



UNIVERSIDADE FEDERAL DO RIO DE JANEIRO
INSTITUTO DE FÍSICA

**Associated vector boson production with b-jets at
LHCb and Beam-Gas Vertexing at LHC for beam
instrumentation**

Valdir Salustino Guimarães

Tese de Doutorado apresentada ao Programa de Pós-Graduação em Física do Instituto de Física da Universidade Federal do Rio de Janeiro - UFRJ, como parte dos requisitos necessários à obtenção do título de Doutor em Ciências (Física).

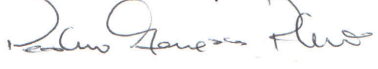
Orientador: Murilo Santana Rangel

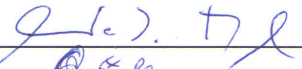
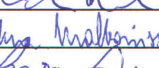
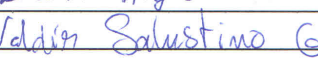
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Ata nº 274 de Defesa de Tese de Doutorado, para concessão do Grau de Doutor em Ciências (Física), realizada em 27 de abril de 2016. Aos vinte e sete dias do mês de abril de dois mil e dezesseis, sala A-343 do Instituto de Física da Universidade Federal do Rio de Janeiro, perante os membros da Banca Examinadora, para a obtenção do Grau de Doutor em Ciências (Física), compareceu o aluno **Valdir Salustino Guimarães**, para a defesa de sua Tese intitulada "Associated Vector boson production with b-jets at LHCb and beam-gas Vertexing at LHC for beam Instrumentation", realizada sob a orientação do professor Murilo Santana Rangel. A Banca Examinadora presente compunha-se dos professores Murilo Santana Rangel (orientador), Emmanuel Gräve de Oliveira, Carsten Hensel, Helena Brandão Malbouisson, Yara do Amaral Coutinho e Eduardo Souza Fraga. O Presidente da Banca Examinadora deu início aos trabalhos às treze horas e trinta minutos, dando a palavra ao candidato, tendo o mesmo cinquenta minutos para a exposição da Tese. Após a exposição o candidato foi arguido pela Banca Examinadora. Terminada essa etapa a Banca reuniu-se e, após o julgamento, foi o candidato considerado aprovado por unanimidade. Para constar, eu, Pedro Menezes Ribeiro, lavrei a presente ata que vai assinada por mim, pelos Membros da Banca Examinadora e pelo candidato. Rio de Janeiro, 27 de abril de 2016,

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À minha sobrinha Maria Fernanda.

Resumo

Produção de bósons vetoriais associada a jatos do quark bottom no LHCb e instrumentação do feixe do LHC por reconstrução de Vértices Feixe-Gás

Valdir Salustino Guimarães

Orientador: Murilo Santana Rangel

Resumo da Tese de Doutorado apresentada ao Programa de Pós-Graduação em Física do Instituto de Física da Universidade Federal do Rio de Janeiro - UFRJ, como parte dos requisitos necessários à obtenção do título de Doutor em Ciências (Física).

Nesta tese medimos a seção de choque da produção associada de bósons vetoriais com jatos do quark bottom no LHCb com energia de centro de massa de 7 e 8 TeV.

O primeiro canal estudado é a produção de $Z+b$ -jatos com $Z/\gamma^* \rightarrow \mu^+\mu^-$ da colisão próton-próton a $\sqrt{s} = 7$ TeV com dados do LHCb coletados em 2011. O segundo canal é o $W + b\bar{b}$, com dois b-jatos e um lépton no estado final. Além do cálculo da seção de choque esse canal é usado para calcular o limite da produção associada do Higgs com um bóson vetorial onde o Higgs decai em um par de quarks bottom ou quarks charme.

Uma das principais fontes de erro sistemático das análises é a resolução e correção da energia dos jatos. A redução desse erro é obtida através da calibração da componente neutra da energia dos jatos, chamado *neutral recovery*, onde funções empíricas da razão entre a energia das partículas carregadas dos jatos e seu momento são determinadas. Essa calibração reduz a resolução da energia dos jatos.

A precisão dos resultados obtidos depende diretamente da calibração absoluta da luminosidade integrada no LHCb. A calibração no LHCb utiliza o escaneamento van der Meer e caracterização do feixe através de colisões feixe-gás. Um detector de vértice de colisões feixe-gás foi desenvolvido baseado neste último método. Nesse experimento contribuimos para o desenvolvimento do software de identificação de padrões e reconstrução de traços, na metrologia dos módulos do detector e no seu sistema de refrigeração.

Palavras-chave: Física de partículas; Física de Altas Energias; Física de Aceleradores.

Abstract

Associated vector boson production with b-jets at LHCb and Beam-Gas Vertexing at LHC for beam instrumentation

Valdir Salustino Guimarães

Orientador: Murilo Santana Rangel

Abstract da Tese de Doutorado apresentada ao Programa de Pós-Graduação em Física do Instituto de Física da Universidade Federal do Rio de Janeiro - UFRJ, como parte dos requisitos necessários à obtenção do título de Doutor em Ciências (Física).

This thesis presents the cross-section measurements of associated vector bosons production with bottom quarks jets at 7 and 8 TeV of centre-of-mass energies. The first channel for cross-section measurement is the $Z+b$ -jet with $Z/\gamma^* \rightarrow \mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 7$ TeV using data collected by the LHCb experiment in 2011. The second channel is the $W + b\bar{b}$, requiring two b-jets and one lepton. Apart from cross-section measurement this channel is also used to calculate limits of the Higgs boson produced in association with a vector boson and decaying into a pair of bottom or charm quarks.

One of the main source of systematic errors in these analyses is the jet energy resolution and correction. Reduction of this error is achieved by performing a calibration of the neutral jet energy component, named neutral recovery, where empirical functions of the ratio between the charged particle energy of the jet and the particle momentum are determined. This method improves the jet energy resolution.

The precision of the results depends directly on the absolute calibration of the integrated luminosity at LHCb. Luminosity calibration at LHCb profits from both van der Meer scan and beam-gas imaging. Based on the latter method, a vertex detector for LHC beam-gas collisions are proposed. Contributions to the development of the pattern recognition and track fitting software, detector modules metrology and cooling system of this experiment are made.

Keywords: Particle physics; High Energy Physics; Accelerator Physics.

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Chapter 1

Introduction

One of the most fundamental question a particle physicist may ask him/herself if “What everything is made of?” The answer of such elementary and naive question is being hunted over the last decades through hadrons and leptons colliders experiments. Nowadays all the sub-particles, which are understood as the basic elements, “the building blocks”, of the matter and anti-matter we know can be divided into two basic groups: fermions and bosons and they are sub-divided according to their interactions described by a set of successful theories called the Standard Model of Particle Physics (SM).

Particles in the SM are divided in three generations according to the particle’s mass, such that heavy particles decay to light particles (daughters) and depending on the type of process their daughters may decay to an even lighter particles until all remaining elementary particles reach mass stability. Elementary particles have intrinsic properties according to their quantum numbers which rules how the particles interact to each other. One fundamental property is the spin which describes particles as bosons, having integer spin, and fermions which have semi-integer values *. Bosons intermediate the interaction between fermions.

Four known interactions rule the Universe as we known: the *gravitational* force, electromagnetic force, weak force and the strong force. Gravitational and electromagnetic

*There are fractional spin’s quasi-particles which occur in two dimensional system but their existence depend on the lattice structure and does not violate the SM predictions

forces are of long range and the remaining two are of short range. Gravitational forces is not described by the SM but since its interaction is much weaker than the three other forces, it is not expected that this interaction affects the results of hadron colliders, specially the Large Hadron Collider (LHC) results. There are several beyond SM models proposing the existence of exotic particles, some of them predicting the existence of *gravitons*, but so far there has been no experimental evidence for these extensions to the SM[†] [2, 3].

In 2013 ATLAS [4] and CMS [5] collaborations presented the results of the discovery of a neutral particle compatible with the SM Higgs boson. The discovery by ATLAS (CMS) is of 5.9 (5.8) standard deviations for proton-proton collisions using combined data set of centre-of-mass energy of 7 and 8 TeV. The integrated luminosity recorded by ATLAS (CMS) is 4.8 (5.1) fb⁻¹ at 7 TeV and 5.8 (5.3) fb⁻¹ at 8 TeV. The current Higgs mass using combined results is $m_H = 125.09 \pm 0.21(\text{stat.} \pm 0.11(\text{syst.}))$ GeV [6]. It is now well stated that all the particles predicted by the SM has been discovered.

The discoveries of the last two SM particles found, the *top* quark[‡] [7, 8] and the *Higgs* boson exemplify the necessity for a large effort for development of new technologies of the particle detectors and accelerators. Development of new magnetic technologies, radio frequency cavities and beam instrumentation and monitoring techniques were crucial to the LHC to reach the proton beam energy collision of $\sqrt{s} = 13$ TeV in 2015 [9] as well as the detector efficiency for identify particles.

The work of this thesis is related to two detectors that shall be discussed in more detail. The first one is the detector of the LHCb collaboration. The LHCb detector is the experimental tool to study vector bosons and bottom quarks production which are discussed in this thesis. The track system of the detector will suffer upgrade from Silicon Tracker Stations to Scintillating Fibres Tracker (SciFi) read by Silicon Photo Multiplier (SiPM)

[†]In February of 2016, the LIGO colaboration released the results of a ‘direct’ observation of gravitational waves [1]. However it is not be associated to a direct detection of graviton particles.

[‡]Discovered at the experiments in the Tevatron

after the LHC Run 2. Since the radiation hardness of the SiPM is yet not completely qualified, the support of a simpler detector using the same technology is desired. The second detector discussed in this thesis is the Beam Gas-Vertexing Demonstrator (BGV) for the LHC beam instrumentation. The BGV uses similar technology of the LHCb track upgrade and is designed to perform Beam Gas Imaging (BGI) of the LHC proton beam.

In the next part of this chapter we turn our attention to the theoretical description of the Standard Model and the phenomenology of the particles collisions at the LHC.

1.1 The Standard Model

As mentioned in the beginning of this chapter four fundamental interactions rule the Universe, as we know. The Standard Model describes the interaction of fields and particles which interact through three forces: the *electromagnetic*, the *weak* and the *strong* forces. In total there are twelve fundamental particles[§]. The three fundamental forces are described as Quantum Field Theories (QFT). The mathematical formulation of these forces is based on *gauge* symmetries within group theory.

Invariance of the Standard Model to the Poincaré global symmetry group, *i.e.* translations, rotations and boosts in spacetime, leads to the law of conservations of momentum, angular momentum and energy. It is formulated by the Noether's theorem. Similarly, the conservation of electromagnetic charges and the associated charges for weak and strong forces result from invariance of the Standard Model to the local symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. $SU(3)_C$ refers to the gauge field theory which describes the interaction of coloured quarks and gluons, Quantum Chromodynamics (QCD), while $SU(2)_L \otimes U(1)_Y$ is the symmetry group corresponding to the electroweak interaction, a unified description of the electromagnetic and weak forces.

The symmetry group has 12 generators that give rise to the force mediators: the eight gluons g of the strong force, the three massive vector bosons, W^+ , W^- and Z^0 which me-

[§]Fundamental in the sense that they are not constituted of other subatomic particles

diates the weak forces and the massless photon γ of the electromagnetic interaction. The Standard Model predicts the existence of one more boson: the spin-0 Higgs boson. This bosons is a consequence of the presence of Higgs field necessary to allows the Electroweak symmetry breaking, which maintain the gauge invariance and naturally generates mass to particles of the model. The Table 1.1 summarises some properties of bosons of the Standard Model.

bosons	Mass [GeV]	Spin	Q/e
γ	0	1	0
Z^0	91.1876 ± 0.0021	1	0
$W^\pm$	80.385 ± 0.015	1	± 1
g	0	1	0
H	125.09 ± 0.24	0	0

Table 1.1: The gauge bosons in the Standard Model. The table summarises the mass, spin, and the electric charge Q of the gauge bosons. The Higgs mass value was extracted from Reference [10] all others has been extracted from Reference [11].

The fermions of the Standard Model are divided in two groups of six quarks and six leptons. The leptons consist of three charged particles, the electron, e , the muon, μ , the tau, τ , and their corresponding neutrino partners, the electron neutrino, ν_e , the muon neutrino, ν_μ , and the tau neutrino, ν_τ . The neutrinos are electrically neutral and are measured to undergo flavour oscillations as they propagate. This measurement implies that the neutrinos have non-zero masses, and that the mass eigenstates are distinct from the flavour eigenstates. These masses have not yet been measured, but are known to be less than 2 eV. To each of these pairs is associated a lepton “flavour” number and each pair composes one “family” generation. The Table 1.2 summarises the properties of the leptons of the Standard Model.

Quarks, like leptons, are paired in three generations, the *up* and the *down* quark form the first generation, followed by the *charm* and the *strange* quark, then the *top* and the *bottom* quark. The quarks are distinct from the other fermions in the Standard Model, they interact via the strong force, exchanging gluons and can not be found free in the

Generation	Particle	Mass [MeV]	Spin	Q/e
1	e	$0.510998928 \pm 0.000000011$	$1/2$	-1
	ν_e	-	$1/2$	0
2	μ	$105.6583715 \pm 0.0000035$	$1/2$	-1
	ν_μ	-	$1/2$	0
3	τ	1776.82 ± 0.16	$1/2$	-1
	ν_τ	-	$1/2$	0

Table 1.2: Flavour eigenstates of the fundamental leptons in the Standard Model, and their mass, spin, and electric charge (Q). Anti-particles are not shown but they have the same mass and spin as their particle partners, but have the opposite electric charge. Extracted from Reference [11].

nature. The set of two or more quarks composes the particles called *hadrons* which can be *mesons* (two-quarks composed), *barions* (three-quarks composed) or even in more exotic states like the pentaquark, composed by 5 quarks [12]. The Table 1.3 shows the quarks of the Standard Model.

Generation	Particle	Mass [MeV]	Spin	Q/e
1	u	$2.3^{+0.7}_{-0.5}$	$1/2$	$+2/3$
	d	$4.8^{+0.5}_{-0.3}$	$1/2$	$-1/3$
2	c	1275 ± 25	$1/2$	$+2/3$
	s	95 ± 5	$1/2$	$-1/3$
3	t	$173070 \pm 520 \pm 720$	$1/2$	$+2/3$
	b	4180 ± 30	$1/2$	$-1/3$

Table 1.3: The quarks of the Standard Model. Anti-particles are not shown, and have the same mass and spin as their particle partners, but have the opposite electric charge. Extracted from Reference [11].

The interaction between the charged fermions and the Electroweak bosons is ruled by chiral states of the fermions: left-handed chiral states interact with $W^\pm$ and right-handed states interact with the Z^0 bosons.

After this briefly introduction of the particles content of the Standard Model we will review the theory formulation and how the particles interact with each other according to the nature of interaction.

1.1.1 Quantum Electrodynamics

Quantum Electrodynamics (QED) is the quantum theory of light and its interaction with matter. It is an *Abelian gauge field theory*, invariant under local $U(1)$ transformations. The charge of the theory is the electric charge. The QED Lagrangian is given by

$$\mathcal{L}_{QED} = \bar{\psi}i(\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (1.1)$$

where the $D_\mu = \partial_\mu + ieA_\mu$ is the covariant derivative which acts on spin 1/2 field ψ with their charge conjugate $\bar{\psi} = \psi^\dagger\gamma^0$. It describes the interaction of a massless photon field A_μ with a spin 1/2 fermion (quark or lepton) of mass m [¶]. The photon field propagation is described by the second term in the Lagrangian, with

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu.$$

For the Lagrangian be invariant under local gauge transformation:

$$\psi \longrightarrow \psi \exp(-ie\phi(x))$$

the photon field should transform like $A^\mu \longrightarrow A^\mu + \partial^\mu\phi(x)$ and be massless, as term representing the mass propagator break the gauge invariance.

At leading order (LO), calculations in QED give finite results. Using Feynman rules is possible to calculate the amplitude and probabilities for several processes in power of the coupling constant $\alpha = e^2/4\pi$. Next-to-leading (NLO) order term in probability for each interaction contain extra terms in power of α . It gives rise to divergences. In order to cancel divergencies it is necessary to use renormalisation by allowing the coupling strength to change with the energy of the process being studied.

[¶]Note that the Dirac gamma matrices are represented by γ^μ with the index μ running from 0 to 3:

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}, \gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}, \gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix},$$

We are also using the Einstein summation convention.

The QED capability of describing the electromagnetic interaction in quantum level has been demonstrated by the measurement of the electron's spin magnetic momentum. Dirac equation predicts the value of $g_s = 2$ of the definition of the spin magnetic momentum of the electron $\vec{\mu}_s = -g_s \mu_B \vec{S}$ where $\vec{S}$ is the electron spin and μ_B the Bohr magneton. However, high order correction in QED lead to a predicted value of $(g_s - 2)/2 = 1159652181.78(0.77) \times 10^{-12}$, while the measured value is $(g_s - 2)/2 = 1159652180.73(0.28) \times 10^{-12}$ [13, 14]. The predicted value differs from the measured in nine parts in ten billions. QED is frequently quoted as the most precisely tested theory of nature.

1.1.2 Electroweak Interaction

The QED was successfully extended to describe the electroweak interaction which describes the nuclear decays. The Lagrangian separates the kinematic terms for the vector boson propagation, the interaction between the vector bosons and the fermions and the terms responsible for generating mass to the particles, without violate the gauge invariance. The Lagrangian can be written as

$$\mathcal{L} = \mathcal{L}_{\text{Bosons}} + \mathcal{L}_{\text{Fermions}} + \mathcal{L}_{\text{Higgs}}, \quad (1.2)$$

where

$$\mathcal{L}_{\text{Bosons}} = -\frac{1}{4}W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} \quad (1.3)$$

with

$$W_{\mu\nu}^i = \partial_\nu W_\mu^i - \partial_\mu W_\nu^i - g_W \epsilon^{ijk} W_\mu^j W_\nu^k, \\ B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu,$$

describes the free vector boson propagation. The B fields is invariant under $U(1)$ while W field is invariant under $SU(2)$ and the structure constant is determined by the ϵ^{ijk} with indices i, j and k running from 1 to 3.

^{||}The number in parentheses represents the uncertainty of the theoretical and experimental values.

The second term in the Lagrangian accounts for the interaction between the vector bosons with the fermions and how the fermion fields propagates. As mentioned before the fermions are placed in left-handed doublets (Ψ_L) and right-handed singlets (ψ_R). Each left-handed doublets is placed with their correspondent generation. For example, first generation quarks doublets are pairs of *up* and *down* and for lepton pairs of *electron* with *electron neutrino*. This term is given by

$$\mathcal{L}_{\text{Fermions}} = \sum_{\text{fermions}} \bar{\Psi}_L \gamma^\mu D_\mu^L \Psi_L + \bar{\psi}_R \gamma^\mu D_\mu^R \psi_R, \quad (1.4)$$

where the covariant derivatives differs between left and right,

$$D_\mu^L = \partial_\mu + ig_W \frac{\tau_i}{2} W_\mu^i + ig_B Y B_\mu, \\ D_\mu^R = \partial_\mu + ig_B Y B_\mu.$$

This Lagrangian term specify that left-handed fermions interact with both W and B field whereas the right-handed fermions interact only with the B field. The matrices τ_i are the generators of $SU(2)$, in the Pauli spin matrices representation. The strength of the interaction between fermions and W bosons is given by g_W and the strength of the interaction between B field with particles carrying hypercharge Y is given by g_B . The vector fields W^1, W^2, W^3 and B are all massless because explicit introduction of mass term in this Lagrangian violates the gauge invariance. Finally, this term is invariant under $SU(2)_L \otimes U(1)_Y$ transformation.

In the final part of the Lagrangian a scalar Higgs field is introduced in order to break the symmetry of the group spontaneously. The coupling of the gauge bosons with the Higgs field results in the massive $W^\pm$ and Z^0 bosons. It also results in the entangling of the $SU(2)$ and $U(1)$ groups as the Z^0 boson and the photon are linear combinations of the massless B and W^3 bosons. The introduction of a complex scalar (Higgs) field, Φ with $\tilde{\Phi} = -i(\Phi^\dagger \tau_2)^T$ breaks the electroweak symmetry by acquiring a non-zero vacuum expectation value. As consequence, the fermions gain naturally Yukawa mass terms,

and through the coupling of the bosons to the scalar field, the bosons also acquire mass terms. In other words the perturbation around the vacuum expectation value couple to both bosons and fermions and it is seen as the interaction of a spin-0 particle with both bosons and fermions [15, 16]. This interpretation led Peter Higgs and François Englert to the Nobel Prize of 2013 after the two experiments at CERN's Large Hadron Collider, ATLAS [4] and CMS [5], discovered a particle compatible with the predicted massive boson.

Assuming massless neutrinos, the last Lagrangian part is given by

$$\mathcal{L}_{\text{Higgs}} = \mathcal{L}_{\text{HB}} + \mathcal{L}_{\text{HL}} + \mathcal{L}_{\text{HQ}}, \quad (1.5)$$

where

$$\begin{aligned} \mathcal{L}_{\text{HB}} &= (D_\mu^L \Phi)^\dagger (D^{L\mu} \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2, \\ \mathcal{L}_{\text{HL}} &= -g_N \bar{\Psi}_{NL} \psi_{NeR} \Phi + h.c., \\ \mathcal{L}_{\text{HQ}} &= -\bar{\Psi}'_{ML} G_{MN} \psi_{Nd'R} \Phi - \bar{\Psi}'_{ML} \tilde{G}_{MN} \psi_{Nu'R} \tilde{\Phi} + h.c. \end{aligned}$$

The terms $\mathcal{L}_{\text{HL}}$ and $\mathcal{L}_{\text{HQ}}$ include sums over *up*-type and *down*-type quarks, and *electron*-type fermions. The hermitian conjugate is included to guarantee that the Lagrangian is hermitian. The coupling strength is proportional to the fermion masses and need to be set separately: in $\mathcal{L}_{\text{HL}}$ is g_N and in $\mathcal{L}_{\text{HQ}}$ is G_{MN} . These two parameters account for several Standard Model parameters. The non-physical massive bosons W^1 and W^2 is combined to form the physical W^+ and W^- bosons, which couple only with the left-handed particles which carry *weak* isospin. The remaining two electrically neutral spin-1 boson fields (W^3 and B) combines each other to form the massive Z field and massless field A , corresponding to the Z^0 boson and the photon respectively,

$$Z^\mu = \cos(\theta_W) W^{3\mu} - \sin(\theta_W) B^\mu, \quad (1.6)$$

$$A^\mu = \sin(\theta_W) W^{3\mu} + \cos(\theta_W) B^\mu. \quad (1.7)$$

In these equations the amount of mixing is defined by the Weinberg mixing angle θ_W which needs to be measured or calculated by the measurement of others Standard Model parameters [17]. It is important to mention that the Z field couple with different strength to left-handed and right-handed particles and, unlike photon field, have longitudinal polarisation.

The weak eigenstates of the quarks are superpositions of the mass eigenstates of the physical quarks. It allows quarks to decay between generations. For example, there is no restriction for a top quark decay to a *strange* or a *down*-type quark and a W^+ (in both cases). The mixing of the mass and weak eigenstates is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [18, 19]. The CKM matrix is described for three rotations angles and one complex phase. The presence of this phase allows for $\mathcal{CP}$ violation. The CKM angles have been measured experimentally and it is stated the CKM are very close to unity. Also the top quark decays $\simeq (95.7 \pm 3.4)\%$ to a bottom quark and a W bosons of the total of decays [11]. It makes the bottom quark physics a fruitful playground for study the top quark properties.

1.1.3 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the gauge theory which describes the strong interaction. There are some similarities with QED where the interaction between the fermions, in this case quarks, is due to particle exchange. They are massless bosons called *gluons*. But unlike QED, these particles carry colour charge and can interact with each other emitting and absorbing gluons.

The QCD Lagrangian is invariant under $SU(3)$ gauge transformations. A gauge group $SU(N_c)$ have dimension N_c , which is the number of colour charges, therefore there are three colour charges, labelled *blue*, *red* and *green*. The number of bosons is $N_c^2 - 1$, hence there are 8 gluons. Each quark carries a single colour. Anti-quarks carry an anti-colour. Gluons are however made up of a superposition colour and anti-colour. Quarks and

gluons are not observed as free particles. What is measured are particles that are made up of colour-anti-colour pairs (mesons) or bound states of the three different (anti)colours (baryons).

The strong interactions are described by the QCD Lagrangian given by

$$\mathcal{L}_{\text{QCD}} = \sum_q i\bar{\psi}_q(\gamma^\mu \mathbf{D}_\mu - m_q \mathbf{I})\psi_q - \frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu}, \quad (1.8)$$

where $q = (u, d, c, s, t, b)$ is the flavour index and m_q is the quark mass. The covariant derivative is defined as

$$\mathbf{D}_\mu = \partial_\mu \mathbf{I} + ig_s G_\mu^a \mathbf{T}_a,$$

where G_μ^a is the gluon field and g_s is the gauge coupling parameter. The gluon propagation terms is given by

$$F_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c$$

The presence of the third term with the constants $f_{abc}(a, b, c = 1, \dots, 8)$ corresponds to the non-abelian properties of QCD. This term allows the gluon field to be self-interactive. It could never be the case for photons because they carry no electrical charge. The self-interaction properties of gluons spread out the QCD charge generating an anti-screening effect. The structure constants f_{abc} are defined by the commutator of its generators $\mathbf{T}^a$ in the fundamental representation as

$$[\mathbf{T}^a \mathbf{T}^b] = if^{abc} \mathbf{T}^c$$

where the indices a, b, c run from 1 to $N_c^2 - 1 = 8$. The generators of the gauge group ($\mathbf{T}^a$) can be represented as eight 3×3 matrices (the Gell-Mann matrices). Like QED, the strong interaction is associated with a coupling strength, $\alpha = g_s^2/4\pi$.

QCD, like QED, contains divergences when particle exchanges are evaluated beyond leading order. As with QED, these divergences can be removed by renormalisation.

Physical observables need to be independent of the arbitrary *renormalization scale*, μ_R . It is the base concept of the renormalisation group. This is achieved through a set of

renormalisation group equations that specify the running of the renormalized parameters as function of the energy. For the arbitrary value of μ_R close to the scale of the momentum transfer Q in a given process, the coupling constant behaves with $\alpha_s(\mu_R^2 \simeq Q^2)$ indicating it is the effective strength of the strong interaction in that process. The coupling strength of the strong interaction varies with the energy of the process being considered (Q) as

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu_R^2)}{1 + \beta_0 \frac{\alpha_s(\mu_R^2)}{\pi} \log \frac{Q^2}{\mu_R^2}} \quad (1.9)$$

where

$$\beta_0 = \frac{11N_c - 2N_f}{12}. \quad (1.10)$$

Observe that $\beta_0 > 0$ since $N_c = 3$ (three colour) and $N_f = 6$ (six fermions) the strong interaction decreases at high energies such that,

$$\lim_{Q^2 \rightarrow \infty} \alpha_s(Q^2) = 0.$$

It leads to the physical interpretation that at very high energy quarks can be described as free particles. This phenomenon is known as *asymptotic freedom*. It is the key point of high energy QCD where quarks bounded in baryonic states may be considered as free particles, as the coupling to each other is small. On the other hand, at low energy α_s is too large to allow for perturbative QCD. At low energy quarks are bound together strongly enough to allow only formation of colourless states which are the observable particles in nature, which is known as *confinement*.

The world average of the coupling constant from different experiments is

$$\alpha_s(M_{Z^0}) = 0.1184 \pm 0.0007,$$

as extracted from [11].

On the other hand non-perturbative QCD is also important in heavy quark production. Especially for the bottom quark production (b -quark). Light quarks u , d and s can be found from different processes: valence quarks in the baryonic states of the proton

beam, perturbative subprocess (at high energy) and non-perturbative (low energy) giving rise to hadronisation. Therefore the informations extracted by identifying light hadrons is ambiguous but it is not the case for b -quarks. They are the heaviest quarks which hadronizes before decay. This property is due to his heaviness whose the mass is relatively higher than the energy scale where the perturbative approach fail. This energy scale can be determined through the Renormalization Group Equation (RGE) derived from Callan-Symanzik equation [20]. The RGE for the coupling constant can be written as

$$\mu_R^2 = \frac{\partial \alpha_s}{\partial \mu_R^2} \beta(\alpha_s) \quad (1.11)$$

where the β -function of QCD is implicitly introduced and can be calculated perturbatively. It is frequently expressed as expansion series of the coupling constant α_s

$$\beta = -2\alpha_s \left[\frac{\alpha_s}{4\pi} \beta_0 + \left(\frac{\alpha_s}{4\pi} \right)^2 \beta_1 + \dots \right] \quad (1.12)$$

with β_0 is already defined in Equation 1.10. But solving the β -function for the first loop one gets

$$\ln \mu_R + \frac{\pi}{\beta_0 \alpha_s(\mu_R^2)} = \ln \Lambda_{\text{QCD}} \quad (1.13)$$

where Λ_{QCD} is the scale which causes $\alpha_s(\Lambda_{\text{QCD}})$ to diverge, thus breaking down the perturbative approach *i.e.* at the limit of $\mu_R \rightarrow \Lambda_{\text{QCD}}$, $\alpha_s(\mu_R^2) \rightarrow \infty$ (confinement). From the world average value of $\alpha_s(M_{Z^0})$ the value for that scale is computed as

$$\Lambda_{\text{QCD}} = (90.6 \pm 3.4) \text{MeV}$$

this value was calculated considering all the six quarks flavour which are calculated using the 4-loop expression for the running of α_s at the mass of the Z^0 bosons of $M_{Z^0} = 91.2$ GeV [11]. The top quark mass is about 1900 times higher than this energy scale.

At LHC most analyses involve production of gluons and quarks. This production is calculated through perturbative Quantum Chromodynamics (pQCD) in short distance degrees of freedom, with colour charged quarks and gluons, while the long distance degree

of freedom seen in the detectors are colour singlet bound states of these degrees of freedom. The evolution between short distance and long distance states can be approximated by distinct steps. The first step is the parton shower when many new gluons and quarks pairs are added to the original state, dominated by partons that have low energy and/or are nearly collinear with the original short distance partons. The next step involves a non-perturbative hadronisation process that organizes the coloured degrees of freedom from the showering into color-singlet hadrons with physical masses. Both steps can be calculated in Monte Carlo programs and are model dependent [21].

After showering, hadronisation and decays of the partons, a set of particle with the same momenta as the parton is observed. Whilst individual particles often contain little direct information about the hard event, if a sufficiently hard parton is emitted in the laboratory frame of reference, then the particles will tend to form a collimated beam. Therefore, jet clustering algorithms are used to determine the final state that produces experimental observables which contain significant and useful information about the partons emitted in the hard process and the QCD processes they undergo in hadronising. Ultimately, the purpose of defining jets is to reduce the complexity of the final state objects whilst retaining the physics information of interest.

The most commonly used jet algorithms are those in the k_T family [22, 23], which are sequential recombination algorithms. Fastjet package [24, 25] have enabled a fast implementation of the clustering algorithm. These use the following algorithm:

- A distance d_{ij} , between any two particles i and j is calculated. The distance between each particle, i , and the beam is also calculated (d_{iB}).
- The minimum distance is considered. If $d_{ij} < d_{iB}$, the two particles are combined into one overall particle. This is typically done by summing their 4-momenta, and using this quantity to define a new particle. The new particle is then included in the list of particles and the original two particles are removed. However, if $d_{ij} > d_{iB}$

the particle is considered to be a jet and removed from the list.

- The process is repeated with the new list of particles until only jets are remaining.

This process provides a list of jets in the event. The distance measures are given by

$$d_{ij} = \min(p_{T\ i}^{2p}, p_{T\ j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \quad (1.14)$$

$$d_{iB} = p_{T\ i}^{2p},$$

where $p_{T\ i}$ is the transverse momentum of particle i and ΔR_{ij} is the relative distance in $\eta - \phi$ space between the particles i and j , given by $\Delta R_{ij}^2 = \Delta \eta_{ij}^2 + \Delta \phi_{ij}^2$. The parameter R is the cone size. For $p = 1$, the algorithm is named k_T , $p = 0$ named Cambridge-Aachen and $p = -1$ named anti- k_T .

In this thesis the anti- k_T algorithm is used since it is a well behaved algorithm with the following characteristics: it is easy to implement theoretically and experimentally, it can be defined at all orders of pQCD (infrared safety), it can be applied before and after hadronisation effects.

1.2 Experimental probes

There are three experimental probes of elementary particle interactions: bound states, decays and scattering. The analyses performed in this thesis are mostly sensitive to decays and scattering. In these analyses, the studied decays are well known: the leptonic final states of the Z and $W^\pm$ decays, decays of top quarks and $H^0 \rightarrow b\bar{b}$. On the other hand, the probed cross-sections are not fully tested in the kinematic region of the analyses presented in this thesis.

The cross-section for some hard process can be calculated using perturbative methods. However, the experiments at the LHC and the Tevatron collide hadrons, not partons. One therefore needs to find out some method for get predictions for the proton collisions, rather than simply predictions for the parton collisions. Here, factorisation theorem and asymptotic freedom are assumed [26].

The cross-section for a given hard process can be calculated and weighted by the probability that the protons contain initial-state partons of the required energy. These probabilities are parton distribution functions (PDFs). This approach is legitimate providing that the interactions between different partons in the same proton are small, which is the case at the high energies where asymptotic freedom applies. The factorisation theorem is mathematically expressed as [27]

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \sigma_{i,j}(p_1, p_2, \alpha_s(\mu^2), Q^2, \mu^2), \quad (1.15)$$

where $\sigma(P_1, P_2)$ is the cross-section for two hadrons with momenta P_1 and P_2 , and where the sum is over all possible initial-state parton contributions, i and j . These partons have momenta $p_1 = x_1 P_1$ and $p_2 = x_2 P_2$, so the integrals are over all possible parton momenta. $\sigma_{i,j}(p_1, p_2, \alpha_s(\mu^2), Q^2, \mu^2)$, is the cross-section for the interaction of these partons, and in pQCD depends upon the renormalisation and factorisation scale (which for simplicity here are set equal to each other, μ^2). The parton distribution functions, f , are dependent upon the scale (μ^2) and the momentum fraction of the partons (x_1 and x_2). x_1 and x_2 are also known as the Bjorken variables.

The factorisation scale separates long and short range physics depending upon the energy scale of study. Long range physics (low momentum parton emission) can be described by the structure of the colliding hadrons, and can be absorbed into the definition of the proton through the parton distribution functions. Higher energy parton emission is considered to be part of the hard process. The actual cross-section measured in nature should not depend upon this scale. However, the predicted cross-section is found to vary with the scale. It is often set to be either the vector boson mass (for inclusive vector boson production), or the transverse momentum of the vector boson in the event (for inclusive vector boson + jet production). When higher orders terms are considered the dependence of the calculated cross-section upon the factorisation scale diminishes, similarly to the way the dependence on the renormalisation scale reduces.

The measurements performed in this thesis are sensitive to low and high values of x_1 and x_2 where f has large uncertainties. Therefore the work of this thesis aims to probe the proton PDF in a phase-space region poorly constrained.

Chapter 2

Experimental tools

In this chapter the experimental tools for the analyses performed during the PhD program are presented. Experimental tools are considered as the hardware machinery, the software frameworks, offline high level softwares, the methods necessary to achieve the results of b -jets measurements and the contributions to the LHC beam monitoring proposed.

In Chapter 1, the Standard Model was presented and some measurable physical quantities introduced. Jets are important observables because measure their parameters allows for better understanding the strong interaction, since jet's content is sensitive to the proton PDF. In order to observe high energetic jets is necessary to design and develop particle accelerators and detectors. Nowadays the highest energetic accelerator in multi-TeV scale is the Large Hadron Colliders (LHC), held by the European Organisation for Nuclear Research (CERN), just outside Geneva, Switzerland*. CERN has been the site of key discoveries such as the neutral currents predicted by electroweak unification first seen by the Gargamelle experiment in 1973 [28]. The $W^\pm$ and Z^0 bosons were discovered by the UA1 experiment at the Super Proton Synchrotron (SPS) pp collider in 1983 [29, 30]. The 27 km circumference Large Electron-Positron collider performed electron-positron collisions between 1989 and 2000 . The accelerator and their experiments prove that three neutrinos families couple with Z^0 boson. At the end of 2000, LEP was shut down and

*The CERN convention was signed in 1953 by the 12 European states to set up a centre for fundamental research to probe the fundamental structure of the universe.

then dismantled in order to make room in the tunnel for the construction of the Large Hadron Collider (LHC).

2.1 The LHC

The approval of the LHC project was given by the CERN Council in December 1994. At that time, the plan was to build a machine in two stages starting with a centre-of-mass energy of 10 TeV, to be upgraded later to 14 TeV. However, intense negotiations secured substantial contributions to the project from non-member states, and in December 1996 the CERN Council approved construction of the 14 TeV machine in a single stage.

The LHC is a synchrotron accelerator, and is used to accelerate and collide both protons and lead ions. The machine crosses the border between France and Switzerland. The Figure 2.1 show a schematic view of LHC site.

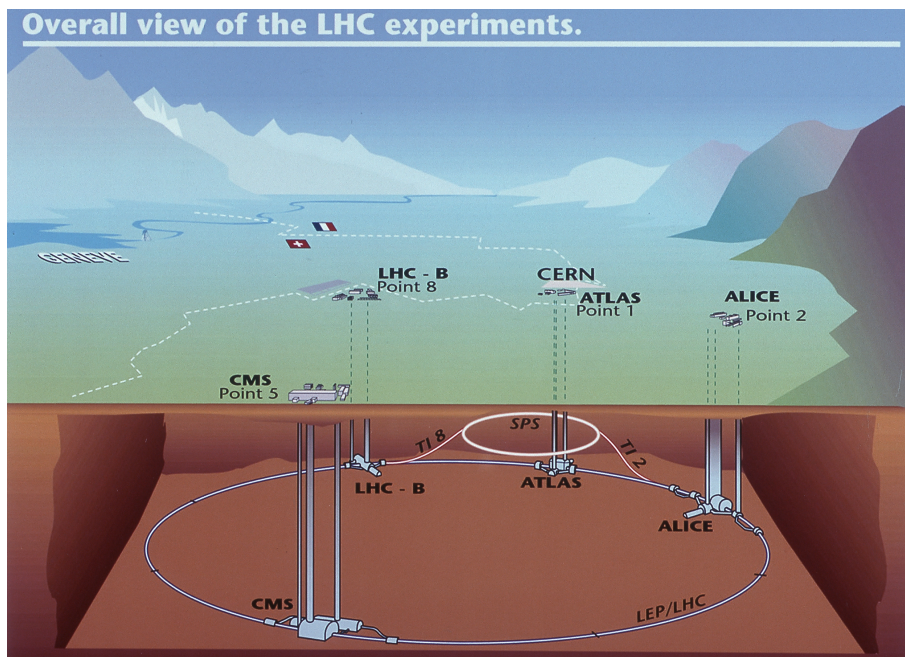


Figure 2.1: Scheme of the LHC site. Source: CERN

The feedstock of the LHC proton beam is hydrogen gas stored in bottles. To extract and accelerate only the proton content of the bottles the hydrogen is ionised. The protons

are then accelerated through a complex accelerator system as is schematically shown in the Figure 2.2. LINAC 2 machine is the first accelerator. This delivers relatively low energy proton (450 MeV) to the Proton Synchrotron booster. The booster feeds Proton Synchrotron (PS) with proton beam of 1.4 GeV. The PS deliver to the SPS proton beam at energy of 25 GeV with the LHC bunch train already developed. The SPS creates the beam structures required for the LHC design and feed the LHC ring with protons bunches of 450 GeV. This entire process takes around 1 hour.

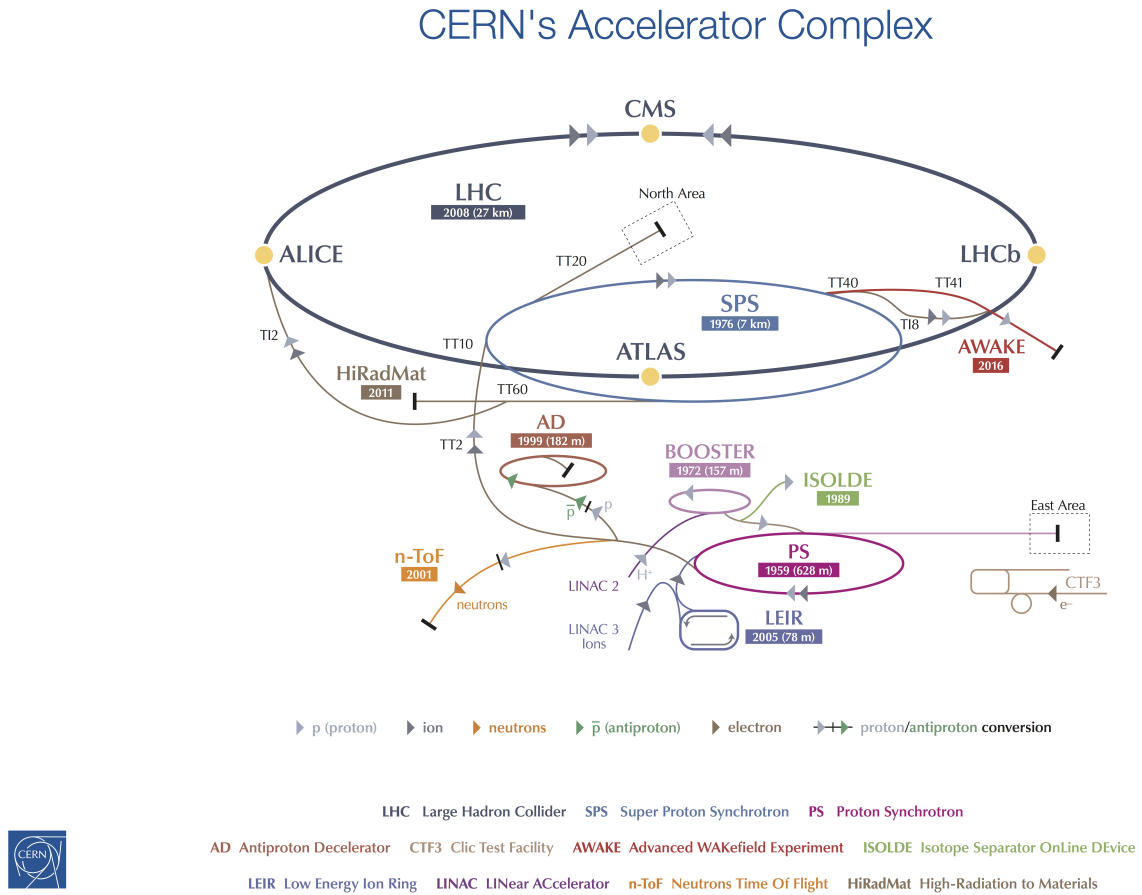


Figure 2.2: Scheme of the LHC accelerator complex. Source: CERN

The proton beam is then accelerated in the LHC ring for about 20 minutes through eight radio frequency (RF) cavities to reach the final energy. The LHC run 1 program accelerates each proton beams at energies of 450 GeV, 3.5 TeV and 4.0 TeV between

2009 and 2012. In 2015 the LHC run 2 collides pp at centre-of-mass energy $\sqrt{s} = 13$ TeV. The LHC beams consist of bunches of protons, designed to be separated by a 25 ns time interval but most runs have collided beams with a bunch spacing of 50 ns. Each bunch contains roughly 1.15×10^{11} protons. The LHC could have up to a maximum of approximately 3600 bunches for beam, but some bunches are left empty to facilitate the transfer of the beam during the injection stages. With the 50 ns bunch spacing each LHC beam in 2011 and 2012 typically contained around 1400 bunches.

The LHC relies on superconducting magnets that are at the edge of present technology. The LHC magnet system cools the magnets to a temperature below 2 K, using superfluid helium, and operates at fields above 8 T. This cooling is managed using super-fluid helium. In total 1232 dipoles control and accelerate the beam. To avoid deterioration of the beam inside the LHC tubes a ultra high vacuum condition is required. The internal pressure is desired to be below 10^{-8} mbar. Dimensionally, the beam is narrow in the transverse plane[†] with width of few millimetres. In the interaction point quadrupoles focus the beam width of around 14 microns wide.

The protons are collided at four main sites around the LHC ring. These sites house four different large detector experiments: two high luminosity experiment, ATLAS [31] (at Point 1) and CMS [32] (at Point 5) which are of “general purpose”, mainly designed to search for the direct production of new particles and search for physics beyond Standard Model and two low luminosity experiment: ALICE [33] (at Point 2), designed to probe collisions of heavy ions to investigate quark-gluon plasma effects and LHCb [34] (at Point 8), where the analysis of this thesis are based on and are presented in details in the next section.

The nominal operating luminosity is 10^{34} cm²s⁻¹, however, the current operating luminosity is typically around 5×10^{33} cm²s⁻¹, yielding around 20-30 proton-proton (pp) interactions in each bunch crossing in the high luminosity detectors. For the low luminos-

[†]The transverse plane is plane defined by the x - y axis in the LHC coordinate system

ity detectors, specially for the LHCb, the luminosity is around $4 \times 10^{32} \text{ cm}^2\text{s}^{-1}$, yielding on average about 2 pp interactions per bunch crossing. This lower luminosity allows the LHCb reconstruct secondary vertices within each pp collisions more efficiently, facilitating the online trigger.

For a complete review of the LHC machine the reader may refer to [35].

2.2 The LHCb

In this section we present the LHCb detector. The detector is the main experimental tool for the vector bosons plus b-jets analyses which encore the principal analyses of the work proposed. Within this section the principal system that have direct impact on the analyses are described in more details.

The LHCb experiment is dedicated to precision measurements of $\mathcal{CP}$ violation and rare decays of B hadrons at the LHC. To achieve these goals the LHCb detector was designed to identify B hadron efficiently. At the LHC, the dominant production mechanisms of bottom quarks are gluon splitting, quark-antiquark annihilation and gluon fusion. Furthermore, from the parton distribution function, colliding low- x with high- x partons give rise to final state particles boosted in the direction of the initial momentum of the partons, close to the beam pipe.

LHCb was designed to be operated at a modest luminosity, $\mathcal{L} = 2 \times 10^{32} \text{ cm}^2\text{s}^{-1}$. With the large $b\bar{b}$ production cross-section of $\sim 500 \mu\text{b}$ expected at an energy of 14 TeV, 10^{12} $b\bar{b}$ pairs would be produced in 10^7 s, corresponding to the canonical one year of data taking. This luminosity was chosen to maximize the probability of single parton interactions per bunch crossing in order to simplify B decay identification. The Figure 2.3 shows this probability.

LHCb is a single-arm spectrometer with forward angular coverage from approximately 10 mrad to 300 (250) mrad in the bending (non-bending) plane. The choice of the detector geometry is motivated by the fact that at high energies both b and $\bar{b}$ -hadrons are

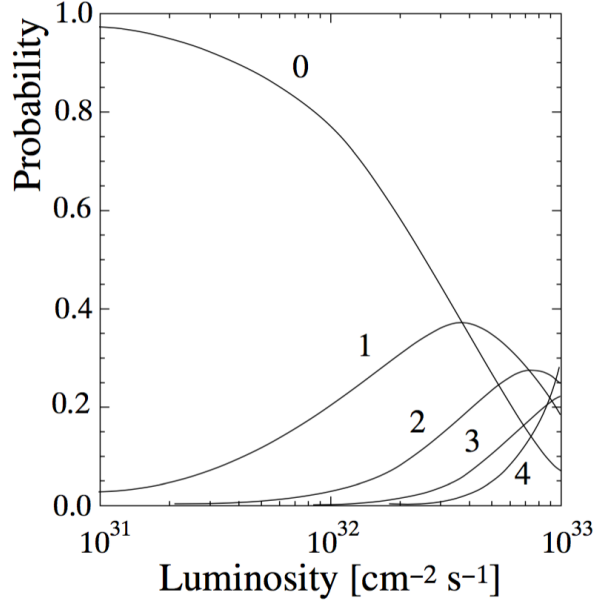


Figure 2.3: Probability for having 0, 1, 2, 3 and 4 pp interactions per bunch crossing as a function of the machine luminosity at LHCb. Extracted from reference [36].

predominantly produced in the same forward cone, a feature exploited in the flavour tag. This is demonstrated in Figure 2.4 where the polar angle of b and $\bar{b}$ -hadrons are plotted. The polar angle is defined with respect to the beam axis in pp centre-of-mass system. The angular coverage of the LHCb detector corresponds to approximately $2.0 < \eta < 4.5$, where the upper limit reflects the size of the beampipe. The layout of the LHCb spectrometer is shown in Figure 2.5. The right-handed coordinate system adopted has the z -axis along the beam, and the y -axis along the vertical.

In the next sections the main components of the LHCb detector are discussed in more details, from the interaction point to the most upstream edge of the detector in the following order:

- **Interface to the LHC machine - Beam pipe;**
- **Track System;**
 - Vertex Locator (VELO);

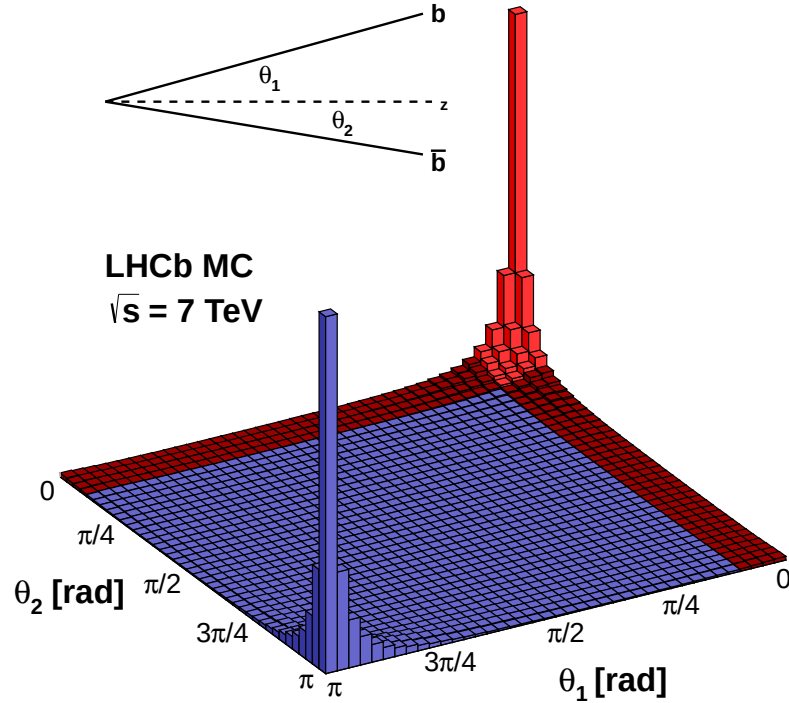


Figure 2.4: Polar angles of b versus $\bar{b}$ quarks produced at the LHC as predicted by PYTHIA8 [37] and CTEQ6 NLO [38]. The red region shows the acceptance of the LHCb detector. The light red region illustrate the amounts of events where both b -quarks are in the LHCb acceptance. It corresponds to around 25% of $b\bar{b}$ pairs produced inside the detector acceptance. Source: The LHCb collaboration.

- Track Turicensis;
- Magnet;
- Main Track Station (T1, T2 and T3);

- **Particle Identification;**

- Ring Imaging Cherenkov (RICH);
 - * RICH 1;
 - * RICH 2;
- Calorimeters;

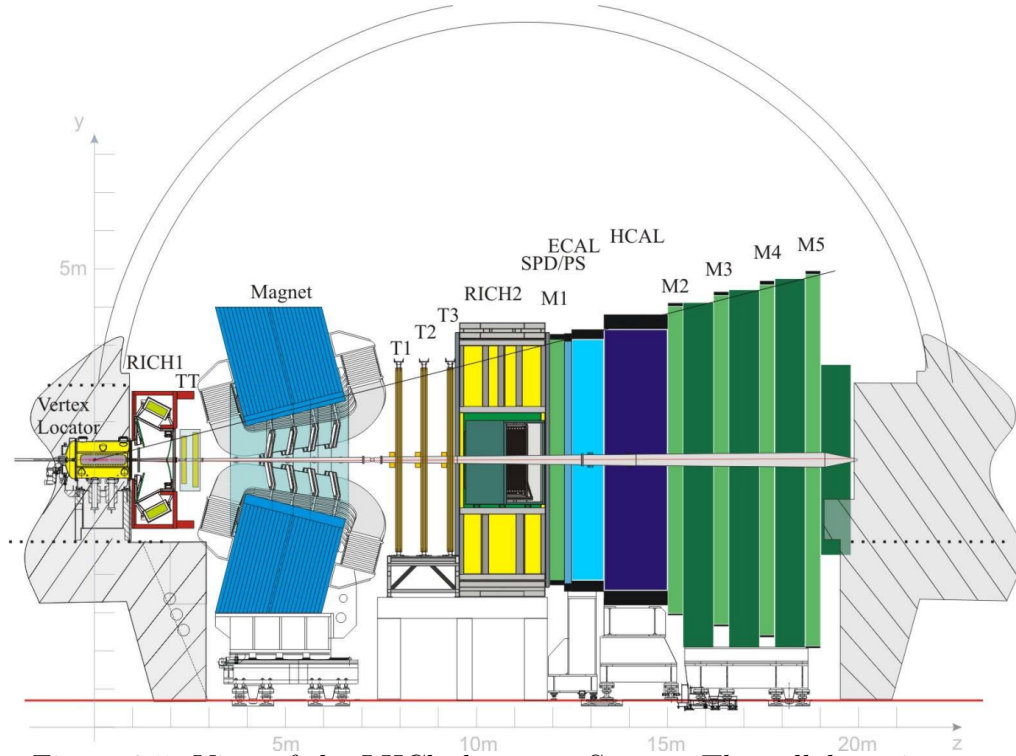


Figure 2.5: View of the LHCb detector. Source: The collaboration.

- * The pad/preshower (SPD/PS)
- * Electromagnetic Calorimeters (ECAL);
- * Hadronic Calorimeters (HCAL);
- * Muon Chambers;

2.2.1 Interface to the LHC machine - Beampipe

The beampipe design is particularly delicate since the LHCb experiment is focussed on the high rapidity region, where the particle density is high. The LHCb experiment is focussed on high rapidity region, where particle density is high. Therefore the choice of the beam pipe is made up to minimise the number of secondaries particles, which depends on the amount of material seen by incident primary the particles. The mass of the beampipe and the presence of flanges and bellows have a direct influence on the occupancy, in particular for the tracking chambers and the RICH detectors. Therefore maximize the transparency is highly required in these critical regions.

The beampipe is represented in Figure 2.6. The illustration includes the forward window of the VELO covering the full LHCb acceptance and the four sections of the beampipe: three closer to the interaction point being made of *beryllium* and the one further away of *stainless steel*.

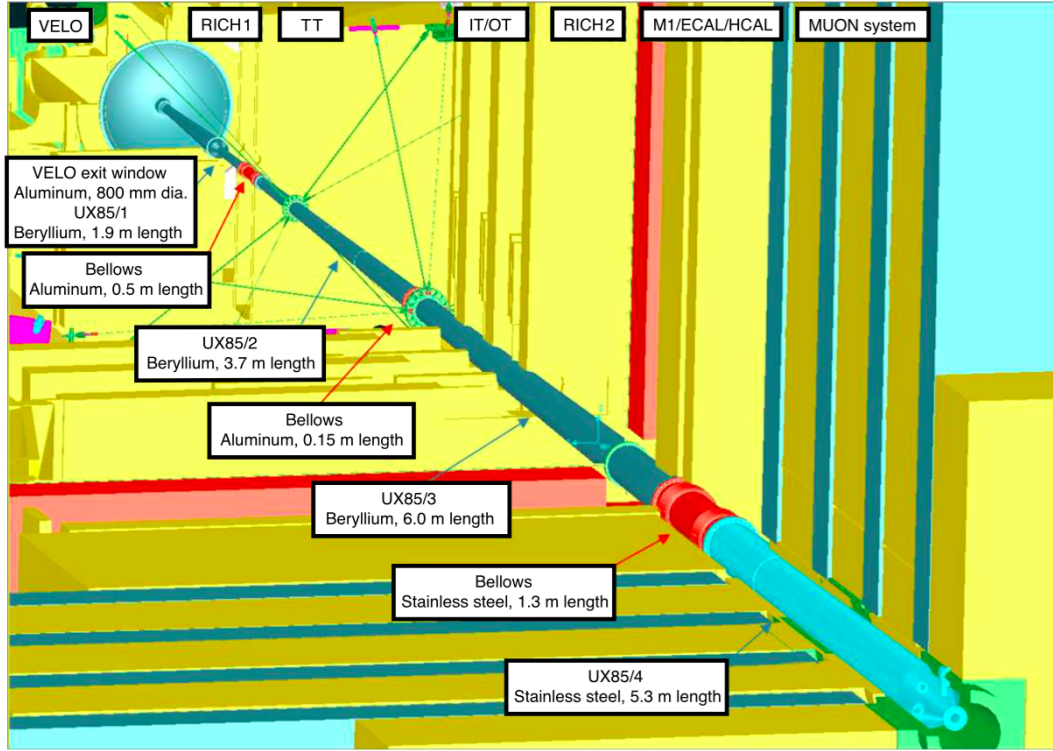


Figure 2.6: Illustration of the LHCb beampipe. The first three pipe segments are made of machined beryllium cones assembled by welding and the fourth of stainless steel. Bellows expansion joints provide interconnect flexibility in order to compensate for thermal expansions and mechanical tolerances. Extracted from reference [34].

Beryllium was chosen for the region close to the interaction point close to because of its high transparency to particles produced. However its toxicity, fragility and high cost are drawbacks. Stainless steel was then chosen for the region with the lowest particle density. Flanges, bellows and the VELO exit window are made of aluminium alloys. The first cone is 1 mm thick, and includes a 25 mrad half-angle cone. The other Beryllium sections range from 1 mm to 2.4 mm thick, and are at half-angles of 10 mrad. The vacuum inside the LHCb beampipe is isolated from the main LHC vacuum, to allow interventions

within the LHCb vacuum system.

2.2.2 The LHCb Track System

The LHCb tracking system consists of the vertex locator system (**VELO**) and four planar tracking stations: the Tracker Turicensis (**TT**) upstream[‡] of the dipole magnet and **T1**, **T2** and **T3** track stations downstream of the magnet. VELO and TT use silicon microstrip detectors. In T1, T2 and T3 stations, silicon microstrips are used in the region close to the beam pipe (Inner Tracker, **IT**) whereas straw-tubes are employed in the outer region of the stations (Outer Tracker, **OT**). The **TT** and the **IT** were developed in a common project called the Silicon Tracker (**ST**).

VELO

The VELO sub-detector consists of a series of silicon modules, each providing a measure of the r and ϕ coordinates, arranged along the beam direction (see Figure 2.7). VELO is designed to perform precise measurements of track coordinates close to the interaction region, which are used to identify the displaced secondary vertices which are a distinctive feature of B and D-hadron decays. A typical B hadron will fly a distance of ~ 7 mm before decaying [39].

The VELO consists of 21 stations, each divided into two modules (left and right) which contains silicon tracking sensors designed to measure the radial and azimuthal positions of any track passing through it, and associated electronic chips which readout this information. At least three VELO hits are required to form a VELO track. It form a ‘track seed’ which together with others sensor’s hits compose the LHCb track. The track reconstruction will be discussed later.

The VELO sensors were designed to measure tracks within a cylindrical geometry, as studies have shown that this allows for faster track reconstruction. These sensors are split

[‡]We refer as ‘*upstream*’ within the detector to refer to regions which are closer to the nominal interaction point in the direction of travel particles through the detector *e.g.* TT is upstream to the magnet. Similarly the ‘*downstream*’ is used to refer to region further away from the interaction point.

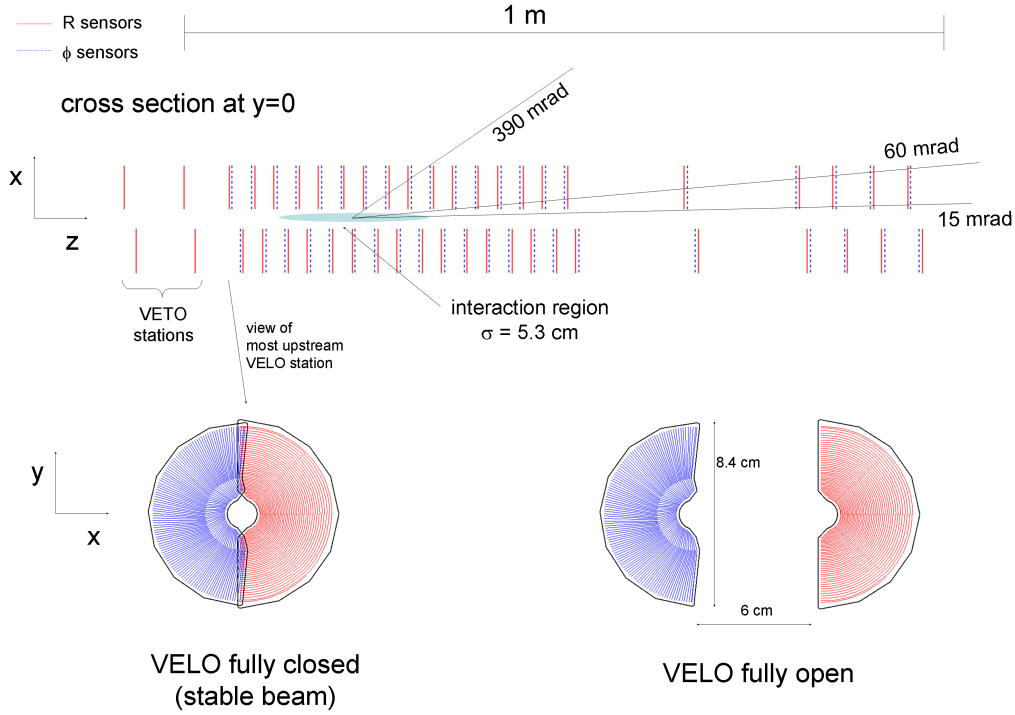


Figure 2.7: Cross section in the (x,z) plane of the VELO silicon sensors, at $y = 0$, with the detector in the fully closed position. The front face of the first module is also illustrated in both the closed and open positions. The two pile-up veto stations are located upstream of the VELO sensors. Extracted from reference [34].

in two; half measure the radial coordinate of the hits (the distance from the beam-line) and the other half measure the azimuthal angles of the hits. The sensors are therefore labelled as R -sensors and ϕ -sensors respectively. By measuring the position of each sensor within the VELO, the zenital coordinate is calculated. Both r - and ϕ -sensor are 300 microns thick, with the active area extending from a radius of 8 mm to a radius of 42 mm, but their inner strip structure is very different. A sensor illustration is shown in the Figure 2.8.

The VELO system is equipped with pile-up veto system made of two perpendicular planes upstream of the VELO sensors. It uses four silicon sensors of the same of the VELO sensors to measure the radial position of tracks. The pile-up system provides the

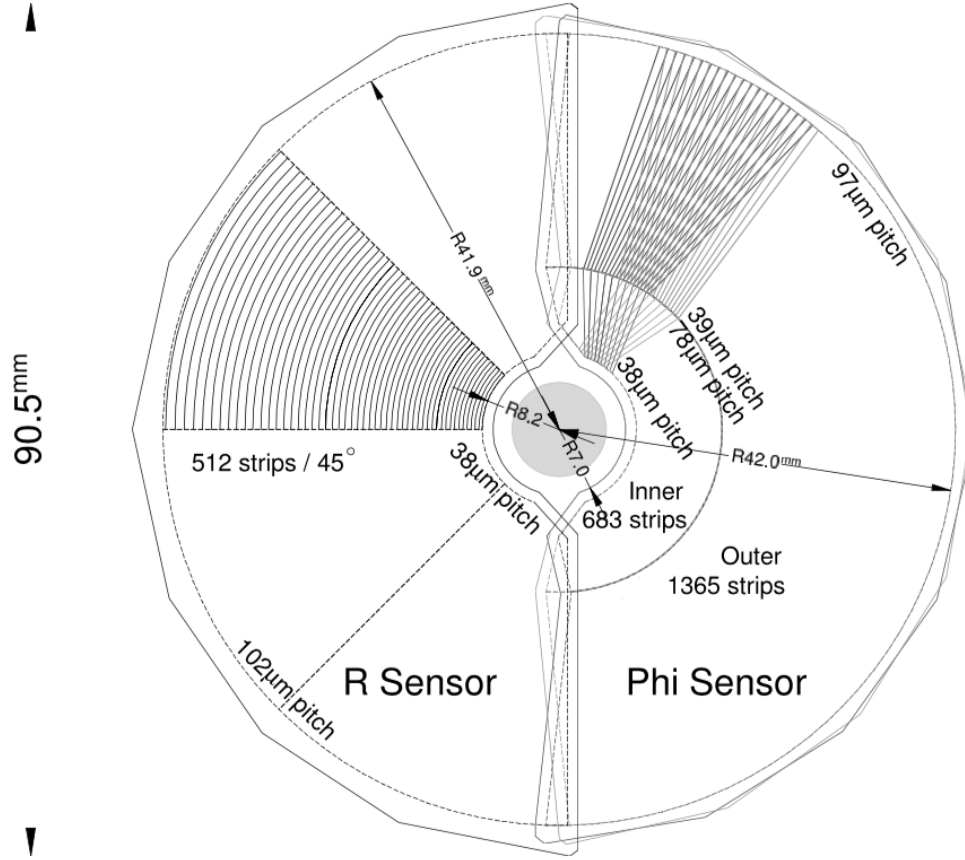


Figure 2.8: Illustration of one VELO sensor closed. The strips of the ϕ -sensor of two adjacent modules are indicated to highlight the stereo angle (angle between the strip lines of the modules). The different arrangement of the bonding pads leads to the slightly larger radius of the r -sensor; the sensitive area is identical. For clarity, only a portion of the strips is illustrated. Observe that the r - and ϕ -sensor overlaps to reduce ‘edge effect’. Extracted from reference [34].

position of the primary vertices candidates along the beam-line and a measure of the total backward charged track multiplicity. The veto modules are shown in the Figure 2.7.

The velo modules are placed inside aluminium boxes to protect the modules from LHC beam electromagnetic fields and to protect the LHC vacuum from potential leaks of the gas in the modules. These boxes are called Radio Frequency (RF)-boxes. The Figure 2.9 illustrate the RF box of half-side of VELO. The boxes are corrugated on their inner faces to enable the two sides of the VELO to slot together and provide the overlap between the

left and right modules. In this region the RF box is known as the RF-foil. The Figure 2.10 illustrate the foil protecting the modules. The RF foil makes the largest contribution of

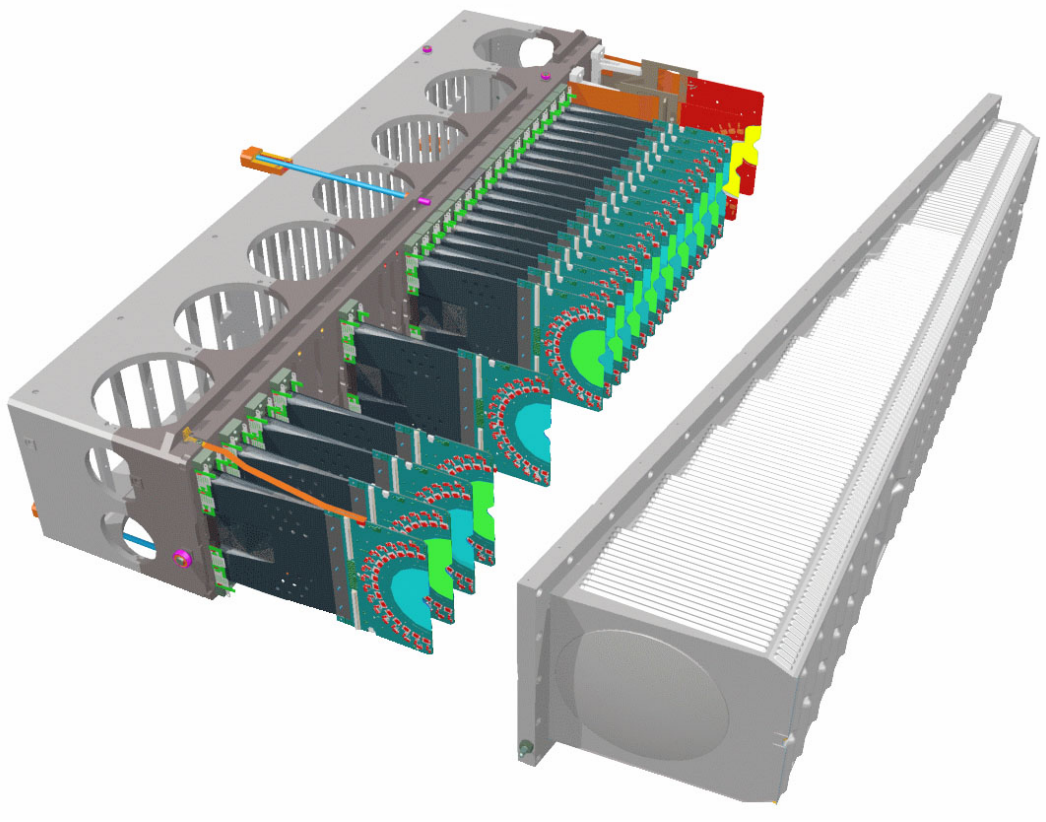


Figure 2.9: Exploded view of the module support and the modules (a), and the RF box (b). The corrugated foil on the front face of the box, which forms a beam passage can be seen. Its form allows the two halves to overlap when in the closed position. Extracted from reference [34].

the VELO to the material budget; the entire VELO corresponds, on average, to $\sim 17.5\%$ of a radiation length. Specially for the *LHCb upgrade* dedicate studies have being done to calculate the best geometry and position of the RF-foil of the new version of the VELO detector. A detailed calculation can be found in the PhD thesis of Daniel Vieira [40].

Silicon Tracker

The Silicon Tracker (ST) comprises two detectors: the Tracker Turicensis (**TT**) and the Inner Tracker (**IT**). Both TT and IT use silicon microstrip sensors with a strip pitch of

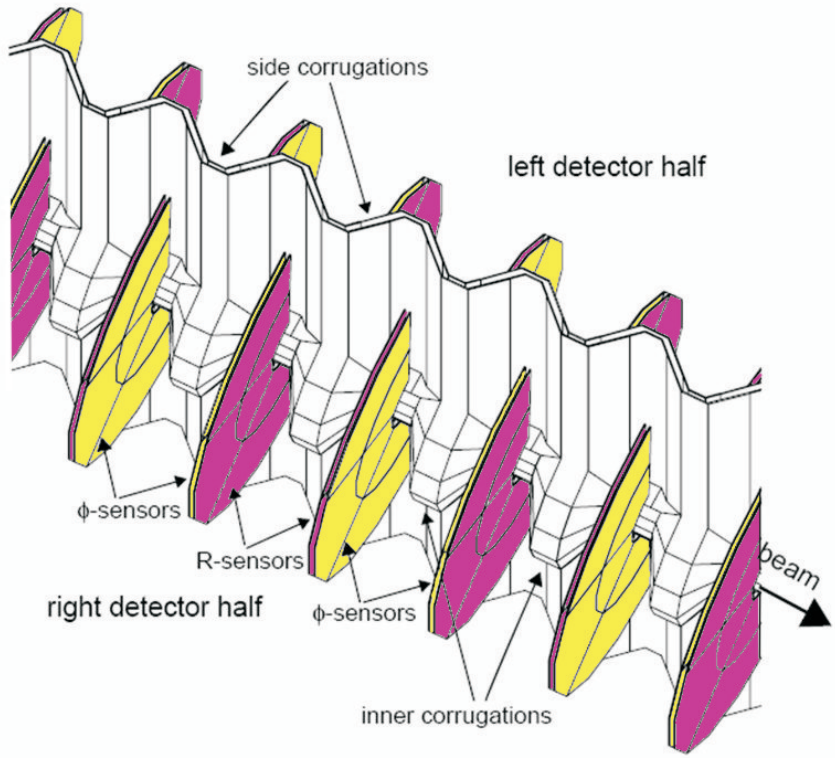


Figure 2.10: RF foil of the VELO detector modelled in GEANT, with the detector halves in the fully closed position. The r - and ϕ -sensors are illustrated with alternate shading. Extracted from reference [34].

about $200 \mu\text{m}$. The TT is a 150 cm wide and 130 cm high planar tracking station that is located upstream of the LHCb dipole magnet and covers the full acceptance of the experiment. The IT covers a 120 cm wide and 40 cm high cross shaped region in the centre of the three tracking stations downstream of the magnet. Each of the four ST stations has four detection layers in an $(x-u-v-x)$ arrangement with vertical strips in the first and the last layer and strips rotated by a stereo angle of -5° and $+5^\circ$ in the second and the third layer, respectively.

The TT has an active area of about 8.4 m^2 with 143360 readout strips of up to 38 cm in length. See Figure 2.11. The presence of a low integrated magnetic field of $\sim 0.15 \text{ Tm}$ between the VELO and the TT (see Figure 2.13) is sufficient to calculate momentum the momentum with resolution between 20%-40%. The trigger selects events with high-

momentum tracks. Since the deflection of these high-momentum tracks is small, a good spatial resolution is required. Therefore, to resolve the deviation from a straight line, it is chosen to build the TT as a silicon strip detector [41].

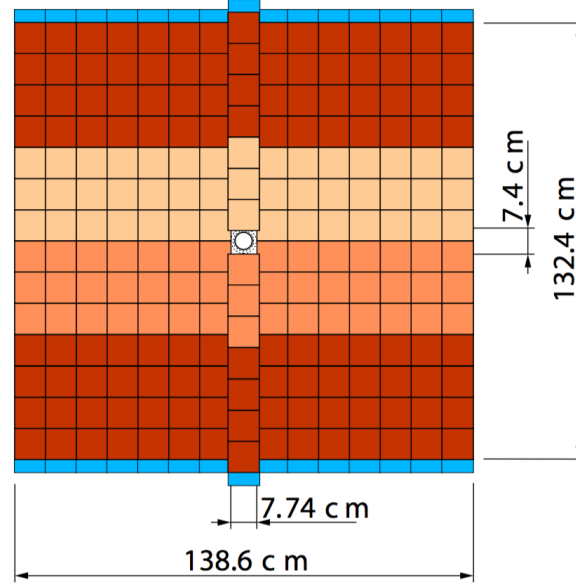


Figure 2.11: Illustration of the x -layer of the TT station. The shadings indicate strip connections. Extracted from reference [41].

The IT has an active area of 4.0 m^2 with 129024 readout strips of either 11 cm or 22 cm in length. The IT is located in the T stations where covers a 120 cm by 40 cm cross-shaped region with an active area of 4.0 m^2 , and corresponds to about 3.5% of a radiation length. This region of the detector sees the highest density of particles passing through it: the IT covers only 2% of the detector acceptance but approximately 20% of tracks pass through it. The Figure 2.12 show a front view of two layers of the IT sensor.

Magnet

The momentum of a charged particles is calculated using as experimental input the radius of curvature of particle passing through a magnetic field. In the LHCb configuration the particles are bend in the horizontal plane ($z - x$) whilst have straight vertical component (straight in the $y - z$ plane).

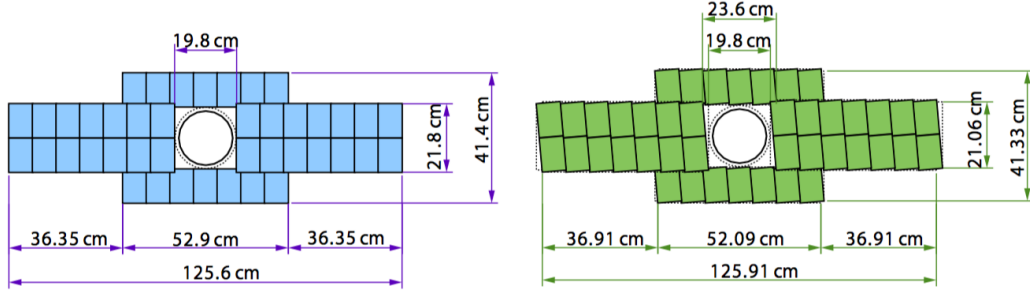


Figure 2.12: Illustration of the (left) x -layer (right) u -layer of the IT. The u - and v - layer are shifted $\pm 5^\circ$ with respect to the y -axis of the LHCb coordinate frame. The IT layers correspond to about 2% of the T-stations (see Figure 2.14) but approximately 20% of the tracks hit the IT. Extracted from reference [41].

The magnet covers the complete LHCb acceptance, with the field aligned in the $\pm y$ -direction. Uniquely at the LHCb, the magnetic field polarity can be switched. This is useful for analyses of asymmetries as many systematic effects can be removed by considering the mean of measurements made with opposite field polarities. The magnet has a peak field strength of 1.1 T, and provides an integrated field strength of ~ 4 T m for tracks of length 10 m. The field strength in each detector is shown in the Figure 2.13.

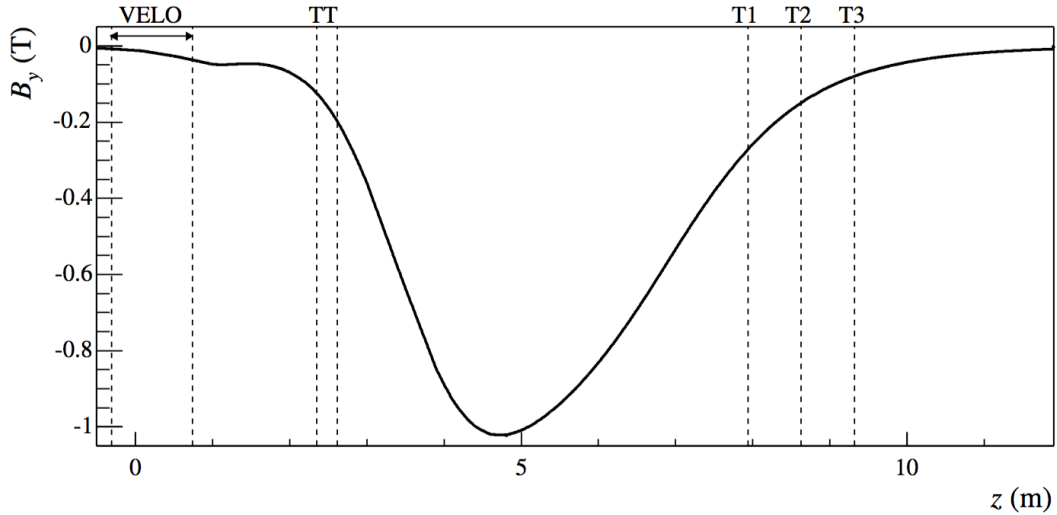


Figure 2.13: Component B_y of the magnet field strength along the beam direction (z). Extracted from reference [41].

Main Track Stations (T1, T2 and T3)

The LHCb track system has three main track stations T1, T2 and T3. Each stations have 4 layers arranged like the IT with the two middle layers shifted $\pm 5^\circ$. In the T stations, the Outer Tracker (**OT**) covers the large region outside the acceptance of the Inner Tracker. Together, the OT and IT compose the T station. The Figure 2.14 show a schematic front view of one x -layer of a T station.

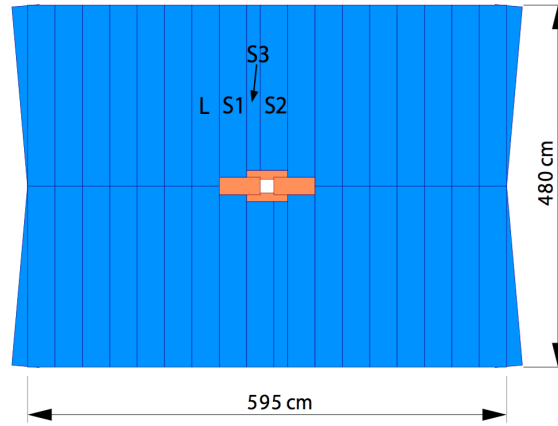


Figure 2.14: Coverage of the IT and OT within the T1-3 stations. Extracted from reference [41].

The OT is a drift-time detector, for the tracking of charged particles and the measurement of their momentum over a large acceptance area. Excellent momentum resolution is necessary for a precise determination of the invariant mass of the reconstructed b -hadrons: a mass resolution of $10 \text{ MeV}/c^2$ for the decay $B_s^0 \rightarrow D_s^- \pi^+$ translates into a required momentum resolution of $\delta p/p \simeq 0.4 \%$. The reconstruction of high multiplicity B decays demands a high tracking efficiency and at the same time a low fraction of wrongly reconstructed tracks.

OT station is designed as an array of individual, gas-tight Kapton straw-tube modules. Each module contains 4.9 mm diameter drift-tubes. The gas (70% Argon, 30% Carbon Dioxide) ensures a drift time below 50 ns, and a resolution of better than 200 microns. The total active area of each station is $5971 \times 4850 \text{ mm}^2$.

The forward geometry of the LHCb detector allows all detector services and supports of the OT to be located outside the detector acceptance. The OT material inside the LHCb acceptance of one station is estimated (four layers of modules, i.e. 8 monolayer panels) is on average equivalent to 3.2% of X_0 . The total OT material sums up to 9.6% of X_0 .

2.2.3 Particle Identification

Particle identification (PID) is a fundamental requirement for LHCb and is provided by Calorimeters (CALO), Muon and Ring Imaging Cherenkov (RICH) sub-detectors. The Calorimeters provide identification of electrons, photons and hadrons in addition to the measurement of their energies and positions. As well as being part of the LHCb trigger, the Muon system provides identification of muons to a very high level of purity, essential for many CP-sensitive measurements that have J/Ψ in their final states [42].

It is essential for the goals of the LHCb to separate pions from kaons in selected B hadron decays. At large polar angles the momentum spectrum is softer while at small polar angles the momentum spectrum is harder; hence the particle identification system consists of two RICH detectors to cover the full momentum range. We discuss separately both RICH detectors since they have different geometry and sensitivity. After we discuss the CALO and Muon system.

RICH Detectors

The RICH sub-detectors detect the Cherenkov radiation emitted by charged particles that pass through them. This, along with knowledge of the particle momenta from the tracking systems, allows particle masses to be determined. The RICH sub-detectors provide particle ID for particles with momenta between 2 GeV and 100 GeV.

RICH detectors discriminate the particle ID by direct detection of the Cherenkov radiation emitted by charged particle crossing a medium with speed faster than the speed

of light in that medium. The radiation is emitted in cone shape whose the cone's angle is related to the speed of the particle. This gives rise to characteristic rings of light formed when a particle traverses the medium. The RICH sub-detectors rely on sophisticated pattern recognition algorithms to search for photons emitted by particles. The upstream detector, RICH I, covers the low momentum charged particle range $\sim 1 - 60$ GeV/c using aerogel and C4F10 radiators, while the downstream detector, RICH II, covers the high momentum range from ~ 15 GeV/c up to and beyond 100 GeV/c using a CF4 radiator.

RICH I has a wide acceptance covering the full LHCb acceptance from ± 25 mrad to ± 300 mrad (horizontal) and ± 250 mrad (vertical) and is located upstream of the magnet to detect the low momentum particles. RICH 2 is located downstream of the magnet and has a limited angular acceptance of $\sim \pm 15$ mrad to ± 120 mrad (horizontal) and ± 100 mrad (vertical) but covers the region where high momentum particles are produced. In both RICH detectors the focusing of the Cherenkov light is accomplished using a combination of spherical and flat mirrors to reflect the image out of the spectrometer acceptance. In the RICH I the optical layout is vertical whereas in RICH II is horizontal. Hybrid Photon Detectors (HPDs) are used to detect the Cherenkov photons in the wavelength range 200–600 nm. The HPDs are surrounded by external iron shields and are placed in MuMetal cylinders to permit operation in magnetic fields up to 50 mT. The RICH detector system and the performance are described below.

RICH I

The RICH 1 detector is located upstream of the LHCb dipole magnet, between the VELO and the Trigger Tracker, see Figure 2.5. It is designed to minimize the material budget within the particle acceptance of RICH I. It has light weight spherical mirrors with all other components of the optical system located outside the acceptance. The

total radiation length of RICH I, including the radiators, is $\sim 8\% X_0$. The HPDs of the RICH detectors, need to be shielded from the magnetic field of the LHCb dipole. Local shields of high-permeability alloy and large iron shield boxes are used to reduce the magnetic field. Additional planar (flat) mirrors are required to reflect the image from the tilted spherical mirrors onto the photon detector planes.

The Figure 2.15 shows a lateral scheme of RICH I detector.

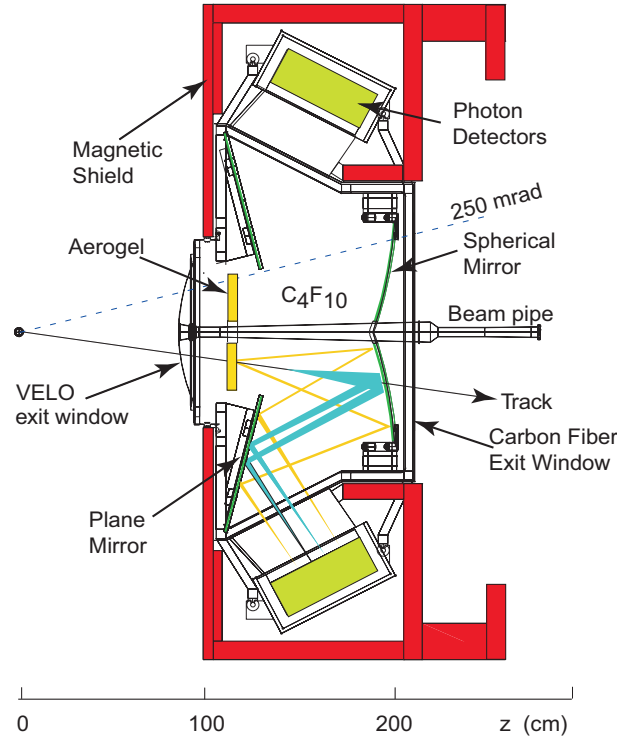


Figure 2.15: Side view schematic layout of the RICH I detector. Extracted from reference [34].

As mentioned before, the radiator media of RICH I is C_4F_{10} and aerogel. Aerogel is the ideal radiator to cover the very difficult range of refractive indices between gas and liquid. Silica aerogel is a colloidal form of quartz, solid but with an extremely low density. Its refractive index is tuneable in the range $1.01 - 1.10$, and is ideal for the identification of particles with momentum of a few GeV/c.

When charged particles cross the RICH 1 detector Cherenkov photons are emitted uniformly along their tracks. These photons are then focused using spherical mirrors of

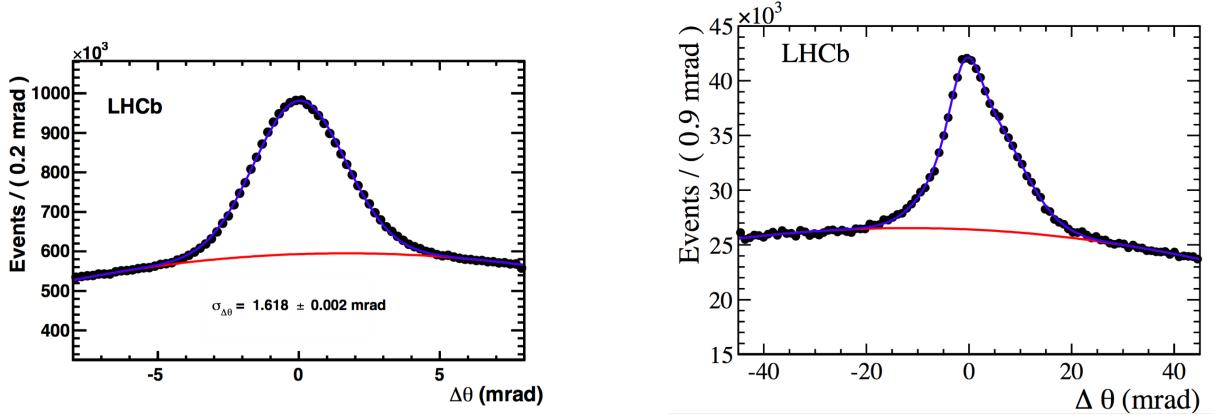


Figure 2.16: Left (right) – $\Delta\theta_C$ distribution of RICH I F_4C_{10} (aerogel). $\Delta\theta_C$ is the difference between data 2011 ($\sqrt{s} = 7$ TeV) and expected values from simulation. The resolution extracted from the fit is 1.618 ± 0.002 mrad for the gas. The disagreement seen between data and simulation for C_4F_{10} are largely attributed to imperfect corrections for distortions in the RICH photon detector images caused by the residual magnetic field in the vicinity of the RICH1 detector. The asymmetry of the aerogel distribution indicates a systematic effect not considered on simulation. The standard deviation is about a factor of 1.8 larger than the expectation from simulation. This discrepancy is, at least partially, explained by the imperfect absorption model of C_4F_{10} gas by the very porous aerogel radiator, with which it is in contact. Extracted from reference [43].

2700 mm of curvature radii, producing rings on a detection plane which are then reflected onto the photon detectors using flat mirrors. These radiators were chosen to provide efficient detection of particles with $1 < p < 60$ GeV.

The resolution of the Cherenkov angle with which the photons, radiated from the particles as they traverse the various radiator volumes was calculated using 2011 data. The distributions for $\Delta\theta_C$, the difference between the reconstructed and expected photon Cherenkov angles, are shown in Figure 2.16 after all detector alignment and calibration procedures have been performed [43].

The values of $\sigma(\theta_C)$, extracted from a simple fit to the $\Delta\theta_C$ distributions, are determined to be 1.618 ± 0.002 mrad for RICH1 gas (C_4F_{10}), comparable with the expectations from simulation of 1.52 ± 0.02 mrad. For aerogel radiator, where the distribution is not symmetric, the standard deviation is estimated to be 5.6 mrad. Even though simulation does not take into account the interaction between the gas and aerogel the RICH I resolu-

tion does not avoid particle identification. The Figure 2.17 shows the Cherenkov angle of several particle's photons. Observe that angle is much large than the detector resolution proving the capability of identify hadrons and even muons.

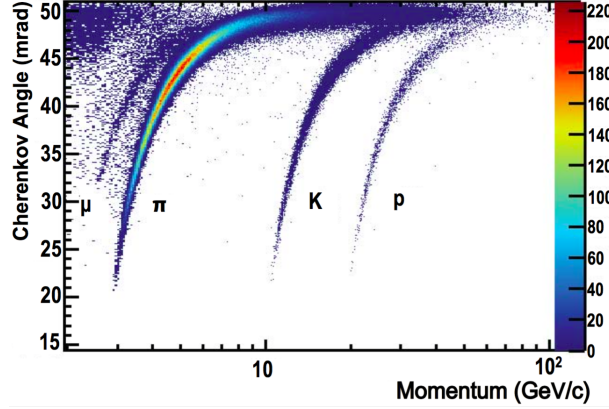


Figure 2.17: Reconstructed Cherenkov angle as a function of track momentum in the C_4F_{10} radiator. Extracted from reference [43].

RICH II

The RICH 2 detector is located between the last tracking station and the first muon station, see Figure 2.5. It contains a CF_4 gas radiator, providing PID from approximately 15 to ≥ 100 GeV/c for particles within the reduced polar angle acceptance of ± 120 mrad (horizontal) and ± 100 mrad (vertical). The refractive index of CF_4 is 1.0005 for light with a wavelength of 400 nm.

A schematics view of RICH 2 detector are shown in Figure 2.18. It is aligned vertically, with its front face positioned at 9500 mm from the interaction point and with a depth of 2332 mm.

Similarly to RICH I the supporting structures and photon detectors need to be placed outside the acceptance of the spectrometer. The requirement that the photon detectors are situated outside the full LHCb acceptance defines the lateral dimensions of the detector.

The total radiation length of RICH 2, including the gas radiator, is about $0.15 X_0$.

The HPDs are located in large iron boxes in order to be shielded from the fringe field of the LHCb dipole. The residual field is between 0.2 and 0.6 mT.

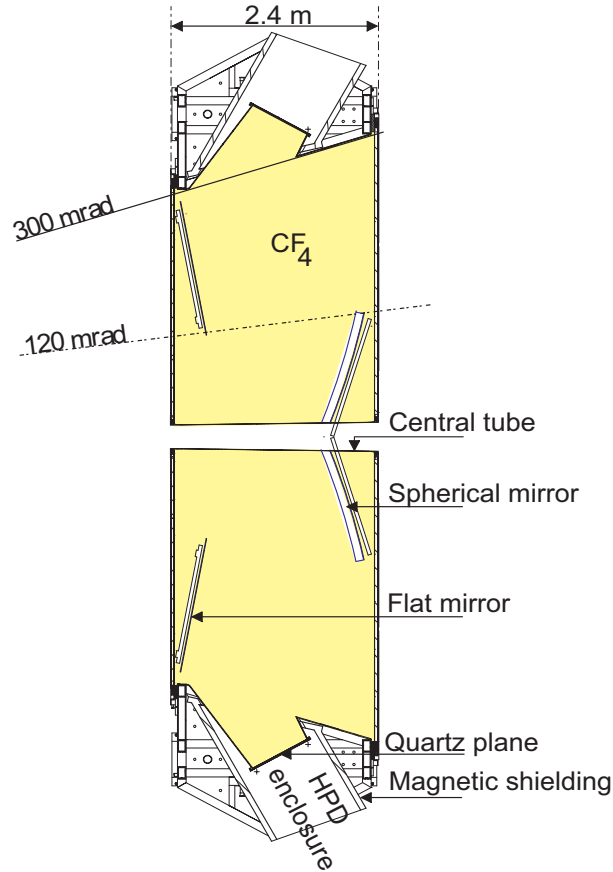


Figure 2.18: Top view schematic of the RICH 2 detector. The design is similar to that of RICH 1. Extracted from reference [43].

2.2.4 Calorimetry

The calorimeter system performs several functions. It selects transverse energy hadron, electron and photon candidates for the first trigger level (L0), which makes a decision $4 \mu s$ after the interaction. It provides the identification of electrons, photons and hadrons as well as the measurement of their energies and positions. The reconstruction with good accuracy of π^0 and prompt photons is essential for flavour tagging and for the study of B-meson decays and therefore is important for the physics program.

A classical structure of an electromagnetic calorimeter followed by a hadron calorimeter has been adopted. The most demanding identification is that of electrons. The electron Level 0 trigger is required to reject 99% of the inelastic pp interactions while providing an enrichment factor of at least 15 in b -events. This is accomplished through the selection of electrons of large transverse energy E_T .

At Level 0, the background to the electron trigger will then be dominated by photon conversions in the upstream spectrometer material, which cannot be identified at this stage. Optimal energy resolution requires the full containment of the showers from high energy photons. For this reason, the thickness of ECAL was chosen to be 25 radiation lengths. On the other hand, the trigger requirements on the HCAL resolution do not impose a stringent hadronic shower containment condition. Its thickness is therefore set to 5.6 interaction lengths due to space limitations.

The PS/SPD, ECAL and HCAL adopt a variable lateral segmentation (shown in figure 2.19) since the hit density varies by two orders of magnitude over the calorimeter surface. In all four cases, the light produced in the organic scintillators is transmitted to photomultiplier tubes (PMT) by optical fibres. The SPD and the PS both consist of a plane of scintillator tiles, separated from each other by a thin lead layer, while the ECAL and HCAL have shashlik and sampling constructions, respectively.

A segmentation into three different sections has been chosen for the ECAL and projectively for the SPD/PS. Given the dimensions of the hadronic showers, the HCAL is segmented into two zones with larger cell sizes.

The main role of the calorimeters in terms of particle identification is to provide for the recognition of photons, electrons and π^0 candidates. Distinguishing charged from neutral particles is performed by studying the presence or absence of tracks in front of the energy deposits.

For energy deposits related to neutral particles, the shape of the cluster is used to distinguish between photons and π^0 candidates. The photon hypothesis is established

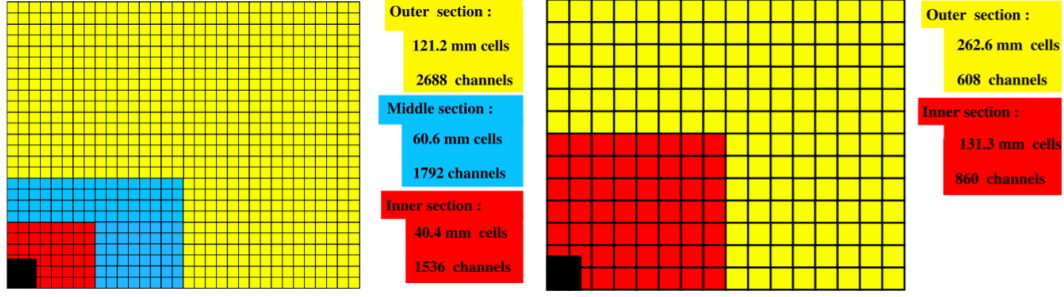


Figure 2.19: Left – Lateral segmentation of the PRS, SPD and ECAL. The layout contains three regions of different granularity, as the particle density varies across the detector. Right – One quadrant of the HCAL. Like the ECAL, the HCAL has sections of different granularity to account for the variation in particle density across the detector. In both figures the innermost black region is the beampipe. This schematic shows only one quadrant of the sub-detectors, and the lines on the schematic do not correspond to the cell sizes. Extracted from reference [34].

by taking into account the possibility that photons convert when interacting with the detector material upstream of the calorimeter. Then neutral particle reconstruction is based on information provided by the four systems (SPD, PS, ECAL and HCAL). In general, the detected signal pulses are longer than the nominal read-out window of 25 ns, and this must be taken into account to minimise spill-over effects. In the ECAL and HCAL detectors, this is performed by first clipping the signal to fit within the read-out window. In the PS and SPD detectors, the effects of spill-over are removed by subtracting a fraction of the signal integrated in the previous clock cycle.

When an energy deposit corresponds to a charged particle, the electron hypothesis is constructed to distinguish electrons from hadrons.

In the following items the SPD/PS, Electromagnetic and Hadronic calorimeters are briefly discussed.

Scintillator Pad Detector and Preshower detector

The SPD is used to separate photons from electrons at the L0 trigger by making use of the fact that it is a binary ‘and therefore very fast’ detector. Charged particles deposit energy in the scintillator material, while neutral particles do not interact. The amount

of deposited energy is converted to a binary 0 or 1 depending on a cell-by-cell threshold value set to minimize photon misidentification while keeping good charged particle identification.

The SPD uses a single bit for each cell to indicate whether or not it was traversed by a charged particle, with a discriminator comparing the energy deposited in the given cell to half of that expected from a minimum ionising particle (MIP).

Misidentification comes mainly from photon conversion in the material before the SPD, but also can come from interactions in the SPD that produce charged particles inside it, and backwards moving charged particles, the so-called back-splash [54], that are generated in the lead absorber or in the ECAL. Test beams showed that photons arriving at the SPD with an energy between 20 and 50 GeV have a misidentification probability of 0.8% when applying a threshold of 0.7 MIPs. The distinction between charged pions and electrons is done by making use of the electromagnetic shower dispersion measured in the PS.

Electromagnetic Calorimeter

The ECAL, is placed at 12.5 m from the interaction point. The outer dimensions of the ECAL match projectively those of the tracking system, $\theta_x < 300$ mrad and $\theta_y < 250$ mrad; the inner acceptance is mainly limited by $\theta_{x,y} > 25$ mrad around the beampipe due to the substantial radiation dose level. The calorimeter is therefore subdivided into inner, middle and outer sections.

The design energy resolution of

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\%, \quad (E \text{ in GeV})^\S$$

results in a B mass resolution of 93 MeV/c² for the $B \rightarrow K^*\gamma$ penguin decay with a high- E_T photon shown in Figure 2.20. The mass resolution obtained for this radiative

[§]The first term in this equation is the statistical fluctuation of the shower while the second comes from the systematic uncertainties of the calibration.

decay is dominated by the ECAL energy resolution [44].

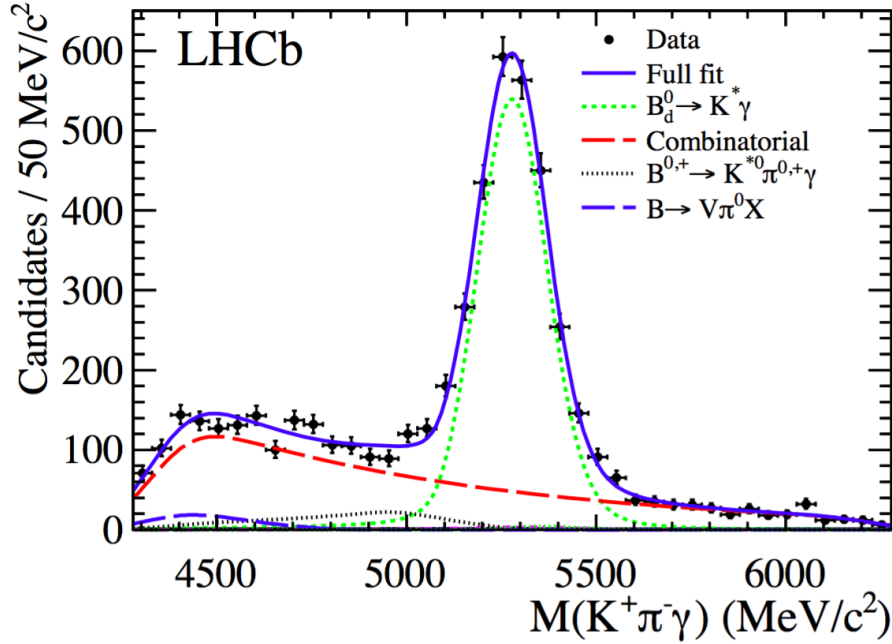


Figure 2.20: Mass distribution of reconstructed $B^0 \rightarrow K^{0*}(K^+\pi^-)\gamma$ candidates obtained in the 2011 data sample. The blue curve corresponds to the mass shape fit. The $K^{0*}\gamma$ signal (green dotted line) and the various background contaminations are shown. Extracted from reference [44].

Hadronic Calorimeter

The HCAL is used mainly for trigger and particle identification. It is a sampling device made from iron and scintillating tiles, as absorber and active material respectively. The special feature of this sampling structure is the orientation of the scintillating tiles that run parallel to the beam axis.

The overall HCAL structure is built at a distance of 13.33 m from the interaction point, with dimensions of 8.4 m in height, 6.8 m in width and 1.65 m in length.

HCAL gives estimation of the hadron energy with a design resolution of

$$\frac{\sigma_E}{E} = \frac{80\%}{\sqrt{E}} \oplus 10\%, \quad (E \text{ in GeV}).$$

It is segmented transversely into square cells of 131.3 mm (inner) and 262.6 mm (outer),

as illustrated in Figure 2.19. Therefore the charged hadron energies is computed using information from the track system.

The calorimeter system comply with a complex mechanical and readout system requirements where particle identification based on calorimeter system is performed through likelihood function which match information from all four detector of the calorimeter system. For a complete review of the particle ID system based on calorimeter information the references [34, 43, 45] can be consulted for a detailed informations.

Muon System

Muon triggering and offline muon identification are fundamental requirements of the LHCb experiment. Muons are present in the final states of many CP-sensitive B decays, in particular the two gold-plated decays, $B_d^0 \rightarrow J/\Psi(\mu^+\mu^-)K_S^0$ and $B_s^0 \rightarrow J/\Psi(\mu^+\mu^-)\phi$. They play a major role in CP asymmetry and oscillation measurements, since muons from semi-leptonic b decays provide a tag of the initial state flavor of the accompanying neutral B mesons. The muon system provides fast information for the high- p_T muon trigger L0 and muon identification for the high-level trigger (HLT) and offline analysis.

The muon system are shown in Figure 2.22. Composed of five stations (M1–M5) of rectangular shape is placed along the beam axis. Muons have a long lifetime $\tau_\mu \simeq 2.2 \mu\text{s}$, which means $c\tau_\mu \simeq 659 \text{ m}$, and a low interaction probability, and thus they fly through the whole detector. Muons are extremely penetrating and therefore muon chambers are installed at the end of the detector, where all other possible charged particles have been filtered.

The full system is composed of 1380 chambers and covers a total area of 435 m^2 . The inner and outer angular acceptances of the muon system are 20 (16) mrad and 306 (258) mrad in the bending (non-bending) plane respectively. This results in an acceptance of about 20% for muons from inclusive b semileptonic decays. Stations M2 to M5 are placed downstream the calorimeters and are interleaved with iron absorbers 80 cm thick

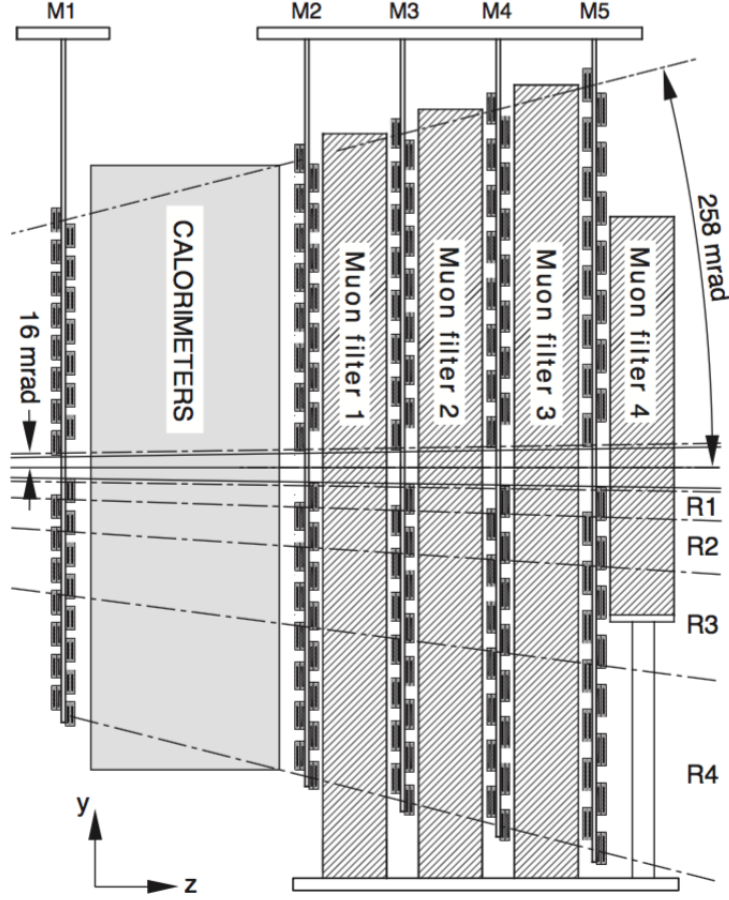


Figure 2.21: Side view of the muon system. Extracted from reference [34].

to select penetrating muons. The minimum momentum of a muon to cross the five stations is approximately 6 GeV/c since the total absorber thickness, including the calorimeters, is approximately 20 interaction lengths. Station M1 is placed in front of the calorimeters and is used to improve the p_T measurement in the trigger. The geometry of the five stations is projective, meaning that all their transverse dimensions scale with the distance from the interaction point. The detectors provide space point measurements of the tracks, providing binary (yes/no) information to the trigger processor and to the DAQ. The information is obtained by partitioning the detector into rectangular logical pads whose dimensions define the x , y resolution. The muon trigger is based on stand-alone muon track reconstruction and p_T measurement and requires aligned hits in all five stations.

Stations M1–M3 have a high spatial resolution along the x coordinate (bending plane). They are used to define the track direction and to calculate the p_T of the candidate muon with a resolution of 20%. Stations M4 and M5 have a limited spatial resolution, their main purpose being the identification of penetrating particles.

The layout of the muon stations is shown in Figure 2.22. Each Muon Station is divided into four regions, R1 to R4 with increasing distance from the beam axis. The linear dimensions of the regions R1, R2, R3, R4, and their segmentations scale in the ratio 1:2:4:8. With this geometry, the particle flux and channel occupancy are expected to be roughly the same over the four regions of a given station. The (x,y) spatial resolution worsens far from the beam axis, where it is in any case limited by the increase of multiple scattering at large angles. The right part of Figure 2.22 shows schematically the partitioning of the station M1 into logical pads and the (x,y) granularity.

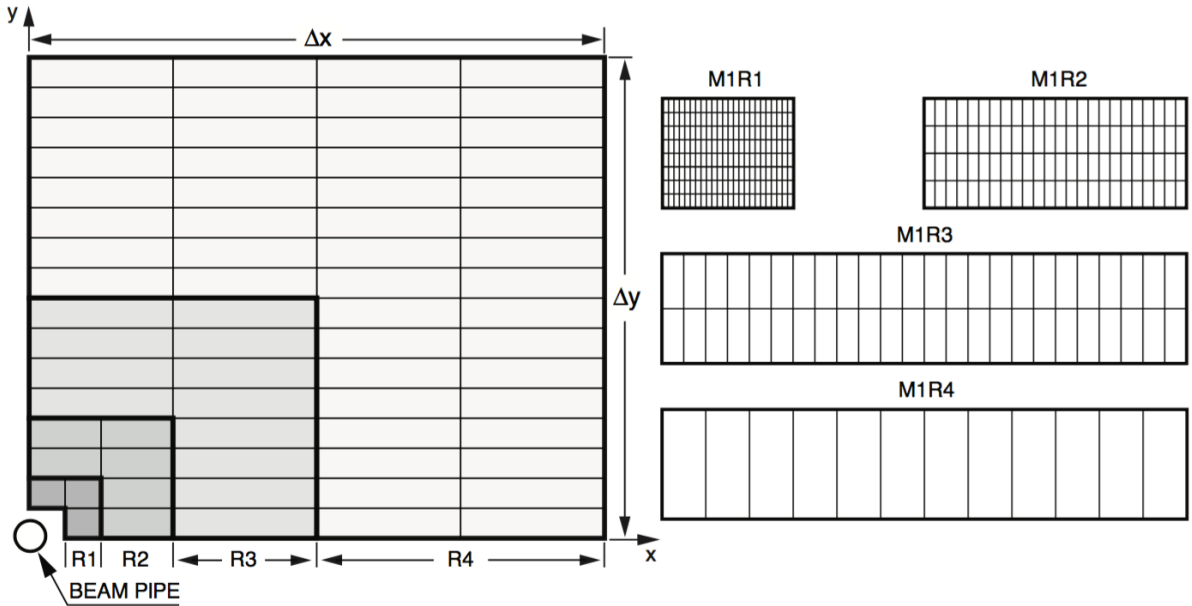


Figure 2.22: Left: front view of a quadrant of a muon station. Each rectangle represents one chamber. Each station contains 276 chambers. Right: division into logical pads of four chambers belonging to the four regions of station M1. In each region of stations M2-M3 (M4-M5) the number of pad columns per chamber is double (half) the number in the corresponding region of station M1, while the number of pad rows per chamber is the same (see table 6.5). Extracted from reference [34].

2.2.5 Trigger System

The LHCb detector was originally designed for an instantaneous luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, much lower than the maximum design luminosity of the LHC, reducing the radiation damage to the detectors and electronics. During the running period of 2012, this design luminosity was doubled to $\mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, which was possible thanks to the excellent performance of both the detector hardware and the trigger system. In these conditions, the average number of visible interactions per bunch crossing is $\mu = 1.6$. Furthermore, the number of interactions per bunch crossing is dominated by single interactions, which facilitates the triggering and reconstruction by assuring low channel occupancy.

Due to the LHC bunch structure and low luminosity, the crossing frequency with interactions visible by the spectrometer is about 10 MHz, which has to be reduced by the trigger to about 3 kHz for 2011 data and 5 kHz for 2012 data run, at which rate the events are written to storage for further offline analysis.

This reduction is achieved in two trigger levels: Level-0 (L0) and the High Level Trigger (HLT). The L0 trigger is implemented using custom made electronics, operating synchronously with the 40 MHz bunch crossing frequency, while the HLT is executed asynchronously on a processor farm, using commercially available equipment. A schematic overview of the LHCb trigger is shown in the Figure 2.23.

With a nominal luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ the bunch crossings with visible pp interactions are expected to contain a rate of about 100 kHz of $b\bar{b}$ -pairs. The expected number of B meson produced play a key role for the trigger design which is briefly presented below.

L0 Trigger

The L0 trigger is hardware based attempting to reconstruct high E_T hadrons, electrons and photons clusters in the calorimeters and two highest p_T muons in each of the four

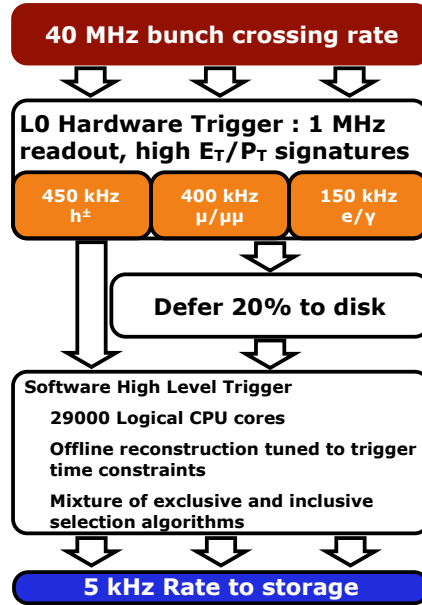


Figure 2.23: The LHCb trigger in 2012. Source: The LHCb Collaboration.

muon chambers. The L0 has also dedicated triggers to accept events with low occupancies of interest for study of central exclusive production, CEP [46].

The L0 trigger is subdivided into three components: the pile-up system, the L0 calorimeter trigger and the L0 muon trigger. Each component is connected to one detector and to the L0 Decision Unit (DU) which collects all information calculated by the trigger systems to evaluate the final decision for each bunch crossing within $4 \mu\text{s}$. This includes the particle time of flight, and all cable and electronic delays, meaning the trigger itself makes the decision within $2 \mu\text{s}$. The L0 DU is based on a specially designed electronic ‘TELL1 board’ [47].

The pile-up system aims at distinguishing between crossings with single and multiple visible interactions. It uses four silicon sensors of the same type as those used in the VELO to measure the radial position of tracks. The pile-up system provides the position of the primary vertices candidates along the beam-line and a measure of the total backward charged track multiplicity. The calorimeter trigger system looks for high E_T hits in the

ECAL and HCAL, indicating the presence of electrons, photons, neutral pions or hadrons. Clusters are formed by adding together the transverse energy of 2×2 calorimeter cells, and selecting those clusters with the highest transverse energy. Information from the PRS and the SPD enables particle identification while muon chambers allow stand-alone muon reconstruction, providing a transverse momentum resolution of about 20 %. The Figure 2.24 show the overview of the L0 trigger.

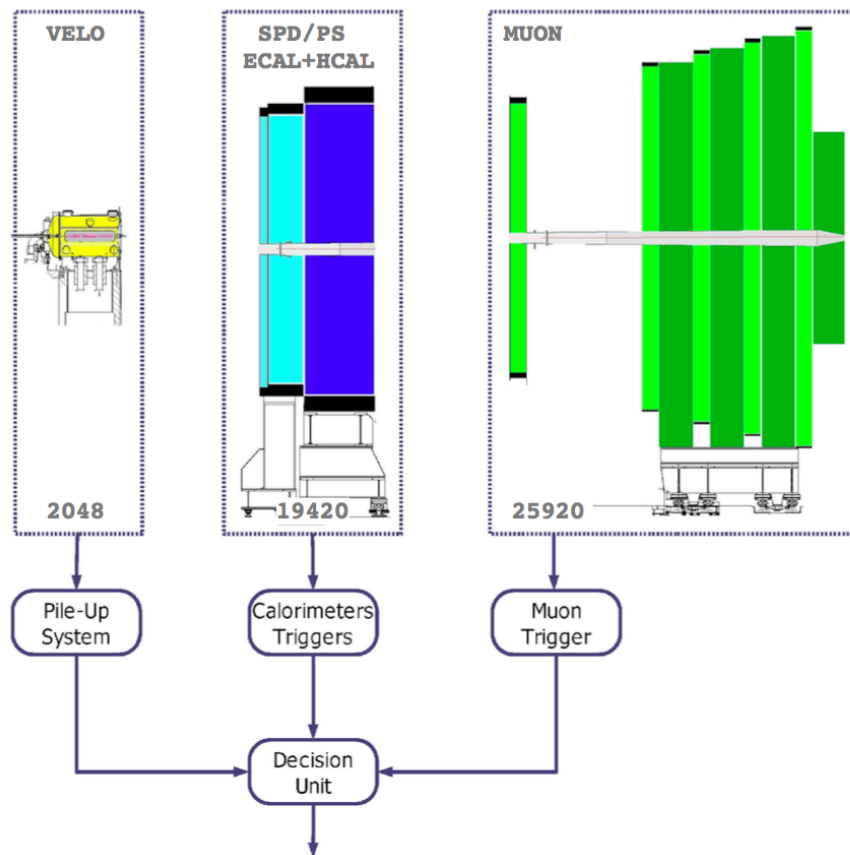


Figure 2.24: L0 trigger. Every 25 ns the pile-up system receives 2048 channels from the pile-up detector, the L0 calorimeters 19420 channels from the scintillating pad detector, preshower, electromagnetic and hadronic calorimeters while the L0 muon handles 25920 logical channels from the muon detector. Extracted from reference [34].

The L0 muon trigger looks for tracks within the muon stations, based on seeds within the M3 station. For each hit in M3, the expected position for hits in M2, M4 and M5 is found by assuming a straight line between the hit and the interaction point. Correspond-

ing hits are sought in these stations. Because the structure of the muon chambers is scaled to provide the same angular coverage, there is a one-to-one correspondence between pads in each chamber. This simplify the implementation of the muon trigger using only logical decisions as track extrapolation is easier and faster with such a design. The technology employed and the computation approach were designed to enable the decision from the DU to be made as quickly as possible. The detector data are serialised, optical links are used as transport media, and high density devices are used to make decisions.

There are different possible ways for the collisions within a bunch crossing to pass the trigger, since there are many trigger lines, and if one of these is passed then the entire event will be read out and recorded. The collection of L0 lines run is limited by the space available to program the L0 decision unit.

To assure that during off-line analysis the trigger conditions are known, the combination of trigger algorithms with their selection parameters will be assigned a unique key, the Trigger Configuration Key (TCK). All trigger configurations with their associated TCK are pre-loaded in the Event Filter Farm (EFF[¶]) before a fill. To change from one trigger configuration to another one, for example to follow the decaying luminosity in a fill, a new TCK must be selected. This TCK is attached by the Time and Fast Control system (TFC) to each event, and it steers the configuration of the algorithms on the EFF and allows full traceability of the used configuration.

A typical selection of the main lines within a TCK is shown in Table 2.1, where their approximate rate are quoted. In addition to the lines shown in the table, there are minimum bias lines, which do not select events at random, and low multiplicity lines, which select events with a low number of SPD hits (nSPD). There are also lines which do not have any requirements on the number of SPD hits, but these are only run once in every 104 collisions. Finally, there are also lines which monitor beam-gas collisions in events where one of the beams contains no protons in that particular beam-beam crossing.

[¶]Described in the next section

To stop a few events with high occupancy dominating the CPU processing time in the software trigger, *global event cuts* (GEC) are applied in the L0 trigger. The dominant GEC is on the number of hits in the SPD. The effect of these requirements depends on the specific physics analysis studied, and will be discussed in the chapter 5.

Trigger	Selection requirements	Rate [kHz]
L0Electron	$n_{\text{SPD}} < 600, E_T > 2.5(3) \text{ GeV}$	160
L0Photon	$n_{\text{SPD}} < 600, E_T > 2.5(3) \text{ GeV}$	80
L0Muon	$n_{\text{SPD}} < 600, p_T > 1.48(1.76) \text{ GeV}$	340
L0Hadron	$n_{\text{SPD}} < 600, E_T > 3.5(3.7) \text{ GeV}$	405
L0DiMuon	$n_{\text{SPD}} < 900, p_{T,1} \times p_{T,2} > 1.296(1.6) \text{ GeV}^2$	75

Table 2.1: Example of L0 trigger lines of LHCb. The ‘non-brackets’ number are events 2011 collision. The table contain also the typical rate of 2011. This number are only for references since the precise frequency depends of the instantaneous luminosity.

High Level Trigger

The High Level Trigger (HLT) consists of a C++ application which runs on every CPU of the Event Filter Farm (EFF). The EFF contains up to 2000 computing nodes where each HLT application has access to all data in one event, and thus, in principle, could execute the off-line selection algorithms. However, given the 1 MHz output rate of the L0 trigger and CPU power limitations, the HLT aims to reject the bulk of the uninteresting events by using only part of the full event data. MonteCarlo simulation were used to determine the HLT design which is thought to have optimal performance within the allowed time budget.

A schematic of the overall trigger flow is shown in Figure 2.25. L0 triggers on having at least one cluster in the HCAL with $E_T^{\text{hadron}} > 3.5 \text{ GeV}$, or the ECAL with $E_T^{e,\gamma,\pi^0} > 2.5 \text{ GeV}$, or a muon candidate in the muon chambers with $p_T^\mu > 1.2 \text{ GeV}$, or $p_T^{\mu_1} + p_T^{\mu_2} > 1 \text{ GeV}$, where μ_1 and μ_2 are the two muons with the largest p_T . The above thresholds are typical for running at a luminosity of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, but depend on luminosity and the relative bandwidth division between the different L0 triggers. All Level-0 calorimeter

clusters and muon tracks above threshold are passed to the HLT as part of the L0 trigger information, and will be referred to as L0 objects henceforward.

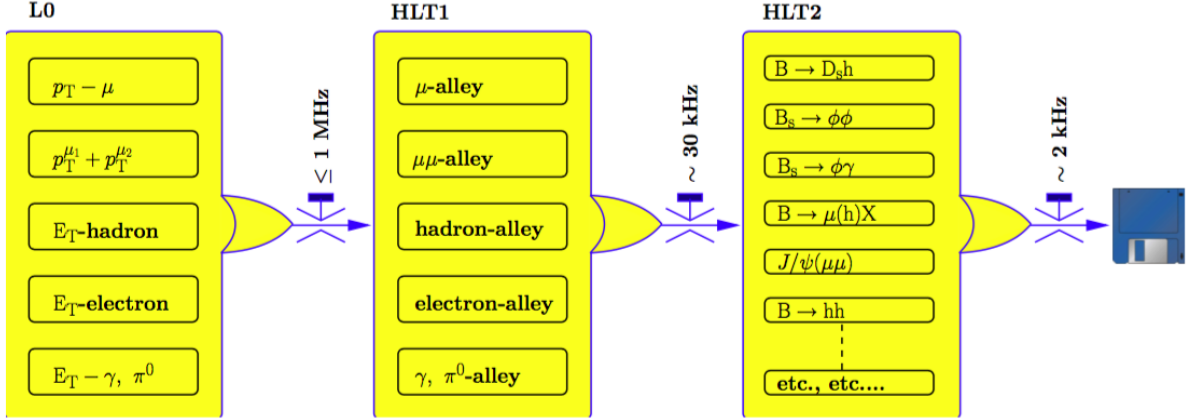


Figure 2.25: Overview of the HLT software. Extracted from reference [34].

The HLT is subdivided in two stages, HLT1 and HLT2. The purpose of HLT1 is to reconstruct particles in the VELO and T-stations corresponding to the L0 objects, or in the case of L0 γ and π^0 candidates to confirm the absence of a charged particle which could be associated to these objects. This is called L0 confirmation.

HLT1 should reduce the rate to a sufficiently low level to allow for full pattern recognition on the remaining events, which corresponds to a rate of about 30 kHz. At this rate HLT2 performs a combination of inclusive trigger algorithms where the B decay is reconstructed only partially, and exclusive trigger algorithms which aim to fully reconstruct B-hadron final states.

The majority of HLT1 ‘lines’ select events containing tracks which are significantly displaced from primary vertex (the pp collision point, abbreviated as PV). This is of particular interest since heavy flavour particles are expected to travel before decaying, creating tracks which do not point to the primary vertices. However, for the studies within this thesis, these trigger lines are not useful, as electroweak bosons decay very rapidly. The main analysis performed during the PhD program is the production of the vector bosons Z^0 and $W^\pm$ associated with jets from quark bottom which are described in

detail in the chapter 5 of this thesis. The lifetime of the Z^0 is about 3×10^{-25} s which gives a distance of flight of about 10^{-17} meters, smallest than the any detector resolution ever build. Therefore only the electron and muon lines, considering lepton final states coming from the PV, are discussed.

The muon triggers in HLT1 start by reconstructing VELO tracks which later on become a muon candidate using information from the muon chambers. The VELO tracks are reconstructed using a Kalman filter based track fit [48, 49]. For every VELO track a search window is implemented in the M3 station by extrapolating the VELO track in a straight line, with the size of the window defined by the expected deflection of a 6 GeV muon in the horizontal plane, and by the expected effect of multiple scattering in the vertical plane. Hits in the window are combined with VELO tracks to form candidate tracks, which are then further combined with hits in M2, M4 and M5. A muon candidate is accepted if it has a hit in M3 matching the VELO track and if the χ^2 fit of the candidate track (containing the VELO track and muons hits) per degree of freedom is less than 25 [50]. Track segments in the OT and IT are also reconstructed. Requiring high momentum tracks reduces the size of the search windows that need to be considered, increasing reconstruction speed. The track momenta are determined using a Kalman filter.

The HLT1 lines used for the data selection presented in the chapter 5 are shown in the Table 2.2. The electron triggers in HLT1 are based on the L0 trigger candidates. The reconstructed L0 electrons are re-analysed, and matching tracks are sought in the tracking stations. The search window is determined based on the position and energy of the ECAL cluster. If a successful search occurs, then a track fit is performed incorporating VELO information. The tracks coming from this search are then also reconstructed using the Kalman filtering [51]. Individual lines using these electron candidates then allow for the selection of events passing specific criteria.

Once the HLT1 has reduced the trigger rate to about 50 kHz, the HLT2 is able to select events based on a complete event reconstruction. This reconstruction is very similar

Trigger	Selection requirements	Fractional rate [%]
Hlt1SingleMuonHighPT	• $p > 8$ GeV • $p_T > 4.8$ GeV • $\chi^2/\text{NDOF} < 4$	1.4
Hlt1SingleElectronNoIP	• $p > 8$ GeV • $p_T > 4.8$ GeV • $\chi^2/\text{NDOF} < 4$	1.4
HLT1DiMuonHighMass	• $p > 6$ GeV • $p_T > 0.5$ GeV • $\chi^2/\text{NDOF} < 4$ • $M_{\mu\mu} > 2.7$ GeV	3.1

Table 2.2: HLT1 lines used for select the vector bosons $W^\pm$ and Z^0 final states candidates. The topological isolation of the bosons is discussed in detail on chapter 5. The fractional rate presented is from the total HLT1 rate. These number are from 2012 collisions.

to the full ‘off-line’ reconstruction. The main differences are that a simplified geometry is used for track fits and that the RICH information is only provided on-demand for a small subset of events. The HLT2 makes use of forward tracking algorithms for all VELO tracks. This technique is also used in the off-line event reconstruction. To save CPU time, reconstructed tracks in the HLT2 must satisfy $p_T > 0.5$ GeV and $p > 5$ GeV. The trigger lines in HLT2 are less generic than those in HLT1, and select events specifically for desired channel. The selection requirements and typical rates for lines used for the study of electroweak production physics are summarised in Table 2.3.

The LHC machine only delivers stable colliding beams for about 30% of the year [52]. In order to use the idle time well at the ERF, about 20% of L0 events are stored locally on hard discs to be processed in the time between the fills. This increases the number of events available for analysis. This technique was introduced in 2012 running with other improvements, allowed the output of the HLT to be increased from 3 kHz in 2011 running to 5 kHz. The efficiency and performance of the trigger lines used within this thesis will be discussed in later chapters 5.

Below is introduced some trigger definitions used when referring to trigger decision at

Trigger	Selection requirements	Rate [Hz]
Hlt2SingleMuonHighPT	• $p_T > 10$ GeV	45
Hlt2SingleTFVHighPtElectron	• $p_T > 15$ GeV • $E_{\text{PRS}} > 50$ • $E_{\text{ECAL}}/p > 0.1$ • $E_{\text{HCAL}} < 20$ GeV	25
Hlt2DiMuonZ	• $M_{\mu\mu} > 40$ GeV	0.05

Table 2.3: HLT2 trigger lines for electroweak production physics studies at LHCb are shown, along with the most important selection requirements and their typical rate. The three lines are not ‘pre-scaled’. Meaning that all the events are considering within clock cycle of data acquisition. ‘Pre-scaled’ trigger lines are configured to select only small fraction of events, as their rate would otherwise be too high. These numbers are for 2012 data.

LHCb.

- **Decision** – refer to whether a trigger line is ‘fired’ or not. Meaning that a particle passed all requirements of the trigger;
- **Trigger on Signal (TOS)** – refer to a particle, (or more generally when a trigger object) pass all the requirements of a trigger line. Usually these candidates are later on selected as signal candidate;
- **Trigger Independent of Signal (TIS)** – refer to an object that can be removed from the event, without changing the condition of this event to be triggered.

2.2.6 Detector Readout System

The Data Acquisition (DAQ) system is responsible for transporting the data taken in a given bunch crossing to permanent storage. This interfaces with the detector, the EFF and the HLT, before transferring the selected events for permanent storage to CERN compute facility. There is also a large buffer of 40 Tb storage system in case the link to CERN is interrupted [53].

The Timing and Fast Control (TFC) system drives all stages of data readout at the

detector. It distributes the beam-synchronous clock, the trigger reset and fast control commands simultaneously across the detector. The Experimental Control System (ECS) is responsible for monitoring the state of the entire detector. It monitors the voltage supply to the different components of the detector, the temperature changes in the detector, gas flows and pressure, and is also responsible for monitoring the trigger, TFC and DAQ systems.

2.2.7 LHCb Software Framework

Every application of the experiment (software) is built within the GAUDI framework [54]. The choice of the GAUDI framework allows to write software which can run both Monte Carlo simulation and data from pp collisions using the same tools. Data persistency is based on the ROOT software [55], a framework designed to manage and analyse large amounts of data. The GAUSS software [56] provides the simulation of physics events by running PYTHIA 6.4 and 8.1 [57], which calculate processes up to Leading Order. The decays of the produced particles are handled either with PYTHIA or through an LHCb-tuned EVTGEN package [58] in the case of B hadrons.

The interaction between particles and the detector material is simulated by Geant4 package [59]. The detector geometry, usually measured during the metrology of pre-assembled parts of the detector are stored in database together with the material budget, used to evaluate the expected scattering angles for several particles.

The energy depositions in the LHCb detector and the L0 trigger are simulated by the BOOLE software package which produce data in the same format as the experiment electronics and DAQ system [60]. From BOOLE, the simulated and the real data can be reconstructed and analysed using the same software since they are in the same format at this stage. The MOORE package [61] is used to run the HLT during data acquisition or offline starting from real data or from the output of BOOLE.

Hits and calorimetric depositions are converted into tracks and, eventually, particles

by BRUNEL [62]. Event reconstruction is performed by BRUNEL both for data and MC events. The DAVINCI software package [63] comprises the analysis and selection tools, such as particle identification algorithms, vertex fitting functions. It is also responsible of the administration and running of the stripping, a process in which events are further selected for physical analyses.

2.2.8 Offline Data Flow

The LHCb software trigger select events which are further stored at the CERN computing facility on tape. However, for ongoing usage the LHCb data are also stored on disc at CERN and at other Tier One sites to be available for offline analyses across the globe [64]. This allows easy access to the data. There is not enough space in disc to store every event readout by the trigger, therefore pre-selections are run before data are uploaded to the Tier One storage sites.

The reconstructed events are saved in a Stripping Data Summary Tape (SDST) file, which contains the necessary information for further event filtering without including the raw data. The SDST files are analysed in order to filter events for physical analyses by making use of the full reconstructed information and with looser timing constraints than in the HLT. This process is known as ‘*stripping*’ the data and finally produces a Data Summary Tape (DST) file, to which the raw data event information is attached. DSTs are the files accessible to scientists for physics analyses. The data are reprocessed several times a year with the improvement of the reconstruction, alignment and stripping software and algorithms.

The stripping is the centralised selection of interesting events run after the reconstruction. Stripped DSTs, stripped events, and stripping selections are the only selections which are run centrally, and therefore the only events and selections which are available for the entire LHCb dataset. The sequence of selections used to create candidates and select the event is called stripping line. Stripping lines are then grouped into streams, sets

of selections of a similar type, selecting similar events. Ideally no analysis should have to work with the output of more than one stream. Each stream build a different DST with the selected events and candidates from that stream.

In the next section the Beam-Gas-Vertexing Demonstrator (BGV) is introduced. The detector is foreseen as the most precise tool for the luminosity measurement and measurement of the LHC beam profile. The detector profits from the VELO readout system and the experiences gained from the Beam-Gas-Imaging of the LHCb beam. The method was applied as part of the absolute luminosity calibration where together with the classic ‘van der Meer’ method [65,66] have the most precise luminosity measurement [67] of all detectors at the LHC.

2.3 The BGV Demonstrator

As previously addressed the BGV Demonstrator is dedicated to the accurate measurement of the LHC transverse beam shapes. The whole project is a collaboration between CERN, the I. Physikalisches Institut B RWTH Aachen and the EPFL Laboratoire de Physique des Hautes Energies which designed, developed, installed and are currently^{||} commissioning the BGV system.

The basic sketch of the BGV system is shown in Figure 2.26 where a small amount of gas is injected into the beam pipe to perform beam shape imaging. This creates a local pressure bump sufficient to produce a rate of the order of 100 Hz per nominal LHC bunch over about 1 m, but have negligible impact on LHC machine operation.

The choice of gas type depends on several parameters and constraints. Neon gas was chosen because it has a large cross-section for proton–gas collisions which have high track multiplicity and by the technical boundary conditions imposed by the machine vacuum system.

The required amount of gas flow is minimised by reducing the vacuum conductance

^{||}During the writing period of this thesis

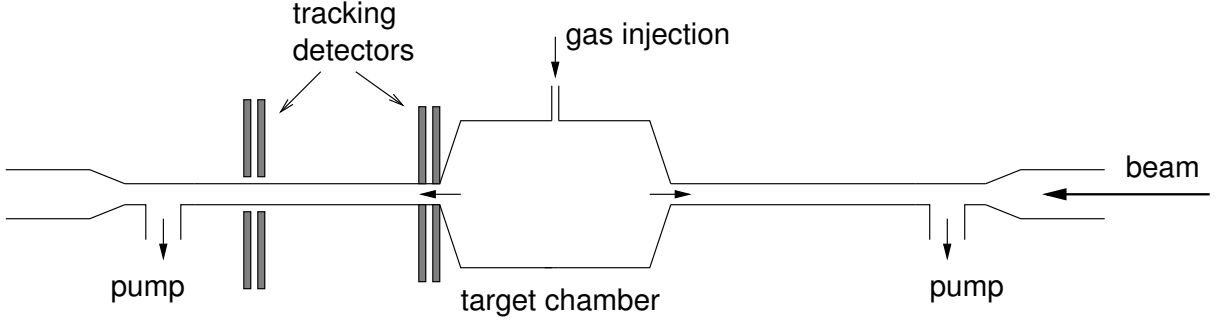


Figure 2.26: Sketch of the BGV Demonstrator. The gas (neon) is constantly flushed to avoid gas saturation inside the chamber which could decrease the pressure. Therefore decreasing the rate. Charged particles created by the proton–gas interaction are reconstructed using the two–station tracking detector. The track resolution and the multiple scattering dominates the vertex resolution. The detector has also two scintillating veto–triggers: one scintillation upstream the gas chamber and one downstream to the trackers, not visible in the figure. Courtesy of M. Ferro-Luzzi.

upstream and downstream of the target chamber. On the downstream side of the target chamber a thin exit window of 2 mm thick is implemented in order to minimize multiple scattering by reducing the material budget as much as possible. Downstream to this window a fibre tracker is used to detect high-energy charged particles and reconstruct the interaction vertex with adequate spatial precision. As discussed in Reference [67] it is crucial to have sufficient vertexing precision to be able to measure the beam shape with good accuracy. The distribution of these vertices gives an accurate image of the transverse distribution of the beam particles.

At the chosen BGV location at LHC Point 4, the beam width ranges from 0.15 to 1 mm and depends on the beam energy and emittance.

A fibre tracker with 0.25 mm pitch is a suitable choice for the LHC BGV demonstrator. The choice of this pitch relied on simulations which show that the minimum distance of approach to the beam axis ~ 23 mm and a distance between detector stations of about 1 m, a tracker with cluster resolution of $\simeq 60 \mu\text{m}$ is sufficient to have a final vertexing resolution good enough for the detector goals. Hence, the BGV demonstrator was designed to provide individual bunch width measurements in transverse directions

with a 5 % statistical accuracy in ~ 3 minutes of data taken. Averaged over all (~ 2500) bunches, such data will allow to obtain a beam width measurement of 1% statistical accuracy in less than a minute. Combined with an independent determination of the optics β functions, the BGV measurements will be used to provide precise values of the transverse emittances either per bunch, or averaged over all bunches of one beam. The systematic uncertainty will be dominated by the understanding of the vertex resolution. This will be discussed later on within this thesis.

There are currently available LHC emittance-measuring devices, but they are limited in terms of operational flexibility and absolute precision due to inherent features of the devices. On the other hand, the BGV system will allow one to overcome these limitations and to perform crucial measurements of the bunch emittances, with improved absolute precision and sufficient refresh rate, in particular during the energy ramp phase of the LHC cycle (which typically lasts a few minutes per TeV). The understanding of the emittance changes during the LHC cycle is essential for achieving the best possible beam quality and for delivering the highest luminosity to the LHC experiments. A direct comparison between the BGV measurement results and those of the existing devices will also facilitate their absolute scale calibration and studies of their systematic uncertainties.

The strategy is to demonstrate the potential of such a beam-gas imaging technique for the LHC with a demonstrator BGV system and, based on these results, design and install a more advanced BGV system on each LHC ring, possibly during Long Shutdown 2.

The BGV system is composed of the following subsystems: a gas target, a tracking detector, a detector cooling system, a level-0 trigger system with custom-made electronics and a high-level trigger/data-acquisition system based on commercially available networking and computing commodities.

In the following subsections of this chapter the BGV system is briefly presented. Contributions to the BGV experiment are presented in Chapter 3.

The gas target

The noble neon gas was chosen as the fixed target. The gas chamber was designed to have a very stable pressure varying less than a factor 2 over the full z -range which are about 1 m long. The nominal pressure inside the gas chamber is up to 6×10^{-8} mbar which for a bunch population of 1.15×10^{11} protons leads to a rate of 100 Hz for the 40 MHz LHC revolution frequency.

Simulation have been performed using Hijing generator [68] through the LHCb software framework. Proton–oxygen (as from here referred to as pA) collisions at $\sqrt{s} = 450$ GeV were simulated because they are very close to proton-neon and simpler to implement. The charged particle distribution is shown in the Figure 2.27. One can see that the average number of particles produced is around 17/collision. Events with high multiplicity tracks are desired because the vertex resolution decreases with the number of tracks [67, 69, 70]. The right plot shows the pseudorapidity distribution where the region between the two lines cover $3 < \eta < 5$. The BGV acceptance are slight smaller and also depends on the position of the PV, see Figure 2.28. Tracks with low pseudorapidity are also preferable because the effect of multiple scattering increase with the transverse distance from the track hit to the beam axis. This effect shall be quantified in detail in the next chapter using simulation.

The tracking system

Each tracking stations will use four modules separated in two stations with the scintillating fibres (SciFi) of $250 \mu\text{m}$ thick, the Silicon Photomultipliers (SiPMs) and the read-out electronics.

The two stations are upstream to the gas chamber exit windows. The ‘Near’ station are few centimetres away from the chamber and the second station (named ‘Far’) is placed about 1 m downstream. The Figure 2.29 show a 3D model of the BGV detector.

Each module is made of two fibre detection planes providing a space resolution of 60

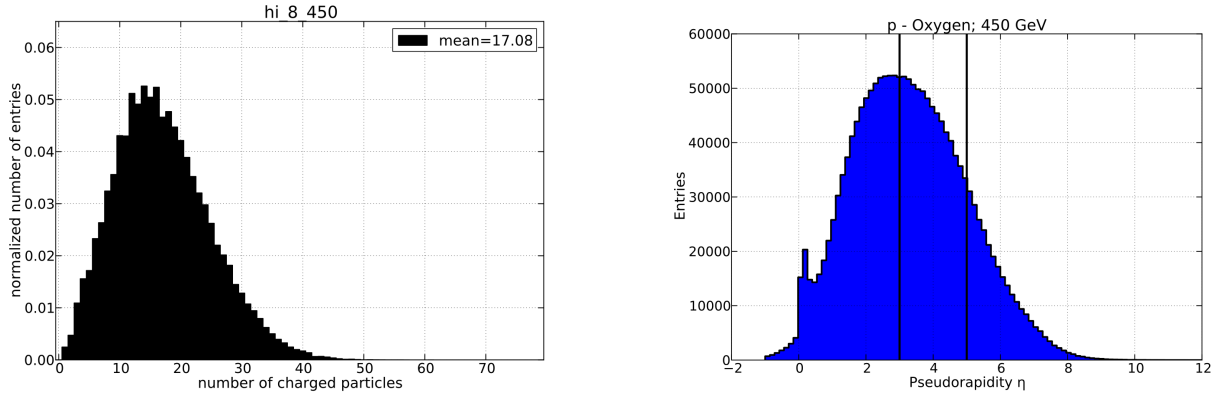


Figure 2.27: Left – Charge particle multiplicity in the proton–oxygen simulation with Hijing generator. Right – Pseudorapidity of the produced charged particle at the same collisions. Source: BGV Collaboration.

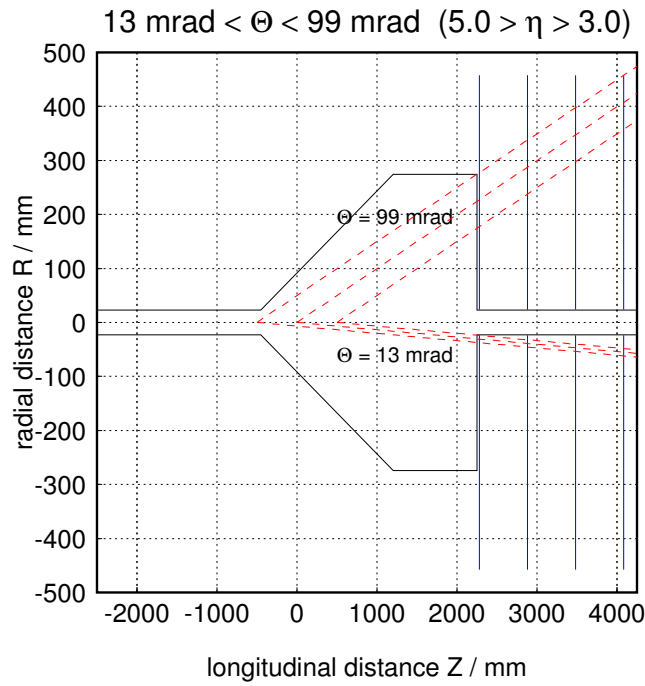


Figure 2.28: BGV pseudorapidity acceptance. The angular coverage depends of the z -position of the primary vertex. Courtesy of M. Ferro-Luzzi.

μm . In order to facilitate the pattern recognition and to perform a three-dimensional track reconstruction the fibre planes are rotated by an angle of 2° with each other. Two scintillating fibre modules are placed one behind the other with an angle of 90° with each

other. One charged particle passing through the fibre tracker of one station will leave two x – y track coordinates. These coordinates are then used to minimise the sum of the *distance of closest approach* of each cluster (line segment) to the particle trajectory (track). The detail strategy of the primary version of the BGV pattern recognition shall be discussed in the next chapter.

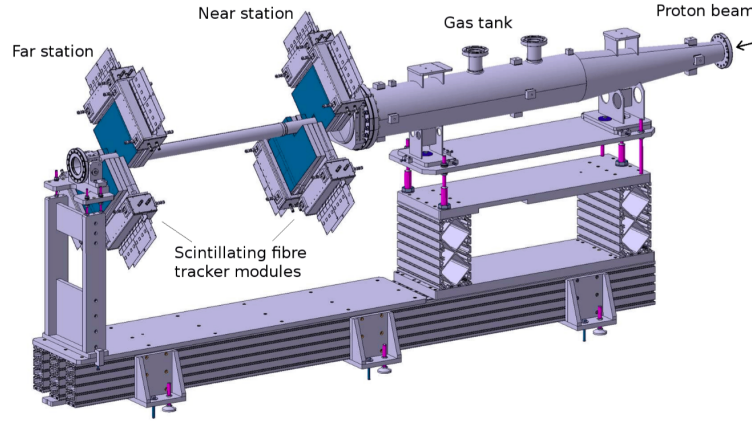


Figure 2.29: Scheme of the BGV Demonstrator [71]. There are also the veto modules: one downstream to the chamber and one upstream to the Far station, not included in this 3D model. Source: BGV Collaboration.

Since the BGV modules are placed very close to the beam pipe it will suffer from the radiation environment. The relevant effect of the radiation on the SiPMs is a significant increase of the dark noise. This noise can be reduced by cooling the SiPMs. The cooling system of the tracker modules is designed to cool the detectors to -40°C but it is most likely not to operate in such low temperature. However, it is sufficient to reach an acceptable noise level for the LHCb Scintillating Fibre Tracker and it is the baseline for the BGV. A temperature stability and uniformity of 2 K over sensors that are biased together is required to avoid too large gain non-uniformity [72].

The SiPMs are located in a cooling enclosure to avoid accumulate humidity in the modules. Dry-air are constantly flushed in the low temperature box. They are mounted against the scintillating fibres and, on the back side, against a cooling pipe. A chiller provides a refrigerant flowing through the pipe. Each module is built of two scintillating

fibre planes; the enclosure hence comprises two cooling pipes and two racks of eight SiPMs. A sketch of the assembled module representing one complete are shown in the Figure 2.30.

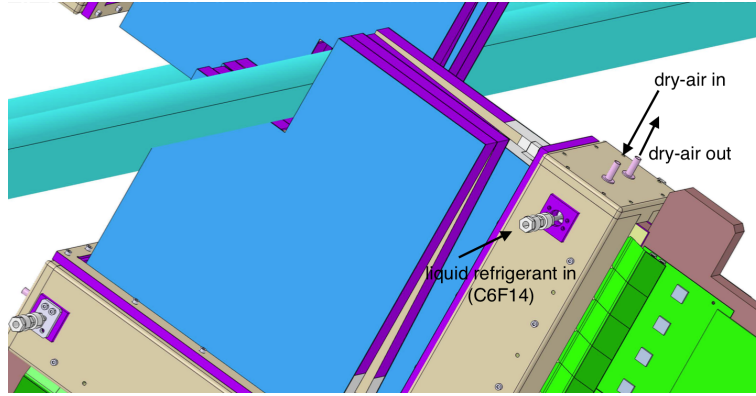


Figure 2.30: Sketch of the BGV modules assembled in the LHC beam pipe. Source: BGV Collaboration.

The design of the modules was chosen to consume a minimum of the cooling power and avoid heat leaks. The presence of discrete heat leaks at the surface of the tracker modules would induce water condensation or even ice formation which might cause damages to the read-out electronics. The surface of the module was therefore coated with carbon fibres in order to homogenise the surface temperature by spreading heat.

Scintillating plastic fibres will be used as the active detector of the tracker modules for the BGV detector. The signal composition is illustrated in Figure 2.31. The signal is translated into a cluster after digitalisation. The cluster within the pattern recognition is described by the geometrical line, are composed by the light yields of several fibres. A particle crossing the fibre plane generates photons through a scintillation process. The particle deposits ionisation energy in the fibre core which excites polymers. The relaxation leads to the emission of photons at a certain energy. A wavelength shifter is added to the scintillation polymer. This material is excited by the scintillation photons and re-emits photons through fluorescence at a longer wavelength which is better transported by the fibre. In the case of the BGV scintillating fibre, a blue emitting fibre of type SCSF-78MJ5 from Kuraray is used. In the near station, the fibre mattresses is made of 4 layers of fibres

whereas in the far station, 5 layers is used. Measurement with cosmic rays shows that passage of charged particle yields approximately 25 photons [73].

The photons are collected directly or via mirror reflection at the opposite side of the SiPM, by a multi-channel SiPMs. SiPMs are based on silicon diodes working in avalanche mode. Electron–hole pairs are generated by the photo absorption in the bulk of the silicon.

The SiPM structure enables a very strong electric field to be created near the positive electrode if the diode is biased by a minimum voltage called *breakdown voltage*. The photoelectron reaching this electrode creates an avalanche, namely it causes a chain ionization resulting in a gain of the order of 10^6 . The gain defines the fixed amount of signal that is produced by all pixels detecting a photon. Each channel of the SiPM comprises a certain number of pixels. Its signal is the sum of all signals generated in the pixels. A weighted mean of the channel signals yields the position of the particle. The Figure 2.31 illustrate this detection principle.

The noise in SiPMs have three base components, the dark count rate (DCR), the pixel-to-pixel cross-talk and the after-pulsing. The DCR is caused by thermally excited electrons in the silicon that trigger an avalanche. This creates dark pulses that are not distinguishable from signal pulses. The pixel-to-pixel cross talk give rise to another photoelectron detection though irradiation of UV frequencies generated by the original avalanche. The third component, after-pulsing, stems from photoelectrons trapped by lattice defects in the silicon. Once they are released, they give rise to an avalanche whose pulse is delayed but indistinguishable from a signal pulse. Regarding to the SiPMs, an increase in the DCR is seen after irradiation. This noise can be reduced by cooling the detector. The cooling capabilities of BGV modules were proved and quantified [74]. In the next chapter of this thesis the BGV cooling plant will be detailed described and their performance measurement presented.

Scintillating fibres of similar properties that of BGV fibres was chosen to replace the

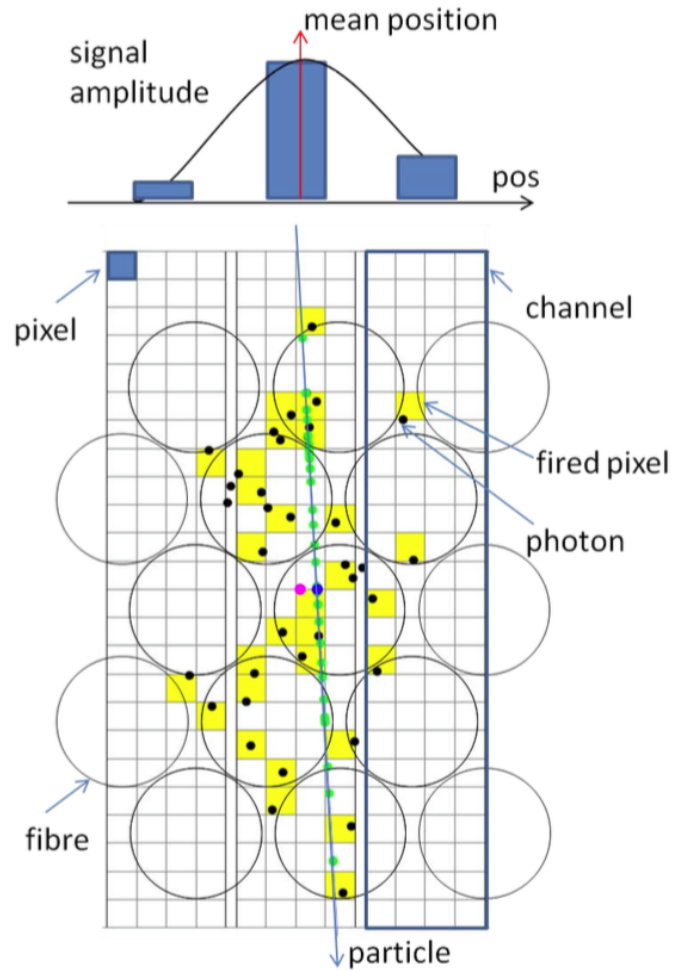


Figure 2.31: Illustration of the photon detection as shown through a perpendicular projection to the fibres direction. The photons produced along the trajectory of the particle are propagated to the fibre end and further to the detector. Each pixel of the detector can detect one photon and the signal proportional to the total number of pixels with signal (coloured pixels) is the signal amplitude per channel illustrated in the top part of the figure. The particle position can be calculated with a weighted mean value of the channel signal. Note that the fibres are not aligned to the detector channels and the photons can arrive at the detector outside the fibre area. Extracted from reference [72].

track system of the LHCb detector. The LHCb upgrade will replace the current track system of silicon and straw tubes with SciFi mattress similar to the BGV arrangement. There is therefore a great research effort concerning scintillating fibres. The number of fibre layers, the photon yield and the resistance to irradiation are open questions. Experience gained with the BGV Demonstrator will hence benefit the LHCb Collaboration

[72].

Trigger, readout and online monitoring

A L0 detector is needed to keep the trigger accept rate below 1.1 MHz. In the case of the BGV, a simple trigger on interaction activity is sufficient. It uses a scintillator array, with an acceptance matched to the BGV acceptance, to detect for each 25 ns bunch slot whether a beam-gas interaction took place or not. In order to enhance the purity of the useful events in the L0-accepted event sample, it is suggested to deploy also veto counters upstream of the tracking detector, in such a way that beam-gas interaction occurring too much upstream can be discarded at L0. The L0 detector readout should provide input signals at 40 MHz to the readout supervisor, i.e. the ODIN board [75]. The Figure 2.32 shows schematically the position of the L0 and VETO scintillators.

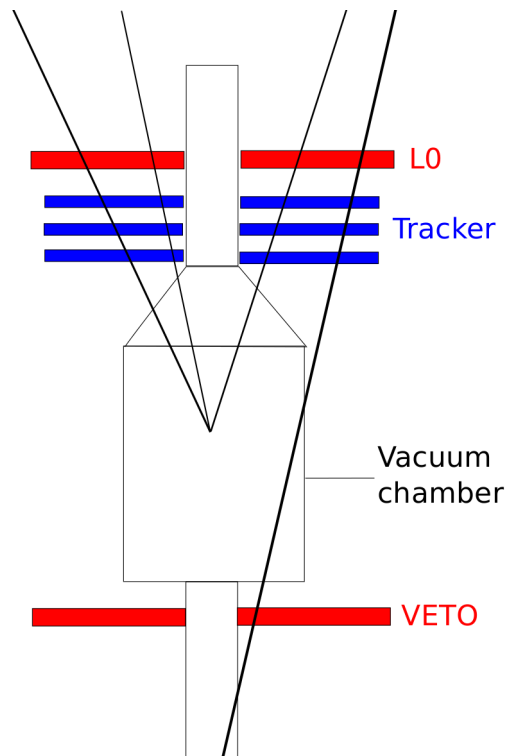


Figure 2.32: Illustration of the BGV L0 trigger. The VETO scintillator detects particles created upstream to the chamber. Events with sufficient multiplicity in the VETO sensor are discarded. Courtesy of M. Ferro-Luzzi.

As in LHCb, the ODIN board orchestrates the triggering and fast control (TFC) [76]. It receives and decodes the LHC BST signals, sends the clock signals to the FE electronics (Beetles and Tell1's), receives signals from the L0 trigger detector, takes the L0 trigger decision (based on the L0 detector signals and the LHC fill pattern) and distributes it to all the FEs. The definition of the technical link from the L0 detector to the ODIN boards can be found in Reference [77].

The HLT of the BGV are currently under development and should be able to run over BGV data and provide results in real time. The expected data output should be of 3 kinds: vertex data (high rate), cluster data (fraction of events), and non-zero suppress (NZS) data, which sends a small fraction of events.

The readout of the BGV will be based on LHCb VELO custom-made electronics. An overview is shown in Figure 2.33. Each SiPM detector is read out by a Beetle FE chip [78] which samples the 128 channels synchronously with the LHC clock at 40 MHz. The Beetles are mounted on a custom-made flex cable. After the L0 trigger accepts the event each Beetle chip sends the analog data of the corresponding clock cycle on four output ports (32 channels per port, time-multiplexed at 40 MHz). The Beetle output rate is limited to 1.1 MHz.

The analog and time-multiplexed output data of 4 Beetle chips are driven over a 60 m long data cable (individually shielded twisted pairs) by four driver cards (DRV) housed on a 'repeater' or 'front-end' board (RPT) situated in the vicinity of the detectors (less than 2 meters away). There is one RPT board per module.

There are 8 SciFi modules arranged in two stations. Each module is composed of two SciFi mattress, one straight and one stereo (2° inclination). Each mattress is readout by 8 SiPM, i.e. 8 Beetles. Thus, there is exactly 1 VELO RPT board and 1 TELL1 per module (each reading out 16 Beetles). The TELL1 board hosts 4 'analog receiver' cards (ARX), one per data cable, which digitize the analog signals. The ADC data are processed by FPGAs (pedestal subtraction, common-mode suppression, clusterization) and sent out as

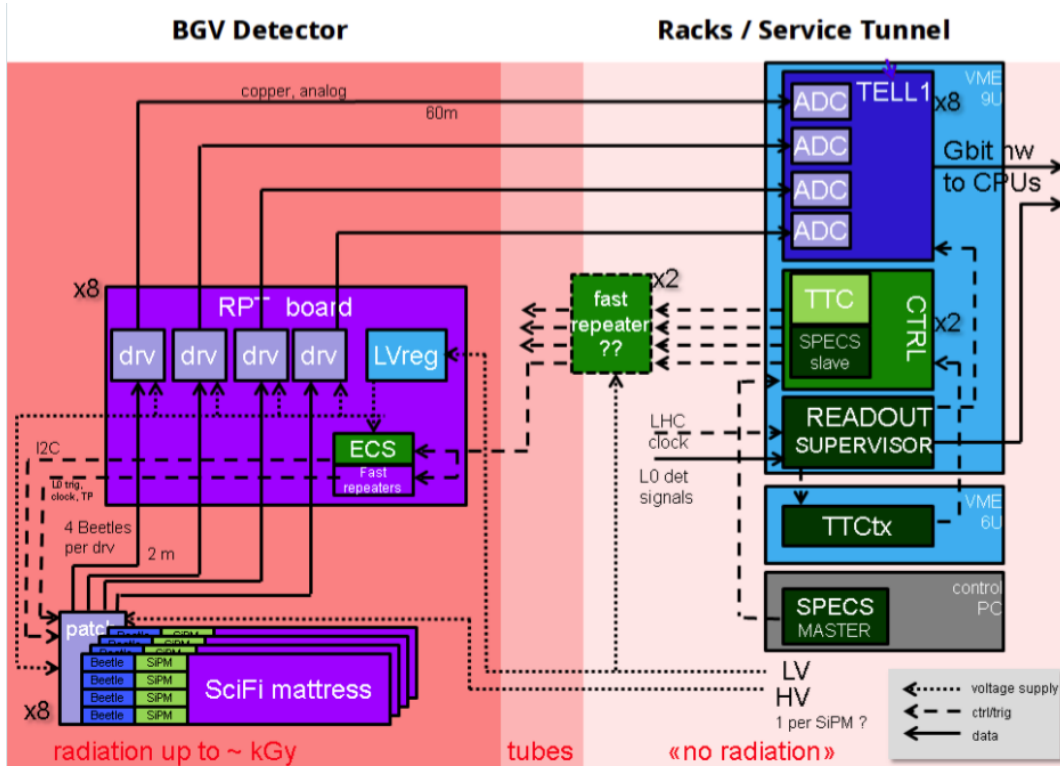


Figure 2.33: Overview of the BGV control and readout electronics. Source: BGV Collaboration.

Multi-Event Packets (MEP), via a Gigabit mezzanine card, to the network switch. The TELL1 receives the receiver's IP address for each MEP from the ODIN board.

The BGV readout system uses the same format as the VELO data. It facilitates the re-usage of the LHCb VELO algorithm to perform either track or vertex fitting. Three types of event data should be found out of the BGV DAQ system: *vertex data*, *cluster data* and *non-zero suppressed (NSZ) data*.

NSZ data are “raw” data needed to monitor pedestal level and noise, to check the overall behaviour of the front-end part. These data are attached to cluster data at a very reduced trigger rate. The ADC values obtained in TELL1 are found there.

The clusters data are needed for online monitoring and pattern recognition and for offline verification of results. It allows to re-do the tracks and vertices, perform alignment, parametrise the vertex resolution corrections, etc. These data are appended to some

events at a reduced rate for monitoring, but it should be possible to increase the rate for dedicated calibration runs. These data are appended to vertex data at a reduced trigger rate.

Finally, vertex data are meant to be used online to make the beam profile. They are produced in the online reconstruction. These are the “final” results, i.e. include already the vertex resolution corrections. The track informations are used to split the vertices where the vertex resolution are calculated.

2.3.1 BGV Vertex Resolution

The beam shape measurement relies on good vertex resolution which in turn, depends on the track quality. The track resolution have direct impact on the vertex resolution by introducing a extrapolation errors. On the other hand, multiple scattering dominates for low momentum particles and increase for with high polar angles**.

In this section the BGV impact parameter resolution is qualified and in the next chapter calculated using simulation. These studies were made by Massimiliano Ferro-Luzzi, my supervisor during my collaboration at the BGV.

Impact parameter resolution

Suppose a particle originates from the point V flying a straight path until arrive at the point S . In point S the particle are effected by multiple scattering or by measurement errors from two space point devices positioned on each side of S , such that the precision of the measurement is as said. At point M it is measured on the xy plane perpendicular to the track direction. We assume that the precision of measure the x and y coordinates of a point are independent and have the same precision. This is is shown in the Figure 2.34. Both the x and y measurements are distributed in the same manner, uncorrelated, and each symmetrically across zero with the function $\rho(x)(= \rho(y))$. This could be due to multiple-scattering in point S or to the measurement error from two space point measuring

**Angle with respect to the beam axis, often discriminated with θ

devices positioned on each side of S , such that the precision of the measurement is as said. The deflection angle α is assumed to be much smaller than 1. For very small deflections, one obtains an impact parameter (IP) $\mathbf{d} = (dx, dy)$ in the plane which is perpendicular to the true trajectory and which contains the point of reference to which we calculate the IP.

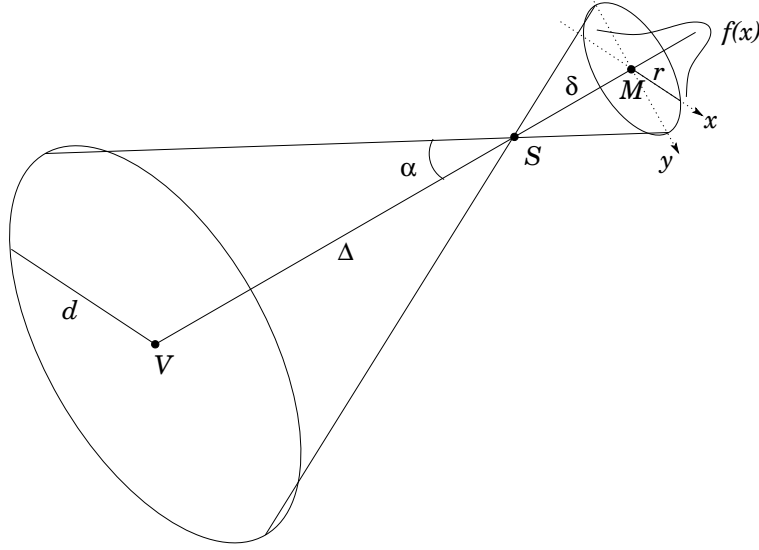


Figure 2.34: Impact parameter resolution. Particles created at point V are detected at point M belonging to the plane perpendicular to particle momentum. The error in x and y position of the point M are propagated by extrapolation given rise to the impact parameter resolution. In this scheme the IP is due measurement error. Multiple scattering effect is not considered at this stage. Courtesy of M. Ferro-Luzzi.

Converting to cylindrical coordinates by defining $r = \sqrt{x^2 + y^2}$ and the surface element by $dx dy = r dr d\phi$, with r distributed as

$$f(x, y) dx dy = \rho(x) \rho(y) dx dy = g(r, \phi) r dr d\phi. \quad (2.1)$$

Observe that r is the radius of the error of the measurement of the point M and $f(x, y) = \rho(x) \rho(y)$ are factored due to the fact that they are independent errors.

It is also assumed that there is no dependence in ϕ and $g(r, \phi)$ can be integrated over ϕ bringing a factor 2π . The length d of the impact parameter is distributed like r but is

amplified by a factor Δ/δ . The mean value of d is given by

$$\langle d \rangle = \frac{\Delta}{\delta} \langle r \rangle = 2\pi \frac{\Delta}{\delta} \int r^2 \cdot g(r) dr \quad (2.2)$$

Considering that both x and y measurements are Gaussian-distributed with RMS $\sigma_x = \sigma_y = \sigma$

$$\rho(x)dx = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}} dx \quad \text{and} \quad \rho(y)dy = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{y^2}{2\sigma^2}} dy$$

therefore,

$$g(r) = \frac{e^{-\frac{r^2}{2\sigma^2}}}{2\pi\sigma^2} \quad (2.3)$$

Using Equation 2.3 into Equation 2.2 and using the identity

$$\int \xi^2 e^{-\xi^2} d\xi = \frac{\sqrt{\pi}}{4} \operatorname{erf}(x) - \frac{e^{-x^2}}{2} x$$

where $\operatorname{erf}(\pm\infty) = \pm 1$ and $\operatorname{erf}(0) = 0$ one can show that

$$\langle d \rangle = \frac{\Delta}{\delta} \sqrt{\frac{\pi}{2}} \sigma. \quad (2.4)$$

This equation shows that the impact parameter resolution increase linearly with the extrapolation Δ and the ‘hit’ resolution σ . The factor δ depends of the distance between the two detector sensors. Therefore increasing the distance between the sensors improves the vertex resolution.

It is worth to remind that the most probably value r_{mpv} is obtained when $\frac{d(rg(r))}{dr} = 0$ which is when $r = \sigma$. Thus,

$$d_{mpv} = \frac{\Delta}{\delta} \sigma = \sqrt{\frac{2}{\pi}} \langle d \rangle. \quad (2.5)$$

Those equations describes how the error in the measurement, or the multiple scattering, affects the vertex resolution. Now lets discuss the impact parameter for the BGV configuration.

Extrapolation error

Lets begin by neglecting any multiple scattering when particles cross the sensor. It is assumed that each BGV sensor measure the ‘hit’ position in two coordinates (z_i, r_i) with finite resolution. Each vertical detector plane $i = 1, 2$ measures r_i with a spatial resolution (rms in the given dimension) of σ_i . Each BGV sensor is at longitudinal distance z_i from the true track origin. Δ_{ij} are the distances between the points i and j . The origin is at $i = 0$. See Figure 2.35.

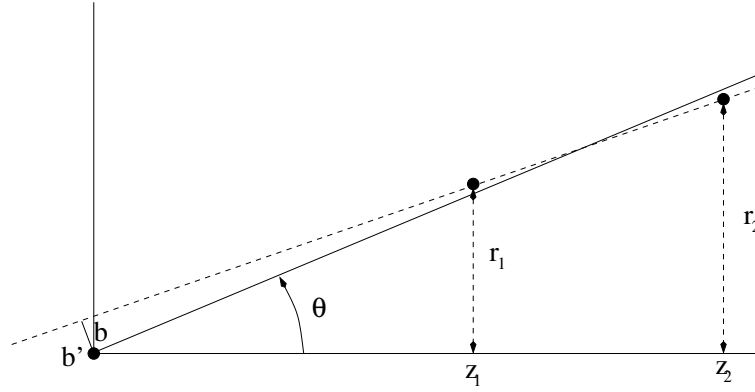


Figure 2.35: Measured points with finite spatial resolution give rise to an impact parameter that increases with increasing extrapolation distance. Courtesy of M. Ferro-Luzzi.

The impact parameter b' is obtained from $b' = b \cos(\theta)$ where

$$b = \frac{r_1 z_2 - r_2 z_1}{z_2 - z_1}.$$

The measurements r_1 and r_2 have the finite error δr_1 and δr_2 respectively. Thus, the error on b' scale as

$$(\delta b')^2 = \left(\frac{z_2}{z_2 - z_1} \delta r_1 \right)^2 + \left(\frac{z_1}{z_2 - z_1} \delta r_2 \right)^2.$$

Considering small angular errors compared to the track angle θ the single dimension signed IP will be given by;

$$\begin{aligned}
\sigma_{\text{extrap}}^2 &= \frac{z_2^2 \sigma_1^2 + z_1^2 \sigma_2^2}{(z_2 - z_1)^2} \cos^2(\theta) = \frac{z_2^2 \sigma_1^2 + z_1^2 \sigma_2^2}{\Delta_{12}^2} \\
&= \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{\Delta_{12}^2 \tan^2(\theta)} = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{(r_2 - r_1)^2} \cos^2(\theta).
\end{aligned} \tag{2.6}$$

In case of constant resolution ($\sigma_i = \sigma$) across the detectors and an almost horizontal track ones obtain the suitable relation for the BGV geometry:

$$\sigma_{\text{extrap}} = \frac{\sqrt{z_2^2 + z_1^2}}{z_2 - z_1} \sigma = \frac{\sqrt{r_2^2 + r_1^2}}{(z_2 - z_1) \cdot \tan(\theta)} \sigma \tag{2.7}$$

Multiple Scattering

In the case of multiple scattering (MS) at S and a detector with infinite resolution, ones has an angular spread in each multiple scattering plane. This spread is written as

$$\sigma_\alpha = \frac{13.6 \text{ MeV}}{\beta p} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \log \frac{x}{X_0} \right). \tag{2.8}$$

The scattering angle gives rise to the transverse displacement of the particle $d_x = \Delta \tan \alpha \approx \Delta \alpha$ ($\alpha \ll 1$). The rms of d_x , σ_{MS} is given by

$$\sigma_{\text{MS}} = \Delta \frac{13.6 \text{ MeV}}{\beta p} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \log \frac{x}{X_0} \right) \approx \Delta \frac{13.6 \text{ MeV}}{\beta p} \sqrt{\frac{x}{X_0}} \tag{2.9}$$

For the detector located behind the MS point, then one can write $r_1 = \Delta \sin(\theta)$ and $p_T = p \sin(\theta)$, which then gives

$$\sigma_{\text{MS}} = r_1 \frac{13.6 \text{ MeV}}{\beta p_T} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \log \frac{x}{X_0} \right) \approx r_1 \frac{13.6 \text{ MeV}}{p_T} \sqrt{\frac{x}{X_0}}. \tag{2.10}$$

On this relations Δ is the distance between the reference point V and the scattering point S before a perfect detector where the point M is, referenced in the Figure 2.34. Therefore, if there is a MS plane between the detector and the reference point, one should move the wall as close as possible to the reference point to minimize the IP error, even if the detector cannot move closer.

2.3.2 Transverse emittance and beam measurement

The BGV Demonstrator is able to measure beam shapes at beam energies E between 450 GeV and 7 TeV. The beam shape in one axis, horizontal or vertical, depends on both the transverse emittance ϵ in that axis and on the beta function β at that location

$$\sigma_{\text{beam}} = \sqrt{\frac{\epsilon \beta m_p}{E}}, \quad (2.11)$$

where m_p is the proton mass.

The installation site of the BGV was chosen such that the beam sizes on the two axis are similar, thus allowing factorise the beam shape in two components. Elliptical beam shape demand more sophisticate analyses. The β function on the BGV location are shown in the Figure 2.36. For a expected value of $\beta = 160$ m the and the typical emittance value $\epsilon = 2.5 \mu\text{m}$ ones expects the beam sizes of $\sigma_{\text{beam}} = 230(910) \mu\text{m}$ at energy of $E = 7(0.54)$ TeV.

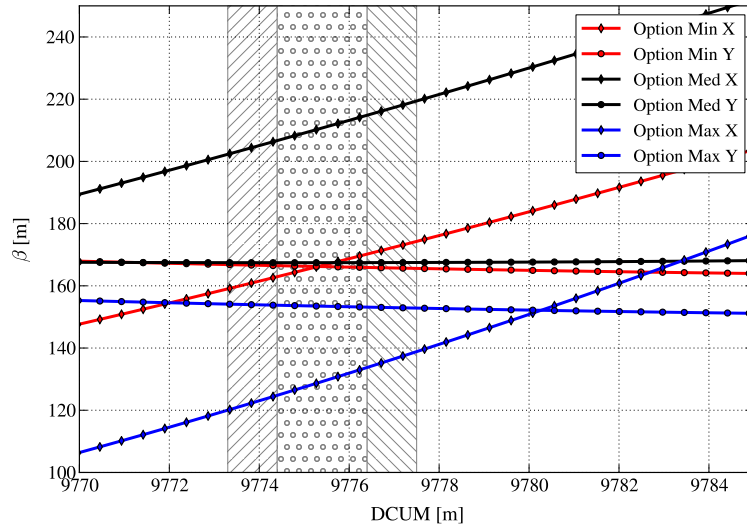


Figure 2.36: Zoom of the β function at the BGV location. The dashed region with circles and slashed is the location of the BGV. The β function is only for the beam 2 and several beam configuration are shown for two beam component. Source: BGV Collaboration.

The precision of the beam size measurement is limited by the vertex resolution σ_{vtx} . If the beam size components are independent on the two axis one can assume they are

Gaussian and the beam size σ_{beam} can be extracted from the raw measurement σ_{raw} written simply as

$$\sigma_{\text{raw}}^2 = \sigma_{\text{vtx}}^2 + \sigma_{\text{beam}}^2. \quad (2.12)$$

To avoid the systematic uncertainty, the vertex resolution should be substantially smaller than the beam size. For the BGV case the vertex resolution can be parametrised as function of the longitudinal distance z and the number of tracks, similarly to the LHCb VELO detector [67]. The knowledge of the vertex resolution allows to apply a deconvolution method to extract the beam size from Equation 2.12.

Neglecting statistical uncertainty on σ_{raw} the relative error of the beam size is calculated from equation 2.12

$$\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} = \left(\frac{\sigma_{\text{vtx}}}{\sigma_{\text{beam}}} \right)^2 \frac{\delta\sigma_{\text{vtx}}}{\sigma_{\text{vtx}}}. \quad (2.13)$$

where $\delta\sigma_{\text{beam}}$ and delta $\delta\sigma_{\text{vtx}}$ denotes the error on the beam size and the vertex resolution respectively. The relative precision of the beam size measurement scales with the ratio $(\sigma_{\text{vtx}}/\sigma_{\text{beam}})^2$ relative to the precision of the vertex resolution. Follow from this relation that if the vertex resolution is about half the beam size, the relative precision of the beam size measurement are approximately one quarter of the relative precision of the vertex resolution.

As was previously addressed two effects dominate the IP, the multiple scattering and extrapolation. One can derive that the IP resolution in one axis is approximately given by adding in quadrature the two effect:

$$\sigma_{\text{IP}}^2 = \sigma_{\text{MS}}^2 + \sigma_{\text{extrap}}^2 \quad (2.14)$$

where σ_{MS} and σ_{extrap} are obtained from equation 2.10 and 2.7 respectively.

Chapter 3

Contributions to the BGV Demonstrator

This chapter contains my own contributions to the BGV demonstrator. The contributions were made during my ‘PhD Sandwich’ program at CERN.

Tree main contributions were made during the development of the detector. Those contributions include both hardware and software developments. In the hardware side, studies of the BGV cooling system were made to understand the physical behaviour of the system, the cooling performance and their stability. Apart from the cooling, the metrology of the BGV modules are performed. The metrology was divided in two steps: perform the single modules metrology (SMM), where the real module assembly precision was extracted by the module geometry measurements. The second step is the metrology of the two-modules assembly (2MA). The 2MA are the set of two modules which are pre-assembled in the laboratory and then sent to the final installation in the tunnel. It is crucial to determine the relative position of the two modules before the assembling. SMM data are used to determine targets positions. Assembling of 2MA aims to install the modules as close as possible to the targets positions. Detailed description and results of the modules metrology is described in the Appendix A.

In the software part the first version of the BGV pattern recognition is developed. The software is able to find track candidate by least-square fitting whose decision is based on

track parameters and quality. The method and the software are described below.

3.1 BGV Pattern Recognition

Generally speaking, pattern recognition is the method of applied mathematics and makes use of statistics, cluster analysis, combinatorial optimisation, and other specialised branches. The goal of pattern recognition is the classification of objects. The range of fields from which objects might be chosen is virtually unlimited and may include from satellite pictures to particle trajectories [79].

In tracking detectors like the BGV tracker, the signals generated by charged particles have to be grouped into track candidates; this is usually called *track finding* or *track search*. From the large variety of methods, the method to be chosen needs to be as fast as possible since it will run online during data taking of the experiment.

The BGV characteristics introduce some difficulties with respect to the track finding and specially to the track quality. Since there are no magnetic field the track momentum is not considered and the usual 5×5 covariant matrix inversion can not be applied: the track parametrisation is often made of two parameters to determine the track offset; two slopes and one parameter to take into account the curvature which depends of the particle charge and the magnetic field. The track curvature facilitate the search because allows to perform an *upstream* tracking which start the search in the most downstream detector plane, and follows the track ‘backwards’ toward the production vertex. This has the advantage that already the first measurements, together with an approximate knowledge of the production vertex, allow at a very early stage a roughly estimation of the track momentum. This prediction decrease the size of search window which decrease the possible numbers of wrong combinatorial track candidates [80]. On the other hand, the absence of magnetic field leads to straight tracks which increases the search windows size and the combinatorial behaviour of track finder associating more wrong cluster to the track. This combinatorial cluster association increase the numbers of *ghost* and *clone*

tracks. Ghost tracks are composed of a set of clusters which cannot be associated to the passage of a unique particle. Usually, simulations are used to develop the software and calculate the ghost rates. Clone tracks are composed mostly from the same clusters but due to wrong cluster association, few clusters (which will be referred as ‘bad’ clusters) were created by another particle. They are called clones because during the combinatorial search for tracks many tracks share the same number of clusters. The addition of few *bad clusters* make the clone tracks to be almost identical.

It is important to notice that ghost and clone track rate are strongly dependent of its definition. In the BGV case a track candidate is composed of eight clusters (there are eight sensitive layers, see the next section). If a *true track* is defined as being made of a set of eight clusters created by the passage of unique charged particle, the efficiency of find ‘true tracks’ will probably be small. Therefore loosening this criteria improves the efficiency. In this version of the pattern recognition, a true track is considered if it is composed of at least 7 good clusters, leaving only one cluster to be wrongly associated. Ideally in the final track selection, no tracks should share any cluster. The clone removal criteria have direct impact on the vertex resolution, therefore dedicate decision is made to chose the best track out of those sharing a certain number of clusters. It shall be discussed later in this chapter.

3.1.1 The BGV – tracker

Within this section the BGV tracker and reconstruction strategy are presented. In the section 2.3 the BGV module were presented. Each single module has two sensitive layers: one layer has the SciFi mattress parallel to the lateral edge. It is called *normal layer* and their clusters are called *normal clusters*. Depending upon the orientation of the module the normal clusters are labelled as *X-* or *Y-clusters*. The opposite sensitive layer have the SciFi mattress tilted by 2° (34.9 mrad) with reference to the lateral edge. This layer is called *stereo layer* and their clusters called *stereo clusters* and are labeled as *Xp-* or

Yp-clusters depending on their orientations. Figure 3.1 shows a frontal view sketch of the first BGV station. Pattern recognition clusters are described as a line segment. Figure 3.2 shows the longitudinal position of the clusters.

Two 3D points defines a clusters. To facilitate the method, a ‘local’ coordinate frame are defined by an anticlockwise rotation of 45° of the ‘global’ BGV reference frame. The right-hand global reference system are similar to the LHCb: u-axis pointing to the center of the LHC ring and v-axis pointing upward. The choice of x- and y-axis as shown in Figure 3.1 is convenient for pattern recognition. In the local frame, normal clusters of the sensors 3 and 7 give only x-positions of the track while normal clusters of the sensors 2 and 6 give only the y-positions. For that reason the normal clusters of the bottom sensors 1 and 5 and the normal clusters of top the sensors 3 and 7 are called Y-clusters (they are parallel to y-axis). Similarly, the normal clusters of the bottom sensors 0 and 4 and the normal clusters of the top sensors 2 and 6 are called X-clusters (parallel to the x-axis). Note that stereo clusters are not parallel to any local reference frame axis but their introduction decreases the number of iteration during the pattern recognition.

Normal and stereo clusters are associated before start the combinatoric loop for track finding. Using simulation, the distance between the top 3D point of the normal cluster and the top 3D point of the stereo clusters are calculated. Figures 3.3 and 3.4 shows the distance between these points. One can see that the distance between the normal and stereo clusters are small for clusters created by the same particle. Therefore it is preferred to perform a loop over a combination of normal-stereo clusters than a loop over all clusters in the event. The cut is chosen to be 15 mm but it can be changed to reach the best performance.

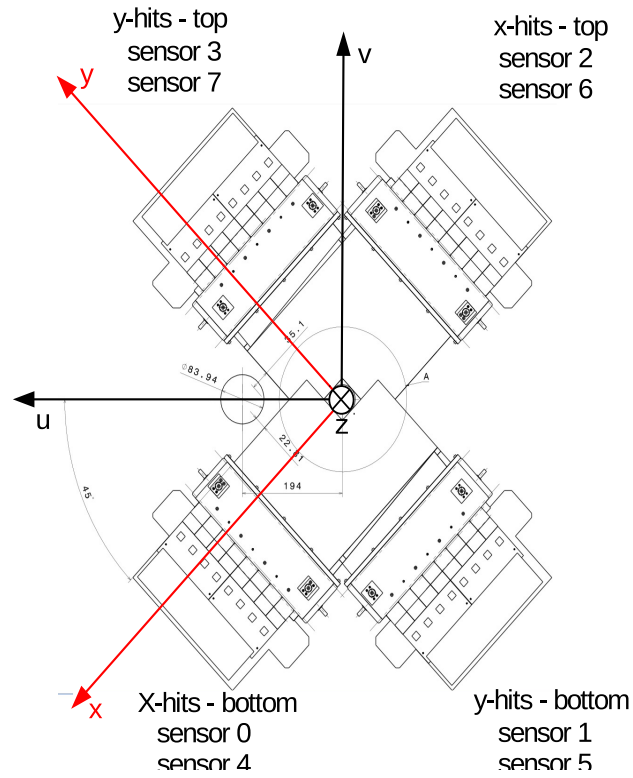


Figure 3.1: Frontal view of downstream BGV station. The right-hand coordinate system is described in the text. The u -axis point to the LHC ring center. v -axis point upward. Sensors 0 and 1 are the bottom downstream sensors and 4 and 5 are the bottom upstream. Sensors 2 and 3 are top downstream sensors and 6 and 7 top upstream sensors. The red x - and y -axis are the defined by the anticlockwise rotation of 45° of uv frame.

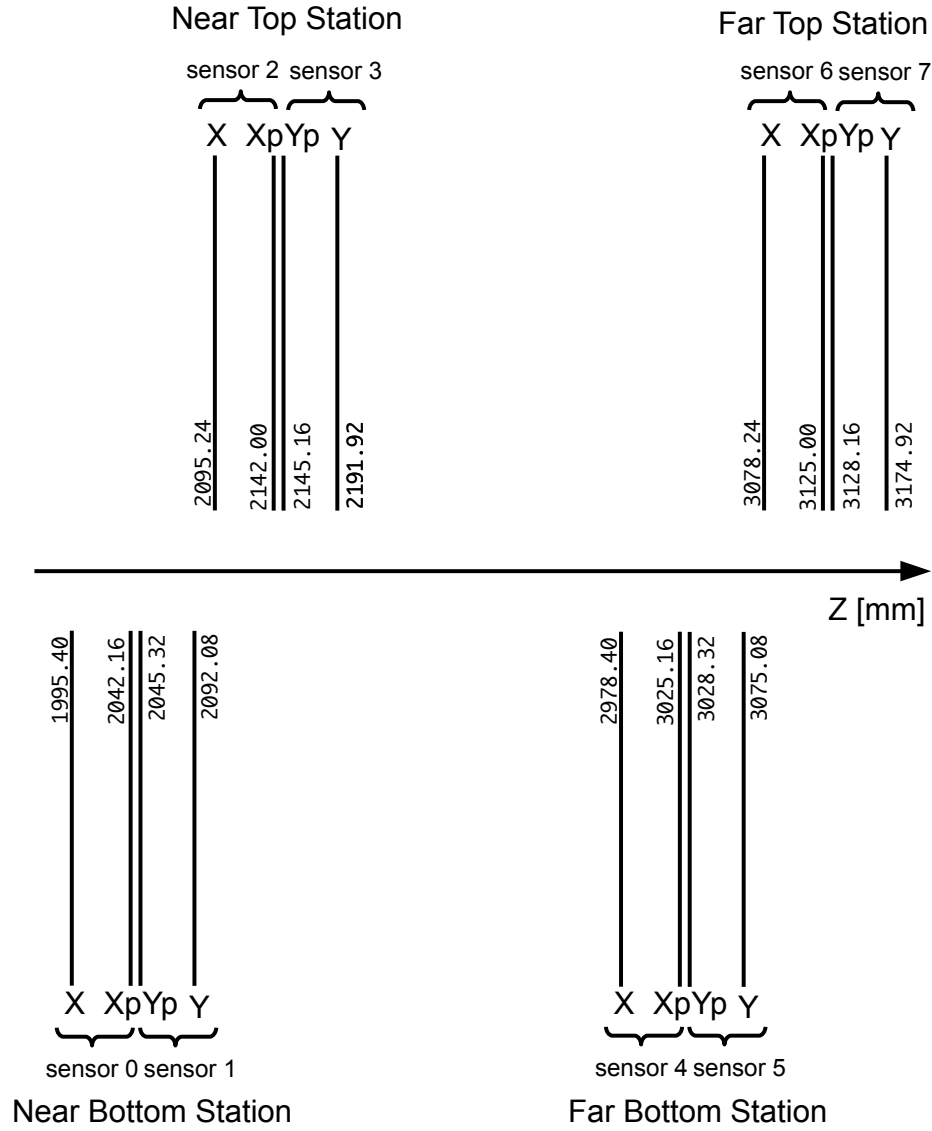


Figure 3.2: Longitudinal position of the clusters. The numbers shown on the lines are their z position in mm. The origin of the reference frame is at the beginning of the gas chamber.

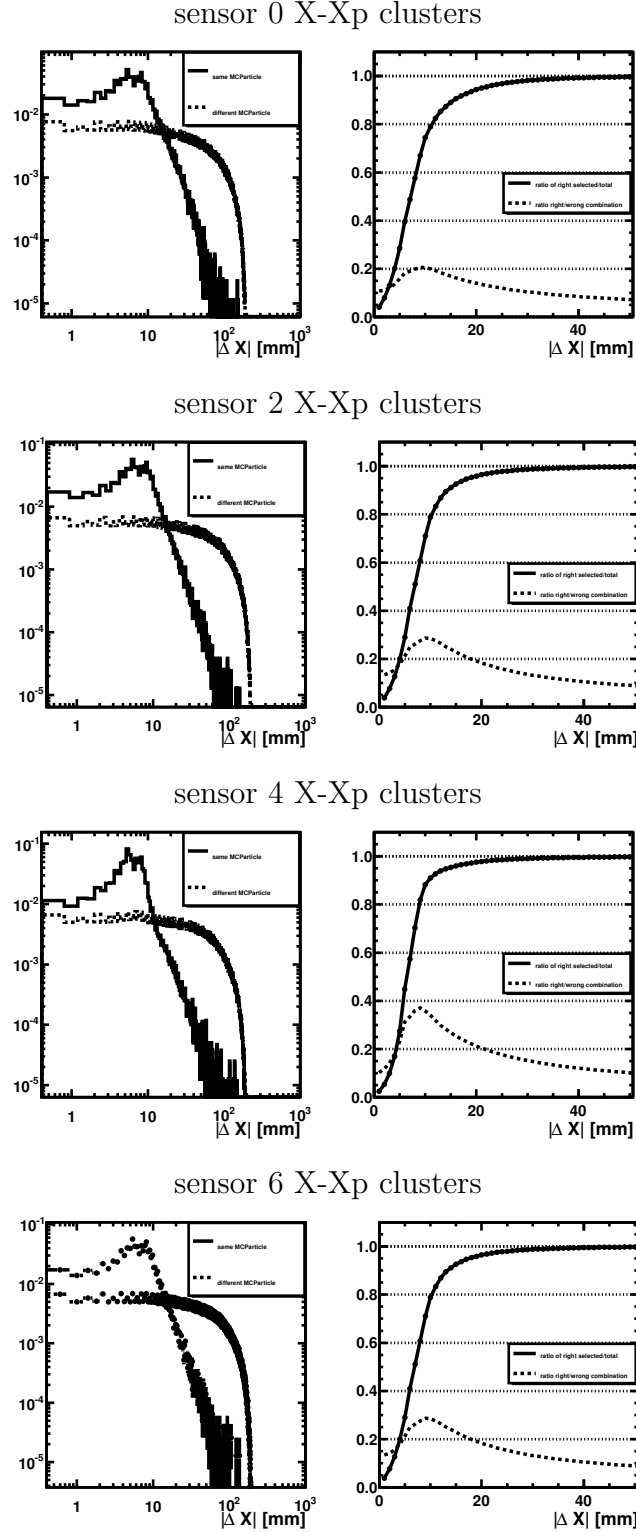


Figure 3.3: Left – Unsigned distance between the top 3D point of the normal cluster (X-cluster) and the top 3D point of the stereo cluster (Xp-cluster). Right – Solid line is the ratio between the number of X-Xp combinations created by the same particle and total number of X-Xp combinations also created by the same particle as function of the unsigned $|\Delta X|$ distance. Dashed line is the number of good combinations (same particle) over the number of wrong combinations (X-Xp combined not created by the same particle). For clarification, on sensor 0 chooses the cut in 20 mm select about 90 % of all X-Xp combinations of clusters created by the same particle but on the final selection it corresponds to less than 20 % of combinations made out of the same particle.

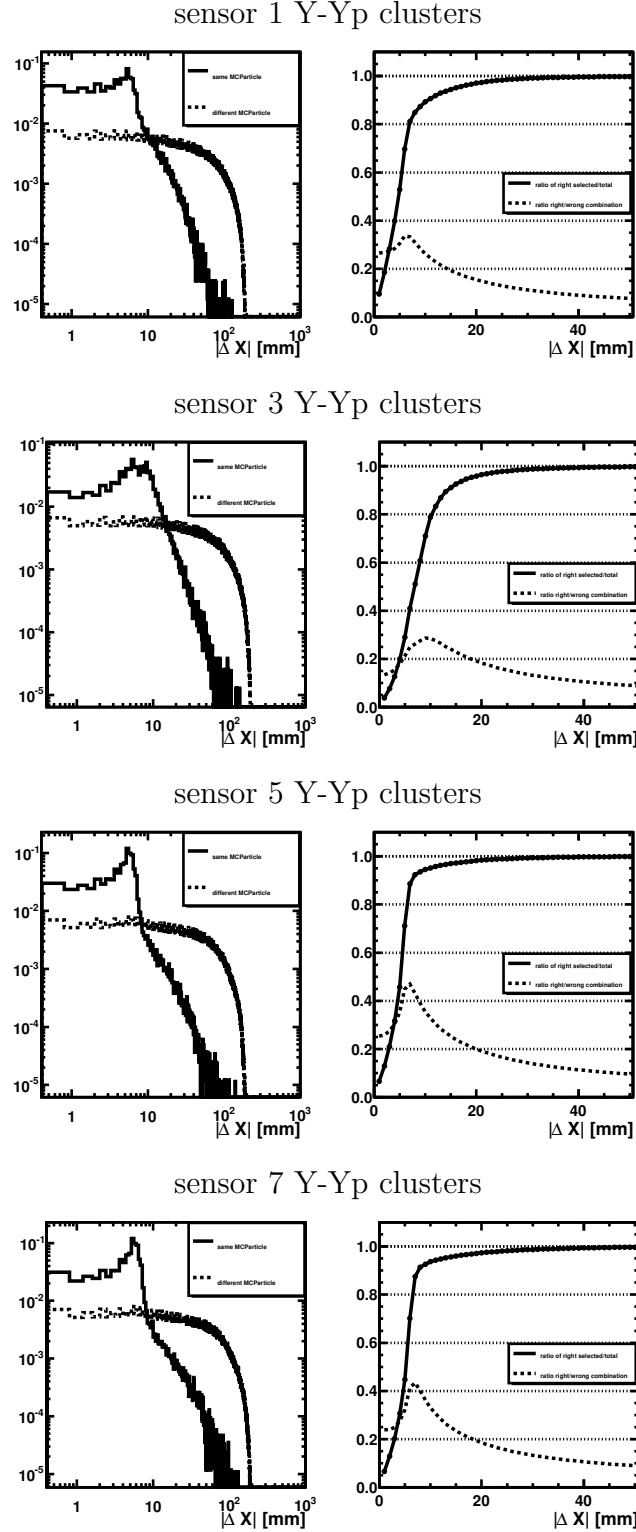


Figure 3.4: Left – Unsigned distance between the top 3D point of the normal cluster (Y-cluster) and the top 3D point of the stereo cluster (Yp-cluster). Right – Solid line is the ratio between the number of Y-Yp combinations created by the same particle and total number of Y-Yp combinations also created by the same particle as function of the unsigned $|\Delta X|$ distance. Dashed line is the number of good combinations (same particle) over the number of wrong combinations (Y-Yp combined not created by the same particle).

3.1.2 Track-seed and track candidate

After the list of combinations associating all possible X-Xp and Y-Yp clusters is done, the pattern recognition starts. To decrease the time consumptions by reducing number of iterations a track-seed is defined. A group of four clusters is selected and an analytical line is defined.

Given four line segments where each of them is defined by two 3D points, the top and the bottom points of the clusters, a unique line solution can be found which defines the ‘line solution’ crossing the set of four ‘line segments’. A straight 3D line is defined by four parameters,

$$\begin{aligned} u(z) &= t_u z + u_0 \\ v(z) &= t_v z + v_0 \end{aligned} \tag{3.1}$$

where t_u and t_v are the slopes of the line and the linear parameters v_0 and u_0 determine the line offset. Clusters is an line segment parallel to the uv plane positioned at z_i ($i = 1, 2, 3, 4$). The clusters’ top and bottom points defines the clusters slopes and offsets. See Figure 3.5. The clusters’ slope $a_i = (T_v - B_v)/(T_u - B_u)$ and the linear parameter $b_i = B_v - a_i B_u$ are known. The v position of a cluster is parametrised as

$$v(u) = a_i u + b_i \tag{3.2}$$

therefore using Equation 3.1 the set of linear equations are build

$$\begin{aligned} a_1 u + b_1 &= t_v z_1 + v_0 \\ a_2 u + b_2 &= t_v z_2 + v_0 \\ a_3 u + b_3 &= t_v z_3 + v_0 \\ a_4 u + b_4 &= t_v z_4 + v_0. \end{aligned} \tag{3.3}$$

There are four parameters to determine: t_u , t_v , u_0 and v_0 . One can show that the solution

of this linear system is given by

$$t_u = \frac{A_{234}C_{123} - A_{123}C_{234}}{B_{123}C_{234} - B_{234}C_{123}} \quad (3.4)$$

$$t_v = \frac{A_{123}}{C_{123}} + t_u \frac{B_{123}}{C_{123}} \quad (3.5)$$

$$u_0 = \frac{t_v(z_1 - z_2) - t_u(z_1 a_1 - z_2 a_2) - (b_1 - b_2)}{a_1 - a_2} \quad (3.6)$$

$$v_0 = b_1 + a_1(t_u z_1 + u_0) - t_v z_1, \quad (3.7)$$

where the coefficients A_{123} , A_{234} , B_{123} , B_{234} , C_{123} and C_{234} are given by

$$A_{123} = (b_1 - b_2)(a_2 - a_3) - (b_2 - b_3)(a_1 - a_2) \quad (3.8)$$

$$A_{234} = (b_2 - b_3)(a_3 - a_4) - (b_3 - b_4)(a_2 - a_3) \quad (3.9)$$

$$B_{123} = (z_1 a_1 - z_2 a_2)(a_2 - a_3) - (z_2 a_2 - z_3 a_3)(a_1 - a_2) \quad (3.10)$$

$$B_{234} = (z_2 a_2 - z_3 a_3)(a_3 - a_4) - (z_3 a_3 - z_4 a_4)(a_2 - a_3) \quad (3.11)$$

$$C_{123} = (z_1 - z_2)(a_2 - a_3) - (z_2 - z_3)(a_1 - a_2) \quad (3.12)$$

$$C_{234} = (z_2 - z_3)(a_3 - a_4) - (z_3 - z_4)(a_2 - a_3). \quad (3.13)$$

The BGV track-seed is defined by the 3D line solution of Equation 3.1 with parameters given by Equations 3.4, 3.5, 3.6 and 3.7. The first two bottom clusters X and Xp (sensor 0) and the last two bottom clusters Y and Yp (sensor 7) are taken to define the bottom track-seeds. Similarly, top track-seeds are composed of the first two top clusters (sensor 2) and the last two top clusters (sensor 7). See Figure 3.2.

Two extra conditions are imposed to check whether track-seeds come from the interaction region or not. The *point of closest approach* (POCA) between the track-seed and the beam axis is calculated. Indeed there are two POCAs, one on the track-seed ($\text{POCA}_{\text{trk-seed}}$) and one on the beam axis (POCA_{TBA}). The *theoretical beam axis* (TBA) was not implemented during the development of the pattern recognition, then it is assumed that the TBA is the z -axis of the BGV coordinate system. However, during real operation the TBA may have an offset from the z -axis. The *distance of closest approach*

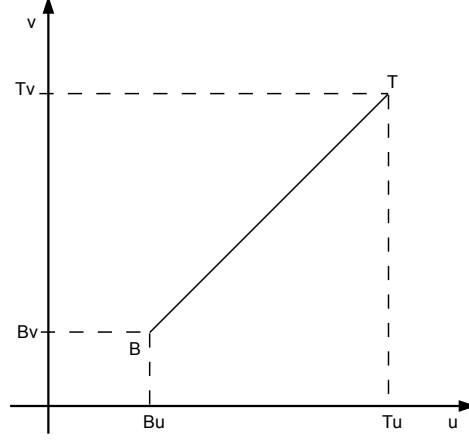


Figure 3.5: Scheme of the cluster orientation on the uv frame. Clusters are parallel to the uv plane and the slope and offset are calculated using the points top T and bottom B.

(DOCA) is defined as the distance between the two POCA. The conditions to select track-seed during the search time are:

- $-1000 < \text{POCA}_{\text{TBA},z} < 2000$ mm;
- $\text{DOCA}_{\text{TBA},\text{trk-seed}} < 40$ mm.

$\text{POCA}_{\text{TBA},z}$ is the z -position of the 3D POCA. These cut values are very preliminary and need to be fine tuned to reach the best balance between efficiency and processing time.

Reconstructible track-seeds are defined as composed by the set of four clusters linked to a reconstructible particle. Figure 3.6 shows the $\text{POCA}_{\text{TBA},z}$ for reconstructible and non reconstructible track-seed. The region of interaction is clearly visible. Due to the large error on the z -coordinate of POCA there is still a tail bellow zero. In BGV simulation there is no gas at $z < 0$, therefore those seeds does not come from collisions with residual gas downstream the gas chamber, but during operation this region should be considered.

The DOCA distributions are shown in Figure 3.7. Observe that the ‘middle’ clusters of the sensors 1 and 4 (bottom track-seed) and sensors 3 and 6 (top track-seed) were not included on any track candidate at this stage. See Figure 3.2 to visualise clusters position.

Once the track-seed is defined, the software starts to add middle clusters to compose track candidates. The criteria to add them are based on DOCA between track-seeds and middle clusters. Figure 3.8 shows the distance between the track-seed and the Y-cluster of the sensor 0 for the set of five clusters linked to a reconstructed particle. Figure 3.9 shows the DOCA between the track-seed and the Yp-cluster of sensor 0. Figure 3.10 and 3.11 show these distances for the X-clusters and Xp-clusters of the sensor 6 respectively. As can be seen that the selection efficiency increases with DOCA and for DOCA = 15 mm, almost 100 % of reconstructible particle are selected. However, loosing this cut increases dramatically the number of ghost track candidates. The left bottom graph of these plots shows the ratio between the number of reconstructible track candidates and the number of ghost track candidates that passes the cut*. The purity of the track selection without any track fit is very small. Most of the ghost candidates are removed after track fit.

3.1.3 Track fit

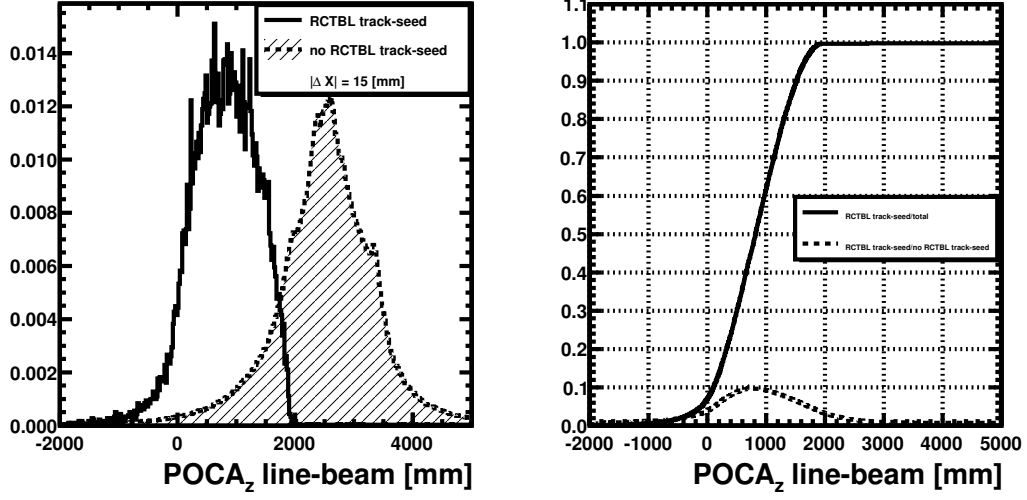
After a list of track candidates is created, a least-square fit is performed to select the good candidates and remove the large number of ghost tracks created by the combinatoric search.

The local reference system facilitates the track fit. The clusters position are rotated by $\pi/4$ according to

$$\begin{aligned} x &= u \cos \theta - v \sin \theta \\ y &= u \sin \theta + v \cos \theta. \end{aligned} \tag{3.14}$$

*Specially in this case *ghost* track candidates are considered if at least one cluster is not linked to a reconstructible particle. These studies are made to understand the efficiency vs purity of the selection and this ‘change of definition’ does not effect the final track finding efficiency of the method.

Top track-seed



Bottom track-seed

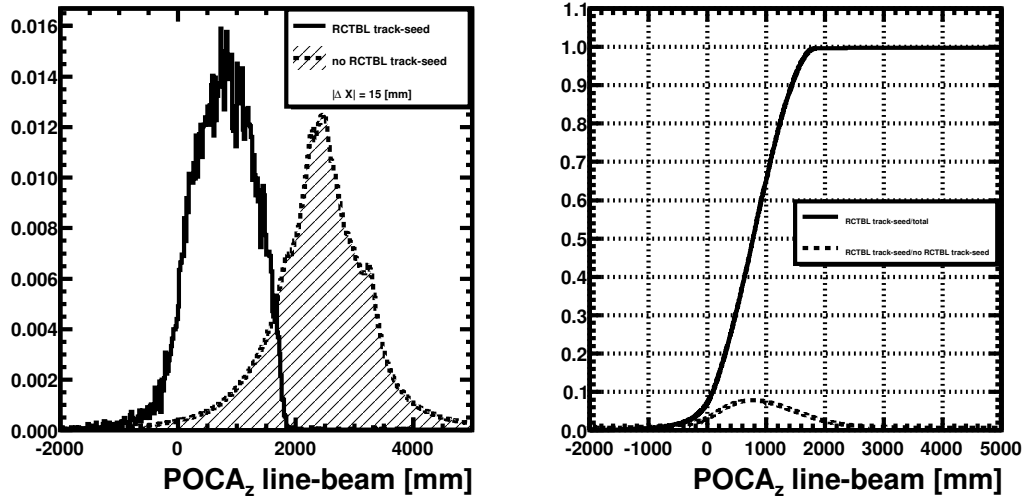
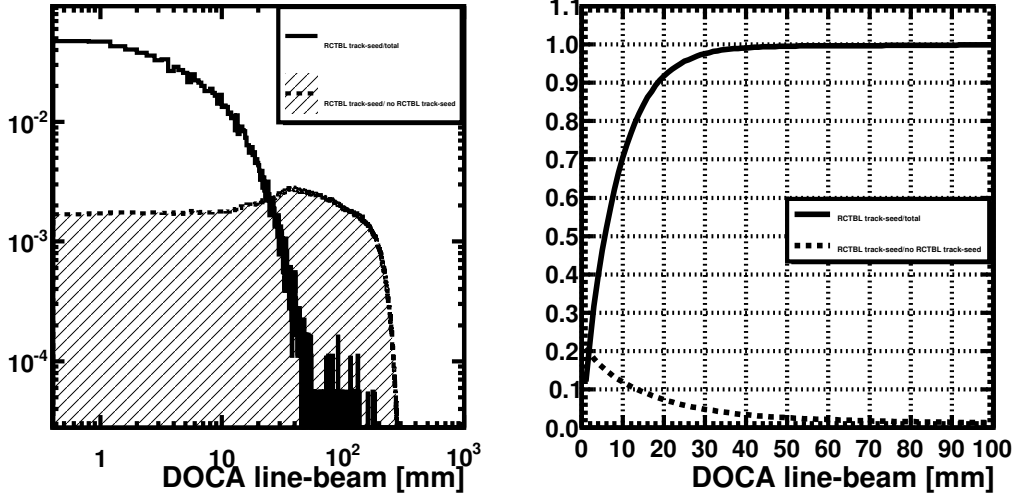


Figure 3.6: Left – Normalised distribution of $POCA_{BTaz}$. Solid line for reconstructible track-seeds and dotted line for no reconstructible track-seeds. Right – Solid line is the ratio of the number of reconstructible track-seeds over the total number reconstructible track-seeds created. Dashed line is the ratio of the number of reconstructible track-seeds over the total number of track-seeds created as function of the cut on $POCA_{BTaz}$. As one can see no reconstructible track-seeds have $POCA_{BTaz}$ higher than 2000 mm, therefore a cut in this value would decrease the number of ‘bad’ track-seed during the seed selection without degrade efficiency.

After this rotation, Y-clusters give only x -positions and X-clusters give only y -positions.

Top track-seed



Bottom track-seed

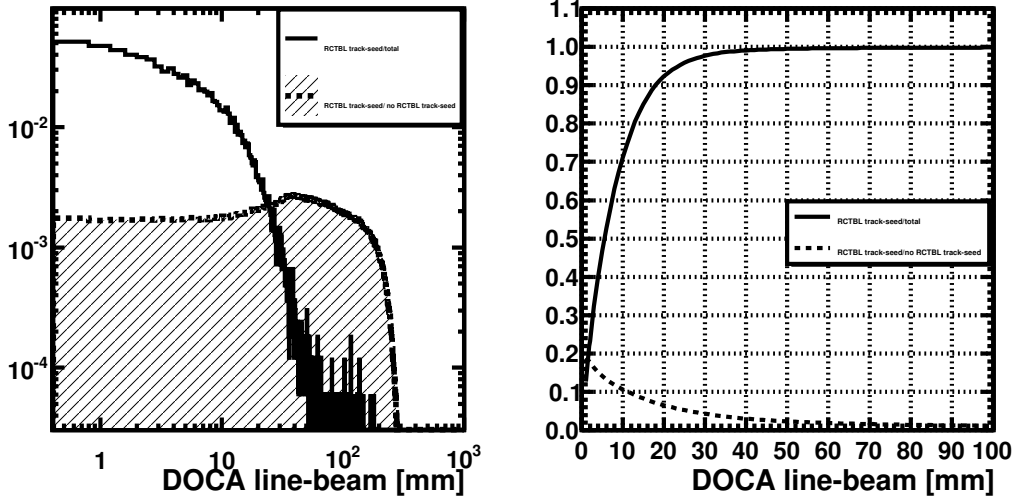


Figure 3.7: Left – Distributions of DOCA between track-seeds and BTA. BTA vector is (0,0,1). Solid (dashed) histogram are track-seeds linked to a reconstructible (no) particle. Right – The solid line shows the ratio of the number of selected track-seeds linked to a reconstructible particle over the total number of track-seeds also linked to a reconstructible particle. The dashed line shows the number of good track-seeds over the total number of selected seeds. As can be seen a cut in DOCA = 20 mm select $\simeq 90\%$ of ‘good track-seeds’ which will constrain the maximum efficiency of the code.

The Xp-clusters resolution σ projected into the local frame is

$$\begin{aligned}\sigma_x &= \frac{\sigma}{\sin \theta_s} \simeq 1.7 \text{ mm} \\ \sigma_y &= \frac{\sigma}{\cos \theta_s} \simeq \sigma,\end{aligned}\tag{3.15}$$

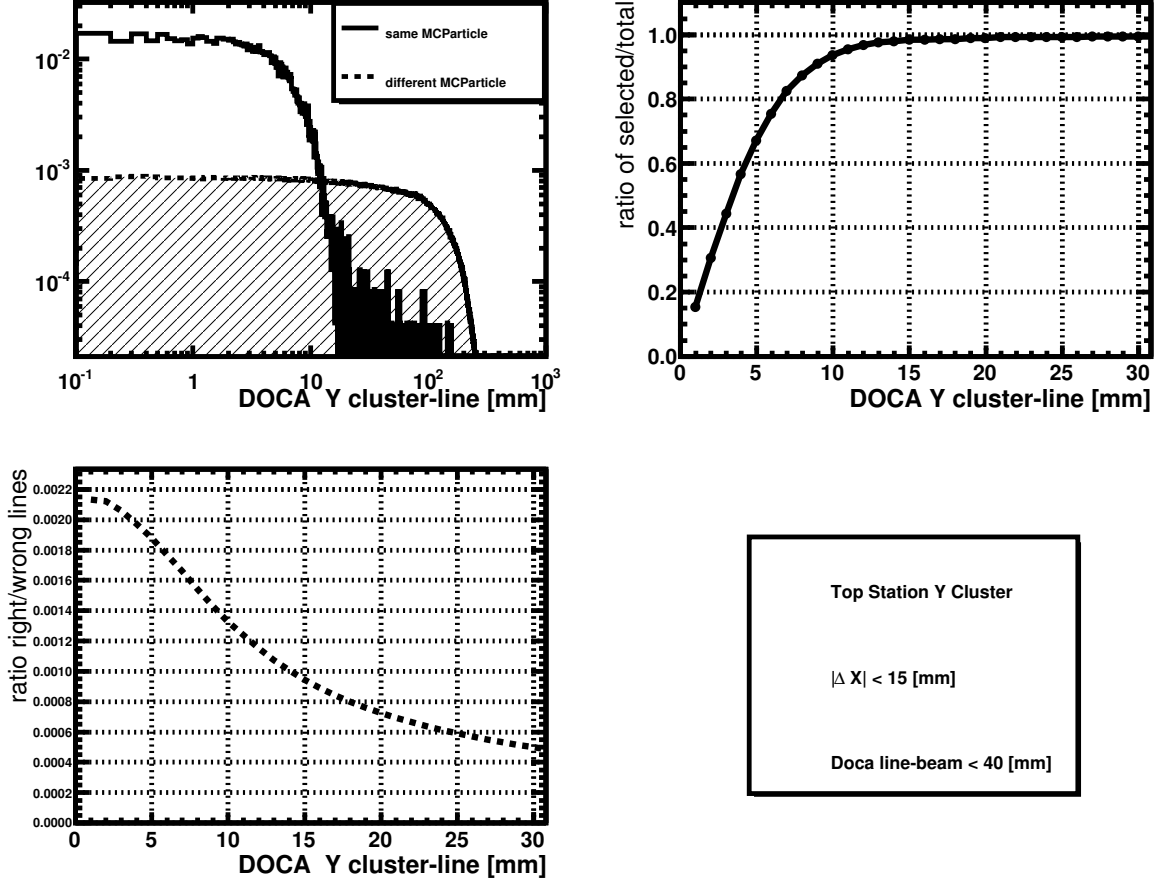


Figure 3.8: Top Left – DOCA between the track-seed and Y-clusters of sensor 0. Solid (dashed) line are for the set of 5 clusters linked to an (non) reconstructible particle. Top Right – Ratio of the number of selected set of 5 clusters linked to the reconstructible particle over the total number of reconstructible particles (selection efficiency as function of the cut). Bottom Left – Ratio of the number of reconstructible particle over the total number of reconstructible as function of the selection cut.

and the Yp-clusters resolution projected in the local frame is

$$\begin{aligned}\sigma_x &= \frac{\sigma}{\cos \theta_s} \simeq \sigma \\ \sigma_y &= \frac{\sigma}{\sin \theta_s} \simeq 1.7 \text{ mm},\end{aligned}\tag{3.16}$$

where $\theta_s = 2^\circ$ is the stereo angle. σ_x projection of Xp-cluster resolution is much larger than σ . Similarly σ_y projection of Yp-cluster resolution is much larger than σ . These projections have negligible contribution for the track χ^2 , hence it is not considered. The strategy is to make an independent fit the x - and y -projections of the track. For that

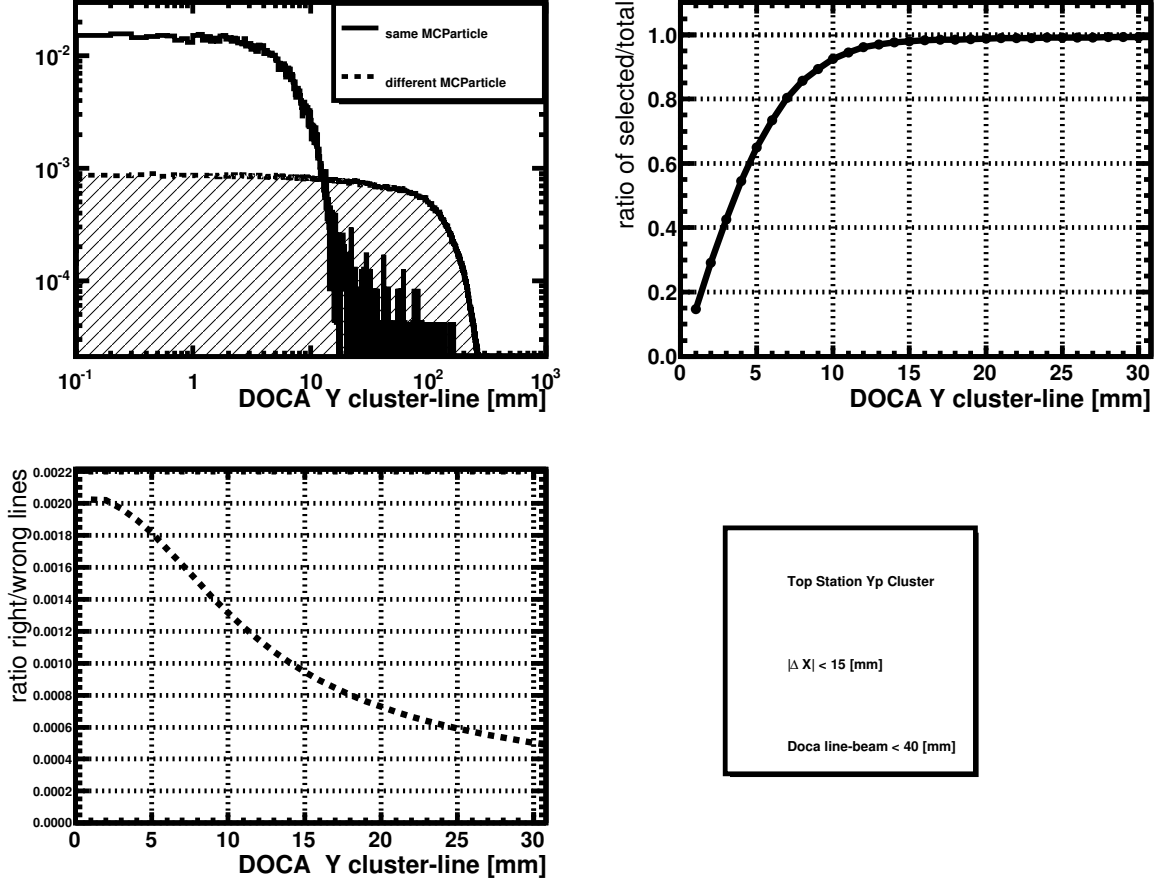


Figure 3.9: Top Left – DOCA between the track-seed and Yp-clusters of sensor 6. Solid (dashed) line are for the set of 5 clusters linked to an (non) reconstructible particle. Top Right – Ratio of the number of selected set of 5 clusters linked to the reconstructible particle over the total number of reconstructible particles (selection efficiency as function of the cut). Bottom Left – Ratio of the number of reconstructible particle over the total number of reconstructible as function of the selection cut.

reason y - and x -positions of normal clusters are used directly. But it is not the case for stereo clusters, their projection into the local frame contributes with two coordinates to the track, and it can not be included directly. Furthermore, the longitudinal distance between normal and stereo layers of a sensor is 46.76 mm. It is too large and avoid use crossing points between normal and stereo clusters. A illustration of a Y- and Yp-clusters in the local frame are shown in Figure 3.12. The stereo hits position is then used as follow: the POCA between the track-seed and the stereo clusters is calculated on the

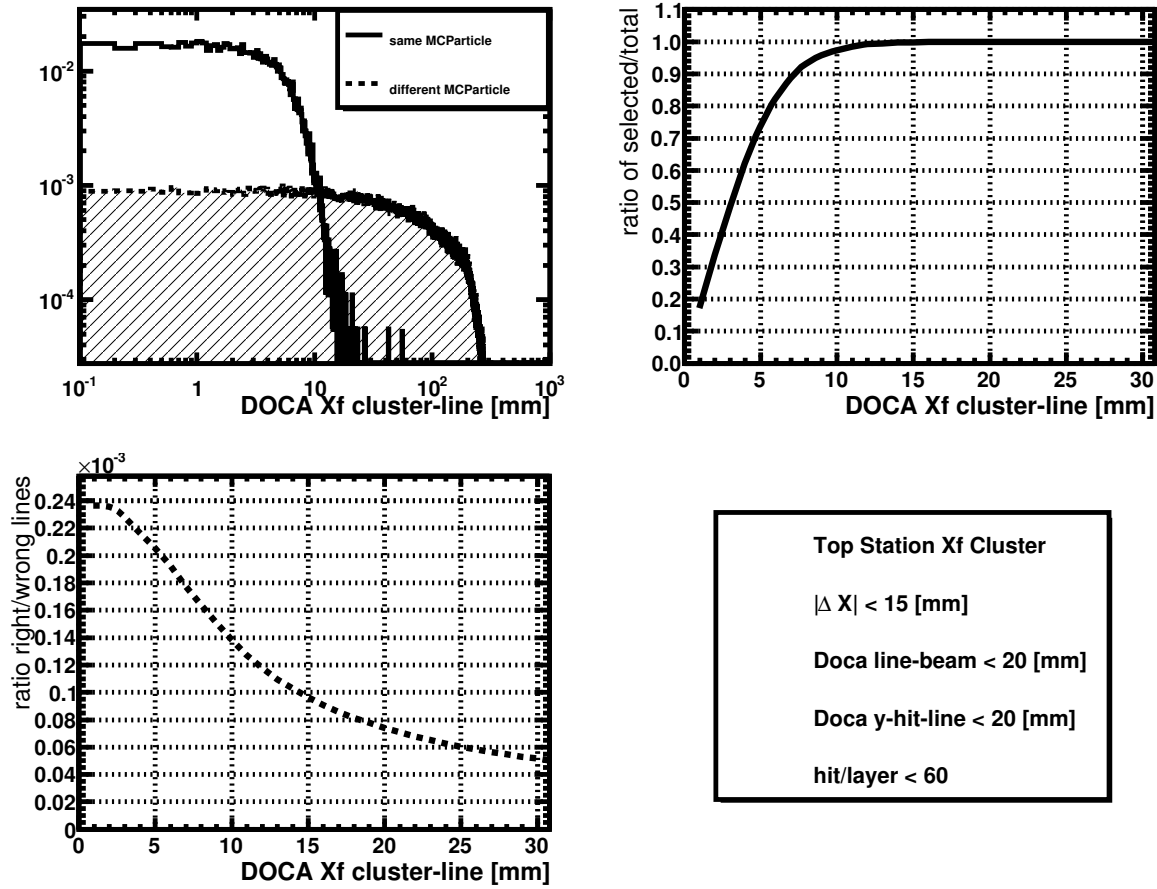


Figure 3.10: Top Left – DOCA between the track-seed and X-clusters of sensor 6. Solid (dashed) line are for the set of 5 clusters linked to an (non) reconstructible particle. Top Right – Ratio of the number of selected set of 5 clusters linked to the reconstructible particle over the total number of reconstructible particles (selection efficiency as function of the cut). Bottom Left – Ratio of the number of reconstructible particle over the total number of reconstructible as function of the selection cut.

track-seed and their (x, y) position used as input to the track fit. Therefore the zx and zy independent least-square fits have four inputs: two normal clusters and two stereo clusters. The stereo clusters with large resolution into the axis are ignored (see Equations 3.15 and 3.16).

The least-square fit calculate two slopes and two offset parameters of the track equation

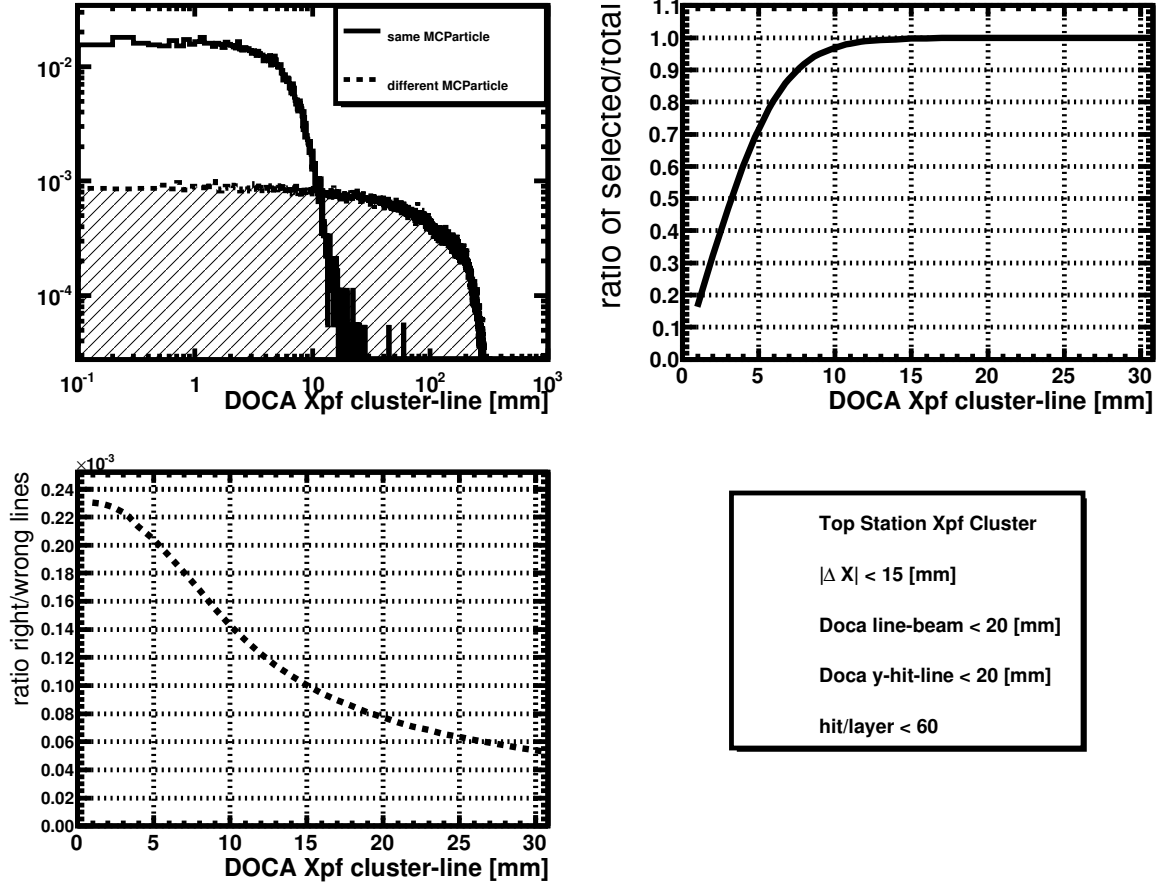


Figure 3.11: Top Left – DOCA between the track-seed and Xp-clusters of sensor 0. Solid (dashed) line are for the set of 5 clusters linked to an (non) reconstructible particle. Top Right – Ratio of the number of selected set of 5 clusters linked to the reconstructible particle over the total number of reconstructible particles (selection efficiency as function of the cut). Bottom Left – Ratio of the number of reconstructible particle over the total number of reconstructible as function of the selection cut.

given by:

$$\begin{aligned} x(z) &= t_x z + x_0 \\ y(z) &= t_y z + y_0. \end{aligned} \quad (3.17)$$

with the track parameters given by

$$\begin{pmatrix} t_x \\ x_0 \end{pmatrix} = \sum_i \begin{pmatrix} \left(\frac{z_i}{\sigma_i}\right)^2 & \frac{z_i}{\sigma_i^2} \\ \frac{z_i}{\sigma_i^2} & \frac{1}{\sigma_i^2} \end{pmatrix}^{-1} \begin{pmatrix} \frac{z_i x_i}{\sigma_i^2} \\ \frac{x_i}{\sigma_i} \end{pmatrix} \quad \text{and} \quad (3.18)$$

$$\begin{pmatrix} t_y \\ y_0 \end{pmatrix} = \sum_i \begin{pmatrix} \left(\frac{z_i}{\sigma_i}\right)^2 & \frac{z_i}{\sigma_i^2} \\ \frac{z_i}{\sigma_i^2} & \frac{1}{\sigma_i^2} \end{pmatrix}^{-1} \begin{pmatrix} \frac{z_i y_i}{\sigma_i^2} \\ \frac{y_i}{\sigma_i} \end{pmatrix}, \quad (3.19)$$

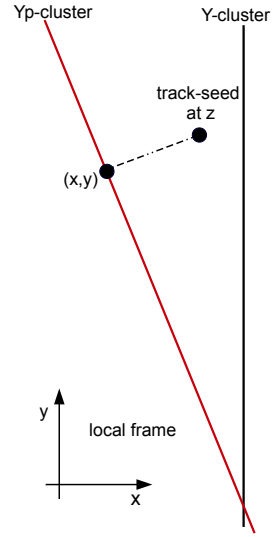


Figure 3.12: Y-cluster and Yp-cluster at the local frame. Yp-clusters positions (x,y) are the POCA between the Yp-cluster and the track-seed at z_i .

where $\sigma_i = \sigma = 60 \mu\text{m}$ is the cluster resolution, z_i is the longitudinal position of the cluster i , and x_i and y_i are the positions of the clusters. The error of the parameters are given by the main diagonal elements of the inverted covariant matrix

$$\begin{aligned}\sigma_{t_x} &= \sqrt{(M^{-1})_{00}}, \\ \sigma_{x_0} &= \sqrt{(M^{-1})_{11}}.\end{aligned}\tag{3.20}$$

After fitting the track, the track-seed is substituted by the fit solution and the fit is iterated up to 10 times or until the variations of the track parameters are smaller than a given value:

- $\Delta t_x < \sigma_{t_x}/B$;
- $\Delta t_y < \sigma_{t_t}/B$;
- $\Delta x_0 < \sigma_{x_0}/B$;

iteration	$t_x \pm 4.06458 \times 10^{-07}$	$x_0 \pm 0.00109954$	$t_y \pm 4.06458 \times 10^{-07}$	$y_0 \pm 0.00107959$
0	-0.0161212	9.01624	0.0308999	85.1196
1	-0.0148014	6.2308	0.030897	85.0756
2	-0.0148006	6.2302	0.0308729	85.1265
3	-0.0148002	6.22936	0.0308729	85.1266
4	-0.0148002	6.22936	0.0308729	85.1266
5	-0.0148002	6.22936	0.0308729	85.1266
6	-0.0148002	6.22936	0.0308729	85.1266
7	-0.0148002	6.22936	0.0308729	85.1266
8	-0.0148002	6.22936	0.0308729	85.1266
9	-0.0148002	6.22936	0.0308729	85.1266

Table 3.1: Example of a track fitting convergence. Left column is the number of track fit iterations as described in the text. The second and third columns are the values obtained by Equation 3.18. The fourth and fifth columns are obtained from Equation 3.19. The track parameters converge after three iterations.

- $\Delta y_0 < \sigma_{y_0}/B$;

where B is a user parameter to control the number of iterations until the track fit converge, usually $B = 10$. Table 3.1 shows the first ten iterations of a track fit. The fit converges for most of the tracks with only 3 iterations and few of them with 4 iterations.

The track fit quality is described in terms of χ^2 per degrees of freedom. The number of degrees of freedom of a linear fit is given by the number of data points (eight) minus the number of track parameters (four). Consequently there are four degrees of freedom. The track χ^2 is defined as

$$\chi^2 = \sum_{i=0}^7 \left(\frac{d_i}{\sigma} \right)^2 \quad (3.21)$$

where d_i is the DOCA between the cluster i and the track. σ is the cluster resolution. Only tracks with $\chi^2/\text{DoF} < 5$ are considered during the selection of tracks candidates.

After the fit converges, the track parameters are computed on BGV frame by invert

rotation

$$\begin{aligned}
 t_u &= t_x \cos \theta - t_y \sin \theta \\
 u_0 &= x_0 \cos \theta - y_0 \sin \theta \\
 t_v &= t_x \sin \theta + t_y \cos \theta \\
 v_0 &= x_0 \sin \theta + y_0 \cos \theta.
 \end{aligned}
 \tag{3.22}$$

Once the track candidates are fitted the identification of clone tracks starts. In the current version of the BGV PR clones tracks are defined as those who share at least one cluster. However one may allow two or more tracks to share one (or even more) clusters after the clone removal procedure. Remember that BGV is aimed to perform beam imaging where vertex resolution is the main source of systematics, see Equation 2.13. Therefore, to improve the precision of beam size measurement the *best track* from those who share clusters is the one which have the smaller DOCA to the BTA. Their clones are then removed.

After removing the clones the desired tracks are copied to the Transiente Event Store to be processed by the vertexing fitting algorithm, which can be implemented directly from the LHCb vertexing algorithms.

In summary, the BGV pattern recognition relies on track-seed finding which are mostly sensitive to the modules alignment. Misalignments of 2MAs have directly impact on track-seed finding which decreases the tracking efficiency. The PR software named `BGVPattern` are written in C++ [81] inside the LHCb Gaudi framework [54]. Figure 3.13 shows the workflow of the code.

Track fit results

- **Distance between tracks to TBA**

Figure 3.14 shows the histogram of u -coordinates of the POCA_{trk} to the TBA and Figure 3.15 shows the v -coordinate of the same POCAs. Note that the simulated the beam size measure 0.155 mm in u -axis and 0.153 mm v -axis and are Gaussian in the both

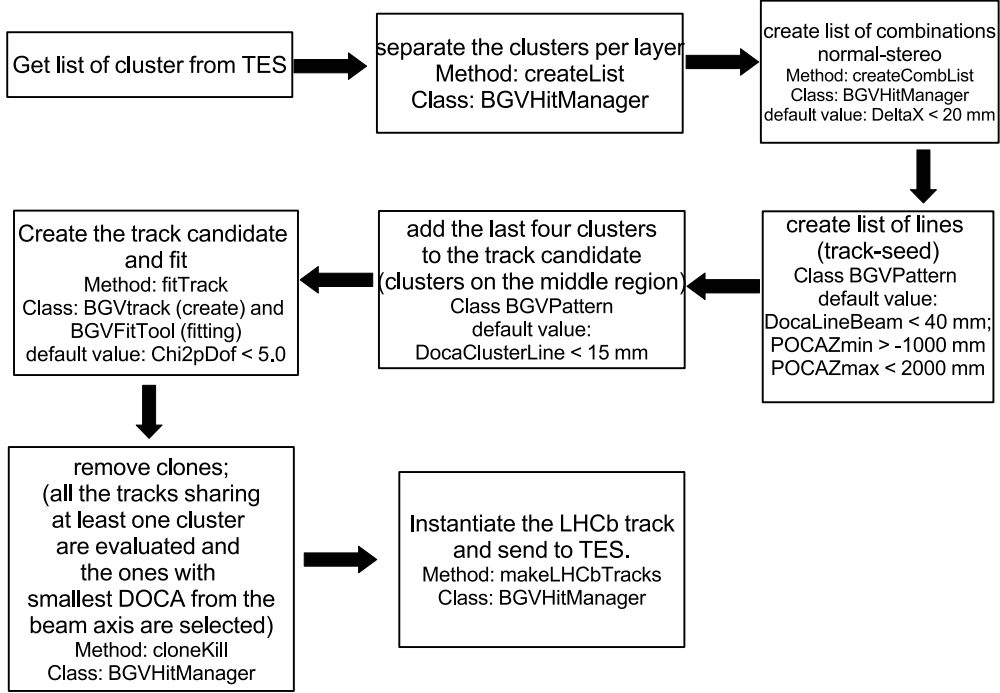


Figure 3.13: Workflow chart of the BGVPattern.

axis. The measured RMS of distributions of $POCA_{\text{trk}}$ is about 1.9 mm. This illustrates that it is necessary to perform vertex fitting where outliers tracks can be excluded from the vertex's tracks. The POCA's z -coordinates are shown in Figure 3.16.

- **Track resolution**

Track resolution and residuals are determined by DOCA between reconstructed track, given by Equation 3.17, and clusters. Signed projections of DOCA into the u - and v -axis are Gaussian distributed whose RMS and width give information about the track resolution. The 3D DOCA distributions of top (bottom) are shown in the Figure 3.17 and its projection into the u - and v -axis is shown in the Figure 3.18 and Figure 3.19 respectively. The overall track resolution is $(23.17 \pm 0.04) \mu\text{m}$ in Δu and $(22.39 \pm 0.04) \mu\text{m}$ in Δv . Even though the resolution is smaller than cluster resolution the real track resolution is expected to be worst. The simulation does not include clusters fired by

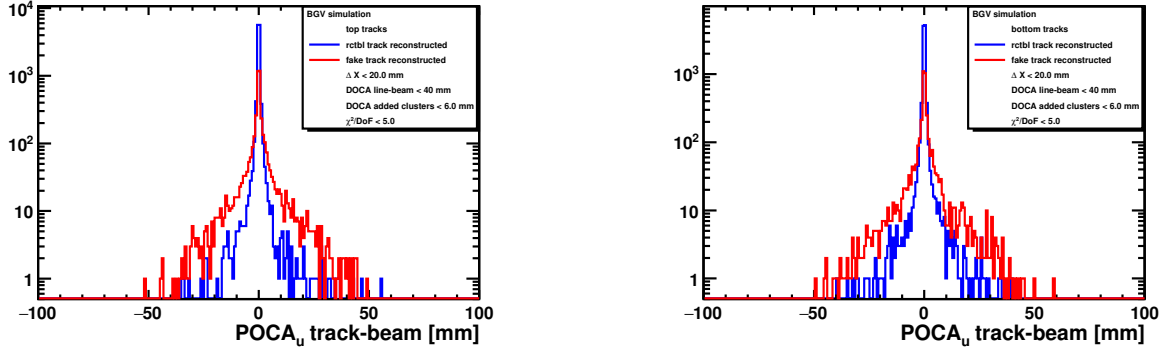


Figure 3.14: The Left (Right) plot shows the distribution of the u -coordinate of the *point of closest approach* of top (bottom) tracks to the beam axis. The POCA is on the track. Blue for reconstructible tracks and red for ghost tracks reconstructed. The non-gaussian distribution of the reconstructible tracks have a RMS of 1.87 mm (1.93 mm) while the non-gaussian distribution of ghost tracks have RMS of 6.98 mm (7.30 mm).

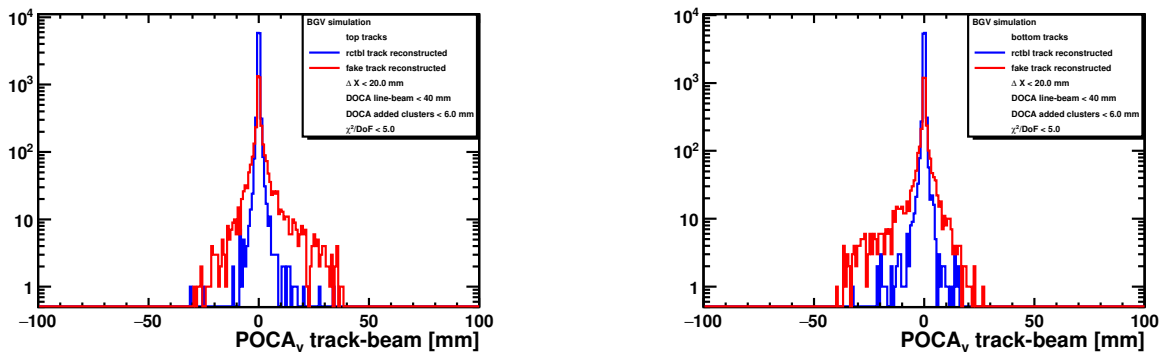


Figure 3.15: The Left (Right) plot shows the histogram of the v -coordinate of the *point of closest approach* of top (bottom) tracks to the beam axis. The POCA is on the track. Blue for reconstructible tracks and red for ghost tracks reconstructed. The non-gaussian distribution of the reconstructible tracks have a RMS of 0.97 mm (1.04 mm) while the non-gaussian distribution of ghost tracks have RMS of 5.11 mm (5.30 mm).

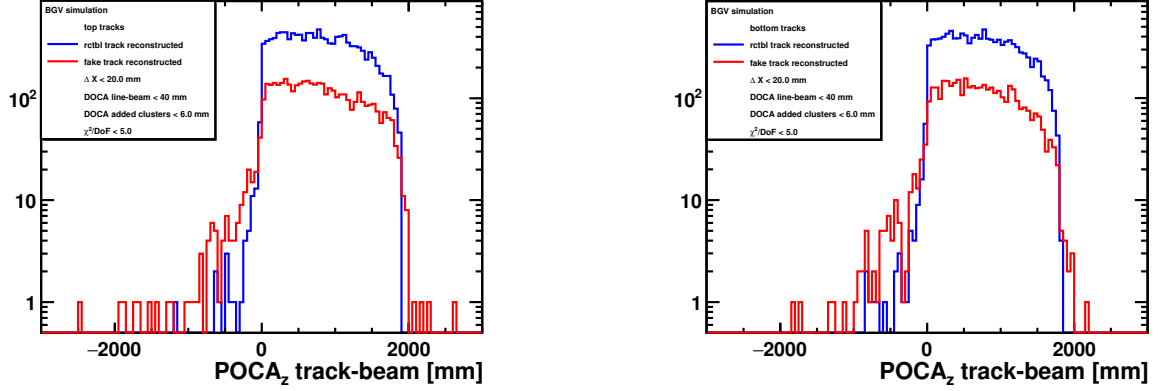


Figure 3.16: The Left (Right) plot shows the histogram of the z -coordinate of the *point of closest approach* of top (bottom) tracks to the beam axis. The POCA is on the track. Blue for reconstructible tracks and red for ghost tracks reconstructed. Note that no reconstructible tracks have POCA after 2 m.

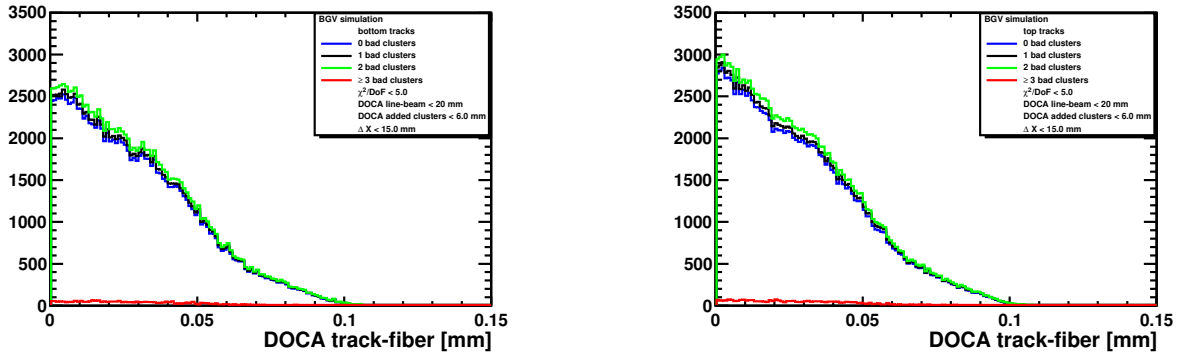


Figure 3.17: Left (Right) plot shows the histogram of the tracks' residue of reconstructed top (bottom) tracks. Blue — histogram of tracks with zero '*bad cluster*'. Black — histogram of tracks with 1 '*bad cluster*'. Green and red histograms for tracks with 2 and 3 or more '*bad clusters*' respectively.

thermal excitation and misalignment of the modules which degrade the tracking efficiency and track quality, although multiple scattering are taken into account in simulation.

• Track χ^2/DoF

The distributions of χ^2/DoF , as defined in Equation 3.21, of reconstructed tracks are shown in the Figure 3.20. The histograms are centred near unity, indicating the simulated cluster resolution of 40 μm is an appropriated choice [†]. χ^2/DoF distributions

[†]40 μm only in simulation. The expected cluster resolution for fibres of 250 μm are 60 μm .

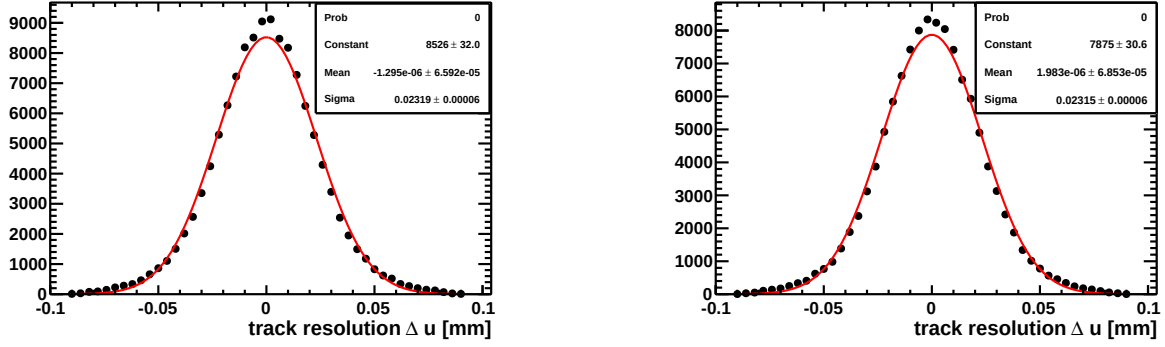


Figure 3.18: Left (Right) – Track resolution as calculated by the u -projection of the top (bottom) tracks' residue. The red curve is a gaussian fit of the distribution. The slightly non-gaussian in the center are thought to be due to imperfections of the cluster digitalisation.

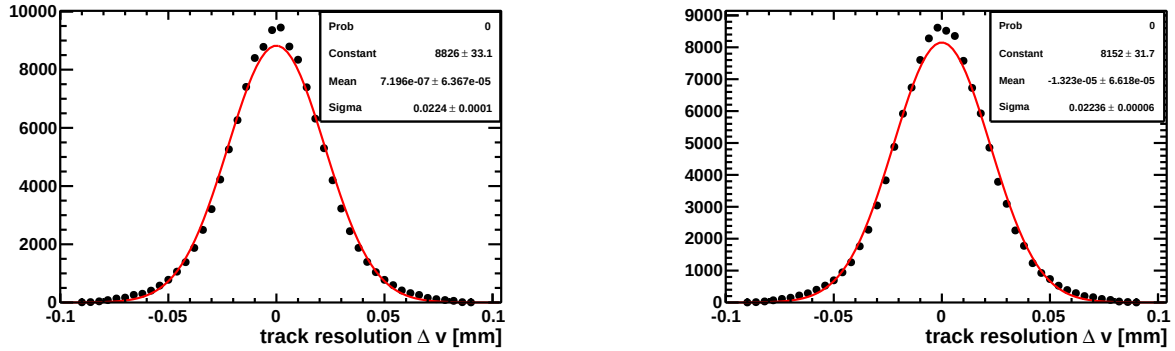


Figure 3.19: Left (Right) – Track resolution as calculated by the v -projection of the top (bottom) tracks' residue. The red curve is a gaussian fit of the distribution. The slightly non-gaussian in the center are thought to be due to imperfection on the cluster digitalisation.

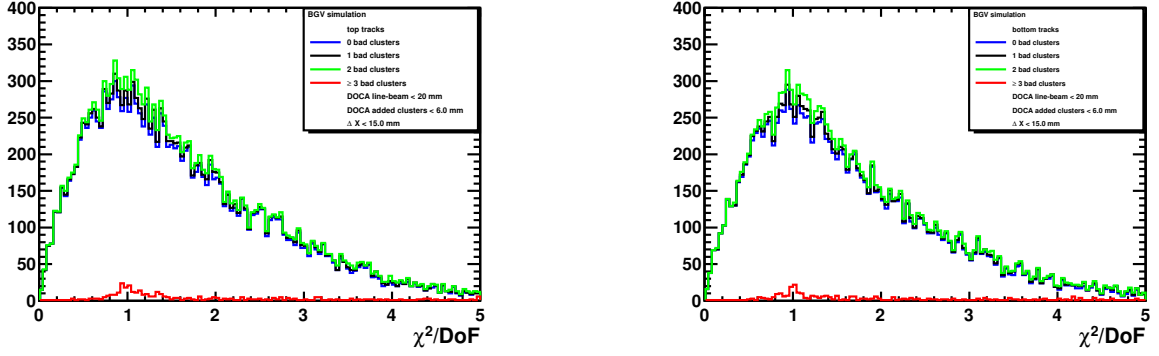


Figure 3.20: Left (Right) – histogram of χ^2/DoF of reconstructed top (bottom) tracks. Blue and black are histogram of reconstructed tracks with zero and one ‘*bad cluster*’ respectively. These tracks are considered as reconstructible tracks. Green and red are tracks reconstructed which contains 2 and 3 or more ‘*bad clusters*’ respectively. They are ghost tracks.

are expected to have dependence on track momentum. Low momentum tracks have large scattering angle while high momentum tracks are less effected by multiple scattering. Figure 3.21 shows the dependence of χ^2/DoF vs track momentum. The track momentum are available only in simulation and are equal to the true particle momentum. Therefore only reconstructible tracks are considered since ghost tracks are not linked to an true particle. Note that χ^2/DoF have a slight decrease with transverse momentum (p_T) bellow 400 MeV. On the other hand χ^2/DoF and p_T of reconstructible tracks have no dependence on z -coordinate of the primary vertex (PV). Figure 3.22 shows the average values of χ^2/DoF and p_T of the reconstructible tracks as function of z -coordinate of PV.

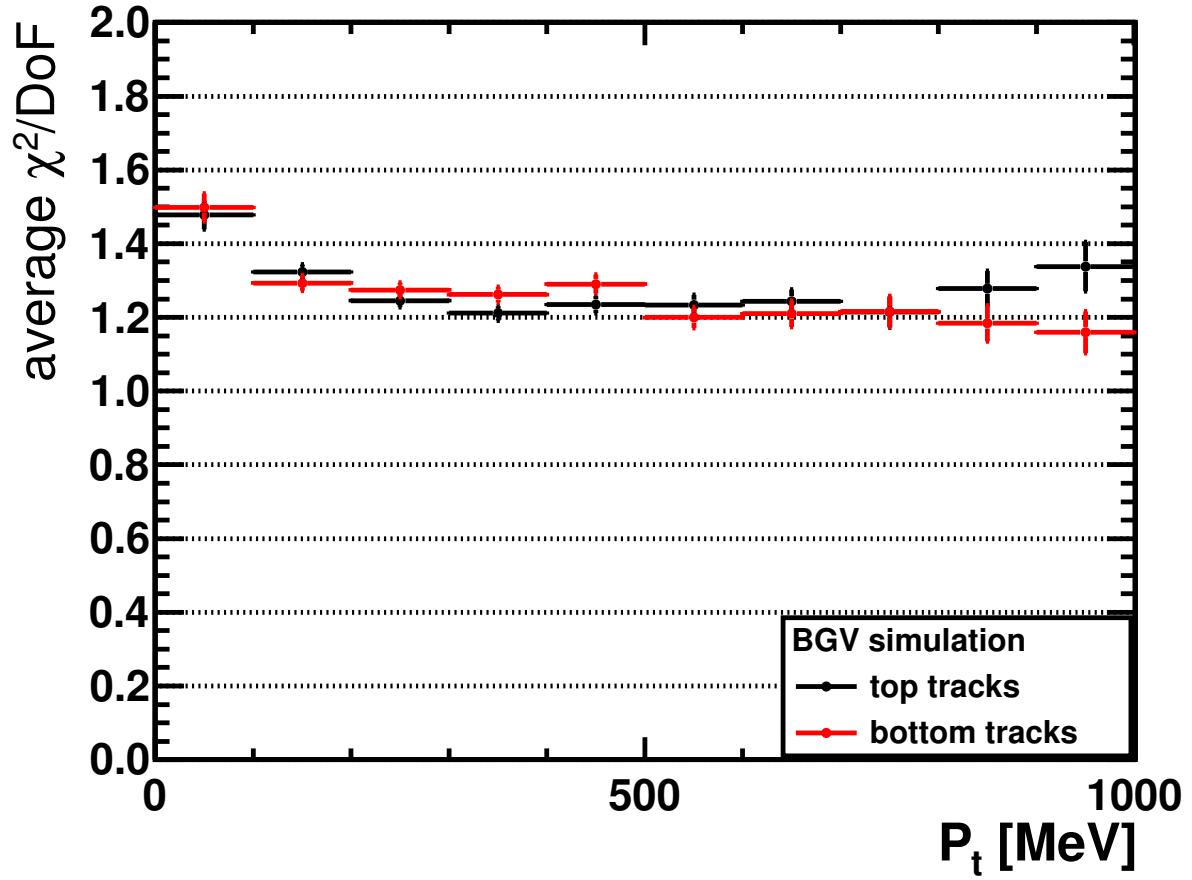


Figure 3.21: The plot shows the average χ^2/DoF of reconstructed tracks linked to a reconstructible as function of the transverse momentum of the particle.

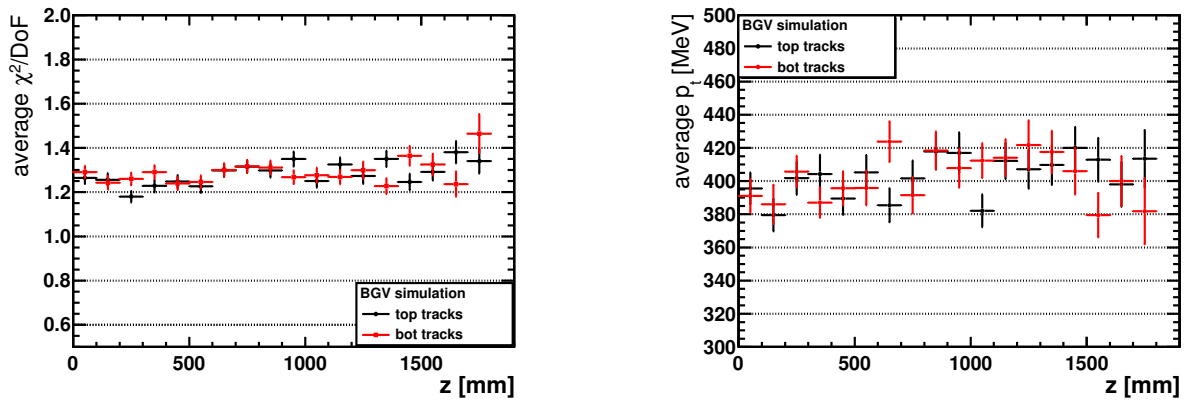


Figure 3.22: Left – Average values of χ^2/DoF as function of the z -position of the PV of reconstructible tracks. Right – Average values of p_T of reconstructible tracks as function of the z -position of PV.

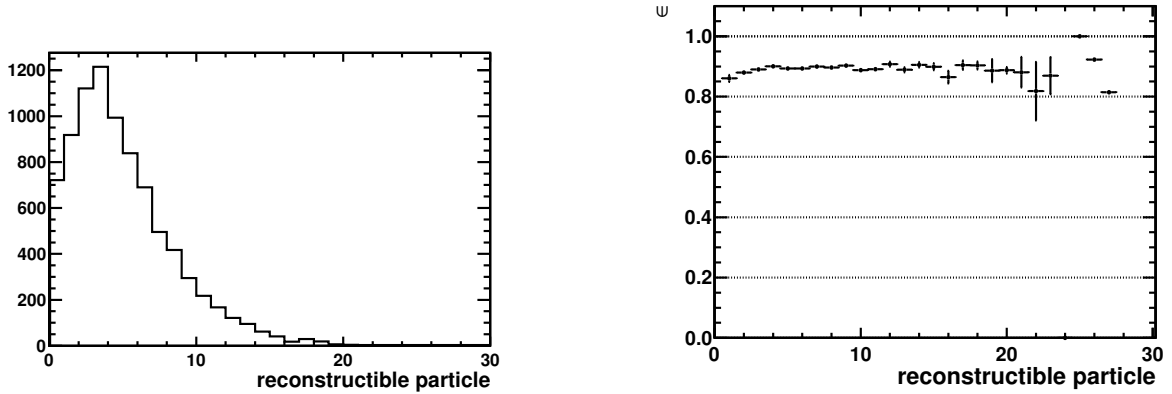


Figure 3.23: Left – Distribution of number of reconstructible particles with at least 7 hits with one missing in the middle sensors. Right – Efficiency of find a reconstructible particle with one missing hit on the middle sensors. It constrains the maximum efficiency of find all reconstructible tracks on events.

3.1.4 Efficiency

The BGV PR requires that the reconstructible particles have a hit on the first two and the last two layers. Therefore the code is only able to reconstruct such particles that miss an hit only in one of the 4 inner layers, sensors 3 and 6 for top tracks and sensors 1 and 4 for bottom tracks. Consequently the track finding efficiency are hardly constrained to the efficiency on find track-seeds of reconstructible tracks. The left plot of Figure 3.23 shows the distribution of the number of reconstructible tracks with at least 7 ‘*good clusters*’. The average number of reconstructible particles per event is $\simeq 5$. The right plot shows the efficiency to find a reconstructible particle with one missing hit on the middle sensors. The efficiency plot shows that about 10% of reconstructible particles have a ‘missing’ hit either in the first two or in the last two layers. These 10% of tracks can not be found by the BGV pattern recognition. Therefore to study the optimal set of cuts to reach the best performance the total number of reconstructible particle are rescaled to the total number of possible track-seeds which can be find by `BGVPattern` *i.e.* the 90% of reconstructed particle which can be find are rescaled to 100 %.

parameter	default value
ΔX	< 20 mm
$\text{DOCA}_{\text{TBA}, \text{trk-seed}}$	< 40 mm
$\text{POCA}_{\text{TBA}, z}$	$[-1000, 2000]$ mm
$\text{DOCA}_{\text{cl}, \text{trk-seed}}$	< 15 mm
χ^2/DoF	< 5

Table 3.2: “Default” value of the **BGVPattern** software. ΔX is the u -projection of the 3D distance between the top position of the normal and stereo clusters. These standard values can be controlled by the software user.

The efficiency ϵ of find a particle is

$$\epsilon = \frac{\langle n \rangle}{N} \quad (3.23)$$

where $\langle n \rangle$ is the average number of reconstructible tracks found and N is the total number of reconstructible tracks. Figure 3.24 shows the efficiency of find reconstructible track-seeds as function the number of reconstructible particles. Almost all reconstructible particles can be find with the chosen cuts of the track-seed selection. Tighten these quantities improve the software processing time but it degrades the efficiency.

The overall efficiency of the BGV PR is also sensitive to the choice of the *best track* out of their clone pool. As mentioned before in this chapter the selected tracks from the clone pool are those who have the smaller DOCA to the TBA. This choice also improves the performance of the clone removal method. Figure 3.25 shows a comparison of three clone removal procedure methods: track with smaller χ^2/DoF , track with χ^2/DoF closest to unity and track with smaller DOCA to TBA. The last method have also the best performance on find true tracks.

Figure 3.26 shows a comparison of the track find efficiency before and after apply the clone removal procedure based on the DOCA to BTA. The left plot represents the default performance of the **BGVPattern**. Between 60% to 75% of all reconstructible particle can be find, depending on the number of reconstructible particles, where $\simeq 20\%$ of the reconstructed tacks are ghosts.

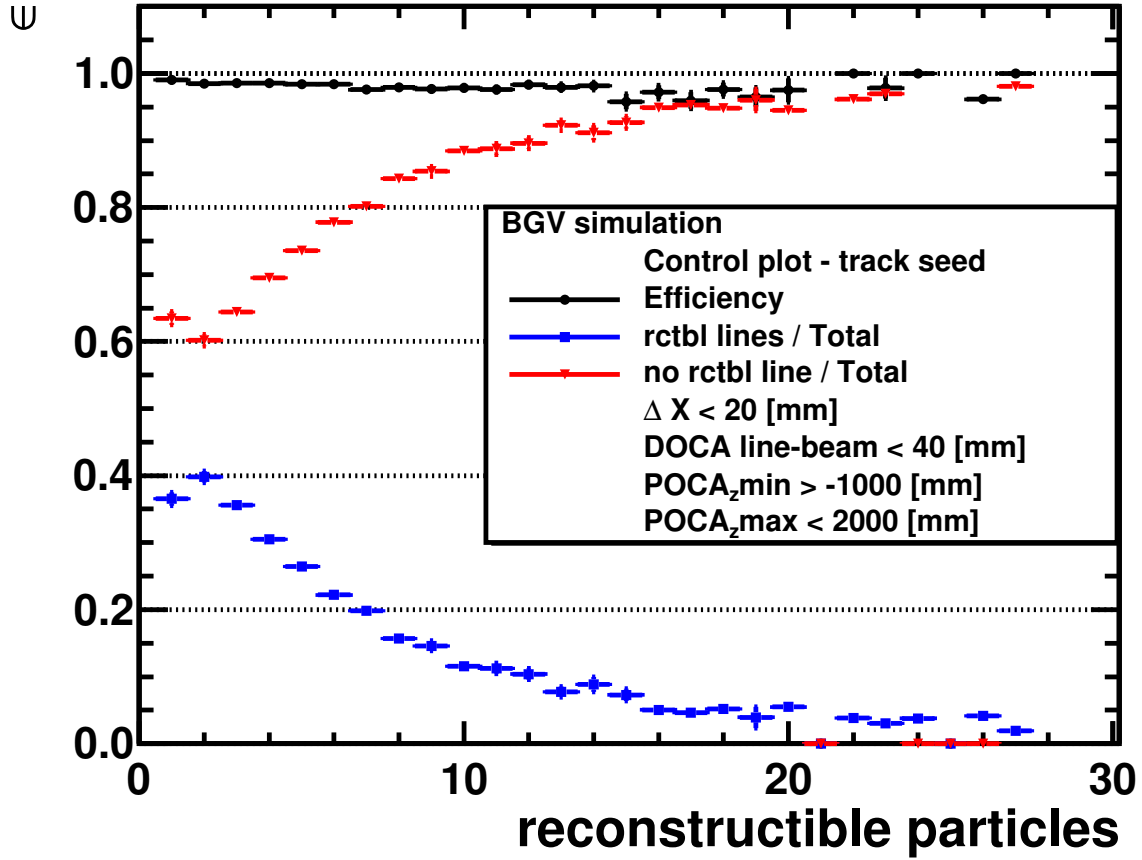


Figure 3.24: Efficiency of find a track-seed as function of the number of reconstructible particles on event. Black – the total efficiency. Blue – the number of reconstructed and reconstructible track-seed over the total number of track-seed reconstructed *i.e.* the purity. Red – the number of reconstructed track-seed which creates a ghost track. Observe that the blue + red = 1. The efficiency plot is made with the cuts: $-1000 < \text{POCA}_{\text{TBA},z} < 2000$ mm $\Delta X < 20$ mm $\text{DOCA}_{\text{TBA},\text{trk-seed}} < 40$ mm.

3.1.5 Speed

In the current LHCb DAQ the modern (fast) nodes can absorb about 800 Hz of full LHCb events. This includes about 20 to 30% deferral, meaning that about 500 Hz can be processed live. Assuming that with CPUs of 2014/15 we can double this rate we can assume 1 kHz of live processing for the LHCb HLT. BGV should be considerably simpler, lets assume that we can get a factor 20. We can take 20 kHz live per node and hence need 25 nodes in the DAQ. Assuming this speed the time to perform tracking and vertexing is

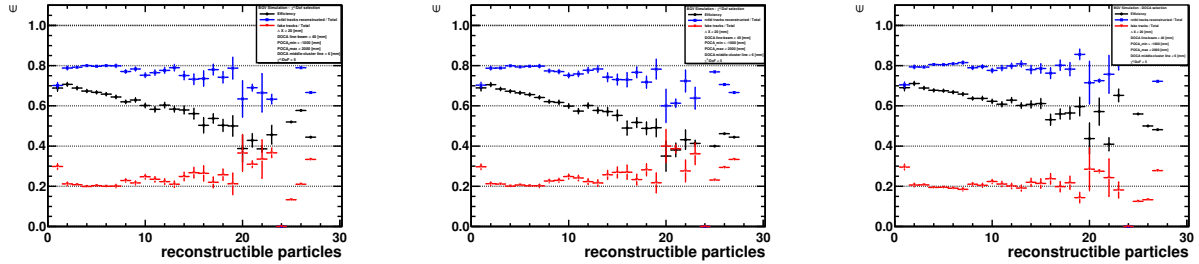


Figure 3.25: Comparison of clone removal procedure on the track find efficiency. All efficiency plots are shown after remove clones. Left – Chose the track with smallest χ^2/DoF from clone pool. Center – Chose the track with χ^2/DoF closest to 1.0. Right – Chose the track with smallest DOCA to TBA. This method is the best for the BGV track find performance.

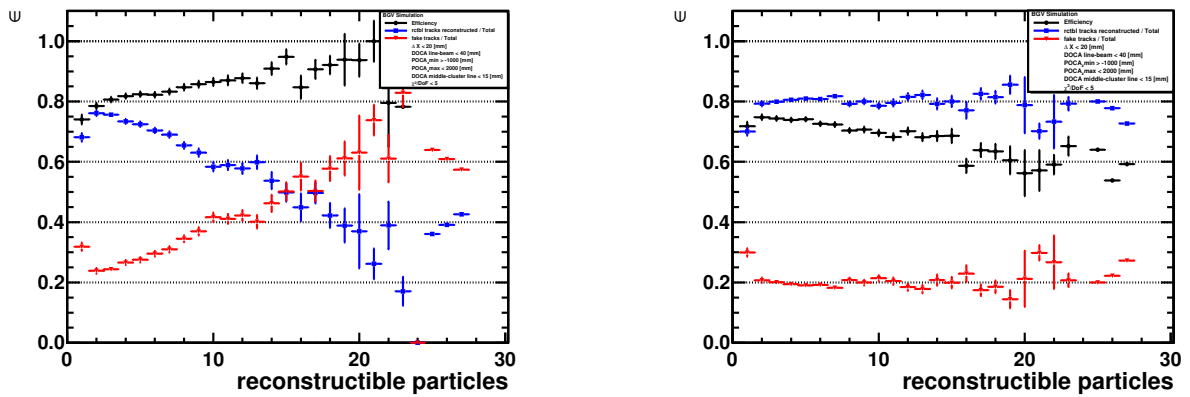


Figure 3.26: Comparison of track find efficiency before (Left) and after (Right) call clone removal procedure based on DOCA to TBA. Black markers is the efficiency. Blue is the number of reconstructible tracks correctly found over the total number of reconstructed tracks *i.e.* purity. Red is the number of ghost tracks over the total numbers of reconstructed tracks. The efficiencies were calculated using “default” values of the parameters shown in the Table 3.2.

0.05 milliseconds. The challenge is write the **BGVPattern** as fast as possible.

The processing time are driven by the number of hits on detector's sensors. The simulated average number of hits is about 164, including hits on all sensitive layers. Furthermore, the number of reconstructible particles grows linearly with the number of hits. Figure 3.27 shows the histogram of the number of hits and average number of reconstructed particles as function of the number of hits. On the other hand, the processing time increases as a polinomial function of the number of hits. Figure 3.28 shows the processing time evaluated at an standard CERN Lxplus machine of 3.73 times the speed of a 2.8 GHz Xeon. On the BGV blade machine is expected about 2 or 3 times faster than on Lxplus. The third degree polinomial fit is

$$\begin{aligned}
 T &= aN_{\text{hits}} + bN_{\text{hits}}^2 + cN_{\text{hits}}^3 \\
 a &= 1.75664 \times 10^{-1} \pm 1.62124 \times 10^{-2} \\
 b &= -3.28756 \times 10^{-3} \pm 3.81638 \times 10^{-4} \\
 c &= 2.25090 \times 10^{-5} \pm 1.93895 \times 10^{-6},
 \end{aligned} \tag{3.24}$$

therefore the average number of hits of 164 its expected the the average computing time of (15 ± 5) milliseconds. There is still an effort to improve the computing time. For instance if the code concentrates in low multiplicity events is possible to perform tracking at 2 or 3 milliseconds, see Figure 3.28.

3.1.6 Impact parameter

The impact parameter (IP) resolution can be calculated on simulation either using the true PV where the IP resolution are computed from distances between reconstructed track to MonteCarlo PV or by reconstructed vertex using reconstructed tracks. The vertex's tracks are then split in two samples where each one fit a independent vertex. The distance between the two independent PV are the 3D IP resolution [70]. However in this thesis no vertex fitting algorithm are implemented for BGV and only MonteCarlo PV are used to calculate the IP resolution.

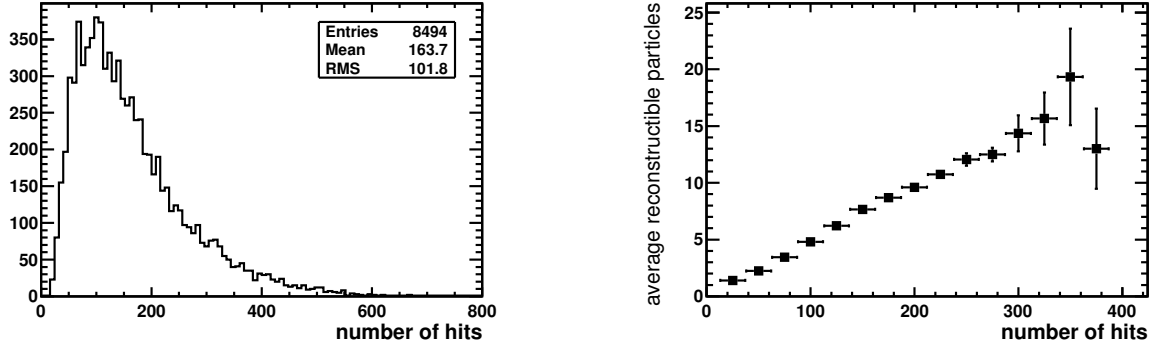


Figure 3.27: Left – Histogram of the number of simulated hits on the BGV. Right – Number of reconstructible particles as function of the number of hits on the detector's layers.

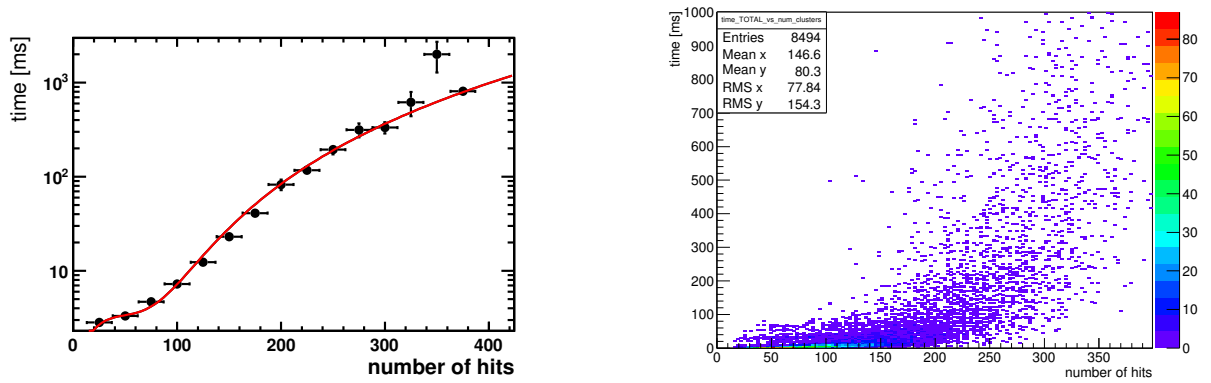


Figure 3.28: Left – Computing time of the `BGVPattern` evaluated at an standard CERN Lxplus machine. A third order polinomial fit is performed. Right – Scatter plot of the computing time in linear scale.

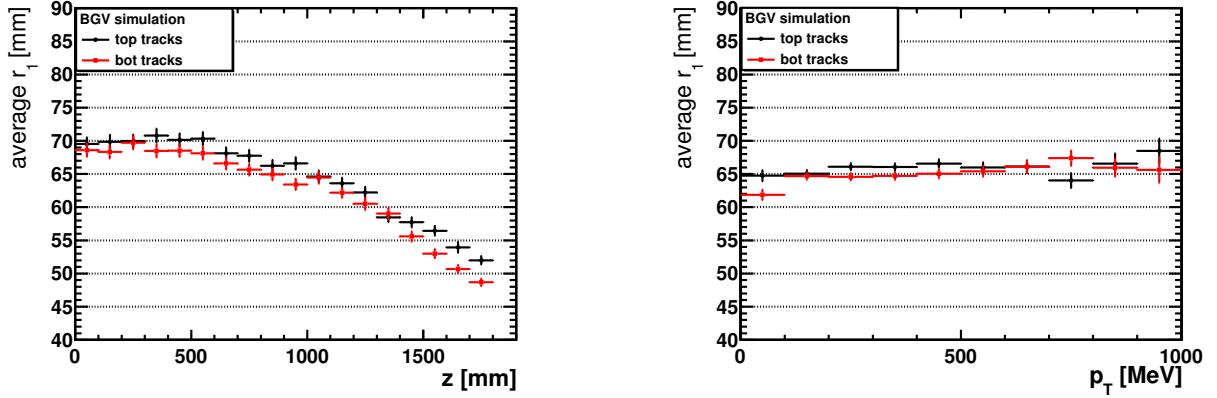


Figure 3.29: Left – Average radial position r_1 of the hits on the first sensor as function of the z -position of PV. Collisions close to the end of the the gas target have small radial acceptance on the first sensor. Right – Average value of r_1 as function of the transverse momentum (p_T) of the tracks. p_T information are only available on simulation. These control plots are used to enlighten the dependence of the IP resolution since it depends on the z -coordinate and track's momentum.

As discussed in the Section 2.3.1, IP resolution depends on both multiple scattering and extrapolation of tracks given by Equation 2.14. Using Equations 2.7 and 2.10 the IP resolution is calculated by

$$\sigma_{IP} = \sqrt{r_1^2 \left(\frac{13.6 \text{ MeV}}{cp_T} \right)^2 \frac{x}{X_0} + \frac{(z_2 - PV_z)^2 + (z_1 - PV_z)^2}{(z_2 - z_1)^2} \cdot \sigma^2} \quad (3.25)$$

where PV_z is the z -position of the PV given by the MonteCarlo simulation, p_T and r_1 are the track's momentum and track's radial position on first sensor respectively and x/X_0 is the amount of material traveled by the particle. r_1 positions are expected to decrease with z and should have no dependence on the transverse momentum of the particles. Figure 3.29 shows these relations.

From simulation the IP resolution of is calculated according to Equation 3.25. Figure 3.30 shows the predicted IP. No reconstructed tracks were used to evaluate IP, only 'true' r_1 , p_T and PV_z were used. The amount of material is about 4.1 % and z_1 and z_2 are the longitudinal position of the center of the first and second modules respectively. Cluster resolution is estimated as 40 μm on simulation. The result shows that multiple scattering dominates the IP resolution. Therefore clusters resolution has a very small impact due

to extrapolation in the BGV situation. However it is not a universal feature. Depending on the detector geometry and the chosen material, multiple scattering and extrapolations may contribute to IP resolution with very different weights.

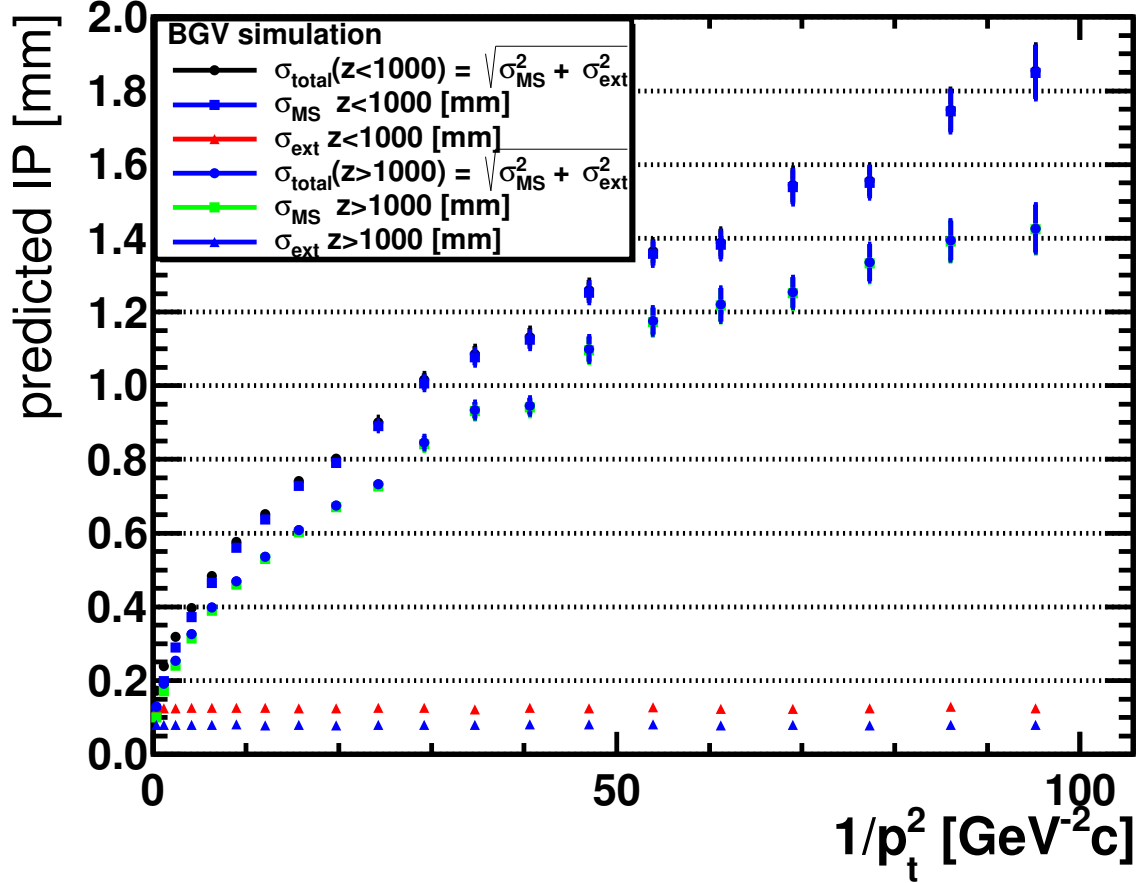


Figure 3.30: Predicted impact parameter as function of $1/p_T^2$ according to Equation 3.25. The plot shows IP resolution of two regions of the gas chamber: $0 \leq z \leq 1000$ mm and $1000 < z \leq 2000$ mm. **Black circles**: total IP of the first half of the gas target. **Blue squares**: multiple scattering contribution to IP of the first half gas target. **Red triangle**: extrapolation contribution to IP of the first half gas target. Observe that **black circle** = $\sqrt{(\text{square blue})^2 + (\text{red triangle})^2}$. Similarly the **blue circles** are the total IP resolution of the second half part of the gas target. **Green squares** are the multiple scattering contribution to IP of the second half part of the gas target. **Blue triangles** are the extrapolation contribution to IP of the second half part of the gas target. Again, observe that **blue circle** = $\sqrt{(\text{square green})^2 + (\text{blue triangle})^2}$. One can conclude from this graph that multiple scattering dominates the BGV IP resolution.

Using only ‘true tracks’ *i.e.* reconstructed tracks linked an particle the IP resolution’s p_T dependence are computed on the first and the second half of the gas target

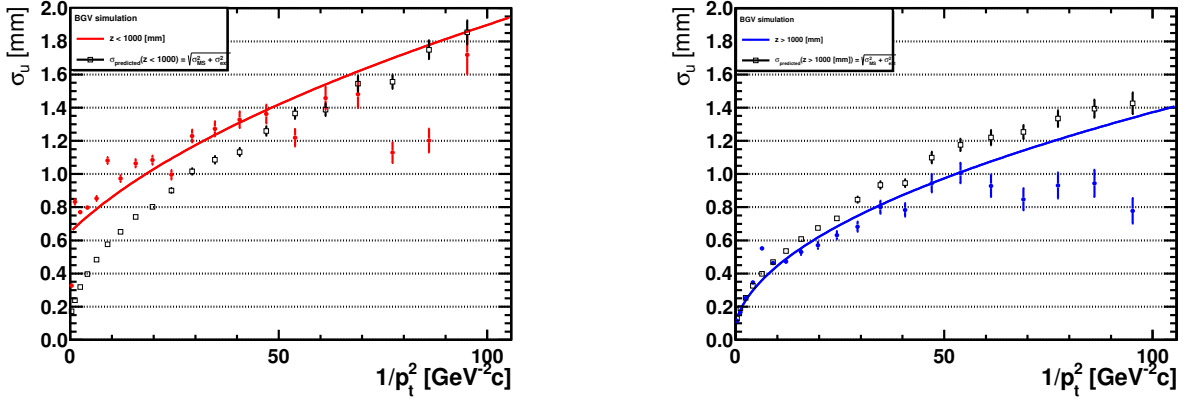


Figure 3.31: IP resolution of the BGV demonstrator. On both plots blank squares are the predicted IP given by Equation 3.25 where only ‘true’ informations are assumed. Left – Red circles are the projection of the 3D IP on the u -axis of the BGV frame in the first half of the gas chamber ($0 \leq z \leq 1000$) mm. The resolution are calculated by DOCA between the reconstructed tracks to the ‘true’ PV. The solid red line is the fit to the red circles. Fit result is: $\sigma_u = \sqrt{b/p_T^2 + a}$, where $a = (0.386 \pm 0.009) \text{ mm}^2$, and $b = (0.0309 \pm 0.0009) \text{ mm}^2 \text{ MeV}^2$. Right – Same as left but for the second half of the gas chamber ($1000 < z \leq 2000$) mm. The fit is: $\sigma_u = \sqrt{b/p_T^2 + a}$ where $a = (0.012 \pm 0.001) \text{ mm}^2$ and $b = (0.0181 \pm 0.0004) \text{ mm}^2 \text{ MeV}^2$. Disagreement between predicted and calculated IP resolution in the first half region are thought to be due under estimations of amount of material crossed by very forward tracks. There is a overlap region between top and bottom sensors whose contributions were not considered.

separately. Figure 3.31 (left) shows this dependence on the first half of the gas chamber, ($0 \leq z \leq 1000$) mm. The computed IP diverges from the predicted by Equation 3.25 for high momentum particles. This divergences can be associated to an underestimation of scattering material for very forward tracks or due to under estimation of extrapolation errors. The right plot of the Figure 3.31 shows the same dependence of the second half of the gas target. There is a better agreement between computed and predicted IP resolution. It shows that the BGV IP resolution can be as good as 0.2 mm depending on the appropriate choice of the z region and the track χ^2/DoF .

Regarding all reconstructed tracks where now ghost tracks are included, it is observed that 3D IP resolution’s projection in u - and v -axis are basically the same and are gaussian distributed. Figure 3.32 shows the projection in both axis. In this result the IP resolution is calculated from the distance between the reconstructed tracks to the PV taken from

simulation. Furthermore Figure 3.21 rise suspicions that multiple scattering effects the ‘track quality’ whose χ^2/DoF have an slight dependence of track momentum. Therefore IP resolution should be dependent of the χ^2/DoF . Figure 3.33 shows this clear dependence that corroborate with the phenomenological understanding of multiple scattering. Indeed this relation is a direct evidence of multiple scattering without knowledge of track p_T . One may obtain an BGV IP resolution bellow 1 mm if only tracks with $\chi^2/\text{DoF} < 2$ have being selected where no restriction on the longitudinal position of PV is imposed.

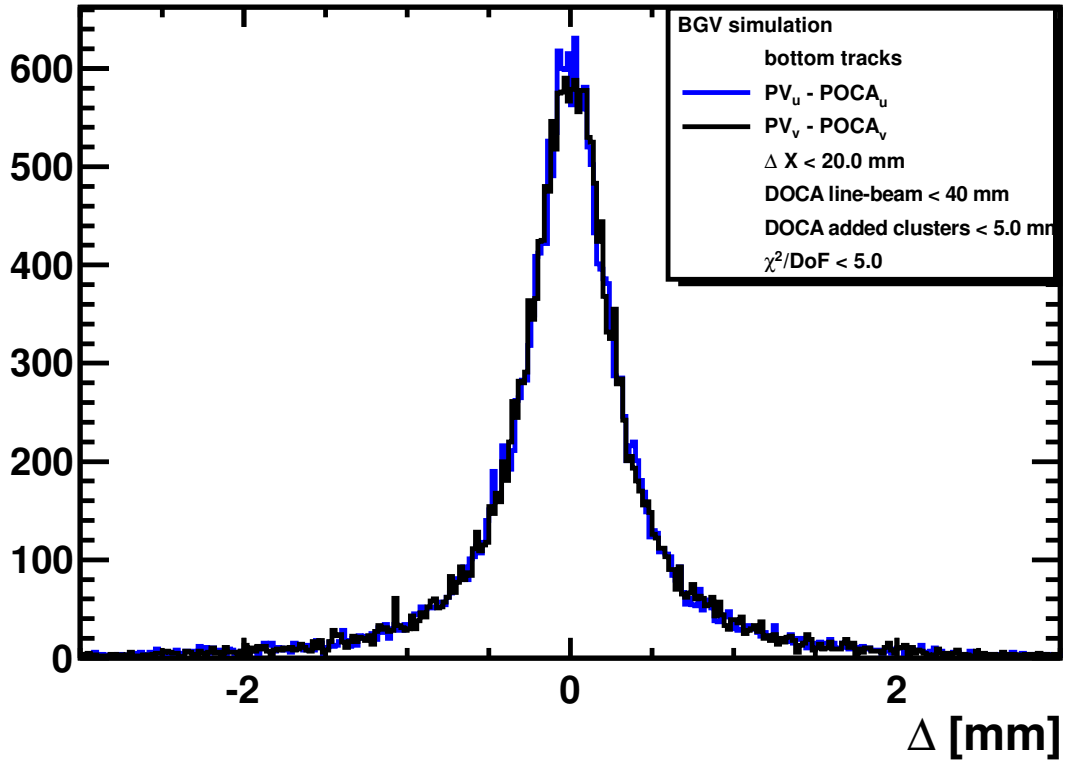


Figure 3.32: Projection of the 3D IP resolution into u and v -axis of the BGV frame. u -axis is the horizontal axis and v -axis the vertical one. 3D IP resolution is the unsigned 3D distance between the POCA_{trk} to the PV. No reconstructed vertex is assumed and PV is the ‘truth’ MonteCarlo vertex. The distribution on both axis are gaussian like.

It is now well stated that longitudinal position of PV is a suitable control variable for reduce IP resolution. Upstream PV near the exit windows of the gas chamber have tracks with small radial coordinate on the first sensor, see the left plot of the Figure 3.29. Errors due to extrapolations are suppressed because distance between the sensors and PV are

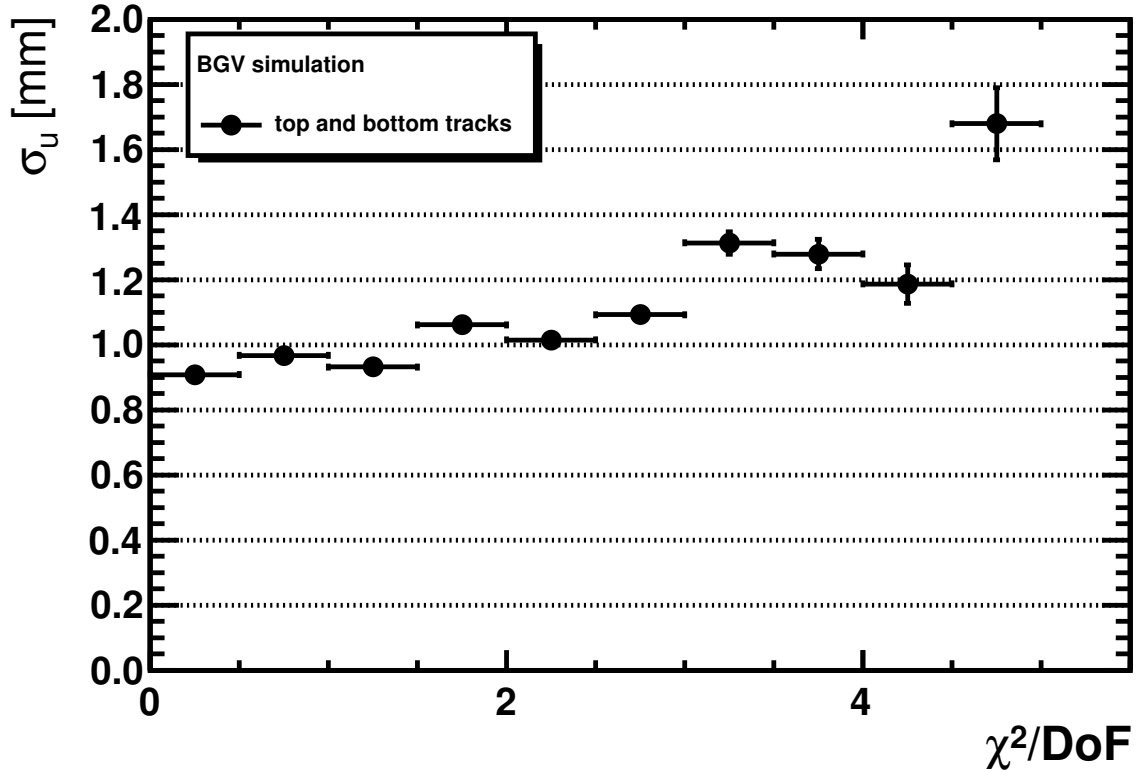


Figure 3.33: BGV IP resolution as function of the reconstructed tracks' χ^2/DoF . IP was calculated only in the u -axis of the BGV frame since horizontal and vertical projection of 3D IP have the same distribution, see Figure 3.32. Each bin of the plot is the RMS of the 3D IP projection.

reduced (see the second term inside the square of Equation 3.25). The dependence of IP resolution vs z -coordinate of the ‘truth’ PV is shown in the Figure 3.34. All reconstructed tracks are considered. The plot show both predicted and calculated IP resolution. One can see that the calculated IP resolution has good agreement with predicted values from Equation 3.25 after $z > 1$ m. However the inclusion of about 20% of ghost tracks[‡] on the final selection degrades IP resolution. With this condition the best IP resolution that `BGVPattern` can reach is 1 mm. Therefore implement more sophisticate methods for identification of ghost tracks on the final track selection is a challenge that still need to be developed.

[‡]Red markers of Figure 3.26 right.

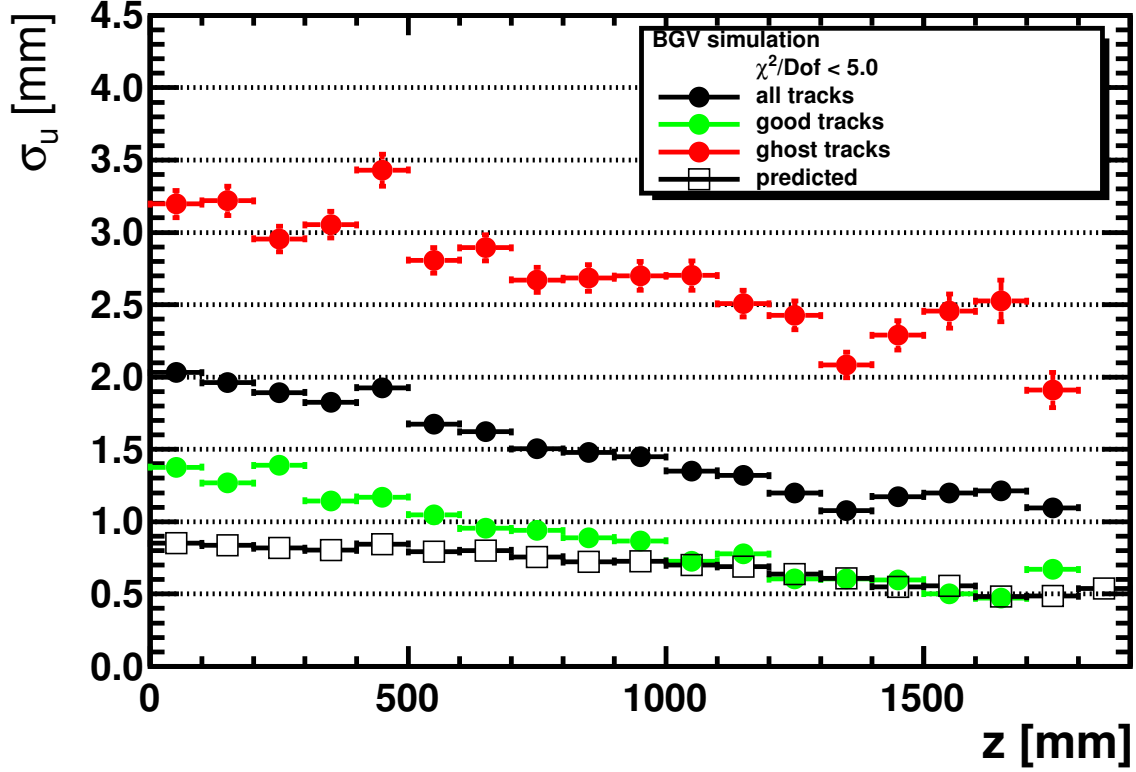


Figure 3.34: IP resolution as function of the z -position of the PV. PV position are extracted from ‘truth’ MonteCarlo. Black circles are the computed IP resolution where both *good* and *ghost* tracks are considered. Green circles are the computed IP resolution where only *good* tracks are considered and red only *ghost* tracks are considered. Empty squares are the predicted IP from Equation 3.25. Disagreement between predicted IP and calculated IP with only *good* tracks on the first half of the gas chamber are thought to be due under estimation of scattering material where very forward tracks reach more frequently the overlap region between top and bottom modules of the first BGV station.

3.2 Detector Cooling System

The design of the modules is similar, apart from size, to the fibre modules that will be used in the LHCb Upgrade [72]. The same scintillating fibres and silicon photomultipliers (SiPM) will be used. The scintillation light generated by the charged particles inside the fibres is collected at the end of the fibres by SiPMs. The SiPMs exhibit a dark current which strongly depends on radiation damage. Therefore, in order to keep the noise at an acceptable level, the SiPMs must be cooled. The larger the exposure, the colder they must be operated. The radiation dose seen in the BGV by the SiPM can be estimated

by simulating the charged particle flux which, at these distances, is expected to dominate over the neutron flux. Assuming 2600 bunches circulating in the LHC for most of the year (10^7 s), each with a beam-gas interaction rate of about 250 Hz between the position of station 2 and 5 m upstream of that position, one arrives at a yearly charged-particle fluency of approximately $4 \times 10^{10} \text{ cm}^{-2}$ at radii between 22 and 26 cm. Since most charged particles are high energy, this can be translated to about $2 \times 10^{10} n_{eq} \text{ cm}^{-2}$ (where n_{eq} stands for “1 MeV neutron equivalent”) and to a dose of about 20 Gy. This corresponds roughly to the exposure of the LHCb Upgrade SiPM for 5 fb^{-1} .

One of the main goals of the BGV project is to acquire experience with the fabrication and operation of such fibre modules at the LHC in an environment that will be similar to the one in LHCb. Among the most difficult challenges is the cooling of the SiPMs. Although for the BGV the temperature requirement may not be as stringent as for the LHCb Upgrade SiPM, a similar requirement is imposed in order to test the design against the more challenging LHCb requirements. Therefore, the SiPM must be operated at a temperature in the range of 20 to 40°C. Cooling of the 2×8 SiPM inside each module is achieved by pressing a cooling pipe onto the row of eight SiPM with springs. Figure 3.35 shows some details of this connection. The cooling pipe is made of stainless steel and is glued with high thermal conductivity glue onto an aluminium plate which makes contact to the SiPMs. There are two such SiPM rows, and therefore two such pipes, per module.

The chiller model is the Julabo Presto A80 [82] which was chosen based on its pump capacities. On the other hand the chiller unit is not qualified for operation in ionizing radiation environment. This leads to the requirement to install the chiller in a radiation shielded area and use a transfer line to the BGV detector. The chosen location for the chiller unit and routing of the transfer line is shown in Figure 3.36. The length of the cooling transfer line is at least 20 m. The BGV detector is installed at LHC tunnel location RA43, at the LHC ring 2, and the chiller unit in the service tunnel UA43.

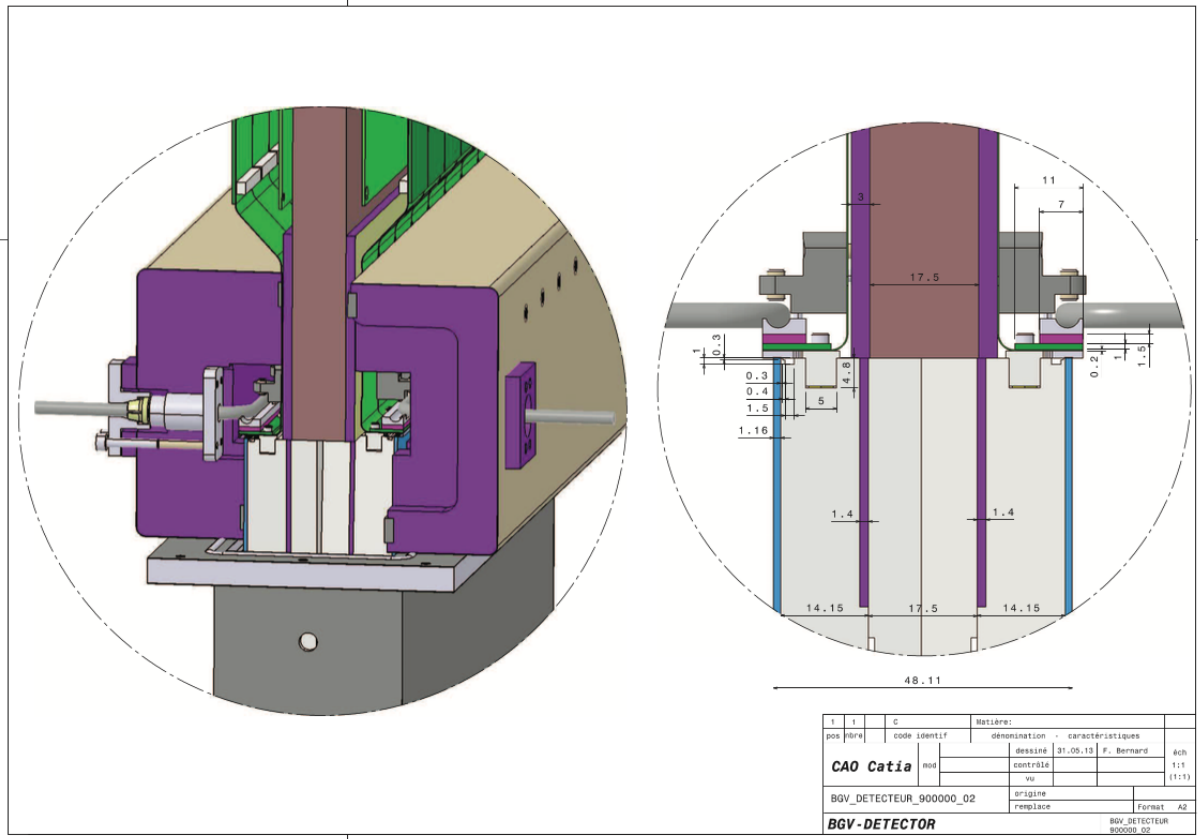


Figure 3.35: View of the cooling connection to the SiPM row inside the module insulating box according to the EPFL design. The module comprises the fibre planes (blue), the flex cables for the read-out of the SiPMs (green) and the cooling enclosure (purple) coated with carbon fibre (light brown). The cooling system (light grey) is made of the pipe glued with aluminium and silver glue on a rectangular heat spreader. A thermopad (pink) is stuck on the heat spreader. The SiPMs (light grey) are placed on an aluminium stiffener (green) and are bonded to the flex cables. Source: BGV Collaboration.

Throughout this section studies performed for the BGV cooling system are presented. The goal is to validate the cooling capabilities of system and have a better understanding of the hydrodynamics properties of the system.

3.2.1 The Liquid Cooling System

The BGV cooling system is based on monofase liquid coolant C6F14 transferred through insulated silicone pipes that drives the flow in low temperature inside stainless steel tubes, called cooling pipes. The basic cooling mechanism is heat exchange where

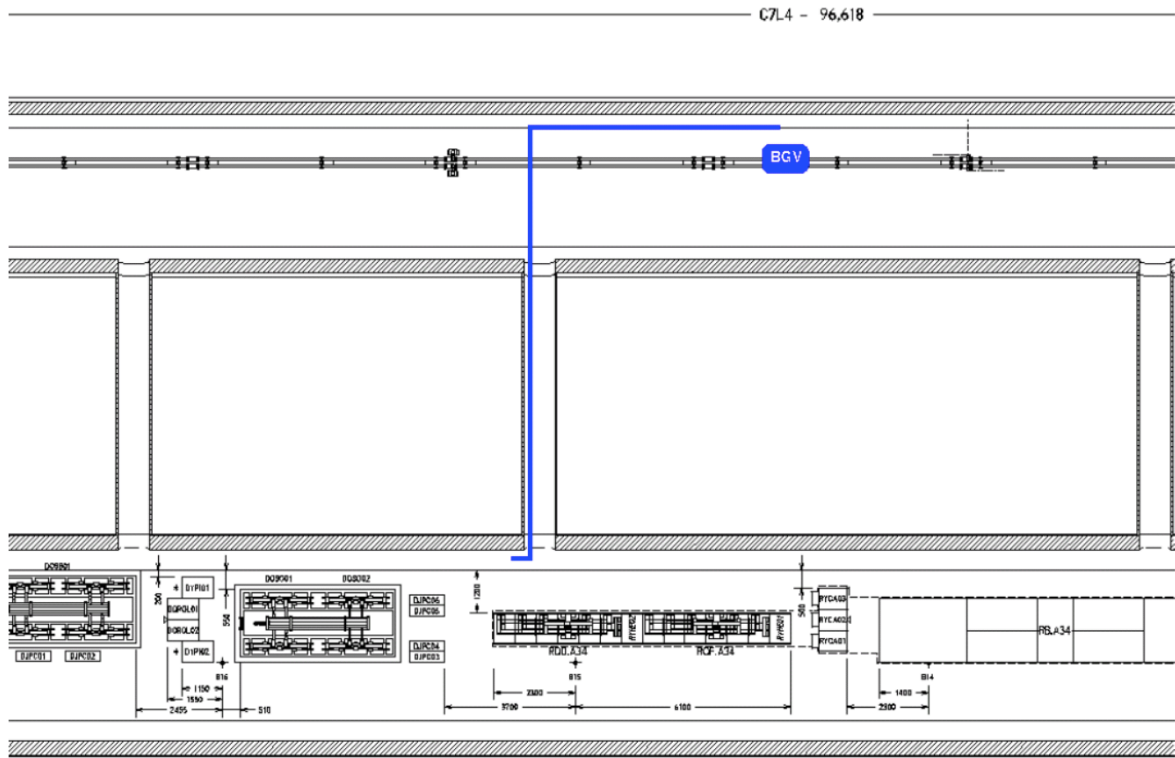


Figure 3.36: Location of the chiller in the LHC service tunnel. The BGV demonstrator are installed into the LHC tunnel location RA43 and the chiller at service tunnel UA43. Source: BGV Collaboration.

the cooling pipes are pressed against the SiPM.

The cooling system consists of a chiller unit, located in the service tunnel UA43, a Transfer Line of ID/OD 16/22 mm, ~ 20 m long transferring the monofase refrigerant liquid from the chiller to the BGV site, one main manifold that divide the flow in 4 parallel lines of ID/OD 9/13 mm, ~ 3 m long, a stainless steel distributors in the end of each ID/OD 9/13 mm pipes which divides the flow in another branch of 4 parallel lines of ID/OD 4/6 mm, ~ 2 m long and finally the cooling pipes of ID/OD 3/4 mm, ~ 30 cm long.

The branch configuration is chosen to have the small restriction to the flow. In total the branch setup is 16×1 , 16 pipes in parallel with 1 in series. Figure 3.37 shows the cooling plant.

Each subcomponent of the cooling system were tested individually and some parameters are discussed in the following subsections. The capability of cooling the SiPM were tested at EPFL in Lausanne by Olivier Girard [74] and the others components are tested at CERN.

Coolant

The largely available coolant 3MTM Performance Fluid PF-5060 is used during the lab tests. The liquid is the perfluorohexane C6F14 which is used in several liquid cooling system at CERN. This coolant is meant to be later replaced by Novec 649 by 3M [83] which has similar properties but have less global warming impact.

Table 3.3 shows the temperature dependence of some thermal properties of C6F14. The lower is the temperature lower is the specific heat, higher are the thermal conductivity and the density. Numerically, for a temperature drop of $\Delta T = -10^\circ\text{C}$ the specific heat decreases 15.3% while the thermal conductivity and the density increases 1.8% and 1.5% respectively. Therefore the cooling performance of the liquid is not effected when low temperature application is needed. On the other hand the temperature dependence of the viscosity is not negligible (see Figure 3.38). The viscosity increases about 20% for $\Delta T = -10^\circ\text{C}$. From the Darcy-Weisbach relation [84] for a fluid with velocity v flowing through a horizontal pipe of diameter D and length L the pressure drop ΔP is given by

$$\Delta P = f \frac{L}{D} \frac{v^2}{2} \quad (3.26)$$

and assuming the simplified Blasius relation for the friction factor $f = 0.316/R_e^{0.25}$ [85], where R_e is the Reynolds number it is easy to show that the ratio of the fluid velocity at a given temperature $v(T)$ to a reference temperature T_0 , $v(T)/v(T_0)$ is

$$\frac{v(T)}{v(T_0)} = \left(\frac{\nu(T_0)\rho(T_0)}{\nu(T)\rho(T)} \right)^{1/8}. \quad (3.27)$$

Figure 3.39 shows the above ratio for the C6F14 for a reference temperature of $T_0 = 20^\circ\text{C}$. One can see that the velocity of the fluid decreases about 16% from 20°C to -40°C .

Therefore to compensate the flow in a given temperature, the pressure drop throughout the system needs to be corrected for. Flow control is important because the temperature stability of the cooling pipes depends on the fluid velocity. On the other hand, the fluid velocity in the cooling pipes should not exceed the cavitation regime. The velocity limit when cavitation becomes significant are given by [86]

$$v_{\text{C6F14}} = v_{\text{H}_2\text{O}} \sqrt{\frac{\rho_{\text{H}_2\text{O}}}{\rho_{\text{C6F14}}}}, \quad (3.28)$$

therefore for 3 mm pipe C6F14 should not exceed a volume flow inside cooling pipes of $\dot{V} \simeq 1.44$ l/min. Cavitation inside the pipes lead to undesired issues: may induce vibration on SiPM, degrade pipe materials and there is also liquid losses by boiling.

C_6F_{14} properties	
Specific heat [$\text{Jkg}^{-1}\text{°C}^{-1}$]	$1014 + 1.554T$
Thermal conductivity [$\text{Wm}^{-1}\text{°C}^{-1}$]	$0.060 - 0.00011T$
Density [kg/m^3]	$1740 - 2.61T$

Table 3.3: Temperature dependence of the Specific heat, Thermal Conductivity and Density given by 3MTM The temperature are in °C.

The Prandtl number[§] of C6F14 are shown in the Figure 3.40. One can see that the momentum diffusivity decrease with temperature indicating that at low temperature the heat transfer are dominated by convection and turbulent flow play the role for heat exchanges.

Chiller

The chosen chiller for the BGV cooling system is the Julabo Presto A80 which provides a maximum pump pressure up to 1.7 bar and nominal cooling capacity of 1.1 kW for ethanol at -40°C . The chiller is not qualified for operation on ionising radiation environment and hence the unit is installed in the service tunnel UA43 and the coolant is transferred by the Long Transfer Line to the detector.

[§]Prandtl number Pr is defined as: $Pr = c_p \mu / k$ where c_p is the specific heat, μ the dynamic viscosity and k the thermal conductivity. As defined, it is the ratio of momentum diffusivity to thermal diffusivity.

The expected heat load onto the coolant at -40°C through the transfer line for the coolant at -40°C is of 200 W. The total power dissipated by the detector is less than 160 W [87] leading to the total power dissipation of ~ 360 W, far below the cooling power of the chiller. The unit has a temperature stability of the coolant in the reservoir between $\pm 0.01^{\circ}\text{C}$ to $\pm 0.05^{\circ}\text{C}$. However, it is observed in the lab that the temperature stability at the cooling pipes have dependence on flow.

The unit is controlled via ethernet by the industrial SCADA system PVSS II from ETM [88]. Many parameters can be adjusted during the real time operation. Figure 3.41 shows the control panel.

Transfer Line

The transfer line of the BGV is made of ID/OD 16/22 mm silicone tube insulated with two Armaflex layers. The inner insulation is the LTD (cryo) type, 25mm thickness covered with NH (halogen free) type, 25 mm thickness, see Figure 3.42. The transfer line drives the coolant from the chiller, located in the service tunnel UA43 to the BGV application at the RA43.

Manifold

The Manifold divides the flow equally into the detector modules. The flow is controlled by 4 valves and is measured by 4 KROHNE H250 flowmeters calibrated to the C6F14 density. There are also two extra valves in the inlet and outlet lines to close the flow if needed. Figure 3.43 shows the Manifold design.

Low temperature tests were performed with C6F14 circulating through the Manifold at -20°C . PT1000 probes and thermal camera were used to measure the temperature of the Manifold. Figure 3.44 shows the temperature profile of the Manifold taken by the thermal camera. The valves have the lowest temperature but is covered by insulation and humidity should not accumulate. Flowmeter surfaces are not covered with insulation but their temperature are not below the dew point in the tunnel. Figure 3.45 shows

the location of the PT1000 probe attached on the lateral side of one of the flowmeters and their measurements. The surface's temperature of the flowmeter stabilises at $\simeq 4^{\circ}\text{C}$ which are far above the dew point in LHC tunnel point 4. The dew point in the LHC is about -15°C . Figure 3.46 shows the dew point in the LHC tunnel point 4 measured by the BGV Temperature and Humidity Measurement System (THMS) [89].

Distributors

The distributors are the final flow splitter of the BGV cooling system. They release the flow equally through 4 lines of $\varnothing 4 \times 6$ mm pipes, $\simeq 1.5$ m long which drive the coolant into the BGV modules. The distributors are the commercial stainless steel manifold manufactured by Serto ®. Figure 3.47 shows the photo of the distributors and the set of insulated distributors of the bottom modules in the BGV setup.

Cooling Pipes

The Cooling Pipes are stainless steel ID/OD 3/4 mm, ≈ 30 cm longer which refrigerates the SiPM's via direct contact. The low temperature coolant flows through the Cooling Pipes which provides heat exchange between the liquid and the SiPM. Together with the ID/OD 4/6 mm silicone tubes it dominates the hydrodynamics resistance of the cooling system.

In Reference [74] a validation of the cooling capabilities of the SiPM by the cooling pipes is presented. Additionally, several tests were performed to measure the resistance introduced by the pipes and determine the optimal branch configuration that is shown in the Figure 3.37, 16×1 .

The pressure drop through the cooling pipes is described by the Darcy-Weisbach equation with an additional term to account for the bend at the two extremities. Figure 3.48 shows a photo of a dummy stainless steel tubes used during the lab tests of similar sizes

that of BGV cooling pipes on the modules. The pressure drop is given by:

$$-\Delta P = f\rho\frac{L}{D}\frac{v_{\text{avg}}^2}{2} + x\rho\frac{v_{\text{avg}}^2}{2} \quad (3.29)$$

where ρ is the fluid density, L and D are the tube length and diameter respectively and v_{avg} is the average velocity of the liquid. f is the so called Darcy-Weisbach frictional term which depends on the flow regime of the liquid. Since C6F14 flowing across the tube is fully turbulent, a good approximation for f is:

$$f = 0.25 \left[\log \left(\frac{e/D}{3.7} + \frac{5.74}{R_e^{0.9}} \right) \right]^{-2}, \quad (3.30)$$

where e is the absolute pipe roughness of the surface. For stainless steel $e \approx 0.015$ mm. R_e is the Reynolds number. On the second term of Equation 3.29, x is the ‘bend factor’ which depends on the radii of curvature of the tube knee. Figure 3.49 shows the comparison between the measured pressure drop, using a pressure sensor connected in the input and output of the tube and the predicted by this relation. One can see that, there is a good agreement between predicted and observed pressure drop. On the other hand, if one assumes the curve of Figure 3.49 as linear, the cooling pipes have an equivalent hydrodynamic resistance of $\approx (0.60 \pm 0.06)$ bar l⁻¹ min⁻¹ for $\dot{V} > 1$ bar.

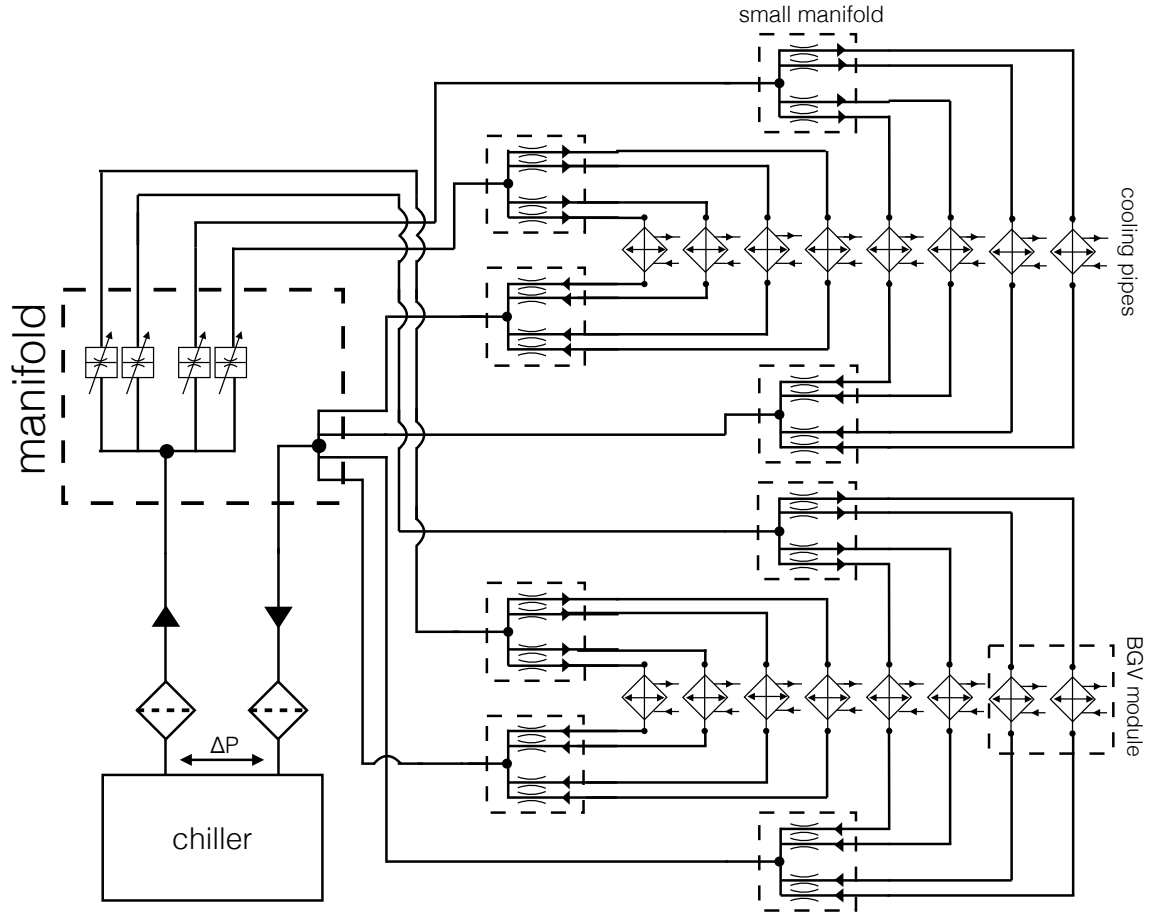


Figure 3.37: The BGV cooling plant. The chiller unit are the core of the cooling system, providing the pressure difference between the input and output connector and the refrigerate the liquid. Leaving the chiller the refrigerant liquid are filtered by a 0.5 mm mesh filter in the beginning of the transfer line on the chiller site (service tunnel RA43). In the end of the transfer line the flow are equally divided in 4 parallel lines of ID/OD 9/13 mm by the manifold. The manifold is equipped with valves and flowmeters to guarantee the flow are equally divided. In the end of each of those ID/OD 9/13 mm pipes small distributors divides the flow in the second set of 4 parallel lines of ID/OD 4/6 mm which finally pass through the ID/OD 3/4 mm stainless steel cooling pipes. The set of 4/6 and 3/4 mm tubes dominates the total resistance of the application. After the liquid pass by the cooling pipes it returns to the chiller and the closed process start again. The total configuration is 16×1 (16 pipes parallels with 1 in series). Observe that one BGV module have 2 cooling pipes, one for each SiPM set.

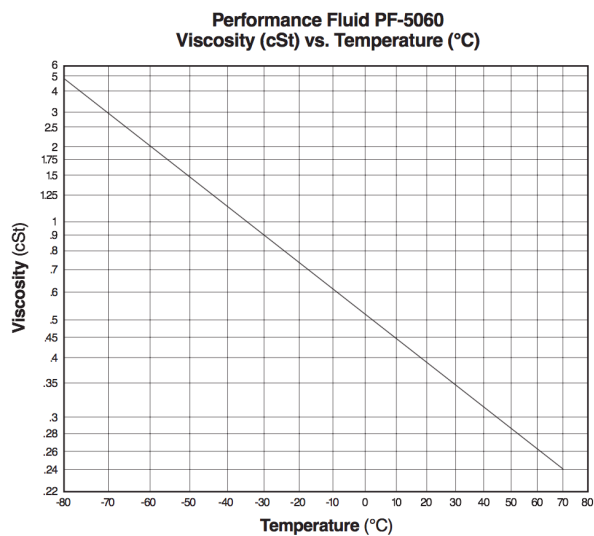


Figure 3.38: C6F14 viscosity dependence with temperature. The viscosity increase $\approx 20\%$ for every 10°C of temperature drop.

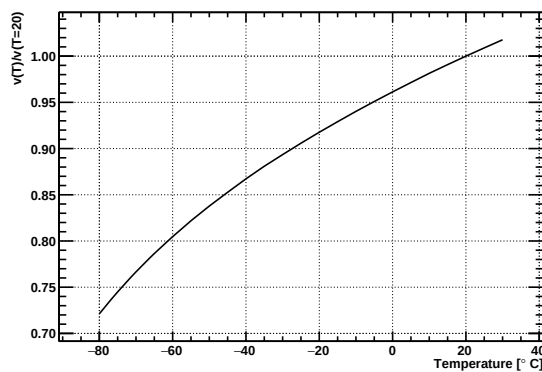


Figure 3.39: Expected drop of the fluid velocity given by equation 3.27. From 20°C to -40°C the velocity decrease about 16% .

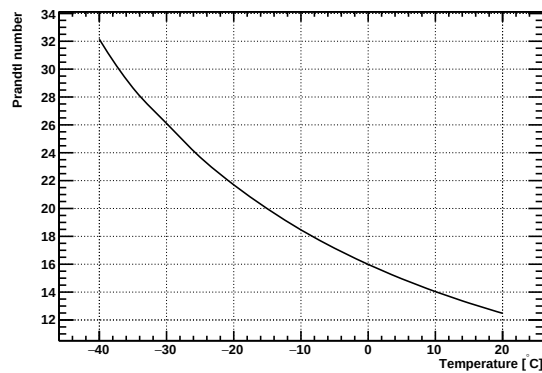


Figure 3.40: Prandtl number for C6F14 as function of the temperature. At low temperature the momentum diffusivity dominates and the heat exchange are dominated by convection.



Figure 3.41: Control panel of the chiller. The panel displays several adjustable parameters of the chiller such as pressure [bar] and temperatures setpoint [°C]. Courtesy of L. Granado Cardoso.



Figure 3.42: Photo taken during the assembling of the transfer line. In blue is the cryogenic type LTD, ID/OD 22/25 mm and gray the halogen free type, ID/OD 75/25 mm.

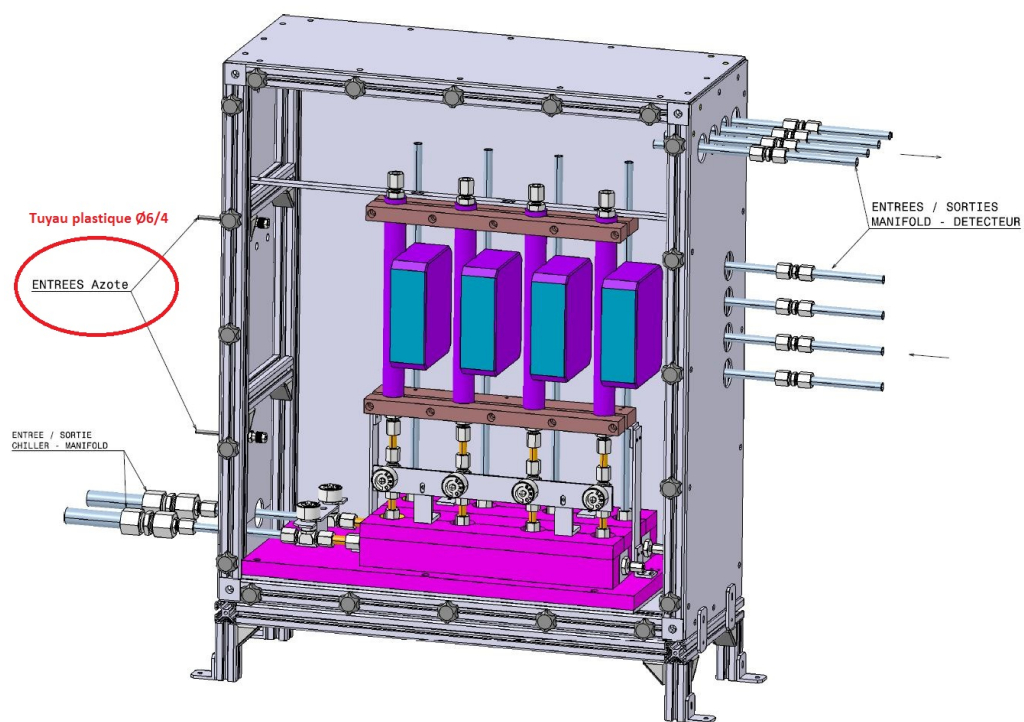


Figure 3.43: Design of the BGV Manifold. Source: BGV Collaboration.

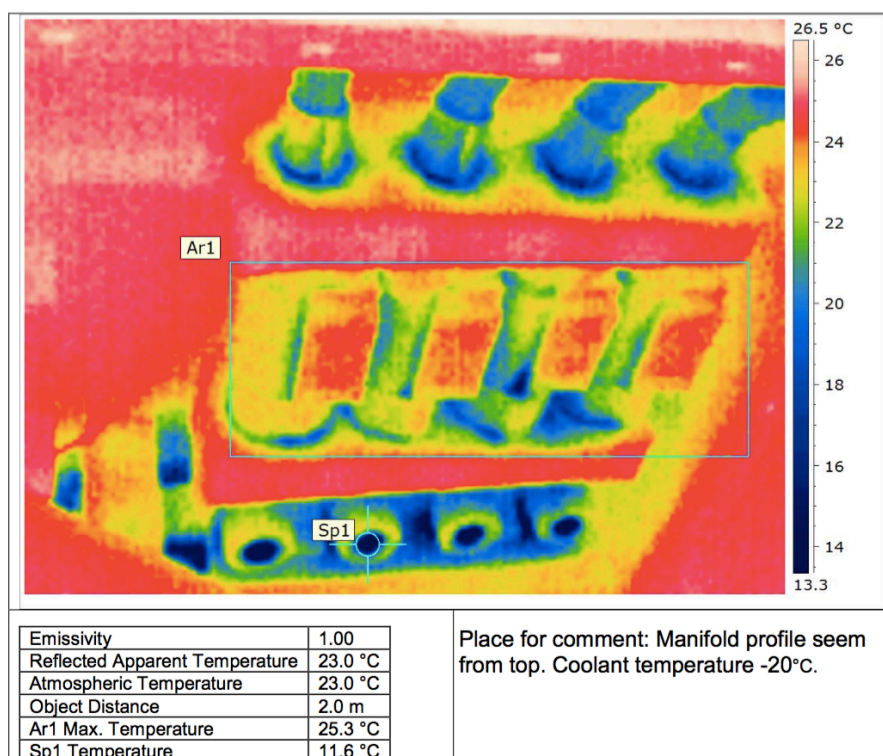


Figure 3.44: Temperature profile of the Manifold with C6F14 at -20°C . The coldest surface is on the metal valves which control the flow into the flowmeters. This valves are covered with insulation and does not have contact with the environmental air.

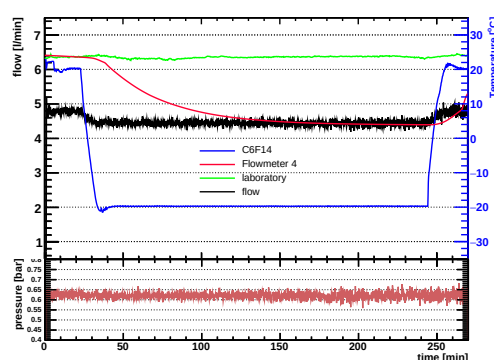


Figure 3.45: Summary of the measurements taken in June 19, 2015. Blue - C6F14 temperature. Pink - flowmeter surface temperature. Green - ambient temperature and black the volume flow. The bottom graph shows the pressure. The pressure sensor have a offset equivalent to 0.6 [mbar]. The plow shows the pressure corrected to the offset.

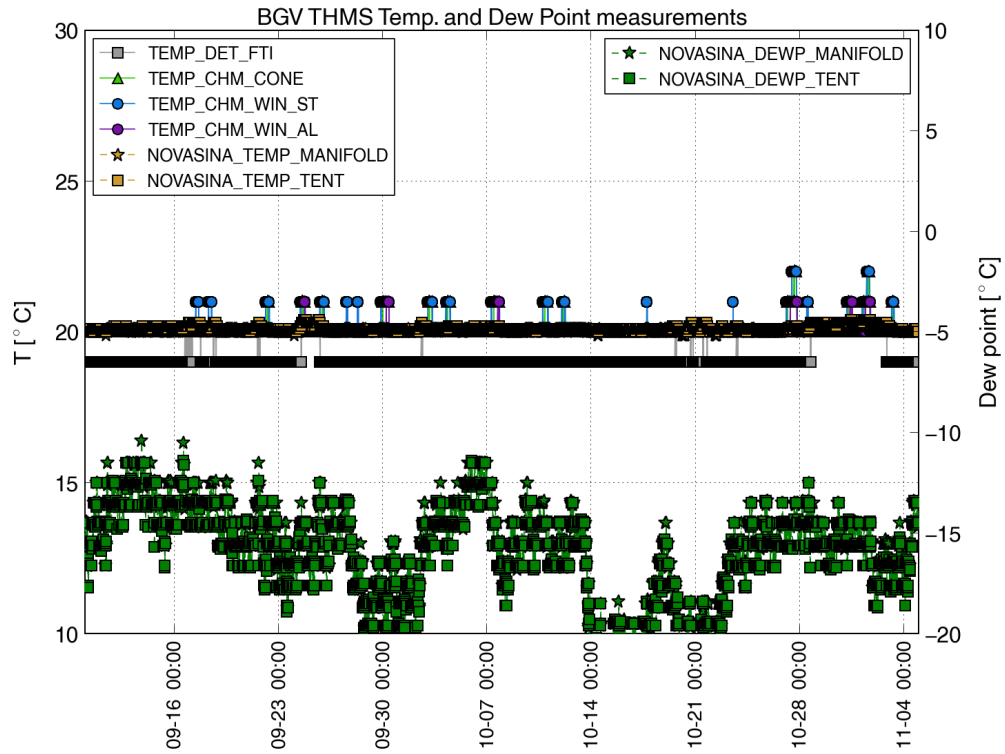


Figure 3.46: Summary of the measurements taken by the THMS in the LHC tunnel point 4. The green stars and squares markers are the dew point measurements. Source: BGV Collaboration.



Figure 3.47: Left – Photo of the distributors of the BGV cooling system taken during the lab tests. Right – Photo of the set of insulated distributors installed in the bottom rack of the BGV setup at the LHC tunnel.

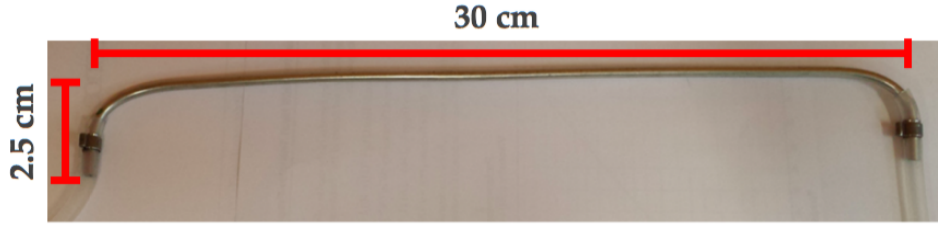


Figure 3.48: Photo of a dummy tube of similar size and shape that of the cooling pipes installed inside the BGV modules to cool down the SiPM temperature.

3.2.2 Hydrodynamics Properties

In the months of November and December 2014 several tests were performed to characterise some properties of the transfer line. The flow regime over the transfer line is expected to be turbulent and the velocity profile fully developed since the entrance region is much smaller than the total length, typically $\approx 10D$ for a turbulent flow. Figure 3.52 shows the evolution of the Reynolds number as function of the volume flow for C6F14 for four temperature set. As one can see above a flow rate of 4.5 l/min the regime is turbulent ($Re > 4000$) for all temperatures. It shall be proved bellow in this section that the total flow of the system is about 4.7 l/min for the chiller pressure set of 0.8 bar, hence the flow over the whole system is turbulent.

Turbulent flow is desired for heat exchange since momentum diffusivity dominates at low temperature, see Figure 3.40. This behaviour is corroborated by the Nusselt number that express the convective heat transfer over conductive heat transfer. Higher values of Nusselt number indicate the heat transfer is dominated by convection. For forced convection in turbulent pipe flow, Gnielinski's formula describe with relative good precision in the nearly turbulent regime the Nusselt number [90]

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7\sqrt{f/8}(Pr^{2/3-1})}. \quad (3.31)$$

Figure 3.51 shows values of the Nusselt number in the Transfer Line. The Nusselt number increases with the flow rate and decreases with temperature. At the BGV flow of 4.7 l/min

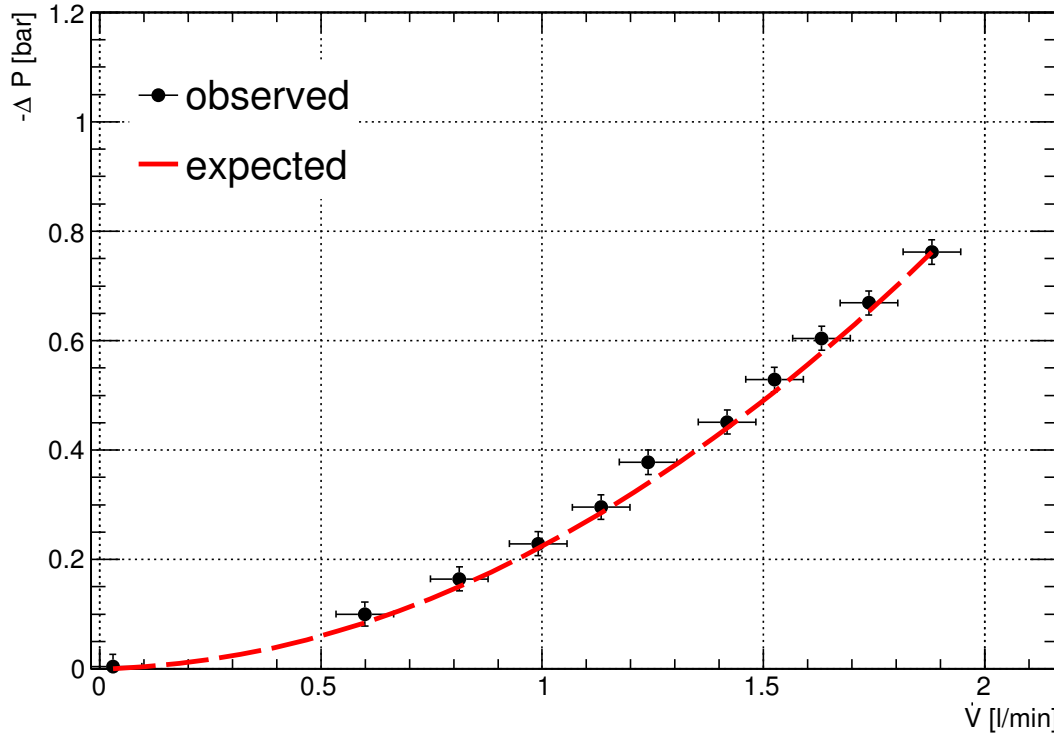


Figure 3.49: Pressure drop through the BGV cooling pipes. The red curve is the predicted values from Equations 3.29 and 3.30 assuming $x = 1.5$, see text. Black circles are the measured values of the volume flow of C6F14 for a given pressure, measured by a pressure sensor.

it is around 120 indicating convection dominates the heat transfer. Therefore increases the coolant flow over the transfer line leads to an increase of the heat losses and more power is needed from the chiller. This relation was quantified during the lab tests. Using the BGV chiller, C6F14 was driven through the transfer line in turbulent regime ($Re \gtrsim 4000$, $\dot{V} \gtrsim 2.82$ l/min). Figure 3.50 shows the characteristic temperature curve of the C6F14 for a target temperature of -50°C . Temperature was measured with PT100 probes inside the transfer line tube. The probes were in direct contact with the coolant. The difference between C6F14 temperature at the input and output of the supply line of the transfer line is also shown and it is around 3°C . It is equivalent to an power dissipation per unity of length of $W/L \simeq 12$ watts/m[¶]. Furthermore, according to Figure 3.38 the C6F14

[¶]Power dissipation calculated with $W = \rho(T)\dot{V}c_p(T)\Delta T$, where $\rho(T)$ is the density, $\dot{V}$ volume flow,

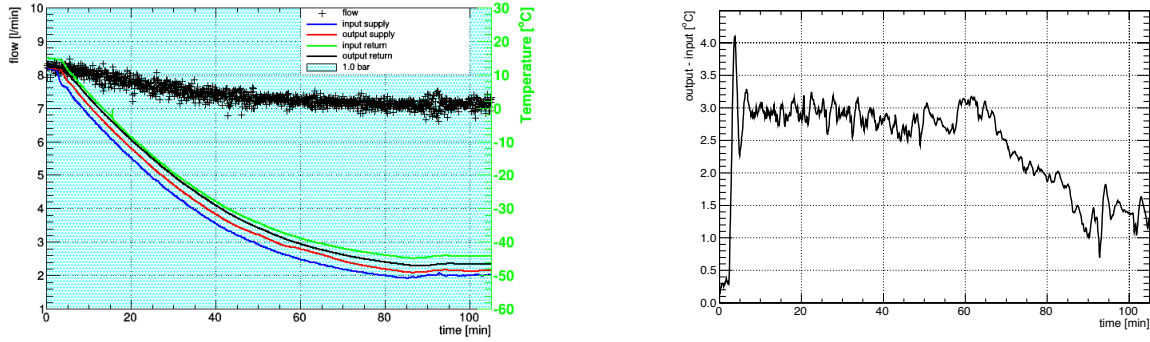


Figure 3.50: Left – Characteristic temperature curve of C6F14 at transfer line (TL). Blue, C6F14 temperature at the beginning of the supply line of the TL. Red, C6F14 temperature at the end of the supply line of the TL. Green is the C6F14 temperature at the beginning of the return line of the TL and solid black C6F14 temperature at the end of the TL. Temperatures are read in the right vertical axis. Black markers are the measured flow (left vertical axis). Volume flow was measure with a Pelton Wheel flowmeter by LitremeterTM, accuracy of $\pm 2\%$. TL is composed of two lines of ≈ 20 m each. One is the supply line feeding the BGV cooling branches and the other is the retur line. Right – C6F14 temperature difference between the input and output of the supply line.

viscosity increases as the liquid temperature decreases.

The resistance of the BGV system is dominated by the ID/OD 4/6 mm silicone tubes and the cooling pipes of the BGV modules. Therefore to study some hydrodynamic properties of the system with a reduced circuit, the transfer line was removed and a specific configuration was set up as shown in the Figure 3.53, such that the total load is similar to the expected load in the LHC tunnel.

Figure 3.55 (left) shows a summary of a data taken with the reduced circuit. C6F14 temperature is measured with PT100 probe inside the output line of the chiller. Hence, it measures directly the coolant temperature. The volume flow and pressure are measured by a Pelton Wheel flowmeter by LitremeterTM, of accuracy of $\pm 2\%$, [91] and a an external piezoresistive transducer pressure sensor, MPX5100/MPX5100DP series [92] respectively. During this test the chiller pressure was set in 0.8 bar. However, it is observed that the chiller pressure set differs from the pressure total pressure drop over the cooling system,

$c_p(T)$ the heat capacity and ΔT the temperature increase along the transfer line.

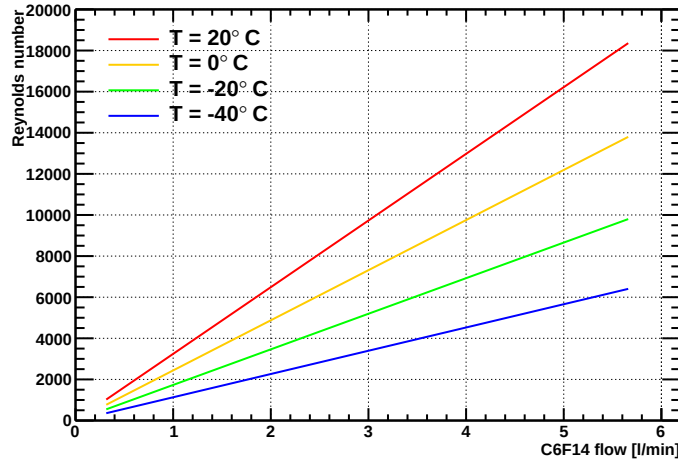


Figure 3.51: Evolution of the Reynolds number with the volume flow for C6F14 through the transfer line. -40 (red), -20 (green), 0 (orange) and 20°C (red). The typical volume flow of the BGV system is ~ 4.7 l/min for the pressure set of 0.8 bar, hence the flow is turbulent over the whole BGV system.

measured by the external pressure sensor. Note that the sensor measures a pressure drop of about 0.6 bar. Figure 3.54 shows an inter-calibration of the pressure sensor and the pressure set on the chiller.

The temperature decreases in a linear regime, with the chiller at the maximum cooling power, as it is shown in the bottom left graph of Figure 3.55. It is equivalent to a cooling power of $(-3.26 \pm 0.03)^\circ\text{C}/\text{min}$. Figure 3.55 (bottom right) shows also the heating regime, which are equivalent to $(4.08 \pm 0.04)^\circ\text{C}/\text{min}$, for a constant chiller pressure set of 0.8 bar. As expected, a volume flow temperature dependence is observed during the lab tests. Left top graph of Figure 3.55 shows this relation. The linear coefficient is measured as $(7.6 \pm 0.2) \text{ millilitre} \cdot \text{min}^{-1}^\circ\text{C}^{-1}$. Note that viscosity temperature dependence of C6F14 is also linear, see Figure 3.38. These measured values can be compared with a theoretical prediction. Equation 3.27 describes a relative velocity drop of a given fluid as function of temperature. Using this relation, the predicted and measured relative drop of velocity are compared, see Figure 3.56. As one can see, there is a good agreement between measured and predicted values. The slight disagreement at very low temperature is thought to be due to bad accuracy of the flowmeter at this temperature.

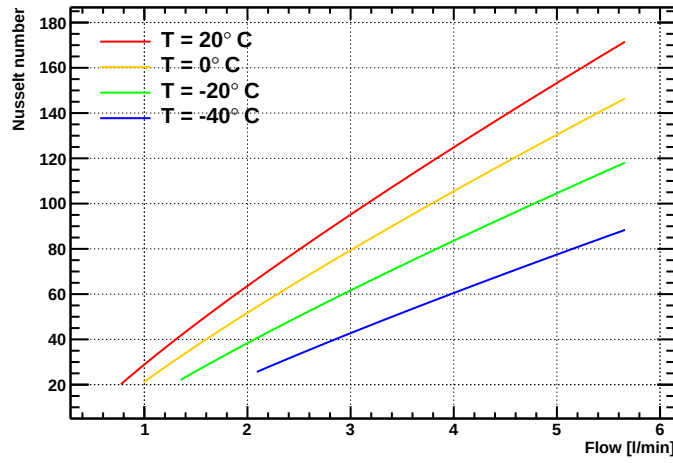


Figure 3.52: Evolution of the Nusselt number with the volume flow for C6F14 through the transfer line. -40 (red), -20 (green), 0 (orange) and 20°C (red). The typical volume flow of the BGV system is ~ 4.7 l/min for the pressure set of 0.8 bar, hence the heat transfer is dominated by convection since the flow regime become turbulent.

One last performance test for the cooling system is understood how the volume flow scales with the pressure drop throughout the system. For this test, similar measurements were made but at fixed temperature and varying the pressure set on the chiller. Figure 3.57 shows the summary of this test. The expected volume flow vs pressure set is compatible with the volume flow measured in the LHC tunnel after the BGV installation. Figure 3.58 shows a comparison between the fitted curve of the Figure 3.57 and the measured total volume flow of C6F14 in the installed BGV cooling plant.

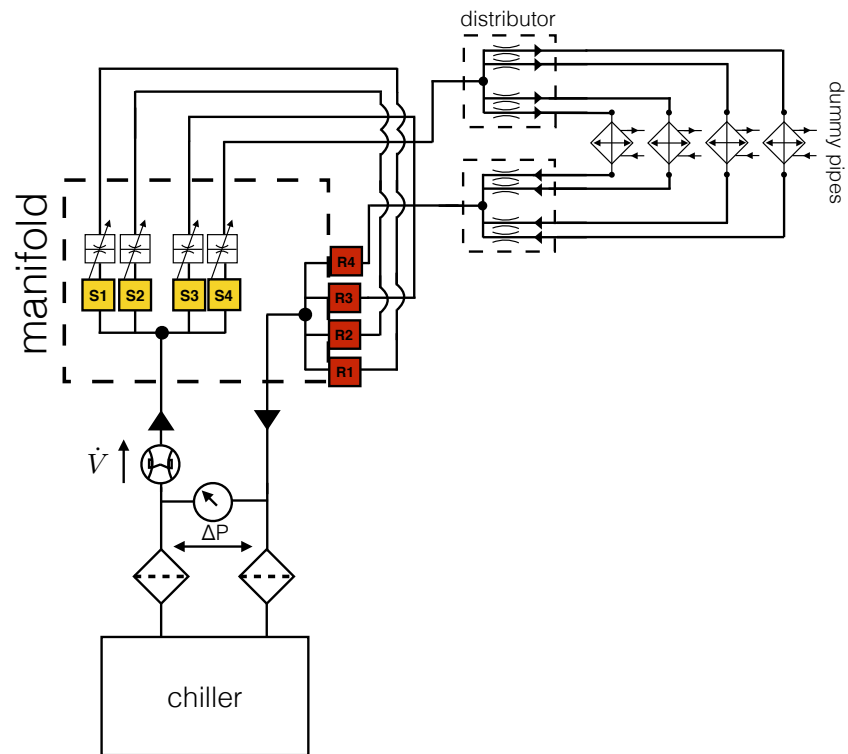


Figure 3.53: Specific configuration for lab tests without transfer line. Only the supply line S4 are loaded with stainless steel (ID/OD 3/4 mm) dummy pipes reproducing similar resistance of the cooling pipes of the BGV modules. Observe that S4 are connect to return R4. The flow on the lines S1→R1 S2→R2 and S3→R3 are controlled by the valves inside the manifold. During circulation and cooling tests all valves are adjusted to have the same flow through the four lines. The total load of the circuit is approximately the same as in the Figure 3.37.

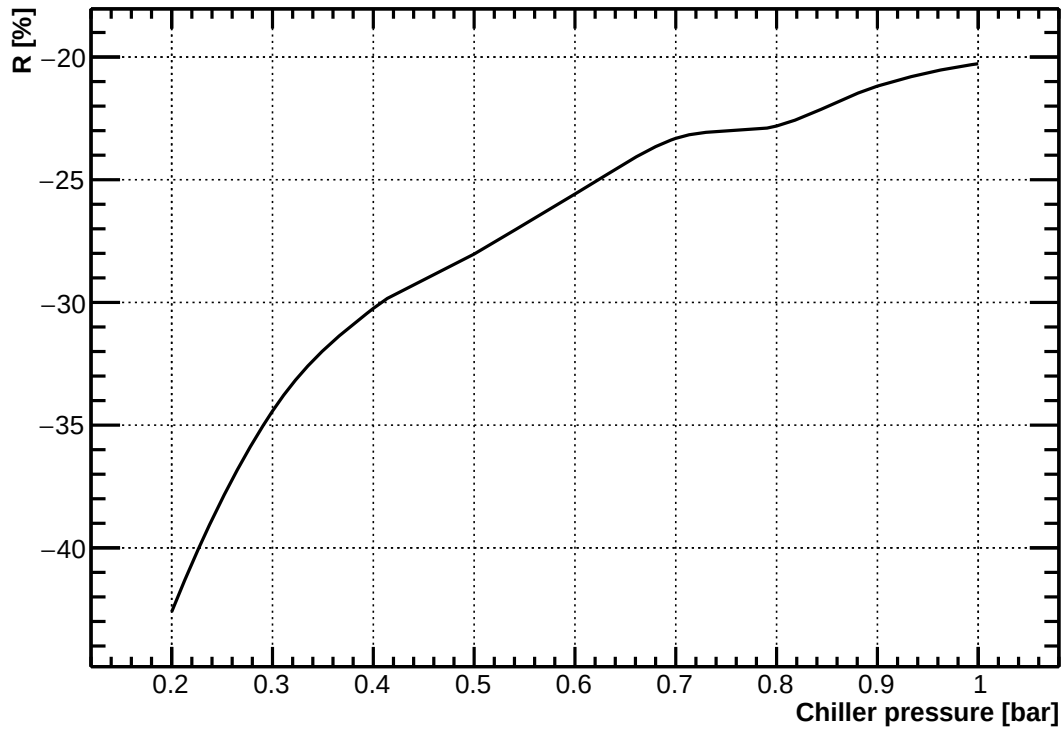


Figure 3.54: Inter-calibration of the pressure set on the chiller and the total pressure drop of the BGV cooling system. R values are defined as: $R = \frac{\langle \Delta P_{\text{meas}} \rangle - \Delta P_{\text{ch}}}{\Delta P_{\text{ch}}}$, where $\langle \Delta P_{\text{meas}} \rangle$ is the average pressure measured by the pressure sensor and ΔP_{ch} is the chiller pressure set.

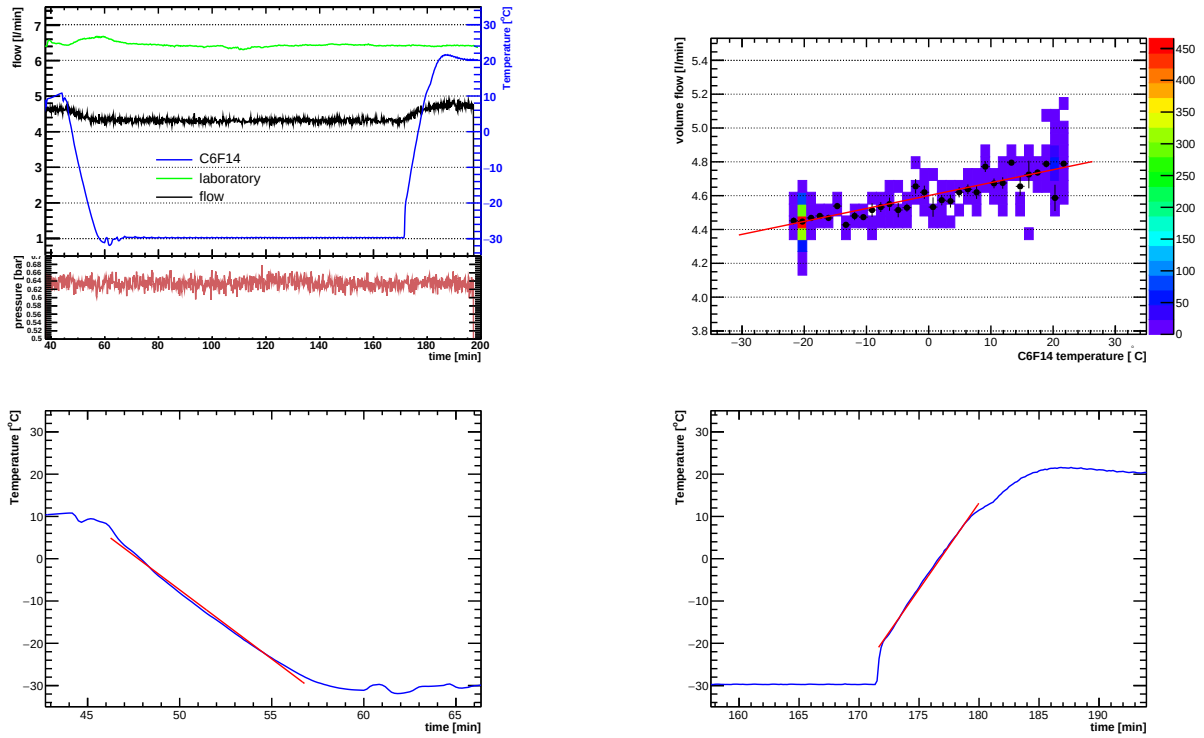


Figure 3.55: Top left – summary of a cooling test performed in laboratory with the small circuit. Green is the lab temperature, blue is the C6F14 temperature measured by a PT100 probe inside the output tube of the chiller (right vertical axis). Black is the volume flow measured by the flowmeter (left vertical axis) and in the bottom pad is the total pressure drop across the circuit as measured by an external piezoresistive transducer pressure sensor, MPX5100/MPX5100DP series [92], see Figure 3.53. Top right – volume flow vs C6F14 temperature. The liquid viscosity increase as the coolant get cold, see Figure 3.38. Red line is the fit to data: $V = a + bT$, $a = (4600 \pm 0.004)$ l/min, $b = (0.0076 \pm 0.0002)$ l·min⁻¹°C. Bottom left – fit to the linear cooling regime of the chiller at maximum power. The red line is the fit: $T(t) = at + b$, $a = (-3.26 \pm 0.03)$ °C/min and $b = (155.99 \pm 1.56)$ °C, where $T(t)$ is the C6F14 temperature as function of the time [min]. Bottom right – fit to the linear warming regime of the chiller at maximum power. The red line fit is: $T(t) = at + b$, $a = (4.08 \pm 0.04)$ °C/min and $b = (-721.25 \pm 6.81)$ °C.

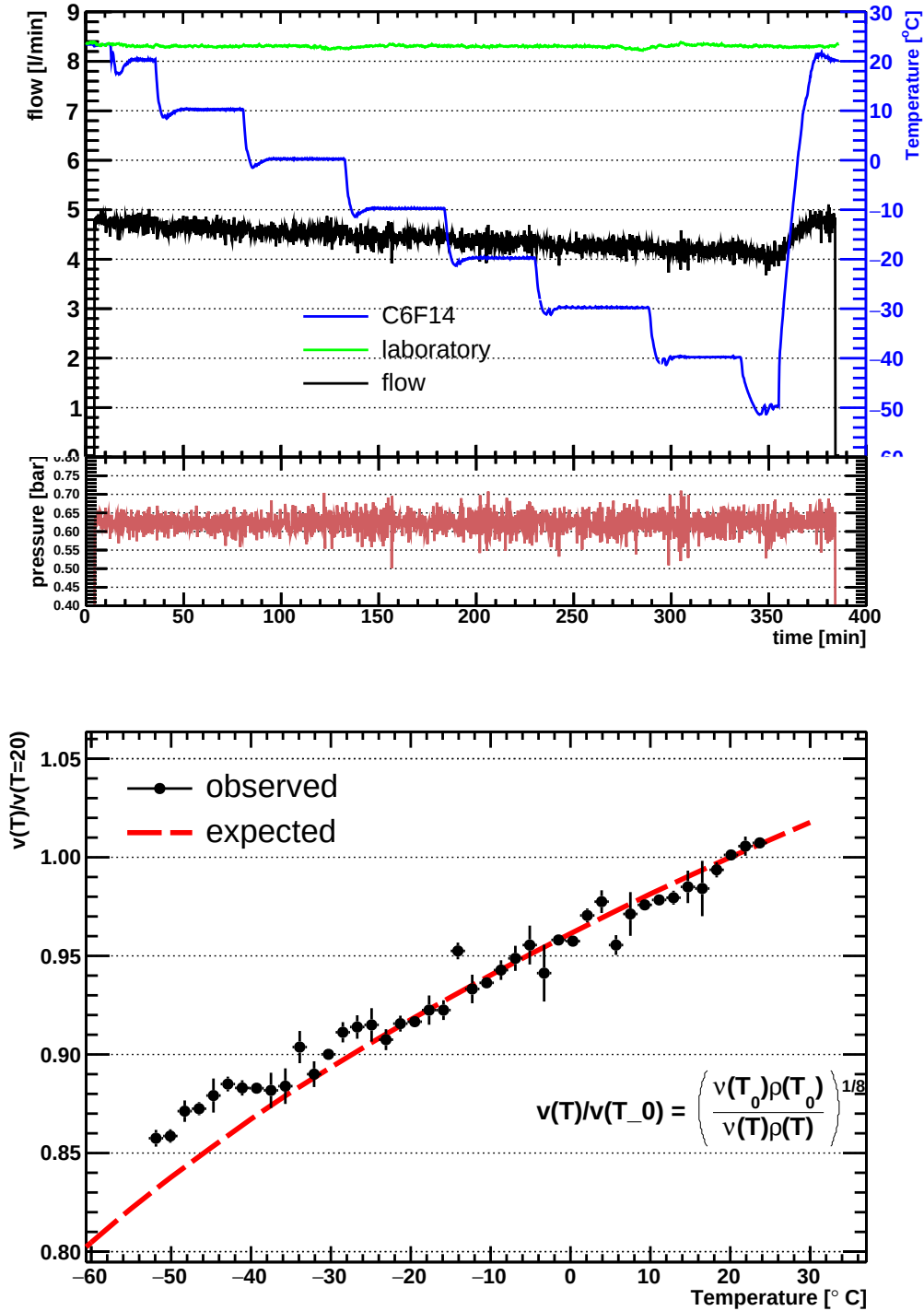


Figure 3.56: Volume flow temperature dependence of the BGV cooling system. The top graph shows the summary of the data taken. Blue is the C6F14 temperature and green the lab temperature (vertical right axis). Black is the volume flow (vertical left axis). The bottom pad is the pressure measured by the external pressure sensor. The top plot shows the measured and expected values from Equation 3.27 for C6F14. There are a good agreement between predicted and measured values. The slight disagreement at low temperature is thought to be due bad accuracy of the flowmeter at low temperature.

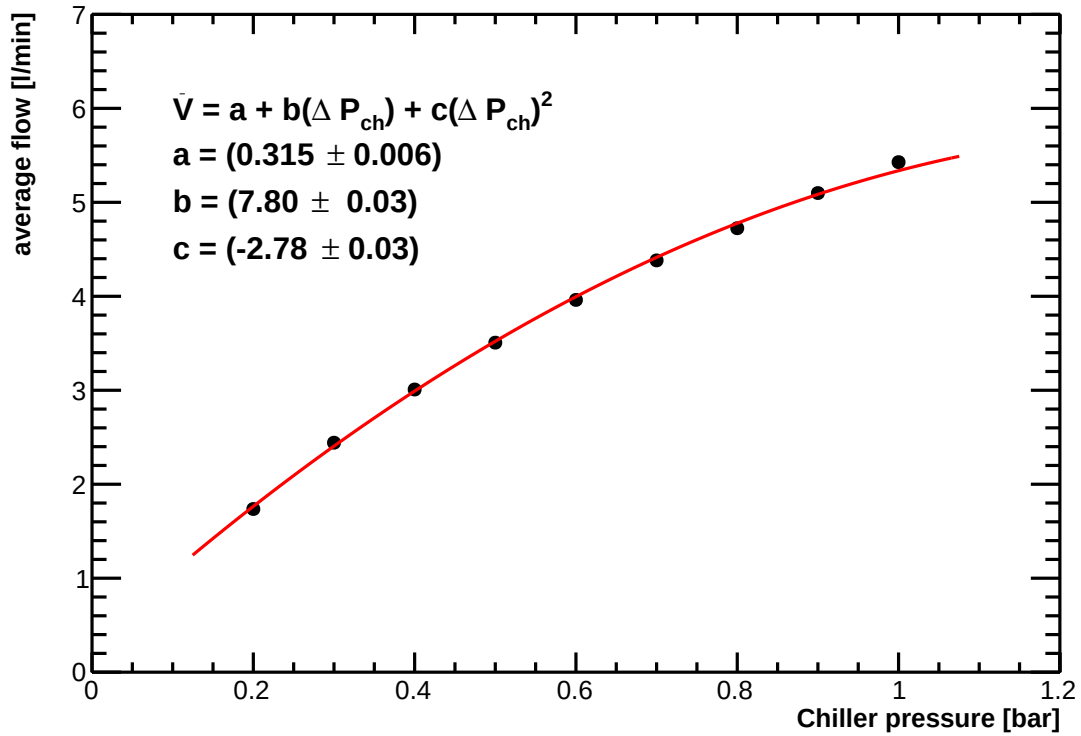
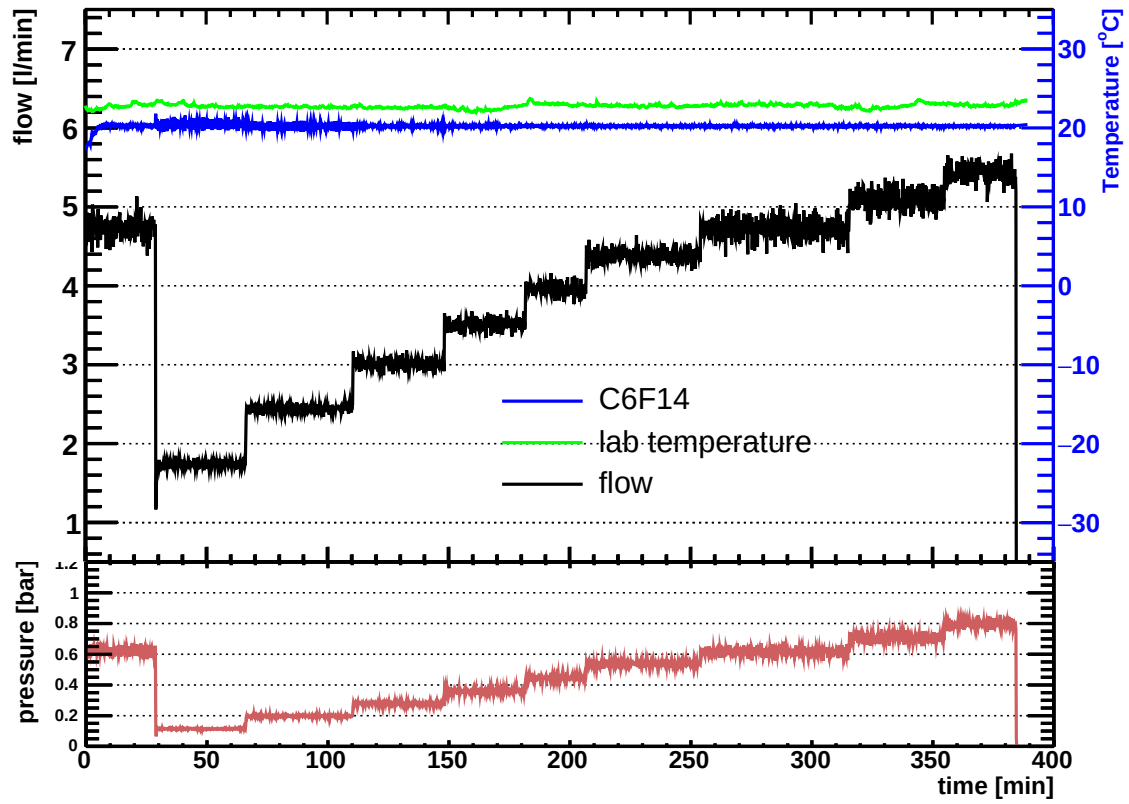


Figure 3.57: Top – summary of the pressure test made on the small cooling circuit of Figure 3.53. Bottom – Result of the volume flow vs chiller pressure fitted to data. Each bin is the average flow at a given pressure set.

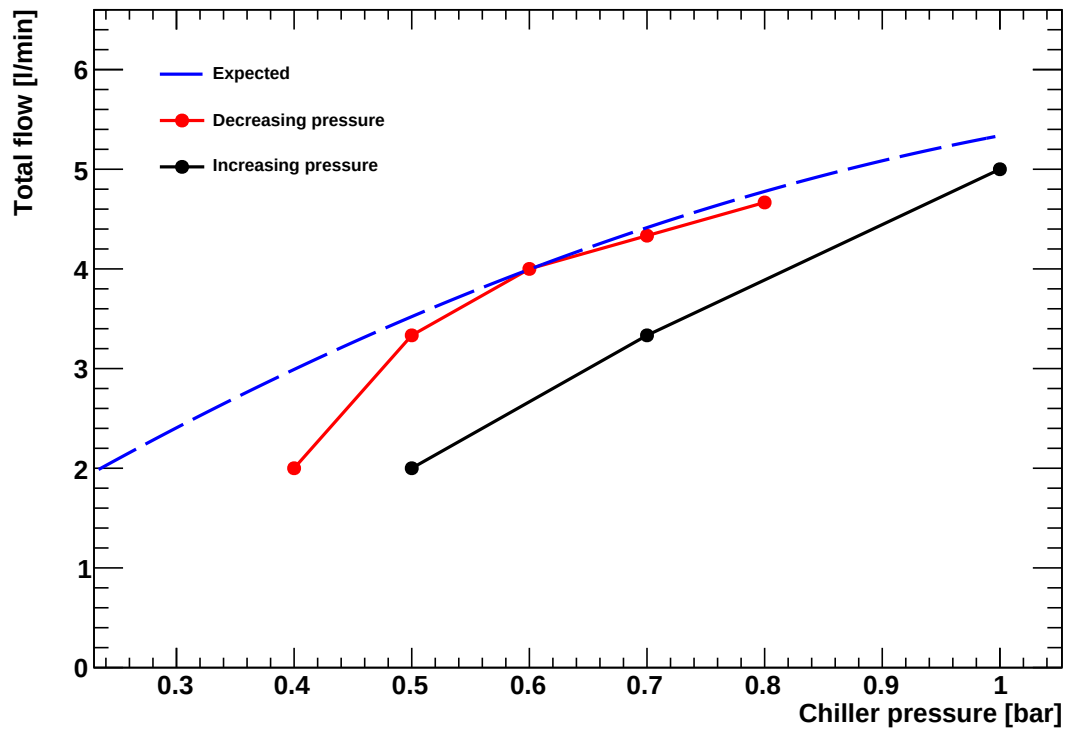


Figure 3.58: Comparison between the expected volume flow of C6F14 in the tunnel and the measured volume flow in the tunnel. The expected volume flow are given by fitted curve of Figure 3.57, indicated by the dashed blue curve, and was obtained using the small circuit during lab tests. The volume flow of C6F14 in the LHC tunnel, after the BGV installation, was measured at $\sim 15^\circ\text{C}$ and read by the flowmeters of the BGV manifold. The flow was measured increasing the pressure, from 0.5 to 1 bar (black curve) and decreasing the pressure from 0.8 to 0.4 bar. The difference between then are thought to be due the inertia of the liquid.

Chapter 4

Jets at LHCb

As discussed in Chapter 1, the purpose of defining jets is to reduce the complexity of the final state objects whilst retaining the physics information of interest. Jets are used for a wide range of physics analyses. The jet production in pp collisions can be seen as a probe of QCD, they are present in many physics processes and represents a huge background for the processes studied in LHCb. On the other hand, jets can be used to probe parton distribution function and study resonance decays. Furthermore, once LHCb cover a unique forward region, LHCb jets measurements allow to probe PDFs at kinematic region not accessible at others LHC experiments. Jet measurements in the very forward region have smaller momentum as compared with jets at central region. A jet with total momentum of 400 GeV in the forward region will have p_T of around 100 GeV for $\eta \sim 2$, and about 40 GeV for $\eta \sim 3$. A hard particle produced with p_T of 400 GeV and with $\eta \sim 2$ would have total momentum in excess of 1 TeV. Therefore, particles with relatively high transverse momentum will have a huge total momentum inside the LHCb acceptance. It became a challenge to reconstruct such energetic particle correctly because the detector response (in general) saturates at high energy. Consequently, once the LHCb is sensitive to jets in a different region to that of ATLAS and CMS: the majority of jets at LHCb have comparatively low transverse momenta and relatively few events contain jets with p_T above 100 GeV.

Heavy flavour jets is also of physic interest. The number of heavy quarks produced in

pp collisions can be measured by associating a hadron inside the jet cone, as is described later in this chapter.

Throughout this chapter the baseline tool and framework for the bottom jet analyses associated with vector bosons at LHCb are discussed. The particle flow approach is the standard LHCb jet reconstruction where contributions were made to improve the method by evaluating the neutral energy of jets content.

4.1 Jet reconstruction

The particle-flow algorithm aims for reconstructing and identifying particles in the event combining all LHCb sub-detectors towards an optimal determination of their direction, energy and identity. This algorithm is designed to use information from throughout the LHCb detector to provide a list of input particles that are subsequently reconstructed into jets. Jet reconstruction algorithms at some other detectors simply use information from calorimeters, running the jet clustering algorithms on a list of calorimeter-based inputs. Such an approach is not feasible at LHCb as the calorimeter cells are relatively large and saturate at high energies. On the other hand, the tracking systems at LHCb enables accurate momentum resolution of charged particles. Therefore, the particle flow approach uses different detector subsystems to measure different particles, improving the jet energy resolution from that which would be achieved from a simple calorimeter based approach. The particle flow algorithm is tuned to optimise the jet energy resolution, using information from tracks where possible, and only uses calorimeter information where no track information is available as for example, photon and neutron depositions in the calorimeters. The detailed treatment of neutral particles are described in details bellows in the section 4.1.1.

The clustering of the list of input particles is handled using the FastJet [24, 25] interface. Jets are reconstructed using the anti- kT algorithm with $R = 0.5$. This value of

R gives reasonably small differences between the hadron level and the parton level* [93], and the jet energy resolution at LHCb shows little variation with values of R in the range 0.4 to 0.7. The chosen value of R is the same as the value used by the CMS experiment, allowing easier comparison with CMS results where applicable. The LHCb software has the ability to reconstruct jets with p_T above 5 GeV, but in this thesis we only consider jets with $p_T > 12$ GeV and $2.0 < \eta < 4.5$. This choice is made up to select only jets with enough energy and momentum resolution, as accounted in Monte Carlo. They are well reconstructed jets. In order to improve the sensitivity to the Higgs signal, however, jet p_T region is tightened to $70 < M_{jj} < 150$ GeV. It will be explained in more detail in the Chapter 5.

An advantage that the LHCb experiment has over the other experiments at the LHC is that collisions at LHCb take place in a low pile-up environment. Collisions at LHCb typically contain only one or two reconstructed primary vertices. Consequently the effects of particles produced in other proton-proton interactions are reduced. Moreover, LHCb profits from an excellent impact parameter resolution from the VELO, and tracks originating from VELO can have requirements to come from primary vertex. Usually the requirements are based on the χ^2 values of the track to the vertex. On the other hand, there is no way to associate calorimeter clusters accurately with an individual vertex, so all calorimeter clusters are considered.

The particle flow algorithm starts by selecting all long tracks from the primary vertex of interest. All downstream tracks are also selected. Informations from RICH I and II are used to determine the most likely particle track, and the corresponding particle mass is used to set the particle four-momentum. No additional track quality requirements are placed on the tracks beyond the standard LHCb track quality requirements. Upstream tracks are also considered for their primary vertex information; the momentum resolution

*At parton level jets is reconstructed using as input parton objects and in the hadron level only hadron is used. This approach is possible only using simulation.

of these tracks is very poor, but the momentum of these tracks is also typically comparatively small, as they are bent out of the detector coverage by the magnetic field. These particles are therefore simply assigned zero momentum within the particle flow algorithm. As the k_T algorithms used to reconstruct jets are infra-red safe, the presence of zero momentum particles in the list of inputs does not change the number of jets or the jet energy [23]. However it increases the number of particles in the jet associated with the primary vertex. This is a useful quantity that will be discussed later, as it is a variable that can be used to reject ‘fake’ jets. If a group of tracks are consistent with a neutral resonance ($V0$, K_s , B , D) then the tracks are removed from the list of inputs (if they were initially included) and instead the resonance is used. Resonant particle will tend to point back to the proton-proton interaction whereas the tracks may have a large impact parameter with respect to the vertex. Where it is possible to reconstruct multiple $V0$ s from the same tracks, the $V0$ with the best vertex χ^2 is used.

In addition to track-based inputs, the particle flow algorithm considers reconstructed neutral particles as inputs for jet reconstruction. Isolated clusters in the electromagnetic and hadronic calorimeters are associated with neutral electromagnetic and hadronic particles respectively. The clusters are considered to be isolated if they are sufficiently far from tracks. This is defined in terms of the χ^2 separation of the cluster from nearby tracks. For clusters in the ECAL, if the χ^2 separation from every track is greater than 25 then the cluster is considered isolated. For clusters in the HCAL, the required separation for a cluster be considered as isolated is chosen to vary with the cluster energy. For cluster transverse energies below 5 GeV the χ^2 separation must be greater than 25, whereas for transverse energies above 5 GeV then the cluster separation must be greater than 16. HCAL clusters are only considered if they have transverse energy greater than 2 GeV.

However, high energetic jets contain many particles produced at small angles with respect to each other. Simply taking isolated neutral particles will underestimate the number of neutral particles in a jet, as some will fall close to tracks. The main advantage

of the particle flow approach is that it allows to recover the neutral content.

For each track in the event, the expected calorimeter deposits in both the ECAL and HCAL are found as functions of the track momentum and the best hypothesis of the track species.

In other words, the algorithm presumes that electrons and hadrons leave different deposits in the calorimeters. This procedure is detailed described below.

4.1.1 Neutral recovery

In the first jet reconstruction version [94], the total energy deposited by neutral particles on the calorimeters were not considered.

To include these clusters of neutral particles hits, one needs to evaluate how much of the track momentum is deposited in the calorimeter, so it is possible to recover the amount of deposited energy by neutral particles. This procedure is the so called *neutral recovery*.

To extract the neutral component of the total jet energy, a single track-cluster association are made: only tracks which are associated to a single cluster on calorimeters are selected. Therefore, comparisons between the energy deposition on the calorimeters with the track momentum are made and the efficiencies for a track to have only one cluster associated on the calorimeter system are calculated.

The simulated events are generated with non-universal cuts. The data sample used is collected with a minimum-bias trigger.

Track-Cluster Selection

To make an association of tracks and clusters in the calorimeters, only long or downstream tracks are of interest, since they are useful to make a proper track-cluster association. About 21 million events of 2011 ($\sqrt{s} = 7$ TeV) data were selected before our track selection.

The requirements used in the track-cluster selection are summarised below:

- only used events with one primary vertex;
- the track is reconstructed as single particle jet with cone size $R = 0.5$;
- $p_T > 50$ MeV - track transverse momentum;
- $E_T > 200$ MeV - cluster transverse energy;
- χ_{ECAL}^2 (χ_{HCAL}^2) < 1 - track-cluster association for ECAL (HCAL);
- no other track associated with the cluster with χ_{ECAL}^2 (χ_{HCAL}^2) < 100 ;
- the track must have inAccECAL (inAccHCAL) flag true for ECAL (HCAL)[†].

χ_{ECAL}^2 (χ_{HCAL}^2) is a measurement of the matching of between the track momentum position in calo-plane and the barycentre of the cluster energy defined as

$$\chi_{\text{CALO}}^2(\mathbf{V}) = (\mathbf{V}_{\text{tr}} - \mathbf{V})^T \mathcal{C}_{\text{cl}}^{-1} (\mathbf{V}_{\text{tr}} - \mathbf{V}) + (\mathbf{V}_{\text{cl}} - \mathbf{V})^T \mathcal{C}_{\text{cl}}^{-1} (\mathbf{V}_{\text{cl}} - \mathbf{V}), \quad (4.1)$$

where $\mathbf{V}_{\text{tr}}$ is the vector of the momentum of the reconstructed track *i.e.* the (x,y) point on the calorimeter reference plane, $\mathcal{C}_{\text{tr}}$ is the 3×3 covariance matrix of $\mathbf{V}_{\text{tr}}$, $\mathbf{V}_{\text{cl}}$ is the vector cluster energy and position, $\mathcal{C}_{\text{cl}}$ is the 3×3 covariance matrix of $\mathbf{V}_{\text{cl}}$. $\chi_{\text{CALO}}^2(\mathbf{V})$ is then minimised with respect to V and the minimum value is used.

The reconstructed tracks are identified as hadrons, electrons or muons. For both data and simulation, the default LHCb particle identification algorithm is used. E/P calibration using ‘*true*’ MC particle identification is also studied. In simulation, (as is in data) each track is associated to a particle ID, given by combinations of informations from RICH detectors and calorimeters. But the ‘*true*’ particle ID given by the simulation is accessible as well and can be used to account for number of tracks miss identified as hadron, muons or leptons. The E/P results using both particle ID (from PID system, and true MC information) are the same, indicating that there is very few amount of tracks miss associated to particles.

[†]The flag true means that extrapolation of the tracks reaches the calorimeters.

The exclusion requirement of close clusters with χ_{ECAL}^2 and $\chi_{\text{HCAL}}^2 < 100$ is to avoid multiple clusters association with the same track which could increase the E/P ratio. For HCAL about 15% of clusters were excluded from the data. In ECAL 9% of events have such contaminations. The correction in E/P using this requirement is less than 1%. This requirements are not applied to the background studies.

The transverse cluster energy is defined as:

$$E_T = \sqrt{E_x^2 + E_y^2} \quad (4.2)$$

where

$$E_x = E \frac{x}{\sqrt{x^2 + y^2 + z^2}}, \quad E_y = E \frac{y}{\sqrt{x^2 + y^2 + z^2}}$$

and (x, y, z) is the position of the barycentre of the cluster on the calorimeter plane. E is the total cluster energy. In the next section the choice for these cuts are explained.

The χ_{ECAL}^2 (χ_{HCAL}^2) of calo-clusters give us information of how close is the track position on the calorimeter plane to the barycentre of the cluster energy [95]. Placing a hard requirement on this variable, is ensured that the cluster have only one associated track. Also is selected only tracks flagged as inAccECAL (inAccHCAL) which means that a extrapolation of the track reaches the calorimeters.

E/P Analysis Strategy

Electron, muons and hadrons have different shower pattern in the calorimeters. Therefore energy and momentum ratios (E/P) are sensitive to the type of interaction and have different mean values for different particle species and momentum. For instance, minimum ionising particles (hereafter referred to as *MIP*) should reach a E/P plateau for high momentum tracks whilst electrons should deposit their total energy in ECAL.

Background

MIP particles, specially muons, deposit a minimum energy in the calorimeter but still have cluster associated to the track. Such cases are undesired and considered as background in

this analysis, since the aim is to estimate the showering energy deposit. To illustrate the *mip* E/P, we select muon tracks as is shown in Figure 4.1. As expect, this distribution

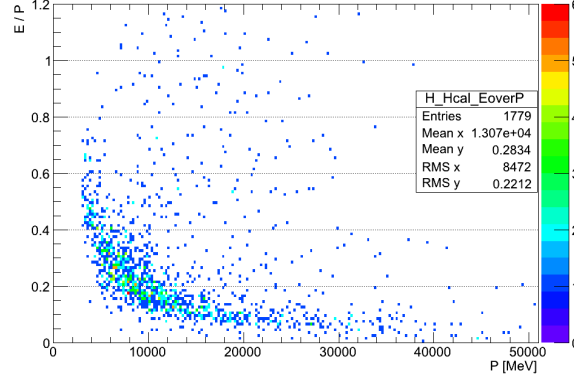


Figure 4.1: 2D scatter plot of E/P vs P of the cluster energy associated to muon tracks in HCAL. The scatter behaves like $1/x$ function indicating that there are no correlations between energy and track momentum. This energy deposition is treated like noise on calorimeter. We can also see the *mip* contribution in Figure 4.4 which shows their transverse energy in both calorimeters.

have an asymptotic limit to zero, showing that the cluster energy is uncorrelated to muon momentum.

In the particle flow method, a looser χ^2_{ECAL} (χ^2_{HCAL}) cut is applied. However, for single track-cluster association, a tight cut is chosen to remove further noise. The effect the hard cut in χ^2_{ECAL} is shown in Figure 4.2. As one can see, this cut selection suppress the MIP component. The same effect of this cut in HCAL can be seen in Figure 4.3.



Figure 4.2: 2D scatter plot of E/P vs P for ECAL. The left is for track and clusters with $\chi^2_{ECAL} < 16$ which is used in Particle Flow algorithm. At right side the same plot but with $\chi^2_{ECAL} < 1$. No cut in transverse energy was applied and long and downstream tracks were selected.



Figure 4.3: 2D scatter plot of E/P vs P for HCAL. The left is for track and clusters with $\chi^2_{HCAL} < 25$ which is used in Particle Flow algorithm. At right side the same plot but with $\chi^2_{HCAL} < 1$. No cut in transverse energy was applied and long and downstream tracks were selected.

In order to suppress MIP background in the track-cluster selection, studies of the transverse cluster energy (E_T) were performed. E_T distributions are sensitive to particle species and at ECAL is calibrated to peak at 100 MeV for muons. Figure 4.4 shows the normalised E_T distribution for muons and hadrons with different χ^2_{ECAL} (χ^2_{HCAL}) and E/P requirements. The low E/P requirement selects the cases where the particles act as MIP. Cut in $E_T = 200$ MeV is chosen to remove most of the MIP contributions mainly from muons. The effect of this cut in the E/P vs P distribution for ECAL and HCAL can be seen in Figure 4.5.

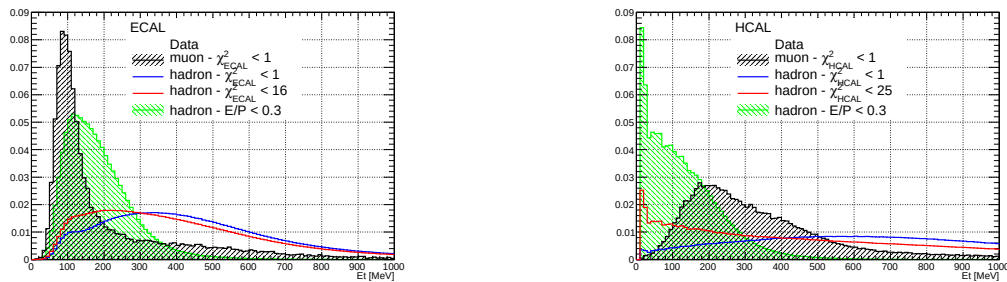


Figure 4.4: The left (right) figure shows the normalized histogram of transverse cluster energy in ECAL (HCAL). The peak component close to 100 MeV for muon ECAL indicates that is dominated by MIP since that is how the calorimeter is calibrated. For HCAL the histogram are shifted to the left and it is thought to be a noise effect.



Figure 4.5: At Left (Right) the plot show the effect of the cut in transverse cluster energy for charged hadrons in ECAL (HCAL). The plot have a cut in 200 MeV. The asymptotic noise component that we saw in Figure 4.1 is suppressed. The muon component visible at the bottom of the left graphs of the Figure 4.2 and 4.3 is removed. Those are the final plots used to account for E/P.

E/P dependences

It is known that ECAL saturation is changing cell by cell and is flat in E_T all over the detector. Also ECAL inner, middle and outer areas have different segmentation and to consider these effects we evaluate E/P for each ECAL area. No differences were found between treating the two HCAL regions either separately or together, so E/P is treated equally over all HCAL areas.

For hadron tracks, three different configurations of track-cluster association is considered depending on whether tracks have only one cluster in both calorimeters or not:

- track which have one cluster only in ECAL (without deposit energy in HCAL), which is referred as *HCAL dependent*.
- track which have one cluster only in HCAL (without deposit energy in ECAL) which is referred as *ECAL dependent*. This is a more rare case.
- all tracks associated to one cluster in ECAL, no matter have cluster in HCAL, which is referred as *HCAL independent*.
- and the reciprocal case of the above item, referred as *ECAL independent*.

Moreover, the sum of the deposited energy on the calorimeter is used to calculate E/P

vs P , when the track have clusters in both calorimeters, always separating in ECAL areas: inner, middle and outer. See left drawing of Figure 2.19.

For electrons we select tracks with cluster only in ECAL.

E/P Fit

To compute E/P from the 2D scatter plot shown above, 1D-projections in one pre-selected momentum range[‡] is calculated by the standard ROOT `Yprojection` method. Then 1D projections are re-binned to an appropriate scale, which depends on the number of entries. From these distributions the histogram mode[§] is selected, whose value is assumed as the average value of E/P and their error is expected to be the width of the bin. Then each bin of E/P fit is the mode of one `Yprojection`[¶].

For tracks associated to a single cluster in one calorimeter the fit to data of E/P vs P is chosen to be

$$\frac{E}{P}(P) = a_1 e^{-a_2 P} + a_3, \quad (4.3)$$

where a_i , $i = (1, 2, 3)$ are free parameters in the fit. This function have a finite value for high momentum range (which is a_3) as well at low momentum limit (which is $a_1 + a_3$).

For tracks associated to a single cluster in both calorimeters the fit to data is:

$$\frac{E}{P}(P) = (a_1 + a_2 P + a_3 P^2) e^{-a_4 P} + a_5. \quad (4.4)$$

This is motivated to describe the effect that for low momentum, E/P is dominated by ECAL while HCAL contributions dominates for high momentum.

Tracks and associated cluster energy deposition are parametrised as function of the track momentum. Both dependent and independent situations are considered. Those

[‡]width of 5 GeV

[§]The mode is the value that appears most often in a set of data.

[¶]In previous studies the same projection was taken. However their mean value was assumed to be given by a gaussian fit. Therefore, this method is constrained by the fact that the projections is supposed be very well fitted by the gaussian distribution which is not the case in some situations for ECAL, especially when it is applied a veto of HCAL. To solve this problem the histogram mode was chosen as the best one. The result using both methods are compatible when the gaussian fit matches very well in all cases.

parametrizations are for 2011 data for both data and MC. Moreover, no change in E/P is verified between 7 TeV and 8 TeV of centre-of-mass energy in both MC and data.

ECAL and HCAL independent

This subsection presents the results divided by the ECAL inner, middle and outer areas. Figure 4.6 shows the E/P fit to data and MC of Equation 4.3 for the three ECAL regions. As one can see there are small deviations from data to MC simulation. For high momentum tracks the deviations are very small, indicating that the cluster saturation is well simulated. For HCAL the saturations cell-by-cell are less distinct and E/P is calculated for the whole calorimeter. Figure 4.7 shows the result of the fit to data from Equation 4.3. As for ECAL, HCAL E/P are very similar, where high energetic hadron tracks leave about $(86 \pm 1)\%$ $[(91 \pm 1)\%]$ of their momentum in the calorimeter for data (MC).

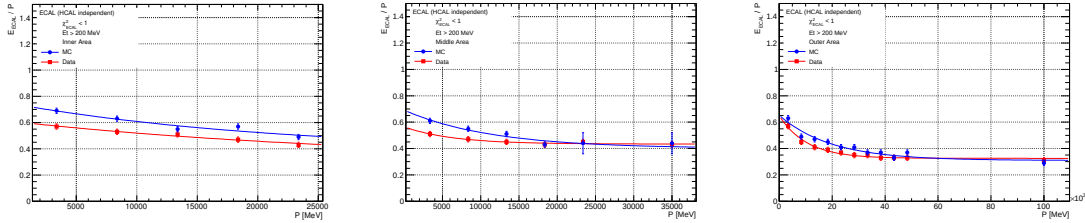


Figure 4.6: Left – E/P vs P for hadron tracks in the inner region of ECAL. Centre – E/P values in the middle region of ECAL. Right – E/P values as function of track momentum in the outer region of ECAL. In all plots: each bin is the histogram mode of the Yprojection of 2D plots of E/P vs P , see text; Red (blue) line is the fit to data (MC) of Equation 4.3. The fit parameters are omitted for simplification. ECAL segmentation is illustrated in Figure 2.19.

ECAL and HCAL dependent

Hadron tracks which have cluster associated to only in ECAL, without depositing energy in HCAL, are expected to have E/P approximately 1. However, depending on the cluster saturation this value can be smaller. Figure 4.8 shows E/P vs P for hadron tracks in ECAL without a cluster associated in HCAL. Since ECAL are downstream to HCAL, no cluster association in HCAL means that hadron tracks stop in ECAL, depositing their

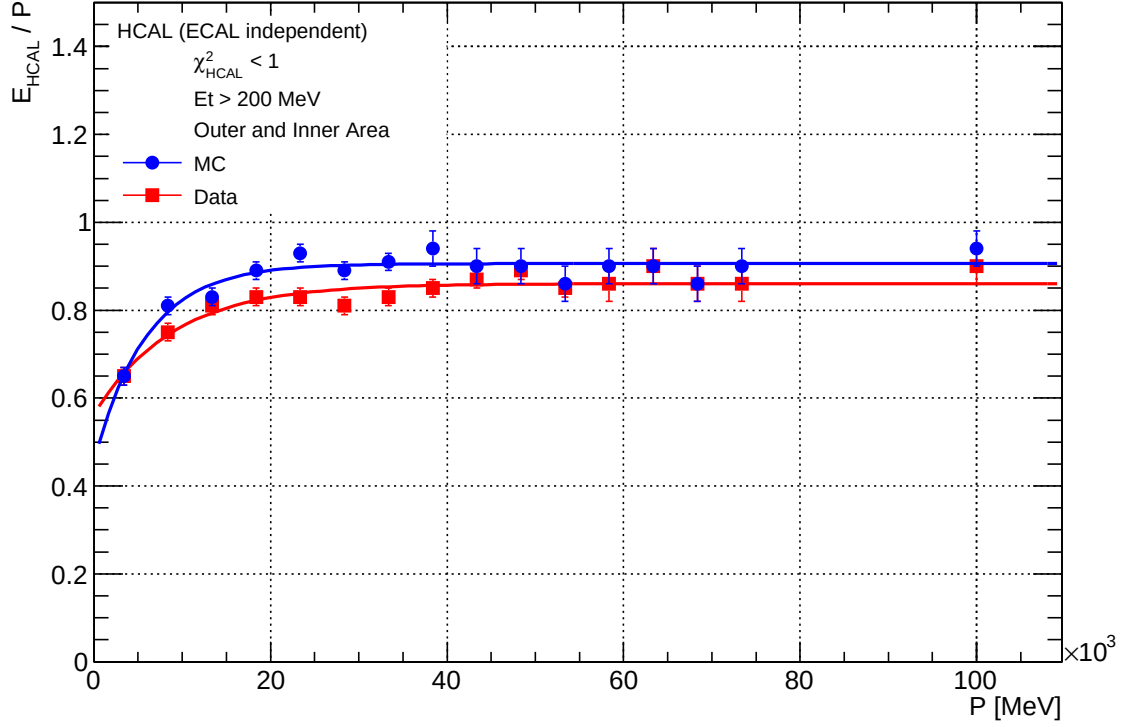


Figure 4.7: E/P as function of the hadron track momentum. Blue (red) markers is the histogram mode of the Yprojection of 2D plots of E/P vs P for data (MC), see text. Solid red (blue) line is the fit to data (MC) of Equation 4.3. The fit parameters results are omitted for simplification.

total energy. It can be seen in the left and center plots of Figure 4.8, where E/P is independent of the track momentum. However, in the outer region where tracks reach the calorimeter near the edge, some tracks may scape the LHCb acceptance and not reach HCAL, whilst their total energy is not deposited in ECAL. It is seen in the E/P dependence with the track momentum in the right plot of the Figure 4.8.

Figure 4.9 shows the case where hadron tracks have a cluster associated only in HCAL. This situation is expected to be rare, considering the clustering efficiency of ECAL. Furthermore, depending of the track momentum multiple scattering in ECAL can shift the track direction, creating a bad track-cluster association in ECAL. Multiple scattering in ECAL is not considered in this study and ECAL track-clustering efficiency is considered as 100 %. Surprisingly, many tracks have clusters in HCAL without “hitting” ECAL.

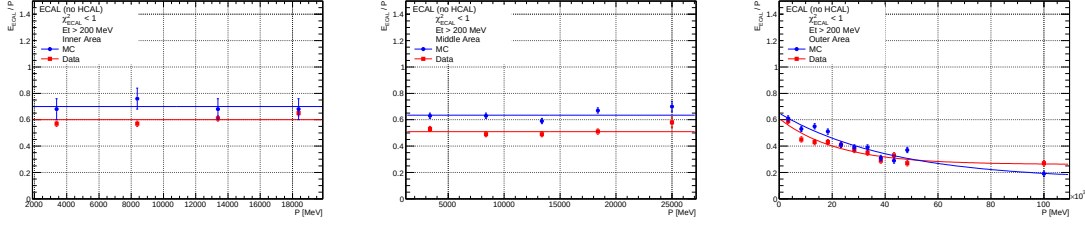


Figure 4.8: Left – E/P vs P in the inner region of ECAL. Centre – E/P vs P in the middle region of ECAL, $P < 25$ GeV. Right – E/P vs P in the outer region of ECAL. Red (blue) markers are average value of E/P for data (MC). The solid red (blue) line is the fit to the data (MC) points. The track selection requires no cluster association in HCAL. Therefore in both inner and middle E/P is independent of the hadron track momentum since the total energy of the particle are deposited in ECAL. However for the outer region of ECAL have track momentum dependence. It is thought to be due high momentum tracks reach ECAL near the edge and escape the LHCb acceptance.

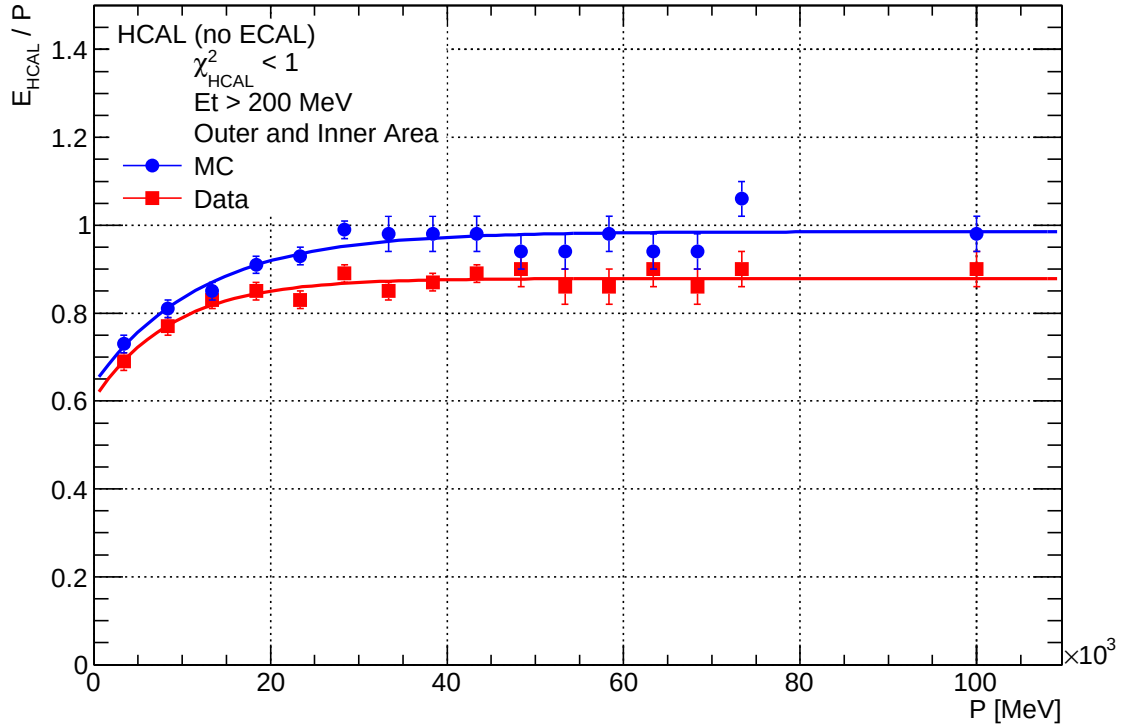


Figure 4.9: HCAL only - whole detector.

The last situation for hadron tracks is when there are cluster association in both calorimeters. Again for ECAL, the inner, middle and outer regions are treated independently. Figure 4.10 shows the plots of E/P vs P for ECAL. As can be see, low momentum

tracks have $E/P \sim 1.0$ whilst is smaller for high energetic tracks. It is a clean evidence of the calorimeter saturation. In the ECAL inner, middle and outer regions the fit to data and MC samples are given by Equation 4.4. The fit parameters results is here omitted for simplicity.

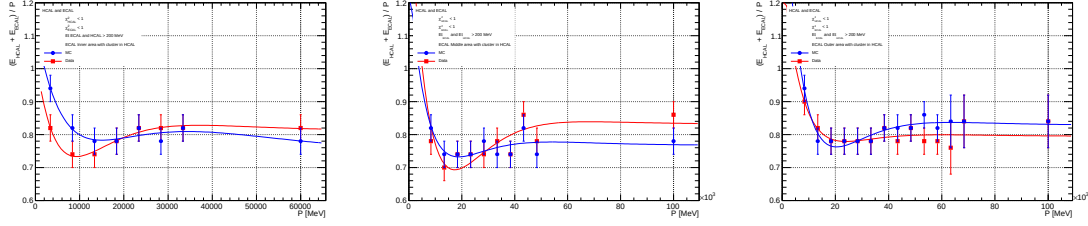


Figure 4.10: E/P vs P in ECAL when hadron tracks have clusters associated in HCAL. The cluster energy is the sum of the energy deposition in ECAL and HCAL. Left – E/P vs P for tracks in the inner region of ECAL. Centre – E/P vs P for tracks in the middle region of ECAL. Right – E/P vs P for tracks in the outer region of ECAL. Red (blue) markers is the histogram mode of the Yprojection of the 2D scatter plot of E/P vs P , see text. Solid red (blue) lines is the fit to data (MC) from Equation 4.4. The fit parameters is omitted for simplicity.

Finally, for electron tracks extrapolated to the HCAL plane, no significant number of HCAL's cluster above background and associated to electron tracks is found. Therefore, the total electron energy is deposited in ECAL. Figure 4.11 shows the E/P vs P for electrons in ECAL. E/P bins are fitted to data and MC according to equation 4.3. As the plot shows, E/P increases with the electron track momentum and for high momentum tracks $E/P \sim 1$.

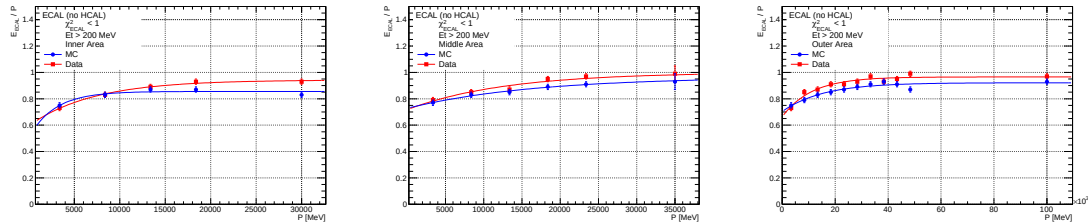


Figure 4.11: E/P of electron tracks in ECAL as function of the track momentum. Left – E/P in the inner region of ECAL. Centre – E/P in the middle region of ECAL. Right – E/P in the outer region of ECAL. Red (blue) markers are the histogram mode of the Yprojection of 2D scatter plots of E/P for data (MC), see text. Solid red (blue) lines is the fit to data (MC) of Equation 4.3.

Track-cluster efficiencies

In order to understand the clustering efficiency for a track to have at least one cluster associated on the calorimeter system of LHCb, the ratio of track to clusters is computed. The number of tracks with clusters which pass the cuts as described in the above section but with no requirement to exclude close clusters with $\chi^2 \leq 100$ is computed. The comparisons are performed for 2012 samples, with centre-of-mass energy of 8 TeV for both MC and data.

Figure 4.12 shows the efficiency for tracks to be matched with a cluster either in ECAL or HCAL. For tracks with cluster in ECAL the efficiency decreases from 70 % to 60% and increases to 70%, becoming flat for $p_T > 3$ GeV. In ECAL, the MC-data discrepancy is of about 10% in the p_T range considered. Such discrepancy is not verified in HCAL which efficiency increases from close to 60% at low momentum to 90% and become flat for p_T higher than 3 GeV.



Figure 4.12: Track-cluster efficiency for ECAL (left) and HCAL (right). Comparison between MC and data can be made. All the tracks selected are in the acceptance region of ECAL or HCAL. The error bars are evaluated by standard root binomial method. Long and downstream tracks were taking into account.

This efficiency increases when all tracks are considered with at least one cluster in ECAL or HCAL. Figure 4.13 shows both efficiencies for data and MC. This efficiency is approximately flat, varying between 90% and 95% and flatness is verified for higher momentum tracks.

To analyse whether the track-cluster efficiency has dependencies on the track recon-

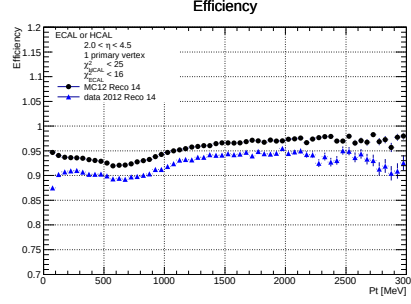


Figure 4.13: Track-cluster efficiency of a track have at least one cluster in ECAL or HCAL. Long and downstream tracks were taken into account. All the tracks selected are in acceptance region of ECAL or HCAL.

struction, the track χ^2 is plotted for tracks with and without cluster association. Figure 4.14 shows the normalised χ^2_{track} histograms of tracks with and without cluster association for ECAL. Figure 4.15 shows the same comparisons for HCAL. One can see that no correlation is found between this variable and the efficiency.



Figure 4.14: Normalized χ^2_{track} histograms of tracks with clusters in ECAL (black) and of tracks with no cluster associated (blue). Long and downstream tracks were taken in to account. No dependency of χ^2_{track} and the efficiency was found. Left-Data. Right-MC



Figure 4.15: Normalized χ^2_{track} histograms of tracks with a cluster in HCAL (black) and of tracks with no cluster associated (blue). Long and downstream tracks were taken in to account. No dependency of χ^2_{track} and the efficiency was found. Left-Data. Right-MC.

The ratio of the number of tracks which have a cluster associated to and are flagged with `inAccECAL` or `inAccHCAL` true is calculated. Figure 4.16 shows this ratio, from where it is concluded that there are no cluster associated with tracks outside the acceptance region of the calorimeters, as expected.

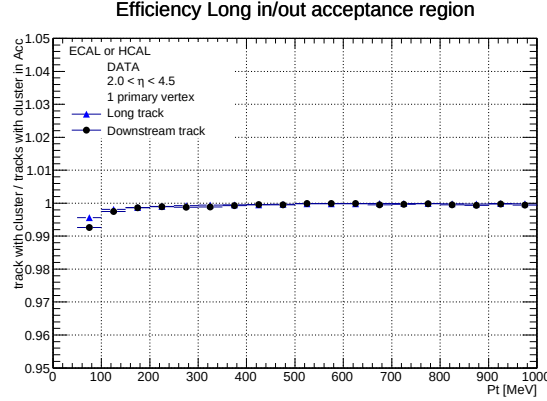


Figure 4.16: Ratio of tracks inside acceptance region with cluster and the tracks with a cluster associated.

4.1.2 Simulated jet reconstruction

Jet reconstruction algorithms are developed using simulated true stable particles at the hadron level. These stable particles are selected after parton shower and hadronisation and are then used as the inputs to be clustered into jets. The same clustering algorithm that is run on the reconstructed particles is run on these true stables MonteCarlo particles.

At LEP, about 60% of the jet transverse momentum is carried by charged particles, and the neutral particles contribute to the remaining 30 % [96]. Neutrinos contribute less than 1% of a jet's p_T (for light-parton-initiated jets). This behaviour is also observed with LHCb simulation [97]. Figure 4.17 shows a comparison of the jet content between clustered jets using truth informations and reconstructed jets^{||} with particle flow inputs. Tracks correspond to roughly 60-68% of the reconstructed jet p_T . Of this contribution, resonant neutral particles which decay to tracks correspond to about 1%. The fraction

^{||}Both plots are then from simulation.

of the reconstructed jet's p_T made up from isolated neutral particles decreases with p_T . At higher p_T jets become more collimated and tend to contain more particles, so fewer neutral particles and clusters are isolated. The fraction of the jet p_T from particles found using the neutral recovery techniques sees a corresponding increase.

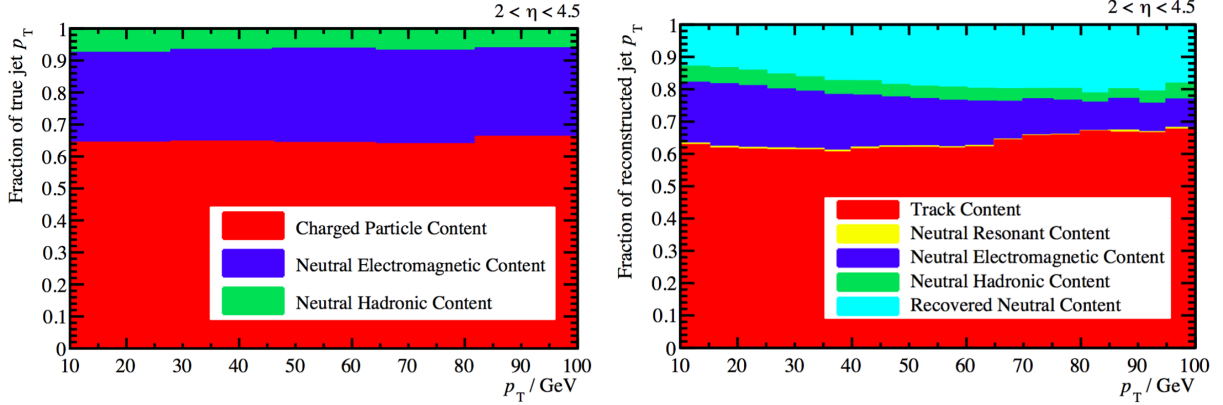


Figure 4.17: Left – The mean fraction of the jet's p_T carried by different types of particles within the jet, at truth level. Right – The mean fraction of the jet's p_T carried by different types of particles within the jet in simulation at reconstructed level. Extracted from Reference [97].

After jet reconstruction a set of quality cuts are applied to minimize the number of ‘fake’ jets, even though about 99% of all jets are reconstructed. These selection requirements were tuned on simulation, with the cut values chosen to remove the majority of bad jets whilst retaining good jets. Based on the reconstructed jets**, the set of quality cuts is [98]:

- at least two particles in the jet pointing back to the PV;
- no one charged particle may have more than 75% of the jet p_T ;
- one charged particle with $p_T > 1.8$ GeV;

4.1.3 Jet energy scale and reconstruction performance

Within the particle flow algorithm the total expected deposit from charged particles (tracks) in each calorimeter cell is compared to the measured non-isolated deposits found

**Reconstructed with simulation.

in the calorimeters. If a cluster of cells shows an excess over the expected energy deposit then the excess is hypothesised to be associated with a neutral particle. To be considered, the cluster must have excess energy greater than 1 GeV. Moreover, calorimeter cells saturate and becomes harder to recover neutral energy deposits. Therefore, not all the energy associated with a jet in the LHCb acceptance can be reconstructed. In addition, in events with pile-up interactions calorimeter clusters and downstream tracks which are not associated with the proton-proton interaction of interest will be considered as particle flow inputs and clustered into jets incorrectly. One must therefore correct the energy of the clustered jets to obtain the best estimate of the energy of the jet at the hadron level.

Jet energy correction (JEC) is a correction to account for detector inefficiency and systematics of the clustering process. The correction is based in term of the four momentum of reconstructed jets as function of the ‘*truth*’ four momentum of the jets at the hadron level. The correction factor k is then,

$$p^\alpha(\text{reco}) = k \cdot p^\alpha(\text{truth}). \quad (4.5)$$

k is found to be dependent of the jet pseudorapidity, number of primary vertices and jet momentum, once jets predominantly consisting of charged particles are expected to be better reconstructed than jets predominantly reconstructed from calorimeter clusters, which are subject to saturation at high energies.

The particle flow performance to measure the total jet energy is evaluated by the jet energy resolution. That way, to consider the resolution with which jets are reconstructed, both in terms of their angular variables, and their transverse momentum, jets at truth level must be compared with the corresponding reconstructed jets (if they exist). Two methods are considered for match jets between the truth level and the reconstructed level:

- truth jets are matched to the nearest reconstructed jets in $\eta - \phi$ space;
- truth jets are matched to the hardest p_T reconstructed jet within a radius of 0.5 in $\eta - \phi$ space.

In the majority of cases the two methods provide the same matching between truth and reconstructed level jets.

Jet energy resolution (JER) is estimated using the width value of the gaussian fit of $\Delta p_T(\text{reco}, \text{truth})$,

$$\Delta p_T(\text{reco}, \text{truth}) = \frac{p_T(\text{reco}) - p_T(\text{truth})}{p_T(\text{truth})}, \quad (4.6)$$

where $p_T(\text{reco})$ and $p_T(\text{truth})$ is the transverse momentum of reconstructed jets and of the truth hadronic jet respectively. Similarly to JEC, JER is sensitive to the number of primary vertices, pseudorapidity and jet transverse momentum [94, 99].

As previously discussed, neutral recovery make use of isolated clusters to recover the neutral energy component. The E/P fits of section 4.1.1 is used to weight the energy deposition in the calorimeters according to the track momentum. This procedure then improve the JER while decrease the correction of the energy. Figure 4.18 shows a comparison between the JER and JEC before and after weight the cluster energy with E/P parametrizations.

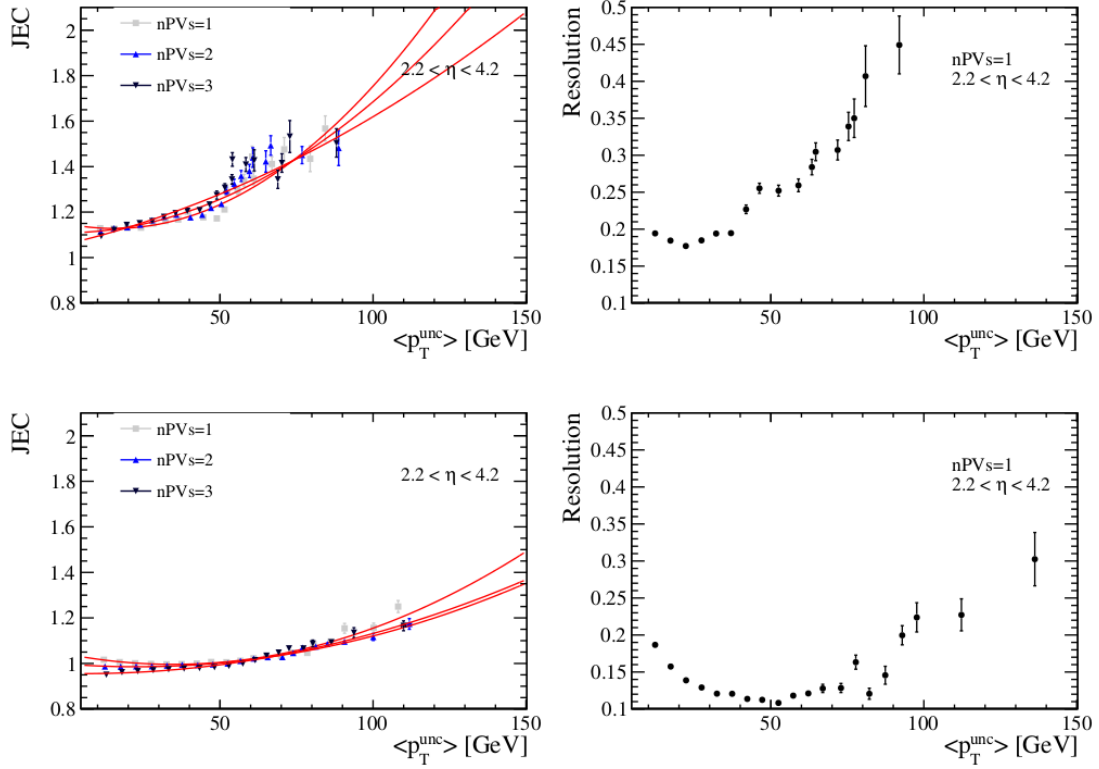


Figure 4.18: Top – JEC (left) and JER (right) as function of the jet transverse momentum at truth level, $\langle p_T^{unc} \rangle$, also referred as uncorrected truth jet p_T , before apply E/P parametrizations of section 4.18 of this thesis. Bottom – The same as top, but after apply E/P parametrizations to weight the cluster energy, depending on the track momentum. The solid red lines are a parabolic fit to the points for 1, 2 and 3 primary vertices.

The resolution is better in events with only one primary vertex. It is expected once particles produced in others collisions may be incorrectly assigned to the jet, degrading the resolution. However, since the particle flow algorithm uses track-based information to reconstruct the majority of the jet p_T , and tracks are assigned to primary vertices, the effect of the presence of additional primary vertices is only about 1% [97]. At low p_T the jet transverse momentum resolution improves as the jet p_T increases, since there are more particles in jets as the p_T increases, so the effect of a mismeasurement of any one particle decreases and an optimal resolution is achieved when the jet p_T is in the range 30–60 GeV. Above this p_T regime, the resolution is worsen because the need for neutral

recovery increases with jet p_T . This process introduces a large uncertainty into the energy of each individual recovered calorimeter cluster, and the jet p_T resolution correspondingly worsens. Moreover, the calorimeter cells start to saturate at higher values of the jet p_T , so less of the jet content is measured, with the jet energy correction becoming larger to correct for this saturation effect. With less of the neutral content of the jet reconstructed and an ‘average’ correction becoming necessary, the jet p_T resolution suffers. Comparison of jet reconstruction at LHCb with and without E/P parametrizations shows that jet p_T resolution are roughly $\sim 10\%$ smaller.

4.2 Bottom jet identification

The LHCb detector features an outstanding capability to identify displaced secondary vertices with respect to the interaction point. Thanks to the VELO precision of reconstruct vertices, both primary and secondary, the LHCb detector is able to perform several analysis involving ‘long-lived’ particles. One of them is the B hadron. Many lifetime and kinematic based properties of the decay of B hadrons are at the basis of the identification of b-quark jets (b-tagging), thus the LHCb detector could prove to be suitable to perform QCD studies based on heavy-quark jets.

The most significant property of the B hadron for their detection is the long B hadron lifetime of about 1.5 ps, which due to the large boost at which they are produced, the average flight distance is of the order of $\mathcal{O} 1$ cm at LHCb. Hence, B hadron decays is characterized by a displaced secondary vertex (SV). The charged particle tracks associated to the SV are distinguishable from the prompt tracks coming from the pp collision by their impact parameter (IP) with respect to the PV. Jets from light flavour hadrons or gluons contain basically no displaced vertex and a suppression of the background due to these component is easy to achieve. On the other hand, c -jets have similar topology due to similar flight distance of c -mesons. So, not only B hadron is associated to displaced vertex. Indeed, any long-lived particle associated to jets can be studied at LHCb [100].

Figure 4.19 illustrates the topology of a c- or b-jet. Other properties of B mesons

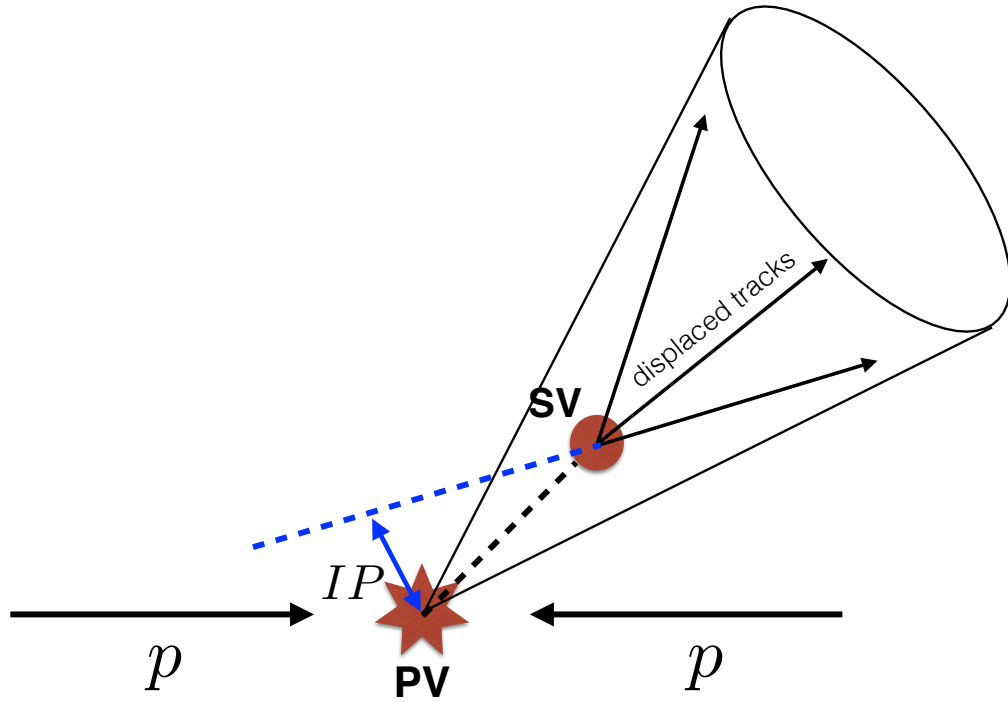


Figure 4.19: Schematic diagram of a B hadron decay that travels a certain distance before decaying at the secondary vertex. The tracks from the decay have a large impact parameter IP . The displaced SV are then associated to a topological candidate.

that may be exploited for background rejection are their large mass and charged track multiplicity in the final state. Due to the hard b fragmentation function the B hadron carries a large fraction of the total jet energy. B hadron mass is composed mainly of the heavy b quark mass. For instance, the electrical neutral B^0 hadron, composed of a d type quark and a anti-bottom quark, have the total mass of (5279.61 ± 0.16) MeV [11]. d quark mass is only $(4.8^{+0.5}_{-0.3})$ MeV while the bottom quark mass is about (4.18 ± 0.03) GeV. Therefore the kinematics of the B hadron production at hadron colliders are dominated by the bottom quark. Identify jets containing B hadrons is then a way to get access to the proton b-quark content. It will be discussed in the next chapter.

Similar to light jet analyses, bottom jets identification studies are performed in simulation and verified in data. The first step of the bottom jet identification (b-tag) is to reconstruct B-hadron candidates, or secondary vertices. This is done by an offline version of the HLT2 Topological trigger algorithm [46]. Potential secondary vertices, significantly separated from the primary vertex, are formed by considering all combinations of two, three and four particles within a jet, where a particle is either a charged track or a V^0 (K_S^0 or Λ). In the online trigger a BDT [101] is used to refine the selection. The tracks are all treated as Kaons to optimise discrimination between b-jets and c-jets, while the V^0 's are unchanged from the default ParticleFlow output.

Two b-tag algorithms are used in this thesis. The first one is based on the trigger strategy with Topo candidates^{††} and the discriminating variable is its corrected mass. This algorithm is used in the Z+b-jet cross-section measurement [102]. The second b-tag method (SV tagger) is based on a more generic secondary vertex reconstruction and it uses multivariate analysis to define discrimination variables: $\text{BDT}_{bc|udsg}$ trained to distinguish heavy-quark jets from light-parton jets and $\text{BDT}_{b|c}$ to separate bottom-quark from charm-quark jets [103].

4.2.1 Topo algorithm

Topo algorithm are used to tag b-jets candidates. It is used on the Z+b-jet cross-section measurement. Usually, Topo candidates should pass quality criteria in order to b-tag the jets. Table 4.1 shows the set of quality cuts to select b-tagged candidates. For jets with multiple Topo candidates, the highest p_T candidate is chosen as the Topo candidate describing the jet. Although the Topo candidate requirement greatly reduces the contamination of jets originating from charm quarks and from light quarks/gluons ($\sim 17\%$ for charm jets and $\sim 1\%$ for light jets - fake rate estimated in simulation), it does not confirm that the jet originates from a bottom quark. Light and charm contamination in the

^{††}A Topo candidate is defined as a displaced vertex reconstructed with two, three or four tracks within the jet cone.

b-tagged sample can be determined with a template fit. The variable to be fitted should be well simulated and discriminant amongst the different jet flavours. The corrected mass of the topological candidates, M_{corr} , fulfil these conditions. It is defined as

$$M_{\text{corr}} = \sqrt{M_{\text{topo}}^2 + p_{\text{miss}}^2} + |p_{\text{miss}}^2|, \quad (4.7)$$

where p_{miss} is the missing momentum transverse to the flight direction inferred from the primary to the secondary vertices. Observe that if the topo candidate flight direction is perfectly aligned with the reconstructed jet direction $p_{\text{miss}}^2 \rightarrow 0$ and M_{topo} is the lowest possible value of the corrected mass.

The M_{corr} templates for bottom jets, charm jets and light jets are taken from MC. The reconstructed jet is matched with a jet reconstructed from MC particles (MCjet). The matching is based on the R distance between the MCjet and the jet. In addition, the MCjet is required to be the highest p_T jet within R less than 0.5. The jets are then classified as:

- light (ℓ -jet): Jets originating from light quark (u,d or s) or gluons. In simulation, light-MCjets are defined as MCjets that have no inputs that are decay products from D or B hadrons.
- charm (c-jet): jets originating from charm quark. In simulation, charm-MCjets are defined as MCjets with at least one input which is a decay product of a charmed hadron, and that have no inputs that are decay products from B hadrons.
- bottom (b-jet): jets originating from bottom quark. In simulation, bottom-MCjets are defined as MCjets with at least one input which is a decay product of a B hadron.

The MC samples used for the template extraction each contain a different fraction of b-jets, c-jets and ℓ -jets. They also represent different physics processes. Figure 4.20 shows the M_{corr} template extracted from each of those samples. They show a similar

Candidate	Cuts
$K^\pm$	$p_T > 500 \text{ MeV}$ $p > 5000 \text{ MeV}$ $\chi^2_{trk} < 5$ $\text{GhostProb}(\text{trk}) < 0.4$ $\text{MIPCHI2DV}(\text{PRIMARY}) > 4$
V^0	$p_T > 500 \text{ MeV}$ $p > 1000 \text{ MeV}$ $\text{MIPCHI2DV}(\text{PRIMARY}) > 4$
Topo	one child with $\text{MIPCHI2DV}(\text{PRIMARY}) > 16$ $\text{BPVVDCHI2} > 100$ $\text{VFASPF}(\text{VCHI2}/\text{VDOF}) < 10$ $\text{SUMPT}(K^\pm, V^0) > 2000 \text{ MeV}$

Table 4.1: Cuts used for the offline version of the Topological reconstruction used for select b-jets, where: MIPCHI2DV is the minimum χ^2 distance of a particle's trajectory to any primary vertex; BPVVDCHI2 is the χ^2 distance between the secondary vertex and the related PV; $\text{VFASPF}(\text{VCHI2}/\text{VDOF})$ is the χ^2 over number of degree of freedom of the Topological candidate end vertex.

behavior across the samples, proving that the process does not affect significantly the M_{corr} distribution.

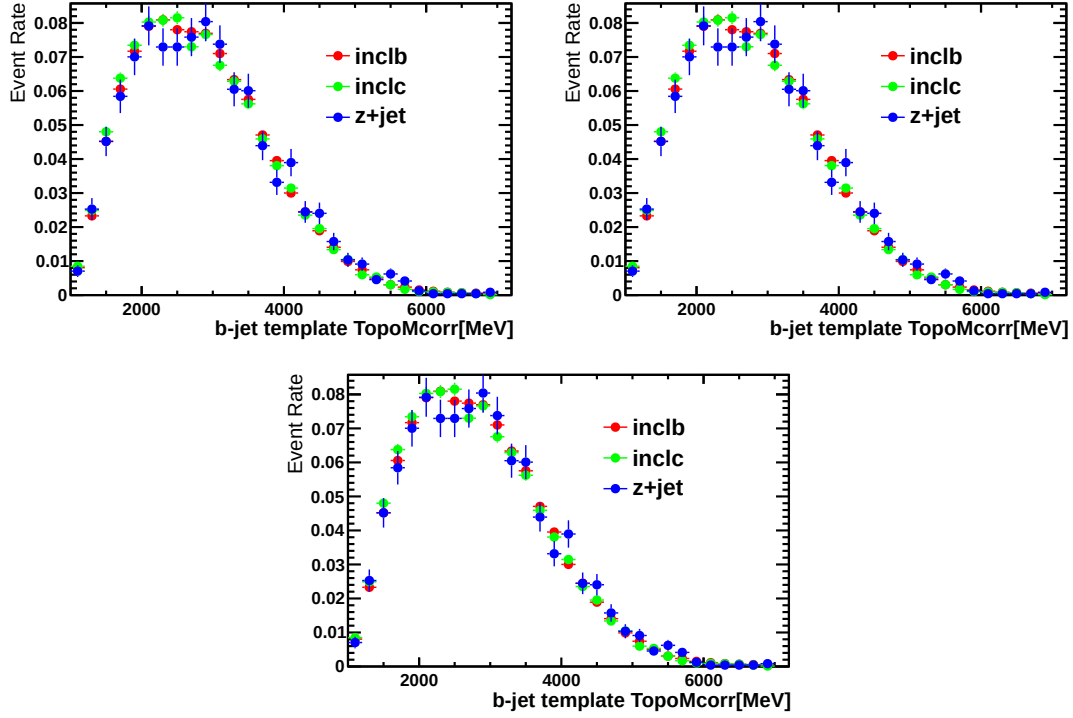


Figure 4.20: M_{corr} templates. Red dot is inclusive b-jet selection, green dot for inclusive c-jet selection and blue dots Z+jet selection.

b-tag efficiency

The b-jet efficiency of ‘b-tagging’ ($\epsilon_{b\text{-tag-b-jet}}$) is used in the Z+b-jet analysis presented in the next chapter to estimate the number of b-jets in the Z+jet sample. There is no data driven procedure to measure the efficiencies and the tag efficiency are calculated only using simulation.

As shown in Figure 4.21, the efficiencies as function of jet p_T and jet η for b-jets and c-jets to have Topo candidate are the same in the different MC samples. The efficiency drops for low jet p_T due to the requirement that a significant fraction of the B-hadron product decays must be inside the jet cone. The jet η dependence is due to the detector borders.

Three samples are added together to valuate the b-jet efficiencies. The efficiencies vary with jet η and jet p_T , as expected (see Figure 4.22). To comply with reasonable statistics and the size of the dependence, the fit to the efficiency with respect to the jet p_T

is divided into 25 bins of jet η . Figure 4.23 shows the fit to the simulated MCjets. Only three bins in jet η are shown for simplicity. In each bin, the fit is given by the function

$$f(p_T) = a(\eta)p_T - b(\eta)p_T e^{-c(\eta)p_T} \quad (4.8)$$

where p_T is the b-tagged jet transverse momentum, dependence of the parameters a , b and c on jet η are given by a third order polynomial fit shown in Figure 4.24. The b-tag efficiency of identify b-jets is used to calculate the cross-section production of b-jets associated with vector bosons.

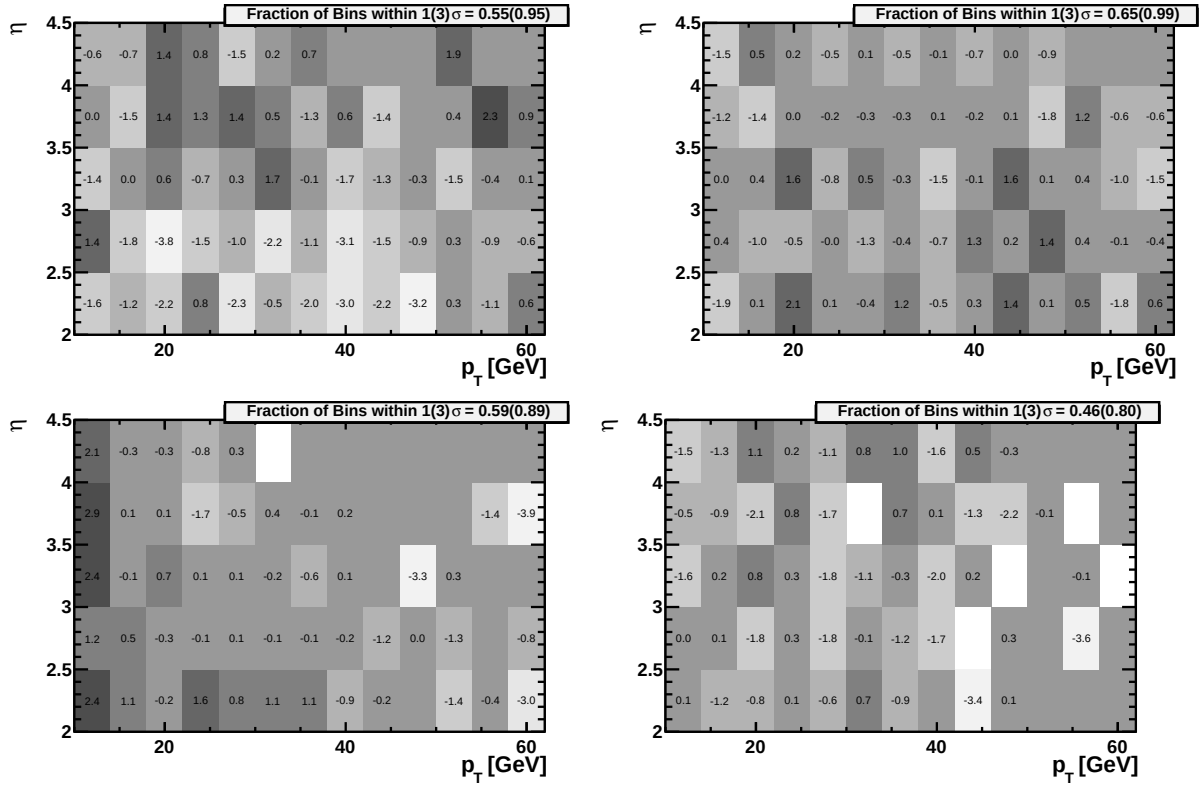


Figure 4.21: The z-axis is defined as $(\frac{\epsilon_1}{\epsilon_2}-1)$, where δ is the error on $\frac{\epsilon_1}{\epsilon_2}$ and ϵ_1 and ϵ_2 are efficiencies as explained below. Top-Left: ϵ_1 (ϵ_2) is b-jet efficiency in $Z + j$ (inclusive b-jet) MC sample. Top-Right: ϵ_1 (ϵ_2) is b-jet efficiency in inclusive c-jet (inclusive b-jet) MC sample. Bottom-Left: ϵ_1 (ϵ_2) is c-jet efficiency in inclusive c-jet (inclusive b-jet) MC sample. Bottom-Right: ϵ_1 (ϵ_2) is ℓ -jet efficiency in inclusive c-jet (inclusive b-jet) MC sample.

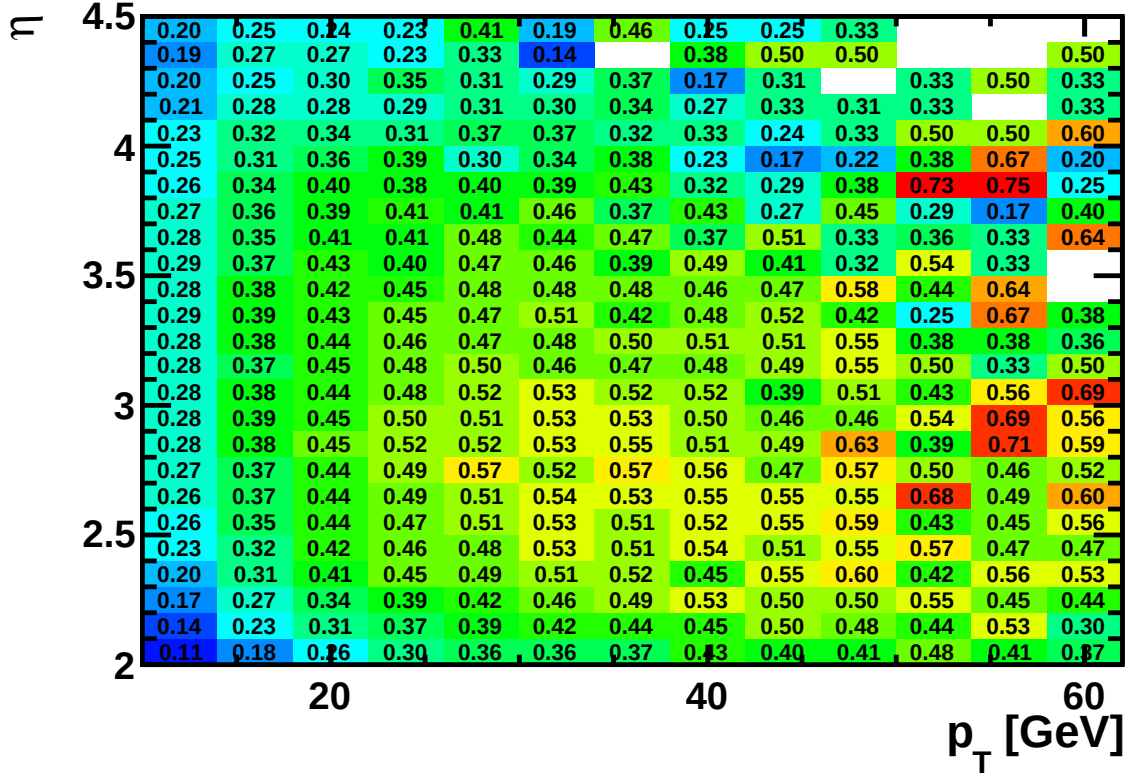


Figure 4.22: b-tag efficiency for b-jets with respect to jet p_T and jet η .

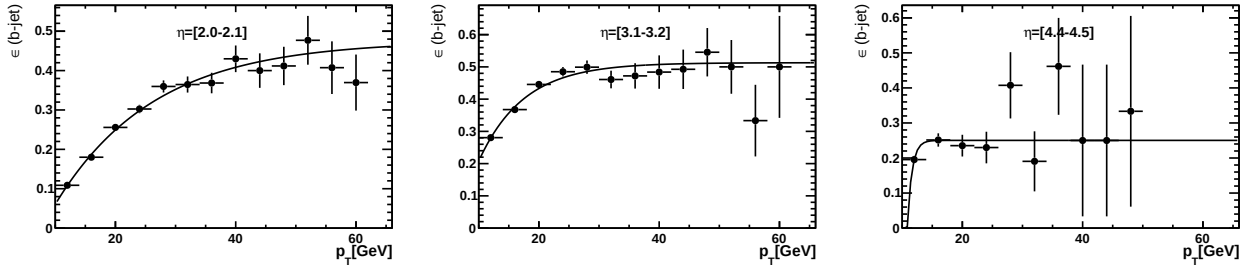


Figure 4.23: b-jet b-tag efficiency in three selected regions of LHCb acceptance. Left – in the bottom edge of LHCb acceptance. Middle – at the middle of the detector acceptance. Right – in the upper edge of LHCb acceptance. The fit function is given by Equation 4.8

4.2.2 SV Tagger

SV tagger is the algorithm used to tag b-jets candidates of the $W + b\bar{b}$ and $W + c\bar{c}$ analyses presented in next chapter of this thesis. The tracks used as inputs to the SV-tagger algorithm are required to have $p_T > 0.5$ GeV and $\chi_{IP}^2 > 16^{\dagger\dagger}$. The χ_{IP}^2 requirement

^{$\dagger\dagger$} χ_{IP}^2 is defined as the difference in χ^2 of a given primary pp interaction vertex (PV) reconstructed with and without the considered track.

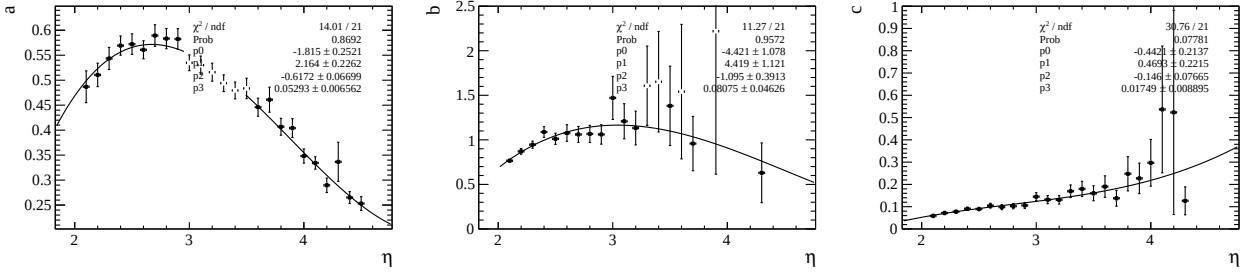


Figure 4.24: Parameterization of the function parameters for b-jet b-tag efficiencies.

is rarely satisfied by tracks reconstructed from particles originating directly from the PV. Hadronic particle identification is not used and, instead, all particles are assigned the pion mass. In contrast to many other jet-tagging algorithms, tracks are not required to have $\Delta R < 0.5$ between the track momentum and jet axis, since for low p_T jets tracks outside of the jet cone help to discriminate between c and b jets.

All possible two-track SVs are built using pairs of the input tracks such that the distance of closest approach between the tracks is less than 0.2 mm, the vertex fit $\chi^2 < 10$ and the two-body mass is in the range $0.4 \text{ GeV} < M < M(B)$, where $M(B)$ is the nominal B^0 mass. The lower mass requirement removes SVs from most strange-particle decays, including the Λ baryon whose computed mass is always below 0.4 GeV when the proton is assigned a pion mass. At this stage tracks are allowed to belong to multiple SVs. Next, all two-track SVs with $\Delta R < 0.5$ relative to the jet axis, where the direction of flight is taken as the PV to SV vector, are collected as candidates for a so-called linking procedure. This procedure involves merging SVs that share tracks until none of the remaining SVs with $\Delta R < 0.5$ share tracks. The SV position is taken to be the weighted average of the 2-body SV positions using the inverse of the 2-body vertex χ^2 values as the weights.

The linking procedure can produce SVs that contain any number of tracks. The linked n -track SVs are required to have $p_T > 2 \text{ GeV}$, significant spatial separation from the PV, and to contain at most one track with $\Delta R > 0.5$ relative to the jet axis. If the SV has only two tracks and a mass consistent with that of the K_s^0 , the SV is rejected. Interactions with material, and strange-particle decays, are suppressed by requiring that the flight distance

divided by the momentum of the SV is less than 1.5 mm/GeV; this quantity serves as a proxy for the hadron lifetime. The SV position is also required to be within a restricted region consistent with that of (b, c) -hadron decays.

The linked n -track SVs are required to have $M_{\text{corr}} > 0.6$ GeV to remove any remaining kaon or hyperon decays. A few percent of jets contain multiple SVs that pass all requirements; in such cases the SV with the highest p_T is chosen. The fraction of multi-SV-tagged jets is consistent in data and simulation.

Two BDTs are used to identify b and c jets: $\text{BDT}_{bc|uds g}$ trained to separate (b, c) jets from light jets and $\text{BDT}_{b|c}$ trained to separate b jets from c jets. Both BDTs are trained on simulated samples of b , c and light jets. The inputs to both BDTs are as follows:

- the SV mass M ;
- the SV corrected mass M_{corr} ;
- the transverse flight distance of the two-track SV closest to the PV;
- the fraction of the jet p_T carried by the SV, $p_T(\text{SV})/p_T(\text{jet})$;
- ΔR between the SV flight direction and the jet;
- the number of tracks in the SV;
- the number of SV tracks with $\Delta R < 0.5$ relative to the jet axis;
- the net charge of the tracks that form the SV;
- the flight distance χ^2 ;
- the sum of all SV track χ^2_{IP} .

For jets that contain an SV passing all of the requirements, the two BDT responses are used to identify the jet as either b , c or light.

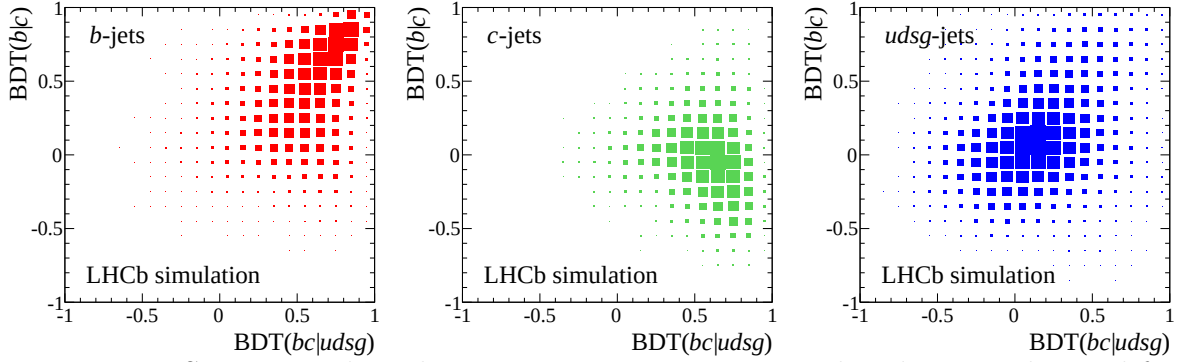


Figure 4.25: SV-tagger algorithm $\text{BDT}_{b|c}$ versus $\text{BDT}_{bc|uds g}$ distributions obtained from simulation for (left) b , (middle) c and (right) ℓ jets.

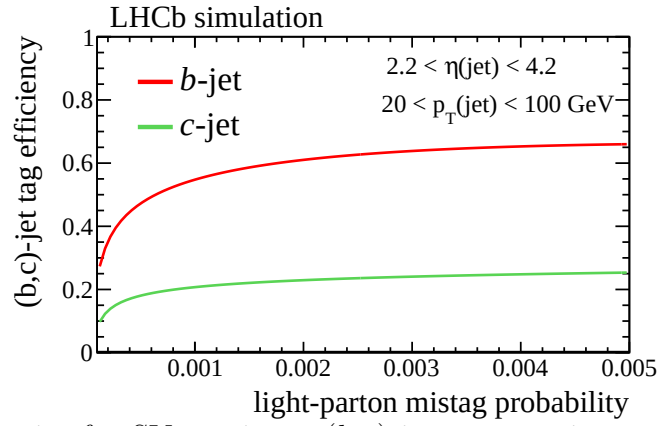


Figure 4.26: Efficiencies for SV-tagging a (b, c) -jet versus mistag probability for a ℓ jet from simulation. The curves are obtained by varying the $\text{BDT}_{bc|uds g}$ requirement.

Figure 4.25 shows the SV-tagger BDT distributions obtained from simulated W +jet events for each jet type. The distributions in the two-dimensional BDT plane of SV-tagged b , c , and ℓ jets are clearly distinguishable. The full two-dimensional distribution is fitted in data to determine the jet flavour content.

The (b, c) -jet efficiencies are nearly uniform for jet $p_T > 20$ GeV and for $2.2 < \eta < 4.2$, but are lower for low- p_T jets and for jets near the edges of the detector. The misidentification probability of ℓ jets is less than 0.1% for low- p_T jets and increases to about 1% at 100 GeV. Figure 4.26 shows the (b, c) -jet efficiencies versus the mistag probability of ℓ jets obtained by increasing the $\text{BDT}_{bc|uds g}$ cut.

The efficiency for identifying a $b(c)$ jet is about 65%(25%) with a probability of

misidentifying a ℓ jet of 0.3% for jets with transverse momentum $p_T > 20 \text{ GeV}$ and pseudorapidity $2.2 < \eta < 4.2$. These values are calculated in data agreed with simulation at 10% level. For ℓ -parton jets the agreement between data and simulation are worst, at about 30% in the identification efficiency, due to soft jets inefficiency [103].

Chapter 5

Z and W bosons production associated with b-jets at LHCb experiment

The analyses of bottom quark production associated to vector bosons at centre-of-mass energy of 7 and 8 TeV at LHCb are presented in this chapter.

Several benchmark studies with b-jets can be performed, including beyond SM (BSM) searches and probe predictions of pQCD. Two production modes are studied in this thesis, Z^* boson production associated to one bottom quark (from here referred to as Z+b-jet) and the production of a pair of bottom quarks with one W boson (from here referred to as $W + b\bar{b}$).

5.1 Motivation

Z+b-jets production cross-section is an important benchmark measurement for perturbative quantum chromodynamics phenomenology of heavy quarks and allows constraints to be placed on backgrounds in studies of the Standard Model Higgs boson and searches for non-SM physics. This measurement is sensitive to the *parton distribution functions* (PDF) in the proton in a phase space region poorly constrained by existing experiments. It also probes Quantum Chromodynamics phenomenology for heavy quarks. The leading

*Throughout this thesis Z includes both the Z^0 and the virtual photon contribution

order diagrams of the $Z+b$ -jet process are shown in the Figure 5.1.

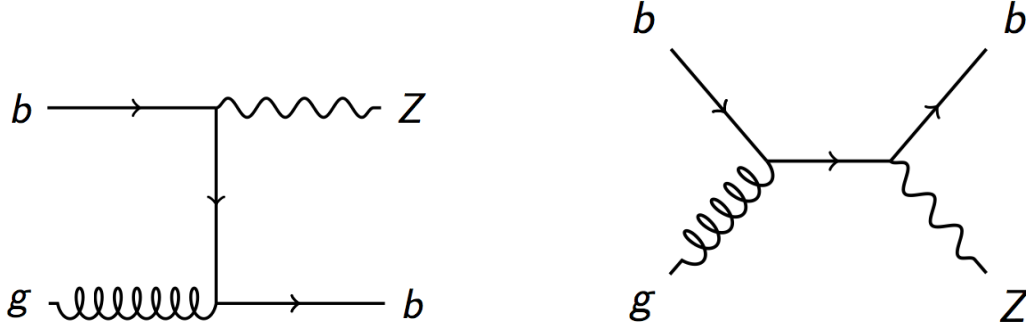


Figure 5.1: Feynman diagrams for the production $Z+b$ -jet.

Complementary to the $Z+b$ -jets, the production of two jets from bottom quarks and one lepton, can probe $W + b\bar{b}$ cross-section. Regarding the bottom quark sector, the selection of one lepton + two bottom quarks final states can be used to perform search for Higgs, with H^0 being produced in association with a W or Z boson and decaying to a $b\bar{b}$ or $c\bar{c}$ pair. Figure 5.2 shows the Feynman diagram of this production. Other processes contribute to the same final state, they are: $Z + b\bar{b}$, $Z + c\bar{c}$ and $W + c\bar{c}$ and WZ but have smaller cross-section calculated at NLO. The production of a pair of Z bosons, where one Z boson decay to a pair of bottom quarks and the other Z boson to a pair of leptons is also background for Higgs search. Figure 5.3 shows the Feynman diagram of these processes.

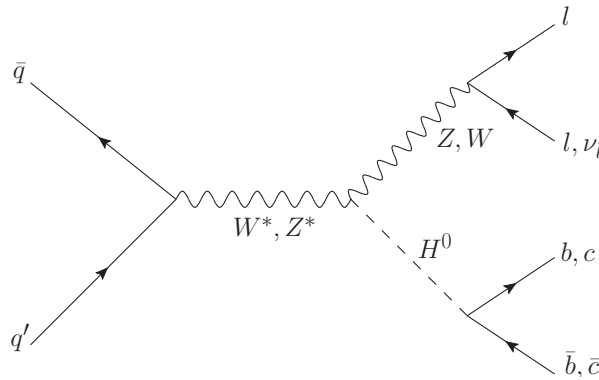


Figure 5.2: Feynman diagram for the production of a Higgs boson produced in association to a W or Z boson, with the final states searched for this analysis.

Most of the production cross-section measurements of bottom quarks associated to vector bosons found in literature are in the pseudorapidity central region. Results from

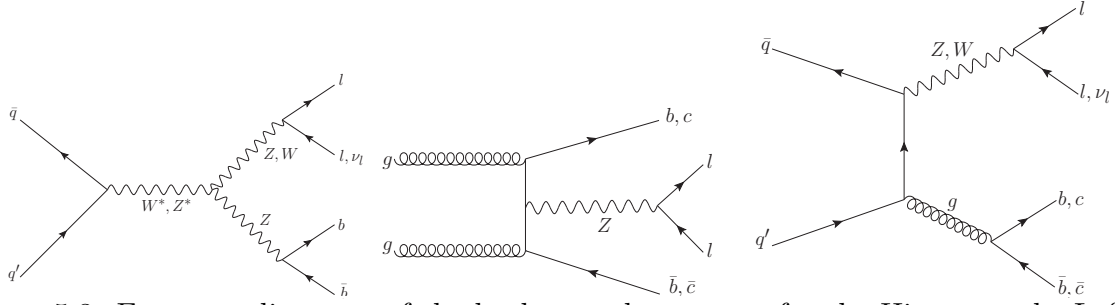


Figure 5.3: Feynman diagrams of the background processes for the Higgs search. Left – Diboson production. Middle – $Z + b\bar{b}$ and $Z + c\bar{c}$ production. Right – $W + b\bar{b}$ and $W + c\bar{c}$ production.

general purpose detectors are used to probe the PDF and hence their uncertainties are smaller in the central region, $|\eta| \lesssim 2.2$. ATLAS [104] and CMS [105] collaborations reported measurements of $Z + b$ -jet production with jet transverse momentum larger than 25 GeV, where they find good agreement with next-to-leading order (NLO) predictions. Similar measurements were performed by the CDF [106] and $D\bar{O}$ [107] collaborations at the Tevatron. However, the dominant contribution of the Tevatron b -jet production comes from the quark-antiquark interaction. The measurement of the cross sections of the $W + b\bar{b}$ mode in the forward region, can also provide experimental inputs for refining the theoretical calculations in perturbative Quantum Chromodynamics (QCD) [108–110]. With similar interest, ATLAS [111] and CMS [112] measured the $W + b\bar{b}$ production in the central pseudorapidity region at $\sqrt{s} = 7$ TeV.

The forward acceptance of the LHCb experiment, with a pseudorapidity coverage in the range $2 < \eta < 5$, probes a kinematic region complementary to that probed by ATLAS and CMS. The LHCb measurements are then sensitive to the PDF in the proton at low and high values of the Bjorken x variable, where the uncertainties are largest. Therefore it is very interesting to improve the PDF in the proton in this region.

Even though our analysis is aimed to measure $W + b\bar{b}$ and $W + c\bar{c}$ productions, top quark production at the pp collisions have the same final state particles that of $W + b\bar{b}$ and $W + c\bar{c}$, which made the analysis also sensitive to top production. Nevertheless top

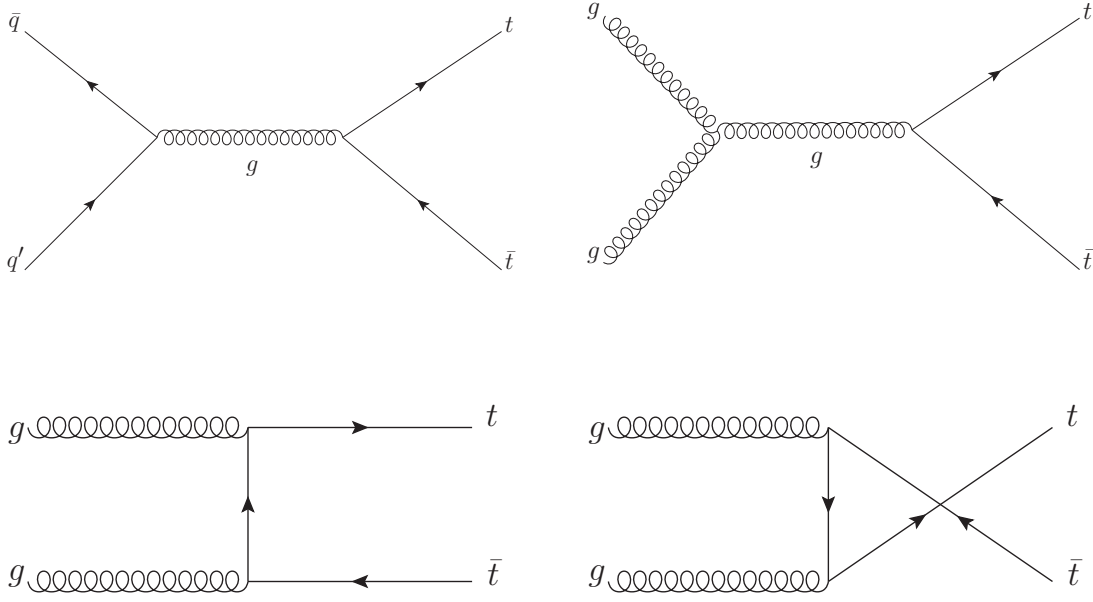


Figure 5.4: Feynmann diagrams for the production of $t\bar{t}$ in $q\bar{q}$ (top left) and gg (top right and bottom right and left) production modes.

is a large background for Higgs search. The study of $t\bar{t}$ in the forward region is also interesting from a theoretical point of view and could be sensitive to search for physics beyond the SM [113]. Furthermore, forward $t\bar{t}$ events can be used to constrain the gluon PDF at large momentum fraction [114]. The $t\bar{t}$ cross section has been studied at ATLAS and CMS using different final states and energies (see, e.g., [115–117]). LHCb has also been able to discover the production of the top quark in the forward region [118]. The Feynman diagrams for the top-pair production are shown in the Figure 5.4.

5.2 $W + b\bar{b}$

The W boson identification is performed by a muon (electron) from the decay $W \rightarrow \mu\nu$ ($W \rightarrow e\nu$). The muon (electron) requirements are described in Section 5.2.1(5.2.2). The W charged lepton candidate is combined with b-tagged jets from the same primary vertex to build $W + b\bar{b}$ candidates. The jet reconstruction, selection and identification follows what is described Chapter 4 of this thesis. If more than one $W + b\bar{b}$ candidate is found,

the candidate with the highest $p_T(\ell + j_0 + j_1)$ is selected. The fraction of events with multiple candidates is about 0.06% (0.02%) for 2012 data in the muon (electron) channel.

The fiducial requirements of the muon/electron and the jets are described in Table 5.1. The distance between the lepton and the jets, $\Delta R(\ell, j)$, is required to be greater than 0.5. The two jets are also required to have $\Delta R(j_0, j_1) > 0.5$. In order to reduce the fake W background, events with $p_T(\ell + j_0 + j_1) < 15 \text{ GeV}$ are removed, where $p_T(\ell + j_0 + j_1)$ is the transverse momentum of the quadri-vector defined by the sum of the quadri-vector of the muon and the quadri-vectors of the two jets (proxy of the neutrino p_T). Events with another charged lepton with opposite charge that pass the quality requirements are also vetoed (second lepton veto).

Table 5.1: Fiducial definitions for $W + b\bar{b}$ production.

object	requirement
muon	$p_T > 20 \text{ GeV}, 2 < \eta < 4.5$
electron	$p_T > 20 \text{ GeV}, 2 < \eta < 4.25$
jets	$12.5 \text{ GeV} < p_T < 100 \text{ GeV}, 2.2 < \eta < 4.2, \Delta R(j_0, j_1) > 0.5$
lepton, jets	$\Delta R(\mu, j) > 0.5$
lepton, jets	$p_T(\mu + j_0 + j_1) > 15 \text{ GeV}$

5.2.1 Muon selection

The muon candidate is required to be responsible to fire the trigger and stripping lines of Table 5.2. In addition, the same requirements as that of References [119, 120] are used with the exception of the cone-based isolation requirements. The muon isolation is defined using the variable $I = \frac{p_T(\mu)}{p_T(j_\mu)}$, where $p_T(j_\mu)$ is the transverse momentum of the jet containing the muon. The jet j_μ is not however required to pass the jet quality criteria described in Chapter 4 and the jet energy correction is not applied.

The muon candidates used to build the $W + b\bar{b}$ candidates are required to pass the tracking quality selection described in Table 5.3. Once the $W + b\bar{b}$ candidate is selected, the muon is required to pass the criteria described in Table 5.4.

line	requirement
LOMuon	$p_T > 1.5 \text{ GeV}, N_{\text{spd}} < 600$
Hlt1SingleMuonHighPT	$p > 8 \text{ GeV}, p_T > 4.8 \text{ GeV}, \chi^2/\text{NDOF} < 4$
Hlt2SingleMuonHighPT	$p_T > 10 \text{ GeV}$
StrippingWMuLine	$p_T > 20 \text{ GeV}$

Table 5.2: Level 0 trigger, high level trigger, and stripping lines used to select muon candidates. p is the muon momentum and p_T their transverse component; N_{spd} is the number of hits in the SPD detector; χ^2/NDOF is muon track fit parameter.

variable	requirement	variable	requirement
$P(\chi^2, \text{NDOF})$	> 0.01	p_T	$> 20 \text{ GeV}$
χ^2/NDOF	< 2.5	η	$> 2.0, < 4.5(4.25)$
N_{TT}	> 0	$\Delta p/p$	$< 10\%$

Table 5.3: Selection applied to muon (electron) candidates. $P(\chi^2, \text{NDOF})$ is the track probability χ^2 , N_{TT} the number of TT hits, η the pseudo-rapidity, and p_T the transverse momentum.

5.2.2 Electron selection

The electron candidate is also required to be responsible for fire the trigger and stripping lines of Table 5.5. The electron candidates used to build the $W + b\bar{b}$ candidates are required to pass the tracking quality selection described in Table 5.3. Once the $W + b\bar{b}$ candidate is selected, the electron is required to pass the criteria described in Table 5.6.

The electrons pass through a significant amount of material before reaching the tracking system, and their energy is degraded by electromagnetic emissions, typically around 25% of their initial energy. Different isolation definitions have been tested to take into account this energy loss, but they provided similar efficiencies and purities. The studies were performed on data by fitting the isolation variable and p_T observables with appropriate templates. In order to keep the electron channel as close as possible to the muon channel, it has been decided to use the same isolation definition: $I = p_T(e)/p_T(j_e)$, where $p_T(j_e)$ is the transverse momentum of the jet containing the electron. Similar to jet j_μ , jet j_e is not required to pass the jet quality criteria described in Chapter 4 and the jet

variable	requirement
$(E_{\text{ECAL}} + E_{\text{HCAL}})/p$	< 0.04
IP	$< 0.04 \text{ mm}$
I	> 0.8

Table 5.4: Requirements applied to muon after $W + b\bar{b}$ candidates are selected. $(E_{\text{ECAL}} + E_{\text{HCAL}})/p$ is the summed electromagnetic and hadronic calorimeter energy over the track momentum, IP the impact parameter, and $I = \frac{p_{\text{T}}(\mu)}{p_{\text{T}}(j_{\mu})}$.

energy correction is also not applied.

In this analysis, the electron channel data are constrained to the 8 TeV collisions. The electron trigger configuration in the 2011 data set changed several times, which would need a big effort to use these data in this work. Therefore, only 2012 data are used for the electron channel.

line	requirement
L0Electron	$E_{\text{T}}(\text{ECAL}) > 3 \text{ GeV}, N_{\text{spd}} < 600$
Hlt1SingleElectronNoIP	$p > 8 \text{ GeV}, p_{\text{T}} > 4.8 \text{ GeV}, \chi^2/\text{NDOF} < 4$
Hlt2SingleTFVHighPtElectron	$p_{\text{T}} > 15 \text{ GeV}, E_{\text{PRS}} > 50 \text{ MeV},$ $E_{\text{ECAL}}/p > 0.1, E_{\text{HCAL}}/p < 0.05$
StrippingWeLine	$E_{\text{HCAL}} < 20 \text{ GeV}$

Table 5.5: Level 0 trigger, high level trigger, and stripping lines used to select electron candidates. $E_{\text{T}}(\text{ECAL})$ is the transverse energy in ECAL; N_{spd} is the number of hits in the SPD detector; p and p_{T} is the electron momentum and their transverse component respectively; χ^2/NDOF is electron track fit parameter. E_{PRS} is the energy deposited in the preshower detector; E_{ECAL}/p and E_{HCAL}/p is the cluster energy over the track momentum of ECAL and HCAL respectively.

5.2.3 Yields

The events (both data and simulation) are first pre-selected by requiring at least one $W + b\bar{b}$ candidate with a lepton passing the trigger and stripping requirements and two reconstructed jets with $p_{\text{T}} > 10 \text{ GeV}$. The data yields after pre-selection are detailed in Tables 5.7-5.9. The retention of the selection after each requirement is detailed in

variable	requirement
$(E_{\text{ECAL}})/p$	> 0.2
$(E_{\text{HCAL}})/p$	< 0.01
IP	$< 0.04 \text{ mm}$
I	> 0.8

Table 5.6: Requirements applied to electron after $W + b\bar{b}$ candidates are selected. $(E_{\text{ECAL}})/p$ is the summed electromagnetic calorimeter energy over the track momentum, $(E_{\text{HCAL}})/p$ the summed hadronic calorimeter energy over the track momentum, IP the impact parameter, and $I = \frac{p_{\text{T}}(e)}{p_{\text{T}}(j_e)}$.

Tables 5.10-5.12.

requirement	number of events	total retention
Pre-selection	302063	100%
$(E_{\text{ECAL}} + E_{\text{HCAL}})/p < 0.04$	126711	41.9%
$N_{\text{TT}} > 0$	113210	37.5%
IP $< 0.04 \text{ mm}$	70032	23.2%
$I > 0.8$	30000	9.93%
Second lepton veto	28790	9.53%
$\Delta R(\ell, j) > 0.5$	24703	8.18%
$p_{\text{T}}(j) > 12.5 \text{ GeV}$	12761	4.22%
$p_{\text{T}}(j) < 100 \text{ GeV}$	12666	4.19%
$\Delta R(j_0, j_1) > 0.5$	12661	4.19%
$\text{BDT}_{bc udsg}(j_0) > 0.2$,	55	0.018%
$\text{BDT}_{bc udsg}(j_1) > 0.2$		
$p_{\text{T}}(\ell + j_0 + j_1) > 15 \text{ GeV}$	45	0.015%

Table 5.7: Yields for 2011 data in the muon channel.

The electron channel is less efficient than the muon channel (see yields) mainly due to the p_{T} threshold and trigger efficiencies. In Figure 5.5, the simulated electron and muon p_{T} distributions are compared after pre-selection. The energy loss in the electron channel with respect to the muon channel is quite large, which increases the inefficiency of this cut by 26%. The trigger efficiency ratio evaluated in simulation for signal after the p_{T} cut is $\frac{\epsilon(\text{TOS};e)}{\epsilon(\text{TOS};\mu)} \approx 0.78$. The total efficiencies ratio due to p_{T} and trigger requirements is $0.75 * 0.78 \approx 0.59$. That is in agreement with the results presented in Tables 5.11-5.12.

requirement	number of events	total retention
Pre-selection	940434	100%
$(E_{\text{ECAL}} + E_{\text{HCAL}})/p < 0.04$	390476	41.5%
$N_{\text{TT}} > 0$	346985	36.9%
$\text{IP} < 0.04 \text{ mm}$	211653	22.5%
$I > 0.8$	90309	9.6%
Second lepton veto	86958	9.25%
$\Delta R(\ell, j) > 0.5$	72161	7.67%
$p_{\text{T}}(j) > 12.5 \text{ GeV}$	37025	3.94%
$p_{\text{T}}(j) < 100 \text{ GeV}$	36549	3.89%
$\Delta R(j_0, j_1) > 0.5$	36530	3.88%
$\text{BDT}_{bc udsg}(j_0) > 0.2,$ $\text{BDT}_{bc udsg}(j_1) > 0.2$	130	0.0138%
$p_{\text{T}}(\ell + j_0 + j_1) > 15 \text{ GeV}$	108	0.0115%

Table 5.8: Yields for 2012 data in the muon channel.

requirement	number of events	total retention
Pre-selection	915001	100%
$E_{\text{ECAL}}/p > 0.2, E_{\text{HCAL}}/p < 0.01$	322189	35.2%
$N_{\text{TT}} > 0$	253070	27.7%
$\text{IP} < 0.04 \text{ mm}$	198956	21.7%
$I > 0.8$	80062	8.75%
Second lepton veto	77368	8.46%
$\Delta R(\ell, j) > 0.5$	66560	7.27%
$p_{\text{T}}(j) > 12.5 \text{ GeV}$	35539	3.88%
$p_{\text{T}}(j) < 100 \text{ GeV}$	35232	3.85%
$\Delta R(j_0, j_1) > 0.5$	35216	3.85%
$\text{BDT}_{bc udsg}(j_0) > 0.2,$ $\text{BDT}_{bc udsg}(j_1) > 0.2$	126	0.0138%
$p_{\text{T}}(\ell + j_0 + j_1) > 15 \text{ GeV}$	84	0.00918%

Table 5.9: Yields for 2012 data in the electron channel.

In addition, the mis-identification background in the electron sample is expected to be higher with respect to the muon sample, therefore data does not scale as the simulation.

requirement	$(W/Z)H^0$	$W + b\bar{b}$	$W + c\bar{c}$	$gg \rightarrow t\bar{t}$	$qq \rightarrow t\bar{t}$	single-t
Pre-selection*	9.6%	5.8%	4.8%	2.1%	2.8%	2.8%
$(E_{\text{ECAL}} + E_{\text{HCAL}})/p < 0.04$	90.2%	92.1%	92.2%	87.4%	87.3%	89%
$N_{\text{TT}} > 0$	86.5%	88.7%	88.9%	83%	83.1%	84.9%
$\text{IP} < 0.04 \text{ mm}$	83.9%	84%	86%	79.8%	79.3%	81.3%
$I > 0.8$	76.1%	78.3%	80.6%	69.3%	69.8%	75.3%
Second lepton veto	70%	78.2%	80.6%	68.8%	68.9%	75.1%
$\Delta R(\ell, j) > 0.5$	63.5%	62.7%	63.8%	62.3%	62.2%	67.7%
$p_{\text{T}}(j) > 12.5 \text{ GeV}$	53.6%	39.5%	38.3%	43.9%	48.8%	51.9%
$p_{\text{T}}(j) < 100 \text{ GeV}$	48.1%	39.2%	38.1%	40%	43.3%	48.1%
$\Delta R(j_0, j_1) > 0.5$	48.1%	39.2%	38%	40%	43.3%	48.1%
$\text{BDT}_{bc udsg}(j_0) > 0.2,$	13.2%	10.1%	1.26%	1.55%	4.62%	1.78%
$\text{BDT}_{bc udsg}(j_1) > 0.2$						
$p_{\text{T}}(\ell + j_0 + j_1) > 15 \text{ GeV}$	12.1%	9.44%	1.17%	1.49%	4.4%	1.67%
expected yields	0.04	19.0	21.9	1.8	2.6	0.8

Table 5.10: Relative retention of the requirement selection for the 2011 simulation in the muon channel. The expected yields of each simulation channels is presented in the last row. *Preselection is the retention with respect the total sample.

requirement	$(W/Z)H^0$	$W + b\bar{b}$	$W + c\bar{c}$	$gg \rightarrow t\bar{t}$	$qq \rightarrow t\bar{t}$	single-t
Pre-selection*	11%	6.5%	5.4%	2.4%	3.4%	3.1%
$(E_{\text{ECAL}} + E_{\text{HCAL}})/p < 0.04$	89.9%	91.8%	91.7%	87%	86.9%	88.9%
$N_{\text{TT}} > 0$	86.1%	88.4%	88.4%	82.5%	82.8%	85%
$\text{IP} < 0.04 \text{ mm}$	83.1%	82.9%	84.4%	79%	78.5%	80.8%
$I > 0.8$	74.7%	76.4%	78.2%	67.7%	68.3%	73.9%
Second lepton veto	68.5%	76.4%	78.2%	67.4%	67.8%	73.7%
$\Delta R(\ell, j) > 0.5$	60.3%	58.1%	57.3%	59.5%	59.7%	64.2%
$p_{\text{T}}(j) > 12.5 \text{ GeV}$	50.5%	36.7%	34%	42%	46.9%	48.9%
$p_{\text{T}}(j) < 100 \text{ GeV}$	44.9%	36.4%	33.8%	37.6%	40.8%	44.8%
$\Delta R(j_0, j_1) > 0.5$	44.9%	36.4%	33.7%	37.6%	40.8%	44.7%
$\text{BDT}_{bc udsg}(j_0) > 0.2,$	11.5%	9.78%	0.862%	1.56%	4.51%	1.94%
$\text{BDT}_{bc udsg}(j_1) > 0.2$						
$p_{\text{T}}(\ell + j_0 + j_1) > 15 \text{ GeV}$	10.6%	9.02%	0.804%	1.49%	4.32%	1.83%
expected yields	0.11	47.2	53.9	6.4	8.5	2.7

Table 5.11: Relative retention of the requirement selection for the 2012 simulation in the muon channel. The expected yields of each simulation channels is presented in the last row. *Preselection is the retention with respect the total sample.

requirement	$(W/Z)H^0$	$W + b\bar{b}$	$W + c\bar{c}$	$gg \rightarrow t\bar{t}$	$qq \rightarrow t\bar{t}$	single-t
Pre-selection*	6.1%	3.5%	3.0%	1.2%	1.8%	1.6%
$E_{\text{ECAL}}/p > 0.2, E_{\text{HCAL}}/p < 0.01$	81.7%	87.3%	88.2%	83.5%	82.6%	85.3%
$N_{\text{TT}} > 0$	81.4%	87.3%	88.2%	83.4%	82.5%	85.3%
$\text{IP} < 0.04 \text{ mm}$	78.7%	82.1%	84.3%	79.9%	78.8%	81.6%
$I > 0.8$	61.6%	67.4%	69.9%	60.4%	60.3%	66%
Second lepton veto	56.5%	67.3%	69.7%	59.1%	58.1%	65%
$\Delta R(\ell, j) > 0.5$	49.9%	51.7%	51.9%	52.2%	51.3%	56.8%
$p_{\text{T}}(j) > 12.5 \text{ GeV}$	41.9%	32.1%	30.8%	37.1%	40.5%	43.6%
$p_{\text{T}}(j) < 100 \text{ GeV}$	37.9%	31.8%	30.6%	33.3%	35.6%	40.2%
$\Delta R(j_0, j_1) > 0.5$	37.9%	31.8%	30.6%	33.3%	35.6%	40.2%
$\text{BDT}_{bc udsg}(j_0) > 0.2,$	9.94%	8.47%	0.74%	1.43%	3.94%	1.66%
$\text{BDT}_{bc udsg}(j_1) > 0.2$						
$p_{\text{T}}(\ell + j_0 + j_1) > 15 \text{ GeV}$	8.98%	7.4%	0.65%	1.36%	3.77%	1.55%
expected yields	0.05	20.3	22.9	2.9	3.7	1.2

Table 5.12: Relative efficiency of the requirement selection for the 2012 simulation in the electron channel. The expected yields of each simulation channels is presented in the last row. *Preselection is the retention with respect the total sample.

5.2.4 Higgs selection

In order to search for the Higgs production associated with a W or Z boson, two selection criteria are changed to improve the sensitivity. The second lepton veto is removed to increase the ZH^0 efficiency. The jet p_{T} threshold is increased to 20 GeV to improve the signal over background ratio since the b-jets from the Higgs decay are harder. Moreover, events outside the dijet invariant mass region of interest are not used ($70 < M_{jj} < 150 \text{ GeV}$). Remainder that dijet invariant mass is defined as

$$M_{jj} = \left(\sum_{i=0}^{i=1} E_i \right)^2 - \left| \sum_{i=0}^{i=1} \vec{p}_{\text{jet}_i} \right|^2$$

where E_i and $\vec{p}_{\text{jet}_i}$ is the energy and momentum of the jet i respectively ($c = 1$).

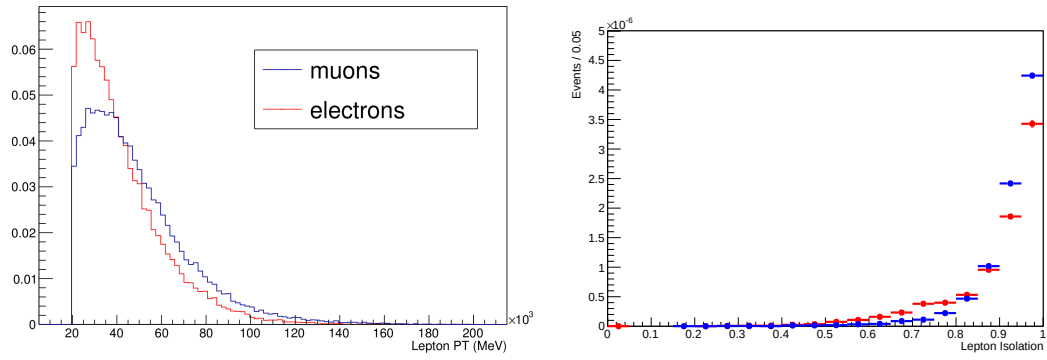


Figure 5.5: p_T distribution of reconstructed leptons matched with the lepton from the W/Z decay after pre-selection in VH simulated events.

5.2.5 Samples

SM expectation

The relevant physics processes for this analysis with W and/or Z production are predicted with simulation. Detailed information about the theoretical calculation of the cross-sections and the event generators used for each process is given in Appendix E. The integrated luminosity of 2012 (2011) data is measured as 1.99 fb^{-1} (0.98 fb^{-1}).

After the generation step where the decays of hadronic particles are described by EVTGEN [58], the interaction of the generated particles with the detector and its response are implemented using GEANT4 [59] as described in Reference. [121]. To compare data with simulation, three aspects of the detector response need to be corrected: Global Event Cut (GEC) efficiency, trigger efficiency and b-tag efficiency.

The data GEC efficiency is taken to be 91% as observed in the Z+jet analysis [122] for 2011. For 2012 we take this to be 88% to account for the 3% lower GEC efficiency observed in 2012 vs 2011 for $Z \rightarrow \mu^+ \mu^-$ events. In simulation, GEC efficiency ranges between 94% and 98% for the relevant SM processes. SM simulation is then correct by a factor of 92% (95%) for 2012 (2011) analysis. Muon and electron show similar number of hits in the SPD (nSPD) distribution, as can be seen in Figure 5.6.

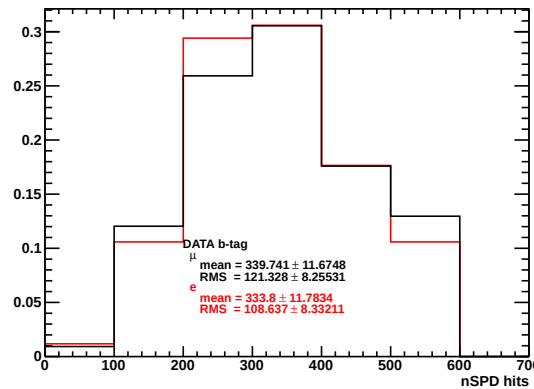


Figure 5.6: nSPD distribution in the electron channel and muon channel for 2012 data.

The LHCb trigger efficiencies of select high- p_T muons are found to be different in

data and simulation [123]. Muons were selected using $Z \rightarrow \mu^+\mu^-$ decay. Using a tag and probe technique, where a TOS muon is considered as tag, the p_T dependence of the trigger efficiency is measured in data and simulation in 10 η bins from 2.0 to 4.5 and 10 p_T bins. The ratio of data and simulation efficiencies in each bin is used as correction factor in simulation.

Electron trigger efficiencies are also different in data and simulation [124] In this study, electrons were selected using $Z \rightarrow e^+e^-$ decay. The efficiency has been calculated separately for electrons and positrons, in bins of electron η and p_T . Using a tag and probe technique, where a TOS electron is considered as tag to probe positron efficiency and vice versa, the p_T dependence of the trigger efficiency is measured in data and simulation in 9 η bins from 2.0 to 4.25. The ratio of data and simulation efficiencies in each bin is used as correction factor in simulation.

Normalised distributions of key variables of the main physics processes are showed in Figure 5.7 for muon 8 TeV simulation.

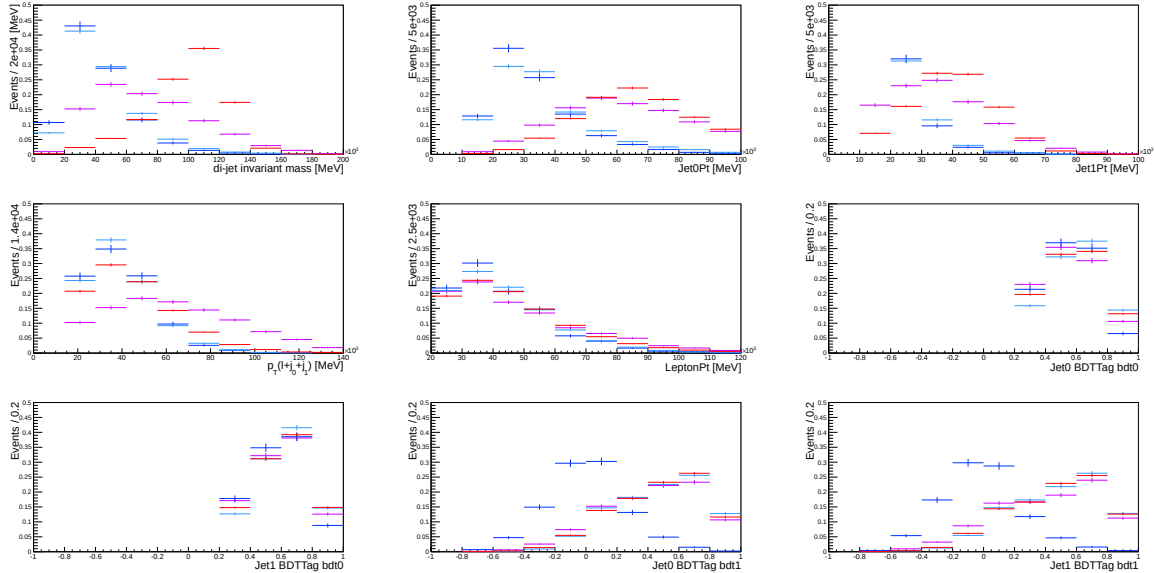


Figure 5.7: Normalised distributions for $t\bar{t}$ (magenta), $W + b\bar{b}$ (light blue), $W + c\bar{c}$ (dark blue) and $(W/Z)H^0 \rightarrow b\bar{b}$ (red) sample for muon 2012 simulation after $W + b\bar{b}$ candidate selection.

Z control sample

A Z control sample is defined to check the analysis strategy for the SM expectation in a QCD free sample. The events are selected with all requirements detailed in Section 5.2, but with the second lepton veto inverted and no requirement on the lepton isolation and IP. The distributions are presented in Figs. 5.8-5.9.

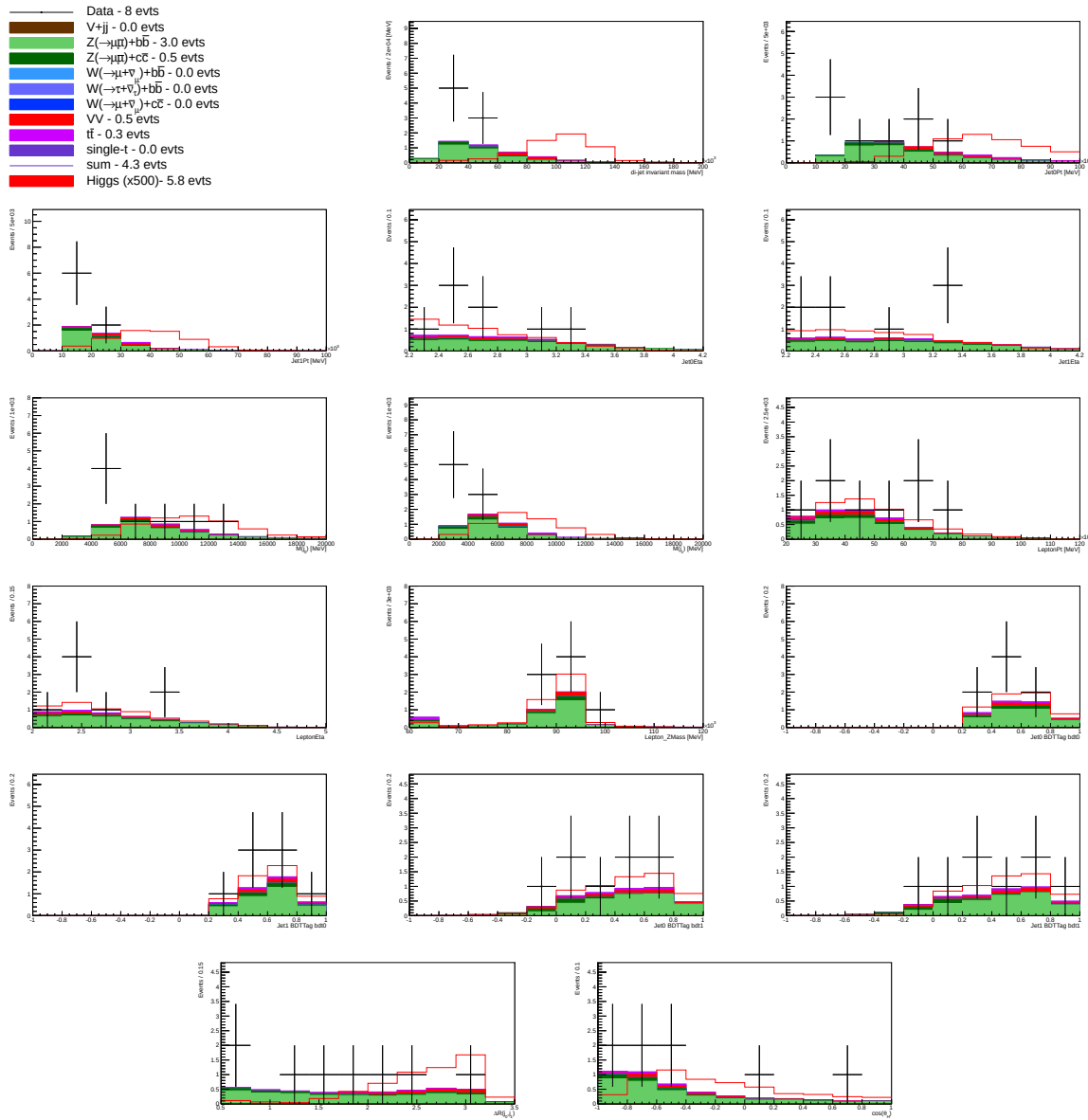


Figure 5.8: Z control sample for muon 2012 data set.

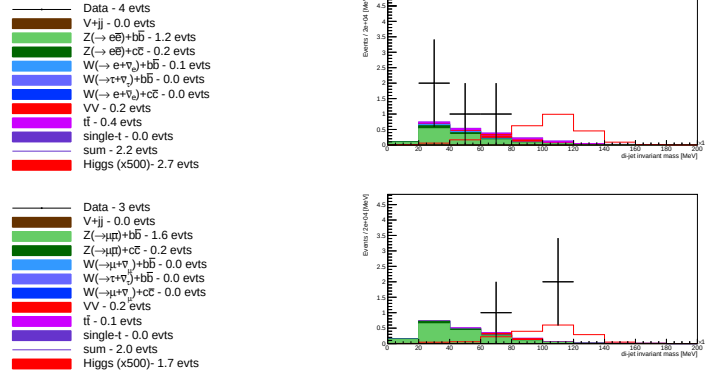


Figure 5.9: Z control sample for electron 2012 (top) and muon 2011 (bottom) data set.

QCD background

QCD background is any event where the charged lepton is not a decay product of either the W or the Z boson. Production of $b\bar{b}$ is expected to be one of the main contributions due to semi-leptonic decay of B-hadrons. Hadron production can be miss-identified as muons due to decay-in-flight or punch-through in the calorimeters. Hadrons can be also miss-identified as electrons since the calorimeter requirements do not offer strong discrimination.

The lepton isolation and impact parameter requirements veto most of the QCD background. The remaining contamination is estimated by using sideband regions. QCD background templates are derived with events where the isolation cut is reversed ($I < 0.8$). The QCD normalisation is derived using events that fail the IP requirement, as defined in Equation 5.1.

$$k_{QCD} = \frac{N(I > 0.8, IP_1 > 0.04 \text{ mm})}{N(I < 0.8, IP_1 > 0.04 \text{ mm})}, \quad (5.1)$$

where $N(I_{cut}, IP_1_{cut})$ is the number of data events subtracted by SM prediction that pass all selection criteria but with the specific I and IP_1 cut. It is assumed that the event topology for QCD background does not depend on the I variable.

The values of k_{QCD} for the different samples are presented in Table 5.13.

sample	k_{QCD}
muon 2011	0.11 ± 0.03
muon 2012	0.020 ± 0.005
electron 2012	0.10 ± 0.03

Table 5.13: Values of k_{QCD} for the different samples

Two main assumptions drive the QCD background estimation: event topology does not depend on the I variable and the I variable has the same shape for both heavy-flavour and mis-identification contributions. These assumptions are studied in section 5.2.10 using control samples.

$W + b\bar{b}$ sample

Events in the $W + b\bar{b}$ sample are compared to SM expectations in Figures 5.10, 5.11 and 5.12. As can be seen there are a relative good agreement between data and Monte Carlo distributions. Difference in absolute values (integral of histograms) is due to the fact that here we are using NLO cross-section estimations and the simulated samples are not fitted to data to extract the measured productions which is compared to theory, it is discussed below in the subsection 5.2.7.

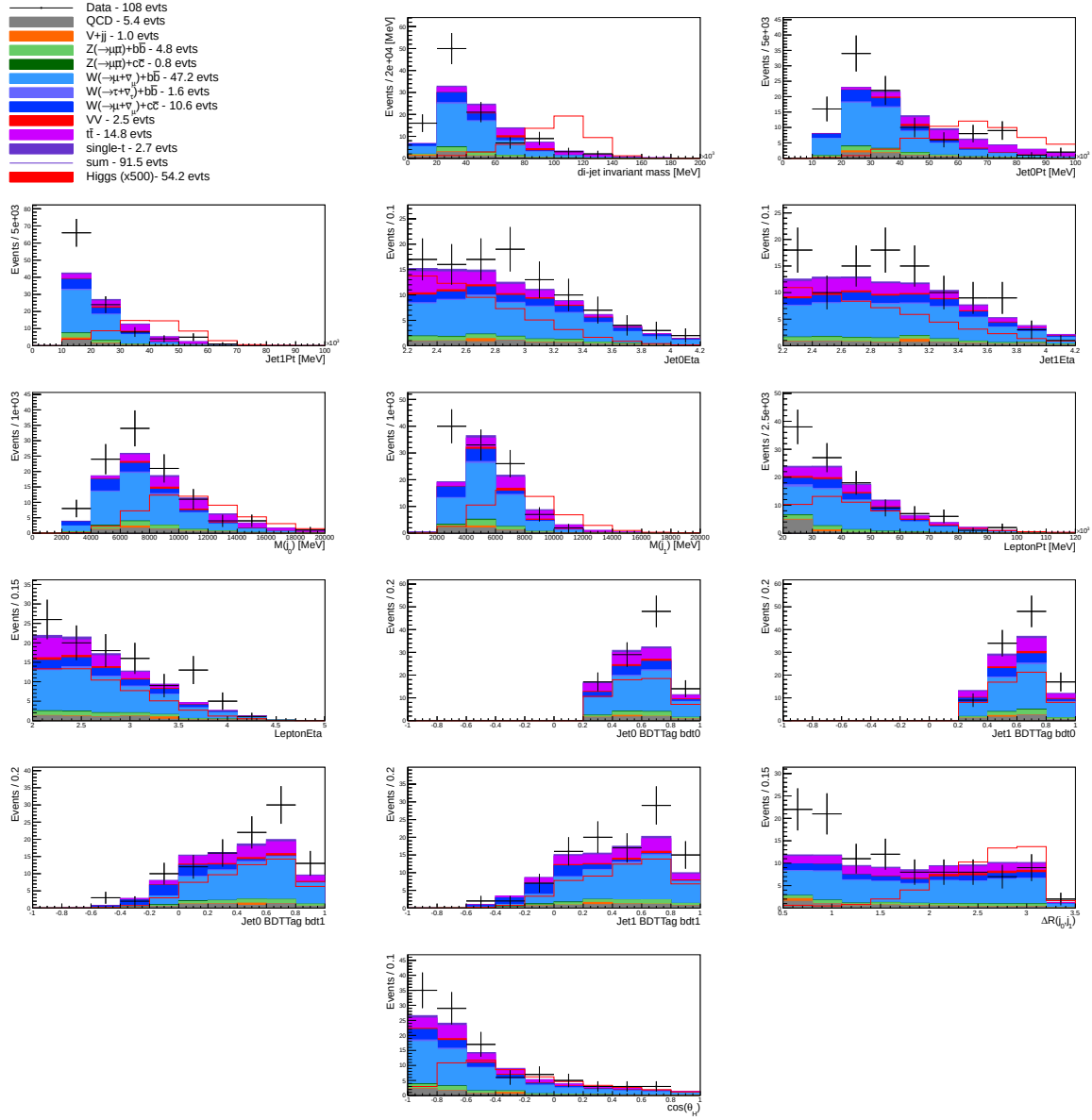


Figure 5.10: $W + b\bar{b}$ comparison between MC samples and muon 2012 data set for several distributions.

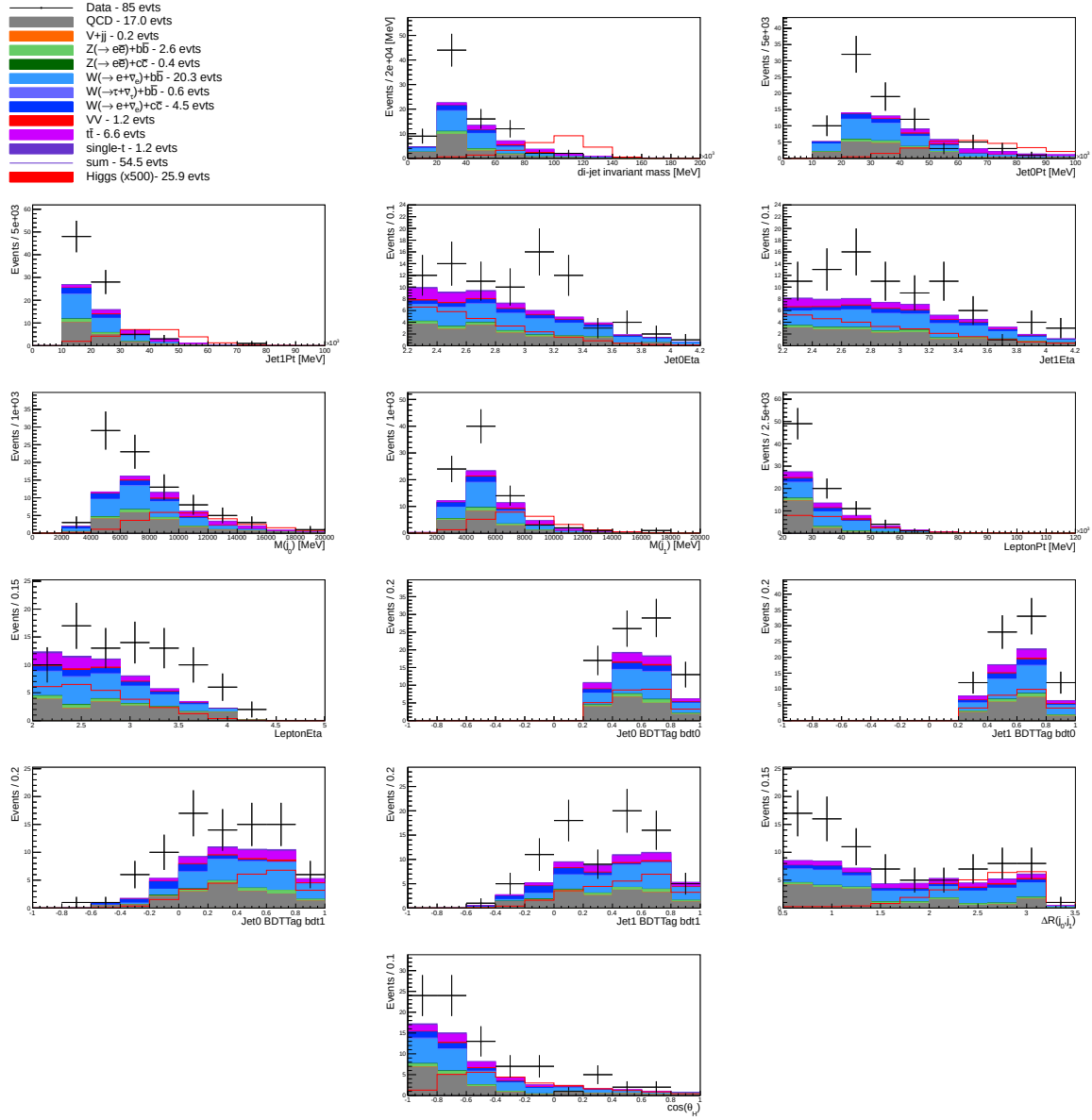


Figure 5.11: $W + b\bar{b}$ comparison between MC samples and electron 2012 data set for several distributions.

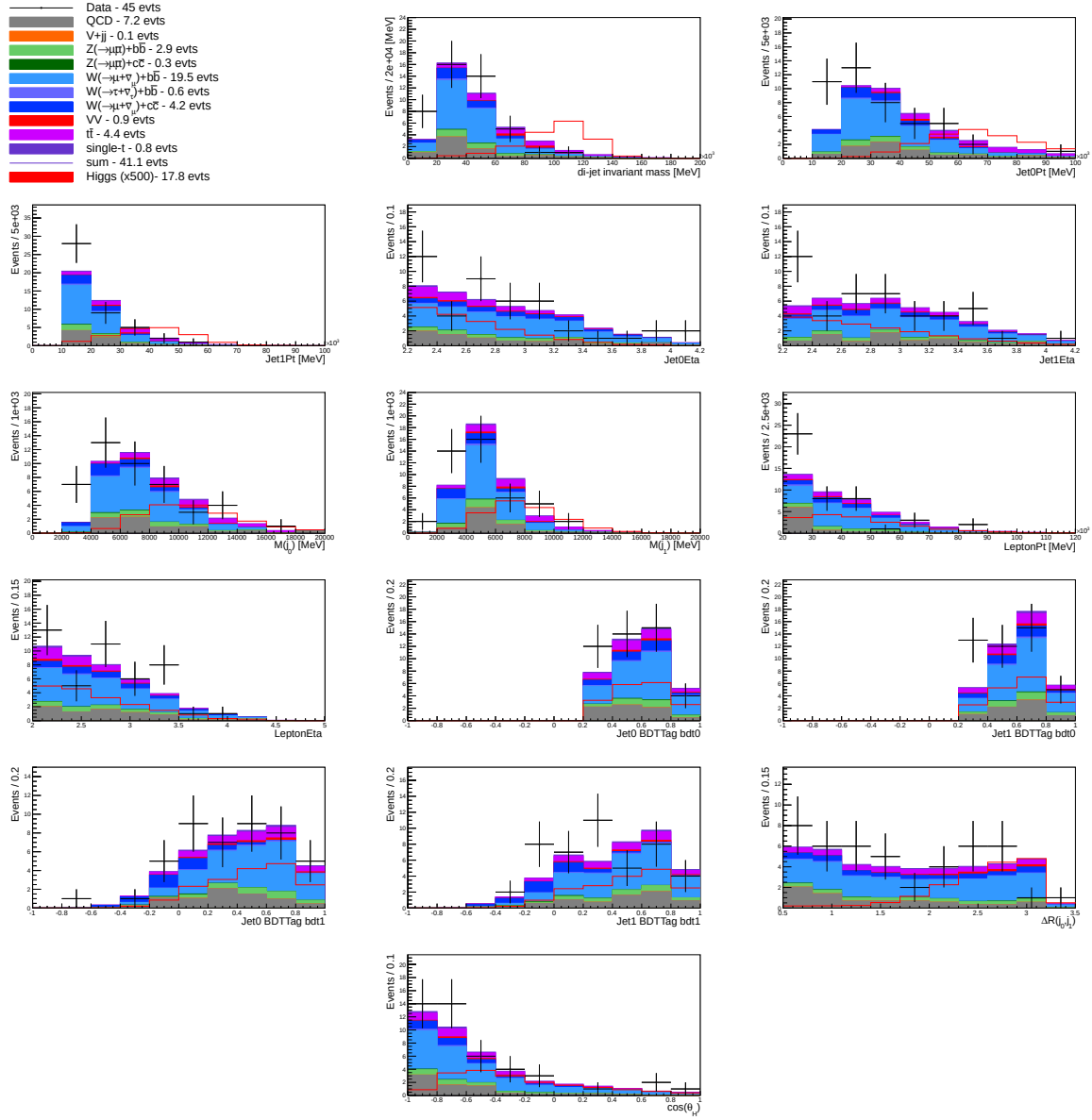


Figure 5.12: $W + b\bar{b}$ comparison between MC samples and muon 2011 data set several distributions.

5.2.6 MVA

The analysis strategy is based on a simultaneous fit to extract the $W^+ + b\bar{b}$, $W^- + b\bar{b}$, $W^+ + c\bar{c}$, $W^- + c\bar{c}$ and $t\bar{t}$ cross sections. $W + b\bar{b}$ and $W + c\bar{c}$ processes can be discriminated by the nature of the jets. And in order to disentangle $W + b\bar{b}$ from $t\bar{t}$ a multivariate classifier (MVA) is used. In the same regard, for the Higgs analysis, the signal $W/Z + H^0(\rightarrow b\bar{b}/c\bar{c})$ has to be separated from $t\bar{t}$ or $W/Z + b\bar{b}/c\bar{c}$ processes. To add discrimination power and non-correlation during the final fit procedure, the MVA output is chosen to be uniform with respect to the dijet invariant mass. Two possibilities are possible to achieve it, either limiting or removing all the variables that have a strong correlation with the dijet mass (e.g. jet kinematic variables) or either uses an MVA that produced a uniform selection efficiency along the dijet mass spectrum. The latter has been chosen and the approach used is following the work described in Reference [125][†].

Reference [125] introduces a Uniformity Boosting Method for Boosted Decision Tree (BDT). The choice has been made after comparing multiple MVA to use the so called uGBkNNFL[‡] (uniform Gradient Boosting (uGB) using a flatness loss (FL) + α AdaLoss based on the k nearest neighbour (kNN)) as described in Ref. [125].

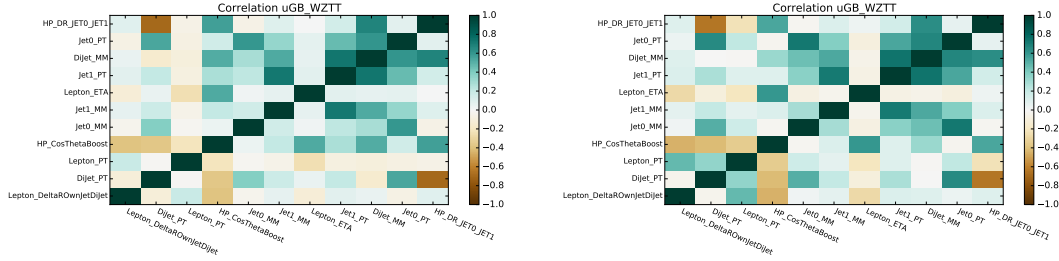
Three uGB per year and lepton family have been trained: 1) $W + b\bar{b}$ vs. $t\bar{t}$, 2) $(W/Z)H^0$ vs. $t\bar{t}$ and 3) $(W/Z)H^0$ vs. $W + b\bar{b}$. The topology of the $W + b\bar{b}$ and $(W/Z)H^0$ decay being very similar, the same set of variables have been chosen to be used to train the two first uGB, while a slightly different set is used for the last uGB. These variables are described in Table 5.14 for the muon (2011+2012) and electron channels and the corresponding distributions are shown in Figs. 5.10-5.11-5.12. Topology (ΔR s, $\cos\theta$) and kinematic (p_T , η) variables and masses are used. Fig. 5.13 shows the correlation matrices for all the variables in the MC used for the training (same correlations for all lepton flavour and center-of-mass energy).

[†]The implementation uses the available package version 0.3.0 here: documentation https://arogozhnikov.github.io/hep_ml/ and github https://github.com/arogozhnikov/hep_ml

[‡]for easier reading this is simply referred as uGB in the rest of this note.

variables	muons/electrons	
	$W + b\bar{b}$ or $(W/Z)H^0$ vs. $t\bar{t}$	$W + b\bar{b}$ vs. $(W/Z)H^0$
p_T^{dijet}	✓	✓
p_T^{lepton}	✓	✓
$\Delta R(\text{jet}_{\text{lepton}}, \text{dijet})$	✓	✓
$M(\text{lepton} + \text{jet}^{\text{hPT}})$		✓
$M(\text{lepton} + \text{jet}^{\text{lPT}})$		✓
η_{lepton}	✓	
$\Delta R(\text{jet}^{\text{hPT}}, \text{jet}^{\text{lPT}})$	✓	✓
$\cos(\theta_{\text{lepton}}^{\text{dijetCM}})$	✓	
M^{jet^i}	✓	✓
$p_T^{\text{jet}^i}$	✓	✓
η^{jet^i}		✓

Table 5.14: Variables used in the different uGB.

Figure 5.13: Correlations between the variables used in the MVA and the dijet mass in the muon channels (2012). right: $t\bar{t}$, left: $W + b\bar{b}$.

Although some MC samples have been generated with different generator (Pythia8, AlpGen or Powheg), all the samples used here come from either Pythia8 or AlpGen, while the Powheg sample in the $t\bar{t}$ channel has been used here to discard variables in the training that depends of the generator (e.g. χ^2 of the Vertex fit of the dijet).

Figure 5.14 shows the Receiver Operating Characteristic (ROC) curve for the training and test samples in each uGB and each lepton and year combination. Figure 5.15 shows the discriminator output. Train and test samples are superimposed and Kolmogorov-Smirnov values are calculated and displayed on the plots.

The uniformity is measured with a Standard Deviation of Efficiency on Bins (SDE) as

in Ref. [125]. This metric is used as it gives the largest deviation compared to a Cramér-von Mises. This measurement of (non-) uniformity corresponds to a weighted standard deviation of bin efficiency from the global efficiency:

$$\text{SDE}(\text{eff}) = \sqrt{\sum_{\text{bin}} \text{weight}_{\text{bin}} (\text{eff}_{\text{bin}} - \text{eff})^2}, \quad (5.2)$$

where $\text{weight}_{\text{bin}}$ is the fraction of events in a specific bin, eff is the global efficiency for a given cut in the output descriptor and eff_{bin} is the efficiency per bin (in our case dijet mass bin) for the same given cut.

For the overall non-flatness, a sum of the square of Equation 5.2 for several cuts is taken:

$$\text{SDE}^2 = \frac{1}{k} \sum_{\text{eff} \in [\text{eff}_1 \dots \text{eff}_k]} \text{SDE}^2(\text{eff}), \quad (5.3)$$

Figure 5.16 represents the efficiency per bin of dijet mass for a global cut efficiency. Equation 5.3 is the weighted sum of these graphs and Table 5.15 is the SDE^2 for the different test samples in the different scenarios. Figures 5.17 to 5.19 show the MC expectation of the different uGB distribution in the $W + b\bar{b}$ channel compared to data.

MC test sample	uGB	$W + b\bar{b}$	$t\bar{t}$	$(W/Z)H^0$
μ 2011	$W + b\bar{b}$ vs. $t\bar{t}$	5.5 %	2.2 %	–
	$(W/Z)H^0$ vs. $W + b\bar{b}$	3.3 %	–	3.2
	$(W/Z)H^0$ vs. $t\bar{t}$	–	4.9 %	3.4 %
μ 2012	$W + b\bar{b}$ vs. $t\bar{t}$	4.5 %	3.9 %	–
	$(W/Z)H^0$ vs. $W + b\bar{b}$	3.7 %	–	2.6 %
	$(W/Z)H^0$ vs. $t\bar{t}$	–	4.8 %	4.0 %
e 2012	$W + b\bar{b}$ vs. $t\bar{t}$	6.5 %	4.7 %	–
	$(W/Z)H^0$ vs. $W + b\bar{b}$	4.5 %	–	2.8 %
	$(W/Z)H^0$ vs. $t\bar{t}$	–	3.5 %	3.5 %

Table 5.15: SDE^2 values for the different uGB in the test samples.

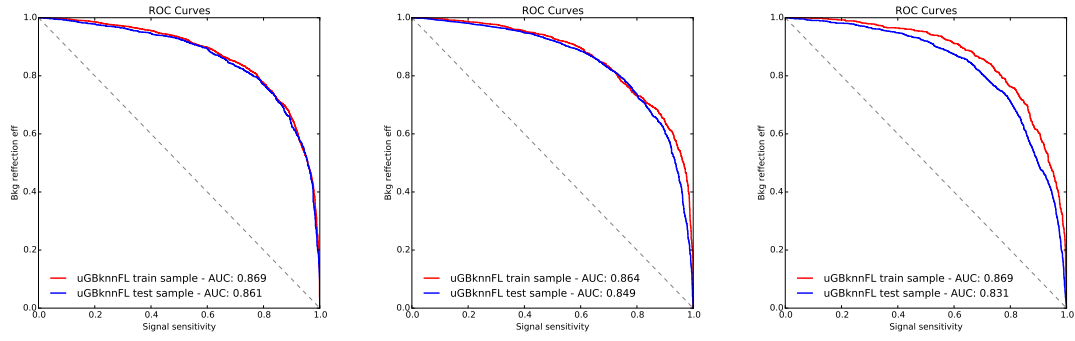


Figure 5.14: ROC curves for uGB $W + b\bar{b}$ vs $t\bar{t}$ (left: muon 2012, middle: muon 2011, right: 2012). Red(Blue) curve is the train(test) sample

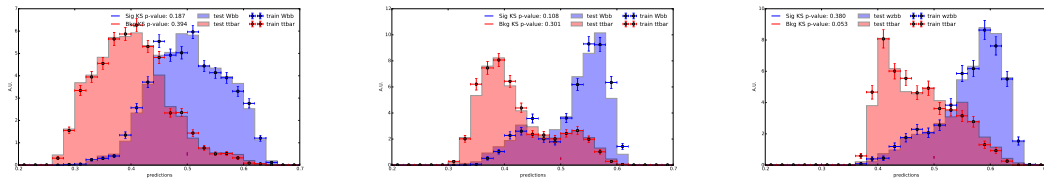


Figure 5.15: Discriminator distributions for uGB $W + b\bar{b}$ vs $t\bar{t}$ (left: muon 2012, middle: muon 2011, right: 2012). Fill(Dots) histograms is the train(test) sample

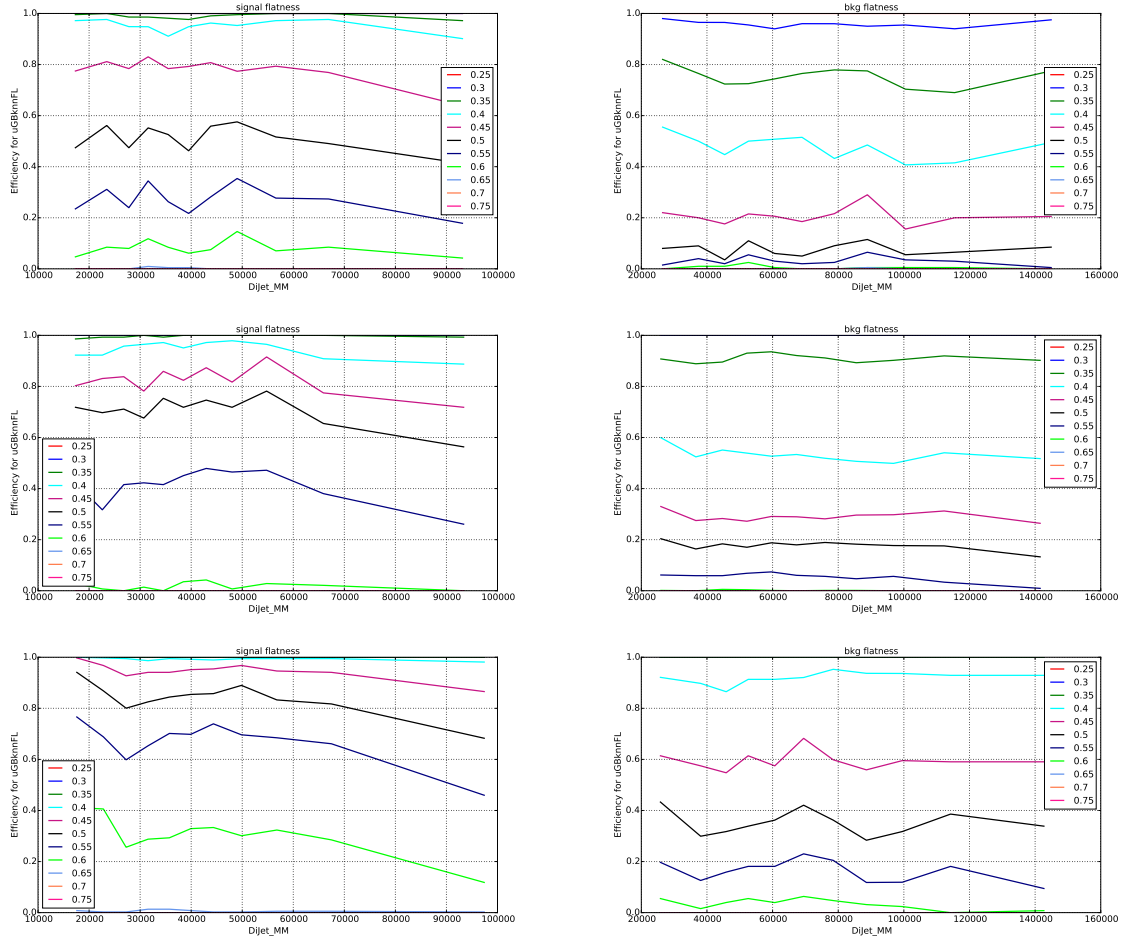


Figure 5.16: Differential efficiencies for global cuts in the discriminator output as a function of the dijet mass. In the $W + b\bar{b}$ channel (left column) and $t\bar{t}$ (right column). top row: muon 2012, middle: muon 2011, bottom: electron.

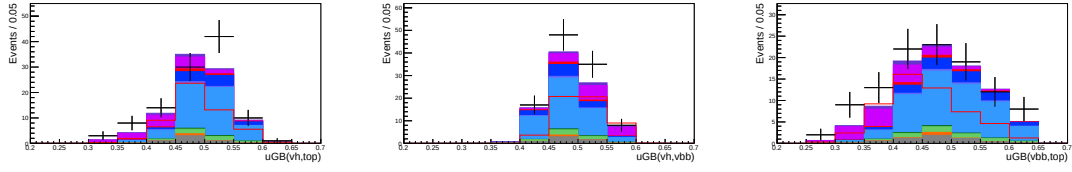


Figure 5.17: $W + b\bar{b}$ sample for muon 2012 data set. Black dots is data with horizontal and vertical bars representing its statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

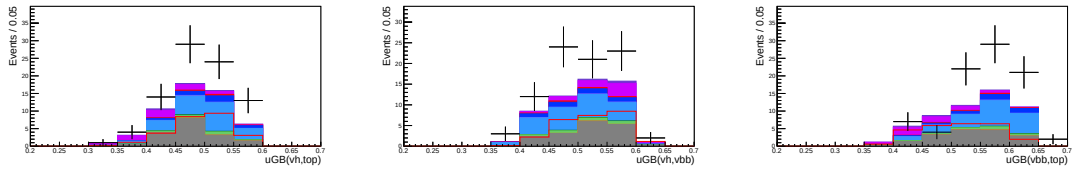


Figure 5.18: $W + b\bar{b}$ sample for electron 2012 data set. Black dots is data with horizontal and vertical bars representing its statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

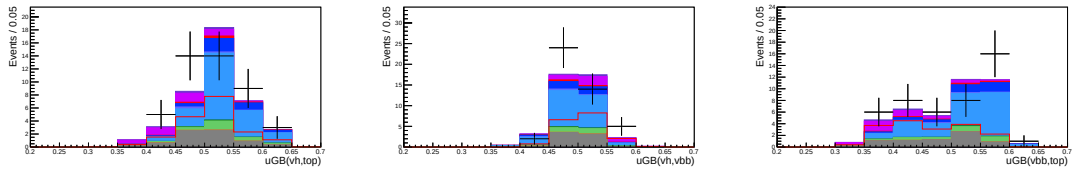


Figure 5.19: $W + b\bar{b}$ sample for muon 2011 data set. Black dots is data with horizontal and vertical bars representing its statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

5.2.7 Fit

Introduction

A unbinned maximum likelihood fit is performed to extract the signal yields of $t\bar{t}$, $W^+ + b\bar{b}$, $W^- + b\bar{b}$, $W^+ + c\bar{c}$ and $W^- + c\bar{c}$ at 8 TeV, while $Z + b\bar{b}$ (also with Z decaying to $\tau\tau$), $Z + c\bar{c}$, $ZZ + WZ$, single top and QCD are treated as background components. These yields can be used to calculate the production cross-section. $W^-(\tau\nu_\tau) + b\bar{b}$ is treated as one more signal component. To extract the signal, four different samples (μ^+ , μ^- , e^+ and e^- , depending on the identity and charge of the lepton) are fitted simultaneously. The fit is 4-dimensional, with 4 variables (m_{jj} , $uGB(t\bar{t} - W + b\bar{b})$, $BDT_{b|c}$ for jet 0 and jet 1) that are considered uncorrelated. For each of the components, templates are extracted from MC simulation or data (for the QCD background), with systematic checks in every case.

Rather than fitting directly for the signal yields, the fit is performed as a function of $K(sample) = N_{sample}^{obs}/N_{sample}^{SM}$, where N_{sample}^{SM} is the SM expected predicted yield in every sample and N_{sample}^{obs} the observed one. Therefore, five K are obtained as a result of the fit, $K(t\bar{t})$, $K(W^+ + b\bar{b})$, $K(W^- + b\bar{b})$, $K(W^+ + c\bar{c})$ and $K(W^- + c\bar{c})$. The first of these enters in the fit of the four samples while $K(W^+)$ ($K(W^-)$) only in the positive (negatives) ones. For $W^\pm(\tau\nu_\tau) + b\bar{b}$, the same $K(W^\pm + b\bar{b})$ is used.

As for the background components, they are fixed to the SM expectations, with possible variations used as a source of systematics.

Fit to data

The fit to 2012 data is shown in Figures 5.20, 5.21, 5.22 and 5.23. The same fits in log scale can be found in Figures 5.24, 5.25, 5.26 and 5.27. The fit results are shown in Table 5.16. The fit significances are shown in Table 5.17. Systematic uncertainties are not included in these preliminary fits.

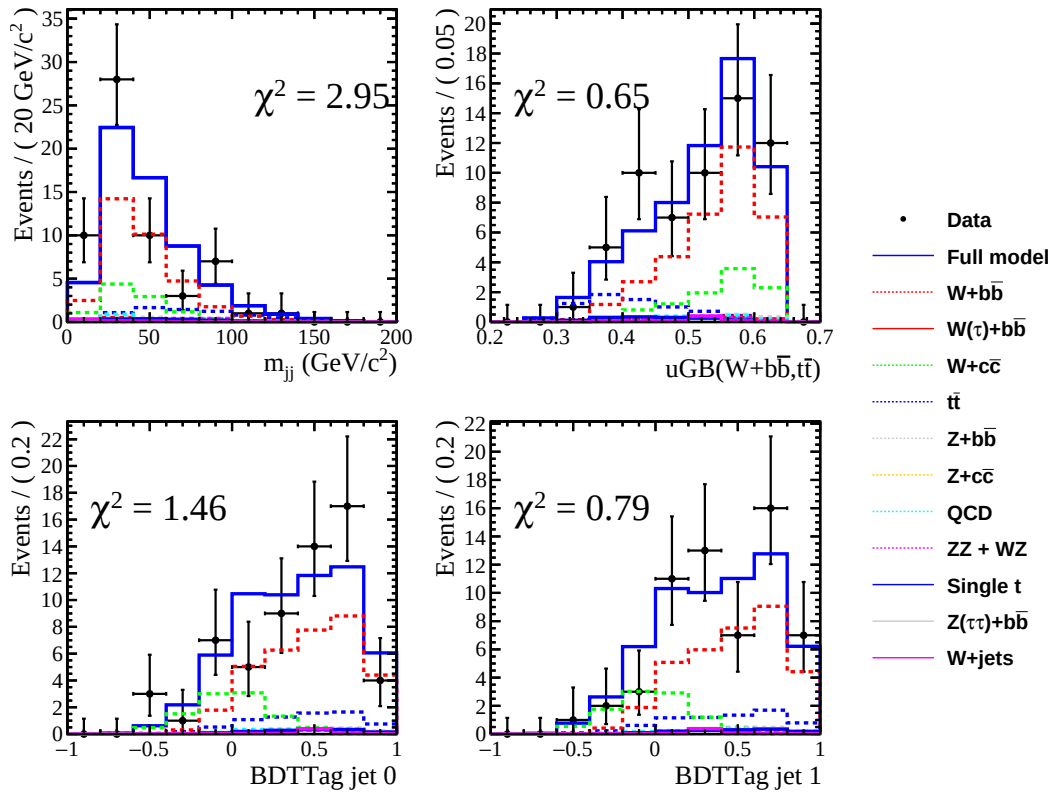


Figure 5.20: Result projection of the simultaneous 2012 data 4D-fit result on the μ^+ sample. The fit results are shown in table 5.16. The χ^2 of each individual component is also shown.

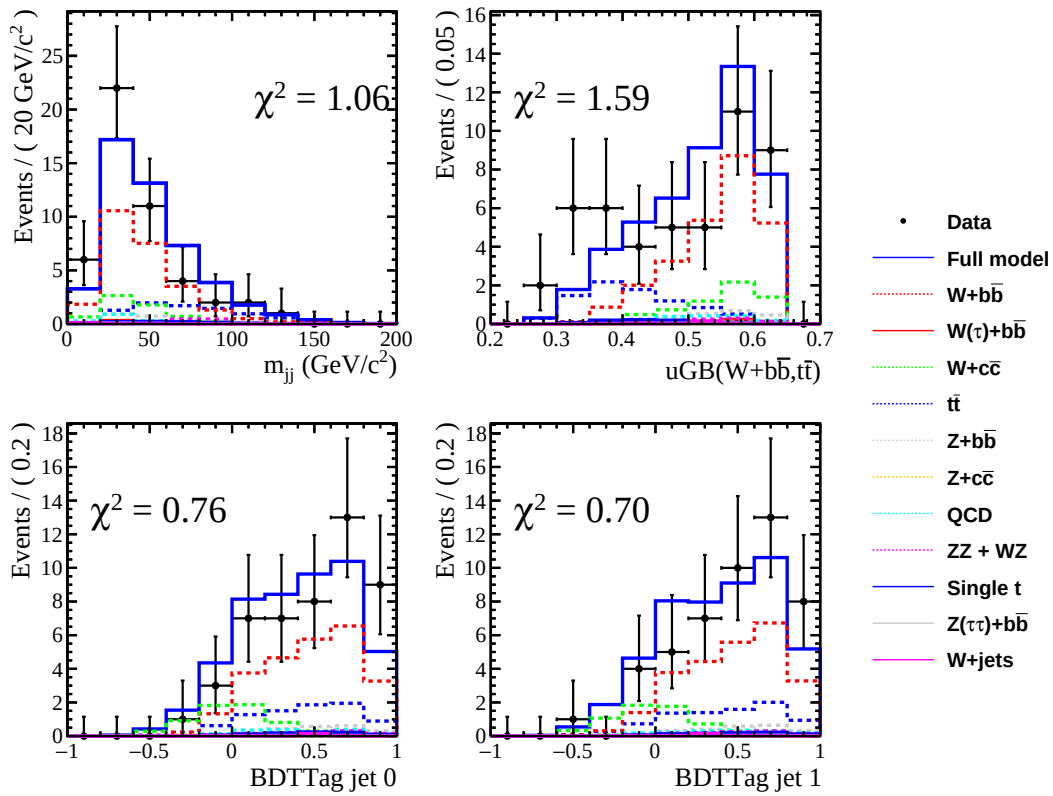


Figure 5.21: Result projection of the simultaneous 2012 data 4D-fit result on the μ^- sample. The fit results are shown in table 5.16. The χ^2 of each individual component is also shown.

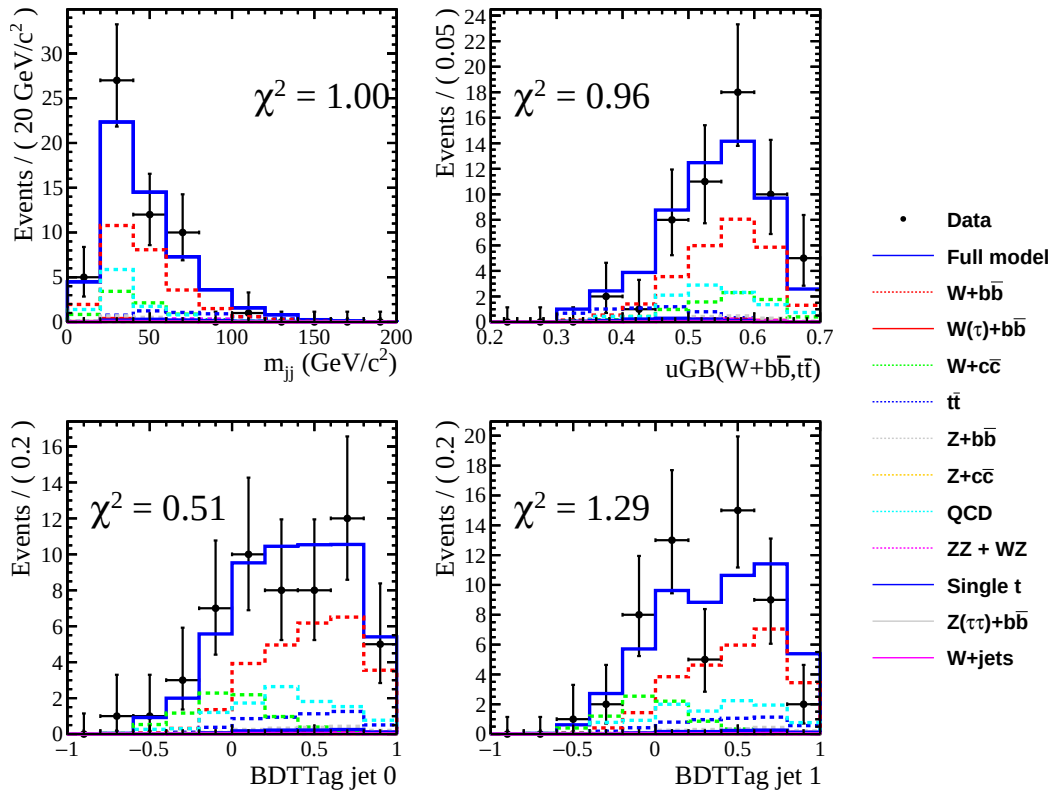


Figure 5.22: Result projection of the simultaneous 2012 data 4D-fit result on the e^+ sample. The fit results are shown in table 5.16. The χ^2 of each individual component is also shown.

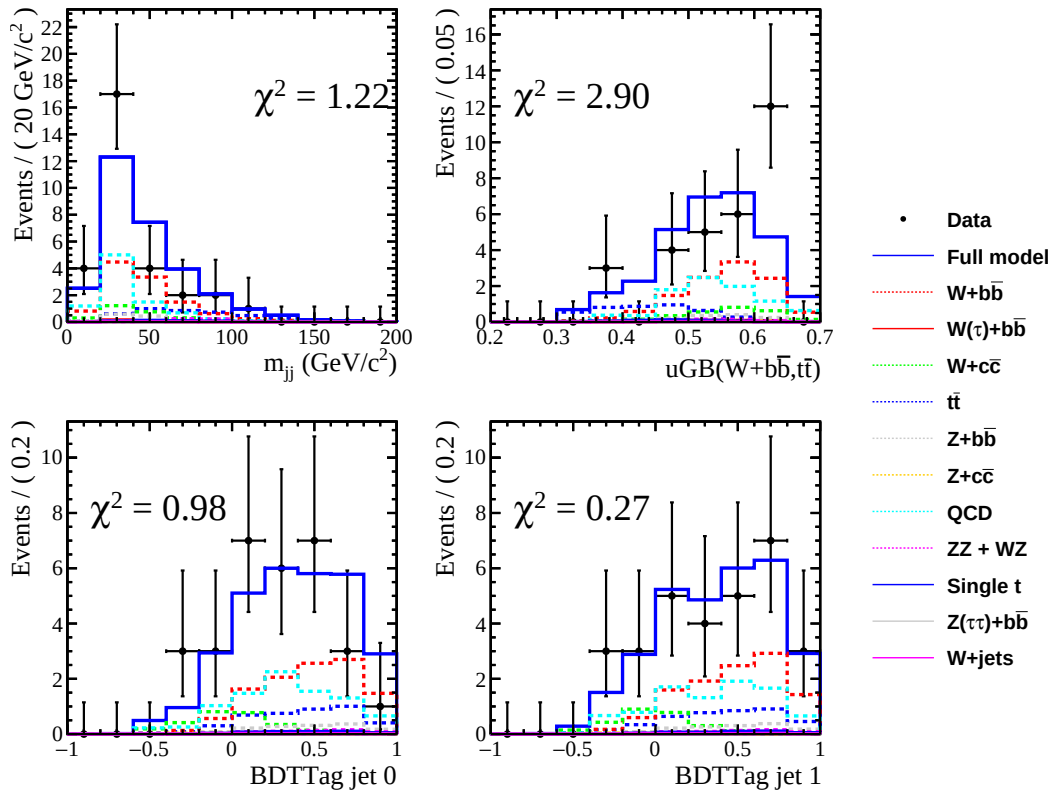


Figure 5.23: Result projection of the simultaneous 2012 data 4D-fit result on the e^- sample. The fit results are shown in table 5.16. The χ^2 of each individual component is also shown.

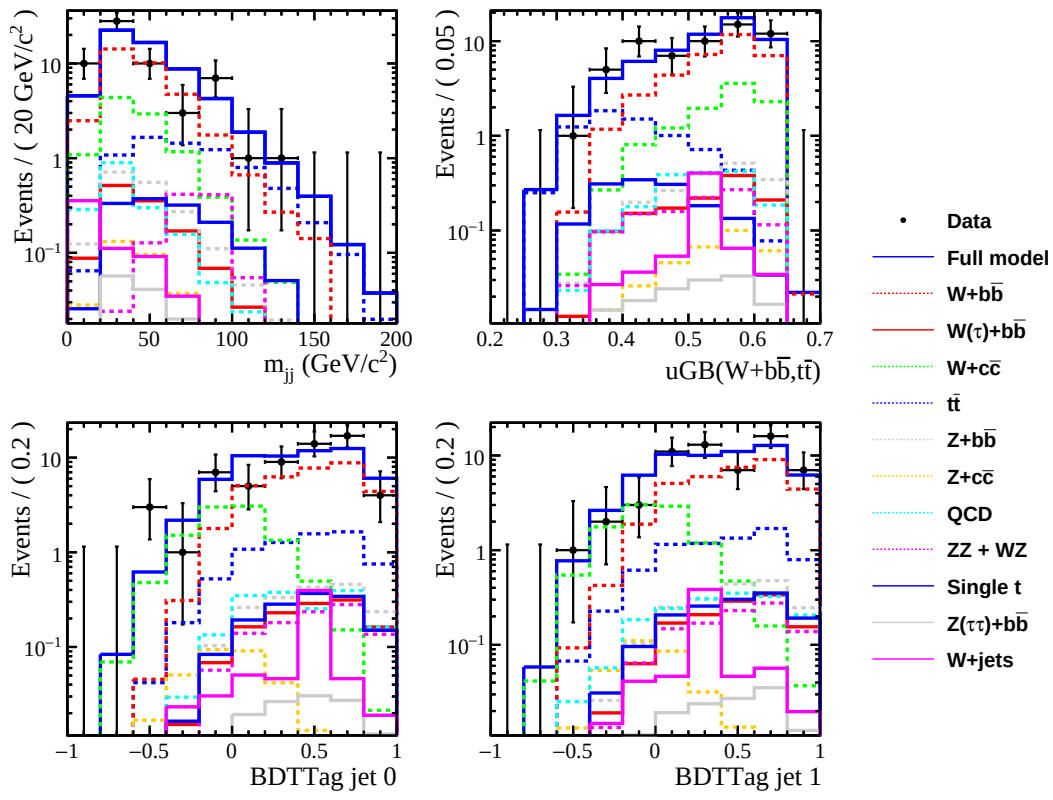


Figure 5.24: Result projection of the simultaneous 2012 data 4D-fit result on the μ^+ sample in logarithmic scale. The fit results are shown in table 5.16.

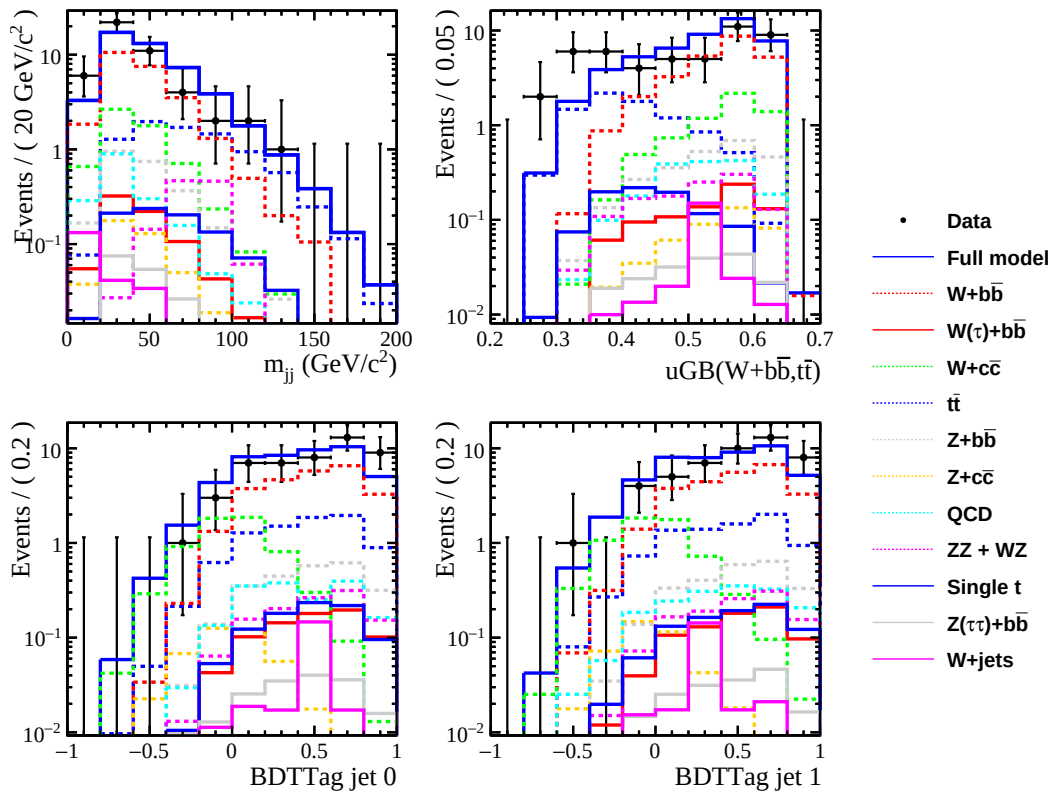


Figure 5.25: Result projection of the simultaneous 2012 data 4D-fit result on the μ^- sample in logarithmic scale. The fit results are shown in table 5.16.

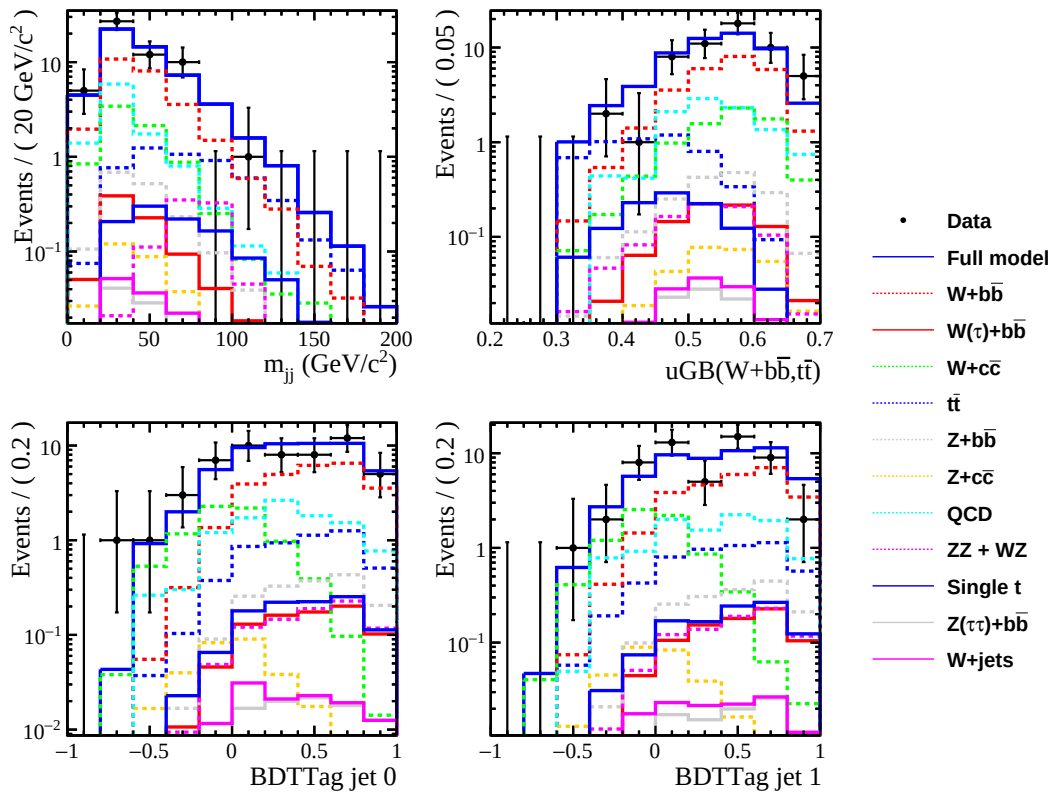


Figure 5.26: Result projection of the simultaneous 2012 data 4D-fit result on the e^+ sample in logarithmic scale. The fit results are shown in table 5.16

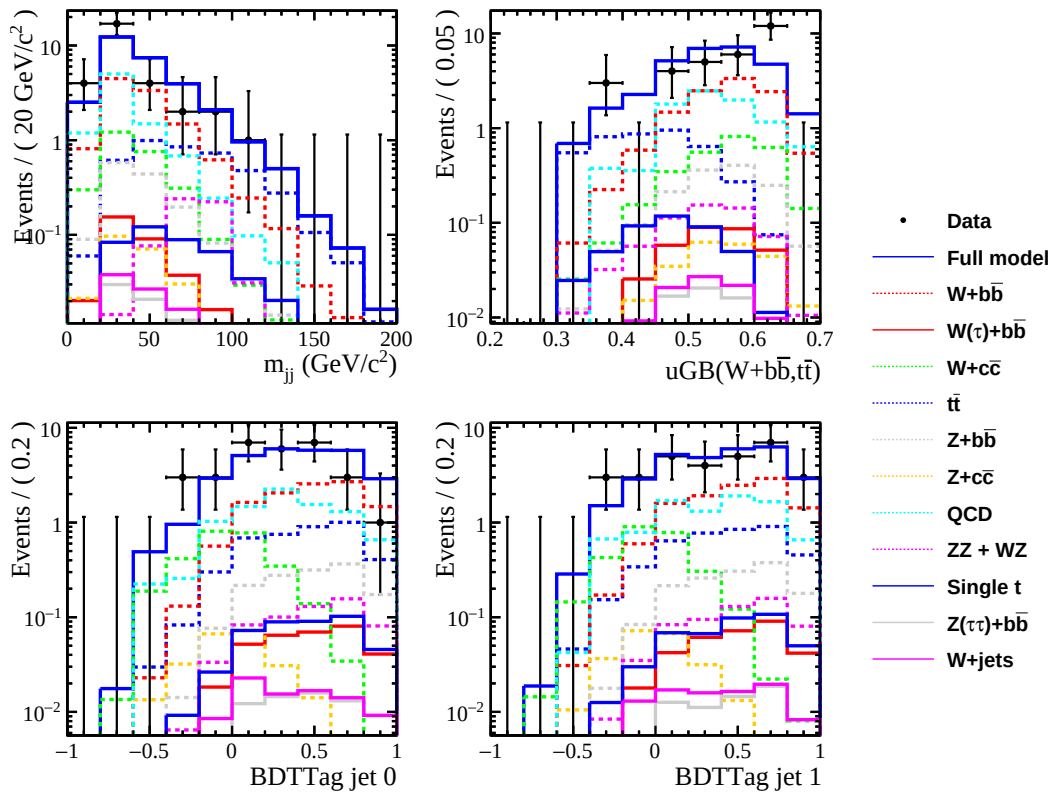


Figure 5.27: Result projection of the simultaneous 2012 data 4D-fit result on the e^- sample in logarithmic scale. The fit results are shown in table 5.16

			μ^-		μ^+		e^+		e^-	
Sample	K^+	K^-	SM prediction	Yield measured	SM prediction	Yield measured	SM prediction	Yield measured	SM prediction	Yield measured
$t\bar{t}$	$1.16^{+0.34}_{-0.30}$		7.63	$8.86^{+2.61}_{-2.28}$	7.19	$8.36^{+2.47}_{-2.15}$	3.18	$3.70^{+1.09}_{-0.95}$	3.38	$3.93^{+1.16}_{-1.01}$
$W + b\bar{b}$	$1.43^{+0.23}_{-0.21}$	$1.50^{+0.32}_{-0.29}$	30.18	$43.17^{+6.91}_{-6.43}$	16.99	$25.51^{+5.50}_{-4.96}$	13.32	$19.05^{+3.05}_{-2.84}$	7.00	$10.51^{+2.27}_{-2.04}$
$W(\tau) + b\bar{b}$	$1.43^{+0.23}_{-0.21}$	$1.50^{+0.32}_{-0.29}$	1.09	$1.56^{+0.25}_{-0.23}$	0.52	$0.78^{+0.17}_{-0.15}$	0.41	$0.59^{+0.09}_{-0.09}$	0.21	$0.31^{+0.07}_{-0.06}$
$W + c\bar{c}$	$0.37^{+0.13}_{-0.11}$	$0.32^{+0.17}_{-0.14}$	34.82	$12.72^{+4.53}_{-3.93}$	19.06	$6.14^{+3.20}_{-2.66}$	14.92	$5.45^{+1.94}_{-1.68}$	8.00	$2.58^{+1.34}_{-1.12}$

Table 5.16: Simultaneous 4D-fit 2012 data results for each of the floated samples in each of the four categories (e and μ^+ and $-\mu^-$). The K results, SM predictions and measured yields are shown. Since the actual fit is to $K(sample) = N_{sample}^{obs}/N_{sample}^{SM}$, the yields shown are the result of $N_{sample}^{SM} \times K(sample)$. Note that these results do not include systematic errors, which are particularly important for the $W + b\bar{b}$ and $W + c\bar{c}$ case.

Sample	Significance
$t\bar{t}$	6.1σ
$W^+ + b\bar{b}$	10.8σ
$W^- + b\bar{b}$	7.8σ
$W^+ + c\bar{c}$	4.8σ
$W^- + c\bar{c}$	2.9σ

Table 5.17: Fit significances, computed without accounting for the systematics.

5.2.8 $(W/Z)H^0 \rightarrow b\bar{b}$ limit

The upper limit on the $(W/Z)H^0 \rightarrow b\bar{b}$ production in the LHCb kinematic region is set using the selected data events. The compatibility of the observed events with a given Higgs Branching Fraction hypothesis is evaluated using the CL_s method [126]. This method provides the compatibility of the observed distribution with the signal plus background hypothesis, CL_{s+b} , and the compatibility with the background only hypothesis, CL_b . The CL_s value is then obtained as $CL_s = CL_{s+b}/CL_b$.

The datasets used for the limit evaluation are the 2012 muon sample, the 2012 electron sample and the 2011 muon sample. The selection requirements are those described in section 5.2, with few exceptions, that define the signal region:

- tighter jet p_T requirement, where both jets must have a p_T greater than 20 GeV;
- the $Z \rightarrow ll$ veto is not applied;
- The complete dijet invariant mass spectrum is considered, but we verified that only events in the range [70,145] GeV of dijet mass contribute significantly to the limit.

The CL_s computation requires as input the data yields, the expected background and the expected signal distributions. These distributions are provided as histograms with a particular binning scheme, described in the next section. The expected background and signal distributions are evaluated using the simulation samples and the theoretical cross-sections. The Data/Monte Carlo corrections described in section 5.2.5 are applied.

Only the QCD background distribution and yield is obtained from the data sideband as described in section 5.2.5.

Three observables are used in the CL_s computation: the dijet invariant mass, the $\text{uGB}((W/Z)H^0 \rightarrow b\bar{b} \text{ vs } W + b\bar{b})$ and the $\text{uGB}((W/Z)H^0 \rightarrow b\bar{b} \text{ vs } t\bar{t})$. The observables distributions in the high dijet mass region are showed in figures 5.28, 5.29, 5.30, 5.31, 5.32 and 5.33. Input histograms take account of possible correlations between the three observables. The expected yields for the relevant background components and the signal as well as the number of observed events in the signal region are reported in Tables 5.18, 5.19 and 5.20.

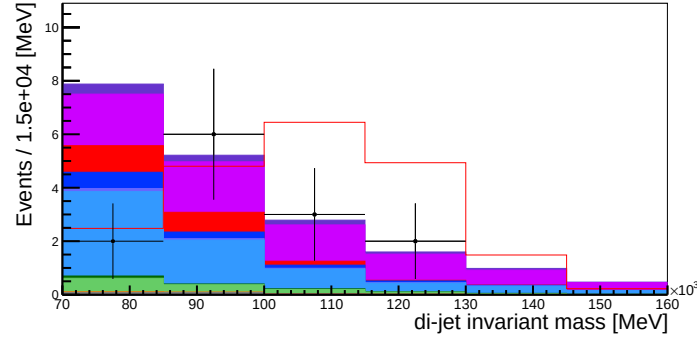


Figure 5.28: Dijet mass distribution of selected data events in the $[70,160]$ GeV range, for the 2012 muon sample. Expected backgrounds and corresponding yields are showed. Black dots is data with horizontal and vertical bars representing it statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

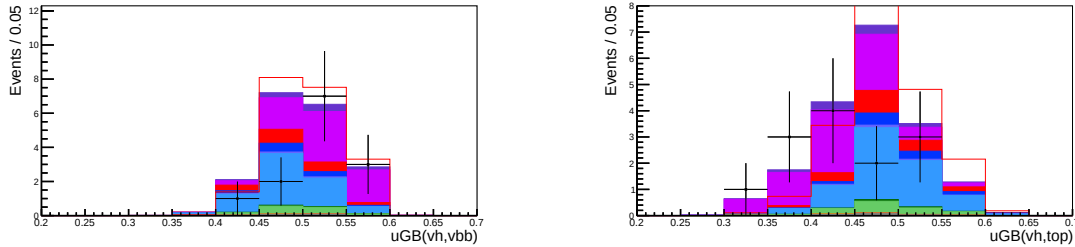


Figure 5.29: uGB distributions of selected data events in the $[70,160]$ GeV dijet mass range, for the 2012 muon sample. Expected backgrounds are showed. Black dots is data with horizontal and vertical bars representing it statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

sample	yield
$Z + b\bar{b}$	1.07
$Z + c\bar{c}$	0.15
$W + b\bar{b}$	6.27
$W + c\bar{c}$	1.06
$t\bar{t} + \text{single-}t$	7.97
VV	1.92
$W \rightarrow \tau\nu_\tau + b\bar{b}$	0.23
$Z \rightarrow \tau\nu_\tau + b\bar{b}$	0.06
QCD	0.2
total	18.8
signal $(W/Z)H^0 \rightarrow b\bar{b}$	0.10
data	13

Table 5.18: Expected yields for the relevant background components, the signal and the number of observed data events in the [70,160] GeV range of dijet mass, for the 2012 muon sample.

sample	yield
$Z + b\bar{b}$	0.50
$Z + c\bar{c}$	0.07
$W + b\bar{b}$	2.80
$W + c\bar{c}$	0.39
$t\bar{t} + \text{single-}t$	3.64
VV	0.87
$W \rightarrow \tau\nu_\tau + b\bar{b}$	0.07
$Z \rightarrow \tau\nu_\tau + b\bar{b}$	0.02
QCD	1.1
total	9.5
signal $(W/Z)H^0 \rightarrow b\bar{b}$	0.047
data	7

Table 5.19: Expected yields for the relevant background components, the signal and the number of observed data events in the [70,160] GeV range of dijet mass, for the 2012 electron sample.

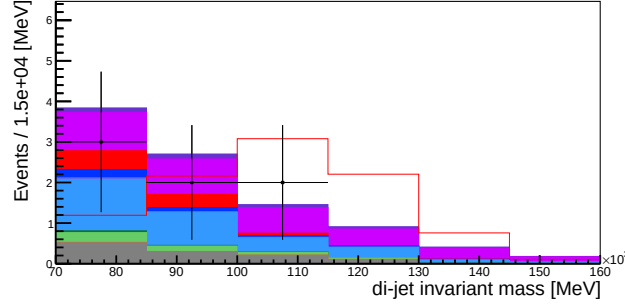


Figure 5.30: Dijet mass distribution of selected data events in the $[70,160]$ GeV range, for the 2012 electron sample. Expected backgrounds are showed. Black dots is data with horizontal and vertical bars representing it statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

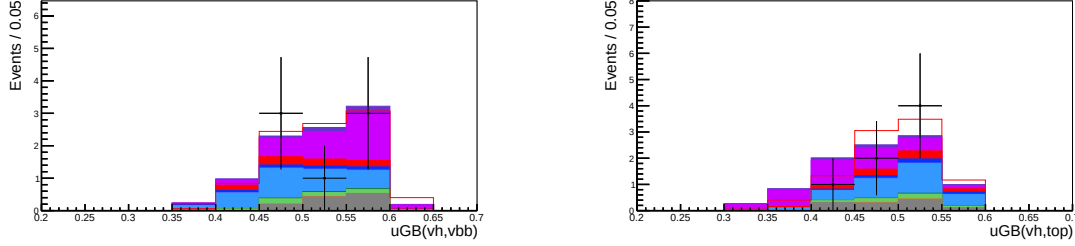


Figure 5.31: uGB distributions of selected data events in the $[70,160]$ GeV dijet mass range, for the 2012 electron sample. Expected backgrounds are showed. Black dots is data with horizontal and vertical bars representing it statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

CL_s are determined for different values of the Higgs Branching Fraction, as a function of the following quantity, normalized to the Standard Model expectation:

$$x = \frac{\sigma(pp \rightarrow (W/Z)H^0 \rightarrow b\bar{b} + X)BF(H \rightarrow b\bar{b})}{[\sigma(pp \rightarrow (W/Z)H^0 \rightarrow b\bar{b} + X)BF(H^0 \rightarrow b\bar{b})]_{SM}}.$$

The $BF(V \rightarrow l + X)$ is simplified in the ratio, since it is measured with good precision and it is considered consistent with the Standard Model. The expected CL_s are evaluated using toy MC as data input, generated with the background-only hypothesis. For each value of x a certain number of toys MC is generated and for each toy MC a CL_s is computed. The median of this CL_s sample is the expected CL_s for the considered value of x . $1-\sigma$ and $2-\sigma$ error bands are evaluated using the same CL_s sample. Expected CL_s are

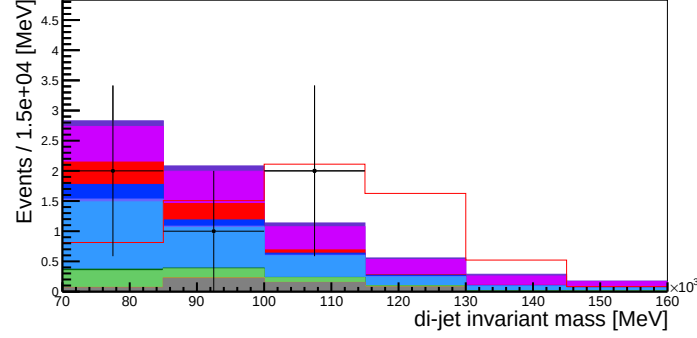


Figure 5.32: Dijet mass distribution of selected data events in the $[70,160]$ GeV range, for the 2011 muon sample. Expected backgrounds and corresponding yields are showed. Black dots is data with horizontal and vertical bars representing it statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

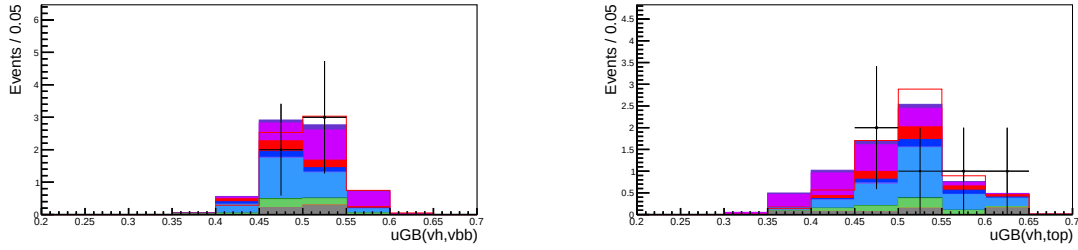


Figure 5.33: uGB distributions of selected data events in the $[70,160]$ GeV dijet mass range, for the 2011 muon sample. Expected backgrounds are showed. Black dots is data with horizontal and vertical bars representing it statistical errors. The color pattern of the simulated samples follows the same as in Figures 5.10, 5.11 and 5.12.

computed as a function of different x values; then, in order to obtain a smooth description of CL_s as a function of x , the following empirical function is fitted to these points:

$$f(x) = e^{a+bx+cx^2},$$

where a , b and c are fit parameters. $1\text{-}\sigma$ and $2\text{-}\sigma$ error bands borders and observed CL_s are fitted with the same function.

5.2.9 $H \rightarrow b\bar{b}$ limit results

In this section the results for the $H \rightarrow b\bar{b}$ limit are presented, using the method described in section 5.2.8. Several tests have been performed to find the optimal binning scheme.

sample	yield
$Z + b\bar{b}$	0.55
$Z + c\bar{c}$	0.05
$W + b\bar{b}$	2.37
$W + c\bar{c}$	0.41
$t\bar{t} + \text{single-}t$	2.42
VV	0.71
$W \rightarrow \tau\nu_\tau + b\bar{b}$	0.09
$Z \rightarrow \tau\nu_\tau + b\bar{b}$	0.02
QCD	0.5
total	7.0
signal $(W/Z)H^0 \rightarrow b\bar{b}$	0.033
data	5

Table 5.20: Expected yields for the relevant background components, the signal and the number of observed data events in the [70,160] GeV range of dijet mass, for the 2011 muon sample.

In these tests systematic uncertainties are not considered. The binning scheme chosen for the measurement is the following:

- 1 bin for events with dijet mass < 70 GeV, 3 mass bins, with equal width in the range [70,115] GeV, and 1 bin for events with mass > 115 GeV;
- 4x4 transformed uGB bins, with equal width in the [0,1]x[0,1] ranges.

The total number of bins for each data sample is 80, for a total of 240 bins for the three datasets, muon 2012, electron 2012 and muon 2011. Systematic uncertainties are treated as nuisance parameters in the CL_s computation. The sources of systematic error included are those described in section 5.3.2. The expected and observed CL_s obtained by using the three datasets together, without applying nuisance parameters, are presented in figure 5.34. The expected CL_s and bands are computed by generating 49k Toys. The expected upper limit on x at 95% Confidence Level is $x < 58.5$, the observed limit is $x < 35.2$. The observed limit is compatible within $2\text{-}\sigma$ from the expectation. By assuming the ratio between the 8 TeV and 7 TeV equal to the Standard Model expectation ($\sigma[pp \rightarrow$

$WH + X; 8 \text{ TeV}] / \sigma[pp \rightarrow WH + X; 7 \text{ TeV}] = 1.22$ and $\sigma[pp \rightarrow ZH + X; 8 \text{ TeV}] / \sigma[pp \rightarrow ZH + X; 7 \text{ TeV}] = 1.24$), we obtain that the observed limit for the $VH(\rightarrow b\bar{b})$ production cross section, with jets and lepton from V in the LHCb kinematic region, at 95 % and 90 % C.L., without systematics, is:

$$\sigma(pp \rightarrow VH + X)BF(H \rightarrow b\bar{b}) < 1.12 \text{ (0.882) } pb, \text{ 95\% (90\%) } CL, \text{ 8 TeV.}$$

$$\sigma(pp \rightarrow VH + X)BF(H \rightarrow b\bar{b}) < 0.726 \text{ (0.572) } pb, \text{ 95\% (90\%) } CL, \text{ 7 TeV.}$$

We also computed the 7 TeV and 8 TeV limits separately, using the electron and muon sample for the 8 TeV limit and the muon sample for the 7 TeV limit. The results, without systematics, are showed in figure 5.35. In this computation the observed limits for the $VH(\rightarrow b\bar{b})$ production cross section at 7 TeV and 8 TeV, with jets and lepton from V in the LHCb kinematic region, at 95 % and 90 % C.L., without systematics, are:

$$\sigma(pp \rightarrow VH + X)BF(H \rightarrow b\bar{b}) < 1.18 \text{ (0.946) } pb, \text{ 95\% (90\%) } CL, \text{ 8 TeV.}$$

$$\sigma(pp \rightarrow VH + X)BF(H \rightarrow b\bar{b}) < 3.22 \text{ (2.62) } pb, \text{ 95\% (90\%) } CL, \text{ 7 TeV.}$$

The observed and expected limits in terms of x , the ratio between the cross section upper limit and the Standard Model cross section, are summarised in Tables 5.21 and 5.22.

5.2.10 Systematics

By the time of the writing of this thesis the systematic uncertainties were not fully implemented. On the other hand, preliminary studies are presented in this section although the cross-section and final limits are not finalised in this thesis.

The systematic uncertainties considered for the cross-section measurements and the Higgs search are detailed below. A list of the systematic errors are presented in Table 5.23.

	95% CL	90% CL
$H \rightarrow b\bar{b}$ 7 TeV + 8 TeV	$x < 35.2$	$x < 27.7$
$H \rightarrow b\bar{b}$ 8 TeV	$x < 37.8$	$x < 30.3$
$H \rightarrow b\bar{b}$ 7 TeV	$x < 156$	$x < 127$

Table 5.21: Observed 95% and 90% Confidence Level limits in terms of x , the ratio between the cross section upper limit and the Standard Model cross section. Nuisance parameters are not applied.

	95% CL	90% CL
$H \rightarrow b\bar{b}$ 7 TeV + 8 TeV	$x < 58.5$	$x < 48.0$
$H \rightarrow b\bar{b}$ 8 TeV	$x < 66.2$	$x < 54.3$
$H \rightarrow b\bar{b}$ 7 TeV	$x < 175$	$x < 141$

Table 5.22: Expected 95% and 90% Confidence Level limits in terms of x , the ratio between the cross section upper limit and the Standard Model cross section. Nuisance parameters are not applied.

Luminosity

The luminosity uncertainty is 2% in 2011 and 1% in 2012 as described in Reference [127].

GEC efficiency

The GEC efficiency vary between the physics processes since the global occupancy of the event types is different. For this variation, we assume a systematic error on the SM expectations of 2% as the simulated samples agree within this level (see Fig. 5.36). This error may appear conservative if compared with the error considered in studies of Reference [128], but in this analysis it is expected that the requirement of two jets increases it.

Muon efficiencies

Muon reconstruction and identification efficiencies in data and simulation were measured in Reference [123]. Trigger efficiencies are found to be slightly different between data and simulation and scale factors are used as described above. Reconstruction and identification

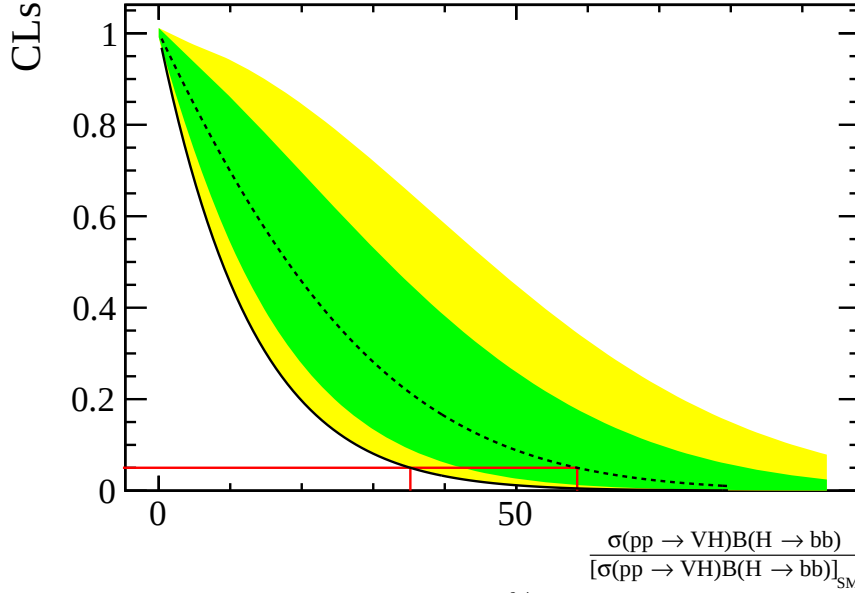


Figure 5.34: Observed and expected CL_s and 95% Confidence Level upper limit obtained by using the 7 TeV and 8 TeV datasets together. Nuisance parameters are not applied. The black dashed line represents the expected CL_s , the green and yellow bands are respectively the $1\text{-}\sigma$ and $2\text{-}\sigma$ bands. The black continuous line represents the observed CL_s . The 0.05 CL_s level is indicated by the red horizontal line.

efficiencies are found to be consistent between data and simulation. The trigger scale factors errors are varied to obtain systematic variation of the SM expectation. This variation affects both the shape and normalisation of the expectations. The average variation on the yield prediction is of about 1.7%. Track and identification efficiencies are considered to be the same between data and simulation within the errors evaluated in Reference [123] and summarised in Table 5.24.

Electron efficiencies

The SM simulation for the electron channel is corrected by data and simulation efficiency differences. The error on this scale factor is of the order of 5% and used as systematic uncertainty on the SM simulation. Track requirements, electron identification and electron p_T threshold efficiencies are not found to be significantly different between simulation and data [124] within an error detailed in Table 5.25.

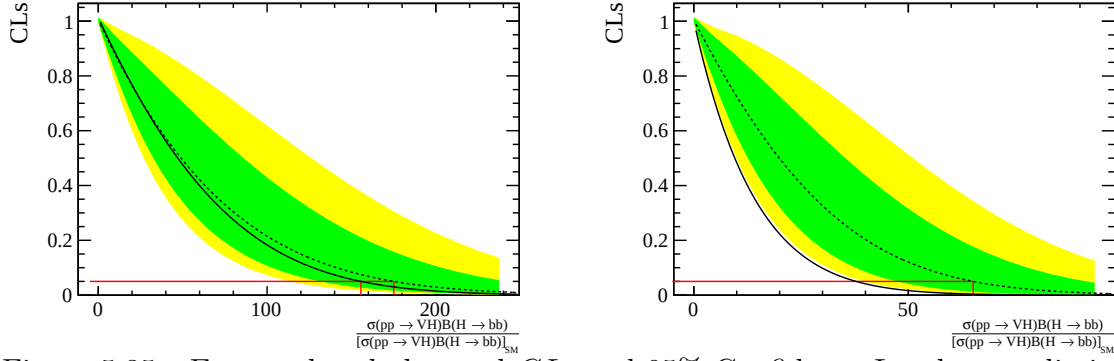


Figure 5.35: Expected and observed CL_s and 95% Confidence Level upper limit for the $H \rightarrow bb$, obtained separately for the 7 TeV sample (left) and the 8 TeV sample (right). Nuisance parameters are not applied. The black dashed line represents the expected CL_s , the green and yellow bands are respectively the $1\text{-}\sigma$ and $2\text{-}\sigma$ error bands. The black continuous line represents the observed CL_s . The 0.05 CL_s level is indicated by the red horizontal line.

Jet energy calibration

The jet energy calibration error is evaluated in Reference [129]. It includes possible biases in the jet energy calibration due to flavour dependence (2%), ghost tracks (1.2%), track momentum resolution ($\sim 1\%$) and simulation and data differences ($\sim 1\%$). To evaluate the impact of the jet energy calibration error in this analysis, the jet selection is done after the jet energy calibration is varied by its error. Table 5.26 shows the impact of this uncertainty on the yields of the main physics processes.

Jet energy resolution

The jet energy resolution error is taken as evaluated in Reference [122]. Events with a $Z \rightarrow \mu^+ \mu^-$ produced back-to-back with a jet are used to estimate the maximum smearing one needs to apply to have simulation and data disagreement higher than 1σ . It is found that the energy resolution in data and simulation are the same within a 10%. To evaluate the impact of the jet energy calibration error in this analysis, the jet selection is done after the jet energy is smeared by 10%. This variation changes the shape and normalisation of the SM predictions. Table 5.27 shows the impact of this uncertainty on the yields of the main physics processes.

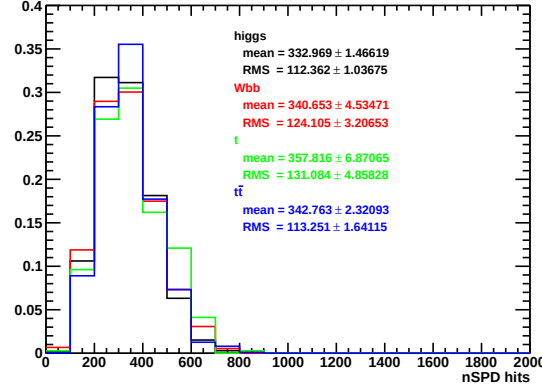


Figure 5.36: nSPD distributions for the relevant physics processes after full selection except the nSPD trigger requirement.

Jet efficiencies

Simulation and data differences for jet reconstruction and identification efficiencies are evaluated in Reference [129]. The error is found to be below 2% for jets with $p_T > 10$ GeV. To evaluate the impact of the jet efficiencies, the SM simulation is weighted by $1 \pm \frac{\delta_{jet}}{\epsilon_{jet}}$. This variation changes the shape and normalisation of the SM predictions. Table 5.28 shows the impact of this uncertainty on the yields of the main physics processes.

Jet b-tag efficiencies

The SM simulation is corrected by data and simulation b-tag efficiency differences as measured in Ref. [103]. The error on this scale factor varies between 5 – 10% for most of the jets. The impact of the b-tag efficiency error is taken into account by varying the weights. This variation changes the shape and normalisation of the SM predictions. Table 5.29 shows the impact of this uncertainty on the yields of the main physics processes.

MC statistics

The MC samples used for the efficiencies computation are statistically limited, which has an associated systematic error. This is treated independently for the electron and muon positive and negative samples.

QCD background

The QCD background is estimated using sideband regions in data. Due to statistical limitation of the QCD sideband regions, the error on the QCD normalisation is large. Moreover, the two assumptions used to estimate the QCD background are studied.

To study the assumption that the event topology does not depend on the I variable, we use two QCD enriched samples: 1) events are required to pass all selection criteria but IP_1 cut is reversed and 2) events are required to pass all selection criteria but the calorimeter lepton identification cuts are reversed and no IP_1 requirement is used. The first sample is used to estimate k_{QCD} and it is expected to be enriched in heavy-flavour decays. The second sample is dominated by mis-identification, but the contamination of heavy-flavour is sizable as it can be observed in the IP_1 distribution.

No systematic effect is observed above the statistical fluctuation. Since the normalisation statistical error is on the order of 30 %, we take this as the systematic error of the QCD background.

Theory

The cross sections are calculated using the MCFM [130] with CT10 PDF [131] as detailed in Appendix E. The prediction is affected by the PDF error (δ_{PDF}), α_s error (δ_{α_s}) and scale uncertainty (δ_μ). The PDF uncertainty is evaluated as suggested in Reference [132]. The α_s uncertainty is evaluated by calculating the cross-sections with three values of $\alpha_s(M_Z)$: 0.117, 0.118 and 0.119. The scale uncertainty is evaluated by calculating the cross-sections varying the scale of the renormalisation and factorisation by a factor of two. The total error is taken as $\sqrt{(\delta_{\text{PDF}}^2 + \delta_{\alpha_s}^2)} + \delta_\mu$.

Fit biases

The assumption that the fit variables are uncorrelated is not 100% true and may be a source of systematic uncertainty. In order to assess this uncertainty, a toy study is

performed. In this study, toy simulations are performed removing (or not) the existing correlations between variables. The bias from the assumption that the variables are uncorrelated are $\leq 10\%$. Therefore, a conservative 10% uncertainty is set for all the fit results. This effect does not affect the Higgs upper limit results.

uGB shape

Different checks on the uGB shapes have been performed in order to see the impact on the final fit. No test showed visible effect. These studies are undergoing at the moment.

$\gamma \rightarrow ee + \text{jet}$

The $\gamma \rightarrow ee + \text{jet}$ is a possible source of background for the electron sample, that lies in the low dijet mass region. It is not included in the background model for the fit and limits determination, since the expected yield is low. To check this, the selection requirements for the $W + b\bar{b}$ cross section measurement are applied to 319837 $\gamma \rightarrow ee + \text{jet}$ simulated events in the LHCb acceptance at 8 TeV; from these only 1 event pass the selection. Considering the theoretical NLO cross section for $\gamma + \text{jet}$ at 8 TeV (47.7 nb for $p_T(\gamma) > 20\text{GeV}$ in the LHCb acceptance), the probability of electron conversion (15%) and the selection efficiency, the expected $\gamma \rightarrow ee + \text{jet}$ yield is estimated to be about 0.36 events. This contamination is treated as a systematic source.

5.2.11 Cross section results

MCFM predictions are used to obtain cross-sections at parton level, i.e., they do not include showering nor hadronization, therefore the kinematical cuts applied to jets can not be predicted by MCFM. Moreover, the cross-sections presented in Appendix E are calculated with looser requirements in the lepton. In order to compare properly the fit results of section 5.2.7 with the theoretical predictions, PYTHIA v8.170 with CT10 PDF set is used to estimate the LHCb experimental cuts efficiency on the top of the parton level MCFM requirements.

The procedure to calculate this efficiency factor consists of selecting events with the generator cuts described in Appendix E to obtain N_{gen} and with the fiducial requirements described in section 5.2 (see table 5.1) to obtain N_{sel} . Jets are reconstructed with FASTJET using the anti-kt algorithm with $R=0.5$ and then matched with a bottom/charm quark. The factor $k = \frac{N_{gen}}{N_{sel}}$ for $W + b\bar{b}$, $W + c\bar{c}$, and $t\bar{t}$ is 0.0284, 0.0199 and 0.0037, respectively. These factors are calculated with a number of events in order to have better than 1% precision. We assume the errors on these factor are negligible. The cross-sections are extracted for muon requirements only.

The observed and expected cross-sections are presented in Table 5.30 and represented in Fig. 5.37 and 5.38.

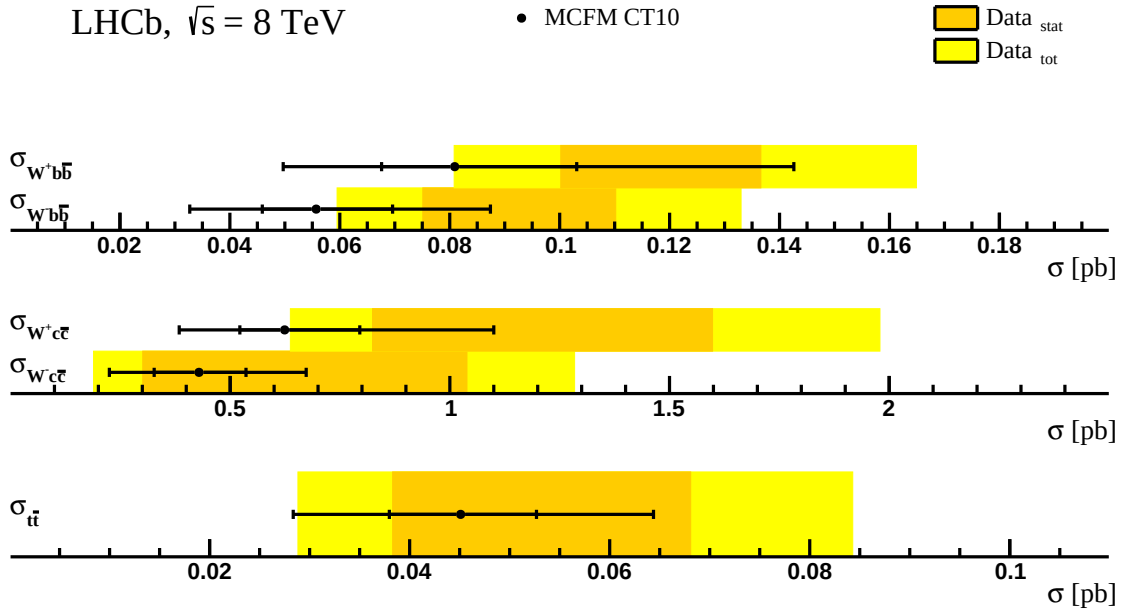


Figure 5.37: Observed cross-sections in pb for all the 2012 channels compared to expected ones from MCFM CT10, where the inner error bars are due to the scale errors.

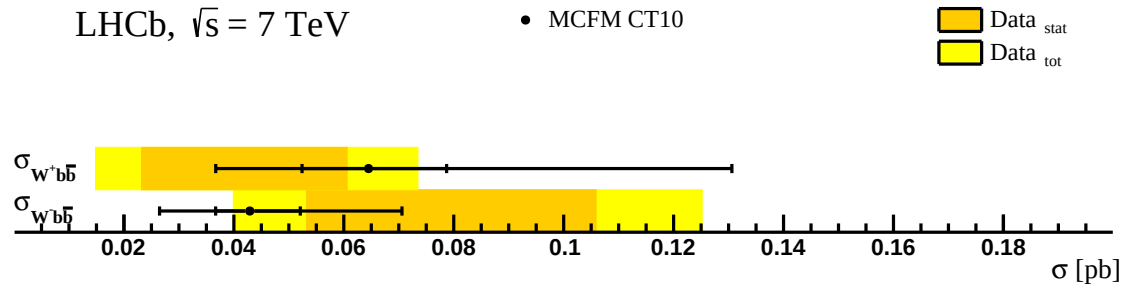


Figure 5.38: Observed cross-sections in pb for the 2011 $W + b\bar{b}$ to expected one from MCFM CT10, where the inner error bars are reflecting the scale error.

Table 5.23: Summary of systematic uncertainties considered and the impact on the predictions.

Source	Impact
Luminosity	Normalisation
GEC	Normalisation
Lepton trigger	Shape+Normalisation
Lepton efficiency	Normalisation
JEC	Shape+Normalisation
JER	Shape+Normalisation
Jet efficiency	Shape+Normalisation
Jet b-tag	Shape+Normalisation
Theory	Normalisation
Fit biases	Normalisation
QCD	Normalisation
MC statistics	Normalisation
$\gamma \rightarrow ee + \text{jet}$	Normalisation
uGB shape	Shape

Table 5.24: Relative systematic uncertainties on muon identification and track reconstruction efficiencies for 2011 and 2012.

efficiency	relative systematic uncertainty for 2011 / 2012
ϵ_{track}	1.5% / 0.8%
ϵ_{ID}	0.4% / 0.6%
total	1.6% / 1.0%

Table 5.25: Systematic uncertainties on electron selection efficiencies.

efficiency	relative systematic uncertainty
ϵ_{track}	0.6%
$\epsilon_{kinematic}$	1.1%
ϵ_{PID}	1.2%
total	1.9%

Table 5.26: Relative yield error due to jet energy calibration error.

Sample	$(W/Z)H^0$	$W + b\bar{b}$	$W + c\bar{c}$	$t\bar{t}$
Muon 2011 JECUP	-1.15%	+1.93%	+2.04%	-0.31%
Muon 2011 JECDW	+0.80%	2.48%	2.51%	+0.38%
Muon 2012 JECUP	-1.27%	+2.03%	+2.11%	-0.65%
Muon 2012 JECDW	+1.05%	1.84%	1.94%	+0.43%
Electron 2012 JECUP	-1.00%	+2.13%	+2.25%	-0.73%
Electron 2012 JECDW	+0.62%	2.07%	2.52%	+0.70%

Table 5.27: Relative yield error due to the jet energy resolution error.

Sample	$(W/Z)H^0 \rightarrow b\bar{b}$	$W + b\bar{b}$	$W + c\bar{c}$	$t\bar{t}$
Muon 2011	-0.74%	-1.72%	-1.31%	-1.02%
Muon 2012	-0.66%	-1.63%	-1.27%	-1.71%
Electron 2012	-1.62%	+0.043%	-2.70%	-1.03%

Table 5.28: Relative yield error due to jet efficiency error.

Sample	$(W/Z)H^0 \rightarrow b\bar{b}$	$W + b\bar{b}$	$W + c\bar{c}$	$t\bar{t}$
Muon 2011 JETEFFUP	+1.63%	+1.21%	+1.18%	+1.54%
Muon 2011 JETEFFDW	-1.61%	-1.20%	-1.17%	-1.53%
Muon 2012 JETEFFUP	+1.62%	+1.22%	+1.19%	+1.55%
Muon 2012 JETEFFDW	-1.61%	-1.21%	-1.18%	-1.54%
Electron 2012 JETEFFUP	+1.62%	+1.22%	+1.19%	+1.54%
Electron 2012 JETEFFDW	-1.60%	-1.21%	-1.19%	-1.53%

Table 5.29: Relative yield error due to b-tag error.

Sample	$(W/Z)H^0 \rightarrow b\bar{b}$	$W + b\bar{b}$	$W + c\bar{c}$	$t\bar{t}$
Muon 2011 BTAGUP	+18.3%	+13.9%	+18.9%	+15.6%
Muon 2011 BTAGDW	-16.7%	-13.0%	-17.3%	-14.4%
Muon 2012 BTAGUP	+18.0%	+13.9%	+19.2%	+15.5%
Muon 2012 BTAGDW	-16.6%	-12.9%	-17.5%	-14.3%
Electron 2012 BTAGUP	+24.2%	+19.8%	+25.3%	+22.0%
Electron 2012 BTAGDW	-20.7%	-17.3%	-21.5%	-19.0%

Table 5.30: Cross-sections in pb.

Process	Expected	Observed
7 TeV		
$W^+ + b\bar{b}$	$0.07^{+0.01}_{-0.01}$ (scale) $^{+0.05}_{-0.02}$ (total)	$0.040^{+0.021}_{-0.017}$ (stat.) $^{+0.013}_{-0.008}$ (syst.)
$W^- + b\bar{b}$	$0.043^{+0.009}_{-0.006}$ (scale) $^{+0.019}_{-0.010}$ (total)	$0.08^{+0.03}_{-0.02}$ (stat.) $^{+0.02}_{-0.01}$ (syst.)
8 TeV		
$W^+ + b\bar{b}$	$0.08^{+0.02}_{-0.01}$ (scale) $^{+0.04}_{-0.02}$ (total)	$0.12^{+0.02}_{-0.02}$ (stat.) $^{+0.03}_{-0.02}$ (syst.)
$W^- + b\bar{b}$	$0.06^{+0.01}_{-0.01}$ (scale) $^{+0.02}_{-0.01}$ (total)	$0.09^{+0.02}_{-0.02}$ (stat.) $^{+0.02}_{-0.02}$ (syst.)
$W^+ + c\bar{c}$	$0.6^{+0.2}_{-0.1}$ (scale) $^{+0.3}_{-0.1}$ (total)	$1.2^{+0.4}_{-0.5}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)
$W^- + c\bar{c}$	$0.4^{+0.1}_{-0.1}$ (scale) $^{+0.1}_{-0.1}$ (total)	$0.7^{+0.4}_{-0.3}$ (stat.) $^{+0.3}_{-0.1}$ (syst.)
$t\bar{t}$	$0.045^{+0.008}_{-0.007}$ (scale) $^{+0.012}_{-0.010}$ (total)	$0.05^{+0.02}_{-0.01}$ (stat.) $^{+0.02}_{-0.01}$ (syst.)

5.3 Z+b-jets

In this section the measurement of the production of Z+b-jet with $Z/\gamma^* \rightarrow \mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 7\text{ TeV}$ using the data collected by the LHCb experiment in 2011 is described. The data set corresponds to an integrated luminosity of 1.0 fb^{-1} .

The presence of a bottom hadron candidate is used to tag the jet as originating from a bottom quark, following Reference [133]. The results are compared to NLO and leading-order (LO) calculations using massless and massive bottom quarks.

5.3.1 Measurement strategy and event selection

The $Z \rightarrow \mu^+\mu^-$ selection follows that described in Reference [134]. Muon tracks in the fiducial volume ($2.0 < \eta(\mu) < 4.5$) are required to have transverse momentum greater than 20 GeV. In order to have good quality muons, the relative uncertainty on the momentum of each muon is required to be less than 10 % and the χ^2 probability for the associated track fit larger than 0.1 %. The dimuon candidate mass is in the 60 – 120 GeV range. The contribution from combinatorial background of $(0.31 \pm 0.06)\%$ evaluated in Reference [134] is neglected.

The jets are required to be reconstructed within the LHCb acceptance ($2.0 < \eta(\text{jet}) < 4.5$) and two transverse momentum thresholds of 10 and 20 GeV are studied. In addition to those kinematic criteria, jets are required to be isolated from the muons of the Z boson decay ($\Delta R(\text{jet}, \mu) > 0.4$), where ΔR is the distance in $\eta - \phi$ space and ϕ is the azimuthal angle.

The Z+b-jet cross-section is determined from the ratio of Z+b-jet to Z+jet event yields corrected for efficiencies and normalized by the Z+jet production cross-section

$$\sigma(\text{Z+b-jet}) = \frac{\varepsilon(\text{Z+jet})}{\varepsilon(\text{Z+b-jet})} \frac{1}{\varepsilon(\text{b-tag})} \frac{N(\text{Z+b-jet})}{N(\text{Z+jet})} \sigma(\text{Z+jet}), \quad (5.4)$$

where $N(\text{Z+b-jet})$ is the observed number of Z+b-jet events, $N(\text{Z+jet})$ is the number of

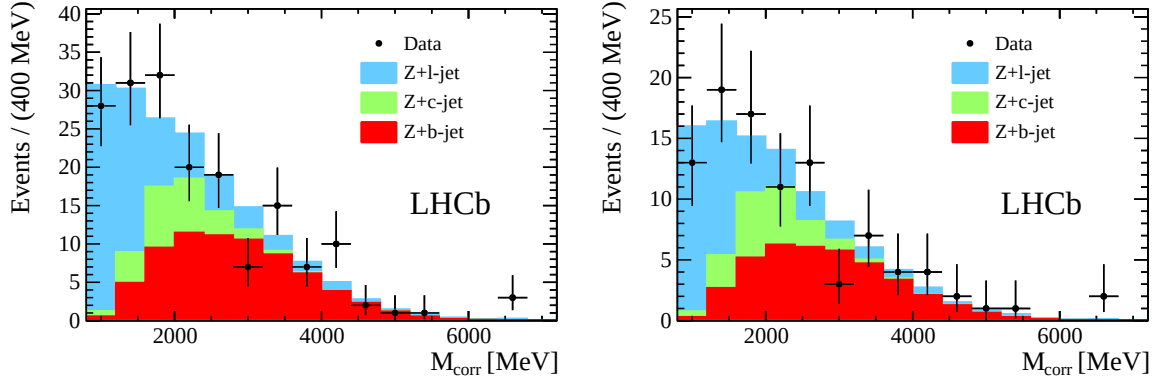


Figure 5.39: M_{corr} distribution for (left) $p_{\text{T}}(\text{jet}) > 10 \text{ GeV}$ and (right) $p_{\text{T}}(\text{jet}) > 20 \text{ GeV}$. Data (black points) are compared to the template fit result. The uncertainties shown are statistical only.

observed Z+jet events, $\varepsilon(\text{Z+jet})/\varepsilon(\text{Z+b-jet})$ is ratio of efficiencies for the reconstruction and selection of Z+jet and Z+b-jet events and $\varepsilon(\text{b-tag})$ is the efficiency of the b-tagging. The production cross-section of Z boson associated with jets, $\sigma(\text{Z+jet})$, was previously measured by LHCb [134]. The same data sample, Z boson selection, jet selection are used but identification of jets originating from bottom quarks is added. By using this approach, the systematic uncertainties and the efficiencies are largely the same as those of Reference [134], except for those related to the b-jet identification.

The Topo algorithm explained in Section 4.2.1 is used for the identification of secondary vertices consistent with the decay of a beauty hadron using tracks that form the jet. The requirement of a TOPO candidate greatly reduces the background of jets originating from light partons (l-jets) and charm quarks (c-jets). The number of b-jets is extracted from an unbinned likelihood fit to the corrected mass (M_{corr}) of the TOPO candidate.

Templates for the M_{corr} distribution of b-jets, c-jets and l-jets are obtained from simulation of Z+jet, inclusive b-hadron and inclusive c-hadron production. The shapes of the templates for b-jets, c-jets and l-jets in these samples show no dependence on the production process nor on the p_{T} of the jet. A template fit to the M_{corr} spectrum in

data is used in the evaluation of $N(\text{Z+b-jet})$. The *sPlot* method [135] is used in order to estimate the b-jet p_T and η spectrum. Figure 5.39 shows the M_{corr} distribution of b-jet candidates with the fit results overlaid.

Jet reconstruction inefficiencies mainly arise from low-momentum particles and calorimeter limitations, therefore no large differences between jets originating from heavy quarks and from light quarks and gluons are expected. Hence, the ratio $\varepsilon(\text{Z+jet})/\varepsilon(\text{Z+b-jet})$ is assumed to be unity, which is confirmed by simulation.

The b-tagging efficiency, $\varepsilon(\text{b-tag})$, is determined in simulation as a function of the jet transverse momentum and pseudorapidity (see Section 4.2.1).

5.3.2 Systematic uncertainties

The systematic uncertainties related to the Z boson reconstruction, unfolding, jet energy calibration and final state radiation are taken from Reference [134]. Systematic errors related to the M_{corr} templates modelling, b-tagging efficiency and jet efficiency flavour dependence are studied in this work.

The systematic uncertainty on the Z boson reconstruction takes account of the contributions from the track reconstruction, trigger efficiencies, muon identification efficiencies and the model used to fit the Z boson mass. The Z boson reconstruction systematic uncertainty is estimated to be 3.5 % [134].

Migrations in the jet transverse momentum distribution are corrected for by unfolding, which refers to the problem of estimating the particle-level distribution of some physical quantity of interest (this case is the jet p_T) on the basis of observations smeared by an imperfect measurement device. This correction is applied to the value of $\sigma(\text{Z+jet})$ measured in Reference [134] and used in Eq. 5.4. Detailed studies show that no dedicated unfolding correction is necessary. The unfolding systematic uncertainty has two contributions. The difference between the SVD [136] and D’Agostini [137] unfolding methods is assigned as one contribution. The second contribution comes from the difference between

the unfolded distribution and the true distribution in an independent simulated sample. This systematic uncertainty is taken from Reference [134] and it is evaluated to be 1.5 %.

An important contribution to the systematic uncertainties related to the jets comes from the jet-energy scale. It is estimated by comparing the transverse momentum of the Z boson and the jet in single jet events, where their momenta are azimuthally opposed, and are expected to be balanced. An additional contribution of 2 % to the jet-energy scale uncertainty comes from the differences between jets initiated from quarks and gluons. The systematic uncertainty of the jet identification is estimated by comparing the number of events in data and simulation with a more stringent selection. The total systematic uncertainty related to jets is 7.8 % as estimated in Reference [134].

The systematic uncertainty associated to final state radiation is obtained by direct comparison to the simulation described above and an additional simulation, using HERWIG++ [138], as in Reference [134]; it is estimated to be 0.2%. The systematic uncertainty associated with the knowledge of the luminosity is estimated to be 3.5 % [67].

Possible systematic variations of the final result due to the extraction of $\varepsilon(\text{b-tag})$ and M_{corr} templates from simulations are controlled using two data samples enriched in b-jets and c-jets. The b-jet (c-jet) enriched sample is selected via one $B^\pm$ ($D^\pm$) hadron candidate decaying to $J/\psi K^\pm$ ($K^\mp \pi^\pm \pi^\pm$) produced with a large azimuthal opening angle with respect to a probe jet. The b-tagging requirement is applied to the probe jet and a template fit is performed. Moreover, three studies are performed: 1) the template fit is performed in two regions of M and b-jet yields are compared with the default values; 2) a looser b-tagging requirement is applied and the b-jet yields after b-tagging efficiency correction are compared with the default values and 3) the M_{corr} template is smeared without degrading the fit performance and the impact on the b-jet yields is studied. The M_{corr} simulation modelling and TOPO candidate reconstruction efficiency studies are found to affect this measurement by up to 15 %.

Using simulation, $\varepsilon(\text{Z+jet})/\varepsilon(\text{Z+b-jet})$ is found to be compatible with unity within

Table 5.31: Relative systematic uncertainty considered for the Z+b-jet cross-section for $p_T(\text{jet}) > 20$ GeV. The relative uncertainties are similar for the 10 GeV threshold. Uncertainties marked with † are from Reference [134].

Source of systematic uncertainty	Relative uncertainty (%)
Z boson reconstruction †	3.5
Unfolding †	1.5
Jet-energy scale, resolution and reconstruction †	7.8
Final state radiation †	0.2
Luminosity	3.5
M_{corr} template and b-tagging	15.0
Jet reconstruction flavour dependence	2.0
Total	17.8

Table 5.32: Relative systematic uncertainty considered for the Z+b-jet cross-section for $p_T(\text{jet}) > 20$ GeV. The relative uncertainties are similar for the 10 GeV threshold. Uncertainties marked with † are from Reference [134].

2%, which is taken as the systematic uncertainty due to the flavour dependence of the jet efficiency.

The systematic uncertainties are summarized in Table 5.31. They are added in quadrature leading to a total systematic error of 17.8%.

5.3.3 Results

There are observed 179 (97) Z+jet events where at least one jet fulfils the b-tagging requirement for the $p_T(\text{jet}) > 10$ GeV (20 GeV) threshold. No events with more than one b-tagged jet are observed. The extended unbinned likelihood fit of the M_{corr} spectrum using Z+l-jet, Z+c-jet and Z+b-jet templates determines 72 ± 15 (39 ± 11) Z+b-jet events for the $p_T(\text{jet}) > 10$ GeV (20 GeV) threshold. The number of candidates corrected for b-tagging efficiency is found to be 198 ± 41 (99 ± 28) for the $p_T(\text{jet}) > 10$ GeV (20 GeV) threshold. Using the measurements of Reference [134], we determine the cross section of Z+b-jet production to be

$$\sigma(\text{Z}/\gamma^*(\mu^+\mu^-)+\text{b-jet}) = 295 \pm 60 \text{ (stat)} \pm 51 \text{ (syst)} \pm 10 \text{ (lumi) fb}$$

for $p_{\text{T}}(\text{jet}) > 10 \text{ GeV}$, and

$$\sigma(\text{Z}/\gamma^*(\mu^+\mu^-)+\text{b-jet}) = 128 \pm 36 \text{ (stat)} \pm 22 \text{ (syst)} \pm 5 \text{ (lumi) fb}$$

for $p_{\text{T}}(\text{jet}) > 20 \text{ GeV}$. These cross-sections are evaluated within the fiducial region $p_{\text{T}}(\mu) > 20 \text{ GeV}$, $60 \text{ GeV} < M(\mu^-\mu^+) < 120 \text{ GeV}$, $2.0 < \eta(\text{jet}) < 4.5$, $2.0 < \eta(\mu) < 4.5$ and $\Delta R(\text{jet}, \mu) > 0.4$.

The measurements are compared to predictions of the Z+b-jet cross-section calculated using MCFM [130] in the same kinematic range as for this measurement. The uncertainties include the PDF and theory uncertainties evaluated by varying independently the renormalization and factorization scales by a factor two around their nominal scales. Neither showering nor hadronization are included in MCFM, therefore the same kinematic requirements applied to jets in the data analysis are applied to the bottom quarks in MCFM. An overall correction is calculated by generating Z+b-jet events with PYTHIA v8.170 with the MSTW08 PDF set [139] where the same acceptance requirements are applied. Jets are reconstructed with FASTJET using the anti- k_{T} algorithm with $R = 0.5$ and then matched with a bottom quark requiring $\Delta R(\text{jet}, \text{b-quark}) < 0.5$. The ratio between the number of events with at least one b-jet that fulfils the kinematic requirements of the measurement and the number of events with at least one b quark that fulfils the LHCb acceptance criteria are used as fragmentation and hadronization correction for the MCFM predictions. The ratio is 0.77 (0.90) for $p_{\text{T}}(\text{jet}) > 10$ (20) GeV. Figure 5.40 shows the cross-section measurements compared to the LO calculation with massive bottom quarks and to LO and NLO calculations neglecting the bottom quark mass.

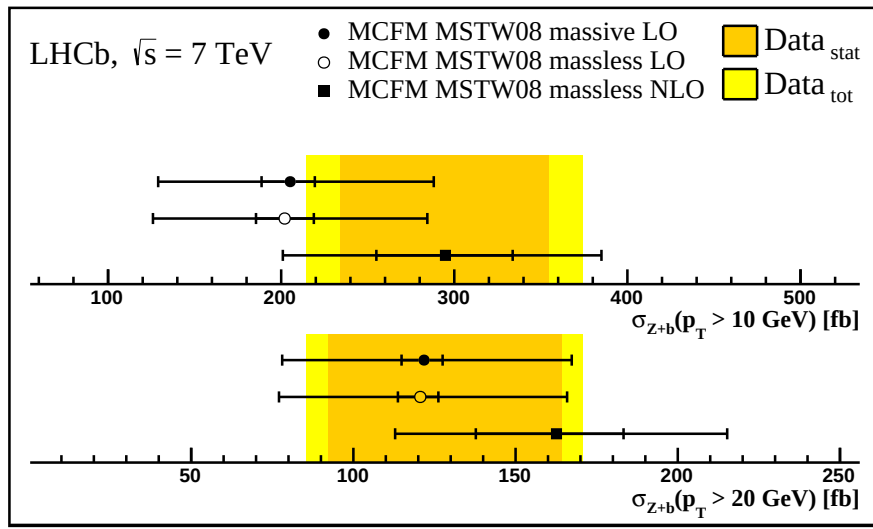


Figure 5.40: Z+b-jet cross-section for two p_T (jet) thresholds. The colour band shows the LHCb measurement (with the inner orange band showing the statistical uncertainty, and the outer yellow band showing the total uncertainty). The points with error bars correspond to the theoretical predictions with the inner error bars indicating their PDF uncertainties. These cross-sections are evaluated within the fiducial region $p_T(\mu) > 20 \text{ GeV}$, $60 \text{ GeV} < M(\mu^-\mu^+) < 120 \text{ GeV}$, $2.0 < \eta(\text{jet}) < 4.5$, $2.0 < \eta(\mu) < 4.5$ and $\Delta R(\text{jet}, \mu) > 0.4$.

Chapter 6

Conclusions and perspectives

Throughout this thesis, several topics of high energy physics are enlightened. Specially regarding the strong force as described by Quantum Chromodynamics in its perturbative limits. The knowledge of parton distribution functions can be improved with the results of the analyses performed in this thesis. The unique forward region of LHCb allows to probe the gluon PDF and the bottom quark in the proton. Therefore, the results of Z+b-jets and $W + b\bar{b}$ analyses presented in this thesis can be used to decrease the uncertainties of the PDF in the forward region.

Determination of energy deposited by isolated charged particles in the LHCb calorimeters is performed both in data and simulation. These results are used in the jet particle flow algorithm improving the jet energy resolution and reducing the correction of jet energy. Track-cluster efficiency is also measured and can be used in future jet reconstruction at LHCb.

The cross-section production of a Z boson or an off-shell photon and a bottom-quark is measured in $\sqrt{s} = 7$ TeV proton-proton collisions corresponding to a integrated 1.0 fb^{-1} of data collected in 2011 by the LHCb collaboration, in the $Z \rightarrow \mu^+\mu^-$ channel. The kinematic region of the calculated cross-section are $2.0 < \eta(\mu) < 4.5$, $p_T(\mu) > 20 \text{ GeV}$, $60 < M(\mu^+\mu^-) < 120 \text{ GeV}$, $p_T(\text{jet}) > 10(20) \text{ GeV}$, $2.0 < \eta(\text{jet}) < 4.5$ and $\Delta R(\text{jet}, \mu) >$

0.4. The measured cross-sections are

$$\sigma(Z/\gamma^*(\mu^+\mu^-)+b\text{-jet}) = 295 \pm 60 \text{ (stat)} \pm 51 \text{ (syst)} \pm 10 \text{ (lumi) fb}$$

for $p_T(\text{jet}) > 10 \text{ GeV}$, and

$$\sigma(Z/\gamma^*(\mu^+\mu^-)+b\text{-jet}) = 128 \pm 36 \text{ (stat)} \pm 22 \text{ (syst)} \pm 5 \text{ (lumi) fb}$$

for $p_T(\text{jet}) > 20 \text{ GeV}$. These values are in agreement with MCFM predictions for massless and massive bottom quark calculations.

Complementary to $Z+b\text{-jet}$, the production of two b or c tagged jets and one high p_T lepton (electron or muon) is studied at centre-of-mass energy of 8 TeV proton-proton collisions. This selection allows to measure the cross section of the $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ processes. Preliminary fit results show good agreement between data and theoretical predictions of $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ SM production in the forward region. Adding to this the 2011 LHCb muon sample ($\sqrt{s} = 7 \text{ TeV}$), the upper limit on the Higgs boson production in association with a W or Z in the decay mode $H^0 \rightarrow b\bar{b}$ is established at LHCb detector. Combined upper limits of $(W/Z)H^0 \rightarrow b\bar{b}$ production in $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ proton-proton collisions are calculated without systematics and found to be 35 times the SM cross-section at 95% CL.

In the fields of Research & Development, contributions were made for a Beam-Gas-Vertexing (BGV) demonstrator to measure the beam size and instantaneous luminosity of the LHC proton beam. A Pattern Recognition software is developed for the BGV. It is based on event samples produced by the BGV Monte Carlo simulation. The algorithm, written in C++, is capable of find and fit tracks from beam-gas interactions, at all LHC energies, with sufficient efficiency for the BGV application. The code is ready to be used with first data and now needs to be optimised for a faster execution. Subsequently, the metrological measurements of the BGV scintillating fibre modules are performed. The modules geometries are measured against the nominal geometry. The metrology of

individual modules, are then used to align the ‘two modules assembly’ which was later on installed in the LHC tunnel during Technical Stop 2.

Other contribution for the BGV was concerning the cooling plant, by setting up a cooling test bench and carried out measurements for the BGV cooling strategy. The transfer line is characterised in terms of thermal losses as a function of the fluid temperature, pressure and flow. The performance of the cooling system for different arrangements of the module cooling pipes is also measured. These studies allows to estimate the flow of C6F14 as function of the its temperature in the LHC underground setup.

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Appendix A

Metrology of the BGV modules

Within this appendix the metrology of the BGV modules are presented in details. The metrology contributions are divided in two steps: perform a *single module metrology* SMM whose data are used to guarantee the precision and quality of the modules assembly and calculate the target positions of the 2MA. The metrology of the BGV modules was performed at CERN in the months of October and November of 2014. From SMM data is also possible to evaluate systematics associated to imperfections of the modules geometry. It are discussed later on this section.

This metrology section begins with a discussion about misalignment between the normal and stereo layers of the BGV modules.

A.1 Stereo angle mismatch

A mismatch of the stereo angle may degrade the track find efficiency if its is not corrected for in the PR software. The set of top or bottom modules have in total 4 bilayers and 4 stereo angles each, used to select pair of normal-stereo hits and create track-seeds candidates. Furthermore, top and bottom tracks are treated independently even when they share clusters in the overlap region between top and bottom modules. Hence with so few hits per axis, one can not afford to have a bad start alignment.

Each cluster is a line-segment defined by two 3D points (top and bottom position of

the cluster). An error of the stereo angle can shift the position of the clusters and induce a bias on the 3D IP of the track-seed relative to TBA.

In principle, it is possible to perform only the software metrology by running the PR software for several numbers of different stereo-angles for each module and then determine the correct stereo-angle from the maximum efficiency.

By introducing a random rotation $\delta\theta$, gaussian distributed with width $\sigma_{\delta\theta}$, for each fibre mattresses the efficiency dependence on the mismatch of the fibre plane can be estimated. The Figure A.1 shows the average efficiency and ghost rate computed by `BGVPattern` for several $\sigma_{\delta\theta}$. As a example of the small rotations $\delta\theta$, Figure A.2 shows the histogram of the X-clusters rotation for $\sigma_{\delta\theta} = 0.005^\circ$ (0.087 mrad). This rotations is made over all sensitive layers. As one can see the efficiency of the code decrease considerable

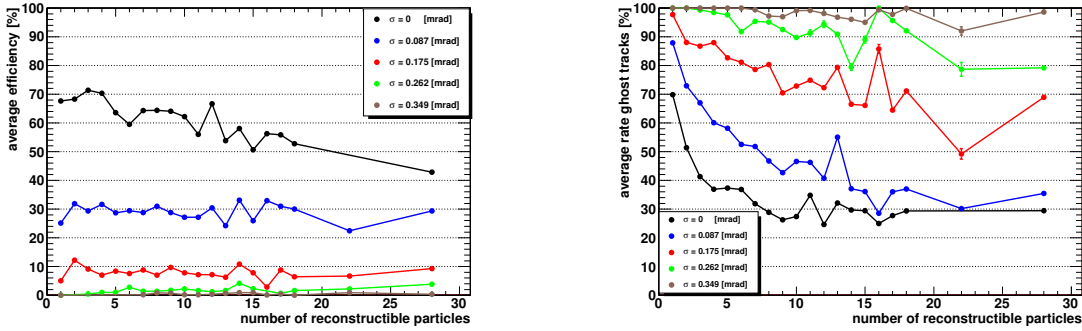


Figure A.1: Left (Right) – Average efficiency (ghost track rate) as a function of the number of reconstructible particles and for different deviations of the modules stereo angles $\sigma_{\delta\theta}$. On both plots: black circles are for no misalignment. Blue, red, green and brown for a $\sigma_{\delta\theta} = 0.087$, $\sigma_{\delta\theta} = 0.175$, $\sigma_{\delta\theta} = 0.262$ and $\sigma_{\delta\theta} = 0.349$ milliradians respectively. These relations were evaluated with 2k events whose for each event we provide a random rotation (gaussian distributed of width $\sigma_{\delta\theta}$) 400 times.

(from $\sim 70\%$ to $\sim 30\%$) when a random rotation of RMS 0.087 mrad is introduced in all sensitive layer. The ghost track rate is also observed to increase with $\sigma_{\delta\theta}$. This relation is expected since a rotation of the mattress displaces good clusters away from the track whereas *bad* clusters may approach. Figure A.3 shows how the misalignment of the fibre mattress affects the χ^2/DoF distribution of reconstructed tracks.

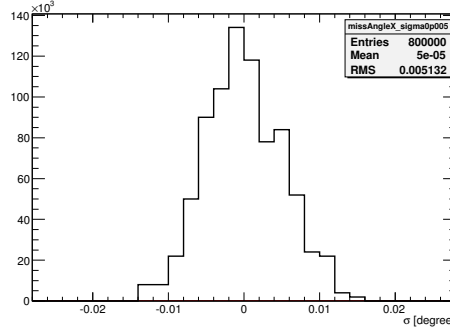


Figure A.2: Histogram of X-cluster rotations for nominal misassembling angle of 0.005 degrees (0.087 mrad).

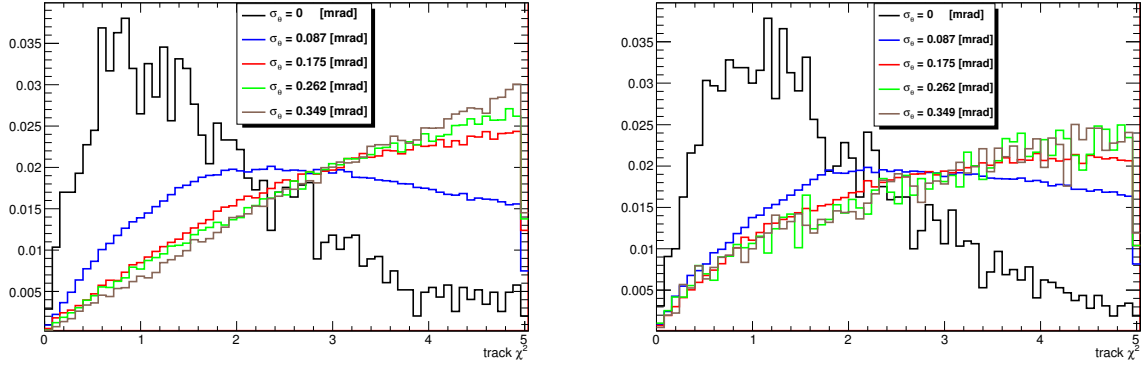


Figure A.3: The left (right) plot shows the normalised histograms of χ^2/DoF of the top (bottom) tracks for several $\sigma_{\delta\theta}$.

A.2 Setup

The metrological measurements were performed at the Metrology Laboratory at CERN - Meyrin during November and December 2014. The measurement machine consists of a high precision Bridge-type Coordinate Measuring Machine (CMM) manufactured by ZEISS: Prismo Ultra; volume ($X = 1200$, $Y = 2400$, $Z = 1000$) [mm]. The precision of the machine is

$$\delta L = 3 + \frac{L[\text{mm}]}{500[\text{mm}]} \quad [\mu\text{m}] \quad (\text{A.1})$$

where L is the 1-dimensional measurement length at 20°C. Then, for a 1D measurement of 0.5 meter the associated error is only 4 μm .

The modules metrology are performed with two sensors: one touching probe scan

(VAST XXT) used to define the reference frame and measure lateral points of the module, as is explained below, and one camera scan (ViScan) with which we measure the fibre position as seen from the top, looking downward into the fibres. The camera sensor also allows us to measure the corners of the modules using an optical method which is also explained latter. With the camera is also possible measure the fibre alignment along the module. However this measurement could not be performed on all modules because the glue thickness, covering the fragile mattresses, avoids to identify the fibre shape.

Figure A.4 shows a photo of the setup with one module mounted on the table of the CMM apparatus in the metrology lab. Figures A.5, A.6 and A.7 illustrate the sphere numbering and the reference frame of the measurements. The reference frame is defined by measuring the centre of each of the three spheres fixed on the module: x -axis pointing from sphere 3 to sphere 1; the origin of the frame is the middle point between these two spheres; y -axis is perpendicular to the plane defined by centre of the spheres 1, 2 and 3 and increases when going from the normal to the stereo side. z -axis complete the right-handed coordinate system. The centre of each spheres is measured by probing the spheres on several points with the touch probe. A spherical fit is performed to this points and the centre of the *fitted sphere* is assumed as the nominal position of the sphere.

In total are measured 18 3D points of each module using the ViScan sensor. Theses points were chosen to evaluate the module sizes, length, stereo angle, and mattress alignment. They are tagged with a unique ID number per module: point 1 to 6 on the normal side, 7 to 12 on the top and 13 to 18 on the stereo side.

To determine a possible misalignment of the fibre mattresses relative to the SiPM slots, four additional points (labeled A, B, C and D) were measured on the module sides, as illustrated in Figure A.8.

After the machine calibration a control test was performed to test the mechanical stability of the sphere holders: the sphere 1 was first measured and then removed from the magnetic support. It is fixed again on the same support and the sphere's centre was

evaluated by the second time. The measured displacement of the sphere's centre before and after remove is negligible.

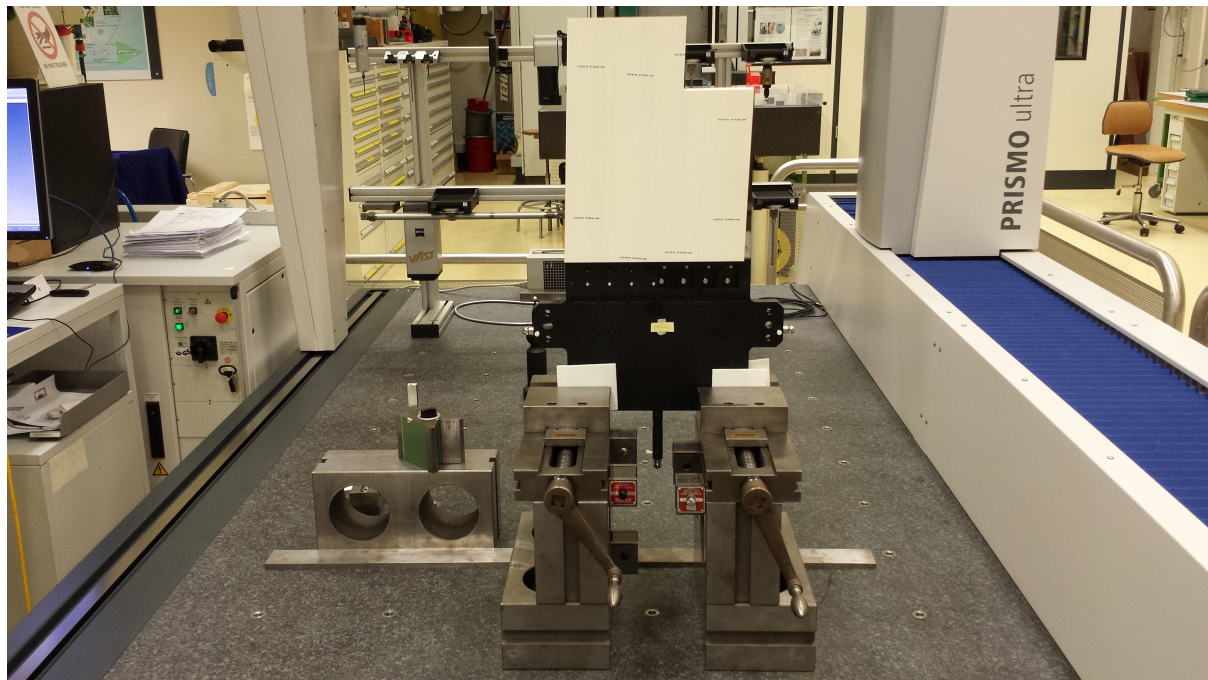


Figure A.4: Photo of the setup mounted on the CMM in the metrology laboratory at CERN.

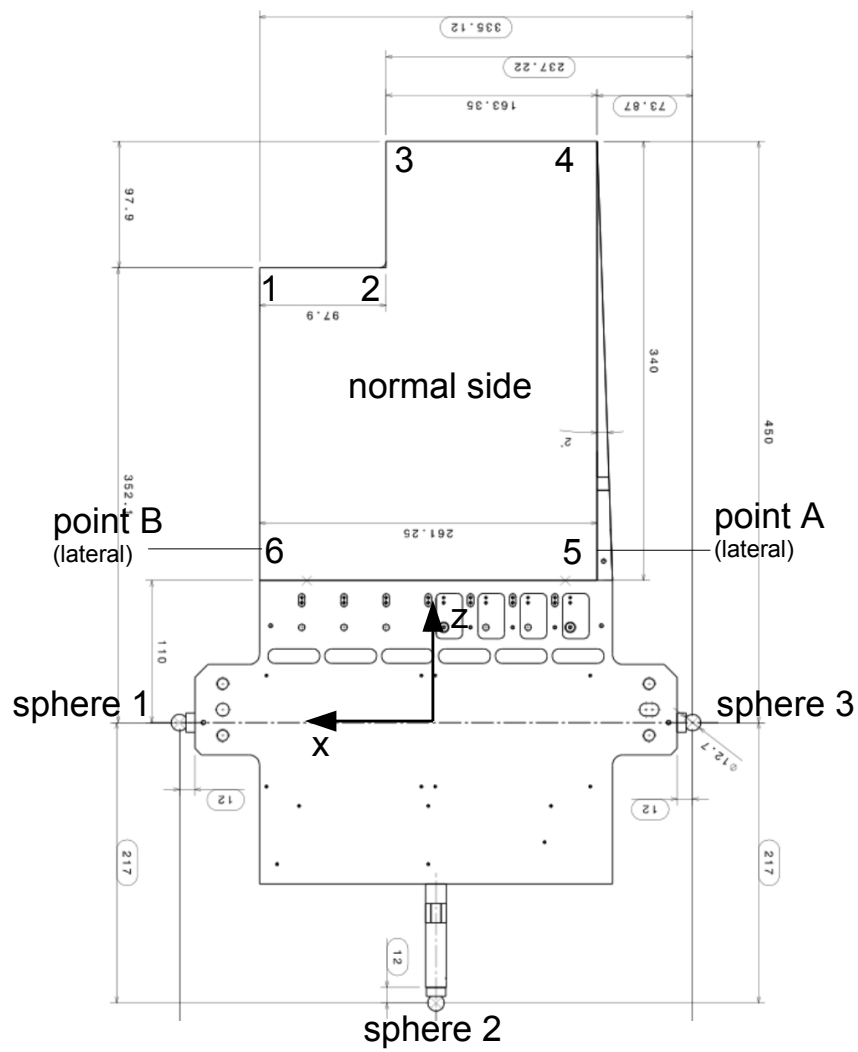


Figure A.5: Schematics of the normal side with the sphere numbering and reference frame's axes as explained in the text.

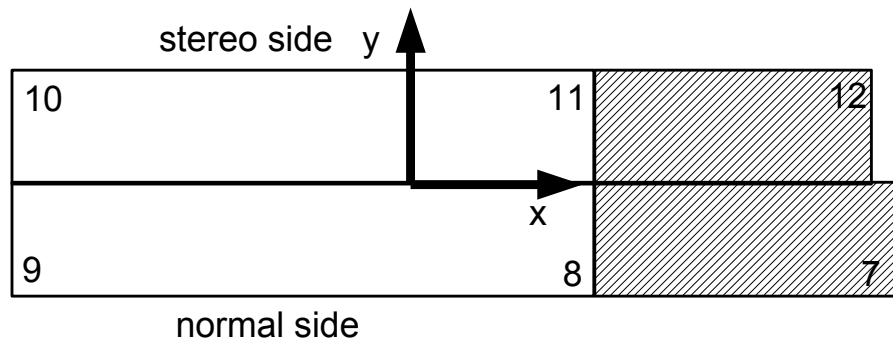


Figure A.6: Illustration of the top view of the BGV module. The numbers 7-12 indicate approximately the position that are measured with the camera (ViScan).

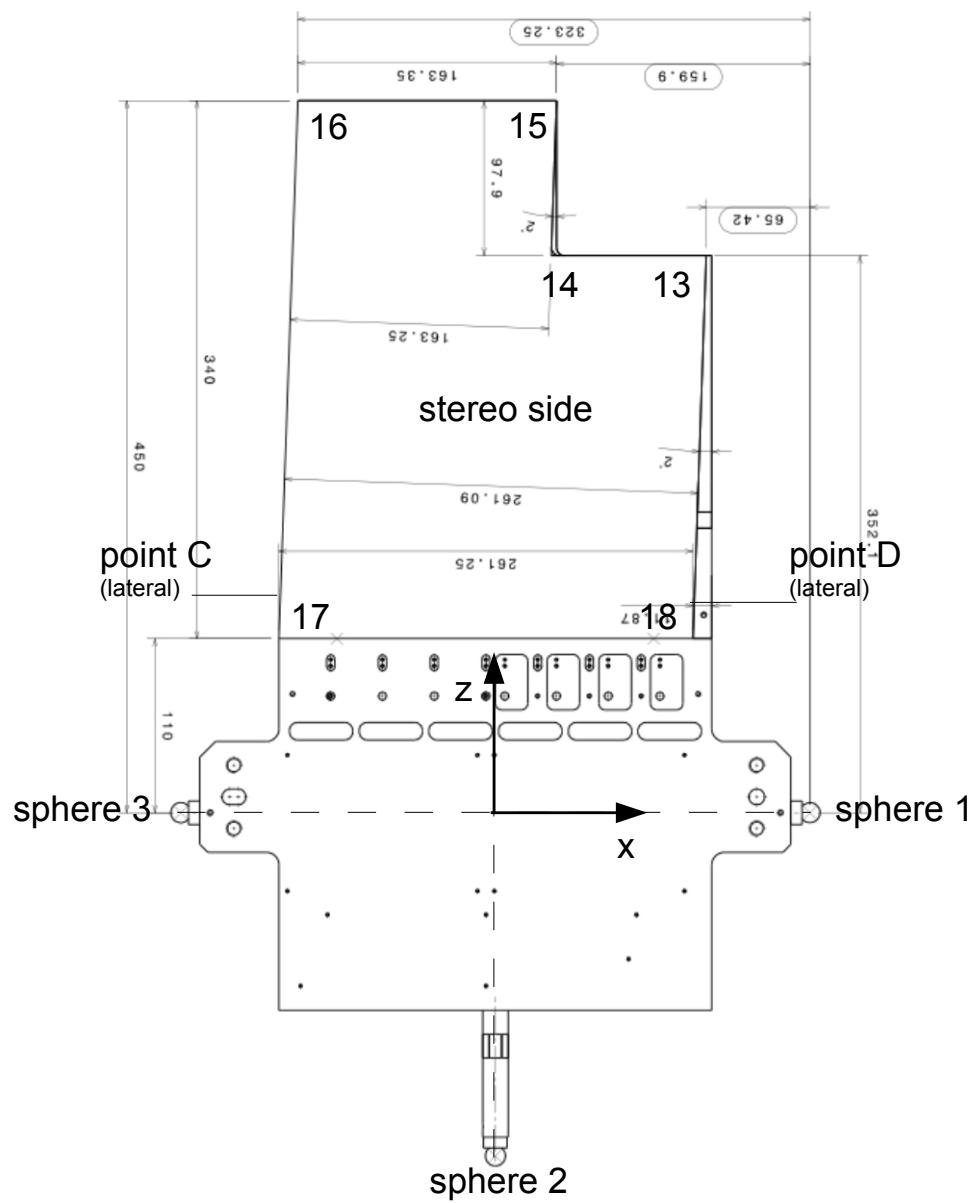


Figure A.7: Schematics of the stereo side with the sphere numbering and reference frame's axis as explained in the text.

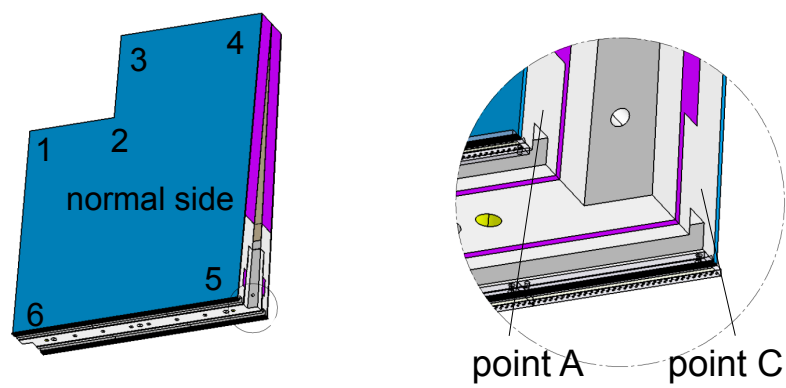


Figure A.8: The figure illustrates the points A and B as seen from the normal side of de module. These points allows us to measure the relative position of the fibre to edge the SiPM.

A.3 Measurement procedure

The measurement procedure follows the scope of the section A.2 and was performed after having defined the reference frame.

A.3.1 Lateral corners

Each lateral corner of the sensitive layers are measured using the follow optical methods*:

- Using ViScan sensor, the CALYPSO software [140] selects a set of points on the lateral edge module chosen by the machine operator. The software provides the best line through the points.
- The same procedure is repeated on the perpendicular edge.
- The crossing point between both fitted lines are the nominal corner and the module geometry are measured using these points.

The Figure A.9 illustrates the best corner position of the the point number 7 of the Module 08-4L.

A.3.2 Fibre position

From the top view looking downwards to the fibre ends one can identify whether the mattresses are of 4 or 5 layers and measure the fibre diameters and positions. The diameter is measured in a similar method as for the corner's position: a bunch of points are selected on the contour of the fibre and the software returns the best-fitting circle. The circle's centre is the nominal value of the fibre position. Figure A.10 shows a photo of the measurement during the metrology.

*remind that “lateral corners” are points 1-6 and 13-18

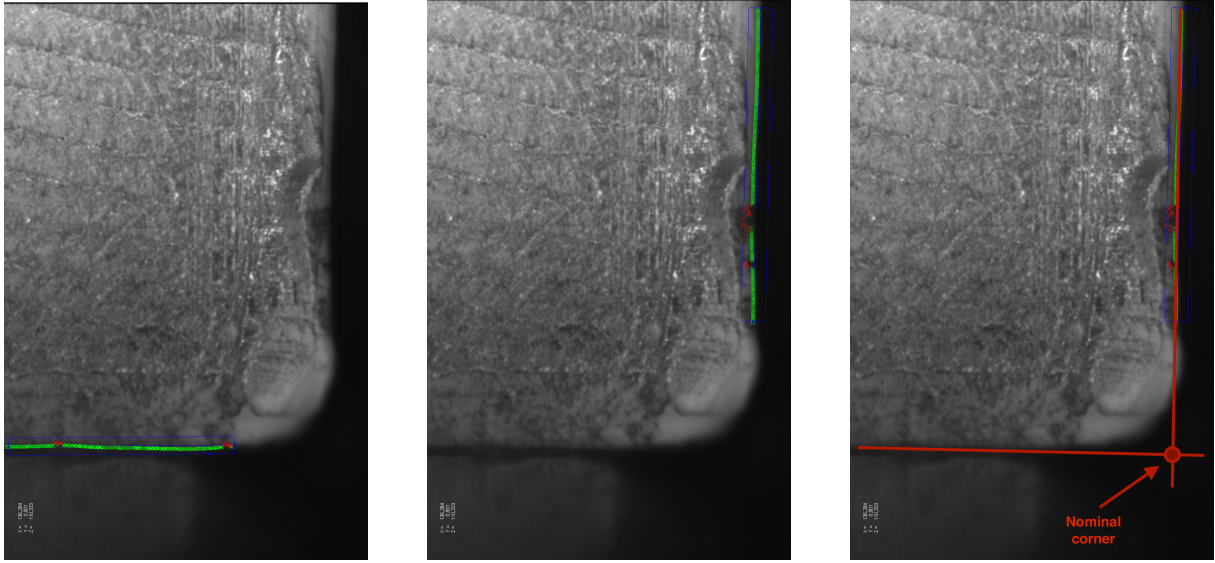


Figure A.9: Left and center – Illustration of selected points on the corner 7 of the Module 08-4L. These points are selected by the machine operator when the software are not able to select them automatically. Right – Illustration of the nominal corner position given by the intersection of both fitted lines.

A.3.3 Stereo angle

As discussed above the stereo angle is a sensitive parameter for the PR. It is measured for all modules using the corner points of the normal and stereo side. However this measurement does guarantee if the mattresses are well aligned along the module. Is it only possible to measure the fibre alignment when the fibre's shape is clearly visible through the blue, as is shown in the Figure A.11. Only on the modules 03 and 04 the fibres shape were visible by the camera scan and the mattresses alignment could be measured directly. In all cases, measurements of the stereo angle from the fibre mattresses or from the module edges is evaluated defining two line segments in both size of the module and the scalar product is taken.

A.3.4 Reference plane and mattresses misalignment

The metrological measurements of the modules relies on the stability of the module's spheres holder. Module geometries are calculated by using as reference the sphere's position. Therefore in order to validate whether the modules metrology can be reused or not

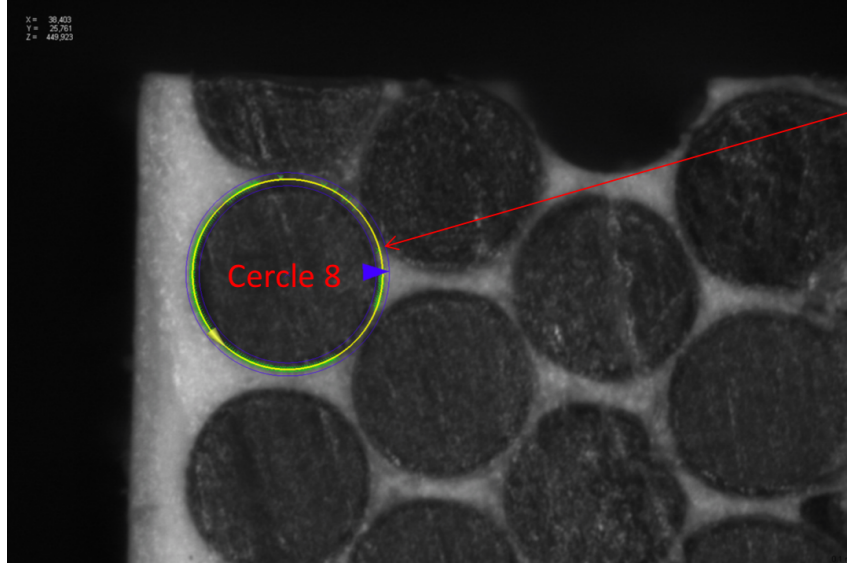


Figure A.10: Measurement of the fibre position. The measured fibre position is the centre of the circle. This measurement is used to determine the glue thickness and the module's size.

the relative angle between the *reference plane* and the *mattresses plane* is calculated such that, on further measurements, one can check if the angle remains the same and if not, correct the position of the points by the change of this angle.

The '*reference plane*' is defined by the centre of the three spheres and the *mattresses plane* is defined by three corner points of one side of the module. Lets define θ_{MR} as the angle between both planes. Observe that θ_{MR} is very sensitive to any displacement of sphere 2 in y or x axis, see Figure A.5.

Misalignment between the *mattresses plane* and the *reference plane* is not an issue itself but the measurements of the corner points relies on the spheres positions. Stability of the sphere holder number 2 can be monitored through the angle between the planes. This angle is the angle between the normal-vectors of both planes. Consider three vectors position $\vec{p}_1$, $\vec{p}_2$ and $\vec{p}_3$ pointing to three points P_1 , P_2 and P_3 on the mattresses plane of the module. The vector

$$\vec{M} = \vec{p}_{21} \times \vec{p}_{31}$$

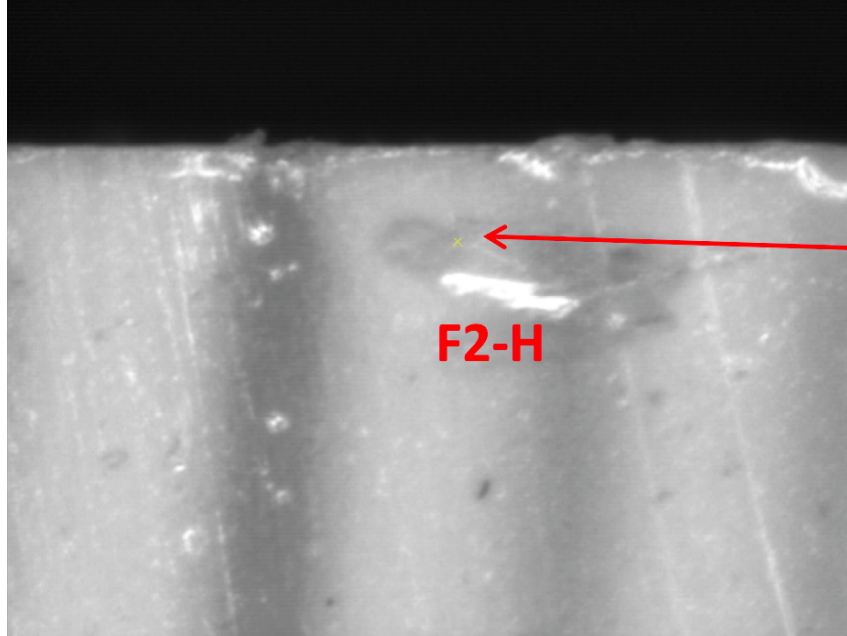


Figure A.11: Example of the fibre alignment of the module 04. The fibre's shape is visible through the glue layer - 'light grey' between two vertical 'dark grey' lines.

is perpendicular to this plane where

$$\vec{p}_{21} = \vec{p}_2 - \vec{p}_1$$

$$\vec{p}_{31} = \vec{p}_3 - \vec{p}_1$$

Similarly, consider $\vec{r}_1$, $\vec{r}_2$ and $\vec{r}_3$ three vectors position pointing to the spheres 1, 2 and 3 respectively. The reference plane is defined by the position of the centre of the three spheres. The vector $\vec{R}$ perpendicular to the reference plane is given by

$$\vec{R} = \vec{r}_{21} \times \vec{r}_{31}$$

where

$$\vec{r}_{21} = \vec{r}_2 - \vec{r}_1$$

$$\vec{r}_{31} = \vec{r}_3 - \vec{r}_1.$$

The angle between the planes is give by the angle between the vectors $\vec{M}$ and $\vec{R}$. Defining the vector $\vec{V}$ such that

$$\vec{V} = \vec{M} \times \vec{R}$$

the angle θ_{MR} between $\vec{M}$ and $\vec{R}$ is given by

$$\theta_{MR} = \sin^{-1} \left(\frac{|\vec{V}|}{|\vec{M}||\vec{R}|} \right) \quad (\text{A.2})$$

where $|\vec{V}|$, $|\vec{M}|$ and $|\vec{R}|$ is the magnitude of the vectors $\vec{V}$, $\vec{M}$ and $\vec{R}$ respectively, see Figure A.12.

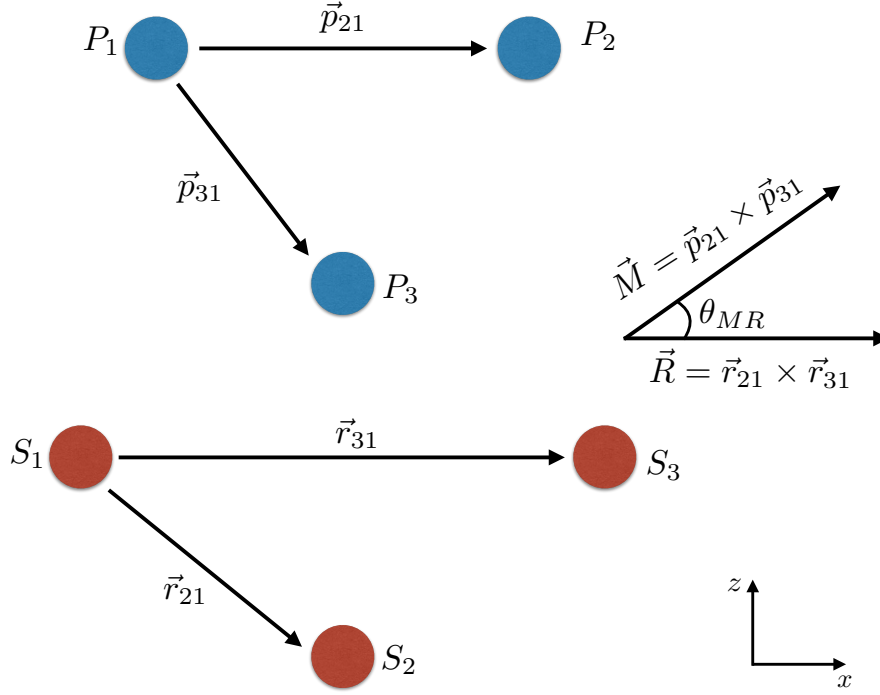


Figure A.12: Illustration of points used to measure the angle between the reference plane and the mattresses plane. The vector $\vec{R}$ and $\vec{M}$ are perpendicular to the mattresses plane and reference plane respectively.

Using the Standard Law of Combinations of Errors of a function $f(x_i)$ for independent parameters x_i with error δx_i

$$\delta f^2 = \sum_i \left(\frac{\partial f}{\partial x_i} \delta x_i \right)^2 \quad (\text{A.3})$$

the propagated error $\delta \theta_{MR}$ of θ_{MR} is given by

$$\delta \theta_{MR} = \frac{\delta \sin \theta_{MR}}{\sqrt{1 - \sin^2 \theta_{MR}}} \quad (\text{A.4})$$

where $\delta \sin \theta_{MR}$ is the error of $\sin \theta_{MR}$ which from equation A.3 is

$$\delta \sin \theta_{MR} = \left[\left(\frac{\delta |\vec{V}|}{|\vec{M}||\vec{R}|} \right)^2 + \left(\frac{|\vec{V}| \delta |\vec{M}|}{|\vec{M}|^2 |\vec{R}|} \right)^2 + \left(\frac{|\vec{V}| \delta |\vec{R}|}{|\vec{M}||\vec{R}|^2} \right)^2 \right]^{1/2}$$

where $\delta|\vec{V}|$, $\delta|\vec{M}|$ and $\delta|\vec{R}|$ is the error of the magnitude of the vectors $\vec{V}$, $\vec{M}$ and $\vec{R}$ respectively. Again from Equation A.3 the error of the module of the vectors are:

$$\begin{aligned}\delta|V| &= \left[\sum_i \left(\frac{V_i \delta V_i}{|\vec{V}|} \right)^2 \right]^{1/2} \\ \delta|M| &= \left[\sum_i \left(\frac{M_i \delta M_i}{|\vec{M}|} \right)^2 \right]^{1/2} \\ \delta|R| &= \left[\sum_i \left(\frac{R_i \delta R_i}{|\vec{R}|} \right)^2 \right]^{1/2}\end{aligned}$$

here δV_i , δM_i and δR_i is the error of the i -component, $i = (x, y, z)$ of the vectors $\vec{V}$, $\vec{M}$ and $\vec{R}$ respectively. It is important to notice that only the error of the y -component of the points P_i and the y -components of the position of the centre of the three spheres have non-negligible contribution to the error of $\theta_{MR}^\dagger$. The error of the components (x, y, z) of the vectors $\vec{M}$, $\vec{R}$ and $\vec{V}$ are summarised in Table A.1.

Therefore using the above expressions into equations A.2 and A.4 we can estimate the misalignment angle between both planes and their associated systematic error. This angle is the control parameter to cross-check the stability of the bottom sphere holder to validate further metrology.

[†]Any displacement in (x, z) -coordinates of $\vec{p}_i$ and $\vec{r}_i$, $i = (1, 2, 3)$ does not change the angle between $\vec{M}$ and $\vec{R}$ and therefore $\delta\theta_{MR}$ should not depend of the error of the (x, z) -component of the key points and spheres position.

Variable	Errors of the components of the vector
	Expression
δM_x	$\delta m \sqrt{2(p_{21_z}^2 + p_{31_z}^2)}$
δM_y	0
δM_z	$\delta m \sqrt{2(p_{21_x}^2 + p_{31_x}^2)}$
δR_x	$\delta m \sqrt{2(r_{21_z}^2 + r_{31_z}^2)}$
δR_y	0
δR_z	$\delta m \sqrt{2(r_{21_x}^2 + r_{31_x}^2)}$
δV_x	$\sqrt{(M_y \delta R_z)^2 + (R_y \delta M_z)^2}$
δV_y	$[(R_x \delta M_z)^2 + (M_z \delta R_x)^2 + (R_z \delta M_x)^2 + (M_x \delta R_z)^2]^{1/2}$
δV_z	$\sqrt{(R_y \delta M_x)^2 + (M_y \delta R_x)^2}$

Table A.1: Errors of the components of the vectors $\vec{M}$, $\vec{R}$ and $\vec{V}$. p_{ij_k} and r_{ij_k} are the k -component of the vector $\vec{p}_{ij}$ and $\vec{r}_{ij}$ respectively, $k = (x, z)$, $i = (2, 3)$ and $j = (1, 3)$. $\delta m = 3 \mu\text{m}$ is the nominal CMM uncertainty. We neglect the error of the (x, z) -components of the centre of the spheres S_i and the error of the (x, z) -components of the key points P_i , $i = (1, 2, 3)$ see, Figure A.12. Therefore $\delta M_y = 0$ and $\delta R_y = 0$.

A.4 SMM Results

The SMM results are summarised as follow: each module edges are tagged according to the corners numbering, *e.g.*, $D_{i,j}$ are the module of the vector defined from the point i to j . When a coordinate upper index is shown, *e.g.*, $D_{i,j}^x$ ($D_{i,j}^{x,y}$) the length is evaluated using only the x (x, y) coordinate(s). If no coordinate upper index is shown the length is 3-dimensional. Note that each side have in total six lengths: from $D_{1,2}$ to $D_{6,1}$ in the normal side and from $D_{13,14}$ to $D_{18,13}$ in the stereo side.

On the top side the lengths are: $D_{7,12}$, $D_{8,11}$ and $D_{9,10}$ see Figure A.6.

Angles are tagged similarly: $\theta_{i,j-k,l}$ is the angle between two vectors: the first one defined from the points i to j on the normal side of the module and the second one defined from the points k to l on the stereo side of the module. If it is evaluated using the

fibre position, the fibre is then discriminated: $F_{B_s}^i$ ($F_{H_s}^i$) are the bottom (top) position[‡] of the i -th fibre on the stereo side. Similarly $F_{B_n}^j$ ($F_{H_n}^j$) is the bottom (top) position of the j -th fibre defined on the normal side of the module. With this fibre definition, $\theta_{F_s^i, F_n^j}$ is the stereo angle evaluated with the fibres F_s^i , and F_n^j . Finally $\theta_{M_n, R}$ ($\theta_{M_s, R}$) is the angle between the normal (stereo) fibre mattresses plane to the reference plane.

The table containing the results are shown in the appendix B.

A.5 2MA

Using the measurements of the individual modules the relative position of the modules on the 2MA was evaluated. 2MA is the set of two modules and compose a half BGV station. The goal of the 2MA alignment procedure is to position the detector modules such as:

- Close to the beam pipe wall: 0.3 mm
- With respect to the LHC plane: perpendicular to the LHC plane, with tilt as the LHC plane
- With good relative position between the modules.

The components of the detector support system are:

- **Detector plates**, each holding 2 SciFi modules, see Figure A.13 left. The assembly shown in Figure 1 is referred to as 2-module Assembly (2MA)
- **Intermediate plates**, see Figure A.13 right.
- **Detector support frame**, see Figure A.13 right.

The position of the modules on the 2MA is calculated considering the following steps:

- For installation and alignment of the Intermediate plates:

[‡]Bottom and top position in the machine reference frame. y -coordinates are positive in the normal side and negative on the stereo side.

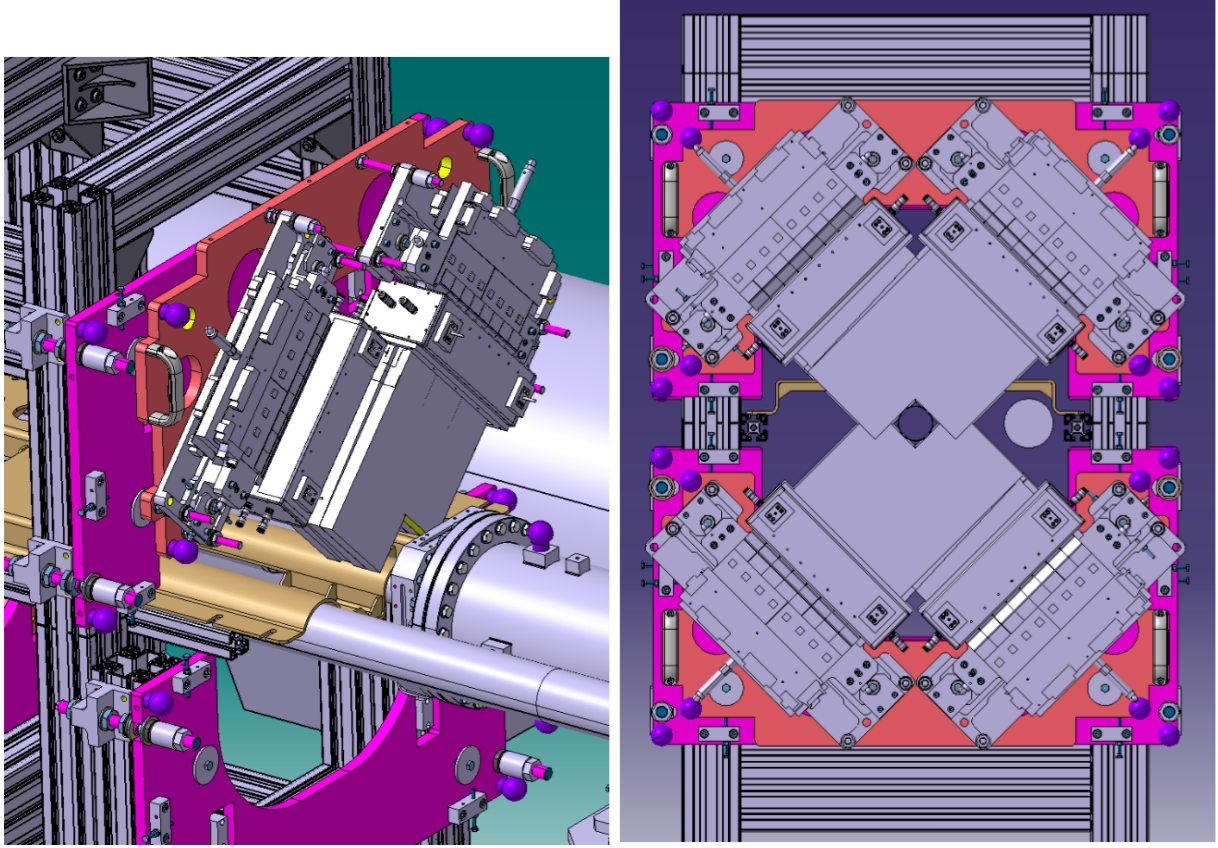


Figure A.13: Left – 3D views showing the Intermediate plates (purple color) and the Detector support frame which supports them. Right – Transverse view of one detector Station. Source: BGV Collaboration.

- Perpendicular to the LHC plane, with tilt as the LHC plane
- Achieved positioning/orientation accuracy: $\mathcal{O}(0.1)$ mm / $\mathcal{O}(0.1)$ mrad.
- Fix the Detector plates to the Intermediate plates:
 - The tilt and transverse position can be adjusted;
 - The other two angles of the Detector plates (slope and yaw) cannot be changed, *i.e.* these two angles are determined by the position of the Intermediate plates;
- This leads to a number of requirements for the position of the detector modules with respect to the Detector plate, discussed below.

To calculate the modules position and orientation on the Detector Plate, the reference frame are defined for the 2MA metrology. Position of the modules are made on a stable marble table. The marble defines the horizontal plane (P1), while the two upper 1.5' targets define the two vertical planes P2 and P3, centered on the target A, as shown in the Figure A.14. A change of coordinates is then applied in order to have the origin in the theoretical centre of the beam pipe. Even if the beam pipe has two different diameters, the alignment of all the 2MA will be based on the 60 [mm] diameter pipe. The reference system is therefore defined by the planes P1, P4 and P6, where P4 passes from the middle point of the targets A and B, and P6 passes from the centre of the beam pipe with external diameter 60 [mm]. The x , y and z -axis are indicated in the drawing with blue lines. Once the reference system is defined, the modules are aligned by placing the small targets attached to the detector modules (C, D, E, F, G and H) in their nominal position with respect to the reference system. It allows to calculate the real position (x , y and z) of the six targets starting from the data obtained from the fiducialisation of the detectors. The nominal coordinates of the two top spheres of the Detector plate (denoted A and B in Figure A.14) are:

$$XA = -489.4\text{mm}, YA = -365\text{mm}$$

$$XB = -489.4\text{mm}, YB = +365\text{mm}.$$

The module fiducialization are given by the points measured during the SMM. The corners points of each side of the module, both normal and stereo side, does not lie in a plane. So, to define the module plane the following method are applied:

- A plane is fitted to the 6 points of the normal and stereo side of the module. Figure A.15 illustrate a plane fit.
- The points are then projected perpendicularly onto the plane to form the module shape.

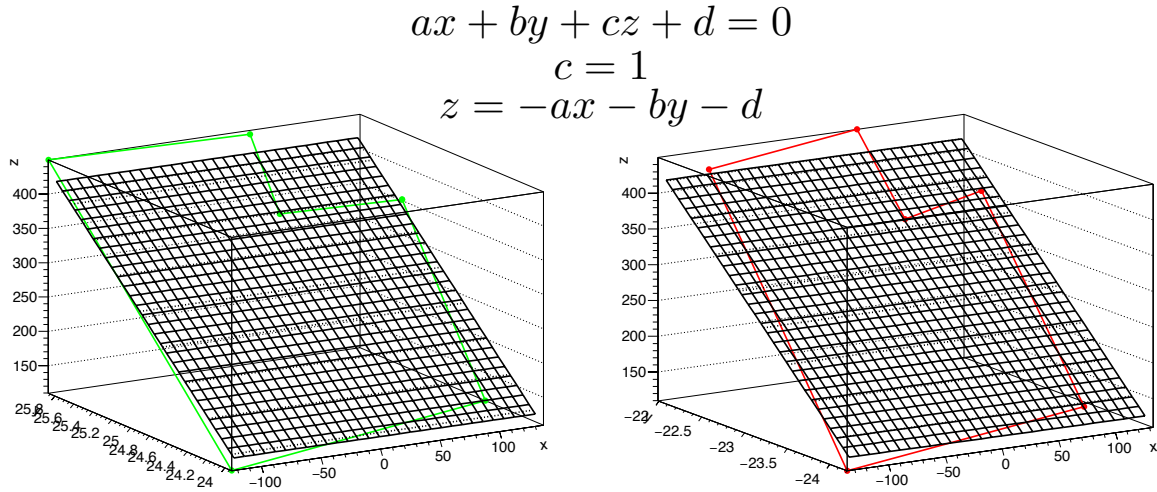


Figure A.15: Example of fit a plane to the corner points of the modules. Left (Right) – is the normal (stereo) side face of a module.

at the nominal 45° with respect to P4 are delicate and for that, a module axis have to be defined. The module axis is defined as to have the average ϕ angles of all straight edges of the modules. Therefore the module axis is sensitive to possible imperfection of the module edges and place position the module axis at 45° made the average ϕ angle of all straight edges of the module to be closest to 45° . The module axes is the line at $\pm 45^\circ$ with respect to plane P4 shown in the Figure A.14. All computations were made using C++ language in the ROOT framework [55]. Figure A.16 shows a illustration of the 2MA using data from SMM as calculated at ROOT.

In total ten BGV modules are built. Five of them with mattresses of 5 layers of scintillating fibres which are installed on the Far station. The other five modules are built with mattresses of 4 layers of scintillating fibres to reduce multiple scattering. The module 4 and module 6-4L are spears. Modules labelled from -1 to -5 have is of 5 layers

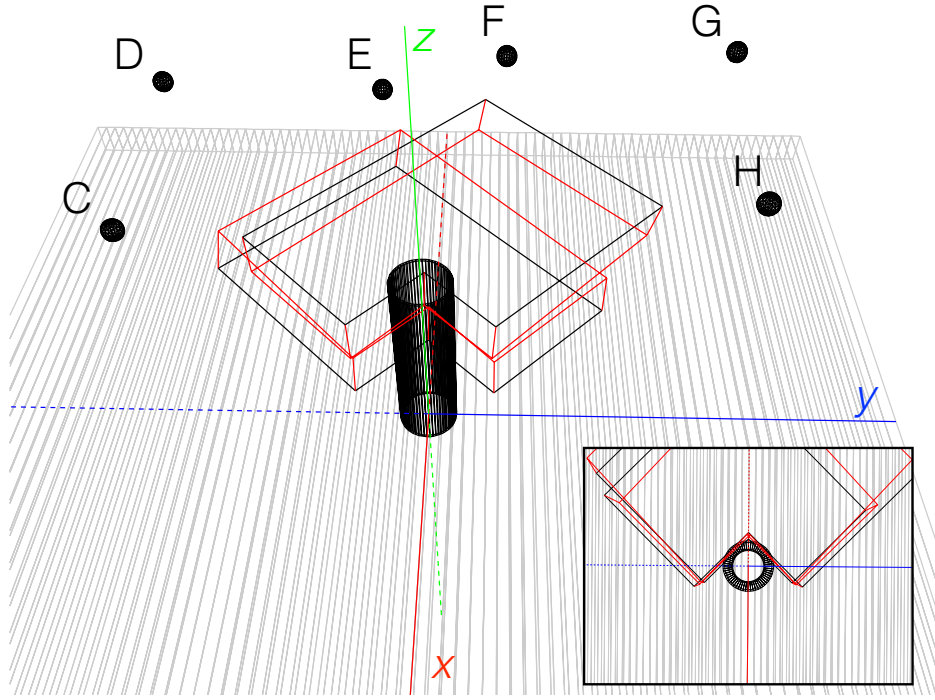


Figure A.16: 2MA alignment as shown by ROOT using data from SMM.

version *e.g.* Module 5, and modules labelled from 6-4L to 10-4L have mattresses of 4 layers, *e.g.* Module 8-4L. To minimize error on the calculation of the spheres position a independent calculations of the sphere position were made by Plamen Hopchev. The results are compatible at few micrometers scale.

The appendix C shows the results of the spheres positions of 2MAs installed on the LHC tunnel.

Appendix B

SMM Results

Results of the SMM metrology are shown here. The BGV have 8 modules. The mattresses of the modules of the first station (Near Station) have 4 layer of scintillating fibres to reduce multiple scattering. The second station (Far Station) have modules with mattresses of 5 layers of scintillating fibres. This choice of the second station is made to increase the light deposition on the SiPM channels.

The BGV have two spare modules, one of each mattresses version. Therefore this appendix have results of ten modules.

B.1 Module 01

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.574 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.699 ± 0.028
Sphere 2	-0.014 ± 0.003	0.000 ± 0.003	-216.922 ± 0.003	12.694 ± 0.028
Sphere 3	-198.574 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.699 ± 0.028

Table B.1: Sphere positions of the module 01. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.956 ± 0.199	97.900
$D_{2,3}$	97.810 ± 0.199	97.900
$D_{3,4}$	163.234 ± 0.329	163.350
$D_{4,5}$	339.688 ± 0.682	340.000
$D_{5,6}$	261.937 ± 0.527	261.250
$D_{6,1}$	242.493 ± 0.488	242.100

Table B.2: Measurements of the normal side of the module 01. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.762 ± 0.099	48.200
$D_{8,11}^{yz}$	47.621 ± 0.098	48.200
$D_{9,10}^{yz}$	48.113 ± 0.099	48.200

Table B.3: Measurements of the top side of the module 01. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.655 ± 0.198	97.900
$D_{14,15}$	97.816 ± 0.199	97.900
$D_{15,16}$	163.559 ± 0.330	163.35
$D_{16,17}$	340.273 ± 0.683	340.21
$D_{17,18}$	261.487 ± 0.526	261.25

Table B.4: Measurements of the stereo side of the module 01. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	47.614 ± 0.098	48.200
$D_{2,14}^y$	48.077 ± 0.099	48.200
$D_{3,15}^y$	47.783 ± 0.099	48.200
$D_{4,16}^y$	48.297 ± 0.100	48.200
$D_{5,17}^y$	48.129 ± 0.099	48.200
$D_{6,18}^y$	48.046 ± 0.099	48.200

Table B.5: The table summarises the thickness of the module 01 including the glue layer.

Variable	Fibre position [mm]			
	x	y	z	diameter
$F_{B_s}^1$	not seen	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen	not seen

Table B.6: Fibre position on the normal and stereo side of the module 01. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	6.87 ± 0.05	0	[mrad]
$\theta_{M_s,R}$	6.68 ± 0.04	0	[mrad]
$\theta_{nf,\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{nf,\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{sf,\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{sf,\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1,F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	2.0674 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	1.9534 ± 0.0010	2.00	[degree]

Table B.7: The table summarises the angles measured on the module. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{nf,\vec{D}_{i,j}}$ ($\theta_{sf,\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1,F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.2 Module 02

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.562 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028
Sphere 2	-0.040 ± 0.003	0.000 ± 0.003	-216.943 ± 0.003	12.694 ± 0.028
Sphere 3	-198.562 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.8: Sphere positions of the module 02. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.941 ± 0.199	97.900
$D_{2,3}$	97.933 ± 0.199	97.900
$D_{3,4}$	163.463 ± 0.330	163.350
$D_{4,5}$	340.175 ± 0.683	340.000
$D_{5,6}$	261.467 ± 0.526	261.250
$D_{6,1}$	242.129 ± 0.487	242.100

Table B.9: Measurements of the normal side of the module 02. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}$	47.716 ± 0.098	48.200
$D_{8,11}$	47.227 ± 0.097	48.200
$D_{9,10}$	47.810 ± 0.099	48.200

Table B.10: Measurements of the top side of the module 02. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.940 ± 0.199	97.900
$D_{14,15}$	97.676 ± 0.199	97.900
$D_{15,16}$	163.461 ± 0.330	163.35
$D_{16,17}$	340.299 ± 0.684	340.21
$D_{17,18}$	261.433 ± 0.526	261.25

Table B.11: Measurements of the stereo side of the module 02. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}$	47.944 ± 0.099	48.200
$D_{2,14}$	48.255 ± 0.099	48.200
$D_{3,15}$	47.543 ± 0.098	48.200
$D_{4,16}$	48.179 ± 0.099	48.200
$D_{5,17}$	49.712 ± 0.102	48.200
$D_{6,18}$	49.596 ± 0.102	48.200

Table B.12: The table summarises the thickness of the module 02 including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen

Table B.13: Fibre position on the normal and stereo side of the module 02. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	5.79 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	5.85 ± 0.05	0	[mrad]
$\theta_{\text{nf},\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{\text{nf},\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1, F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	1.9890 ± 0.0013	2.00	[degree]
$\theta_{4,5-16,17}$	1.9891 ± 0.0010	2.00	[degree]

Table B.14: The table summarises the angles measured on the module 02. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{\text{nf},\vec{D}_{i,j}}$ ($\theta_{\text{sf},\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1, F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.3 Module 03

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.554 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028
Sphere 2	-0.017 ± 0.003	0.000 ± 0.003	-217.015 ± 0.003	12.694 ± 0.028
Sphere 3	-198.554 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.15: Sphere positions of the module 03. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.578 ± 0.198	97.900
$D_{2,3}$	97.559 ± 0.198	97.900
$D_{3,4}$	163.503 ± 0.330	163.350
$D_{4,5}$	340.202 ± 0.683	340.000
$D_{5,6}$	260.993 ± 0.525	261.250
$D_{6,1}$	242.600 ± 0.488	242.100

Table B.16: Measurements of the normal side of the module 03. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.834 ± 0.099	48.200
$D_{8,11}^{yz}$	47.729 ± 0.098	48.200
$D_{9,10}^{yz}$	48.065 ± 0.099	48.200

Table B.17: Measurements of the top side of the module 03. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.846 ± 0.199	97.900
$D_{14,15}$	97.812 ± 0.199	97.900
$D_{15,16}$	163.728 ± 0.330	163.35
$D_{16,17}$	340.433 ± 0.684	340.21
$D_{17,18}$	261.455 ± 0.526	261.25

Table B.18: Measurements of the stereo side of the module 03. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	47.813 ± 0.099	48.200
$D_{2,14}^y$	48.010 ± 0.099	48.200
$D_{3,15}^y$	47.775 ± 0.099	48.200
$D_{4,16}^y$	48.187 ± 0.099	48.200
$D_{5,17}^y$	47.996 ± 0.099	48.200
$D_{6,18}^y$	48.219 ± 0.099	48.200

Table B.19: The table summarises the thickness of the module 03 including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	-58.799 ± 0.003	-23.889 ± 0.003	110.073 ± 0.003
$F_{H_s}^1$	-46.936 ± 0.003	-22.534 ± 0.003	450.030 ± 0.003
$F_{B_n}^1$	-17.018 ± 0.003	24.315 ± 0.003	109.654 ± 0.003
$F_{H_n}^1$	-17.176 ± 0.003	25.387 ± 0.003	449.781 ± 0.003

Table B.20: Fibre position on the normal and stereo side of the module 03. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	4.31 ± 0.05	0	[mrad]
$\theta_{M_s,R}$	4.64 ± 0.03	0	[mrad]
$\theta_{nf,\vec{D}_{1,6}}$	0.7905 ± 0.0215	0	[mrad]
$\theta_{nf,\vec{D}_{4,5}}$	0.6409 ± 0.0176	0	[mrad]
$\theta_{sf,\vec{D}_{13,18}}$	0.3537 ± 0.0215	0	[mrad]
$\theta_{sf,\vec{D}_{16,17}}$	0.7880 ± 0.0176	0	[mrad]
$\theta_{F_s^1,F_n^1}$	2.0258 ± 0.0010	2.00	[degree]
$\theta_{1,6-13,18}$	1.9841 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	2.0079 ± 0.0010	2.00	[degree]

Table B.21: The table summarises the angles measured on the module 03. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{nf,\vec{D}_{i,j}}$ ($\theta_{sf,\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1,F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.4 Module 04

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.572 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028
Sphere 2	0.014 ± 0.003	0.000 ± 0.003	-216.956 ± 0.003	12.694 ± 0.028
Sphere 3	-198.572 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.22: Sphere positions of the module 04. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.806 ± 0.199	97.900
$D_{2,3}$	97.675 ± 0.198	97.900
$D_{3,4}$	163.238 ± 0.329	163.350
$D_{4,5}$	340.325 ± 0.684	340.000
$D_{5,6}$	260.926 ± 0.525	261.250
$D_{6,1}$	242.531 ± 0.488	242.100

Table B.23: Measurements of the normal side of the module 04. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.998 ± 0.099	48.200
$D_{8,11}^{yz}$	47.563 ± 0.098	48.200
$D_{9,10}^{yz}$	48.252 ± 0.100	48.200

Table B.24: Measurements of the top side of the module 04. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.891 ± 0.199	97.900
$D_{14,15}$	97.779 ± 0.199	97.900
$D_{15,16}$	163.238 ± 0.329	163.35
$D_{16,17}$	340.611 ± 0.684	340.21
$D_{17,18}$	261.704 ± 0.526	261.25

Table B.25: Measurements of the stereo side of the module 04. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	48.062 ± 0.099	48.200
$D_{2,14}^y$	47.921 ± 0.099	48.200
$D_{3,15}^y$	47.745 ± 0.098	48.200
$D_{4,16}^y$	48.327 ± 0.100	48.200
$D_{5,17}^y$	48.254 ± 0.100	48.200
$D_{6,18}^y$	48.355 ± 0.100	48.200

Table B.26: The table summarises the thickness of the module 03 including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	4.284 ± 0.003	-23.910 ± 0.003	109.862 ± 0.003
$F_{H_s}^1$	16.038 ± 0.003	-22.034 ± 0.003	450.168 ± 0.003
$F_{B_n}^1$	-16.018 ± 0.003	24.157 ± 0.003	109.678 ± 0.003
$F_{H_n}^1$	-15.833 ± 0.003	25.750 ± 0.003	449.855 ± 0.003

Table B.27: Fibre position on the normal and stereo side of the module 04. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	5.56 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	5.40 ± 0.03	0	[mrad]
$\theta_{nf,\vec{D}_{1,6}}$	1.6969 ± 0.0215	0	[mrad]
$\theta_{nf,\vec{D}_{4,5}}$	1.0697 ± 0.0176	0	[mrad]
$\theta_{sf,\vec{D}_{13,18}}$	1.0911 ± 0.0215	0	[mrad]
$\theta_{sf,\vec{D}_{16,17}}$	0.4013 ± 0.0176	0	[mrad]
$\theta_{F_s^1, F_n^1}$	1.9476 ± 0.0010	2.00	[degree]
$\theta_{1,6-13,18}$	1.7903 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	1.9322 ± 0.0010	2.00	[degree]

Table B.28: The table summarises the angles measured on the module 04. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{nf,\vec{D}_{i,j}}$ ($\theta_{sf,\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1, F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.5 Module 05

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.572 ± 0.003	0.000 ± 0.003	(0.000 ± 0.003)	12.700 ± 0.028
Sphere 2	0.014 ± 0.003	0.000 ± 0.003	(-216.956 ± 0.003)	12.694 ± 0.028
Sphere 3	-198.572 ± 0.003	0.000 ± 0.003	(0.000 ± 0.003)	12.700 ± 0.028

Table B.29: Sphere positions of the module 05. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.813 ± 0.199	97.900
$D_{2,3}$	97.347 ± 0.198	97.900
$D_{3,4}$	163.442 ± 0.330	163.350
$D_{4,5}$	340.267 ± 0.684	340.000
$D_{5,6}$	261.286 ± 0.526	261.250
$D_{6,1}$	242.447 ± 0.488	242.100

Table B.30: Measurements of the normal side of the module 05. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	48.059 ± 0.099	48.200
$D_{8,11}^{yz}$	47.647 ± 0.098	48.200
$D_{9,10}^{yz}$	47.893 ± 0.099	48.200

Table B.31: Measurements of the top side of the module 05. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.729 ± 0.198	97.900
$D_{14,15}$	97.842 ± 0.199	97.900
$D_{15,16}$	163.407 ± 0.330	163.35
$D_{16,17}$	340.422 ± 0.684	340.21
$D_{17,18}$	261.336 ± 0.526	261.25

Table B.32: Measurements of the stereo side of the module 05. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	48.043 ± 0.099	48.200
$D_{2,14}^y$	48.049 ± 0.099	48.200
$D_{3,15}^y$	47.727 ± 0.098	48.200
$D_{4,16}^y$	47.923 ± 0.099	48.200
$D_{5,17}^y$	48.511 ± 0.100	48.200
$D_{6,18}^y$	48.571 ± 0.100	48.200

Table B.33: The table summarises the thickness of the module 03 including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen

Table B.34: Fibre position on the normal and stereo side of the module 05. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	3.04 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	4.77 ± 0.03	0	[mrad]
$\theta_{\text{nf},\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{\text{nf},\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1, F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	1.9853 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	2.0040 ± 0.0010	2.00	[degree]

Table B.35: The table summarises the angles measured on the module 05. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{\text{nf},\vec{D}_{i,j}}$ ($\theta_{\text{sf},\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1, F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.6 Module 06-4L

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.564 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028
Sphere 2	-0.055 ± 0.003	0.000 ± 0.003	-216.965 ± 0.003	12.696 ± 0.028
Sphere 3	-198.564 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.36: Sphere positions of the module 06-4L. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.809 ± 0.199	97.900
$D_{2,3}$	97.824 ± 0.199	97.900
$D_{3,4}$	163.343 ± 0.330	163.350
$D_{4,5}$	340.393 ± 0.684	340.000
$D_{5,6}$	261.365 ± 0.526	261.250
$D_{6,1}$	242.477 ± 0.488	242.100

Table B.37: Measurements of the normal side of the module 06-4L. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.488 ± 0.098	47.800
$D_{8,11}^{yz}$	47.472 ± 0.098	47.800
$D_{9,10}^{yz}$	47.613 ± 0.098	47.800

Table B.38: Measurements of the top side of the module 06-4L. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.897 ± 0.199	97.900
$D_{14,15}$	97.837 ± 0.199	97.900
$D_{15,16}$	163.291 ± 0.330	163.35
$D_{16,17}$	340.551 ± 0.684	340.21
$D_{17,18}$	261.299 ± 0.526	261.25

Table B.39: Measurements of the stereo side of the module 06-4L. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	47.584 ± 0.098	47.800
$D_{2,14}^y$	47.636 ± 0.098	47.800
$D_{3,15}^y$	47.498 ± 0.098	47.800
$D_{4,16}^y$	47.798 ± 0.099	47.800
$D_{5,17}^y$	48.068 ± 0.099	47.800
$D_{6,18}^y$	48.066 ± 0.099	47.800

Table B.40: The table summarises the thickness of the module 06-4L including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen

Table B.41: Fibre position on the normal and stereo side of the module 06-4L. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	3.54 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	4.31 ± 0.03	0	[mrad]
$\theta_{\text{nf},\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{\text{nf},\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1, F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	2.0663 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	2.0055 ± 0.0010	2.00	[degree]

Table B.42: The table summarises the angles measured on the module 06-4L. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{\text{nf},\vec{D}_{i,j}}$ ($\theta_{\text{sf},\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1, F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.7 Module 07-4L

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.555 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.701 ± 0.028
Sphere 2	0.029 ± 0.003	0.000 ± 0.003	-216.958 ± 0.003	12.694 ± 0.028
Sphere 3	-198.555 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.43: Sphere positions of the module 07-4L. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.810 ± 0.199	97.900
$D_{2,3}$	97.905 ± 0.199	97.900
$D_{3,4}$	163.444 ± 0.330	163.350
$D_{4,5}$	340.368 ± 0.684	340.000
$D_{5,6}$	261.398 ± 0.526	261.250
$D_{6,1}$	242.323 ± 0.488	242.100

Table B.44: Measurements of the normal side of the module 07-4L. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.707 ± 0.098	47.800
$D_{8,11}^{yz}$	47.420 ± 0.098	47.800
$D_{9,10}^{yz}$	47.571 ± 0.098	47.800

Table B.45: Measurements of the top side of the module 07-4L. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.931 ± 0.199	97.900
$D_{14,15}$	97.875 ± 0.199	97.900
$D_{15,16}$	163.457 ± 0.330	163.35
$D_{16,17}$	340.516 ± 0.684	340.21
$D_{17,18}$	261.476 ± 0.526	261.25

Table B.46: Measurements of the stereo side of the module 07-4L. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	47.939 ± 0.099	47.800
$D_{2,14}^y$	47.736 ± 0.098	47.800
$D_{3,15}^y$	47.598 ± 0.098	47.800
$D_{4,16}^y$	47.952 ± 0.099	47.800
$D_{5,17}^y$	48.169 ± 0.099	47.800
$D_{6,18}^y$	48.113 ± 0.099	47.800

Table B.47: The table summarises the thickness of the module 07-4L including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen

Table B.48: Fibre position on the normal and stereo side of the module 07-4L. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	5.12 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	5.07 ± 0.03	0	[mrad]
$\theta_{\text{nf},\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{\text{nf},\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1, F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	1.9921 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	2.0140 ± 0.0010	2.00	[degree]

Table B.49: The table summarises the angles measured on the module 07-4L. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{\text{nf},\vec{D}_{i,j}}$ ($\theta_{\text{sf},\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1, F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.8 Module 08-4L

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.561 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.701 ± 0.028
Sphere 2	-0.022 ± 0.003	0.000 ± 0.003	-216.977 ± 0.003	12.694 ± 0.028
Sphere 3	-198.561 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.50: Sphere positions of the module 08-4L. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.875 ± 0.199	97.900
$D_{2,3}$	97.898 ± 0.199	97.900
$D_{3,4}$	163.396 ± 0.330	163.350
$D_{4,5}$	340.188 ± 0.683	340.000
$D_{5,6}$	261.157 ± 0.525	261.250
$D_{6,1}$	242.311 ± 0.488	242.100

Table B.51: Measurements of the normal side of the module 08-4L. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.546 ± 0.098	47.800
$D_{8,11}^{yz}$	47.634 ± 0.098	47.800
$D_{9,10}^{yz}$	47.782 ± 0.099	47.800

Table B.52: Measurements of the top side of the module 08-4L. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.867 ± 0.199	97.900
$D_{14,15}$	97.911 ± 0.199	97.900
$D_{15,16}$	163.273 ± 0.330	163.35
$D_{16,17}$	340.382 ± 0.684	340.21
$D_{17,18}$	261.386 ± 0.526	261.25

Table B.53: Measurements of the stereo side of the module 08-4L. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	47.861 ± 0.099	47.800
$D_{2,14}^y$	47.839 ± 0.099	47.800
$D_{3,15}^y$	47.844 ± 0.099	47.800
$D_{4,16}^y$	47.928 ± 0.099	47.800
$D_{5,17}^y$	48.036 ± 0.099	47.800
$D_{6,18}^y$	48.077 ± 0.099	47.800

Table B.54: The table summarises the thickness of the module 08-4L including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen

Table B.55: Fibre position on the normal and stereo side of the module 08-4L. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	5.12 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	5.49 ± 0.03	0	[mrad]
$\theta_{\text{nf},\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{\text{nf},\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1, F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	1.9793 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	2.0312 ± 0.0010	2.00	[degree]

Table B.56: The table summarises the angles measured on the module 08-4L. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{\text{nf},\vec{D}_{i,j}}$ ($\theta_{\text{sf},\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1, F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.9 Module 09-4L

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.543 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.701 ± 0.028
Sphere 2	-0.115 ± 0.003	0.000 ± 0.003	-216.995 ± 0.003	12.694 ± 0.028
Sphere 3	-198.543 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.57: Sphere positions of the module 09-4L. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.443 ± 0.198	97.900
$D_{2,3}$	97.946 ± 0.199	97.900
$D_{3,4}$	163.181 ± 0.329	163.350
$D_{4,5}$	340.280 ± 0.684	340.000
$D_{5,6}$	261.229 ± 0.525	261.250
$D_{6,1}$	242.359 ± 0.488	242.100

Table B.58: Measurements of the normal side of the module 09-4L. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.605 ± 0.098	47.800
$D_{8,11}^{yz}$	47.308 ± 0.098	47.800
$D_{9,10}^{yz}$	47.681 ± 0.098	47.800

Table B.59: Measurements of the top side of the module 09-4L. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.862 ± 0.199	97.900
$D_{14,15}$	98.028 ± 0.199	97.900
$D_{15,16}$	163.250 ± 0.330	163.35
$D_{16,17}$	340.364 ± 0.684	340.21
$D_{17,18}$	261.472 ± 0.526	261.25

Table B.60: Measurements of the stereo side of the module 09-4L. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	47.849 ± 0.099	47.800
$D_{2,14}^y$	47.619 ± 0.098	47.800
$D_{3,15}^y$	47.404 ± 0.098	47.800
$D_{4,16}^y$	47.876 ± 0.099	47.800
$D_{5,17}^y$	47.928 ± 0.099	47.800
$D_{6,18}^y$	48.060 ± 0.099	47.800

Table B.61: The table summarises the thickness of the module 09-4L including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen

Table B.62: Fibre position on the normal and stereo side of the module 09-4L. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	4.34 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	4.09 ± 0.03	0	[mrad]
$\theta_{\text{nf},\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{\text{nf},\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1, F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	2.0056 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	1.9593 ± 0.0010	2.00	[degree]

Table B.63: The table summarises the angles measured on the module 09-4L. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{\text{nf},\vec{D}_{i,j}}$ ($\theta_{\text{sf},\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1, F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

B.10 Module 10-4L

Spheres	Spheres position [mm]			
	x	y	z	diameter
Sphere 1	198.569 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028
Sphere 2	-0.159 ± 0.003	0.000 ± 0.003	216.989 ± 0.003	12.694 ± 0.028
Sphere 3	-198.569 ± 0.003	0.000 ± 0.003	0.000 ± 0.003	12.700 ± 0.028

Table B.64: Sphere positions of the module 10-4L. The sphere center are used to define the reference frame. The errors are given by the machine precision. The diameter length is taken into account to evaluate their error.

Key distances	Normal side [mm]	
	measured	nominal
$D_{1,2}$	97.847 ± 0.199	97.900
$D_{2,3}$	98.041 ± 0.199	97.900
$D_{3,4}$	163.308 ± 0.330	163.350
$D_{4,5}$	340.240 ± 0.683	340.000
$D_{5,6}$	261.154 ± 0.525	261.250
$D_{6,1}$	242.285 ± 0.488	242.100

Table B.65: Measurements of the normal side of the module 10-4L. The measured values are followed by their errors which are evaluated according to the CMM precision.

Key distances	Top [mm]	
	measured	nominal
$D_{7,12}^{yz}$	47.519 ± 0.098	47.800
$D_{8,11}^{yz}$	47.290 ± 0.098	47.800
$D_{9,10}^{yz}$	47.754 ± 0.099	47.800

Table B.66: Measurements of the top side of the module 10-4L. These measurements does not include the glue layer thickness used to glue the fibres. The lengths subindexes are of the Figure A.6.

Key distances	Stereo side [mm]	
	measured	nominal
$D_{13,14}$	97.725 ± 0.198	97.900
$D_{14,15}$	97.911 ± 0.199	97.900
$D_{15,16}$	163.461 ± 0.330	163.35
$D_{16,17}$	340.417 ± 0.684	340.21
$D_{17,18}$	261.227 ± 0.525	261.25

Table B.67: Measurements of the stereo side of the module 10-4L. The measured values are followed by their errors which are evaluated according to the CMM precision. The lengths subindexes are of the Figure A.7 for comparisons.

Key distances	Module thickness [mm]	
	measured	nominal
$D_{1,13}^y$	47.678 ± 0.098	47.800
$D_{2,14}^y$	47.704 ± 0.098	47.800
$D_{3,15}^y$	47.401 ± 0.098	47.800
$D_{4,16}^y$	47.937 ± 0.099	47.800
$D_{5,17}^y$	48.218 ± 0.099	47.800
$D_{6,18}^y$	48.042 ± 0.099	47.800

Table B.68: The table summarises the thickness of the module 10-4L including the glue layer.

Variable	Fibre position [mm]		
	x	y	z
$F_{B_s}^1$	not seen	not seen	not seen
$F_{H_s}^1$	not seen	not seen	not seen
$F_{B_n}^1$	not seen	not seen	not seen
$F_{H_n}^1$	not seen	not seen	not seen

Table B.69: Fibre position on the normal and stereo side of the module 10-4L. $F_{B_s}^1$ ($F_{H_s}^1$) are the bottom (top) position of the fibre on the stereo side. Similarly $F_{B_n}^1$ ($F_{H_n}^1$) are the bottom (top) position of the fibre on the normal side of the module. The glue layer is thick enough to avoid identify the fibres through the camera contrast.

Angles	Angles measured		
	measured	nominal	unity
$\theta_{M_n,R}$	4.74 ± 0.03	0	[mrad]
$\theta_{M_s,R}$	5.66 ± 0.03	0	[mrad]
$\theta_{\text{nf},\vec{D}_{1,6}}$	not seen	0	[mrad]
$\theta_{\text{nf},\vec{D}_{4,5}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{13,18}}$	not seen	0	[mrad]
$\theta_{\text{sf},\vec{D}_{16,17}}$	not seen	0	[mrad]
$\theta_{F_s^1,F_n^1}$	not seen	2.00	[degree]
$\theta_{1,6-13,18}$	1.9984 ± 0.0014	2.00	[degree]
$\theta_{4,5-16,17}$	2.0133 ± 0.0010	2.00	[degree]

Table B.70: The table summarises the angles measured on the module 10-4L. $\theta_{M_n,R}$ ($\theta_{M_s,R}$) is the angle between the normal (stereo) mattress plane and the reference plane (see text). $\theta_{\text{nf},\vec{D}_{i,j}}$ ($\theta_{\text{sf},\vec{D}_{i,j}}$) is the angle between the normal (stereo) fibre and the vector defined by the key points i and j . These values indicate the precision of the alignment of the fibre mattress along the module. $\theta_{F_s^1,F_n^1}$ is the stereo angle measured directly between both fibres and $\theta_{i,j-k,l}$ is the stereo angle measured between the vectors defined by the key points i , j and k , l .

Appendix C

2MA Results

Results of the 2MA's position. Here is shown the position of the spheres C, D, E, F, G and H as shown in Figure A.16 of section A.5. The spheres positions are the target position for the metrology and assembling of 2MA on laboratory.

Spheres	Spheres position [mm]		
	x	y	z
C	-178.705	-362.138	95.283
D	-472.481	-375.164	94.116
E	-459.517	-81.333	95.497
F	-178.709	362.225	145.868
G	-472.564	375.425	146.750
H	-459.660	81.579	146.194

Table C.1: Position of the spheres of the 2MA-1, Near Bottom. Modules 2 and 3.

Spheres	Spheres position [mm]		
	x	y	z
C	-178.739	-362.244	95.648
D	-472.546	-375.205	94.324
E	-459.563	-81.416	95.169
F	-459.543	81.899	145.911
G	-472.113	375.749	146.533
H	-178.320	362.321	145.901

Table C.2: Position of the spheres of the 2MA-2, Far top. Modules 1 and 5.

Spheres	Spheres position [mm]		
	x	y	z
C	-178.725	-361.987	95.529
D	-472.634	-374.969	94.687
E	-459.523	-81.221	95.475
F	-459.525	81.229	145.837
G	-472.509	375.180	146.914
H	-178.775	362.117	146.089

Table C.3: Position of the spheres of the 2MA-3, Near top. Modules 9-4L and 10-4L.

Spheres	Spheres position [mm]		
	x	y	z
C	-178.852	-362.042	95.3187
D	-472.645	-375.01	94.3896
E	-459.591	-81.182	95.4902
F	-178.732	362.09	146.084
G	-472.575	375.112	147.224
H	-459.556	81.2978	146.288

Table C.4: Position of the spheres of the 2MA-4, Near Bottom. Modules 7-4L and 8-4L.

Appendix D

Comparison between 2011 and 2012 data at LHCb for single track-cluster analyses

D.1 Track-cluster efficiency comparisons between 7 and 8 TeV of centre-of-mass energy at LHCb.

As was said in the section 4.1.1, E/P does not change between data 2012 ($\sqrt{s} = 8$ TeV) and 2011 ($\sqrt{s} = 7$ TeV), and the same for MonteCarlo simulation. However the calorimeter efficiency changes. Figure D.1 (D.2) shows the comparison of the efficiency of the calorimeters which have a cluster associated to a track, between 2011 and 2012 samples for ECAL (HCAL). 2012 data is less efficient indicating the ageing of detector and would be need a new recalibration to recover the efficiency. For MC the 2011 and 2012, have a good agreement.



Figure D.1: Comparison between the ECAL efficiency for data (left) and MC (right). The blue and black markers are for centre-of-mass energy collisions of 8 and 7 TeV respectively. Long and downstream tracks were taken into account.



Figure D.2: Comparison between the HCAL efficiency for data (left) and MC (right). The blue and black markers are centre-of-mass energy collisions of 8 and 7 TeV respectively. Long and downstream tracks were taken into account.

D.2 E/P comparisons between 7 and 8 TeV of centre-of-mass energy collisions for Data and MC

Comparisons between E/P of 2011 and 2012 for data. For MC the comparison is similar, the track and cluster reconstruction simulation, follows the same procedure as in data. As was pointed out in the section 4.1.1 no change is found between those samples.

Similarly, when selected ECAL clusters associated to electron tracks no discrepancies were found.

D.2.1 HCAL independent - hadron



Figure D.3: Comparison of E/P between 2011 and 2012 samples for data (left) and MC (right). The 2012 samples are more spread since we have less events.

D.2.2 HCAL only - hadron



Figure D.4: Comparison of E/P between 2011 and 2012 samples for data (left) for and MC (right). The 2012 samples are more spread since we have less events.

D.2.3 ECAL - independent - hadron

ECAL inner



Figure D.5: Comparison of E/P between 2011 Reco12a and 2012 Reco14 samples for data for ECAL independent.

D.2.4 ECAL middle

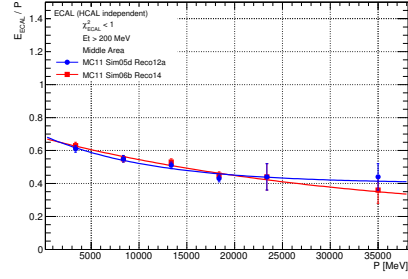
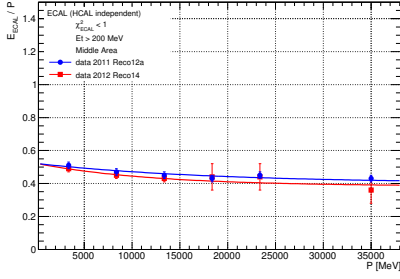


Figure D.6: Comparison of E/P between 2011 Reco12a and 2012 Reco14 samples for data for ECAL independent.

D.2.5 ECAL outer

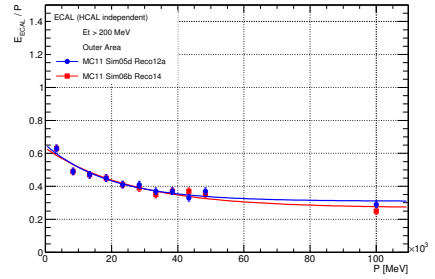
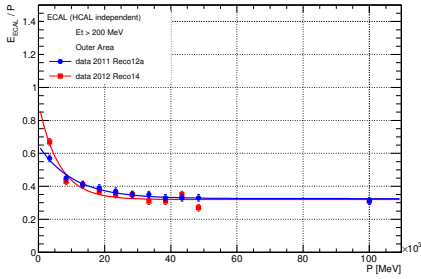


Figure D.7: Comparison of E/P between 2011 Reco14 and 2012 Reco12a samples for data for HCAL dependent. The 2012 samples are more spread since we have less events.

Appendix E

Theory predictions

All theoretical predictions necessary for $W + b\bar{b}$ analysis were done using the package GMC FM. This package is a modified version of the MCFM v8.6 [130] that allows the LHCb users to submit the jobs to calculate the cross sections to the grid. The CT10 PDF v5.8 [131] set is used in all calculations. The cross sections calculations were done in the same way that they were performed in the W+jet measurement [128].

All cross sections evaluated in this section are calculated using the requirements of the decfile* corresponding to each process (see Table E.1 and E.2). However, some requirements that are in the decfiles could not be implemented in the GMC FM. On these cases, the efficiency of the requirement is evaluated using Gauss and the total cross section is corrected. For instance, since the MCFM does not decay taus in the final state of the processes, the efficiency of muons and electrons coming from those taus with the same requirements defined in the decfile is used to correct the total cross section of the $Z(\tau\tau) + b\bar{b}$ and $W(\tau\nu) + b\bar{b}$. The cross section of the $W + c\bar{c}$ is also a special case because it is not possible to calculate it directly using the MCFM. The ratio $W + c\bar{c}$ to $W + b\bar{b}$ calculated at ALPGEN, 2.16, is used to evaluate the $W + c\bar{c}$ cross section using the $W + b\bar{b}$ cross section.

The evaluation of the PDF uncertainty (δ_{PDF}) is done using 53 different PDFs and the uncertainty is combined using the hessian approach while each uncertainty of the other

*Decfiles are configuration files of Monte Carlo production at LHCb.

sources is combined using the envelope method. We considered that the contribution that comes from the uncertainty in the masses of the charm, bottom and top quarks are neglectible as it is reported in the Reference [128]. The renormalization and scale uncertainty (δ_{sf}) are obtained varying their values multiplying it by a factor 2 and 1/2 in all possible combinations. The uncertainty of the strong coupling (δ_{α_s}) is evaluated using the $\alpha_s(M_Z)$ defined in the NLO PDF sets (0.117, 0.118 and 0.119). The total cross section uncertainty (δ_{total}) is calculated as follows:

$$\delta_{total} = \sqrt{(\delta_{\alpha_s}^2 + \delta_{PDF}^2)} + \delta_{sf}. \quad (\text{E.1})$$

If more than one process contributes to the total cross-section, the uncertainty of the sum of the processes is used to evaluate the total cross-section uncertainty. The most relevant cross-sections for this analysis are shown in the Table E.4 and Table E.3 for 7 *TeV* and 8 *TeV* respectively.

Table E.1: Summary of the simulations selection used to evaluate the cross sections. Unless stated otherwise, in the LHCb acceptance stands for $\theta < 400$ mrad.

Sample	Decfile	Requirements
t	41900003	The top quark decays to Wb and the W decays leptonically. One lepton is required to be in the LHCb acceptance with $p_T(l) > 17$ GeV.
$q\bar{q} \rightarrow t\bar{t}$ $gg \rightarrow t\bar{t}$	41900006 41900007	One lepton from W is required to be in the LHCb acceptance with $p_T(l) > 17$ GeV and two b quarks coming from t quarks.
$W(\mu\nu)c\bar{c}$ $W(e\nu)c\bar{c}$	42971005 42981000	Two c quarks in the LHCb acceptance with $p_T > 3$ GeV and one lepton in LHCb acceptance with $p_T > 10$ GeV
$Z(\mu\mu)b\bar{b}$ $Z(ee)b\bar{b}$	42912007 42922000	Two b quarks in the LHCb acceptance with $p_T > 3$ GeV and one lepton in LHCb acceptance with $p_T > 10$ GeV.
$Z(\mu\mu)c\bar{c}$ $Z(ee)c\bar{c}$	42972000 42982000	Two c quarks in the LHCb acceptance with $p_T > 3$ GeV and one lepton in LHCb acceptance with $p_T(l) > 10$ GeV.
$W(\tau\nu)b\bar{b}$ $Z[\tau\tau]b\bar{b}$	42901000 42902000	Two b quarks in the LHCb acceptance with $pt(b) > 3$ GeV and μ or e coming from the τ in the LHCb acceptance with $p_T(\tau) > 10$ GeV.
$W(\mu\nu e\nu)Z(bb)$ $Z(\mu\mu e\nu)Z(bb)$	42921005 42912005	Two b quarks in the LHCb acceptance coming from the Z boson and lepton in the LHCb acceptance with $p_T(l) > 5$ GeV.
$W(\tau\nu)$	42300000	Tau in the LHCb acceptance with $p_T(\tau) > 4$ GeV.
$W(\mu\nu)j$	42311011	Muon in the LHCb acceptance ($\theta(\mu) < 420$ mrad) with $p_T > 17$ GeV.

Table E.2: MC processes info used in the simulation steps. The trigger are Trig0x409f0045(Trig0x40760037) for year 2012(2011) and the Stripping is 20(20r1).

Decay	Decfile	Generator	Gauss ²⁰¹¹ 2012	DDDB	SIMCOND
t	41900003	Pythia 8	v45r7	20130929	20130522
$t\bar{t}$	41900006 41900007	Pythia 8	v45r3,4,5,10 v45r5,9,10	20130503,0929 20130929	20130503,22 20130522
$Z(ee) + b\bar{b}$	42922000	AlpGen	v45r10	20130929	20130522
$Z(ee) + c\bar{c}$	42982000	AlpGen	v45r10	20130929	20130522
$Z(\mu\mu) + jet$	42112022	Pythia 8	v45r4	20130503	20130503
$Z(\mu\mu) + b$	42112053	Pythia 8	v45r7	20130929	20130522
$Z(\mu\mu) + c$	42112052	Pythia 8	v45r7	20130929	20130522
$Z(\mu\mu) + c\bar{c}$	42972000	AlpGen	v45r10	20130929	20130522
$Z(\mu\mu) + b\bar{b}$	42912007	AlpGen	v45r10	20130929	20130522
$Z(\tau\tau)$	42100000	Pythia 8	v45r3	20130503	20130503
$Z(\tau\tau) + b\bar{b}$	42902000	AlpGen	v45r10	20130929	20130522
$W(e\nu) + jet$	42321010	Pythia 8	v45r10	20130929	20130522
$W(e\nu) + b\bar{b}$	42921008	AlpGen	v45r10	20130929	20130522
$W(e\nu) + c\bar{c}$	42981000	AlpGen	v45r10	20130929	20130522
$W(\mu\nu) + jet$	42311011	Pythia 8	v45r4 v45r7,9	20130503 20130929	20130503 20130522
$W(\mu\nu) + bjet$	42971002	Pythia 6	v45r4	20150503	20130503
$W(\mu\nu) + cjet$	42971001	Pythia 6	v45r4	20150503	20130503
$W(\mu\nu) + b\bar{b}$	42911000	AlpGen	v45r10	20130929	20130522
$W(\mu\nu) + c\bar{c}$	42971005	AlpGen	v45r10	20130929	20130522
$W(\tau\nu) + jet$	42300010	Pythia 8	v45r10	20130929	20130522
$W(\tau\nu) + b\bar{b}$	42901000	AlpGen	v45r10	20130929	20130522
$Z(ee \mu\mu)Z(bb)$	42912005	Pythia 8	v45r10	20130929	20130522
$W(e\nu \mu\nu)Z(bb)$	42921005	Pythia 8	v45r10	20130929	20130522
$WW(1l15)$	42021000	Pythia 8	v45r3 v45r9	20130503 20130929	20130503 20130522
$WZ(1l15)$	42021001	Pythia 8	v45r3 v45r9	20130503 20130929	20130503 20130522

Table E.3: The cross section of each process is shown in the σ column with the total theoretical uncertainty according to the equation E.1. The percentual contribution of each uncertainty source was normalized by the nominal value.

Sample	Decfile	Energy	Order	$\sigma(\text{pb})$	δ_{sf}	δ_{α_s}	δ_{PDF}	δ_{stat}
t	41900003	8000.0	lo	$1.89^{+20.7\%}_{-10.9\%}$	$+17.6\%$ -9.2%	$+0.0\%$ 0.0%	$+3.2\%$ -1.7%	$+0.99\%$ -0.99%
t	41900003	8000.0	nlo	$2.57^{+11.4\%}_{-25.0\%}$	$+8.2\%$ -24.8%	$+3.2\%$ 0.2%	$+0.0\%$ -0.0%	$+2.41\%$ -2.41%
$t\bar{t}(\text{sum})$	41900006	8000.0	lo	$7.48^{+41.8\%}_{-29.1\%}$	$+34.9\%$ -23.9%	$+0.0\%$ 0.0%	$+6.9\%$ -5.2%	$+0.18\%$ -0.18%
$gg \rightarrow t\bar{t}$	41900006	8000.0	lo	$5.67^{+46.7\%}_{-32.3\%}$	$+37.6\%$ -25.4%	$+0.0\%$ 0.0%	$+9.1\%$ -6.9%	$+0.00\%$ -0.00%
$q\bar{q} \rightarrow t\bar{t}$	41900007	8000.0	lo	$1.81^{+20.3\%}_{-15.4\%}$	$+18.6\%$ -13.6%	$+0.0\%$ 0.0%	$+1.7\%$ -1.8%	$+0.00\%$ -0.00%
$t\bar{t}(\text{sum})$	41900006	8000.0	nlo	$12.19^{+26.0\%}_{-21.3\%}$	$+16.8\%$ -15.8%	$+2.6\%$ 1.8%	$+8.8\%$ -5.2%	$+0.47\%$ -0.47%
$Z(ee)bb$	42922000	8000.0	lo	$0.32^{+27.5\%}_{-20.5\%}$	$+24.9\%$ -17.9%	$+0.0\%$ 0.0%	$+2.5\%$ -2.7%	$+0.27\%$ -0.27%
$Z(ee)bb$	42922000	8000.0	nlo	$0.82^{+110.5\%}_{-279.2\%}$	$+23.6\%$ -49.0%	$+28.9\%$ 69.1%	$+82.0\%$ -219.6%	$+10.34\%$ -10.34%
$Z(\mu\mu) + c\bar{c}$	42972000	8000.0	lo	$0.59^{+27.9\%}_{-19.2\%}$	$+25.3\%$ -17.9%	$+0.0\%$ 0.0%	$+2.6\%$ -1.3%	$+0.31\%$ -0.31%
$Z(\mu\mu) + c\bar{c}$	42972000	8000.0	nlo	$1.36^{+22.0\%}_{-31.2\%}$	$+17.0\%$ -18.4%	$+4.0\%$ 4.9%	$+2.9\%$ -11.8%	$+3.20\%$ -3.20%
$Z(\mu\mu)b\bar{b}$	42912007	8000.0	lo	$0.32^{+27.5\%}_{-20.5\%}$	$+24.9\%$ -17.9%	$+0.0\%$ 0.0%	$+2.5\%$ -2.7%	$+0.27\%$ -0.27%
$Z(\mu\mu)b\bar{b}$	42912007	8000.0	nlo	$0.82^{+110.5\%}_{-279.2\%}$	$+23.6\%$ -49.0%	$+28.9\%$ 69.1%	$+82.0\%$ -219.6%	$+10.34\%$ -10.34%
$Z(\tau\tau)b\bar{b}$	42902000	8000.0	lo	$0.07^{+25.5\%}_{-21.6\%}$	$+24.2\%$ -18.4%	$+0.0\%$ 0.0%	$+1.3\%$ -3.2%	$+0.26\%$ -0.26%
$Z(\tau\tau)b\bar{b}$	42902000	8000.0	nlo	$0.20^{+58.4\%}_{-565.4\%}$	$+12.6\%$ -314.9%	$+2.4\%$ 23.3%	$+45.8\%$ -249.4%	$+12.17\%$ -12.17%
$W(\mu\nu) + b\bar{b}$	42911000	8000.0	lo	$1.86^{+27.7\%}_{-20.7\%}$	$+25.5\%$ -18.3%	$+0.0\%$ 0.0%	$+2.2\%$ -2.4%	$+0.14\%$ -0.14%
$W(\mu\nu) + b\bar{b}$	42911000	8000.0	nlo	$4.80^{+39.8\%}_{-21.5\%}$	$+26.4\%$ -16.9%	$+5.3\%$ 0.0%	$+12.3\%$ -4.6%	$+1.61\%$ -1.61%
$W^- + b\bar{b}$	42911000	8000.0	lo	$0.78^{+28.4\%}_{-21.5\%}$	$+25.5\%$ -18.3%	$+0.0\%$ 0.0%	$+2.9\%$ -3.2%	$+0.19\%$ -0.19%
$W^- + b\bar{b}$	42911000	8000.0	nlo	$1.96^{+31.9\%}_{-23.7\%}$	$+24.9\%$ -17.6%	$+3.0\%$ 0.0%	$+6.3\%$ -6.1%	$+0.93\%$ -0.93%
$W^+ + b\bar{b}$	42911000	8000.0	lo	$1.08^{+27.8\%}_{-20.9\%}$	$+25.5\%$ -18.3%	$+0.0\%$ 0.0%	$+2.4\%$ -2.6%	$+0.19\%$ -0.19%
$W^+ + b\bar{b}$	42911000	8000.0	nlo	$2.85^{+48.8\%}_{-22.1\%}$	$+27.4\%$ -16.4%	$+6.9\%$ 0.0%	$+20.3\%$ -5.7%	$+2.64\%$ -2.64%
$W(\mu\nu) + c\bar{c}$	42971005	8000.0	lo	$20.44^{+27.7\%}_{-20.7\%}$	$+25.5\%$ -18.3%	$+0.0\%$ 0.0%	$+2.2\%$ -2.4%	$+29.89\%$ -29.89%
$W(\mu\nu) + c\bar{c}$	42971005	8000.0	nlo	$52.89^{+39.8\%}_{-21.5\%}$	$+26.4\%$ -16.9%	$+5.3\%$ 0.0%	$+12.3\%$ -4.6%	$+29.93\%$ -29.93%
$W(\tau\nu)b\bar{b}$	42901000	8000.0	lo	$0.37^{+27.3\%}_{-20.7\%}$	$+25.4\%$ -18.3%	$+0.0\%$ 0.0%	$+1.9\%$ -2.4%	$+0.12\%$ -0.12%
$W(\tau\nu)b\bar{b}$	42901000	8000.0	nlo	$1.05^{+28.1\%}_{-21.0\%}$	$+24.8\%$ -17.8%	$+3.0\%$ 2.5%	$+1.4\%$ -2.0%	$+0.37\%$ -0.37%
$Z(ee \mu\mu)Z(bb)$	42912005	8000.0	lo	$0.03^{+2.2\%}_{-7.5\%}$	$+0.0\%$ -5.5%	$+0.0\%$ 0.0%	$+2.2\%$ -2.0%	$+0.11\%$ -0.11%
$Z(ee \mu\mu)Z(bb)$	42912005	8000.0	nlo	$0.04^{+20.3\%}_{-99.4\%}$	$+7.8\%$ -2.0%	$+0.7\%$ 0.0%	$+12.5\%$ -97.4%	$+0.50\%$ -0.50%
$W(e\nu \mu\nu)Z(bb)$	42921005	8000.0	lo	$0.04^{+2.1\%}_{-6.8\%}$	$+0.0\%$ -4.3%	$+0.0\%$ 0.0%	$+2.1\%$ -2.5%	$+0.26\%$ -0.26%
$W(e\nu \mu\nu)Z(bb)$	42921005	8000.0	nlo	$0.06^{+27.9\%}_{-20.4\%}$	$+9.1\%$ -1.0%	$+12.0\%$ 0.0%	$+14.5\%$ -19.4%	$+0.79\%$ -0.79%

Table E.4: The cross section of each process is shown in the σ column with the total theoretical uncertainty according to the equation E.1. The percentual contribution of each uncertainty source was normalized by the nominal value.

Sample	Decfile	Energy	Order	$\sigma(\text{pb})$	δ_{sf}	δ_{α_s}	δ_{PDF}	δ_{stat}
t	41900003	7000.0	lo	$1.33^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.64\%$ -0.64%
t	41900003	7000.0	nlo	$1.83^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+3.01\%$ -3.01%
$t\bar{t}(\text{sum})$	41900006	7000.0	lo	$4.93^{+43.6\%}_{-30.1\%}$	$+36.1\%$ -24.5%	$+0.0\%$ 0.0%	$+7.5\%$ -5.6%	$+0.11\%$ -0.11%
$gg \rightarrow t\bar{t}$	41900006	7000.0	lo	$3.62^{+49.7\%}_{-33.9\%}$	$+39.3\%$ -26.2%	$+0.0\%$ 0.0%	$+10.3\%$ -7.7%	$+0.00\%$ -0.00%
$q\bar{q} \rightarrow t\bar{t}$	41900007	7000.0	lo	$1.31^{+21.0\%}_{-16.1\%}$	$+19.2\%$ -14.0%	$+0.0\%$ 0.0%	$+1.7\%$ -2.0%	$+0.00\%$ -0.00%
$t\bar{t}(\text{sum})$	41900006	7000.0	nlo	$8.03^{+28.6\%}_{-47.7\%}$	$+15.8\%$ -23.9%	$+1.3\%$ 2.6%	$+12.8\%$ -23.7%	$+0.47\%$ -0.47%
$Z(ee)$	42122000	7000.0	lo	$327.61^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.04\%$ -0.04%
$Z(ee)$	42122000	7000.0	nlo	$372.95^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.11\%$ -0.11%
$Z(ee)bb$	42922000	7000.0	lo	$0.24^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.27\%$ -0.27%
$Z(ee)bb$	42922000	7000.0	nlo	$0.96^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+22.73\%$ -22.73%
$Z(ee)c\bar{c}$	42982000	7000.0	lo	$0.46^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.34\%$ -0.34%
$Z(ee)c\bar{c}$	42982000	7000.0	nlo	$1.01^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+1.17\%$ -1.17%
$Z(\mu\mu)$	42112001	7000.0	lo	$327.61^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.04\%$ -0.04%
$Z(\mu\mu)$	42112001	7000.0	nlo	$372.95^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.11\%$ -0.11%
$Z(\mu\mu) + jet$	42112022	7000.0	lo	$310.81^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.08\%$ -0.08%
$Z(\mu\mu) + jet$	42112022	7000.0	nlo	$315.41^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.59\%$ -0.59%
$Z(\mu\mu) + c$	42112052	7000.0	lo	$3.01^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.20\%$ -0.20%
$Z(\mu\mu) + c$	42112052	7000.0	nlo	$4.72^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.53\%$ -0.53%
$Z(\mu\mu) + b$	42112053	7000.0	lo	$2.39^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.21\%$ -0.21%
$Z(\mu\mu) + b$	42112053	7000.0	nlo	$3.46^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.63\%$ -0.63%
$Z(\mu\mu) + c\bar{c}$	42972000	7000.0	lo	$0.46^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.34\%$ -0.34%
$Z(\mu\mu) + c\bar{c}$	42972000	7000.0	nlo	$1.01^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+1.17\%$ -1.17%
$Z(\mu\mu)b\bar{b}$	42912007	7000.0	lo	$0.24^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.27\%$ -0.27%
$Z(\mu\mu)b\bar{b}$	42912007	7000.0	nlo	$0.96^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+22.73\%$ -22.73%
$Z(\tau\tau)$	42100000	7000.0	lo	$299.22^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.04\%$ -0.04%
$Z(\tau\tau)$	42100000	7000.0	nlo	$342.80^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.07\%$ -0.07%
$Z(\tau\tau)b\bar{b}$	42902000	7000.0	lo	$0.05^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.29\%$ -0.29%
$Z(\tau\tau)b\bar{b}$	42902000	7000.0	nlo	$0.08^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+58.99\%$ -58.99%
$W(e\nu) + jet$	42321010	7000.0	lo	$2602.87^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.08\%$ -0.08%
$W(e\nu) + jet$	42321010	7000.0	nlo	$2710.38^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.59\%$ -0.59%
$W(e\nu)b\bar{b}$	42921008	7000.0	lo	$1.47^{+27.7\%}_{-20.8\%}$	$+25.5\%$ -18.4%	$+0.0\%$ 0.0%	$+2.2\%$ -2.4%	$+0.14\%$ -0.14%
$W(e\nu)b\bar{b}$	42921008	7000.0	nlo	$3.78^{+59.2\%}_{-21.4\%}$	$+21.6\%$ -17.1%	$+4.1\%$ 0.1%	$+37.4\%$ -4.3%	$+0.70\%$ -0.70%
$W(e\nu)c\bar{c}$	42981000	7000.0	lo	$16.15^{+27.7\%}_{-20.8\%}$	$+25.5\%$ -18.4%	$+0.0\%$ 0.0%	$+2.2\%$ -2.4%	$+29.89\%$ -29.89%
$W(e\nu)c\bar{c}$	42981000	7000.0	nlo	$41.64^{+59.2\%}_{-21.4\%}$	$+21.6\%$ -17.1%	$+4.1\%$ 0.1%	$+37.4\%$ -4.3%	$+29.90\%$ -29.90%
$W(\mu\nu) + jet$	42311010	7000.0	lo	$2602.87^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.08\%$ -0.08%

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Table E.4 – continued from previous page

Sample	Decfile	Energy	Order	$\sigma(\text{pb})$	δ_{sf}	δ_{α_s}	δ_{PDF}	δ_{stat}
$W(\mu\nu) + jet$	42311010	7000.0	nlo	$2710.38^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.59\%$ -0.59%
$W(\mu\nu) + jet$	42311011	7000.0	lo	$2231.27^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.09\%$ -0.09%
$W(\mu\nu) + jet$	42311011	7000.0	nlo	$2329.36^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.61\%$ -0.61%
$W(\mu\nu) + bjet$	42971002	7000.0	lo	$0.05^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.11\%$ -0.11%
$W(\mu\nu) + bjet$	42971002	7000.0	nlo	$0.07^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+1.75\%$ -1.75%
$W(\mu\nu) + b\bar{b}$	42911000	7000.0	lo	$1.47^{+27.7\%}_{-20.8\%}$	$+25.5\%$ -18.4%	$+0.0\%$ 0.0%	$+2.2\%$ -2.4%	$+0.14\%$ -0.14%
$W(\mu\nu) + b\bar{b}$	42911000	7000.0	nlo	$3.78^{+59.2\%}_{-21.4\%}$	$+21.6\%$ -17.1%	$+4.1\%$ 0.1%	$+37.4\%$ -4.3%	$+0.70\%$ -0.70%
$W^- + b\bar{b}$	42911000	7000.0	lo	$0.62^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.20\%$ -0.20%
$W^- + b\bar{b}$	42911000	7000.0	nlo	$1.51^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+1.07\%$ -1.07%
$W^+ + b\bar{b}$	42911000	7000.0	lo	$0.85^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.20\%$ -0.20%
$W^+ + b\bar{b}$	42911000	7000.0	nlo	$2.27^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.93\%$ -0.93%
$W(\mu\nu) + c$	42971001	7000.0	lo	$30.68^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.09\%$ -0.09%
$W(\mu\nu) + c$	42971001	7000.0	nlo	$48.44^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+3.26\%$ -3.26%
$W(\mu\nu) + c\bar{c}$	42971005	7000.0	lo	$16.15^{+27.7\%}_{-20.8\%}$	$+25.5\%$ -18.4%	$+0.0\%$ 0.0%	$+2.2\%$ -2.4%	$+29.89\%$ -29.89%
$W(\mu\nu) + c\bar{c}$	42971005	7000.0	nlo	$41.64^{+59.2\%}_{-21.4\%}$	$+21.6\%$ -17.1%	$+4.1\%$ 0.1%	$+37.4\%$ -4.3%	$+29.90\%$ -29.90%
$W(\tau\nu)$	42300000	7000.0	lo	$2148.68^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.06\%$ -0.06%
$W(\tau\nu)$	42300000	7000.0	nlo	$2487.86^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.09\%$ -0.09%
$W(\tau\nu)b\bar{b}$	42901000	7000.0	lo	$0.30^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.12\%$ -0.12%
$W(\tau\nu)b\bar{b}$	42901000	7000.0	nlo	$0.85^{+2.4\%}_{-2.7\%}$	$+0.0\%$ -0.0%	$+2.4\%$ 2.7%	$+0.0\%$ -0.0%	$+0.39\%$ -0.39%
$Z(ee \mu\mu)Z(bb)$	42912005	7000.0	lo	$0.03^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.17\%$ -0.17%
$Z(ee \mu\mu)Z(bb)$	42912005	7000.0	nlo	$0.03^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.45\%$ -0.45%
$W(e\nu \mu\nu)Z(bb)$	42921005	7000.0	lo	$0.03^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.27\%$ -0.27%
$W(e\nu \mu\nu)Z(bb)$	42921005	7000.0	nlo	$0.04^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+1.34\%$ -1.34%
$WW(1l15)$	42021000	7000.0	lo	$3.26^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.13\%$ -0.13%
$WW(1l15)$	42021000	7000.0	nlo	$4.56^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.25\%$ -0.25%
$WZ(1l15)$	42021001	7000.0	lo	$0.72^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.11\%$ -0.11%
$WZ(1l15)$	42021001	7000.0	nlo	$1.10^{+0.0\%}_{-0.0\%}$	$+0.0\%$ -0.0%	$+0.0\%$ 0.0%	$+0.0\%$ -0.0%	$+0.28\%$ -0.28%