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Use of the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel to control the flavour tagging in LHCb

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Introduction

LHCb is an experiment dedicated to the study of CP violation and rare decays in the sector of b-hadrons. One of its goal is to perform the first measurement of the phase ϕ_s of the CKM matrix element V_{ts} which is one of the fundamental parameters of the Standard Model. It is connected to the transition probability between a top quark and a strange quark. The phase ϕ_s can be extracted from time dependent CP asymmetries of $B_s^0 \rightarrow J/\psi\phi$ decays. For this measurement, one need to tag the initial flavour state of the B_s^0 meson. This procedure, called “flavour tagging”, has a certain probability to be wrong. The wrong tag fraction, or “mistag” need to be determined using a B_s^0 decay to flavour specific final state. For this purpose, the $B_s^0 \rightarrow D_s^- \pi^+$ channel has already been studied [24]. In this report, we investigate the possibility to use $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ decays to measure the B_s^0 mistag rate in LHCb.

In chapter 1, we explain the interest of CP violation in the b-hadron sector, with emphasis on the measurement of the angle ϕ_s .

After a brief description of the LHCb detector in chapter 2, we describe in chapter 3 the flavour tagging algorithm and the methods used to control its performances in real data.

In chapter 4, we describe the selection of the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel, compute the expected number of events per year, also called annual yield, and study the background.

In chapter 5, we compare the tagging performances between the CP channel $B_s^0 \rightarrow J/\psi\phi$ and two “control channels” : $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$. We investigate how these performances vary depending on how the event has been triggered and selected. We also study how the momentum correlation between the “signal B meson” and the “tagging B meson” vary in control and CP channel.

Eventually, we conclude on the usefulness of the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel to control the mistag rate in LHCb.

Chapter 1

Motivations

1.1 CP violation

The CP transformation is the product of two operators : the charge conjugation and the parity. Under C, all the internal quantum numbers of a particle like the electromagnetic charge are changed into their opposite. Under P, the handedness of the space is reversed, meaning that $\vec{x}$ becomes $-\vec{x}$. Under CP a left handed electron becomes a right handed positron.

If CP was an exact symmetry, the laws of nature should be the same for matter and antimatter, and most phenomena are C and P symmetric, and therefore CP symmetric. It is the case for most of the interactions. But the weak interaction violates C and P in the strongest way. This enables some rare processes that do not conserve CP, as discovered in the neutral kaon system in 1964[1], and in 2000 for the neutral B decays [2].

The CP violation is described mathematically by a complex phase in the Yukawa couplings. This phase clearly appears when we represent those couplings under the form of a 3×3 unitary matrix in the basis of mass eigenstates. This matrix, also called CKM¹ matrix, gives the W-boson coupling between an up type antiquark ($\bar{u}, \bar{c}, \bar{t}$) and a down type quark (d, s, b).

This coupling, known as KM² mechanism, is represented by a charged current interaction :

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} \bar{u}_{Li} \gamma^\mu (V_{CKM})_{ij} d_{Lj} W_\mu^\pm + \text{h.c.} \quad (1.1)$$

Here, $i, j = 1, 2, 3$ are the generation numbers. The elements of V_{CKM} are represented as below :

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.2)$$

A general 3×3 unitary matrix depends on three real angles and six phases, but the freedom to redefine the phases of the quark mass eigenstate can be used to remove five of the phases, leaving a single physical phase, the Kobayashi–Maskawa phase, responsible

¹CKM : Cabibbo–Kobayashi–Maskawa

²KM : Kobayashi–Maskawa

for the CP violation in the Standard Model. The general form of this matrix is [17] :

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \quad (1.3)$$

where θ_{ij} is the mixing angle between the “generations”, and with $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$ for the “generation” labels $i, j = 1, 2, 3$.

The liberty of parametrization with three angles and one phase can be clearly seen by choosing an explicit parametrization. The extended Wolfenstein parametrization [3, 4] is very useful, because it shows the strong hierarchy between the elements of the CKM matrix. It is given by :

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6) \quad (1.4)$$

Here, $\lambda = \sin \theta_{12} \simeq 0.22$, $A\lambda^2 = \sin \theta_{23}$, and $A\lambda^3(\rho - i\eta) = \sin \theta_{13}e^{-i\delta_{13}}$.

The unitarity of the CKM matrix implies nine relations which can be represented as triangles in the complex plane, but only two are relevant (fig. 1.1) because the 7 other relations lead to flat triangles. The two relations are given by :

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (1.5)$$

$$V_{tb}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0 \quad (1.6)$$

The angles of the first triangle (equation 1.5), given by :

$$\alpha \equiv \arg \left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right), \quad (1.7)$$

$$\beta \equiv \arg \left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right), \quad (1.8)$$

$$\gamma \equiv \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right), \quad (1.9)$$

The second triangle gives the angle :

$$\phi_s \equiv 2(\pi - \arg(V_{ts})) \quad (1.10)$$

relevant for us.

These angles are physical quantities that can be measured by CP asymmetries in B decays.

The phase of V_{ts} (ϕ_s) is a fundamental parameter of the Standard Model which has never been measured. Its measurement is one of the main goals of LHCb. It can be accessed through the decays of $B_s^0 \rightarrow J/\psi\phi$.

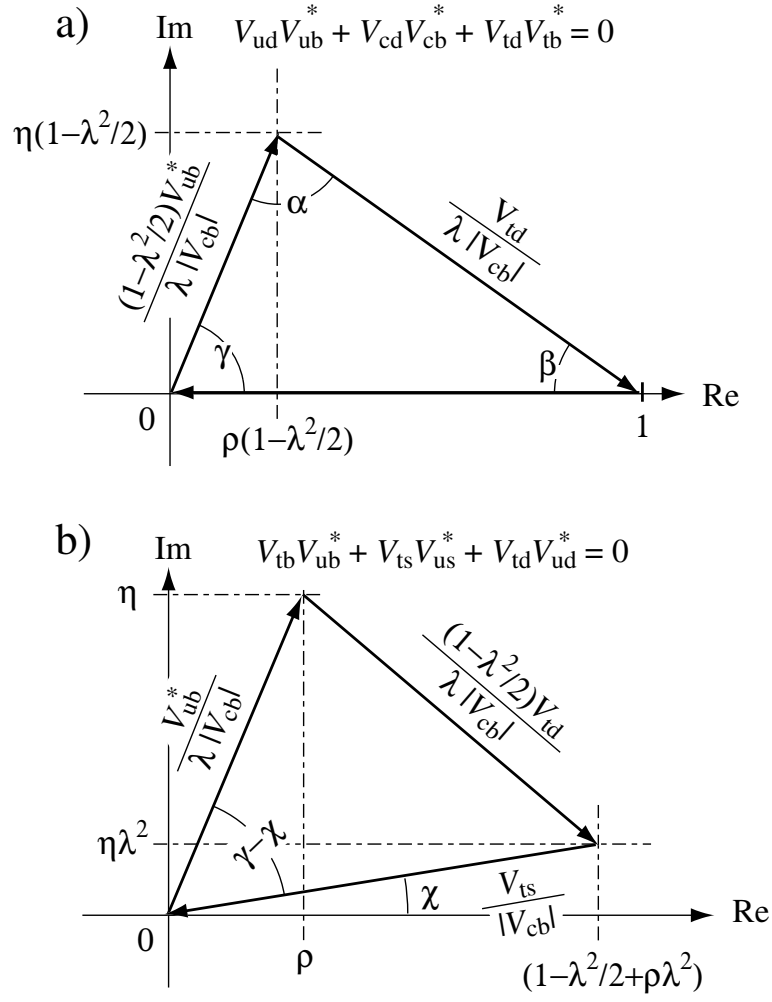


Figure 1.1: Graphical representation of the unitarity constraints : a) $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, and b) $V_{tb}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0$, as triangles in the complex plane [8].

1.2 Extraction of ϕ_s through the asymmetry of $B_s^0 \rightarrow J/\psi\phi$ decays

$B_s^0 \rightarrow J/\psi\phi$ is the counter part of the $B^0 \rightarrow J/\psi K_S^0$ to extract $\sin 2\beta$. The extraction of the angle ϕ_s is based upon the fact that B_s^0 can oscillate. The oscillation mechanism is well described in [17], and it is represented in fig. 1.2.

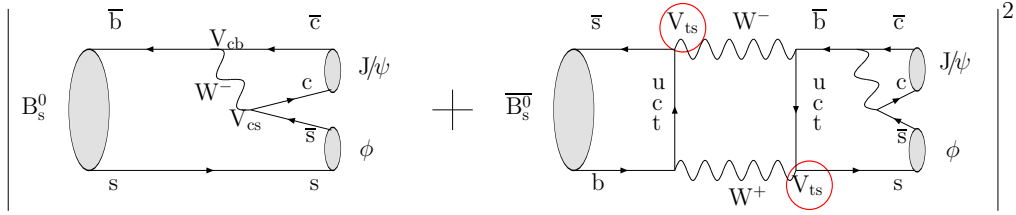
Knowing this mechanism, we are able to extract the angle ϕ_s .

The CP asymmetry is defined as the differences in decay rates between particles and anti-particles :

$$\mathcal{A}(t) = \frac{N(B_s^0 \rightarrow J/\psi\phi)(t) - N(\bar{B}_s^0 \rightarrow J/\psi\phi)(t)}{N(B_s^0 \rightarrow J/\psi\phi)(t) + N(\bar{B}_s^0 \rightarrow J/\psi\phi)(t)} \quad (1.11)$$

with N is a number of events of the type designated in the braces.

The decay amplitude of $B_s^0 \rightarrow J/\psi\phi$ is proportional to



$B_s^0 \rightarrow J/\psi\phi$ is a mixture of CP-even and CP-odd. The decay rate can be written as follows [7] :

$$\begin{aligned} \Gamma(B_s^0(t) \rightarrow f_e) &\propto e^{-\Gamma_L t} + e^{-\Delta\Gamma_s t} \sin \phi_s \sin(\Delta m_s t) \\ \Gamma(\bar{B}_s^0(t) \rightarrow f_e) &\propto e^{-\Gamma_L t} - e^{-\Delta\Gamma_s t} \sin \phi_s \sin(\Delta m_s t) \\ \Gamma(B_s^0(t) \rightarrow f_o) &\propto e^{-\Gamma_H t} + e^{-\Delta\Gamma_s t} \sin \phi_s \sin(\Delta m_s t) \\ \Gamma(\bar{B}_s^0(t) \rightarrow f_o) &\propto e^{-\Gamma_H t} - e^{-\Delta\Gamma_s t} \sin \phi_s \sin(\Delta m_s t) \end{aligned}$$

where Δm_s ($\Delta\Gamma_s$) is the mass (decay width) difference between the B_s^0 meson mass eigenstates (Heavy and Light), and ϕ_s is the phase we have to determine. This is further described in [8].

In the asymmetry formula (eq. 1.11), the initial state is before an eventual oscillation, so the initial state flavour has to be determined. This tagging procedure will be presented in chapter 3. But before, we will present the LHCb detector.

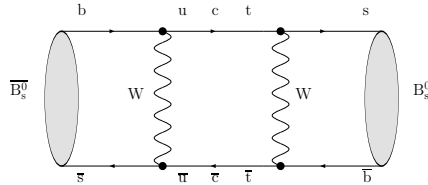


Figure 1.2: Oscillation mechanism for the B_s^0 system.

Chapter 2

The LHCb detector

2.1 Overview

The LHC located at CERN will produce proton–proton collisions with a center of mass energy of 14 TeV.

The LHC will be installed in the underground cavern of the Large Electron–Positron (LEP) collider. It has four crossing regions, occupied by the experiments ATLAS, CMS, ALICE, and LHCb. The instantaneous luminosity at the LHCb point is $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, and the bunch crossing frequency is 40MHz, which corresponds to a collision every 25 ns.

The LHCb experiment is specialized in the beauty sector. Fig.2.1 shows the angular correlation of the b–hadrons produced at LHC simulated with PYTHIA. It indicates that the two B–hadrons are most likely to be produced in a forward (or backward) direction. This explains the global geometry of our detector (see fig. 2.2). The physics in the beauty sector needs very precise measurements in different fields. It needs a very accurate localisation of the vertexes, in order to resolve the fast B_s^0 oscillation ; it requires also a good identification of the particles and an excellent track reconstruction efficiency, to reconstruct precisely different channels. It also needs a good trigger system, even for non–leptonic modes.

In this chapter we briefly discuss the interest and the goal of each detector parts.

2.2 Trackers

The tracking system is composed of two sub–detectors : the vertex locator and the tracking stations. It aims to reconstruct the tracks of the charged particles propagating through the detector.

2.2.1 VELO

The vertex locator, or VELO, aims to determine the position of the different vertexes, and give information about the pile–up events. It is a set of semi–circular disks, placed on a moving support (it has to be away from the beam during injection, and close when taking

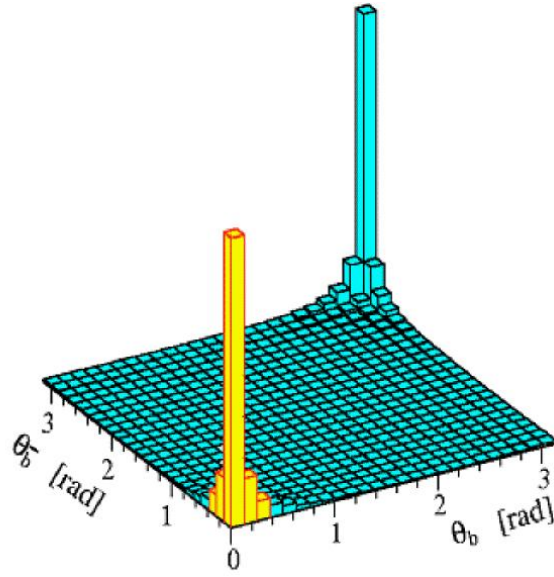


Figure 2.1: Correlation between the emission of the b quark and the $\bar{b}$ quark, with respect to the beam axis.

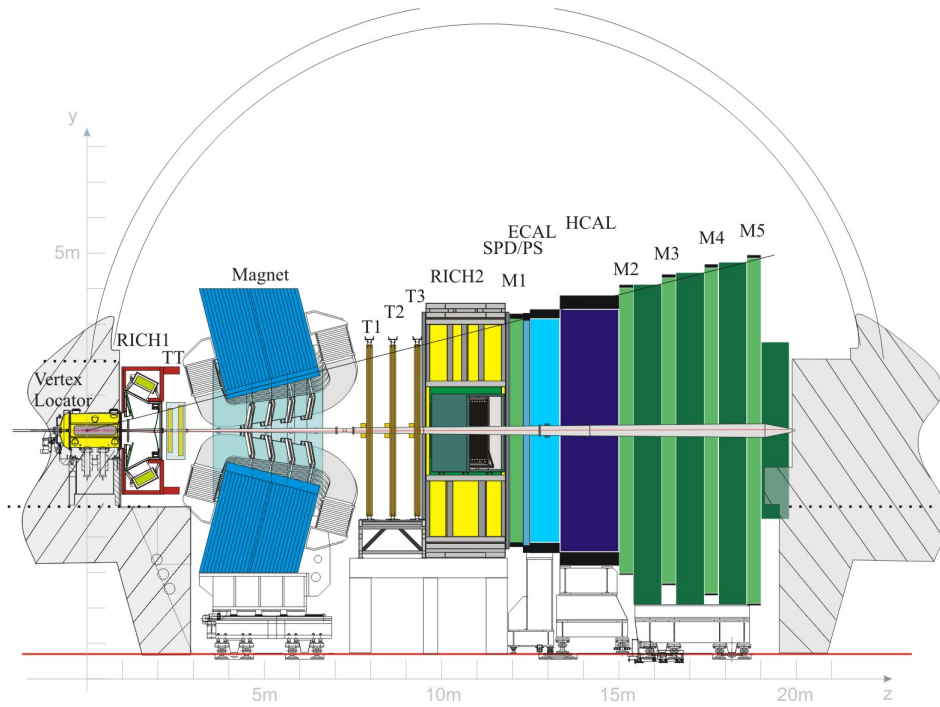


Figure 2.2: View of the LHCb detector along the bending plane.

data). Its resolution is about $30 \mu\text{m}$ on the impact parameter¹. A part of the VELO is also used to reject multiple proton–proton interactions at the trigger level. Fig. 2.3 gives an overview of the vertex locator and fig. 2.4 gives a close view of the two types of silicon sensors.

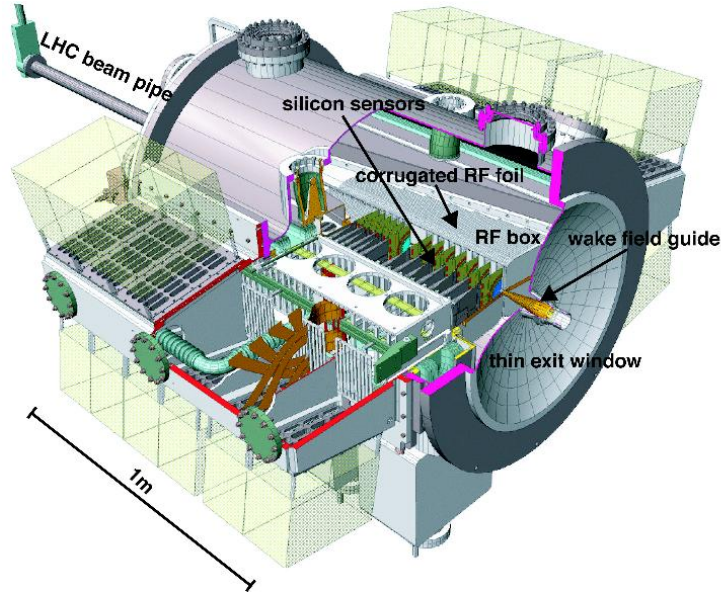


Figure 2.3: Overview of the VELO detector

2.2.2 Tracking stations

The tracking stations goals are to provide a momentum resolution below half a percent and a B mass resolution below $15 \text{ MeV}/c^2$. They are separated in 2 sets : the first one is between the first RICH and the magnet (TT : Trigger Tracker), and the second one is between the magnet and the second RICH (T1–T2–T3). The first set is just composed of silicium pads, whereas the second one is composed of both silicium pads and straw tubes chambers. The resolution of the silicium pads is better than $70 \mu\text{m}$ on the spacial position of the hits.

2.3 Magnet

The magnet goal is to curve the trajectories of the charged particles to measure their momenta. It is a warm magnet contrary to ATLAS or CMS, to allow regular reversion of the field, in order to reduce experimental systematics on the CP measurement. The strength of the field is 4 Tm.

¹Impact parameter : distance of closest approach from a point to a line. Here it is the distance between a vertex and a track.

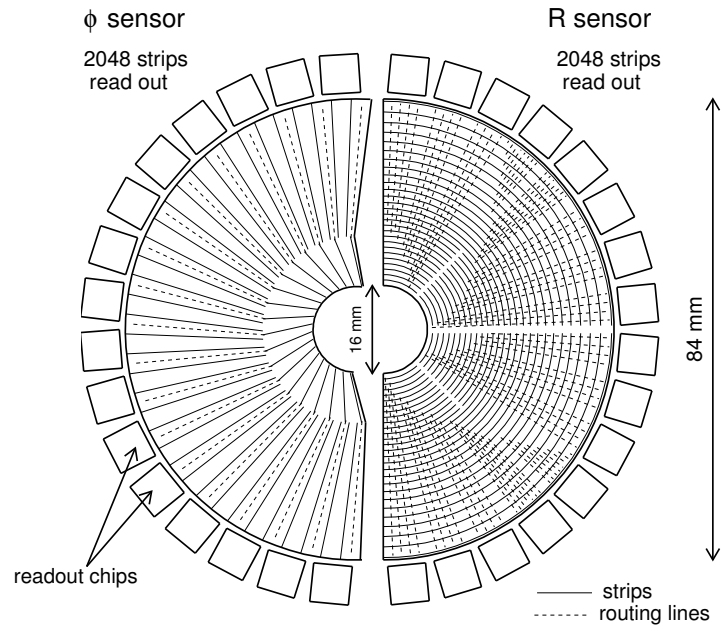


Figure 2.4: View of the two types of silicon sensors for the VELO detector

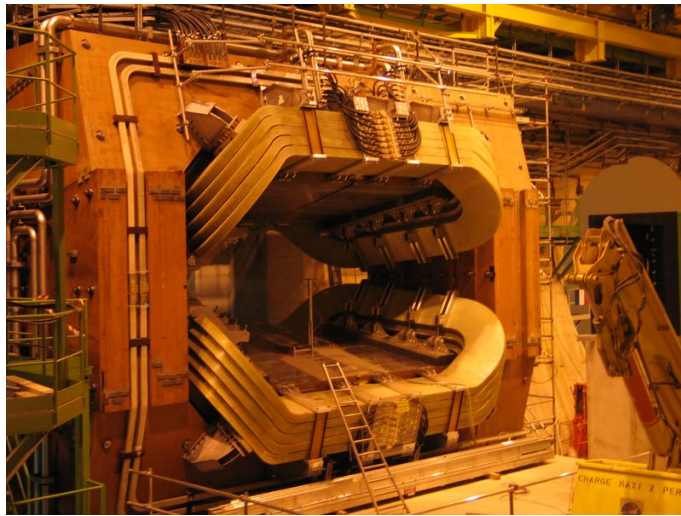


Figure 2.5: Picture of LHCb magnet.

2.4 RICHs

The Ring Imaging CHerenkov detectors (see fig. 2.6) make the identification of the particles with the information provided by the tracking stations, using the Cherenkov Effect. They are designed to give a 3 sigma separation between pions and kaons for a momen-

tum between 3 and 80 GeV/c.

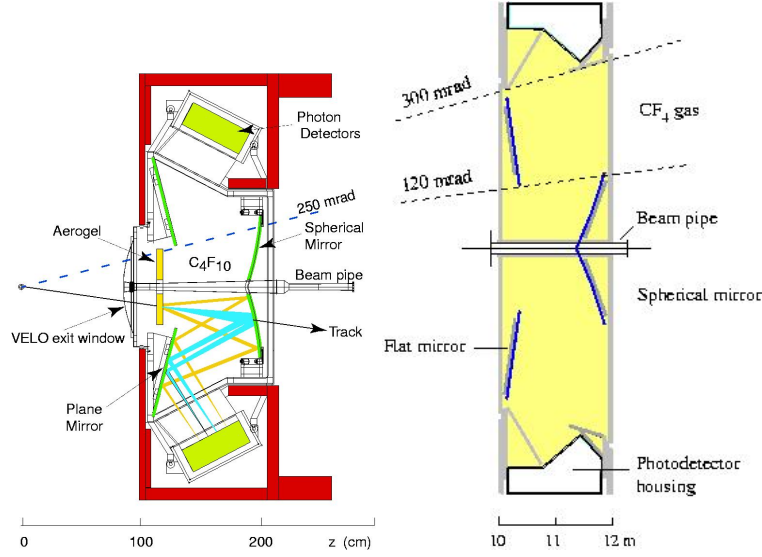


Figure 2.6: Overview of RICH1 and RICH2.

2.5 Calorimeters

The calorimeters are used to detect and measure the energy of electrons, hadrons and photons. It consists of a scintillating pad detector, a preshower, a shashlik electromagnetic calorimeter, and a hadronic calorimeter made of steel and scintillating tiles. Their goal for trigger is to look for high E_T hadrons, electrons and photon clusters.

2.6 Muon Detectors

The muon system provides muon identification, and is crucial for the first level of trigger, as it will trigger on high p_T muons.

The muon detectors are a set of five stations, one before the calorimeters, and four after the calorimeters, interlayered with iron shields. They are a set of multi-wire proportional chambers. The efficiency to find a muon from B decays is around 95% for a pion misidentification rate below 1%.

2.7 Trigger systems

The trigger systems [9] is one of the greatest challenge for LHCb, as it is supposed to be very fast and efficient. Its goal is to select only events “interesting” for physics, while reducing the rate from 40 MHz (one collision every 25 ns) to 2 kHz to cope with the

limited capacity of the data storage. It is composed of three levels, the first is a hardware level, and the two second are software triggers.

The purpose of the first level of trigger (L0) is to reduce the LHC beam crossing rate from 40 MHz, to 1 MHz, a rate where all sub-systems could be used for trigger decision. Hence L0 reconstructs the highest E_T hadron, electron, and photon cluster in the calorimeter ; and the two highest p_T muons in the muon chambers. Events can be rejected based on global event variables like the track multiplicity and the number of pp-interactions, as reconstructed by the Pile-Up system in the VELO. This level of trigger reduces the rate to approximately 1 MHz.

The second level of trigger (L1) uses the information from L0, the VELO and the TT (Trigger Tracker). It reconstructs the tracks in the VELO, and matches these tracks to L0-muons or Calorimeter clusters to identify them and measure their momenta. The events are selected based on tracks with a large p_T and a significant impact parameter to the primary vertex.

The high level trigger (HLT) uses all the available information. The HLT starts with the reconstruction of the VELO tracks and the primary vertex, independently of the L1 information. Then the tracks are linked to the hits left in the T1, T2, and T3 stations. The final selection of interesting events is a combination of confirming the L1 decision with better resolution, and selection cuts dedicated to specific final states.

Chapter 3

Tagging the flavour in LHCb

3.1 Introduction to tagging

In LHCb, b-hadrons are mainly produced in pairs. In the following, we will call “signal” b-hadron the one we try to reconstruct (e.g. $B_s^0 \rightarrow J/\psi\phi$), while the other one is called “tagging B” and is referred as “opposite side” with respect to the signal.

The flavour tagging is the determination of the initial state flavour of a neutral B. There are several methods to determine this flavour, exploiting “same side” and “opposite side” with respect to the signal, as illustrated on fig. 3.1, and described in [10].

3.1.1 Opposite side tagging

This tagging algorithm concerns the b-hadron accompanying the reconstructed B meson under study, as shown in fig.3.1. The lepton in a semileptonic b decay and the kaon in a $b \rightarrow c \rightarrow s$ chain are searched. The charge of the secondary vertex reconstructed from b-decay products gives some additional information. When the accompanying b-hadron is a neutral B meson, due to the possibility of flavour oscillations, all these methods have an intrinsic dilution.

The opposite side leptons are required to have a momentum greater than 5 GeV/c, and a transverse momentum (p_T) greater than 1.2 GeV/c, to reduce the contributions from $b \rightarrow c \rightarrow \ell$ decays which tag the wrong charge (see fig.3.1). If there are multiple possibilities, the one with the highest p_T is used.

For the selection of the opposite side kaon, a momentum greater than 3 GeV/c, a p_T greater than 0.4 GeV/c, and an impact parameter with respect to the primary vertex with significance IP/σ_{IP} greater than 3.7 are required. The cuts are set to enhance the contribution of kaons from B decays with respect to the kaons produced in fragmentation.

An inclusive reconstruction of the opposite b-hadron is done by the inclusive reconstruction of the secondary vertex, when there are no kaons nor leptons in the opposite side. Two tracks are used as seeds. These tracks have to be *long* tracks¹ and must satisfy kinematic cuts which increase the probability to come from a b-hadron. If the two tracks have an invariant mass compatible with a K_S^0 , they are excluded. Other tracks are then

¹Long tracks are tracks which have left hits on each detector, from the VELO to the T3 station.

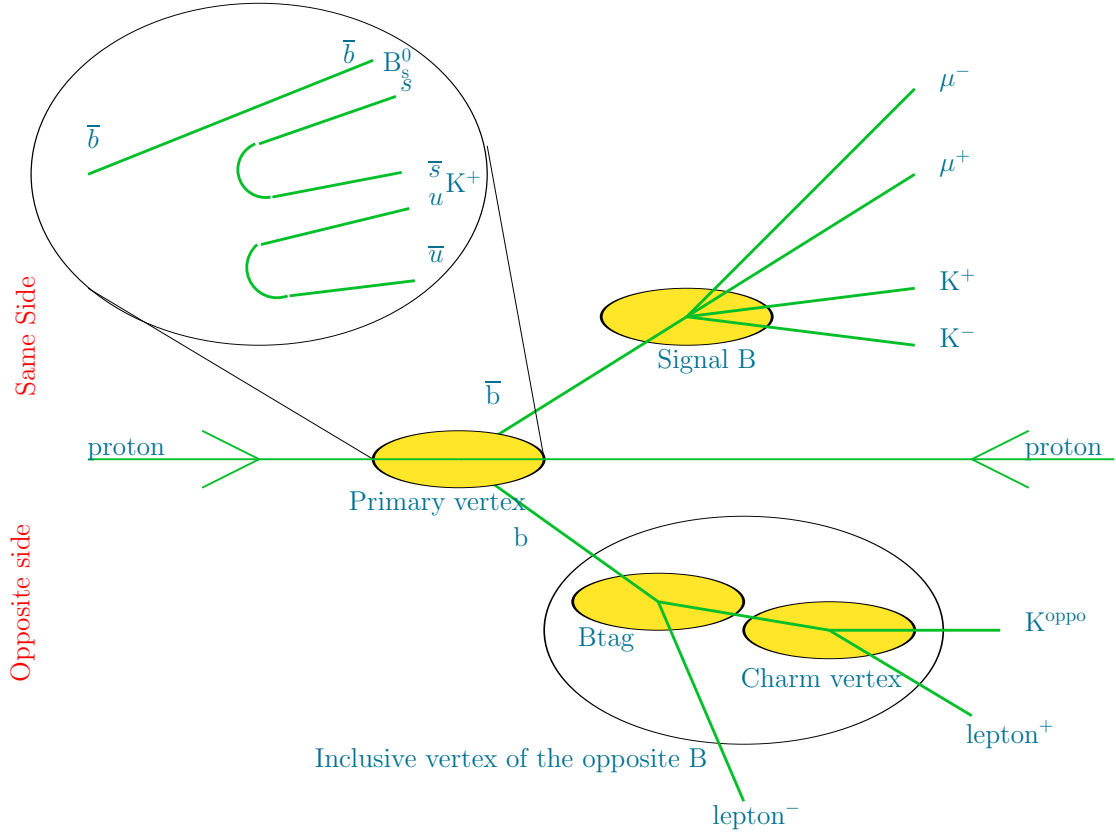


Figure 3.1: Scheme representing the different sources of information for the tagging in LHCb. In this example, the signal B is a $B_s^0 \rightarrow J/\psi(\mu\mu)\phi(KK)$. On same side the kaon from fragmentation is used as a tagger. Two leptons and a kaon are present on the opposite side. The lepton from the Btag and the lepton from the charm have an opposite charge which increases the dilution

included if they satisfy more kinematic criteria on the impact parameter, vertex χ^2 , and distance from the primary vertex.

The cuts presented here are summarized in table 3.1.

3.1.2 Same side tagging

The same side tagging determine directly the initial flavour of the signal B meson exploiting the correlation in the fragmentation decay chain. It is used to tag B_s^0 or B^0 mesons. As shown in the figure 3.2, if a B_s^0 ($\bar{b}s$) is produced in the fragmentation of a $\bar{b}$ quark, an extra $\bar{s}$ quark is available to form, for example, a kaon. This kaon is charged in about 50% of the cases, and neutral in the other cases. These kaons are coming from the primary vertex and are correlated in phase space with the B_s^0 meson. They are selected with an impact parameter with respect to the primary vertex with a significance IP/σ_{IP} lower than 2.5, an absolute difference in pseudo-rapidity $|\Delta\eta|$ with respect to the reconstructed B_s^0 lower than 1, a difference in ϕ angle $|\Delta\phi|$ lower than 1.1, and Δm lower than 1.5,

a)	cut	value	b)	cut	value
	momentum	$> 5 \text{ GeV}/c$		momentum	$> 3 \text{ GeV}/c$
	p_T	$> 1.2 \text{ GeV}/c$		p_T	$> 0.4 \text{ GeV}/c$
				IP/σ_{IP}	> 3.7

Table 3.1: Selection cuts for : a) the opposite side lepton ; and b) for the opposite side kaon.

where Δm is the difference between the mass of the $B_s^0 K$ combination and the mass of the reconstructed B_s^0 . The momentum and p_T are respectively required to be greater than $4 \text{ GeV}/c$ and $0.4 \text{ GeV}/c$. For a B^0 study, the same side pion (see fig. 3.3) with a different set of cuts, not discussed here are used.

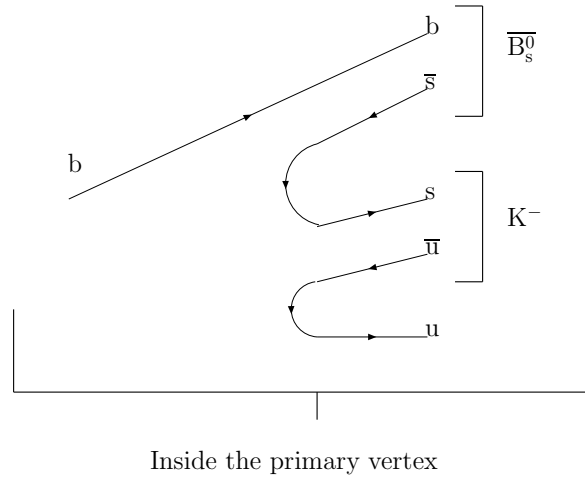


Figure 3.2: Creation of the same side kaon

The cuts shown before are listed in the table 3.2.

3.1.3 Effective tagging efficiency

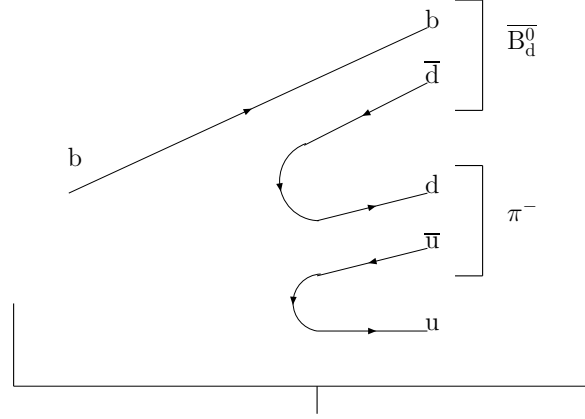
This tagging procedure gives information on the initial flavour of our signal B meson. But this flavour tagging is not perfect, and can give false information, or no information at all. We define three quantities :

- the tagging efficiency :

$$\epsilon_{\text{tag}} = \frac{R + W}{R + W + U}, \quad (3.1)$$

- the fraction of mistag events :

$$\omega = \frac{W}{R + W} \quad (3.2)$$



Inside the primary vertex

Figure 3.3: Creation of the same side pion

cut	value
IP/σ_{IP}	< 2.5
$ \Delta\eta $	< 1
$ \Delta\phi $	< 1.1
Δm	$< 1.5 \text{ GeV}/c^2$
momentum	$> 4 \text{ GeV}/c$
p_T	$> 0.4 \text{ GeV}/c$

Table 3.2: Selection cuts for the same side kaon.

- and finally, the effective tagging efficiency :

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}(1 - 2\omega)^2 = \varepsilon_{\text{tag}}D^2 \quad (3.3)$$

Here, R is the number of correctly tagged events, W is the number of incorrectly tagged events, and U is the number of untagged events. $D = 1 - 2\omega$ is called the dilution. The measured asymmetry is proportional to it.

The mistag has to be the lowest as possible and the efficiency and effective tagging efficiency have to be the greatest as possible. The tagging power appears in the statistical uncertainty on the measured CP asymmetries. The measured asymmetry is related to the real asymmetry taking into account the mistag.

To see this, let R_m be the measured decay rate of $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ and $\overline{R}_m$ its conjugate. Let also R be the theoretical decay rate for the same channel. We have :

$$R_m(t) = (1 - \omega)R(t) + \omega\overline{R}(t) \quad (3.4)$$

$$\overline{R}_m(t) = \omega R(t) + (1 - \omega)\overline{R}(t) \quad (3.5)$$

Let the measured asymmetry as a function of the true asymmetry be given by :

$$\mathcal{A}_m = \frac{\overline{R}_m(t) - R_m(t)}{\overline{R}_m(t) + R_m(t)} = (1 - 2\omega) \frac{\overline{R}(t) - R(t)}{\overline{R}(t) + R(t)} = (1 - 2\omega)\mathcal{A} \quad (3.6)$$

The statistical error on the measured asymmetry is given by :

$$\mathcal{A} = \frac{\mathcal{A}_m}{1 - 2\omega} \Rightarrow \sigma_{\mathcal{A}} = \frac{\sigma_{\mathcal{A}_m}}{1 - 2\omega} \quad (3.7)$$

We can easily see that $1 - \mathcal{A}_m^2 = \frac{4R_m \overline{R_m}}{(R_m + \overline{R_m})^2}$.

Using a quadratic propagation of the errors for eq. 3.6, we get :

$$\sigma_{\mathcal{A}_m}^2 = \frac{1 - \mathcal{A}_m^2}{(R_m + \overline{R_m})} = \frac{1 - \mathcal{A}_m^2}{N_m} = \frac{1 - \mathcal{A}_m^2}{\epsilon_{tag} N} \quad (3.8)$$

Where N_m is the number of tagged events, and N the total number of events.

Finally, using eq. 3.8 in eq. 3.7, we get the incertitude on the asymmetry :

$$\sigma_{\mathcal{A}} = \frac{\sqrt{1 - \mathcal{A}_m^2}}{\sqrt{N} \sqrt{\epsilon_{tag}} (1 - 2\omega)} \propto \frac{1}{\sqrt{\epsilon_{tag}} (1 - 2\omega)} \quad (3.9)$$

To minimize this incertitude, one has to maximize $\boxed{\epsilon_{tag}(1 - 2\omega)^2}$, which is the effective tagging efficiency presented before.

The three following paragraphs show how the mistag rate can be measured in real data.

3.2 Measuring the mistag rate in the real data

3.2.1 Measuring the mistag using the amplitude of the oscillations

If the final state of a B_s^0 decay is not a CP eigenstate, like in the channel $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, we have access to the *final* flavour of the b quark present in the meson. The tagging algorithm returns the *initial* flavour of the b quark. So we can tag the B_s^0 meson with a flag saying if it has mixed or not. Mathematical developments enables us to say that :

$$\frac{N_{B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu}^{\text{tag unmix}} - N_{B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu}^{\text{tag mix}}}{N_{B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu}^{\text{tag unmix}} + N_{B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu}^{\text{tag mix}}} \propto (1 - 2\omega) \cos(\Delta m_s t) \quad (3.10)$$

$N_{B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu}^{\text{tag unmix}}$ is the number of events were the B_s^0 has been identified has NOT having oscillated, $N_{B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu}^{\text{tag mix}}$ is the number of events were the B_s^0 has been identified has having oscillated. So fitting the oscillation of the B_s^0 mesons gives us access to the mistag rate. Δm_s is the parameter presented in the motivation chapter, and t is the proper time of the B_s^0 candidate.

Taking into account the proper time resolution (σ_t), it can been shown that the error on the measured amplitude (and the total mistag rate) is given [11] by :

$$\sigma_{\text{amposcill}} \propto \frac{1}{\sqrt{N} e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2}} \quad (3.11)$$

To work, this method requires an excellent proper time resolution, in order to resolve the fast B_s^0 oscillations.

3.2.2 Measuring the opposite side mistag

The opposite side mistag can be very simply determined using a self-tagged channel like $B^+ \rightarrow J/\psi K^+$. Its initial flavour is determined using the opposite side tagging algorithm and it is compared to the sign of the reconstructed B. It is then possible to calculate the mistag rate of the opposite side tagging, using the formula 3.2, as the number of uncorrectly tagged and correctly tagged events is known. The B^0 channels with a flavour specific final state can also be used, because even if this meson oscillates in 17% of the cases, this oscillation is really well known, and the amplitude of the oscillation method can be used to extract the opposite side mistag rate. Among others, the channel with the highest statistics available for the opposite side measurement are $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$, $B^+ \rightarrow \bar{D}^0 \mu^+ \nu_\mu$, $B^+ \rightarrow J/\psi K^+$, etc.

3.2.3 Measuring the same side mistag with the double tagging method

This method [12] is based upon a sample of B_s^0 mesons with both same side and opposite side taggers available.

Let t_{OS} and t_{SS} be two flavour taggers of opposite side and same side (i.e. Kaons, muons, electrons, etc.), with ω_{OS} and ω_{SS} the corresponding mistag rates, and ε_{OS} and ε_{SS} the tagging efficiencies. As said before (in previous section) the quantity ω_{OS} is supposed to be known, and ω_{SS} has to be measured. Let N_T the total number of events of a B_s^0 sample. If the two taggers are uncorrelated, the total number of events which are double tagged is given by :

$$N_{DT} = \varepsilon_{OS} \times \varepsilon_{SS} \times N_T \quad (3.12)$$

The number of events where the two taggers gave the same answer is given by N_{AGREE} and the fraction F , given by N_{AGREE}/N_{DT} , is the probability that the taggers agree :

$$F = P(t_{OS}^R) P(t_{SS}^R) + P(t_{OS}^W) P(t_{SS}^W) \quad (3.13)$$

where $P(t_{OS(SS)}^{R(W)})$ is the probability that $t_{OS}(t_{SS})$ is right (wrong). We can also express this in terms of the mistag rates :

$$F = (1 - \omega_{OS})(1 - \omega_{SS}) + \omega_{OS}\omega_{SS} \quad (3.14)$$

and then :

$$\omega_{SS} = \frac{1 - \omega_{OS} - F}{1 - 2\omega_{OS}} \quad (3.15)$$

with the error, $\sigma(\omega_{SS})$, given by :

$$\sigma(\omega_{SS})^2 = \frac{(1 - 2F)^2}{(1 - 2\omega_{OS})^4} \sigma(\omega_{OS})^2 + \frac{1}{(1 - 2\omega_{OS})^2} \frac{F(1 - F)}{N_{DT}} \quad (3.16)$$

where $\sigma(\omega_{OS})$ is the error on the opposite side mistag.

To get the best error on the same side kaon mistag, one needs :

- the highest possible B_s^0 sample to increase N_{DT} ,

- the smallest error on the opposite side mistag, which can be determined from B^0 or B^+ decays to flavour specific final states as explained in previous section.

The first bullet is the reason why we investigate $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ in this report.

In the next chapter, we discuss the selection of this channel, and show that we have a very high number of events per year.

Chapter 4

Selection of $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$

The $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel is potentially interesting [13] because of its relatively high branching ratio [17] ($BR^{vis} = 4.3 \times 10^{-3}$). It was not yet studied as an interesting physics channel because of the missing neutrino, which introduces bias in the measurement of the momentum and the measured mass.

In this chapter, we discuss the selection of this channel. We explain in the details the cuts, the selection results with an emphasis on the proper time resolution which is important for tagging, as explained in chapter 3. We also study the background, with some ideas of solutions to reduce it.

4.1 Monte Carlo simulation and expected $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ production

This analysis and selection has been made on Monte Carlo events, generated using PYTHIA. The tracks are then propagated through the detector using GEANT4 and a full reconstruction program.

Instead of using exclusive $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, we have generated a cocktail of 496 k events, using the branching fractions indicated in the table below. When present, the τ are forced to decay to $\mu \nu_\mu \nu_\tau$.

Decay	BR
$B_s^0 \rightarrow D_s^* \rightarrow \pi^0 D_s \mu$	0.0490
$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	0.0210
$B_s^0 \rightarrow D_{s0}^* \mu, D_{s0}^* \rightarrow \pi^0 D_s^* \rightarrow \pi^0 D_s$ and $B_s^0 \rightarrow D_{s1}' \mu, D_{s1}' \rightarrow \gamma D_s^* \rightarrow \pi^0 D_s$	0.0080
$B_s^0 \rightarrow D_{s(0,1)}^{(*,')} \tau \nu_\tau$	0.00477
$D_s^- \Rightarrow K^+ K^- \pi^-$	0.048712

We have created this cocktail because :

- it is closer to reality,
- taking into account the channel $B_s^0 \rightarrow D_s^* \mu \nu_\mu$ potentially increases the number of B_s^0 for the double tagging.

The expected number of $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ produced by year in LHCb is approximately 810 million, using the numbers above. This important result is obtained using the next formula :

$$S = L_{int} \times \sigma_{b\bar{b}} \times 2 \times f_{B_s^0} \times BR_{vis} \quad (4.1)$$

Here, L_{int} is the integrated luminosity over one year, given by :

$$L_{int} = 2 \text{ fb}^{-1} \quad (10^7 \text{ s at } L_{\text{instantaneous}} = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}) \quad (4.2)$$

$\sigma_{b\bar{b}}$ is the cross section of production of the $b\bar{b}$ pair at 14 TeV, equal to $500 \mu\text{b}$; the factor 2 represents the fact that we have two b quarks to compose the particle we want ; $f_{B_s^0}$ is the the fraction of weakly decaying B_s^0 mesons, equal to 10% ; BR_{vis} is the total branching ratio, equal to :

$$BR(B_s^0 \Rightarrow D_s^- \mu^+ \nu_\mu) \times BR(D_s^- \Rightarrow K^+ K^- \pi^-) = 8.277\% \times 4.871\% = 4.031 \times 10^{-3} \quad (4.3)$$

For the background study described in section 4.3.4, we used 33 million inclusive $b\bar{b}$ events, which is considered as the main source of background.

4.2 Choice of selection cuts

The reconstruction is done in two steps, as in this decay we have two particles, a D_s and a μ , that we have to reconstruct. The decay is represented with the diagram 4.1, and its topology is represented in fig. 4.2. Both B_s^0 and D_s mesons fly, leading to a geometry with 3 vertexes.

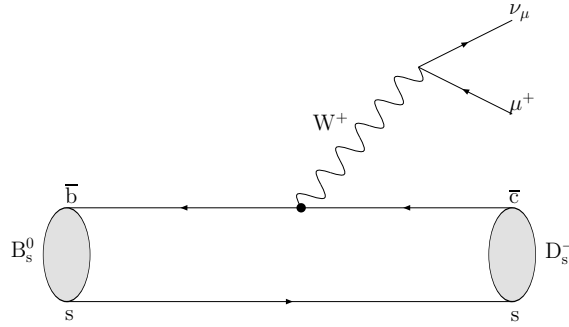


Figure 4.1: Feynman diagram of the decay $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$.

The following cuts have been optimized to get the best ratio B/S following [13, 14].

Selection of the muon

As the number of muons per event is expected to be lower than the number of $D_s^\mp$, the selection starts with the selection of the muon. By this mean, the analysis time is reduced as all the events are not necessarily processed.

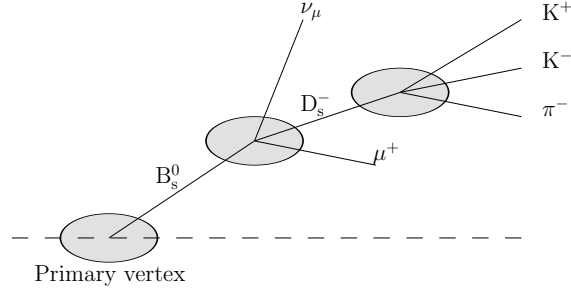


Figure 4.2: Topology of the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel.

To select the muons corresponding to our channel, we apply the standard cut for LHCb on the $\Delta \ln \mathcal{L}_{\mu\pi}$ (fig. 4.3), $\Delta \ln \mathcal{L}_{\mu K}$, and $\Delta \ln \mathcal{L}_{\mu p}$, requiring that they are strictly positive.

The muon is required to have a transverse momentum greater than 1 GeV/c to ensure that it comes from a B meson and not from an other light decay. To check that it does not come from the primary vertex, it has to have an impact parameter significance greater than 3 with respect to all the primary vertices.

The cuts are summarized in table 4.1.

If a muon is found in the event, a tentative of reconstruction of the $D_s^\mp$ is performed.

Reconstruction of the $D_s^\mp$

For simplicity, only inclusive decays $D_s^\mp \Rightarrow K^+ K^- \pi^-$ are reconstructed, this means that only the initial state ($D_s^\mp$) is searched, and not the intermediate resonances like ϕ or K^{*0} . The kaons and the pion have to be selected. This goal needs a good identification of the kaons, which is done with the RICH detectors. The $\Delta \ln \mathcal{L}_{K\pi}$ has to be greater than 0 for both kaons and less than 0 for the pion (fig. 4.4). This is a standard cut in LHCb.

The kaons and pion have to have a transverse momentum (p_T) greater than 500 MeV/c, which is to get the best chance of having the kaons and the pion coming from a D decay, and not from the primary vertex or from an other decay. To reduce even more the number of particles coming from the primary vertex, a cut is performed on the impact parameter significance with respect to the primary vertices, asked to be greater than 3.

Then the reconstruction process vertexes the three tracks, which mean that it looks at the space origin of the tracks, and see if the tracks come from the same space point. This is done with a cut on the vertex χ^2 , which represents the reliability of the vertexing. It has to be less than 10 (see fig. 4.5), which is not standard in LHCb as the standard is less than 30.

Then, the invariant mass of the $K^+ K^- \pi^-$ is required to be inside a window 20 MeV/c² wide around the nominal D_s mass of 1969 MeV/c² (fig.4.6). The D_s mass resolution is 5.2 MeV/c².

Finally, the reconstructed D_s is required to have a transverse momentum greater than 1.5 GeV/c, to ensure that this meson really comes from a B meson and not from the primary vertex.

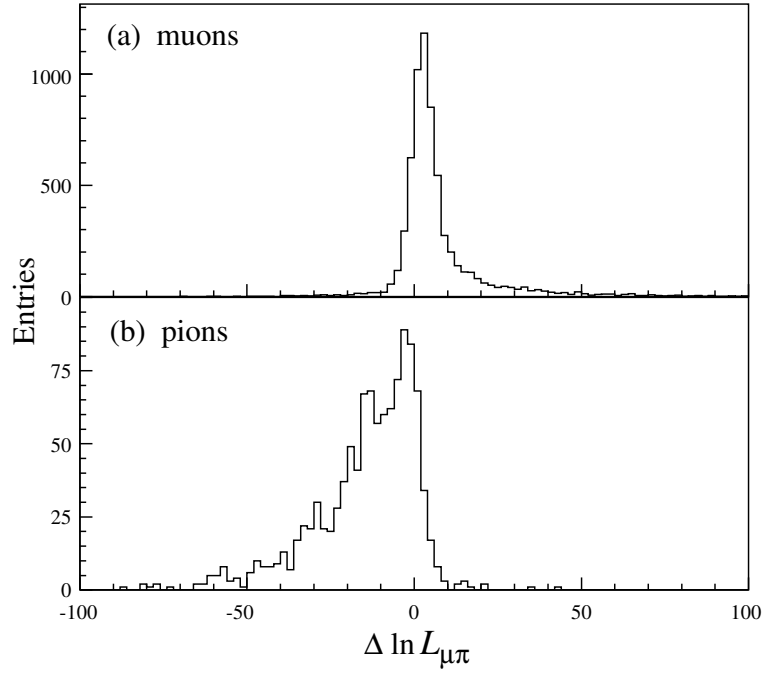


Figure 4.3: Separation criteria between muons and pions. It is represented using a $\Delta \ln \mathcal{L}_{\mu\pi}$. The distribution for $\Delta \ln \mathcal{L}_{\mu K}$ and $\Delta \ln \mathcal{L}_{\mu p}$ are similar.

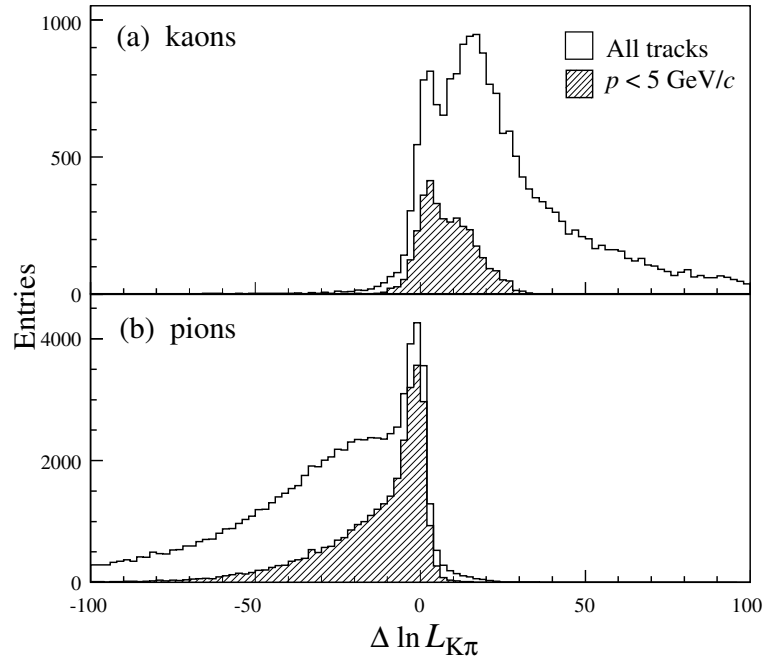


Figure 4.4: $\Delta \ln \mathcal{L}_{K\pi}$ for two different momentum.

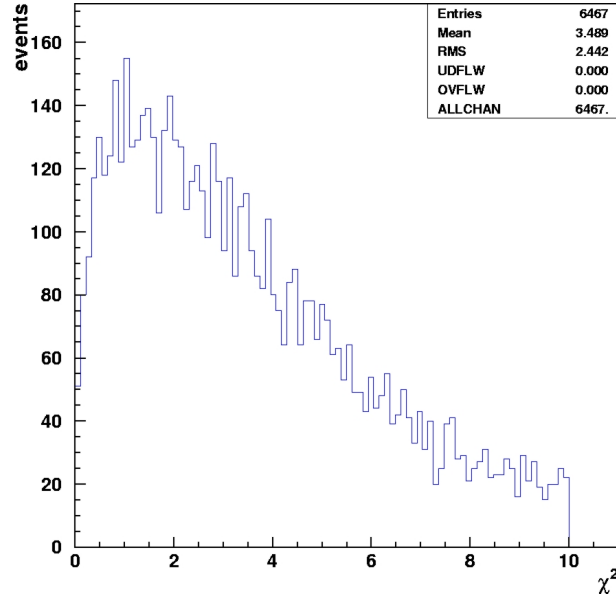


Figure 4.5: $K^+K^-\pi^-$ vertex χ^2

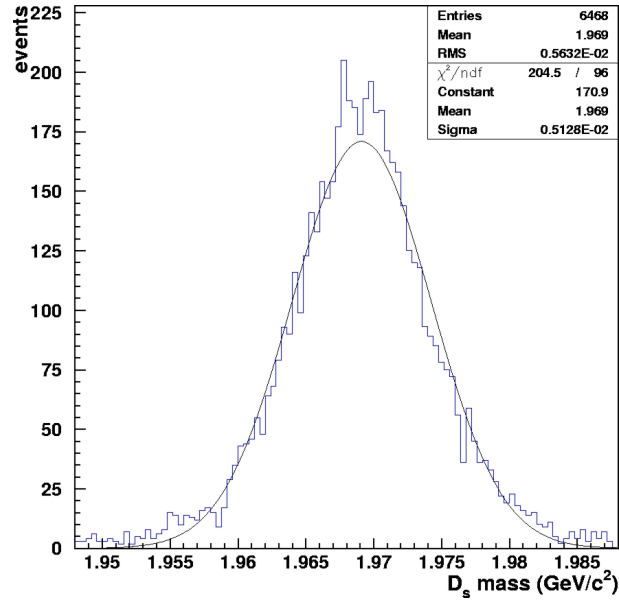


Figure 4.6: Reconstructed $K^+K^-\pi^-$ invariant mass in GeV/c^2 . The resolution is $5.12 \text{ MeV}/c^2$.

A summary of the cuts can be found in table 4.2.

Reconstruction of the B_s^0

When vertexing the muon and the reconstructed D_s , the vertex χ^2 is required to be smaller than 10 (see fig. 4.7). The vertex has to have a good precision on the position, as it is necessary to have the best resolution on the end-vertex to measure the lifetime of the reconstructed B_s^0 . More over, the space separation between the $D_s\mu$ vertex and the D_s end-vertex has to be greater than 1 mm, to limitate the number of muons coming from the decay chain of the charmed meson.

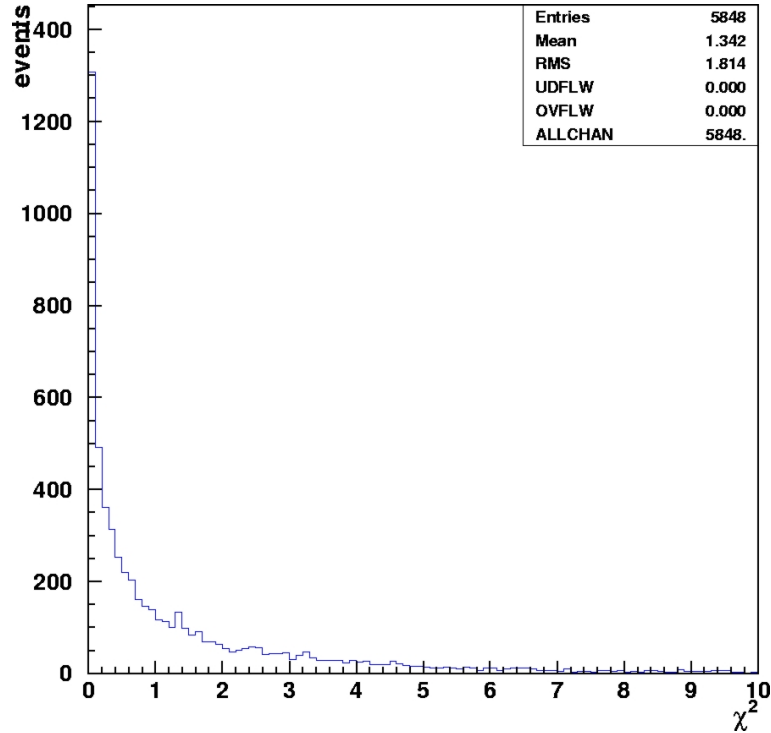


Figure 4.7: Vertex χ^2 of the $D_s\mu$ pair.

It is also required that the cosine of the angle between the direction of the momentum and the straight line between the primary vertex and the $D_s\mu$ vertex is greater than 0.999. This cut is used to have the best orientation of the B , and to have also a control on the momentum taken by the neutrino (see fig. 4.8).

The last cut is on the reconstructed B_s^0 mass. The neutrino is estimated to take about 20% of the B_s^0 momentum. This is why the reconstructed B_s^0 has to have a mass between $3 \text{ GeV}/c^2$ and $5.4 \text{ GeV}/c^2$ (see fig. 4.9).

After this set of cuts, figure 4.11 shows that the number of reconstructed B_s^0 is not 1 ; mainly because an error can occur when associating the muons and the D_s ¹. This problem could be solved by selecting only the B_s^0 with the lowest vertex χ^2 , or the lowest impact parameter significance.

¹It can happen that there are two $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ in the event, but it is rare ($\text{BR}=1.85 \times 10^{-5}$).

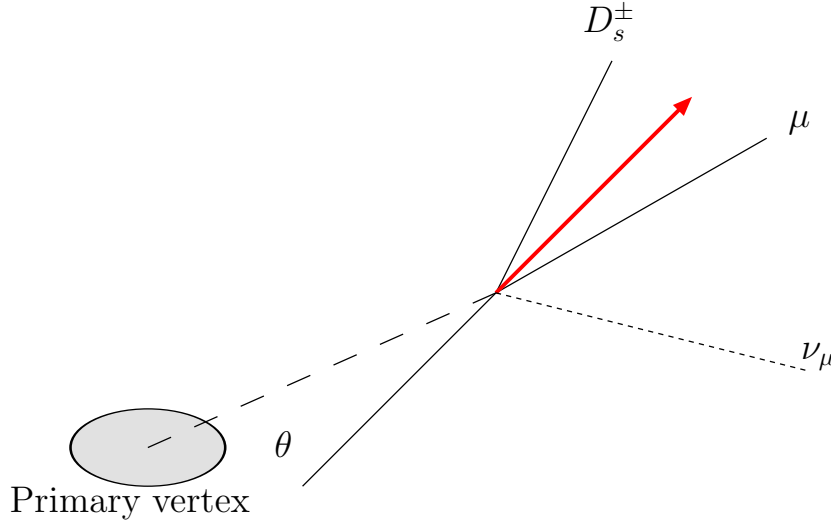


Figure 4.8: Visualization of angle between the $D_s\mu$ momentum (arrow) and the straight line between the primary vertex and the $D_s\mu$ vertex

The cuts described here are summarized in table 4.3.

The total efficiency of the reconstruction is discussed in the next paragraph.

4.3 Selection results

The number of generated signal events was 496000. On these, 4913 events were selected, corresponding to a selection efficiency of $0.99 \pm 0.01\%$. This efficiency is without trigger. Considering the trigger, after L0, L1, and HLT, 1686 events are selected, corresponding to an efficiency of $0.34 \pm 0.01\%$. The respective efficiency for the trigger levels are :

- Events passing L0 : $84.1 \pm 0.5\%$
- Events passing L1 after L0 : $81.6 \pm 0.6\%$
- Events passing HLT after L0 and L1 : $50.0 \pm 0.9\%$

4.3.1 Annual yield

The total efficiency is given by :

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{accep}} \times \varepsilon_{\text{effisel}} \quad (4.4)$$

where $\varepsilon_{\text{accep}}$ is the acceptance² efficiency, equal here to 0.3471, and $\varepsilon_{\text{effisel}}$ is the total selection efficiency, including reconstruction and trigger efficiency. In our case, as 1686 events

²Probability to have at least one b-hadron in a cone of 400 mrad with respect to the beam axis.

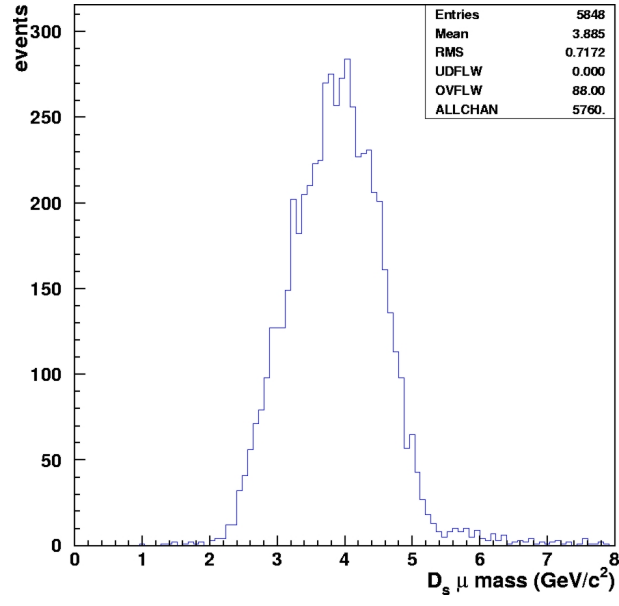


Figure 4.9: $D_s\mu$ invariant mass in GeV/c^2

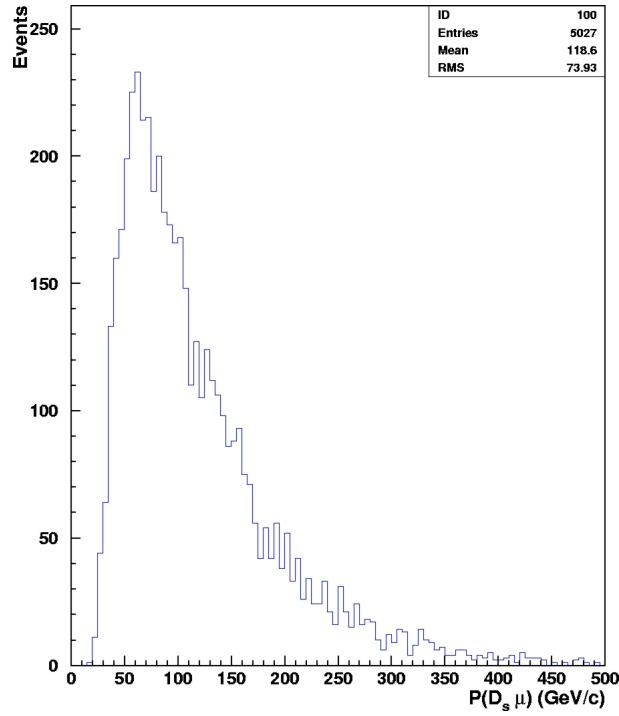


Figure 4.10: $D_s\mu$ momentum in GeV/c

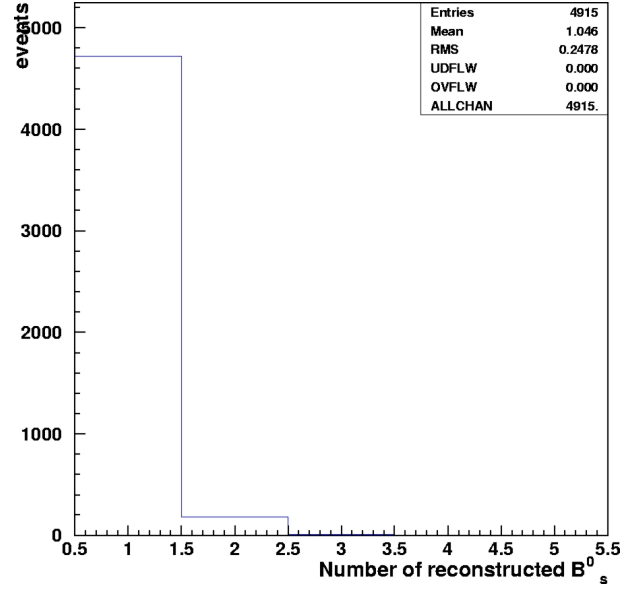


Figure 4.11: Number of reconstructed $D_s\mu$ in signal sample. The mean value is 1.046.

cut	value
$\Delta \ln \mathcal{L}_{\mu\pi}$	> 0
$\Delta \ln \mathcal{L}_{\mu K}$	> 0
$\Delta \ln \mathcal{L}_{\mu p}$	> 0
$p_{T\mu}$	$> 1 \text{ GeV}/c$
Impact parameter	> 3

Table 4.1: Cuts applied for the selection of the muons

cut	value
$\Delta \ln \mathcal{L}_{K\pi}$	> 0
$\Delta \ln \mathcal{L}_{Kp}$	> -3
$\Delta \ln \mathcal{L}_{K\mu}$	> 0
$p_{TK-\pi}$	$> 500 \text{ MeV}/c$
Impact parameter	> 3
vertex χ^2	< 10
D_s mass window	$\pm 20 \text{ MeV}/c^2$
p_{TD_s}	$> 1.5 \text{ GeV}/c$

Table 4.2: Cuts applied for the selection of the D_s

were triggered ($L0 \times L1 \times HLT$) and selected over 496000 signal events, the total efficiency is given by :

$$\varepsilon_{\text{tot}} = 0.3471 \times \frac{1686}{496000} = 11.5 \times 10^{-4} \quad (4.5)$$

The calculation of the annual yield also uses the total visible branching ratios, which are measured in previous experiments [16, 17], different from the numbers used in the beginning of this chapter, as in the generation, these numbers were not available. The total visible branching ratio is then given by :

$$\begin{aligned} \text{BR}(B_s^0 \Rightarrow D_s^- \mu^+ \nu_\mu) \times \text{BR}(D_s^- \Rightarrow K^+ K^- \pi^-) &= 8.277\% \times 5.2\% \\ &= 4.3 \times 10^{-3} \end{aligned} \quad (4.6)$$

Here, $\text{BR}(B_s^0 \Rightarrow D_s^- \mu^+ \nu_\mu)$ is the total visible branching ratio for the cocktail of signal events.

Finally, the annual yield is given by :

$$S = L_{\text{int}} \times \sigma_{b\bar{b}} \times 2 \times f_{B_s^0} \times \text{BR}_{\text{vis}} \times \varepsilon_{\text{tot}} \quad (4.7)$$

ε_{tot} is the total efficiency, the other numbers have been introduced in the begining of this chapter.

With the numbers, the expected annual yield is :

$$S = 2 \text{ fb}^{-1} \times 500 \mu\text{b} \times 2 \times 10\% \times 4.3 \cdot 10^{-3} \times 11.5 \cdot 10^{-4} = 989929 \quad (4.8)$$

So as a conclusion, 990 k events are expected per years, which places this channel at the first place as source of reconstructed B_s^0 .

Figure 4.12 shows the ratio between the reconstructed B momentum and the true B momentum. The mean value is 0.78, and not 1. This is due to the missing neutrino in the reconstruction, which takes in average 22% of the momentum.

4.3.2 B momentum correction

To take into account the missing neutrino, in the B_s^0 reconstruction, a correcting term is added to its momentum. Instead of adding simply 22%, the correcting term is a function of the $D_s \mu$ invariant mass. Indeed the higher the $D_s \mu$ mass is and the lower the contribution of the neutrino is. For this, the correlation between the ratio (reconstructed B momentum) / (true B momentum) and the $D_s \mu$ invariant mass is plotted (fig.4.13). A fit of the distribution with a second degree polynome (f) depending on the $D_s \mu$ mass is then performed. The difference at high $D_s \mu$ invariant mass is understood as beeing a result of the reconstruction of the D_s . The explanation can be found in Appendix A

$$\begin{cases} p_{B_s^0}^{\text{reco notcorrected}} = p_{D_s \mu} \\ p_{B_s^0}^{\text{reco corrected}} = \frac{p_{D_s \mu}}{f(M_{D_s \mu})} \end{cases} \quad (4.9)$$

The second relation above is applied, giving the plot 4.14. As expected the momentum resolution $(15.4\%)^3$ is smaller than channels without neutrinos, like $B_s^0 \rightarrow D_s^- \pi^+$ [8].

³This resolution is similar for the exculsive channels $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ and $B_s^0 \rightarrow D_s^* \mu \nu_\mu$.

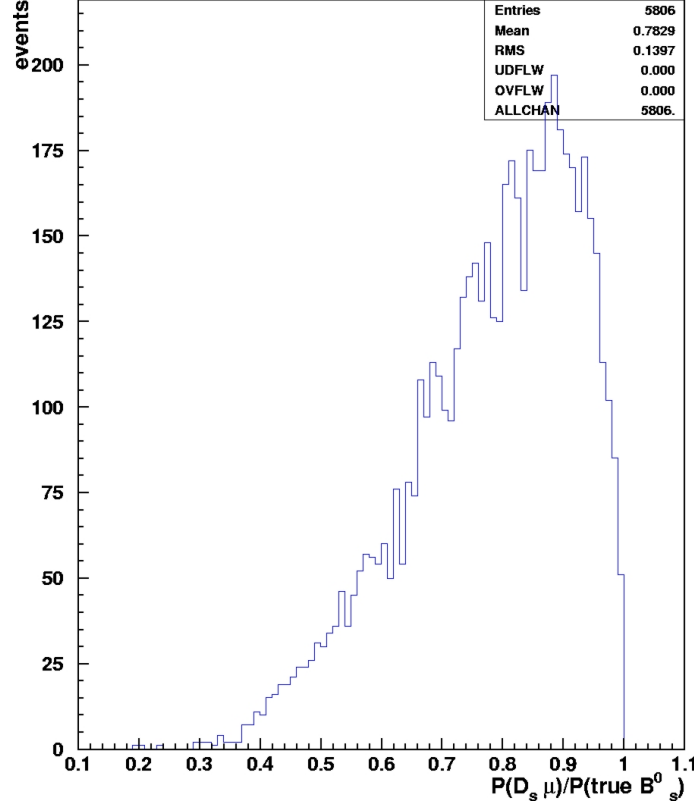


Figure 4.12: Ratio between the reconstructed B momentum and the true B momentum. The mean value is lower than 1 due to the missing neutrino.

4.3.3 Resolution on reconstructed information

Figure 4.15 represents the correlation between the absolute value of the reconstructed angle ϕ (geometrical angle with respect to the beam axis, not the ϕ_s angle) and the absolute value of the true angle ϕ . The correlation is good, and it shows that this angle can be used as a cut in the selection of the same side kaon (see chapter 3). Fig. 4.16 shows the correlation between the reconstructed pseudo-rapidity η^4 and the true η . Here again, the correlation is good, and so it is possible to use the same side kaon. The fig. 4.17 shows the resolution of η and ϕ indicating that the resolutions are good.

One of the most important information about the reconstructed B is the time of flight, as it is used to determine the oscillation frequency, and is used in the measurement of the amplitude of the oscillations. It is calculated using the decay length (resolution on plot 4.18), the reconstructed and corrected momentum, and the mass. In the detector frame, the relation is :

$$t^{\text{reco}} = \frac{\ell m}{p^{\text{reco}} c} \quad (4.10)$$

ℓ stands for the flight distance, p^{reco} stands for the reconstructed and corrected momentum, c is the speed of light in a vacuum, and m is the B_s^0 meson's mass, equal to $5.370 \text{ GeV}/c^2$.

⁴ $\eta = -\ln \tan \frac{\theta}{2}$

cut	value
vertex χ^2	< 5
$V_z(D_s) - V_z(D_s\mu)$	$> 1 \text{ mm}$
$\cos \theta$	> 0.999
B_s^0 mass window	$3 \text{ GeV}/c^2 < m(B_s^0) < 5.4 \text{ GeV}/c^2$

Table 4.3: Cuts applied for the selection of the B_s^0 . V_z is the position on the z axis of the vertex of the argument, and θ is the angle described in figure 4.8. The mass window is not centered on the B_s^0 nominal mass because of the missing neutrino.

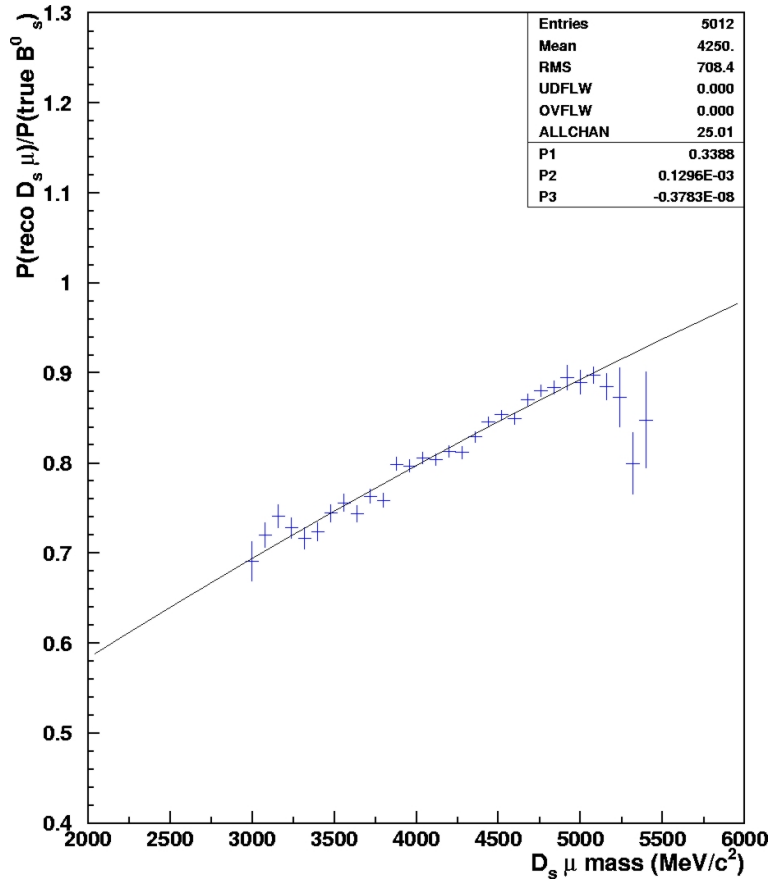


Figure 4.13: Correlation plot between the ratio (reconstructed B momentum) / (true B momentum) and the $D_s \mu$ invariant mass. The black line is the result of a fit with a second degree polynomial. The parameters are in the lower box.

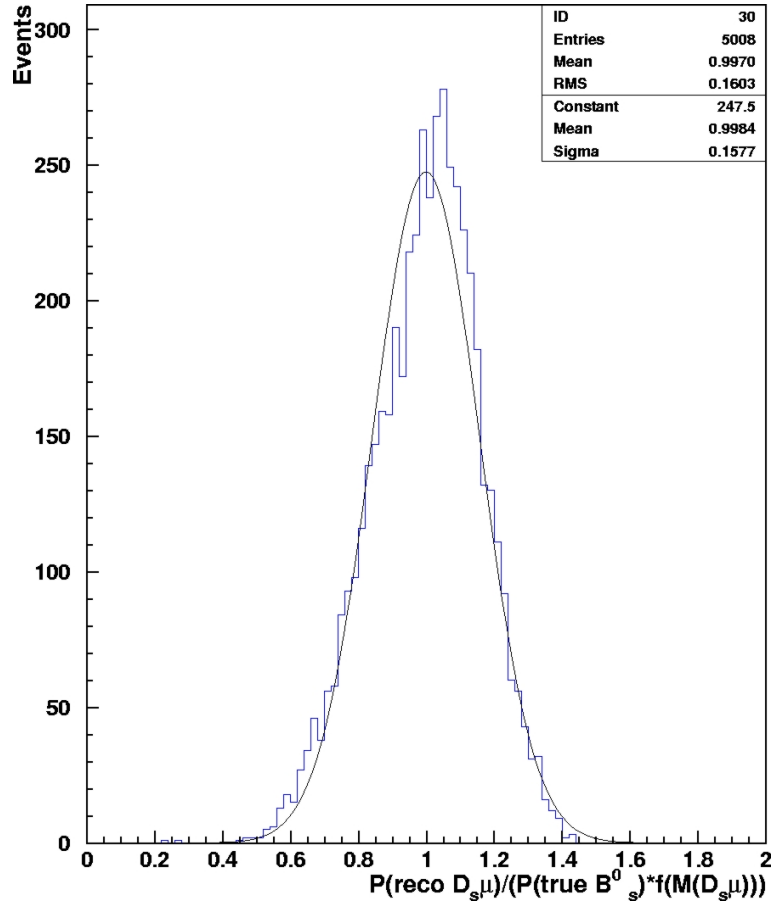


Figure 4.14: Corrected B_s^0 momentum with the correlation function presented in fig. 4.13. The black line is a fit with a simple Gaussian. The resolution is 15.4%.

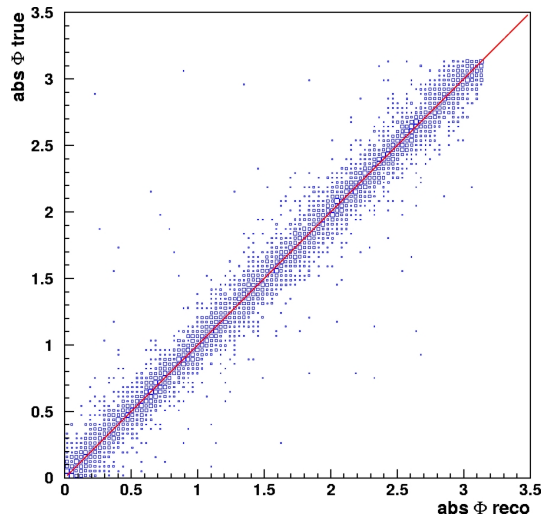


Figure 4.15: Reconstructed versus true ϕ angle of the signal B.

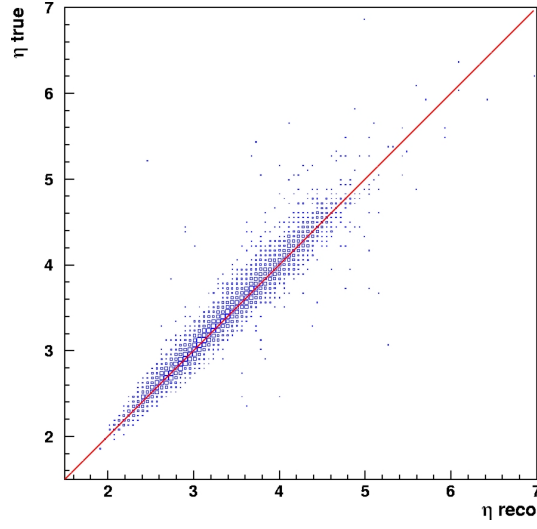


Figure 4.16: Reconstructed versus true pseudo-rapidity η of the signal B.

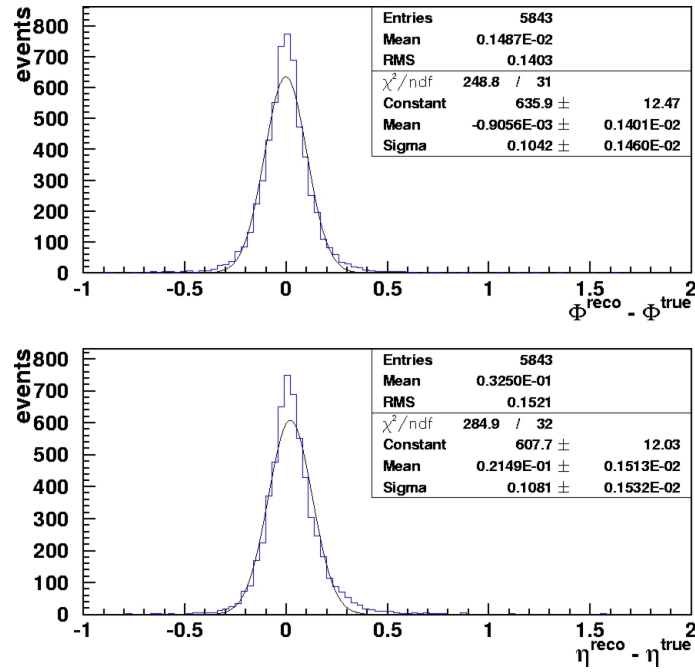


Figure 4.17: Resolution on ϕ and η of the signal B.

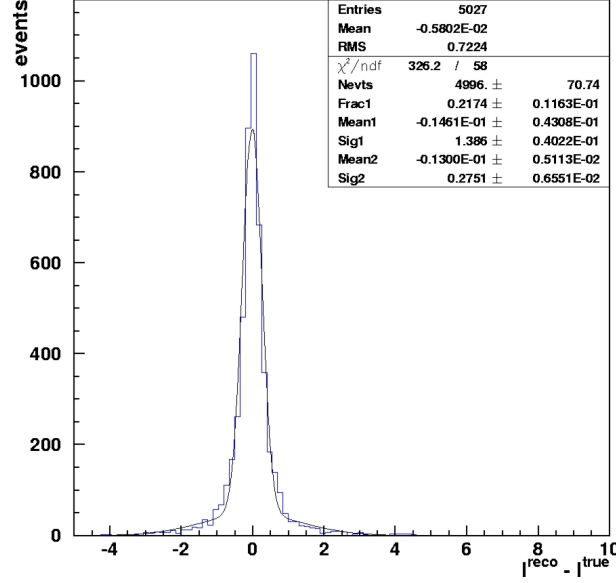


Figure 4.18: Difference between the reconstucted decay length and the true decay length. The mean value is $-5.8 \pm 10 \mu\text{m}$, compatible with 0.

The plot 4.19 is a result of this formula, applied to the data. The mean lifetime is $1.68 \pm 0.03 \text{ ps}$.

The true B decay length resolution is represented on fig. 4.20. The resolution is approximately three times worse than $B_s^0 \rightarrow D_s^- \pi^+$ [8]. This is due to the neutrino. This result is important because it indicates that the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel, with the selection cuts we used, is not competitive with $B_s^0 \rightarrow D_s^- \pi^+$ to extract the mistag from oscillation amplitude fit.

The annual yield of $B_s^0 \rightarrow D_s^- \pi^+$ is approximately 100 k events with an error on the mean lifetime of $\langle \sigma_t \rangle = 50 \text{ fs}$ [20] while the yield of $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ with our selection is approximately 1 million events per year (i.e. $10 \times$ more) with an error on the B_s^0 mean lifetime of $\langle \sigma_t \rangle = 170 \text{ fs}$. From these and eq. 3.11, the expected statistical uncertainty on the total mistag obtained from a fit of the oscillation amplitude (see section 3.2.1) can be estimated. The statistical error on the mistag using $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ is :

$$\frac{\sqrt{10} e^{-\frac{1}{2}(\sigma_t^{B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu} \Delta m_s)^2}}{e^{-\frac{1}{2}(\sigma_t^{B_s^0 \rightarrow D_s^- \pi^+} \Delta m_s)^2}} = 25 \text{ times higher than } B_s^0 \rightarrow D_s^- \pi^+. \quad (4.11)$$

From this naive comparison, we conclude that to be competitive with $B_s^0 \rightarrow D_s^- \pi^+$, the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ selection has to be improved a lot in order to select events with a better proper time resolution.

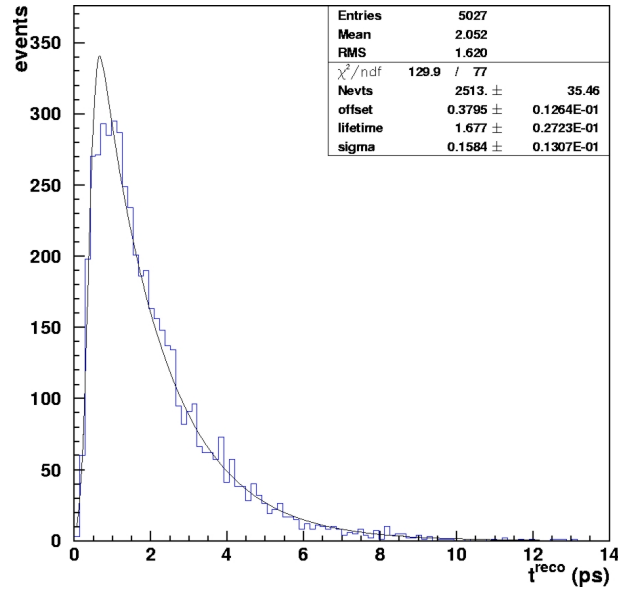


Figure 4.19: Reconstructed B_s^0 lifetime using the corrected momentum. We have the mean lifetime in the lower box, equal to 1.68 ± 0.03 ps.

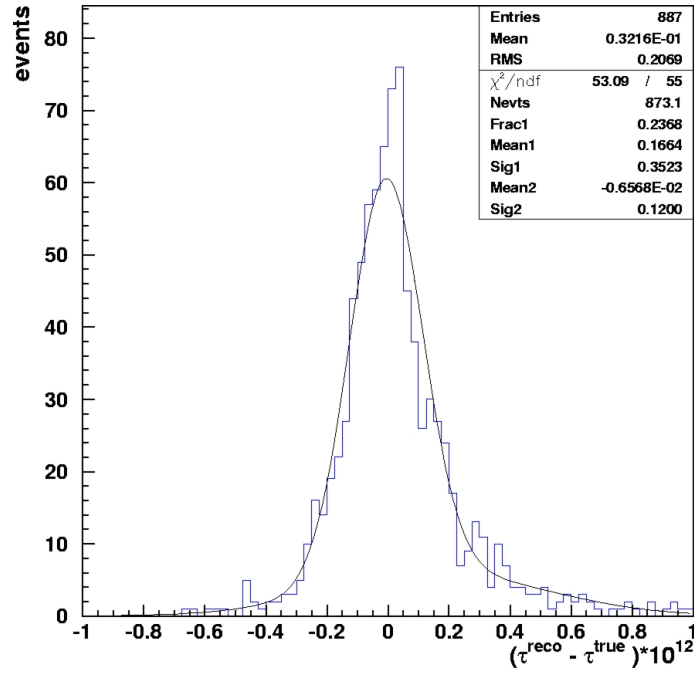


Figure 4.20: Lifetime difference between the reconstructed B and the true B meson. The black curve is a fit with two Gaussians, which parameters are available in the lower box.

4.3.4 Background study

The analysis has been done on approximately 33 million inclusive $b\bar{b}$ events⁵.

Our algorithm is ran with a loose cut of $\pm 200 \text{ MeV}/c^2$ on the D_s mass to see what kind of background contamination is present. 1241 events are kept after selection.

For the analysis, only the events where we have only one reconstructed D_s and one reconstructed muon are considered. This case is to avoid confusions because in some cases, it is possible to have two or more reconstructed D_s and more than two muons (see fig. 4.21 and fig. 4.22) which leads to more than one reconstructed B_s^0 (see fig. 4.23). This cut reduces the previous number of 1241 to 1044 events, corresponding to a loss of $15.8 \pm 1.0\%$.

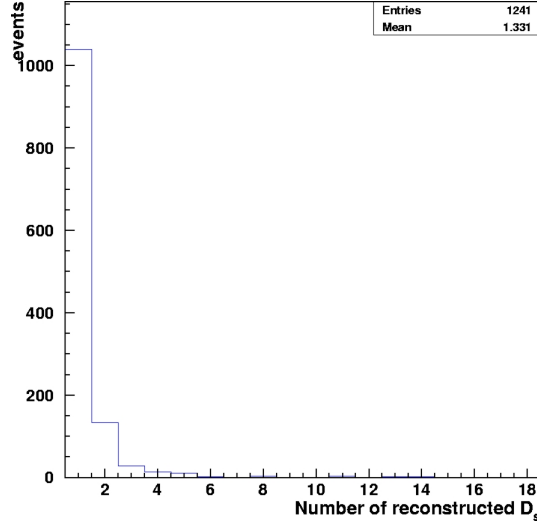


Figure 4.21: Number of reconstructed D_s per event in background sample.

The study is done in four steps : first, we check in our events the number of events where the pair composed of the reconstructed D_s and the reconstructed μ has a charge equal to 0, which is the charge of the B_s^0 ; and the number of events where the charge of the pair is not 0. The result is that our sample contains 887 event with the correct charge, corresponding to $85.0 \pm 1.1\%$ of the sample, and 157 with the wrong charge, corresponding to $15.0 \pm 1.1\%$.

To estimate the level of background, the reconstructed D_s mass for both charges is studied, giving two histograms, fig. 4.24. On the first histogram (a), there are not only some D_s , but many $D^\pm$, which are part of our background. The second histogram (b) is the combinatorial background, because it corresponds to events where we have associated a D and a μ not linked to a same $B_{(s)}^0$. The number of events in this histogram is what is expected as a combinatorial background in the first one as statistically there is the same chance to associate a D_s and a μ with the wrong charge and a D_s and a μ with the right charge.

⁵To speed up the analysis, these 33 M are reduced to 904208 events, applying preselections (i.e. a set of loose obvious cuts).

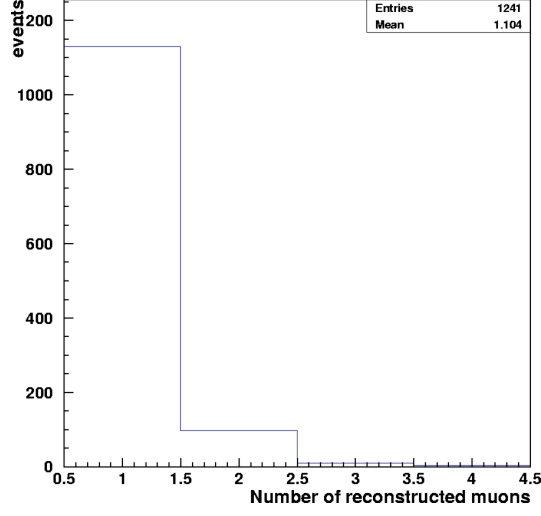


Figure 4.22: Number of reconstructed muons per events in background sample.

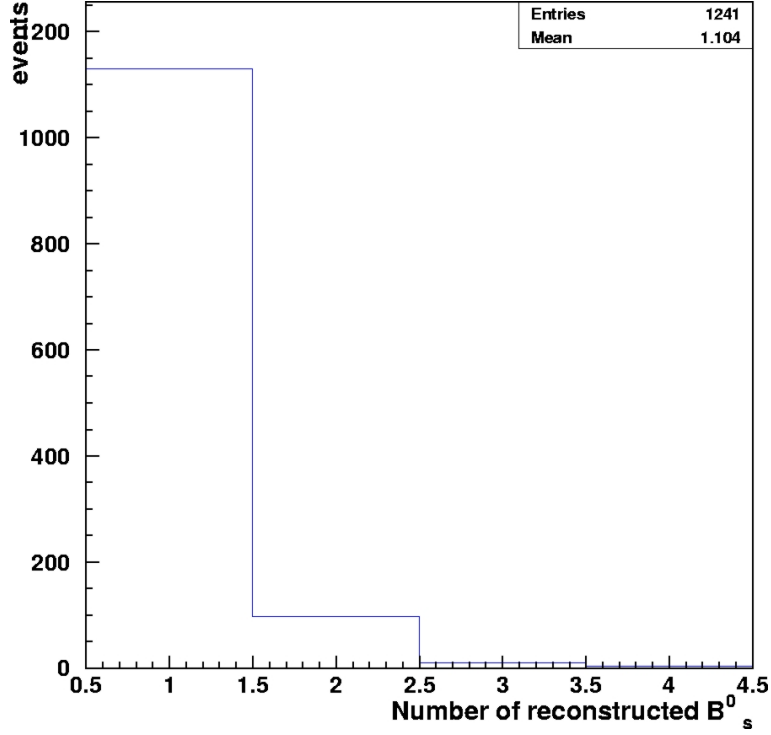


Figure 4.23: Number of reconstructed B_s^0 per event in the background sample.

The third step consist in tightening the D_s mass to have the final selection cut of $\pm 20 \text{ MeV}/c^2$ around the nominal D_s mass of $1969 \text{ MeV}/c^2$. By this mean, the number of events not interesting is reduced, and 353 events are inside the mass window for the first histogram, and 12 in the second.

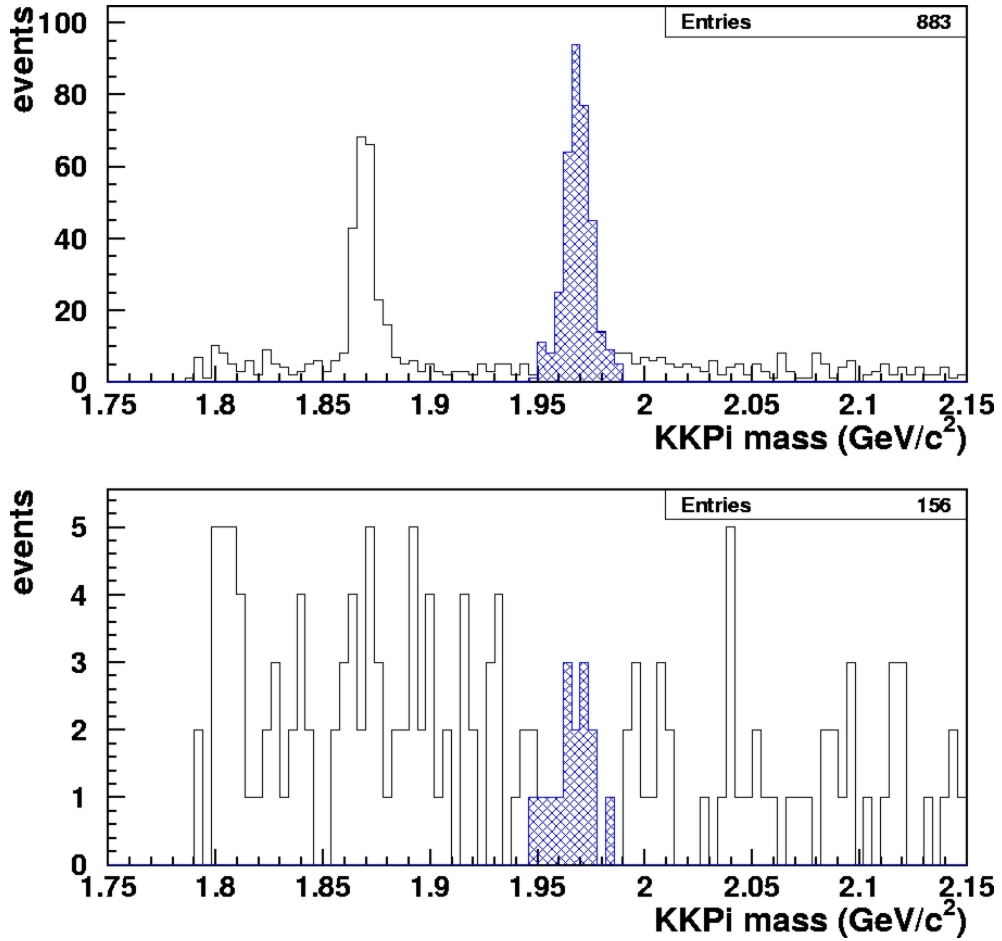


Figure 4.24: Reconstructed $K^+K^-\pi^-$ invariant mass for : a) $D_s \mu$ charge equal 0 ; b) $D_s \mu$ charge not equal 0. The first peak in plot (a) are events were the $K^+K^-\pi^-$ invariant mass is centered on the $D^\pm$ mass, and the second peak on the same plot is for a $K^+K^-\pi^-$ invariant mass centered on the D_s mass ($\text{BR}(D^- \Rightarrow K^+K^-\pi^-) = 0.0083$, $\text{BR}(D_s^- \Rightarrow K^+K^-\pi^-) = 0.048$). The shaded area correspond to events inside the final selection cut on the D_s mass. Those events are the one that will be reconstructed with the data.

The last step uses the Monte Carlo truth to check in those 353 events those which are signal events which are 229 events. Those events are the interesting events in the whole. All the numbers presented here can be found in table 4.4.

cut	number of event	efficiency
Total number of events	33×10^6	100%
Final selection	1241	$(3.8 \pm 0.1) \times 10^{-3}\%$
Number of D_s and $\mu = 1$	1044	$84.1 \pm 1.0\%$
Charge of $D_s \mu = 0$	887	$85.0 \pm 1.1\%$
D_s mass window $\pm 20 \text{ MeV}/c^2$	353	$39.7 \pm 1.6\%$
Real $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ events	229	$64.9 \pm 2.5\%$
Overall efficiency		$(6.9 \pm 0.4) \times 10^{-4}\%$

Table 4.4: Cuts and efficiencies in the background analysis. All efficiencies are calculated with respect to the previous cut, except the overall efficiency, which is the number of true $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ events on the total number of events.

The other 126 events are the background that cannot be removed with standard selection cuts, and its composition has to be known, to find new cuts to apply. In Appendix E, some typical events of background with the decay trees of the B produced in the event are displayed.

There are two ways of studying the background. The first method is analyzing it by “brute force”, which means looking at all the events one by one by hand, and try to extract the information, or the use a standard LHCb tool [15], which tells if an event is a background event and say why it is a background event. Both methods are compared here, but only a sample of 50 events in the 126 events of background will be analysed by hand.

Brute force analysis

Two main sources of background are extracted. The first one is the muon, and the second one is the D meson.

Reconstructed muon as a source of background

To study the muons with the Monte Carlo truth, an associator is used, giving to a reconstructed particle the corresponding Monte Carlo (MC) particle. This associator is based on comparison criterion's : momentum, numbers of hits left in the detector, and impact parameter with respect to the primary vertex. It's a tool one can call during the execution of the selection algorithm.

On 50 events, 2 have a muon mis-id, which means that the muon is in fact a pion. This is due to the cut on the $\Delta \ln \mathcal{L}_{\mu\pi}$, which could be tightened a bit. The other 48 events can be

separated in three main categories : 29 events come from a cascade (decay chain like $b \rightarrow c \rightarrow \mu$), 5 events have muons coming from another type of particle, like kaons or pions, and the remaining 14 events have a muon really coming from a B meson. Unfortunately only 6 events have a muon coming from the B meson considered as signal. The remaining 8 events are events where the muon come from the opposite side B meson.

To reduce the amount of event of this type, one solution to be investigated can be to put an upper limit of the impact parameter of the muon, which could have as effect to select only muons coming from the decay of the B meson and not from the decay of a charm meson. This kind of cut would remove some events, and the effect on the signal should be further studied.

Reconstructed D_s meson as a source of background

To study the charmed meson, the use of associators have been drawn aside as their efficiency on composite particles is very low. A reconstructed D_s meson is a composite particle as it is reconstructed using two kaons and a pion. So for the analysis, the true B's in the events are used, and especially their daughters.

On the 50 reconstructed D, only 36 were real D_s , the remaining were due to Kaon-Pion identification errors (6 events) and to fortuitous association of kaons and pions (8 events), where some particles coming from different particles were used, or even coming from the primary vertex.

In the 36 true D_s , 13 came really from a B_s^0 , 12 came from a B^0 , 10 came from B^+ and 1 came from a Λ_b baryon.

To reduce the number of this kind of events, it can be required that there are not many particles coming from the same space point, in that way the number of B daughters can be controlled, removing by the same time the events where we have a B giving two D mesons.

It is made clear that the main source of contamination are the events where the B meson decayed in two D mesons, with one which could give a muon, and the other could be a D_s .

Use the standard background categorization tool

This tool [15] has been developed to perform a "standard" analysis of the background in the LHCb collaboration. It uses the Monte Carlo truth to analyze the event. It looks for a true B meson which has kinematical properties near the ones of the reconstructed B, and then looks at each level of the decay chain if all the particles used match the truth. The result of this is a classification of the events, shown in fig. 4.25, page 43. Table 4.5 the correspondance between the values of the abscissa and the physical interpretation is given.

In this table, the category Signal corresponds to the events where all the decay chain used for the reconstruction matches the Monte Carlo truth.

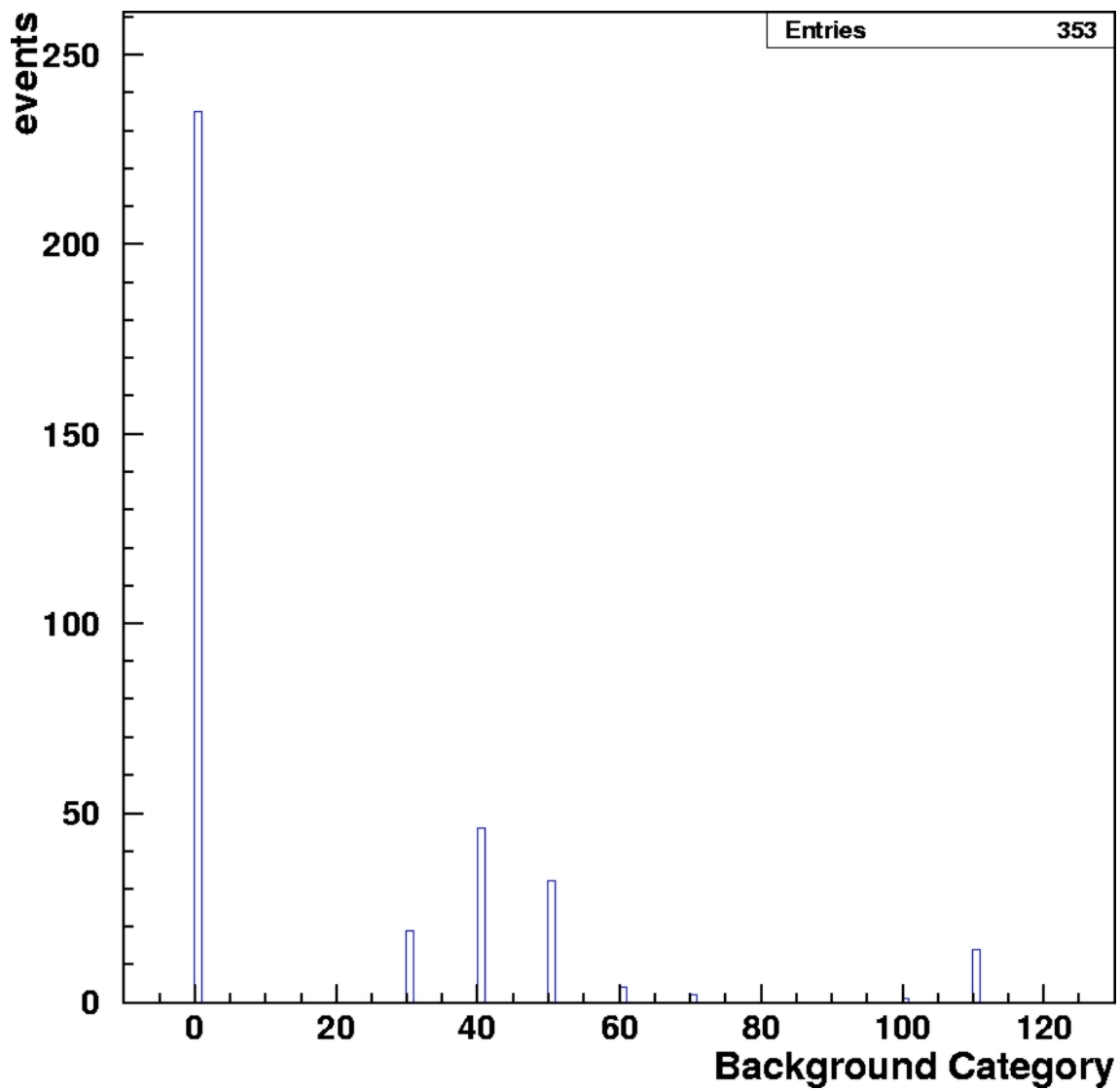


Figure 4.25: Classification of the events using the standard LHCb tool. The signification of each bins can be found in table 4.5 and in the text.

bin number	signification
0	Signal
30	Reflection
40	Partially reconstructed physics background
50	Low mass background
60	Ghost track
70	Track from Primary Vertex
100	Pile up events
110	bb events

Table 4.5: Signification of each bins of fig. 4.25.

The Reflection is when the reconstructed B is correctly reconstructed according to the Monte Carlo truth but one element of the decay chain has not been identified correctly, for example a D_s is reconstructed with two kaons and a pion, but in fact one of the kaons was a pion, but the reconstructed D_s is a real D_s .

The Partially reconstructed physics background is when a particle has been missed in the reconstruction which implied a false reconstruction of the B.

The Low mass background is the same as before, but it did not lead to a wrong B, but only a B with a lower mass.

Ghost tracks are tracks reconstructed with false hits in the detector, due to electronic noise, or due to a mis-association of the hits.

The next category represents tracks from primary vertex. This category tells us that we used tracks coming from the primary vertex.

The Pile up events are events where tracks from a pile-up event have been used.

The last category tells us that we used tracks coming from anything, but signal events.

With this analysis, we show that the main source of background is due to the fact that we missed a particle in the decay, and then we made a wrong reconstruction of the B. This might be lowered if we ask that there are not too many particles coming from the same vertex, for example when a B gives two D mesons among which there is one D_s , we could try to exclude the second D. The second category, the Low mass background, is expected as we are using an inclusive decay channel and we miss the intermediate particles in the decay for the reconstruction. The Reflection category is also expected as our selection of the kaons and the pion is not based on a tight selection cut on the $\Delta \ln \mathcal{L}_{K\pi}$.

4.3.5 Conclusion on the background study

The main source of background has been identified as events $B \rightarrow DD\bar{X}$, with a chain like $b \rightarrow c \rightarrow \mu$. These events could be removed if more severe cuts on the impact parameter of the muon were applied.

With the standard tool, we extracted the part of the events corresponding to the signal (category 0) and the part corresponding to the pure background (category different from

0).

As we have selected 126 events of background and 229 events of signal among the 33 M $b\bar{b}$ events, the bckground over signal ratio is :

$$B/S = \frac{126}{229} = 0.55 \pm 0.06 \quad (4.12)$$

This ratio can be improved for example by tightening the cuts on $\Delta \ln \mathcal{L}_{K\pi}$, to have $B/S = 0.33 \pm 0.06$, but this decreases the number of events we select by a factor 1.1.

This ratio is important, as when we estimate the mistag that will be measured in the data, the background has to be taken into account. The formula we use is :

$$\omega_{\text{tot}} = \frac{\omega_{\text{signal}} + \frac{B}{S}\omega_{\text{background}}}{1 + \frac{B}{S}} \quad (4.13)$$

where ω_{signal} is the mistag determined using a sample of signal events, and $\omega_{\text{background}}$ is the mistag mesured in a background sample, which should be compatible with 50%. This formula shows the dilution of the measured mistag in the data⁶.

4.3.6 Conclusion on tagging potentiallity of $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$

$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ events are not competitive with $B_s^0 \rightarrow D_s^- \pi^+$ to extract the mistag rates from the oscillation amplitude fit, due to the relatively bad proper time resolution. However, since we trigger and select approximately 1 million $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ events per year, this channel is very useful to improve the uncertainty on the same side mistag rate using the double tagging method, as explained in chapter 3.

The error on the same side mistag σ_{SS} can be improved from 1.4% ($B_s^0 \rightarrow D_s^- \pi^+$) to 0.5%, using the formula 3.16, assuming for an opposite side tagging efficiency of 49.4%, a same side tagging efficiency of 30.5%, an opposite side mistag of $35.4 \pm 0.02\%$ ⁷, a same side mistag rate of 33.7%, and a total number of events equal to $N_T = 1 \times 10^6$ for $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, and $N_T = 100 \times 10^3$ for $B_s^0 \rightarrow D_s^- \pi^+$.

⁶This part of the analysis has not been presented due to biases in the opposite side taggers, which gave a mistag not compatible with 50%. This has to be clarified.

⁷The error on the mistag has been estimated for 8 million self-tagged events (see section 3.2.2,[18]). We use the following formula :

$$\sigma(\omega_{OS} N_{evt}) = \sqrt{\frac{\omega_{OS} \times (1 - 2\omega_{OS})}{\varepsilon_{OS} \times N_{evt}}}$$

where ω_{OS} is the opposite side mistag.

Chapter 5

Comparison between $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, and $B_s^0 \rightarrow D_s^- \pi^+$

As explained in the chapter 3, one cannot measure the mistag in real data for channels where the final state is a CP eigenstate, like $B_s^0 \rightarrow J/\psi\phi$. To solve this problem, we use a so-called control channel, which has a flavour specific final state like $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ or $B_s^0 \rightarrow D_s^- \pi^+$. In this chapter we present a comparison of the tagging performances between $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, $B_s^0 \rightarrow J/\psi\phi$, and $B_s^0 \rightarrow D_s^- \pi^+$. We present the cuts applied for the selection of $B_s^0 \rightarrow J/\psi(\mu\mu)\phi$ and $B_s^0 \rightarrow D_s^- \pi^+$ channels. We compare the tagging performances for the three channels. We also see that there is a performance dependence on the trigger, and we use this information to separate our samples in different sub-samples depending on the trigger. Finally, we see a method one has to use to make a channel become a control channel, with a procedure of reweighting.

5.1 Selection of the $B_s^0 \rightarrow J/\psi(\mu\mu)\phi$ and $B_s^0 \rightarrow D_s^- \pi^+$

The cuts described here are given in [19] for the selection of $B_s^0 \rightarrow J/\psi(\mu\mu)\phi$, and in [20] for the selection of $B_s^0 \rightarrow D_s^- \pi^+$.

5.1.1 Selection of $B_s^0 \rightarrow J/\psi(\mu\mu)\phi$

J/ψ and ϕ selection

All final states particles (muons and kaons) are required to have a transverse momentum greater than 500 MeV/c to reduce background from secondary interactions with the material of the detector.

The J/ψ selection requires a vertex χ^2 less than 9, and the mass window must be ± 50 MeV/c² around the nominal J/ψ mass.

The ϕ meson is reconstructed using its decay into K^+K^- . The $\Delta \ln \mathcal{L}_{K\pi}$ is required to be greater than 0, the two kaons are asked to have opposite charge, and they must come from a same vertex, asking that the vertex χ^2 be less than 40. The invariant mass of the pair is required to be within 20 MeV/c² of the nominal ϕ mass. Finally, to reduce

the number of ϕ coming from the primary vertexes, the reconstructed ϕ has to have a momentum greater than 12 GeV/c.

B selection

The selection of the B_s^0 consists in simply combine the J/ψ and the ϕ candidates, requiring that the four tracks (the two muons and the two kaons) come from the same space point, asking that the vertex χ^2 is less than 20, and consistent within 50 MeV/c² with the nominal B_s^0 mass.

5.1.2 Selection of $B_s^0 \rightarrow D_s^- \pi^+$

D_s and π selection

For the D_s reconstruction, all decay products have to have a transverse momentum greater than 300 MeV/c. The bachelor pion is required to have a transverse momentum greater than 700 MeV/c. For the D_s reconstruction, the sum of all the decay particles transverse momentum must be greater than 2200 MeV/c. For the kaon, $\Delta \ln \mathcal{L}_{K\pi}$ must be greater than -5 , and for the pion $\Delta \ln \mathcal{L}_{\pi K}$ must be greater than -5 .

The D_s selection requires a vertex χ^2 lower than 10. The impact parameter significance IP/σ_{IP} , with respect to the production vertex of the D_s , of all the particles used in the reconstruction of the D_s must be greater than 1. The used particles' invariant mass must be consistent within ± 15 MeV/c² around the nominal D_s mass. The impact parameter significance IP/σ_{IP} , with respect to the primary vertex, of the D_s must be greater than 2. The D_s vertex is required to be more than 4.5 standard deviation away from the primary vertex among the z coordinate.

B_s^0 selection

The first requirement on the reconstructed B_s^0 is on its vertex χ^2 , asking it to be lower than 4. The B_s^0 impact parameter significance is required to be less than 3. In this selection a cut on the angle θ presented in fig. 4.8 is used, asking it to be greater than 0.99997. Finally, only the events where the reconstructed B_s^0 has a mass within ± 50 MeV/c² around the nominal B_s^0 mass are selected.

5.1.3 Annual yields

The expected annual yields for $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow D_s^- \pi^+$ are given in table 5.1. We also give the ratio B/S .

Our analysis is based upon 106719 $B_s^0 \rightarrow J/\psi \phi$ events and 93867 $B_s^0 \rightarrow D_s^- \pi^+$ events¹. We saw in chapter 4 that we selected 4913 $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ events after all final cuts, reduced to 4229 if we apply the first level of trigger (L0).

¹The events are reduced from original collection using DaVinci v12r16, applying the L0 trigger.

channel	annual yield	B/S
$B_s^0 \rightarrow J/\psi(\mu\mu)\phi$	131 k	0.12
$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	990 k	0.55
$B_s^0 \rightarrow D_s^- \pi^+$	120 k	0.4

Table 5.1: Annual yield and B/S for $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, and $B_s^0 \rightarrow D_s^- \pi^+$. The number are extracted from [22].

5.2 Comparisons of tagging performances

Once the selection is done, one can look at the results.

As we are interested in tagging, we compare the efficiencies, mistag, and effective tagging efficiency of the three channels. The results are given in table 5.2, after the trigger levels $L0$ and $L1$, and final selection.

	$B_s^0 \rightarrow J/\psi\phi$	$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	$B_s^0 \rightarrow D_s^- \pi^+$
ε_{tag}	55.0 ± 0.2	58.8 ± 0.7	59.4 ± 0.2
ω	34.9 ± 0.2	33.3 ± 1.0	32.1 ± 0.2
ε_{eff}	5.0 ± 0.1	6.6 ± 0.8	7.7 ± 0.3

Table 5.2: **Overall** tagging results for $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, and $B_s^0 \rightarrow D_s^- \pi^+$ after $L0 \times L1$ and final selection. The values are in %.

In this table, we clearly see that the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel is an “intermediate channel”. Indeed, there is one muon (two in $B_s^0 \rightarrow J/\psi\phi$) and one D_s (one in $B_s^0 \rightarrow D_s^- \pi^+$). As we want to use this channel as a control channel, we have already made a first step. Previous studies [23, 24] showed that the fact that $B_s^0 \rightarrow D_s^- \pi^+$ is better than $B_s^0 \rightarrow J/\psi\phi$ in the tagging performances is mainly due to trigger consideration, but we will come to it in section 5.3.

One can now look at the detail of the tagging results, considering separately the same and opposite side. We can find the results in table 5.3 and table 5.4.

	$B_s^0 \rightarrow J/\psi\phi$	$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	$B_s^0 \rightarrow D_s^- \pi^+$
ε_{tag}	28.0 ± 0.1	33.3 ± 0.8	30.5 ± 0.2
ω	34.2 ± 0.3	31.9 ± 1.3	33.7 ± 0.3
ε_{eff}	2.8 ± 0.1	4.4 ± 0.6	3.2 ± 0.1

Table 5.3: Results of **same side** tagging for $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, and $B_s^0 \rightarrow D_s^- \pi^+$, after $L0 \times L1$ and final selection. The values are in %.

These two tables indicates that the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel is better for the same side tagging than for the opposite side tagging. We have investigated several possibilities to understand the differences. There is not obvious reason why there should be more

	$B_s^0 \rightarrow J/\psi\phi$	$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	$B_s^0 \rightarrow D_s^- \pi^+$
ε_{tag}	41.9 ± 0.2	45.7 ± 0.8	46.7 ± 0.2
ω	37.2 ± 0.2	38.4 ± 1.2	34.6 ± 0.3
ε_{eff}	2.8 ± 0.5	2.5 ± 0.5	4.4 ± 0.2

Table 5.4: Results of **opposite side** tagging for $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ and $B_s^0 \rightarrow D_s^- \pi^+$, after $L0 \times L1$ and final selection. The values are in %.

kaons in the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel than in the $B_s^0 \rightarrow J/\psi\phi$ one, because the generation of the fragmentation particles is supposed to be independant of the signal decay. An other possibility could be that the selection of the same side kaon in the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel was not optimized. There could be some differences due to the fact that the reconstructed B_s^0 in the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel is not well defined, because of the missing neutrino. We looked at the cuts applied for the selection of the same side kaons for the three channels (see appendix C), but we found that the cuts were correctly optimized.

The next step is to consider all the systematic effect that can influence the mistag rates. The first is at triggering level, because the triggers are based on kinematic cuts, which can affect the tagging results [21]. In the next section, we will look at the influence of the trigger on the tagging performances.

5.3 Comparison of tagging performances depending on trigger

For a given event, the trigger can fire on the signal B itself or on the other B in the event, and can even fire on both. These different possibilities have an impact on the tagging performances. For instance, for events where the tagging B fires the L1 line based on impact parameter cuts, the bias in the lifetimes will lead to a greater probability of this B having oscillated. In order to apply the measurement from a control channel to a CP mode, it is necessary to classify the events which have been triggered in a same manner.

5.3.1 Trigger subcategories

The Buffer Tampering Tool [25] masks the signal decay products and re-runs the trigger algorithms, in order to determine which tracks have been used to trigger the event. This allows the following classification :

- TIS : Triggered Independently of Signal (The event is still selected even without the signal particle hits) ;
- TOS : Triggered On Signal (The event passes the trigger only if signal particles are kept and the rest removed) ;
- TOB : Triggered On Both (when all the tracks are needed, the ones coming from the signal decay and the others).

We can represent schematically this classification using the fig. 5.1.

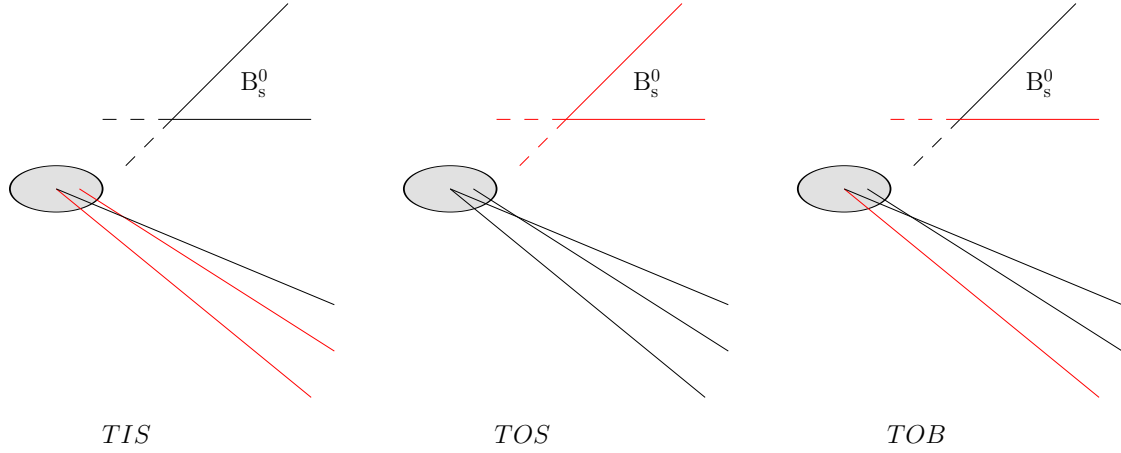


Figure 5.1: TIS TOS TOB representation. The red lines represent the particles used for the trigger.

An event can be TIS and TOS at the same time (TIS+TOS), but it is not TOB. TOB events are excluded from the analysis as they are not expected to be comparable among channels, because they are not triggered neither on a signal particle nor a tagging particle so the same behavior cannot be expected.

For historical reasons, the high level trigger is not considered neither, but future analysis will take it into account.

As we have to distinguish between the L0 and L1 trigger, four classes can be considered :

1. L0TIS L1TIS
2. L0TIS L1TOS
3. L0TOS L1TIS
4. L0TOS L1TOS

It is important to notice here that TIS+TOS events will be considered as TIS events so as to not bias the category and choose an exclusive classification, i.e. without repeating them in the TOS category. As these events are triggered independently of the signal, even if they are TOS, they should have the same behavior independently of the signal decay. So L0 TOS (or L1 TOS) are only L0 TOS (L1TOS) but L0 TIS (L1 TIS) are also L0 TIS+TOS (L1 TIS+TOS).

We expect that the tagging performance of events triggered independently of the signal (TIS) should be approximately the same for different channels, increasing the acceptance on the opposite B, thus increasing the efficiency and mistag for opposite B tags.

For TOS events, one will have lower momentum B_{tag} and less opposite side tags than in the TIS one, so worse tagging performance is expected. Besides, the acceptance and p_T

cuts used to trigger on the signal bias the kinematics of the tagging B due to kinematic correlations between the two B's, so a global same performance is not expected.

We expect that muon channels are mostly triggered on signal, as in the LHCb experiment, we look for high p_T muons for the first level of trigger (L0).

In table 5.5, we have the repartition of the number of events for each of the three channels we are studying depending on the trigger classification discussed before. We

	$B_s^0 \rightarrow J/\psi\phi$	$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	$B_s^0 \rightarrow D_s^- \pi^+$
L0TIS L1TIS	7.0 ± 0.1	10.6 ± 0.5	15.2 ± 0.2
L0TIS L0TOS	19.0 ± 0.1	27.4 ± 0.7	37.3 ± 0.2
L0TOS L1TIS	7.4 ± 0.1	5.8 ± 0.4	3.2 ± 0.1
L0TOS L1TOS	63.7 ± 0.2	46.2 ± 0.8	28.3 ± 0.2
TOB events	2.6 ± 0.1	9.6 ± 0.5	15.9 ± 0.1

Table 5.5: Repartition in percentage of the events of the three channels $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$, and $B_s^0 \rightarrow D_s^- \pi^+$ for each trigger subsamples.

see that $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ is an intermediate channel, due to the single muon, which makes it close to $B_s^0 \rightarrow J/\psi\phi$, and the D_s which makes it close to the $B_s^0 \rightarrow D_s^- \pi^+$.

The next step is to compare the tagging results for these three channels considering the trigger subsamples. In table 5.6, we can find all the results depending on the trigger subsamples. The numbers presented here are best seen in fig. 5.2.

		$B_s^0 \rightarrow J/\psi\phi$	$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	$B_s^0 \rightarrow D_s^- \pi^+$
TIS TIS	ε_{tag}	74.1 ± 0.5	76.0 ± 2.1	74.9 ± 0.4
	ω	31.8 ± 0.6	36.1 ± 2.7	30.2 ± 0.5
	εD^2	9.8 ± 0.7	5.8 ± 2.3	11.7 ± 0.6
TIS TOS	ε_{tag}	59.3 ± 0.4	58.2 ± 1.5	58.9 ± 0.3
	ω	34.7 ± 0.4	33.0 ± 1.9	34.3 ± 0.4
	εD^2	5.5 ± 0.3	6.7 ± 1.5	5.8 ± 0.3
TOS TIS	ε_{tag}	69.6 ± 0.5	77.0 ± 2.8	72.0 ± 0.9
	ω	34.2 ± 0.7	32.2 ± 3.5	30.7 ± 1.1
	εD^2	6.9 ± 0.6	9.7 ± 3.9	10.7 ± 1.3
TOS TOS	ε_{tag}	49.7 ± 0.2	51.9 ± 1.2	49.8 ± 0.4
	ω	35.6 ± 0.3	32.3 ± 1.5	33.0 ± 0.5
	εD^2	4.1 ± 0.2	6.5 ± 1.1	5.7 ± 0.3

Table 5.6: TIS TOS tagging results for the three considered channels. All numbers are in %.

As expected, the tagging efficiencies for TISTIS and TISTOS samples are comparable. In fact, as the opposite B is independent of the signal, every channel has an equal chance

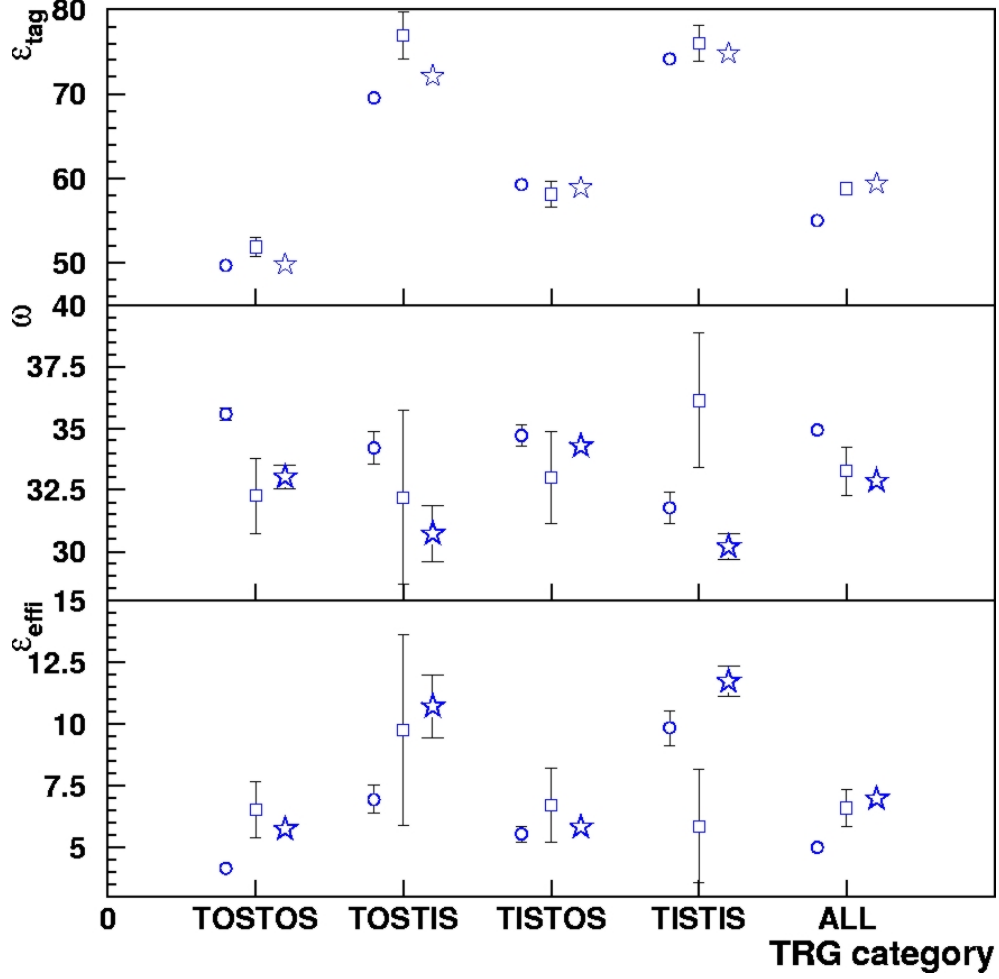


Figure 5.2: Graphical representation of table 5.6 for the three channels : $B_s^0 \rightarrow J/\psi \phi$ (circles), $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ (squares), and $B_s^0 \rightarrow D_s^- \pi^+$ (stars).

to get a specific opposite B, and the tagging efficiency is dominated by opposite side tagging by a factor 2. However, the mistag rates are not compatible. This is not expected, but we cannot explain this for the moment. The same analysis done tagger by tagger showed that the opposite side electrons and muons were responsible for these differences, but there are no clue to understand why.

We will let the TISTIS category aside for the moment, and concentrate on the TOSTOS category. We see in this fig. 5.2 that the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel is worst in mistag than $B_s^0 \rightarrow J/\psi \phi$, but is comparable to $B_s^0 \rightarrow D_s^- \pi^+$ within the errors. The efficiencies are comparable. As we want to use $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ as a control channel, we have to make its mistag close to $B_s^0 \rightarrow J/\psi(\mu\mu)\phi$. This is done using a procedure of reweighting of the mistag by the transverse momentum.

5.3.2 Reweighting of the mistag

The idea of this procedure is to consider that the trigger bias the selection of the signal as it uses several kinematic cuts, specially on the momentum. If the event is triggered on the signal, it means that the reconstructed B will have a momentum shifted to higher values, due to the fact that the particles coming from it have been used for trigger, asking that they have a momentum (and/or energy) greater than certain value (see chapter 2, trigger section). The tagging B will also have its momentum biased, as the two B's in the event are correlated. In fig. 5.3, we have the comparison between the transverse momenta of the three considered channels, for TOS TOS category. It indicates this bias, as the three curves are not superposed.

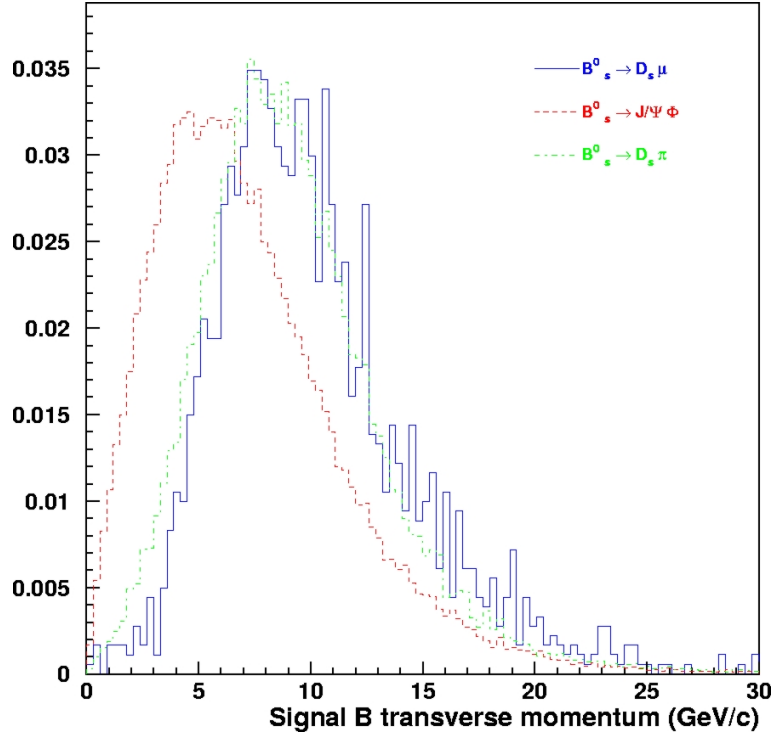


Figure 5.3: Signal B transverse momentum for the three channels $B_s^0 \rightarrow J/\psi\phi$ ($\langle p_T \rangle = 7.2 \text{ GeV}/c$), $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ ($\langle p_T \rangle = 10.1 \text{ GeV}/c$), and $B_s^0 \rightarrow D_s^- \pi^+$ ($\langle p_T \rangle = 9.2 \text{ GeV}/c$), for the TOS TOS category. The difference between the three channels are due to trigger.

We suppose that the tagging performances are the same for all channels for a point of phase space, after separating in trigger sub-samples, and we are then able to connect the mistag of the control channel to the CP one. It consists in measuring the mistag rate of the control channel in bins of signal B phase space, ω_i . We use the transverse momentum as phase space.

The correlation between the mistag and the transverse momentum is represented in figure 5.4.

The next step is to reweight the mistag of the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel. We use the

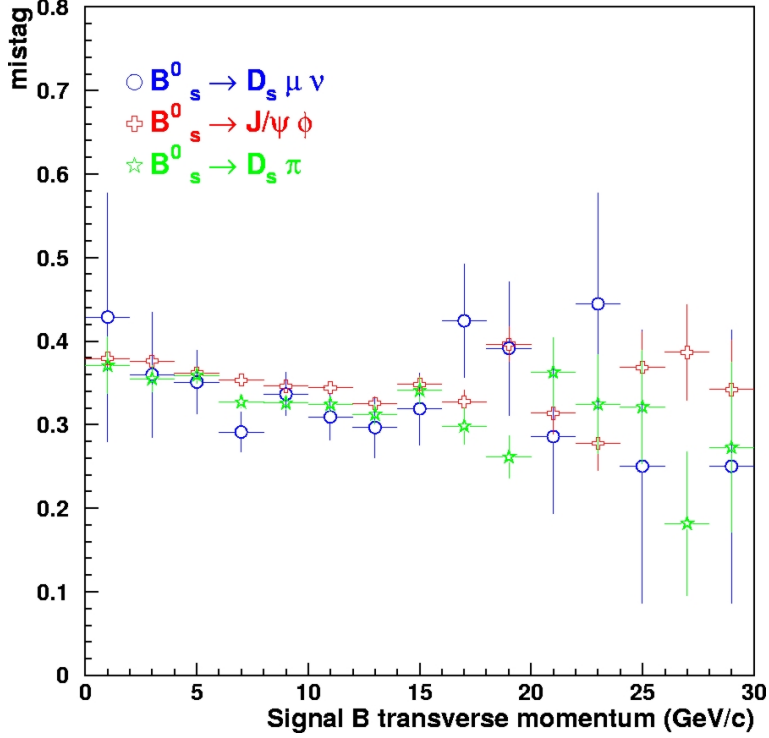


Figure 5.4: Mistag vs p_T for $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ (circles), $B_s^0 \rightarrow J/\psi \phi$ (crosses), and $B_s^0 \rightarrow D_s^- \pi^+$ (stars) for TOSTOS triggered events. The bins for the transverse momentum are 2 GeV/c wide.

formula [24] :

$$\langle \omega \rangle = \frac{\sum_i N_i^{J/\psi} \omega_i}{\sum_i N_i^{J/\psi}} \quad (5.1)$$

$N_i^{J/\psi}$ is the number of $B_s^0 \rightarrow J/\psi \phi$ events with a B_s^0 having a transverse momentum inside a tight window of ± 2 GeV/c (bin i , see fig. 5.5), described before, and ω_i is the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ mistag of the same bin i . The error on the reweighted mistag is given by [24] :

$$\delta^2 \langle \omega \rangle = \frac{1}{\left(\sum_i N_i^{J/\psi} \right)^2} \sum_i \left[(\omega_i - \langle \omega \rangle)^2 N_i^{J/\psi} + \left(N_i^{J/\psi} \right)^2 \delta \omega_i^2 \right] \quad (5.2)$$

5.3.3 Results of reweighting

The previous method gives us the table 5.7. The channels $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ and $B_s^0 \rightarrow J/\psi \phi$ are made compatible within the errors, but these errors are large due to poor statistics. For the $B_s^0 \rightarrow D_s^- \pi^+$ channel, it is possible to say that the mistag are compatible within 3 standard deviation with the $B_s^0 \rightarrow J/\psi \phi$ channel. The analysis must nevertheless be done with more statistics to confirm this result.

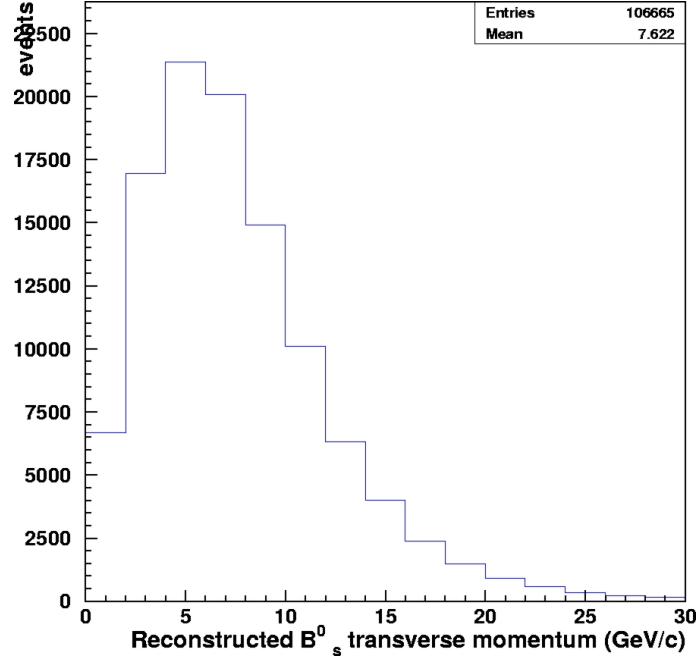


Figure 5.5: Reconstructed B_s^0 transverse momentum for $B_s^0 \rightarrow J/\psi\phi$. $N_i^{J/\psi}$ is the content of each bins.

	Before reweighting	After reweighting
$B_s^0 \rightarrow J/\psi(\mu\mu)\phi$	35.6 ± 0.3	35.6 ± 0.3
$B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$	32.3 ± 1.5	33.1 ± 2.3
$B_s^0 \rightarrow D_s^- \pi^+$	33.0 ± 0.5	33.9 ± 0.6

Table 5.7: Mistag rates (in percentages) for the three channels, before and after reweighting. The $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ and $B_s^0 \rightarrow J/\psi\phi$ channels are now compatible within the errors.

Conclusion

The measurement of the ϕ_s angle is one of the first goal of the LHCb experiment. This observable will be extracted from time dependant CP asymmetries of $B_s^0 \rightarrow J/\psi\phi$ decays. This measurement requires the estimation of the initial state flavour of the b quark contained in the B_s^0 meson. The fact that the final state of $B_s^0 \rightarrow J/\psi\phi$ is a CP eigenstate makes the measurement of its mistag rate in real data impossible. The $B_s^0 \rightarrow D_s^- \pi^+$ channel is usually considered to control the mistag B_s^0 rate. This mistag can be extracted, either from a fit of the B_s^0 oscillation amplitude, which requires an excellent proper time resolution ; or from the double tagging method. In this last one, we exploit events where same side and opposite side flavour tags are available.

In this report, we have investigated for the first time the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel to control the mistag, because of its high branching ratio. The selection of this channel is delicate, because it is a semi-leptonic decay. As the neutrino takes a part of the kinematic information, the reconstruction is not perfect, specially the momentum. We can nevertheless correct this momentum, and achieve a resolution of 15%. The main source of background are $B \rightarrow DDX$ events, where X could be anything, and the muon comes from $b \rightarrow c \rightarrow \mu$ cascade decays.

The outcome of our selection is a background over signal ratio of 0.5, and we are able to select approximately 1 million $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ events per year, after trigger. This is about 10 times more than $B_s^0 \rightarrow D_s^- \pi^+$. The proper time resolution is approximately 175 fs, i.e. 3 times worse than $B_s^0 \rightarrow D_s^- \pi^+$. This means that the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel is not competitive with $B_s^0 \rightarrow D_s^- \pi^+$ for the mistag extraction using amplitude fit, with our current selection.

However, the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ events should be very useful to extract the same side mistag using the double tagging method. Indeed, we have estimated that $\sigma_{\omega_{SS}}$ could be improved from 1.4% to 0.5%, since they multiply by approximately 10 the number of available B_s^0 events with respect to the $B_s^0 \rightarrow D_s^- \pi^+$ alone.

We have also carefully checked the tagging performance differences between the CP channel $B_s^0 \rightarrow J/\psi\phi$ and the two control channels $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$. The expected differences due to trigger biases and to kinematic correlations between the two b-hadrons have been studied. We conclude that the tagging performances of $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ are “in between” $B_s^0 \rightarrow J/\psi\phi$ and $B_s^0 \rightarrow D_s^- \pi^+$ and that it could certainly be used, provided the proper time resolution is improved by a new selection.

Appendix A

Difference in correlation

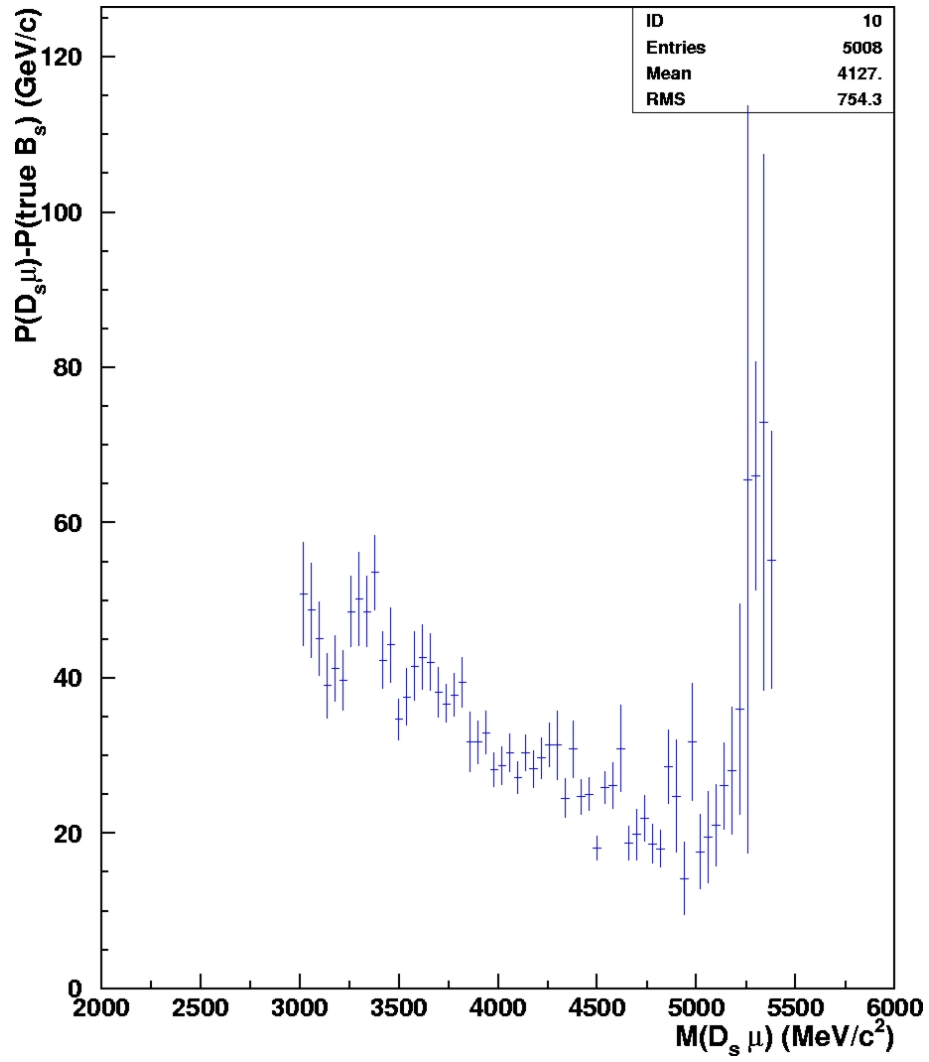
This Appendix treats the question about the events in plot 4.13 for a high $D_s \mu$ invariant mass. We try to explain the reason why the points are not aligned anymore.

In fact, as mentionned in section 4.1, the reconstructed D_s can be a daughter of a D_s^* decaying to a pion or a photon and a D_s . To understand where the difference comes from, one has to see that the daughters of the original B_s^0 take a part of the available energy. This energy corresponds to the mass and momentum of the B_s^0 . Lets take an example :

- Let the neutrino of the B_s^0 decay take one third of the total available energy, referred as E_T . This implies that the two other particles ($D_s^{(*)}$ and μ) take two third of the total energy. The $D_s^{(*)}$ can then take an energy ($E_{D_s^{(*)}}$) in a range between $m_{D_s^{(*)}}$ and $\frac{2}{3}E_T - m_\mu$ (we know from plot 4.10 that $E_T \gg m_{D_s^{(*)}}$). The two limits correspond respectively to the case where the $D_s^{(*)}$ is at rest and to the case where the $D_s^{(*)}$ takes all the energy and the muon is left at rest.
- Now lets imagine that the $D_s^{(*)}$ is a D_s^* . In that case it should decay following $D_s^* \rightarrow \pi^0 D_s$ or $D_s^* \rightarrow \gamma D_s$. In that case, the energy taken by the D_s is at least m_{D_s} and at most $E_{D_s^*}$ (corresponding to $D_s^* \rightarrow \gamma D_s$).
- From the first point, we can conclude that the energy that the D_s can take is included between m_{D_s} and $\frac{2}{3}E_T - m_\mu$, as $m_{D_s} < m_{D_s^*}$.
- If we generalize, and let the neutrino take an energy ε , then the D_s can take an energy between m_{D_s} and $(1 - \varepsilon)E_T - m_\mu$. If ε is small, like in the case where the $D_s \mu$ invariant mass is close to the nominal B_s^0 mass, the range of energy that can be taken by the D_s can be huge (if the energy provided by the B_s^0 is huge). As the D_s mass is a constant, with the fundamental relation $E^2 = p^2 c^2 + m^2 c^4$, the variation of the momentum is also huge.

So when the $D_s \mu$ invariant mass is close to the nominal B_s^0 mass, it is logical that the ratio $(P(D_s \mu)/P(P_{B_s^0}^{true}))$ is not close to 1, and even, it should be completely random between ~ 0 and 1.

An other way to see this phenomenon is to study the correlation between the $D_s \mu$ invariant mass and the difference between the reconstructed momentum and the true momentum.



Here again, we clearly see that the difference suffers a severe divergence for high $D_s \mu$ invariant mass.

Appendix B

Verification of true lifetime

In this little appendix, we check that the mean lifetime of the true B_s^0 corresponds to the previously measured value [17]. On fig. B.1, we see that the mean lifetime is equal to 1.55 ± 0.02 ps. We see that there are four sigma separation with the expected value of 1.461 [26].

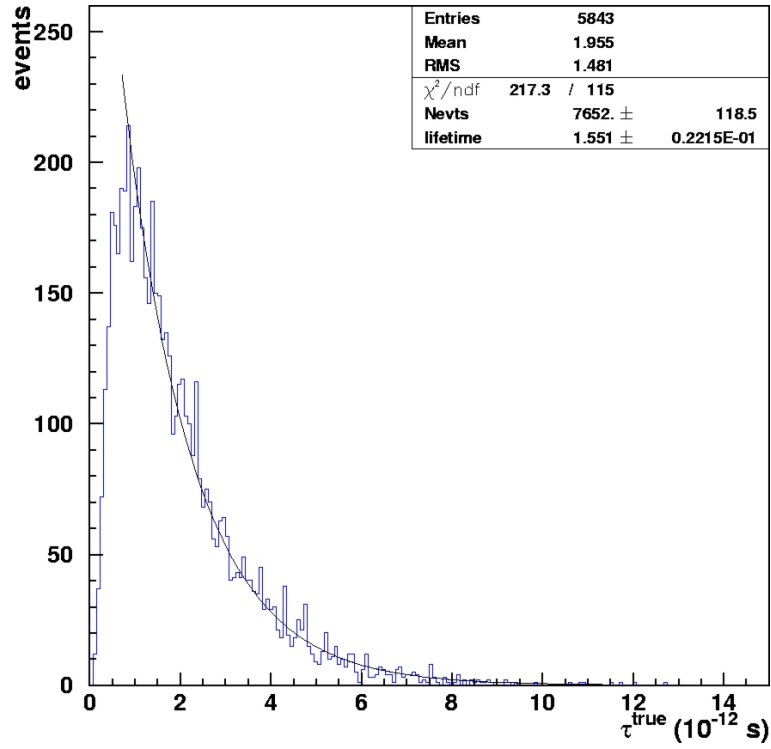


Figure B.1: True lifetime of our signal B_s^0 . The mean lifetime is equal to 1.55 ± 0.02 ps.

Appendix C

Verification of the same side kaon selection cuts

In this appendix we summarize the choice we made in the selection of the same side kaon, and we show that the optimization done for the $B_s^0 \rightarrow D_s^- \pi^+$ channel is also correct for the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel. We are only interested in the cuts that concern the signal B, because the cuts like the impact parameter significance are not dependent of the reconstructed B meson. The remaining cuts are the cuts on $|\Delta\eta|$, $|\Delta\phi|$, and Δm , where Δm is the difference between the invariant mass of the pair $B_s^0 K$ and the invariant mass of the reconstructed B_s^0 . These cuts depend on the kinematics of the reconstructed B and as we have a missing neutrino in our channel, we saw that the momentum was biased. The table C.1 is here to recall the cuts used in the algorithm for the selection of the same side kaon. In the plots below, the arrow shows the optimal selection cut value.

cut	value
IP/σ_{IP}	< 2.5
$ \Delta\eta $	< 1
$ \Delta\phi $	< 1.1
Δm	$< 1.5 \text{ GeV}/c^2$
momentum	$> 4 \text{ GeV}/c$
p_T	$> 0.4 \text{ GeV}/c$

Table C.1: Selection cuts for the same side kaon.

All these optimization cuts are compatible with the one already used for the selection of the same side kaon.

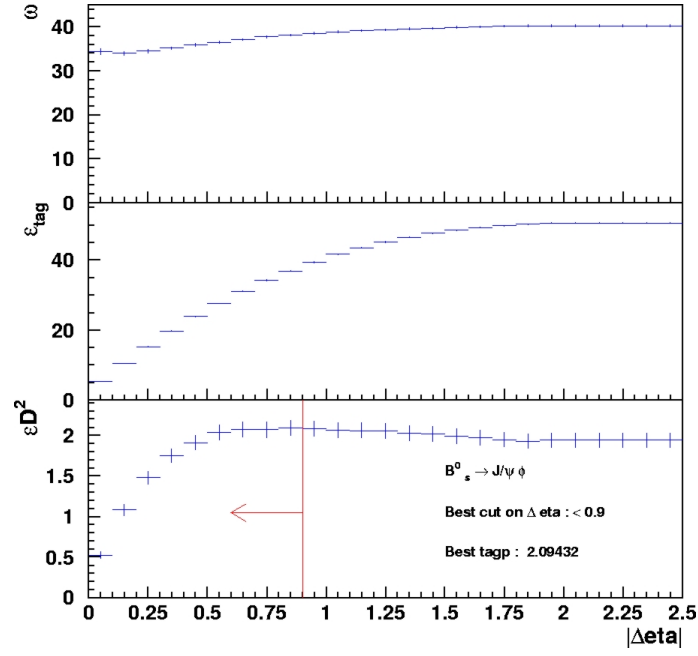


Figure C.1: Optimization of the $|\Delta\eta|$ cut for the same side kaon, in the $B_s^0 \rightarrow J/\psi \phi$ channel

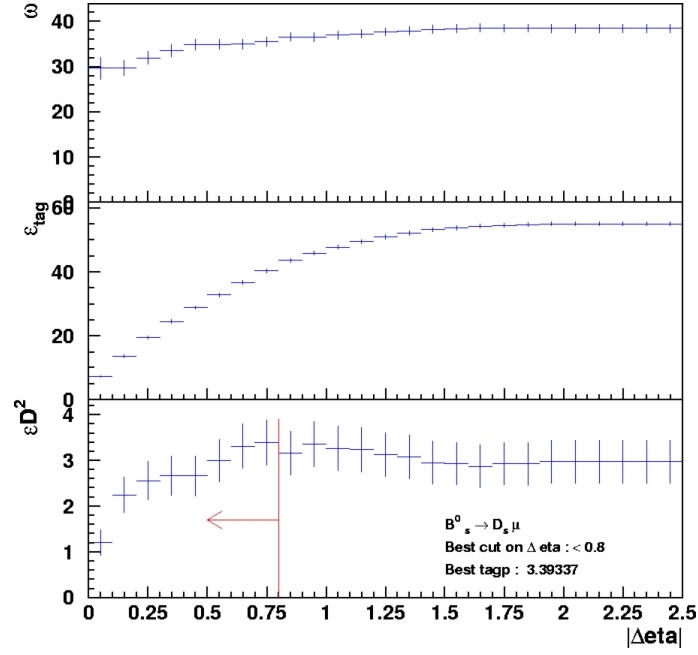


Figure C.2: Optimization of the $|\Delta\eta|$ cut for the same side kaon, in the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel

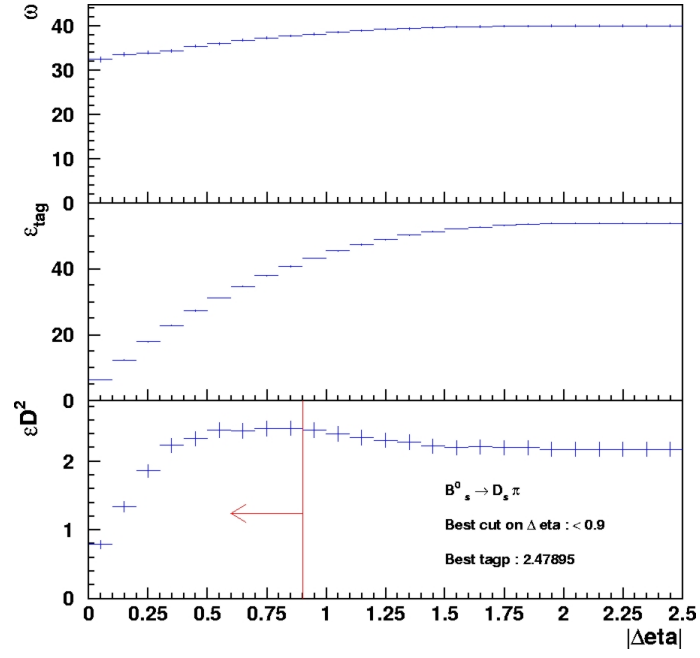


Figure C.3: Optimization of the $|\Delta\eta|$ cut for the same side kaon, in the $B_s^0 \rightarrow D_s^- \pi^+$ channel

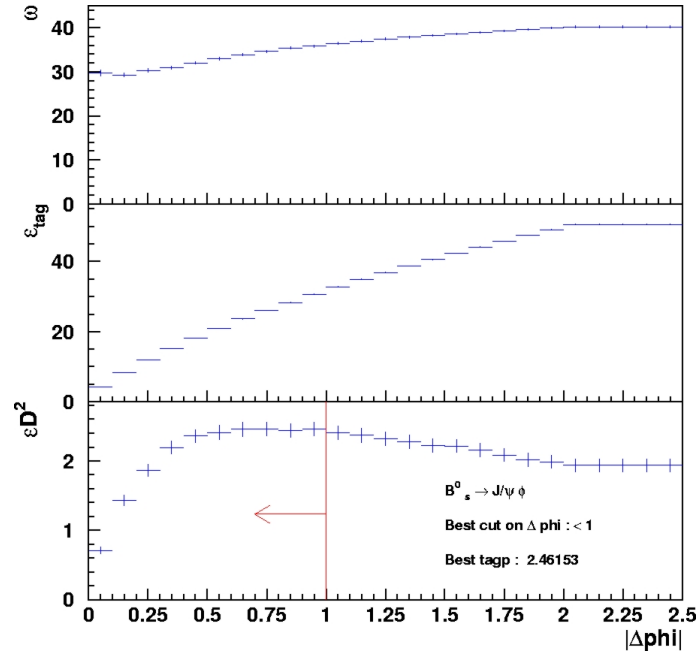


Figure C.4: Optimization of the $|\Delta\phi|$ cut for the same side kaon, in the $B_s^0 \rightarrow J/\psi \phi$ channel

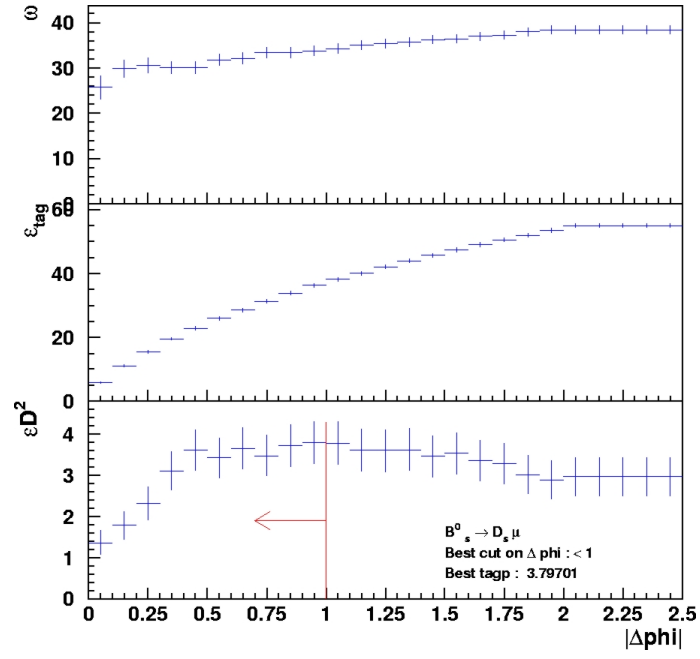


Figure C.5: Optimization of the $|\Delta\phi|$ cut for the same side kaon, in the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel

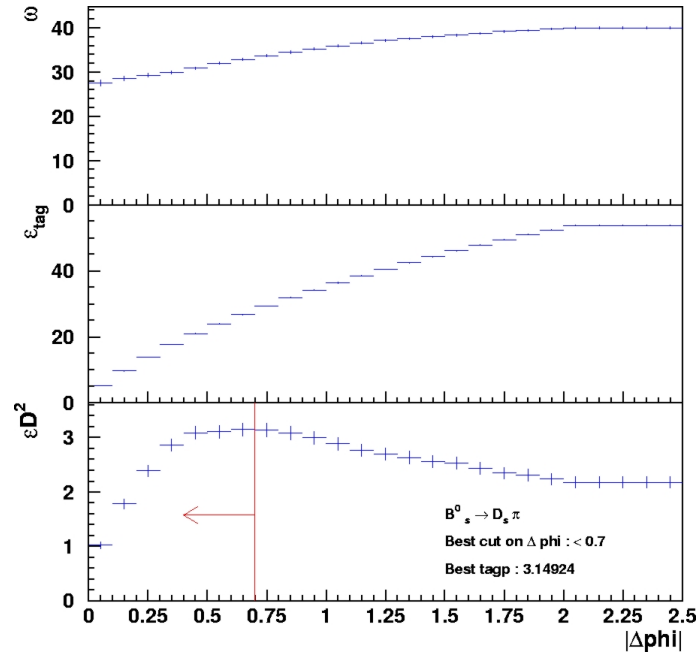


Figure C.6: Optimization of the $|\Delta\phi|$ cut for the same side kaon, in the $B_s^0 \rightarrow D_s^- \pi^+$ channel

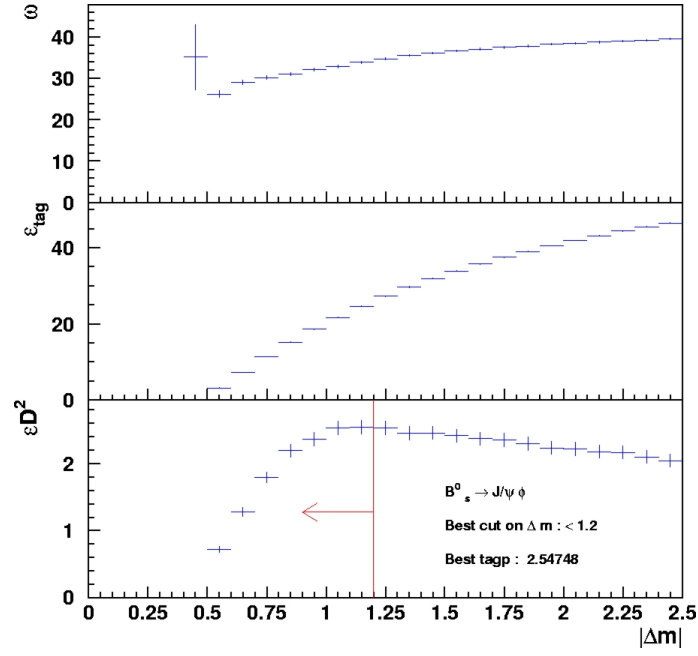


Figure C.7: Optimization of the $|\Delta m|$ cut for the same side kaon, in the $B_s^0 \rightarrow J/\psi \phi$ channel

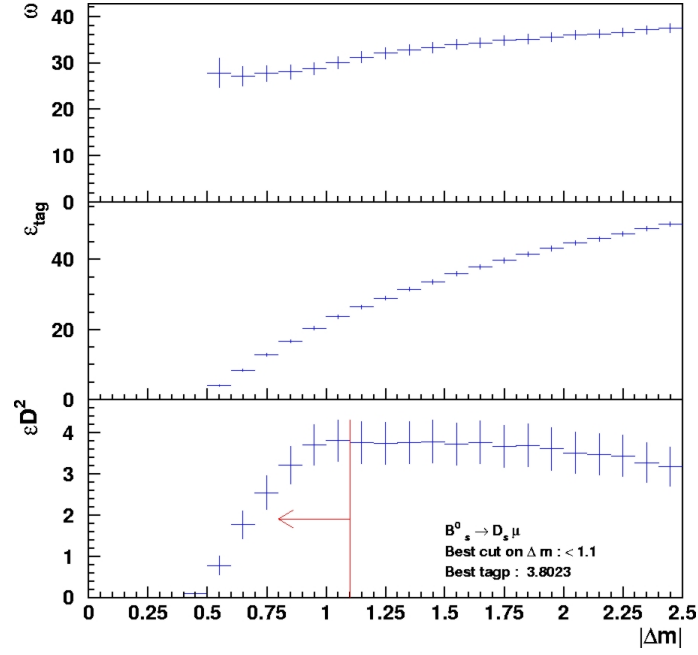


Figure C.8: Optimization of the $|\Delta m|$ cut for the same side kaon, in the $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$ channel

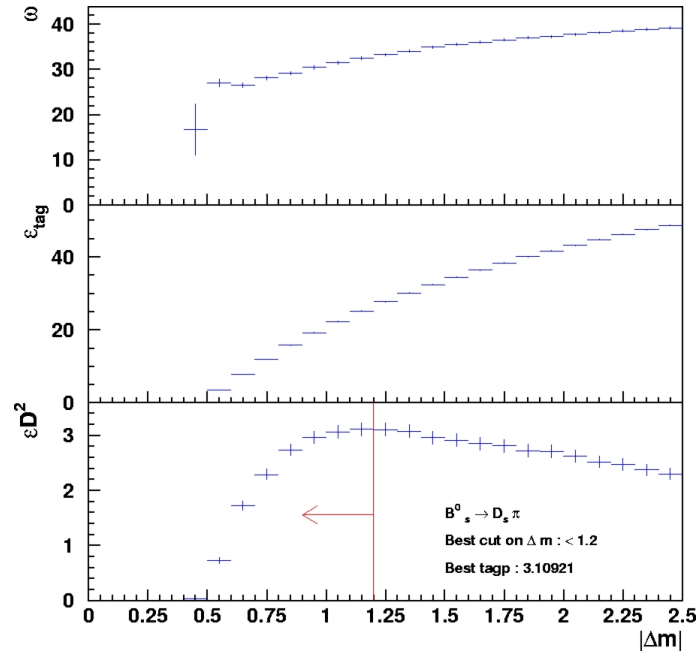


Figure C.9: Optimization of the $|\Delta m|$ cut for the same side kaon, in the $B_s^0 \rightarrow D_s^- \pi^+$ channel

Appendix D

Tagging versus Trigger

In this appendix, we present the general results of the trigger dependancy of the tagging. This will be presented under the form of arrays.

		TOS TOS	TOS TIS	TIS TOS	TIS TIS	ALL
SS kaon	ε_{tag}	26.2 ± 0.2	30.3 ± 0.5	30.8 ± 0.3	32.3 ± 0.6	28.0 ± 0.1
	ω	33.4 ± 0.4	36.4 ± 1.0	33.8 ± 0.6	37.6 ± 1.0	34.2 ± 0.3
	ε_{eff}	2.9 ± 0.1	2.2 ± 0.3	3.2 ± 0.2	2.0 ± 0.3	2.8 ± 0.1
OS Muon	ε_{tag}	1.5 ± 0.0	5.0 ± 0.3	10.5 ± 0.2	34.3 ± 0.6	5.9 ± 0.1
	ω	34.0 ± 1.5	36.0 ± 2.5	29.6 ± 1.0	29.9 ± 0.9	31.0 ± 0.6
	ε_{eff}	0.2 ± 0.0	0.4 ± 0.4	1.7 ± 0.2	5.5 ± 0.5	0.9 ± 0.1
OS Electron	ε_{tag}	2.5 ± 0.1	6.1 ± 0.3	4.0 ± 0.1	7.0 ± 0.3	3.4 ± 0.1
	ω	29.9 ± 1.1	29.7 ± 2.1	33.9 ± 1.7	32.2 ± 2.1	31.2 ± 0.8
	ε_{eff}	0.4 ± 0.0	1.0 ± 0.2	0.4 ± 0.1	0.9 ± 0.2	0.5 ± 0.0
OS kaon	ε_{tag}	24.7 ± 0.2	46.9 ± 0.6	29.3 ± 0.3	45.1 ± 0.6	28.9 ± 0.1
	ω	39.1 ± 0.4	35.0 ± 0.8	38.5 ± 0.6	35.8 ± 0.9	38.2 ± 0.3
	ε_{eff}	1.2 ± 0.1	4.2 ± 0.5	1.5 ± 0.2	3.7 ± 0.4	1.6 ± 0.1
Vertex	ε_{tag}	17.8 ± 0.2	36.5 ± 0.6	21.6 ± 0.3	33.7 ± 0.6	21.3 ± 0.1
	ω	39.8 ± 0.5	35.7 ± 0.9	41.1 ± 0.8	37.6 ± 1.0	39.2 ± 0.3
	ε_{eff}	0.7 ± 0.1	3.0 ± 0.4	0.7 ± 0.1	2.1 ± 0.3	1.0 ± 0.1
Same Side comb	ε_{tag}	26.2 ± 0.2	30.3 ± 0.5	30.8 ± 0.3	32.3 ± 0.6	28.0 ± 0.1
	ω	33.4 ± 0.4	36.4 ± 1.0	33.8 ± 0.6	37.6 ± 1.0	34.2 ± 0.3
	ε_{eff}	2.9 ± 0.1	2.2 ± 0.3	3.2 ± 0.2	2.0 ± 0.3	2.8 ± 0.1
Oppo side comb	ε_{tag}	37.0 ± 0.2	66.3 ± 0.5	48.3 ± 0.4	73.5 ± 0.5	44.3 ± 0.2
	ω	39.4 ± 0.3	35.4 ± 0.7	37.6 ± 0.5	32.7 ± 0.7	37.8 ± 0.2
	ε_{eff}	1.7 ± 0.1	5.7 ± 0.5	3.0 ± 0.2	8.8 ± 0.7	2.6 ± 0.1
All tag	ε_{tag}	49.7 ± 0.2	69.6 ± 0.5	59.3 ± 0.4	74.1 ± 0.5	55.0 ± 0.2
	ω	35.6 ± 0.3	34.2 ± 0.7	34.7 ± 0.4	31.8 ± 0.6	34.9 ± 0.2
	ε_{eff}	4.1 ± 0.2	6.9 ± 0.6	5.5 ± 0.3	9.8 ± 0.7	5.0 ± 0.1

Table D.1: Table for $B_s^0 \rightarrow J/\psi(\mu\mu)\phi$. Vertical designates the trigger sub-sample, and ALL corresponds to no separation in trigger sub-samples. The horizontal corresponds to the tagging category, and the All tag is after the combinaison of all the taggers.

		TOS TOS	TOS TIS	TIS TOS	TIS TIS	ALL
SS Kaon	ε_{tag}	30.3 ± 1.1	34.8 ± 3.1	34.5 ± 1.4	40.2 ± 2.4	33.3 ± 0.8
	ω	28.5 ± 1.9	36.2 ± 5.4	33.9 ± 2.5	37.8 ± 3.8	31.9 ± 1.3
	ε_{eff}	5.6 ± 1.0	2.6 ± 2.1	3.6 ± 1.1	2.4 ± 1.5	4.4 ± 0.6
OS Muon	ε_{tag}	1.8 ± 0.3	6.1 ± 1.6	9.6 ± 0.9	31.4 ± 2.3	7.8 ± 0.4
	ω	36.4 ± 8.4	21.4 ± 11.0	26.2 ± 4.3	41.4 ± 4.4	34.5 ± 2.7
	ε_{eff}	0.1 ± 0.2	2.0 ± 2.0	2.2 ± 0.8	0.9 ± 0.9	0.7 ± 0.3
OS Electron	ε_{tag}	3.0 ± 0.4	10.0 ± 2.0	4.1 ± 0.6	6.9 ± 1.3	4.2 ± 0.3
	ω	27.8 ± 6.1	26.1 ± 9.2	40.9 ± 7.9	42.9 ± 9.4	35.4 ± 2.7
	ε_{eff}	0.6 ± 0.3	2.3 ± 1.8	0.1 ± 0.2	0.1 ± 0.4	0.4 ± 0.2
OS Kaon	ε_{tag}	27.5 ± 1.0	47.0 ± 3.3	30.5 ± 1.4	47.1 ± 2.5	31.9 ± 0.7
	ω	40.0 ± 2.2	31.5 ± 4.5	39.2 ± 2.7	37.5 ± 3.5	38.9 ± 1.4
	ε_{eff}	1.1 ± 0.5	6.4 ± 3.1	1.4 ± 0.7	2.9 ± 1.7	1.6 ± 0.4
Vertex	ε_{tag}	17.6 ± 0.9	42.2 ± 3.3	21.8 ± 1.3	37.0 ± 2.4	23.4 ± 0.7
	ω	40.6 ± 2.7	41.2 ± 5.0	40.9 ± 3.2	41.7 ± 4.0	41.5 ± 1.6
	ε_{eff}	0.6 ± 0.4	1.3 ± 1.5	0.7 ± 0.5	1.0 ± 1.0	0.7 ± 0.3
Same Side comb	ε_{tag}	30.3 ± 1.1	34.8 ± 3.1	34.5 ± 1.4	40.2 ± 2.4	33.3 ± 0.8
	ω	28.5 ± 1.9	36.2 ± 5.4	33.9 ± 2.5	37.8 ± 3.8	31.9 ± 1.3
	ε_{eff}	5.6 ± 1.0	2.6 ± 2.1	3.6 ± 1.1	2.4 ± 1.5	4.4 ± 0.6
Oppo side comb	ε_{tag}	38.3 ± 1.1	74.3 ± 2.9	47.7 ± 1.5	72.5 ± 2.2	48.0 ± 0.8
	ω	39.2 ± 1.9	32.2 ± 3.6	38.1 ± 2.1	40.5 ± 2.9	38.8 ± 1.1
	ε_{eff}	1.8 ± 0.6	9.5 ± 3.8	2.7 ± 1.0	2.6 ± 1.6	2.4 ± 0.5
All tag	ε_{tag}	51.9 ± 1.2	77.0 ± 2.8	58.2 ± 1.5	76.0 ± 2.1	58.8 ± 0.8
	ω	32.3 ± 1.5	32.2 ± 3.5	33.0 ± 1.9	36.1 ± 2.7	33.3 ± 1.0
	ε_{eff}	6.5 ± 1.1	9.7 ± 3.9	6.7 ± 1.5	5.8 ± 2.3	6.6 ± 0.8

Table D.2: Table for $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$. Vertical designates the trigger sub-sample, and ALL corresponds to no separation in trigger sub-samples. The horizontal corresponds to the tagging category, and the All tag is after the combinaison of all the taggers.

		TOS TOS	TOS TIS	TIS TOS	TIS TIS	ALL
SS kaon	ε_{tag}	28.4 ± 0.3	30.1 ± 1.0	31.1 ± 0.3	32.3 ± 0.4	30.5 ± 0.2
	ω	31.4 ± 0.6	29.9 ± 1.7	35.8 ± 0.5	35.2 ± 0.8	33.7 ± 0.3
	ε_{eff}	3.9 ± 0.3	4.9 ± 0.9	2.5 ± 0.2	2.8 ± 0.3	3.2 ± 0.1
OS Muon	ε_{tag}	1.3 ± 0.1	1.4 ± 0.4	11.8 ± 0.2	33.0 ± 0.5	11.4 ± 0.1
	ω	29.6 ± 2.8	38.9 ± 5.0	30.3 ± 0.8	30.1 ± 0.8	30.5 ± 0.5
	ε_{eff}	0.2 ± 0.1	0.2 ± 0.2	1.8 ± 0.2	5.2 ± 0.4	1.7 ± 0.1
OS Electron	ε_{tag}	2.1 ± 0.1	6.4 ± 0.5	4.1 ± 0.1	7.9 ± 0.3	4.2 ± 0.1
	ω	28.7 ± 2.2	34.7 ± 3.9	31.5 ± 1.4	32.9 ± 1.6	31.0 ± 0.8
	ε_{eff}	0.4 ± 0.1	0.6 ± 0.3	0.6 ± 0.1	0.9 ± 0.2	0.6 ± 0.1
OS kaon	ε_{tag}	23.6 ± 0.3	49.2 ± 1.0	28.9 ± 0.3	45.5 ± 0.5	30.9 ± 0.2
	ω	37.7 ± 0.7	32.9 ± 1.4	37.9 ± 0.6	33.2 ± 0.7	36.5 ± 0.3
	ε_{eff}	1.4 ± 0.2	5.7 ± 0.9	1.7 ± 0.2	5.1 ± 0.4	2.2 ± 0.1
Vertex	ε_{tag}	16.7 ± 0.3	41.6 ± 1.0	21.1 ± 0.2	37.1 ± 0.5	23.4 ± 0.2
	ω	37.5 ± 0.8	33.2 ± 1.5	39.0 ± 0.6	37.6 ± 0.8	38.0 ± 0.4
	ε_{eff}	1.0 ± 0.1	4.7 ± 0.9	1.0 ± 0.1	2.3 ± 0.3	1.3 ± 0.1
Same Side comb	ε_{tag}	28.4 ± 0.3	30.1 ± 1.0	31.1 ± 0.3	32.3 ± 0.4	30.5 ± 0.2
	ω	31.4 ± 0.6	29.9 ± 1.7	35.8 ± 0.5	35.2 ± 0.8	33.7 ± 0.3
	ε_{eff}	3.9 ± 0.3	4.9 ± 0.9	2.5 ± 0.2	2.8 ± 0.3	3.2 ± 0.1
Oppo side comb	ε_{tag}	34.8 ± 0.3	70.2 ± 1.0	47.9 ± 0.3	74.7 ± 0.4	49.4 ± 0.2
	ω	37.5 ± 0.6	34.0 ± 1.2	36.1 ± 0.4	31.8 ± 0.5	35.4 ± 0.3
	ε_{eff}	2.2 ± 0.2	7.2 ± 1.1	3.7 ± 0.2	9.9 ± 0.6	4.2 ± 0.1
All tag	ε_{tag}	49.8 ± 0.4	72.0 ± 0.9	58.9 ± 0.3	74.08 ± 0.4	59.4 ± 0.2
	ω	33.0 ± 0.5	30.7 ± 1.1	34.3 ± 0.4	30.2 ± 0.5	32.9 ± 0.2
	ε_{eff}	5.7 ± 0.3	10.7 ± 1.3	5.8 ± 0.3	11.7 ± 0.6	7.0 ± 0.2

Table D.3: Table for $B_s^0 \rightarrow D_s^- \pi^+$. Vertical designates the trigger sub-sample, and ALL corresponds to no separation in trigger sub-samples. The horizontal corresponds to the tagging category, and the All tag is after the combinaison of all the taggers.

Appendix E

Typical decay tree

Here, we present a typical decay tree which had to be analysed when studying the background composition.

Name	E MeV	M MeV	P MeV	Pt MeV	phi mrad
B+	97430.82	5278.90	97287.71	12155.51	2986.01
+++>D+	42824.60	1869.30	42783.79	5325.40	2797.65
+++>K* (892) ~0	11448.42	896.10	11413.30	1382.40	2704.09
+++>K-	10751.74	493.68	10740.40	1301.41	2608.34
+++>pi+	699.11	139.57	685.04	151.80	-2618.27
+++>p+	1081.36	938.27	537.57	214.97	-2749.30
+++>mu+	22844.65	105.66	22844.40	2919.23	2779.28
+++>nu_mu	8529.11	-0.00	8529.11	1046.37	2973.19
+++>D* (2010) ~0	41101.75	2006.70	41052.73	5556.98	-3127.98
+++>D~0	35533.74	1864.50	35484.79	4786.74	-3131.89
+++>K+	21555.51	493.68	21549.86	3457.57	-3065.10
+++>pi-	8259.03	139.57	8257.85	1150.96	3080.72
+++>pi0	5719.20	134.98	5717.61	240.86	2481.27
+++>gamma	999.59	0.00	999.59	18.47	573.86
+++>gamma	4719.62	0.00	4719.62	247.58	2551.73
+++>e+	3877.10	0.51	3877.10	202.24	2547.60
+++>e-	842.51	0.51	842.51	45.34	2570.15
+++>gamma	5568.00	-0.00	5568.00	770.51	-3103.70
+++>pi-	4155.01	139.57	4152.66	188.09	2977.51
+++>N/A	2954.52	2809.25	915.05	405.33	1263.81
+++>pi-	737.28	139.57	723.95	363.12	-2205.37
+++>p+	1166.97	938.27	693.88	627.06	2124.56
+++>K+	9349.47	493.68	9336.43	1260.04	3036.09
Name	E MeV	M MeV	P MeV	Pt MeV	phi mrad
B~0	73320.34	5279.20	73130.03	1028.81	1111.41
+++>D_s-	26006.21	1968.50	25931.61	706.83	-2955.99

+-->phi(1020)	20686.02	1019.40	20660.88	874.40	-2146.62
+-->K+	11799.26	493.68	11788.92	590.22	-2061.95
+-->K-	8886.72	493.68	8872.99	290.62	-2319.21
+-->pi-	5320.24	139.57	5318.41	641.36	1918.54
+-->D*_s+	27970.41	2112.40	27890.53	1091.10	740.81
+-->D_s+	26186.75	1968.50	26112.66	1087.10	857.09
+-->rho(770)+	13533.75	769.90	13511.83	456.91	1684.05
+-->pi+	5486.06	139.57	5484.28	319.63	-3008.31
+-->pi0	8049.98	134.98	8048.85	562.83	1080.25
+-->gamma	5932.70	-0.00	5932.70	442.57	957.58
+-->gamma	2117.27	0.00	2117.27	134.93	1493.22
+-->e+	1482.40	0.51	1482.40	94.41	1488.37
+-->e-	634.87	0.51	634.87	40.52	1504.52
+-->eta_prime	12650.72	957.77	12614.41	847.29	449.03
+-->rho(770)0	11939.43	771.10	11914.51	686.34	556.17
+-->pi+	4327.64	139.57	4325.39	536.06	925.40
+-->mu+	3411.10	105.66	3409.46	440.30	984.86
+-->nu_mu	911.33	0.00	911.33	99.33	679.21
+-->pi-	7608.71	139.57	7607.43	268.65	-247.82
+-->gamma	714.37	-0.00	714.37	180.48	30.22
+-->gamma	1783.66	-0.00	1783.66	126.63	-740.31
+-->K~0	19343.72	497.67	19337.32	468.52	740.86
+-->KL0	19343.72	497.67	19337.32	468.52	740.86

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