 5.16, the two-peak shape of the δB_y distributions in Figures 5.14-5.15 is explained. It is due to different regions in z (Figure 5.16, top right). The B_y measurements in absolute value are smaller than expected in the upstream and part of the magnet regions. As z increases, at the end of the magnet and in the downstream region, they become larger than the simulated values.

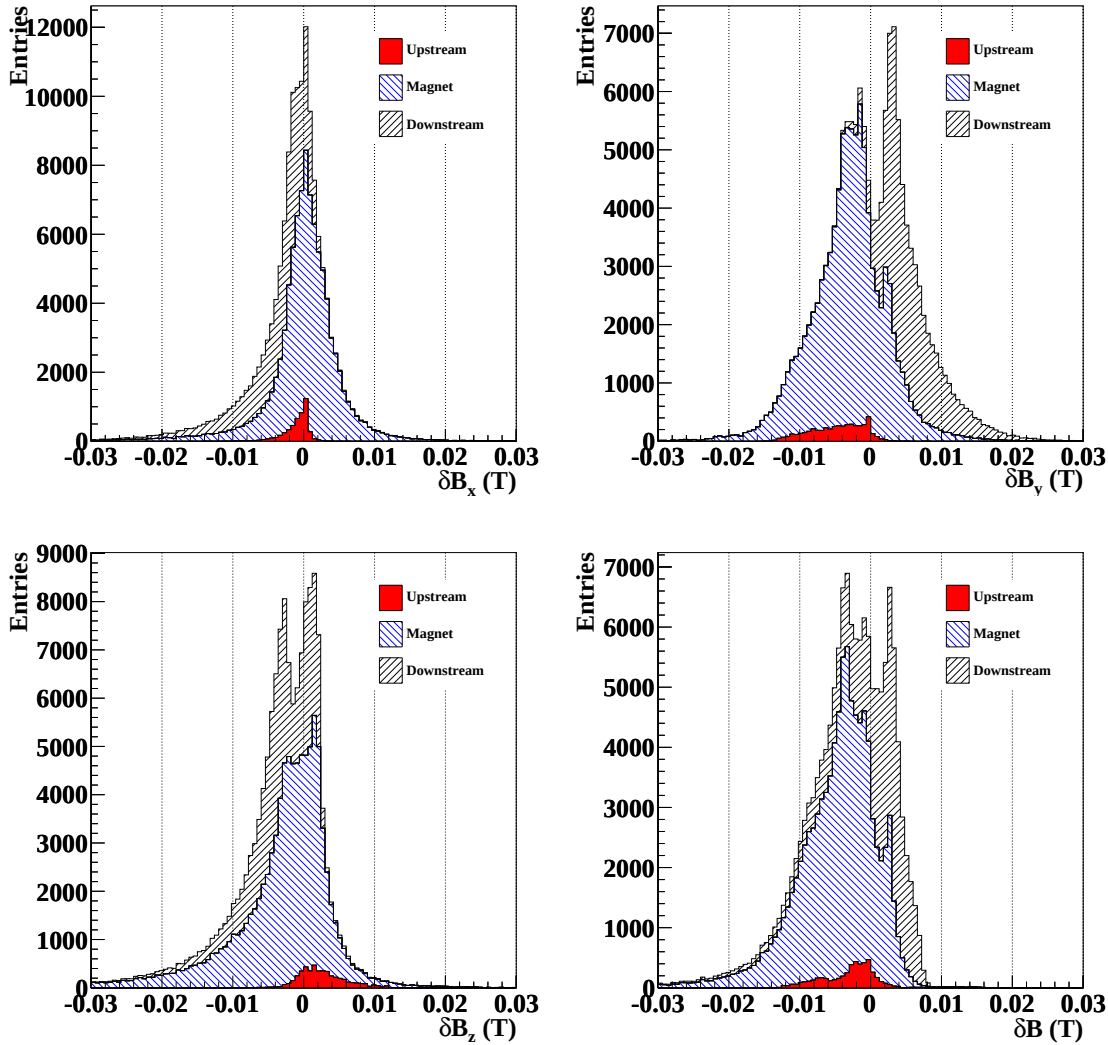


Figure 5.16: Residuals between the measurements and interpolated values for different regions in z .

To confirm the up-down asymmetry deduced from Figure 5.15, differences between measurements taken at same space coordinates in absolute value but in different quadrants, are studied. The residuals are calculated following Equation 5.1 and are shown in Figure 5.17. The residuals between measurements from the two up quadrants Q1 and Q2 (Q12, $\sim 89,200$ entries) or the two down ones Q3 and Q4 (Q34, $\sim 105,900$ entries) are similar. They are smaller than the residuals between one up and one down quadrants (Q13, $\sim 117,300$ entries and Q24 $\sim 73,800$ entries), which confirms the up-down asymmetry in the magnetic field measurements. This up-down asymmetry can be a real effect that could come from a tilt of the magnet for example. However, it could also be a fake effect due to possible imprecisions in the positioning of the measurement device in the LHCb cavern during the 2005 campaign, such as a tilt of the measurement plane. This issue will be treated in Chapter 6.

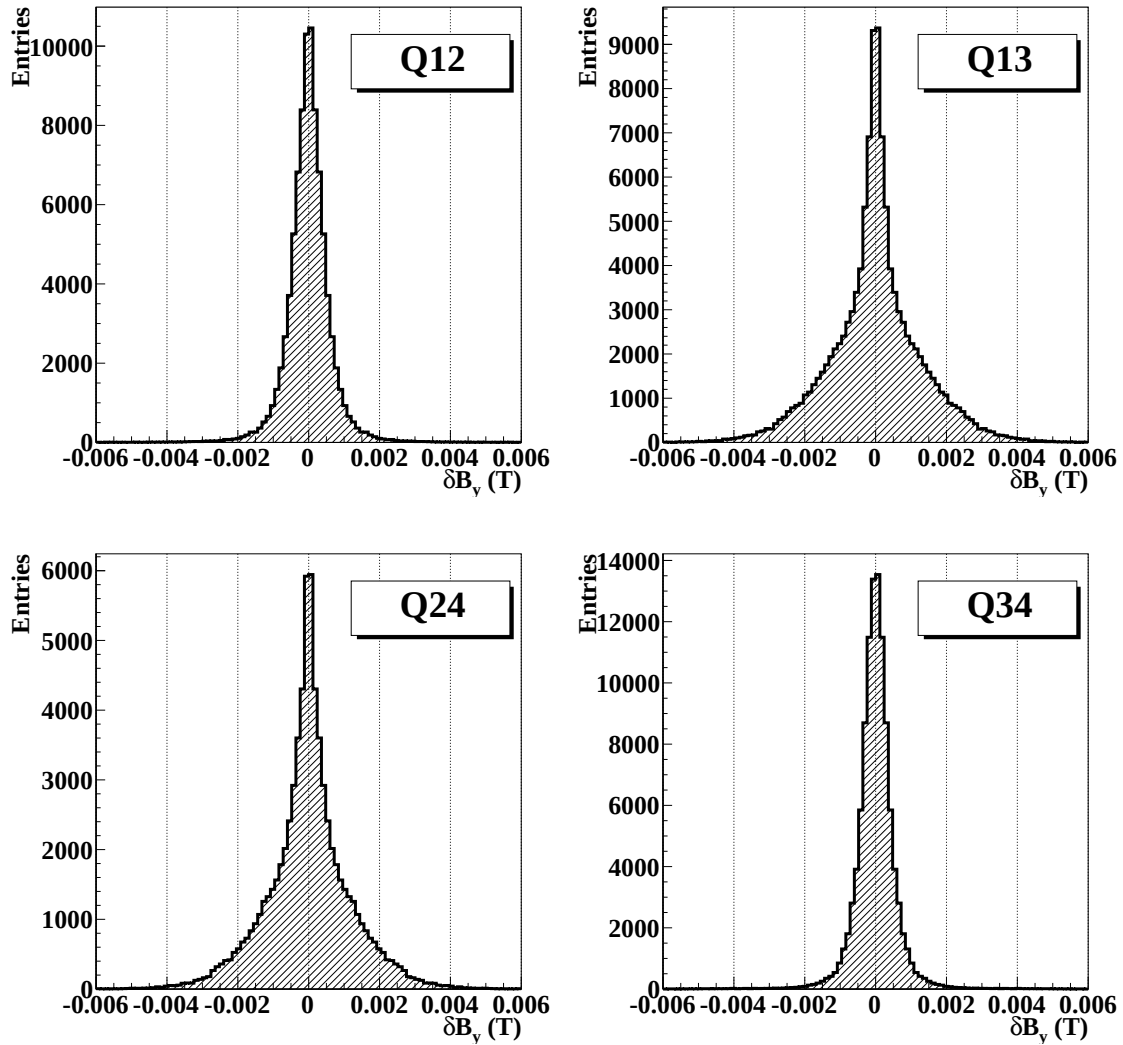


Figure 5.17: δB_y residuals between the measurements from different quadrants with same absolute space coordinates.

5.3.6 Comparisons Between the Two Magnet Polarities

The measurements taken with the up polarity of the dipole magnet are cleaned of the unphysical peaks. A comparison between them and the cleaned measurements of Subsection 5.3.2 is shown in Figure 5.18 for the three field components and the total field. The residuals are calculated following Equation 5.1. A good agreement is observed, as the average resolutions from double-Gaussian fits are of a few 10^{-4} T for all the magnetic field components. This suggests that using one common description for both polarities would be a reasonable assumption. This idea is pursued in Section 5.7.

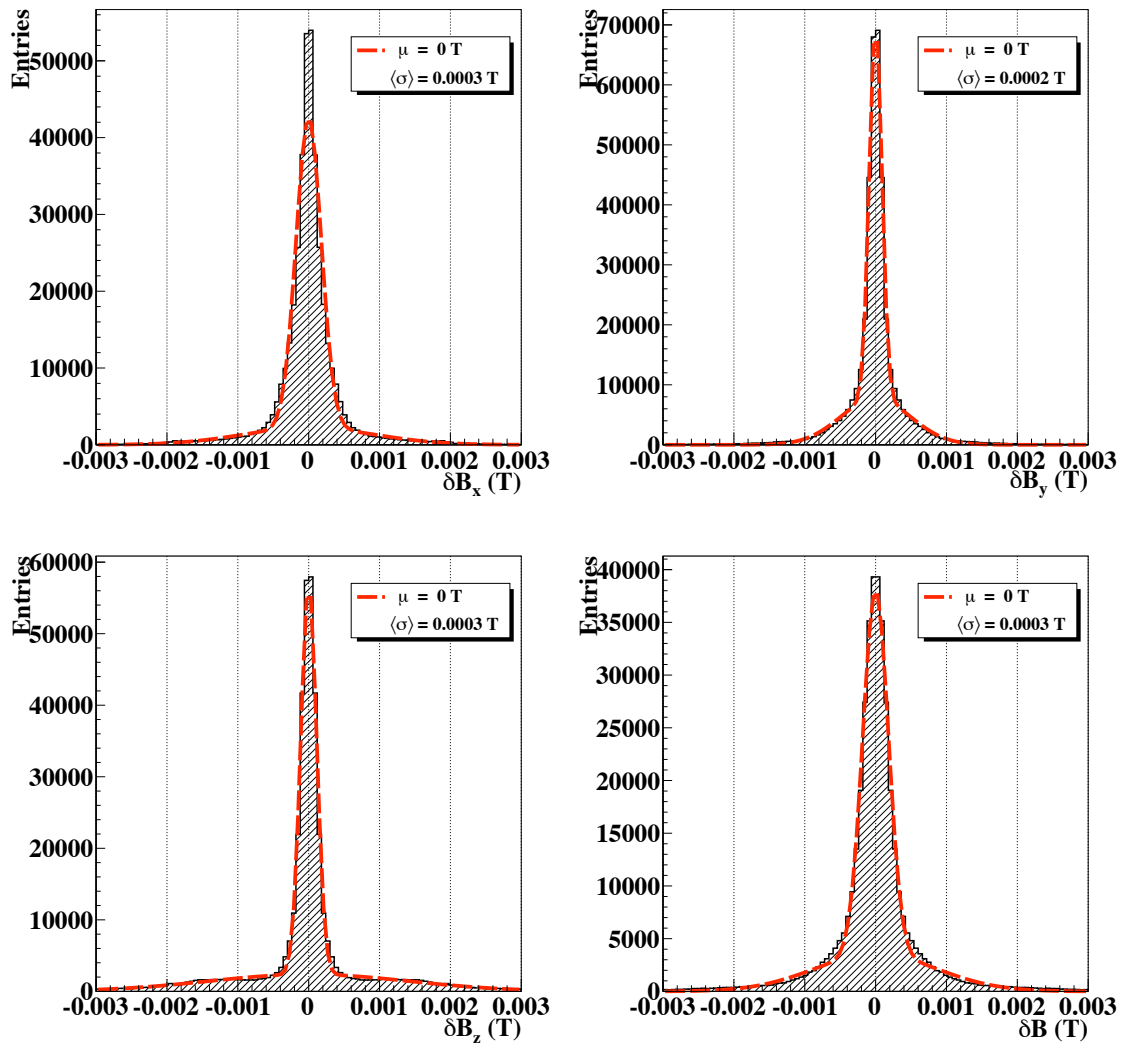


Figure 5.18: Residuals between the down and up polarity measurements .

5.4 Theoretical Overview of the Parameterization Method

To derive a realistic field map, the available ingredients are: A set of TOSCA simulated values $\mathbf{B}_{\text{sim}}(\vec{x}_i)$ at positions $\{\vec{x}_i\}$ regularly placed on a grid, covering a space Ω_{sim} and a set of measured values $\mathbf{B}_{\text{meas}}(\vec{y}_j)$ at positions $\{\vec{y}_j\}$ that are not necessarily regularly distributed in space, covering a space Ω_{meas} .

The fit is performed for all the dimensions simultaneously using Chebychev polynomials [93, 94]. The fitting function is given by:

$$f(\vec{x}_i) = \sum_l c_l m_l(\vec{x}_i) \quad (5.3)$$

where c_l are coefficients to be determined in the fit and m_l are functions forming the fitting basis. For a simple polynomial basis, $m_l(x_i, y_i, z_i)$ is of the form $x_i^a y_i^b z_i^c$.

Chebychev monomials are chosen, as they are known to be the best approximation polynomials for continuous functions. In particular, they minimize the oscillation effects, called *Runge's phenomenon*, which are observed for high-order polynomial fit/interpolation [95]. The $m_l(x, y, z)$ functions are of the form $T_m(x)T_n(y)T_p(z)$, where $T_k(u)$ is the k^{th} order Chebychev polynomial for the variable u . The recurrence relation linking subsequent orders is recalled:

$$\begin{aligned} T_{k+1}(u) &= 2uT_k(u) - T_{k-1}(u) \\ T_0(u) &= 1 \\ T_1(u) &= u \end{aligned} \quad (5.4)$$

The goal is to find the optimal number of terms in the development and the optimal coefficients that minimize:

$$S = \sum_i \frac{(B_i - f(\vec{x}_i))^2}{\sigma_i^2} \quad (5.5)$$

where the sum is over the $\vec{x}_i$ representing the positions at which the input data are available.

The first obvious criterion to control the convergence is to set up a minimum threshold ε under which the ultimate relative error should be. One definition for this criterion is:

$$\frac{S}{\sum_i \frac{B_i^2}{\sigma_i^2}} < \varepsilon \quad (5.6)$$

On top of that, the order to which the development should be done can be specified, for each of the dimensions. However, a systematic method is still missing to limit the number of terms in the analytical representation and choose only the terms that are relevant for the minimization. As an example, if the number of terms per dimension is set to 10, then a $10^3 \times 10^3$ matrix has to be inverted to solve the least square minimization, without knowing whether all the terms in the development are relevant or whether the order of development is sufficient to reach the accuracy. In the following, a method is set up to decide a priori whether a term is relevant or not.

Optimizing the Set of Basis Functions

To optimize the set of m_l functions, their minimization power is estimated with respect to the least square. To do this, it is useful to recombine these functions into a set of orthogonal functions. This can be achieved following a *Gram-Schmidt orthogonalization procedure* [93, 94]. In the following, the measurement errors are omitted to ease the notations.

Let $\mathcal{M}_{ij}$ be the matrix element defined as $\mathcal{M}_{ij} = m_j(\tilde{x}_i)$. For N measurements and M m_l functions, $\mathcal{M}$ is a $N \times M$ matrix. $\mathbf{B}$ is defined as the N -elements data vector and $\mathbf{c}$ as the M -elements coefficients vector. Equation 5.5 can be rewritten as:

$$S = (\mathbf{B} - \mathcal{M} \cdot \mathbf{c})^2 \quad (5.7)$$

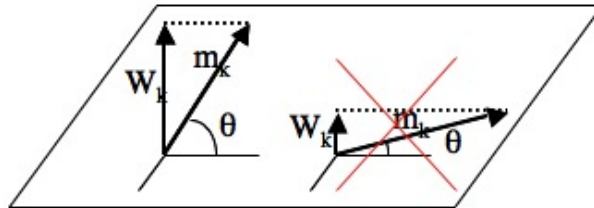
The columns of $\mathcal{M}$ correspond to the vectors $\mathbf{m}$ which components represent the values of the m_l functions at the nodes $\tilde{x}_i$. There are M such vectors and they do not necessarily form a free system. To remove the degeneracies, a new orthogonal basis $\mathbf{w}$ of P vectors ($P < M$) is built using the Gram-Schmidt algorithm:

$$\begin{aligned} \mathbf{w}_1 &= \mathbf{m}_1 \\ \mathbf{w}_k &= \mathbf{m}_k - \sum_{p=1}^{k-1} \frac{\mathbf{m}_k \cdot \mathbf{w}_p}{(\mathbf{w}_p)^2} \mathbf{w}_p \quad (k > 1) \end{aligned} \quad (5.8)$$

By construction, $\mathbf{w}_n \cdot \mathbf{w}_m = 0$ if $n \neq m$. In other words, a given $\mathbf{w}_k$ is always orthogonal to the space spanned by $\{\mathbf{w}_1, \dots, \mathbf{w}_{k-1}\}$.

The maximum order P of the $\mathbf{w}$ basis is determined as follows. Assuming the set of functions $\mathbf{m}_1, \dots, \mathbf{m}_{k-1}$ is already chosen, a criterion to decide whether it is worth adding the function m_k has to be set up. This can be done in two ways:

- $\mathbf{m}_k$ must have a significant component perpendicular to the hyperplane spanned by $\{\mathbf{w}_1, \dots, \mathbf{w}_{k-1}\}$. In other words, a cut is put on the angle θ between $\mathbf{m}_k$ and $\mathbf{w}_k$.



- The contribution of $\mathbf{m}_k$ to the potential reduction of the least square, which can be shown to be $\Delta S_k = \frac{(\mathbf{w}_k \cdot \mathbf{B})^2}{(\mathbf{w}_k)^2}$, must be above a certain threshold to be tuned.

The first criterion has been found to be more powerful and is therefore the one used. With this method, it is possible to decide about the optimal set of functions to be used before solving for the coefficients of the development.

Solving

After the procedure described in the previous paragraph, the set of P functions, $\mathcal{M}^r$ and coefficients $\mathbf{c}^r$ is reduced. Minimizing Equation 5.7 with respect to the c coefficients leads to the solution:

$$\mathbf{c}^r = (\mathcal{M}^{r,T} \mathcal{M}^r)^{-1} \cdot (\mathcal{M}^{r,T} \mathbf{B}) \quad (5.9)$$

The fit errors of the coefficients are the diagonal element of the $P \times P$ covariance matrix $(\mathcal{M}^{r,T} \mathcal{M}^r)^{-1}$.

Adding Constraints

In absence of currents in the mapping volume, the magnetic field satisfies both $\nabla \cdot \vec{B} = 0$ and $\nabla \times \vec{B} = \mathbf{0}$. This leads for each component to $\Delta B_i = 0$.

This condition can be injected in the minimization by adding *Lagrange multipliers*. The function to be minimized is then:

$$S = (\mathbf{B} - \mathcal{M}^r \cdot \mathbf{c}^r)^2 + \lambda^T \cdot \mathbf{G} \cdot \mathbf{c}^r \quad (5.10)$$

Where $\mathbf{G}$ is the Laplacian matrix, $\mathbf{G}_{ij} = \Delta m_i(x_j)$ and λ represents the N Lagrange multipliers vector. Minimizing with respect to $\mathbf{c}^r$ and λ leads to:

$$\mathcal{M}^{r,T} \mathcal{M}^r \cdot \mathbf{c}^r + \mathbf{G} \cdot \lambda = \mathcal{M}^{r,T} \mathbf{B} \quad (5.11)$$

$$\mathbf{G}^T \cdot \mathbf{c}^r = 0 \quad (5.12)$$

Or, in a global $(P + N) \times (P + N)$ matricial notation:

$$\begin{pmatrix} \mathcal{M}^{r,T} \mathcal{M}^r & \mathbf{G} \\ \mathbf{G}^T & 0 \end{pmatrix} \begin{pmatrix} \mathbf{c}^r \\ \lambda \end{pmatrix} = \begin{pmatrix} \mathcal{M}^{r,T} \mathbf{B} \\ \mathbf{0} \end{pmatrix} \quad (5.13)$$

Now, the matrix to inverse is of size $(P + N) \times (P + N)$. This immediately points out the problem of imposing the constraint at the measurements points. If N is big compared to P , the system is over-constrained and singularities appear in the solving. An alternative approach to this would be to apply the constraints to a limited number of appropriately chosen points.

5.5 Parameterization Method Validation

Before applying the three-dimensional fitting method to the measurements, the method has first to be validated. This is done by fitting the values coming from the Simulated Magnetic Field Map using the method explained in Subsection 5.4.

5.5.1 Fit Region Definition

Due to the complexity of the magnetic field behavior, particularly in the magnet region, several fit regions are defined in the LHCb active geometry. The boundary choice results from a compromise between three requirements:

- Achieving the target precision of $\sim 10^{-3}$ T.
- Minimizing the number of regions to reduce the number of boundaries where discontinuities of the magnetic field component could occur.
- Minimizing the number of terms in the parameterizations to prevent oscillating behaviors.

Moreover, the geometric delimitations of the regions are designed as simply as possible. To define appropriate regions, cuts on the acceptance angles⁸, on the magnetic field gradients⁹ or on the (x, y, z) LHCb coordinates have been considered. The simplest region definition relies on cuts on the z coordinate only, for the B_x , B_y and B_z components. Fifteen regions are obtained (Figure 5.19, top), five in the upstream region ($z = [-50, 300]$ cm with boundaries at $z = 100, 150, 200$ and 240 cm), seven in the magnet region ($z = [300, 800]$ cm with boundaries at $z = 410, 470, 510, 610, 670$ and 730 cm) and three in the downstream region ($z = [800, 1000]$ cm with boundaries at $z=850$ and 900 cm).

Each slice in z has been defined in such a way that the largest region possible is kept and still satisfies the target precision. This has been achieved first for the most important component B_y . Then, the same cuts have been applied for the B_x and B_z components, for which the relative precision has been checked to reach the desired precision.

⁸Because of the design of the LHCb forward spectrometer and the particle tracks trajectories in the acceptance region, an analytic description of the magnetic field components with respect to the acceptance angles has been thought to be optimal. The cuttings on the acceptance angles in the bending plane (up to 300 mrad) and in the non-bending plane (up to 250 mrad) have shown a good performance for angles up to 10 mrad. For larger angles, additional cuts are required to achieve the target relative precision, for example on the LHCb (x, y, z) coordinates. This creates a considerable number of regions and results in a complicate partitioning, as cuts on the acceptance angles and on the LHCb coordinates are used simultaneously.

⁹The choice of the cuts is driven by the field variations. Regions where the field gradients are big will be smaller and/or will require more terms in the parameterization than the ones where the field variations are smoother. This method results in a very complicate partitioning. Moreover, as the behaviors of the B_x , B_y and B_z gradients are not the same for a given region, different cuttings should be introduced for each magnetic field component.

The locations of these cuts do not systematically correspond to physical positions of detectors. However, the cut at $z = 100$ cm corresponds to the beginning of the RICH1 detector and the cut at $z = 470$ cm corresponds to the peak position of the B_y component on the z axis ($x=0$ cm, $y=0$ cm) (Figure 5.19, bottom).

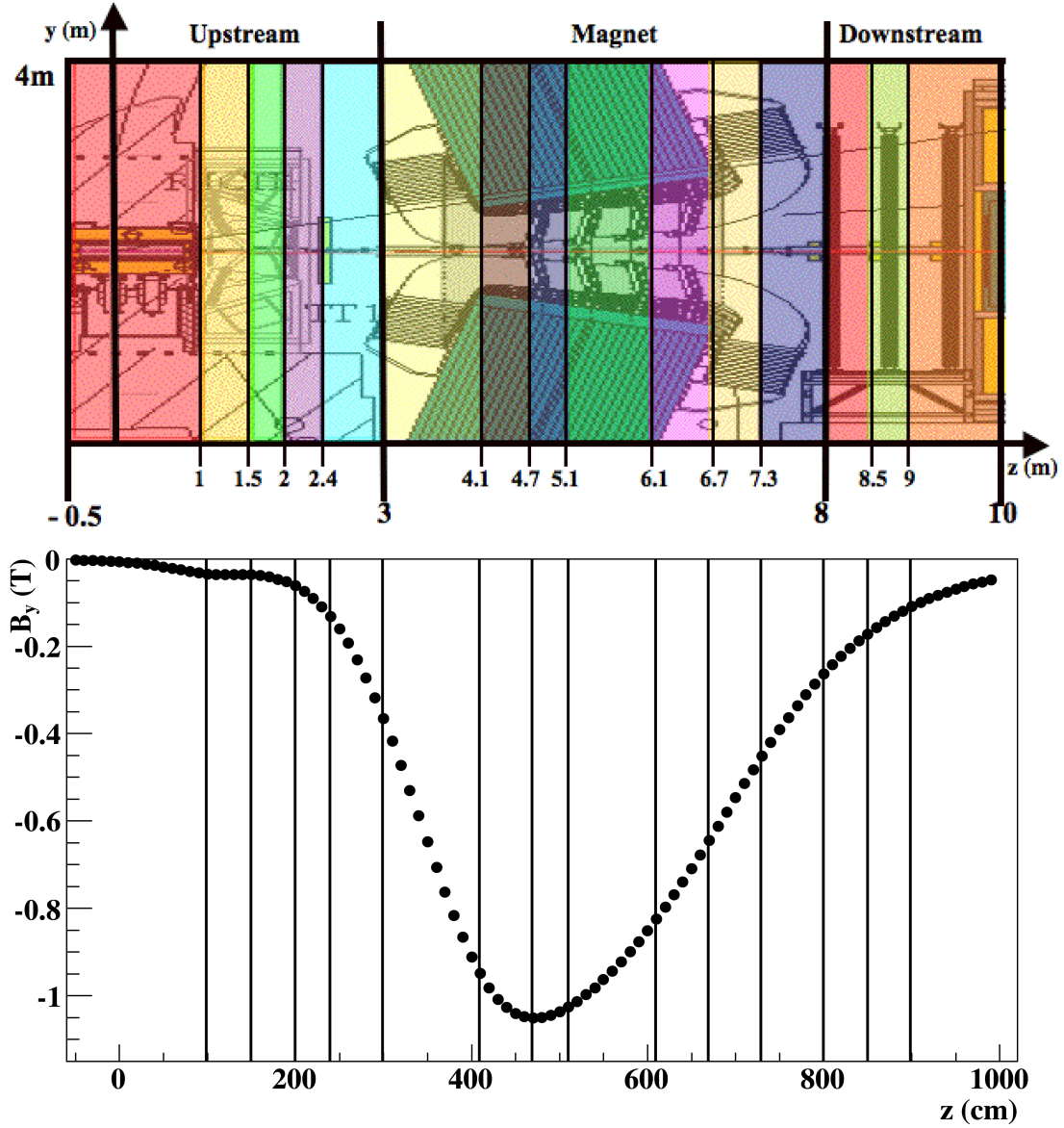


Figure 5.19: Set of cuts along the LHCb z coordinate (black lines at $z=100, 150, 200, 240, 300, 410, 470, 510, 610, 670, 730, 800, 850$ and 900 cm) delimiting fifteen regions, in which the B_x , B_y and B_z component behaviors are independently described by analytic parameterizations.

Since the magnetic field is distorted more strongly when approaching the coils, the field variations are faster in the $[y_{\max}-30, y_{\max}]$ region (Figure 5.20) ($y_{\max} = \tan(\theta_y) \cdot z$), resulting in an increased number of terms in the parameterizations.

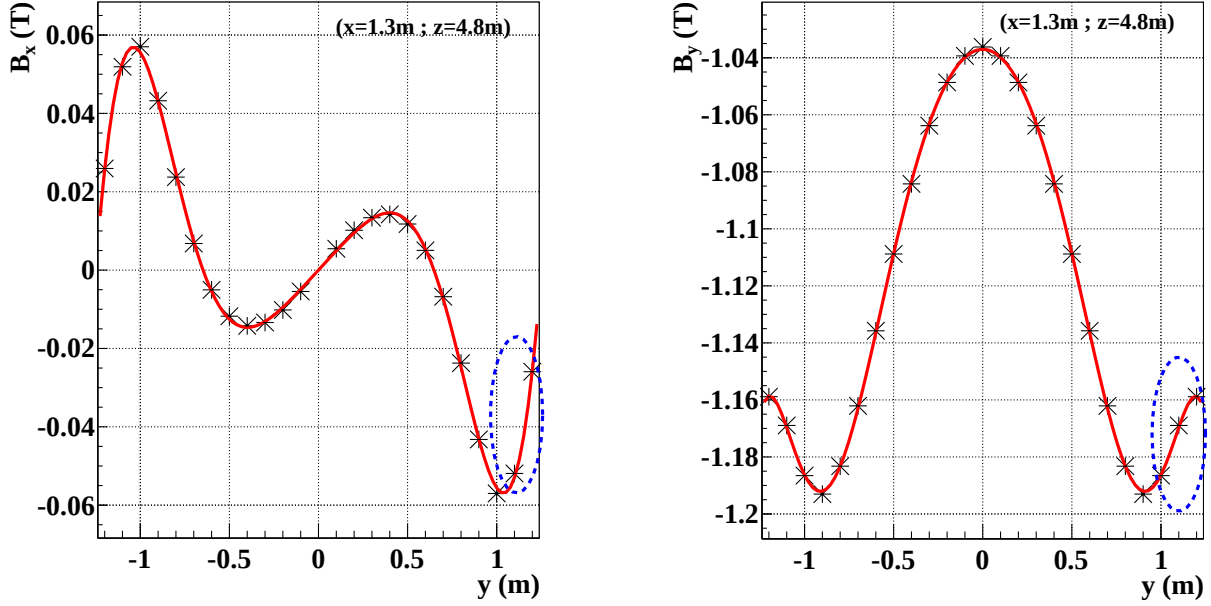


Figure 5.20: B_x (left) and B_y (right) variations as a function of y for $z=4.8$ m and $x=1.3$ m. The simulated values (stars) are fitted by a polynomial function (full line). The magnetic field components corresponding to the three biggest y values (delimited by the dashed lines) vary in a different way than the ones corresponding to smaller y values.

A detailed study has shown a considerable improvement of the goodness of the parameterizations when the regions $[0, y_{\max} - 30 \text{ cm}]$ and $[y_{\max} - 30 \text{ cm}, y_{\max}]$ are separately fitted in the magnet region [85] (Figure 5.21). Indeed, if the whole $[0, y_{\max}]$ range is fitted at once, good results are obtained on the fitting nodes, but instabilities are observed between them. These oscillations are attributed to the considerable number of terms in the parameterizations (≥ 300). Cutting finer on the z coordinate does not really improve the mapping while splitting the region in y removes the oscillatory effects.

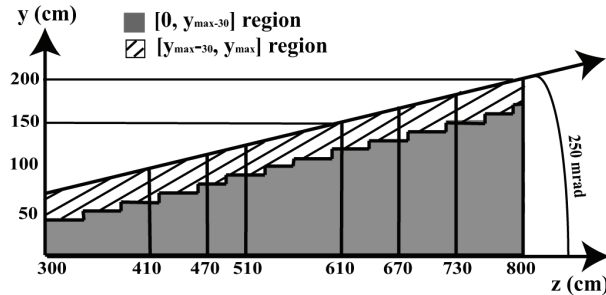


Figure 5.21: The $[0, y_{\max}-30 \text{ cm}]$ (filled) and $[y_{\max}-30 \text{ cm}, y_{\max}]$ (dashed) regions in the magnet, delimited by the boundaries at $z=410, 470, 510, 610, 670$ and 730 cm and the acceptance boundary in the non-bending plane of 250 mrad.

5.5.2 Results

With the simultaneous fitting technique, it has been possible to map the full LHCb acceptance with a sensible accuracy.

The fits end up with a number of terms in the different parameterizations varying approximately from 50 to 150 and Chebychev monomials up to order 9, depending on the complexity of the magnetic field behavior inside the regions and the size of the regions themselves [85].

The distributions of the residuals between the parameterized and the simulated values have resolutions of $\sim 10^{-4}$ T for each magnetic field component and for the total magnetic field.

5.5.3 Validation of the Parameterization

The validation of the parameterization is performed in three steps:

1. Good Matching between the simulated and parameterized values in slices of one coordinate.
2. Check at the boundaries between the different fit regions.
3. Comparison of the $\int B dl$ of the two maps using the LHCb software.

These are described in the following.

Simulated-Parameterized Value Matching in Slices of One Coordinate

Slices of the three magnetic field components are plotted as a function of x for combinations of the y and z coordinates inside the LHCb acceptance. The same tests are performed for slices as a function of y and finally as a function of z . These visual checks ensure that no significant mismatches of the parameterization with the input simulated values are observed, within the fit regions or at the boundaries between regions.

As an example, Figures 5.22-5.23 show comparisons between the simulated values (black dots) and the parameterized values (red triangles) for the B_x (top), B_y (middle) and B_z (bottom) components on the z axis ($x=0, y=0$) cm, at ($x=50, y=50$) cm, at ($x=100, y=100$) cm and ($x=150, y=150$) cm. The agreement is very good for all components.

The B_x and B_z component values at the centre ($x=0, y=0$) cm are expected to be zero from the (anti-) symmetry requirements and fluctuations related to the intrinsic precision of the fit are therefore observed (Figure 5.22). These components have sizable values as soon as x and y get away from the beam axis, in which case the fluctuations become negligible (Figure 5.23).

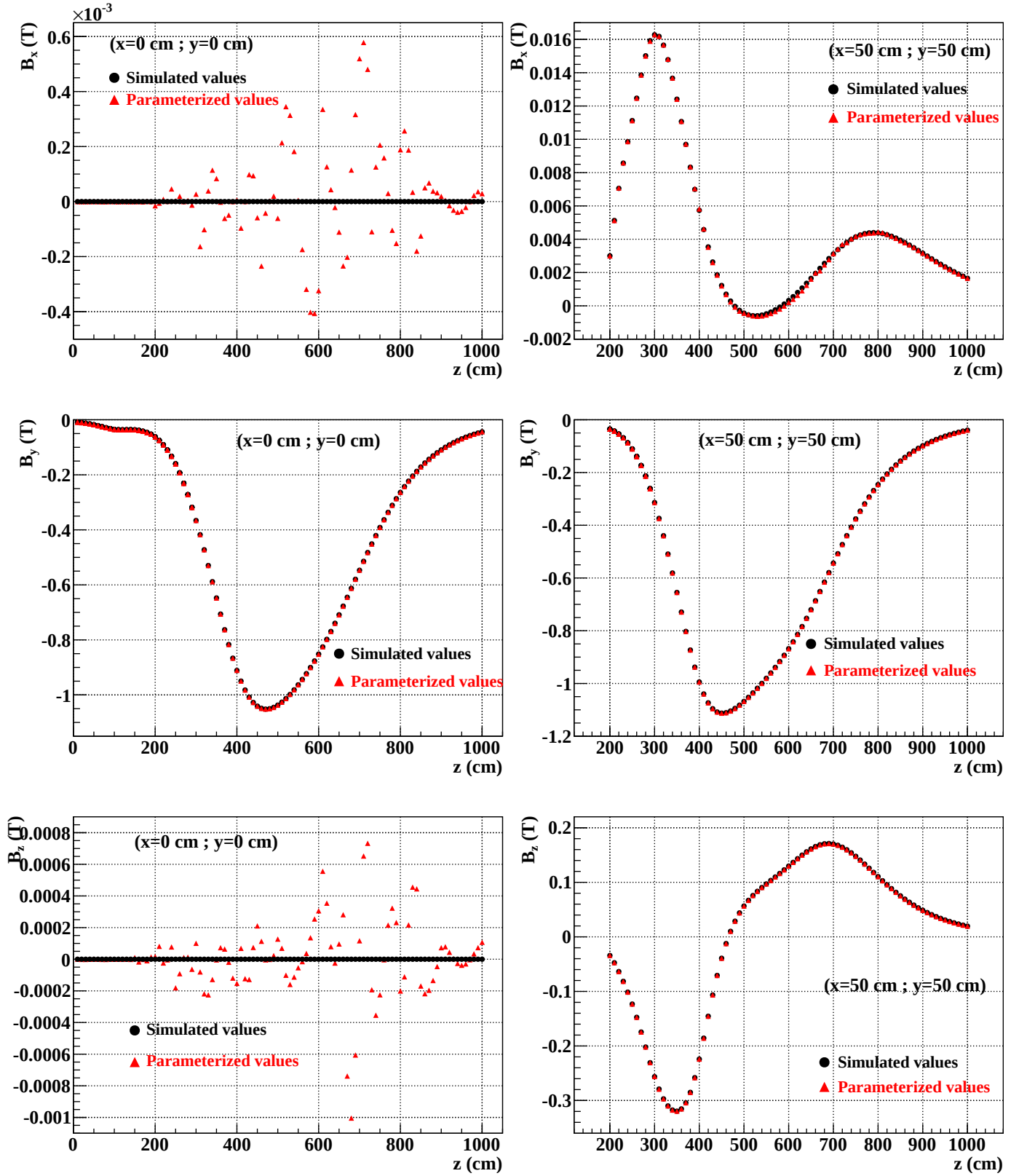


Figure 5.22: Comparisons between the simulated and parameterized values for the B_x (top), B_y (middle) and B_z (bottom) components as a function of z for $(x=0, y=0)$ cm (left) and $(x=50, y=50)$ cm (right).

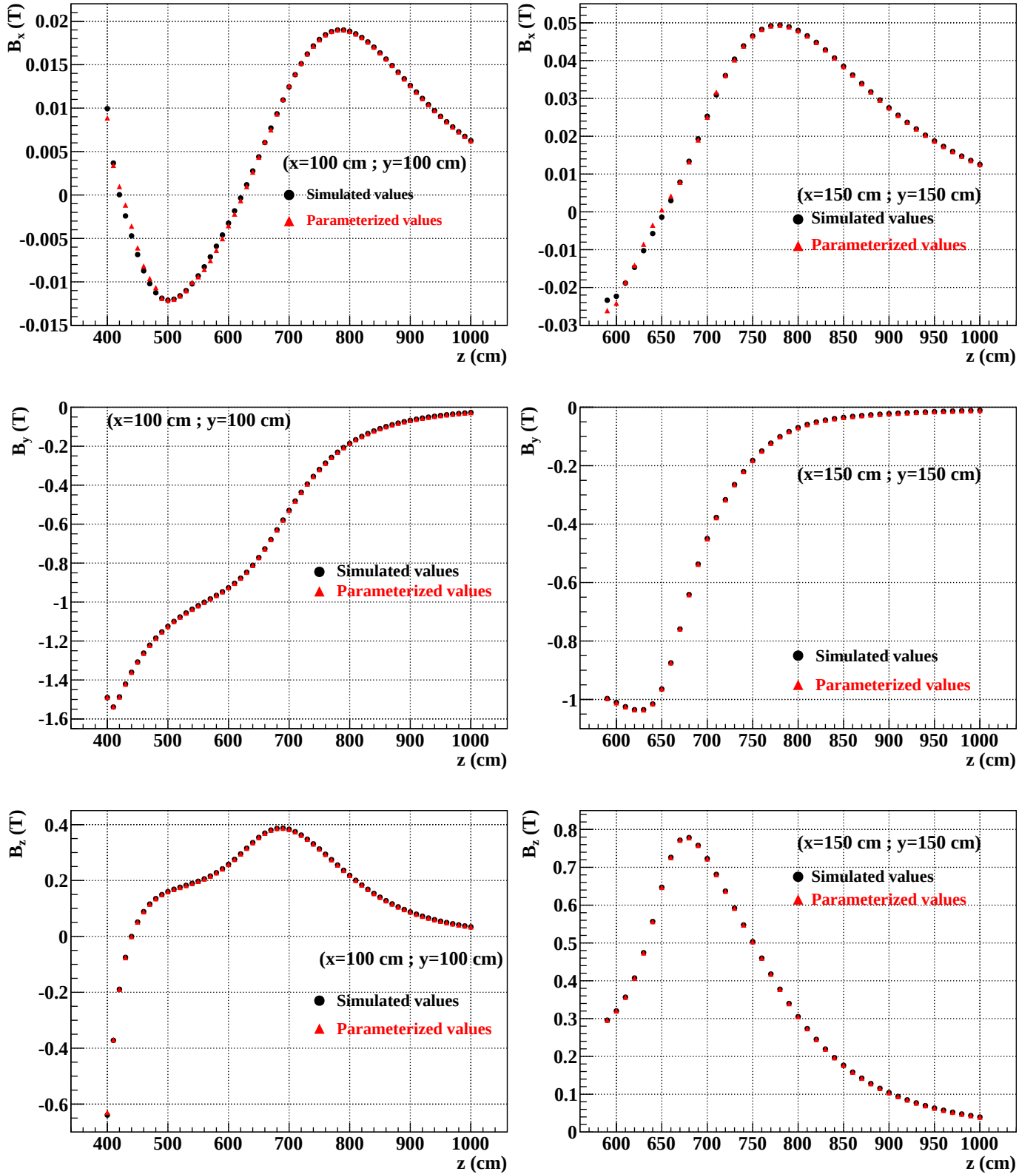


Figure 5.23: Comparisons between the simulated and parameterized values for the B_x (top), B_y (middle) and B_z (bottom) components as a function of z for $(x=100, y=100)$ cm (left) and $(x=150, y=150)$ cm (right).

Check at the Boundaries between the Different Fit Regions

To tackle boundary problems, the fit regions of Figure 5.19 are extended to take into account the first or last set of values belonging to the next or previous regions respectively, such that all the regions used for fitting overlap. However, the continuity between adjacent regions at their boundaries need to be checked, as the parameterizations are obtained for all the regions separately. For this, the relative discrepancy is defined as:

$$\frac{\Delta B}{B_{\text{mean}}} = \frac{B_{\text{region 1}} - B_{\text{region 2}}}{B_{\text{mean}}} \quad (5.14)$$

Figure 5.24 (top, left) shows the relative discrepancies for the B_y component at the $z = 470$ cm boundary. In general, the relative discrepancies have been found to be of the same order of the fit precision for each magnetic component. At the boundaries, the magnetic field values are calculated for each component on the 10 cm-grid using the two available parameterizations. The residuals between these two values obtained as explained in Subsection 5.3.4 and are shown in Figure 5.24 for the fourteen z boundaries together. Resolutions of $\sim 10^{-4}$ T are found for the three field components.

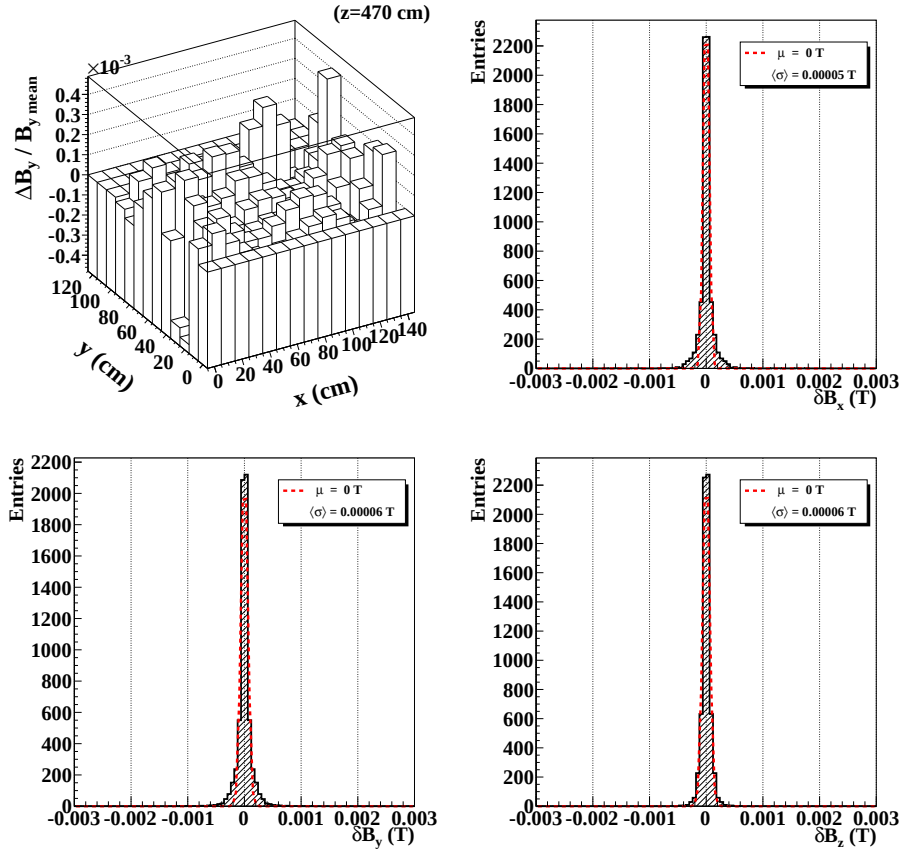


Figure 5.24: Relative discrepancy of the B_y component as a function of x and y at the $z=470$ cm boundary (top, left) and residual distributions between the two available parameterizations at each z boundary for each magnetic field component (top, right and bottom).

To ameliorate further the matching at the z boundaries, the average of the values coming from the two different parameterizations is used when producing the final magnetic field map.

Comparison between the $\int B d\vec{l}$ of the two Maps

To estimate the goodness of the parameterization with respect to the Simulated Magnetic Field Map, a numerical integration of the bending vector $\int \vec{B} \times d\vec{l}$ (mentioned as $Bd\vec{l}$ in what follows) is calculated and compared for the two cases using the LHCb software. The integration is performed between the LHCb origin and $z = 950$ cm for 100,000 values of track slopes t_x and t_y , randomly generated in the ranges $[-0.3, 0.3]$ rad and $[-0.25; 0.25]$ rad, respectively. Since (x, z) is the bending plane, the main component is $Bd\vec{l}_x$, the two others are expected to have a null average.

Figure 5.25 shows the distributions of the components of the bending vector. All the components remain unchanged. Analyzing the changes as a function of the track slopes in Figure 5.26, a good agreement is also established. The main component, $Bd\vec{l}_x$, is observed to have a quadratic dependence with respect to the track slopes, while flat distributions of $Bd\vec{l}_y$ as a function of t_x and t_y and $Bd\vec{l}_z$ as a function of t_y are observed. $Bd\vec{l}_z$ is linearly dependent of t_x .

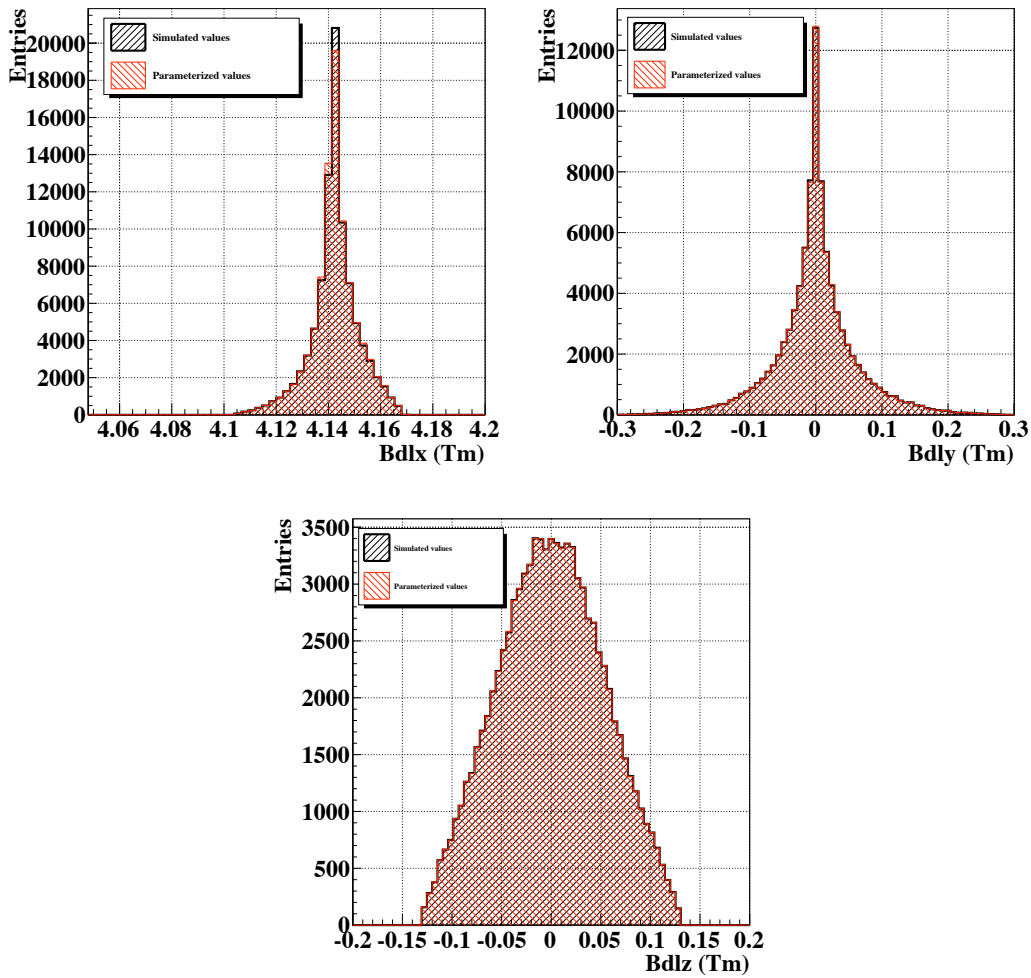


Figure 5.25: Components of the bending vector $\int \vec{B} \times d\vec{l}$. Histograms for the simulated values (black hatched with positive slope) are compared with the one of the parameterized values (red hatched with negative slope). A good agreement is observed.

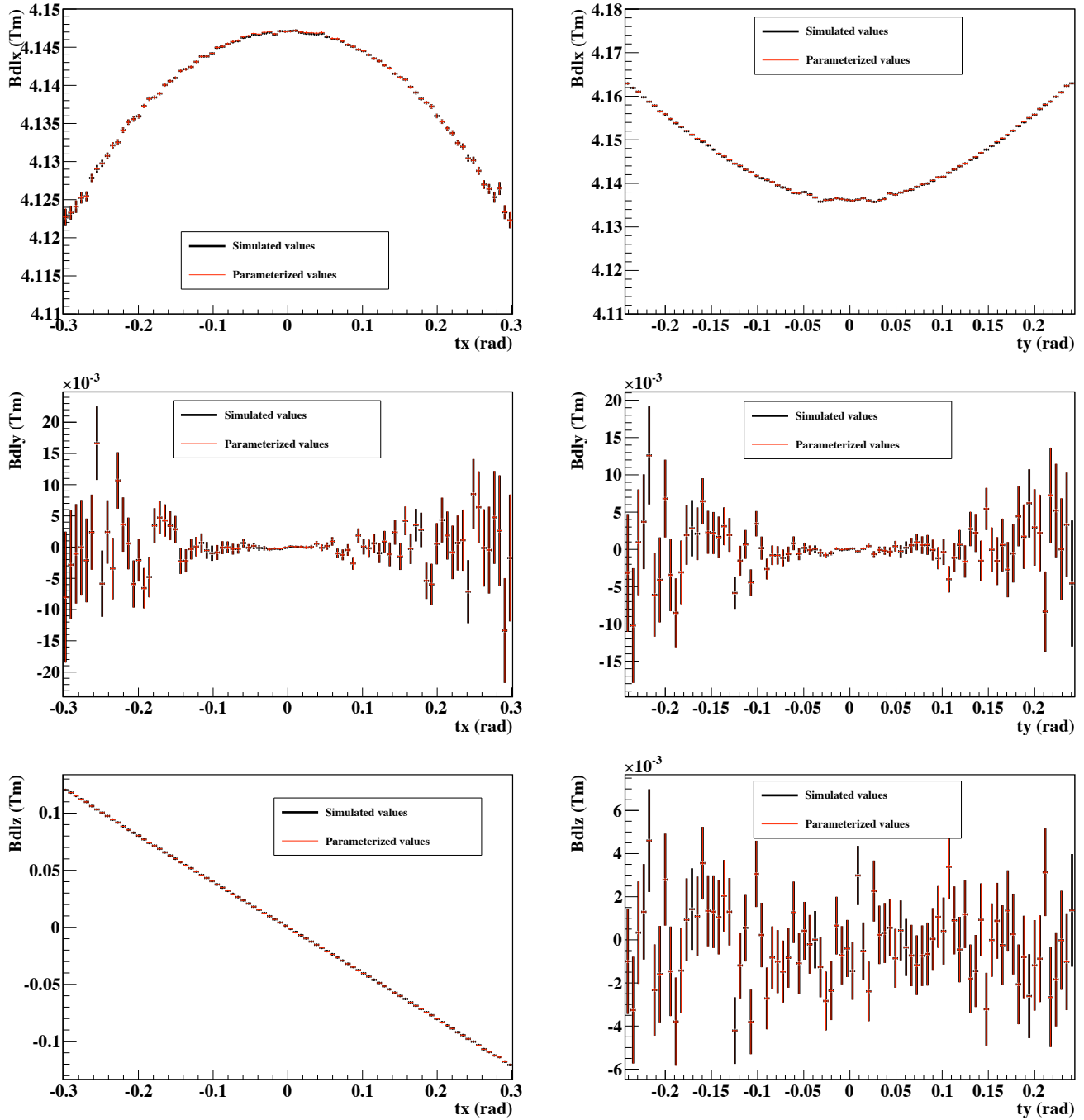


Figure 5.26: Components of the bending vector $\int \vec{B} \times \vec{dl}$ as a function of the track slopes t_x and t_y . Flat distributions are found for $Bdly$ and $Bdlz$ as a function of t_y . A linear dependence is observed for $Bdlz$ as a function of t_x . Quadratic variations are found for the main $Bdlx$ component. In all cases, the parameterized values (red thin histogram) are perfectly superimposed on the simulated values (black thick histogram).

5.5.4 Magnetic Field Service

In the LHCb software, the default service for the magnetic field, *MagneticFieldSvc*, uses a linear interpolation to derive the field vector at any point from a regular grid of data points. At first, a new service, called *AnalyticFieldSvc*, has been implemented, in which the field is computed using the three dimensional Chebychev expansion. Even though this parameterization benefits from the recursive relation between the subsequent polynomials, it raised a timing issue as an order of magnitude in speed was lost in the track fit. Therefore, the linear interpolation picture is kept, but a corrected grid is produced using the final parameterized description of the magnetic field. Since measurements show asymmetries in the (x, y) plane, the obtained grid map is four times bigger than the simulated grid map, in which the $x - y$ (anti-)symmetry is used to derive the field components.

Grid Size

Dedicated tests have been performed to study the effects of the grid size, hence the impact of the interpolation error. The benchmark variables used for these tests are the momentum resolution and the position of the extrapolated tracks at the entry of the T-stations. The principle of the test is to generate a track sample with a given grid size and reconstruct the same sample with a different grid size. The difference between 5 cm and 10 cm grid sizes produces no significant degradation for both the momentum resolution and the precision of the extrapolation. Therefore, the 10 cm-grid size is kept, as it results in a smaller field map to be supported and downloaded by the LHCb software.

Reading Magnet Conditions From Database

The field service has been upgraded to allow reading magnet conditions from database. The software allows the reading of the current value circulating in the coils, the polarity, the field map files name as well as scale factors. It is also possible to modify the field map calibration files in running.

5.6 The LHCb Measured Magnetic Field Map

As the three-dimensional simultaneous fitting method has been validated in Section 5.5, it can be used to create the LHCb Measured Magnetic Field Map based on measurements. The additional challenge of working with measurements compared to simulated values is that they do not cover the whole LHCb acceptance, as explained in Subsection 5.3.3. Consequently, an extrapolation method has to be developed for the regions where no measurement is available.

5.6.1 The Residual Parameterization

To prevent from high-order polynomial and stability problems, the method relies on the calculation of the residuals δB_i between the measurements B_{meas} and the simulated values B_{sim} , $\delta B_i = B_{\text{meas},i} - B_{\text{sim},i}$ [87]¹⁰. Two-dimensional distributions of these residuals are shown in Figure 5.28 for the three regions in z and for each magnetic field component. These distributions show a quite smooth behavior and are not expected to require high-order polynomial terms to be precisely described.

The calculation of the residuals is performed at the measurements points. The parameterization of the simulated values obtained in Section 5.5 is used to calculate the magnetic field values at the measurement points. Using the parameterization allows a gain in precision on the values calculated compared to using the linear interpolation of the simulated values. The final map is then derived using the extrapolation of the parameterizations of the residuals r_{extr} over the full acceptance, $B_{\text{final}}(x_i) = B_{\text{sim}}(x_i) + r_{\text{extr}}$.

¹⁰Several methods were considered for the extrapolation. The first method tried consisted in parameterizing the measurements directly, as for the simulated value in Section 5.5, and use the polynomial fit functions obtained to calculate the magnetic field values also in the regions without measurements. This straightforward method turned out to be not optimal for the following reason. Even though it has allowed the accuracy of 10^{-3} T to be reached in the measurement region, the polynomials obtained are up to order 9. These high-order terms can be very sensitive to oscillations or divergences and therefore need to be controlled very carefully. Therefore, it is not possible to rely on them to extend the map to regions without measurements, as close to the LHCb acceptance boundaries where the magnetic field varies significantly (Figure 5.20).

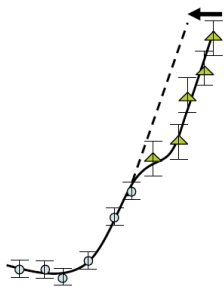


Figure 5.27: Iterative extrapolation method.

To control the fit behavior in the regions uncovered by the measurements, the second method tried combined information from the measurements and the simulated values. The principle of the method is depicted in Figure 5.27. A combined set of measurements (circles) and simulated values (triangles) is fitted using the three-dimensional fit. Since the final parameterization is expected to match the measurements rather than the simulation, more weight is given to measurements. In the regions without measurements, the fit is driven by the simulated values, but is not expected to match them exactly. To do so, the fit is applied to the combined set a first time. The simulation points are then replaced by points obtained from this first parameterization. These are again combined with the measurements and a new fit is performed. The fit iteration stops when most of the residuals between the measurements and the parameterization at order k are less than $\sim 5 \cdot 10^{-4}$ T. While this method allows data fit and extrapolation, the matching of data and simulation is not always stable, especially in regions where the field component values are small.

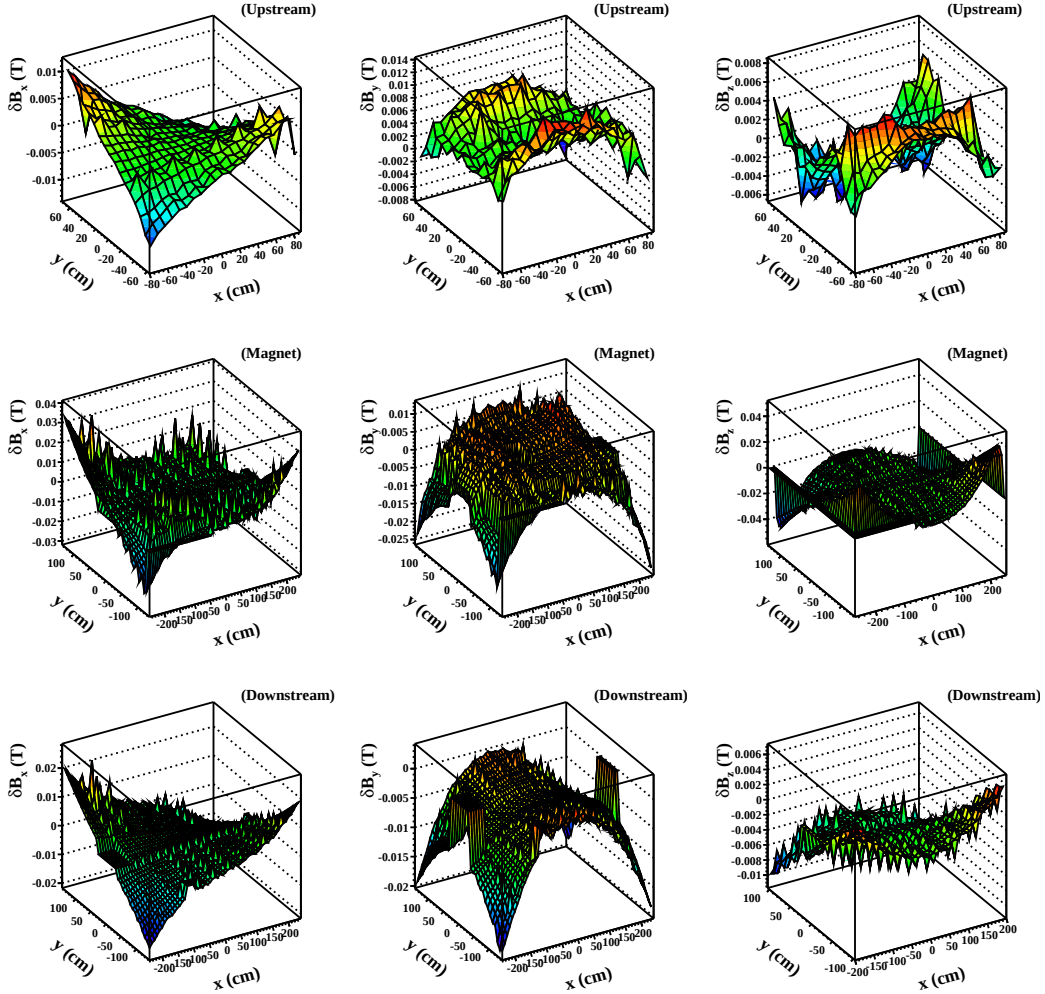


Figure 5.28: $\delta B_i = B_{\text{meas},i} - B_{\text{sim},i}$ residual distributions for the upstream, magnet and downstream regions.

The extrapolation of the fit function to the regions without measurements is checked as follows. The coordinates of the simulated points are used to compute parameterized values in the whole LHCb acceptance. The resulting distributions are checked to extend smoothly from the measurement region to the LHCb acceptance boundaries.

5.6.2 Results

The cleaning of the measurements detailed in Section 5.3 ensures that no biases are introduced in the fit due to unphysical values. Moreover, average values are computed in points where several measurements are still available after cleaning, such that each space point entering in the fit has the same weight, hence no points are favored due to their redundancy. Due to the simpler form of the residuals compared to the field variations, the number of fit regions of Figure 5.19 is reduced to twelve, removing the boundaries at 100 cm and 730 cm. The number of terms in the parameterizations is of $O(10)$ and the monomial are of order 3–4.

Contrary to the Simulated Magnetic Field Map, where the values are (anti-)symmetric between the different quadrants, and hence only one quadrant needed to be parameterized, the measurements show some asymmetries between the different quadrants, as explained in Subsection 5.3.5. Therefore the residual parameterizations are obtained in a given fit region in z for the four quadrants at one time, resulting in asymmetric parameterization functions. The largest corrections generally occur for large x and/or y values, which means that the simulation accounts better for the measurements in the central region of the transverse plane than in the edges.

Figures 5.29-5.31 illustrate the residuals between the parameterized values and the measurements (red hatched distributions). Gaussian fits to these distributions give resolutions $\sim 10^{-3}$ T. The difference between the interpolated simulated values and the measurements is overlaid to visualize the size of the corrections needed (black distribution).

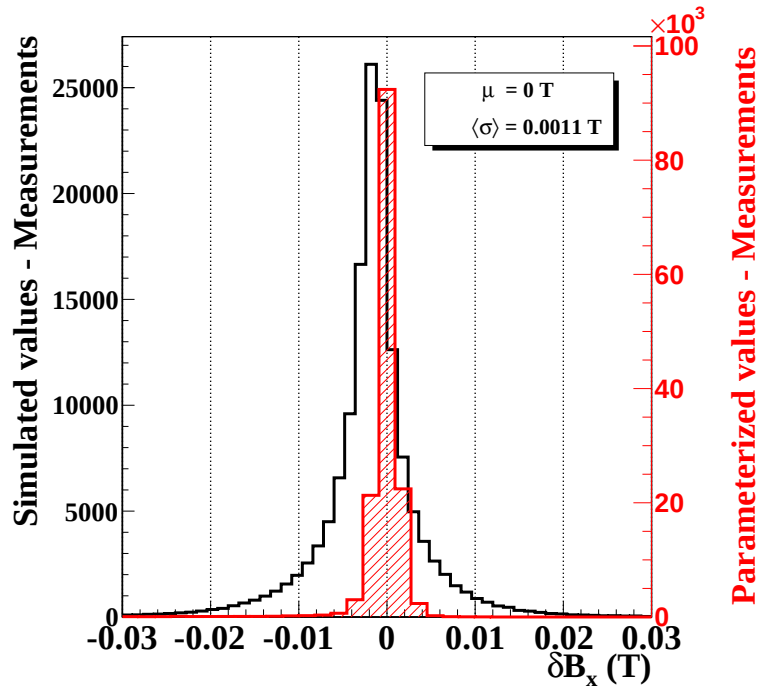


Figure 5.29: δB_x residuals between the measurements and the parameterized values (red hatched histogram). A Gaussian fit gives a resolution ~ 0.001 T. The residuals between the measurements and the simulated values are also shown (black histogram).

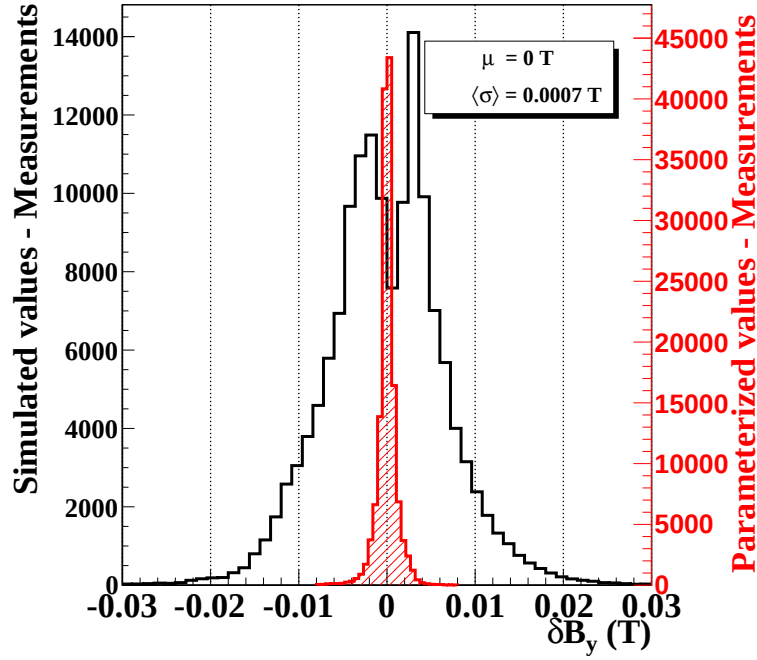


Figure 5.30: δB_y residuals between the measurements and the parameterized values (red hatched histogram). A Gaussian fit gives a resolution ~ 0.001 T. The residuals between the measurements and the simulated values are also shown (black histogram).

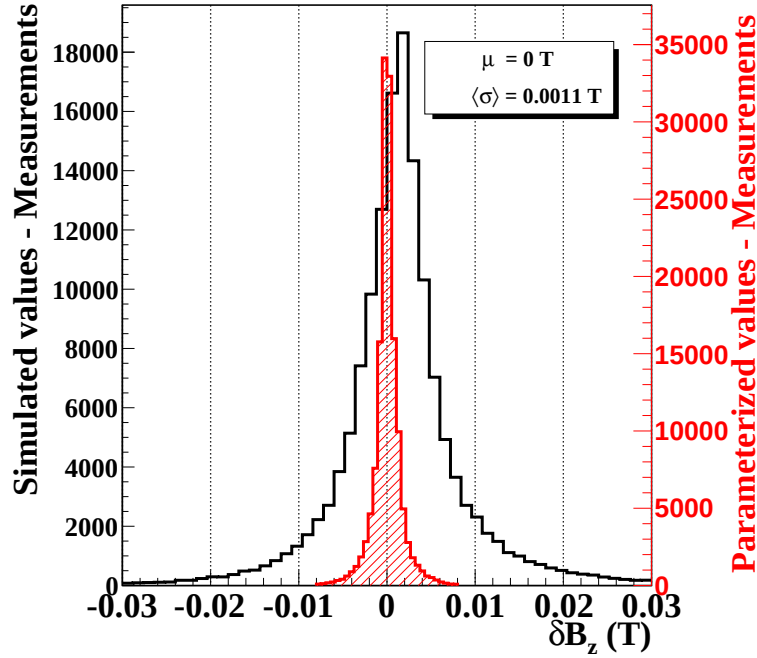


Figure 5.31: δB_z residuals between the measurements and the parameterized values (red hatched histogram). A Gaussian fit gives a resolution ~ 0.001 T. The residuals between the measurements and the simulated values are also shown (black histogram).

5.6.3 Validation of the Parameterization

The three steps of the validation procedure of Subsection 5.5.3 are applied in the following to the LHCb Measured Magnetic Field Map.

Parameterized Value - Measurement Matching in Slices of One Coordinate

Slices as a function of z of the B_y and B_z measurements (blue stars), parameterized values of the measurements (red triangles) and simulated values (black dots) are shown in Figure 5.32 for different x and y values. As expected, a good agreement is observed between the measurements and the parameterized values, which differ from the simulated values.

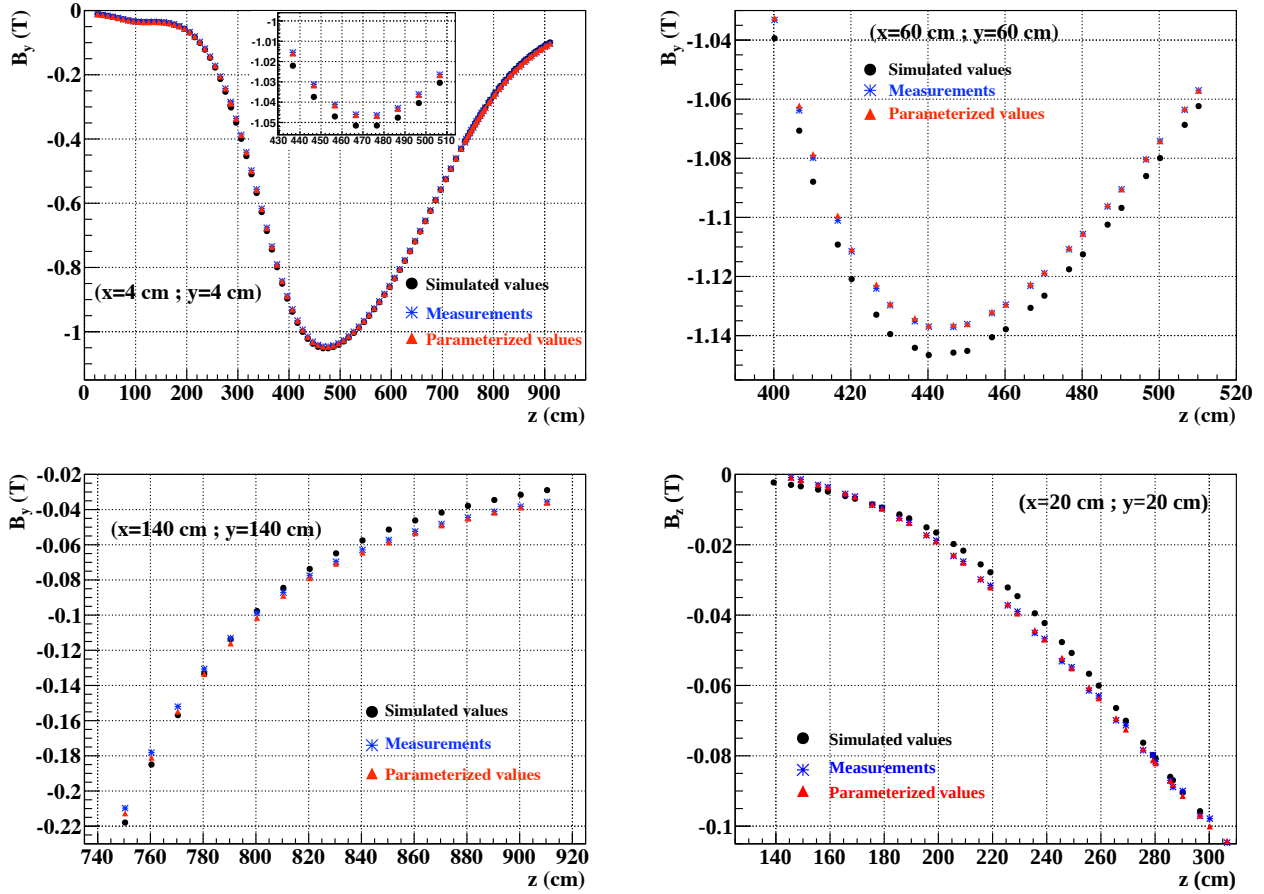


Figure 5.32: Comparisons between the measurements (blue stars), the parameterized values (red triangles) and the simulated values (black dots) for the B_y component as a function of z at $(x=4, y=4)$ cm (top, left with a zoomed view on the z axis), $(x=60, y=60)$ cm (top, right), $(x=140, y=140)$ cm (bottom left) and for the B_z component at $(x=20, y=20)$ cm (bottom, right).

Check at the Boundaries between the Different Fit Regions

Points on a 10 cm-grid in x and y inside the LHCb acceptance are generated for the eleven z values located at the fit region boundaries. The magnetic field components are calculated using the two available parameterizations. Their residuals are calculated as explained in Subsection 5.3.4 and their distributions are shown in Figure 5.33 for the three magnetic field components. From (double-)Gaussian fits, the average resolutions are ~ 0.001 T, ~ 0.0004 T and ~ 0.0006 T for B_x , B_y and B_z respectively. These residual distributions also contain values calculated in the extrapolating regions, where a good matching between the two parameterizations is also observed.

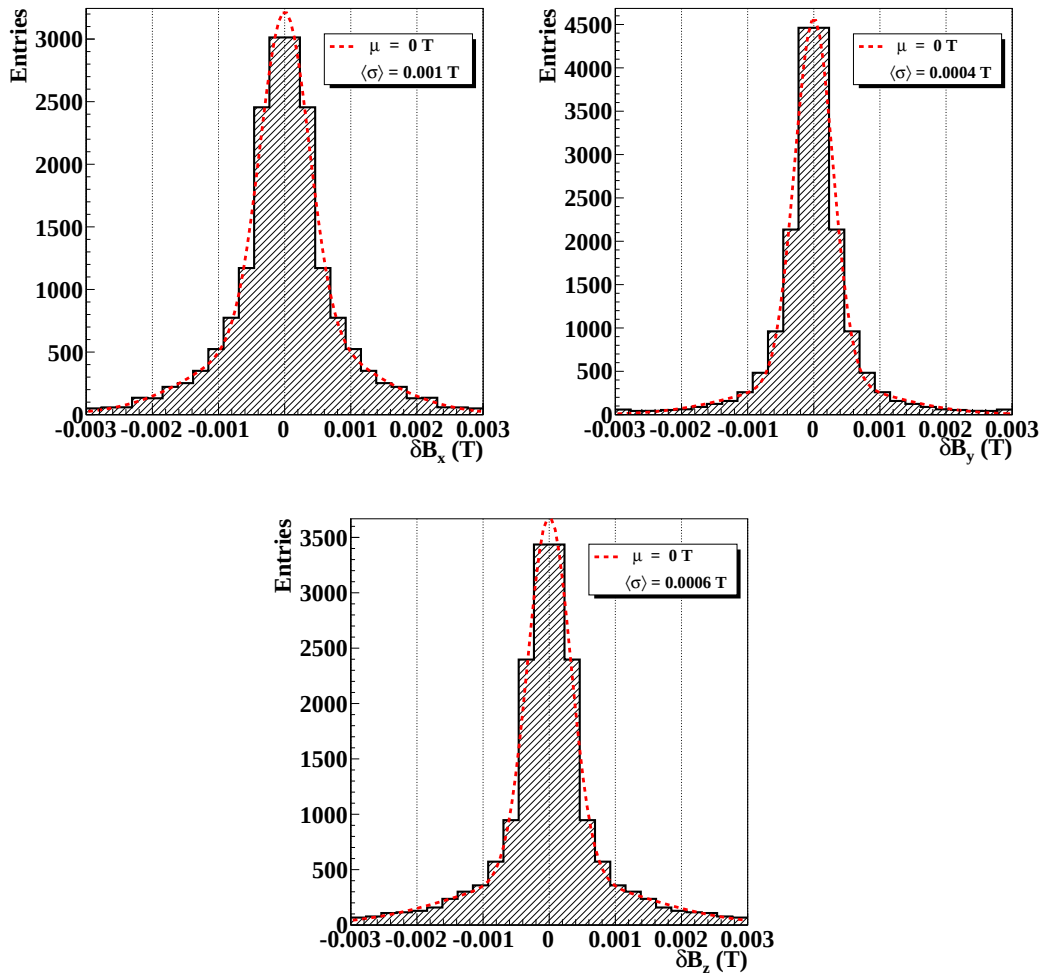


Figure 5.33: Residual distributions between values calculated every 10 cm using the two available parameterizations in all the z boundary planes.

Comparison between the $\int Bdl$ of the two Maps

A numerical integration of the bending vector $\int Bdl$ is performed as explained in Subsection 5.5.3. Figure 5.34 shows the distributions of the bending vector components for values obtained using the Simulated Magnetic Field Map (black hatched histogram with positive slope) and the ones obtained using the Measured Magnetic Field Map (red hatched histogram with negative slope). The Bdl_z component remains almost unchanged while Bdl_x and Bdl_y are affected. Bdl_y is shifted upwards by 8×10^{-3} on average, while Bdl_x is shifted downwards by 0.6%, on average.

Analyzing the changes as a function of the track slopes (Figure 5.35), shifted distributions for Bdl_x and Bdl_y are observed, the Bdl_x components for the values using the Measured Magnetic Field Map being significantly lower than for the Simulated Map. A change in slope in Bdl_z as a function of t_x is also observed. Bdl_z as a function of t_y is not significantly affected.

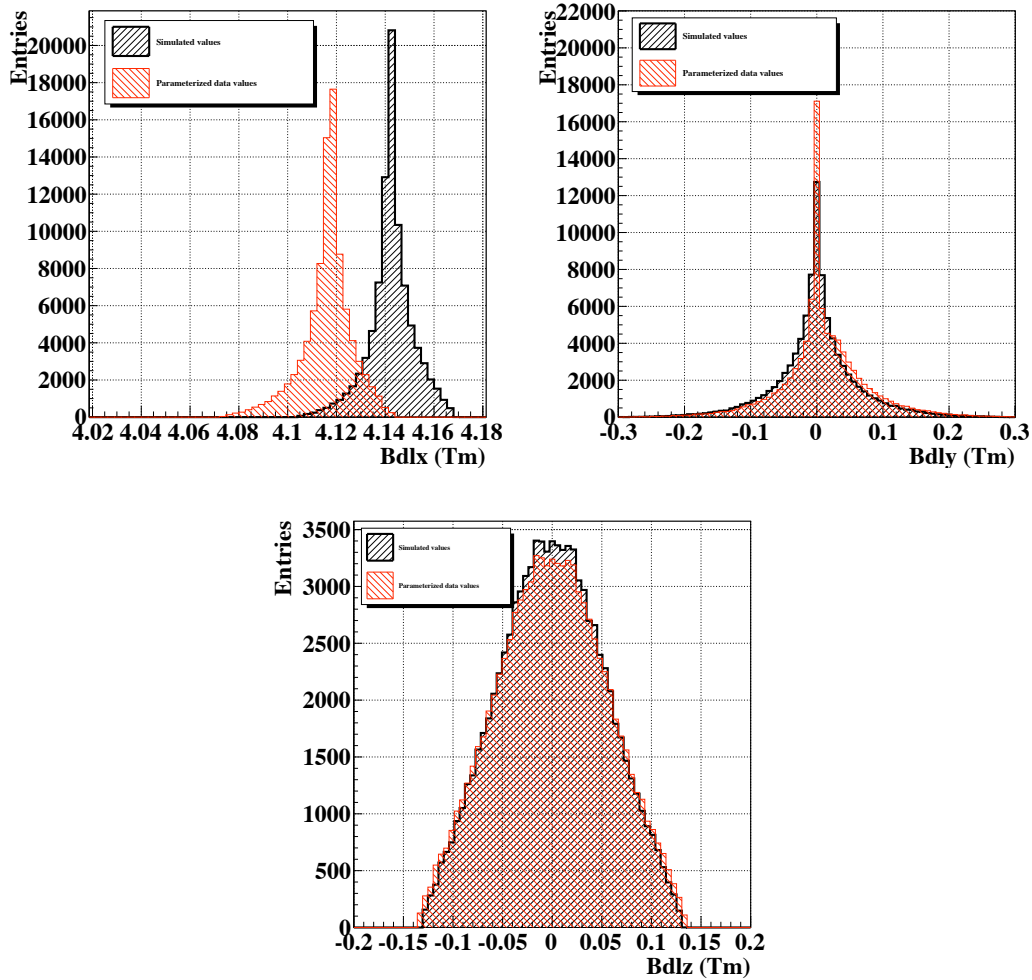


Figure 5.34: Components of the bending vector $\int Bdl$. Histograms for the simulated values (black hatched with positive slope) are compared with the ones of the measured parameterized values (red hatched with negative slope). Significant differences are observed for Bdl_x and Bdl_y .

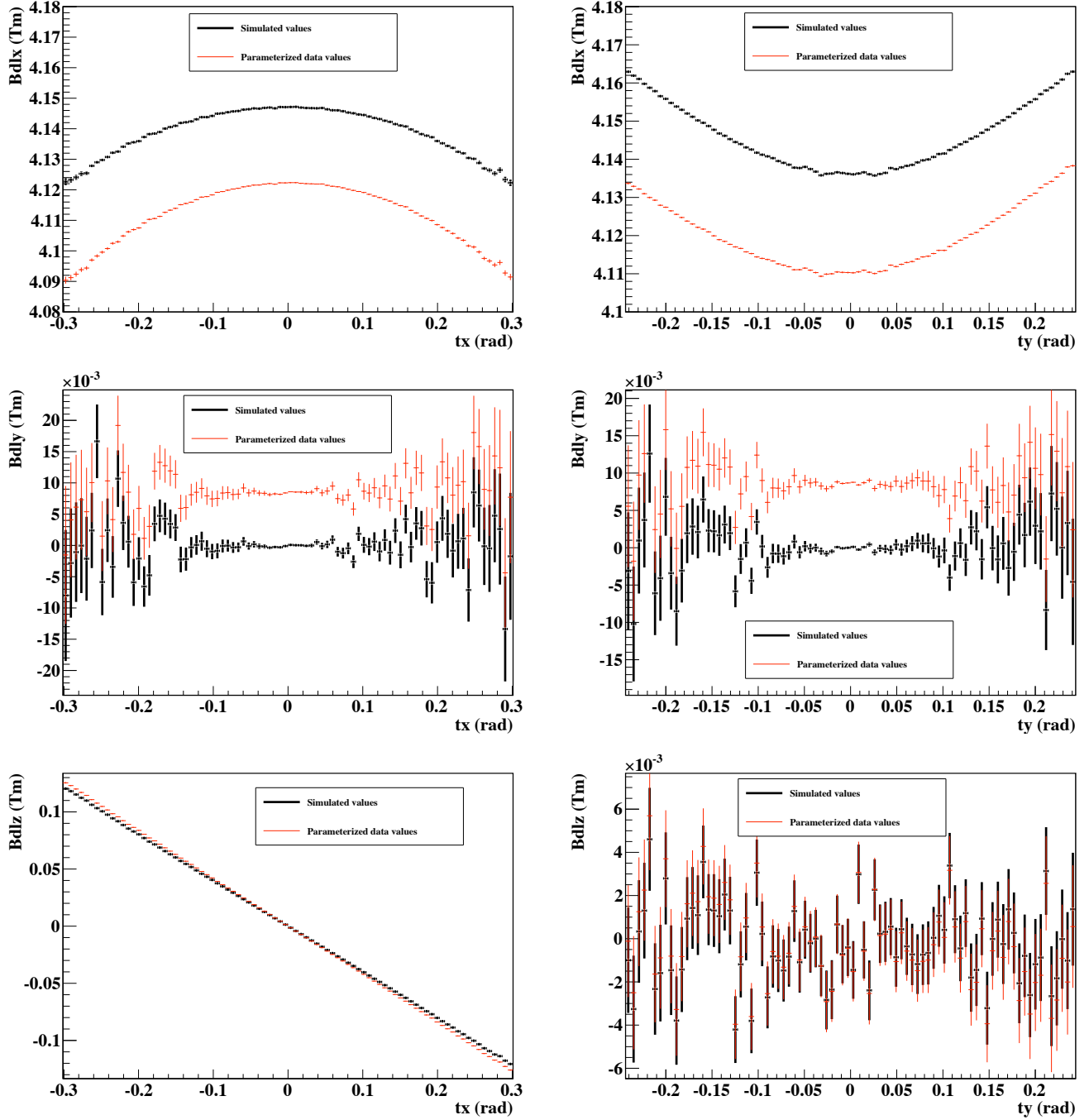


Figure 5.35: Components of the bending vector $\int B dl$ as a function of the track slopes t_x and t_y . Shifted distributions are found for $Bdlx$ and $Bdly$ and a change a slope in $Bdlz$ as a function of t_x between the simulated values and the measured parameterized values. $Bdlz$ as a function of t_y is not significantly modified.

5.7 Towards a Unique Map

The LHCb Measured Magnetic Field Map described in Section 5.6 has been obtained for the down polarity of the LHCb magnet and has been divided in four descriptions (one for each quadrant). A similar description has been obtained for the up polarity of the dipole magnet [88], resulting in a total of eight different parts composing the magnetic field map in the LHCb software. The idea of simplifying the magnetic field description has emerged from the two following observations [96]:

1. *Comparison between the up and down polarity measurements (Subsection 5.3.6).* Figure 5.18 shows that the magnetic field components measured for both polarities agree within $\sim 3 \times 10^{-4}$ T. This brings to the conclusion that using one description for both polarities is a reasonable assumption, reducing the number of maps from eight to four.
2. *The x -symmetry in the measurements (Subsection 5.3.5).* Figure 5.14 shows that an x -symmetry is observed in the measurements for B_y and B_z . The asymmetry for the B_x component explained in Subsection 5.3.5 could be neglected for the following reasons. First, it is the weakest magnetic field component, the total magnetic field being dominated by the B_y and then the B_z components. Second, using $K_S \rightarrow \pi^+ \pi^-$ from real data, it has been observed that a negligible amount of candidates are reconstructed from two pions going through two diagonal quadrants (Q1-Q4 or Q2-Q3). In this case, the asymmetry could matter, as the bending vector integral would depend on which diagonal they went through. Neglecting the x -asymmetry in B_x , the number of maps would be reduced to two. However, as the MagneticFieldSvc is already designed to take into account four maps, this simplification is not yet performed and one map per quadrant is kept.

Due to the up-down asymmetry of Figure 5.15, the map cannot a priori be further simplified. However, the origin of the up-down asymmetry needs to be understood. If it is a fake effect coming from the measurement campaign, then the magnetic field description could be further simplified. The final answer to this issue is given by real data and is explained in Subsection 6.6.1.

Momentum Scale Calibration Using 2009/2010 Real Data

In order to make precision measurements of particle masses and to understand the proper time distribution of B decays, a good calibration of the momentum scale is needed. As the momentum is measured from the curvature of the charged particle trajectories in the magnetic field, the magnetic field map of Chapter 5, which is used in the reconstruction, must be validated using real data [97]. This can be achieved by studying the reconstructed masses of known resonances, such as K_s , Λ , J/ψ and Υ . The peak positions give information on the global $\int B \cdot dl$ and the width on more local systematic variations. The impact on physics of the differences between the measured and simulated magnetic field maps must be evaluated, in order to determine discriminating criteria between the two maps. For this, various test methods are validated with Monte Carlo data by generating events with one field and reconstructing the same events with the same or the other field and compare the results. The methods are then applied to $K_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p^+\pi^-$ and $\bar{\Lambda} \rightarrow p^-\pi^+$ decays coming from 2009 and 2010 real data. They are reconstructed using either the measured or the simulated magnetic field maps. From a comparison of the results, the description the closest to the real magnetic field is kept. Further improvements could be then applied to the chosen magnetic field map for a better description. From the same studies, an additive correction factor α to the momentum scale is obtained. As this factor should be universal, it can be calculated for one resonance and validated using the results for other resonances.

Track reconstruction at LHCb is described in Section 6.1. The method of calibrating the momentum scale is presented in Section 6.2 and possible effects which could change this it are listed. Section 6.3 summarizes the selection criteria to select $K_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p^+\pi^-$ and $\bar{\Lambda} \rightarrow p^-\pi^+$ events from the 2009/2010 Monte Carlo and real data. The validation of the calibration method using MC data is established in Section 6.4, together with a study of systematics due to different magnetic field descriptions. Results for 2009 real data are given in Section 6.5 and in Section 6.6 using 2010 real data.

6.1 Offline Track Reconstruction

Track reconstruction consists of two steps: *pattern recognition* and *fitting*. The task of pattern recognition is to find all the tracks by assigning correctly hits to them. After this, track parameters are accurately estimated by a Kalman Filter based fit. These estimates are used in the event reconstruction to match the tracks to particle identification objects, such as RICH rings, calorimeter clusters or muon candidates. In the physics analysis, they allow the determination of the primary and secondary vertices and to calculate invariant masses.

6.1.1 Pattern Recognition

During pattern recognition [98], track segments in the VELO and the T-stations, called *seeds*, are first reconstructed. These seeds are then possibly matched to each other or to additional hits from the other tracking systems to extend the tracks.

As the magnetic field is low in the VELO detector, VELO hits are collected along straight lines. No momentum information is provided by these track segments, called *VELO seeds*. The *T seeds* are reconstructed from clusters in the IT and OT stations by a standalone algorithm. As the magnetic field is moderate in this region, the trajectory is parameterized from three hits as a parabola to take into account the non-negligible fringe field. Then, other x hits close by are added. The confirmation of the track candidate in the x projection is made using stereo hit information. Quality cuts are applied to clean the T track sample.

Different types of tracks are classified according to the detectors in which they have hits (Figure 6.1) [99].

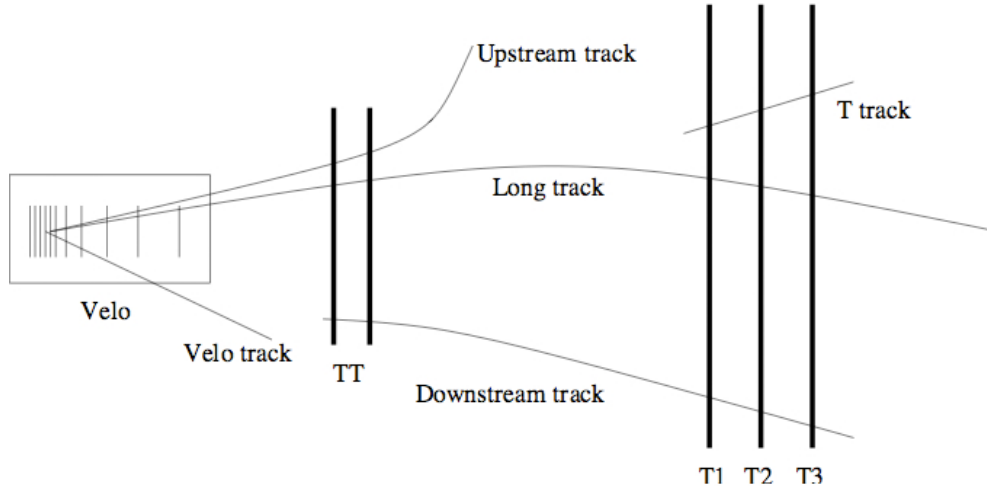


Figure 6.1: Track Types at LHCb [99].

- **Long Tracks.** These traverse the entire tracking system, from the VELO to the T-stations. As they have accurate track parameters, they are the most important tracks used in the B decay studies. They are reconstructed using two algorithms: the *forward tracking* and the *track matching* with a tracking efficiency of 95%. The two algorithms are explained in the following.

The forward tracking algorithm takes VELO seeds as input. Adding one cluster of the T-stations to the track defines the trajectory in the T-stations. Using a parameterization of this trajectory, additional clusters are searched for in the others layers of the T-stations. The candidate is kept if it satisfies some quality criteria. Then, TT hits in a window around the predicted position are added. This algorithm reconstructs $\sim 95\%$ of the long tracks.

The track matching algorithm matches T seeds with VELO seeds that have not been used by the forward tracking algorithm. The momentum of the T seeds is first estimated using the *p_T-kick method* [100]. This is used to extrapolate the T seed to a plane located behind the last VELO station, at $z_{\text{match}} = 752$ mm, using a 5th-order Runge-Kutta method [101]. The VELO seeds are extrapolated using a straight line to the same z . Correct matches are selected using a χ^2 criterion. Once the track is built, TT hits are associated to it. This algorithm accounts for the reconstruction of $\sim 5\%$ of the long tracks.

- **Upstream Tracks.** These only traverse the VELO and TT station, before being bent out of the acceptance by the magnet due to their low momentum. Due to their poor momentum resolution, $\delta p/p \sim 10 - 20\%$, they are mainly used in RICH1 reconstruction.

The *upstream tracking algorithm* takes VELO seeds as input, which have not been used in the forward tracking nor track matching to reconstruct long tracks. Upstream tracks are confirmed if the seeds are matched to at least three TT hits.

- **Downstream Tracks.** These only traverse the TT and T-stations and have no hits in the VELO. They are used for reconstructing particles decaying outside of the VELO acceptance, such as K_s^0 .

The *downstream tracking algorithm* takes T seeds as input, which have not been used in the forward tracking nor track matching to reconstruct long tracks. The seeds are extrapolated to TT and hits are searched for.

- **VELO Tracks.** These only traverse the VELO detector and are reconstructed from VELO seeds not used in the previous algorithms. They correspond to particles flying in the backward direction or outside of the LHCb acceptance covered by the VELO. They are also usually emitted at large polar angles, which allows primary vertex measurements of high accuracy.
- **T tracks.** These only leave information in the T-stations and are reconstructed from T seeds not used in the previous algorithms. They are usually produced in secondary interactions and are used in RICH2 reconstruction. They have a poor momentum resolution, of $\delta p/p \sim 10 - 20\%$.

Tracks that share a high percentage of their hits are called *clones* [99]. In this case, the track with the higher number of hits is kept only, the other being discarded by the *clone-killing algorithm*. If two or more clones have the same number of hits, then the one of highest quality (χ^2) is retained. *Ghost tracks* are tracks reconstructed from many wrong hits [99].

In a typical $b\bar{b}$ event, about 99 tracks are reconstructed, of which ~ 26 are long tracks, ~ 6 upstream tracks, ~ 14 downstream tracks, ~ 34 VELO tracks and ~ 19 T tracks [102].

6.1.2 Track Fit using Kalman Filter

Once the tracks are found, their trajectories are refitted to determine the optimal estimates of the track parameters and the corresponding covariance matrix [100]. A track is modeled by a set of straight line segments along the beam axis. At a given z value, five track parameters are sufficient for a complete description of the track state, which are summarized in a vector $\vec{x}$, called *state vector*:

$$\vec{x} = \begin{pmatrix} x \\ y \\ t_x = \partial x / \partial z \\ t_y = \partial y / \partial z \\ q/p \end{pmatrix} \quad (6.1)$$

where x and y are two position coordinates, t_x and t_y are two tangent directions, and the fifth parameter depends on the momentum p obtained from the curvature in the magnetic field and on the signed charge of the particle $q = \pm 1$. The state vector $\vec{x}$ together with its covariance matrix C are referred to as the *track state*. The location of the track states is chosen at the measurement planes. The combination of a measurement and a track state is called a *node*.

To fit the tracks, a *bi-directional Kalman filter* is used [103], which is based on the χ^2 minimization of the measurements on the tracks. The measurements are added one-by-one in the fit, updating at each step the track state at the current node. By forming a weighted average of the forward and backward filters, optimal estimates of track parameters at all measurements are obtained. The starting planes are located at both upstream and downstream extremities of the LHCb detector.

The Kalman filter offers several advantages. Due to its iterative nature, it does not require time-consuming inversions of large matrices, which distinguishes it from global methods of fitting the whole trajectory at once. The Kalman filter offers the possibility to correct for energy loss and multiple scattering processes arising from the interaction of the particles with the material of the detector and for magnetic field effects. At the end of the fit, the particle trajectory is known throughout the whole detector, making easier the matching of the tracks with RICH rings, calorimeter clusters or muon candidates. Three steps are defined in the Kalman fit:

1. **Prediction.** In the forward direction, the track state at node k is predicted using the track state at the previous node $k - 1$.
2. **Filter Phase.** In the filter phase, the predicted track state is updated using the measurement information at node k , providing the best estimate of the trajectory based on the measurements included so far. The prediction and filter phases are re-iterated until all the measurements are included in the track. At the last node ($k = n$), the track state has the best estimate, as it includes the information of all the previous nodes.
3. **Smoothing.** The prediction and filter phases are repeated for the reverse direction. Smoothing is performed by averaging the results of the two filtered states at each node coming from the fit in the forward and backward directions.

6.2 Momentum Scale Calibration Method

6.2.1 Theoretical Overview

Given two particles d_1 and d_2 of energy and momenta $(E_{d_1}, \vec{p}_{d_1})$ and $(E_{d_2}, \vec{p}_{d_2})$ respectively, their invariant mass is given by [104]:

$$m_{d_1 d_2}^2 = (E_{d_1} + E_{d_2})^2 - (\vec{p}_{d_1} + \vec{p}_{d_2}) \cdot (\vec{p}_{d_1} + \vec{p}_{d_2}) \quad (6.2)$$

In the following, the two particles d_1 and d_2 are assumed to originate from the decay $P \rightarrow d_1 d_2$ of a mother particle P . Under the hypothesis that the magnetic field scale is wrong by an additive constant α , the momentum of each daughter particle needs to be scaled by a factor $(1 + \alpha)$. The relation between α and the mass difference Δm between the measured $m_{d_1 d_2}$ and PDG m_P mother mass is established below.

Two-body Decay with Daughter Particles of Same Masses

If the two daughters particles have the same mass, the invariant mass $m_{d_1 d_2}$ of Equation 6.2 can be simplified after a 1st-order Taylor expansion in (m/p) , with $c=1$ and $m_i^2 \ll p_i^2$:

$$m_{d_1 d_2}^2 = 2m_d^2 + 2E_{d_1}E_{d_2} - 2p_{d_1}p_{d_2}\cos\theta \quad \text{with} \quad E = p \left(1 + \frac{m^2}{p^2}\right)^{1/2} \quad \text{and} \quad (1+x)^{1/2} \simeq 1 + \frac{1}{2}x + \dots$$

hence $m_{d_1 d_2}^2 \simeq m_d^2 R + 2 \cdot (p_{d_1}p_{d_2} - \vec{p}_{d_1} \cdot \vec{p}_{d_2})$ (6.3)

with m_d the PDG mass [105] of the daughter particles and R given by:

$$R = 2 + \frac{p_{d_1}}{p_{d_2}} + \frac{p_{d_2}}{p_{d_1}} \quad (6.4)$$

If the measured momentum is wrong by a factor α , the PDG mass of the mother particle m_P is:

$$m_P^2 \simeq m_d^2 R + 2 \cdot (1 + \alpha)^2 \cdot (p_{d_1}p_{d_2} - \vec{p}_{d_1} \cdot \vec{p}_{d_2}) \quad (6.5)$$

Subtracting Equation 6.3 from Equation 6.5 results in:

$$m_{d_1 d_2}^2 \simeq \frac{m_P^2 - m_d^2 R}{(1 + \alpha)^2} + m_d^2 R \quad (6.6)$$

If $\alpha \ll 1$ $\left(\frac{1}{(1+\alpha)} \simeq 1 - 2\alpha + \dots\right)$, the relation between the mass difference, $\Delta m = m_{d_1 d_2} - m_P$, and α simplifies to:

$$\Delta m \simeq \alpha \cdot \frac{m_d^2 R - m_P^2}{m_P} \quad (6.7)$$

Equation 6.7 is used for the $K_s \rightarrow \pi^+ \pi^-$ decay, with $m_P = 497.7 \text{ MeV}/c^2$ and $m_d = 139.6 \text{ MeV}/c^2$.

For $J/\psi \rightarrow \mu^+ \mu^-$, as $m_d^2 \ll m_P^2$, this reduces to [106]:

$$\Delta m \simeq \alpha \cdot m_P \quad (6.8)$$

Another way for the momentum to be biased is a poorly tuned energy loss description. In this case, a correction factor, $p' = p - \beta_{\text{ion}}$, has to be made to the momenta of the daughter particles. Under the hypothesis that the opening angle θ is small, that the decay is symmetric ($p_{d1} \sim p_{d2}$) and the correction β_{ion} is the same for both particles, Equation 6.3 becomes:

$$\begin{aligned}
 m_{d_1 d_2}^2 &\simeq m_d^2 \left[2 + \frac{p_{d_2}}{p_{d_1}} + \frac{p_{d_1}}{p_{d_2}} \right] + 2p_{d_1} p_{d_2} \overbrace{(1 - \cos \theta)}^{2 \sin^2 \frac{\theta}{2} \simeq 2 \cdot \frac{\theta^2}{4}} \simeq 4m_d^2 + p_{d_1} p_{d_2} \theta^2 \\
 m_P^2 &\simeq 4m_d^2 + (p_{d_1} - \beta_{\text{ion}})(p_{d_2} - \beta_{\text{ion}})\theta^2 \simeq 4m_d^2 + p_{d_1} p_{d_2} \theta^2 - \beta_{\text{ion}}(p_{d_1} + p_{d_2}) \cdot \theta^2 + \dots \\
 \text{hence} \\
 m_{d_1 d_2}^2 - m_P^2 &\simeq \beta_{\text{ion}} \cdot (p_{d_1} + p_{d_2}) \cdot \theta^2
 \end{aligned} \tag{6.9}$$

Two-body Decay with Daughter Particles of Different Masses

If the daughter particles have different masses, the $m_d^2 R$ term of Equation 6.6 is generalized to:

$$h = m_{d_1}^2 + m_{d_2}^2 + \frac{p_{d_2}}{p_{d_1}} \cdot m_{d_1}^2 + \frac{p_{d_1}}{p_{d_2}} \cdot m_{d_2}^2 \tag{6.10}$$

Equation 6.7 is rewritten as:

$$\Delta m \simeq \alpha \cdot \frac{h - m_P^2}{m_P} \tag{6.11}$$

Equation 6.11 is used in the case of the $\Lambda \rightarrow p^+ \pi^-$ and $\bar{\Lambda} \rightarrow p^- \pi^+$ decays, with $m_P = 1115.7 \text{ MeV}/c^2$, $m_{d_1} = 938.3 \text{ MeV}/c^2$ and $m_{d_2} = 139.6 \text{ MeV}/c^2$.

6.2.2 Possible Effects Affecting the Calibration

Biases in the reconstructed momentum scale can be due to several effects: an inaccurate description of the alignment of the LHCb detectors, the use in the track fit of an incomplete description of the particle energy loss or an incorrect magnetic field map. In order to disentangle the contributions of each of these effects, an understanding of how these effects depend on the decay kinematics is needed. This is described in the following.

1. Energy Loss Description

Charged particles moving through matter lose energy by exciting or ionizing indirectly atoms through their interaction with the electrons of the material. The mean energy loss per unit distance is described by the *Bethe-Bloch formula* [107]:

$$-\frac{dE}{dx} = \frac{4\pi e^4 \mathcal{N}_A Z \rho}{A m_e c^2 \beta^2} \left[\ln \left(\frac{2m_e \beta^2 \gamma^2}{I} \right) - \beta^2 - \frac{\delta}{2} \right] \tag{6.12}$$

where E is the energy of the particle, x the distance travelled by the particle, e the charge of the electron, $\mathcal{N}_A$ the Avogadro number, Z the number of protons in the atoms constituting the surrounding matter, ρ the material density, A the atomic mass of the atoms, $\beta = v/c$ with v the velocity of the particle and c the speed of light, m_e the rest mass of the electron, $\gamma = 1/\sqrt{1-\beta^2}$, I the mean excitation energy of the material and δ the correction for the density effect. In general, dE/dx is expressed in energy per unit of distance per unit of density ($\text{MeV g}^{-1} \text{ cm}^2$).

Under the assumption that the excitation energy I does not vary significantly with the material type and that the dependence on $\beta\gamma$ of the energy loss is small, then Equation 6.12 reduces to:

$$\frac{dE}{dx} = c_{\text{ion}} \frac{Z\rho}{A} \quad (6.13)$$

Equation 6.13, referred to as the *simple energy loss description*, was used in the track fit of earlier LHCb software versions, because it does not require the implementation of the information related to I and δ for all material types present in the LHCb spectrometer. The c_{ion} free parameter was tuned to minimize biases of reconstructed momenta compared to their true values. It had been estimated to $c_{\text{ion}} \sim 354 \text{ MeV mm}^2 \text{ mol}^{-1}$ for DC06 Monte Carlo sample [100]. No further tuning has been performed since then.

If the energy loss description is poorly tuned, then low momentum tracks are mostly affected, as $\Delta m \simeq \sqrt{p_d}$ (Equation 6.9).

2. Magnetic Field Description

As detailed in Section 5.2, the magnetic field is computed by a linear interpolation of values located on a grid of $10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$ cubic cells covering the LHCb acceptance. The TOSCA finite element package was used to simulate a first field map. This map agrees reasonably well with measurements made in the LHCb cavern in December 2005, apart from the region upstream of the magnet where a correction was needed (Figure 5.6) [91]. This partially corrected map, referred to as *simulated magnetic field map* (Subsection 5.3.1), was used for the generation of DC06 Monte Carlo samples.

To achieve the momentum precision of $\delta p/p \sim 0.4\%$ required at LHCb, a precise description of the magnetic field is essential. The *measured magnetic field map* presented in Section 5.6, which is based on the measurements, has replaced in the LHCb software the simulated magnetic field map and is used for studies with 2009 real data. A newer map describing the up and down polarities together (Section 5.7) is used in the case of 2010 real data.

There are two main differences between the simulated and measured maps. First, the simulated magnetic field map has a $\int B dl$ that is $\sim 7 \times 10^{-3}$ larger than the measured map (Subsection 5.6.3). This is attributed to the known expansion of the coils by $\sim 8 \text{ mm}$ when the magnet is powered, which is not taken into account in the simulated description. Second, the measured map has a large asymmetry between the up and down quadrants, the field being weaker for $y > 0$ (Subsection 5.3.5). This up-down asymmetry may be a real effect coming from tilts or shifts in the positioning of the magnet or maybe

due to imprecision in positioning the measuring device. These two differences are used to discriminate between the two maps, together with a discriminating variable based on geometry properties of the $K_s \rightarrow \pi^+ \pi^-$ decays, which is introduced in Subsection 6.4.2.

In the case the magnetic field description is off by an overall scale α , then no dependence of Δm should be seen as a function of the momentum of the mother particle p_P (Equations 6.7, 6.8 and 6.11).

Both L-L and D-D mass resolutions are dominated by the opening angle measurement. Monte Carlo studies indicate that candidates reconstructed from two downstream tracks are expected to be more sensitive to the magnetic field. This is due to the fact that they decay in the field and hence their opening angle measurement depends on the field components. On the other hand for candidates reconstructed from two long tracks, the opening angle is measured by the VELO detector independently of the magnetic field. Therefore, they are only sensitive to the field scale.

3. Alignment Description

The alignment procedure at LHCb is introduced in Section 4.5. The minimized χ^2 of Equation 4.1 is invariant under linear combinations of the alignment parameters. This phenomenon is called *weak mode* (Figure 6.2) [108]. The simplest example of a weak mode is a global shift of the T1-T3 tracking stations in the z direction. More complicated examples exist such as a global rotation of the T-stations in x about the centre of the magnet, as shown in Figure 6.2.

To remove weak modes, constraints can be applied by using Lagrange multipliers or by cutting on the corresponding eigenvectors from a spectral analysis. The system can also be constrained by aligning one detector with respect to another fixed one, or by fixing degrees of freedom.

A charged particle going through the dipole magnet will be mostly bent in the $x-z$ plane, as the main magnetic field component is B_y (Chapter 5). The change of slopes before the magnet, $t_{x,i}$, and after it, $t_{x,f}$, depends on the integrated magnetic field along the trajectory [108]:

$$\Delta t_x \simeq \frac{q}{\sqrt{p_x^2 + p_z^2}} \int B_y dz = \omega I_B \quad (6.14)$$

where $\omega = \frac{q}{p}$ is called the *curvature* and $I_B = \int B_y dz$ is the integral of the B_y component along the trajectory.

In the case of misalignments, a curvature ω_0 for a default geometry is biased to a new value ω' as:

$$\omega' = \omega_0 + \Delta\omega + \omega_0\eta \quad (6.15)$$

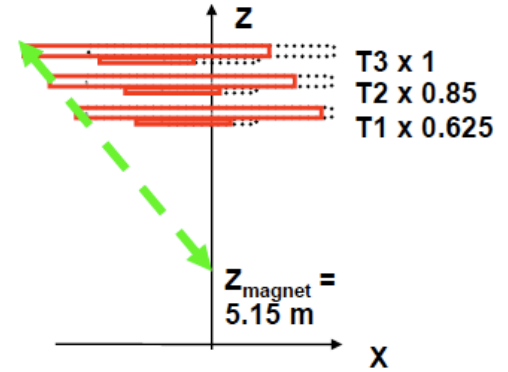


Figure 6.2: Main weak modes at LHCb: global rotation of the T-stations in x about the centre of the magnet [108].

where $\Delta\omega$ is called the *curvature bias* and corresponds to an offset and the $\omega_0\eta$ term is referred to as *curvature scale bias*.

In the following, the $J/\psi \rightarrow \mu^+\mu^-$ decay is used to understand how the presence of misalignments can be qualitatively detected. In this case, the invariant mass of Equation 6.2 simplifies to:

$$m_{\text{inv}}^2 \simeq 2p_+p_-(1 - \cos\theta) \quad (6.16)$$

where p_+ and p_- are the momenta of the two positively-charged and negatively-charged daughter particles respectively and θ is the opening angle. The effects of the curvature bias $\Delta\omega$ and of the curvature scale bias $\omega_0\eta$ of Equation 6.15 are treated separately [108].

The curvature bias $\Delta\omega$ can be translated into a bias in the invariant mass. The corresponding bias momentum equals:

$$p'_\pm = \frac{\pm 1}{\omega_0 + \Delta\omega} = \frac{\pm 1/\omega_0}{1 + \frac{\Delta\omega}{\omega_0}} \quad \xrightarrow{|\Delta\omega| \ll |\omega_0|} \quad p'_\pm \simeq p_\pm \left(1 - \frac{\Delta\omega}{\omega_0}\right) \quad (6.17)$$

Inserting Equation 6.17 in Equation 6.16, the biased invariant mass value m' is obtained:

$$m'^2 \simeq [1 + (p_- - p_+)\Delta\omega] \cdot m^2 \quad \rightarrow \quad m' \simeq \left(1 + \frac{(p_- - p_+)}{2}\Delta\omega\right) \cdot m \quad (6.18)$$

Therefore, to first order, the mass bias depends on the difference in momenta between the two daughter particles p_- and p_+ . This effect corresponds to a common translation in the x direction of the tracking stations (weak mode) [108]. For the K_s and $\Lambda(\bar{\Lambda})$ cases, such an interpretation is not valid, as the simplification leading to Equation 6.16 does not hold. However, if a dependence is observed between the mass bias and the difference in momenta, then the presence of misalignments is qualitatively confirmed.

The curvature scale bias results in a bias in the momentum and mass scale. Similarly to Equation 6.17, the corresponding biased momentum is given by:

$$p'_\pm = \frac{\pm 1}{\omega_0 + \omega_0\eta} \quad (6.19)$$

A similar development than for the curvature bias leads to the biased invariant mass:

$$m'^2 \simeq (1 - 2\eta) \cdot m^2 \quad \rightarrow \quad m' \simeq (1 - \eta) \cdot m \quad (6.20)$$

As a second order effect, the mass is therefore affected in the same way as for a scaled magnetic field. This effect corresponds to a common translation in the z direction of the tracking stations (weak mode) [108].

Different versions of the alignment are used with 2009 real data (v.5, v.7 and v.7 with improvements), corresponding to different sets of degrees of freedom aligned during the minimization procedure. With 2010 real data, only the most recent version (v.3) is used [109].

6.3 K_s , Λ and $\bar{\Lambda}$ Samples and Selections

The 2009/2010 real data samples and the corresponding Monte Carlo samples used in the momentum calibration study are described in the following, together with the pre-selection and selection cuts applied on the $K_s \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p^+ \pi^-$ and $\bar{\Lambda} \rightarrow p^- \pi^+$ decays.

6.3.1 Data Samples

The 2009/2010 Monte Carlo and real data samples used in the momentum scale calibration are presented in what follows. Version v25r0 of the software package DaVinci is used for 2009 real data and version v25r4p1 for 2010 real data.

2009 real data

The 2009 real data were taken at a centre of mass energy $\sqrt{s} = 900$ GeV with the VELO detector opened by 15 mm for safety reasons, as the beam was broader and had a larger crossing angle. The magnetic field was switched on at nominal current intensity ($I = 5.85$ kA) using the down polarity (the B_y vertical component pointing down). A minimum bias trigger based on calorimeter information was used to collect events. The trigger criteria required a transverse energy $E_T > 240$ MeV for the less energetic cluster reconstructed in the HCAL and a number of hits in the SPD higher than 2.

The information of the RICH detectors is not needed for the momentum scale calibration. Therefore, to maximize the amount of 2009 real data that can be used in this analysis, data collected with three different data-taking configurations of the LHCb spectrometer are merged together. The first configuration includes all detectors in, the second excludes the RICH1 detector and the third one excludes additionally the RICH2 detector.

2010 real data

The 2010 real data used in this analysis have been taken at $\sqrt{s} = 7$ TeV with the VELO detector closed and all the detectors in. Sets of data have been obtained using both polarities of the dipole magnet switched on at nominal current intensity. Only a small part of the total dataset has been used in the following studies.

A similar trigger on the calorimeter information as for 2009 real data is used ($E_T > 240$ MeV, SPD hits > 2) together with an other trigger, which consists in accepting different types of events at given rates without any cuts applied at L0-level trigger, called *micro bias trigger*¹.

¹In the LHC machine, the beam traversing the whole LHCb spectrometer before reaching the interaction point is called *beam 2*, *beam 1* entering into the VELO detector from the upstream part. Four different event types are recorded: The first one corresponds to collisions of the two beams (*beam-beam* events), the second and third ones to events where only one of the two beams is circulating (*beam-empty* or *empty-beam* events depending if beam 1 or beam 2 is missing) and the fourth one to events where there are no beams (*empty-empty* events). For the micro-bias trigger line, at least one track recorded in the VELO or the T-stations is required at the HLT software level.

2009/2010 Monte Carlo Data

The Monte Carlo data samples correspond to minimum bias events produced in same experimental conditions as for the 2009/2010 real data: for centre of mass energies of 0.9/7 TeV, with the VELO detector opened by 15 mm/closed and using the down polarity/both polarities of the magnetic field.

6.3.2 Event Selection

Pre-Selection

Before the offline selection process, the events have passed both the hardware-level trigger and a software based pre-selection. The pre-selection cuts are summarized in Table 6.1 and are the same for 2009 and 2010 real data.

Table 6.1: Pre-selection cuts for the $K_s \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p^+ \pi^-$ and $\bar{\Lambda} \rightarrow p^- \pi^+$ decays.

Common Pre-Selection Cuts	
Track Quality χ^2/ndof	< 25
Track Momentum p	$> 1.5 \text{ GeV}/c$
Secondary Vertex Quality χ^2	< 25
Z position of the Secondary Vertex	$< 2200 \text{ mm}$
Impact Parameter Quality χ^2	< 100
Proper Lifetime $c\tau$ (L-L candidates)	$> 1 \text{ mm}$
(D-D candidates)	$> 10 \text{ mm}$
Specific Cuts for K_s^0	
Mass Window m	$\pm 100 \text{ MeV}/c^2$
Specific Cuts for $\Lambda/\bar{\Lambda}$	
Mass Window m	$\pm 50 \text{ MeV}/c^2$

During reconstruction, the tracks are refitted. This allows profiting from improvements in alignment and to study the energy loss and magnetic field descriptions.

Offline Selection

The offline selection is designed to optimize the purity of the selected events. The selection has been developed on the $K_s \rightarrow \pi^+ \pi^-$ decay, including a veto on the mass of $\pm 12 \text{ MeV}/c^2$ on the Λ hypothesis. The selection is applied without further tuning to the $\Lambda \rightarrow p^+ \pi^-$ and $\bar{\Lambda} \rightarrow p^- \pi^+$ decays, except for the cuts on the mass. The selection cuts summarized in Table 6.2 are applied to 2009 and 2010 data.

The candidate types used in this study are either candidates reconstructed from two long tracks, called *L-L type*, or candidates reconstructed from two downstream tracks, called *D-D type* (Section 6.1).

Table 6.2: Offline Selection Cuts for the $K_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p^+\pi^-$ and $\bar{\Lambda} \rightarrow p^-\pi^+$ decays.

Common Offline Selection Cuts	
Impact Parameter Significance $IPS > 3$	
Track Momentum $p > 2 \text{ GeV}$	
Z Position of the Secondary Vertex = $[0, 220] \text{ cm}$	
Flight Distance to Primary Vertex $FD > 20 \text{ mm}$	
Direction Angle $\cos(\theta) > 0.99995$	
Additional Cuts for K_s	Additional Cuts for Λ ($\bar{\Lambda}$)
Mass window $m_{K_s} \in [460, 540] \text{ MeV}/c^2$	Mass window $m_{\Lambda(\bar{\Lambda})} \in [1100, 1130] \text{ MeV}/c^2$
Mass Veto $\pm 12 \text{ MeV}/c^2$ on Λ hypothesis	Mass Veto $\pm 18 \text{ MeV}/c^2$ on K_s hypothesis

Λ - $\bar{\Lambda}$ Separation using the Armenteros-Podolanski Plot

As the Λ and $\bar{\Lambda}$ daughter particles do not cover the same kinematical phase space, Λ and $\bar{\Lambda}$ are separated for calculation of the correction factor α . In addition, the Λ and $\bar{\Lambda}$ have different systematics as one has a proton and the other an antiproton, which is like flipping the magnet polarity. To distinguish between Λ and $\bar{\Lambda}$, the Armenteros-Podolanski plot is used [110]. This technique is useful to analyze the decay of a parent particle into two tracks with opposite charges, when particle identification information is not used. For each event, the transverse component of the positive track p_T^+ is plotted versus the quantity a :

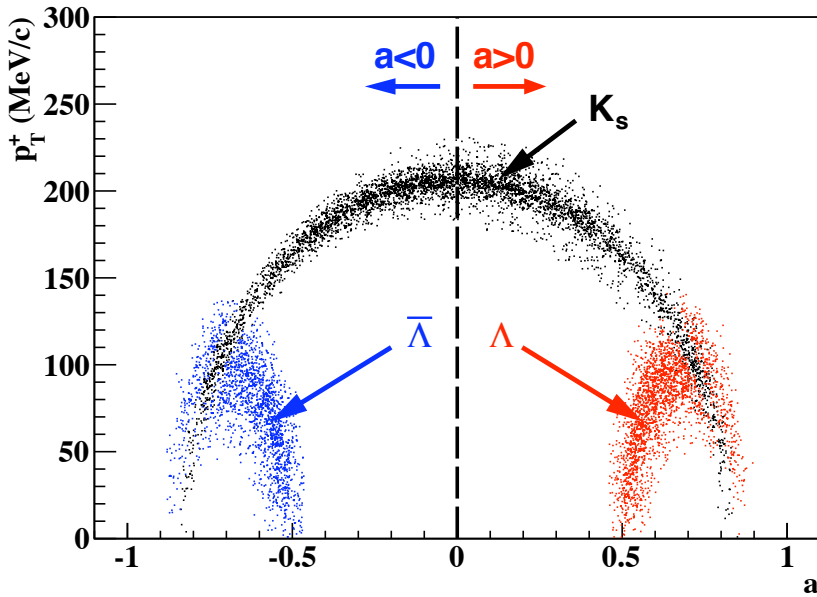
$$a = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-} \quad (6.21)$$

with p_L^+ and p_L^- the longitudinal components of the momentum of the positive and negative tracks.

The points corresponding to different decays are located on contours that are easily distinguishable. This is due to the fact that kinematics of these decays are different.

As an example in Figure 6.3, offline-selected $\Lambda \rightarrow p^+\pi^-$ decays (red) from real data are separated from $\bar{\Lambda} \rightarrow p^-\pi^+$ decays (blue) requiring $a > 0$.

The veto cut on the $\Lambda/\bar{\Lambda}$ mass under the K_s hypothesis allows the removal of the background (black).

**Figure 6.3:** Armenteros-Podolanski plot to separate Λ and $\bar{\Lambda}$.

The numbers of triggered and offline selected L-L and D-D K_s , Λ and $\bar{\Lambda}$ candidates are given in Table 6.3 for 2009 and 2010 real data.

Table 6.3: Number of triggered and selected L-L and D-D K_s , Λ and $\bar{\Lambda}$ candidates from the 2009 (down polarity) and 2010 (down and up polarities) real data.

candidates / data type	L-L K_s	L-L Λ	L-L $\bar{\Lambda}$	D-D K_s	D-D Λ	D-D $\bar{\Lambda}$
2009 (down)	1,124	220	172	4,756	1,651	1,259
2010 (down)	55,159	408,535	425,675	42,288	189,218	177,081
2010 (up)	54,102	381,997	353,207	40,950	178,241	167,026

6.4 Monte Carlo Studies

6.4.1 Validation of the Momentum Scale Calibration Method

Before applying the method to real data, it is validated with simulation. In the following, this is shown for 2009 Monte Carlo L-L K_s candidates.

The momentum calibration method is applied as explained at the beginning of Section 6.5.1 on the triggered and offline-selected 2009 Monte Carlo candidates from Section 6.3.2. The distribution of the R values of Equation 6.4 is shown in Figure 6.4 (left). The mean value, $R_{\text{mean}} = 4.64$, is used in the calculation of α .

Figure 6.4 (right) shows α as a function of the average momentum values p_{mean} of each bin. The $\alpha = 0.0001 \pm 0.0001$ value obtained from a fit of a constant to the distribution is consistent with zero. As no bias is observed, it is safe to apply the method to real data.

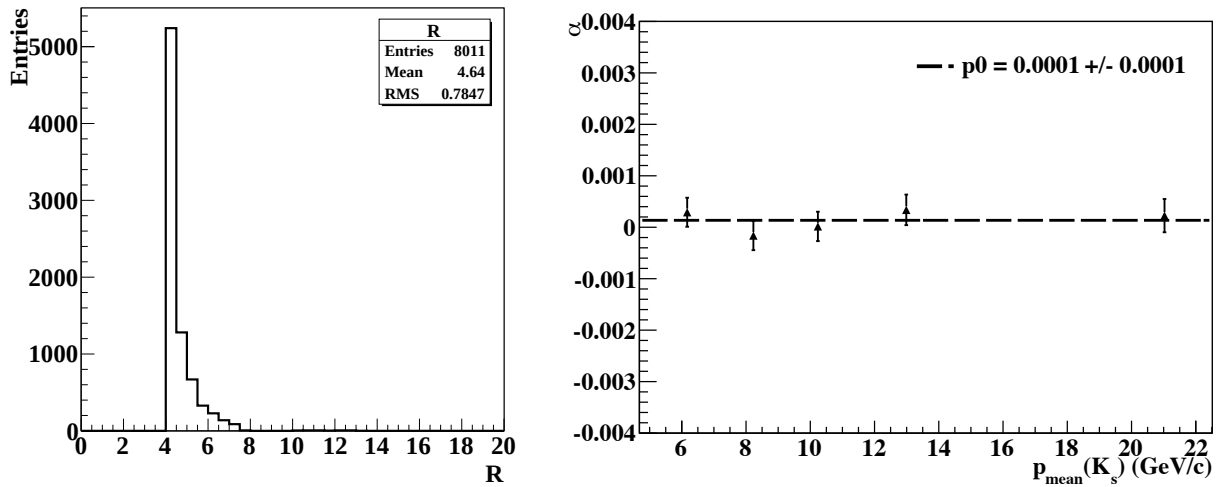


Figure 6.4: R distribution with $R_{\text{mean}}=4.64$ for 2009 Monte Carlo data L-L K_s candidates (left) and corresponding α factor as a function of p_{mean} (right). The best fit to a constant, $\alpha = 0.0001 \pm 0.0001$, is consistent with zero.

6.4.2 Magnetic Field Systematics

The effects on physics of the differences between the symmetric simulated or asymmetric measured field maps explained in Subsection 6.2.2 are studied with Monte Carlo data. The effect of the global scale difference between the two descriptions on reconstructed mass peak values is first estimated. Then, local studies about the up-down asymmetry present in the magnetic field measurements are performed. The impact on mass resolutions is investigated. These results are followed by the description of a method based on the geometrical properties of $K_s \rightarrow \pi^+ \pi^-$ decays, which can be used to discriminate between the two maps.

1. Global Scale of the Reconstructed Mass Distributions

To study the global scale of the reconstructed mass distributions, $\sim 360,000$ events of MC09 inclusive $J/\psi \rightarrow \mu^+ \mu^-$ are used. The MC09 data are generated using the measured magnetic field map. At the reconstruction stage, either map is used. Only a mass window cut of $\pm 300 \text{ MeV}/c^2$ is applied on the mass of the L0-triggered candidates without any HLT cut.

To fit the reconstructed $\mu^+ \mu^-$ mass distribution, the radiative tail due to the emission of photons from $J/\psi \rightarrow \mu^+ \mu^- \gamma$ processes has to be taken into account. A *Crystal Ball (CB)* function is used [111]. It consists of a Gaussian with mean μ_{CB} and width σ_{CB} , which is combined with an n_{CB} -power law tail starting from a value $x_{\text{transition}}$. This value depends on σ_{CB} and on a free parameter α_{CB} , as $x_{\text{transition}} = \mu_{CB} - \sigma_{CB} \cdot \alpha_{CB}$. The CB function is given by²:

$$\begin{aligned} x \geq \mu_{CB} - \sigma_{CB} \cdot \alpha_{CB} : \quad & \text{CB}(x) = \frac{1}{\sqrt{2\pi}\sigma_{CB}} \exp\left(-\frac{1}{2}\left(\frac{x - \mu_{CB}}{\sigma_{CB}}\right)^2\right) \\ x < \mu_{CB} - \sigma_{CB} \cdot \alpha_{CB} : \quad & \text{CB}(x) \simeq |x - \mu_{CB}|^{-n_{CB}} \end{aligned} \quad (6.22)$$

The total fit function to be applied to the $\mu^+ \mu^-$ reconstructed mass distribution is detailed in Equation 6.23. To give a good fit, a second Gaussian component is needed. The means of the CB and of the additional Gaussian are constrained to be the same μ value. The background contribution is modeled by a 1st-order P_1 function with parameter p_1 . The parameters f_G and f_{CB} are the fractions of the additional Gaussian and of the CB function respectively.

$$F_{\text{fit}}^{J/\psi} = f_G \cdot \mathcal{G}(\mu, \sigma_G) + f_{CB} \cdot \text{CB}(\mu, \sigma_{CB}, \alpha_{CB}, n_{CB}) + (1 - f_G - f_{CB}) \cdot P_1(p_1) \quad (6.23)$$

Figure 6.5 shows the fit result to the MC09 Monte Carlo $J/\psi \rightarrow \mu^+ \mu^-$ candidates reconstructed using the measured magnetic field map. The reconstructed J/ψ mass value is $\mu = 3096.80 \pm 0.03 \text{ MeV}/c^2$. Using the simulated magnetic field map leads to the reconstructed mass distribution of Figure 6.6. The fit values of all the parameters are consistent with those obtained using the measured map, except for the mean $\mu = 3118.19 \pm 0.03 \text{ MeV}/c^2$. Hence a scale factor $S = 0.9931$.

²A positive α_{CB} value results in a tail on the left of the mass peak, while a negative one would give a tail on the right.

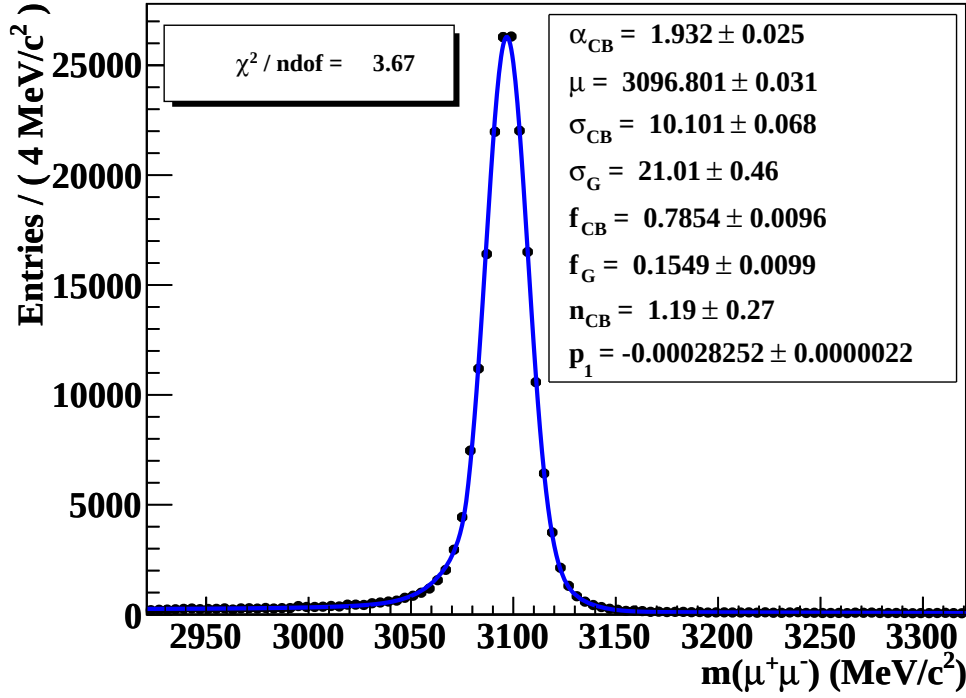


Figure 6.5: Reconstructed MC09 $\mu^+\mu^-$ mass distribution using the measured field map. The reconstructed J/ψ mass is $\mu = 3096.80 \pm 0.03 \text{ MeV}/c^2$.

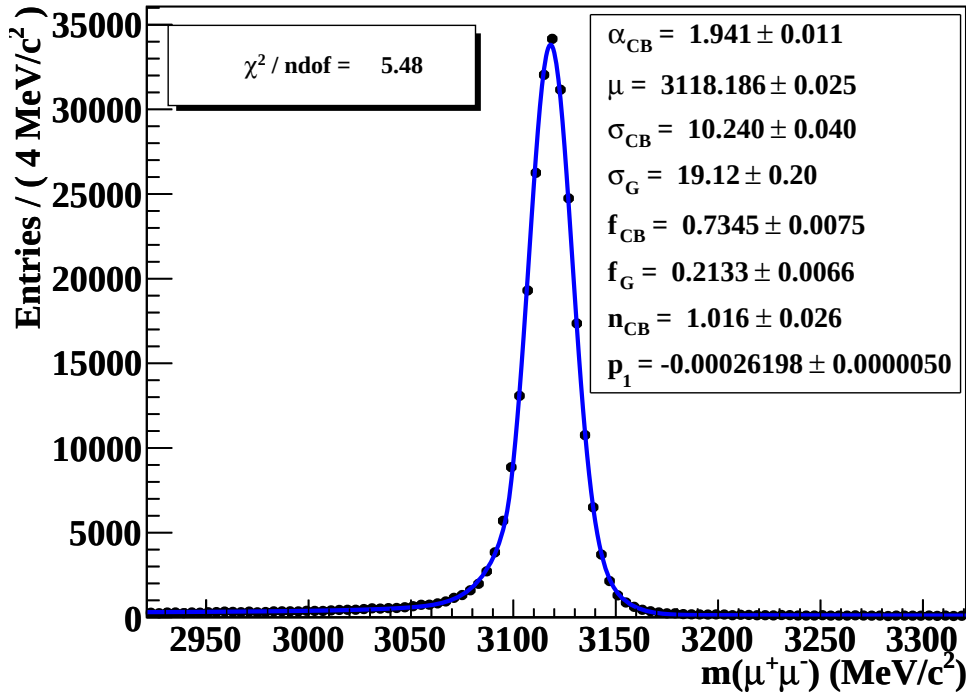


Figure 6.6: Reconstructed MC09 $\mu^+\mu^-$ mass distribution using the simulated field map. The reconstructed J/ψ mass is $\mu = 3118.19 \pm 0.03 \text{ MeV}/c^2$.

2. Up-Down Asymmetry

Simulated magnetic field values that are (anti-)symmetric between the four $(x \geq 0, y \geq 0)$ cm, $(x \geq 0, y \leq 0)$ cm, $(x \leq 0, y \geq 0)$ cm and $(x \leq 0, y \leq 0)$ cm quadrants inside the LHCb acceptance are naturally expected given the shape of the magnet. However, magnetic field measurements do not reproduce fully this (anti-)symmetries, as explained in Subsection 5.3.5. Therefore, it has to be established if the asymmetries observed in the measurements are real or fake. The following studies using the MC09 Monte Carlo inclusive $J/\psi \rightarrow \mu^+ \mu^-$ sample show that this issue can be solved with events coming from real data.

To study the up-down asymmetry, the selected MC09 J/ψ candidates are reconstructed using the symmetric simulated magnetic field map. Information about the x and y coordinates of the trajectories followed by the charged tracks is collected during the reconstruction stage at given z coordinates. Two values of z are used, $z = 250$ cm and $z = 850$ cm, which are located at both the upstream and downstream sides of the magnet. The reconstructed candidates are divided into two samples, by requiring that the two μ tracks go through the upper part of the magnet ($y > 0$ cm at $z = 250$ cm and $z = 850$ cm) or that they both belong to the down part of the magnet ($y < 0$ cm at $z = 250$ cm and $z = 850$ cm). The reconstructed masses for both cases are shown in Figures 6.7 and 6.8 respectively. The mean values obtained are $\mu_{\text{up}} = 3119.90 \pm 0.02 \text{ MeV}/c^2$ (Figure 6.7) and $\mu_{\text{down}} = 3116.92 \pm 0.06 \text{ MeV}/c^2$ (Figure 6.8), corresponding to a $\sim 3 \text{ MeV}/c^2$ difference. If this effect is seen on the real data, it would be evidence that the simulated map is correct.

Figures 6.7-6.8 also show that magnetic field values in the upper part of the magnet are more different between simulation and measurements than the ones from the down part, as μ_{up} is further away from the expected mass value $m_{J/\psi} = 3096.9 \text{ MeV}/c^2$. As the simulated field is globally stronger than the measurements (Figures 6.5-6.6), the measured field is hence weaker in the upper part of the magnet than in the lower part.

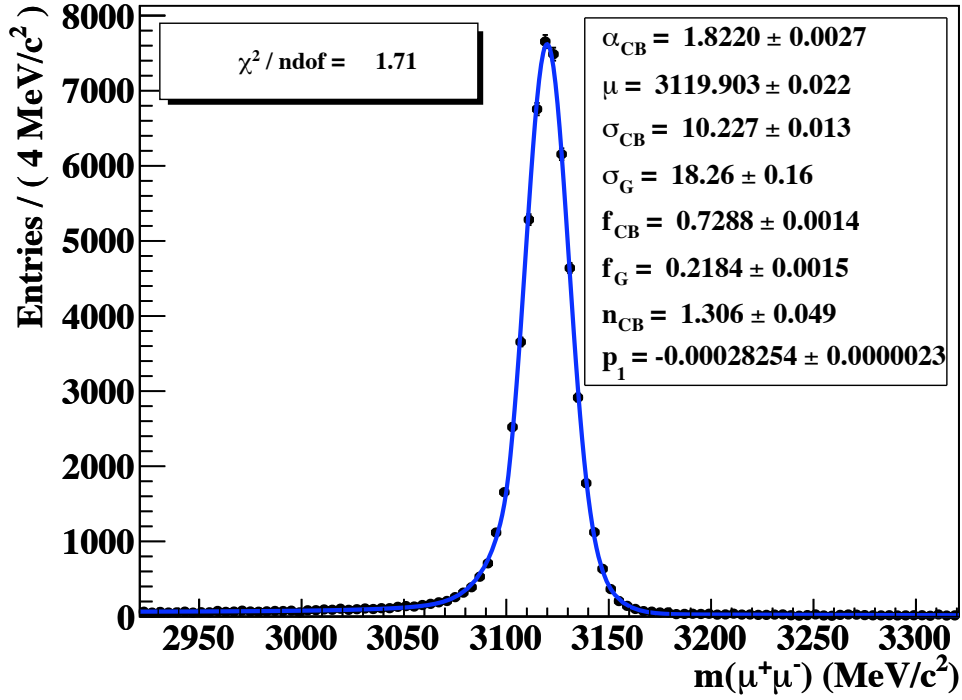


Figure 6.7: Reconstructed MC09 $\mu^+\mu^-$ mass distribution for μ^+ and μ^- passing through the upper part of the magnet using the simulated field map. The reconstructed J/ψ mass is $\mu_{\text{up}} = 3119.90 \pm 0.02 \text{ MeV}/c^2$.

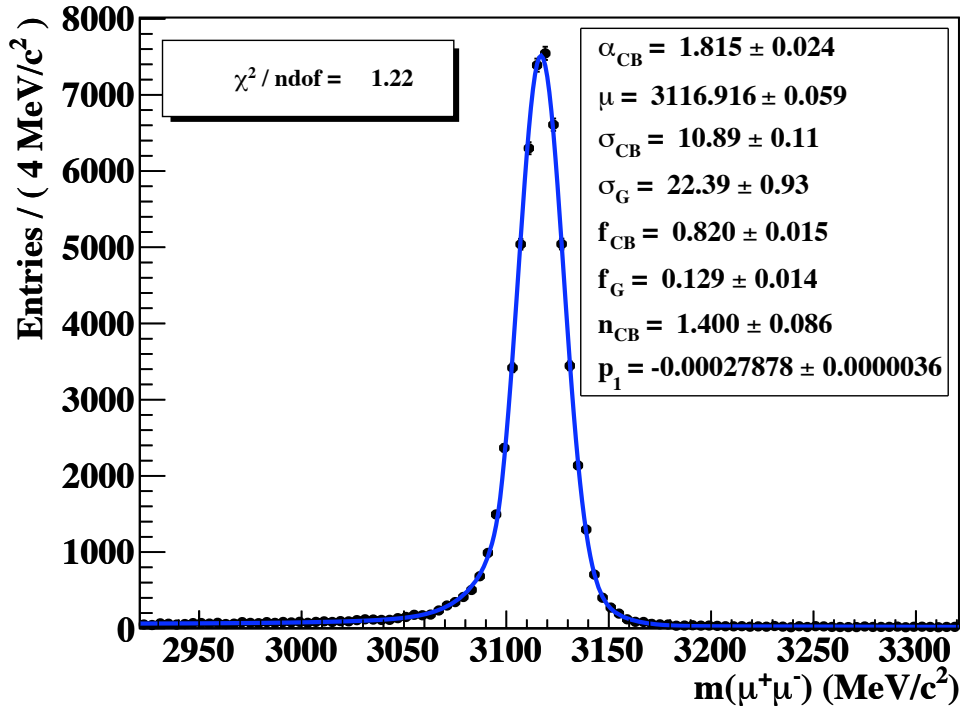


Figure 6.8: Reconstructed MC09 $\mu^+\mu^-$ mass distribution for μ^+ and μ^- passing through the down part of the magnet using the simulated field map. The reconstructed J/ψ mass is $\mu_{\text{down}} = 3116.92 \pm 0.06 \text{ MeV}/c^2$.

3. Mass Resolutions

The impact of the magnetic field description on the mass resolution is studied by reconstructing 2010 Monte Carlo K_s candidates generated using the measured field map, using for the reconstruction either the measured or the simulated maps. The resolutions are obtained from Gaussian fits to the reconstructed mass distributions in bins of the momentum.

As can be seen from Figure 6.9, the mass resolutions of D-D candidates (bottom) are more sensitive to the choice of the magnetic field map than for L-L candidates (top). Indeed, a worsening of $\sim 5\%$ is observed for D-D K_s candidates (bottom) when refitting with the simulated field map (red dots) compared to reconstructing with the measured map (black triangles), which is accompanied by a loss of $\sim 1\%$ of candidates when using the simulated map. For L-L candidates, no significant differences are observed (top).

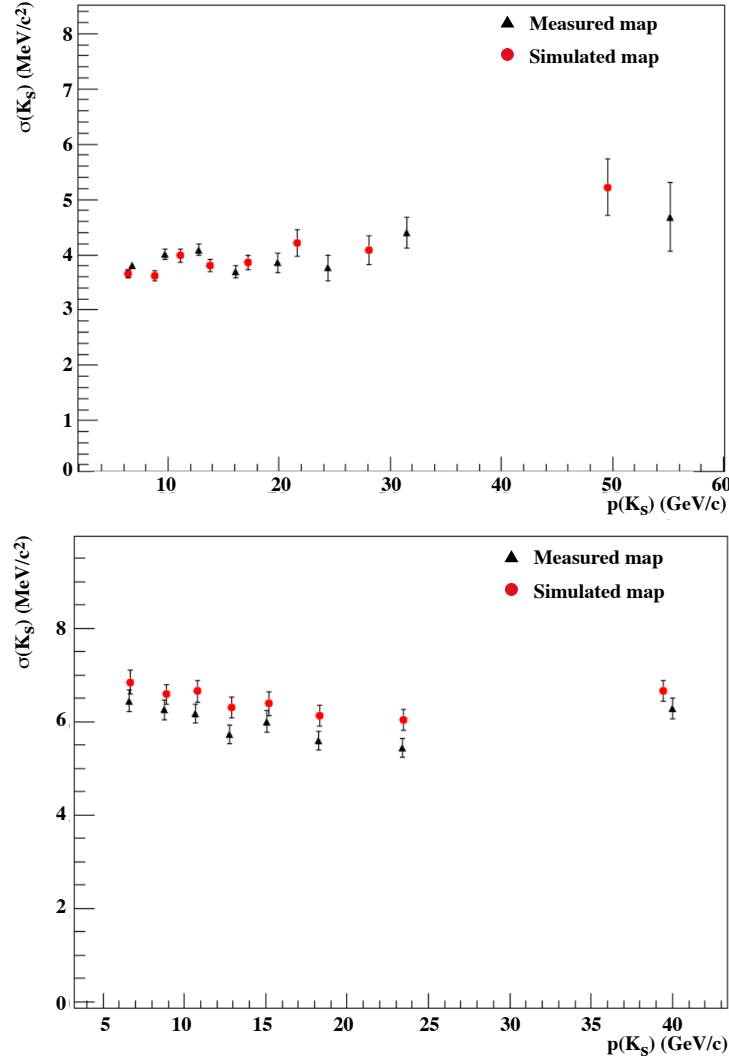


Figure 6.9: Mass resolutions as a function of p for 2010 Monte Carlo L-L (top) and D-D (bottom) K_s candidates reconstructed using the measured (black triangle) or the simulated (red dots) magnetic field maps.

4. Decay Plane Dependence

The mass difference Δm of Equation 6.7 is studied in bins of the angle ϕ between the normal to the decay plane and the y axis corresponding to the direction of the main magnetic field component. No dependence is expected between these two quantities.

The results are shown in Figure 6.10 for 2010 Monte Carlo L-L (left) and D-D (right) K_s candidates using the measured (top) and simulated (bottom) magnetic field maps. A clear bias is observed in the distribution of the D-D K_s using the simulated map, while the corresponding distribution for L-L candidate is flat. As explained in Section 6.2.2, the D-D candidates are expected to be more sensitive to the magnetic field description than the L-L candidates. This variable will be studied using 2010 real data to determine whether the simulated or measured map describes the best the data.

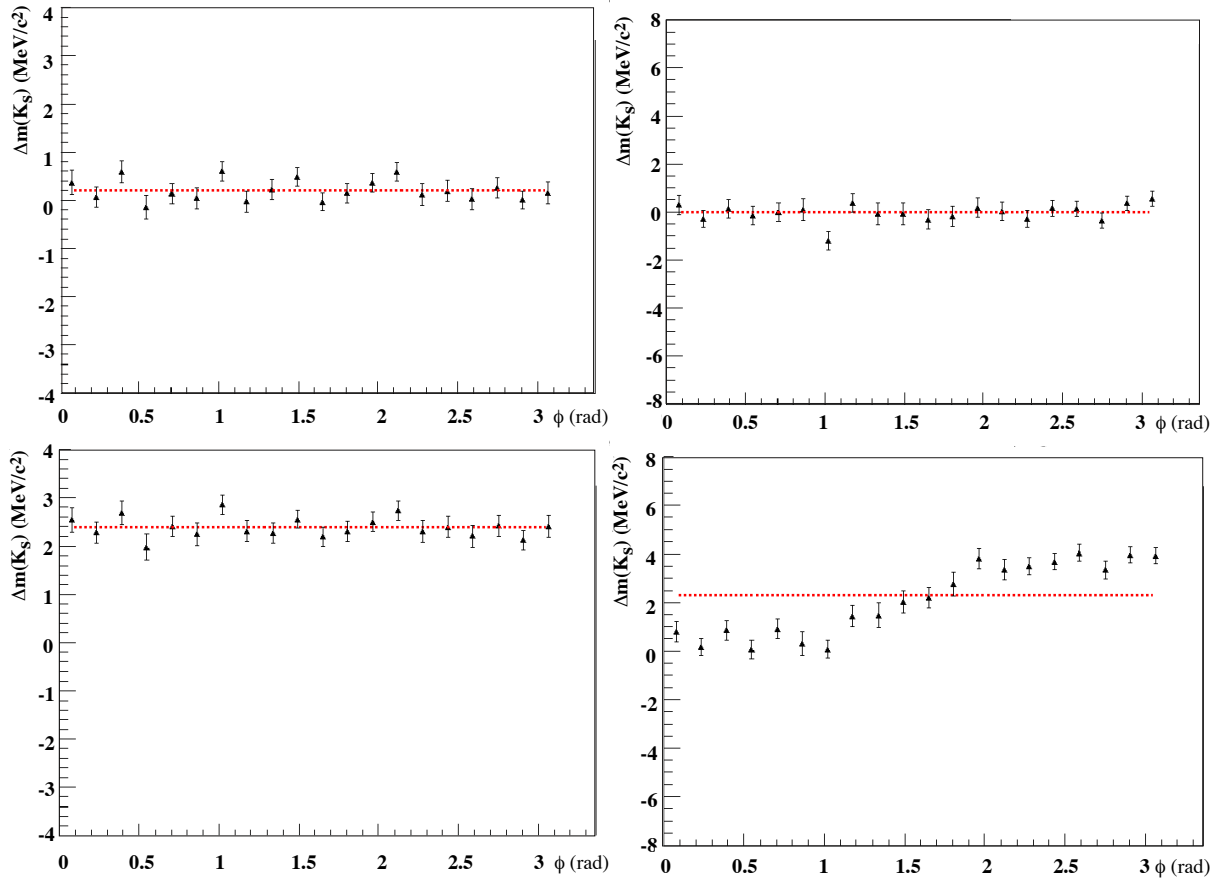


Figure 6.10: Mass difference Δm in bins of ϕ , the angle between the normal to the $K_s \rightarrow \pi^+ \pi^-$ decay plane and the main magnetic field direction (y axis), for L-L (left) and D-D (right) K_s candidates using the measured (top) and simulated (bottom) magnetic field maps.

6.5 Results with 2009 Real Data

The L-L K_s candidates coming from 2009 real data are used to quantify the effects of different energy loss, magnetic field and alignment descriptions explained in Subsection 6.2.2. First, a calculation of the momentum scale factor α using 2009 real data L-L K_s candidates is explained.

6.5.1 Momentum Scale Factor Calculation

As mentioned in Section 6.2.2, the scale factor α is expected to be independent of the momentum of the mother particle p_P . The factor α is therefore calculated in bins of p_P . Each bin contains an equal number of candidates. Once the second unknown term R of Equation 6.7 is computed, the α values are represented as a function of the average values p_{mean} of the momenta of a given bin. The distribution is fitted with a constant function to obtain the average momentum scale factor α .

Δm calculation

In each bin of p_P , the mass distribution of the candidates is fitted using tools from the RooFit package [112]. The fit function F_{fit} consists in a single Gaussian $\mathcal{G}$ of mean μ and width σ modelling the signal contribution together with a constant function of parameter p_0 representing the background, as given in Equation 6.24. The mean μ is used to calculate Δm . The signal fraction f is a free parameter in the fit. As an illustration, the reconstructed mass distributions of L-L K_s candidates from 2009 real data distributed in five bins and their fits are shown in Figure 6.11 (top, middle and bottom left).

$$F_{\text{fit}} = f \cdot \mathcal{G}(\mu, \sigma) + (1 - f) \cdot p_0 \quad (6.24)$$

R Estimation

The mean value of the R distribution of the selected candidates is used for the calculation of the field scale for 2009 real data. This method was validated using the Monte Carlo to lead to a correct scale factor determination in Subsection 6.4.1. As the mean value of the R distribution is affected by the background contribution, a sideband subtraction is performed to the selected candidates³.

³The total mass distribution is first fitted using Equation 6.24 to obtain its resolution σ , as shown in Figure 6.11 (bottom right). The signal region is defined as $m_{K_s} \pm 4 \cdot \sigma$, where m_{K_s} is the expected mass value of the K_s resonance. From the boundaries of the signal region, the background regions extend at each sides up to $m_{K_s} \pm 6 \cdot \sigma$. The background subtraction consists in filling two histograms, one with the events belonging to the signal region and the other with the events belonging to the background region. The R value is estimated from the remaining candidates of the subtraction of the latter to the former histogram.

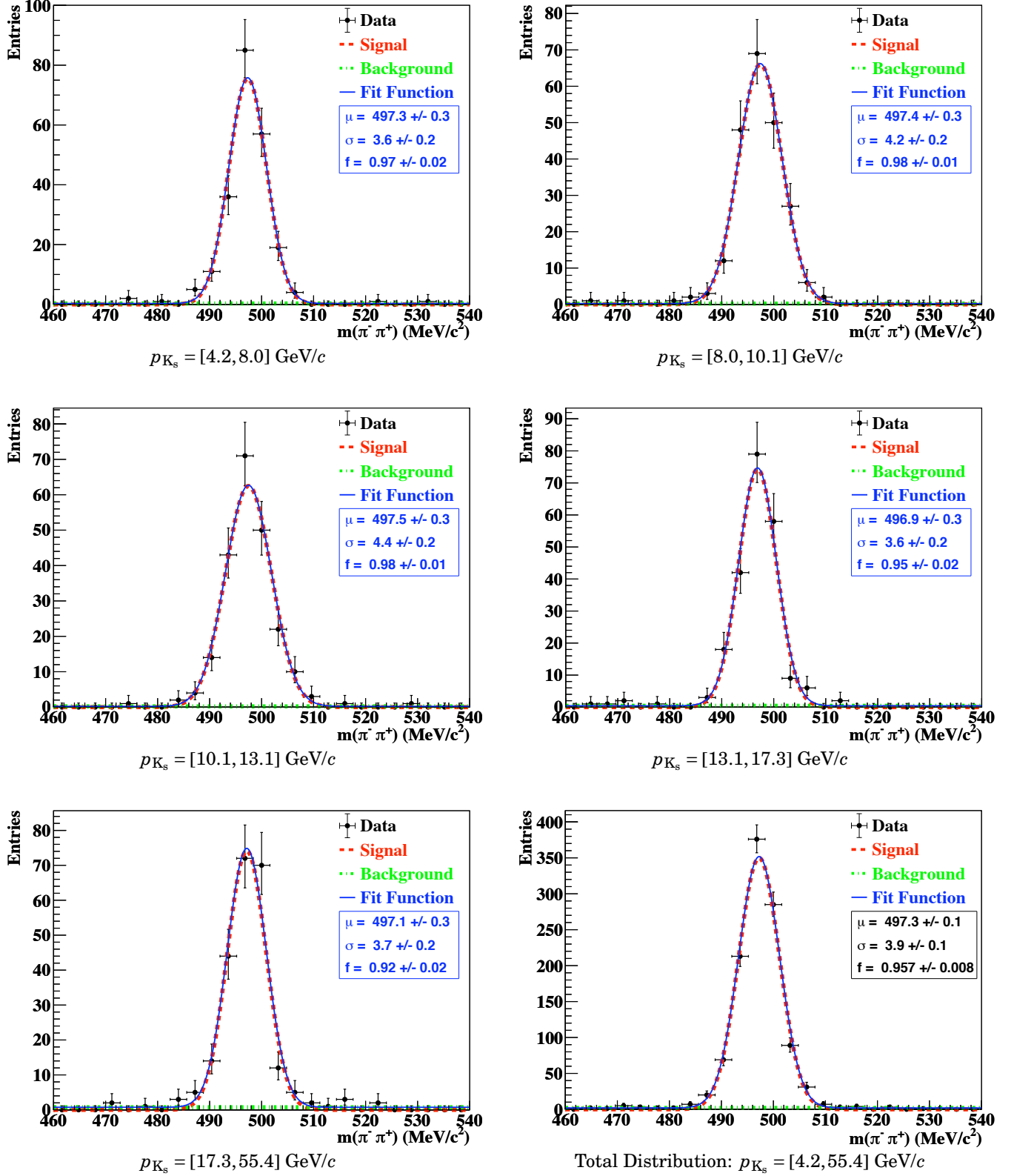


Figure 6.11: Reconstructed mass distributions of 2009 real data L-L K_s candidates in five bins of p_{K_s} (top, middle, bottom left). The mean μ of the Gaussian fits is used in the calculation of Δm . The resolution σ of the Gaussian fit to the total distribution (bottom right) is used in the background subtraction method.

As shown in Figure 6.11, the mean μ are all below the expected K_s mass value $m_{PDG}(K_s) = 497.67 \text{ MeV}/c^2$. The global momentum scale is expected to be corrected by a scale factor α value such that it becomes bigger than one. The mean value of the R distribution is $R_{\text{mean}} = 4.72$.

The result for the additive scale factor α obtained with 2009 real data L-L K_s candidates is shown in Figure 6.12 (left). It is found to be $\alpha = -0.0014 \pm 0.0004$ ⁴.

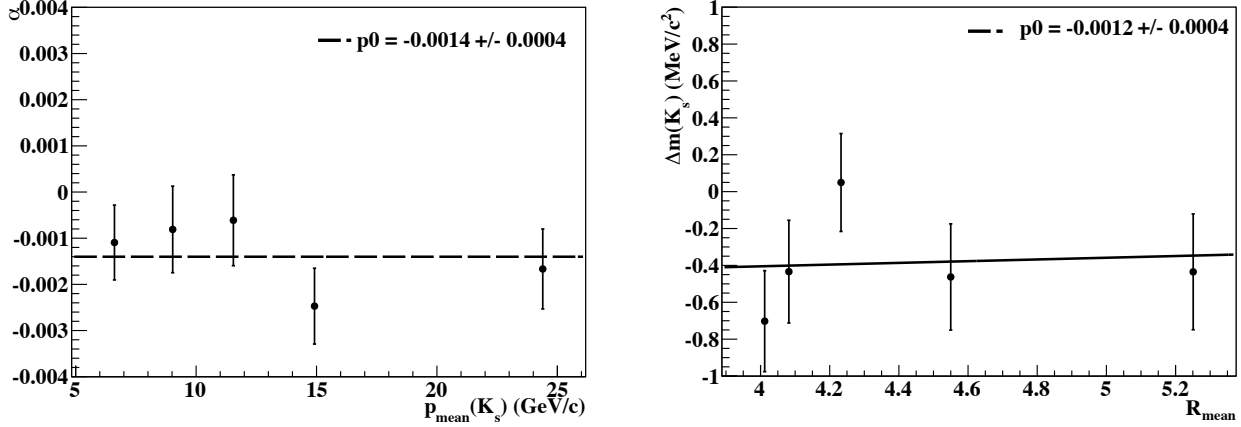


Figure 6.12: α as a function of the average value of p per bin for 2009 real data L-L K_s candidates. The best fit to a constant gives $\alpha = -0.0014 \pm 0.0004$ (left). As a check, a fit of the Δm distribution as a function of the average value of R per bin is performed using Equation 6.25 (right). The fit value obtained, -0.0012 ± 0.0004 , is in good agreement with the value obtained for α .

To check the validity of the result, Δm is plotted in bins of R instead (Figure 6.12, right). The distribution is fitted using the one-parameter function f_R derived from Equation 6.7:

$$f_R(R) = -\alpha \cdot \frac{m_\pi^2 \cdot R - m_{K_s}^2}{m_{K_s}} \quad (6.25)$$

The fit parameter obtained, $\alpha = -0.0012 \pm 0.0004$, is consistent with $\alpha = -0.0014 \pm 0.0004$.

The α factor will be recalculated using K_s candidates with higher statistics coming from 2010 real data and validated using Λ and $\bar{\Lambda}$ candidates in Subsection 6.6.4.

⁴The minus sign comes from the fact that $m_\pi^2 R$ is smaller than m_p^2 in Equation 6.7.

6.5.2 Effect of Energy Loss Description

Using the simple energy loss description of Subsection 6.2.2, the result for 2009 real data L-L K_s candidates is shown in Figure 6.13, together with the result obtained using the full Bethe-Bloch formula, called *detailed* E_{loss} in Figure 6.13.

A global shift of $-6 \cdot 10^{-4}$ is observed between using one or the other energy loss descriptions. The $\alpha = -0.0020 \pm 0.0004$ value found using the simplified description is further away from zero than the result $\alpha = -0.0014 \pm 0.0004$ obtained with the Bethe-Bloch formula.

The same shift is observed when using the corresponding Monte Carlo candidates. This means that the hypotheses made to obtain the simple energy loss description are correct at a 10^{-3} -level and that this shift could be (partially) corrected by re-tuning the c_{ion} parameter of Equation 6.13 on MC09 Monte Carlo data.

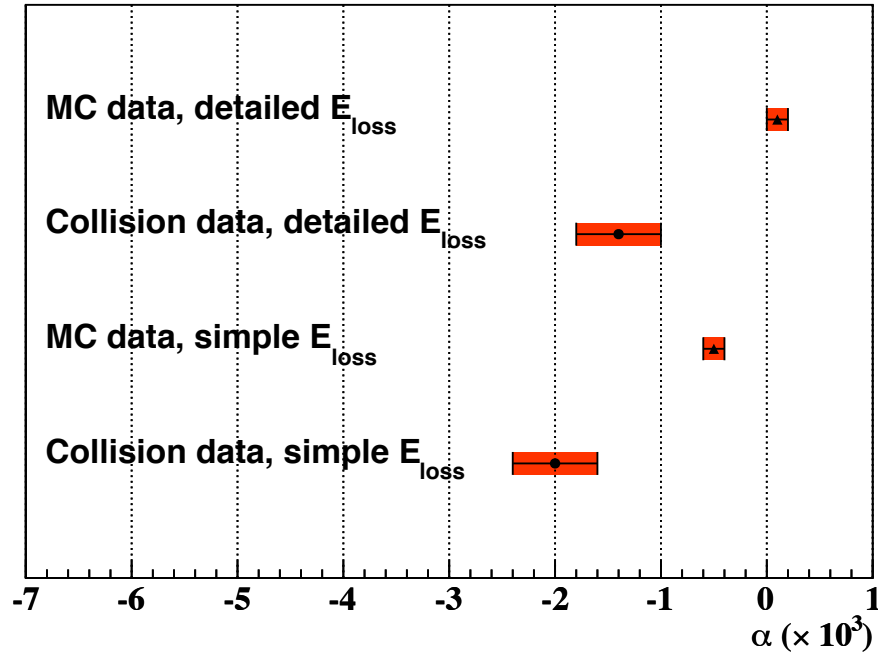


Figure 6.13: α for Monte Carlo (triangle) and 2009 real (circle) data L-L K_s candidates using the simple energy loss ($\alpha = -0.0005 \pm 0.0001$, $\alpha = -0.0020 \pm 0.0004$) or the Bethe-Bloch ($\alpha = +0.0001 \pm 0.0001$, $\alpha = -0.0014 \pm 0.0004$) descriptions.

6.5.3 Effect of Magnetic Field Description

Results obtained using the simulated magnetic field map are compared with those obtained with the measured map using 2009 L-L K_s candidates. The reconstructed mass values using the simulated magnetic field map are in worse agreement with the expected mass value. The obtained factor $\alpha = +0.0059 \pm 0.0004$ is ~ 4.2 times bigger than the one obtained with the measured magnetic field map (Figure 6.14).

This therefore shows that the global scale of the measured magnetic field map is in much better agreement with the 2009 real data than the one of the simulated map.

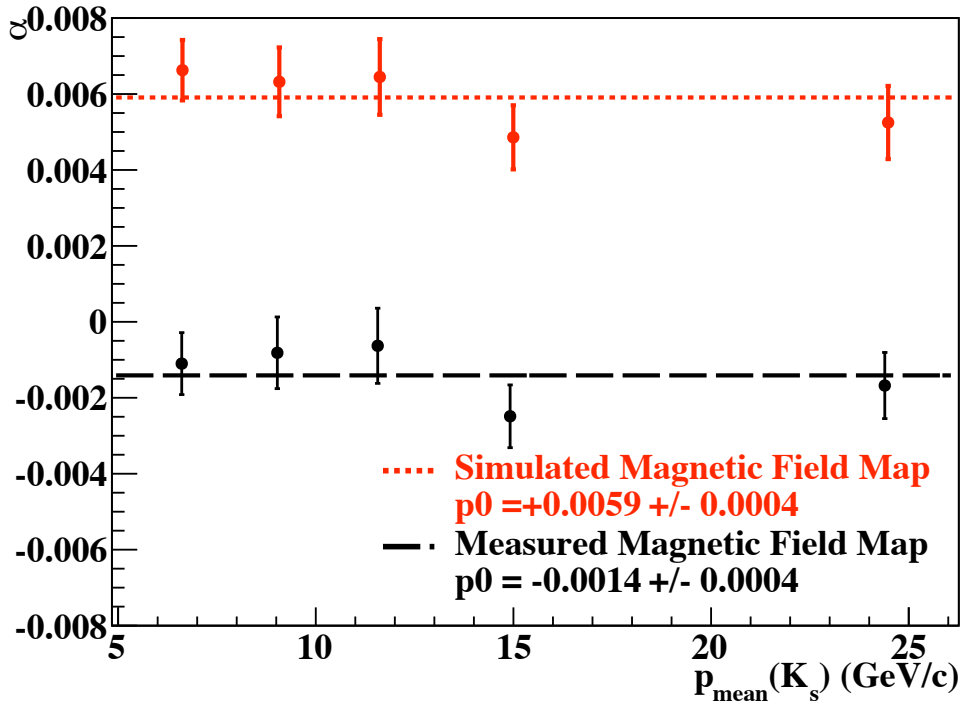


Figure 6.14: α as a function of the average value of p per bin for real data L-L K_s candidates reconstructed using the simulated (red small dash line) or the measured (black long dash line) magnetic field maps. The fits to a constant give $\alpha = +0.0059 \pm 0.0004$ and $\alpha = -0.0014 \pm 0.0004$ respectively.

To first order, the difference between the simulated and measured maps in bins of p_T is a simple scaling of 0.0073. This value is in agreement with the scale factor $S = 0.9931$ obtained with the tests performed on Monte Carlo J/ψ candidates in Section 6.4.2.

6.5.4 Effect of Alignment Description

The effect of the alignment description on the momentum scale calibration is tested. As explained in Subsection 6.2.2, Δm is expected to be independent of $(p^+ - p^-)$, the difference in momenta between the positive and negative daughter tracks. If a slope is found in the distribution, it means that the alignment description is not accurate. Such an effect cannot be explained by the magnetic field description, as it would affect similarly p^+ and p^- and hence not lead to a slope feature.

No slope is found for L-L K_s candidates from 2009 real data, as shown in Figure 6.15 (left). An additional check is made by looking at the mass difference as a function of the azimuthal angle ϕ of the VELO detector. As the reconstructed Δm should not depend on the measured ϕ , a flat distribution is also expected, which is observed in Figure 6.15 (right).

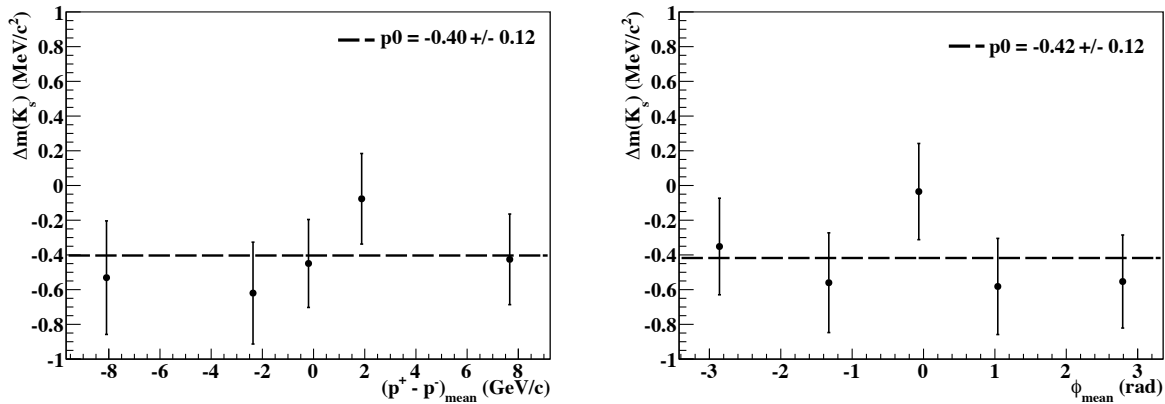


Figure 6.15: $\Delta m = \mu - m_{K_s}$ as a function of the difference in momenta between the positive and negative tracks (left) and as a function of the ϕ polar angle in the VELO detector (right) for 2009 real data L-L K_s candidates.

The alignment description is still evolving. Therefore, it is interesting to look at how the α factor value is affected by the use of different descriptions. Figure 6.16 shows the results obtained for two versions (v.5, v.7) prior to the one used for the result obtained in Figure 6.12 (left) for 2009 real data L-L K_s candidates (v.7+improvement). The results are summarized in Table 6.4. No significant dependence on the alignment description is observed.

Table 6.4: Fits results to a constant for 2009 real data L-L K_s candidates for different alignment descriptions.

Alignment v.5	Alignment v.7	Alignment v.7 + Improvement
-0.0015 ± 0.0004	-0.0019 ± 0.0004	-0.0014 ± 0.0004

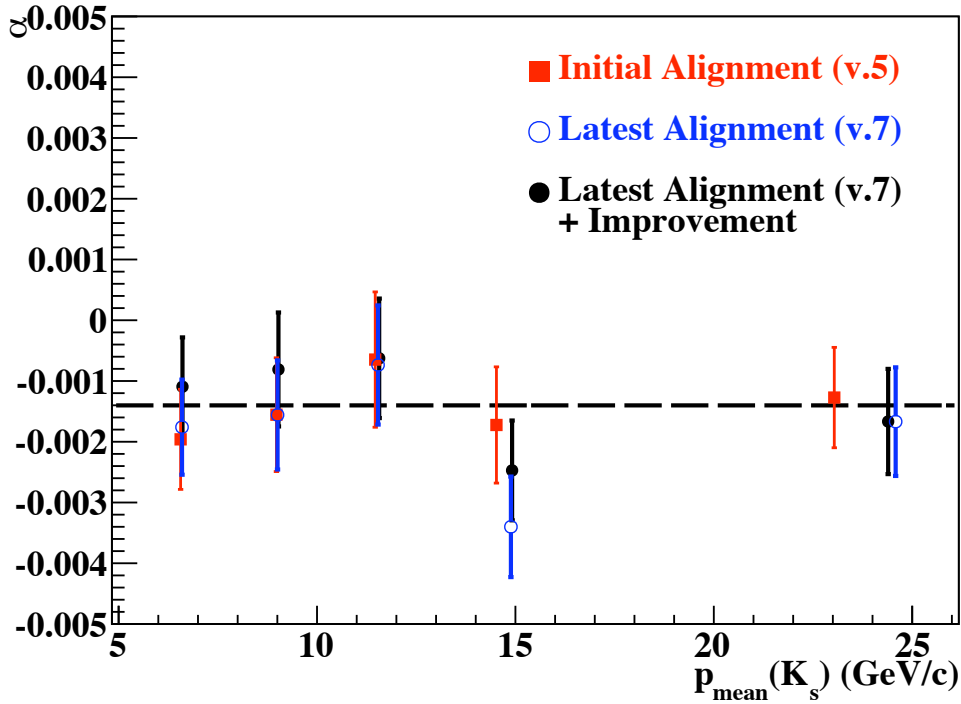


Figure 6.16: α as a function of p_{mean} for 2009 real data L-L K_s candidates reconstructed using the initial (red square), the latest (blue empty circle) and an improved version of the latest (black circle) alignment descriptions.

6.5.5 Magnetic Field Systematics

Global Scale of the Reconstructed Mass Distribution

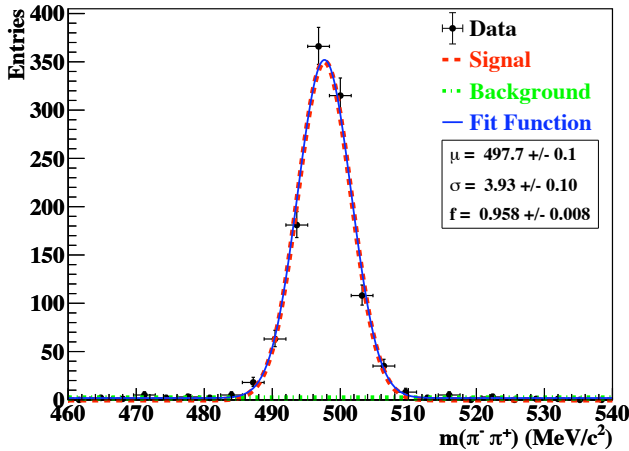


Figure 6.17: Reconstructed $\pi^+\pi^-$ mass distribution from 2009 real data candidates using the measured field map together with the correction factor $\alpha=-0.0014$.

The factor $\alpha = -0.0014$ is used in the service dedicated to the magnetic field of the LHCb software together with the measured map (Subsection 5.5.4). An example is shown in Figure 6.17 for 2009 real data L-L K_s candidates.

The fitted mean $\mu = 497.7 \pm 0.1 \text{ MeV}/c^2$ agrees perfectly with the expected value $m_{K_s} = 497.67 \text{ MeV}/c^2$.

6.6 Results with 2010 Real Data

From the four magnetic field systematics presented in Subsection 6.4.2, it has already been observed using 2009 real data that the global scale of the reconstructed mass distributions using the measured magnetic field map is in better agreement with real data than the one of the simulated map (Figure 6.14). The three other magnetic field systematics are tested in the following using L-L or D-D K_s candidates coming from 2010 real data.

6.6.1 Up-Down Asymmetry

The impact on physics of the up-down asymmetry described in Section 6.4.2 using MC09 Monte Carlo inclusive $J/\psi \rightarrow \mu^+ \mu^-$ has been investigated using 2010 real data⁵. A relative effect of 0.1% is expected in the mass distributions of K_s decays reconstructed from tracks going through the upper part or the down part of the magnet using the measured map, in case the up-down asymmetry is a fake effect. On the other hand, if the up-down asymmetry is real, then no shift between the two reconstructed masses will be observed when using the measured map, but with the simulated map. In the K_s case, the 0.1% effect expected corresponds to a $\sim 0.5 \text{ MeV}/c^2$ difference between the two mass distributions.

Results obtained for L-L K_s candidates are shown in Figure 6.18 for $\pi^\pm$ tracks going through the upper part of the magnet (left) and for two tracks going through the down part (right) using the measured magnetic field map (top) or the simulated one (bottom). The fit results are summarized in Table 6.5.

Table 6.5: Gaussian fits results for 2010 real data L-L K_s candidates reconstructed from $\pi^\pm$ going through different parts of the magnet and using different magnetic field descriptions.

	Upper Part	Lower Part
Measured Map	497.2 ± 0.1	497.2 ± 0.1
Simulated Map	499.6 ± 0.1	499.0 ± 0.1

The two results for the measured map are consistent (Table 6.5), while a difference of $0.6 \text{ MeV}/c^2$ is observed in the results using the simulated map, which corresponds to the $\sim 0.1\%$ effect expected⁶. The up-down asymmetry is therefore a real effect.

⁵Due to the smaller size of the dataset, it was not possible to perform this study using 2009 real data.

⁶The higher value for the upper part than the lower one is expected as the residuals between the two magnetic field descriptions are known to be larger in the top part of the magnet (Section 5.3.5).

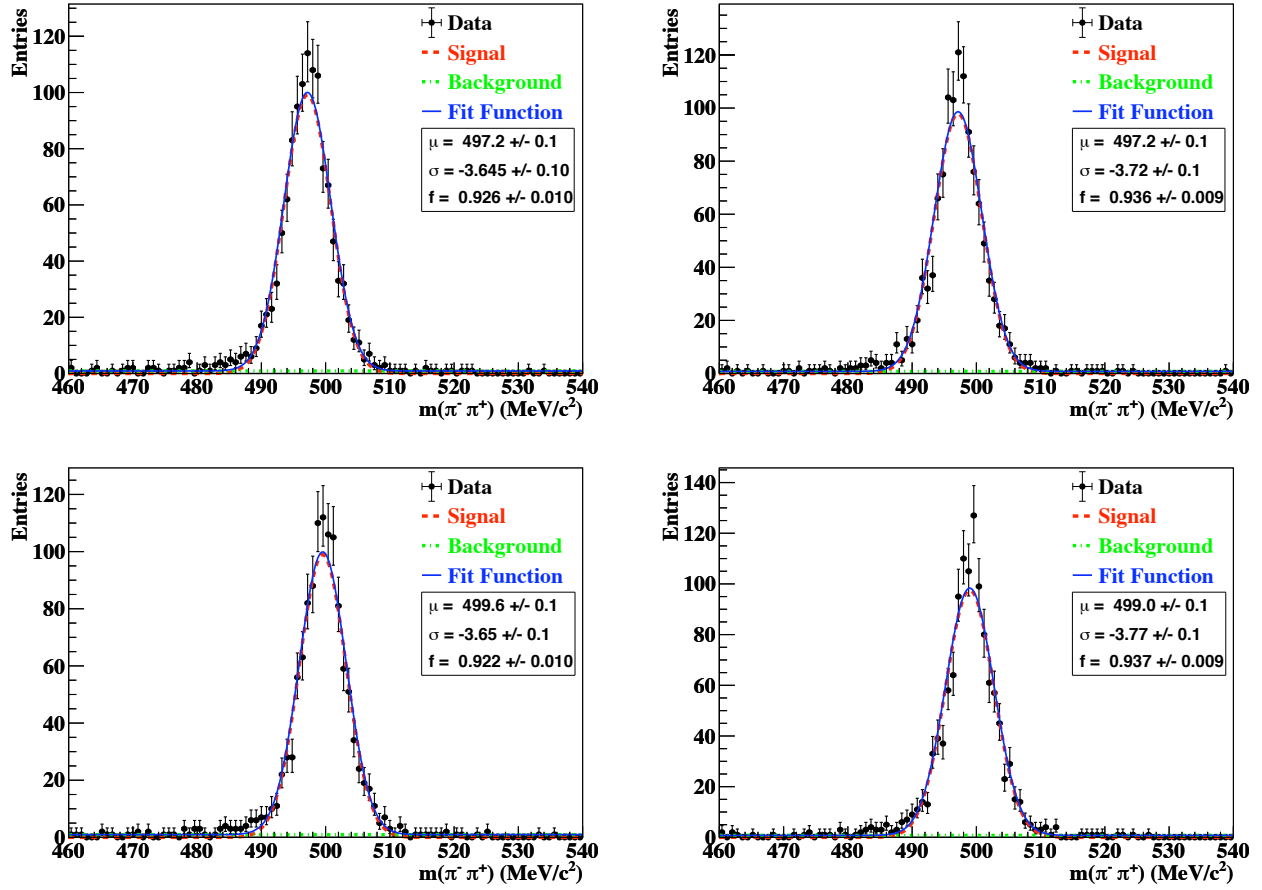


Figure 6.18: Mass distribution of real data L-L π^+ and π^- passing through the upper part (left) or down part (right) of the magnet reconstructed using the measured (top) or simulated (bottom) field maps.

6.6.2 Mass Resolutions

The D-D K_s candidates from 2010 real data are reconstructed using either the measured or simulated maps with the down polarity of the magnet. From Monte Carlo studies, a 5% effect is expected between the mass resolutions for the two cases, as explained in Subsection 6.4.2. This effect is not observed in real data, as shown in Figure 6.19. This could be because it is hidden by the worse resolution in real data, $\sigma_{\text{rec}} = 7.3 \text{ MeV}/c^2$, compared to the expected resolution $\sigma_{\text{exp}} = 5.9 \text{ MeV}/c^2$ for D-D K_s candidates.

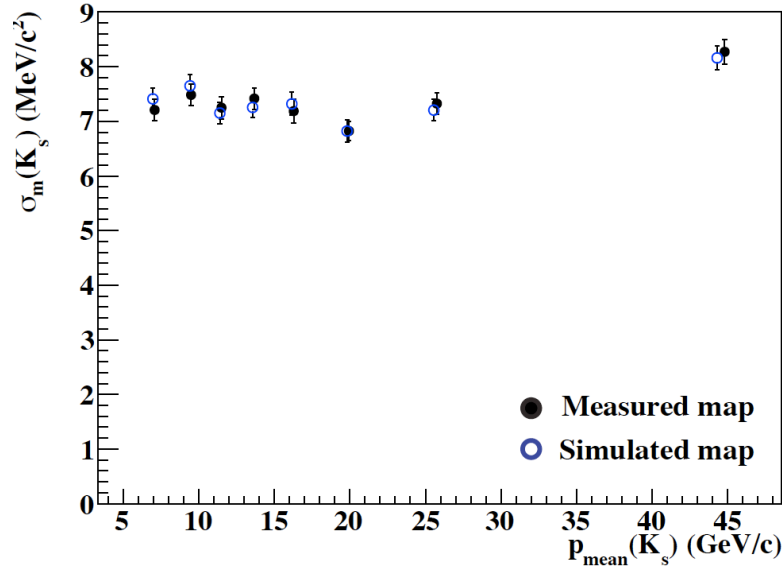


Figure 6.19: Mass resolution σ in bins of p_{mean} for 2010 real data D-D K_s candidates. Results using the measured map for the down polarity (black filled dots) are compared to the ones for the simulated field map (blue empty dots).

6.6.3 Decay Plane Dependence

Results for the mass difference Δm in bins of the angle ϕ between the normal to the decay plane and the y axis direction are shown in Figure 6.20 for 2010 real data D-D K_s candidates.

A comparison of the distributions for the up (red dots) and down (black triangles) polarities show a similar shape (top). This shape is not a simple scaling, but is the same for both polarities, however flipped with the magnet polarity. It could be interpreted as an overcorrection of the simulated map. The simulated map (empty blue dots, bottom) gives a shape that is similar to the one predicted from the Monte Carlo studies of Subsection 6.4.2, hence disfavoring the simulated map.

Validation of the Measured Magnetic Field Map

From the observed decay plane dependence and the fact that the up-down asymmetry of the field is seen in the data, the choice of the measured map is validated. It can now be used to calculate a correction factor for the residual global scale difference between the expected mass peak values and the reconstructed values of K_s , Λ and $\bar{\Lambda}$ resonances from early 2010 data.

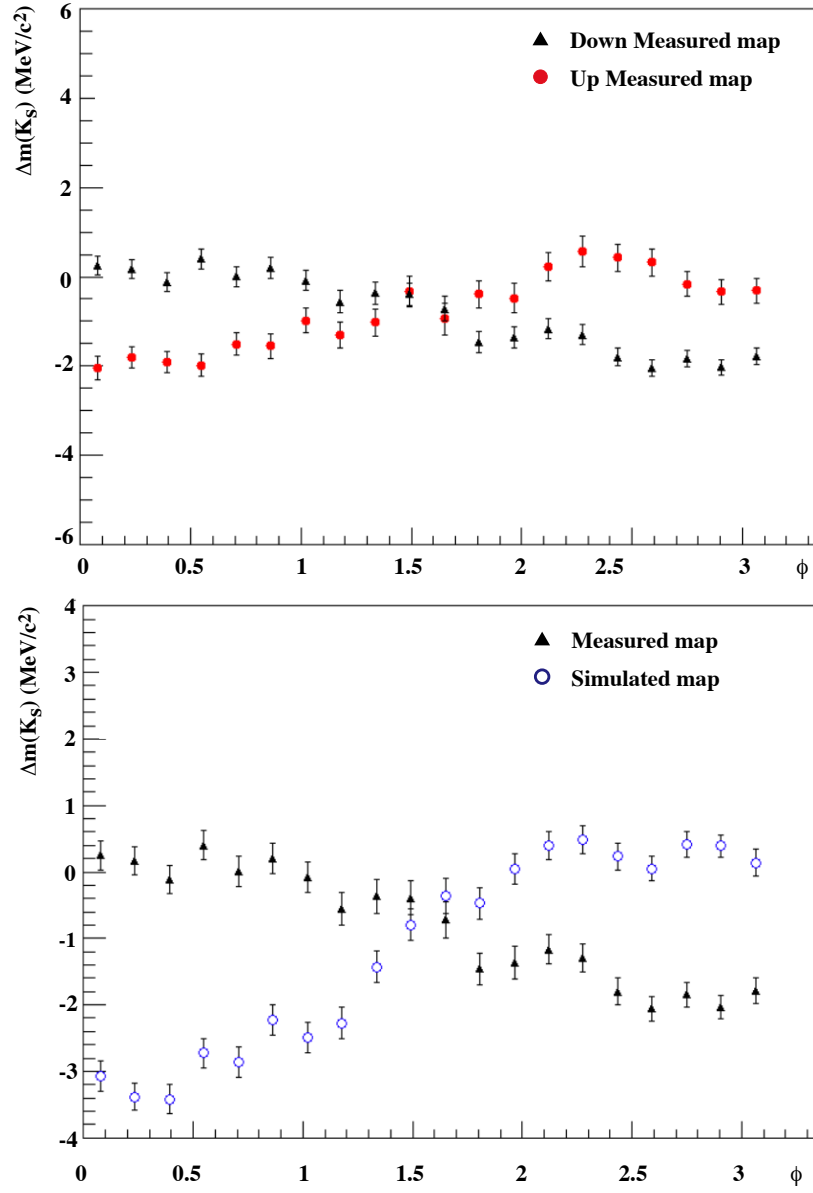


Figure 6.20: Mass difference Δm in bins of ϕ for 2010 real data D-D K_S candidates. The results using the measured map for the positive polarity (black filled triangles) are compared on the left to the ones for the negative polarity (red filled dots) and on the right, to the ones for the simulated field map (blue empty dots).

6.6.4 Momentum Scale Factor Calculation

The momentum scale is calculated using events of Table 6.3 coming from early 2010 runs. A comparison between the two magnet polarities has also become possible. The method explained in Subsection 6.5.1 is used, except for the calculation of R , which is improved by using a per-event estimate instead of an average value per bin. This is valid for the calculation of h for Λ and $\bar{\Lambda}$ candidates. A linear function is used to model the background description in Equation 6.24 for the Λ and $\bar{\Lambda}$ cases.

As an illustration, the distribution of α as a function of the momentum for L-L K_S candidates recorded with the down polarity is shown in Figure 6.21. The distribution has a slope at low momenta, while the distribution at higher momenta is flatter. The slope feature is attributed to an alignment effect. This assumption is supported by the following studies performed on 2010 real data: K_S candidates recorded in presence of a magnetic field are reconstructed using the alignment corresponding to the case where the magnet is switched off. The same feature as in Figure 6.21 for low momenta is observed, however with a larger slope. Using the alignment corresponding to the case where the magnet is on, the bias at low momenta is reduced, hence illustrating the role played by the alignment description on this slope feature [113].

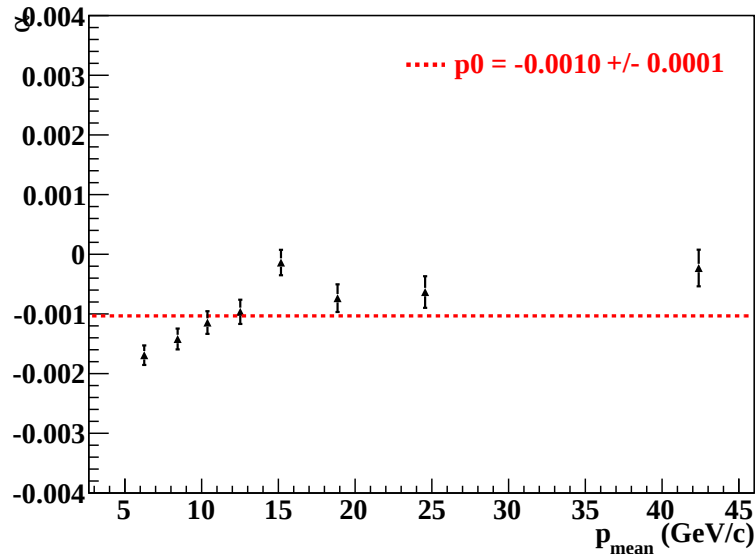


Figure 6.21: α as a function of the average value of p per bin for 2010 real data L-L K_S candidates (down polarity).

The results obtained for α are shown for both polarities in Figure 6.22, for L-L (top) and D-D (bottom) K_S , Λ and $\bar{\Lambda}$ candidates.

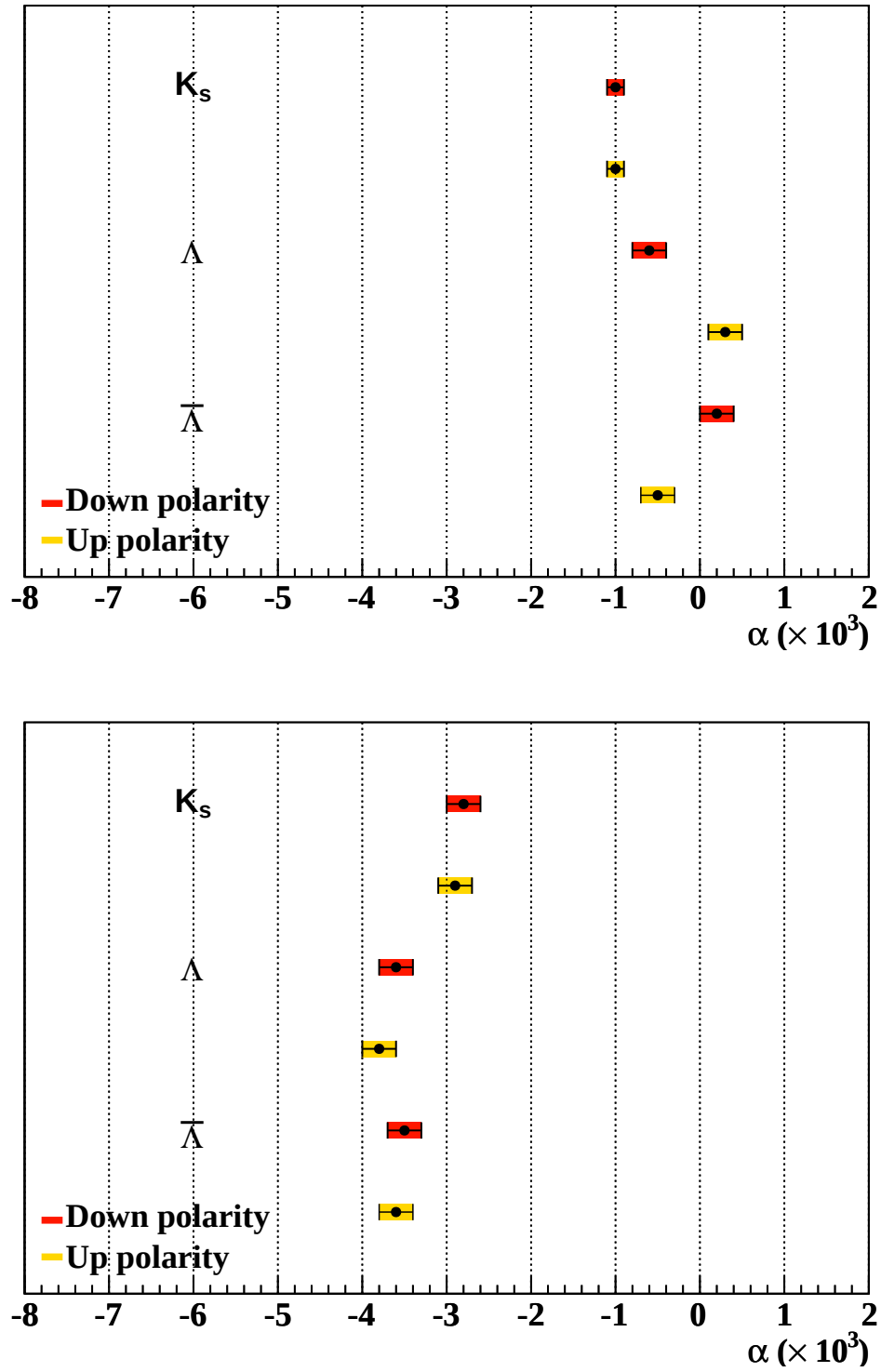


Figure 6.22: α for 2010 real data L-L (top) and D-D (bottom) K_s , Λ and $\bar{\Lambda}$ candidates taken with the down (red) and up (yellow) polarities of the magnet.

Several observations are made:

1. The α value found for L-L candidates is smaller than the one for D-D candidates. From the results of Figure 6.22, the weighted average value obtained for L-L candidates is $\alpha = -0.0007 \pm 0.0001$ against $\alpha = -0.0034 \pm 0.0001$ for D-D candidates. One reason for this is that D-D candidates are more sensitive to the magnetic field than L-L candidates. Another possibility is that it points to a problem in the relative alignment between the Tracker Turicensis and the VELO.
2. The L-L Λ ($\bar{\Lambda}$) candidates recorded with the down (up) polarity of the dipole magnet have the same α factor as the $\bar{\Lambda}$ (Λ) candidates with the reverse polarity. The two sets of α values slightly differ, which is explained as follows. When reconstructing L-L candidates from 2010 data taken with the down or up polarities of the dipole magnet, small differences are observed for small or large values of the decay plane angle ϕ , as shown in Figure 6.23 for K_s candidates. At intermediate values of ϕ , the decaying particles have almost no p_x component, hence all the x component of the momentum is acquired by the kick of the magnetic field. At small or large ϕ values, the decaying particles have a significant p_x component. The kick of the magnet can add or subtract to it according to the charge of the particles, resulting in particles being kicked in or out of the magnet. These particles are considered to be responsible for the differences observed in Figure 6.22.

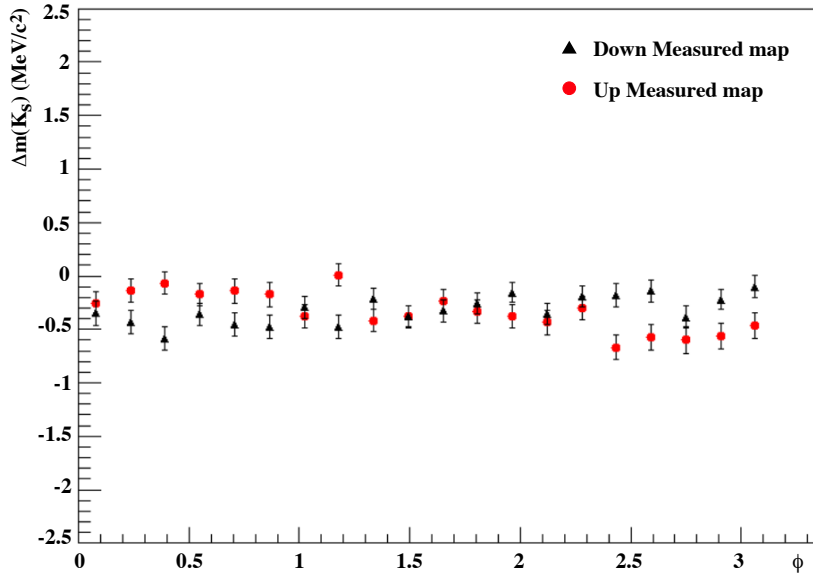
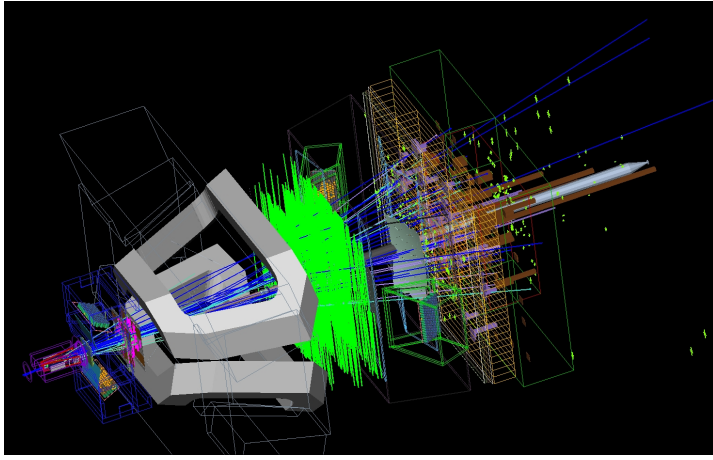


Figure 6.23: Mass difference Δm in bins of ϕ for 2010 real data L-L K_s candidates, for the positive polarity (black triangles) and the negative polarity (red dots).

3. Small differences are observed between the results for the K_s and the $\Lambda/\bar{\Lambda}$ results discussed in point 2. It can be explained by the same effect than in point 2. It could also come from different momentum ranges covered for the candidates, as well as possible material effects.

The α scale factor to correct the momentum scale is hence found to be of order 10^{-3} .



7

The Time-Dependent Angular Analysis to Untagged $B_s^0 \rightarrow J/\psi\phi$ Events

Decays of B_s^0 mesons to $J/\psi\phi$ either directly or through $B_s^0 - \bar{B}_s^0$ oscillations lead to the CP violating phase $\phi_s^{J/\psi\phi}$. In the Standard Model, this phase is predicted to be $\phi_s^{J/\psi\phi} \equiv -2\beta_s = -0.0360^{+0.0020}_{-0.0016}$ rad [105], with β_s the smallest angle of the unitary triangle of the CKM matrix relevant to B_s^0 . This phase is hence one of the CP observables with the smallest theoretical uncertainty. A precise measurement of $\phi_s^{J/\psi\phi}$ could therefore lead to an indirect discovery of New Physics, in case new particles would contribute to the $B_s^0 - \bar{B}_s^0$ box diagram and hence modify the $\phi_s^{J/\psi\phi}$ value from its Standard Model expectation. This makes it a key measurement at LHCb. On the way to this measurement, an analysis without tagging the flavor of the B_s^0 at production will be first performed. In this chapter, sensitivity studies for the parameters that can be determined at LHCb from the time-dependent angular analysis to untagged $B_s^0 \rightarrow J/\psi\phi$ events are presented, considering both Standard Model and New Physics scenarios [114].

In Section 7.1, the formalism describing the $B_s^0 \rightarrow J/\psi\phi$ decay and the angular analysis principle are introduced. In Section 7.2, a summary of the latest measurements obtained at the Tevatron on $\phi_s^{J/\psi\phi}$ is given. The $B_s^0 \rightarrow J/\psi\phi$ offline selection developed in [115] is summarized in Section 7.3, where the $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ control channels are also introduced. Section 7.4 details the fit model used in the analysis, including signal and background contributions. The angular acceptance parameterization developed in Section 7.6 can be used for the signal component [116]. The fit procedure of Section 7.5 is applied to the sensitivity studies for the time-dependent angular analysis to untagged $B_s^0 \rightarrow J/\psi\phi$ events. Results are given in Section 7.7 [114]. The tagged analysis, which will bring the ultimate measurement of $\phi_s^{J/\psi\phi}$, is briefly introduced in Section 7.8.

7.1 Phenomenology

7.1.1 The CKM Picture

In the Standard Model, the only interaction vertices that do not conserve flavor are the couplings between W bosons and quarks. In the Lagrangian of the SM, the part describing these couplings in terms of the mass eigenstates is given by [117]:

$$\mathcal{L}_W = -\frac{g_2}{\sqrt{2}} (\bar{u}_L, \bar{c}_L, \bar{t}_L) \gamma^\mu V_{\text{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^\dagger + \text{h.c.} \quad (7.1)$$

with g_2 the gauge coupling related to the gauge group $SU_L(2)$, γ^μ the Dirac matrices, $W_\mu^{(\dagger)}$ the field describing the charged W boson and V_{CKM} the 3×3 unitary *Cabibbo-Kobayashi-Maskawa (CKM) matrix* containing the strength of the flavor-changing weak decays [18]:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \underset{|V_{ij}| \text{ magnitudes}}{=} \begin{pmatrix} 0.97419 \pm 0.00022 & 0.22570 \pm 0.00100 & 0.00359 \pm 0.00016 \\ 0.22560 \pm 0.00100 & 0.97334 \pm 0.00023 & 0.04150^{+0.00100}_{-0.00110} \\ 0.00874^{+0.00026}_{-0.00037} & 0.04070 \pm 0.00100 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix} \quad (7.2)$$

To parameterize the CKM matrix, four parameters are required. One useful parameterization shown in Equation 7.4, called *Wolfenstein parameterization*, is an expansion in terms of the small parameter $\lambda = \sin(\theta_C)$, where θ_C the Cabibbo angle¹, and with three additional real parameters (ρ, η, A). The four Wolfenstein parameters are to first order [18]:

$$A = 0.814^{+0.021}_{-0.022} \quad \rho = 0.135^{+0.031}_{-0.016} \quad \eta = 0.349^{+0.015}_{-0.017} \quad \lambda = 0.2257^{+0.0009}_{-0.0010} \quad (7.3)$$

The CP violation arises from the η parameter, while (ρ, A, λ) conserve CP. V_{CKM} can be approximated as

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad (7.4)$$

taken terms up to λ^3 . When considering next-to-leading order corrections in λ , which are needed for the study of the $B_s^0 - \bar{B}_s^0$ mixing phase, the CKM matrix is expanded to $\mathcal{O}(\lambda^6)$:

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 - \lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + (1 - 2(\rho + i\eta))A^2\lambda^{5/2} & 1 - \lambda^2/2 - (1 + 4A^2)\lambda^4/8 & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 + (1 - 2(\rho - i\eta))A\lambda^4/2 & 1 - A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^7) \quad (7.5)$$

with:

$$\bar{\rho} = \rho \cdot (1 - \lambda^2/2) \quad \text{and} \quad \bar{\eta} = \eta \cdot (1 - \lambda^2/2) \quad (7.6)$$

¹This angle was introduced by Nicolas Cabibbo to preserve the universality of the weak interaction.

In the Standard model, the parameter measuring the strength of CP violation is called the *Jarlskog parameter* J_{CP} . It is given by [118]:

$$J_{\text{CP}} = \left| \Im(V_{i\alpha} V_{j\beta} V_{i\beta}^* V_{j\alpha}^*) \right|, \quad (i \neq j, \alpha \neq \beta) \quad (7.7)$$

CP is violated if the imaginary part of the products of the CKM matrix elements is different from zero, hence if $J_{\text{CP}} \neq 0$. Using Equations 7.4 and 7.5, J_{CP} is rewritten as [102]:

$$J_{\text{CP}} \simeq \lambda^6 A^2 \eta (1 - \lambda^2/2) + \mathcal{O}(\lambda^{10}) \sim 10^{-5} \quad (7.8)$$

CP violation effects are therefore small in the Standard Model. New sources of CP violation could potentially be brought by New Physics contributions.

The Unitary Triangles

From the unitarity condition of the CKM matrix (arising from rotation matrix properties)

$$V_{\text{CKM}}^\dagger V_{\text{CKM}} = V_{\text{CKM}} V_{\text{CKM}}^\dagger = \mathbb{1} \quad (7.9)$$

a set of twelve equations can be extracted of the form

$$\sum_k V_{ki} V_{kj}^* = \delta_{ij} \quad (7.10)$$

For any combination of i and j , with i different from j , a constraint on three complex numbers is obtained, which forms in the complex plane the sides of a triangle [119]. There are six choices for i and j , hence the six triangles shown in Figure 7.1 (not to scale), which are called *unitary triangles*. Their shapes are different, but they cover the same area, which is equal to $0.5 \cdot J_{\text{CP}}$ [120]. The orthogonality relations corresponding to each triangle are given by

$$\begin{aligned} (\text{ds}): V_{\text{ud}} V_{\text{us}}^* + V_{\text{cd}} V_{\text{cs}}^* + V_{\text{td}} V_{\text{ts}}^* &= 0 \\ (\text{sb}): V_{\text{us}} V_{\text{ub}}^* + V_{\text{cs}} V_{\text{cb}}^* + V_{\text{ts}} V_{\text{tb}}^* &= 0 \\ (\text{db}): V_{\text{ud}} V_{\text{ub}}^* + V_{\text{cd}} V_{\text{cb}}^* + V_{\text{td}} V_{\text{tb}}^* &= 0 \\ (\text{cu}): V_{\text{ud}}^* V_{\text{cd}} + V_{\text{us}}^* V_{\text{cs}} + V_{\text{ub}}^* V_{\text{cb}} &= 0 \\ (\text{tc}): V_{\text{cd}}^* V_{\text{td}} + V_{\text{cs}}^* V_{\text{ts}} + V_{\text{cb}}^* V_{\text{tb}} &= 0 \\ (\text{tu}): V_{\text{ud}}^* V_{\text{td}} + V_{\text{us}}^* V_{\text{ts}} + V_{\text{ub}}^* V_{\text{tb}} &= 0 \end{aligned} \quad (7.11)$$

All the triangles of Figure 7.1 are squashed, except for the (db) and (tu) triangles that have sides of comparable size of $\mathcal{O}(\lambda^3)$. The following four angles of the unitary triangles are of particular interest for the CP violating processes,

$$\gamma = \arg\left(-\frac{V_{\text{ud}} V_{\text{ub}}^*}{V_{\text{cd}} V_{\text{cb}}^*}\right) \quad \beta = \arg\left(-\frac{V_{\text{cd}} V_{\text{cb}}^*}{V_{\text{td}} V_{\text{tb}}^*}\right) \quad \beta_s = \arg\left(-\frac{V_{\text{ts}} V_{\text{tb}}^*}{V_{\text{cs}} V_{\text{cb}}^*}\right) \quad \beta_K = \arg\left(-\frac{V_{\text{us}} V_{\text{ud}}^*}{V_{\text{cs}} V_{\text{cd}}^*}\right) \quad (7.12)$$

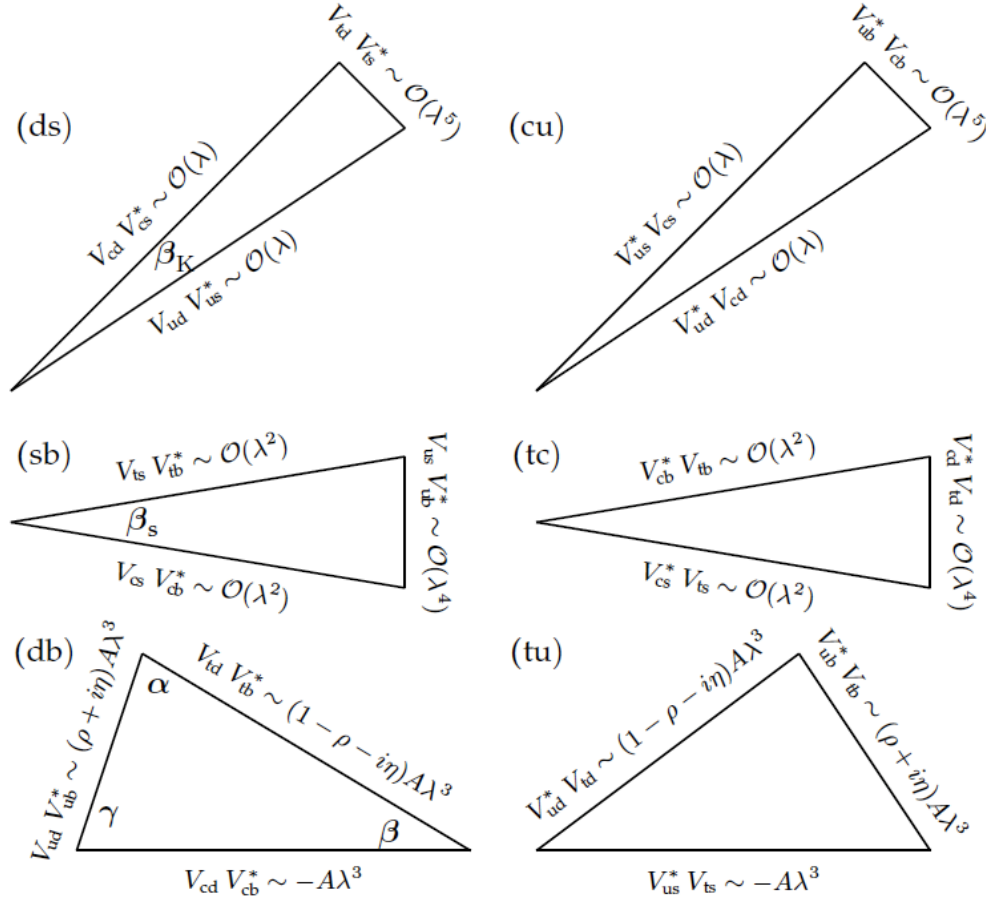


Figure 7.1: The unitary triangles in the complex plane using the leading order Wolfenstein parameterization [102].

where γ and β appear in the same (db) triangle, while β_s and β_K appear in the (sb) and (ds) triangles respectively (Figure 7.1). All these phases can be related to the CP-violating parameter η . For instance, the β_s angle is expressed in terms of the Wolfenstein parameterization by:

$$\beta_s = \arg \left[1 - \lambda^2 \left(\frac{1}{2} - \rho - i\eta \right) + O(\lambda^4) \right] \simeq \lambda^2 \eta \quad (7.13)$$

Using the measurements of Equation 7.3, it is predicted to be $2\beta_s = 0.0360_{-0.0016}^{+0.0020}$ rad [18].

The current experimental results and constraints on the (db) triangle are given in the $(\bar{\rho}, \bar{\eta})$ plane (Figure 7.2, top) and for the (sb) triangle in the $(\bar{\rho}_s, \bar{\eta}_s)$ plane (Figure 7.2, bottom) [121], where the $(\bar{\rho}, \bar{\eta})$ and $(\bar{\rho}_s, \bar{\eta}_s)$ planes are defined by:

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \quad \text{and} \quad \bar{\rho}_s + i\bar{\eta}_s = -\frac{V_{us} V_{ub}^*}{V_{cs} V_{cb}^*} \quad (7.14)$$

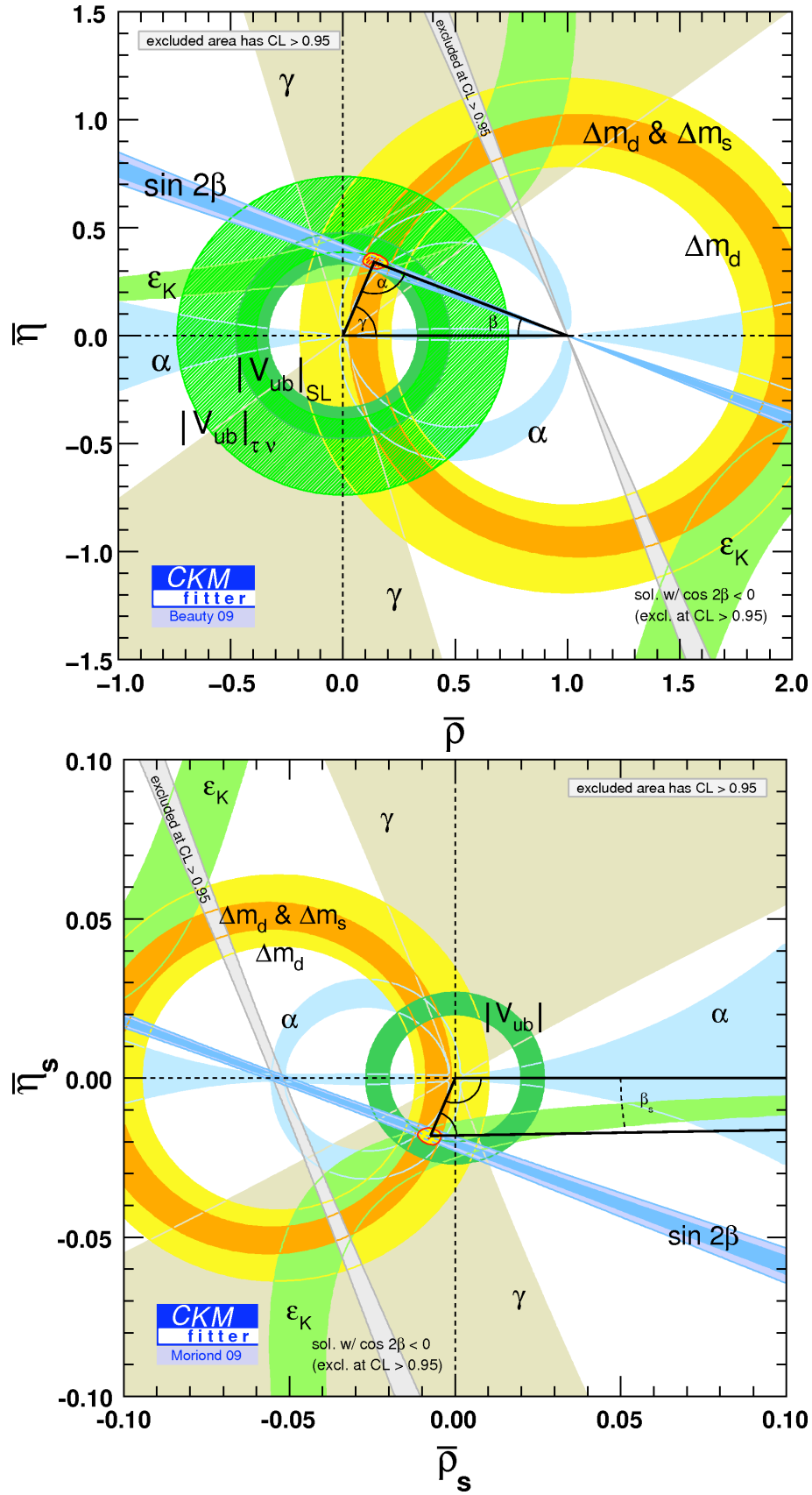


Figure 7.2: Current experimental constraints of the (db) triangle in the $(\bar{\rho}, \bar{\eta})$ plane (top) and on the (sb) triangle in the $(\bar{\rho}_s, \bar{\eta}_s)$ plane (bottom) [122].

7.1.2 The CP Violating Weak Phase $\phi_s^{J/\psi\phi}$ in a Nutshell

B_s^0 mesons can decay into $J/\psi\phi$ through tree and penguin processes driven by $\bar{b} \rightarrow \bar{c}c\bar{s}$ quark level transitions (Figure 7.3). The tree diagram dominates with a single weak phase $\Phi_D = \arg(V_{cs}V_{cb}^*)$.

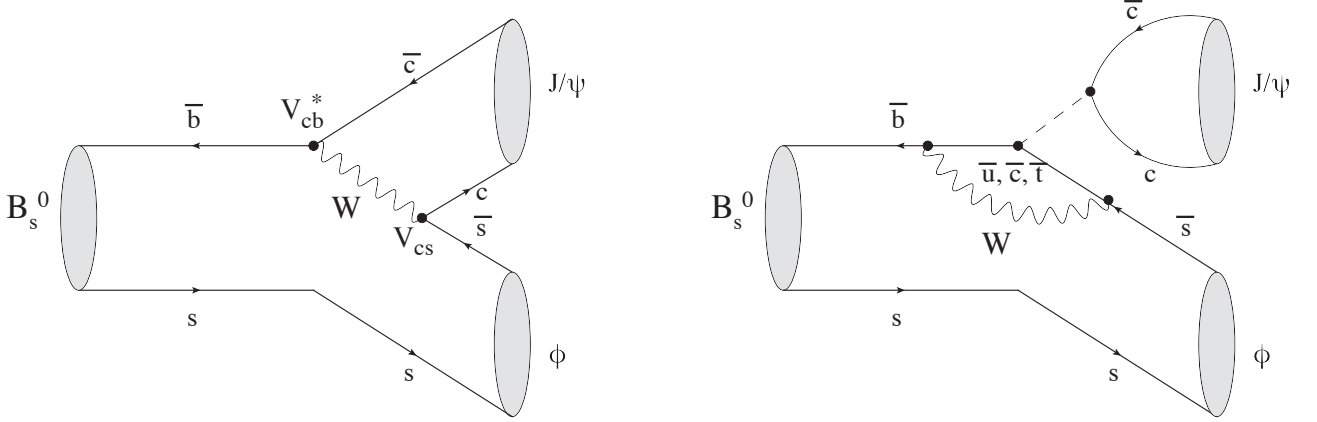


Figure 7.3: Decay topologies contributing to $B_s^0 \rightarrow J/\psi\phi$ in the Standard Model: Tree diagram (left) and Penguin diagram (right).

Before decaying into $J/\psi\phi$, B_s^0 mesons can also first oscillate into $\bar{B}_s^0$ through box diagrams, as shown in Figure 7.4. In the Standard Model, the B_s^0 mixing phase is $\Phi_M = 2 \cdot \arg(V_{ts}V_{tb}^*)$.

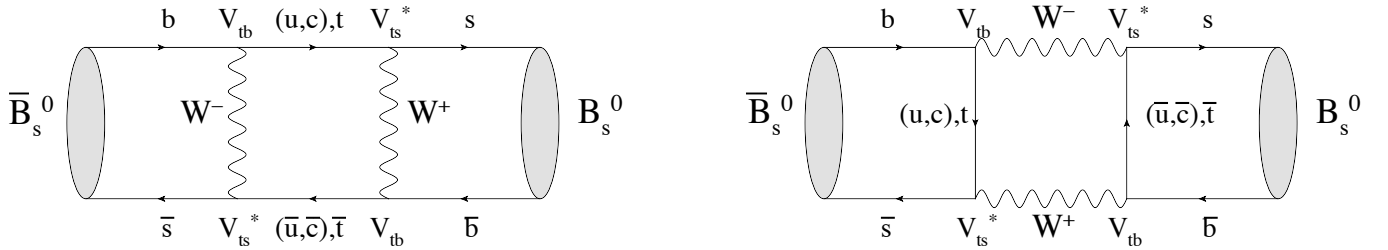


Figure 7.4: Diagrams responsible of $B_s^0 - \bar{B}_s^0$ mixing in the Standard Model.

The interference between the two possible paths to $J/\psi\phi$ gives rise to the CP violating phase $\phi_s^{J/\psi\phi}$ expressed in terms of the decay and mixing phases as:

$$\phi_s^{J/\psi\phi} = \Phi_M - 2 \cdot \Phi_D \quad (7.15)$$

In the Standard Model, $\phi_s^{J/\psi\phi} = -2 \cdot \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$, which is equal to $-2\beta_s$, with β_s introduced in Subsection 7.1.1. The $\phi_s^{J/\psi\phi}$ phase is therefore predicted to be very small, $\phi_s^{J/\psi\phi} = -0.0360_{-0.0016}^{+0.0020}$ rad [18]. However, new particles could contribute to the $B_s^0 - \bar{B}_s^0$ box diagram and have the potential to modify $\phi_s^{J/\psi\phi}$ significantly from its expectation (by changing the value of Φ_M). Thanks to the high precision of the Standard Model $\phi_s^{J/\psi\phi}$ prediction, measured deviations would then easily be interpreted as clear signs of New Physics. This is the reason why this measurement is one of the most promising to search indirectly for New Physics at LHCb.

7.1.3 The Angular Analysis

$B_s^0 \rightarrow J/\psi \phi$ is a pseudo-scalar to vector-vector decay. Since J/ψ and ϕ are vector mesons, they can have an even or odd relative orbital angular momentum ℓ in the final state ($\ell = 0, 1, 2$). Due to total angular momentum conservation, the final state is therefore an admixture of CP-even ($\ell=0,2$) and CP-odd ($\ell=1$) states. The resulting admixture tends to dilute (or cancel) the overall CP asymmetry. If the different CP components could be separated statistically by some method, then the CP information would be obtained without dilution. Such a method is called *Angular Analysis*.

It is possible to perform the angular analysis of the decay products in three different bases: the *transversity basis*, the *helicity basis* or the *partial wave decomposition*. They are equivalent, but lead to different physical observables. In the helicity formalism, the angular analysis is performed in terms of the spin angular momentum $\vec{S}$, while the orbital angular momentum $\vec{L}$ is used in the partial wave decomposition formalism. These two bases are indeed equivalent, as the total angular momentum $\vec{J} = \vec{L} + \vec{S}$ is conserved. Some advantages in using the helicity formalism will be discussed in Section 7.6.

A priori, the transversity formalism does not result from such an easy interpretation of quantum mechanics. It has been however developed, because it has the great advantage of leading directly to the measurement of CP violation quantities of interest, what the helicity formalism does not offer. It is therefore the one adopted by the LHCb experiment to perform the $\phi_s^{J/\psi \phi}$ measurement to the tagged $B_s^0 \rightarrow J/\psi \phi$ signal events. Consequently, it is also the one used for the sensitivity studies to the untagged fit of Section 7.7.

In the following, the three formalisms are introduced and the passages to go from the helicity and partial wave decomposition bases to the transversity one are given.

The Transversity Basis

In the transversity basis, the three decay product angles are given by $\Omega_{\text{TR}} = \{\theta, \psi, \varphi\}$ (Figure 7.5) [123]. In the J/ψ rest frame coordinate system, the x direction is defined by the direction of the ϕ particle. The y axis is defined by the plane of the K^+K^- system, with $p_y(K^+) > 0$, so that the z axis is the normal to that plane. The direction of the positive lepton (μ^+) in the J/ψ rest frame is given by the polar and azimuthal angles, θ and φ , and ψ is the angle between the x axis and the K^+ in the ϕ meson rest frame. The angle definitions are the same for B_s^0 or $\bar{B}_s^0$ candidates.

The transversity basis leads directly to the measurement of the CP violation quantities of interest. Indeed, the three time-dependent amplitudes associated to this basis are called A_0 , $A_{\parallel}$ and $A_{\perp}$, corresponding to relative orbital angular momenta between the J/ψ and ϕ particles of $\ell = 0$, $\ell = 2$ and $\ell = 1$ respectively. At $t = 0$ s, $|A_0|^2$ and $|A_{\parallel}|^2$ represent together the CP-even quantity present in the initial state, while $|A_{\perp}|^2$ represents the CP-odd one.

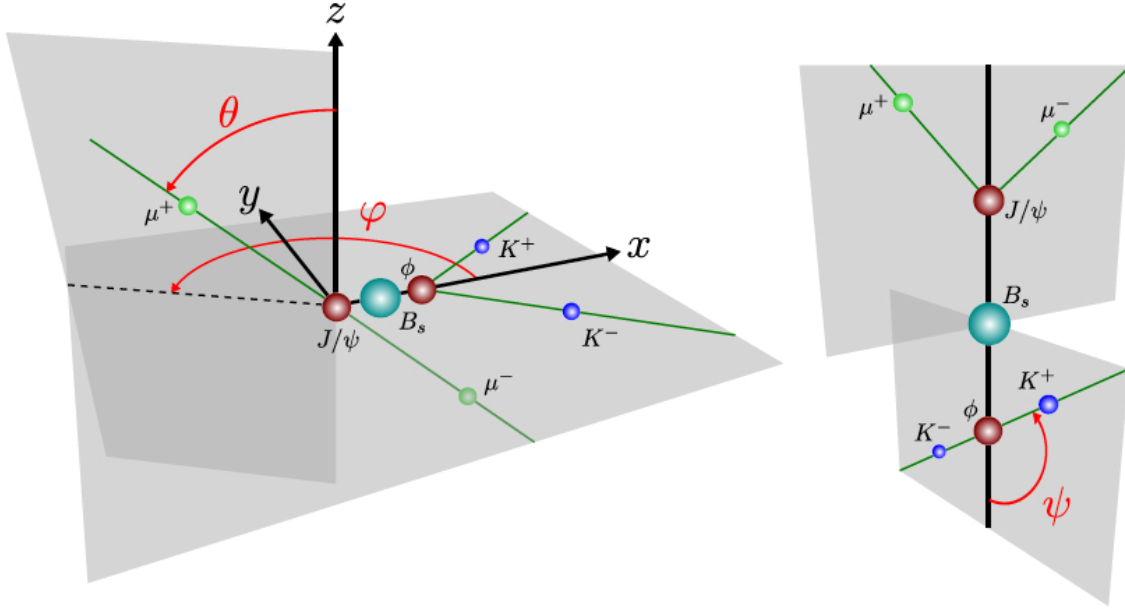


Figure 7.5: Decay product angles $\Omega_{\text{TR}} = \{\theta, \psi, \phi\}$ in the transversity basis. θ and ϕ are the polar and azimuthal angles of the μ^+ in the J/ψ rest frame. ψ is the angle between the x axis and the K^+ in the ϕ rest frame.

The Helicity Basis

The helicity λ is defined as the projection of the spin $\vec{S}$ onto the momentum direction $\hat{p}$,

$$\lambda = \vec{S} \cdot \hat{p} \quad \text{with} \quad \hat{p} = \frac{\vec{p}}{|\vec{p}|} \quad (7.16)$$

In the helicity basis, the three decay product angles are given by $\Omega_{\text{HEL}} = \{\theta_{\text{H}}, \psi, \chi\}$ (Figure 7.6). Two different z axes are defined, one in the direction of the J/ψ in the B_s^0 rest frame, called z , and one in the direction of the ϕ , called z' . The x and x' axes associated to the rest frames of the J/ψ and the ϕ are chosen to be the same, however defined in an arbitrary manner, as they have no influence on the definitions of the angles. The y and y' axes result from the requirement of having right-handed coordinate systems and are therefore pointing to opposite directions.

The polar angle of the positive lepton (μ^+) in the J/ψ rest frame is called θ_{H} and the polar angle of the K^+ in the ϕ rest frame is called ψ . The ψ angle is equivalent to the one defined in the transversity basis, hence its name. The angle between the two decay planes is called χ , starting from the K^+ and going towards the μ^+ with a rotation around the z direction, which is the direction of the B_s^0 momentum in the ϕ rest frame. The definitions of the angles are the same for B_s^0 or $\bar{B}_s^0$ candidates.

The helicity basis can easily be interpreted in quantum mechanics as a study of the spin angular momentum. The three time-dependent amplitudes associated to this base are called H_{+1} , H_0 and H_{-1} , corresponding to helicities $\lambda = +1$, $\lambda = 0$ and $\lambda = -1$ respectively. At $t = 0$ s, $|H_{+1(-1)}|^2$ represents the final state where the J/ψ and the ϕ particles have helicities $\lambda = +1(-1)$ each and $|H_0|^2$ of $\lambda = 0$. More details about the helicity values are given in Subsection 7.1.5.

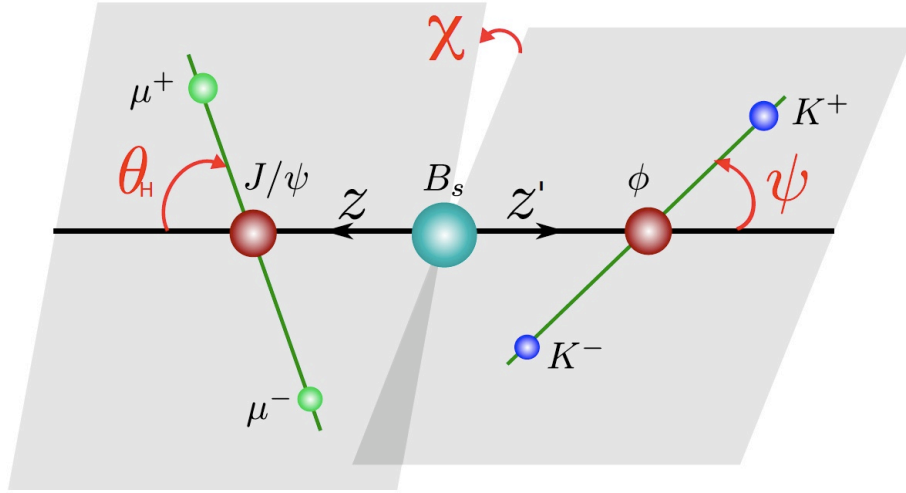


Figure 7.6: Decay product angles $\Omega_{\text{HEL}} = \{\theta_H, \psi, \chi\}$ in the helicity basis. θ_H is the polar angle of the positive lepton (μ^+) in the J/ψ rest frame and ψ is the polar angle of the K^+ in the ϕ rest frame. χ is the angle between the two decay planes, starting from the K^+ and going towards the μ^+ with a rotation around the z direction.

The helicity amplitudes are related to the ones of the transversity basis by

$$H_0 = A_0 \quad ; \quad H_{+1} = \frac{A_{\parallel} + A_{\perp}}{\sqrt{2}} \quad ; \quad H_{-1} = \frac{A_{\parallel} - A_{\perp}}{\sqrt{2}} \quad (7.17)$$

and the angles by

$$\begin{aligned} \cos(\theta_H) &= \sin(\theta) \cdot \cos(\phi) \\ \cos(\chi) \cdot \sin(\theta_H) &= \sin(\theta) \cdot \sin(\phi) \\ \sin(\chi) \cdot \sin(\theta_H) &= \cos(\theta) \end{aligned} \quad (7.18)$$

Partial Wave Decomposition

The angular analysis can be also described in terms of the S-, P- and D-wave amplitudes related to the orbital angular momentum between the J/ψ and ϕ [124], linked to the transversity amplitudes by:

$$S = \frac{1}{\sqrt{3}}(\sqrt{2}A_{\parallel} - A_0) \quad ; \quad P = A_{\perp} \quad ; \quad D = \frac{1}{\sqrt{3}}(A_{\parallel} + \sqrt{2}A_0) \quad (7.19)$$

Calculation for the Transversity and Helicity Angles

Each decay is evaluated in the rest frame of the mother particle, where the helicity or transversity angles are evaluated. As the four-vector components are given in the reference system where the B_s^0 is moving, they have to be boosted. A first boost is performed to the rest frame of the B_s^0 meson. A second boost brings the four-vectors to the rest frames of the appropriate J/ψ and ϕ mother particles². The angle calculation is performed with the help of the momentum vectors of the different particles.

²This procedure is not the equivalent to boosting directly the four-vectors in the J/ψ and ϕ mother rest frame [125].

7.1.4 Derivation of the Time Evolution Equations

The derivation of the time dependence explained here follows from [126]. The neutral $B_s^0 \sim \bar{b}s$ and $\bar{B}_s^0 \sim b\bar{s}$ mesons have definite flavors ($|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ *flavor eigenstates*) with corresponding quantum numbers F given in Table 7.1. The $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ states are also eigenstates of the strong and electromagnetic interactions. However, since flavor is not conserved in the weak interaction, mixing between B_s^0 and $\bar{B}_s^0$ mesons can occur (Figure 7.4).

Table 7.1: Flavor quantum numbers corresponding to B_s^0 and $\bar{B}_s^0$ mesons.

	Flavor Quantum Numbers F		
	Beauty B	Strangeness S	Charm C
B_s^0	1	-1	0
$\bar{B}_s^0$	-1	1	0

Due to $B_s^0 - \bar{B}_s^0$ mixing, let's consider a state $|\psi(t)\rangle$, which is initially a superposition of the flavor eigenstates $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$:

$$|\psi(0)\rangle = a(0)|B_s^0\rangle + b(0)|\bar{B}_s^0\rangle \quad (7.20)$$

At $t = 0$ s, the relative strength between the different forces of nature suggest that only the strong and electromagnetic interactions act between the flavor eigenstates. When evolving with time, $|\psi(t)\rangle$ additionally acquires components for possible decay final states $\{|f_1\rangle, |f_2\rangle, |f_3\rangle, \dots\}$ due to weak interactions:

$$|\psi(t)\rangle = a(t)|B_s^0\rangle + b(t)|\bar{B}_s^0\rangle + \underbrace{c_1(t)|f_1\rangle + c_2(t)|f_2\rangle + c_3(t)|f_3\rangle + \dots}_{\sum_k c_k(t)|f_k\rangle} \quad (7.21)$$

The time evolution of the state $|\psi(t)\rangle$ is described by the *Schrödinger equation*

$$i \frac{\partial}{\partial t} |\psi(t)\rangle = \left(\underbrace{H_s + H_w + H_{em}}_{H_{tot}} \right) |\psi(t)\rangle \quad (7.22)$$

where H_{tot} is the total Hamiltonian including the effects of all the present interactions: H_s for the strong, H_w for the weak and H_{em} for the electromagnetic interactions. Assuming that the total Hamiltonian is Hermitian, hence $H_{tot} = H_{tot}^\dagger$, it follows that:

$$|a(t)|^2 + |b(t)|^2 + \sum_k |c_k(t)|^2 = 1 \quad (7.23)$$

Equation 7.22 can now be solved using the following initial conditions at $t = 0$ s:

$$|a(0)|^2 + |b(0)|^2 = 1 \quad c_k(0) = 0, \forall k \quad (7.24)$$

The *Dirac representation* $|\psi(t)\rangle_D$ is introduced, as it allows the isolation of the H_w contribution of interest from the H_s and H_{em} ones. $|\psi(t)\rangle_D$ is related to the Schrödinger representation $|\psi(t)\rangle$ by:

$$|\psi(t)\rangle = e^{-i(H_s + H_{em})t} |\psi(t)\rangle_D \quad (7.25)$$

and the Schrödinger Equation 7.22 consequently becomes:

$$i \frac{\partial}{\partial t} |\psi(t)\rangle_D = \underbrace{e^{i(H_s + H_{em})t} H_w e^{-i(H_s + H_{em})t}}_{V(t)} |\psi(t)\rangle_D \quad (7.26)$$

with $V(t)$ the new time-dependent Hamiltonian. $|\psi(t)\rangle_D$ can be re-expressed using Equation 7.21 and by introducing the operators $\hat{a}(t)$, $\hat{b}(t)$ and $\hat{c}_k(t)$:

$$|\psi(t)\rangle_D = \underbrace{e^{i(H_s + H_{em})t} a(t)}_{\hat{a}(t)} |B_s^0\rangle + \underbrace{e^{i(H_s + H_{em})t} b(t)}_{\hat{b}(t)} |\bar{B}_s^0\rangle + \sum_k \underbrace{e^{i(H_s + H_{em})t} c_k(t)}_{\hat{c}_k(t)} |f_k\rangle \quad (7.27)$$

Inserting Equation 7.27 into Equation 7.26 leads to:

$$i \frac{\partial}{\partial t} \hat{a}(t) |B_s^0\rangle + i \frac{\partial}{\partial t} \hat{b}(t) |\bar{B}_s^0\rangle + \sum_f i \frac{\partial}{\partial t} \hat{c}_f(t) |f\rangle = V(t) \hat{a}(t) |B_s^0\rangle + V(t) \hat{b}(t) |\bar{B}_s^0\rangle + \sum_k V(t) \hat{c}_k(t) |f_k\rangle \quad (7.28)$$

Operating Equation 7.28 on the left with the $\langle B_s^0|$, $\langle \bar{B}_s^0|$ and $\langle f|$ states gives

$$i \frac{\partial}{\partial t} \hat{a}(t) = \langle B_s^0 | H_w | B_s^0 \rangle \hat{a}(t) + \langle B_s^0 | H_w | \bar{B}_s^0 \rangle \hat{b}(t) + \sum_k e^{i(M_{B_s} - E_k)t} \langle B_s^0 | H_w | f_k \rangle \hat{c}_k(t) \quad (7.29)$$

$$i \frac{\partial}{\partial t} \hat{b}(t) = \langle \bar{B}_s^0 | H_w | B_s^0 \rangle \hat{a}(t) + \langle \bar{B}_s^0 | H_w | \bar{B}_s^0 \rangle \hat{b}(t) + \sum_k e^{i(M_{B_s} - E_k)t} \langle \bar{B}_s^0 | H_w | f_k \rangle \hat{c}_k(t) \quad (7.30)$$

$$i \frac{\partial}{\partial t} \hat{c}_k(t) = e^{i(E_k - M_{B_s})t} \langle f_k | H_w | B_s^0 \rangle \hat{a}(t) + e^{i(E_k - M_{B_s})t} \langle f_k | H_w | \bar{B}_s^0 \rangle \hat{b}(t) + \sum_{k'} e^{i(E_k - E_{k'})t} \langle f_k | H_w | f_{k'} \rangle \hat{c}_{k'}(t) \quad (7.31)$$

using the fact that $|B_s^0\rangle$, $|\bar{B}_s^0\rangle$ and $|f_k\rangle$ are eigenstates of $(H_s + H_{em})$. E_k is the energy of the final state f_k . M_{B_s} is the mass of the B_s^0 or $\bar{B}_s^0$ meson, which are the same under CPT invariance of the strong and electromagnetic interactions.

The computation of the exact solution for the time evolution is quite complicated due to the numerous terms contained in Equation 7.28. However, it can be simplified when taking into consideration the *Weisskopf-Wigner approach* [127]. In this approach, the weak interaction between the different final states f_k , $\langle f_k | H_w | f_{k'} \rangle$, is neglected. Therefore, the integral over the time of Equation 7.31, $\hat{c}_k(t)$, only depends on $\hat{a}(t)$ and $\hat{b}(t)$, where the terms of second order in H_w have been neglected and the initial conditions of Equation 7.24 were used:

$$\hat{c}_k(t) = \lim_{\varepsilon \rightarrow +0} \frac{e^{i(E_k - M_{B_s})t}}{M_{B_s} - E_k + i\varepsilon} \left(\langle f_k | H_w | B_s^0 \rangle \hat{a}(t) + \langle f_k | H_w | \bar{B}_s^0 \rangle \hat{b}(t) \right) \quad (7.32)$$

The small imaginary part $i\varepsilon$ indicates the way to go around the pole at $E_k = M_{B_s}$. Equation 7.32 can be introduced in Equations 7.29 and 7.30 to eliminate $\hat{c}_k(t)$. The development is done for $i \frac{\partial}{\partial t} \hat{a}(t)$ in Equation 7.34 with the help the following relation given in terms of the Dirac distribution $\delta(x)$ and the Cauchy principal value $\mathcal{P}$:

$$\lim_{\varepsilon \rightarrow +0} \frac{1}{x + i\varepsilon} = \mathcal{P} \left(\frac{1}{x} \right) - i\pi \delta(x) \quad (7.33)$$

$$\begin{aligned}
i \frac{\partial}{\partial t} \hat{a}(t) &= \langle B_s^0 | H_w | B_s^0 \rangle \hat{a}(t) + \langle B_s^0 | H_w | \bar{B}_s^0 \rangle \hat{b}(t) \\
&+ \mathcal{P} \left(\sum_k \frac{\langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | B_s^0 \rangle \hat{a}(t) + \langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | \bar{B}_s^0 \rangle \hat{b}(t)}{M_{B_s} - E_k} \right) \\
&- i\pi \sum_k \left(\langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | B_s^0 \rangle \hat{a}(t) + \langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | \bar{B}_s^0 \rangle \hat{b}(t) \right) \delta(M_{B_s} - E_k) \\
&= \left[\langle B_s^0 | H_w | B_s^0 \rangle + \sum_k \mathcal{P} \left(\frac{\langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | B_s^0 \rangle}{M_{B_s} - E_k} \right) - i\pi \sum_k \langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | B_s^0 \rangle \delta(M_{B_s} - E_k) \right] \hat{a}(t) \\
&+ \left[\langle B_s^0 | H_w | \bar{B}_s^0 \rangle + \sum_k \mathcal{P} \left(\frac{\langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | \bar{B}_s^0 \rangle}{M_{B_s} - E_k} \right) - i\pi \sum_k \langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | \bar{B}_s^0 \rangle \delta(M_{B_s} - E_k) \right] \hat{b}(t)
\end{aligned} \tag{7.34}$$

A similar development can be done for $i \frac{\partial}{\partial t} \hat{b}(t)$. The $\hat{a}(t)$ and $\hat{b}(t)$ operators are then replaced by the coefficients $a(t)$ and $b(t)$ using the definitions introduced in Equation 7.27. The original Schrödinger equation is reduced to :

$$i \frac{\partial}{\partial t} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \Lambda \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \tag{7.35}$$

The complex matrix Λ can be expressed as the sum of a Hermitian and an anti-Hermitian part (with $|1\rangle = |B_s^0\rangle$ and $|2\rangle = |\bar{B}_s^0\rangle$):

$$\Lambda = M - i \frac{\Gamma}{2} = \begin{pmatrix} M_{11} - i\Gamma_{11}/2 & M_{12} - i\Gamma_{12}/2 \\ M_{21} - i\Gamma_{21}/2 & M_{22} - i\Gamma_{22}/2 \end{pmatrix} \tag{7.36}$$

The 2×2 M and Γ matrices are Hermitian, hence $M = M^\dagger$ and $\Gamma = \Gamma^\dagger$, and are respectively referred to as the *Mass* and *Decay matrices*. The effective potential Λ is no longer Hermitian ($\Lambda^\dagger \neq \Lambda$), as a consequence of the Weisskopf-Wigner approximation.

The diagonal terms of M and Γ are responsible for the flavor-conserving transitions $B_s^0 \rightarrow B_s^0$ and $\bar{B}_s^0 \rightarrow \bar{B}_s^0$. They are given by:

$$M_{11} = M_{B_s} + \langle B_s^0 | H_w | B_s^0 \rangle + \sum_k \mathcal{P} \left(\frac{\langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | B_s^0 \rangle}{M_{B_s} - E_k} \right) \tag{7.37}$$

$$M_{22} = M_{B_s} + \langle \bar{B}_s^0 | H_w | \bar{B}_s^0 \rangle + \sum_k \mathcal{P} \left(\frac{\langle \bar{B}_s^0 | H_w | f_k \rangle \langle f_k | H_w | \bar{B}_s^0 \rangle}{M_{B_s} - E_k} \right) \tag{7.38}$$

$$\Gamma_{11} = 2\pi \sum_k |\langle B_s^0 | H_w | f_k \rangle|^2 \delta(M_{B_s} - E_k) \tag{7.39}$$

$$\Gamma_{22} = 2\pi \sum_k |\langle \bar{B}_s^0 | H_w | f_k \rangle|^2 \delta(M_{B_s} - E_k) \tag{7.40}$$

The possible decays states f_k in M_{11} and M_{22} include all the virtual and real B_s^0 or $\bar{B}_s^0$ decay states. This is not the case for Γ_{11} and Γ_{22} , where physical (real) states only are possible due to the delta distribution $\delta(M_{B_s} - E_k)$ ensuring energy conservation. M_{11} and Γ_{11} represent the mass and width of the B_s^0 meson, while M_{22} and Γ_{22} are the corresponding values for $\bar{B}_s^0$ meson. As Λ is symmetric under

the CPT operator, B_s^0 mesons and their $\bar{B}_s^0$ antiparticles are enforced to have the same mass and width, hence $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$.

The off-diagonal terms are associated with flavor-changing transitions $B_s^0 \leftrightarrow \bar{B}_s^0$, via off-shell intermediate states through M_{12} (dispersive part of Λ_{12}) or via on-shell intermediate states through $0.5 \cdot \Gamma_{12}$ (absorptive part of Λ_{12}).

$$M_{12} = \langle B_s^0 | H_w | \bar{B}_s^0 \rangle + \sum_k \mathcal{P} \left(\frac{\langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | \bar{B}_s^0 \rangle}{M_{B_s} - E_k} \right) \quad (7.41)$$

$$\Gamma_{12} = 2\pi \sum_k \langle B_s^0 | H_w | f_k \rangle \langle f_k | H_w | \bar{B}_s^0 \rangle \delta(M_{B_s} - E_k) \quad (7.42)$$

In Equations 7.41 and 7.42, the sums are taken over the final states f_k common to B_s^0 and $\bar{B}_s^0$. They can be virtual or real for M_{12} , while they have to be real for Γ_{12} due to the delta distribution $\delta(M_{B_s} - E_k)$ ensuring energy conservation.

The Lambda matrix of Equation 7.36 can be rewritten as

$$\Lambda = \begin{pmatrix} \Lambda & \Lambda_{12} \\ \Lambda_{21} & \Lambda \end{pmatrix} \quad \text{with :} \quad \Lambda = M - i\frac{\Gamma}{2}, \quad \Lambda_{12} = M_{12} - i\frac{\Gamma_{12}}{2} \quad \text{and} \quad \Lambda_{21} = M_{12}^* - i\frac{\Gamma_{12}^*}{2} \quad (7.43)$$

and Equation 7.35 as

$$i \frac{\partial a(t)}{\partial t} = \Lambda a(t) + \Lambda_{12} b(t) \quad (7.44)$$

$$i \frac{\partial b(t)}{\partial t} = \Lambda_{21} a(t) + \Lambda b(t) \quad (7.45)$$

Differentiating Equation 7.44 with respect to t

$$i \frac{\partial^2 a(t)}{\partial t^2} = \Lambda \frac{\partial a(t)}{\partial t} + \Lambda_{12} \frac{\partial b(t)}{\partial t} \quad (7.46)$$

and inserting Equation 7.45 by replacing the $b(t)$ term using Equation 7.44 gives :

$$\frac{\partial^2 a(t)}{\partial t^2} + 2i\Lambda \frac{\partial a(t)}{\partial t} + (\Lambda_{12}\Lambda_{21} - \Lambda^2)a(t) = 0 \quad (7.47)$$

The general solution of the differential Equation 7.47 is of the form

$$a(t) = C_+ e^{-i\lambda_+ t} + C_- e^{-i\lambda_- t} \quad (7.48)$$

with $C_{\pm}$ arbitrary constants. Inserting Equation 7.48 into 7.47 leads to the eigenvalues :

$$\lambda_{\pm}^2 - 2\Lambda\lambda_{\pm} - (\Lambda_{12}\Lambda_{21} - \Lambda^2) = 0 \quad \rightarrow \quad \lambda_{\pm} = \Lambda \pm \sqrt{\Lambda_{12}\Lambda_{21}} = m_{\pm} - \frac{i}{2}\Gamma_{\pm} \quad (7.49)$$

with

$$m_{\pm} = \Re(\lambda_{\pm}) = M \pm \Re(\Lambda_{12}\Lambda_{21})^{1/2} \quad (7.50)$$

and

$$\Gamma_{\pm} = -2\Im(\lambda_{\pm}) = \Gamma \mp 2\Im(\Lambda_{12}\Lambda_{21})^{1/2} \quad (7.51)$$

The $C_{\pm}$ arbitrary constants of Equation 7.48 are defined by the initial condition. For an initially $|B_s^0\rangle$ state, $a(t) = 1$ and $b(t) = 0$, leading to $C_+ = C_- = 1/2$. Knowing $a(t)$, $b(t)$ can be derived using Equation 7.44. If only $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ are considered, the solution of Equation 7.22 becomes

$$|B_s^0(t)\rangle = a(t)|B_s^0\rangle + b(t)|\bar{B}_s^0\rangle = g_+(t)|B_s^0\rangle + \zeta g_-(t)|\bar{B}_s^0\rangle \quad (7.52)$$

where

$$g_{\pm}(t) = \frac{1}{2} \left(e^{-i\lambda_+ t} \pm e^{-i\lambda_- t} \right) \quad \text{and} \quad \zeta = \sqrt{\frac{\Lambda_{21}}{\Lambda_{12}}} \quad (7.53)$$

For an initially pure $|\bar{B}_s^0\rangle$ state, the time evolution is described by :

$$|\bar{B}_s^0(t)\rangle = \frac{1}{\zeta} g_-(t)|B_s^0\rangle + g_+(t)|\bar{B}_s^0\rangle \quad (7.54)$$

The eigenstates of Λ , $|B_+\rangle$ and $|B_-\rangle$,

$$\Lambda |B_{\pm}\rangle = \lambda_{\pm} |B_{\pm}\rangle \quad (7.55)$$

corresponding to the eigenvalues λ_+ and λ_- respectively are given by

$$|B_{\pm}\rangle = \frac{1}{\sqrt{1+|\zeta|^2}} \left(|B_s^0\rangle \pm \zeta |\bar{B}_s^0\rangle \right) \quad (7.56)$$

The complex number q/p is introduced as :

$$\frac{q}{p} = e^{in\pi} \zeta = e^{in\pi} \sqrt{\frac{\Lambda_{21}}{\Lambda_{12}}} \quad (7.57)$$

where $n = \{0, 1\}$ parameterizes the sign of the square-root operation of the complex number. The p and q complex coefficients satisfy the normalization condition:

$$|p|^2 + |q|^2 = 1 \quad (7.58)$$

The physical eigenstates of the Λ Hamiltonian are defined as the light $|B_L\rangle$ and heavy $|B_H\rangle$ states of masses and widths (M_L, Γ_L) and (M_H, Γ_H) respectively. Using Equations 7.56-7.57, they are given by

$$|B_L\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle \quad (7.59)$$

$$|B_H\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle \quad (7.60)$$

The eigenvalues of $|B_L\rangle$ and $|B_H\rangle$ are computed using Equations 7.49-7.51

$$\begin{aligned} \lambda_{H,L} &= (M_{B_s} - \frac{i}{2}\Gamma_s) \pm \sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)} \\ &= (M_{B_s} \pm \frac{\Delta m_s}{2}) - \frac{i}{2}(\Gamma_s \mp \frac{\Delta\Gamma_s}{2}) \\ &= M_{H,L} - \frac{i}{2}\Gamma_{H,L} \end{aligned} \quad (7.61)$$

by introducing $M_{B_s} = 0.5 \cdot (M_H + M_L) = M_{11} = M_{22}$, $\Gamma_s = 0.5 \cdot (\Gamma_L + \Gamma_H) = \Gamma_{11} = \Gamma_{22}$, $\Delta m_s = M_H - M_L$ and $\Delta \Gamma_s = \Gamma_L - \Gamma_H$. By definition, $\Delta \Gamma_s > 0$.

The time evolutions of initial $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ states of Equations 7.52 and 7.54 become [128]

$$|B_s^0(t)\rangle = g_+(t)|B_s^0\rangle + \frac{q}{p}g_-(t)|\bar{B}_s^0\rangle \quad (7.62)$$

$$|\bar{B}_s^0(t)\rangle = \frac{p}{q}g_-(t)|B_s^0\rangle + g_+(t)|\bar{B}_s^0\rangle \quad (7.63)$$

with the Equation corresponding to Equation 7.53:

$$g_{\pm}(t) = \frac{1}{2} \left(e^{-i(M_L - i\Gamma_L/2)t} \pm e^{-i(M_H - i\Gamma_H/2)t} \right) \quad (7.64)$$

Equation 7.64 can be rewritten in terms of M_{B_s} , Γ_s , Δm_s and $\Delta \Gamma_s$ as

$$g_{\pm}(t) = e^{-iM_{B_s}t} e^{-\Gamma_s t/2} \left[\frac{1}{2} \left(e^{-\frac{\Delta \Gamma_s}{4}t} e^{+i\frac{\Delta m_s}{2}t} \pm e^{+\frac{\Delta \Gamma_s}{4}t} e^{-i\frac{\Delta m_s}{2}t} \right) \right] \quad (7.65)$$

or

$$g_+(t) = e^{-iM_{B_s}t} e^{-\Gamma_s t/2} \left[+\cosh\left(\frac{\Delta \Gamma_s t}{4}\right) \cos\left(\frac{\Delta m_s t}{2}\right) - i \cdot \sinh\left(\frac{\Delta \Gamma_s t}{4}\right) \sin\left(\frac{\Delta m_s t}{2}\right) \right] \quad (7.66)$$

$$g_-(t) = e^{-iM_{B_s}t} e^{-\Gamma_s t/2} \left[-\sinh\left(\frac{\Delta \Gamma_s t}{4}\right) \cos\left(\frac{\Delta m_s t}{2}\right) + i \cdot \cosh\left(\frac{\Delta \Gamma_s t}{4}\right) \sin\left(\frac{\Delta m_s t}{2}\right) \right] \quad (7.67)$$

with the following properties

$$g_{\pm}(t)g_{\pm}^*(t) = \frac{e^{-\Gamma_s t}}{2} \left[\pm \cos(\Delta m_s t) + \cosh\left(\frac{\Delta \Gamma_s t}{2}\right) \right] \quad (7.68)$$

$$g_+^*(t)g_-(t) = \frac{e^{-\Gamma_s t}}{2} \left[+i \sin(\Delta m_s t) - \sinh\left(\frac{\Delta \Gamma_s t}{2}\right) \right] \quad (7.69)$$

$$g_-^*(t)g_+(t) = \frac{e^{-\Gamma_s t}}{2} \left[-i \sin(\Delta m_s t) - \sinh\left(\frac{\Delta \Gamma_s t}{2}\right) \right] \quad (7.70)$$

The light and heavy mass eigenstates have exponential evolution laws with well defined mass and decay widths :

$$\begin{aligned} |B_L(t)\rangle &= e^{-i\lambda_L t} |B_L\rangle = e^{-i(M_L - i\Gamma_L/2)t} (p |B_s^0\rangle + q |\bar{B}_s^0\rangle) \\ |B_H(t)\rangle &= e^{-i\lambda_H t} |B_H\rangle = e^{-i(M_H - i\Gamma_H/2)t} (p |B_s^0\rangle - q |\bar{B}_s^0\rangle) \end{aligned} \quad (7.71)$$

Assuming that the initial state was a B_s^0 meson, the probabilities for finding a B_s^0 or $\bar{B}_s^0$ at a time t is given by:

$$|\langle B_s^0 | B_s^0(t) \rangle|^2 = |g_+(t)|^2 \quad (7.72)$$

$$|\langle \bar{B}_s^0 | B_s^0(t) \rangle|^2 = |g_-(t)|^2 \left| \frac{q}{p} \right|^2 \quad (7.73)$$

Similar relations are found for an initial $\bar{B}_s^0$

$$|\langle B_s^0 | \bar{B}_s^0(t) \rangle|^2 = |g_-(t)|^2 \left| \frac{p}{q} \right|^2 \quad (7.74)$$

$$|\langle \bar{B}_s^0 | \bar{B}_s^0(t) \rangle|^2 = |g_+(t)|^2 \quad (7.75)$$

In the transversity basis introduced in Subsection 7.1.3, a B_s^0 meson can decay into three possible polarization final states f_λ , with $\lambda = \{0, ||\}$ for CP-even and $\lambda = \{\perp\}$ for CP-odd. Using Equations 7.62-7.63, the amplitudes for the B_s^0 and $\bar{B}_s^0$ mesons decaying into the same final state f_λ at a time t equal to, with H_{eff} an effective operator of the weak interaction:

$$A_\lambda(B_s^0(t) \rightarrow f_\lambda) = \langle f_\lambda | H_{\text{eff}}^\dagger | B_s^0(t) \rangle = g_+(t) A_\lambda + \frac{q}{p} g_-(t) \bar{A}_\lambda = A_\lambda \left(g_+(t) + \frac{q}{p} \frac{\bar{A}_\lambda}{A_\lambda} g_-(t) \right) \quad (7.76)$$

$$\bar{A}_\lambda(\bar{B}_s^0(t) \rightarrow f_\lambda) = \langle f_\lambda | H_{\text{eff}} | \bar{B}_s^0(t) \rangle = g_+(t) \bar{A}_\lambda + \frac{p}{q} g_-(t) A_\lambda = \bar{A}_\lambda \left(g_+(t) + \frac{p}{q} \frac{A_\lambda}{\bar{A}_\lambda} g_-(t) \right) \quad (7.77)$$

CP violation can arise in three different places: in decay, in mixing and in the interference between decay and mixing. The latter is called *mixing-induced CP violation*. The amount of CP violation coming from these three types are quantified by the following terms:

- $\bar{A}_\lambda/A_\lambda$ quantifies the CP violation in decay. CP violation is present if $|\bar{A}_\lambda/A_\lambda| \neq 1$.
- q/p quantifies the CP violation in mixing. CP violation is present if $|q/p| \neq 1$.
- $\phi_s^{J/\psi\phi}$ quantifies the mixing-induced CP violation. CP violation is present if $\phi_s^{J/\psi\phi} \neq 0$.

In the following, it is assumed that $\bar{f} = f$ and that there is no CP violation in the decay nor in the mixing. The $\bar{A}_\lambda/A_\lambda$ and q/p terms are discussed. They will lead to the definition of the weak phase $\phi_s^{J/\psi\phi}$, which is the parameter of interest to be measured in this analysis.

The $\bar{A}_\lambda/A_\lambda$ Term

As A_λ is complex, it can be expressed as a function of its module and argument, with the argument corresponding to the sum of a CP conserving strong interaction phase of the final state δ_λ and a CP violating weak phase Φ_λ :

$$A_\lambda = \langle f_\lambda | H_{\text{eff}}^\dagger | B_s^0 \rangle \cdot e^{i(\delta_\lambda - \Phi_\lambda)} = |A_\lambda| \cdot e^{i(\delta_\lambda - \Phi_\lambda)} \quad (7.78)$$

To compute $\bar{A}_\lambda = \langle f_\lambda | H_{\text{eff}} | \bar{B}_s^0 \rangle \cdot e^{i(\delta_\lambda + \Phi_\lambda)}$, the CP symmetry relations for the initial $|B_s^0\rangle$, $|\bar{B}_s^0\rangle$ states

$$\text{CP} |B_s^0\rangle = e^{+i\xi} |\bar{B}_s^0\rangle \quad (7.79)$$

$$\text{CP} |\bar{B}_s^0\rangle = e^{-i\xi} |B_s^0\rangle \quad (7.80)$$

and for the final $|f_\lambda\rangle$ states

$$\text{CP} |f_\lambda\rangle = e^{+i\rho} |\bar{f}_\lambda\rangle \quad (7.81)$$

are needed, with ξ and ρ arbitrary phases. If $|f_\lambda\rangle$ is a CP-eigenstate, then

$$\text{CP} |f_\lambda\rangle = \eta_{\text{CP}}(f_\lambda) |f_\lambda\rangle \quad (7.82)$$

with $\eta_{\text{CP}}(f_\lambda)$ the CP-eigenvalue of the final state f_λ .

The calculation of $\bar{A}_\lambda$ gives (with $\bar{f} = f$ and $\lambda = \{0, ||, \perp\}$):

$$\begin{aligned}\bar{A}_\lambda &= \langle f_\lambda | H_{\text{eff}} | \bar{B}_s^0 \rangle \cdot e^{i(\delta_\lambda + \Phi_\lambda)} = \langle f_\lambda | (CP)^\dagger (CP) H_{\text{eff}} (CP)^\dagger (CP) | \bar{B}_s^0 \rangle \cdot e^{i(\delta_\lambda + \Phi_\lambda)} \\ &= \eta_{CP}(f_\lambda) e^{-i\xi} \cdot \langle f_\lambda | (CP) H_{\text{eff}} (CP)^\dagger | B_s^0 \rangle \cdot e^{i(\delta_\lambda + \Phi_\lambda)} \\ &= \eta_{CP}(f_\lambda) e^{-i\xi} \cdot |A_\lambda| \cdot e^{i(\delta_\lambda + \Phi_\lambda)}\end{aligned}\quad (7.83)$$

The $\bar{b} \rightarrow \bar{c}c\bar{s}$ decay amplitude of Figure 7.3 has tree (A_T), electroweak and QCD penguin amplitudes ($A_{P,\{u,c,t\}}$):

$$A(\bar{b} \rightarrow \bar{c}c\bar{s}) = V_{cs} V_{cb}^* (A_T + A_{P,c}) + V_{us} V_{ub}^* A_{P,u} + V_{ts} V_{tb}^* A_{P,t} \quad (7.84)$$

Using the unitarity condition of the (sb) triangle given in Equation 7.11, the decay amplitude is re-expressed as:

$$\begin{aligned}A(\bar{b} \rightarrow \bar{c}c\bar{s}) &= V_{cs} V_{cb}^* (A_T + A_{P,c} - A_{P,t}) + V_{us} V_{ub}^* (A_{P,u} - A_{P,t}) \\ \text{with: } V_{cs} V_{cb}^* &\sim A \lambda^2 (1 - \lambda^2/2) \\ \text{and : } V_{us} V_{ub}^* &\sim A \lambda^4 (\rho - i\eta)\end{aligned}\quad (7.85)$$

The contribution of the ($A_{P,u} - A_{P,t}$) terms is suppressed with respect to the one of ($A_T + A_{P,c} - A_{P,t}$) by a factor $\sim \lambda^2 \simeq 0.05$, leading to a single weak phase Φ_D for the $B_s^0 \rightarrow J/\psi \phi$ decay³:

$$\Phi_D = \arg(V_{cs} V_{cb}^*) \quad (7.86)$$

Using this relation, Equations 7.78 and 7.83 are rewritten as:

$$A_\lambda = |A_\lambda| \cdot e^{i(\delta_\lambda - \Phi_D)} \quad ; \quad \bar{A}_\lambda = \eta_{CP}(f_\lambda) e^{-i\xi} \cdot |A_\lambda| \cdot e^{i(\delta_\lambda + \Phi_D)} \quad (7.87)$$

The $\bar{A}_\lambda/A_\lambda$ is hence equal to:

$$\frac{\bar{A}_\lambda}{A_\lambda} = \eta_{CP}(f_\lambda) e^{i(2\Phi_D - \xi)} \quad (7.88)$$

The q/p Term

In the Standard Model, the $B_s^0 - \bar{B}_s^0$ mixing is characterized by a mixing phase Φ_M :

$$\Phi_M = 2 \cdot \arg(V_{ts} V_{tb}^*) \quad (7.89)$$

The q/p factor is related to the mixing phase Φ_M as:

$$\frac{q}{p} = e^{-i(\Phi_M - \xi)} \quad (7.90)$$

³The limits of this assumptions are taken into account in the theoretical uncertainty.

The $\phi_s^{J/\psi\phi}$ Term

Equations 7.88 and 7.90 are not observables, as they both depend on the arbitrary phase ξ . However, their product is independent on the phase convention. Therefore, a new phase $\phi_s^{J/\psi\phi}$ is introduced, which is the CP violating observable that will be measured:

$$\phi_s^{J/\psi\phi} = -\arg\left(\frac{\bar{A}_\lambda}{A_\lambda} \cdot \frac{q}{p}\right) = \Phi_M - 2\Phi_D \quad (7.91)$$

Decay Rate Calculation in the Transversity Basis

The decay rate $\Gamma(B_s^0(t) \rightarrow f)$ of B_s^0 mesons into the final state f is obtained by calculating the modulus squared of Equation 7.76 for each possible combination of polarization states (λ_i, λ_j) using Equations 7.68-7.70:

$$\Gamma(B_s^0(t) \rightarrow f) = \sum_{\lambda_i, \lambda_j} A_{\lambda_i} A_{\lambda_j}^* \quad (7.92)$$

where the following components are obtained:

$$|A_{\{0, \parallel, \perp\}}(t)|^2 = |A_{\{0, \parallel, \perp\}}|^2 e^{-\Gamma_s t} \left[\cosh\left(\frac{\Delta\Gamma_s}{2} t\right) - \eta_{CP} \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s}{2} t\right) + \eta_{CP} \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.93)$$

$$A_{\parallel}(t) \cdot A_0^*(t) = |A_{\parallel}| |A_0| e^{-\Gamma_s t} e^{i(\delta_{\parallel} - \delta_0)} \left[\cosh\left(\frac{\Delta\Gamma_s}{2} t\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s}{2} t\right) + \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.94)$$

$$A_{\perp}(t) \cdot A_0^*(t) = |A_{\perp}| |A_0| e^{-\Gamma_s t} e^{i(\delta_{\perp} - \delta_0)} \left[\cos(\Delta m_s t) - i \sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s}{2} t\right) - i \cos(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.95)$$

$$A_{\perp}(t) \cdot A_{\parallel}^*(t) = |A_{\perp}| |A_{\parallel}| e^{-\Gamma_s t} e^{i(\delta_{\perp} - \delta_{\parallel})} \left[\cos(\Delta m_s t) - i \sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s}{2} t\right) - i \cos(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.96)$$

The three transversity amplitudes are not independent. They are related to each other by:

$$|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1 \quad (7.97)$$

The time-dependent quadratic and interfering amplitude terms relevant for the transversity basis (see Tables 7.1.5 and 7.1.5) are given in Equations 7.98-7.103 for B_s^0 mesons. They are obtained by inserting the proper η_{CP} values ($\eta_{CP} = +1$ for CP-even, $\eta_{CP} = -1$ for CP-odd) in Equation 7.93 and by calculating the real part of Equation 7.94 and the imaginary parts of Equations 7.95 and 7.96. By an allowed phase convention choice, the δ_0 strong phase is set to zero.

Similar calculations for $\bar{B}_s^0$ mesons starting from Equation 7.77 show that all the terms containing Δm_s change their sign (Equations 7.104-7.109). As can be seen from Equations 7.101-7.103 and 7.107-7.109, the strong phases are measured through interference terms only.

$$|A_0(t)|^2 = |A_0|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.98)$$

$$|A_{\parallel}(t)|^2 = |A_{\parallel}|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.99)$$

$$|A_{\perp}(t)|^2 = |A_{\perp}|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.100)$$

$$\begin{aligned} \Im\{A_{\parallel}^*(t)A_{\perp}(t)\} = & |A_{\parallel}||A_{\perp}|e^{-\Gamma_s t} \cdot \left[-\cos(\delta_{\perp} - \delta_{\parallel}) \sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right. \\ & \left. + \sin(\delta_{\perp} - \delta_{\parallel}) \cos(\Delta m_s t) - \cos(\delta_{\perp} - \delta_{\parallel}) \cos(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \end{aligned} \quad (7.101)$$

$$\Re\{A_0^*(t)A_{\parallel}(t)\} = |A_0||A_{\parallel}|e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \cdot \cos(\delta_{\parallel}) \quad (7.102)$$

$$\begin{aligned} \Im\{A_0^*(t)A_{\perp}(t)\} = & |A_0||A_{\perp}|e^{-\Gamma_s t} \cdot \left[-\cos(\delta_{\perp}) \sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right. \\ & \left. + \sin(\delta_{\perp}) \cos(\Delta m_s t) - \cos(\delta_{\perp}) \cos(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \end{aligned} \quad (7.103)$$

$$|\bar{A}_0(t)|^2 = |\bar{A}_0|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.104)$$

$$|\bar{A}_{\parallel}(t)|^2 = |\bar{A}_{\parallel}|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.105)$$

$$|\bar{A}_{\perp}(t)|^2 = |\bar{A}_{\perp}|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \quad (7.106)$$

$$\begin{aligned} \Im\{\bar{A}_{\parallel}^*(t)\bar{A}_{\perp}(t)\} = & |\bar{A}_{\parallel}||\bar{A}_{\perp}|e^{-\Gamma_s t} \cdot \left[-\cos(\delta_{\perp} - \delta_{\parallel}) \sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right. \\ & \left. - \sin(\delta_{\perp} - \delta_{\parallel}) \cos(\Delta m_s t) + \cos(\delta_{\perp} - \delta_{\parallel}) \cos(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \end{aligned} \quad (7.107)$$

$$\Re\{\bar{A}_0^*(t)\bar{A}_{\parallel}(t)\} = |\bar{A}_0||\bar{A}_{\parallel}|e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \cdot \cos(\delta_{\parallel}) \quad (7.108)$$

$$\begin{aligned} \Im\{\bar{A}_0^*(t)\bar{A}_{\perp}(t)\} = & |\bar{A}_0||\bar{A}_{\perp}|e^{-\Gamma_s t} \cdot \left[-\cos(\delta_{\perp}) \sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right. \\ & \left. - \sin(\delta_{\perp}) \cos(\Delta m_s t) + \cos(\delta_{\perp}) \cos(\phi_s^{J/\psi\phi}) \sin(\Delta m_s t) \right] \end{aligned} \quad (7.109)$$

The eight physics parameters to be determined in the analysis are summarized here

- The mass difference: $\Delta m_s = M_H - M_L$
- The width difference: $\Delta\Gamma_s = \Gamma_L - \Gamma_H$
- The B_s^0 meson lifetime τ_s or equivalently: $\Gamma_s = 1/\tau_s$
- The fraction of CP-odd component at $t = 0$ s: $|A_{\perp}|^2$
- The fraction of CP-even component at $t = 0$ s corresponding to $\ell = 0$: $|A_0|^2$
- The parallel CP conserving strong phase: $\delta_{\parallel} = \arg(A_{\parallel}A_0^*)$
- The perpendicular CP conserving strong phase: $\delta_{\perp} = \arg(A_{\perp}A_0^*)$
- The CP violating weak phase $\phi_s^{J/\psi\phi}$

Time-Integral of the Transversity Quadratic and Interfering Terms

The integrals over time of Equations 7.98-7.103 will be needed in the angular acceptance studies of Section 7.6. They are equal to:

$$\int_0^\infty |A_0(t)|^2 dt = |A_0|^2 \left[\frac{\Gamma_s}{\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4}} - \cos(\phi_s^{J/\psi\phi}) \frac{\Delta\Gamma_s}{2(\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4})} + \sin(\phi_s^{J/\psi\phi}) \frac{\Delta m_s}{\Gamma_s^2 + (\Delta m_s)^2} \right] \quad (7.110)$$

$$\int_0^\infty |A_{||}(t)|^2 dt = |A_{||}|^2 \left[\frac{\Gamma_s}{\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4}} - \cos(\phi_s^{J/\psi\phi}) \frac{\Delta\Gamma_s}{2(\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4})} + \sin(\phi_s^{J/\psi\phi}) \frac{\Delta m_s}{\Gamma_s^2 + (\Delta m_s)^2} \right] \quad (7.111)$$

$$\int_0^\infty |A_{\perp}(t)|^2 dt = |A_{\perp}|^2 \left[\frac{\Gamma_s}{\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4}} + \cos(\phi_s^{J/\psi\phi}) \frac{\Delta\Gamma_s}{2(\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4})} - \sin(\phi_s^{J/\psi\phi}) \frac{\Delta m_s}{\Gamma_s^2 + (\Delta m_s)^2} \right] \quad (7.112)$$

$$\begin{aligned} \int_0^\infty \Im\{A_{||}^*(t)A_{\perp}(t)\}dt &= |A_{||}||A_{\perp}| \left[-\cos(\delta_{\perp} - \delta_{||}) \sin(\phi_s^{J/\psi\phi}) \frac{\Delta\Gamma_s}{2(\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4})} \right. \\ &\quad \left. + \sin(\delta_{\perp} - \delta_{||}) \frac{\Gamma_s}{\Gamma_s^2 + (\Delta m_s)^2} - \cos(\delta_{\perp} - \delta_{||}) \cos(\phi_s^{J/\psi\phi}) \frac{\Delta m_s}{\Gamma_s^2 + (\Delta m_s)^2} \right] \end{aligned} \quad (7.113)$$

$$\int_0^\infty \Re\{A_0^*(t)A_{||}(t)\}dt = |A_0||A_{||}| \left[\frac{\Gamma_s}{\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4}} - \cos(\phi_s^{J/\psi\phi}) \frac{\Delta\Gamma_s}{2(\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4})} + \sin(\phi_s^{J/\psi\phi}) \frac{\Delta m_s}{\Gamma_s^2 + (\Delta m_s)^2} \right] \cdot \cos(\delta_{||}) \quad (7.114)$$

$$\begin{aligned} \int_0^\infty \Im\{A_0^*(t)A_{\perp}(t)\}dt &= |A_0||A_{\perp}| \left[-\cos(\delta_{\perp}) \sin(\phi_s^{J/\psi\phi}) \frac{\Delta\Gamma_s}{2(\Gamma_s^2 - \frac{(\Delta\Gamma_s)^2}{4})} \right. \\ &\quad \left. + \sin\delta_{\perp} \frac{\Gamma_s}{\Gamma_s^2 + (\Delta m_s)^2} - \cos(\delta_{\perp}) \cos(\phi_s^{J/\psi\phi}) \frac{\Delta m_s}{\Gamma_s^2 + (\Delta m_s)^2} \right] \end{aligned} \quad (7.115)$$

7.1.5 Derivation of the Angular Dependence

The angular dependence is first established in the helicity formalism for the $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay following the development of [129], where a pseudo-scalar B_s^0 meson decays into the two spin-1 particles, J/ψ and ϕ , with J/ψ decaying into two leptons ($\mu^+\mu^-$) and ϕ into two spin-zero particles (K^+K^-). The relations obtained are then expressed in the transversity formalism.

Let's introduce two right-handed coordinate systems, one at rest, xyz , and a moving one, XYZ , with the Z axis brought into an arbitrary direction $\vec{n}$. The rotated XYZ system can be described with respect to xyz by the angles $\vec{\Omega} = (\alpha, \beta, \gamma)$ of the 323 Euler representation [130], which are depicted in Figure 7.7.

A first rotation $\alpha(0 \leq \alpha \leq 2\pi)$ is performed about the z axis. It is followed by a rotation $\beta(0 \leq \beta \leq \pi)$ about the new location (y') of the y axis, and by a final rotation of angle $\gamma(0 \leq \gamma \leq 2\pi)$ about the final position (Z) of the z axis.

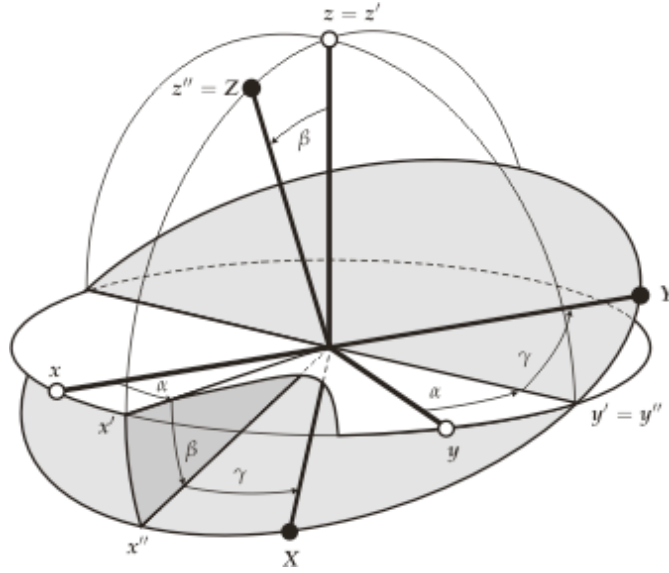


Figure 7.7: The position of the XYZ coordinate system rotated with respect to the xyz coordinate system at rest can be described by the Euler angles α , β and γ of the 323 Euler representation [131].

The α and β angles correspond to the spherical angles φ and θ of the new axis Z with respect to xyz :

$$\alpha = \varphi \quad ; \quad \beta = \theta \quad (7.116)$$

Let's suppose that the wave functions ψ_{jm} ($m = -j, \dots, j$) describe in the xyz coordinate system a state with a given value j of the total angular momentum. The index m corresponds to the projection of j on the quantization axis z , $m = j_z$. The same state is described in the XYZ coordinate system by the functions $\psi_{jm'}$, with m' the projection of j on the quantization axis Z . In quantum mechanics, the rotation of angles $\vec{\Omega} = \{\alpha, \beta, \gamma\}$ of ψ_{jm} is generated by the angular momentum vector operator $\vec{J}$ [132]:

$$\mathcal{R}(\vec{\Omega})\psi_{jm} = e^{-i\vec{\Omega} \cdot \vec{J}}\psi_{jm} \quad (7.117)$$

with $\mathcal{R}$ the rotation operator. The transformation from ψ_{jm} to $\psi_{jm'}$ under this rotation is described by the general matrix element of Equation 7.118, which defines the so-called *Wigner D-matrix* [130]:

$$D_{m'm}^j(\alpha, \beta, \gamma) = \langle jm' | \mathcal{R}(\alpha, \beta, \gamma) | jm \rangle \quad (7.118)$$

An important property of the Wigner D-matrix follows from the commutation of $\mathcal{R}(\alpha, \beta, \gamma)$ with the anti-unitary time reversal operator T ,

$$\langle jm' | \mathcal{R}(\alpha, \beta, \gamma) | jm \rangle = \langle jm' | T^\dagger \mathcal{R}(\alpha, \beta, \gamma) T | jm \rangle = (-1)^{m'-m} \langle j, -m' | \mathcal{R}(\alpha, \beta, \gamma) | j, -m \rangle^* \quad (7.119)$$

where the $T|jm\rangle = (-1)^{j-m}|j, -m\rangle$ and $(-1)^{2j-m'-m} = (-1)^{m'-m}$ properties have been used. The relation between the Wigner D-matrix and its charge conjugate can be re-written as:

$$D_{m'm}^j(\alpha, \beta, \gamma)^* = (-1)^{m'-m} D_{-m'-m}^j(\alpha, \beta, \gamma) \quad (7.120)$$

The direction of the quantization axis Z is described by the two spherical angles $\alpha = \varphi$ and $\beta = \theta$ (Figure 7.7). Hence, the γ angle can be arbitrarily chosen, a convenient choice being $\gamma = 0$.

D -matrix elements with the second index equal to zero can be related to spherical harmonic functions $\mathcal{Y}$ [129]:

$$D_{m,0}^\ell(\alpha, \beta, 0) = \sqrt{\frac{4\pi}{2\ell+1}} \mathcal{Y}_{\ell m}^*(\beta, \alpha) \quad (7.121)$$

with the following properties

$$\mathcal{Y}_{\ell,m}^* = (-1)^m \mathcal{Y}_{\ell,-m} \quad (7.122)$$

$$\int \mathcal{Y}_{\ell m}^*(\vec{\Omega}) \mathcal{Y}_{\ell' m'}(\vec{\Omega}) d\vec{\Omega} = \delta_{\ell\ell'} \delta_{mm'} \quad (7.123)$$

In the helicity formalism, the matrix element of the decay $|\mathcal{M}|^2$ is given by Equation 7.124 [129]. It depends on the total angular momenta of the daughter particles, $j_{J/\psi}$ and j_ϕ , on the time-dependent helicity amplitudes H_λ and on the Wigner D -matrix elements $D_{\lambda,\alpha}^{jP}(\phi_P, \theta_P, 0)$.

$$|\mathcal{M}|^2 = \sum_{\alpha=\pm 1} \left| \sum_{\lambda=0,\pm 1} \left(\frac{2j_{J/\psi}+1}{4\pi} \right)^{1/2} \left(\frac{2j_\phi+1}{4\pi} \right)^{1/2} H_\lambda D_{\lambda,\alpha}^{j_{J/\psi}*}(\vec{\Omega}_{J/\psi}) D_{\lambda,0}^{j_\phi*}(\vec{\Omega}_\phi) \right|^2 \quad (7.124)$$

The λ represents the helicity of the spin-1 particles $P = \{J/\psi, \phi\}$. In the B_s^0 meson rest frame, the daughter particles J/ψ and ϕ are moving in opposite directions with helicities $\lambda_{J/\psi}$ and λ_ϕ respectively. Along the J/ψ direction, the resulting total helicity is equal to $\lambda_{B_s^0} = \lambda_{J/\psi} - \lambda_\phi$. As B_s^0 is pseudoscalar, hence $\lambda_{B_s^0} = 0$, then $\lambda_{J/\psi}$ must equal to λ_ϕ . Due to the spin-1 nature of the J/ψ and ϕ , the three possible helicity states are $(\lambda_{J/\psi}, \lambda_\phi) = (+1, +1), (0, 0)$ or $(-1, -1)$ (Figure 7.8), whence the sum over $\lambda = 0, \pm 1$ with identical symbols used for the J/ψ and ϕ D -matrix elements of Equation 7.124. The three H_λ amplitudes are associated to each of these states, namely H_{+1} , H_0 and H_{-1} .

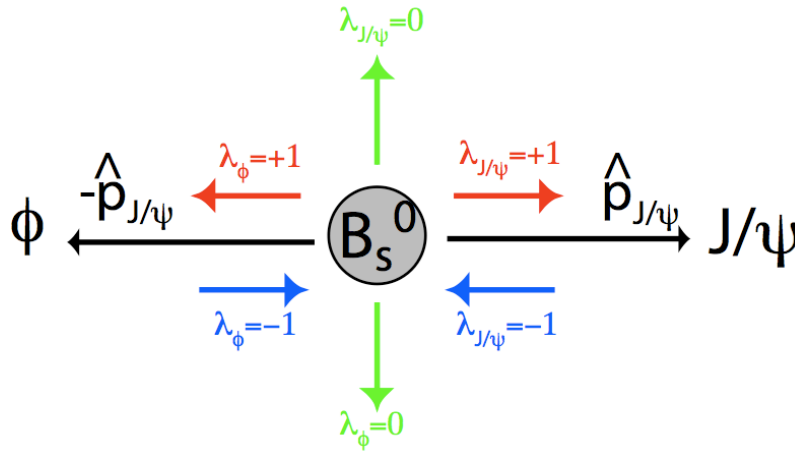


Figure 7.8: Three possible helicity states for the J/ψ and ϕ particles, $(\lambda_{J/\psi}, \lambda_\phi) = (+1, +1)$ (red), $(0, 0)$ (green) or $(-1, -1)$ (blue).

As J/ψ and ϕ further decay into two particles each, the helicities α of the final states have to be taken into account, which explains the sum over α of Equation 7.124. As $K^\pm$ particles are spinless particles, hence $\lambda_{K^+} = \lambda_{K^-} = 0$, the decay $\phi \rightarrow K^+ K^-$ has only one helicity $\alpha = 0$. This explains the term $\alpha = 0$ in the D -matrix element of the $\phi \rightarrow K^+ K^-$ decay. On the other hand, the final state of $J/\psi \rightarrow \mu^+ \mu^-$ can have two possible helicity states, since the $\mu^\pm$ are spin-1/2 particles. In the J/ψ rest frame, they are $(\lambda_{\mu^+}, \lambda_{\mu^-}) = (+\frac{1}{2}, -\frac{1}{2})$ or $(-\frac{1}{2}, +\frac{1}{2})$, which satisfy to the total angular momentum conservation (Figure 7.9). These two helicity states correspond to $\alpha = +1$ and $\alpha = -1$ respectively⁴. This explains the dependence on α of the D -matrix element for the $J/\psi \rightarrow \mu^+ \mu^-$ decay.

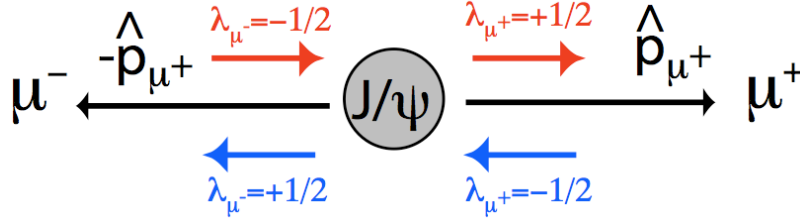


Figure 7.9: Two possible helicity states for the μ^+ and μ^- particles, $(\lambda_{\mu^+}, \lambda_{\mu^-}) = (+\frac{1}{2}, -\frac{1}{2})$ (red) or $(-\frac{1}{2}, +\frac{1}{2})$ (blue).

The angular dependences are defined by the polar and azimuthal angles of the positive final state particles μ^+ and K^+ inside the rest frame of their mothers, J/ψ and ϕ . They are given by $\vec{\Omega}_{J/\psi} = (\theta_H, \chi, 0)$ for the μ^+ and $\vec{\Omega}_\phi = (\psi, \varphi, 0)$ for the K^+ respectively (Figure 7.10).

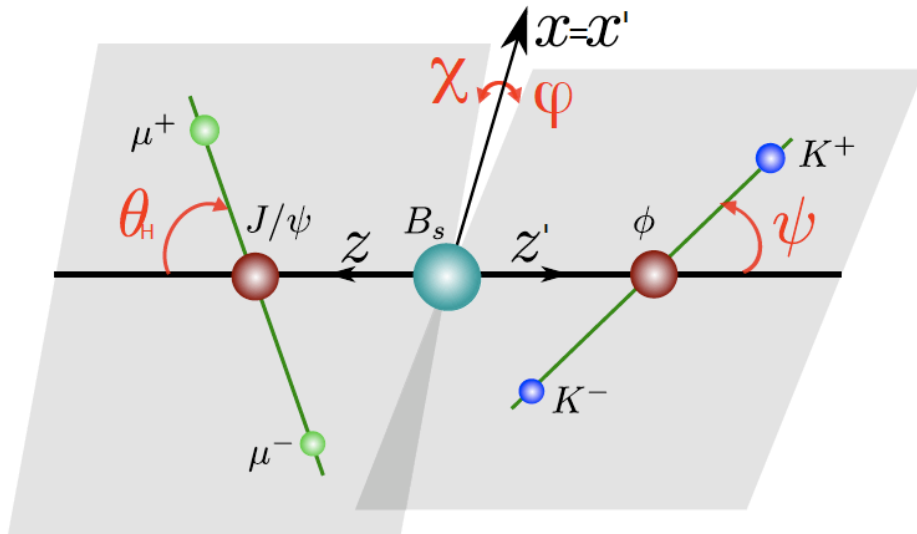


Figure 7.10: Decay product angles $\vec{\Omega}_{J/\psi} = \{\theta_H, \chi, 0\}$ and $\vec{\Omega}_\phi = \{\psi, \varphi, 0\}$ in the helicity basis. θ_H is the polar angle of the μ^+ in the J/ψ rest frame and ψ is the polar angle of the K^+ in the ϕ rest frame. χ is the azimuthal angle between the J/ψ decay plane and the x axis and φ the azimuthal angle between the ϕ decay plane and the x' axis ($x = x'$).

⁴In the J/ψ rest frame, the μ^+ is moving a direction $\hat{p}$ with helicity λ_{μ^+} and the μ^- is moving in the $-\hat{p}$ direction with helicity λ_{μ^-} . The total helicity is equal to $\alpha = \lambda_{\mu^+} - \lambda_{\mu^-}$.

Expanding and re-arranging Equation 7.124 results in [129]:

$$|\mathcal{M}|^2 = \left(\frac{2j_{J/\psi} + 1}{4\pi} \right) \left(\frac{2j_\phi + 1}{4\pi} \right) \sum_{\alpha=\pm 1} \sum_{\lambda, \lambda'=0, \pm 1} H_\lambda H_{\lambda'}^* D_{\lambda, \alpha}^{j_{J/\psi}*}(\vec{\Omega}_{J/\psi}) D_{\lambda', \alpha}^{j_{J/\psi}}(\vec{\Omega}_{J/\psi}) D_{\lambda, 0}^{j_\phi*}(\vec{\Omega}_\phi) D_{\lambda', 0}^{j_\phi}(\vec{\Omega}_\phi) \quad (7.125)$$

Using the D -matrix property of Equation 7.120 and inserting the double D summations

$$D_{m'_1 m_1}^{j_1}(\vec{\Omega}_1) D_{m'_2 m_2}^{j_2}(\vec{\Omega}_2) = \sum_{j_3=|j_1-j_2|}^{j_1+j_2} \langle j_1 m_1, j_2 m_2 | j_3 m_3 \rangle \langle j_1 m'_1, j_2 m'_2 | j_3 m'_3 \rangle D_{m'_3 m_3}^{j_3}(\vec{\Omega}_3) \quad (7.126)$$

gives⁵

$$\begin{aligned} |\mathcal{M}|^2 &= \left(\frac{2j_{J/\psi} + 1}{4\pi} \right) \left(\frac{2j_\phi + 1}{4\pi} \right) \\ &\cdot \sum_{\lambda, \lambda'=0, \pm 1} H_\lambda H_{\lambda'}^* \sum_{\alpha=\pm 1} (-1)^\alpha \sum_{j_L, j_R=0, 1, 2} \langle 1\alpha, 1-\alpha | j_L 0 \rangle \langle 1\lambda, 1-\lambda' | j_L m'_L \rangle D_{-m'_L, 0}^{j_L}(\vec{\Omega}_{J/\psi}) \\ &\quad \times \langle 10, 1-0 | j_R 0 \rangle \langle 1\lambda, 1-\lambda' | j_R m'_R \rangle D_{-m'_R, 0}^{j_R}(\vec{\Omega}_\phi) \\ &= -2 \left(\frac{3}{4\pi} \right)^2 \sum_{\lambda, \lambda'=0, \pm 1} H_\lambda H_{\lambda'}^* \sum_{j_L, j_R=0, 2} \langle 11, 1-1 | j_L 0 \rangle \langle 1\lambda, 1-\lambda' | j_L \lambda - \lambda' \rangle D_{\lambda'-\lambda, 0}^{j_L}(\vec{\Omega}_{J/\psi}) \\ &\quad \times \langle 10, 1-0 | j_R 0 \rangle \langle 1\lambda, 1-\lambda' | j_R \lambda - \lambda' \rangle D_{\lambda'-\lambda, 0}^{j_R}(\vec{\Omega}_\phi) \quad (7.127) \end{aligned}$$

Inserting Equation 7.121 leads to:

$$\begin{aligned} |\mathcal{M}|^2 &= -2 \left(\frac{3}{4\pi} \right)^2 \\ &\cdot \sum_{\lambda, \lambda'=0, \pm 1} H_\lambda H_{\lambda'} \sum_{j_L, j_R=0, 2} \frac{4\pi}{\sqrt{2j_L+1} \sqrt{2j_R+1}} \langle 11, 1-1 | j_L 0 \rangle \langle 1\lambda, 1-\lambda' | j_L \lambda - \lambda' \rangle \mathcal{Y}_{j_L, \lambda'-\lambda}^*(\vec{\Omega}_{J/\psi}) \\ &\quad \times \langle 10, 1-0 | j_R 0 \rangle \langle 1\lambda, 1-\lambda' | j_R \lambda - \lambda' \rangle \mathcal{Y}_{j_R, \lambda'-\lambda}^*(\vec{\Omega}_\phi) \quad (7.128) \end{aligned}$$

Defining the moments $T_{j_L j_R m}$ of the angular distributions with $m = \lambda - \lambda'$:⁶

$$T_{j_L j_R m} = \int \int |\mathcal{M}|^2 \mathcal{Y}_{j_L, m}(\vec{\Omega}_{J/\psi}) \mathcal{Y}_{j_R, m}(\vec{\Omega}_\phi) d\vec{\Omega}_\phi d\vec{\Omega}_{J/\psi} \quad \text{with} \quad T_{j_L j_R -m} = T_{j_L j_R m}^* \quad (7.129)$$

the decay matrix element of Equation 7.128 becomes:

$$|\mathcal{M}|^2 = \sum_{j_L=0, 2} \sum_{j_R=0, 2} \sum_{m=0, \pm 1, \pm 2} T_{j_L j_R m} \mathcal{Y}_{j_L, m}^*(\vec{\Omega}_{J/\psi}) \mathcal{Y}_{j_R, m}^*(\vec{\Omega}_\phi) \quad (7.130)$$

From the comparison of Equations 7.128 and 7.130, the moments $T_{j_L j_R -m}$ are expressed in terms of the helicity amplitudes H_λ and $H_{\lambda'}$ as:

$$T_{j_L j_R -m} = \frac{-9}{2\pi} \frac{1}{\sqrt{2j_L+1}} \frac{1}{\sqrt{2j_R+1}} \times \sum_{\lambda, \lambda'=0, \pm 1} \langle 11, 1-1 | j_L 0 \rangle \langle 1\lambda, 1-\lambda' | j_L m \rangle \langle 10, 10 | j_R 0 \rangle \langle 1\lambda, 1-\lambda' | j_R m \rangle H_\lambda H_{\lambda'}^* \quad (7.131)$$

⁵The $j_L = 1$ terms cancel because of the sum over α on the Clebsch-Gordan coefficient $\langle 1\alpha 1 - \alpha | j_L 0 \rangle$ and the $j_R = 1$ terms disappear because of the coefficient $\langle 10, 10 | j_R 0 \rangle$.

⁶In the B_s^0 meson rest frame, the z axis is defined by the direction of the J/ψ momentum, implying that the projection of the J/ψ spin on the z axis verifies $m_{J/\psi} = \lambda$, and $m_\phi = -\lambda'$.

Helicity Angles with Helicity Amplitudes

Using the Clebsch-Gordan coefficients, the moments of Equation 7.131 are calculated for all possible (j_L, j_R, m) combinations [129]. They are given in Table 7.2 with the corresponding spherical harmonic terms.

Table 7.2: Moments for the possible (j_L, j_R, m) pairs and corresponding spherical harmonic functions.

j_L	j_R	m	$4\pi \cdot T_{j_L j_R m}$	$\mathcal{Y}_{j_L, m}^*(\Omega_{J/\psi}) \mathcal{Y}_{j_R, m}^*(\Omega_\phi)$
0	0	0	$2(H_{+1}H_{+1}^* + H_{-1}H_{-1}^* + H_0H_0^*)$	$\sqrt{\frac{1}{4\pi}} \cdot \sqrt{\frac{1}{4\pi}}$
0	2	0	$\frac{2}{\sqrt{5}}(2H_0H_0^* - H_{+1}H_{+1}^* - H_{-1}H_{-1}^*)$	$\sqrt{\frac{1}{4\pi}} \cdot \sqrt{\frac{5}{16\pi}}(3\cos^2\psi - 1)$
2	0	0	$\frac{1}{\sqrt{5}}(H_{+1}H_{+1}^* + H_{-1}H_{-1}^* - 2H_0H_0^*)$	$\sqrt{\frac{5}{16\pi}}(3\cos^2\theta_H - 1) \cdot \sqrt{\frac{1}{4\pi}}$
2	2	0	$-\frac{1}{5}(H_{+1}H_{+1}^* + H_{-1}H_{-1}^* + 4H_0H_0^*)$	$\sqrt{\frac{5}{16\pi}}(3\cos^2\theta_H - 1) \cdot \sqrt{\frac{5}{16\pi}}(3\cos^2\psi - 1)$
2	2	-1	$-\frac{3}{5}(H_0H_{-1}^* + H_{+1}H_0^*)$	$\sqrt{\frac{15}{8\pi}}\sin\psi\cos\psi e^{+i\varphi} \cdot \sqrt{\frac{15}{8\pi}}\sin\theta_H\cos\theta_{He}^{+i\chi}$
2	2	1	$-\frac{3}{5}(H_0H_{+1}^* + H_{-1}H_0^*)$	$-\sqrt{\frac{15}{8\pi}}\sin\psi\cos\psi e^{-i\varphi} \cdot \sqrt{\frac{15}{8\pi}}\sin\theta_H\cos\theta_{He}^{-i\chi}$
2	2	-2	$-\frac{6}{5}H_{+1}H_{-1}^*$	$\sqrt{\frac{15}{32\pi}}\sin^2\psi e^{+2i\varphi} \cdot \sqrt{\frac{15}{32\pi}}\sin^2\theta_{He}^{+2i\chi}$
2	2	2	$-\frac{6}{5}H_{-1}H_{+1}^*$	$\sqrt{\frac{15}{32\pi}}\sin^2\psi e^{-2i\varphi} \cdot \sqrt{\frac{15}{32\pi}}\sin^2\theta_{He}^{-2i\chi}$

The coordinate system is chosen such that φ of Figure 7.10 is zero, hence all the azimuthal angular dependence is concentrated in χ . Using $(e^{i\chi} + e^{-i\chi}) = 2\cos(\chi)$ and $(e^{i\chi} - e^{-i\chi}) = 2i\sin(\chi)$, the component by component additions of Table 7.2, with calculating the real and imaginary parts for the interfering terms, give the results of Table 7.1.5 [133]. $|H_{+1}(t)|^2$ and $|H_{-1}(t)|^2$ are observed to have the same angular dependence $f_k^{\text{HEL}}(\theta_H, \psi, \chi)$.

Table 7.3: Angular functions $f_k^{\text{HEL}}(\theta_H, \psi, \chi)$ related to the time-dependent terms $h_k(t)$ of the helicity basis.

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k^{\text{HEL}}(\theta_H, \psi, \chi) [\times 64\pi/9]$
1	$ H_0(t) ^2$	$ \bar{H}_0(t) ^2$	$4\cos^2\psi \cdot \sin^2\theta_H$
2	$ H_{+1}(t) ^2$	$ \bar{H}_{+1}(t) ^2$	$\sin^2\psi \cdot (1 + \cos^2\theta_H)$
3	$ H_{-1}(t) ^2$	$ \bar{H}_{-1}(t) ^2$	$\sin^2\psi \cdot (1 + \cos^2\theta_H)$
4	$\Im\{H_{+1}^*(t)\bar{H}_{-1}(t)\}$	$\Im\{\bar{H}_{+1}^*(t)\bar{H}_{-1}(t)\}$	$-2\sin^2\psi \cdot \sin^2\theta_H \cdot \sin 2\chi$
5	$\Re\{H_{+1}^*(t)H_{-1}(t)\}$	$\Re\{\bar{H}_{+1}^*(t)\bar{H}_{-1}(t)\}$	$-2\sin^2\psi \cdot \sin^2\theta_H \cdot \cos 2\chi$
6	$\Im\{(H_{+1}(t) - H_{-1}(t))^* \cdot H_0\}$	$\Im\{(\bar{H}_{+1}(t) - \bar{H}_{-1}(t))^* \cdot H_0\}$	$-\sin 2\psi \cdot \sin 2\theta_H \cdot \sin \chi$
7	$\Re\{(H_{+1}(t) + H_{-1}(t))^* \cdot H_0\}$	$\Re\{(\bar{H}_{+1}(t) + \bar{H}_{-1}(t))^* \cdot H_0\}$	$-\sin 2\psi \cdot \sin 2\theta_H \cdot \cos \chi$

Helicity Angles with Transversity Amplitudes

In the analysis, the time-dependent terms and the angular functions factorize. Therefore, the helicity amplitudes of Table 7.2 can be expressed in terms of the transversity amplitudes using Equation 7.17. This change has the advantage of leading directly to CP quantities of interest, while keeping the helicity basis for the angular analysis.

The elements of the decay matrix $|\mathcal{M}|^2$ of Equation 7.130 are given in Table 7.4. The $\Re\{A_\perp A_0^*\}$, $\Re\{A_\perp A_\parallel^*\}$ and $\Im\{A_\parallel A_0^*\}$ terms vanish. The corresponding spherical harmonics using the helicity angles are the same as given in Table 7.2.

Table 7.4: Moments for the possible (j_L, j_R, m) pairs (transversity amplitudes).

j_L	j_R	m	$4\pi \cdot T_{j_L j_R m}$
0	0	0	$2 \cdot (A_\parallel ^2 + A_\perp ^2 + A_0 ^2)$
0	2	0	$\frac{2}{\sqrt{5}}(- A_\parallel ^2 - A_\perp ^2 + 2 A_0 ^2)$
2	0	0	$\frac{1}{\sqrt{5}}(A_\parallel ^2 + A_\perp ^2 - 2 A_0 ^2)$
2	2	0	$-\frac{1}{5}(A_\parallel ^2 + A_\perp ^2 + 4 A_0 ^2)$
2	2	-1	$-\frac{3\sqrt{2}}{5}(\Re\{A_\parallel A_0^*\} + i\Im\{A_\perp A_0^*\})$
2	2	1	$-\frac{3\sqrt{2}}{5}(\Re\{A_\parallel A_0^*\} - i\Im\{A_\perp A_0^*\})$
2	2	-2	$-\frac{3}{5}(A_\parallel ^2 - A_\perp ^2 + 2i\Im\{A_\perp A_\parallel^*\})$
2	2	2	$-\frac{3}{5}(A_\parallel ^2 - A_\perp ^2 - 2i\Im\{A_\perp A_\parallel^*\})$

The angular functions $f_k^{\text{HEL}}(\theta_H, \psi, \chi)$ associated to the non-vanishing time-dependent quadratic and interfering terms of the transverse basis $h_k(t)$ ($\bar{h}_k(t)$ for $\bar{B}_s^0$) are given in Table 7.1.5 [134].

Table 7.5: Angular functions $f_k^{\text{HEL}}(\theta_H, \psi, \chi)$ in the helicity basis related to the time-dependent terms $h_k(t)$ expressed in the transversity basis.

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k^{\text{HEL}}(\theta_H, \psi, \chi)[\times 64\pi/9]$
1	$ A_0(t) ^2$	$ \bar{A}_0(t) ^2$	$4\cos^2\psi \cdot \sin^2\theta_H$
2	$ A_\parallel(t) ^2$	$ \bar{A}_\parallel(t) ^2$	$\sin^2\psi \cdot (1 + \cos^2\theta_H - \sin^2\theta_H \cdot \cos 2\chi)$
3	$ A_\perp(t) ^2$	$ \bar{A}_\perp(t) ^2$	$\sin^2\psi \cdot (1 + \cos^2\theta_H + \sin^2\theta_H \cdot \cos 2\chi)$
4	$\Im\{A_\parallel^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\}$	$2\sin^2\psi \cdot \sin^2\theta_H \cdot \sin 2\chi$
5	$\Re\{A_0^*(t)A_\parallel(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\}$	$-\sqrt{2}\sin 2\psi \cdot \sin 2\theta_H \cdot \cos \chi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\sqrt{2}\sin 2\psi \cdot \sin 2\theta_H \cdot \sin \chi$

In Table 7.1.5, $|A_\parallel(t)|^2$ and $|A_\perp(t)|^2$ do not have the same angular dependence $f_k^{\text{HEL}}(\theta_H, \psi, \chi)$.

Transversity Angles with Transversity Amplitudes

The helicity angles are replaced by the transversity ones using Equation 7.18. The angular functions $f_k^{\text{TR}}(\theta, \psi, \varphi)$, associated to each amplitude and interfering terms $h_k(t)$ ($\bar{h}_k(t)$ for $\bar{B}_s^0$) of Table 7.1.5, are given in Table 7.1.5 [135].

Table 7.6: Angular functions $f_k^{\text{TR}}(\theta, \psi, \varphi)$ in the transversity basis related to the time-dependent terms $h_k(t)$ expressed in the transversity basis.

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k^{\text{TR}}(\theta, \psi, \varphi)[\times 32\pi/9]$
1	$ A_0(t) ^2$	$ \bar{A}_0(t) ^2$	$2\cos^2\psi \cdot (1 - \sin^2\theta \cdot \cos^2\varphi)$
2	$ A_{ }(t) ^2$	$ \bar{A}_{ }(t) ^2$	$\sin^2\psi \cdot (1 - \sin^2\theta \cdot \sin^2\varphi)$
3	$ A_{\perp}(t) ^2$	$ \bar{A}_{\perp}(t) ^2$	$\sin^2\psi \cdot \sin^2\theta$
4	$\Im\{A_{ }^*(t)A_{\perp}(t)\}$	$\Im\{\bar{A}_{ }^*(t)\bar{A}_{\perp}(t)\}$	$-\sin^2\psi \cdot \sin 2\theta \cdot \sin\varphi$
5	$\Re\{A_0^*(t)A_{ }(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_{ }(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi \cdot \sin^2\theta \cdot \sin 2\varphi$
6	$\Im\{A_0^*(t)A_{\perp}(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_{\perp}(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi \cdot \sin 2\theta \cdot \cos\varphi$

In Equations 7.98-7.103 and similarly for 7.104-7.109, there exists a two-fold ambiguity under the following simultaneous changes:

$$\phi_s^{J/\psi\phi} \longleftrightarrow \pi - \phi_s^{J/\psi\phi} \quad \text{and} \quad \Delta\Gamma_s \longleftrightarrow -\Delta\Gamma_s \quad \text{and} \quad \delta_{\perp} \longleftrightarrow \pi - \delta_{\perp} \quad \text{and} \quad \delta_{||} \longleftrightarrow 2\pi - \delta_{||} \quad (7.132)$$

Up to now, only the K^+K^- P-wave amplitude in the vicinity of the $\phi(1020)$ is taken into account. However, the K^+K^- meson pair can have both a S-wave and a P-wave angular momentum states. The S-wave contribution can be non-resonant or due to the $f_0(980)$ resonance. The S-wave contribution and its interference with the P-wave should be inserted in the fit model. From B-factory results, a S-wave component of 5-10% may be expected [136].

When the K^+K^- pair is in the S-wave state, the angular momentum conservation at the B_s^0 decay vertex implies that the system $J/\psi K^+K^-$ is in the P-wave state ($\ell = 1$). The resulting CP eigenvalue of the system is given by $\text{CP} = -1^{\ell} = -1$ and the angular distribution at the J/ψ decay is in $(1 - \sin^2(\theta)\cos^2(\varphi))$ in the transversity basis (Table 7.1.5) and in $(\sin^2\theta_H)$ in the helicity basis (Table 7.1.5) [134].

In addition to prevent biases in the measured value of $\phi_s^{J/\psi\phi}$ (up to 10%), the interference can be used to solve the strong phase ambiguity by measuring the sign of $\cos(\phi_s^{J/\psi\phi})$, if it is large enough [134].

7.1.6 Differential $B_s^0 \rightarrow J/\psi\phi$ Decay Rates

The differential decay rates for B_s^0 and $\bar{B}_s^0$ are given in Equations 7.133 and 7.134 respectively. Using the transversity amplitudes, the $f_k^{\text{TR}}(\vec{\Omega}_{\text{TR}})$ functions are defined in Table 7.1.5 and the $f_k^{\text{HEL}}(\vec{\Omega}_{\text{HEL}})$ in Table 7.1.5.

$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi\phi)}{dt d\vec{\Omega}_{\text{TR/HEL}}} \propto \sum_{k=1}^6 h_k(t) f_k^{\text{TR/HEL}}(\vec{\Omega}_{\text{TR/HEL}}) \quad (7.133)$$

$$\frac{d^4\Gamma(\bar{B}_s^0 \rightarrow J/\psi\phi)}{dt d\vec{\Omega}_{\text{TR/HEL}}} \propto \sum_{k=1}^6 \bar{h}_k(t) f_k^{\text{TR/HEL}}(\vec{\Omega}_{\text{TR/HEL}}) \quad (7.134)$$

In the untagged analysis of $B_s^0 \rightarrow J/\psi\phi$, the differential decay rates of the B_s^0 and the $\bar{B}_s^0$ are equally added and weighted by a factor 0.5 to satisfy to the value of the total decay rate (Equation 7.135). As the angular functions, $f_k^{\text{TR}}(\theta, \psi, \varphi)$ for the transversity basis or $f_k^{\text{HEL}}(\theta_H, \psi, \chi)$ for the helicity basis, are the same for both $h_k(t)$ and $\bar{h}_k(t)$ (Tables 7.1.5, 7.1.5), only the time-dependent terms get modified as $u_k(t) = 0.5 \cdot (h_k(t) + \bar{h}_k(t))$, using $|A_j(t)| = |\bar{A}_j(t)|$ with $j = \{0, \parallel, \perp\}$:

$$\frac{d^4\Gamma(B_s^0/\bar{B}_s^0 \rightarrow J/\psi\phi)}{dt d\vec{\Omega}_{\text{TR/HEL}}} = 0.5 \cdot \frac{d^4\Gamma(B_s^0 \rightarrow J/\psi\phi)}{dt d\vec{\Omega}_{\text{TR/HEL}}} + 0.5 \cdot \frac{d^4\Gamma(\bar{B}_s^0 \rightarrow J/\psi\phi)}{dt d\vec{\Omega}_{\text{TR/HEL}}} \propto \sum_{k=1}^6 u_k(t) f_k^{\text{TR/HEL}}(\vec{\Omega}_{\text{TR/HEL}}) \quad (7.135)$$

$$u_1(t) = \frac{1}{2} \cdot \left(|A_0(t)|^2 + |\bar{A}_0(t)|^2 \right) = |A_0|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \quad (7.136)$$

$$u_2(t) = \frac{1}{2} \cdot \left(|A_{\parallel}(t)|^2 + |\bar{A}_{\parallel}(t)|^2 \right) = |A_{\parallel}|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \quad (7.137)$$

$$u_3(t) = \frac{1}{2} \cdot \left(|A_{\perp}(t)|^2 + |\bar{A}_{\perp}(t)|^2 \right) = |A_{\perp}|^2 e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \quad (7.138)$$

$$u_4(t) = \frac{1}{2} \cdot \left(\Im\{A_{\parallel}^*(t)A_{\perp}(t)\} + \Im\{\bar{A}_{\parallel}^*(t)\bar{A}_{\perp}(t)\} \right) = |A_{\parallel}||A_{\perp}| e^{-\Gamma_s t} \cdot \left[-\sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \cdot \cos(\delta_{\perp} - \delta_{\parallel}) \quad (7.139)$$

$$u_5(t) = \frac{1}{2} \cdot \left(\Re\{A_0^*(t)A_{\parallel}(t)\} + \Re\{\bar{A}_0^*(t)\bar{A}_{\parallel}(t)\} \right) = |A_0||A_{\parallel}| e^{-\Gamma_s t} \cdot \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \cdot \cos(\delta_{\parallel}) \quad (7.140)$$

$$u_6(t) = \frac{1}{2} \cdot \left(\Im\{A_0^*(t)A_{\perp}(t)\} + \Im\{\bar{A}_0^*(t)\bar{A}_{\perp}(t)\} \right) = |A_0||A_{\perp}| e^{-\Gamma_s t} \cdot \left[-\sin(\phi_s^{J/\psi\phi}) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \cdot \cos(\delta_{\perp}) \quad (7.141)$$

All the terms containing the Δm_s parameter vanish, as they have opposite signs in Equations 7.98-7.103 and Equations 7.104-7.109. The resulting untagged analysis therefore counts seven free physical parameters ($|A_0|^2$, $|A_{\perp}|^2$, Γ_s , $\Delta\Gamma_s$, $\delta_{\parallel}$, $\delta_{\perp}$, $\phi_s^{J/\psi\phi}$).

One-Angle Decay Rate in the Transversity Basis

When integrated over two angles, the differential decay rate of Equation 7.133 gives:

$$\frac{d^2\Gamma}{d\cos\theta dt} = \frac{3}{8} \left[(|A_0(t)|^2 + |A_{\parallel}(t)|^2) (2 - \sin^2\theta) + 2|A_{\perp}(t)|^2 \sin^2\theta \right] \quad (7.142)$$

$$\frac{d^2\Gamma}{d\cos\psi dt} = \frac{3}{4} \left[2|A_0(t)|^2 \cos^2\psi + (|A_{\parallel}(t)|^2 + |A_{\perp}(t)|^2) \sin^2\psi \right] \quad (7.143)$$

$$\frac{d^2\Gamma}{d\varphi dt} = \frac{1}{2\pi} \left[|A_0(t)|^2 \left(\frac{3}{2} - \cos^2\varphi \right) + |A_{\parallel}(t)|^2 \left(\frac{3}{2} - \sin^2\varphi \right) + |A_{\perp}(t)|^2 \right] \quad (7.144)$$

In Equation 7.142 only, $|A_0(t)|^2$ and $|A_{\parallel}(t)|^2$ have the same coefficients. As a consequence, the $|A_0(t)|^2$ parameter can be removed, simplifying the fit function by keeping only $|A_{\perp}(t)|^2$ as CP amplitude ($|A_0(t)|^2 + |A_{\parallel}(t)|^2 = 1 - |A_{\perp}(t)|^2$). This explains why Equation 7.142 is usually used in one-angle studies compared to Equations 7.143 and 7.144.

7.1.7 Indirect Searches for New Physics in $B_s^0 \rightarrow J/\psi\phi$

The hierarchy problem of the Higgs sector in the Standard Model has initiated almost all the theoretical searches for models beyond the SM. These models are however constrained by two types of data, electroweak precision and flavor data. In flavor physics, CP violation in the $B_s^0 - \bar{B}_s^0$ mixing is a prime candidate for the discovery of New Physics contributions [137, 138].

The off-diagonal elements $M_{12} = M_{21}^*$ and $\Gamma_{12} = \Gamma_{21}^*$ of the decay matrix of Equation 7.36 correspond to $B_s^0 - \bar{B}_s^0$ mixing. As Γ_{12} is dominated by real states to which B_s^0 and $\bar{B}_s^0$ mesons may decay with tree diagrams, it is therefore mostly given by light particles containing u or c quarks. The M_{12} term is dominated by the exchange of virtual heavy states in loops. These contributions contain t quarks or could be some of the predicted SUSY sparticles. Therefore, if there is New Physics in the $B_s^0 - \bar{B}_s^0$ mixing, it is expected to manifest itself significantly in the mass matrix elements, not in the width matrix ones. A new complex parameter Δ_s is introduced to represent New Physics contributions to M_{12} [139]:

$$M_{12} = M_{12}^{\text{SM}} \cdot \Delta_s \quad (7.145)$$

with

$$\Delta_s = |\Delta_s| \cdot e^{i\phi_s^\Delta} \quad (7.146)$$

where ϕ_s^Δ represents the New Physics contribution to the $\phi_s^{J/\psi\phi}$ phase:

$$\phi_s^{J/\psi\phi} = -2\beta_s(\text{SM}) + \phi_s^\Delta \quad (7.147)$$

7.2 Latest Results from the Tevatron on $\phi_s^{J/\psi\phi}$

The DØ and CDF experiments at Fermilab are working on the time-dependent angular analysis to tagged $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ events. In their analyses, the CDF collaboration uses a neural network to select the B_s^0 signal events while the DØ selection is cut-based. They both report two-dimensional profile likelihoods and *Confidence-Level (CL) contours* in the $\beta_s - \Delta\Gamma$ plane (with $-2\beta_s = \phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s = \Delta\Gamma$ in their notation), which account for the non-Gaussian behavior of the uncertainties. The results on $\phi_s^{J/\psi\phi}$ are calculated in two different ways, CDF quoting intervals with a given confidence level and DØ quoting a central value with asymmetric errors.

The results presented at the Rencontres de Moriond in March 2010 [140] were based on ~ 3000 and ~ 2000 B_s^0 signal events for CDF and DØ experiments respectively, corresponding to a luminosity of 2.8 fb^{-1} each. The results obtained for $\Delta\Gamma_s$, τ_s and $\phi_s^{J/\psi\phi}$ are summarized in Table 7.7. The Δm_s parameter was constrained to $17.77 \pm 0.12 \text{ ps}^{-1}$.

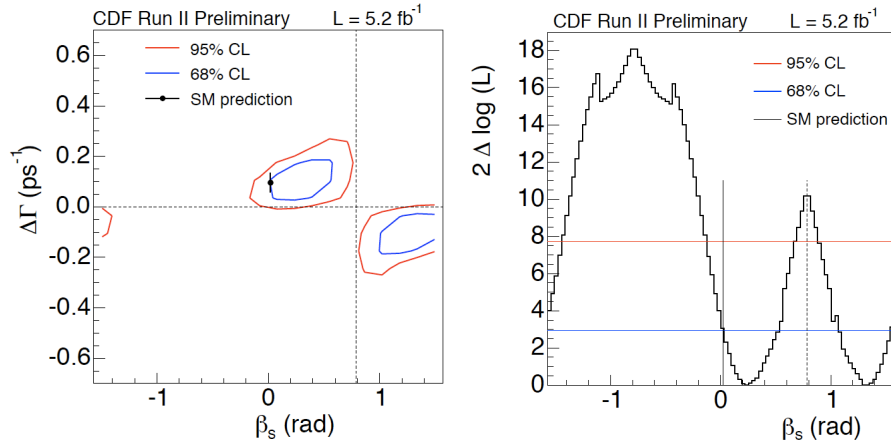
To estimate the deviation of the result from the Standard Model expectation, the *p-value* is calculated. It represents the chance of rejecting the SM hypothesis when it is true. The lower the p-value, the less likely the result is if the SM hypothesis is true, and consequently the more significant the result is. The combination of the CDF and DØ results of Table 7.7 has a p-value of 3.4% [141].

Table 7.7: $\Delta\Gamma_s$, τ_s and $\phi_s^{J/\psi\phi}$ results from the CDF and DØ collaborations presented at the Rencontres de Moriond in March 2010 [140].

Parameter	DØ Experiment	CDF Experiment
$\Delta\Gamma_s$ [ps^{-1}]	0.19 ± 0.07	0.02 ± 0.05
τ_s [ps]	1.52 ± 0.06	1.53 ± 0.04
$\phi_s^{J/\psi\phi}$ [rad]	$-0.57^{+0.25}_{-0.30}$	$[-0.56, -2.58]$ (68%)

Since then, the CDF experiment has updated its result on $\phi_s^{J/\psi\phi}$ using 5.2 fb^{-1} of data [142]. The two-dimensional profile likelihood and the 68% and the 95% CL contours are shown in Figure 7.11 (left). The p-value is 44%, which means that the new result is in better agreement with the Standard Model than the previous ones (Table 7.7). The two solutions arising from the two-fold ambiguity explained in Subsection 7.1.4 are still equally probable and it is not yet possible to choose one over the other. From the β_s scan of Figure 7.11 (right), the following solutions are obtained for two different confidence levels, with a p-value of 31%:

- $\beta_s \in [0.02, 0.52] \cup [1.08, 1.55]$ at 68% CL
- $\beta_s \in [-0.13, 0.68] \cup [0.89, \pi/2] \cup [-\pi/2, -1.44]$ at 95% CL

**Figure 7.11:** Updated result on β_s from CDF [142]: two-dimensional profile likelihood (left) and β_s scan (right).

Fixing β_s to zero, the B_s^0 lifetime τ_s and the amplitudes $|A_{||}|^2$ and $|A_0|^2$ have been measured by CDF in the tagged analysis. Constraints are given on $\Delta\Gamma_s$ and the strong phase $\delta_\perp$ (Table 7.8) [142]⁷.

Table 7.8: Latest results (June 2010) from the CDF experiment assuming $\beta_s = 0$ [142].

Parameter	Value	$\sigma(\text{stat})$	$\sigma(\text{syst})$
τ_s [ps]	1.53	± 0.025	± 0.012
$\Delta\Gamma_s$ [ps^{-1}]	0.075	± 0.035	± 0.010
$ A_{ } ^2$	0.231	± 0.014	± 0.015
$ A_0 ^2$	0.524	± 0.013	± 0.015
$\delta_\perp$ [rad]	2.95	± 0.640	± 0.070

⁷The $\delta_{||}$ strong phase is floating in the fit. However, pull studies have shown non Gaussian behavior for this parameter, explaining why no best fit value is quoted for it. The Δm_s parameter is constrained within its error to its measured value in [143] using Gaussian constraints (see Subsection 7.7.2).

7.3 Selection of $B_s^0 \rightarrow J/\psi\phi$ and Control Channels $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$

7.3.1 Overview of the $B_s^0 \rightarrow J/\psi\phi$ Events at LHCb

According to the PYTHIA event generator [42], $b\bar{b}$ are produced dominantly by the processes displayed in Figure 7.12. The *pair creation* includes *gluon fusion* ($gg \rightarrow b\bar{b}$) and *quark-antiquark annihilation* ($q\bar{q} \rightarrow b\bar{b}$). *Flavor excitation* happens when a virtual heavy $b(\bar{b})$ quark from the sea quarks of one incoming proton scatters with a parton of the other proton and ends up on its mass shell ($b(\bar{b})q \rightarrow b(\bar{b})q$, $b(\bar{b})g \rightarrow b(\bar{b})g$). *Gluon splitting* is a mechanism in which the $b\bar{b}$ pair is produced in the parton shower from a transition $g \rightarrow b\bar{b}$ [102]. The contributions of these mechanisms to the $b\bar{b}$ production at LHCb with at least one b hadron with all its decay products in the LHCb acceptance are $\sim 16\%$ for pair creation, $\sim 57\%$ for flavor excitation and the remaining $\sim 27\%$ for gluon splitting.

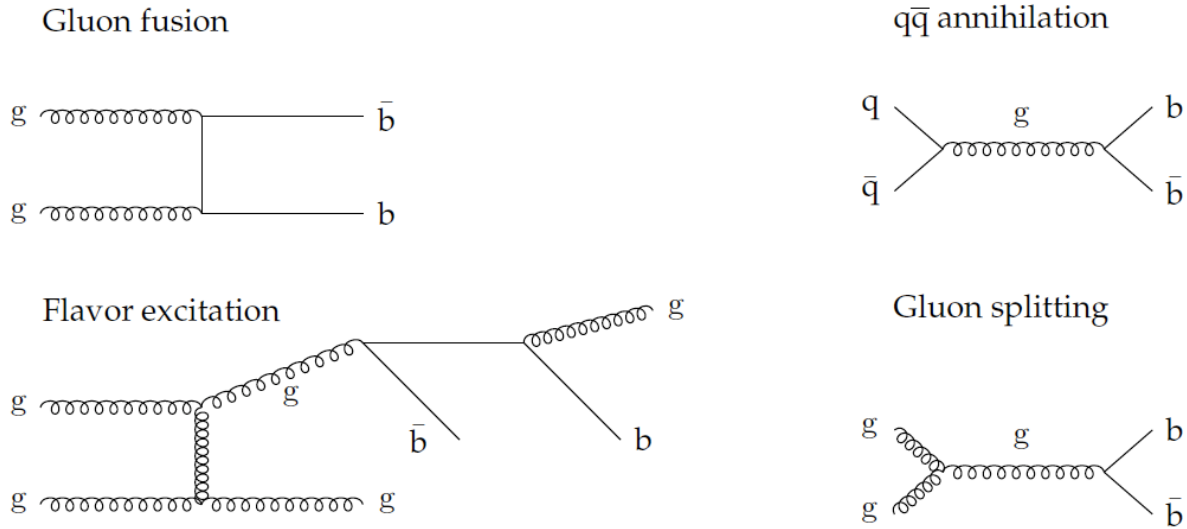


Figure 7.12: Dominant production mechanisms of $b\bar{b}$ at LHCb (QCD leading order) [102].

Once the $\bar{b}$ quarks are produced, the s quarks needed to form B_s^0 mesons result from hadronization processes. In their rest frames, B_s^0 mesons have small lives, $\tau \sim 1.5 \cdot 10^{-12}$ s, corresponding to $c\tau \sim 450 \mu\text{m}$. In the laboratory, where they are detected by the LHCb spectrometer, their flight distance f_d depends on their mass m and momentum p as:

$$f_d = \frac{p}{m} \cdot c \cdot \tau \quad (7.148)$$

For momenta of $\sim 50 \text{ GeV}/c$, flight distances are typically of $\sim 4 \text{ mm}$. Then, the B_s^0 mesons of interest decay weakly into J/ψ and ϕ particles. The J/ψ decay predominantly electromagnetically into two muons and the ϕ strongly into two charged kaons, which are practically instantaneous (total widths $\Gamma(J/\psi) = 93.2 \text{ keV}/c^2$, $\Gamma(\phi) = 4.26 \text{ MeV}/c^2$ [18]). As for the muons ($m(\mu) = 105.7 \text{ MeV}/c^2$ [18]) and kaons ($m(K^\pm) = 493.7 \text{ MeV}/c^2$ [18]), they fly several meters through the LHCb spectrometer and are hence the detectable particles of the decay.

7.3.2 The $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ Control Channels

The flavor specific $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ channels are used as control channels in the $B_s^0 \rightarrow J/\psi\phi$ angular study, with K^{*0} decaying strongly into $K^+\pi^-$. Their yields are 4 and 8 times more abundant than that of $B_s^0 \rightarrow J/\psi\phi$, respectively. These channels are used as control channels to estimate the mistag rates and check the proper time calibration.

The $B^0 \rightarrow J/\psi K^{*0}(K^+\pi^-)$ channel has the same angular properties as $B_s^0 \rightarrow J/\psi\phi$. It will therefore be also used to validate the angular acceptances corrections [144] and the fit procedure. The fitted values of the amplitudes and the strong phase differences will be compared with those already obtained by other experiments [145, 146, 147, 148].

As an illustration, the first event display of a $B^+ \rightarrow J/\psi K^+$ candidate obtained at LHCb with 2010 real data at $\sqrt{s} = 7$ TeV is shown in Figure 7.13 (top). The collection of $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ has therefore started. The first candidates collected from real data with an integrated luminosity of 12.8 nb^{-1} are shown in Figure 7.13 (bottom). Of the 112 and 65 candidates obtained in the mass windows of $\pm 50 \text{ MeV}/c^2$ and $\pm 60 \text{ MeV}/c^2$ for the B^0 and B^+ respectively, 4 and 8 remain after requiring proper times $t > 0.15 \text{ ps}$ and $t > 3\sigma_t$, with $\sigma_t = 53 \text{ fs}$ for B^0 , 58 fs for B^+ .

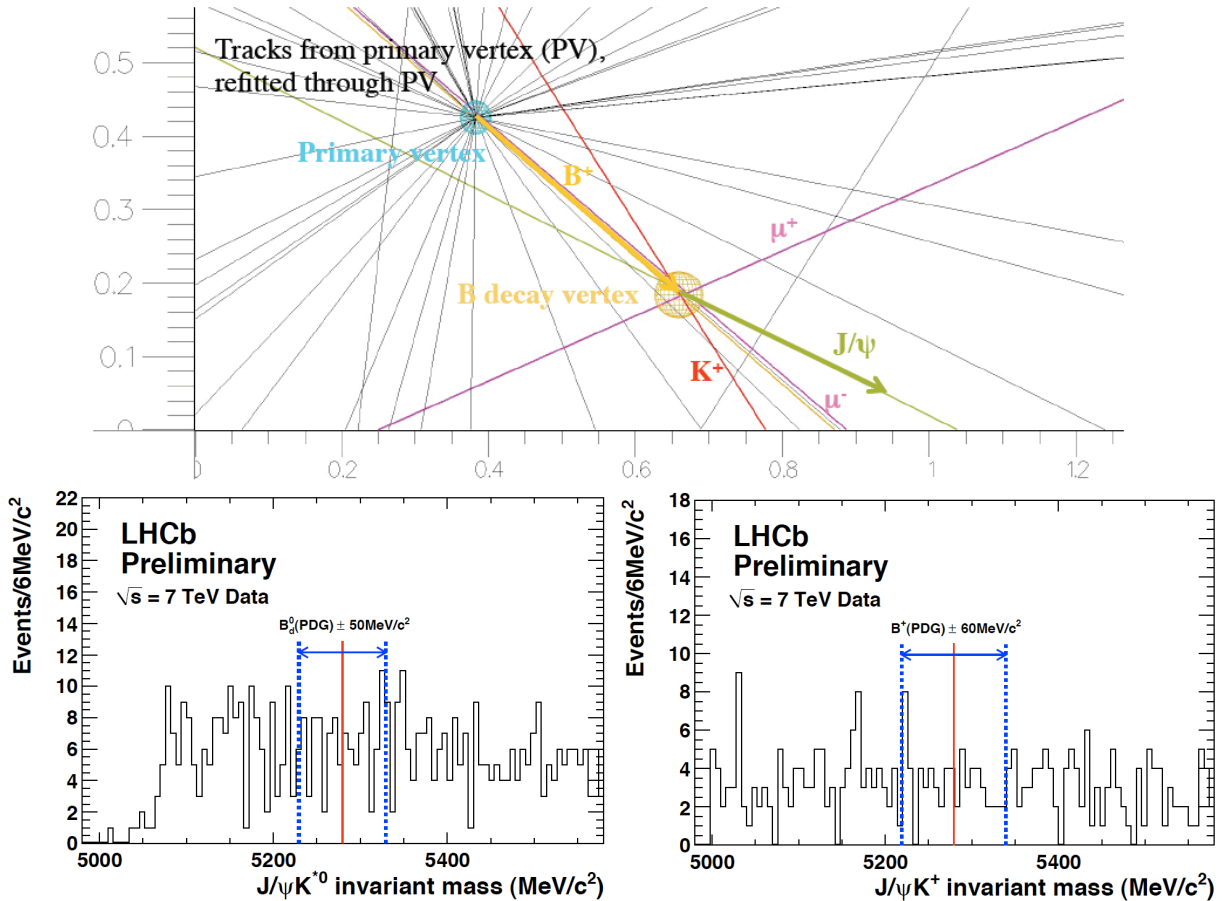


Figure 7.13: Event display of the first $B^+ \rightarrow J/\psi K^+$ signal candidate at LHCb (top) and distributions of the $B^0 \rightarrow J/\psi K^{*0}$ (bottom, left) and $B^+ \rightarrow J/\psi K^+$ (bottom, right) candidates collected at LHCb in 12.8 nb^{-1} of 2010 real data at $\sqrt{s}=7 \text{ TeV}$ [149, 150].

7.3.3 The $B_s^0 \rightarrow J/\psi\phi$ Trigger Selection

The LHCb trigger structure is detailed in Section 2.7. The trigger selection for $B_s^0 \rightarrow J/\psi\phi$ should maintain the same philosophy as for its offline selection (Subsection 7.3.4), by not biasing the proper time and by being as similar as possible between the signal and control channels. The L0-trigger efficiency on selected events, $\varepsilon_{L0}/\varepsilon_{sel}$, which is computed from a OR of the different lines relevant to the $B_s^0 \rightarrow J/\psi\phi$ event selection at the first level of trigger, is given in Table 7.9, as well as the relative contribution of each line to it. The L0- μ , no GEC line (Section 2.7) provides alone almost 97% of the L0-triggers [123]. The L0 trigger cuts used are summarized in Table 7.10.

Table 7.9: L0-trigger efficiency ($\varepsilon_{L0}/\varepsilon_{sel}$) and relative contribution of each trigger line [123].

$\varepsilon_{L0}/\varepsilon_{sel}$ (%)	93.9 ± 0.1
L0 lines	Relative contribution
L0- μ , no GEC	96.70 ± 0.06
L0- μ , GEC	71.7 ± 0.2
L0-di μ , no GEC	69.6 ± 0.2
L0-hadron	4.5 ± 0.7
L0- $\gamma/e^\pm$	11.5 ± 0.5

Table 7.10: L0 trigger selection for the DC06 Monte Carlo samples based on the calorimeter trigger, the Global Event Cuts and the muon trigger [123].

Calorimeter Trigger			Global Event Cuts				Muon Trigger		
E_T^{hadron} (GeV)	E_T^e (GeV)	E_T^γ (GeV)	$m_{\text{track}}^{\text{PU}}$	$n_{\text{tracks}}^{\text{vtx}}$	E_T^{tot} (GeV)	$m_{\text{track}}^{\text{SPD}}$	p_T^μ (no GEC) (GeV)	p_T^μ (GEC) (GeV)	$ p_T^{\mu 1} + p_T^{\mu 2} $ (GeV)
> 3.5	> 3.5	> 3.5	< 112	< 3	> 5	< 280	> 1.5	> 1.3	> 1.5

The total efficiency of the HLT1-trigger μ lines is $\sim 91\%$, with a minimum bias rate of ~ 17 kHz. It is composed of 78% of lifetime biased single- μ line, 79.4% of lifetime unbiased di- μ line (81.4% adding the lifetime unbiased single- μ line) and 48.2% of lifetime biased di- μ line [123].

The Inclusive $J/\psi \rightarrow \mu\mu$ HLT2 Line:

In the $B_s^0 \rightarrow J/\psi\phi$ angular analysis, the common part of the event that can be reconstructed in the tracking stations at HLT level for the signal $B_s^0 \rightarrow J/\psi\phi$ and the $B^{0/+} \rightarrow J/\psi K^{*0/+}$ control channels is the two muons coming from the J/ψ . The inclusive line is therefore designed to trigger on $J/\psi \rightarrow \mu\mu$ candidates. A simplified Kalman track fit (Subsection 6.1.2)⁸ is used to fit the muon track candidates. These are required to form a common vertex with a $\chi_{\text{vertex}}^2 < 7$ and to have a transverse momentum $p_T > 500$ MeV/c. A 3σ -cut around the nominal J/ψ mass is also applied, where the resolution σ is 14 MeV/c². No cut of the impact parameter is applied to keep the selection unbiased in proper time. Using this line, the channels of interested are selected with an efficiency above 95% calculated on offline selected events passing the previous trigger levels.

⁸As the CPU time is dominated by the location of intersections with the detector material in the Kalman track fit, a simplification of the material service with rough geometry resolution is used in the simplified version of the fit.

The HLT2 Exclusive Selection of $B \rightarrow J/\psi(\mu\mu)X$ Channels

The design of the HLT2 exclusive selections for the $B_s^0 \rightarrow J/\psi\phi$ signal and $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ control channels follows three main criteria. First, the cuts defined at the HLT2 level should follow the same philosophy as the ones applied offline (Section 7.3.4), to prevent distortions of the proper time and angular distributions with respect to the offline selection. Secondly, the selections should use a set of common cuts wherever possible in order to keep similar phase spaces for calibration purposes. Finally, the tagging performance should not be modified. Specific cuts are then added for each channel separately to lower the minimum bias rate while attempting to respect the three criteria.

The studies are performed with the v21r0 version of the physics analysis software application DaVinci. 500,000 DC06 $B_s^0 \rightarrow J/\psi\phi$, $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ events and 898,876 minimum bias events are used in the analysis. The minimum bias events are L0-stripped and correspond to a sample of 15,006,227 events for a time of 1.03 s of real data taking. Only signal events that have been L0- and HLT1-triggered and that have been offline-selected are used.

The offline and online HLT2 signal distributions are compared to estimate the degradation of performance in the online environment, resulting in a tuning (loosening or removal) of the offline cuts. Whenever possible, identical cuts are applied on the selection variables common to the three channels. The second step is to compare the HLT2 signal, combinatorial, and minimum bias distributions and add more specific HLT2 cuts to each channel to achieve a minimum bias rate of a few Hz. The offline-online and online-background comparisons are explained in Appendix A.0.1

1. *Offline Signal - Online HLT2 Signal Comparisons:* The distributions of the transverse momentum p_T are found to agree reasonably well globally. Therefore, the HLT2 cuts are set at the same values as for the offline selections. The B-vertex χ^2 , and especially the mass distributions, are broader online than offline. Therefore, the cuts on these quantities are relaxed in the HLT2 environment. The track χ^2 shows a different behavior between offline and online. This is because the offline quantity results from a multi-pass bidirectional Kalman fit, while the online quantity is the χ^2 of the forward pattern recognition.
2. *Online HLT2 Signal - Combinatorial and Minimum Bias Comparisons:* The cut on the transverse momentum of the muon has been raised from 500 MeV/c offline to 800 MeV/c, to reduce the minimum bias rate and combinatorics, and hence speed up the processing time. The cuts on the vertex χ^2 for J/ψ , ϕ and K^{*0} do not have any significant effect on the minimum bias rate. However, they allow the selection of only one or two candidates at each vertex instead of several hundred, which lowers the CPU time. As they have similar distributions than offline, the HLT2 cuts are set at similar values than the offline cuts⁹.

⁹The cuts for ϕ and K^{*0} , which are $\chi^2/\text{ndof} < 20$ in offline, are set to $\chi^2/\text{ndof} < 25$ in HLT2. For J/ψ , the offline cut is at $\chi^2/\text{ndof} < 6$. It is set at $\chi^2/\text{ndof} < 25$ in HLT2 to agree better with the cuts for the other daughter particles.

The HLT2 selection cuts¹⁰ are summarized in Table 7.11. They are also depicted in Figures A.1-A.58 of Appendix A.0.1.

Table 7.11: HLT2 selection cuts for the $B \rightarrow J/\psi(\mu\mu)X$ channels.

Common cuts		
$p_T(\mu) > 800 \text{ MeV}/c$ $\mu\text{-track } \chi^2/\text{ndof} < 8$ $p_T(J/\psi) > 1000 \text{ MeV}/c$ $m(J/\psi) \pm 80 \text{ MeV}/c^2$ $J/\psi \text{ vertex } \chi^2/\text{ndof} < 25$ $m(B) \pm 300 \text{ MeV}/c^2$ $B \text{ vertex } \chi^2/\text{ndof} < 6$		
Channel specific cuts		
$B_s^0 \rightarrow J/\psi\phi$	$B^0 \rightarrow J/\psi K^{*0}$	$B^+ \rightarrow J/\psi K^+$
$p_T(\phi) > 1000 \text{ MeV}/c$	$p_T(K^{*0}) > 1000 \text{ MeV}/c$	$p_T(K^+) > 1300 \text{ MeV}/c$
$\phi\text{-vertex } \chi^2/\text{ndof} < 25$	$K^{*0}\text{-vertex } \chi^2/\text{ndof} < 25$	
$m(\phi) < 1045 \text{ MeV}/c^2$	$m(K^{*0}) \pm 120 \text{ MeV}/c^2$	
	$p_T(B^0) > 2000 \text{ MeV}/c$	

The *selection efficiency* is defined as the number of offline selected generated signal events that pass the L0, HLT1 and HLT2 selections divided by the number of generated signal event passing the L0 and HLT1 triggers and offline selections. From Table 7.12, similar selection efficiencies are observed for the three channels. The loss of efficiency with respect to offline is mainly due to the tighter cut on the muon transverse momentum.

Table 7.12: Selection efficiencies [%] for the $B \rightarrow J/\psi(\mu\mu)X$ channels.

$B_s^0 \rightarrow J/\psi\phi$	$B^0 \rightarrow J/\psi K^{*0}$	$B^+ \rightarrow J/\psi K^+$
77.21	78.45	78.28

The *total trigger efficiency* of the HLT2 exclusive $B_s^0 \rightarrow J/\psi\phi$ line is lower than the one reached by the inclusive $J/\psi \rightarrow \mu\mu$ line [123]:

$$\varepsilon_{\text{trigger}} = \varepsilon_{\text{L0}} \times \varepsilon_{\text{HLT1}} \times \varepsilon_{\text{HLT2,exclusive}} = 93.9\% \times 80\% \times 77\% \sim 57.8\% \quad (7.149)$$

$$\varepsilon_{\text{trigger}} = \varepsilon_{\text{L0}} \times \varepsilon_{\text{HLT1}} \times \varepsilon_{\text{HLT2,inclusive}} = 93.9\% \times 80\% \times 95\% \sim 70\% \quad (7.150)$$

with ε_{L0} the first level trigger efficiency with respect to offline selected events, $\varepsilon_{\text{HLT1}}$ the efficiency of the HLT1 lifetime unbiased di-muon alley with respect to offline selected and L0-triggered events, $\varepsilon_{\text{HLT2,inclusive}}$ $\varepsilon_{\text{HLT2,exclusive}}$ the efficiencies of the inclusive $J/\psi \rightarrow \mu\mu$ and exclusive $B_s^0 \rightarrow J/\psi\phi$ lines with respect to L0-, HLT1-triggered and offline-selected events.

¹⁰Cuts on the track- χ^2 and on the momentum of $K^\pm$ and $\pi^\pm$ defined in the offline selections are not used in the HLT2 environment, as they result in a significant drop in efficiency without rejecting much background. No particle identification cut is applied at online level.

The *trigger rate* R of minimum bias events passing L0, HLT1 and HLT2 at an operational luminosity of $\mathcal{L} \sim 2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, and assuming a visible cross-section of 102.4 mb, is given by:

$$R = r_{\text{BC}} \cdot \varepsilon_{\text{MB/L0}} \cdot \varepsilon_{\text{HLT1} \cdot \text{HLT2}} \quad (7.151)$$

where r_{BC} is the bunch crossing rate with at least one interaction (14.67 MHz), $\varepsilon_{\text{MB/L0}} = 0.0599$ is the efficiency of L0 trigger applied to minimum bias events, $\varepsilon_{\text{HLT1} \cdot \text{HLT2}}$ is the fraction of L0-stripped minimum bias events selected by the HLT1 and the HLT2 cuts.

The selected minimum bias candidates are classified in different categories:

- *Ghost*. At least one final-state particle used to form the candidate is a ghost, which is a track that does not match to any Monte Carlo particle.
- *From Primary Vertex*. The candidate particle has at least one final state daughter coming directly from the primary vertex or a short lived resonance, and the event is not a pile-up.
- *All From Same Primary Vertex*. The candidate particle final state daughters all come from the same primary vertex or from short lived resonances from the same primary vertex.
- *All From Different Primary Vertices*. The final-state particles used to form the candidate are matched to true particles from at least two different collisions.
- $b\bar{b}$. At least one final-state particle used to form the candidate is matched to a true decay product of a b-hadron, in the scenario that there is no ghost nor pile-up detected.

To achieve a rate of a few Hz in each channel, as requested by the LHCb triggering system, the cuts of Table 7.11 are not sufficient, especially for the two control channels. The corresponding numbers are given in brackets in Table 7.13. To lower the rates, a method relying on prescaling the sidebands is used¹¹.

In the prescaling method, different regions are defined within the mass distributions to which different *Prescaling Factors (PF)* are applied. In the signal region, all the events are kept, hence $PF = 1$, while only a reduced fraction is retained for the side bands, $0 < PF < 1$.

The prescaling method is applied to the B mass distributions. In the $\pm 300 \text{ MeV}/c^2$ B mass window, two different boxes are defined. The first one represents the region with $m(B) \pm 100 \text{ MeV}/c^2$ and it called *signal box*. The second one contains masses $m(B) \pm 300 \text{ MeV}/c^2$ and is called *combinatorics box*. The prescaling factors PF are set to 1 for the signal box and to 0.05 for the combinatorial box. The 0.05 value is a reasonable starting point for the analysis, while being a good compromise between the amount of events to be kept in the side bands and the final minimum bias rates to be reduced down to a few Hz.

¹¹The HLT2 selection cuts could be tightened, especially the p_T cuts. However, this could induce a significant loss in the selection efficiencies, as well as potentially introduce biases. A refit of the tracks could be considered to improve the mass resolutions and therefore allow narrower mass window cuts. However, refitting tracks is relatively time-consuming.

Table 7.13 shows the trigger rates using the prescaling technique. The signal categories to which the remaining minimum bias candidates belong are also given.

When comparing the trigger rates obtained with the prescaling method with the ones obtained without prescaling (given in brackets in Table 7.13), they are typically reduced by a factor of two, even though a factor of 0.05 is applied on 2/3 of the B mass window, corresponding to the combinatorics boxes. This is due to the fact that without prescaling, already half of the events have candidates in the signal boxes, which remain when the sidebands are prescaled.

Table 7.13: Trigger rates, number of events and nature of the selected minimum bias candidates after prescaling the B mass window.

	$B_s^0 \rightarrow J/\psi \phi$	$B^0 \rightarrow J/\psi K^{*0}$	$B^+ \rightarrow J/\psi K^+$
Minbias Rate [Hz]	3.0 ± 1.7 (5.9 ± 2.4)	14.8 ± 3.8 (24.6 ± 4.9)	8.9 ± 3.0 (19.7 ± 4.4)
Total Number of Events	3 (6)	15 (25)	9 (20)
Ghosts	0 (0)	9 (16)	0 (6)
From Primary Vertex	4 (6)	17 (47)	8 (17)
All From Same Primary Vertex	0 (0)	5 (10)	4 (7)
From Different Primary Vertices	2 (3)	4 (6)	1 (2)
b $\bar{b}$	0 (1)	0 (1)	0 (1)

The trigger rates are $\sim 3 \pm 2$ Hz, $\sim 15 \pm 4$ Hz and $\sim 9 \pm 3$ Hz for the $B_s^0 \rightarrow J/\psi \phi$, $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ channels respectively¹². The combined trigger rate is 17.7 ± 4.2 Hz (32.5 ± 5.7 Hz without prescaling), which is much lower than the trigger rate of the inclusive $J/\psi \rightarrow \mu^+ \mu^-$ line of ~ 200 Hz¹³.

Using the HLT2 inclusive or exclusive trigger lines hence results from a compromise between the selection efficiency achieved and the trigger rate obtained. In the first years of data-taking, inclusive selections are favored, as they are based on simpler selection cuts than exclusive lines. With an increased luminosity, exclusive selections will be a good remedy to handle high trigger rates.

¹²These rates could be even further reduced if needed, by lowering the values of the prescaling factors PF used for the combinatorics boxes.

¹³The main contribution to background comes from prompt J/ψ .

7.3.4 The $B_s^0 \rightarrow J/\psi\phi$ Offline Selection

The following studies are based on the $B_s^0 \rightarrow J/\psi\phi$ offline selection described in [115] using Monte Carlo events generated in the *LHCb Data Challenge 2006 (DC06)*. In this cut-based selection, each cut is chosen sequentially, with a maximization of the number of signal event for a given reasonable background level. This method offers the possibility of studying the impact of each single variable on the analysis. The offline selection has been especially designed to fulfill the two following criteria:

- *Minimizing the proper time and angular acceptance distortions (defined in Section 7.6).* These have to be minimized and be made as similar as possible among the signal and the control channels (angular and proper time acceptances for the $B^0 \rightarrow J/\psi K^{*0}$ channel ; proper time acceptance for the $B^+ \rightarrow J/\psi K^+$ channel). As a consequence, the corrections to apply for the distortions would be lower, reducing the associated systematic errors. Using a lifetime unbiased selection has also an advantage of using the negative tail of the proper time distribution to estimate its resolution. Moreover, as the CP-even and CP-odd components have different proper time distributions, cutting away part of the proper time spectrum would affect them differently, affecting indirectly the angular distributions given by the superposition of the two CP-components [123].
- *Selecting as similar as possible among the signal and control channels.* This ensures that the selected b-hadrons have similar total and transverse momentum distributions. This is important to allow the tagging performance determined on the B^0 and B^+ control channels to be applied on the B_s^0 channel with minimal correction¹⁴.

The offline selection profits from the information provided by the RICHs devices, which is mostly used to discriminate between $\pi^\pm$, $K^\pm$ and p (Subsection 2.6.1). Once the Cherenkov rings are associated to tracks of the event, a logarithmic likelihood is computed starting with the pion mass hypothesis for all particles. A best *Particle IDentification (PID)* hypothesis is obtained for each track by optimizing iteratively the log-likelihood. The *Difference in Log-Likelihood (DLL)* between a given PID hypothesis and the pion hypothesis is available for physics analyses, which is given for a particle A by [27]:

$$DLL_A = \Delta \ln \mathcal{L}_{A\pi} = \ln \mathcal{L}_A - \ln \mathcal{L}_\pi = \ln \frac{\mathcal{L}_A}{\mathcal{L}_\pi} \quad (7.152)$$

with $\mathcal{L}_A$ the likelihood of the A hypothesis combined from the various identification devices. The DLL between two particles hypotheses A and B is derived as:

$$\Delta \ln \mathcal{L}_{AB} = \Delta \ln \mathcal{L}_{A\pi} - \Delta \ln \mathcal{L}_{B\pi} \quad (7.153)$$

The $J/\psi \rightarrow \mu^+ \mu^-$ part is selected almost identically for the three channels with the cuts summarized in Table 7.14. For the $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ channels, cuts on the PID likelihood, $\Delta \ln \mathcal{L}_{K\pi}$, are added to lower the amount of muons coming from decays in flight that can fake a J/ψ candidate¹⁵. This background is removed by the tight ϕ mass window cut in the $B_s^0 \rightarrow J/\psi\phi$ case.

¹⁴In the untagged analysis, this requirement does not hold. An optimized selection is described in [115].

¹⁵The difference between π and μ is neglected in the RICH particle ID information, hence $\Delta \ln \mathcal{L}_{K\pi} = \Delta \ln \mathcal{L}_{K\mu}$. A fake J/ψ can be made adding a real μ with a π or K decaying in flight. If it is a pion, it cannot be detected. If it is a kaon, it will likely pass through RICH1 before decaying, whence the usefulness of this cut.

This page is a parenthesis in the description of the offline selection to illustrate the $J/\psi \rightarrow \mu^+\mu^-$ candidates that have been recorded in 2010 with the LHCb spectrometer. They correspond to a sample of 12.8 nb^{-1} at a centre of mass energy of 7 TeV (June 1st 2010).

The $J/\psi \rightarrow \mu^+\mu^-$ mass distribution is shown in Figure 7.14 (top) [151]. The candidates have been selected by much looser cuts than the ones developed on the DC06 Monte Carlo data and given in Table 7.14.

J/ψ candidates coming from B -decays have been recorded in this 2010 data sample. They are observed from the distribution of pure signal J/ψ pseudo proper times t_z , which are defined by:

$$t_z = \frac{\Delta z}{p_z} \cdot m(J/\psi) \quad (7.154)$$

where p_z is the projection of the J/ψ momentum on the beam direction and Δz is the z distance between the primary vertex and the decay vertex. They are characterized by large values of t_z (Figure 7.14, bottom).

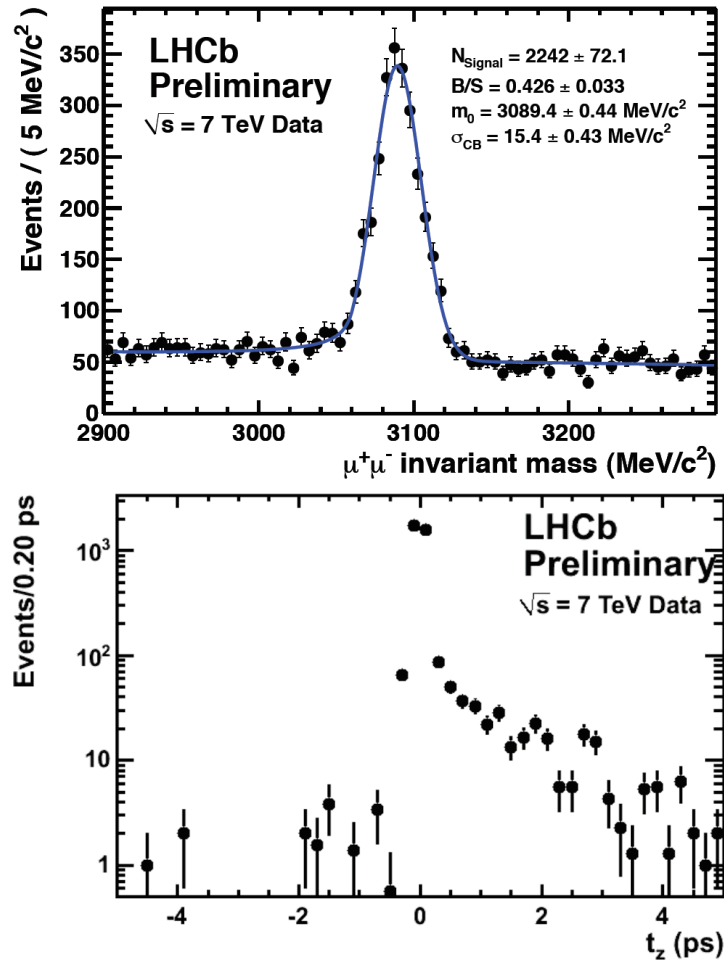


Figure 7.14: $\mu^+\mu^-$ invariant mass distribution (top) and pseudo proper time distribution of pure signal (bottom) corresponding to a sample of 12.8 nb^{-1} from 2010 real data at $\sqrt{s}=7 \text{ TeV}$ recorded at LHCb. B candidates are observed at large values of t_z [149, 150].

Only the events that survive the J/ψ selection are used as input for the ϕ , K^{*0} and $K^\pm$ selections. This is due to the fact that the J/ψ act as a filter, which lowers significantly the background for the selection of the second daughter particles of the B mesons belonging to the $B \rightarrow J/\psi X$ family. The selection cuts applied for the three decay modes are summarized in Table 7.14.

To illustrate the usefulness of the cuts on the PID likelihood $\Delta \ln \mathcal{L}_{K\pi}$, inclusive K^+K^- candidates from 2009 real data at $\sqrt{s} = 900$ GeV are used. Figure 7.15 shows their mass distribution, without using the PID information (top) and after applying it (bottom), where the ϕ signal mass peak (red line) appears clearly from the remaining background (green line).

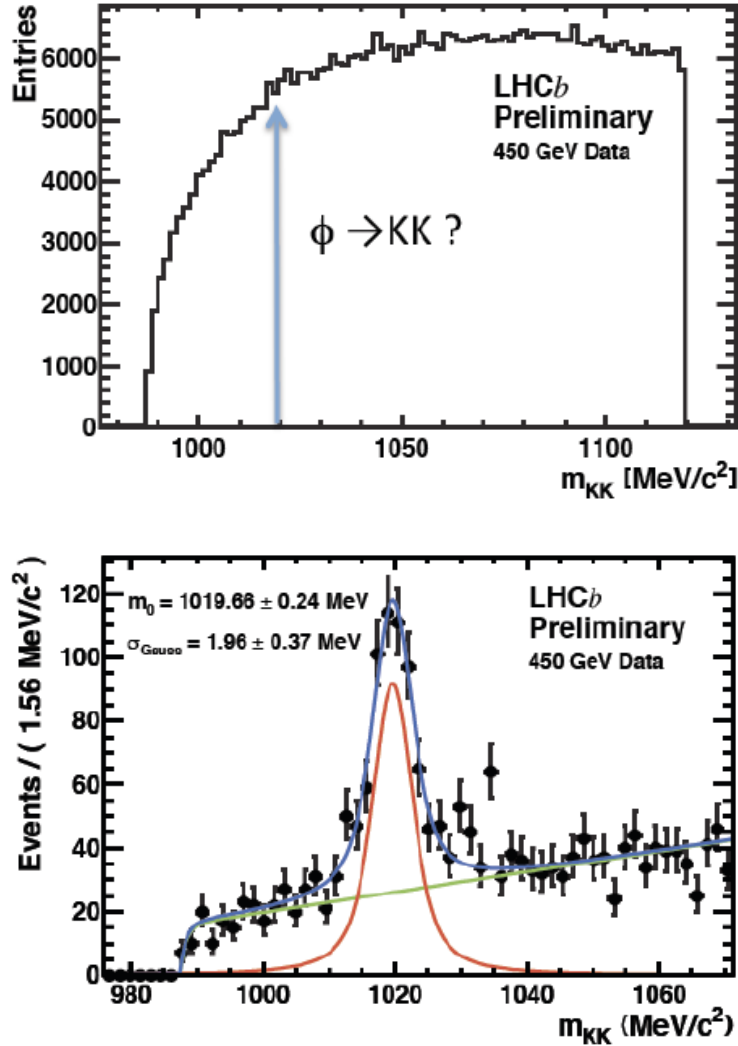


Figure 7.15: Inclusive K^+K^- invariant mass distribution from 2009 real data at $\sqrt{s}=900$ GeV before (top) and after (bottom) applying the PID information provided by the RICH detectors. The signal peak (red line) is clearly distinguishable from the background component (green line) [152].

The B_s^0 , B^0 and B^+ mesons are selected using the same criteria based on a vertex quality cut $\chi_{\text{vtx}}^2 < 5$ and an *Impact Parameter Significance (IPS)* cut¹⁶ with respect to the primary vertex, $\text{IPS} < 5$. If several primary vertices are found, the one with the smallest IPS is chosen. An additional cut on the B^0 transverse momentum, $p_T > 2 \text{ GeV}/c$, is used to lower the prompt background that has a lower average p_T . As the masses of the B^0 and B^+ are close, true $B^+ \rightarrow J/\psi K^+$ events associated with a prompt pion from the underlying event need to be removed from the selected $B^0 \rightarrow J/\psi K^{*0}$ sample. This is performed by removing events from $B^0 \rightarrow J/\psi K^{*0}$ where the J/ψ and the K^+ alone have an invariant mass compatible with the B^+ mass within $\pm 60 \text{ MeV}/c^2$. The removal of this background is important, as it populates the upper sideband of the mass spectrum, which is needed to estimate the background properties under the B^0 signal peak [115]. If several B candidates are selected for one event, the one with the smallest $\chi_{\text{vtx}}^2/\text{nDoF}$ is kept.

Table 7.14: Offline selection cuts for the $B_s^0 \rightarrow J/\psi \phi$ signal and $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ control channels [115].

Common cuts		
J/ψ Selection		
$\Delta \ln \mathcal{L}_{\mu\pi} > -5$		
$\mu \text{ track } \chi_{\text{track}}^2/\text{nDoF} < 3$		(< 5 for $B_s^0 \rightarrow J/\psi \phi$)
$p_T(\mu) > 500 \text{ MeV}/c$		
$\Delta \ln \mathcal{L}_{K\pi} < 5$		(none for $B_s^0 \rightarrow J/\psi \phi$)
$J/\psi \chi_{\text{vtx}}^2/\text{nDoF} < 6$		
$p_T(J/\psi) > 1 \text{ GeV}/c$		
$ M(\mu\mu) - M(J/\psi) < 3\sigma (= 42 \text{ MeV}/c^2)$		
B meson Selection		
$B \chi_{\text{vtx}}^2/\text{nDoF} < 5$		
$\text{IPS}(B) < 5$		
$ M(X) - M(B) < \pm 300 \text{ MeV}/c^2$		
Channel specific cuts		
$B_s \rightarrow J/\psi(\mu\mu)\phi(KK)$	$B^0 \rightarrow J/\psi(\mu\mu)K^*(K\pi)$	$B^+ \rightarrow J/\psi(\mu\mu)K^+$
φ Selection	K^{*0} Selection	K[±] Selection
$\Delta \ln \mathcal{L}_{K\pi} > 0$	$\Delta \ln \mathcal{L}_{K\pi} > 0$	$\Delta \ln \mathcal{L}_{K\pi} > 0$
	$\Delta \ln \mathcal{L}_{Kp} > -2$	$\Delta \ln \mathcal{L}_{Kp} > -2$
$K^\pm \text{ track } \chi_{\text{track}}^2/\text{nDoF} < 10$	$K^\pm \text{ and } \pi \text{ track } \chi_{\text{track}}^2/\text{nDoF} < 10$	$K^\pm \text{ track } \chi_{\text{track}}^2/\text{nDoF} < 4$
$p(K^\pm) > 2 \text{ GeV}/c$	$p(K^\pm) \text{ and } p(\pi^\pm) > 2 \text{ GeV}/c$	$p(K^\pm) > 10 \text{ GeV}/c$
$p_T(\phi) > 1 \text{ GeV}/c$	$p_T(K^{*0}) > 1 \text{ GeV}/c$	$p_T(K^\pm) > 1.3 \text{ GeV}/c$
$\phi \chi_{\text{vtx}}^2/\text{nDoF} < 20$	$K^{*0} \chi_{\text{vtx}}^2/\text{nDoF} < 20$	
$ M(KK) - M(\phi) < 3\sigma$	$ M(K\pi) - M(K^{*0}) < 2\sigma$	
B⁰ Selection		
$p_T(B^0) > 2 \text{ GeV}/c$		
$ M(\mu\mu K) - M(B^+) > 60 \text{ MeV}/c^2$		

After the offline selection, the transverse momentum distributions are compared for the B_s^0 , B^0 and B^+ mesons to ensure that they are the same [123].

¹⁶The impact parameter significance is equal to the impact parameter (IP) divided by its error σ_{IP} , where IP is the perpendicular distance from the primary vertex to the line defined by the B_s^0 meson momentum vector.

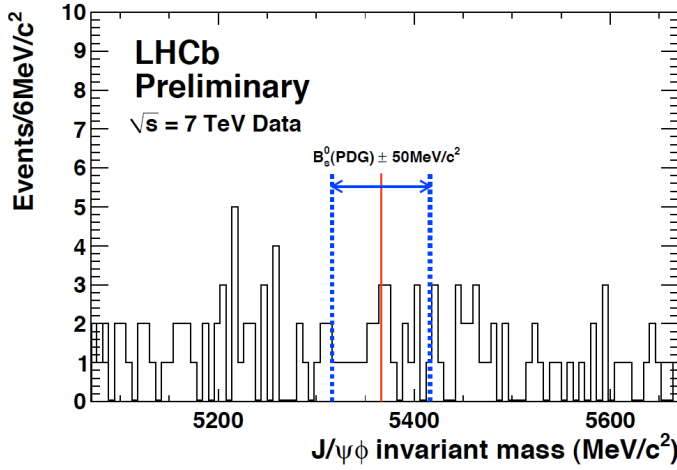


Figure 7.16: $B_s^0 \rightarrow J/\psi\phi$ candidates collected at LHCb in 12.8 nb^{-1} of 2010 real data ($\sqrt{s}=7 \text{ TeV}$) [149].

From 12.8 nb^{-1} of 2010 real data, 23 B_s^0 candidates have been selected in the narrow mass window of $\pm 50 \text{ MeV}/c^2$ with looser cuts than those of Table 7.14 (Figure 7.16). Only one candidate remains after applying the cut on the proper time explained in Subsection 7.3.2 for B^0 and B^+ .

Offline Selection of MC09 $B_s^0 \rightarrow J/\psi\phi$ Events

For the studies of Section 7.6, the full MC09 Monte Carlo $B_s^0 \rightarrow J/\psi\phi$ event sample is used, on which the cuts of Table 7.14 are applied. The number of processed events and the number of events that are L0-, HLT1-triggered and offline-selected are given in Table 7.15. The v24r4 version of the DaVinci package is used.

Table 7.15: MC09 $B_s^0 \rightarrow J/\psi\phi$ events processed and number of which are L0- HLT-triggered and offline-selected.

Events processed	Events L0-, HLT1-triggered and offline-selected
10,657,141	1,132,009

Annual Event Yield

The annual event yield S is calculated as [123]:

$$S = \mathcal{L}_{\text{int}} \times \sigma_{b\bar{b}} \times 2 \times f_{u,d,s} \times \text{BR}_{\text{vis}} \times \epsilon_{\text{tot}} \quad (7.155)$$

with $\mathcal{L}_{\text{int}}$ the integrated luminosity (2 fb^{-1} for one nominal year), $\sigma_{b\bar{b}}$ the $b\bar{b}$ production cross section (Table 7.3.4 ; 500 mb is used for the present signal yield estimations), the factor 2 accounting for the pair production of b quarks, $f_{u,d,s}$ the B meson production fraction (Table 7.3.4), BR_{vis} the visible branching fraction for the decay modes concerned (Table 7.3.4) and ϵ_{tot} the total efficiency given by:

$$\epsilon_{\text{tot}} = \epsilon_{\text{gen}} \times \epsilon_{\text{presel/gen}} \times \epsilon_{\text{sel/presel}} \times \epsilon_{\text{L0/sel}} (\times \epsilon_{\text{HLT/L0}}) \quad (7.156)$$

where ϵ_{gen} is the cut efficiency at generator level taking into account the requirement of having the two b hadrons inside the LHCb geometrical acceptance. The $\epsilon_{\text{presel/sel}}$ combines the acceptance efficiency for having all the decay products inside the LHCb geometrical acceptance with the reconstruction and

preselection cut efficiencies, where the preselection cuts are given in [115]. The $\varepsilon_{\text{sel/pre sel}}$ is the selection efficiency compared to the pre-selected events. The $\varepsilon_{\text{L0/sel}}$ is the efficiency of the L0-level trigger decision with respect to the selected events. The total selection efficiencies and the annual yields for one nominal year of data taking are given in Table 7.3.4 for the selected and L0-triggered events without or with applying the HLT1 trigger decision. These numbers do not account for the large uncertainty of $\sim 40\%$ on the σ_{bb} value at 14 TeV [42] nor for the branching fraction of $B_s^0 \rightarrow J/\psi\phi$ which is known with an accuracy of $\sim 35\%$ [18].

Table 7.16: Production cross sections at 14 TeV predicted by the DC06 Monte Carlo simulation [42, 43]. The double arrow $\Rightarrow$ indicates the existence of possible intermediate states. As an example, $\text{pp} \Rightarrow J/\psi X$ includes $\text{pp} \rightarrow b \rightarrow J/\psi X$. The prompt J/ψ cross section is $\sigma_{\text{pp} \rightarrow J/\psi X} \equiv \sigma_{\text{Pr}} = \sigma_{\text{pp} \Rightarrow J/\psi X} - \sigma_{\text{pp} \rightarrow b \Rightarrow J/\psi X} = 0.266 \text{ mb}$ [123].

Cross section	Value [mb]
σ_{pp}	102.9
$\sigma_{\text{pp} \rightarrow \text{bb}}$	0.698
$\sigma_{\text{pp} \Rightarrow J/\psi X}$	0.286
$\sigma_{\text{pp} \rightarrow b \Rightarrow J/\psi X}$	0.0204

Table 7.17: Branching fractions for all decays and B meson production fractions. Values from PDG and from the DC06 Monte Carlo simulation are indicated [123].

Branching fraction	PDG [18]	DC06
$\text{BR}(J/\psi \rightarrow \mu^+ \mu^-)$	$(5.93 \pm 0.06) \times 10^{-2}$	5.933×10^{-2}
$\text{BR}(J/\psi \rightarrow e^+ e^-)$	$(5.94 \pm 0.06) \times 10^{-2}$	5.933×10^{-2}
$\text{BR}(K^{*0} \rightarrow K^+ \pi^-)$	~ 1	66.57×10^{-2}
$\text{BR}(\phi \rightarrow K^+ K^-)$	$(49.2 \pm 0.6) \times 10^{-2}$	49.10×10^{-2}
$\text{BR}(B^0 \rightarrow J/\psi K^{*0})$	$(1.33 \pm 0.06) \times 10^{-3}$	1.291×10^{-3}
$\text{BR}(B_s^0 \rightarrow J/\psi \phi)$	$(9.3 \pm 3.3) \times 10^{-4}$	13.5×10^{-4}
$\text{BR}(B^+ \rightarrow J/\psi K^+)$	$(1.007 \pm 0.035) \times 10^{-3}$	1.008×10^{-3}
$\text{BR}_{\text{vis}}(B_s^0 \rightarrow J/\psi(\mu^+ \mu^-)\phi(K^+ K^-))$	$(2.71 \pm 0.96) \times 10^{-5}$	3.93×10^{-5}
$\text{BR}_{\text{vis}}(B_s^0 \rightarrow J/\psi(e^+ e^-)\phi(K^+ K^-))$	$(2.72 \pm 0.96) \times 10^{-5}$	3.93×10^{-5}
$\text{BR}_{\text{vis}}(B^0 \rightarrow J/\psi(\mu^+ \mu^-)K^{*0}(K\pi))$	$(5.25 \pm 0.24) \times 10^{-5}$	5.10×10^{-5}
$\text{BR}_{\text{vis}}(B^+ \rightarrow J/\psi(\mu^+ \mu^-)K^+)$	$(5.9 \pm 0.2) \times 10^{-5}$	5.98×10^{-5}
$f_u (\%)$	39.9 ± 1.1	40.5
$f_d (\%)$	39.9 ± 1.1	40.5
$f_s (\%)$	11.0 ± 1.2	10.0

For an integrated luminosity of 2 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$, the signal yields are estimated at 156,000 (117,000) for $B_s^0 \rightarrow J/\psi\phi$, 650,000 (489,000) for $B^0 \rightarrow J/\psi K^{*0}$ and 1,250,000 (942,000) for $B^+ \rightarrow J/\psi K^+$ modes after applying the L0-level trigger decision (+ the HLT1 trigger decision) (Table 7.3.4).

Table 7.18: Total selection efficiency ε_{tot} [%] before HLT1 (left), untagged event yield for selected and L0-triggered events (middle), and including HLT1 (right). The event yields correspond to an integrated luminosity of 2 fb^{-1} [123].

Channel	ε_{tot} [%]	Event yield after L0	Event yield after L0+HLT1
$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-)\phi(K^+ K^-)$	2.61 ± 0.01	156,000	117,000
$B^0 \rightarrow J/\psi(\mu^+ \mu^-)K^{*0}(K\pi)$	1.54 ± 0.01	648,000	489,000
$B^+ \rightarrow J/\psi(\mu\mu)K^+$	2.61 ± 0.01	1,248,000	942,000

7.3.5 Background Contributions

Two categories of background events are studied [115], *prompt* and *long-lived*.

The prompt background is due to accidental combinations of tracks produced at the primary vertex and together with true J/ψ . The invariant mass distribution of $B_s^0 \rightarrow J/\psi\phi$ candidates obtained from the $J/\psi \rightarrow \mu\mu$ inclusive Monte Carlo sample, containing $\sim 93\%$ of prompt J/ψ and $\sim 7\%$ of $B_{u,d,s} \rightarrow J/\psi X$ events, is shown in Figure 7.17 (left). The dark-filled histogram is the signal distribution centered on the B_s^0 nominal mass and the white-filled histogram the prompt background contribution. The reconstructed proper time distribution of the prompt background component only is shown in Figure 7.17 (right). The fit of a Gaussian function¹⁷ to the Monte Carlo data results in a resolution $\sigma_t \sim 0.043$ ps.

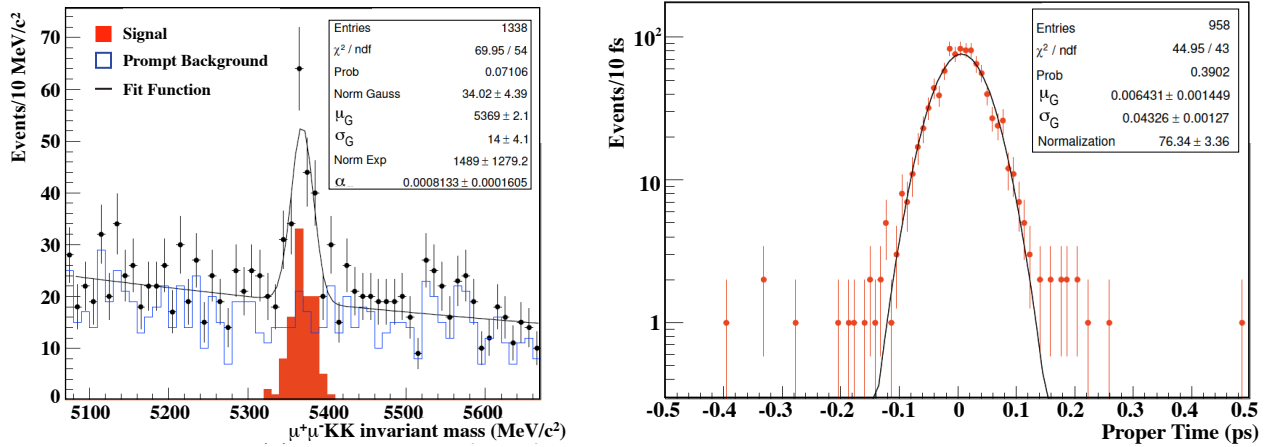


Figure 7.17: Invariant mass distribution of $B_s^0 \rightarrow J/\psi\phi$ candidates (signal and prompt background) in the $J/\psi \rightarrow \mu\mu$ inclusive sample containing $\sim 93\%$ of prompt J/ψ and $\sim 7\%$ of $B_{u,d,s} \rightarrow J/\psi X$ events (left). Reconstructed proper time distribution for the prompt background component only (right) [123].

The long-lived background has at least one track coming from a secondary vertex from b- or c-hadron decay and is dominated by real J/ψ . The invariant mass distribution of $B_s^0 \rightarrow J/\psi\phi$ candidates coming from $B_{u,d,s} \rightarrow J/\psi X$ samples is shown in Figure 7.18 (left). The dark-filled histogram is the signal distribution and the white-filled histogram the long-lived background. The reconstructed proper time distribution of the long-lived background component only is given in Figure 7.18 (right). It is fitted with a double exponential convolved with a double Gaussian function to describe the effect of the resolution. The fit gives the two slopes to be $\tau_1 = 0.18$ ps and $\tau_2 = 1$ ps with a relative fraction $f_{\tau_1} \sim 0.72$, and the resolution for the dominant Gaussian to be $\sigma_t = 0.039$ ps.

¹⁷A Gaussian distribution $\mathcal{G}$ centered at x_0 and of width σ_x is given as a function of the variable x as:

$$\mathcal{G}(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left(-\frac{1}{2}\left(\frac{x-x_0}{\sigma_x}\right)^2\right)$$

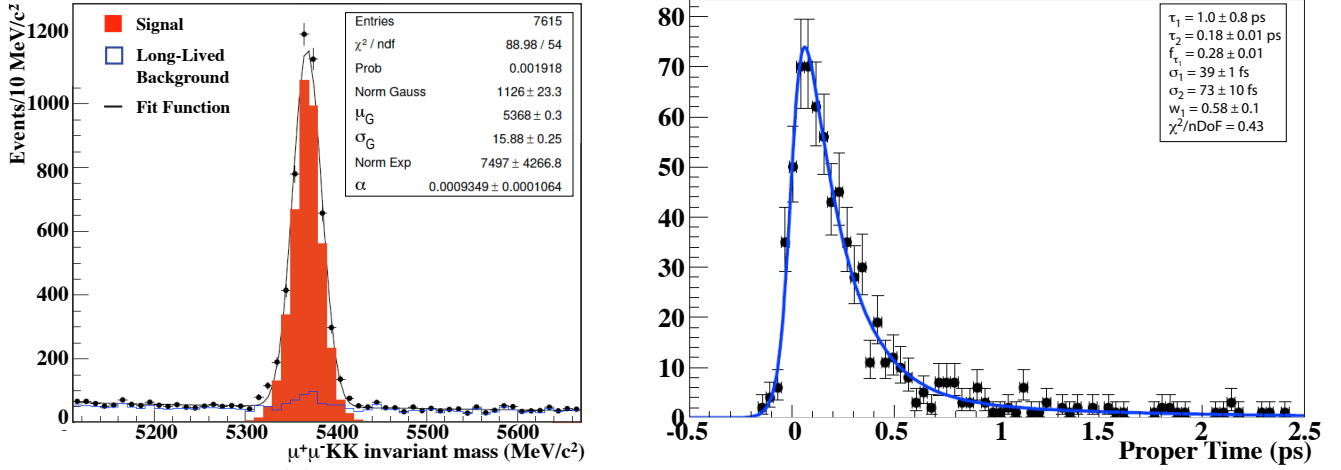


Figure 7.18: Invariant mass distribution of $B_s^0 \rightarrow J/\psi\phi$ candidates (signal and long-lived background) in the $B_{u,d,s} \rightarrow J/\psi X$ sample (left). Reconstructed proper time distributions for the long-lived background component only (right) [123].

The *Background over Signal ratios* (B/S) for the signal and control channels in a $\pm 50 \text{ MeV}/c^2$ mass window around the nominal B meson mass are given in Table 7.19 for both types of background¹⁸. The predominance of the prompt background is due to the fact that no cut on the impact parameter of any track is made in the lifetime unbiased offline selection. The larger background contributions for the B^0 channel compared to the B_s^0 and B^+ ones come from K^{*0} due to its wide mass width.

Table 7.19: B/S ratio estimated in $\pm 50 \text{ MeV}/c^2$ mass window for prompt and long-lived backgrounds for the three different channels [123].

Channel	B_{Pr}/S	B_{LL}/S
$B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$	1.6 ± 0.6	0.51 ± 0.08
$B^0 \rightarrow J/\psi(\mu\mu)K^{*0}(K\pi)$	5.2 ± 0.3	1.53 ± 0.08
$B^+ \rightarrow J/\psi(\mu\mu)K^+$	1.6 ± 0.2	0.29 ± 0.06

As the $\phi_s^{J/\psi\phi}$ phase is extracted from a fit to time-dependent decay angular distributions, the impact of the background on the sensitivity depends not only on the total contamination in the signal region, but also on its proper time and angular distributions. Even though the prompt background is dominant (Table 7.19), it is expected to have a smaller impact on the $\phi_s^{J/\psi\phi}$ sensitivity than the long-lived background, since it is concentrated in a region of a small proper time ($t < 0.2 \text{ ps}$). Moreover, its proper time distribution is well separated by the fit procedure [115].

For real data, the background will be extrapolated from the sidebands of the invariant B_s^0 mass distribution to describe the background in the signal region. Then the proper time and decay angular distributions for the background will be parameterized for the fit.

¹⁸A detailed explanation of how these numbers have been calculated is given in [123].

7.4 The Fit Model

The fit model presented here is defined in [153] (version v2) as the latest available official model recommended by the LHCb β_s working group to be used for sensitivity studies to $\phi_s^{J/\psi\phi}$. It is therefore the one used in Section 7.7. The model comprises three parts, the proper time, the angular and the mass models, which are described in the following separately for each the signal, long-lived background and prompt background contributions.

7.4.1 The Model for Proper Time Distribution

Signal

The time-dependent terms $u_k(t)$ of Equations 7.136-7.141 of the untagged analysis are convolved with a proper time resolution function $PR_S(t)$ describing the resolution of the LHCb spectrometer on the proper time measurement. The symbol $\otimes$ is used for the convolution.

$$u'_k(t) = u_k(t) \otimes PR_S(t) \quad (7.157)$$

with the $PR_S(t)$ resolution function being a triple Gaussian

$$PR_S(t) = f_{(t,S,1)} \cdot \mathcal{G}(\mu_{(t,S,1)}, \sigma_{(t,S,1)}) + f_{(t,S,2)} \cdot \mathcal{G}(\mu_{(t,S,2)}, \sigma_{(t,S,2)}) + (1 - f_{(t,S,1)} - f_{(t,S,2)}) \cdot \mathcal{G}(\mu_{(t,S,3)}, \sigma_{(t,S,3)}) \quad (7.158)$$

Instead of using a triple Gaussian in the fit model, a single Gaussian with a mean proper time resolution $\langle\sigma_{(t,S)}\rangle$ is used, which is calculated as:

$$\langle\sigma_{(t,S)}\rangle = \sqrt{f_{(t,S,1)} \cdot \sigma_{(t,S,1)}^2 + f_{(t,S,2)} \cdot \sigma_{(t,S,2)}^2 + (1 - f_{(t,S,1)} - f_{(t,S,2)}) \cdot \sigma_{(t,S,3)}^2} \quad (7.159)$$

In Monte Carlo studies only, the proper time resolution can be obtained by fitting the $PR_S(t)$ function to the residual distribution between the reconstructed and generated proper times of the L0-, HLT1-triggered and selected Monte Carlo $B_s^0 \rightarrow J/\psi\phi$ signal events. This is not possible for real data. Instead, the proper time resolution will be estimated from a fit to the reconstructed proper time using an exponential function with an average lifetime τ_{eq} convolved with a single Gaussian to model the resolution. τ_{eq} can be expressed as a function of the two states composing the B_s^0 meson that evolve in time with τ_L and τ_H . In order to derive this function, Equation 7.142 is rewritten in terms of Γ_s

$$\begin{aligned} \frac{d^2\Gamma}{dt d\cos\theta} \propto & (1 - |A_\perp|^2) e^{-\Gamma_s t} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s^{J/\psi\phi}) \cdot \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \cdot (1 + \cos^2\theta) \\ & + |A_\perp|^2 e^{-\Gamma_s t} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos(\phi_s^{J/\psi\phi}) \cdot \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \cdot (1 - \cos^2\theta) \cdot 2 \end{aligned} \quad (7.160)$$

and is integrated over $d\cos(\theta)$:

$$\begin{aligned} \frac{d\Gamma}{dt} \propto & e^{-\Gamma_s t} \left[(|A_\perp|^2 + (1 - |A_\perp|^2)) \cdot \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \\ & + e^{-\Gamma_s t} \left[(|A_\perp|^2 \cos(\phi_s^{J/\psi\phi}) - (1 - |A_\perp|^2) \cos(\phi_s^{J/\psi\phi})) \cdot \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \right] \end{aligned} \quad (7.161)$$

Using $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and $\Gamma_s = 0.5 \cdot (\Gamma_L + \Gamma_H)$, and expressing the $\cosh(\frac{1}{2} \cdot \Delta\Gamma_s t)$ and $\sinh(\frac{1}{2} \cdot \Delta\Gamma_s t)$ in terms of exponentials, it gives:

$$\begin{aligned} \frac{d\Gamma}{dt} &\propto e^{-\frac{(\Gamma_L + \Gamma_H)}{2} t} \left[|A_\perp|^2 + (1 - |A_\perp|^2) \right] \cdot \frac{1}{2} \left(e^{\frac{(\Gamma_L - \Gamma_H)}{2} t} + e^{-\frac{(\Gamma_L - \Gamma_H)}{2} t} \right) \\ &\quad + e^{-\frac{(\Gamma_L + \Gamma_H)}{2} t} \left[|A_\perp|^2 \cos(\phi_s^{J/\psi\phi}) - (1 - |A_\perp|^2) \cos(\phi_s^{J/\psi\phi}) \right] \cdot \frac{1}{2} \left(e^{\frac{(\Gamma_L - \Gamma_H)}{2} t} - e^{-\frac{(\Gamma_L - \Gamma_H)}{2} t} \right) \\ &\propto [|A_\perp|^2 + (1 - |A_\perp|^2)] \cdot \frac{1}{2} (e^{-\Gamma_H t} + e^{-\Gamma_L t}) \\ &\quad + \cos(\phi_s^{J/\psi\phi}) \cdot [|A_\perp|^2 - (1 - |A_\perp|^2)] \cdot \frac{1}{2} (e^{-\Gamma_H t} - e^{-\Gamma_L t}) \end{aligned} \quad (7.162)$$

τ_{eq} is obtained by integrating Equation 7.162 over t from 0 to ∞ and taking its inverse:

$$\begin{aligned} \tau_{\text{eq}} = \frac{1}{\Gamma} &= \left((1 - \cos(\phi_s^{J/\psi\phi})) \frac{|A_0|^2}{2} + (1 - \cos(\phi_s^{J/\psi\phi})) \frac{|A_{||}|^2}{2} + (1 + \cos(\phi_s^{J/\psi\phi})) \frac{|A_\perp|^2}{2} \right) \tau_H + \\ &\quad \left((1 + \cos(\phi_s^{J/\psi\phi})) \frac{|A_0|^2}{2} + (1 + \cos(\phi_s^{J/\psi\phi})) \frac{|A_{||}|^2}{2} + (1 - \cos(\phi_s^{J/\psi\phi})) \frac{|A_\perp|^2}{2} \right) \tau_L. \end{aligned} \quad (7.163)$$

In the $B_s^0 \rightarrow J/\psi\phi$ DC06 Monte Carlo event generation, $\tau_L = 1.391$ ps and $\tau_H = 1.538$ ps have been used, leading to $\tau_{\text{eq}} = 1.415$ ps [123]. From the fit of the true and reconstructed proper time distributions, this value has been found back within the errors [115]. An average resolution $\langle\sigma_{(t,S)}\rangle = 0.039$ ps is obtained, with similar results for the $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$ control channels and from a fit of the prompt component of the background [153].

The measurement of the proper time t is the result of a combination of the distance between the primary and B_s^0 decay vertices and the B_s^0 momentum. Its uncertainty is dominated by the former. The proper time resolution model can thus be improved by taking into account the vertex position uncertainties varying from event to event (dt), leading to a per-event proper time resolution model [154].

However, studies indicate that for data statistics below 2 fb^{-1} , using per event proper time uncertainties instead of a constant proper time error does not significantly improve the sensitivity to $\phi_s^{J/\psi\phi}$ [123]. Therefore, the constant proper time resolution $\langle\sigma_{(t,S)}\rangle = 0.039$ ps is used in the sensitivity studies of Section 7.7, together with the assumption of a flat proper time acceptance [153]. This assumption is discussed in Section 7.6.

Long-Lived Background

In Monte Carlo studies, the proper time of the long-lived background is obtained by fitting with a fit function $P_{\text{LL}}(t)$ the proper time distribution of events coming from the $B_{u,d,s} \rightarrow J/\psi X$ inclusive sample, after removing the signal contribution (Figure 7.18, right). $P_{\text{LL}}(t)$ is a double exponential decay function convolved with a single Gaussian function:

$$P_{\text{LL}}(t) = \left(f_{(t,\text{LL},1)} \cdot e^{-\frac{t}{\tau_{(t,\text{LL},1)}}} + (1 - f_{(t,\text{LL},1)}) \cdot e^{-\frac{t}{\tau_{(t,\text{LL},2)}}} \right) \otimes \mathcal{G}(t, \sigma_{t,\text{LL}}) \quad (7.164)$$

Using DC06 events, the mean lifetimes are found to be $\tau_{(t,LL,1)} = 0.161$ ps and $\tau_{(t,LL,2)} = 1.114$ ps with a relative fraction $f_{(t,LL,1)} = 0.78$ and the width is found to be $\sigma_{(t,LL)} = 0.066$ ps [153]¹⁹.

Prompt Background

In Monte Carlo studies, the proper time of the prompt background is obtained by fitting with a fit function $P_{Pr}(t)$ the proper time distribution of events coming from the $J/\psi \rightarrow \mu\mu$ inclusive sample, after removing the signal contribution (Figure 7.18, right). $P_{Pr}(t)$ is a single Gaussian:

$$P_{Pr}(t) = \mathcal{G}(\mu_{(t,Pr)}, \sigma_{(t,Pr)}) \quad (7.165)$$

Using DC06 events, the width is found to be $\sigma_{(t,Pr)} = 0.044$ ps [153]¹⁹.

7.4.2 The Model for Angular Distribution

Signal

The angular functions $f_k^{TR}(\theta, \psi, \varphi)$ and $f_k^{HEL}(\theta_H, \psi, \chi)$ for the decay final states of the signal are defined in Table 7.1.5 for the transversity basis and in Table 7.1.5 for the helicity basis. In principle, they must be convolved with angular resolution functions $AR_{(S, \Omega_{TR/HEL,i})}(f(\Omega_{TR/HEL,i}))$, with $\Omega_{TR} = \{\theta, \psi, \varphi\}$ for the transversity angles or $\Omega_{HEL} = \{\theta_H, \psi, \chi\}$ for the helicity ones, to take into account the effect of the LHCb spectrometer on the angle measurements:

$$\begin{aligned} f_k'^{TR}(\theta, \psi, \varphi) &= f_k^{TR}(\theta, \psi, \varphi) \otimes AR_{S,\theta}(\cos(\theta)) \otimes AR_{S,\psi}(\cos(\psi)) \otimes AR_{S,\varphi}(\varphi) \\ f_k'^{HEL}(\theta_H, \psi, \chi) &= f_k^{HEL}(\theta_H, \psi, \chi) \otimes AR_{S,\theta_H}(\cos(\theta_H)) \otimes AR_{S,\psi}(\cos(\psi)) \otimes AR_{S,\chi}(\chi) \end{aligned} \quad (7.166)$$

The angular resolutions have been estimated for the angles of the transversity basis to be 27 mrad for θ , 27 mrad for φ and 20 mrad for ψ from triple-Gaussian fits to the residual distribution between the reconstructed and the generated angles of L0-, HLT1-triggered and offline-selected DC06 signal $B_s^0 \rightarrow J/\psi \phi$ events [123]. These angular resolution distributions are not included in the model used for the sensitivity studies [153].

The angular acceptance dependence for the signal is also neglected in the fit model [153]. However, a description of the angular acceptance is developed using MC09 Monte Carlo data in Section 7.6, where the importance of taking them eventually into account in the analysis on real data is highlighted.

¹⁹The values quoted here are nearly identical to the parameters extracted from the fits to the distributions of Figures 7.17-7.18. The small differences arise from the fact that the selection analyses kept evolving after the parameters were frozen for the fit studies.

Long-Lived and Prompt Background

Flat angular distribution models $A_{LL}(\Omega_{TR/HEL})$ and $A_{Pr}(\Omega_{TR/HEL})$ are used in the fit model for the long-lived and prompt background components respectively [153]. No description of the angular acceptance variations is added to the fit model. However, some acceptance variations in the decay angles have been observed for the long-lived background, which are the result of the non-negligible fraction of partially reconstructed signal events. For the prompt component, no acceptance variations in the decay angles are observed, which is due to the fact that most of the events come from combinatorics [123].

7.4.3 The Model for Mass Distribution

Signal

The mass distribution for the signal is obtained by fitting the $\mu^+\mu^-K^+K^-$ invariant mass distribution of the L0-, HLT1-triggered and offline-selected $B_s^0 \rightarrow J/\psi\phi$ events with a triple-Gaussian $M_S(m)$:

$$M_S(m) = f_{(m,S,1)} \cdot \mathcal{G}(\mu_{(m,S,1)}, \sigma_{(m,S,1)}) + f_{(m,S,2)} \cdot \mathcal{G}(\mu_{(m,S,2)}, \sigma_{(m,S,2)}) + (1 - f_{(m,S,1)} - f_{(m,S,2)}) \cdot \mathcal{G}(\mu_{(m,S,3)}, \sigma_{(m,S,3)}) \quad (7.167)$$

The average mass resolution $\langle\sigma_{(m,S)}\rangle$ is calculated as:

$$\langle\sigma_{(m,S)}\rangle = \sqrt{f_{(m,S,1)} \cdot \sigma_{(m,S,1)}^2 + f_{(m,S,2)} \cdot \sigma_{(m,S,2)}^2 + (1 - f_{(m,S,1)} - f_{(m,S,2)}) \cdot \sigma_{(m,S,3)}^2} \quad (7.168)$$

For DC06 Monte Carlo data, the average mass resolution obtained is $\langle\sigma_{(m,S)}\rangle = 16.2 \text{ MeV}/c^2$ [153].

Long-Lived Background

The mass distribution for the long-lived background is obtained by fitting the $\mu^+\mu^-K^+K^-$ invariant mass distribution of the $B_{u,d,s} \rightarrow J/\psi X$ inclusive sample with an exponential function $M_{LL}(m)$, after removing the signal contribution (Figure 7.18, left).

$$M_{LL}(m) = e^{-\alpha_{(m,LL)} \cdot m} \quad (7.169)$$

The slope is found to be $\alpha_{(m,LL)} = 0.001 \text{ (MeV}/c^2)^{-1}$ [153]¹⁹.

Prompt Background

The mass distribution for the prompt background is obtained by fitting the $\mu^+\mu^-K^+K^-$ invariant mass distribution of the $J/\psi \rightarrow \mu\mu$ inclusive sample with an exponential function $M_{Pr}(m)$, after removing the signal contribution (Figure 7.17, left).

$$M_{Pr}(m) = e^{-\alpha_{(m,Pr)} \cdot m} \quad (7.170)$$

The slope is found to be $\alpha_{(m,Pr)} = 0.0006 \text{ (MeV}/c^2)^{-1}$ [153]¹⁹.

7.4.4 The Full Fit Model

The *Probability Density Function (PDF)* for the proper time, angles and mass for the signal, $S(t, \Omega_{\text{TR/HEL}}, m)$, can be factorized between that of Equation 7.135 (corrected for taking into account the convolution with the proper time resolution model leading to the $u'_k(t)$ terms of Equation 7.157) and that for the invariant mass distribution of Equation 7.167:

$$S(t, \Omega_{\text{TR/HEL}}, m) = \left(\sum_{k=1}^6 u'_k(t) f_k^{\text{TR/HEL}}(\Omega_{\text{TR/HEL}}) \right) \cdot M_S(m) \quad (7.171)$$

The probability density function for the proper time, angles and mass for the long-lived background, $B_{LL}(t, \Omega_{\text{TR/HEL}}, m)$, is given by

$$B_{LL}(t, \Omega_{\text{TR/HEL}}, m) = P_{LL}(t) \cdot A_{LL}(\Omega_{\text{TR/HEL}}) \cdot M_{LL}(m) \quad (7.172)$$

and for the prompt background $B_{Pr}(t, \Omega_{\text{TR/HEL}}, m)$ by

$$B_{Pr}(t, \Omega_{\text{TR/HEL}}, m) = P_{Pr}(t) \cdot A_{Pr}(\Omega_{\text{TR/HEL}}) \cdot M_{Pr}(m) \quad (7.173)$$

The total probability density function, $\mathcal{P}_{tot}$, for the proper time, angles and mass for the signal, long-lived background and prompt background is the sum of the three contributions weighted by the fractions of the signal $f_S = 0.30$ and of the long-lived background $f_{LL} = 0.15$ [153]:

$$\mathcal{P}_{tot} = f_S \cdot S(t, \Omega_{\text{TR/HEL}}, m) + f_{LL} \cdot B_{LL}(t, \Omega_{\text{TR/HEL}}, m) + (1 - f_S - f_{LL}) \cdot B_{Pr}(t, \Omega_{\text{TR/HEL}}, m) \quad (7.174)$$

The fractions and detector parameters used in the fit model are summarized in Table 7.20.

Suggestions to Improve the Fit Model

In order to improve further the fit model summarized in Table 7.20, the following items relevant to the untagged analysis should be added:

- Angular acceptance dependence and angular resolutions ($f_k^{\text{TR/HEL}}$) for the signal component
- Long-lived background angular acceptance dependence
- $b - \bar{b}$ production asymmetry, if needed²⁰

In a longer term with high statistics (at the tagged analysis stage), the (non-)resonant contributions to the $K^+ K^-$ S-wave final state (Subsection 7.1.5) and the penguin contributions neglected in Equation 7.86 should be added [137].

²⁰This could potentially introduce oscillations in the proper time distribution of untagged $B_s^0 \rightarrow J/\psi \phi$ events.

Table 7.20: Parameters used for the toy Monte Carlo sensitivity studies for the fit to untagged $B_s^0 \rightarrow J/\psi \phi$ events.

DC06 MC Studies	Signal	Prompt Background	Long-Lived Background
Number of selected B_s^0 events in a $\pm 50 \text{ MeV}/c^2$ signal mass window (2 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$)	117,000	210,600 ($B/S = 1.8$)	58,500 ($B/S = 0.5$)
Proper Time Model	$S(t)$	$P_{\text{Pr}}(t) = \mathcal{G}(\mu, \sigma)$ with $\mu = 0 \text{ ps}$, $\sigma = 0.044 \text{ ps}$	$P_{\text{LL}}(t) = [f \cdot \exp(-t/\tau_1) + (1-f) \cdot \exp(-t/\tau_2)] \otimes \mathcal{G}(\mu, \sigma)$ with $f = 0.78$, $\tau_1 = 0.161 \text{ ps}$, $\tau_2 = 1.114 \text{ ps}$, $\mu = 0 \text{ ps}$, $\sigma = 0.066 \text{ ps}$
Angular Model	No Acceptance Dependence $S(\Omega_{\text{TR/HEL}})$ No Resolution, No Acceptance Dependence	$A_{\text{Pr}}(\Omega_{\text{TR/HEL}})$ (flat) No Acceptance Dependence	$A_{\text{LL}}(\Omega_{\text{TR/HEL}})$ (flat) No Acceptance Dependence
Mass Model	$M_S(m) = \mathcal{G}(\mu, \langle \sigma_{(m,S)} \rangle)$ with $\mu = 5.3664 \text{ GeV}/c^2$, $\langle \sigma_{(m,S)} \rangle = 16.2 \text{ MeV}/c^2$	$M_{\text{Pr}}(m) = \exp(-\alpha \cdot m)$ with $\alpha = 0.0006 (\text{MeV}/c^2)^{-1}$	$M_{\text{LL}}(m) = \exp(-\alpha \cdot m)$ with $\alpha = 0.001 (\text{MeV}/c^2)^{-1}$

7.5 Fit Procedure

The physics parameters $\lambda_{\text{phys}} = \{|A_0|^2, |A_\perp|^2, \Delta\Gamma_s, \Gamma_s, \delta_{||}, \delta_\perp, \phi_s^{J/\psi\phi}\}$ are determined by an unbinned log likelihood method from the measured event physics attributes $X_e = \{t, \Omega_{\text{TR/HEL}}, m\}$. The detector parameters $\lambda_{\text{det}} = \{\sigma_m, \sigma_t\}$ ²¹ and the background properties are also taken into account in the probability density function $\mathcal{P}_{\text{tot}}$ ²². Grouping together the physics and detector parameters as $\lambda = \{\lambda_{\text{phys}} + \lambda_{\text{det}}\}$, the likelihood function $\mathcal{L}$ of N events is expressed as:

$$\mathcal{L} = \prod_e^N \mathcal{P}_{\text{tot}}(X_e; \lambda) \quad (7.175)$$

Instead of maximizing the likelihood product $\mathcal{L}$ of Equation 7.175, the negative logarithmic likelihood $\mathcal{L}'$ is minimized. The numerical instabilities arising from a large number of multiplications to be performed are hence prevented. $\mathcal{L}'$ is given by:

$$\mathcal{L}' = - \sum_e^N \ln(\mathcal{P}_{\text{tot}}(X_e; \lambda)) \quad (7.176)$$

Two independent fitters are used to perform the unbinned likelihood fit to the untagged $B_s^0 \rightarrow J/\psi\phi$ events for the sensitivity studies of Section 7.7. The first fitter, called *P2VV fitter*, is implemented in python language [155] and uses pre-defined functions available in the RooFit package [112]. The minimization uses by default the MIGRAD algorithm of the MINUIT package [156], which returns symmetric errors. The second fitter, called *Heidelberg fitter*, is implemented using the C++ coding language [157]. The minimization is also performed with the MIGRAD algorithm.

Once the fit is achieved, both fitters provide displays showing the projections of the PDF on the basis angles and proper time, together with the CP-even and CP-odd contributions determined from the output fit values. An illustration of such displays is shown for the transversity angles in Figure 7.19, where only the signal contribution has been used in the generation and fit.

²¹The proper time and angular acceptances should be included in the detector parameters.

²²In the tagged analysis, there is one additional physics parameter, Δm_s , one additional physics attribute q (the initial B_s^0 meson flavor tag) and one additional detector parameter, ω the mistag rate.

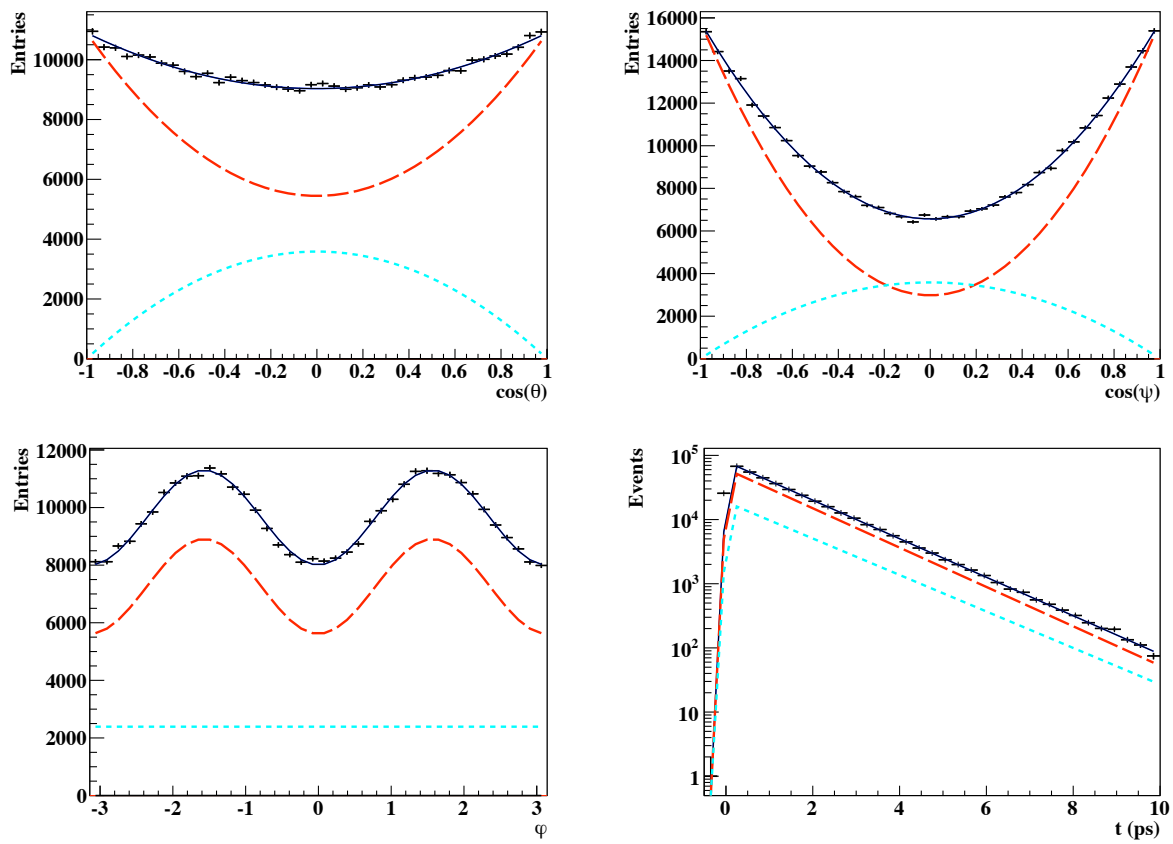


Figure 7.19: Angular and proper time distributions of the signal toy Monte Carlo data (black histogram), with the CP-even (red long-dashed line) and CP-odd (cyan short-dashed) components determined from the output fit values.

7.6 Angular Acceptance Parameterization

Given a certain region in space, the *acceptance* is defined as the number of events selected in the region divided by the number of events expected by theory. In an ideal case, the acceptance distribution in space is one everywhere, as all the events predicted by theory are selected. In a real case, non-flat acceptance shapes with less than one appear. To obtain unbiased estimations of the parameters entering in the analysis, acceptances as a function of the decay angles have to be taken into account in the fit. Neglecting them leads to significant biases, especially in the calculation of the parameters $|A_0|^2$ and $|A_\perp|^2$, as will be demonstrated in Subsection 7.6.4.

Due to possible correlation between the acceptances in three decay angles, one method of implementing the acceptance description is to define a three-dimensional histogram, where each dimension represents one angular function [123]. To smoothen the angular acceptance description, three-dimensional parameterizations of this histogram have been developed. The parameterization uses the same multi-dimensional fitting method detailed in Subsection 5.4, which takes into account the correlations between the angular acceptances. Parameterizations using both the transversity and helicity bases are given in Subsection 7.6.3.

7.6.1 Origin of the Angular Acceptance Distortions

Acceptance distortions can be due to the geometrical acceptance covered by the LHCb detector, the event reconstruction program or the event selection cuts. The total variation of the acceptance due to these contributions is found to be $\sim 11\%$ [123, 158].

In the following, an estimation of the angular acceptance variation due to the LHCb geometrical acceptance is given. For this study, 1,000,000 $B_s^0 \rightarrow J/\psi\phi$ signal events have been generated²³ with and without imposing the LHCb geometrical acceptance during the generation. The imposed constraint is: four tracks identified as $\mu^{+/-}$ and $K^{+/-}$ are in the LHCb acceptance for an event to be reconstructed as a $B_s^0 \rightarrow J/\psi\phi$ decay. When one or more of those tracks leave the LHCb acceptance, the event is not recorded, hence contributing to the angular shape of the acceptance.

In Figures 7.20-7.22²⁴, distributions of the decay angles $(\cos(\theta), \cos(\psi), \varphi)$ in the transversity basis are plotted (left) for theory (red line) and for the generated MC events (black histogram), without (top) and with (bottom) applying the cut on the LHCb geometrical acceptance, as well as the acceptance values (right). Similar plots for the angles in the helicity basis are shown in Figures 7.23-7.25²⁴. Before the cut, fluctuations of order $\sim 3\%$ are observed ($\sim 2\%$ for χ). After the cut, acceptance variations are of $\sim 4.5\%$ for $\cos(\theta)$ and $\cos(\psi)$, $\sim 6\%$ for φ and $\sim 10\%$ for $\cos(\theta_H)$. The acceptance on χ is not affected by the cut.

²³The v37r5 version of the Gauss package [41] is used for the generation of $B_s^0 \rightarrow J/\psi\phi$ events using MC09 settings.

²⁴In order to better estimate the differences between the decay angle distributions for theory and for the generated $B_s^0 \rightarrow J/\psi\phi$ events and the angular acceptance variations, small boxes are inserted in the bottom right of the Figures, which are a zoomed view on the y axis of the distributions.

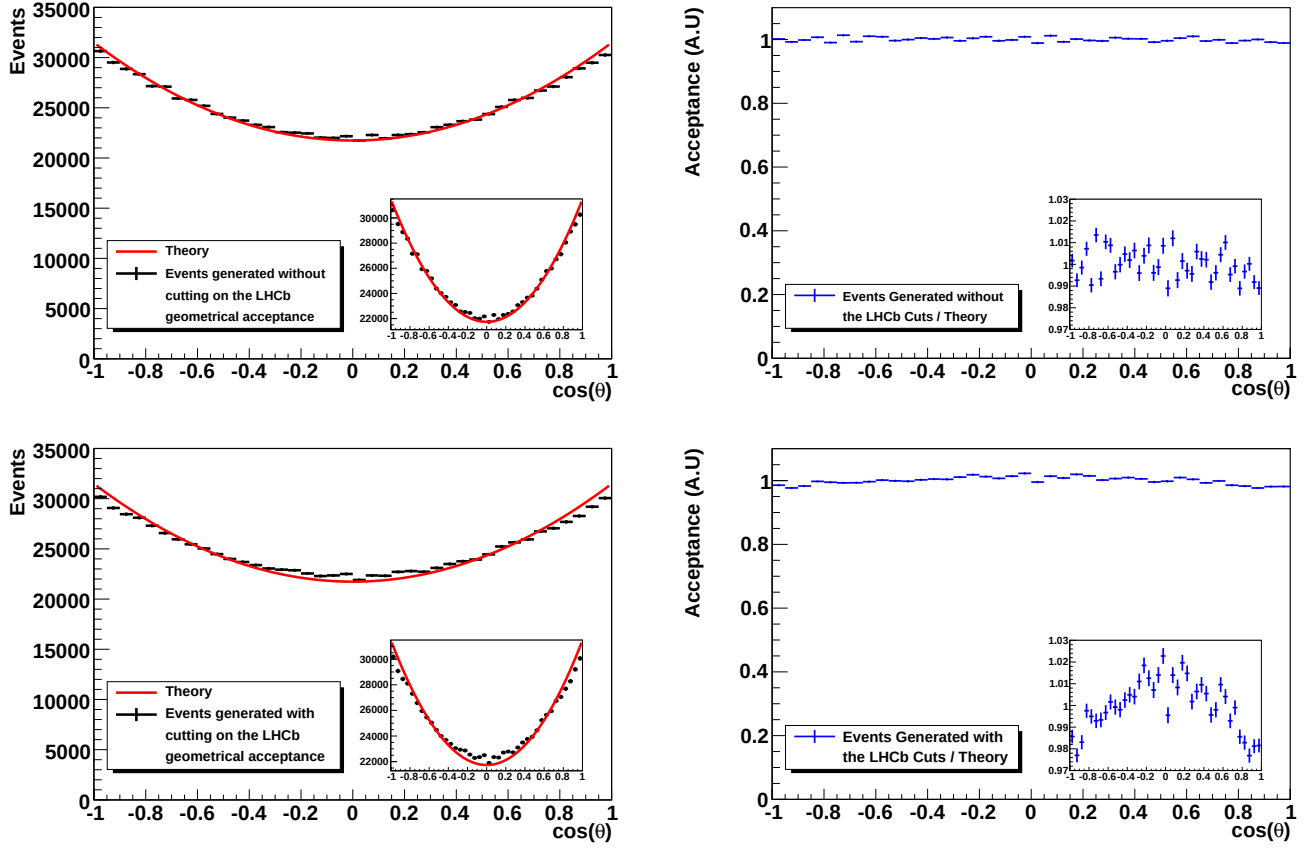


Figure 7.20: $\cos(\theta)$ distribution at generation level (left) and corresponding acceptances (right), without (top) and with (bottom) applying a cut on the LHCb geometrical acceptance.

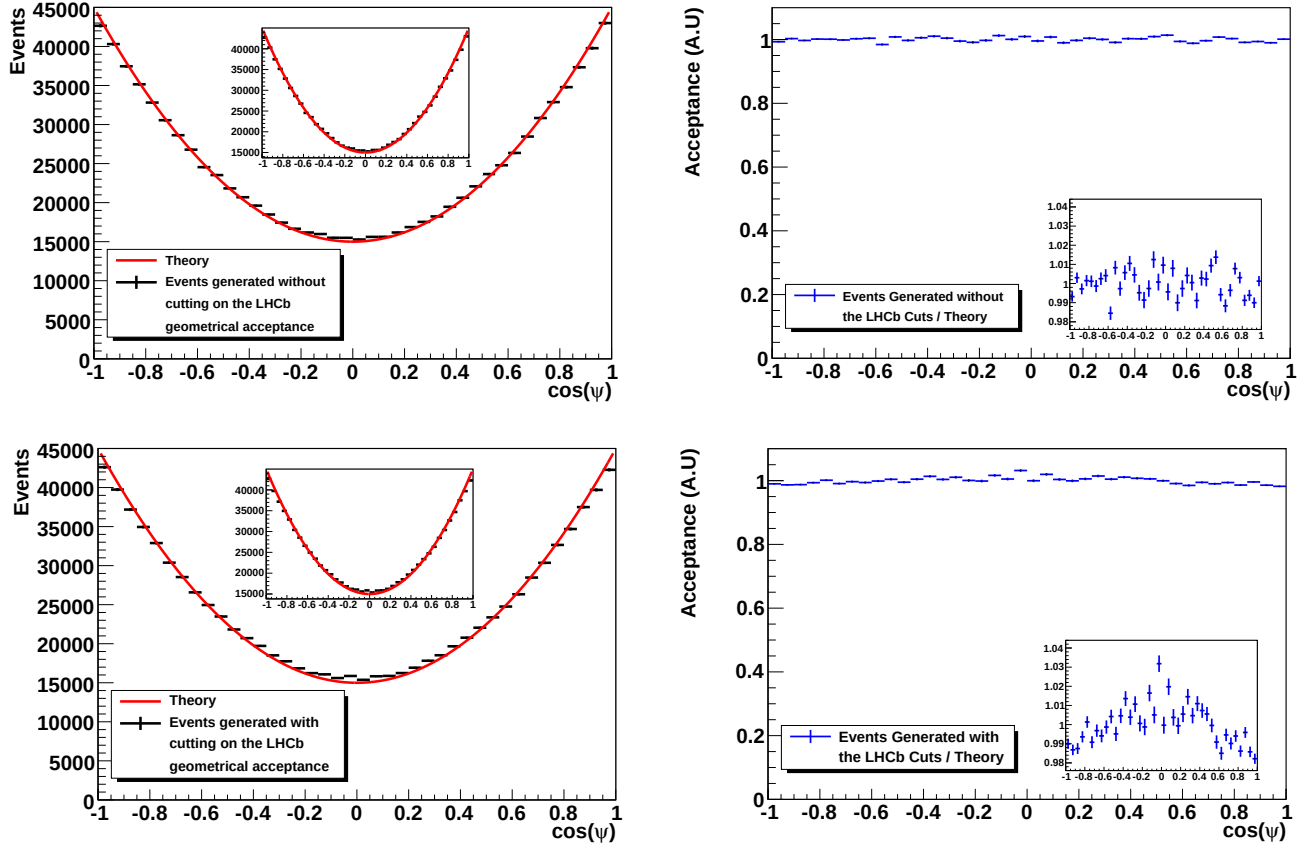


Figure 7.21: $\cos(\psi)$ distribution at generation level (left) and corresponding acceptances (right), without (top) and with (bottom) applying a cut on the LHCb geometrical acceptance.

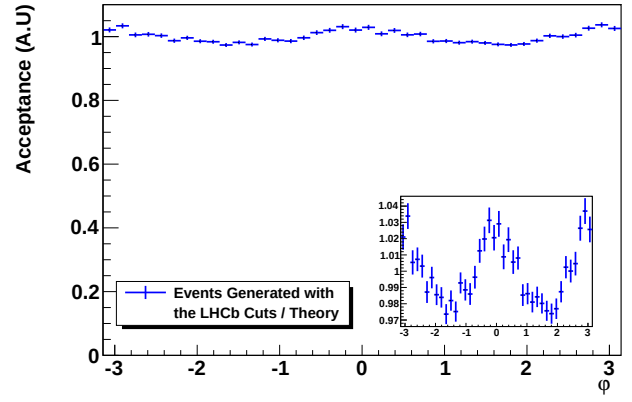
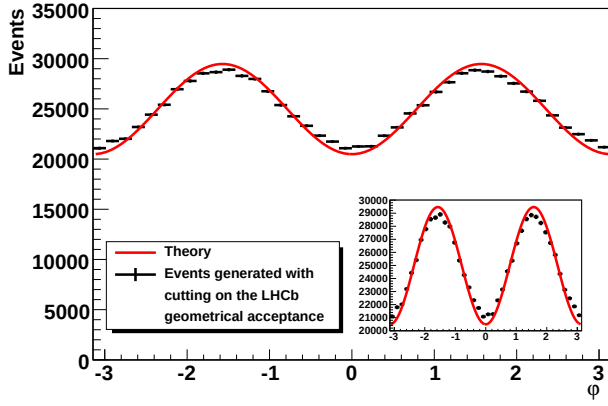
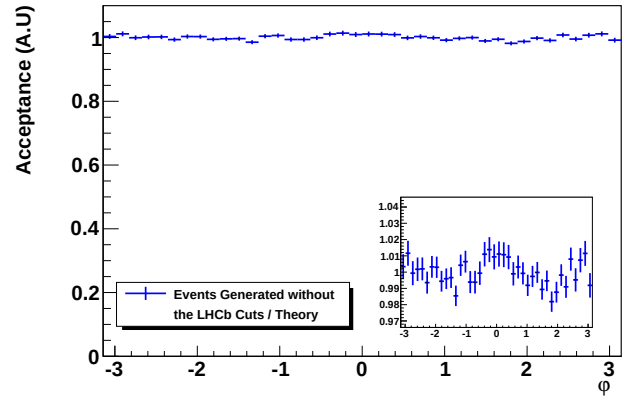
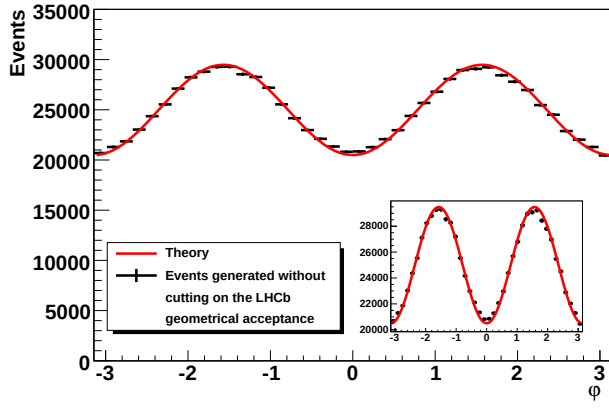


Figure 7.22: ϕ distribution at generation level (left) and corresponding acceptances (right), without (top) and with (bottom) applying a cut on the LHCb geometrical acceptance.

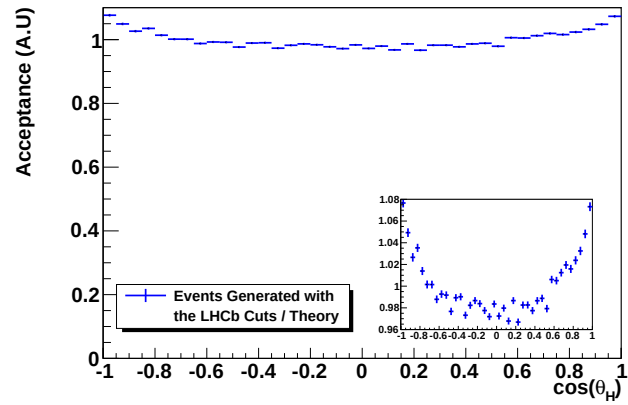
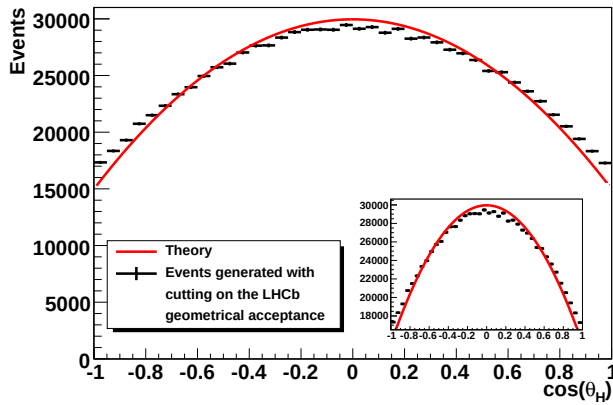
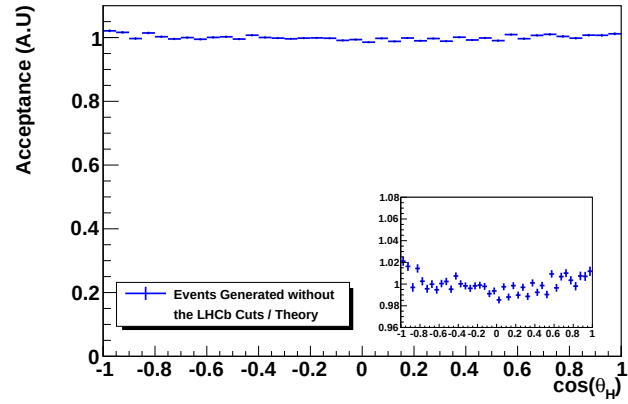
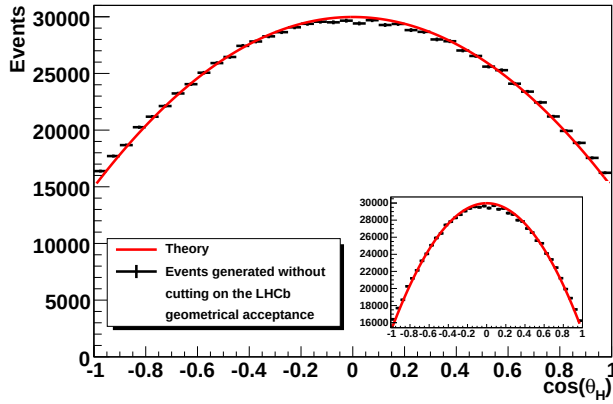


Figure 7.23: $\cos(\theta_H)$ distribution at generation level (left) and corresponding acceptances (right), without (top) and with (bottom) applying a cut on the LHCb geometrical acceptance.

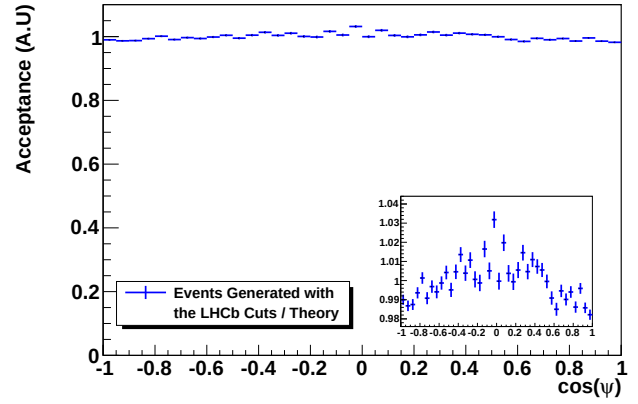
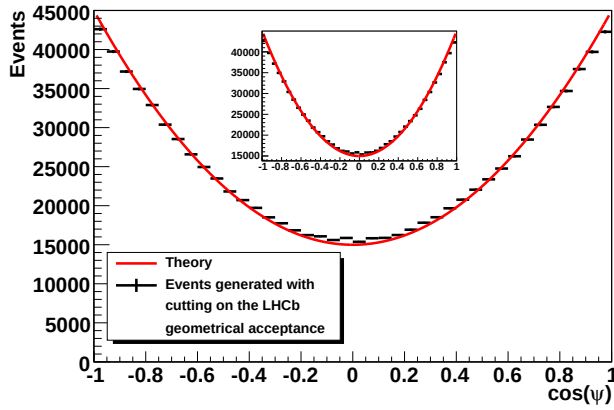
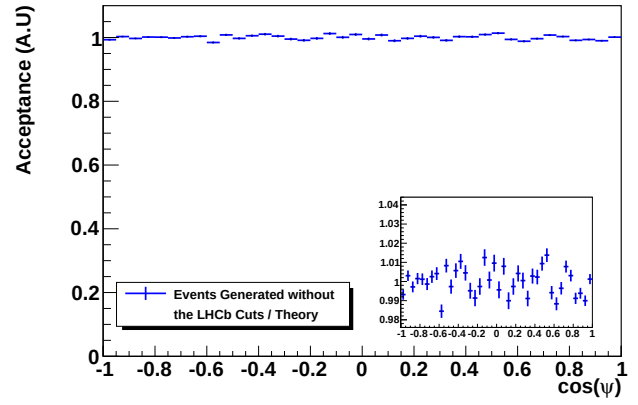
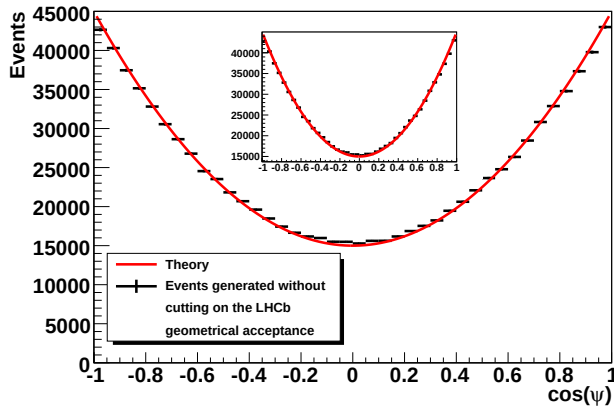


Figure 7.24: $\cos(\psi)$ distribution at generation level (left) and corresponding acceptances (right), without (top) and with (bottom) applying a cut on the LHCb geometrical acceptance.

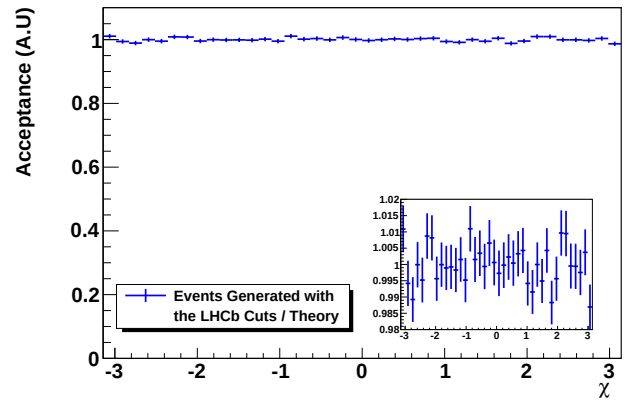
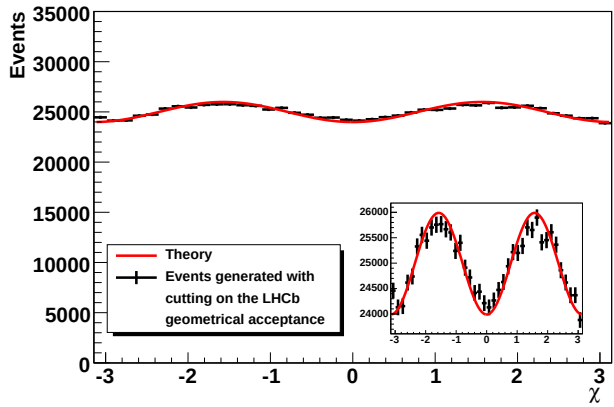
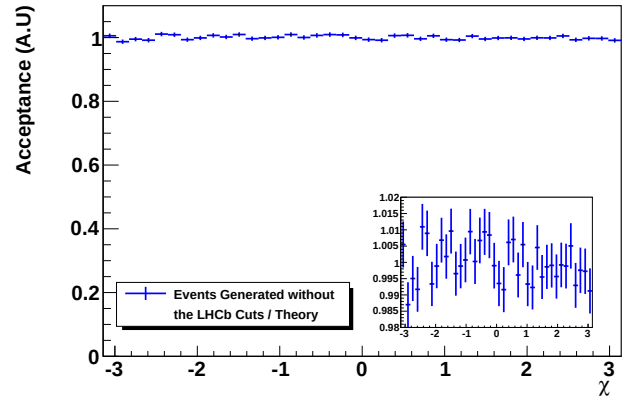
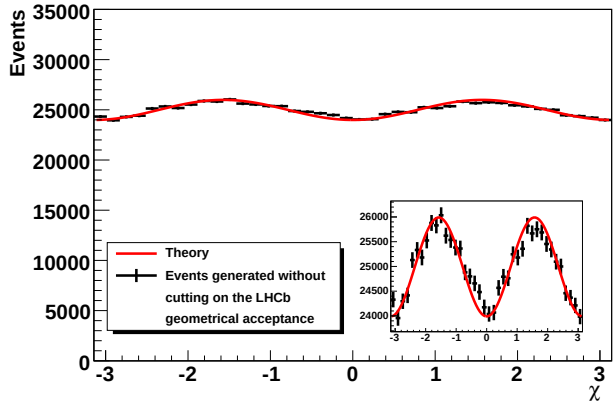


Figure 7.25: χ distribution at generation level (left) and corresponding acceptances (right), without (top) and with (bottom) applying a cut on the LHCb geometrical acceptance.

7.6.2 Angular Acceptance Calculation

The angular acceptances are calculated from the total sample of MC09 $B_s^0 \rightarrow J/\psi\phi$ events. 8000 bins are defined in the three-dimensional angular acceptance histogram, i.e. 20 bins evenly distributed in the allowed interval of each angular function. Inside of one three-dimensional bin, the angular acceptance value is obtained as follows:

- The numerator is the number of L0- and HLT1-triggered and offline-selected generated MC09 $B_s^0 \rightarrow J/\psi\phi$ events without applying a tagging decision on the flavor of the B_s^0 meson at production (Table 7.15). The selection cuts used are the ones presented in Section 7.3.
- The denominator is the number of events predicted by Equation 7.177²⁵. Equation 7.177 is obtained by integrating Equation 7.135 over the proper time using Equations 7.110-7.115.

$$\frac{d^3\Gamma_{\text{tot}}}{d\Omega_{\text{TR/HEL}}} = 0.5 \frac{d^3\Gamma(B_s^0 \rightarrow J/\psi\phi)}{d\Omega_{\text{TR/HEL}}} + 0.5 \frac{d^3\Gamma(\bar{B}_s^0 \rightarrow J/\psi\phi)}{d\Omega_{\text{TR/HEL}}} \quad (7.177)$$

The theoretical function is scaled to have the same total number of events as the total number of the selected events in the numerator. This has as a consequence that all the angular acceptances are distributed around one.

Two-Dimensional Distributions of the Decay Angle Functions

Figures 7.26-7.28 show two-dimensional distributions of the decay angles integrated over one angle in the transversity basis for the selected MC09 events (left) and the corresponding theoretical distributions (middle). The acceptances resulting from a division of the former histogram by the latter are also shown (right). Similar distributions are given for the helicity basis in Figures 7.29-7.31.

In the transversity basis, the variation of the acceptance in the φ angle is especially noticeable (Figures 7.27-7.28, right). In the helicity basis, almost no acceptance effect is observed for the χ angle (Figures 7.30-7.31, right). As the total angular acceptance variation has to be the same in the two bases, the angular acceptance variation in $\cos(\theta)$ and φ is concentrated in the helicity basis in θ_H , $\cos(\psi)$ being common to both bases [135].

²⁵This relation corresponds to the untagged case, as the MC09 data have been generated without any asymmetry between B_s^0 and $\bar{B}_s^0$ mesons.

Transversity Basis

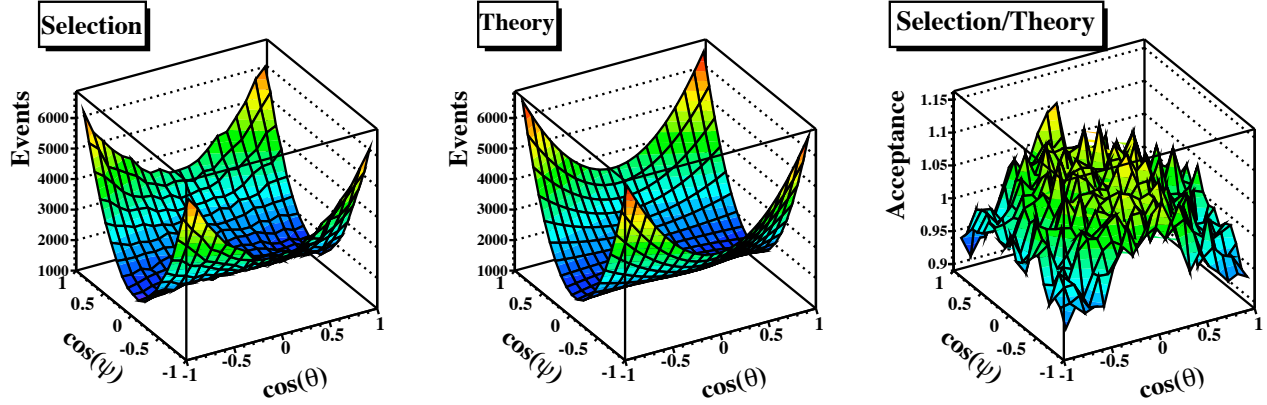


Figure 7.26: $\cos(\theta)$ - $\cos(\psi)$ two-dimensional distribution of the selected MC09 $B_s^0 \rightarrow J/\psi \phi$ events (left), of the corresponding distribution predicted by theory (middle) and resulting acceptance (right).

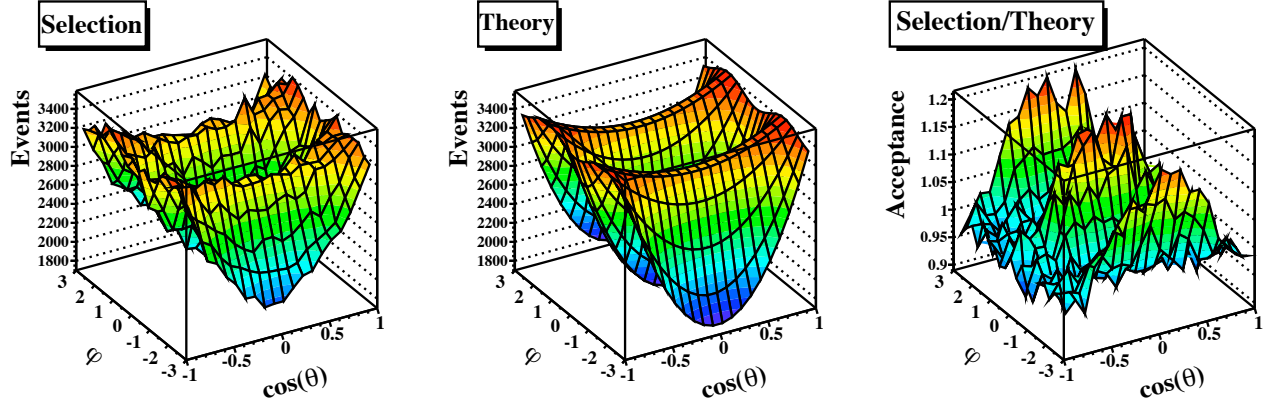


Figure 7.27: $\cos(\theta)$ - ϕ two-dimensional distribution of the selected MC09 $B_s^0 \rightarrow J/\psi \phi$ events (left), of the corresponding distribution predicted by theory (middle) and resulting acceptance (right).

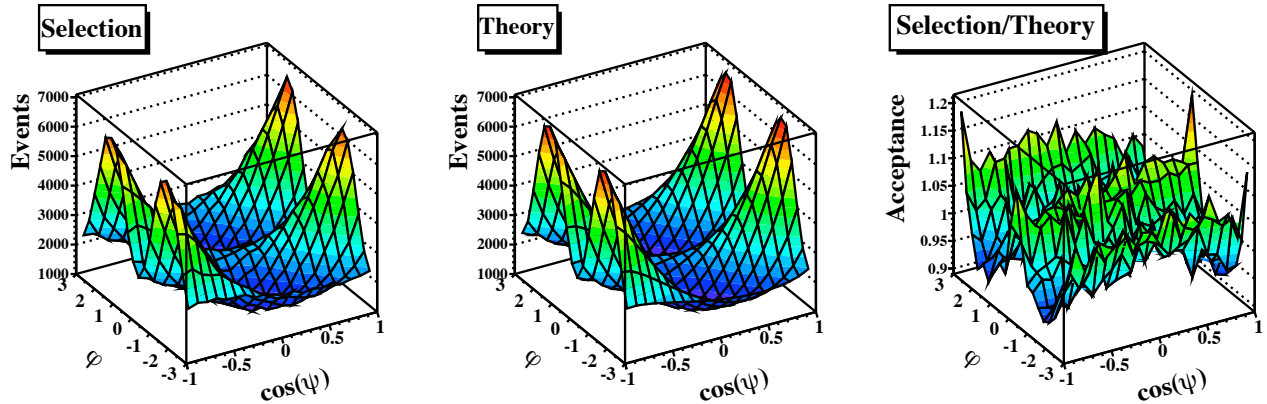


Figure 7.28: $\cos(\psi)$ - ϕ two-dimensional distribution of the selected MC09 $B_s^0 \rightarrow J/\psi \phi$ events (left), of the corresponding distribution predicted by theory (middle) and resulting acceptance (right).

Helicity Basis

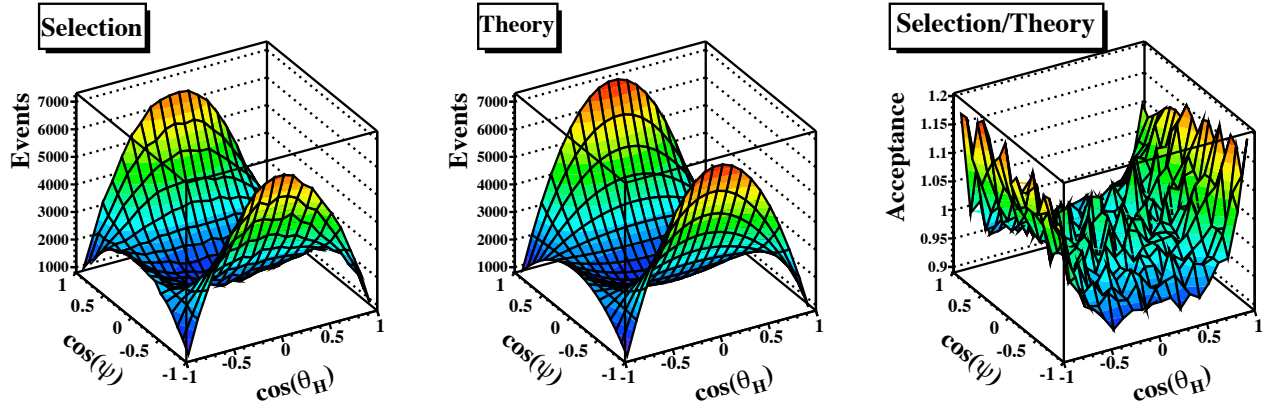


Figure 7.29: $\cos(\theta_H)$ - $\cos(\psi)$ two-dimensional distribution of the selected MC09 $B_s^0 \rightarrow J/\psi \phi$ events (left), of the corresponding distribution predicted by theory (middle) and resulting acceptance (right).

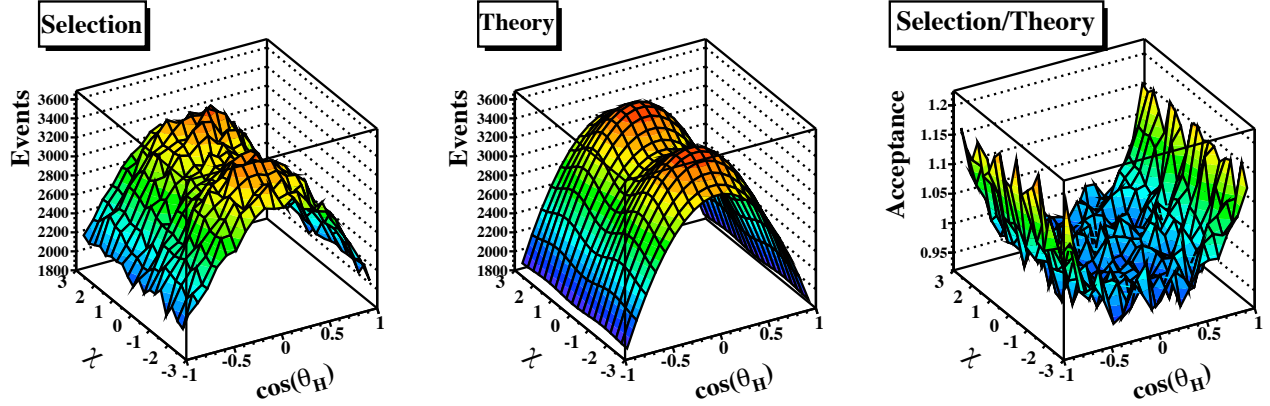


Figure 7.30: $\cos(\theta_H)$ - χ two-dimensional distribution of the selected MC09 $B_s^0 \rightarrow J/\psi \phi$ events (left), of the corresponding distribution predicted by theory (middle) and resulting acceptance (right).

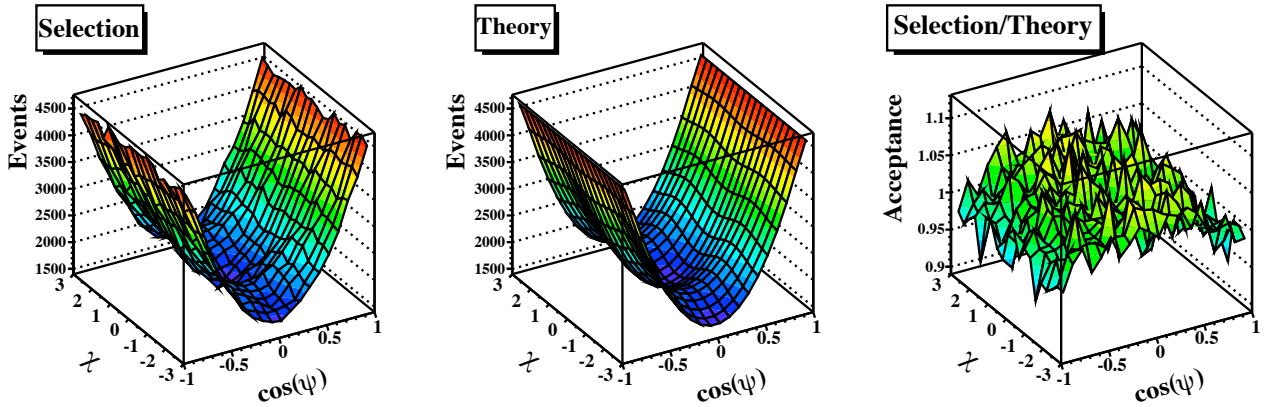


Figure 7.31: $\cos(\psi)$ - χ two-dimensional distribution of the selected MC09 $B_s^0 \rightarrow J/\psi \phi$ events (left), of the corresponding distribution predicted by theory (middle) and resulting acceptance (right).

7.6.3 Angular Acceptance Parameterization

To determine multidimensional parameterizations of the acceptances, $A_{\text{param}}(\mathbf{r})$, in terms of the angular functions $\mathbf{r} = (\cos(\theta), \cos(\psi), \phi)$ for the transversity basis and $\mathbf{r} = (\cos(\theta_H), \cos(\psi), \chi)$ for the helicity basis, the least square procedure explained in Subsection 5.4 is used. In this case, the quantity to be minimized (Equation 5.5) is rewritten as:

$$S = \sum_i \frac{(A_{\text{histo}} - A_{\text{param}}(r_i))^2}{\sigma_i^2} \quad (7.178)$$

where A_{histo} are the values coming from the three-dimensional angular acceptance histogram. The c_l coefficients of Equation 5.3 and the orders m , n , p of the Chebychev monomials $T_m(r_1)$, $T_n(r_2)$ and $T_p(r_3)$ obtained from the fit are given in Table 7.21 for the transversity basis and Table 7.22 for the helicity basis²⁶. The number of terms for the parameterization in the helicity basis is smaller than for the parameterization in the transversity basis, which is due to the complex acceptance variation in the ϕ angle, as explained in Subsection 7.6.2.

Table 7.21: c_l coefficients and combination of Chebychev monomials $T_m T_n T_p$ for the transversity basis.

List of Terms	c_l	$m(T_m(\cos(\theta)))$	$n(T_n(\cos(\psi)))$	$p(T_p(\phi))$
1	-0.0106925	0	0	0
2	+0.0178818	0	0	2
3	-0.044207	2	0	0
4	-0.0245174	0	2	0
5	+0.02885	0	0	4
6	-0.0237846	2	0	2
7	+0.0086622	4	0	0
8	-0.017512	0	0	6
9	-0.0457417	2	0	4

Table 7.22: c_l coefficients and combination of Chebychev monomials $T_m T_n T_p$ for the helicity basis.

List of Terms	c_l	$m(T_m(\cos(\theta_H)))$	$n(T_n(\cos(\psi)))$	$p(T_p(\chi))$
1	+0.0130731	0	0	0
2	+0.077389	2	0	0
3	-0.0277041	0	2	0
4	+0.0265217	1	1	2
5	+0.0238798	4	0	0

The results of the fit with the transversity basis show no correlation between $\cos(\psi)$ and the two other angular functions. From Figure 7.32, it can indeed be observed that the variations in the $\cos(\theta) - \phi$ plane, representing the correlations of $\cos(\psi)$ with them, are much less pronounced than in the $\cos(\theta) - \cos(\psi)$ and $\cos(\psi) - \phi$ planes. One correlation term is found between χ and the other angles of the helicity basis, which is reflected in the $\cos(\theta_H) - \cos(\psi)$ plane of Figure 7.32.

Figures 7.33-7.35 show distributions of the decay angle acceptance integrated over one angle (left) in the transversity basis, the parameterizations (middle) and the residuals obtained by subtracting the latter to the former (right). Similar distributions are given for the helicity basis in Figures 7.36-7.38. The residuals distributions show no biases for all cases, as they are centered on zero.

²⁶Tests performed on DC06 Monte Carlo data give similar results (number of terms, coefficients and powers).

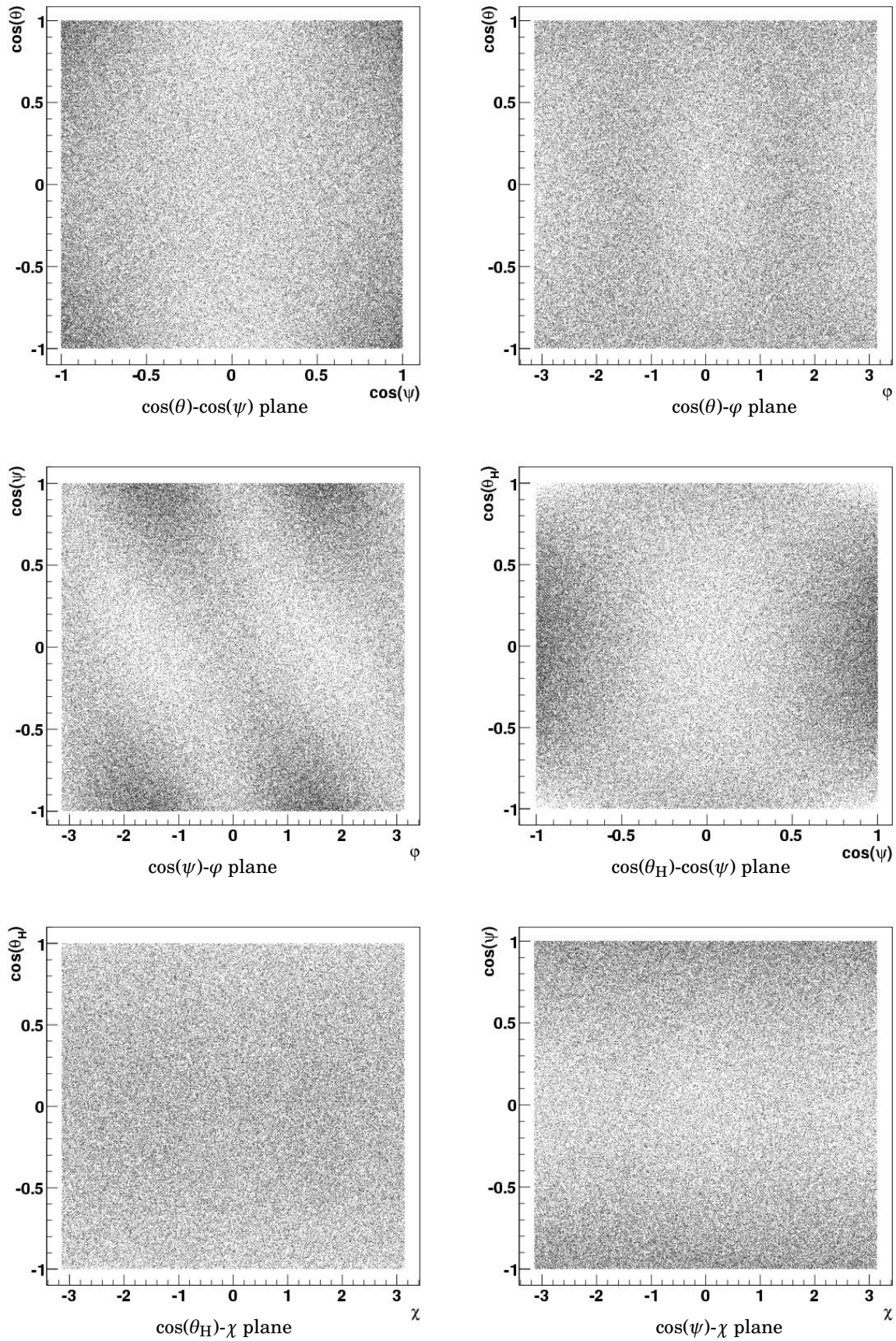


Figure 7.32: Angular distributions projected on different planes for the transversity and helicity bases.

Transversity

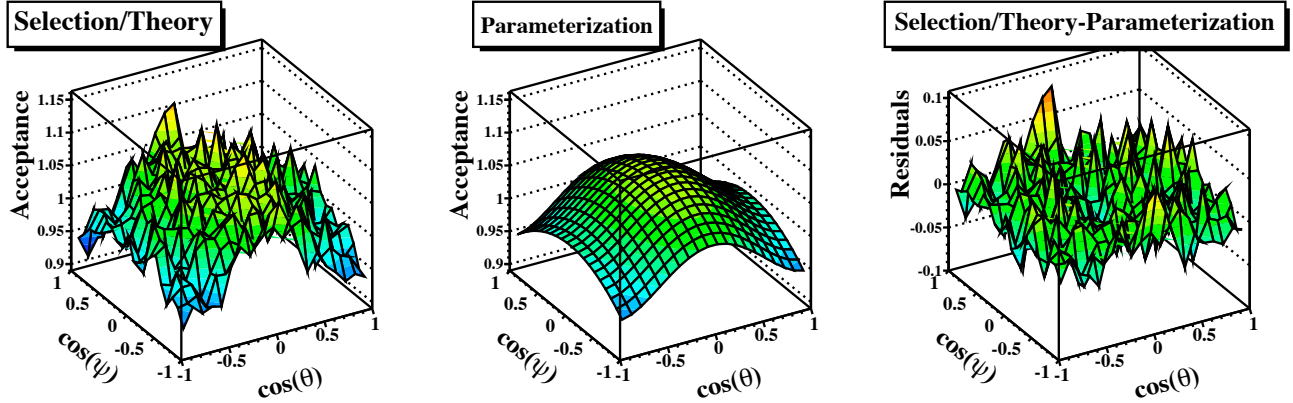


Figure 7.33: $\cos(\theta)$ - $\cos(\psi)$ two-dimensional distributions of the angular acceptance (left) for the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events, of the corresponding parameterization (middle) and of the residuals obtained by subtracting the latter to the former (right).

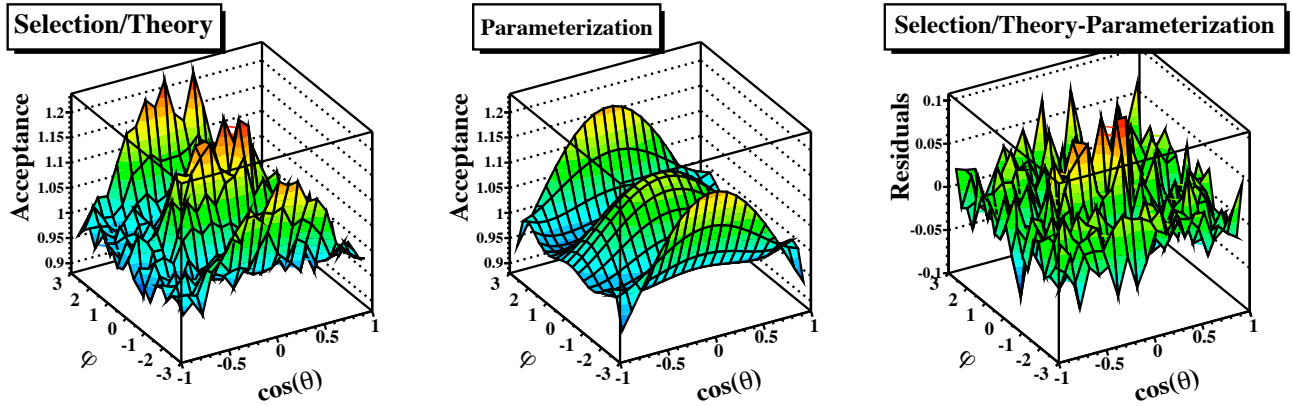


Figure 7.34: $\cos(\theta)$ - ϕ two-dimensional distributions of the angular acceptance (left) for the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events, of the corresponding parameterization (middle) and of the residuals obtained by subtracting the latter to the former (right).

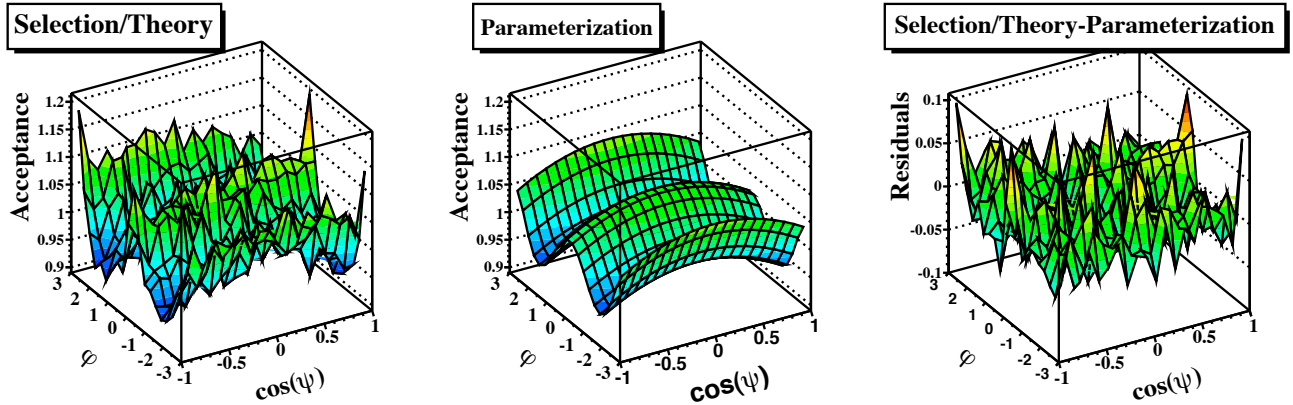


Figure 7.35: $\cos(\psi)$ - ϕ two-dimensional distributions of the angular acceptance (left) for the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events, of the corresponding parameterization (middle) and of the residuals obtained by subtracting the latter to the former (right).

Helicity

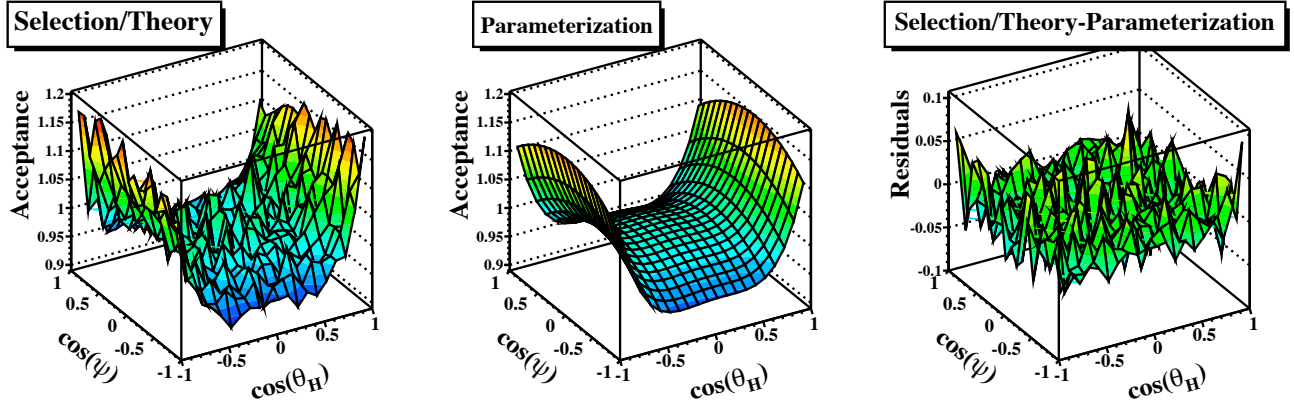


Figure 7.36: $\cos(\theta_H)$ - $\cos(\psi)$ two-dimensional distributions of the angular acceptance (left) for the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events, of the corresponding parameterization (middle) and of the residuals obtained by subtracting the latter to the former (right).

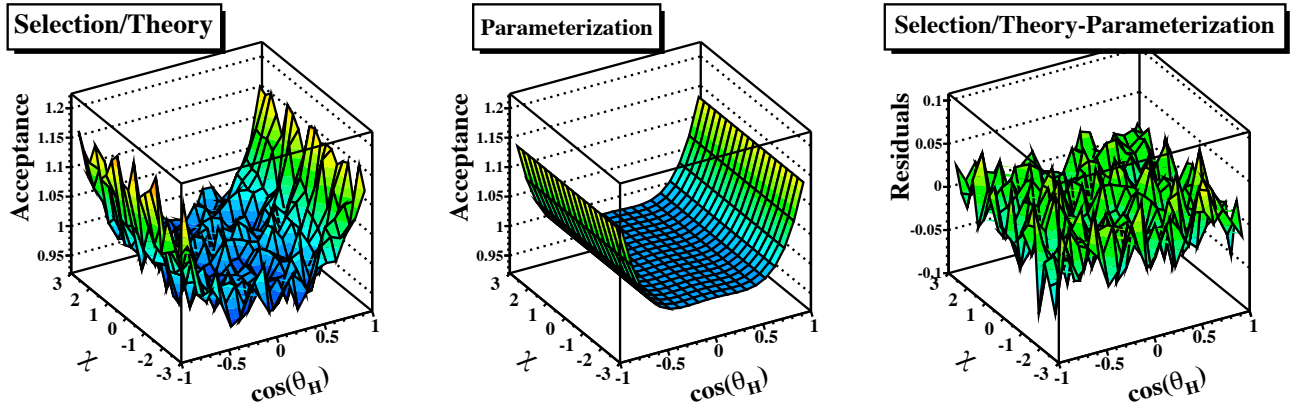


Figure 7.37: $\cos(\theta_H)$ - χ two-dimensional distributions of the angular acceptance (left) for the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events, of the corresponding parameterization (middle) and of the residuals obtained by subtracting the latter to the former (right).

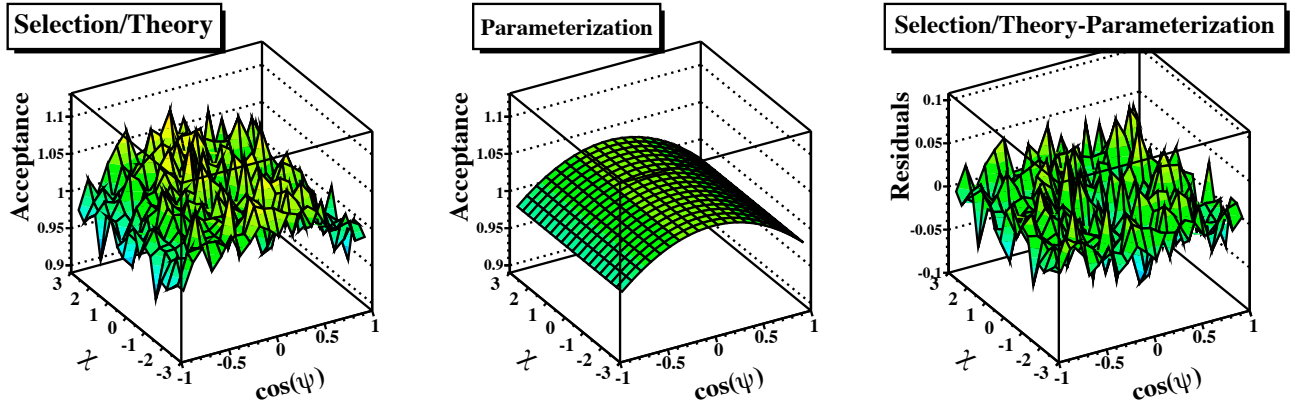


Figure 7.38: $\cos(\psi)$ - χ two-dimensional distributions of the angular acceptance (left) for the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events, of the corresponding parameterization (middle) and of the residuals obtained by subtracting the latter to the former (right).

7.6.4 Validation of the Acceptance Parameterization

1. Oscillating / Diverging behavior of the Parameterizations

A first check consists in ensuring that the parameterized acceptance does not oscillate between the fitted points nor diverges at the edges of the three-dimensional histogram. For this, 8,000,000 equally spaced acceptance values are calculated from the parameterization inside the space allowed by the angular functions. No oscillation nor divergence at the edges have been observed.

2. One-Angle Distributions of the Angular Acceptance

Figures 7.39-7.44²⁷ (left) show the distributions of the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events (black histogram) for each angular function of the transversity/helicity bases and the corresponding theoretical distributions (red line). On the resulting acceptances (right, blue histogram) are superimposed the parameterizations integrated over the two other angles (green line). A good matching between the integrated parameterization and the integrated acceptance variations is observed for all cases.

3. Time-Dependent Angular Fit to Untagged MC09 $B_s^0 \rightarrow J/\psi\phi$ Events

To validate the parameterizations, three-dimensional angular fits to the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events are performed using the P2VV package [155], first without using the acceptance corrections, then including them as multiplicative factors $\varepsilon(d\Omega_{\text{TR/HEL}})$ to the theoretical Equation 7.177:

$$\left(\frac{d^3\Gamma_{\text{tot}}}{d\Omega_{\text{TR/HEL}}} \right)_{\text{acceptance incl.}} = \left(0.5 \frac{d^3\Gamma(B_s^0 \rightarrow J/\psi\phi)}{d\Omega_{\text{TR/HEL}}} + 0.5 \frac{d^3\Gamma(\bar{B}_s^0 \rightarrow J/\psi\phi)}{d\Omega_{\text{TR/HEL}}} \right) \cdot \varepsilon(d\Omega_{\text{TR/HEL}}) \quad (7.179)$$

To perform the fits, the total set of selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events is divided into nine samples of 117,000 events each, corresponding to 2 fb^{-1} of data at nominal energy ($\sqrt{s} = 14 \text{ TeV}$). The input parameter values are set to the values used for the generation of the MC09 Monte Carlo data summarized in Table 7.6.4 [159], which have to be retrieved in the output fit value distributions.

Table 7.24 shows the average parameter values obtained from untagged fits. In both bases, biases are observed for the $|A_0|^2$ and $|A_\perp|^2$ parameters without acceptance corrections (highlighted in yellow). They cancel with the use of the three-dimensional parameterizations. This shows that even if the acceptances are rather flat ($\leq 10\%$ effect), their corrections cannot be neglected in the fit [123]. Biases observed for Γ_s without angular acceptance corrections still remain after applying the angular acceptance corrections (highlighted in yellow).

²⁷In order to better estimate the differences between the decay angle distributions for theory and for the selected MC09 $B_s^0 \rightarrow J/\psi\phi$ events and the angular acceptance variations, small boxes are inserted in the bottom right of the Figures, which are a zoomed view on the y axis of the distributions.

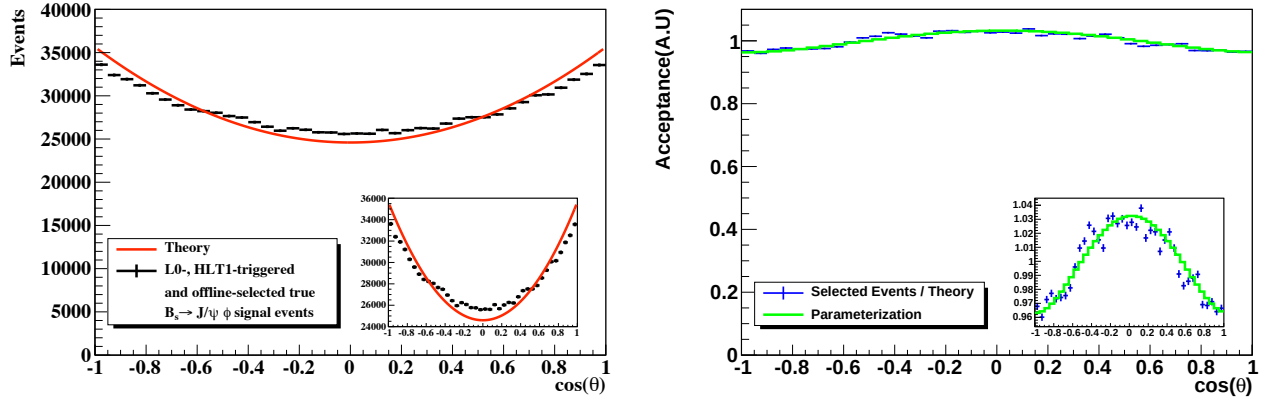


Figure 7.39: $\cos(\theta)$ distribution of the selected $B_s^0 \rightarrow J/\psi \phi$ events (black histogram) and of the theoretical distribution (red curve) (left), and corresponding acceptance (blue histogram) with the integral of the parameterization over two angles superimposed (green line) (right).

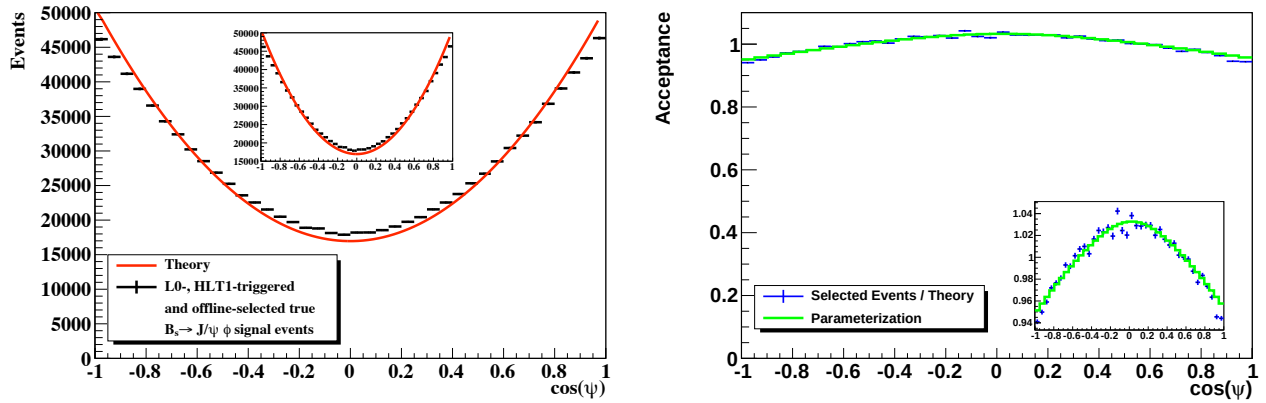


Figure 7.40: $\cos(\psi)$ distribution of the selected $B_s^0 \rightarrow J/\psi \phi$ events (black histogram) and of the theoretical distribution (red curve) (left), and corresponding acceptance (blue histogram) with the integral of the parameterization over two angles superimposed (green line) (right)

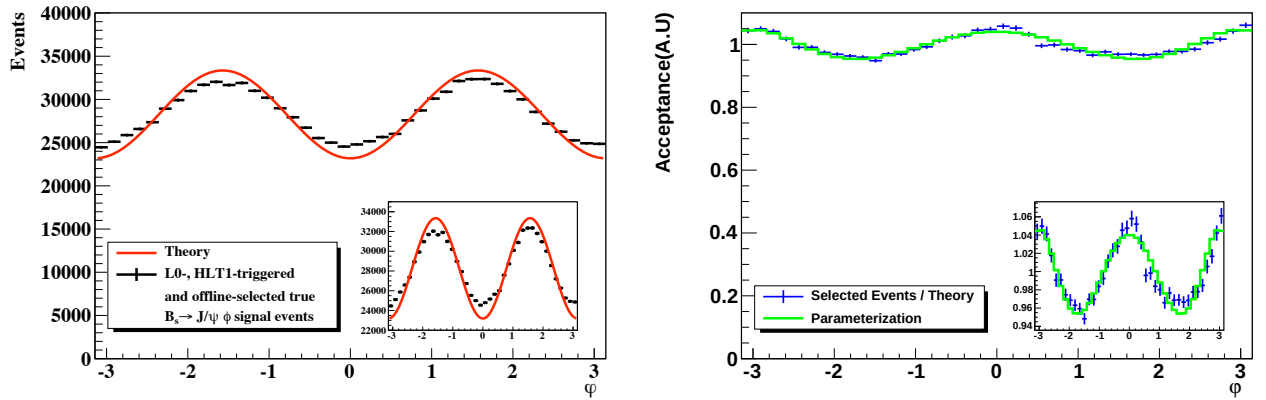


Figure 7.41: ϕ distribution of the selected $B_s^0 \rightarrow J/\psi \phi$ events (black histogram) and of the theoretical distribution (red curve) (left), and corresponding acceptance (blue histogram) with the integral of the parameterization over two angles superimposed (green line) (right)

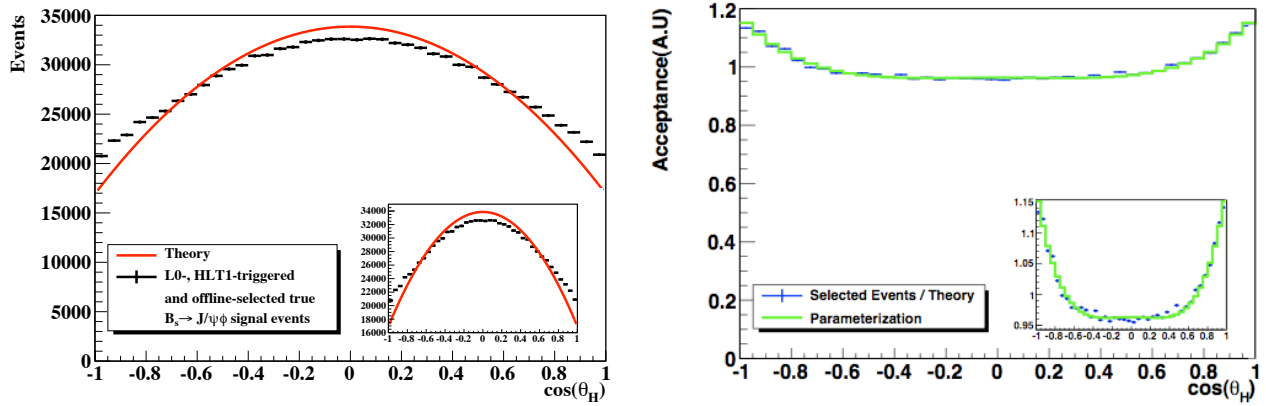


Figure 7.42: $\cos(\theta_H)$ distribution of the selected $B_s^0 \rightarrow J/\psi \phi$ events (black histogram) and of the theoretical distribution (red curve) (left), and corresponding acceptance (blue histogram) with the integral of the parameterization over two angles superimposed (green line) (right)

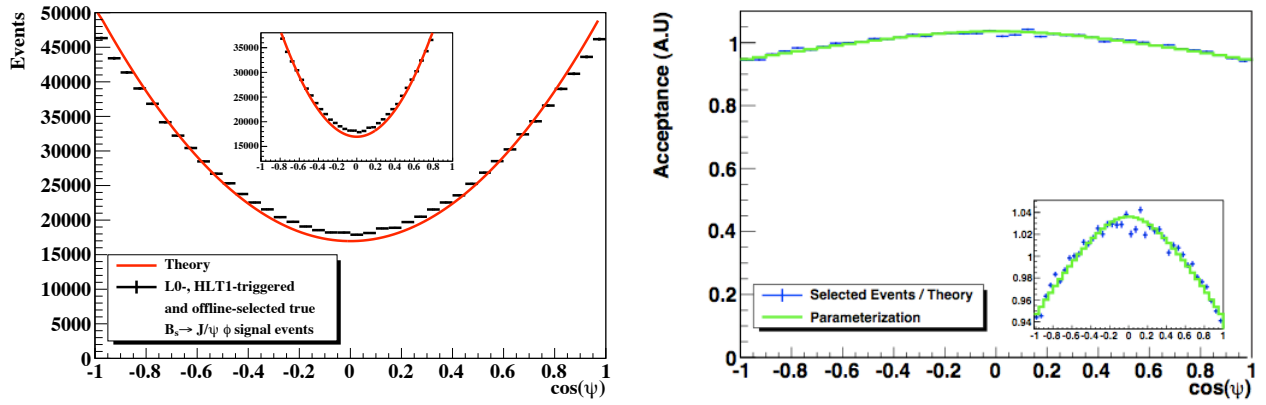


Figure 7.43: $\cos(\psi)$ distribution of the selected $B_s^0 \rightarrow J/\psi \phi$ events (black histogram) and of the theoretical distribution (red curve) (left), and corresponding acceptance (blue histogram) with the integral of the parameterization over two angles superimposed (green line) (right)

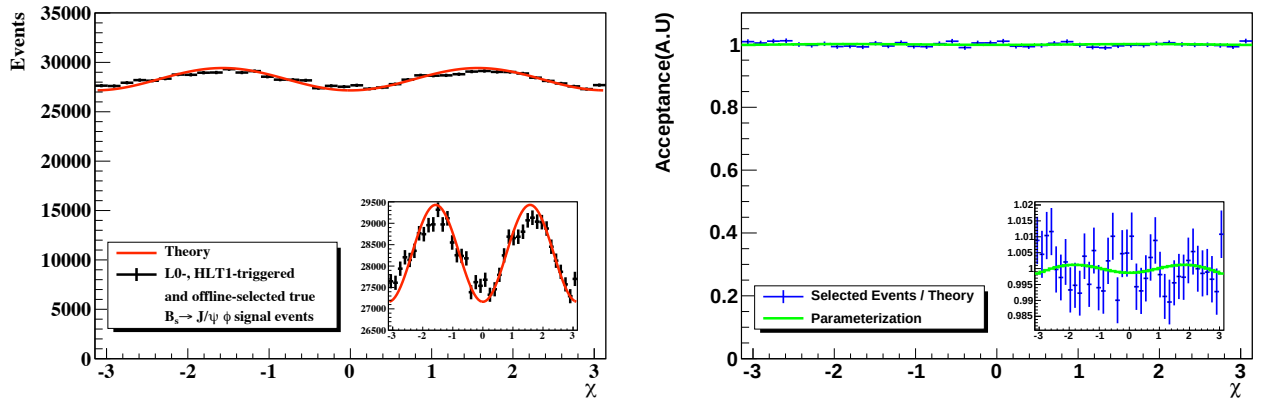


Figure 7.44: χ distribution of the selected $B_s^0 \rightarrow J/\psi \phi$ events (black histogram) and of the theoretical distribution (red curve) (left), and corresponding acceptance (blue histogram) with the integral of the parameterization over two angles superimposed (green line) (right)

Table 7.23: B_s^0 parameters used in the generation of the MC09 $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$ sample [159]. From the values of the B_s^0 lifetime $\tau_s=1.472$ ps and $\Delta\Gamma_s$, the lifetime of the B_s^0 mass eigenstates can be derived, $\tau_H=1.5369$ ps and $\tau_L=1.407$ ps.

Parameter	Value
$\Gamma_s=1/\tau_s$	0.6793 ps^{-1}
Δm_s	17.8 ps^{-1}
$\Delta\Gamma_s$	0.060 ps^{-1}
$ A_{\parallel} ^2$	0.24
$\delta_{\parallel}$	2.5 rad
$ A_0 ^2$	0.6
δ_0	0.0 rad
$ A_{\perp} ^2$	0.16
$\delta_{\perp}$	-0.17 rad
$\phi_s^{J/\psi\phi}$	-0.04 rad

Table 7.24: Fitted parameters averaged over nine samples of 117,000 untagged $B_s^0 \rightarrow J/\psi\phi$ signal events in the transversity (TR) and helicity (HEL) bases without acceptance corrections (left) and with using the angular acceptance parameterization (right). Biases ($>3\sigma$) are highlighted in yellow.

Basis	Parameters	Input value	No Correction For Acceptance		Parameterization	
			Result	σ from nominal	Result	σ from nominal
TR	$ A_0 ^2$	0.600	0.572 ± 0.003	-9.3	0.598 ± 0.003	-0.7
	$ A_{\perp} ^2$	0.160	0.173 ± 0.003	+4.3	0.158 ± 0.003	-0.7
	$\Gamma_s [\text{ps}^{-1}]$	0.679	0.696 ± 0.003	+5.7	0.694 ± 0.003	+5.0
	$\Delta\Gamma_s [\text{ps}^{-1}]$	0.060	0.052 ± 0.009	-0.9	0.059 ± 0.009	-0.1
HEL	$ A_0 ^2$	0.600	0.572 ± 0.003	-9.3	0.600 ± 0.003	+0.0
	$ A_{\perp} ^2$	0.160	0.173 ± 0.003	+4.3	0.158 ± 0.003	-0.7
	$\Gamma_s [\text{ps}^{-1}]$	0.679	0.695 ± 0.003	+5.3	0.694 ± 0.003	+5.0
	$\Delta\Gamma_s [\text{ps}^{-1}]$	0.060	0.054 ± 0.009	-0.7	0.059 ± 0.009	-0.1

The biases on Γ_s are due to the unexpected non-flat variation of the proper time acceptance after reconstruction and offline selection (Figure 7.45, bottom right) compared to the unbiased shapes at generation level (without/with cutting on the LHCb acceptance) (Figure 7.45, top and middle).

The large proper time acceptance variation observed in Figure 7.45 (bottom right) is assumed to be mainly uncorrelated with the angular acceptance variation²⁸. The proper time acceptance distribution of Figure 7.45 (bottom right) is fitted by a second-order polynomial function $f(t) = S \cdot (1 + k_1 \cdot t + k_2 \cdot t^2)$, with S an arbitrary scale factor, resulting in $k_1 = 0.0028 \pm 0.0012 \text{ ps}^{-1}$ and $k_2 = -0.0026 \pm 0.0002 \text{ ps}^{-1}$. If the proper time acceptance description is included in the fit, the bias on Γ_s of Table 7.24 disappears, and gives $\Gamma_s = 0.682 \pm 0.003 \text{ ps}^{-1}$ for the transversity and helicity bases.

The fact that the initial parameters used in the generation of MC09 $B_s^0 \rightarrow J/\psi\phi$ events are found back is not only a validation of the angular acceptance parameterizations, but also of the fit procedure to untagged events that is used in the Subsection 7.7 to perform sensitivity studies.

²⁸Correlations between angular and proper time acceptance variations can be expected if $\Delta\Gamma_s \neq 0$ [160]. However, the resulting slope in the proper time acceptance is expected to be ~ 3 times smaller than what observed [123]. The origin of the large distortion observed in MC09 data is not yet fully understood, but possible reasons could be that the VELO tracking efficiency may depend on the z position of the B vertex. It could also be due to the limited length of the VELO detector that could cause the drop of B reconstruction efficiency at large proper time.

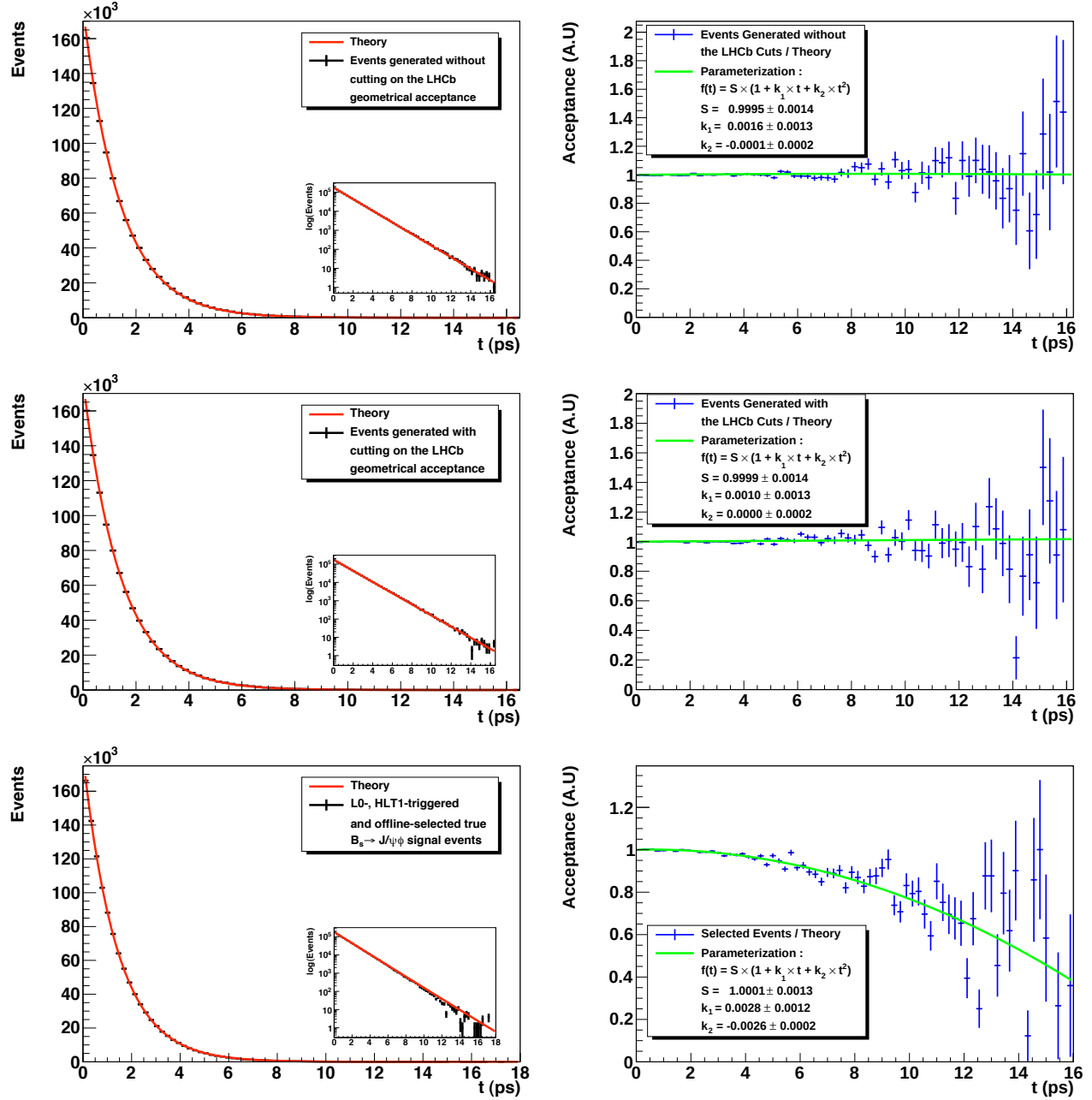


Figure 7.45: Proper time distributions (left) at generation level without (top) or with (middle) applying a cut on the LHCb acceptance and after reconstruction and offline selection (bottom). The small boxes inserted on the bottom right of the distributions show the same proper time distributions in a logarithmic scale instead. The corresponding acceptances (right) show no bias at generated level (without/with the geometrical cut on the LHCb acceptance), while the proper time acceptance after reconstruction and offline selection is biased (bottom). This bias is hence not due to the cut on the LHCb acceptance at generation level.

7.7 Time-Dependent Angular Analysis to Untagged $B_s^0 \rightarrow J/\psi\phi$ Events

Compared to the time-dependent angular analysis to tagged $B_s^0 \rightarrow J/\psi\phi$ events that will eventually bring the most precise measurement of $\phi_s^{J/\psi\phi}$, the fit to untagged $B_s^0 \rightarrow J/\psi\phi$ events has the advantage of being independent of the understanding of the tagging. It is also less demanding regarding the proper time resolution, as it does not need to resolve the fast $B_s^0 - \bar{B}_s^0$ oscillations. Indeed, the Δm_s parameter characterizing the frequency of the $B_s^0 - \bar{B}_s^0$ mixing vanish in the untagged analysis (Equations 7.136-7.141). The fit to untagged $B_s^0 \rightarrow J/\psi\phi$ events is therefore one of the first steps that will be performed with real data towards $\phi_s^{J/\psi\phi}$.

The time-dependent angular analysis to untagged $B_s^0 \rightarrow J/\psi\phi$ events is a complicated procedure, including a simultaneous fit to several distributions, each depending on a number of unknown parameters. To estimate the measurement uncertainty, a *Toy Monte Carlo* technique is used. A simplified model of the measurement is build and a large number of identical jobs is performed, each with a different random number seed.

In the following studies, only the jobs for which the fit has converged are taken into account. For each physics parameter with input value x_{input} , the distributions of the returned best fit value, x_{fit} , the estimated error obtained from the covariance matrix of the fit, σ_x and the pull, Δx , defined in Equation 7.180 are plotted.

$$\Delta x = \frac{x_{\text{fit}} - x_{\text{input}}}{\sigma_x} \quad (7.180)$$

The sensitivity to the parameter x is defined as the width of the Gaussian fitted to the distribution of the returned values x_{fit} , which is checked to be consistent with the average of the fitted σ_x distribution. The pull distributions are examined to determine whether there are biases in the parameter determination. They are fitted with a Gaussian function. If the fit is not biased, the pull distribution should be centered to zero with a unit width.

The two P2VV [155] and Heidelberg [157] fitters explained in Section 7.5 are used in the sensitivity studies to cross-check the results²⁹. Whenever possible, different scenarios are studied for the integrated luminosity per nominal year of data taking at $\sqrt{s} = 14$ TeV: 2 fb^{-1} , 0.2 fb^{-1} and 0.1 fb^{-1} . The numbers of generated $B_s^0 \rightarrow J/\psi\phi$ events for the three statistical scenarios are obtained from Table 7.20 by scaling the integrated luminosity. They are given in Table 7.7.

²⁹The event generation is performed by each fitter separately.

Table 7.25: Input from simulation used in the generation of standalone simplified Monte Carlo data and defined in [153] (version v2). The numbers correspond to a signal mass window of $\pm 50 \text{ MeV}/c^2$.

Input from Simulation	Value
Background/Signal Ratio	
B_{prompt}/S	1.8
$B_{\text{long-lived}}/S$	0.5
Total Event Number (S+B) ($\sqrt{s} = 14 \text{ TeV}$)	
2.0 fb^{-1}	386,100
0.2 fb^{-1}	38,600
0.1 fb^{-1}	19,305

The input values of the seven physics parameters used in the fit to untagged $B_s^0 \rightarrow J/\psi \phi$ events are summarized in Table 7.7 [153]. These are based on constraints existing on Γ_s and $\Delta\Gamma_s$. The input values of the other physics parameters rely on measurements performed in the $B^0 \rightarrow J/\psi K^{*0}$ channel, except for the Standard Model $\phi_s^{J/\psi\phi}$ input value coming from an early 2008 estimate. The New Physics value for $\phi_s^{J/\psi\phi}$ is based on the latest result quoted by the DØ experiment given in Table 7.7³⁰.

Table 7.26: Physics parameters input values used in the fit to untagged $B_s^0 \rightarrow J/\psi \phi$ events [153] (version v2). The δ_0 is set to zero by an allowed convention choice. The $|A_{\parallel}|^2$ parameter equals $|A_{\parallel}|^2 = 1 - |A_0|^2 - |A_{\perp}|^2 = 0.211$ [145].

Parameter	Value	Units	Source
Γ_s	0.680	ps^{-1}	[18]
$\Delta\Gamma_s$	0.049	ps^{-1}	[18]
$\delta_{\parallel}$	-2.93	rad	[145]
$ A_0 ^2$	0.556	-	[145]
$ A_{\perp} ^2$	0.233	-	[145]
$\delta_{\perp}$	2.91	rad	[145]
$\phi_s^{J/\psi\phi}(\text{SM})$	-0.0368	rad	[121]
$\phi_s^{J/\psi\phi}(\text{NP})$	-0.6000	rad	Table 7.7

The detector parameters are kept fixed in the following studies³¹.

³⁰This value is illustrative. It would need some re-tuning given the latest CDF result (Figure 7.11).

³¹The average value of the signal mass distribution, $m_{B_s^0}$, is also fixed in the fit.

7.7.1 Standard Model Assumption

The $|A_0|^2$, $|A_\perp|^2$ and Γ_s parameters have recently been measured by the CDF experiment, as quoted in Table 7.8. Until now, $\Delta\Gamma_s$ and $\delta_\perp$ are only constrained by the measurements. The statistical uncertainties associated to the $|A_0|^2$, $|A_\perp|^2$ and Γ_s CDF measurements can be lowered significantly at LHCb and the $\Delta\Gamma_s$ parameter can be measured assuming the Standard Model prediction for $\phi_s^{J/\psi\phi}$.

To perform the measurements, the $\phi_s^{J/\psi\phi}$ value is set to zero in the fit model to untagged $B_s^0 \rightarrow J/\psi\phi$. As a consequence, the terms containing the $\delta_\perp$ strong phase in Equations 7.139 and 7.141 cancel. There is still an access to the strong phase $\delta_\parallel$ through Equation 7.140.

From 300 Toy Monte Carlo jobs, it is observed that all the parameter input values are well retrieved and the errors calculated correctly, except for $\delta_\parallel$. Indeed, in the distribution of the fitted $\delta_\parallel$ values, several values are found to be equal to $-\pi$, as shown in Figure 7.46 (top). According to the MINUIT package returned message, the values at $-\pi$ result from successful minimizations.

To understand the origin of the fit output values at $-\pi$, a new parameterization, $a = \cos(\delta_\parallel)$, is introduced in the fit model. The jobs are redone using the same seeds than used previously. The distribution of the fitted $\cos(\delta_\parallel)$ values is shown in Figure 7.46 (middle), which is Gaussian-distributed. Some values are found to be smaller than -1, which correspond to unphysical regions probed during the minimization process. The possibility of having cosine values smaller than -1 is explained by the fact that the fit is not constrained anymore by the bounds imposed by the cosine function itself. Looking at the correlations between the $\delta_\parallel$ output values at $-\pi$ and the values of $\cos(\delta_\parallel)$ belonging to unphysical regions (Figure 7.46, bottom), a full correlation is observed.

To estimate the parameter sensitivities, the jobs corresponding to output fit values $\delta_\parallel = -\pi$ can therefore be considered as failed fits and removed. However, the errors on the remaining $\delta_\parallel$ output fit values are not calculated properly, resulting in an asymmetric pull distribution. Hence, sensitivity results are given using the $a = \cos(\delta_\parallel)$ parameter instead, for which the errors are correctly calculated. Three statistical scenarios are studied: 2 fb^{-1} , 0.2 fb^{-1} and 0.1 fb^{-1} of data. The results are given in the upper parts of Tables 7.27, 7.28 and 7.29 respectively. In each case, 300 Toy Monte Carlo jobs are performed.

The sensitivities to the $|A_0|^2$, $|A_\perp|^2$, Γ_s and $\Delta\Gamma_s$ parameters are found to be ± 0.003 , ± 0.004 , $\pm 0.003 \text{ ps}^{-1}$ and $\pm 0.009 \text{ ps}^{-1}$ respectively for the 2 fb^{-1} scenario. The sensitivity to $\cos(\delta_\parallel)$ is $\pm 0.015 \text{ rad}$. For the lower statistics cases, 0.2 fb^{-1} and 0.1 fb^{-1} , the sensitivities scale as $\sqrt{N}$, with N the number of $B_s^0 \rightarrow J/\psi\phi$ events. With only 0.1 fb^{-1} of untagged data at $\sqrt{s} = 14 \text{ TeV}$, the statistical uncertainties are of the same order of magnitude as the latest CDF results summarized in Table 7.8 obtained with a fit to tagged $B_s^0 \rightarrow J/\psi\phi$ events. Moreover, the sensitivities quoted for $|A_0|^2$, $|A_\perp|^2$, Γ_s and $\Delta\Gamma_s$ at 2 fb^{-1} are of the same order than the ones obtained from the tagged fit at LHCb [123].

The angular acceptance parameterization of Section 7.6, not used by default in the fit model, is added to check its impact on the sensitivity results. The results given in the lower part of Tables 7.27-7.29 show no differences with the sensitivity values obtained without angular acceptance description.

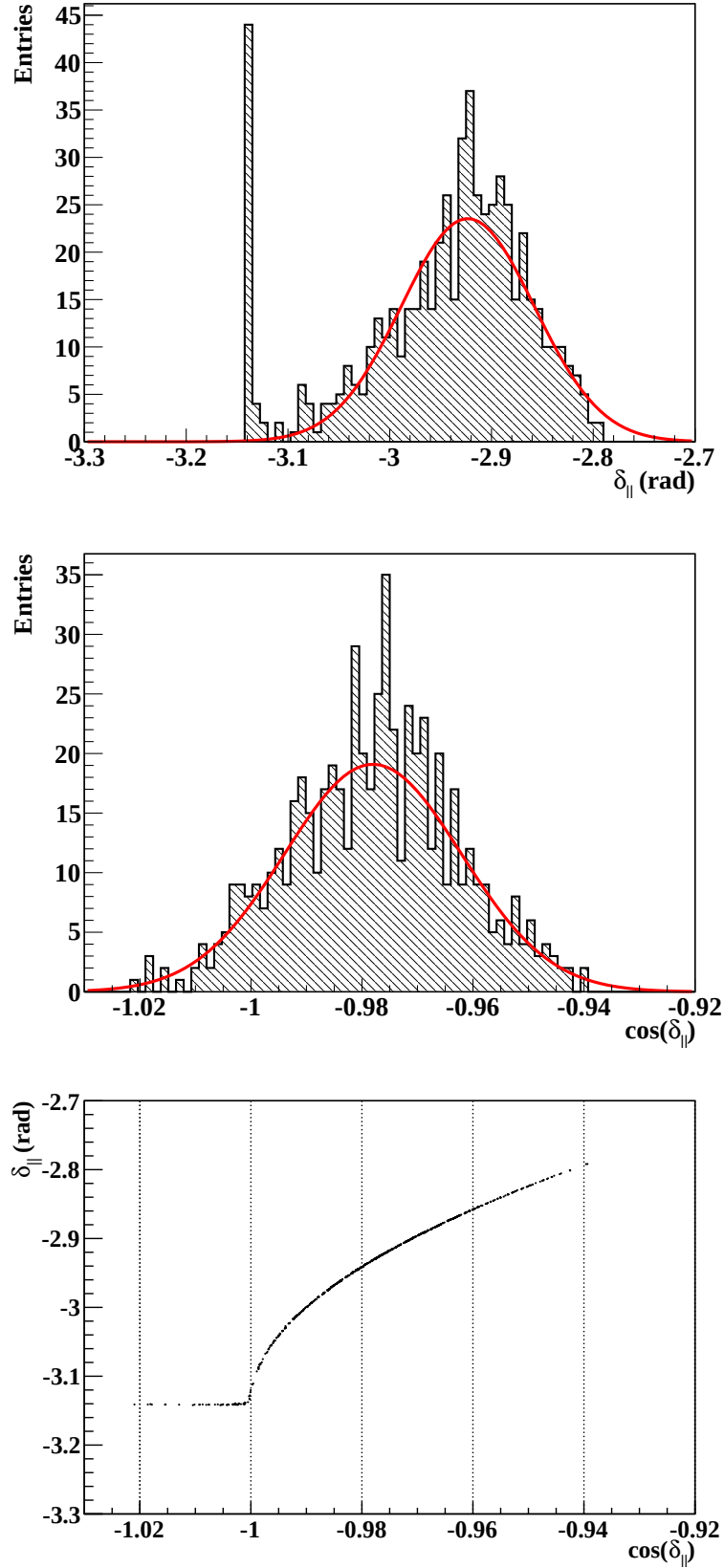


Figure 7.46: $\delta_{||}$ (top) and $a = \cos(\delta_{||})$ (middle) output fit value distributions obtained for the 2 fb^{-1} statistical scenario. The output fit values $\delta_{||} = -\pi$ (top) are fully correlated (bottom) with the values belonging to the unphysical region $\cos(\delta_{||}) < -1$ (middle).

Table 7.27: Sensitivities and pull distribution parameters obtained for 2 fb^{-1} (Standard Model assumption).

Parameters	Value and Sensitivity	Pull Mean	Pull Width
$ A_0 ^2$	0.556 ± 0.003	-0.03 ± 0.06	1.03 ± 0.04
$ A_\perp ^2$	0.233 ± 0.004	$+0.04 \pm 0.06$	1.00 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.680 ± 0.003	-0.05 ± 0.06	1.04 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.049 ± 0.009	-0.02 ± 0.06	0.96 ± 0.04
$\alpha = \cos(\delta_{ })$	-0.978 ± 0.015	-0.03 ± 0.06	0.99 ± 0.04
Effect of Angular Acceptances (P2VV Fitter)			
$ A_0 ^2$	0.556 ± 0.003	-0.08 ± 0.06	1.04 ± 0.04
$ A_\perp ^2$	0.233 ± 0.004	$+0.11 \pm 0.06$	1.05 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.680 ± 0.003	-0.03 ± 0.06	1.04 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.049 ± 0.008	$+0.02 \pm 0.06$	1.00 ± 0.04
$\alpha = \cos(\delta_{ })$	-0.981 ± 0.015	-0.14 ± 0.06	1.01 ± 0.04

Table 7.28: Sensitivities and pull distribution parameters obtained for 0.2 fb^{-1} (Standard Model assumption).

Parameters	Value and Sensitivity	Pull Mean	Pull Width
Result With P2VV Fitter			
$ A_0 ^2$	0.556 ± 0.009	-0.04 ± 0.06	1.05 ± 0.04
$ A_\perp ^2$	0.234 ± 0.012	$+0.05 \pm 0.06$	1.03 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.680 ± 0.009	-0.03 ± 0.06	0.97 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.048 ± 0.025	-0.03 ± 0.06	1.00 ± 0.04
$\alpha = \cos(\delta_{ })$	-0.984 ± 0.048	-0.10 ± 0.06	1.00 ± 0.04
Effect of Angular Acceptances (P2VV Fitter)			
$ A_0 ^2$	0.555 ± 0.008	-0.09 ± 0.06	1.05 ± 0.04
$ A_\perp ^2$	0.235 ± 0.012	$+0.15 \pm 0.06$	1.02 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.680 ± 0.009	-0.01 ± 0.06	0.99 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.046 ± 0.026	-0.09 ± 0.06	1.03 ± 0.04
$\alpha = \cos(\delta_{ })$	-0.987 ± 0.048	-0.15 ± 0.06	1.03 ± 0.04

Table 7.29: Sensitivities and pull distribution parameters obtained for 0.1 fb^{-1} (Standard Model assumption).

Parameters	Value and Sensitivity	Pull Mean	Pull Width
Result With P2VV Fitter			
$ A_0 ^2$	0.555 ± 0.012	-0.06 ± 0.06	1.10 ± 0.04
$ A_\perp ^2$	0.233 ± 0.017	$+0.01 \pm 0.06$	1.08 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.681 ± 0.012	$+0.01 \pm 0.06$	1.00 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.049 ± 0.037	$+0.03 \pm 0.06$	1.00 ± 0.04
$\alpha = \cos(\delta_{ })$	-0.978 ± 0.070	$+0.05 \pm 0.06$	1.02 ± 0.04
Effect of Angular Acceptances (P2VV Fitter)			
$ A_0 ^2$	0.556 ± 0.011	-0.03 ± 0.06	0.97 ± 0.04
$ A_\perp ^2$	0.234 ± 0.016	$+0.05 \pm 0.06$	0.94 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.681 ± 0.012	$+0.00 \pm 0.06$	0.99 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.046 ± 0.036	-0.04 ± 0.06	1.04 ± 0.04
$\alpha = \cos(\delta_{ })$	-0.988 ± 0.068	-0.10 ± 0.06	1.00 ± 0.04

It should be noted that when the $\delta_{||}$ input value is further away from $-\pi$, $\delta_{||} = -2.78$ rad for example, no output fit value at $-\pi$ is observed in the distribution, as shown in Figure 7.47 for 2 fb^{-1} of data.

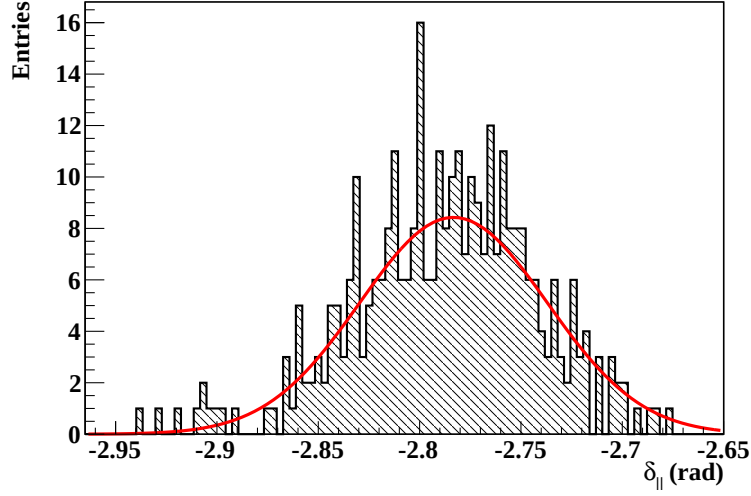


Figure 7.47: $\delta_{||}$ output fit value distribution using an input value $\delta_{||} = -2.78$ rad.

The associated sensitivity values and pull distribution parameters are given in Table 7.30. The sensitivity to $\delta_{||}$ is ± 0.046 rad.

Table 7.30: Sensitivities and pull distribution parameters for 2 fb^{-1} of Toy Monte Carlo data using $\delta_{||} = -2.78$ rad as input value (Standard Model assumption).

Parameters	Value and Sensitivity	Pull Mean	Pull Width
$ A_0 ^2$	0.556 ± 0.003	-0.03 ± 0.06	0.99 ± 0.04
$ A_{\perp} ^2$	0.233 ± 0.004	$+0.10 \pm 0.06$	1.04 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.680 ± 0.003	-0.02 ± 0.06	1.01 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.048 ± 0.008	-0.08 ± 0.06	0.99 ± 0.04
$\delta_{ } [\text{rad}]$	-2.783 ± 0.046	-0.07 ± 0.06	1.00 ± 0.04

7.7.2 New Physics Scenario

In the Standard Model scenario, the sensitivity to $\phi_s^{J/\psi\phi}$ arises from the $\sin(\phi_s^{J/\psi\phi})$ terms, the $\cos(\phi_s^{J/\psi\phi})$ terms being almost insensitive due to the very small $\phi_s^{J/\psi\phi}$ expectation value. Luckily, $\sin(\phi_s^{J/\psi\phi})$ terms remain in two terms entering in the untagged formula (Equations 7.139, 7.141). However, they also depend on the strong phases $\delta_{||}$ and $\delta_{\perp}$ that have to be determined simultaneously in the fit. In the New Physics scenario, where the $\phi_s^{J/\psi\phi}$ value is set at 0.6 (Table 7.7), it is possible that the sensitivity is enhanced by the $\cos(\phi_s^{J/\psi\phi})$ terms.

If all the physics parameters are left free in the fit, the strong and weak phases cannot be measured³². Indeed, the $\delta_{\perp}$ input value, $\delta_{\perp} = 2.91$ rad, cannot be retrieved from the $\delta_{\perp}$ output fit value distribution shown in Figure 7.48 (left) for 2 fb^{-1} of Toy Monte Carlo data³³. The $\delta_{||}$ output fit value distribution is similar to the one of Figure 7.46 (top), where several $\delta_{||}$ values are found to be $-\pi$ for an input value $\delta_{||} = -2.93$ rad. The $\phi_s^{J/\psi\phi}$ output fit value distribution is shown in Figure 7.48 (right), where the input value $\phi_s^{J/\psi\phi} = -0.6$ cannot be retrieved either. Therefore, in order to measure $\phi_s^{J/\psi\phi}$ with a fit to untagged $B_s^0 \rightarrow J/\psi\phi$ events, the strong phases cannot be left free in the fit.

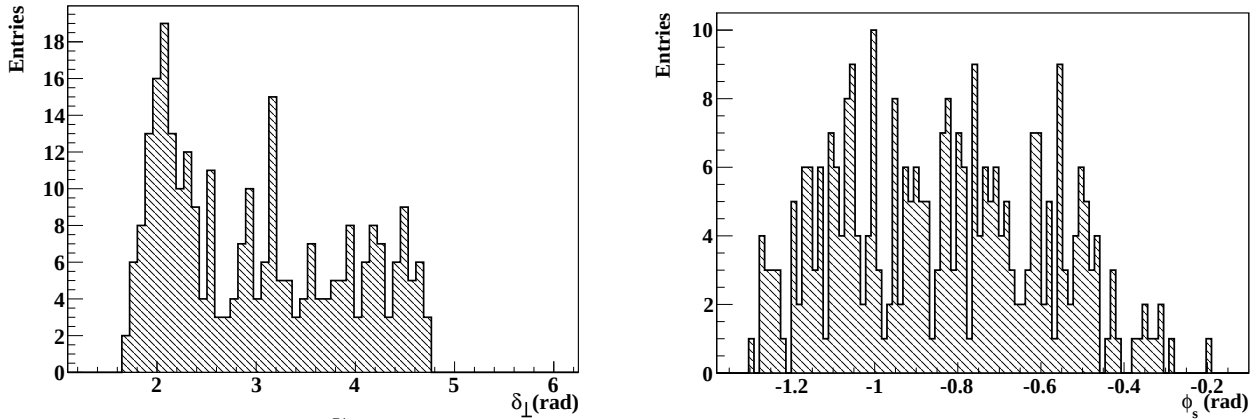


Figure 7.48: $\delta_{\perp}$ (left) and $\phi_s^{J/\psi\phi}$ (right) output fit value distributions obtained for 2 fb^{-1} of Toy Monte Carlo data, with all the physics parameters free in the fit. The input values of 2.91 rad for $\delta_{\perp}$ and -0.6 rad for $\phi_s^{J/\psi\phi}$ cannot be retrieved from the distributions.

The $\delta_{||}$ and $\delta_{\perp}$ strong phases have been measured by the Babar experiment in the $B^0 \rightarrow J/\psi K^{*0}$ channel to be $\delta_{||} = -2.93 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$ and $\delta_{\perp} = 2.91 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})$ [145]. Under flavor symmetry, it is reasonable to assume that they are similar for the $B_s^0 \rightarrow J/\psi\phi$ channel. They are indeed expected to be equal within a similar precision of a few percent of π (or $\sim 10^\circ$) [135]. Therefore, the strong phases δ_i ($i = \{||, \perp\}$) are constrained during the fit procedure using Gaussian error distributions to the values $\delta_{\text{meas},i}$ measured by Babar, which are called *Gaussian constraints*³⁴.

³²Small biases are also observed for Γ_s and $\Delta\Gamma_s$.

³³This is not the case for the tagged fit, where the $\delta_{\perp}$ input value is retrieved without any problem [123].

³⁴This method has been used by the DØ collaboration in the analysis to tagged $B_s^0 \rightarrow J/\psi\phi$ events [161].

The negative logarithmic likelihood of Equation 7.176 is modified as:

$$\mathcal{L}'' = -\sum_e^N \ln(\mathcal{P}_{\text{tot}}(X_e; \lambda)) + \sum_i \frac{(\delta_i - \delta_{\text{meas},i})^2}{2\sigma_{\text{meas},i}^2} \quad (7.181)$$

where $\sigma_{\text{meas},i}$ are the measurement uncertainties.

The sensitivity and pull distribution fit parameters are given in Table 7.31 for 1000 Toy Monte Carlo jobs at 2 fb^{-1} using external Gaussian constraints on both $\delta_{\parallel}$ and $\delta_{\perp}$. The σ_{meas} is set to 0.18 rad, which is larger than the uncertainty on the $\delta_{\parallel}$ and $\delta_{\perp}$ measurements, reducing the strength of the constraints in the fit. The distributions of the $\delta_{\parallel}$, $\delta_{\perp}$ and $\phi_s^{J/\psi\phi}$ output fit value are shown in Figure 7.49.

Table 7.31: Sensitivities and pull distribution parameters obtained with 2 fb^{-1} of Toy Monte Carlo data.

Parameters	Value and Sensitivity	Pull Mean	Pull Width
$ A_0 ^2$	$+0.556 \pm 0.003$	-0.03 ± 0.03	1.03 ± 0.02
$ A_{\perp} ^2$	$+0.233 \pm 0.004$	$+0.01 \pm 0.03$	0.97 ± 0.02
$\Gamma_s [\text{ps}^{-1}]$	$+0.680 \pm 0.003$	$+0.08 \pm 0.03$	1.04 ± 0.02
$\Delta\Gamma_s [\text{ps}^{-1}]$	$+0.050 \pm 0.009$	$+0.10 \pm 0.03$	0.96 ± 0.02
$\phi_s^{J/\psi\phi}$	-0.609 ± 0.200	-0.04 ± 0.03	1.04 ± 0.02
$\delta_{\parallel} [\text{rad}]$	-2.926 ± 0.064	$+0.10 \pm 0.03$	1.09 ± 0.02
$\delta_{\perp} [\text{rad}]$	$+2.910 \pm 0.177$	$+0.00 \pm 0.03$	0.99 ± 0.02

The sensitivities to the $|A_0|^2$, $|A_{\perp}|^2$, Γ_s and $\Delta\Gamma_s$ parameters are found to be ± 0.003 , ± 0.004 , $\pm 0.003 \text{ ps}^{-1}$ and $\pm 0.009 \text{ ps}^{-1}$ respectively, which are similar to the ones of Table 7.27.

The sensitivity to $\delta_{\perp}$ is equal to $\sigma_{\text{meas}} = 0.18 \text{ rad}$, which means that it is fully dominated by the external constraint, whereas the sensitivity to $\delta_{\parallel}$ of $\pm 0.06 \text{ rad}$ is dominated by the parameter determination with data, as being smaller than σ_{meas} .

The sensitivity to $\phi_s^{J/\psi\phi}$ is $\pm 0.20 \text{ rad}$ for 2 fb^{-1} of data at $\sqrt{s} = 14 \text{ TeV}$ ³⁵. A comparison with the sensitivity expected from the time-dependent analysis to tagged events at LHCb is made in the next Sub-section.

³⁵No sensitivity studies are performed for the 0.2 and 0.1 fb^{-1} of data. Biases in $\Delta\Gamma_s$ and underestimations of the errors for $\phi_s^{J/\psi\phi}$ have been observed for these statistical scenarios, in the case the strong phases were fixed (Appendix A.0.2). Similar observations are hence expected for the case discussed here in which the strong phases are Gaussian-constrained.

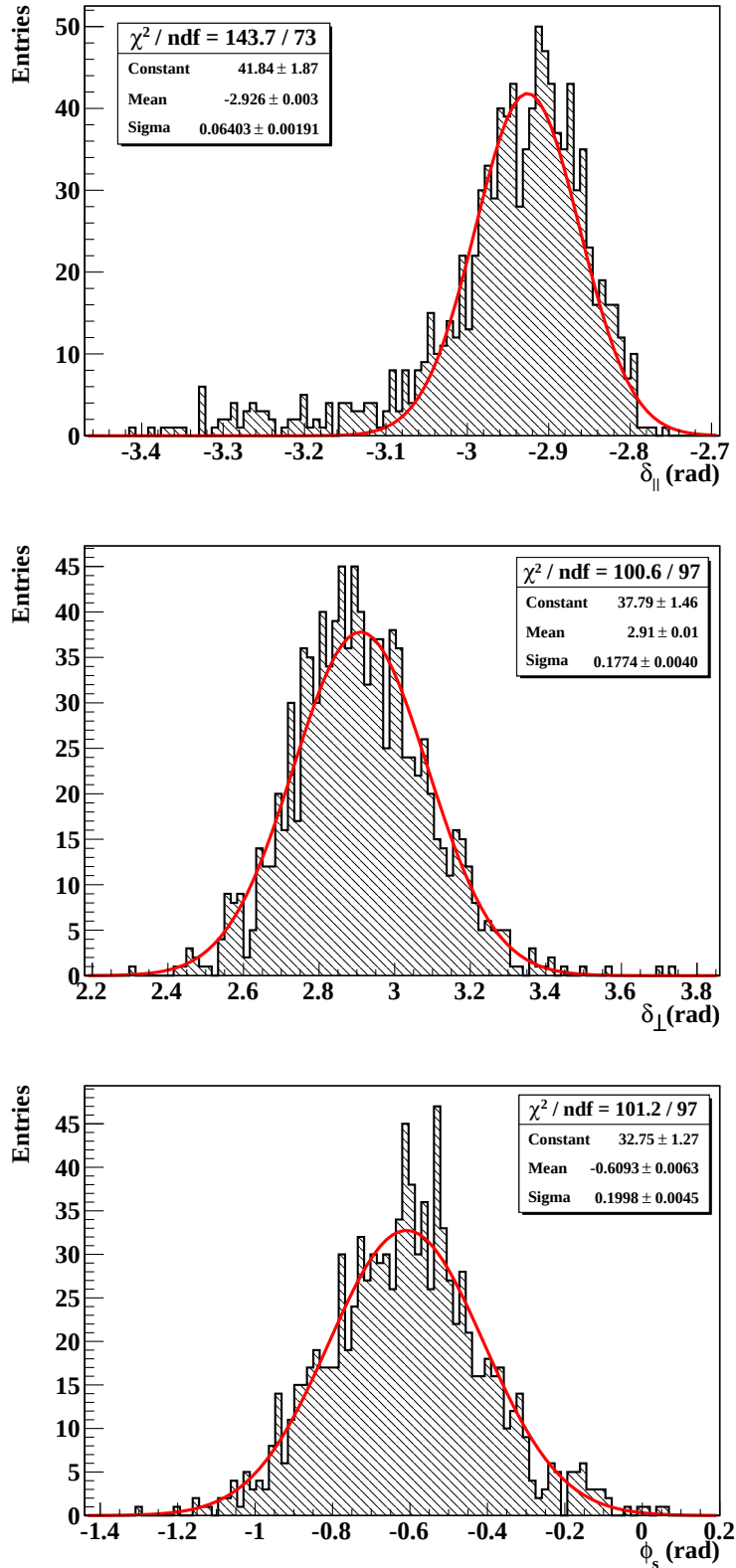


Figure 7.49: $\delta_{||}$ (top), $\delta_{\perp}$ (middle) and $\phi_s^{J/\psi\phi}$ (bottom) output fit value distributions obtained for 2 fb⁻¹ of toy Monte Carlo data, with strong phases Gaussian-constrained with $\sigma = 0.18$ rad.

7.8 Time-Dependent Angular Analysis to Tagged $B_s^0 \rightarrow J/\psi\phi$ Events

In the time-dependent angular analysis to tagged $B_s^0 \rightarrow J/\psi\phi$ events, two additional ingredients compared to the fit to untagged $B_s^0 \rightarrow J/\psi\phi$ events need to be fully understood:

1. *The proper time resolution:* An excellent proper time resolution is needed to resolve the fast $B_s^0 - \bar{B}_s^0$ oscillations. The precision that LHCb is expected to reach on the B meson proper time calculation is $\sigma_t \sim 0.040$ ps [123].
2. *The tagging:* The tagging needs to have a high efficiency ε_{tag} with a low and well known wrong tag fraction ω ³⁶. The identification of the initial flavor of the reconstructed B mesons will be done by different dedicated algorithms based on *Opposite-Side (OS)* or *Same-Side (SS)* taggers [162, 163].

Compared to the untagged case, an additional parameter is present, Δm_s , which has already been measured precisely [18]. Before measuring $\phi_s^{J/\psi\phi}$, Δm_d in the $B^0 \rightarrow J/\psi K^{*0}$ decay and $\sin(2\beta)$ in the $B^0 \rightarrow J/\psi K_s^0$ decay will be measured to validate the flavor tagging calibration procedure [164]. The Δm_s parameter will be measured in the $B_s^0 \rightarrow D_s^- \pi^+$ decay to validate that the B_s^0 oscillations can be resolved adequately [165].

An expected performance for the $\phi_s^{J/\psi\phi}$ measurement at the LHCb experiment is shown in Figure 7.50 for different integrated luminosities, for a LHC centre of mass energy of 14 TeV. The lines above and below the sensitivity curve indicate uncertainties coming from the $b\bar{b}$ cross-section and the visible branching ratio of $B_s^0 \rightarrow J/\psi\phi$.

The Standard Model prediction of $2\beta_s$, 0.0368, bounded by its uncertainties, is also drawn. The black line shows the combined CDF/DØ uncertainty scaled to 18 fb^{-1} .

With an integrated luminosity of 2 fb^{-1} , the statistical uncertainty $\sigma(\phi_s^{J/\psi\phi})$ is expected to be smaller than ± 0.04 rad.

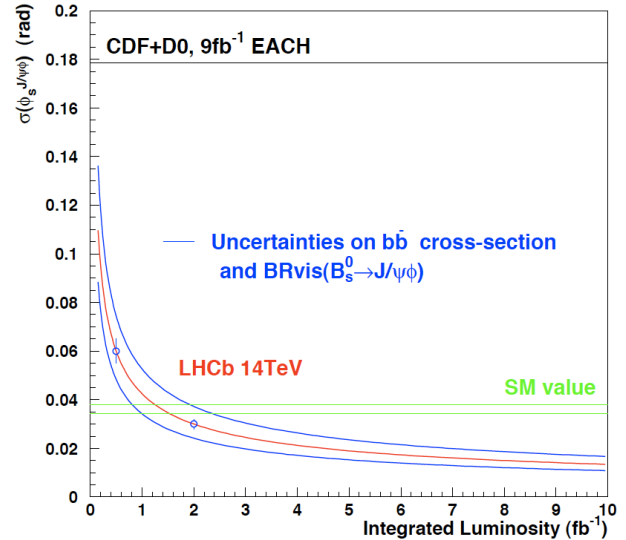


Figure 7.50: Statistical uncertainty on $\phi_s^{J/\psi\phi}$ versus the integrated luminosity at a LHC centre of mass energy $\sqrt{s} = 14 \text{ TeV}$ [123].

³⁶The *tagging efficiency* ε_{tag} is defined as the number of signal-selected and tagged events divided by the total number of selected events, and the *wrong tag fraction* ω is defined as the fraction of wrongly tagged events divided by the total number of tagged events.

Conclusions

The measurement of the CP violating phase $\phi_s^{J/\psi\phi}$ is one of the most important measurements that will be performed at LHCb. In the Standard Model, this phase is predicted to be $\phi_s^{J/\psi\phi} = -0.0360^{+0.0020}_{-0.0016}$ rad, which makes it one of the CP observables with the smallest theoretical uncertainty. New physics contributions could significantly modify this prediction.

The CP-even and CP-odd components are present in the $J/\psi\phi$ final state due to the pseudoscalar to vector-vector nature of the $B_s^0 \rightarrow J/\psi\phi$ decay, with different relative orbital angular momentum between the J/ψ and ϕ . To extract the phase, $\phi_s^{J/\psi\phi}$, the time dependent decay rates for initial B_s^0 and $\bar{B}_s^0 \rightarrow J/\psi\phi$ are studied as a function of the decay angles of the final states. After the first level and the high level trigger decisions, $\sim 117,000$ $B_s^0 \rightarrow J/\psi\phi$ events are expected to be selected in 2 fb^{-1} of data at $\sqrt{s} = 14 \text{ TeV}$. The $\phi_s^{J/\psi\phi}$ measurement is challenging, as it requires various experimental techniques to be perfectly under control, such as proper time and angular resolutions, background rejection, flavor tagging, and fit with multi parameters. Also, the variation of the acceptance in the decay angles, which is due to the geometrical acceptance of the LHCb detector, the event reconstruction program and the event selection cuts, need to be properly taken into account in the fit model. For this, three-dimensional parameterizations of the angular acceptances have been developed in this thesis.

With early data, a simplified time-dependent angular analysis can be performed, which does not require the flavor of the B_s^0 meson at production to be known. Studies presented in this thesis show that with 2 fb^{-1} of data at $\sqrt{s} = 14 \text{ TeV}$, a sensitivity to $\phi_s^{J/\psi\phi}$ of ± 0.20 rad is expected, in the case of a New Physics scenario, i.e. large CP violation effect ($\phi_s^{J/\psi\phi} \sim 0.60$ rad). If the phase is small as expected by the Standard Model, other parameters can be measured, such as the amplitudes of the CP-even and CP-odd components, $(|A_0|^2 + |A_{||}|^2)$ and $|A_{\perp}|^2$, the B_s^0 meson lifetime $\tau_s = 1/\Gamma_s$, and the width difference $\Delta\Gamma_s$ between the two mass eigenstates. With only 0.2 fb^{-1} of data at $\sqrt{s} = 14 \text{ TeV}$, these measurements would become more precise statistically than the latest results quoted by the CDF experiment (June 2010).

At LHCb, the innermost area around the beam pipe of the tracking stations located after the dipole magnet is covered by the Inner Tracker detector. It uses a p^+ -on-n silicon microstrip technology with a strip pitch of $198 \mu\text{m}$. In this thesis, the assembly procedure of the Inner Tracker performed in a clean environment at CERN is described. By Summer 2008, the Inner Tracker was assembled, fully operational and installed in the LHCb experimental cavern.

A precise alignment of the tracking system and an accurate description of the magnetic field are of prime importance to reach a very good momentum resolution. As detailed in this thesis, the positions of the silicon microstrip sensors of the Inner Tracker have been measured with an accuracy of $\pm 0.05 \text{ mm}$ by theodolite. The positions of the protection boxes containing the silicon sensors in the LHCb experimental cavern have been adjusted by several iterations of survey measurements with an accuracy of $\pm 0.5 \text{ mm}$ in x and y and $\pm 1 \text{ mm}$ in z .

After the magnet construction, magnetic field measurements were taken with Hall probes for both polarities of the magnet in December 2005 in the LHCb experimental cavern. They are used in this thesis to provide a description of the magnetic field for the reconstruction of real data. A multidimensional fit method using Chebychev polynomials is used to obtain the measured magnetic field map divided in several regions. The method was first tested with the simulated field map and a precision of $\sim 10^{-3}$ T is reached to describe the three magnetic field components.

Several differences are observed between the simulated and the measured magnetic field maps. First, the simulated field map has a $\int \vec{B} \cdot d\vec{l}$ that is $\sim 7 \times 10^{-3}$ times larger than the measured map. This is attributed to the known expansion of the coils by ~ 8 mm when the magnet is powered, which is not taken into account in the simulated description. Second, an asymmetry between the up and down parts of the dipole magnet is observed for the measured magnetic field, while the simulated magnetic field does not have this by design. Monte Carlo studies with inclusive $J/\psi \rightarrow \mu^+ \mu^-$ decays show that this asymmetry leads to a 0.1% difference between masses reconstructed from tracks going through the upper or lower parts of the magnet. Using reconstructed mass distributions of $K_s \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p^+ \pi^-$ and $\bar{\Lambda} \rightarrow p^- \pi^+$ decays from early 2010 data, the global scale of the measured field map is better than that of the simulated field map. Moreover, looking at K_s candidates reconstructed from tracks going through the upper or lower parts of the magnet, the up-down asymmetry of the magnetic field measurements is found to be a real effect. Hence, the measured magnetic field map is used for the reconstruction of events.

To correct for the residual global scale difference between the expected mass peak values of known resonances and the reconstructed values using the measured field map, a momentum scale calibration is performed in this thesis using K_s , Λ and $\bar{\Lambda}$ candidates from early 2010 data. For instance, the mass resolutions expected from Monte Carlo studies and reconstructed for L-L K_s candidates are $\sigma_{\text{exp}} = 3.9 \text{ MeV}/c^2$ and $\sigma_{\text{rec}} = 4.2 \text{ MeV}/c^2$ and for D-D candidates $\sigma_{\text{exp}} = 5.9 \text{ MeV}/c^2$ and $\sigma_{\text{rec}} = 7.3 \text{ MeV}/c^2$. For candidates reconstructed from two long tracks, a mean momentum scale $\alpha = -0.0007 \pm 0.0001$ is found. For candidates reconstructed from two downstream tracks, $\alpha = -0.0034 \pm 0.0001$ is obtained. The difference between the values for the two types of candidates could result from the relative alignment between the Tracker Turicensis (TT) and the VELO, since TT plays a significant role in the reconstruction of downstream tracks, while it has a limited impact in the reconstruction of long tracks.

Appendix A

A.0.1 HLT2 Exclusive Selections for $B \rightarrow J/\psi(\mu\mu)X$ Channels

In the following Figures, the HLT2 selection cuts are represented by the green dashed vertical lines with arrows specifying whether they are lower/upper limit cuts.

Offline-Online Comparisons

In Figures A.1-A.29, HLT2 signal distributions (black hatched area) of selection variables are compared with the offline distributions (area delimited by a blue point-dashed line). For better comparisons, the offline selection cuts have been relaxed (only loose cuts on the masses are used), such that their signal distributions cover the whole range of the online distributions. The offline-online comparisons show that the transverse momentum p_T (Figures A.5-A.6 for B_s^0 ; Figures A.15-A.18 for B^0 ; Figures A.25-A.27 for B^+) and distributions are similar in both environments¹. Therefore, the HLT2 cuts are set at the same values as for offline.

Other distributions differ between offline and HLT2, the B-vertex χ^2 (Figure A.4 for B_s^0 ; Figure A.14 for B^0 ; Figure A.24 for B^+) and the mass distributions (Figures A.8-A.10 for B_s^0 ; Figures A.19-A.21 for B^0 ; Figures A.28-A.29 for B^+). As these HLT2 distributions are broader online than offline, the cuts on these quantities are relaxed in the HLT2 environment. The mass window cuts are set at about three times the average width of the distributions, except for ϕ for which only an upper limit is defined. The track χ^2 (Figure A.1 for B_s^0 ; Figure A.11 for B^0 ; Figure A.22 for B^+) shows a different behaviour between offline and online. In offline, the value comes from a multi-pass bidirectional Kalman filter. In online, the χ^2 of the forward pattern recognition is used instead.

HLT2 Signal, Combinatorics and Minimum Bias Comparisons

In Figures A.30-A.58, HLT2 signal distributions (black positive-slope hatched area) of selection variables are compared with combinatorics (area delimited by a blue point-dashed line) and minimum bias (red negative-slope hatched area) distributions.

The HLT2 exclusive selections aim at accepting signal events with high efficiency, while rejecting minimum bias events. In the case of transverse momenta p_T cuts (Figures A.34-A.35 for B_s^0 ; Figures A.44-A.47 for B^0 ; Figures A.54-A.56 for B^+), the cuts have been kept to the offline values, except for the muons where the p_T cut has been raised from > 500 MeV/c offline to > 800 MeV/c, this to reduce the minimum bias rate and combinatorics, and hence speed up the processing time.

Cuts on the J/ψ , ϕ and K^{*0} vertex- χ^2 do not have any significant effect on the minimum bias rate as shown in Figures A.31-A.32 for B_s^0 , Figures A.41-A.42 for B^0 and Figure A.52 for B^+ . However, they allow the selection of only one or two candidates at each vertex, which lowers the CPU time. As they have similar distributions than offline (Figures A.2-A.3 for B_s^0 ; Figures A.12-A.13 for B^0 ; Figures A.23 for B^+), the HLT2 cuts are set at similar values than the offline cuts.

¹In Figures A.5-A.6 and A.15-A.16, loose mass cuts of ± 200 MeV/c² are applied on the ϕ and K^{*0} masses compared to the B^+ case, where a discrepancy is observed between the offline and online distributions (Figures A.25-A.26). When removing the loose mass cuts on the ϕ and K^{*0} , similar discrepancies between offline and online distributions of $p_T(\mu)$ and $p_T(J/\psi)$ are obtained for the B_s^0 and B^0 cases.

$$B_s^0 \rightarrow J/\psi(\mu\mu)\phi(K^+K^-)$$

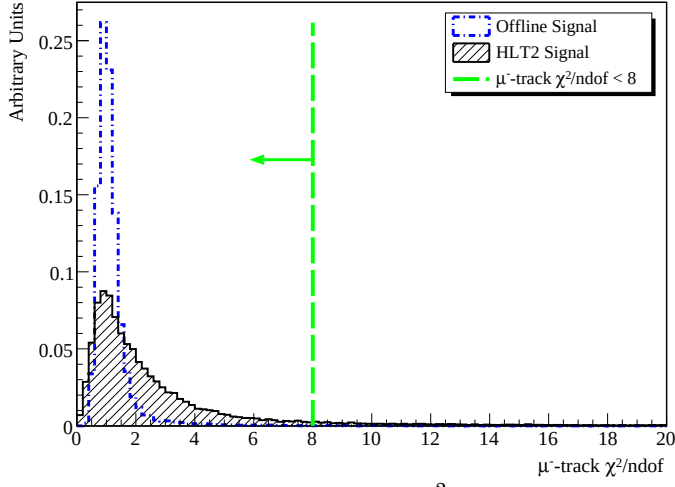


Figure A.1: μ^- -track χ^2/ndof .

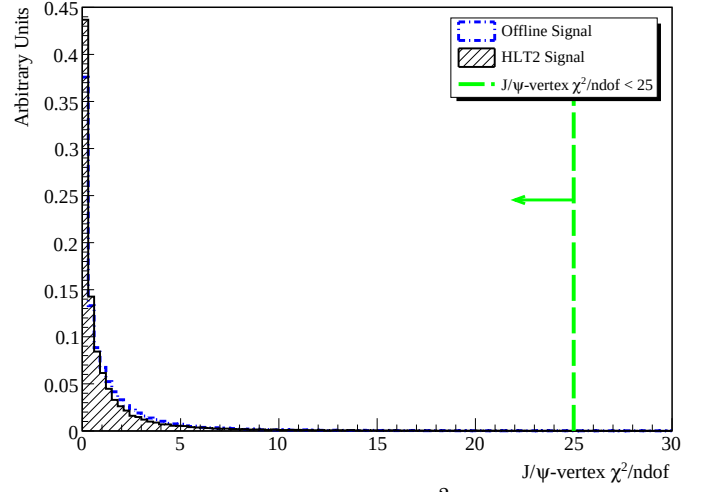


Figure A.2: J/ψ -vertex χ^2/ndof .

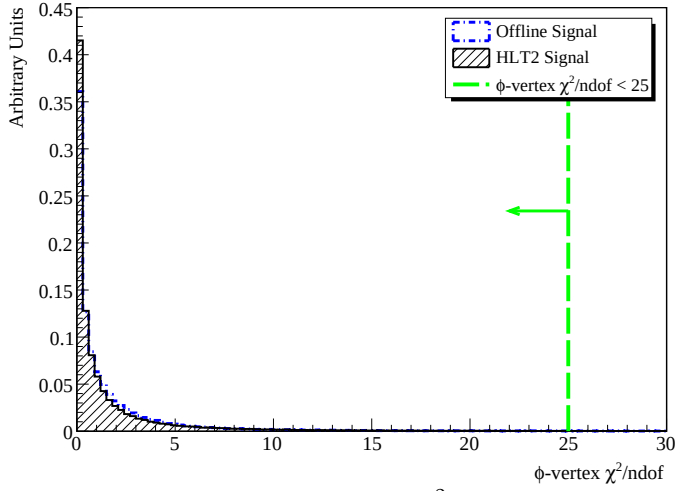


Figure A.3: ϕ -vertex χ^2/ndof .

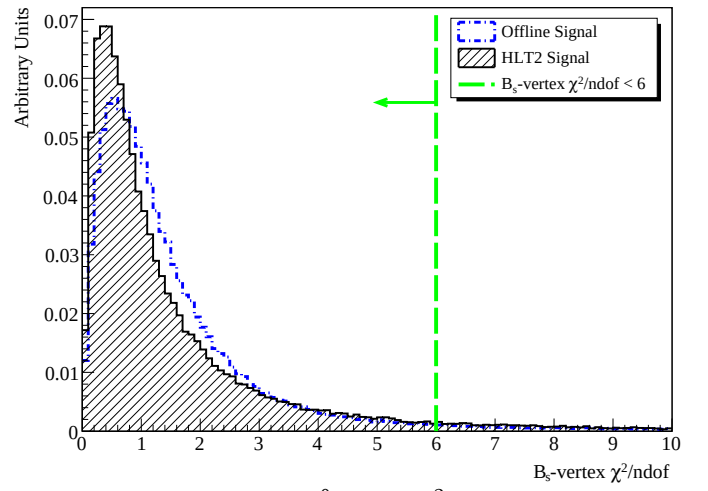


Figure A.4: B_s^0 -vertex χ^2/ndof .

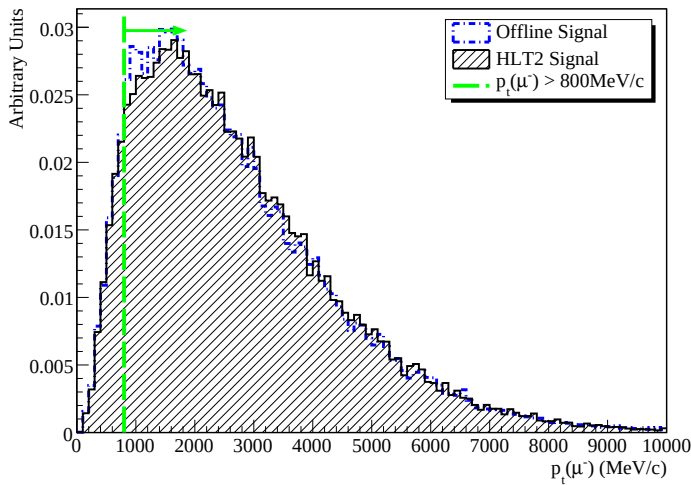


Figure A.5: $p_T(\mu^-)$.

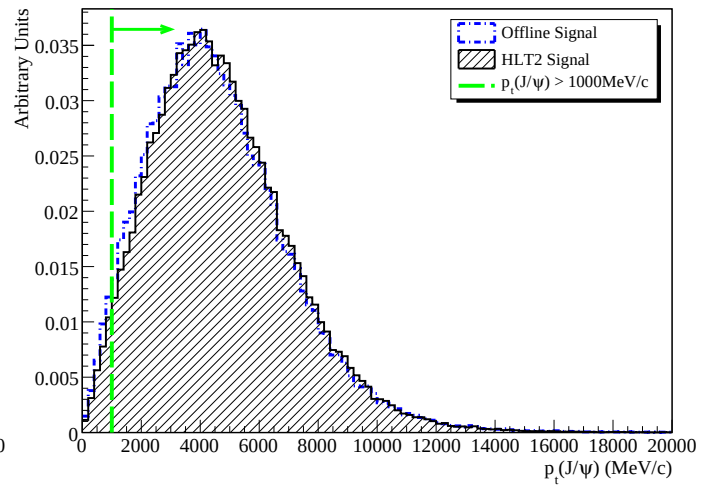
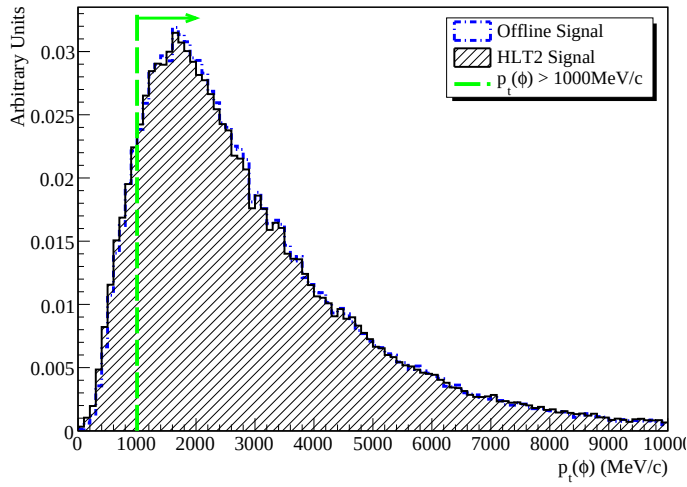
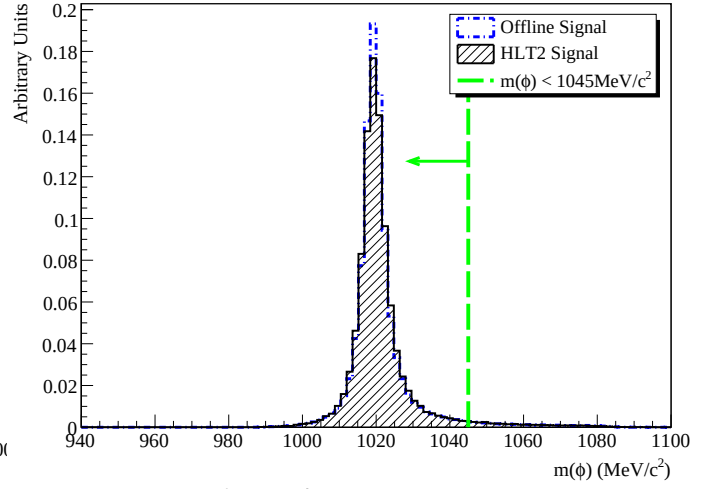
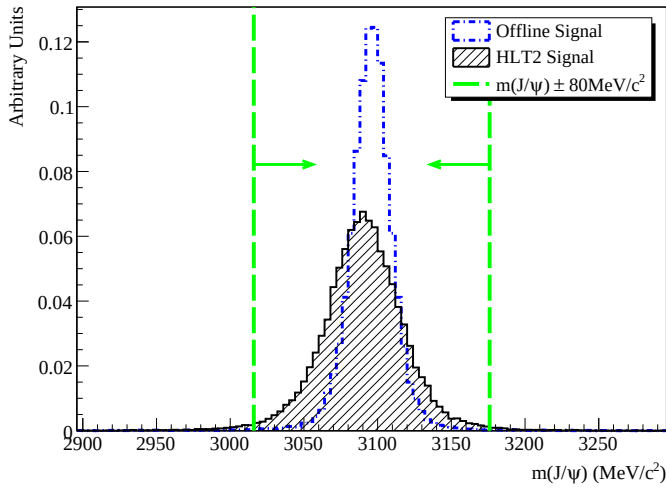
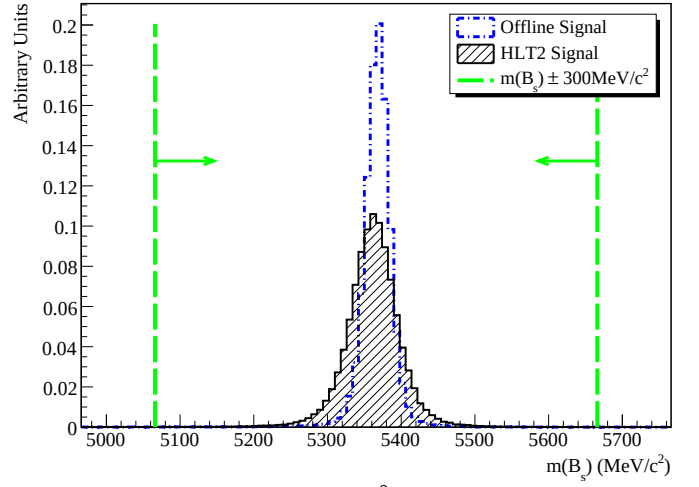
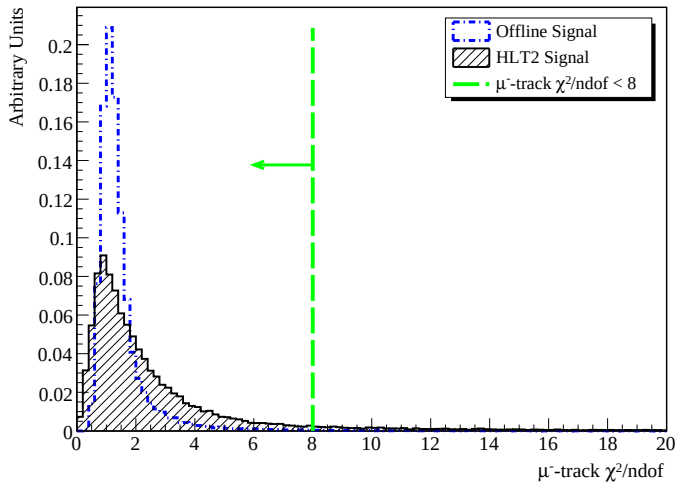
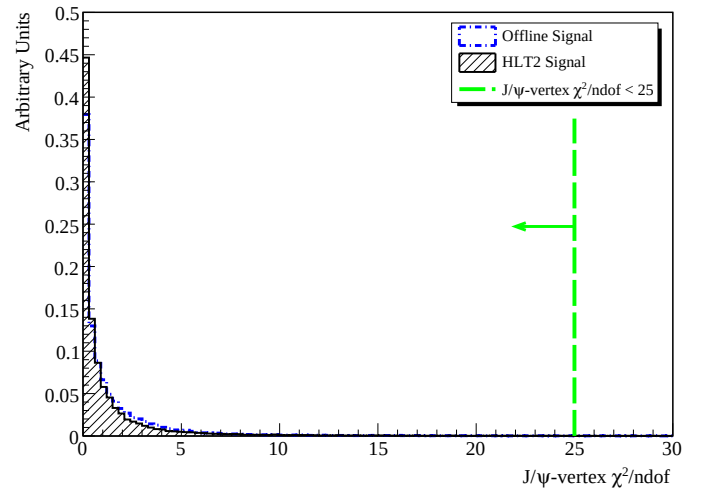


Figure A.6: $p_T(J/\psi)$.

Figure A.7: $p_T(\phi)$.Figure A.8: ϕ mass.Figure A.9: J/ψ mass.Figure A.10: B_s^0 mass.

$$B^0 \rightarrow J/\psi(\mu\mu)K^{*0}(K\pi)$$

Figure A.11: μ^- -track χ^2/ndof .Figure A.12: J/ψ -vertex χ^2/ndof .

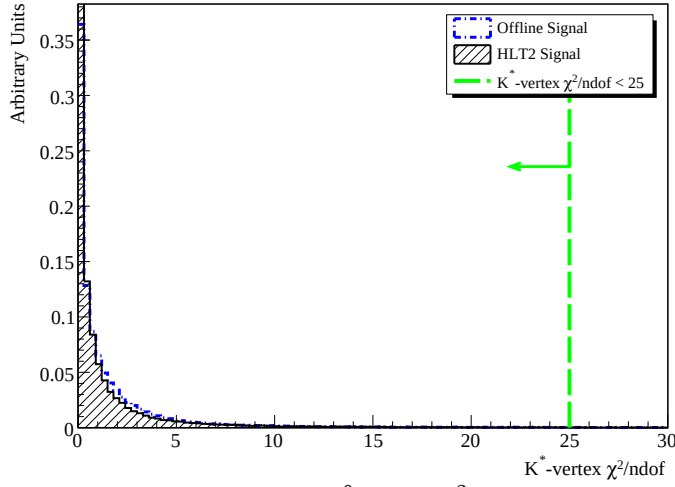


Figure A.13: K^{*0} -vertex χ^2/ndof .

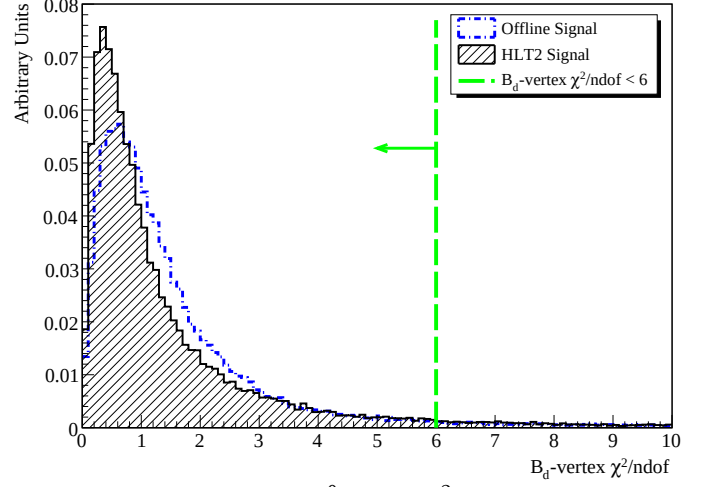


Figure A.14: B^0 -vertex χ^2/ndof .

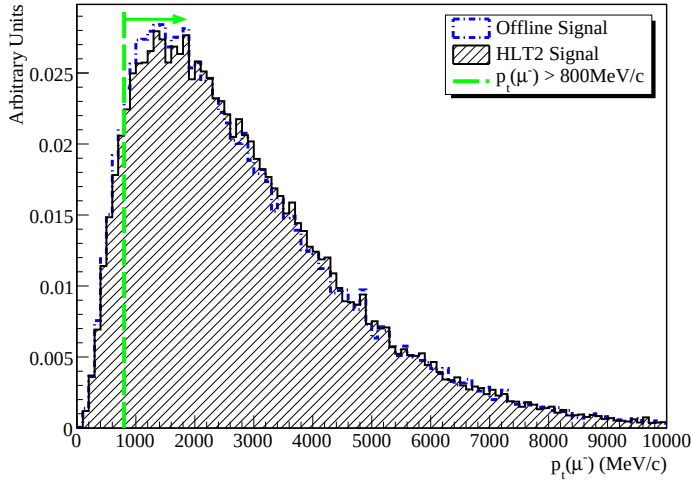


Figure A.15: $p_T(\mu^-)$.

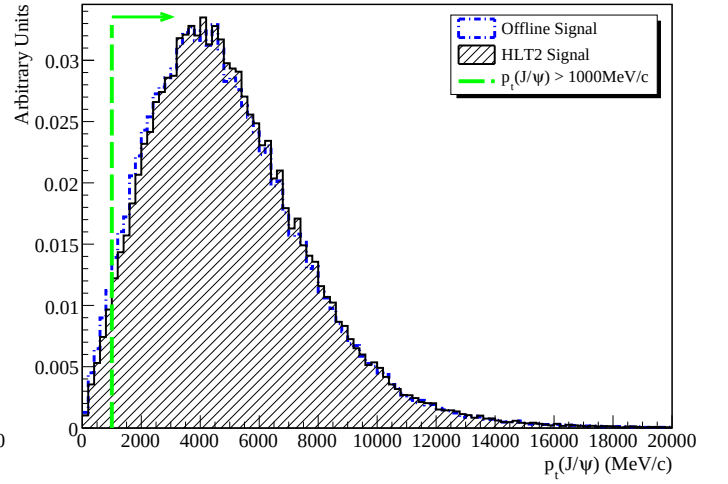


Figure A.16: $p_T(J/\psi)$.

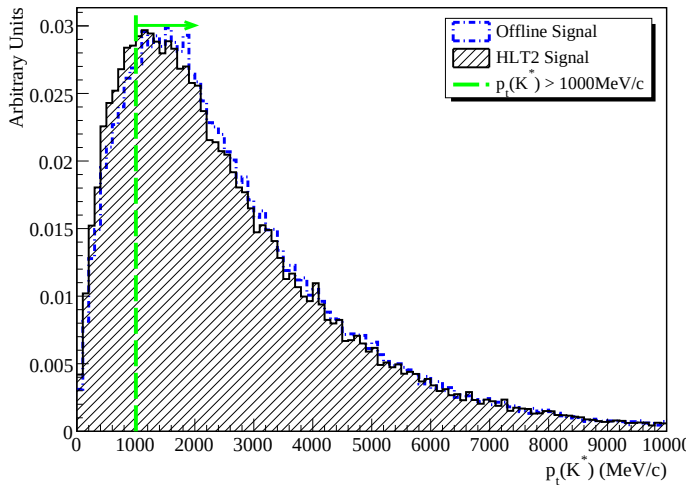


Figure A.17: $p_T(K^{*0})$.

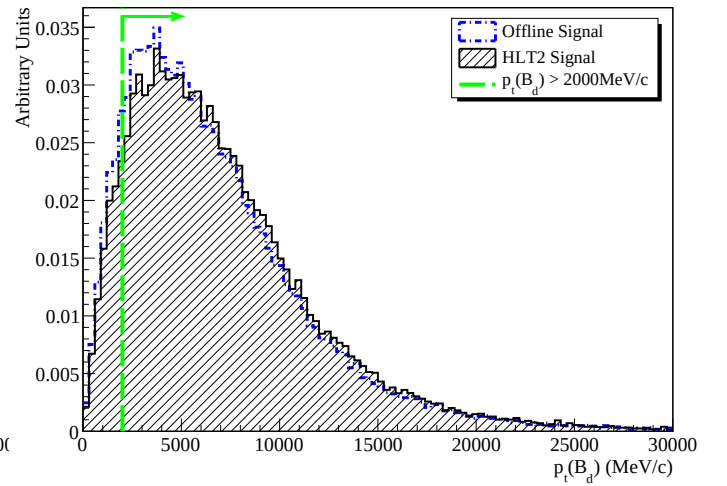


Figure A.18: $p_T(B^0)$.

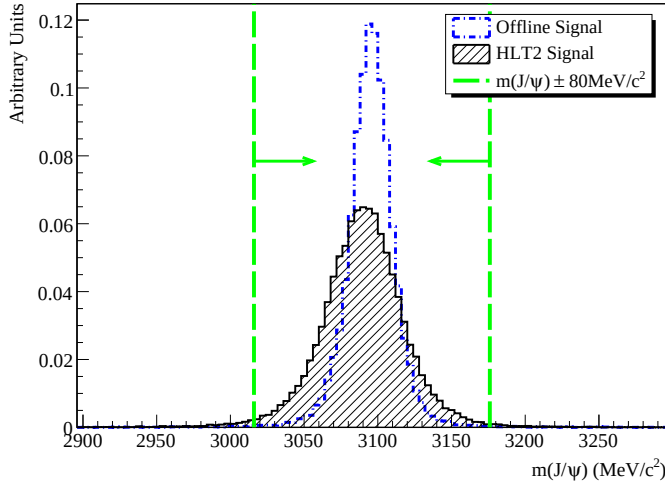


Figure A.19: J/ψ mass.

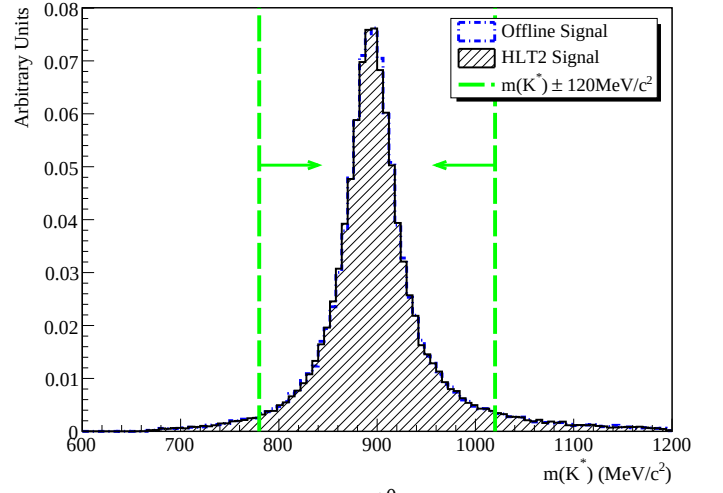


Figure A.20: K^{*0} mass.

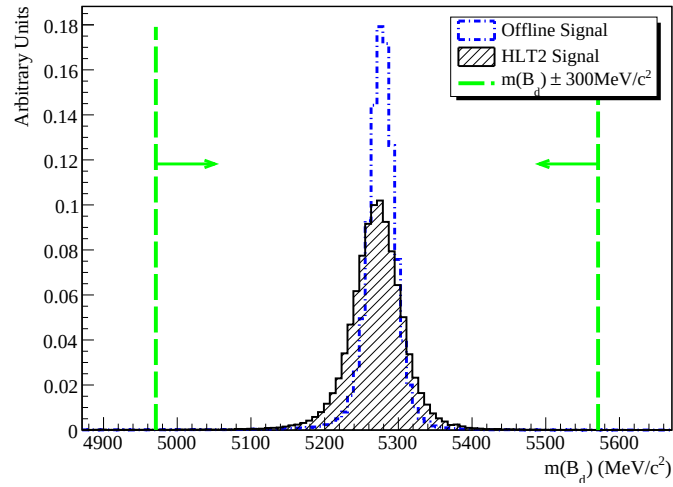


Figure A.21: B^0 mass.

$$B^+ \rightarrow J/\psi(\mu\mu)K^+$$

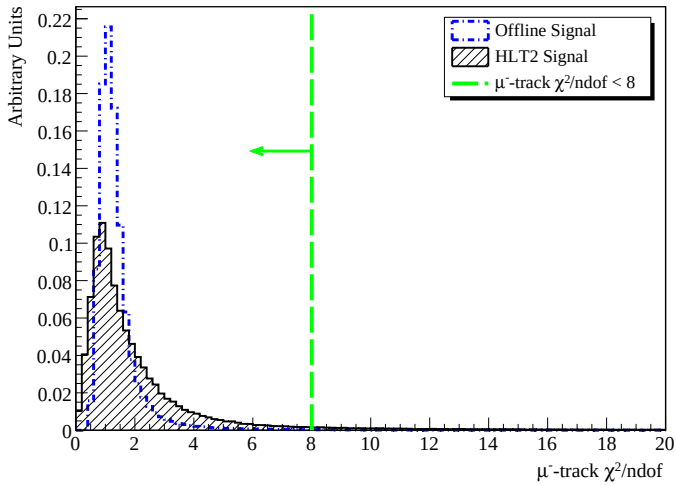


Figure A.22: μ^- -track χ^2/ndof .

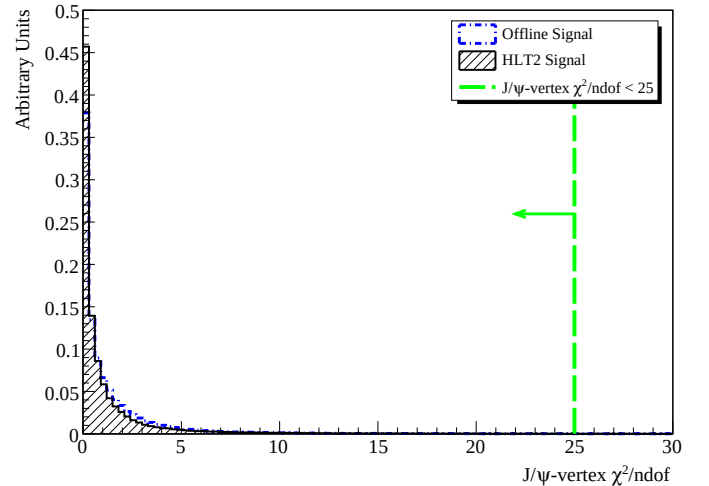


Figure A.23: J/ψ -vertex χ^2/ndof .

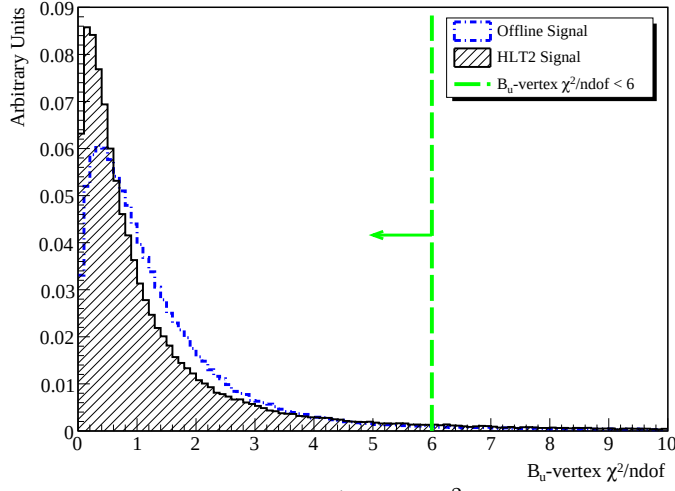


Figure A.24: B^+ -vertex χ^2/ndof .

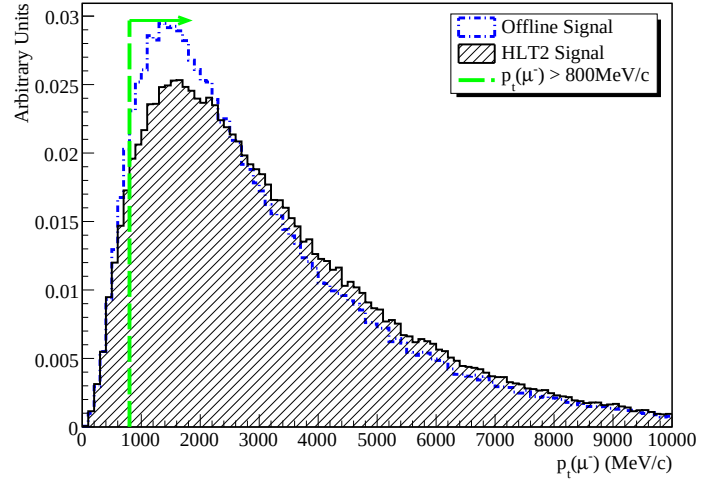


Figure A.25: $p_T(\mu^-)$.

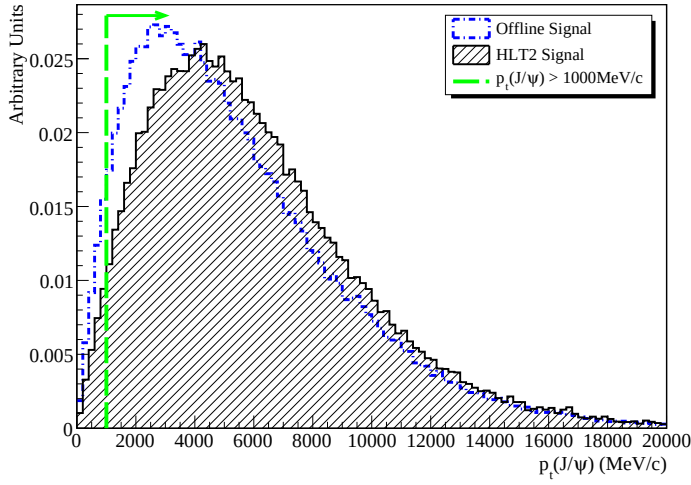


Figure A.26: $p_T(J/\psi)$.

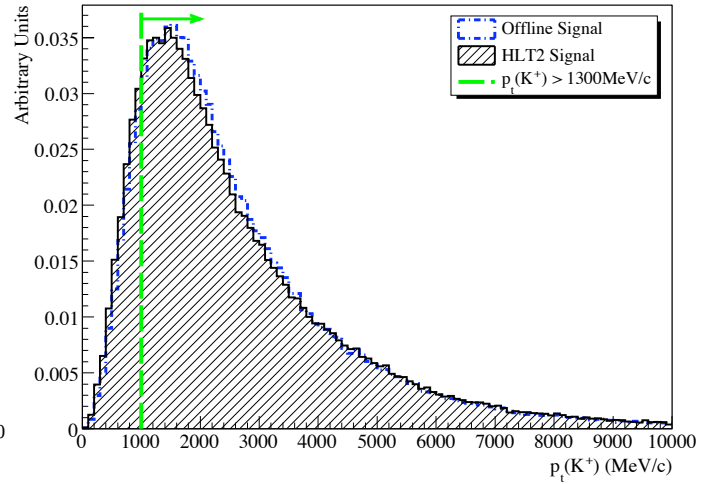


Figure A.27: $p_T(K^+)$.

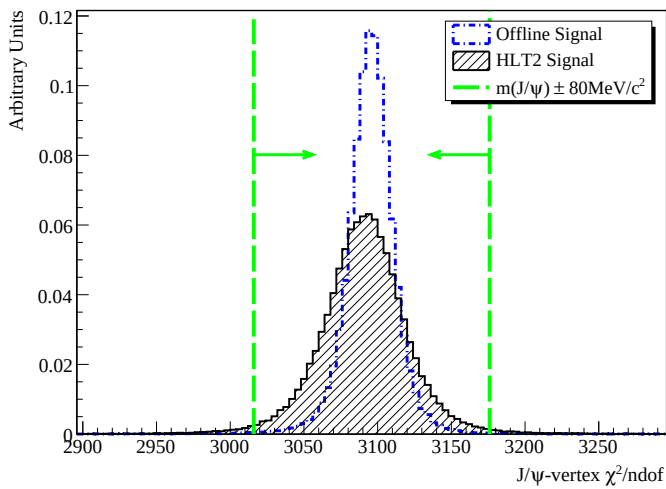


Figure A.28: J/ψ mass.

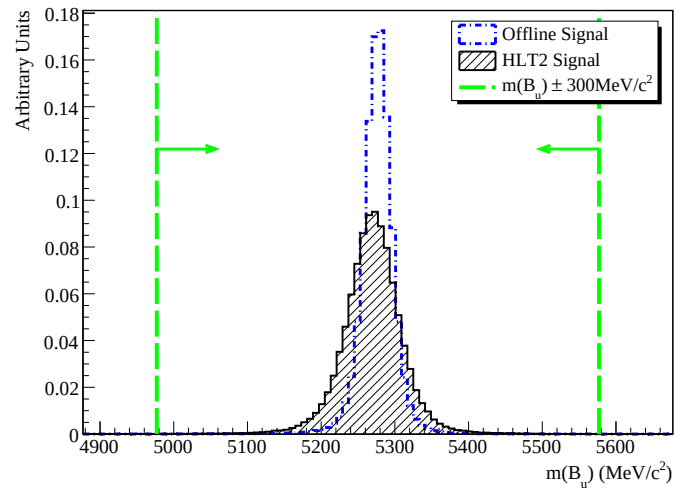


Figure A.29: B^+ mass.

$$B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$$

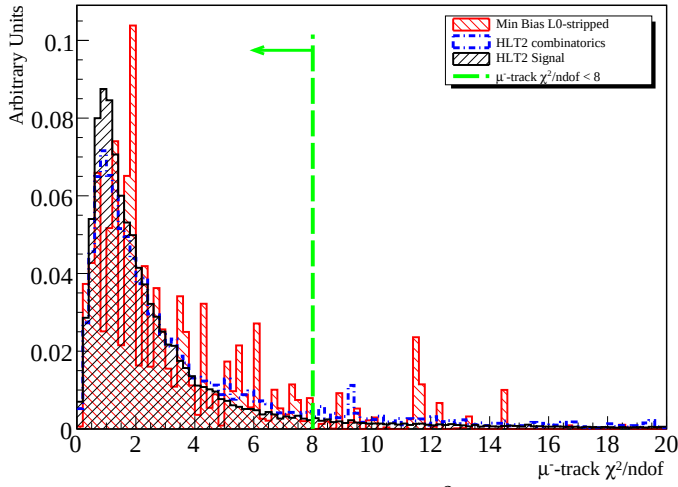


Figure A.30: μ^- -track χ^2/ndof .

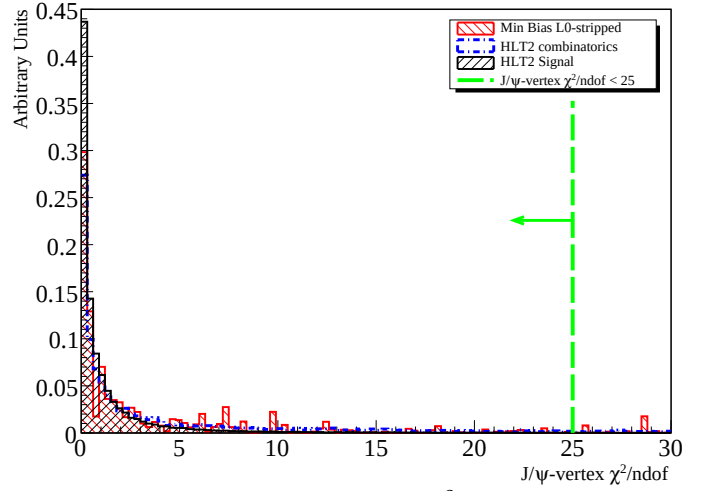


Figure A.31: J/ψ -vertex χ^2/ndof .

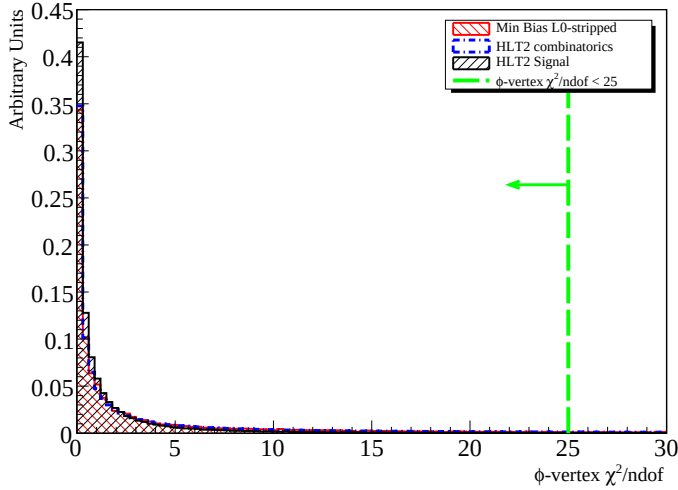


Figure A.32: ϕ -vertex χ^2/ndof .

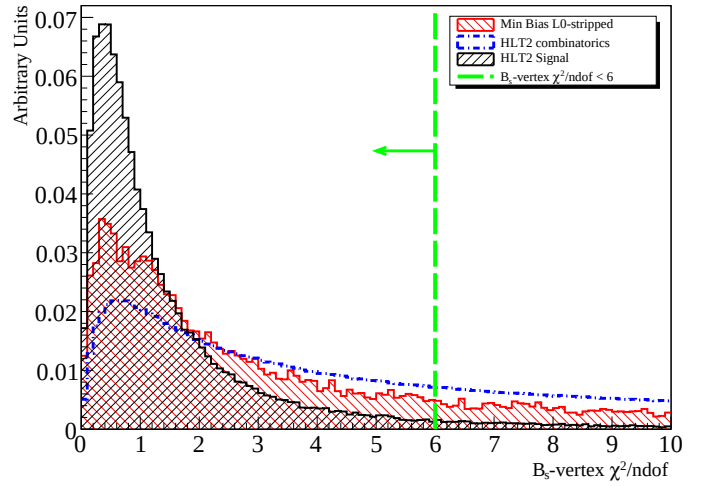


Figure A.33: B_s^0 -vertex χ^2/ndof .

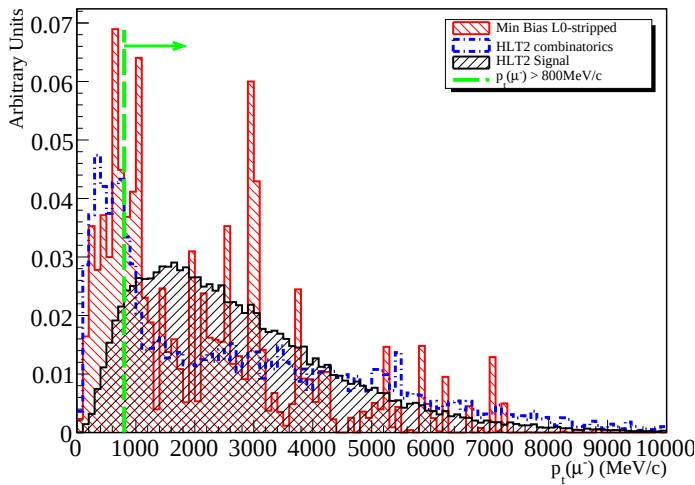


Figure A.34: $p_T(\mu^-)$.

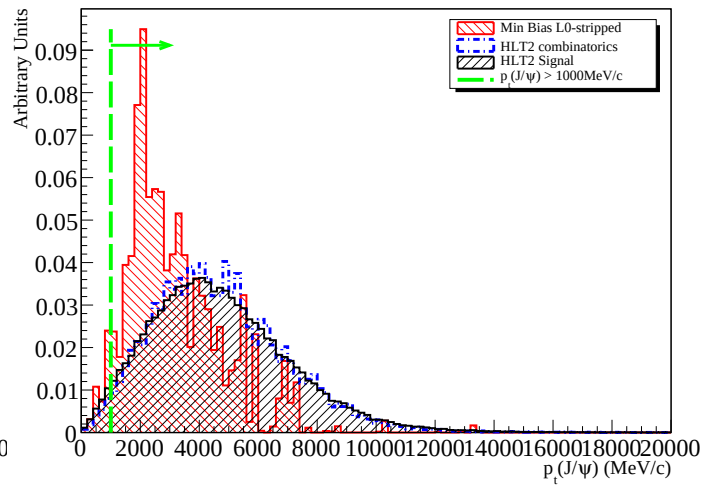
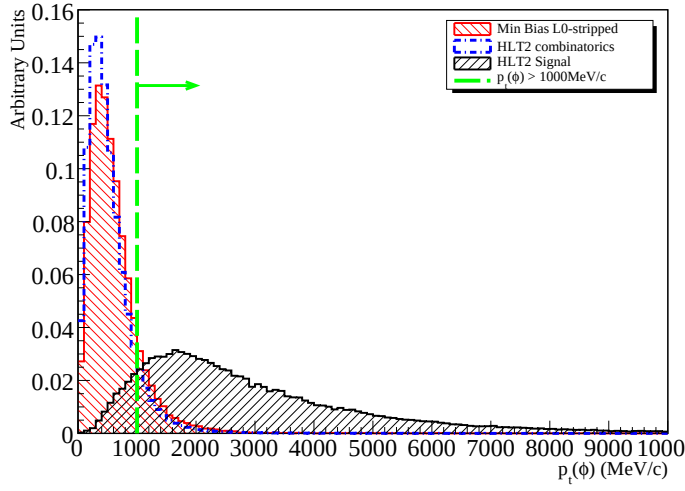
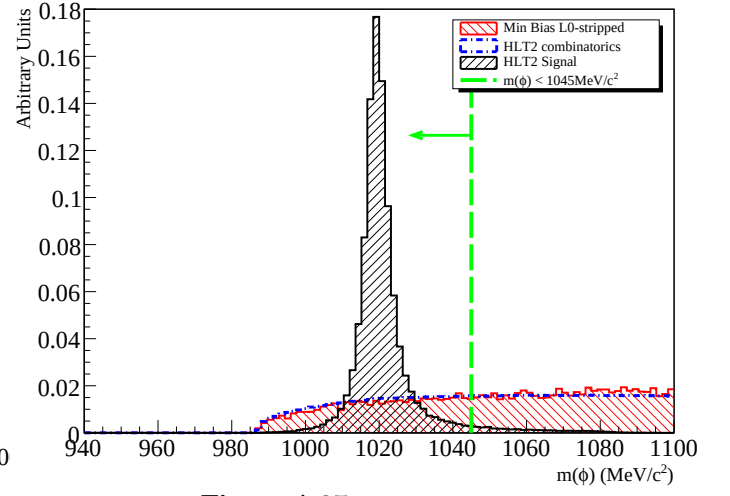
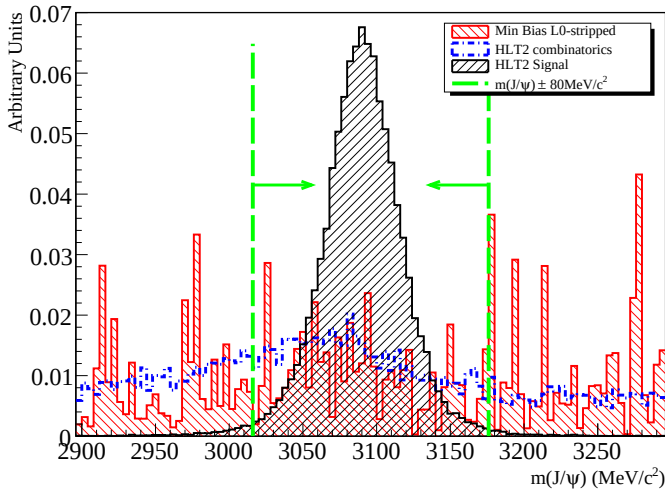
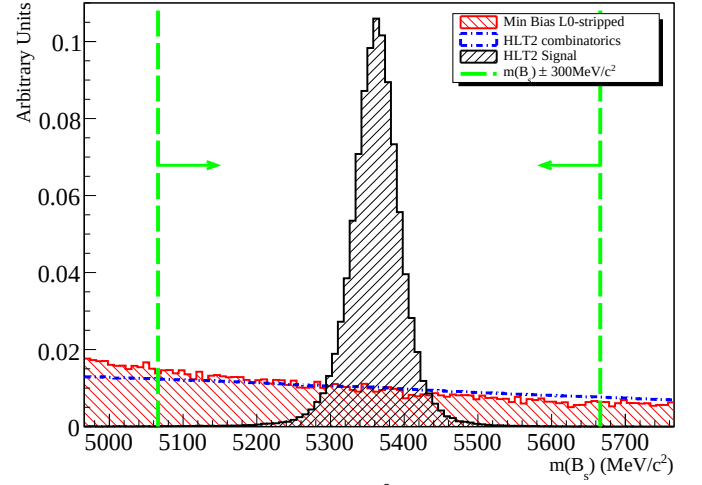
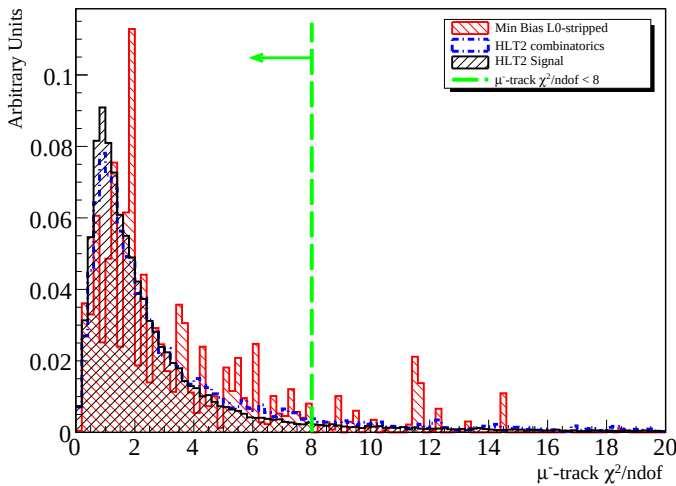
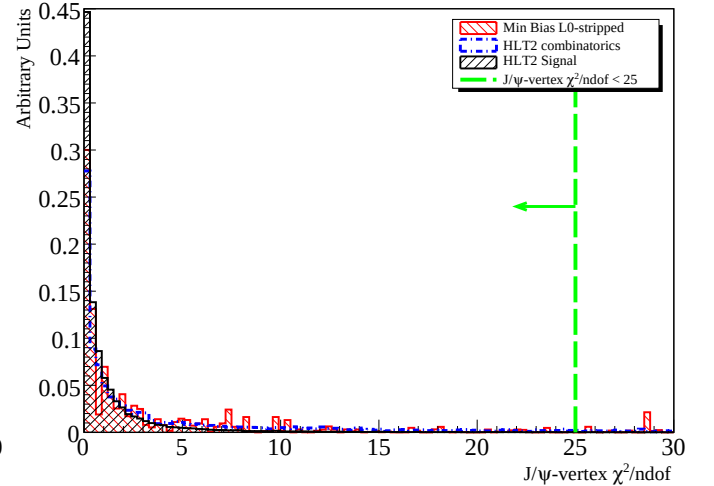


Figure A.35: $p_T(J/\psi)$.

Figure A.36: $p_T(\phi)$.Figure A.37: ϕ mass.Figure A.38: J/ψ mass.Figure A.39: B_s^0 mass.

$$B^0 \rightarrow J/\psi(\mu\mu)K^{*0}(K\pi)$$

Figure A.40: μ^- -track χ^2/ndof .Figure A.41: J/ψ -vertex χ^2/ndof .

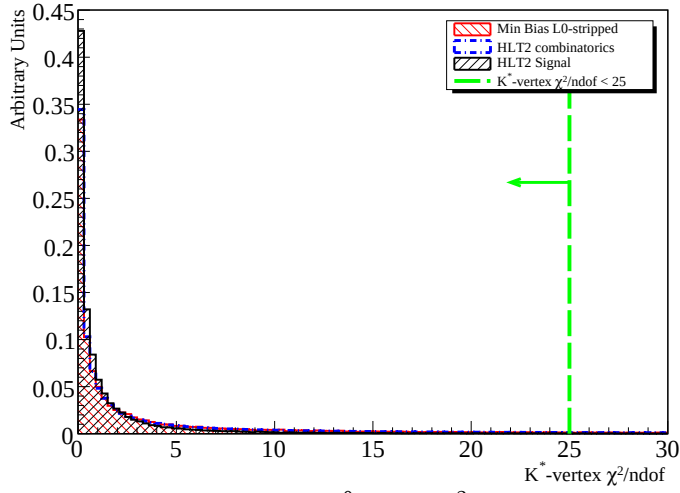


Figure A.42: K^{*0} -vertex χ^2/ndof .

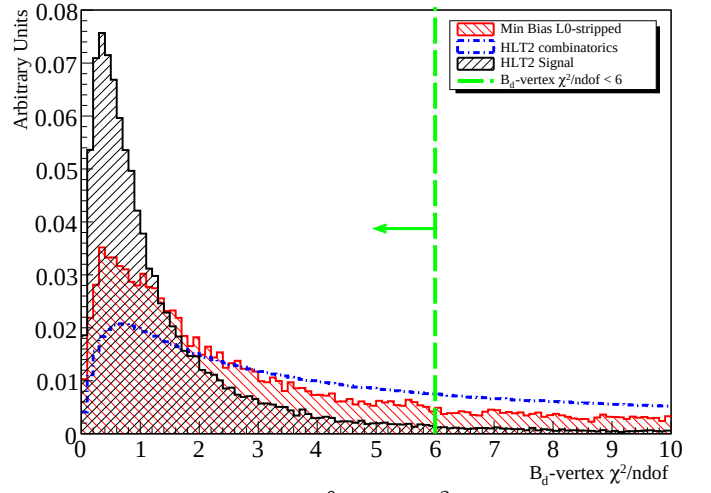


Figure A.43: B^0 -vertex χ^2/ndof .

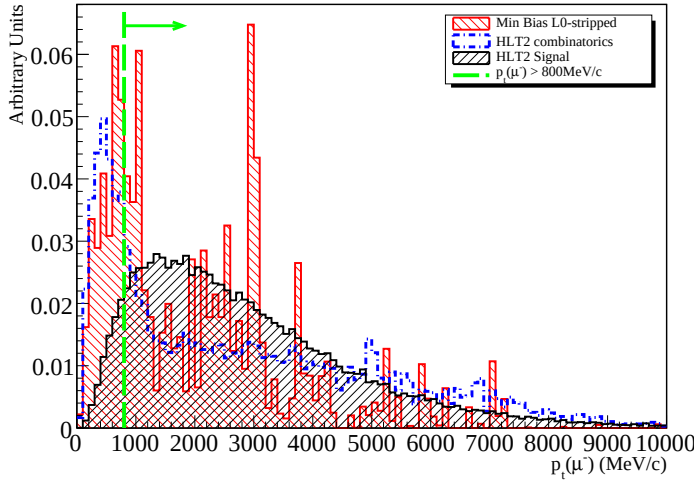


Figure A.44: $p_T(\mu^-)$.

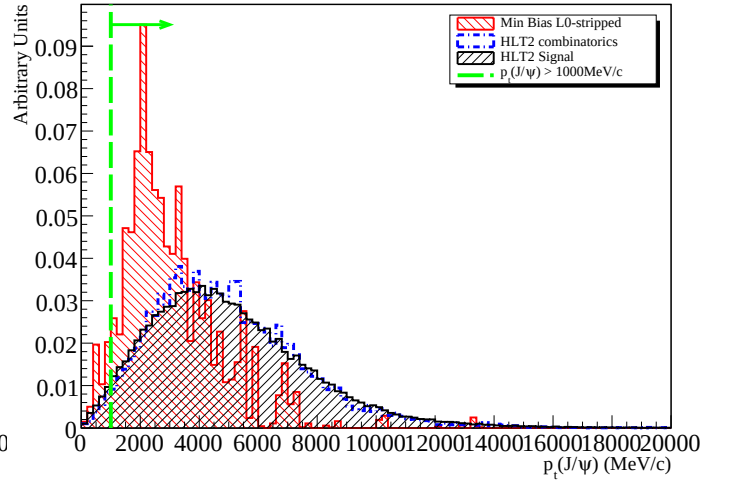


Figure A.45: $p_T(J/\psi)$.

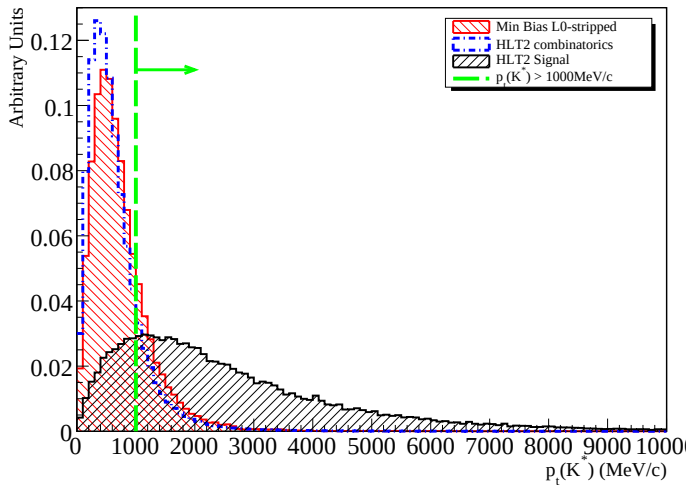


Figure A.46: $p_T(K^{*0})$.

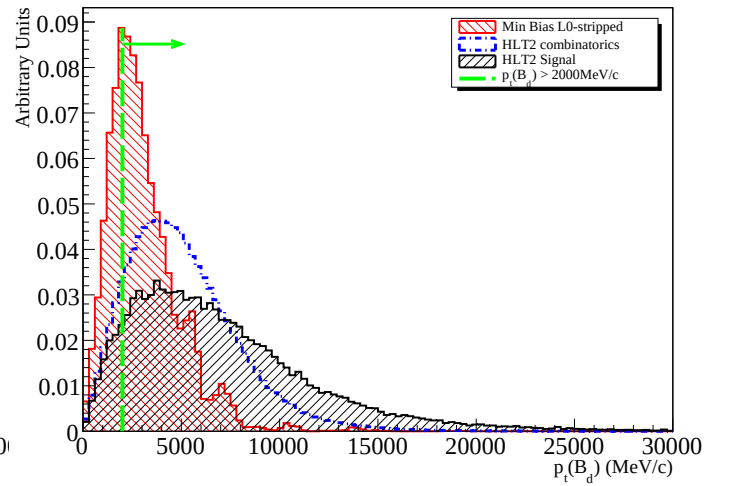


Figure A.47: $p_T(B^0)$.

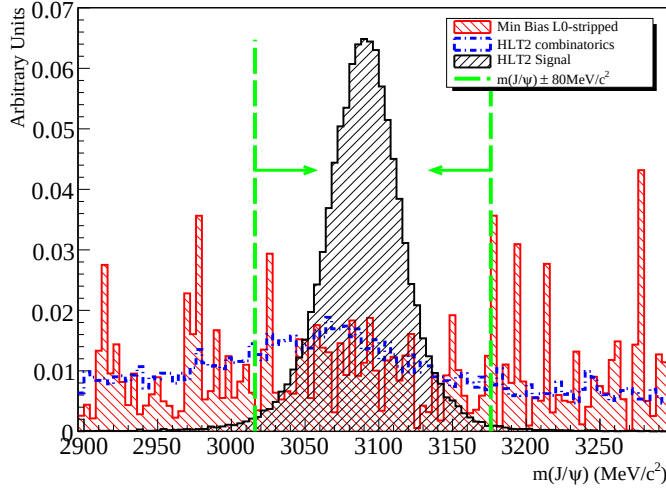


Figure A.48: J/ψ mass.

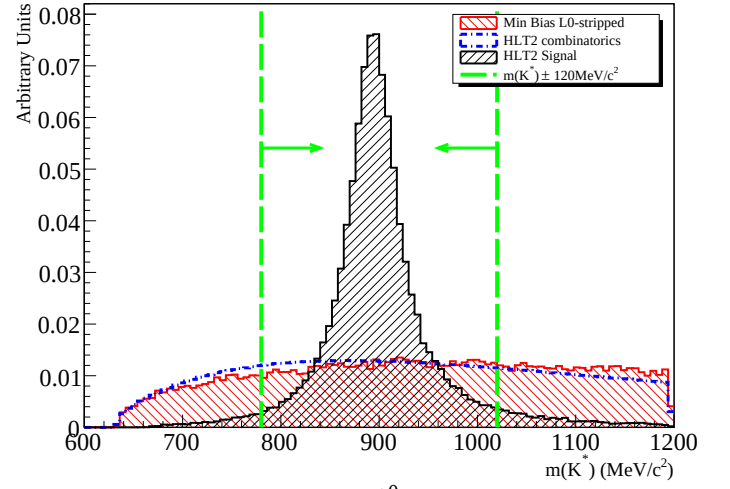


Figure A.49: K^{*0} mass.

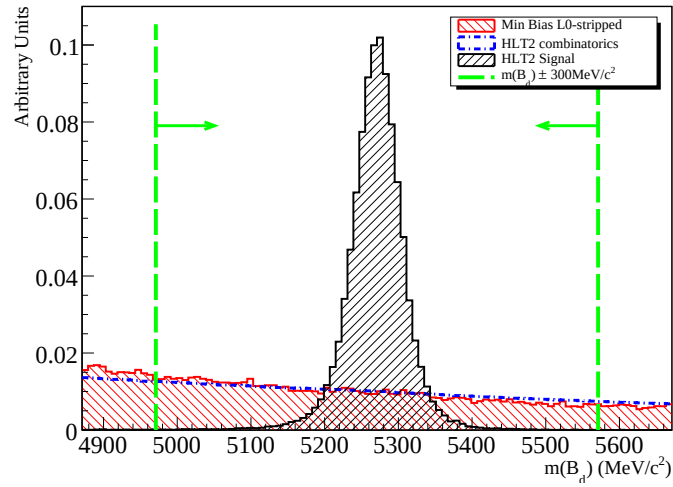


Figure A.50: B_d mass.

$$B^+ \rightarrow J/\psi(\mu\mu)K^+$$

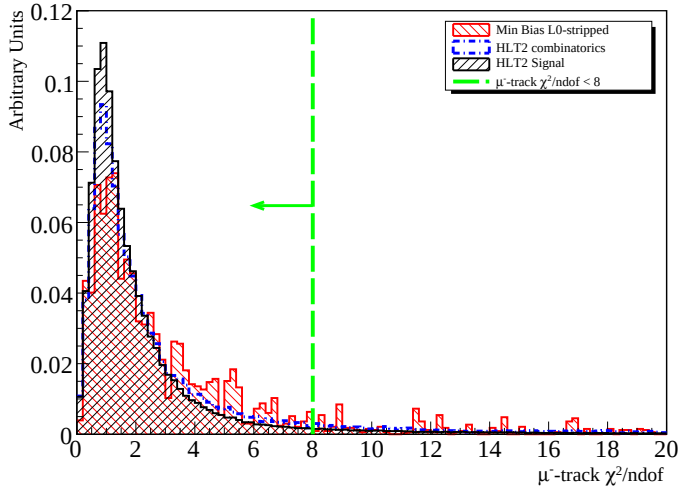


Figure A.51: μ^- -track χ^2/ndof .

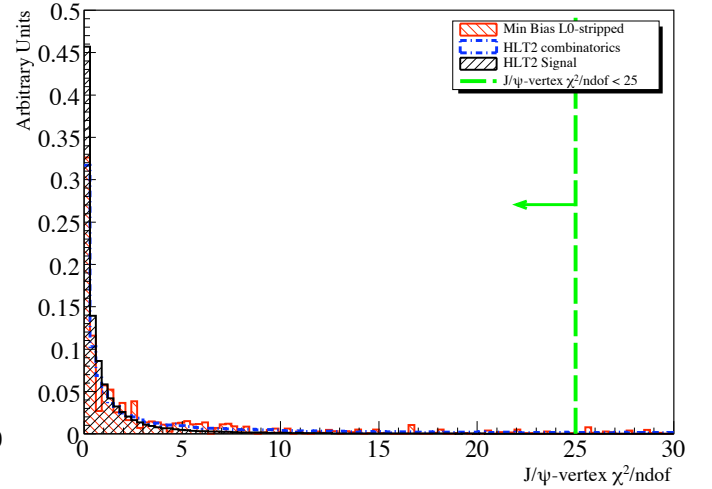
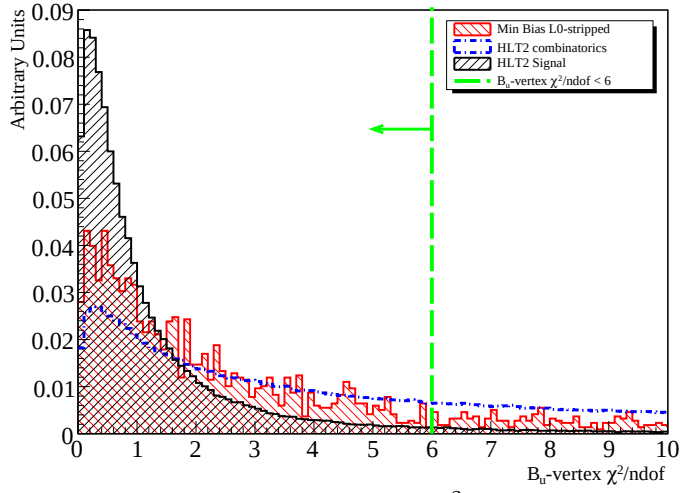
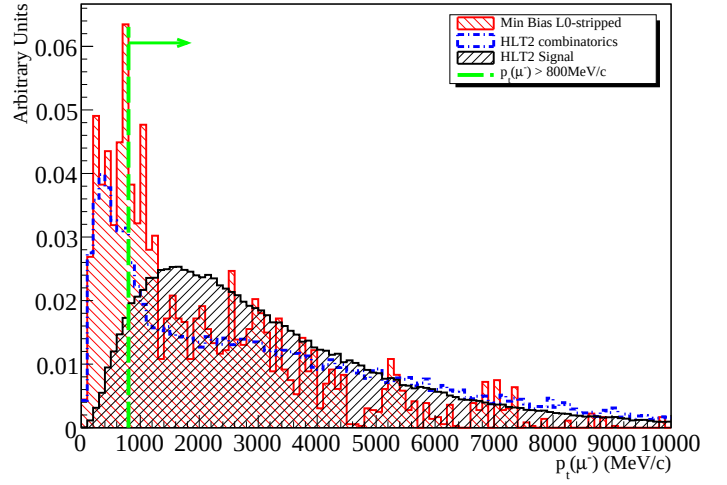
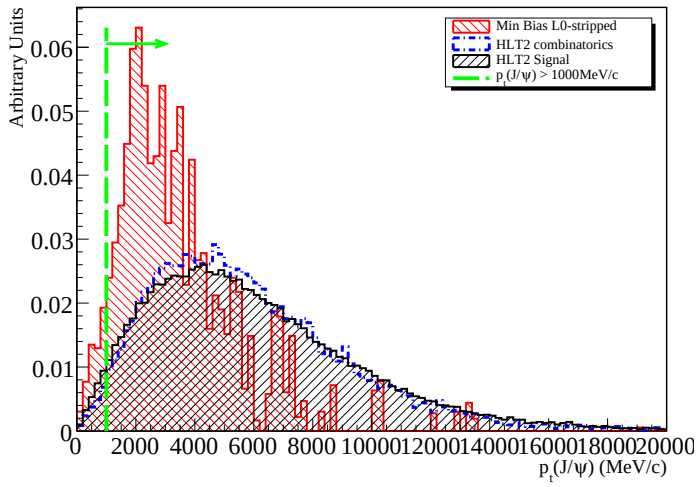
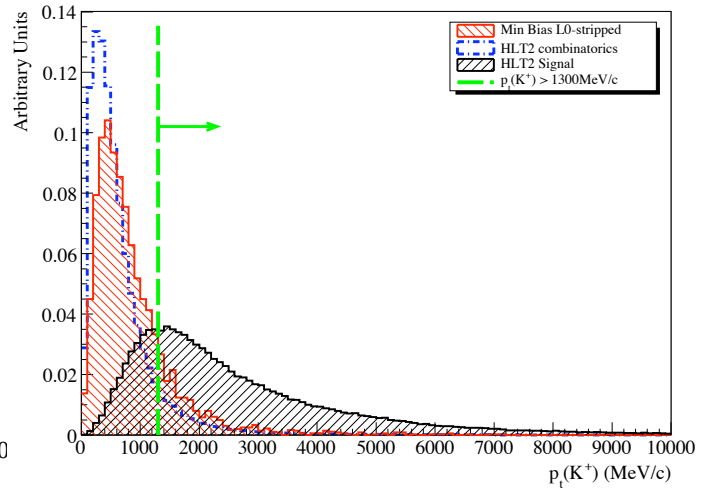
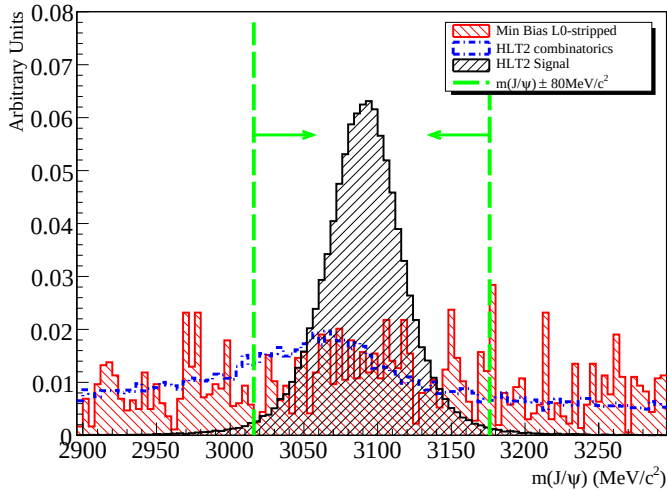
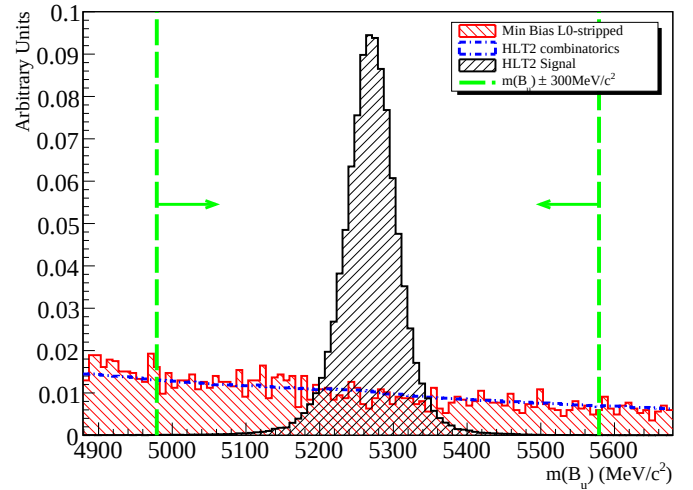


Figure A.52: J/ψ -vertex χ^2/ndof .

Figure A.53: B^+ -vertex χ^2/ndof .Figure A.54: $p_T(\mu^-)$.Figure A.55: $p_T(J/\psi)$.Figure A.56: $p_T(K^+)$.Figure A.57: J/ψ mass.Figure A.58: B^+ mass.

Validation of the HLT2 Exclusive Selections

The trigger selections are designed to introduce minimal distortion to the distribution of the event observables which are studied in the analysis. These observables include the proper time τ and, in the $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$ and $B^0 \rightarrow J/\psi(\mu\mu)K^{*0}(K\pi)$ cases, also the decay angular distributions $\cos(\theta)$, $\cos(\psi)$ and φ defined in Subsection 7.1.3. The proper time and angular acceptance histograms are drawn, where the numerator is the distribution of generated signal events passing the L0, HLT1 and HLT2 cuts and the denominator is the distribution of generated signal events passing the L0 and HLT1 decisions.

The acceptance histograms are shown in Figure A.59 for B_s^0 , A.60 for B^0 and A.61 for B^+ . The histogram flatness is tested by fitting them with a first-order polynomial function and observing that the first-order term coefficients are compatible with zero.

$$B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$$

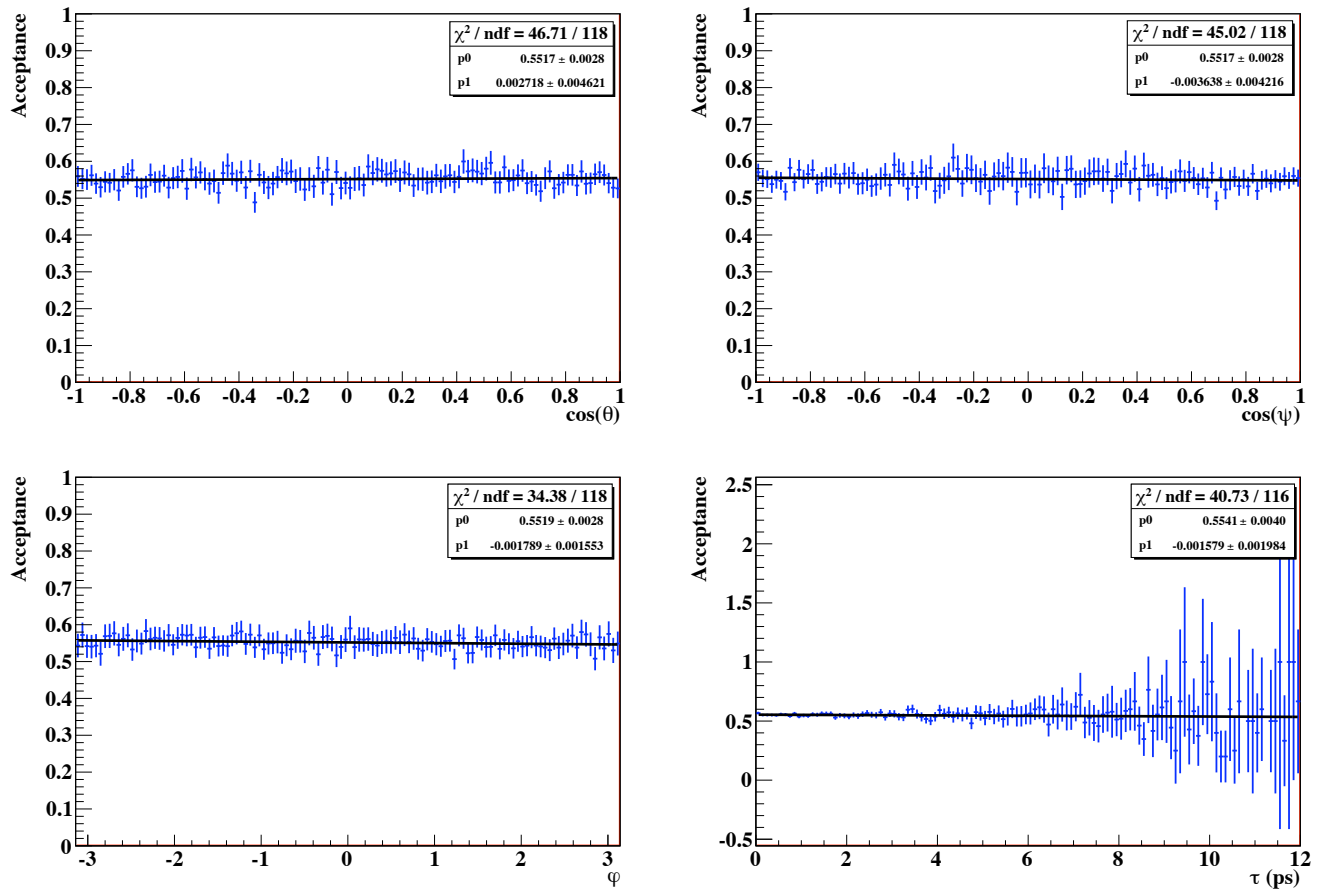


Figure A.59: $\cos(\theta)$, $\cos(\psi)$, φ angular and proper time acceptance histograms.

$$B^0 \rightarrow J/\psi(\mu\mu)K^{*0}(K\pi)$$

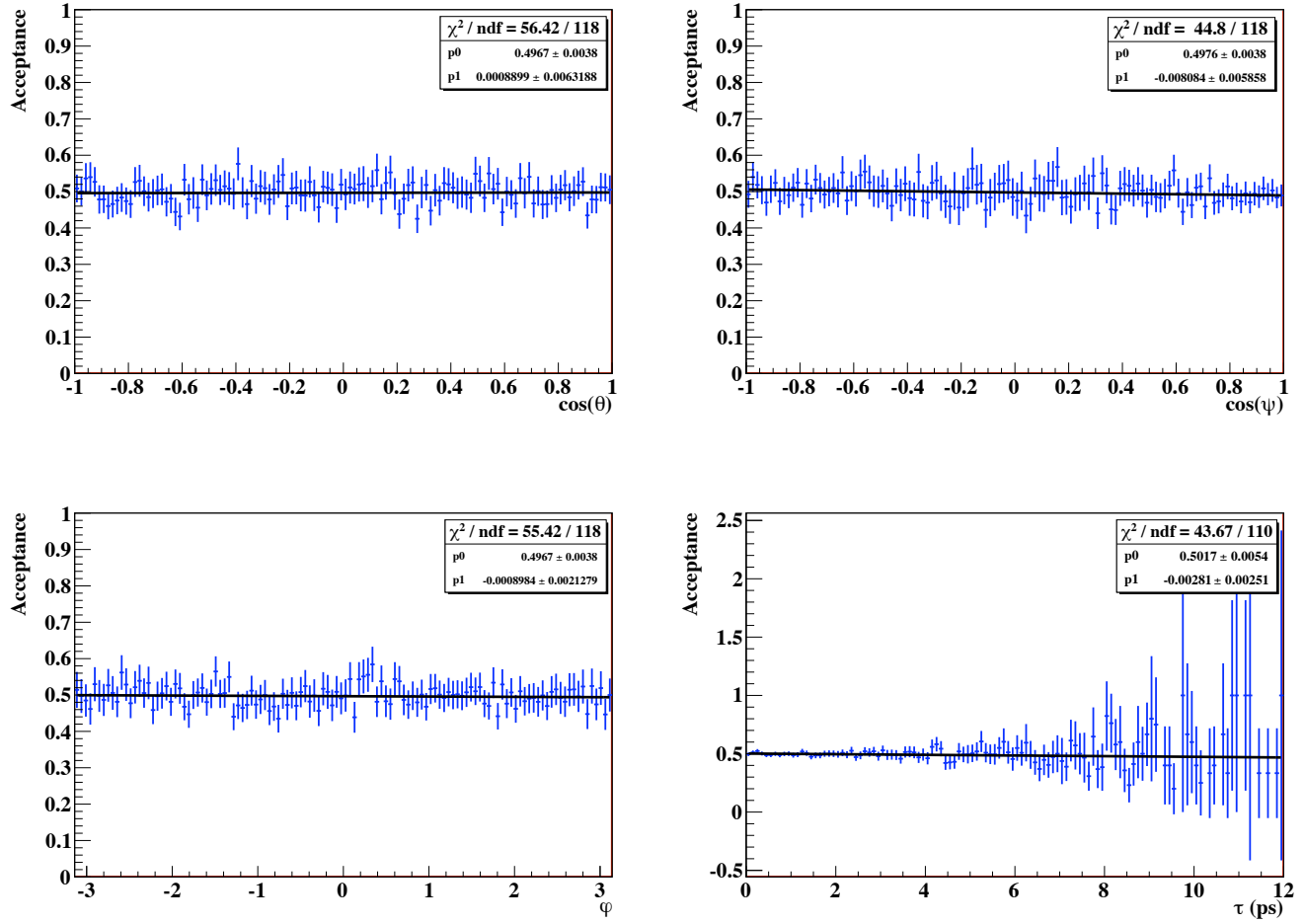


Figure A.60: $\cos(\theta)$, $\cos(\psi)$, φ angular and proper time acceptance histograms.

$$B^+ \rightarrow J/\psi(\mu\mu)K^+$$

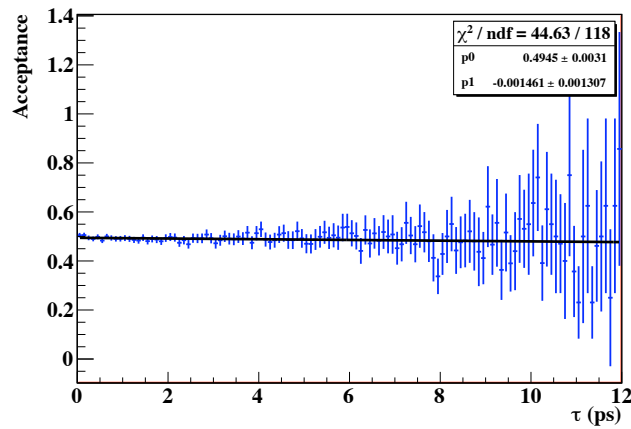


Figure A.61: Proper time acceptance histogram.

A.0.2 New Physics Scenario with Fixing the Strong Phases

A possibility to solve the problem in the determination of the $\delta_{||}$ and $\delta_{\perp}$ strong phases would be to fix them. This solution is not optimal, as it requires an external knowledge. The $\delta_{||}$ and $\delta_{\perp}$ strong phases measured by the Babar collaboration in the $B^0 \rightarrow J/\psi K^{*0}$ channel [145] would be used, as they should be similar to the ones of the $B_s^0 \rightarrow J/\psi \phi$ channel under flavor symmetry. This assumption seems reasonable, as they are expected to be equal within a similar precision of a few percent of π (or $\sim 10^\circ$) [135].

Sensitivity results are given in Table A.1 for 2 fb^{-1} of data. The sensitivity to $\phi_s^{J/\psi\phi}$ is $\pm 0.19 \text{ rad}$.

Table A.1: Sensitivities and pull distribution parameters obtained for 2 fb^{-1} of Toy Monte Carlo data.

Parameters	Value and Sensitivity	Pull Mean	Pull Width
Results With P2VV Fitter			
$ A_0 ^2$	0.556 ± 0.003	-0.05 ± 0.06	1.01 ± 0.04
$ A_{\perp} ^2$	0.233 ± 0.003	$+0.06 \pm 0.06$	0.98 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.680 ± 0.003	$+0.10 \pm 0.06$	1.03 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.049 ± 0.008	$+0.04 \pm 0.06$	1.02 ± 0.04
$\phi_s^{J/\psi\phi} [\text{rad}]$	-0.610 ± 0.181	-0.07 ± 0.06	0.99 ± 0.04
Validation With Heidelberg Fitter			
$ A_0 ^2$	0.556 ± 0.003	$+0.06 \pm 0.06$	1.02 ± 0.04
$ A_{\perp} ^2$	0.233 ± 0.004	-0.06 ± 0.06	0.95 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.680 ± 0.003	-0.04 ± 0.06	1.03 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.050 ± 0.009	$+0.12 \pm 0.06$	0.94 ± 0.04
$\phi_s^{J/\psi\phi} [\text{rad}]$	-0.589 ± 0.188	$+0.06 \pm 0.06$	1.03 ± 0.04

Sensitivity results are given in Table A.2 for 0.2 fb^{-1} of Toy Monte Carlo data. No sensitivity to $\phi_s^{J/\psi\phi}$ is left. A bias in the $\Delta\Gamma_s$ pull distribution is observed and the errors are underestimated for $\phi_s^{J/\psi\phi}$, as the pull distribution widths equal ~ 1.2 (Table A.2) (highlighted in yellow).

Table A.2: Sensitivities and pull distribution parameters obtained with 0.2 fb^{-1} of Toy Monte Carlo data (biases highlighted in yellow).

Parameters	Value and Sensitivity	Pull Mean	Pull Width
Result With P2VV Fitter			
$ A_0 ^2$	0.556 ± 0.008	$+0.03 \pm 0.06$	0.98 ± 0.04
$ A_{\perp} ^2$	0.232 ± 0.011	-0.07 ± 0.06	1.00 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.681 ± 0.009	$+0.04 \pm 0.06$	1.01 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	$+0.060 \pm 0.026$	$+0.41 \pm 0.06$	0.97 ± 0.04
$\phi_s^{J/\psi\phi} [\text{rad}]$	-0.567 ± 0.566	-0.02 ± 0.06	1.19 ± 0.04
Validation With Heidelberg Fitter			
$ A_0 ^2$	0.556 ± 0.009	$+0.03 \pm 0.06$	0.94 ± 0.04
$ A_{\perp} ^2$	0.234 ± 0.013	$+0.04 \pm 0.06$	0.93 ± 0.04
$\Gamma_s [\text{ps}^{-1}]$	0.682 ± 0.010	$+0.15 \pm 0.06$	0.97 ± 0.04
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.057 ± 0.029	$+0.29 \pm 0.06$	0.91 ± 0.04
$\phi_s^{J/\psi\phi} [\text{rad}]$	-0.570 ± 0.647	$+0.04 \pm 0.06$	1.22 ± 0.04

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Curriculum Vitæ(CV)

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Present Position

OCT 2006 - SEP 2010 PhD Student under the supervision of Prof. Nakada, EPFL.

Education

OCT 2006 - SEP 2010 Doctoral School, EPFL.

AUG 2008 2008 Hadron Collider Physics Summer School, Fermilab, US.

JAN 2008 2008 CHIPP PhD Winter School, Näfels, Switzerland.

OCT 2005 - MAR 2006 Master Thesis in Biophysics (Prof. Meister), EPFL.

"Propagation intracellulaire et intercellulaire du Ca^{2+}
dans les cellules de muscle lisse en culture". GRADE: 6.0 / 6.0

OCT 2003 - MAR 2006 Master in Physics, EPFL. GRADE: 5.7 / 6.0

OCT 2001 - OCT 2003 Bachelor Equivalent in Physics, EPFL. GRADE: 5.5 / 6.0

AUG 1998 - JUL 2001 Baccalaureate (Latin), Porrentruy. GRADE: 5.8 / 6.0

Doctoral School Lectures attended

2009 Gaseous Particle Detectors, Dr. Sharma, CERN.

2008 Physics of CP violation and B decays, Prof. Nakada, EPFL.

2007 Beyond Standard Model (Part II) (1 credit), Prof. Altarelli, Roma.

2007 Beyond Standard Model (Part I) (1 credit), Prof. Altarelli, Roma.

2007 Statistics for Physicists (3 credits), Dr. James, CERN.

2007 Real Time Data Acquisition (1 credit), Dr. Häefeli, EPFL.

2007 Standard Model (4 credits), Prof. Mühlleitner, Annecy.

2006 From LEP to LHC (1 credit), Dr. Mele, CERN.

2006 Silicon Pixel Detectors (1 credit), Dr. Riedler, CERN.

Teaching Experience

- 2007 - 2009 Expert at oral examinations (Dr. Tran, Prof. North, Prof. Meylan).
SEP 2008 - DEC 2009 Nuclear and Particle Physics introductory course (2h/week),
Prof. Schneider, 5th-6th Physics Department, EPFL.
FEV 2008 - JUL 2008 General Physics course (2h/week),
Dr. Tran, 1st-2nd Biology Faculty, UNIL.
OCT 2007 - JAN 2008 General Physics course (2h/week),
Dr. Tran, 1st-2nd Geosciences Faculty, UNIL.
OCT 2006 - JUL 2007 Semester laboratories in Nuclear Physics (1day/week),
Dr. Tentindo, 5th-6th Physics Department, EPFL.

Internships

- 2006 Summer Student Program, CERN (2 months).
Internship in the ATLAS experiment (Prof. Santoni), Clermont-Ferrand, CERN.
2005 MaNEP Program (1 month).
Internship in numerical simulation (Prof. Hasler), LANOS, EPFL.

Conferences

- JUNE 2010 Prospects for CP violation at LHCb (Talk),
2010 PLHC Conference, DESY, Hamburg, Germany.
MAY 2009 $2\beta_s$ Measurement at LHCb (Poster),
2009 FPCP Conference, Lake Placid (NY), US.
SEP 2007 Parameterization of the LHCb magnetic field map (Poster),
2007 CHEP Conference, Victoria (BC), Canada.

Posters at the Research Day, EPFL

- APR 2008 Contribution to the LHCb experiment.
APR 2008 B-Physics at LHCb.
NOV 2006 The LHCb Inner Tracker.

Activities

- 2009 - 2010 PhD student representative at the EPFL Physics Department Teaching Committee.
2009 - 2010 Authorized Escort for LHCb experiment visits.
2006 - 2010 Member of the Swiss Institute of Particle Physics (CHIPP).
2009 Selected for the 5th French-Speaking Mentoring Program.
2002 - 2006 EPFL student representative at the EPFL Ethics Committee.

Publication List.

- The LHCb Collaboration, The LHCb Detector at the LHC, JINST 3 S08005, 2008.
 - G. Conti et al., Inner Tracker Survey Strategy, CERN Report LHCb-2008-068.
 - G. Conti, F. Blanc, IT Survey Measurements : Analysis and Implementation in the LHCb Software, CERN Report LHCb-2008-069.
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 - G. Conti, A. Hicheur, Parameterization of the LHCb Magnetic Field Map, Proceeding of the 2007 CHEP Conference (Poster), Victoria (BC), Canada
 - G. Conti, A. Hicheur, Parameterization of the LHCb Magnetic Field Map, CERN Report LHCb-2007-093.
 - A. Keune, A. Hicheur, G. Conti, Magnetic Field Parameterizations, CERN Report LHCb-INT-2010-002.
 - G. Conti, M. Needham, Momentum Scale Calibration using Resonances from 2009/2010 data, CERN Report LHCb-INT-2010-048.
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 - The LHCb Collaboration, Roadmap for selected key measurements of LHCb, CERN Report LHCb-PUB-2009-029.
 - G. Conti et al., Angular Acceptance Parameterization for $B_s^0 \rightarrow J/\psi \phi$ Studies, CERN Report LHCb-INT-2010-046.
 - G. Conti et al., Sensitivity Studies of the Time-Dependent Angular Analysis to Untagged $B_s^0 \rightarrow J/\psi \phi$ Events, CERN Report LHCb-INT-2010-047.
 - G. Conti, Prospects for CP violation at LHCb, Proceeding of the 2010 PLHC conference.