

A Measurement of the $B_s^0 \rightarrow K^+ K^-$ Lifetime at the LHCb Experiment

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Abstract

The LHCb experiment was constructed to search for new physical phenomena not predicted by the Standard Model of particle physics in high energy proton-proton collisions at the Large Hadron Collider (LHC). In 2010 LHCb accumulated an integrated luminosity of 37.66 pb^{-1} at a centre-of-mass energy of 7 TeV.

The $B_s^0 \rightarrow K^+ K^-$ decay mode is sensitive to the existence of beyond the Standard Model physics and the presence of such new physics may be detected through a precise measurement of its mean lifetime. The effective $B_s^0 \rightarrow K^+ K^-$ lifetime $\tau_{K^+ K^-}$ is measured relative to the $B^0 \rightarrow K^+ \pi^-$ lifetime $\tau_{B \rightarrow K \pi}$ in order to control the effect of proper time bias due to selection acceptance. The difference of inverse lifetimes $\Delta\Gamma_{K^+ K^-} \equiv 1/\tau_{K^+ K^-} - 1/\tau_{B \rightarrow K \pi}$ is measured as $\Delta\Gamma_{K^+ K^-} = 0.013 \pm 0.045(\text{stat}) \pm 0.005(\text{syst}) \pm 0.001(\text{model}) \text{ ps}^{-1}$. Using the world average of the mean B^0 lifetime the effective $B_s^0 \rightarrow K^+ K^-$ lifetime is measured as $\tau_{K^+ K^-} = 1.490 \pm 0.100(\text{stat}) \pm 0.012(\text{syst}) \pm 0.002(\text{model}) \pm 0.007(\text{input}) \text{ ps}$, consistent with the Standard Model prediction.

In addition, a Bayesian method to correct for proper time acceptance bias in relative lifetime measurements is presented and studies are performed using the decay modes $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$. A study of the quantity y_{CP} , which is sensitive to new sources of CP violation in the D^0 system, is presented in the context of this acceptance correction method.

Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective degree committee.

Harry Victor Cliff

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Preface

The Standard Model of particle physics, developed during the latter half of the 20th century, is one of the greatest achievements of modern science, describing a wide range of physical phenomena with stunning accuracy. However, there is growing evidence that the Standard Model is not a complete theory of matter: an explanation for the preponderance of matter over antimatter in the Universe requires new sources of Charge-Parity (CP) violation, observations by astronomers have demonstrated the need for a new form of weakly interacting “Dark Matter” to explain the motions of galaxies and the Hierarchy Problem between the Higgs mass and the Planck scale cannot be explained without extensions of the Standard Model.

New physics beyond the Standard Model is required to address many of these problems and such theories bring with them a complement of new particles and phenomena that can be probed at collider experiments. The Large Hadron Collider (LHC) has been constructed at CERN near Geneva primarily to collide protons at energies of 14 TeV in the hope of producing some of these new particles, as well as to test for the existence of the Standard Model Higgs boson. The LHCb experiment is a detector at the LHC designed to make precision measurements of processes involving b and c quarks which are sensitive to new physics.

The B^0 meson system is an excellent laboratory in which to search for evidence of beyond the Standard Model processes. This dissertation presents the first measurement of the $B_s^0 \rightarrow K^+ K^-$ lifetime, a quantity sensitive to new physics, made at the LHCb experiment using the 2010 data set. A novel approach to correct for proper decay time bias due to particle selections is also described. This method is tested and explored in the context of a measurement of the new physics-sensitive lifetime ratio y_{CP} which can be measured using the $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$ decay modes.

Chapter 1 describes the theoretical motivations for making measurements of the $B_s^0 \rightarrow K^+ K^-$ lifetime and y_{CP} . Chapter 2 describes the LHC and the LHCb experiment as well as my contribution to the operation and monitoring of the RICH detectors of LHCb. Chapter 3 describes the methods used to select the $B_s^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow K^+ K^-$ decay modes and Chapter 4 outlines the simulated data used to perform studies for these measurements. The techniques for correcting selection acceptance bias in $B_s^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow K^+ K^-$ are explored in Chapter 5. The measurement of the $B_s^0 \rightarrow K^+ K^-$ lifetime is described in detail in Chapter 6 and the systematic uncertainties associated with this measurement are presented in Chapter 7. Finally, the results and conclusions of this dissertation are summarised in Chapter 8.

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Chapter 1

Theoretical Motivation

“Physics is like sex. Sure, it may give some practical results, but that’s not why we do it.”

— Richard Feynman

Human beings have been trying to understand the nature of matter for well over two millennia. The oldest recorded account of what the world is made of comes from Thales of Miletus who lived in the sixth century BC. He was one of the first philosophers to reject mystical explanations of natural phenomena in favour of the rigorous application of logic and as such he has earned the somewhat dubious title of the “first physicist”. Thales proposed that all the stuff of the world was formed from a single element, water, with solids and gases formed from compressed and rarefied water. Today our best theory of matter is somewhat more complex, but nonetheless remarkably economical. The Standard Model [1–3] attempts to describe all of nature in terms of just 25 fundamental particles. Twelve make up matter: six quarks (d, u, s, c, b, t) and six leptons ($e^-, \nu_e, \mu^-, \nu_\mu, \tau^-, \nu_\tau$). All the atomic matter in the Universe is made from just three of these with electrons whizzing around a nucleus made of up and down quarks. Another twelve are gauge bosons, responsible for transmitting three of the four fundamental forces: the photon of electromagnetism, the W^-, W^+ and Z^0 of the weak force and the eight gluons of the strong force. Particle number 25 is the famous Higgs boson; hypothesised to be responsible for the masses of all fundamental particles. The Higgs is the final piece required to complete the Standard Model puzzle but to date no experiment has been able to present convincing evidence of its existence.

The Standard Model is stunningly successful in describing a vast range of physical processes with great accuracy. For example, measurements of the anomalous magnetic dipole moment of the electron have been used to verify quantum electrodynamics to a precision greater than one part in a billion [4, 5]. However, there remain a number of serious issues that the Standard Model fails to address in its current form. Only three of the four known fundamental forces are described; like the batteries in an eagerly awaited Christmas present, gravity is not included. Besides this, other questions remain: How did matter achieve dominance over antimatter in the early Universe? What is the dark matter that supposedly prevents galaxies from falling apart made from? Why is the Higgs mass so much smaller than the Planck scale?

Attempts to address these problems have led to extensions of the Standard Model such as supersymmetry [6], which accounts for the hierarchy problem between the Higgs mass and Planck scale by invoking a symmetry between fermions and bosons, doubling the number of fundamental particles. Such “new physics” (NP) particles may be detected both directly and indirectly at particle colliders. Direct detection involves producing these particles in high energy collisions and then searching for the characteristic signatures left by their decays. Indirect methods look for the influence of new physics on established Standard Model processes; if a measurement differs from the Standard Model prediction this suggests evidence of new physics.

A precise measurement of the effective lifetime of the $B_s^0 \rightarrow K^+K^-$ decay mode may provide indirect evidence for the existence of new physics particles. This chapter outlines the theoretical motivation for making a measurement of the $B_s^0 \rightarrow K^+K^-$ lifetime. Section 1.1 explores quark mixing in the Standard Model and Section 1.2 describes the phenomenon of B mixing. Section 1.3 explains how a measurement of the effective $B_s^0 \rightarrow K^+K^-$ lifetime makes it possible to detect new physics and Section 1.3.2 describes the current experimental status of the measurement.

Another promising location in which to search for evidence of physics beyond the Standard Model is in the $D^0 - \bar{D}^0$ system. Evidence of significant mixing and/or CP violation in the decay mode $D^0 \rightarrow K^+K^-$ may also indicate the presence of new physics. This topic is explored in Section 1.4 along with a description of the current experimental status of this measurement. Throughout this dissertation the charge-conjugates of each decay mode are implied unless stated otherwise. For instance $B_s^0 \rightarrow K^+K^-$ stands for both $B_s^0 \rightarrow K^+K^-$ and $\bar{B}_s^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+K^-$ stands for both $D^0 \rightarrow \pi^+K^-$ and $\bar{D}^0 \rightarrow \pi^-K^+$.

1.1 Quark Mixing in the Standard Model

In the Standard Model the weak and electromagnetic forces arise from a $SU(2) \times U(1)_Y$ gauge symmetry of the Lagrangian. Explicit fermion mass terms of the form

$$m\bar{\psi}\psi = m(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R) \quad (1.1)$$

are not permitted since the left-handed and right-handed components of the fermion fields, ψ_L and ψ_R , transform differently under $SU(2)$:

$$\psi_L \xrightarrow{SU(2)} \psi'_L = e^{-i\omega^a \mathbf{T}^a} \psi_L \quad (1.2)$$

$$\psi_R \xrightarrow{SU(2)} \psi'_R = \psi_R \quad (1.3)$$

and so $m\bar{\psi}\psi$ is not $SU(2)$ gauge invariant. Instead, the fermions acquire mass through the introduction of a scalar $SU(2)$ doublet Φ which is better known as the “Higgs” field [7]. This produces gauge invariant Yukawa interaction terms when the Higgs field acquires a vacuum expectation value, giving the fermions mass. The Yukawa term for the quark fields is

$$\mathcal{L}_{Yukawa} = -[Y_d]_{ij}\bar{q}_L^i\Phi d_R^j - [Y_u]_{ij}\bar{q}_L^i\Phi^c u_R^j + \text{h.c.} \quad (1.4)$$

where q_L are the three left-handed quark doublets (one for each generation), d_R and u_R are the three right-handed down-type and up-type quark singlets, $[Y_d]_{ij}$ and $[Y_u]_{ij}$ are the 3×3 Yukawa coupling matrices and “h.c.” stands for “Hermitian conjugate”. The off-diagonal elements of the Yukawa matrices couple quarks of different generations. However, a change of basis may be performed that diagonalises the Yukawa matrices thus eliminating all intergenerational couplings. The resulting quark fields are then the *physical* eigenstates of the quarks with definite mass:

$$q_L = \left[\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \right] \quad (1.5)$$

$$d_R = \left[d_R, s_R, b_R \right] \quad (1.6)$$

$$u_R = \begin{bmatrix} u_R & c_R & t_R \end{bmatrix}. \quad (1.7)$$

However, this rotation of the quark fields makes it apparent that the $W^\pm$ bosons do not couple directly to the physical eigenstates of the quarks. The charged-current weak interaction term in the Lagrangian is

$$\mathcal{L}_W = -\frac{g}{2\sqrt{2}} \left[\bar{u}\gamma^\mu(1-\gamma^5)\tilde{d}W_\mu^- + \bar{c}\gamma^\mu(1-\gamma^5)\tilde{s}W_\mu^- + \bar{t}\gamma^\mu(1-\gamma^5)\tilde{b}W_\mu^- + \text{h.c.} \right] \quad (1.8)$$

where $\tilde{q}$ are the *weak* eigenstates of the quarks. The weak eigenstates are superpositions of the physical eigenstates and are related by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [8, 9] $\mathbf{V}_{\text{CKM}}$:

$$\begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} = \mathbf{V}_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.9)$$

The structure of the charged-current weak interaction therefore allows mixing between the different quark generations and is referred to as *flavour changing*. $\mathbf{V}_{\text{CKM}}$ is a 3×3 unitary matrix which may be written as

$$\mathbf{V}_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.10)$$

where each element is complex and is proportional to the amplitude for a particular weak transition. For instance, the amplitude for a b quark to decay to a u quark (emitting a W^-) is proportional to V_{ub} whereas the amplitude for a t quark to decay to a b quark (emitting a W^+) is proportional to V_{tb}^* .

In general, a 3×3 complex matrix has 18 independent parameters (nine entries, each with a real and imaginary part). The unitarity of the CKM matrix reduces this to nine and a further five are absorbed by relative phase changes between the quark fields. This leaves four independent parameters: three mixing angles and a complex phase. The fact that elements of the CKM matrix may be complex allows Charge-Parity (CP) conservation violation to occur within the framework of the Standard Model.

The CKM matrix can be represented using the Wolfenstein parametrisation [10]:

$$\mathbf{V}_{\text{CKM}} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & \lambda^3 A (\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & \lambda^2 A \\ \lambda^3 A (1 - \rho - i\eta) & -\lambda^2 A & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad (1.11)$$

where λ , A , ρ and η are fundamental parameters of the Standard Model and have been measured by experiment as $\lambda = 0.2253 \pm 0.0007$, $A = 0.808^{+0.022}_{-0.015}$, $\rho = 0.132^{+0.022}_{-0.014}$, $\eta = 0.341 \pm 0.013$ [11]. Experiments at the LHC, including LHCb, will be sensitive to higher order terms (λ^4 and greater) of the CKM matrix. This representation makes it clear that the intergenerational weak couplings of the quarks are small compared to couplings between u -type and d -type type quarks within the same generation. In the case of the third generation, the t and b quarks couple almost exclusively to each other.

The unitarity of the CKM matrix ($\mathbf{V}_{\text{CKM}} \mathbf{V}_{\text{CKM}}^\dagger = \mathbf{V}_{\text{CKM}}^\dagger \mathbf{V}_{\text{CKM}} = \mathbf{I}$ where $\mathbf{I}$ is the identity matrix) produces six orthogonality conditions:

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0, \quad (1.12)$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0, \quad (1.13)$$

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0, \quad (1.14)$$

$$V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0, \quad (1.15)$$

$$V_{td}^* V_{ud} + V_{ts}^* V_{us} + V_{tb}^* V_{ub} = 0, \quad (1.16)$$

$$V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0. \quad (1.17)$$

These conditions may be represented visually as triangles in the complex plane. Equation 1.13, which governs $b \rightarrow d$ transitions in B^0 mixing, is special amongst the unitarity triangles in that all its sides are of order $A\lambda^3$ and is usually referred to as “the unitarity triangle”. An illustration of the unitarity triangle is shown in Figure 1.1. The rescaling of the sides of the triangle by a factor of $V_{cd}V_{cb}^*$ gives the the base unit length and sets the apex at coordinates $(\bar{\rho}, \bar{\eta})$ where

$$\bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}. \quad (1.18)$$

The angles of the triangle α , β and γ are defined as

$$\alpha = \tan^{-1} \left(\frac{\bar{\eta}}{\bar{\eta}^2 + \bar{\rho}(\bar{\rho} - 1)} \right) \quad \beta = \tan^{-1} \left(\frac{\bar{\eta}}{1 - \bar{\rho}} \right) \quad \gamma = \tan^{-1} \left(\frac{\bar{\eta}}{\bar{\rho}} \right). \quad (1.19)$$

There are also corresponding triangles for $b \rightarrow s$ transitions explored through B_s^0 mixing, $c \rightarrow u$ transitions in D^0 mixing and $s \rightarrow d$ transitions in K^0 mixing. These correspond to Equations 1.14, 1.15 and 1.12 respectively.

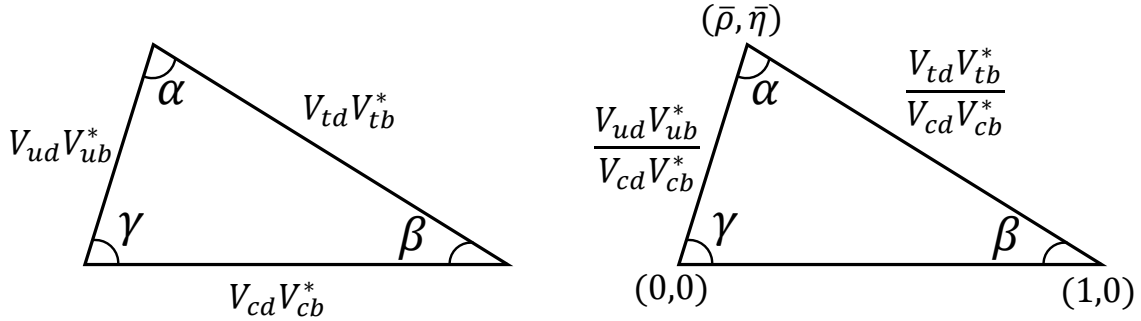


Figure 1.1: The unitarity triangle of the CKM matrix. Left: the triangle as expressed by Equation 1.13. Right: the triangle scaled by $V_{cd}V_{cb}^*$ defining $\bar{\rho}$ and $\bar{\eta}$.

All measurements of the lengths of the sides (from decay and mixing rates) and angles (from CP asymmetries) of the unitarity triangles should fit together. Any new physics contributions to mixing or CP violation may alter the angles and sides of the triangles so that they no longer fit the CKM picture. Thus, overconstraining the sides and angles of the unitarity triangles is an excellent way to probe for new physics. The current experimental status of the unitarity triangle is shown in Figure 1.2.

New physics beyond the Standard Model is likely to influence processes which are dominated by Feynman diagrams containing loops. Conversely, processes dominated by direct quark transitions without loops or “tree-level” diagrams are unlikely to be affected by new physics. It is therefore interesting to compare the CKM picture in Figure 1.2 with that obtained from tree-dominated processes only, which is shown in Figure 1.3. A comparison of the two plots shows that there is currently no evidence of new physics affecting the CKM mechanism as both results are consistent with one another.

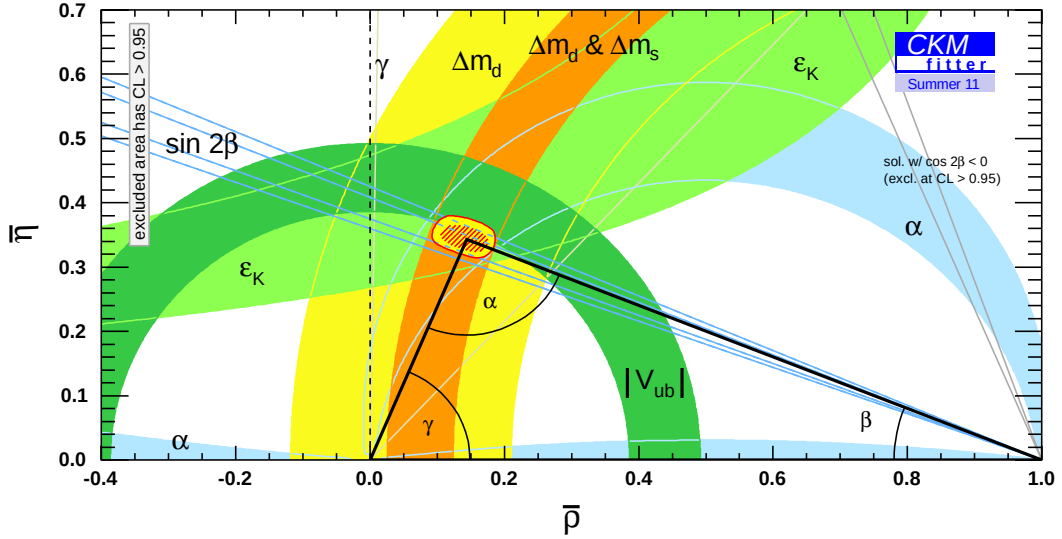


Figure 1.2: The global CKM fit in the small $(\bar{\rho}, \bar{\eta})$ plane. The red hashed region of the global combination corresponds to 68% confidence limit [12].

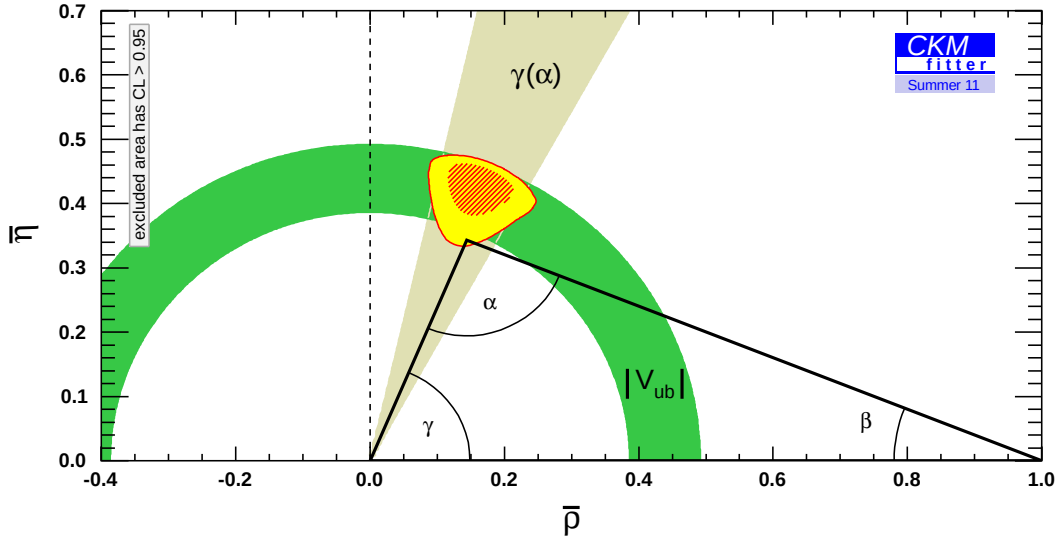


Figure 1.3: The CKM fit for tree processes only in the small $(\bar{\rho}, \bar{\eta})$ plane. The red hashed region of the global combination corresponds to 68% confidence limit [12].

1.2 B_s^0 Meson Mixing

B mesons are quark-antiquark bound states containing a beauty (or bottom, depending on taste) quark. The neutral B mesons, of which there are two classes labelled B^0

(containing a down quark and a beauty antiquark) and B_s^0 (containing a strange quark and a beauty antiquark), exhibit transitions between their two weak eigenstates in a process referred to as *mixing*. This is a direct result of quark mixing due to the W boson and so by studying neutral B mesons it is possible to explore the structure of the CKM matrix, determine the extent of CP violation in the Standard Model and search for signs of new physics phenomena.

The theoretical description of B_s^0 mixing is outlined in this section, following the discussion presented in [13]. The formalism for B^0 mixing (and indeed D^0 and K^0 mixing) is identical although the parameters have different values. In the Standard Model, transitions occur between the B_s^0 and $\bar{B}_s^0$ weak states through interactions involving at least two W bosons. The lowest order Feynman diagrams for these interactions are shown in Figure 1.4. Such transitions have at least four weak vertices and consequently the amplitude for B_s^0 mixing is predicted to be very small. The influence of new physics may therefore appear as a large modification to the expected amplitude, making the B_s^0 system an excellent probe for beyond the Standard Model effects.

The $B_s^0 - \bar{B}_s^0$ meson system evolves according to the time-dependent Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2} \mathbf{\Gamma} \right) \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} \quad (1.20)$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are the 2×2 Hermitian *mass* and *decay* matrices. $B_s^0 - \bar{B}_s^0$ transitions are responsible for the off-diagonal elements of the mass matrix

$$\mathbf{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{11} \end{pmatrix} \quad (1.21)$$

and the decay matrix

$$\mathbf{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{11} \end{pmatrix}. \quad (1.22)$$

The simultaneous conservation of Charge, Parity and Time reversal (CPT) symmetry requires that $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$. The *light* and *heavy* physical eigenstates are

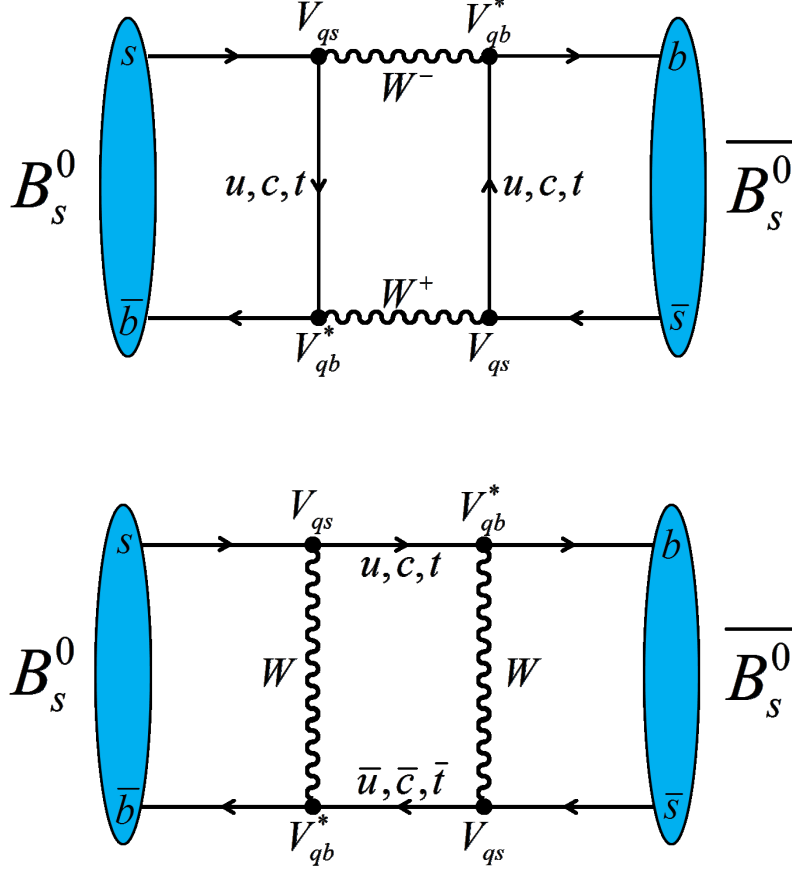


Figure 1.4: The lowest order Feynman box diagrams for $B_s^0 - \bar{B}_s^0$ mixing.

the eigenvectors of $\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$

$$|B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \quad (1.23)$$

$$|B_H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \quad (1.24)$$

with eigenvalues $m_L - i\Gamma_L/2$ and $m_H - i\Gamma_H/2$ respectively and where $|p|^2 + |q|^2 = 1$.

A CP reflection transforms one weak eigenstate into the other:

$$\widehat{CP}|B_s^0\rangle = |\bar{B}_s^0\rangle \quad (1.25)$$

$$\widehat{CP}|\bar{B}_s^0\rangle = |B_s^0\rangle, \quad (1.26)$$

and so if $p = q = 1/\sqrt{2}$ then the physical eigenstates are also CP eigenstates. However, the complex phase of the CKM matrix gives rise to a complex phase in the ratio of p

and q which demonstrates that the physical and CP eigenstates are not the same.

The physical eigenstates evolve with time according to

$$|B_L(t)\rangle = |B_L\rangle e^{-i(m_L - i\Gamma_L/2)t} \quad (1.27)$$

$$|B_H(t)\rangle = |B_H\rangle e^{-i(m_H - i\Gamma_H/2)t} \quad (1.28)$$

and so inverting Equations 1.23 and 1.24 we find that a pure B_s^0 or $\bar{B}_s^0$ state at $t = 0$ will evolve according to

$$|B_s^0(t)\rangle = \frac{1}{2p} (|B_L\rangle e^{-i(m_L - i\Gamma_L/2)t} + |B_H\rangle e^{-i(m_H - i\Gamma_H/2)t}) \quad (1.29)$$

$$|\bar{B}_s^0(t)\rangle = \frac{1}{2q} (|B_L\rangle e^{-i(m_L - i\Gamma_L/2)t} - |B_H\rangle e^{-i(m_H - i\Gamma_H/2)t}). \quad (1.30)$$

At this point it is useful to define the quantities m_s , Δm_s , Γ_s and $\Delta\Gamma_s$:

$$m_s \equiv \frac{m_H + m_L}{2} \quad \Delta m_s \equiv m_H - m_L \quad (1.31)$$

$$\Gamma_s \equiv \frac{\Gamma_L + \Gamma_H}{2} \quad \Delta\Gamma_s \equiv \Gamma_L - \Gamma_H \quad (1.32)$$

where m_s is the mean mass of the B_s^0 system, Δm_s is the mass difference, Γ_s is the mean width and $\Delta\Gamma_s$ is the width difference. Under these definitions both Δm_s and $\Delta\Gamma_s$ are positive. Expressing Equations 1.29 and 1.30 in terms of the weak eigenstates the time-dependent decay rates become:

$$|B_s^0(t)\rangle = f_+(t)|B_s^0\rangle + \frac{q}{p}f_-(t)|\bar{B}_s^0\rangle \quad (1.33)$$

$$|\bar{B}_s^0(t)\rangle = \frac{p}{q}f_-(t)|B_s^0\rangle + f_+(t)|\bar{B}_s^0\rangle \quad (1.34)$$

where

$$f_{\pm}(t) \equiv \frac{1}{2} e^{-i(m_s - i\frac{\Gamma_s}{2})t} \left[e^{i(\Delta m_s + i\frac{\Delta\Gamma_s}{2})t/2} \pm e^{-i(\Delta m_s + i\frac{\Delta\Gamma_s}{2})t/2} \right]. \quad (1.35)$$

In the Standard Model the off-diagonal elements of the mass and decay matrices can be calculated from theory whereas experiments are able to measure the mass and width differences of the physical eigenstates. It is therefore necessary to express Δm_s and $\Delta\Gamma_s$ in terms of M_{12} and Γ_{12} if the validity of the theory is to be established. It is helpful to

define the $B_s^0 - \bar{B}_s^0$ mixing phase

$$\phi_s \equiv \arg \left(-\frac{M_{12}}{\Gamma_{12}} \right). \quad (1.36)$$

Solving for the eigenvalues and eigenvectors of $\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$ yields:

$$\Delta m_s = 2|M_{12}| \left[1 + \mathcal{O} \left(\left| \frac{\Gamma_{12}}{M_{12}} \right|^2 \right) \right], \quad (1.37)$$

$$\Delta \Gamma_s = 2|\Gamma_{12}| \cos \phi_s \left[1 + \mathcal{O} \left(\left| \frac{\Gamma_{12}}{M_{12}} \right|^2 \right) \right] \quad (1.38)$$

where an expansion in $|\Gamma_{12}/M_{12}|$ has been made since it is known empirically that $|\Gamma_{12}| \ll |M_{12}|$. Likewise, p/q may be written in terms of the small parameter

$$a \equiv \text{Im} \left(\frac{\Gamma_{12}}{M_{12}} \right) = \left| \frac{\Gamma_{12}}{M_{12}} \right| \sin \phi_s \quad (1.39)$$

such that

$$\frac{p}{q} = -e^{-i\phi_M} \left[1 - \frac{a}{2} \right] + \mathcal{O} \left(\left| \frac{\Gamma_{12}}{M_{12}} \right|^2 \right) \quad (1.40)$$

where ϕ_M is defined as

$$\phi_M \equiv \arg(M_{12}). \quad (1.41)$$

Having set up the necessary machinery it is now possible to start to ask more interesting questions, such as what is the decay rate to a specific final state? To answer this question it is first convenient to define a few more parameters. The amplitudes for B_s^0 and $\bar{B}_s^0$ to decay to final state f :

$$A_f \equiv \langle f | B_s^0 \rangle \quad \bar{A}_f \equiv \langle f | \bar{B}_s^0 \rangle \quad (1.42)$$

and the important parameter:

$$\lambda_f \equiv \frac{p}{q} \frac{\bar{A}_f}{A_f} \simeq -e^{-i\phi_M} \frac{\bar{A}_f}{A_f} \left[1 - \frac{a}{2} \right]. \quad (1.43)$$

The time-dependent decay rates can then be expressed as

$$\Gamma(B_s^0(t) \rightarrow f) = \mathcal{N}_f |\langle f | B_s^0(t) \rangle|^2 \quad (1.44)$$

$$\Gamma(\bar{B}_s^0(t) \rightarrow f) = \mathcal{N}_f |\langle f | \bar{B}_s^0(t) \rangle|^2 \quad (1.45)$$

where $\mathcal{N}_f$ is a normalisation factor that depends only on kinematics. Using Equations 1.33 and 1.34 and the above definitions and relations one arrives at complete expressions for the time-dependent decay rates in terms of m_s , Δm_s , Γ_s and $\Delta\Gamma_s$:

$$\begin{aligned} \Gamma(B_s^0(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 e^{-\Gamma_s t} & \left\{ \frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta\Gamma_s t}{2} + \frac{1 - |\lambda_f|^2}{2} \cos(\Delta m_s t) \right. \\ & \left. - \text{Re}(\lambda_f) \sinh \frac{\Delta\Gamma_s t}{2} - \text{Im}(\lambda_f) \sin(\Delta m_s t) \right\}, \end{aligned} \quad (1.46)$$

$$\begin{aligned} \Gamma(\bar{B}_s^0(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 (1 + a) e^{-\Gamma_s t} & \left\{ \frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta\Gamma_s t}{2} - \frac{1 - |\lambda_f|^2}{2} \cos(\Delta m_s t) \right. \\ & \left. - \text{Re}(\lambda_f) \sinh \frac{\Delta\Gamma_s t}{2} + \text{Im}(\lambda_f) \sin(\Delta m_s t) \right\}. \end{aligned} \quad (1.47)$$

If the asymmetries

$$\mathcal{A}_{\Delta\Gamma} = -\frac{2\text{Re}(\lambda_f)}{1 + |\lambda_f|^2} \quad \mathcal{A}_{CP}^{mix} = -\frac{2\text{Im}(\lambda_f)}{1 + |\lambda_f|^2} \quad \mathcal{A}_{CP}^{dir} = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \quad (1.48)$$

are defined, where $(\mathcal{A}_{\Delta\Gamma})^2 + (\mathcal{A}_{CP}^{dir})^2 + (\mathcal{A}_{CP}^{mix})^2 = 1$, the decay rate expressions are then somewhat simplified to

$$\begin{aligned} \Gamma(B_s^0(t) \rightarrow f) = \frac{1}{2} \mathcal{N}_f |A_f|^2 (1 + |\lambda_f|^2) e^{-\Gamma_s t} & \left\{ \cosh \frac{\Delta\Gamma_s t}{2} + \mathcal{A}_{CP}^{dir} \cos(\Delta m_s t) \right. \\ & \left. + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_s t}{2} + \mathcal{A}_{CP}^{mix} \sin(\Delta m_s t) \right\}, \end{aligned} \quad (1.49)$$

$$\begin{aligned} \Gamma(\bar{B}_s^0(t) \rightarrow f) = \frac{1}{2} \mathcal{N}_f |A_f|^2 (1 + a) (1 + |\lambda_f|^2) e^{-\Gamma_s t} & \left\{ \cosh \frac{\Delta\Gamma_s t}{2} - \mathcal{A}_{CP}^{dir} \cos(\Delta m_s t) \right. \\ & \left. + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_s t}{2} - \mathcal{A}_{CP}^{mix} \sin(\Delta m_s t) \right\}. \end{aligned} \quad (1.50)$$

1.2.1 The Decay Rate for Untagged B_s^0 Mesons

It is expected that B_s^0 and $\bar{B}_s^0$ mesons will be produced in almost equal quantities at LHCb since neither particle shares a valence quark with the proton. In this case Equations 1.49 and 1.50 can be combined to obtain the time-dependent decay rate for

untagged B_s^0 mesons:

$$\begin{aligned}\Gamma[f, t] &= \Gamma(B_s^0(t) \rightarrow f) + \Gamma(\bar{B}_s^0(t) \rightarrow f) \\ &= \mathcal{N}_f |A_f|^2 (1 + |\lambda_f|^2) e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta\Gamma_s t}{2} + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_s t}{2} \right\} + \mathcal{O}(a). \quad (1.51)\end{aligned}$$

Using $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ and neglecting terms of order a , this becomes

$$\Gamma[f, t] \simeq \frac{1}{2} \mathcal{N}_f |A_f|^2 (1 + |\lambda_f|^2) \left\{ (1 - \mathcal{A}_{\Delta\Gamma}) e^{-\Gamma_L t} + (1 + \mathcal{A}_{\Delta\Gamma}) e^{-\Gamma_H t} \right\}. \quad (1.52)$$

This is a rather intuitive expression with two exponential decay distributions, one for each physical eigenstate. Using these results it is now possible to consider the specific case of the decay $B_s^0 \rightarrow K^+ K^-$.

1.3 Searching for New Physics with $B_s^0 \rightarrow K^+ K^-$

As shown in Equation 1.38 the width difference in the B_s^0 system is related to the B_s^0 mixing phase ϕ_s :

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \simeq |\Gamma_{12}| \cos \phi_s. \quad (1.53)$$

In the Standard Model it is predicted to be small with $\phi_s^{SM} = (-2.1 \pm 0.1)^\circ$ [12] such that $\cos \phi_s \approx 1$. Any new physics phenomena are unlikely to affect Γ_{12} since it is dominated by CKM-favoured $b \rightarrow c\bar{c}s$ tree level decays. However, new physics may affect ϕ_s which is likely to be increased thus reducing $\Delta\Gamma_s$ according to:

$$\Delta\Gamma_s = |\Gamma_{12}| \cos(\phi_s^{SM} + \phi_s^{NP}) \quad (1.54)$$

where ϕ_s^{NP} is additional phase due to new physics. A measurement of $\Delta\Gamma_s$ may therefore be used to constrain beyond the Standard Model effects.

CP violation in mixing is predicted to be small in the Standard Model and so the

physical and CP eigenstates are expected to be approximately equal such that

$$|B_L\rangle \approx |B_{\text{even}}\rangle = \frac{1}{\sqrt{2}} (|B_s^0\rangle + |\bar{B}_s^0\rangle) \quad (1.55)$$

$$|B_H\rangle \approx |B_{\text{odd}}\rangle = \frac{1}{\sqrt{2}} (|B_s^0\rangle - |\bar{B}_s^0\rangle). \quad (1.56)$$

In this case a possible approach to measure $\Delta\Gamma_s$ would be to make direct measurements of Γ_L and Γ_H . For example, the $L = 1$ orbital angular momentum state of the decay mode $B_s^0 \rightarrow J/\psi\phi$ could be used to measure Γ_H as the final state is CP-odd and the decay proceeds via CKM-favoured $b \rightarrow c\bar{c}s$ tree processes, eliminating possible contributions from new physics. In this case $\mathcal{A}_{\Delta\Gamma} = 1$ and the measured decay time distribution would be proportional only to $e^{-\Gamma_H t}$. In the same way, Γ_L could be measured using the $B_s^0 \rightarrow D_s^+ D_s^-$ decay mode, where the final state is CP-even, $\mathcal{A}_{\Delta\Gamma} = -1$ and the decay goes as $e^{-\Gamma_L t}$.

Unfortunately, in the case of $B_s^0 \rightarrow K^+ K^-$ life is not so simple. A complication arises since the decay is predicted to be dominated by penguin diagrams as the lowest order $b \rightarrow u\bar{u}s$ tree process is CKM-suppressed. Examples of lowest order tree and penguin Feynman diagrams are shown in Figure 1.5. If new physics particles exist then they may enter the decay in the penguin loops and effectively move $\mathcal{A}_{\Delta\Gamma}$ away from -1 such that the Γ_H component plays a larger role. In any case, if the B_s^0 mixing phase ϕ_s is enlarged due to beyond the Standard Model physics, then the physical and CP eigenstates no longer coincide meaning that the light and heavy physical states have increased amplitudes to decay to the odd and even CP states respectively.

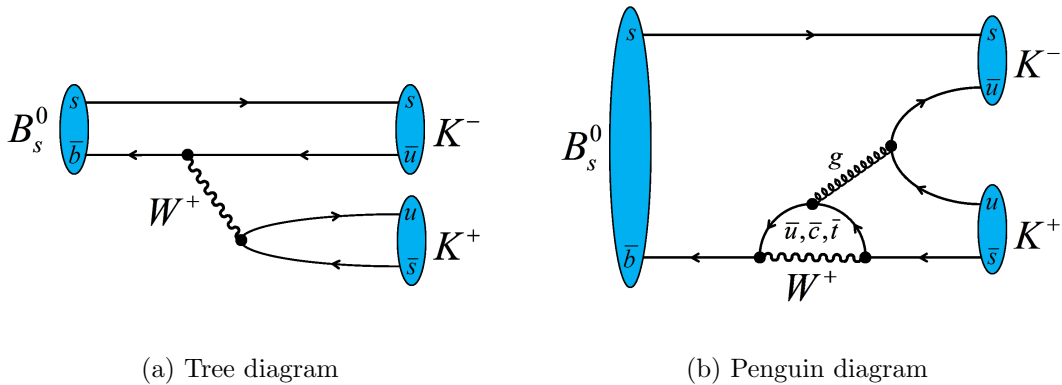


Figure 1.5: The lowest order Standard Model Feynman tree and penguin diagrams for the $B_s^0 \rightarrow K^+ K^-$ decay.

In general the decay time for $B_s^0 \rightarrow K^+ K^-$ follows

$$\Gamma[K^+ K^-, t] \propto (1 - \mathcal{A}_{\Delta\Gamma})e^{-\Gamma_L t} + (1 + \mathcal{A}_{\Delta\Gamma})e^{-\Gamma_H t}. \quad (1.57)$$

A particularly useful and simple observable is the *effective* $B_s^0 \rightarrow K^+ K^-$ lifetime which is defined as

$$\tau_{K^+ K^-} = \frac{\int_0^\infty t \Gamma[K^+ K^-, t] dt}{\int_0^\infty \Gamma[K^+ K^-, t] dt}. \quad (1.58)$$

This is also the result obtained if Equation 1.57 is fitted with a single exponential of the form $\propto e^{-t/\tau_{K^+ K^-}}$ as shown in [14]. The effective lifetime is related to the light and heavy widths according to [15]

$$\tau_{K^+ K^-} = \frac{(1 - \mathcal{A}_{\Delta\Gamma})/\Gamma_L^2 + (1 + \mathcal{A}_{\Delta\Gamma})/\Gamma_H^2}{(1 - \mathcal{A}_{\Delta\Gamma})/\Gamma_L + (1 + \mathcal{A}_{\Delta\Gamma})/\Gamma_H}. \quad (1.59)$$

This can be written in terms of the ratio

$$y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s} \quad (1.60)$$

and the mean B_s^0 lifetime τ_{B_s} , such that

$$\frac{\tau_{K^+ K^-}}{\tau_{B_s}} = \frac{1}{1 - y_s^2} \frac{1 + 2\mathcal{A}_{\Delta\Gamma}y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}y_s}. \quad (1.61)$$

Therefore, a measurement of the effective lifetime can be used to constrain y_s and detect new physics affecting the mixing phase ϕ_s , if a measurement of $\mathcal{A}_{\Delta\Gamma}$ is available.

1.3.1 Standard Model Prediction of The Effective $B_s^0 \rightarrow K^+ K^-$ Lifetime

The results and figures presented in this section are taken from [15]. It is apparent from Equation 1.61 that in order to make a prediction of $\tau_{K^+ K^-}$, it is necessary to calculate both $\Delta\Gamma_s/\Gamma_s$ and $\mathcal{A}_{\Delta\Gamma}$. The prediction of $\mathcal{A}_{\Delta\Gamma}$ is problematic as it depends upon hadronic parameters. Both experimental and theoretical inputs must be used to arrive at a result. For example, the prediction requires knowledge of $\mathcal{A}_{CP}^{dir}$ which is currently unknown for $B_s^0 \rightarrow K^+ K^-$. The authors of [15] therefore take the value measured for the decay $B^0 \rightarrow K^+ \pi^-$ which differs only from $B_s^0 \rightarrow K^+ K^-$ in the

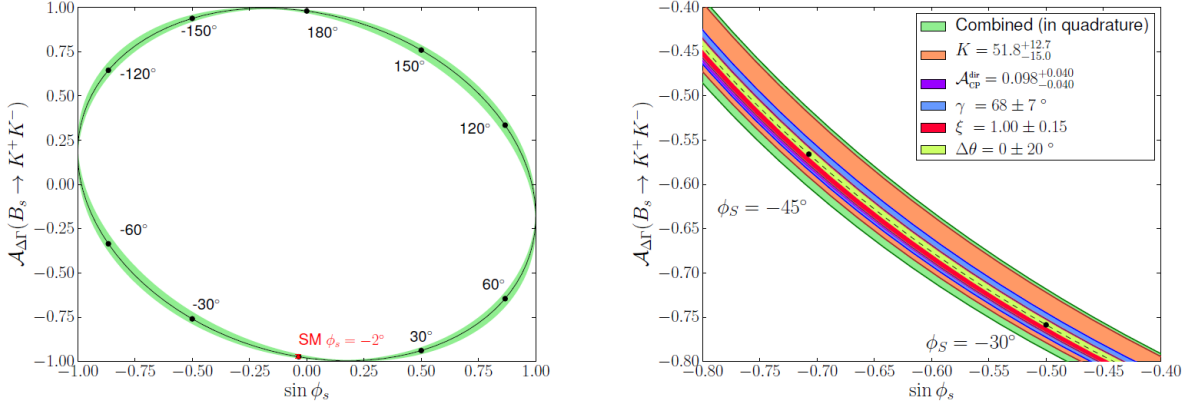


Figure 1.6: Left panel: correlation between $\mathcal{A}_{\Delta\Gamma}$ and $\sin \phi_s$. Right panel: errors associated with the input observables/parameters, zoomed in for a NP region of $-25^\circ \geq \phi_s \geq -50^\circ$ and overlaid on top of one another [15]. The legend lists the error contributions from largest to smallest.

exchange of a spectator quark. The Standard Model Prediction for $\mathcal{A}_{\Delta\Gamma}$ is then

$$\mathcal{A}_{\Delta\Gamma}^{SM} = -0.972^{+0.014}_{-0.009}. \quad (1.62)$$

Figure 1.6 shows how $\mathcal{A}_{\Delta\Gamma}$ varies with the mixing phase ϕ_s .

The final value required is a prediction of $\Delta\Gamma_s/\Gamma_s$. The latest prediction from [16] is:

$$\frac{\Delta\Gamma_s}{\Gamma_s} = (7.4 \pm 2.4) \times 10^{-2}. \quad (1.63)$$

Combining these results the authors arrive at a prediction of

$$\frac{\tau_{K^+ K^-}}{\tau_{B_s}} = 0.9411^{+0.0011}_{-0.0006} \bigg|_{\mathcal{A}_{\Delta\Gamma}} \frac{+0.0173}{-0.0165} \bigg|_{\frac{\Delta\Gamma_s}{\Gamma_s}} = 0.9411^{+0.017}_{-0.017}. \quad (1.64)$$

Taking the latest measurement of the mean B_s^0 lifetime, $\tau_{B_s} = 1.477 \pm 0.022$ ps [17], the Standard Model prediction for the $B_s^0 \rightarrow K^+ K^-$ effective lifetime is found to be:

$$\tau_{K^+ K^-}|_{SM} = 1.390 \pm 0.032 \text{ ps}. \quad (1.65)$$

Figure 1.7 shows the correlation between $\tau_{K^+ K^-}$ and ϕ_s , from which it can be seen that a 1% measurement of $\tau_{K^+ K^-}$ will provide an excellent opportunity to discover large new physics contributions to ϕ_s . The ambiguity in ϕ_s can be resolved through the measurement of CP violation in mixing for $B_s^0 \rightarrow K^+ K^-$.

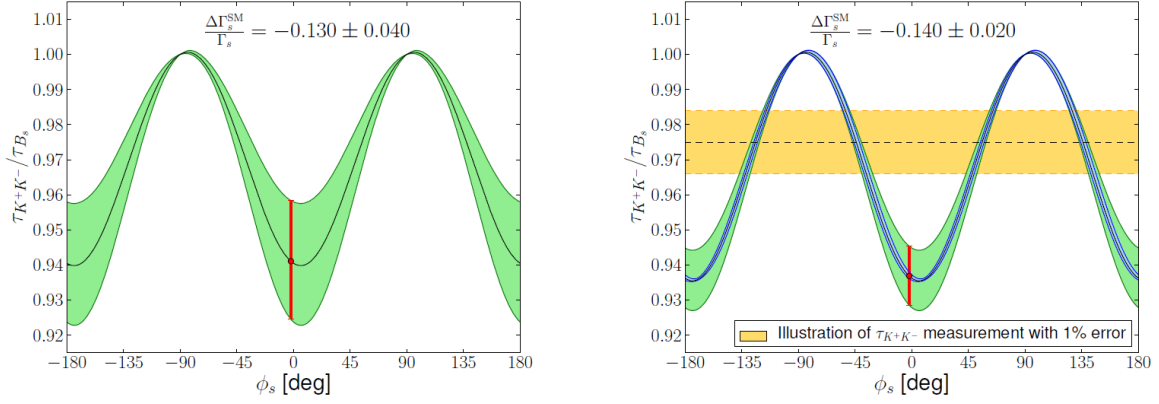


Figure 1.7: The dependence of $\tau_{K^+K^-}$ on the B_s^0 mixing phase [15]. Left panel: uses $\Delta\Gamma_s/\Gamma_s$ from Equation 1.63. Right panel: illustration of the impact of a measurement of $\tau_{K^+K^-}$ with 1% uncertainty. The narrow band on the curve corresponds to the errors of the input quantities entering our prediction of $\mathcal{A}_{\Delta\Gamma}$.

1.3.2 Current Experimental Status

To date, the only publically available measurement of $\tau_{K^+K^-}$ is due to the CDF experiment [18, 19]:

$$\tau_{K^+K^-} = 1.53 \pm 0.18(\text{stat}) \pm 0.02(\text{syst}) \text{ ps} \quad (1.66)$$

which is consistent with the Standard Model prediction. However, the uncertainties are too large to draw any conclusions on the presence of new physics. There is therefore a clear need for a more precise evaluation of the $B_s^0 \rightarrow K^+K^-$ lifetime.

The current world best measurement of ϕ_s has been made by the LHCb experiment in the channels $B_s^0 \rightarrow J/\psi\phi$ [20] and $B_s^0 \rightarrow J/\psi f^0$ [21]. The combination of the two results gives a value for one of the two ambiguous solutions $\phi_s \leftrightarrow \pi - \phi_s$ of

$$\phi_s = 0.03 \pm 0.16 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ rad} \quad (1.67)$$

which is consistent with the Standard Model expectation, though there remains the possibility of discovering new physics with increased precision. Figure 1.8 shows how the result from $B_s^0 \rightarrow J/\psi\phi$ compares with the Standard Model prediction in the ϕ_s , $\Delta\Gamma_s$ plane.

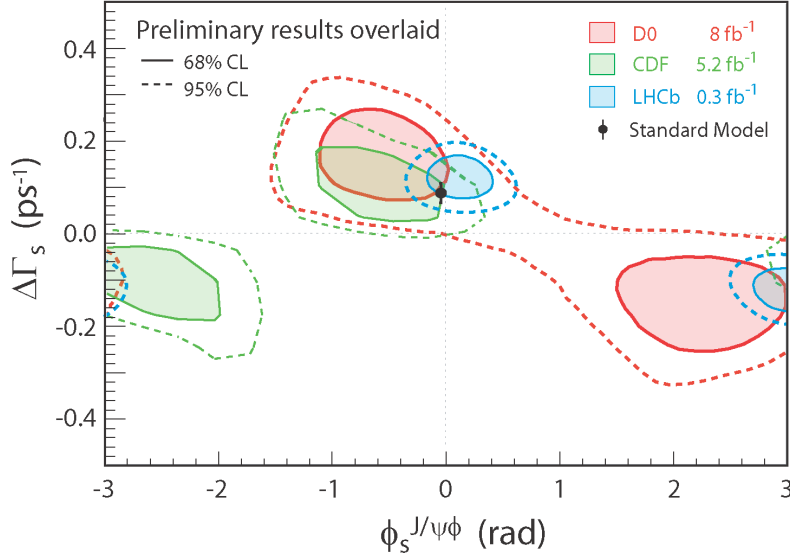


Figure 1.8: The ϕ_s , $\Delta\Gamma_s$ plane with exclusion regions from the LHCb $B_s^0 \rightarrow J/\psi\phi$ result, D0 and CDF [22]. One of the two favoured regions is consistent with the Standard Model prediction.

1.4 Mixing and CP Violation in D^0 Decays

The neutral $D^0(c\bar{u})$ system may exhibit mixing analogous to that observed in the B^0 and B_s^0 systems. However, within the framework of the Standard Model, $D^0 - \bar{D}^0$ mixing is expected to vanish in the limit of exact $SU(3)$ flavour symmetry [23]. Furthermore, both the mixing and the decays of D^0 mesons are dominated by the first and second generations meaning that CP violation can be neglected in both. However, the presence of new physics beyond the Standard Model may introduce CP violation to the mixing amplitude and so evidence of significant mixing with CP violation may indicate the presence of new physics.

The formalism of D^0 mixing is similar to that of B^0 mixing. The mass eigenstates are written

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle \quad (1.68)$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle \quad (1.69)$$

where the average mass and width are given by

$$m_D \equiv \frac{m_1 + m_2}{2}, \quad \Gamma_D \equiv \frac{\Gamma_1 + \Gamma_2}{2} \quad (1.70)$$

and the mass and width differences written as

$$x \equiv \frac{m_2 - m_1}{\Gamma_D}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma_D}. \quad (1.71)$$

As with B^0 mixing the decay amplitudes to a final state f are given by

$$A_f \equiv \langle f | D^0 \rangle, \quad \bar{A}_f \equiv \langle f | \bar{D}^0 \rangle \quad (1.72)$$

and the complex parameter

$$\lambda_f \equiv \frac{p \bar{A}_f}{q A_f} \quad (1.73)$$

is defined.

Mixing and CP violation in the D^0 system can be studied through the decays $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$ at LHCb. For proper time $t \lesssim 1/\Gamma_D$ the time-dependent decay rates can be approximated as

$$\begin{aligned} \Gamma [D^0(t) \rightarrow K^+ K^-] &= e^{-\Gamma_D t} |A_{K^+ K^-}|^2 \{1 + [\text{Re}(\lambda_{K^+ K^-}) y \\ &\quad - \text{Im}(\lambda_{K^+ K^-}) x] \Gamma_D t\} \end{aligned} \quad (1.74)$$

$$\begin{aligned} \Gamma [\bar{D}^0(t) \rightarrow K^+ K^-] &= e^{-\Gamma_D t} |\bar{A}_{K^+ K^-}|^2 \{1 + [\text{Re}(\lambda_{K^+ K^-}^{-1}) y \\ &\quad - \text{Im}(\lambda_{K^+ K^-}^{-1}) x] \Gamma_D t\} \end{aligned} \quad (1.75)$$

$$\Gamma [D^0(t) \rightarrow \pi^+ K^-] = e^{-\Gamma_D t} |A_{\pi^+ K^-}|^2 \quad (1.76)$$

$$\Gamma [\bar{D}^0(t) \rightarrow \pi^- K^+] = e^{-\Gamma_D t} |\bar{A}_{\pi^- K^+}|^2. \quad (1.77)$$

As stated previously, these decays are dominated by the physics of the first and second generations and so direct CP violation in decay will be negligible. Indirect CP violation is parametrised by

$$\left| \frac{p}{q} \right| = R_m, \quad \lambda_{K^+ K^-} = -R_m e^{i\phi_D} \quad (1.78)$$

where R_m is a real, positive dimensionless number and ϕ_D is a phase. CP violation in mixing occurs for $R_m \neq 1$ and CP violation in the interference of decays, with and

without mixing, occurs for $\sin \phi_D \neq 0$. Using these parameters, Equations 1.74 - 1.77 can be re-expressed as

$$\Gamma [D^0(t) \rightarrow K^+ K^-] = e^{-\Gamma_D t} |A_{K^+ K^-}|^2 [1 - R_m (y \cos \phi_D - x \sin \phi_D) \Gamma_D t] \quad (1.79)$$

$$\Gamma [\bar{D}^0(t) \rightarrow K^+ K^-] = e^{-\Gamma_D t} |A_{K^+ K^-}|^2 [1 - R_m^{-1} (y \cos \phi_D + x \sin \phi_D) \Gamma_D t] \quad (1.80)$$

$$\Gamma [D^0(t) \rightarrow \pi^+ K^-] = \Gamma [\bar{D}^0(t) \rightarrow \pi^- K^+] = e^{-\Gamma_D t} |A_{\pi^+ K^-}|^2. \quad (1.81)$$

If the above decay rates are modelled as pure exponential distributions then the time-integrated decay rates are given by

$$\hat{\Gamma} (D^0 \rightarrow K^+ K^-) = \Gamma_D [1 + R_m (y \cos \phi_D - x \sin \phi_D)] \quad (1.82)$$

$$\hat{\Gamma} (\bar{D}^0 \rightarrow K^+ K^-) = \Gamma_D [1 + R_m^{-1} (y \cos \phi_D + x \sin \phi_D)] \quad (1.83)$$

$$\hat{\Gamma} (D^0 \rightarrow \pi^+ K^-) = \hat{\Gamma} (\bar{D}^0 \rightarrow \pi^- K^+) = \Gamma_D. \quad (1.84)$$

In the analysis described in this dissertation the initial flavour of the D^0 mesons (D^0 or $\bar{D}^0$) is unknown and so the mean $D \rightarrow K^+ K^-$ decay rate is the relevant quantity. In the presence of a production asymmetry

$$A_p = \frac{R_{D^0} - R_{\bar{D}^0}}{R_{D^0} + R_{\bar{D}^0}} \quad (1.85)$$

where R_{D^0} and $R_{\bar{D}^0}$ are the production rates of D^0 and $\bar{D}^0$ mesons respectively, the mean $D \rightarrow K^+ K^-$ decay rate is given by

$$\begin{aligned} \hat{\Gamma} (D \rightarrow K^+ K^-) &= \frac{1 + A_p}{2} \hat{\Gamma} (D^0 \rightarrow K^+ K^-) + \frac{1 - A_p}{2} \hat{\Gamma} (\bar{D}^0 \rightarrow K^+ K^-) \\ &= \frac{\Gamma_D}{2} \{2 + y \cos \phi_D [(R_m + R_m^{-1}) + A_p (R_m - R_m^{-1})] \\ &\quad - x \sin \phi_D [(R_m - R_m^{-1}) + A_p (R_m + R_m^{-1})]\}. \end{aligned} \quad (1.86)$$

The production asymmetry is considered in the case of $D^0 - \bar{D}^0$ mixing since while $\bar{D}^0(u\bar{c})$ meson shares a valence u quark with the proton the $D^0(c\bar{u})$ meson does not and so the production asymmetry is expected to be significant for D mesons produced in proton-proton collisions. With this information it is possible to calculate the interesting

quantity

$$y_{CP} \equiv \frac{\hat{\Gamma}(D \rightarrow K^+ K^-)}{\hat{\Gamma}(D^0 \rightarrow \pi^+ K^-)} - 1 \quad (1.87)$$

$$= \frac{1}{2} \{ y \cos \phi_D [(R_m + R_m^{-1}) + A_p (R_m - R_m^{-1})] - x \sin \phi_D [(R_m - R_m^{-1}) + A_p (R_m + R_m^{-1})] \}. \quad (1.88)$$

In the absence of CP violation ($\phi_D = 0$, $R_m = 1$) y_{CP} is equal to y . Therefore, precise measurements of y and y_{CP} can be used to determine the presence of CP violation in the D^0 system.

1.4.1 Current Experimental Status

Measurements of y_{CP} have been made by the BELLE and BABAR collaborations. The BELLE collaboration studied a sample of $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$ decays where the initial flavour of the D^0 meson was tagged by reconstructing $D^{*+} \rightarrow D^0 \pi_s$ where π_s is a low momentum (slow) pion [24]. They find

$$y_{CP} = 1.31 \pm 0.32(\text{stat}) \pm 0.25(\text{syst})\%. \quad (1.89)$$

This result shows evidence of D^0 mixing irrespective of the presence of CP violation at the 3.2σ level.

A similar analysis by BABAR using tagged D^0 decays [25] finds

$$y_{CP} = 1.24 \pm 0.39(\text{stat}) \pm 0.13(\text{syst})\% \quad (1.90)$$

and a second analysis, using an independent sample of D^0 mesons where the initial flavour is not determined [26], finds

$$y_{CP} = 1.12 \pm 0.26(\text{stat}) \pm 0.22(\text{syst})\%. \quad (1.91)$$

The combination of these two results gives

$$y_{CP} = 1.16 \pm 0.22(\text{stat}) \pm 0.18(\text{syst})\% \quad (1.92)$$

and excludes the no-mixing hypothesis at 4.1σ . At the current world average of y_{CP} ,

a formal 5σ discovery of D^0 mixing will require a combined statistical and systematic uncertainty below 0.24% which can be provided through a combination of the 2010 and 2011 LHCb datasets.

Chapter 2

The Large Hadron Collider and the LHCb Experiment

“In every branch of knowledge the progress is proportional to the amount of facts on which to build, and therefore to the facility of obtaining data.”

— James Clerk Maxwell

The LHCb detector [27–29] was constructed primarily to study hadrons containing b and c quarks produced in proton-proton collisions at the Large Hadron Collider (LHC). The primary goals of the LHCb collaboration are the search for evidence of new sources of CP violation not explained by the Standard Model CKM mechanism and, more broadly, to discover evidence of new physics and distinguish between new physics models. As described in Chapter 1, the B^0 , B_s^0 and D^0 systems are excellent locations in which to search for such effects.

2.1 The Large Hadron Collider

The LHC [30] is a 26.7 km accelerator and collider housed in a roughly circular tunnel originally constructed for the Large Electron-Positron collider (LEP) at the European Organisation for Nuclear Research (CERN). The tunnel is between 45 m and 170 m below ground level and slopes gently upwards towards the Jura mountains at an angle of 1.4° . Whereas LEP accelerated oppositely-charged electrons and positrons within

a single ring, the LHC collides hadrons with like-charges and therefore requires two separate rings with counter-rotating beams. These beams are brought into collision simultaneously at four points around the ring. Each collision point is located within a subterranean cavern housing a purpose-built particle detector. Moving clockwise around the LHC ring from the main CERN site the four detectors are: ATLAS at Point 1, ALICE at Point 2, CMS at Point 5 and LHCb at Point 8. A diagram of the LHC ring including the positions of the detectors is shown in Figure 2.1.

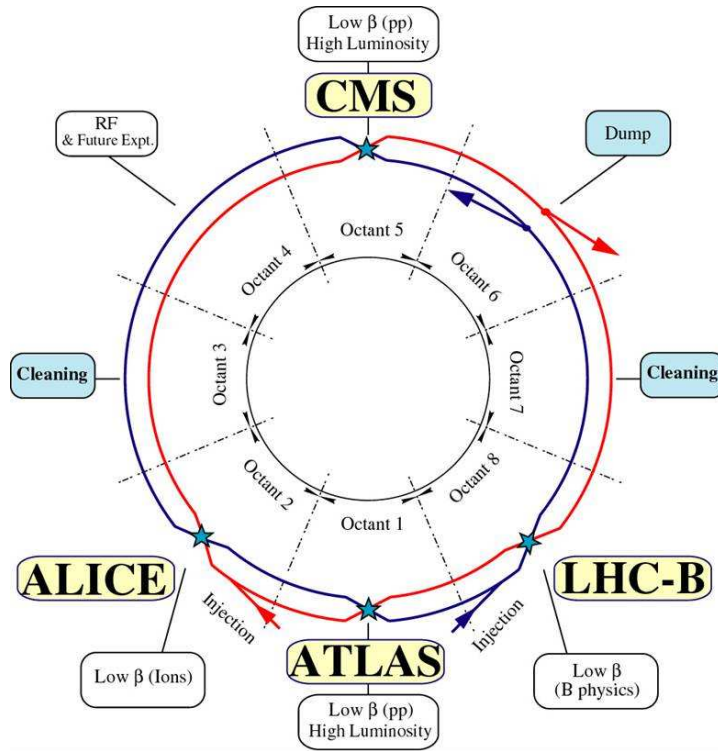


Figure 2.1: A schematic of the LHC and the positions of the four main detectors [31].

ATLAS and CMS are “general purpose” detectors designed to discover and study a wide range of new physical phenomena that may appear at the LHC. They are barrel shaped machines that cover the full 4π steradians angular acceptance with the exception of a narrow region around the beam pipe. ALICE is a specialised detector designed primarily to study an exotic state of matter known as “quark-gluon plasma” which is produced in the collisions of lead ions during designated running periods of the accelerator.

The LHC was designed to accelerate protons to an energy of 7 TeV and collide them with a combined centre-of-mass energy of 14 TeV. However, following an incident in 2008 which caused serious damage to a portion of the machine, the collider was restarted

in late 2009 and achieved the first collisions at a reduced centre-of-mass energy of 7 TeV in March 2010. The instantaneous luminosity L of the collider determines the rate of a particular class of event R_{event} according to

$$R_{event} = L\sigma_{event} \quad (2.1)$$

where σ_{event} is the cross-section for that event. The peak design luminosity of the LHC is $10^{34} \text{ cm}^2\text{s}^{-1}$ for ATLAS and CMS and $10^{32} \text{ cm}^2\text{s}^{-1}$ for LHCb. The predicted $b\bar{b}$ production cross-section at 14 TeV is $500 \mu\text{b}$ and so the expected rate of $b\bar{b}$ pair production at LHCb is 50,000 per second when the LHC is running under design conditions.

Protons for the LHC beams are incrementally accelerated through the CERN accelerator complex before injection into the LHC. They flow through a chain of accelerators: Linac2 (50 MeV) - Proton Synchrotron Booster (1.4 GeV) - Proton Synchrotron (25 GeV) - Super Proton Synchrotron (450 GeV). A schematic of the LHC injector chain is shown in Figure 2.2.

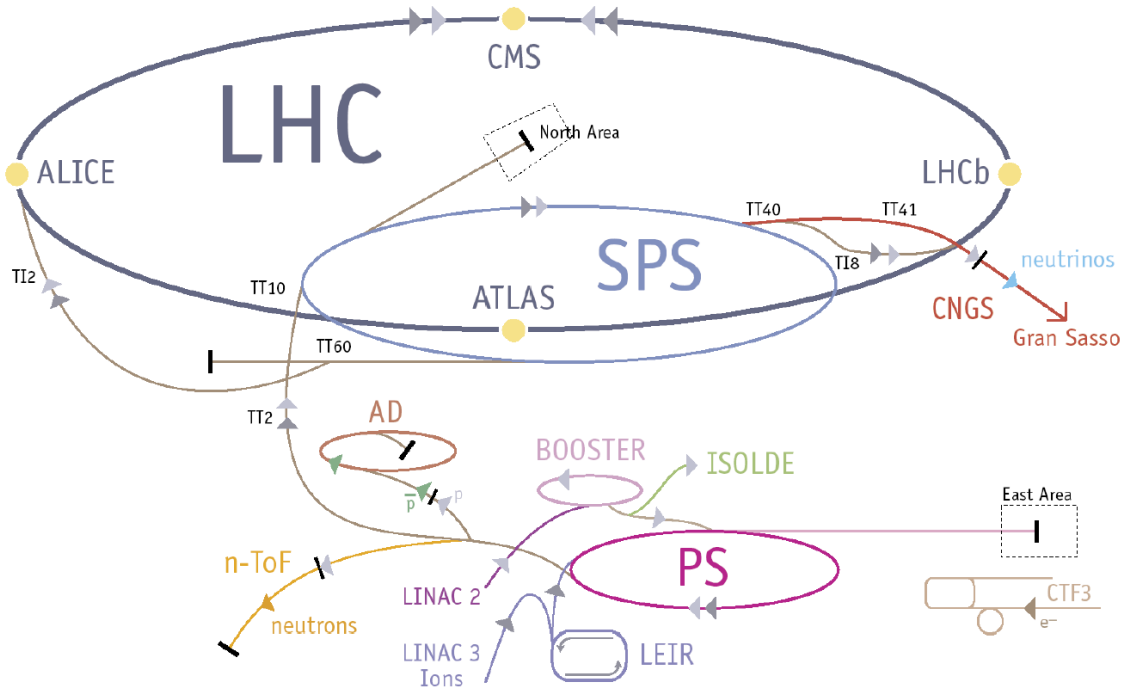


Figure 2.2: The LHC injector chain [32]. PS is the Proton Synchrotron and SPS is the Super Proton Synchrotron.

The two rings of the LHC are housed within a “twin bore” accelerator due to space limitations in the old LEP tunnel. The proton beams are steered using 1,232 super-

conducting dipole magnets with a peak field strength of above 8 T and 392 quadrupole magnets are used to keep the beams focused. The dipole magnets are cooled to below 2 K using superfluid helium. The protons are accelerated using superconducting radiofrequency cavities housed in a single straight section of the LHC tunnel.

Each proton beam consists of a series of “bunches” containing up to 1.15×10^{11} protons with a maximum of 2,808 bunches per beam. The bunches are separated by 25 ns giving a maximum collision rate of 40 MHz. At the maximum energy per beam of 7 TeV each proton is travelling at $0.999999991c$ or about 3 ms^{-1} slower than the speed of light.

2.1.1 Performance during 2010

During 2010 the LHC ran with an energy per beam of 3.5 TeV and a centre of mass energy of 7 TeV. By the end of the run the peak luminosity at LHCb reached almost $2 \times 10^{32} \text{ cm}^2\text{s}^{-1}$ with only 344 colliding bunches, a factor of eight fewer than the maximum. As a result the average number of proton-proton interactions per bunch crossing μ exceeded 2.5, presenting a serious challenge for the LHCb experiment which was designed to run with $\mu = 0.4$. Nonetheless LHCb achieved a data taking efficiency of 89%, recording 37.66 pb^{-1} of a total delivered luminosity of 42.15 pb^{-1} . The integrated luminosity over the year 2010 is shown in Figure 2.3.

The $b\bar{b}$ production cross-section at a centre-of-mass energy of 7 TeV was measured by LHCb as $\sigma(pp \rightarrow b\bar{b}X) = 284 \pm 20(\text{stat}) \pm 49(\text{syst}) \mu\text{b}$ [33]. Thus, an estimated 10 billion $b\bar{b}$ pairs were available to the LHCb experiment during 2010.

2.2 The LHCb Detector

The LHCb detector is housed in a cavern at Point 8 that was previously the home of the DELPHI [35] experiment. It is a single-arm spectrometer with an angular acceptance of 10 mrad to 300 mrad in the horizontal plane and 10 mrad to 250 mrad in the vertical plane with respect to the beam-pipe. The LHCb coordinate system has the z -axis aligned along the beam direction, pointing from the VELO to the muon stations, and the y -axis points vertically upwards from the detector towards the sky. The polar and azimuthal angles θ and ϕ are defined in the usual way for spherical polar coordinates with respect

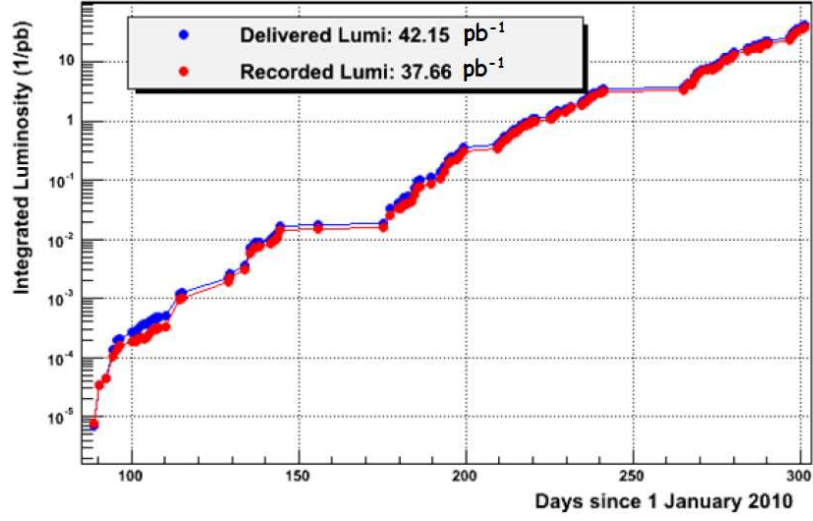


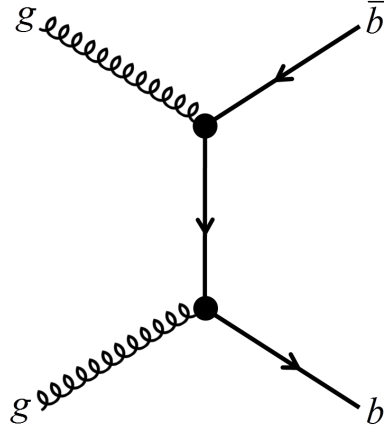
Figure 2.3: The integrated luminosity delivered to and recorded by the LHCb experiment throughout 2010 [34].

to the x , y and z axes.

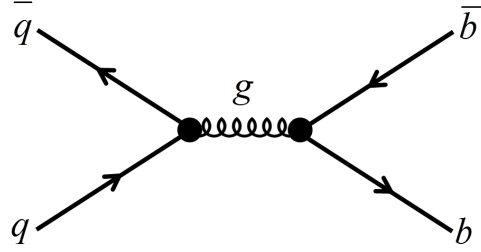
The shape of the LHCb detector was motivated by the predicted angular distribution of b quark production at the LHC. $b\bar{b}$ pair production at hadron colliders is dominated by gluon-gluon fusion (hard scattering) and quark-antiquark annihilation (hard QCD scattering), flavour excitation (semi-hard scattering) and gluon splitting (soft scattering). The leading order Feynman diagrams for these processes are shown in Figure 2.4. The full range of b -hadrons are produced at LHCb including B^0 , $B^\pm$, B_s^0 , $B_c^\pm$, Υ and b -baryons.

Figure 2.5 shows a two-dimensional plot of the polar angles of b versus $\bar{b}$ quarks produced through these processes predicted by the Pythia [36] generator. $b\bar{b}$ pairs are produced predominantly in the forward and backward directions where the angles of flight of the two quarks are positively correlated. Thus, if one quark from the $b\bar{b}$ pair flies within the LHCb geometrical acceptance then the other is also likely to do so. Despite covering only around 4% of the total solid angle the LHCb experiment accepts around 40% of all heavy-quarks (c , b , t) produced in the LHC collisions and so the single-arm design achieves both economy and good physics coverage.

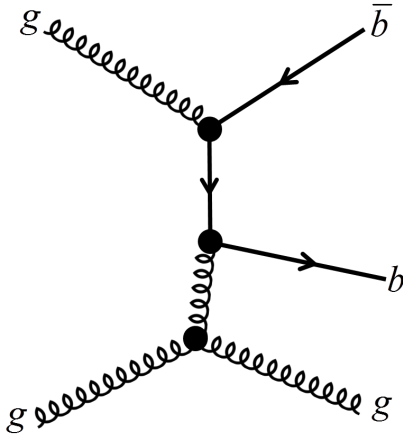
Time-dependent flavour physics measurements require excellent proper time and mass resolutions and the ability to distinguish different classes of charged hadrons and leptons ($\pi^\pm$, $K^\pm$, $p^\pm$, $e^\pm$, $\mu^\pm$). Moving along the beam direction from the interaction point, the detector follows a similar design to more conventional barrel-shaped devices



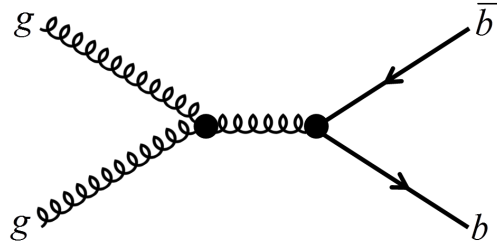
(a) gluon-gluon fusion



(b) quark-antiquark annihilation



(c) flavour excitation



(d) gluon splitting

Figure 2.4: Leading order Feynman diagrams for $b\bar{b}$ production mechanisms at the LHC.

with a tracking system followed by a magnet, calorimeters and muon chambers. However, LHCb also features two Ring-Imaging Cherenkov (RICH) detectors for identifying pions, kaons and protons. The vertex locator (VELO) also provides excellent track finding and hence allows high resolution reconstruction of vertices for precise determination of flight distances and impact parameters. A diagram of the LHCb detector is shown in

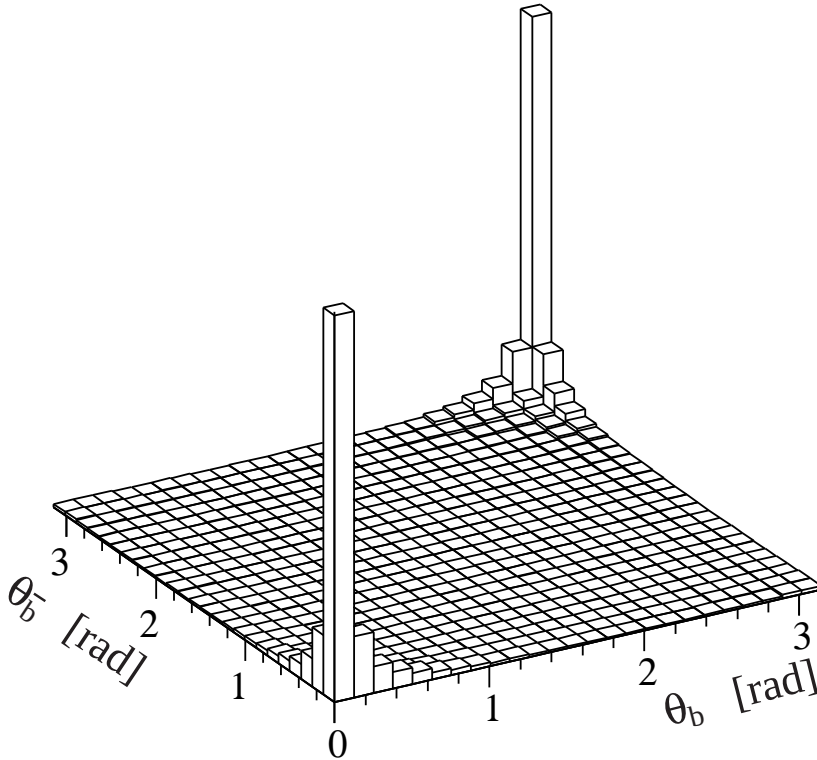


Figure 2.5: The polar angles of b versus $\bar{b}$ quarks produced at the LHC predicted by the Pythia [36] generator [28].

Figure 2.6 and a photograph in Figure 2.7. The tracking system is described in Section 2.2.2, the LHCb magnet in Section 2.2.1, the detector elements involved in particle identification are described in Section 2.2.3 and the LHCb trigger architecture is outlined in Section 2.2.4.

2.2.1 Magnet

In common with almost all particle physics experiments, LHCb uses a magnetic field to bend the paths of charged particles as they fly through the detector so that their momenta can be measured. The magnetic field is supplied by a warm dipole magnet [37], a photograph of which is shown in Figure 2.8. The magnet covers the full LHCb acceptance and generates a maximum field strength of 1 T.

The magnet design required that long tracks (those reaching the calorimeters) experience an integrated field of 4 Tm whilst also requiring a magnetic field of less than 2 mT inside the two RICH detectors. The two saddle coils are hollow, each carrying a 25 cm channel for cooling. The conductor has a specific resistance of below 28 Ωm at

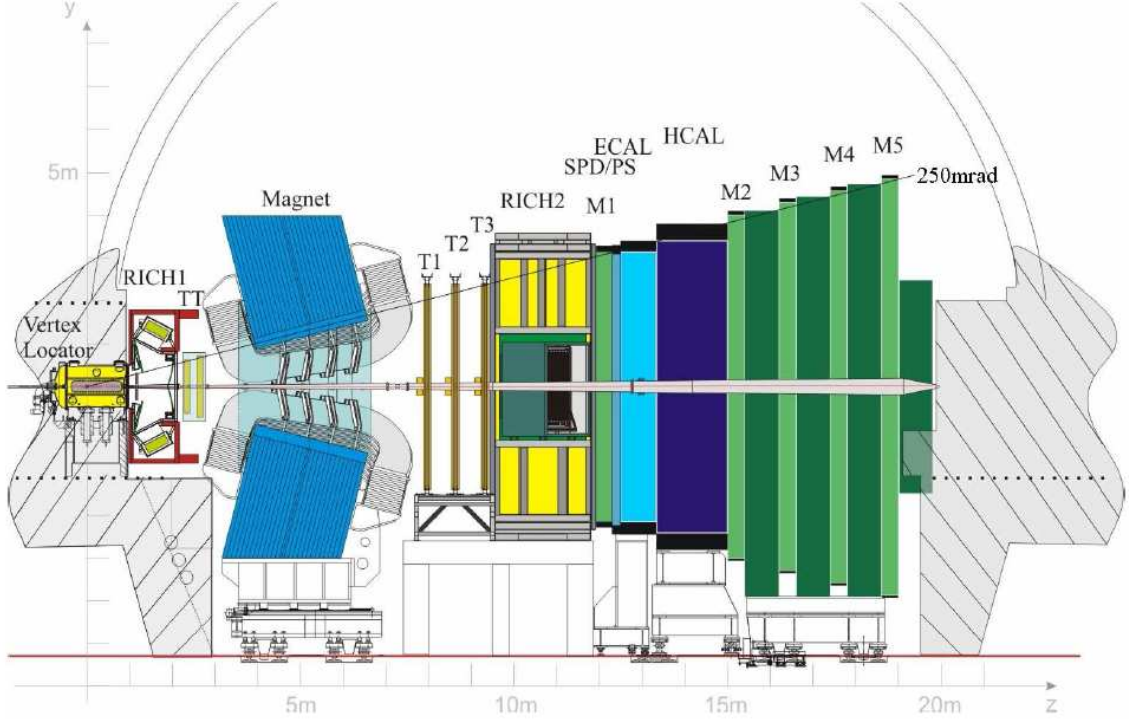


Figure 2.6: A side projection of the LHCb detector [27]. The z axis is along the beam-pipe and the y -axis is in the vertical direction. The interaction region is located on the left of the image within the VELO detector.

20°C and each coil weighs 27 tons. The polarity of the magnetic field may be swapped between “up” and “down” which is extremely useful in determining systematic effects due to charge asymmetries associated with the detector.

In order to make precise measurements of momentum the form of the magnetic field must be known to high precision. A field mapping survey has been carried out using Hall probes and the three components of the magnetic field are known to a relative precision of 4×10^{-4} throughout the tracking volume. The magnetic field strength as a function of the z -coordinate in the detector as measured by this survey is shown in Figure 2.9.

2.2.2 Tracking

Accurate measurement of the trajectories of particles produced in collisions is essential for all physics analyses at LHCb. The combination of the path of a particle with knowledge of the LHCb magnetic field allows the particle’s momentum to be measured. Precise tracking also allows for the location and separation of interaction and decay

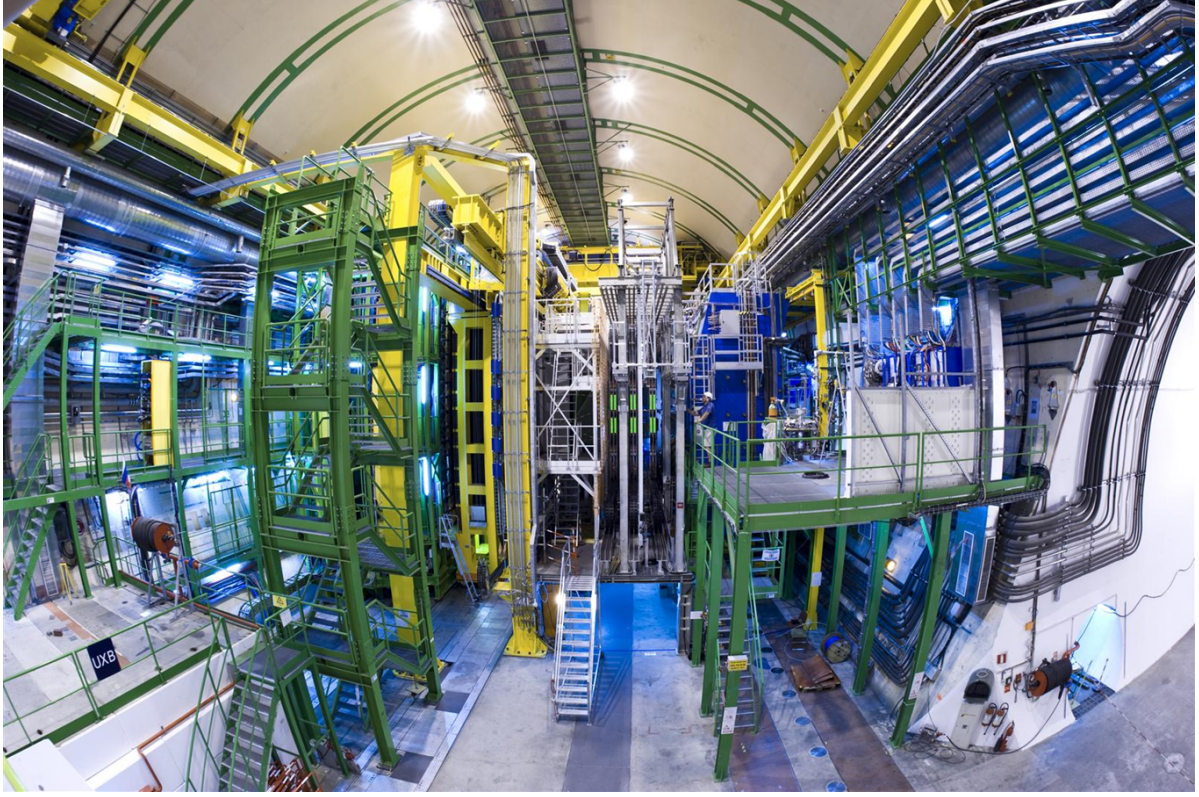


Figure 2.7: A fish-eye lens photograph of the LHCb detector [22]. The VELO detector is to the right of the image and the muon stations to the left.

vertices which in turn can be used to determine important quantities such as the masses of decaying particles and their proper decay times.

Precision tracking is performed using the VELO detector which is described in Section 2.2.2.1. Full trajectories are reconstructed using information from the VELO combined with hits in the Silicon Tracker (Section 2.2.2.2) and the Outer Tracker (Section 2.2.2.3). The overall performance of the tracking system during 2010 is described in Section 2.2.2.4. For the purpose of this discussion it is helpful to define the *upstream* and *downstream* directions which point from the muon stations towards the VELO and vice versa.

2.2.2.1 Vertex Locator

The VELO detector [38] is designed to make precise measurements of particle trajectories very close to the interaction region. This allows the separation of primary vertices (due to proton-proton interactions) and secondary vertices (due to the decays of short-lived

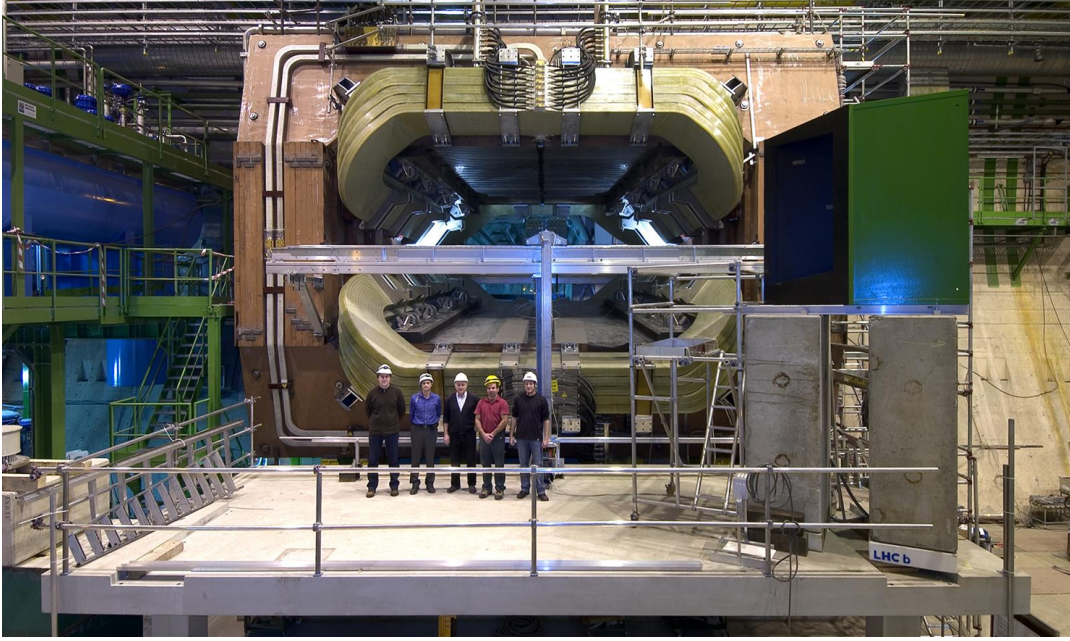


Figure 2.8: A photograph of the LHCb magnet with members of the LHCb Collaboration for scale [22]. The interaction region is located behind the magnet.

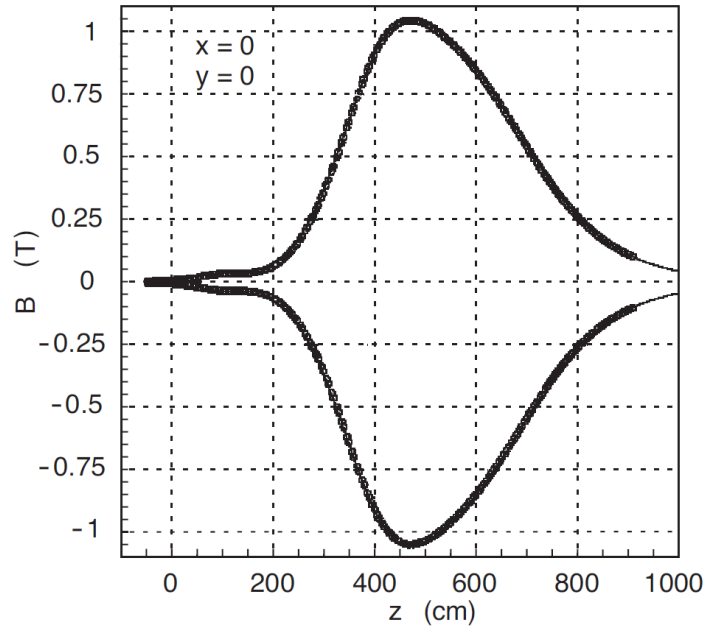


Figure 2.9: The magnetic field strength as a function of z in LHCb from the magnetic field mapping survey [27]. The two curves are the magnetic field strengths for the magnet in the “up” and “down” polarities.

particles). The separation of primary and decay vertices allows the calculation of the flight distance of a short-lived particle which, combined with momentum information,

can be used to measure the particle's proper decay time. The main requirements for the VELO detector are:

- Full coverage of the LHCb downstream acceptance.
- High signal to noise ratio.
- An overall channel efficiency of over 99%.
- High cluster resolution.
- Radiation hardness.

The VELO detector is composed of 21 stations, each made of two silicon modules, arranged along the beam axis. A photograph of one half of the VELO detector is shown in Figure 2.10. The modules accommodate both azimuthal and radial sensors which provide measurements of the r and ϕ coordinates with respect to the beam axis. The positions of the sensors with respect to the module are known to better than $50\text{ }\mu\text{m}$ perpendicular to the beam and $800\text{ }\mu\text{m}$ along the beam axis.

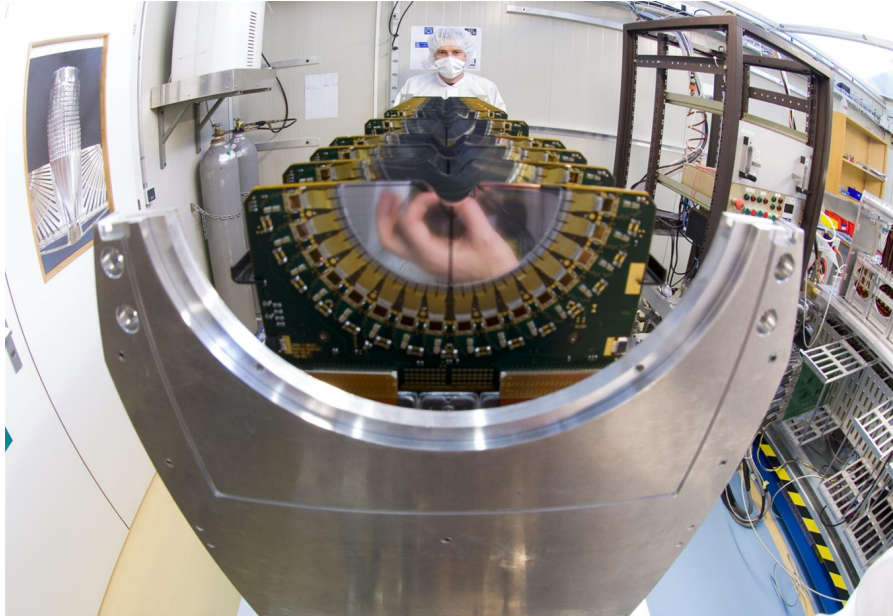


Figure 2.10: A photograph of the VELO modules during the assembly of the VELO, looking along the beam direction [22]. Only one module of each station is shown.

During normal operation, the VELO sensors are required to be closer to the LHC beam than the maximum beam diameter during injection. Direct contact between the

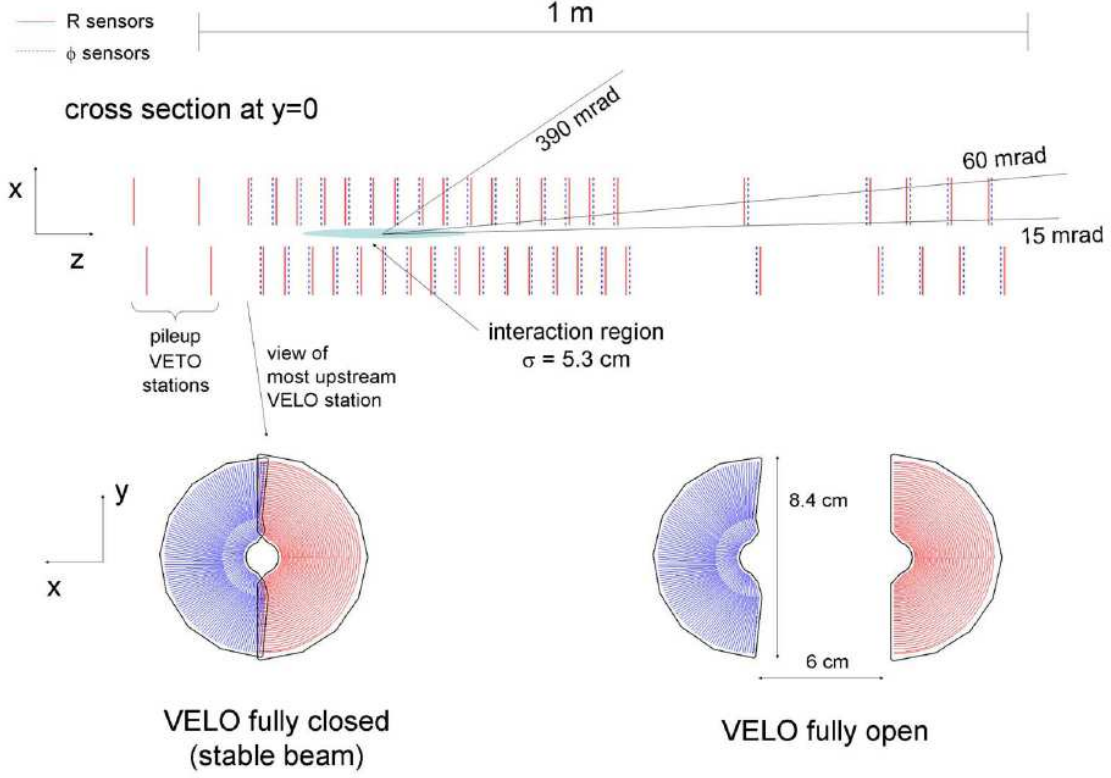


Figure 2.11: A cross-section of the VELO detector in the x - z plane with $y = 0$ with the modules in the closed position [27]. The front face of the first module looking down the beam pipe is also shown.

LHC beam and the VELO would be catastrophic for the LHCb detector and so the modules are retractable and are only put into the fully closed position when stable beams have been established. During collisions the sensitive regions of the silicon modules are just 8 mm from the beam. Figure 2.11 shows a cross-section of the VELO in the fully closed position. The VELO vacuum is separated from the LHC vacuum by radio frequency (RF) foils which also prevent electrical pickup in the VELO due to the LHC beam current. The position of the RF foil with respect to the VELO modules is shown in Figure 2.12.

2.2.2.2 Silicon Tracker

The term “Silicon Tracker” (ST) includes the Tracker Turicensis (TT) located upstream of the dipole magnet and the Inner Tracker (IT) [39] which is located downstream of

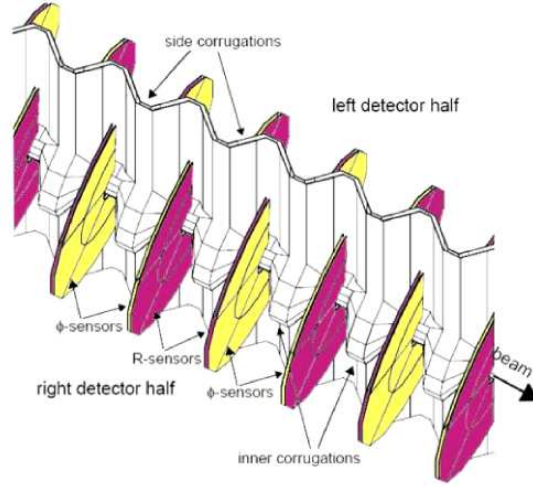


Figure 2.12: A view of the VELO detector with the detector box cut away revealing the positions of the VELO modules in the closed position relative to the RF foil [27].

the dipole magnet. The purpose of the ST is to allow the reconstruction of particle trajectories throughout the LHCb detector acceptance. The key requirement of the ST detectors is a spatial resolution of less than $50\ \mu\text{m}$. This is achieved using silicon microstrips with a strip pitch of $200\ \mu\text{m}$.

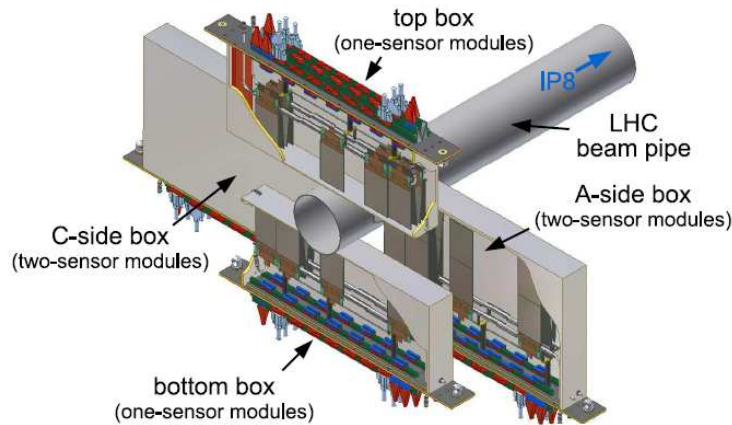


Figure 2.13: A view of the Inner Tracker detector boxes in their cross-shaped arrangement around the LHCb beam-pipe [27].

The TT is situated between the dipole magnet and the RICH1 detector and covers the full LHCb acceptance. The IT modules are situated at the centre (nearest the beam pipe) of the three tracking stations (T1-T3) located between the dipole magnet and the

RICH2 detector. The IT covers a cross-shaped region 120 cm wide and 40 cm high as illustrated in Figure 2.13.

2.2.2.3 Outer Tracker

The Outer Tracker (OT) [40] covers the LHCb acceptance in the tracking stations T1-T3 not covered by the IT. It is a drift-time detector designed to provide a spatial resolution of around 200 μm . The OT is composed of an array of straw-tube modules with inner diameters of 4.9 mm. The gas-tight tubes are filled with 70% argon and 30% carbon dioxide, a mixture which provides a fast drift-time of less than 50 ns.

2.2.2.4 Performance

The performance of the LHCb tracking system has been measured using data taken during 2010 and the results are presented in [41]. The results are summarised here.

Tracking Efficiency A high efficiency for finding and reconstructing tracks is crucial for flavour physics measurements, especially when reconstructing decay chains with a large number of final state particles. The track finding efficiency has been measured using $K_S^0 \rightarrow \pi^+\pi^-$ decays and is found to be greater than 95% for all tracks with a transverse momentum greater than 100 MeV/c. The tracking efficiency as a function of transverse momentum is shown in Figure 2.14.

Momentum Resolution High momentum resolution at LHCb is essential for a number of reasons. First, momentum criteria are used extensively in the trigger and selections to isolate events with physics interest. Momentum measurements are also used to reconstruct the masses of decaying particles, determine particle identity and reconstruct proper decay times. The nominal momentum resolution has been measured as $\Delta p/p = 0.35\% - 0.55\%$ depending upon the momentum of the track.

Impact Parameter Resolution The impact parameter IP of a track is defined as the distance of closest approach between the extrapolated particle track and the primary proton-proton collision vertex. High impact parameter resolution is important as the LHCb trigger imposes requirements on the impact parameter of tracks in order to locate

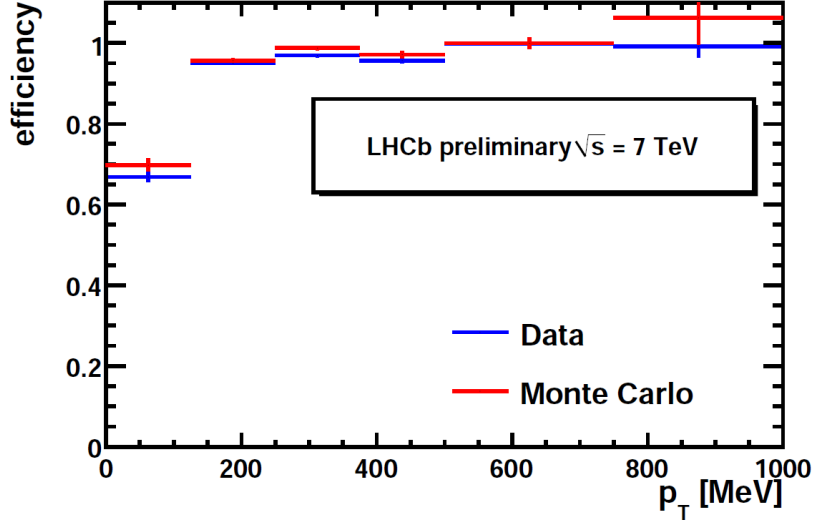


Figure 2.14: The tracking efficiency as a function of transverse momentum calculated from $K_S^0 \rightarrow \pi^+\pi^-$ from LHCb 2010 data compared with the performance predicted by GEANT4-based Monte Carlo simulations [41].

displaced vertices from B and D meson decays. The impact parameter resolution is found to be $\sigma_{IP} = (20 + 29/p_T) \mu\text{m}$ where p_T is the transverse momentum of the track in GeV/c . This is somewhat worse than the resolution predicted by simulation and the cause of this discrepancy is under investigation. Nonetheless, this reduced resolution does not rule out any part of the LHCb physics program.

Vertex Resolutions Good vertex resolution is crucial for making time-dependent measurements at LHCb and also in the selection of interesting events. The vertex resolution has been measured as $78 \mu\text{m}/\sqrt{N}$ in the x and y directions and $456 \mu\text{m}/\sqrt{N}$ in the z direction, where N is the number of tracks used in the vertex fit.

Proper Time Resolution Precise reconstruction of the proper decay time of particles is self-evidently essential for all time-dependent measurements at LHCb. The reconstructed proper time depends both upon the vertex and momentum resolution of the detector. The proper decay time resolution at LHCb has been measured as approximately 50 fs using $J/\psi \rightarrow \mu^+\mu^-$ decays as discussed in [41] and [42].

2.2.3 Particle Identification

The ability to distinguish different types of particle from one another is essential for many flavour physics analyses, especially those involving purely hadronic final states. The LHCb experiment uses the combined outputs of the calorimeters, muon chambers and RICH detectors to assign a likelihood to be either a muon, electron, proton, pion or kaon to each track. The RICH detectors are especially important in separating pions from kaons. The operation and performance of particle identification (PID) at LHCb is described in what follows.

2.2.3.1 RICH Detectors

At LHCb, identification of charged hadrons is performed using two RICH detectors [43]. When a charged particle travels faster than the local speed of light in a medium it radiates electromagnetic radiation known as Cherenkov radiation [44]. The angle between the particle's flight direction and the direction of travel of the emitted wavefront is known as the Cherenkov angle θ_C and is related to the speed of the particle v by

$$\theta_C = \frac{c}{nv} \quad (2.2)$$

where n is the refractive index of the medium. This is illustrated in Figure 2.15. Therefore, the speed of the particle can be calculated from a measurement of θ_C and, combined with a measurement of the particle's momentum, its rest mass and hence its identity can be determined. The two RICH detectors operate on this principle. RICH1 is situated upstream of the magnet and gives PID coverage in the low-momentum range while RICH2 is located downstream of the magnet and gives coverage in the high-momentum range.

RICH1 The RICH1 detector provides PID information for charged particles with momenta between 1-60 GeV/ c and covers the full LHCb geometrical acceptance. Two radiators are employed: 5cm thick silica aerogel tiles arranged around the beam-pipe followed by 1m of C₄F₁₀ gas. A schematic side view of RICH1 is shown in Figure 2.16.

The light emitted in the radiators is focused by circular mirrors onto plane mirrors which reflect the light onto an array of Hybrid Photon Detectors (HPDs) which are sensitive to Cherenkov photons with wavelengths in the range 200-600 nm. The HPDs

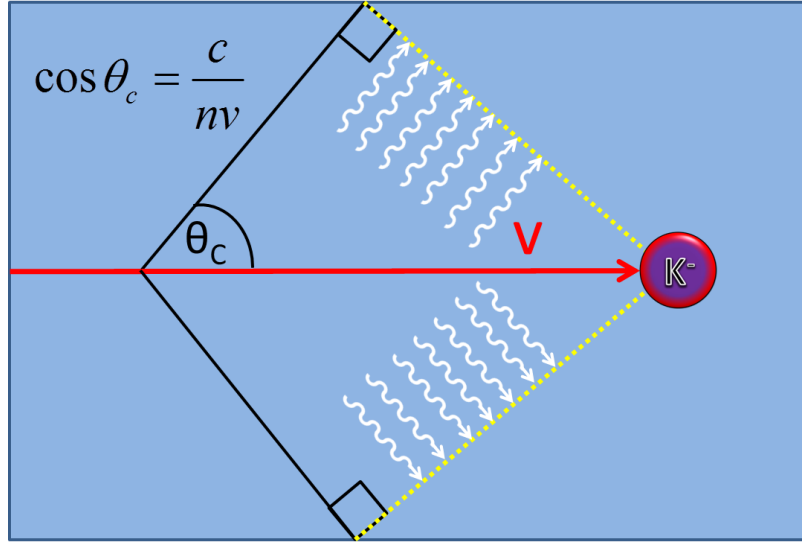


Figure 2.15: An illustration of Cherenkov radiation emitted by a charged particle in a medium with refractive index n .

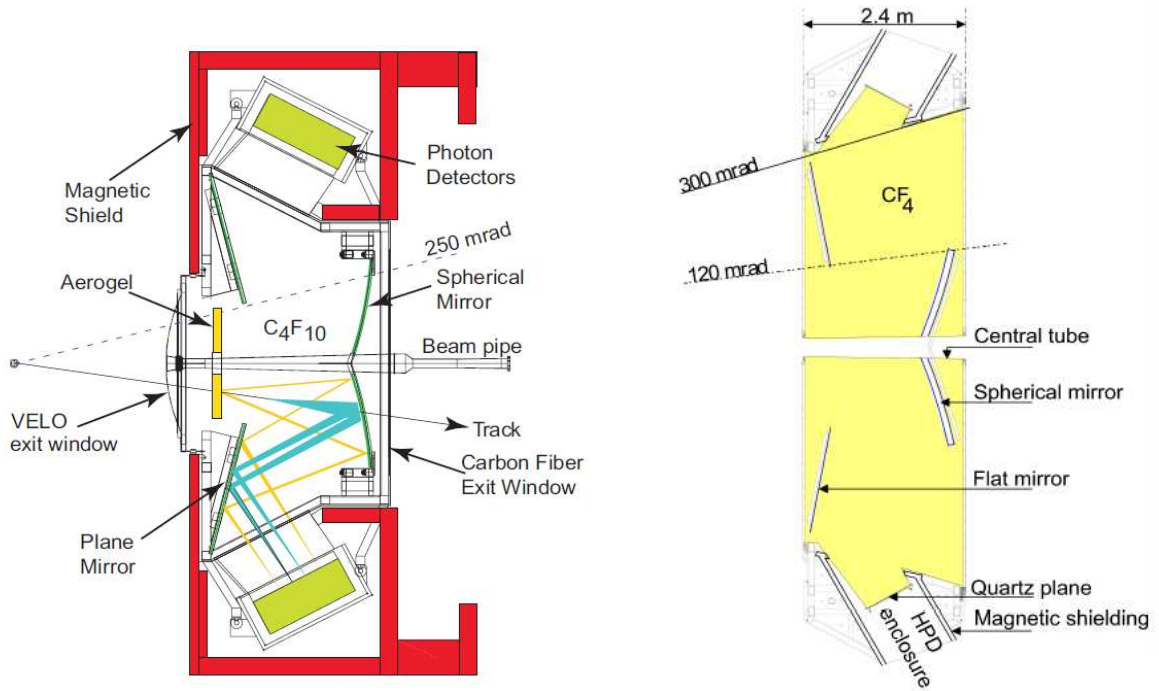


Figure 2.16: Schematic side views of the RICH1 (left) and RICH2 (right) detectors [27].

are protected from the LHCb magnetic field by surrounding MuMetal cylinders. A photograph of an array of HPDs is shown in Figure 2.17. At the end of 2010 the Cherenkov angle resolution of RICH1 was 1.75 mrad compared to a predicted resolution

of 1.55 mrad from Monte Carlo simulated data [45].



Figure 2.17: Photograph of the RICH1 upper HPD box [46].

RICH2 RICH2 provides momentum coverage in the range 15-100 GeV/ c and has an angular acceptance of ± 120 mrad in the x direction and ± 100 mrad in the y direction with respect to the beam axis. While RICH2 does not cover the full geometrical acceptance of LHCb it does cover the range where high momentum particles are produced. A schematic view of RICH2 is shown in Figure 2.16.

RICH2 uses a CF_4 radiator and a similar mirror arrangement to RICH1. As with RICH1, Cherenkov photons are detected by HPDs. The expected Cherenkov angle as a function of momentum for the RICH1 and RICH2 radiators is shown in Figure 2.18 which illustrates the separation power of the RICH system for different particles over a wide momentum range. At the end of 2010 the Cherenkov angle resolution of RICH2 was 0.73 mrad compared to a predicted resolution of 0.66 mrad from Monte Carlo simulated data [45].

RICH Readout During the three years of my doctoral research my main technical responsibility was for the RICH Level 1 (L1) readout electronics, specifically for the L1 control software. In this section the general architecture of the RICH readout system is described along with some detail of the L1 control and monitoring software.

The first level of readout from the RICH HPDs are binary pixel chips which are integrated into the HPDs themselves. These are connected to Level-0 (L0) readout boards which are mounted on the detector. Two pixel chips (and hence HPDs) are linked to each L0 board. Optical links then carry data from the on-detector electronics

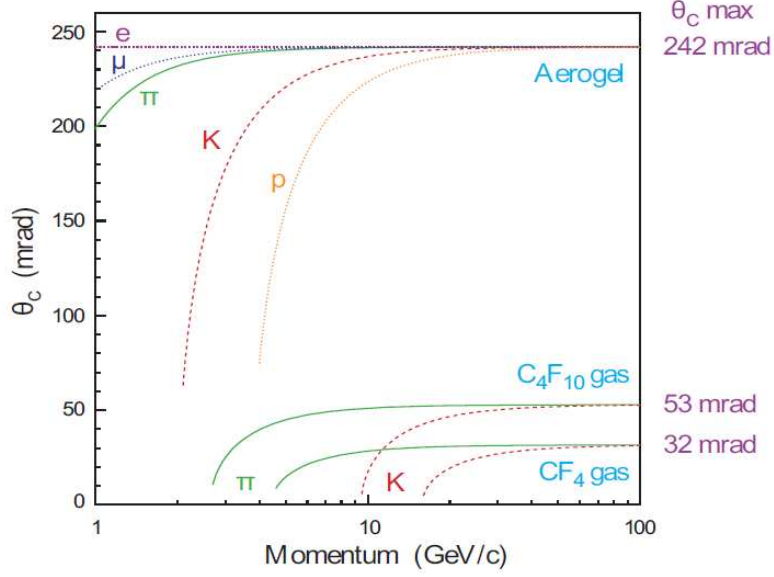


Figure 2.18: The expected Cherenkov angle for different particles as a function of momentum for the three RICH radiators [27].

to L1 readout boards, or UKL1 boards [47], which are located about 100 m from the LHCb detector in the counting room. Each L1 board can carry up to 36 channels (HPDs).

The main functions of the L1 boards are to:

- Reduce the event data size by performing zero-suppression.
- Multiplex and format the data for transmission to the data acquisition (DAQ) and event building network.
- Isolate the readout network from corrupt data produced by the L0 boards as a result of radiation-induced or other upsets.
- Provide an interface to the Timing and Control (TTC) system and the Detector Control System (DCS).

The control software for the L1 boards is implemented using PVSS [48], in common with all LHCb detector control software. The main purpose of the L1 control software is to allow configuration of the boards before the start of a run, starting and stopping a run and resetting the boards in case of errors or upsets. The PVSS project also allows

the user to bring up a wide variety of information concerning the performance of the L1 system for monitoring and debugging.

A substantial part of my work on the PVSS project involved implementing the automatic channel disabling (also referred to as “HPD Disabling”) functionality. The L1 boards have the ability to disable input channels from HPDs that are malfunctioning. This is required as misbehaving channels may send large quantities of corrupt data that may disrupt event flow and lead to dead-time. This is done at the L1 rather than L0 level as if the data being sent is corrupt there is no guarantee that the L0 board is functioning correctly.

A channel can be disabled automatically in two ways. Event errors may be detected directly by the L1 board, in which case after three consecutive error events the channel is automatically disabled. In case of more subtle errors not detected by the L1 board the RICH monitoring software detects these and publishes a list of malfunctioning HPDs which the PVSS project reads in and disables. A list of currently disabled HPDs is maintained in a dedicated panel of the PVSS project. Disabled channels can be recovered by resetting the L0 and L1 systems.

Another task was the implementation of the masking of noisy pixels. A list of known noisy pixels which send large amounts of data is maintained in a datapoint of the PVSS project. Single pixels may generate a large quantity of data since as soon as any data is sent from an HPD an additional overhead due to headers is generated. At the start of a run the project reads in this list and disables the connection to each of these noisy pixels. This functionality may be activated/deactivated for RICH1 and RICH2 independently as required.

2.2.3.2 Calorimeters

The calorimeter system [49] of LHCb performs a number of important roles: high transverse energy clusters in the calorimeters are used for L0 triggering, the calorimeter is used for reconstruction of π^0 s and photons, the locations of hits in the calorimeters are used in track reconstruction and the calorimeters are important for the identification of hadrons, electrons and photons.

In common with other particle physics experiments the calorimeter system is composed of an electromagnetic calorimeter (ECAL) followed by a hadronic calorimeter (HCAL). Figure 2.19 shows the ECAL and HCAL during installation of the LHCb de-



Figure 2.19: The electromagnetic calorimeter (left) and hadronic calorimeter (right) during installation of the LHCb detector at Point 8 [27].

tector. Electrons and photons leave clusters in the ECAL whereas both charged and neutral hadrons deposit the bulk of their energy in the HCAL. The ECAL is segmented along the beam axis. First a scintillator pad detector (SPD) is used to separate neutral particles such as photons and π^0 from charged particles such as electrons. The SPD is followed by a thin lead converter and then a preshower (PS) detector which provides separation between electrons and charged pions. The information from the SPD and PS is used for the L0 trigger. After the PS comes the main bulk of the ECAL which is made from alternating layers of scintillator and lead and is used to measure the energy of electromagnetic showers. Both the ECAL and the HCAL are segmented into regions of differing cell size which is optimised for the average occupancy of the detectors. The ECAL has three regions of different cell size while the HCAL has two.

The calorimeters all work along the same lines: particles pass through a layer of scintillator producing scintillation-light, this light is then carried by wavelength shifting fibres to a photomultiplier and detector. Clusters of scintillator light are associated with tracks and summed to find the total energy of the particle. The design energy resolution, σ_E of the calorimeter cells is

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 1\% \quad (2.3)$$

where E is energy [49].

2.2.3.3 Muon System

Muons are produced in many of the B decays of interest to the LHCb experiment, for example the $B_s^0 \rightarrow \mu^+ \mu^-$ decay mode which is sensitive to new physics and the so-called “gold-plated” $B^0 \rightarrow J/\psi(\mu^+ \mu^-) K_S^0$ and $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \phi$ modes which can be used to measure CP asymmetries. Muons can also be used to tag the initial flavour of $B_{(s)}^0$ mesons which decay semi-leptonically. Information from the the muon system at LHCb is used in both the L0 and high-level triggers as well as in offline analysis.

There are five rectangular-shaped muon stations [50] (M1-M5) positioned along the beam axis. M1 is stationed upstream of the calorimeters to improve muon track reconstruction and hence the transverse momentum measurement for the trigger. M2-M5 are located downstream of the calorimeters and are interspersed with 80cm thick iron absorbers to select high momentum muons. Given the radiation-thickness of the calorimeter and these absorbers, the minimum momentum required for a muon to penetrate all five stations is approximately 6 GeV/c. A side view of the muon system is shown in Figure 2.20.

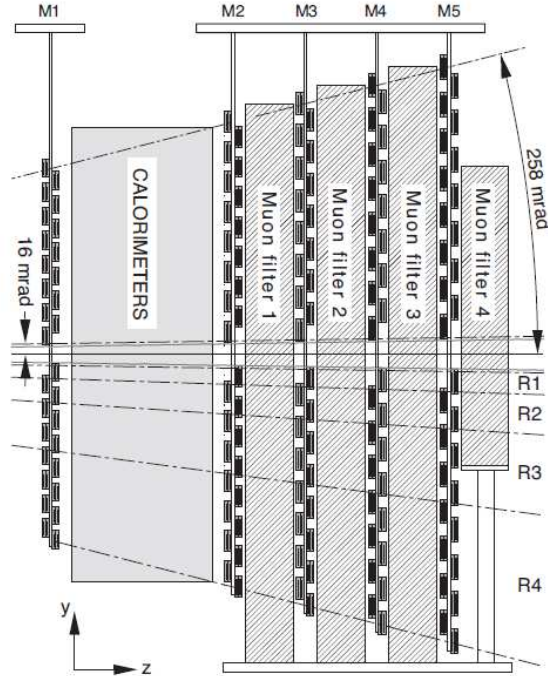


Figure 2.20: A side view of the LHCb muon system showing M1 upstream of the calorimeter and M2-M5 downstream of the calorimeter [27].

The muon stations house a total of 1,380 chambers, 1,368 of which are Multi Wire

Proportional Chambers containing a mixture of Argon, Carbon Dioxide and Carbon Tetrafluoride. The inner region of M1 contains 12 triple-GEM chambers which are chosen for their radiation-hardness due to the high levels of radiation experienced upstream of the calorimeter.

Stations M1-M3 have high spatial resolution in the bending plane of the magnet (x direction) in order to achieve a standalone transverse momentum measurement to within 20%. M4 and M5 are primarily for the detection of highly penetrating muons and have reduced spatial resolution.

2.2.3.4 Performance

In order to assess the performance of the combined PID system, pure samples of $e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$ and $p^\pm$ were obtained from the channels $\gamma \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$, $K_S^0 \rightarrow \pi^+\pi^-$, $\phi \rightarrow K^+K^-$ and $\Lambda^0 \rightarrow p^\pm\pi^\mp$ which are selected from the first $65 \mu\text{b}^{-1}$ of $\sqrt{s} = 7 \text{ TeV}$ LHCb data as described in [51]. All modes are selected using purely kinematic criteria with the exceptions of $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$ where PID constraints are made on one daughter and the other used for the study.

PID information is presented in the form of the difference of log-likelihoods ($\Delta\log\mathcal{L}_{X-Y}$) between two different particle hypotheses X and Y . These variables are calculated by an algorithm that takes information from the whole event, not just the individual track. The likelihood calculation takes information from the tracking, RICH, calorimeters and muon system and combines them to produce the $\Delta\log\mathcal{L}$ values.

Hadron Identification Identification of hadrons is performed by the two RICH detectors. The performance of the RICH system in identifying protons and kaons with respect to pions is shown in Figure 2.21. We see that the RICH system offers excellent separation power between protons, kaons and pions but that this performance degrades as the momentum of the particle increases towards $100 \text{ GeV}/c$. The ability to separate kaons from pions is particularly important in the measurement of the $B_s^0 \rightarrow K^+K^-$ lifetime as will be discussed later.

Muon Identification The performance of the muon system is shown in Figure 2.22. Integrated across momentum the loose cut used has an efficiency for muons of $(97.3 \pm 1.2)\%$. The efficiencies for pions and kaons that penetrate the HCAL to reach the

downstream muon chambers integrated across momentum are $(2.35 \pm 0.04)\%$ and $(1.67 \pm 0.06)\%$ respectively.

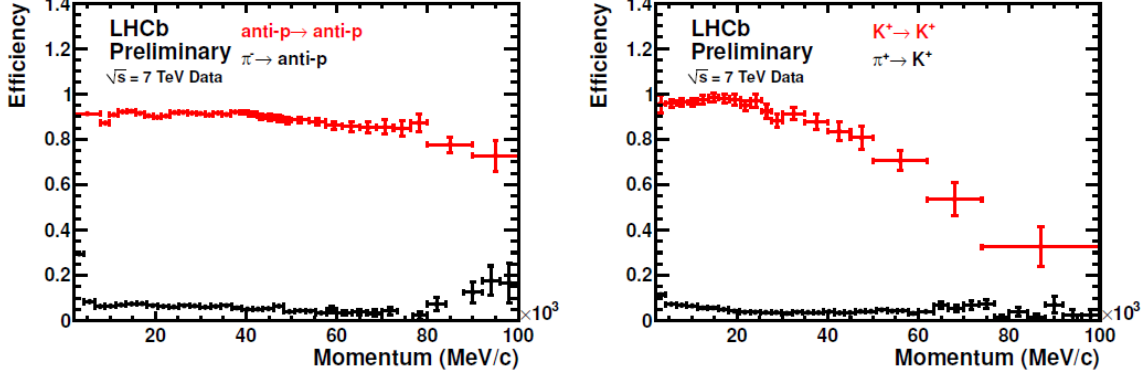


Figure 2.21: The performance of the RICH detectors in identifying hadrons as a function of momentum [51]. Left: the efficiency of a $\Delta\log\mathcal{L}_{p-\pi} > 5$ cut for protons (red) and pions (black). Right: the efficiency of a $\Delta\log\mathcal{L}_{K-\pi} > 5$ cut for kaons (red) and pions (black).

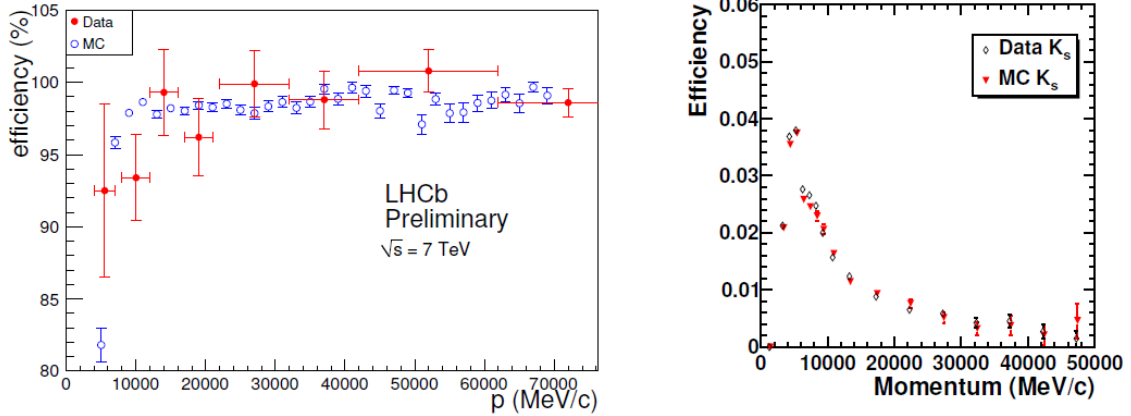


Figure 2.22: The performance of the muon system in identifying muons as a function of momentum [51]. Left: the efficiency of a loose muon identification cut for muons is shown for both data and Monte Carlo (MC) simulation. Right: the efficiency of the same loose cut for pions for both data and MC simulation.

2.2.4 Trigger

With the LHC running under design conditions the rate of pp interactions producing at least two tracks within the LHCb acceptance is 10 MHz. The LHCb detector is only able to write data to tape at a rate of 2 kHz requiring the trigger to reject 4,999 out of every

5,000 events. Decays of B mesons used in CP violation and new physics measurements falling within the LHCb acceptance occur at a rate of approximately 10-100 Hz. The LHCb trigger must also therefore be able to identify these relatively rare signals buried within a large amount of uninteresting background.

The LHCb trigger [52] has three levels. The first stage is a hardware trigger known as the “Level 0” (L0) trigger which reduces the rate from 10 MHz to 1 MHz. This is followed by two software “High Level Triggers”, HLT1 and HLT2, which reduce the rate to 50 kHz and 2 kHz respectively.

2.2.4.1 L0

The L0 trigger is based in hardware and uses only basic information from the calorimeters and muon system. The L0 muon trigger algorithms or “lines” rely on the standalone momentum reconstruction capability of the muon system which has a resolution of approximately 20%. There are two muon lines: a single muon trigger and a di-muon trigger which look for one and two high momentum muons in the muon stations respectively. Hadrons, electrons and photons are triggered through dedicated lines which use information from the SPD, PS, ECAL and HCAL.

2.2.4.2 HLT1

Both HLTs are based on C++ and run on a dedicated computer farm with up to 2,000 nodes. HLT1 has access to all the information from the LHCb detector. However, a full reconstruction cannot be performed due to timing restrictions; each event must be processed in less than 12 ms. During 2010 the design of HLT1 evolved to exploit the excellent performance of the LHC to the full. In the early stages of data taking a “confirmation” strategy was adopted whereby the L0 decision is confirmed by associating tracks to the L0 calorimeter clusters or muon segments. This was done by a number of logical structures called “alleys”, one for each L0 trigger line. Each alley was targeted at a particular category of particles (hadrons, electrons, muons, photons etc.) and each contained a number of lines designed to select specific decays or processes.

As discussed in Section 2.1.1 the average number of interactions per bunch crossing exceeded 2.5 at the end of 2010 while the detector and original trigger architecture was designed to cope with around 0.4 interactions per bunch crossing. Furthermore, the instantaneous luminosity increased dramatically over the year with the last few fills of

2010 responsible for around 50% of the data collected. This point is illustrated by Figure 2.23.

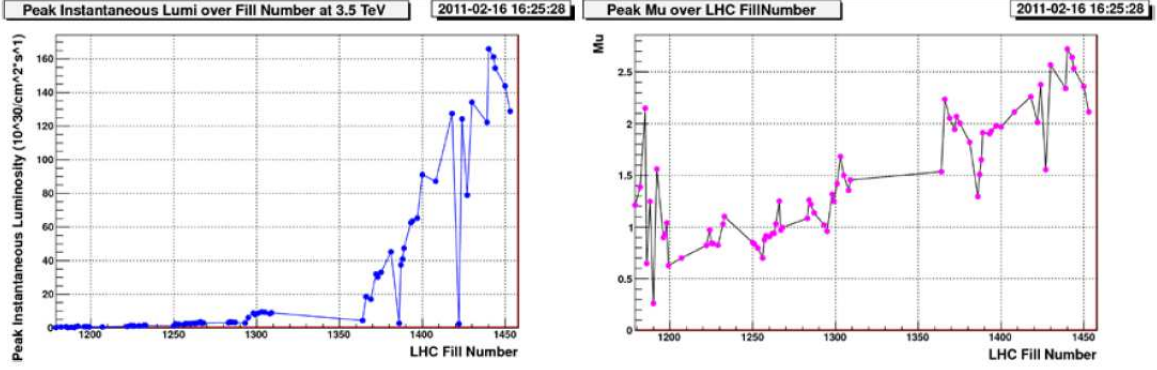


Figure 2.23: The peak luminosity versus fill number (left) and the mean number of pp interactions per bunch crossing (μ) versus fill number (right) [53].

Events with multiple interaction vertices tend to have larger numbers of tracks and much higher detector occupancy, increasing the time taken by the trigger to process each event and also the amount of data recorded. These challenging conditions required a change of strategy. A single track trigger [54], designed to be efficient for a wide range of signal modes, particularly hadronic decays of B and D mesons, replaced a large number of HLT1 triggers, thus allowing the trigger to have high efficiency for physics channels while also keeping within the 12 ms per event timing budget. This trigger relies on the fact that B mesons are produced with large momenta of the order 100 GeV/ c and fly on average 1 cm from the interaction point. As a result at least one of their daughters generally has large momentum, transverse momentum and impact parameter with respect to the interaction point. The single track trigger therefore looks for a single, displaced, high momentum track in the event.

The introduction of this trigger signalled the end of the L0 confirmation strategy for hadrons, as the single track trigger runs without reference to the L0 triggered objects. Due to the extremely busy nature of the events it was also necessary to introduce “global event cuts” (GECs) on SPD hit multiplicity in order to reject events with very large numbers of tracks. The single track trigger is responsible for triggering the majority of $B \rightarrow h^+h^-$ (where h stands for any of K , π or p) decays and so is of particular interest in the analysis presented here. In addition to the single track hadron trigger, a single track muon trigger was also run which uses the L0 triggered muon and reconstructs tracks left in the VELO and tracking stations. Additionally there were also muon, di-muon and electron trigger lines.

2.2.4.3 HLT2

HLT1 reduces the event rate to around 50 kHz allowing HLT2 to perform a reconstruction that closely resembles the full offline reconstruction, with some shortcuts to save time. HLT2 is composed of a large number of different trigger lines, each one tailored for a specific physics analysis. Many of these lines perform fits of decay vertices and calculate the distances of flight, momenta, masses and proper decay times of decaying particles.

There are two lines which select the majority of $B \rightarrow h^+h^-$ candidates: the “B2HH” HLT2 line which is specifically designed for this purpose and the two-body topological line which is an inclusive selection designed to select a wide range of two-body decays.

2.2.5 The LHCb Software Suite

Once data has passed the trigger it must be processed in order to be used in physics analyses. The following section describes the software suite that has been developed at LHCb both for simulation and processing of data.

2.2.5.1 The Gaudi Framework

All LHCb software is based on a common C++ framework known as Gaudi [55, 56]. This shared software infrastructure allows experiment-wide changes to be implemented smoothly and ensures that all tools and algorithms are available across the experiment, rather than being specific to a single process or dataset.

Algorithms developed under the Gaudi framework are stored separately of any particular dataset, simulated or real, and interact with data through the Transient Store (TS). A “Conditions Database” [57] contains the information required to describe the current running conditions of the experiment and this may be changed frequently throughout the lifetime of the experiment. The Conditions Database also allows simulated data to be produced under the same conditions as experienced by the real detector. A full detector description is also implemented under the Gaudi framework.

2.2.5.2 Simulation

The simulation software at LHCb has been developed to provide simulated events that mirror the data as much as possible. The Gauss application [58] simulates the underlying event and flight of particles through the detector. The Gauss application uses Pythia [36] to simulate the proton-proton collision and production of particles. The EvtGen application [59] calculates the flight of these particles through the LHCb volume and their decays.

2.2.5.3 Digitisation

The response of the detector to simulated events is handled by the Boole application [60]. Boole uses a model of the LHCb detector based on GEANT4 [61] to simulate the detector’s digital output. The digitised information then passes through the same trigger, reconstruction and analysis chain as used for the real data.

2.2.5.4 Reconstruction

The digitised output of the detector, real or simulated, is reconstructed using the Brunel application. The reconstruction stage essentially takes digital information and produces data which is of physical interest e.g. momentum, energy and PID measurements. Brunel takes track hits and performs fits to produce track objects with defined trajectories and momenta. It also takes clusters in the calorimeters to reconstruct the energies of particles and performs a combined reconstruction of the RICH, calorimeter and muon detector outputs to generate PID information for each track. The output of Brunel is a fully reconstructed dataset known as a “Data Storage Tape” (DST) file.

2.2.5.5 Analysis

The main analysis program used at LHCb is the DaVinci application. DaVinci takes track objects from Brunel and performs vertex fits to produce both primary and decay vertices. The program can then calculate a wide variety of kinematic quantities such as masses of decayed particles, distances of flight, proper decay times and so on. DaVinci also allows the implementation of particle selection sequences and is used in the Stripping procedure described in Sections 3.3.2 and 3.4.2. The output of DaVinci is either a ROOT

ntuple file used directly in measurements or a DST file which can then be processed further if desired.

Chapter 3

Event Selection

“I hate not having a plan. We’re looking for a needle in a haystack. Actually, its more like we’re looking for a needle in a pile of needles. A needle would stand out in a haystack.”

— Criminal Minds

3.1 Introduction

This chapter describes the selection of $B \rightarrow h^+h^-$ and $D \rightarrow h^+h^-$ decay modes at LHCb. $B \rightarrow h^+h^-$ refers to a set of two body B meson decays to charmless, charged hadrons which includes the modes: $B_s^0 \rightarrow K^+K^-$, $B_s^0 \rightarrow \pi^+K^-$, $B_s^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow K^+K^-$, $B^0 \rightarrow K^+\pi^-$ and $B^0 \rightarrow \pi^+\pi^-$. $D \rightarrow h^+h^-$ refers to the decay modes: $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$. Section 3.2 outlines the general principles of the selection of two body decays, Section 3.3 describes the full selection procedure for $B \rightarrow h^+h^-$ decays used in the measurement of the $B_s^0 \rightarrow K^+K^-$ lifetime and Section 3.4 describes the selection of $D \rightarrow h^+h^-$ decays for the y_{CP} analysis.

3.2 Selecting Two Body Decay Modes

Finding a particle decay at a hadron collider is a bit like trying to do a children’s puzzle. Or at least, a rather unusual puzzle where the pieces, instead of lying neatly on the table

top, are flying through the air so fast that if you blink you'll miss them. Not only that, flying alongside, mixed up with them are a whole load of other pieces from other puzzles, quite often many hundreds. Worse still, most of the puzzle pieces look very similar, and pieces from different puzzles will quite happily fit together to give a rather convincing, if misleading picture. The challenge for the player is to identify the correct puzzle pieces in the blizzard of cardboard shapes and put them together in the right order.

In the same way, physicists working at LHCb are faced with the challenge of reassembling an unstable particle from its decay products. In the case of a $B_s^0 \rightarrow K^+ K^-$ decay the two charged tracks left by the kaons are in most cases, two out of hundreds of other charged tracks produced in the event. A brute force attempt might be to randomly pick pairs of tracks, add their four-momenta together and calculate the mass of their hypothetical “mother” particle. This isn't a sensible approach for two reasons. First, taking a typical event with around 100 tracks, there will be 4,950 different possible ways of selecting a pair, 4,949 of which will be pairings of tracks that didn't come from the decay of interest. The vast majority of pairings will involve the misassociation of tracks to produce a fictitious particle or what is commonly referred to as *combinatorial background*. Dealing with combinatorial background is one of the most significant challenges faced by physicists making precision measurements at hadron colliders.

The second reason why randomly associating pairs of tracks is a bad idea is that there isn't enough time. Like the player in our now somewhat tortured puzzle analogy, the LHCb experiment doesn't have the resources to form close to 5,000 random pairs (or indeed 160,000 triplets if you are unfortunate enough to work on a three body decay) per bunch crossing. Fitting a decay vertex is computationally demanding and timing restrictions in the L0 and HLT1 triggers preclude its use.

The only alternative then is to try to identify tracks likely to have come from an interesting decay before any kind of combination is carried out. Broadly speaking there are two parameters of a track that are indicative of its “interestingness”. The first is the momentum of the particle. Hadrons containing heavy quarks tend to be produced with momenta of the order of tens of GeV/c with a significant component perpendicular to the beam-pipe (“transverse momentum”). Coupled with a large rest mass the decays of these particles generally produce tracks with high momentum and transverse momentum. Conversely, tracks produced by soft interactions of protons tend to have lower momentum and tend to fly along or close to the beam-pipe. Making minimum requirements on track momentum and transverse momentum is therefore an excellent way to isolate tracks likely to have come from a decay of interest.

The impact parameter of a track, defined as the distance of closest approach between an extrapolated track and the primary interaction vertex, is also an excellent discriminator. Both B and D mesons have mean lifetimes of the order of picoseconds and so will fly on average around 1 cm before decaying. As a result a large fraction of tracks coming from B and D decays will originate at a point displaced from the interaction vertex and will have large impact parameters. This point is illustrated in Figure 3.1 which shows how the impact parameters of two kaons are related to the flight distance of the B_s^0 meson. Conversely, most uninteresting background arises at the interaction vertex and so by making a minimum impact parameter requirement the signal purity is greatly enhanced.

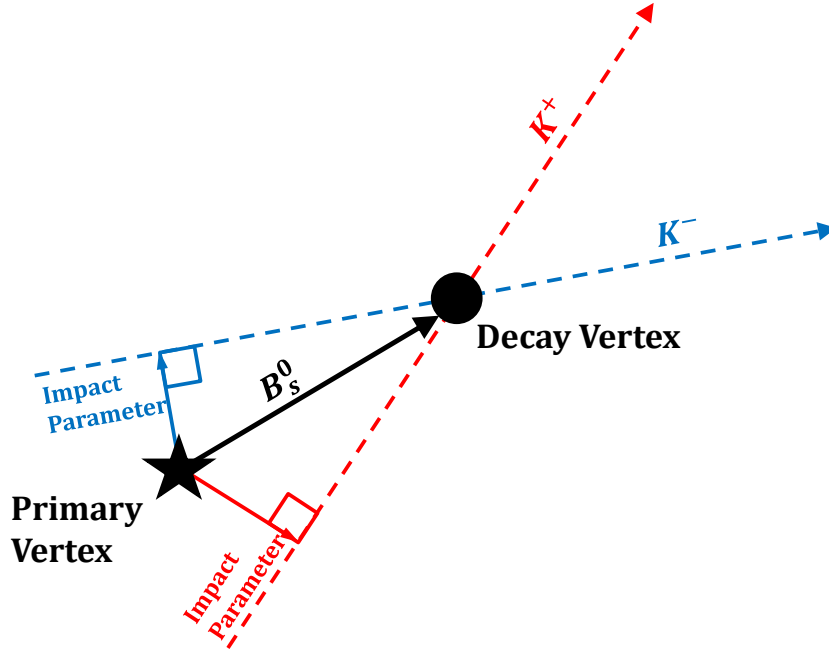


Figure 3.1: A cartoon of a $B_s^0 \rightarrow K^+ K^-$ decay illustrating how the impact parameters of the kaon tracks are related to the flight distance of the B_s^0 meson.

In addition to momentum and impact parameter criteria, it is also helpful to make minimum requirements on track quality. At LHCb a Kalman fit [62] is used to obtain the track momentum and covariance matrix from which the χ^2 per degree of freedom of the fit is determined. A non-negligible fraction of tracks at LHCb are so called *ghosts*, which are essentially fictitious tracks produced when a set of unrelated hits is fitted as one track. Ghosts tend to have poor track fit qualities and so by requiring that the track χ^2 per degree of freedom be below a certain threshold we can eliminate a large proportion of this category of background.

Once the “interesting” tracks in an event have been identified, these tracks can be combined to establish whether they are likely to have come from a decay of interest. For a two body decay each selected track is combined with every other selected oppositely charged track in the event and further requirements made on their combination before a vertex fit is carried out. By assuming a particular decay hypothesis, for instance K^+K^- , the invariant mass m of the combination of two tracks can be calculated where

$$m^2 = [(E_a, \vec{p}_a) + (E_b, \vec{p}_b)]^2 = (E, \vec{p})^2 = E^2 - |\vec{p}|^2 \quad (3.1)$$

and E is energy, $\vec{p}$ is three-momentum and the subscripts a and b label the two daughter particles. The value of m can be required to fall close to the known mass of the particle of interest, thus excluding background from the data set. Another common requirement is that the momentum of the combination $\vec{p}$ must exceed a threshold and that the two tracks come within a certain distance of one another.

After this combination stage the decay vertex is finally fitted to produce a *candidate* particle. The χ^2 per degree of freedom of the vertex fit can be used to remove poor quality decay vertices. Knowledge of the decay vertex location can also be used to calculate the distance of flight of the candidate particle from the primary vertex and the impact parameter of the candidate with respect to the primary vertex. Combined with the calculated momentum the distance of flight can then be used to calculate the proper decay time t of the candidate where

$$t = \frac{|\vec{L}|m}{|\vec{p}|} \quad (3.2)$$

where L is a vector joining the primary and decay vertices. All these parameters can be used in selections to obtain a purer sample of true decays.

Having outlined the principles of selecting two body decay modes the specific selections of $B \rightarrow h^+h^-$ and $D \rightarrow h^+h^-$ decays will be discussed in Sections 3.3 and 3.4 respectively.

3.3 Selection of $B \rightarrow h^+h^-$ Events

3.3.1 Trigger

The first stage of any selection at LHCb is made by the trigger. The trigger differs from offline selections in that it selects “events” as opposed to tracks or candidate particles. If all trigger levels fire then the complete digitised information produced by the LHCb detector during the bunch-crossing is recorded to disk to be analysed offline. The L0 and HLT1 triggers can roughly be thought of as triggering on interesting tracks whereas the HLT2 triggers generally perform a more detailed reconstruction and fire on composite candidate particles formed from the combination of a number of tracks.

As described in Chapter 2 the LHCb trigger evolved throughout 2010 in order to best exploit the LHC running conditions. A particular set of trigger settings is labelled with a Trigger Configuration Key (TCK) and 14 different TCKs were used during 2010. The integrated luminosities taken with each of these TCKs are listed in Table 3.1 along with the corresponding L0 thresholds and SPD hit multiplicity criteria. Almost half of the 37.66 pb^{-1} collected was taken using the TCKs 0x002e002a and 0x002e002c, and it is these that will be considered in the following discussion. Both these TCKs have very similar settings with the exception of the global event cut on SPD hit multiplicity where 0x002e002a requires a value < 900 and 0x002e002c a value < 450 .

All triggered events from all TCKs and trigger lines were used in the $B_s^0 \rightarrow K^+K^-$ lifetime measurement in order to maximise available statistics. However, the dominant trigger lines for $B \rightarrow h^+h^-$ candidates will be discussed for the L0, HLT1 and HLT2 in what follows. For the purposes of this discussion it is helpful to define the terms TOS (triggered on signal) and TIS (triggered independent of signal). If a candidate is described as TOS for some trigger line, this simply means that trigger line fired due to that candidate. In the case of a two body decay, either the trigger fired on the reconstructed two body candidate or on one or both of the tracks independently. If a candidate is TIS, this means that the trigger fired as a result of some other part of the event and did not use any of the candidate’s tracks. If a candidate is neither TOS nor TIS then it is TUS (trigger used signal). In this case the trigger fired on the candidate or its constituent tracks combined with another part of the event.

TCK	Integrated Luminosity (nb ⁻¹)	SPD Requirement (hit multiplicity)	L0e (MeV)	L0 γ (MeV)	L0Hadron (MeV)
0x1D0030	157.4	900	3000	4400	2600
0x1F0031	102.2	450	3000	4400	3600
0x1E0030	2117.1	900	3000	4400	2600
0x1F0029	3078.8	900	3000	4400	3600
0x24002A	1212.6	900	3000	3200	3600
0x24002C	1356.9	450	3000	3200	3600
0x25002A	35.2	900	3000	3200	3600
0x25002C	1946.2	450	3000	3200	3600
0x2B002A	1839.1	900	3000	3200	3600
0x2A002A	4179.1	900	3000	3200	3600
0x2A002C	468.5	450	3000	3200	3600
0x2E002C	8911.2	450	3000	3200	3600
0x2E002A	8668.9	900	3000	3200	3600
0x2D002B	2.5	900	3000	3200	3600

Table 3.1: The TCKs used during 2010 at LHCb along with the corresponding integrated luminosities, SPD requirements and L0 transverse energy thresholds in MeV [63].

3.3.1.1 L0

Of the offline selected $B \rightarrow h^+h^-$ candidates (those making it into the final dataset) 63.7% were TOS and 60.2% were TIS with respect to the sum of all L0 lines^a. Of the candidates triggered on signal 94.0% were triggered by the L0 Hadron trigger which has a minimum transverse energy threshold of 3.6 GeV for both 0x002e002a and 0x002e002c TCKs. The remainder were triggered by a combination of the electron and muon trigger lines. Of the candidates triggered independently of signal the dominant trigger lines were the Hadron (56.3%) and Muon (41.9%) triggers.

^aIt should be noted that a candidate can be both TOS and TIS at the same time and this is easily seen if we consider an event containing two true $B_s^0 \rightarrow K^+K^-$ decays. The trigger may fire twice for a given event and therefore on both decays. When the trigger fires on the first decay the first decay is TOS and the second decay is TIS and when the trigger fires on the second decay the reverse is true.

3.3.1.2 HLT1

93.0% of offline selected $B \rightarrow h^+h^-$ candidates were triggered on signal by the HLT1, with 23.1% triggered independently of signal. Of the TOS candidates 84.0% were triggered by the single track trigger^b described in Section 2.2.4.2. Most of the TIS candidates were due to the HLT1 L0 muon confirmation trigger and the single track trigger. The selection criteria used by the HLT1 single track trigger are listed in Table 3.2 where p is momentum, p_T transverse momentum and IP impact parameter with respect to the closest (“best”) interaction vertex.

Criterion
$p_T > 1.85 \text{ GeV}/c$
$p > 13.3 \text{ GeV}/c$
$IP > 0.11 \text{ mm}$
$IP\chi^2 > 34$
Track χ^2 per degree of freedom < 3
Number of track hits > 9
Number of missed VELO hits < 3

Table 3.2: Criteria for candidates passing the Hlt1TrackAllL0 trigger line for both 0x002e002a and 0x002e002c TCKs. At least one of the two $B \rightarrow h^+h^-$ tracks must satisfy these conditions for the candidate to be triggered on signal.

3.3.1.3 HLT2

In the HLT2 95.0% of offline selected $B \rightarrow h^+h^-$ candidates were TOS with only 12.1% triggered independently of signal. The two dominant HLT2 lines for these decays are the purpose designed $B \rightarrow h^+h^-$ trigger (“Hlt2B2HH”) and the inclusive two body topological trigger (“TopoOSTF2Body”) which triggered 84.6% and 86.0% of the candidates respectively. The selection criteria for these two trigger lines are listed in Tables 3.3 and 3.4. In these tables nDOF is the number of degrees of freedom of the track Kalman fit, m_{comb} is the invariant mass of the combined tracks, DOCA (distance of closest approach) is the smallest distance between the two tracks, FD (flight distance) is the distance between the interaction vertex and decay vertex, m_B is the fitted mass of the B candidate

^bLabelled “Hlt1TrackAllL0”.

and θ is the angle between the line joining the the decay vertex to the interaction vertex and the momentum vector of the B candidate. m_{comb} and m_B may differ since m_{comb} is calculated from the momenta of the two tracks quoted at reference points which are not, in general, the same as the decay vertex. In contrast, the calculation of m_B uses the momenta of the two tracks at the decay vertex.

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h^-}) > 700 \text{ MeV}/c$ $\max(p_T^{h^+}, p_T^{h^-}) > 2400 \text{ MeV}/c$ $\min(IP^{h^+}, IP^{h^-}) > 0.08 \text{ mm}$ $\max(IP^{h^+}, IP^{h^-}) > 0.24 \text{ mm}$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 5$
Combination	$4800 \text{ MeV}/c^2 < m_{comb} < 5800 \text{ MeV}/c^2$ $\text{DOCA} < 0.1 \text{ mm}$
Mother	$IP^B < 0.1 \text{ mm}$ $FD^B > 2.2 \text{ mm}$

Table 3.3: Criteria for candidates passing the Hlt2B2HH trigger line for both 0x002e002a and 0x002e002c TCKs. B candidates are reconstructed assuming a pion mass hypothesis for both daughters.

3.3.2 Stripping Selection

Due to processing and bandwidth limitations it is not possible for each researcher to analyse the entire LHCb dataset independently. Instead, data is processed centrally through a process known as “stripping”. Each physics analysis group submits stripping lines which are designed to reconstruct and select particular decays or physics processes. All stripping lines are then run centrally over the entire dataset to produce smaller “stripped” datasets which contain only the elements relevant to the particular analysis. In the case of $B \rightarrow h^+h^-$ only the B candidates, their tracks and the interaction vertex are saved to the stripped dataset. These stripped datasets are saved on computer farms distributed across the globe and can be analysed by individual researchers using the world wide computing GRID developed by CERN for the distributed analysis of LHC data. The data used in this dissertation was processed using the “Stripping12b” version

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h^-}) > 500 \text{ MeV}/c$ $\min(p^{h^+}, p^{h^-}) > 5000 \text{ MeV}/c$ $\min(IP\chi_{h^+}^2, IP\chi_{h^-}^2) > 16$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 5$
Combination	$m_{comb} < 7000 \text{ MeV}/c^2$ $\text{DOCA} < 0.1 \text{ mm}$
Mother	$FD\chi_B^2 > 64 \text{ mm}$ $\cos\theta > 0$ $IP\chi_B^2 > 16 \text{ OR } m_B > 2500 \text{ MeV}/c^2$

Table 3.4: Criteria for candidates passing the Hlt2TopoOSTF2Body trigger line for both 0x002e002a and 0x002e002c TCKs. B candidates are reconstructed assuming a kaon mass hypothesis for both daughters.

of the stripping algorithms and includes a mixture of data taken with both the “up” and “down” magnet polarities.

The stripping line for $B \rightarrow h^+h^-$ decays, labelled “Hb2Charged2Body”, closely mirrors the HLT2 trigger line and was formulated for the measurement of CP asymmetries in $B \rightarrow h^+h^-$ decays [64, 65]. However, the selection used is also ideal for the $B_s^0 \rightarrow K^+K^-$ lifetime measurement. All candidates are reconstructed assuming a $B^0 \rightarrow \pi^+\pi^-$ decay hypothesis and the selection criteria are listed in Table 3.5. The output of this stripping line from the full 2010 LHCb dataset is shown in Figure 3.2 in the form of the $\pi^+\pi^-$ invariant mass spectrum. A broad peak due to $B \rightarrow h^+h^-$ decay modes is clearly visible between approximately 5,100 and 5,300 MeV/c^2 .

3.3.3 Offline Selection

After passing through the trigger and stripping processes the data yields a clear $B \rightarrow h^+h^-$ peak in the B invariant mass spectrum as is visible in Figure 3.2. The B candidates are produced by the stripping under a $\pi^+\pi^-$ decay hypothesis. In order to obtain the correct invariant masses and proper decay times for the lifetime analysis the candidates are re-reconstructed under both K^+K^- and $K^\pm\pi^\mp$ decay hypotheses. Further selections are then applied. First a selection based on kinematical quantities, similar to the stripping selection, is applied in order to enhance the significance of the $B \rightarrow h^+h^-$

signal. Finally, the PID capabilities of the LHCb experiment are employed in order to separate the various final states.

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h^-}) > 700 \text{ MeV}/c$ $\max(p_T^{h^+}, p_T^{h^-}) > 2400 \text{ MeV}/c$ $\min(IP^{h^+}, IP^{h^-}) > 0.08 \text{ mm}$ $\max(IP^{h^+}, IP^{h^-}) > 0.2 \text{ mm}$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 5$
Combination	$4500 \text{ MeV}/c^2 < m_{comb} < 6500 \text{ MeV}/c^2$ $\text{DOCA} < 0.08 \text{ mm}$
Mother	$4800 \text{ MeV}/c^2 < m_B < 5800 \text{ MeV}/c^2$ $IP^B < 0.06 \text{ mm}$ $FD^B > 1.8 \text{ mm}$

Table 3.5: Hb2Charged2Body stripping requirements for $B \rightarrow h^+h^-$ candidates reconstructed assuming a pion mass hypothesis for both daughters.

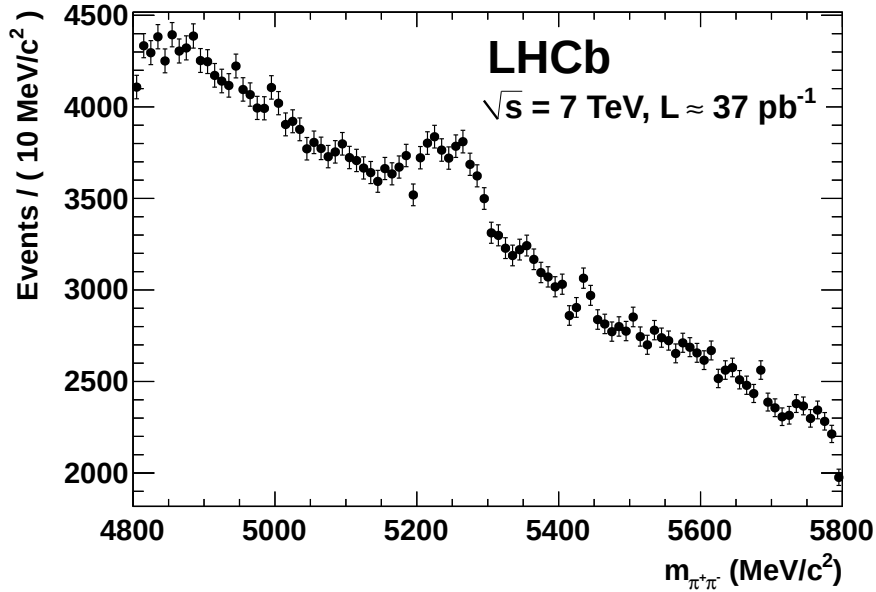


Figure 3.2: The $\pi^+\pi^-$ invariant mass spectrum produced by the Hb2Charged2Body stripping line when run over the full 37.66 pb^{-1} 2010 LHCb dataset. Note that the minimum value on the y axis is non-zero.

3.3.3.1 Kinematic Selection

The offline kinematic selection was designed to maximise the signal significance of the broad $B \rightarrow h^+h^-$ peak which is dominated by the modes $B^0 \rightarrow K^+\pi^-$, $B_s^0 \rightarrow K^+K^-$, $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$. A simple set of criteria are imposed, however the selection was inspired by a neural network analysis performed using the NeuroBayes package [66]. The network was trained to distinguish signal from combinatorial background using $B \rightarrow h^+h^-$ data passed by the stripping selection. An example of this approach is given in more detail in [67]. A cut was made on the network output which gave the maximum value of $S/\sqrt{S+B}$, where S and B are signal and background yields respectively. The resulting peak was then used as a “clean” sample of $B \rightarrow h^+h^-$ decays to compare kinematic distributions with the background from the side bands. Using this information a set of criteria was devised which gave a signal peak with the same value of $S/\sqrt{S+B}$ as produced by the neural network. The criteria used are listed in Table 3.6 and the $\pi^+\pi^-$ invariant mass spectrum after the application of these criteria is shown in Figure 3.3.

3.3.3.2 Particle Identification Selection

The channels $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ are both required for the measurement of the effective $B_s^0 \rightarrow K^+K^-$ lifetime. It is therefore necessary to separate these channels from the $B \rightarrow h^+h^-$ mixture. The decay modes present in the 4800-5800 MeV/ c^2 mass window are listed in Table 3.7 along with their estimated relative abundances. The RICH detectors allow separation of charged pions, kaons and protons and this PID capacity is used to split the data into the $K^\pm\pi^\mp$ and K^+K^- final states. The $\Delta\log\mathcal{L}_{K-\pi}$ (defined in Section 2.2.3) distributions of the full $B \rightarrow h^+h^-$ 2010 dataset after the offline kinematic selection are shown in Figure 3.4.

K^+K^- Selection Since the PID distributions in Monte Carlo simulations do not yet reflect those seen in the data, a data-driven approach was used to devise the PID selections. For the K^+K^- final state the aim is to reduce contamination from $B^0 \rightarrow K^+\pi^-$, $B_s^0 \rightarrow \pi^+K^-$ and $B^0 \rightarrow \pi^+\pi^-$ as much as possible. Under the K^+K^- decay hypothesis all these modes have invariant mass distributions that overlap the $B_s^0 \rightarrow K^+K^-$ distribution with mean values below the B_s^0 mass. Consequently, if the signal peak

Criterion Type	Criterion
Daughter	$\max(p_T^{h^+}, p_T^{h^-}) > 2700 \text{ MeV/c}$ $\min(IP\chi_{h^+}^2, IP\chi_{h^-}^2) > 100$ $\max(IP\chi_{h^+}^2, IP\chi_{h^-}^2) > 200$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 3$
Mother	$p_T^B > 1200 \text{ MeV/c}$ $IP\chi_B^2 < 12$

Table 3.6: Offline kinematic criteria for selecting $B \rightarrow h^+h^-$ candidates.

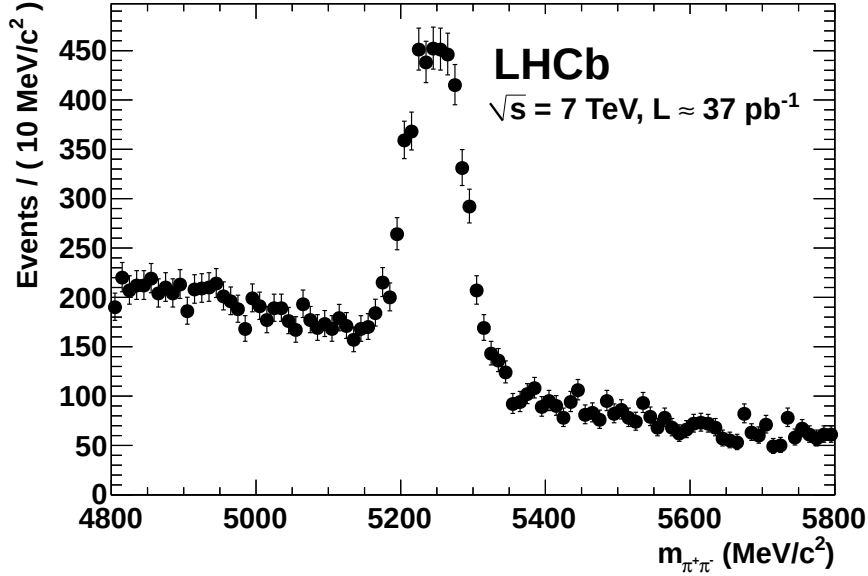


Figure 3.3: The $\pi^+\pi^-$ invariant mass spectrum produced by the offline kinematic selection for the full 37.66 pb^{-1} 2010 LHCb dataset.

of a $B_s^0 \rightarrow K^+K^-$ dataset containing significant contamination from $B^0 \rightarrow K^+\pi^-$, $B_s^0 \rightarrow \pi^+K^-$ or $B^0 \rightarrow \pi^+\pi^-$ is modelled using a Gaussian distribution then the fitted mean of this function will be significantly lower than the true B_s^0 mass. This point is illustrated in Figure 3.5 where a clear low-mass shoulder due predominantly to $B^0 \rightarrow K^+\pi^-$ is visible to the left of the signal peak for the plot with the most relaxed PID requirement. As the PID constraint is made stricter the mean of the Gaussian increases towards the known B_s^0 mass.

The mean of the Gaussian distribution fitted to the $B_s^0 \rightarrow K^+K^-$ peak was used as a metric to indicate the level of contamination. Figure 3.6 shows how the mean of

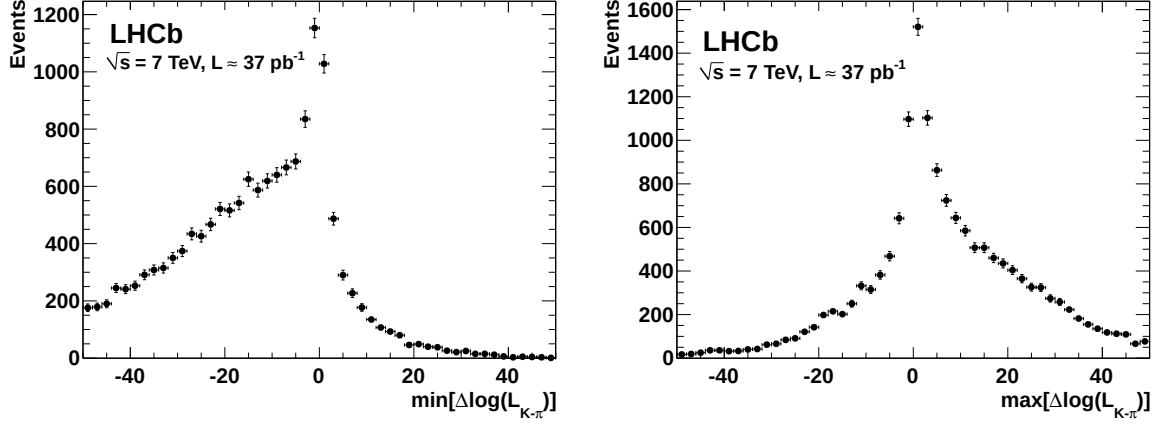


Figure 3.4: $\Delta\log\mathcal{L}_{K-\pi}$ distributions of $B \rightarrow h^+h^-$ candidates passing the offline kinematic selection from the 2010 LHCb dataset. The plot on the left (right) shows the smaller (larger) of the two daughters' $\Delta\log\mathcal{L}_{K-\pi}$.

Channel	Hadronization Fraction	Branching Ratio	Relative Abundance
$B_s^0 \rightarrow K^+K^-$	0.101	2.65×10^{-5}	1
$B_s^0 \rightarrow \pi^+K^-$	0.101	5.0×10^{-6}	0.19
$B^0 \rightarrow K^+\pi^-$	0.403	1.9×10^{-5}	2.86
$B^0 \rightarrow \pi^+\pi^-$	0.403	5.16×10^{-6}	0.78
$B^0 \rightarrow K^+K^-$	0.403	1.5×10^{-7}	0.02
$\Lambda_b^0 \rightarrow p^+K^-$	0.092	5.0×10^{-6}	0.17
$\Lambda_b^0 \rightarrow p^+\pi^-$	0.092	3.2×10^{-6}	0.11

Table 3.7: Estimated relative abundances of decay modes with significant yields in the 4800-5800 MeV/ c^2 mass window [11]. The charge conjugate decays are implied.

this Gaussian $m_{B_s^0}$ varies as both daughters are required to have a minimum value of $\Delta\log\mathcal{L}_{K-\pi}$. $m_{B_s^0}$ increases as the minimum value of $\Delta\log\mathcal{L}_{K-\pi}$ is increased to reach a rough plateau after $\min(\Delta\log\mathcal{L}_{K-\pi}) > 7$. A cut of $\min(\Delta\log\mathcal{L}_{K-\pi}) > 8$ is chosen in order to balance the requirement for low contamination against the need for maximum statistics.

In addition to $K - \pi$ separation, requirements are also made on $K - p$, $K - \mu$ and $K - e$ in order to minimise other backgrounds, particularly those from $\Lambda_b^0 \rightarrow p^+K^-$ and $\Lambda_b^0 \rightarrow p^+\pi^-$. The final PID criteria for the K^+K^- final state are listed in Table 3.8. The final offline selected K^+K^- invariant mass distribution is shown in Figure 3.7 where a

clear $B_s^0 \rightarrow K^+ K^-$ peak is visible.

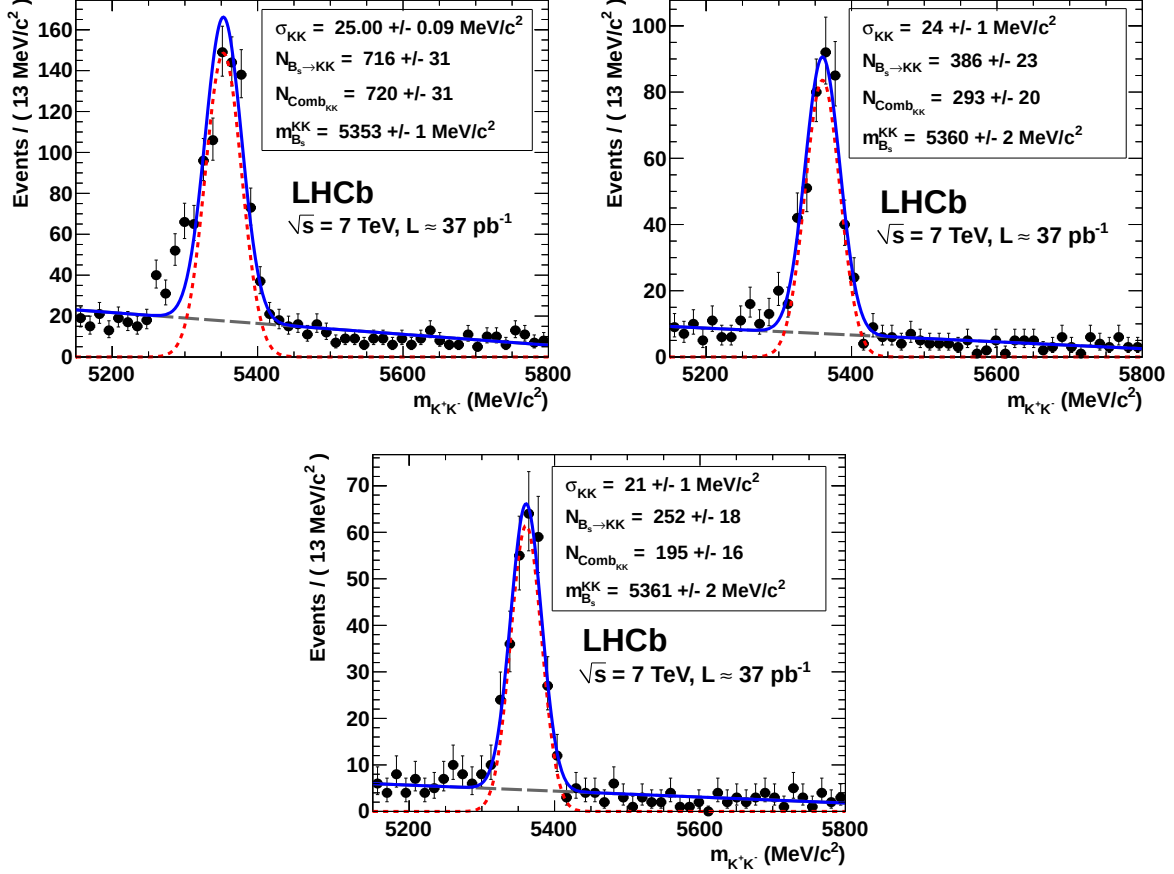


Figure 3.5: A set of fits to the K^+K^- invariant mass spectrum for different requirements on $\Delta \log \mathcal{L}_{K-\pi}$ for the kaons using the 2010 LHCb dataset. The peak is modelled by a Gaussian distribution and the background by a first order polynomial. From left to right the requirements imposed are $\Delta \log \mathcal{L}_{K-\pi} > 0$, $\Delta \log \mathcal{L}_{K-\pi} > 5$ and $\Delta \log \mathcal{L}_{K-\pi} > 10$ for both kaons.

PID Criteria
$\Delta \log \mathcal{L}_{K-\pi} > 8$
$\Delta \log \mathcal{L}_{K-p} > -5$
$\Delta \log \mathcal{L}_{K-e} > 0$
$\Delta \log \mathcal{L}_{K-\mu} > 0$

Table 3.8: K^+K^- final state PID selection, applied to both final state particles.

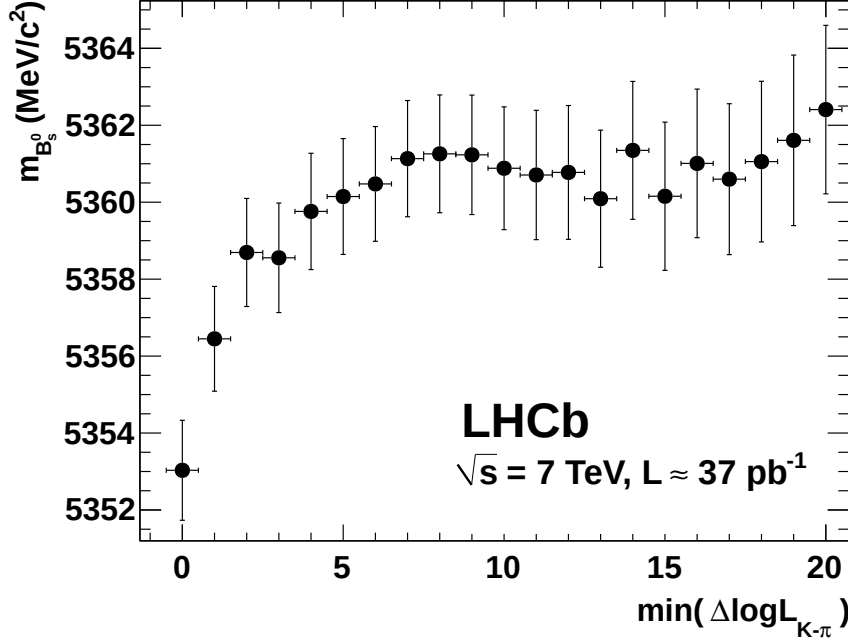


Figure 3.6: The mean of a Gaussian fitted to the $B_s^0 \rightarrow K^+ K^-$ mass peak as a function of the minimum requirement on $\Delta\log\mathcal{L}_{K-\pi}$ for the full 37.66 pb^{-1} 2010 LHCb dataset.

$K^\pm\pi^\mp$ Selection A similar technique was used to optimise the $K^\pm\pi^\mp$ final state selection. However, in this case the metric chosen was the ratio of the yields of the decay modes $B_s^0 \rightarrow \pi^+ K^-$ and $B^0 \rightarrow K^+ \pi^-$. The $K^\pm\pi^\mp$ mass spectrum was fitted with two Gaussian distributions to model these two signals. In the event of substantial contamination from either $B_s^0 \rightarrow K^+ K^-$ or $B^0 \rightarrow \pi^+ \pi^-$ an over-estimation of the amount of $B_s^0 \rightarrow \pi^+ K^-$ signal would occur since these modes have a mean mass close to that of the $B_s^0 \rightarrow \pi^+ K^-$ peak under the $K^\pm\pi^\mp$ hypothesis. Figure 3.8 shows examples of fits to the $K^\pm\pi^\mp$ spectrum with the $\Delta\log\mathcal{L}_{K-\pi}$ requirement on the pion becoming stricter from left to right. As a harder $\Delta\log\mathcal{L}_{K-\pi}$ cut is imposed a reduction in the height of the “ $B_s^0 \rightarrow \pi^+ K^-$ ” peak is visible.

Figure 3.9 shows the ratio of the $B_s^0 \rightarrow \pi^+ K^-$ and $B^0 \rightarrow K^+ \pi^-$ yields as a function of the pion PID cut. The kaon is required to satisfy $\Delta\log\mathcal{L}_{K-p} > 8$, which is taken from the $K^+ K^-$ selection. The ratio stabilises when $\min(\Delta\log\mathcal{L}_{K-\pi}^{h^+}, \Delta\log\mathcal{L}_{K-\pi}^{h^-}) < -5$. The full list of cuts for the $K^\pm\pi^\mp$ final state are given in Table 3.9. The final offline selected $K^\pm\pi^\mp$ invariant mass distribution is shown in Figure 3.10 where a clear $B^0 \rightarrow K^+ \pi^-$ peak is visible along with a high-mass shoulder due to $B_s^0 \rightarrow \pi^+ K^-$.

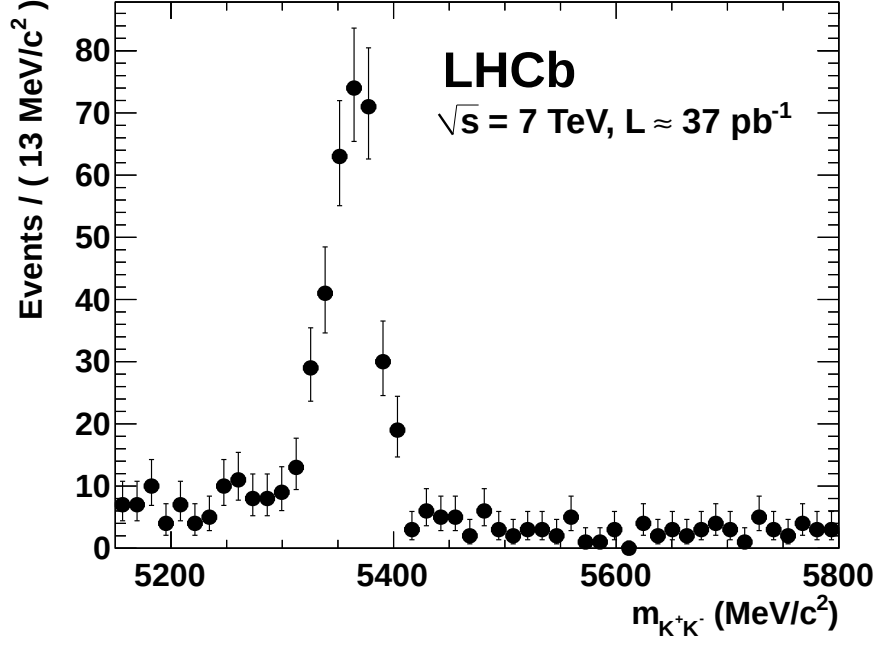


Figure 3.7: The offline selected K^+K^- mass distribution with a clear $B_s^0 \rightarrow K^+K^-$ mass peak for the full 37.66 pb^{-1} 2010 LHCb dataset.

Particle	PID Criteria
K	$\Delta \log \mathcal{L}_{K-\pi} > 8$ $\Delta \log \mathcal{L}_{K-p} > -5$ $\Delta \log \mathcal{L}_{K-e} > 0$ $\Delta \log \mathcal{L}_{K-\mu} > 0$
π	$\Delta \log \mathcal{L}_{K-\pi} < -5$ $\Delta \log \mathcal{L}_{p-\pi} < 0$ $\Delta \log \mathcal{L}_{e-\pi} < 0$ $\Delta \log \mathcal{L}_{\mu-\pi} < 0$

Table 3.9: $K^\pm \pi^\mp$ final state PID selection.

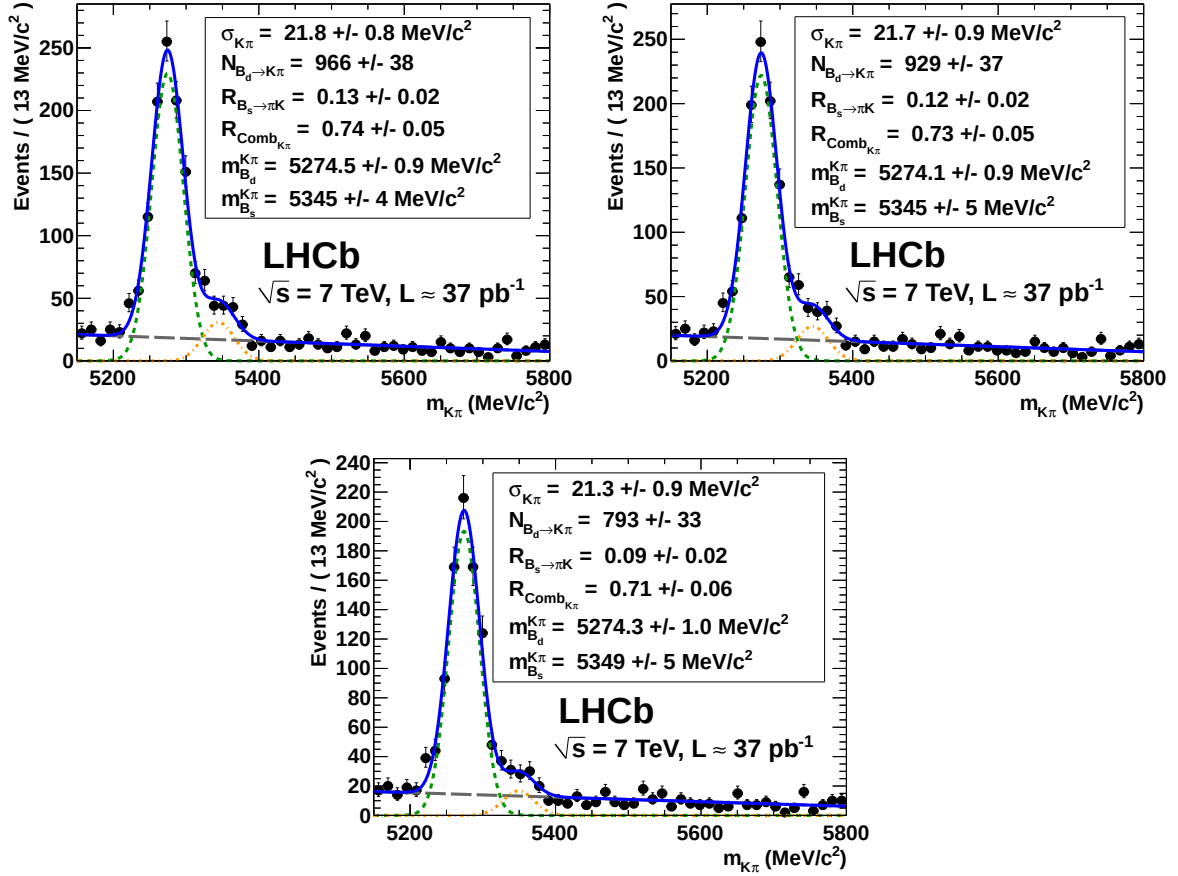


Figure 3.8: A set of fits to the $K^\pm\pi^\pm$ invariant mass spectrum for different requirements on $\Delta\log\mathcal{L}_{K-\pi}$ for the pion using the 2010 LHCb dataset. The $B^0 \rightarrow K^+\pi^-$ (green, medium dashes) and $B_s^0 \rightarrow \pi^+K^-$ (orange, short dashes) peaks are modelled by Gaussian distributions and the background by a first order polynomial (grey, long dashes). From left to right the requirements imposed are $\Delta\log\mathcal{L}_{K-\pi} < 0$, $\Delta\log\mathcal{L}_{K-\pi} < -1$ and $\Delta\log\mathcal{L}_{K-\pi} < -5$ for the pion. In all cases the kaon must satisfy $\Delta\log\mathcal{L}_{K-\pi} > 8$.

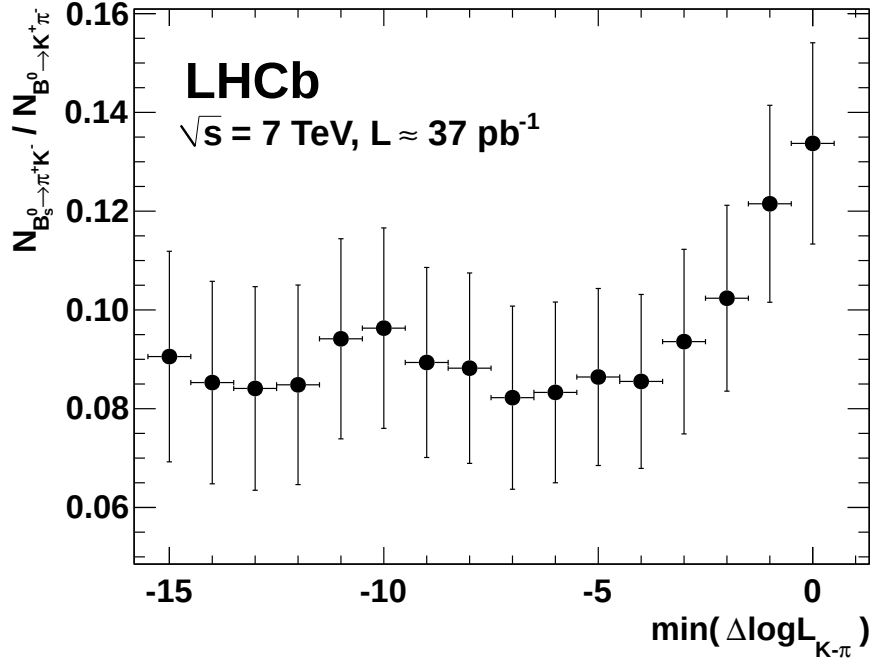


Figure 3.9: The ratio of the fitted yields of $B_s^0 \rightarrow \pi^+ K^-$ and $B^0 \rightarrow K^+ \pi^-$ as a function of a cut on the minimum $\Delta \log \mathcal{L}_{K-\pi}$ of the two final state tracks.

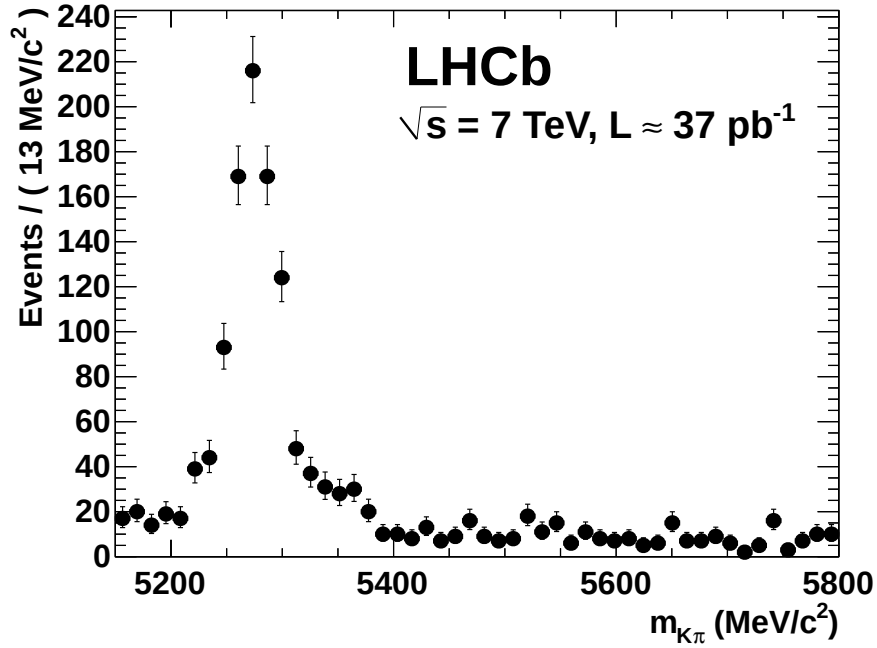


Figure 3.10: The offline selected $K^\pm \pi^\mp$ mass distribution with a clear $B^0 \rightarrow K^+ \pi^-$ peak and $B_s^0 \rightarrow \pi^+ K^-$ high-mass shoulder for the full 37.66 pb^{-1} 2010 LHCb dataset.

3.4 Selection of $D \rightarrow h^+ h^-$ Events

In the case of the $B \rightarrow h^+ h^-$ selection the key challenge is to extract a rare signal from a very large amount of data, obtaining just a few hundred candidates from the 2010 dataset. The charm production cross-section has been measured at LHCb as [68]

$$\sigma(pp \rightarrow c\bar{c}X) = 6.10 \pm 0.93 \text{ mb.} \quad (3.3)$$

This large charm production rate makes designing a $D \rightarrow h^+ h^-$ selection an entirely different problem, with many millions of candidates potentially present in the final dataset. This great abundance of D decays makes obtaining a sample relatively straightforward, however the limiting factor is the amount of data that can be recorded due to bandwidth and disk space restrictions. Even with zero background it would be impossible to record every $D \rightarrow h^+ h^-$ event and so any selection must attempt to almost entirely eliminate background in order to maximise the quantity of useful data. This is especially important for the stripping and offline selections.

3.4.1 Trigger

The configuration of the trigger during 2010 described in Section 3.3.1 also applies to the 2010 $D \rightarrow h^+ h^-$ dataset. It is important to note that the L0 and HLT1 triggers were designed primarily to be most efficient for decays of b -hadrons (although the need for charm physics was also considered) and as a result their efficiencies for D decays is somewhat reduced compared to B decays. Nonetheless, the much larger D meson production rate means that a very large dataset can be selected even with triggers that are not optimal for charm physics.

Another feature peculiar to the triggering of $D \rightarrow h^+ h^-$ decays is that a candidate described “Triggered Independent of Signal” (TIS), may not in fact have been triggered independently of itself. A significant fraction of D mesons are produced in the decays of B mesons, for instance decays of the form $B \rightarrow D^0 X$, where X denotes a non-specific particle. These D decays are described as “secondary” since they are produced in the decay of another particle. “Prompt” candidates come directly from $c\bar{c}$ production in the primary interaction. In many cases where a candidate is passed as TIS the X is in fact the cause of the trigger. The properties of the X are correlated with those of the D and so while the trigger did not fire directly on the D , TIS candidates may still

be affected by trigger biases. Unfortunately, due to the large number of different decay modes producing a secondary D , many of which contain neutrinos, it is impractical to reconstruct the full chain in order to eliminate these decay modes. Instead, prompt and secondary D mesons must be separated statistically and this is one of the greatest challenges in making charm lifetime measurements.

3.4.1.1 L0

The stringent transverse energy requirements used in the L0 trigger (see Table 3.1) effectively remove around 92% of $D \rightarrow h^+h^-$ decays (estimated from full LHCb Monte Carlo simulated data). Of the candidates passing the stripping selection 50.0% were TOS and 66.9% were TIS with respect to the sum of all L0 lines. 82% of the TOS candidates were triggered by the L0 Hadron trigger with the remainder triggered by the muon and electron lines. The dominant sources of TIS candidates are the muon (49.3%) and the hadron (45.2%) lines.

3.4.1.2 HLT1

85.6% and 27.3% of stripped $D \rightarrow h^+h^-$ candidates were TOS and TIS with respect to the sum of all HLT1 lines respectively. Of the TOS candidates 92.4% were triggered by the single track trigger described in Table 3.2. Of the TIS candidates 62.4% were triggered by the single track trigger which suggests the presence of a significant fraction of secondary D decays. This is investigated further in Chapter 5.

3.4.1.3 HLT2

80.1% of stripped candidates were TOS with respect to the sum of all HLT2 lines while only 9.8% were TIS. Of the TOS candidates the vast majority, 98.2%, were triggered by the “Hlt2CharmOSTF2Body” trigger line which was designed by the LHCb Charm Working Group to select $D \rightarrow h^+h^-$ decays. The requirements imposed by this trigger are listed in Table 3.10.

The “Hlt2CharmOSTF2Body” trigger line has a narrow mass window around the D^0 mass from 1,839-1,889 MeV/ c^2 in order to keep the retention rate of the line down as much as possible. Unfortunately at the time of writing it was not anticipated that such a narrow mass window would make fitting the sidebands of the $D \rightarrow h^+h^-$ spectrum

very challenging. Fortunately, another trigger line, “Hlt2CharmOSTF2BodyWideMass” was also run which had a wider mass window of 1,700-2,100 MeV/ c^2 . However, this line was “prescaled” by a factor of 0.01, meaning that the trigger was only active for 1% of events. The requirements imposed by the wide mass window trigger are listed in Table 3.11. The wide mass trigger differs only from the narrow mass trigger in that requirements on the transverse momentum and vertex χ^2 of the D candidate are not imposed.

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h^-}) > 800 \text{ MeV}/c$ $\max(p_T^{h^+}, p_T^{h^-}) > 1500 \text{ MeV}/c$ $\min(p^{h^+}, p^{h^-}) > 5000 \text{ MeV}/c$ $\min(IP\chi_{h^+}^2, IP\chi_{h^-}^2) > 2$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 5$
Combination	$m_{comb} < 2100 \text{ MeV}/c^2$ $\text{DOCA} < 0.1 \text{ mm}$
Mother	$1839 \text{ MeV}/c^2 < m_D < 1889 \text{ MeV}/c^2$ $p_T > 2000 \text{ MeV}/c$ $FD\chi^2 > 25$ $\cos\theta > 0.99985$ $\text{Vertex } \chi^2/\text{nDOF} < 10$

Table 3.10: Criteria for candidates passing the Hlt2CharmOSTF2Body trigger line for both 0x002e002a and 0x002e002c TCKs. D candidates are reconstructed assuming K^+K^- , $K^\pm\pi^\mp$ and $\pi^+\pi^-$ decay hypotheses. An additional requirement is made that both daughters have the same “best” primary vertex (the primary vertex which their extrapolated tracks approach most closely).

3.4.2 Stripping Selection

The $D \rightarrow h^+h^-$ stripping lines were developed collaboratively to select candidates for use in lifetime measurements. The stripping line selects “untagged” candidates, i.e. those where the initial flavour of the D meson (D^0 or $\bar{D}^0$) is unknown. The lines “DhhPromptD2KK”, “DhhPromptD2KPi” and “D2hhPromptD2PiPi” were designed to

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h^-}) > 800 \text{ MeV}/c$ $\max(p_T^{h^+}, p_T^{h^-}) > 1500 \text{ MeV}/c$ $\min(p^{h^+}, p^{h^-}) > 5000 \text{ MeV}/c$ $\min(IP\chi_{h^+}^2, IP\chi_{h^-}^2) > 2$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 5$
Combination	$m_{comb} < 2100 \text{ MeV}/c^2$ $\text{DOCA} < 0.1 \text{ mm}$
Mother	$1700 \text{ MeV}/c^2 < m_D < 2100 \text{ MeV}/c^2$ $FD\chi^2 > 25$ $\cos \theta > 0.99985$

Table 3.11: Criteria for candidates passing the Hlt2CharmOSTF2BodyWideMass trigger line for both 0x002e002a and 0x002e002c TCKs. D candidates are reconstructed assuming K^+K^- , $K^\pm\pi^\mp$ and $\pi^+\pi^-$ decay hypotheses. An additional requirement is made that both daughters have the same “best” primary vertex (the primary vertex which their extrapolated tracks approach most closely).

select untagged $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays respectively. The expected relative abundances of each $D \rightarrow h^+h^-$ decay mode are listed in Table 3.12. A complimentary stripping which selects “tagged” $D \rightarrow h^+h^-$ decays from $D^{*+} \rightarrow D^0\pi^+$ and $D^{*-} \rightarrow \bar{D}^0\pi^-$ where the flavour of the D^0 is indicated by the charge of the pion is described in [69]. The selection requirements used in the untagged stripping lines are listed in Table 3.13. These stripping requirements were those used in the version “Stripping14”.

Channel	Branching Ratio	Relative Abundance
$D^0 \rightarrow K^+K^-$	3.96×10^{-3}	0.10
$D^0 \rightarrow \pi^+K^-$	3.87×10^{-2}	1
$D^0 \rightarrow \pi^+\pi^-$	1.4×10^{-3}	0.036

Table 3.12: Estimated relative abundances of $D \rightarrow h^+h^-$ decay modes [11]. The charge conjugate decays are implied.

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h^-}) > 800 \text{ MeV}/c$ $\max(p_T^{h^+}, p_T^{h^-}) > 1500 \text{ MeV}/c$ $\min(p^{h^+}, p^{h^-}) > 5000 \text{ MeV}/c$ $\min(IP\chi_{h^+}^2, IP\chi_{h^-}^2) > 9$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 3$
Combination	$1765 \text{ MeV}/c^2 < m_{comb} < 1965 \text{ MeV}/c^2$ $\text{DOCA} < 0.07 \text{ mm}$ $p_T > 2000 \text{ MeV}/c$ $p > 5000 \text{ MeV}/c$
Mother	$FD\chi^2 > 40$ $\cos\theta > 0.9999$ $\text{Vertex } \chi^2/\text{nDOF} < 10$
PID $D^0 \rightarrow K^+K^-$	$\min(\Delta\log\mathcal{L}_{K-\pi}) > 0$ $\max(\Delta\log\mathcal{L}_{K-\pi}) > 5$
PID $D^0 \rightarrow \pi^+K^-$	$\min(\Delta\log\mathcal{L}_{K-\pi}) < 0$ $\max(\Delta\log\mathcal{L}_{K-\pi}) > 5$
PID $D^0 \rightarrow \pi^+\pi^-$	$\max(\Delta\log\mathcal{L}_{K-\pi}) < 5$

Table 3.13: Criteria for candidates passing the “D2hhPrompt” stripping lines for untagged $D \rightarrow h^+h^-$ decays. D candidates are reconstructed assuming K^+K^- , $K^\pm\pi^\mp$ and $\pi^+\pi^-$ decay hypotheses and the corresponding PID requirements are applied. All tracks are required to be “long”, meaning that they have hits in the VELO, tracking stations and calorimeters.

3.4.3 Offline Selection

Due to the stringent nature of the stripping requirements it is not necessary to impose any further offline requirements in order to enhance signal purity. Candidates are required to be either TOS with respect to the L0Hadron trigger or TIS with respect to the global L0 decision. In addition, candidates are required to be TOS with respect to Hlt1TrackAllL0 and one of Hlt2CharmOSTF2Body or Hlt2CharmOSTF2BodyWideMass. The resulting invariant mass distributions of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+K^-$ candidates passing the Hlt2CharmOSTF2Body trigger for the full 2010 dataset are shown in Figures 3.11 and 3.12 respectively. The $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+K^-$ invariant mass distributions of candidates passing the Hlt2CharmOSTF2BodyWideMass trigger are shown

in Figures 3.13 and 3.14 respectively.

In Figures 3.11 and 3.12 the mass cut-off due to the narrow HLT2 mass window is visible at around 1,840 MeV/c^2 and 1,890 MeV/c^2 and is especially pronounced in Figure 3.11 due to the higher level of K^+K^- combinatorial background. However, the HLT2 cut-off does not appear as a sharp edge as it is smeared by the difference in mass resolution between the trigger and the offline software.

In Figure 3.14 it is clear that there is very little background to the $D^0 \rightarrow \pi^+K^-$ peak. However, the level of background for $D^0 \rightarrow K^+K^-$ in Figure 3.13 is much higher with a combination of combinatorial background, partially reconstructed background on the low-mass side and a mis-reconstructed $D^0 \rightarrow \pi^+K^-$ shoulder on the high-mass side.

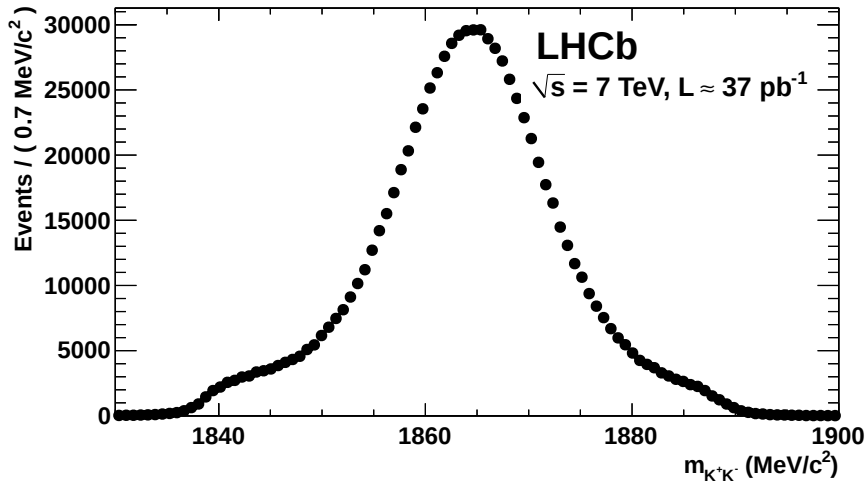


Figure 3.11: The offline selected K^+K^- mass distribution with a clear $D^0 \rightarrow K^+K^-$ mass peak for the full 37.66 pb^{-1} 2010 LHCb dataset. Candidates have passed the Hlt2CharmOSTF2Body trigger line.

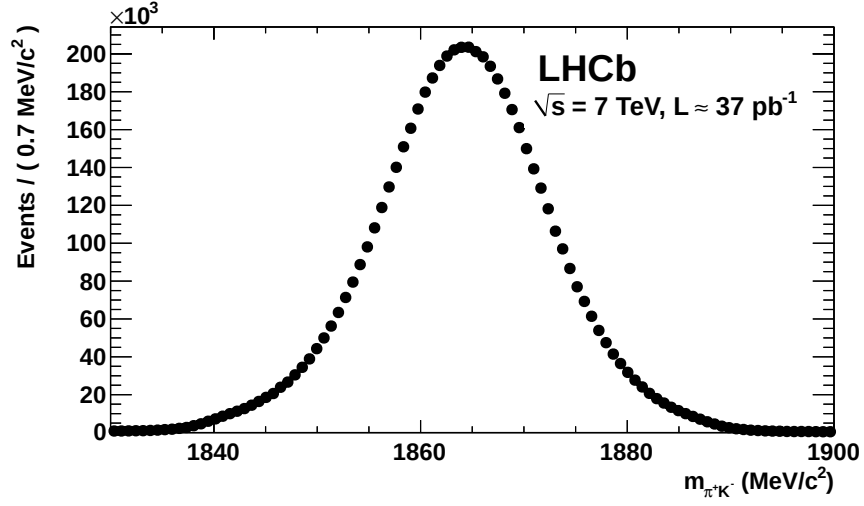


Figure 3.12: The offline selected $\pi^\pm K^\mp$ mass distribution with a clear $D^0 \rightarrow \pi^+ K^-$ mass peak for the full 37.66 pb^{-1} 2010 LHCb dataset. Candidates have passed the Hlt2CharmOSTF2Body trigger line.

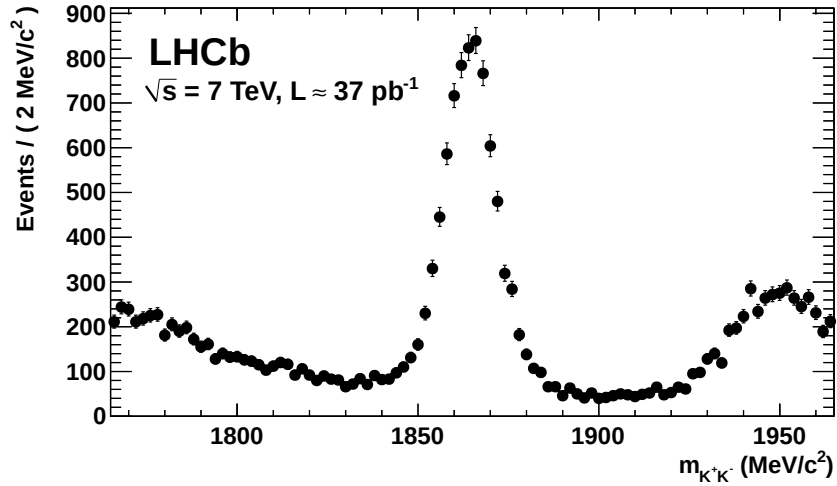


Figure 3.13: The offline selected $K^+ K^-$ mass distribution with a clear $D^0 \rightarrow K^+ K^-$ mass peak for the full 37.66 pb^{-1} 2010 LHCb dataset. Candidates have passed the Hlt2CharmOSTF2BodyWideMass trigger line.

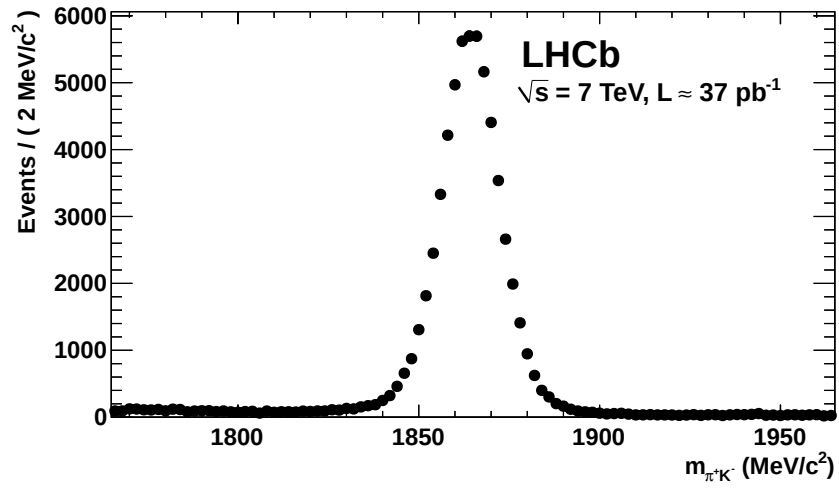


Figure 3.14: The offline selected $\pi^{\pm}K^{\mp}$ mass distribution with a clear $D^0 \rightarrow \pi^+K^-$ mass peak for the full 37.66 pb^{-1} 2010 LHCb dataset. Candidates have passed the Hlt2CharmOSTF2BodyWideMass trigger line.

3.4.4 Proper Time Unbiased Selection

The triggers and selections described previously introduce a bias into the proper time distributions of selected candidates due to the requirements on impact parameter, distance of flight and so on. In order to avoid the problem of correcting this bias an attempt was made to develop a proper time unbiased selection and trigger. These selections make no requirements on parameters correlated with proper decay time and instead make a minimum requirement on proper time itself, giving a clean and easily understood cut-off while rejecting short-lived combinatorial background.

The first step in the development of this proper time unbiased approach was a proof-of-principle stripping selection. This selection is labelled “D2hhLTUnbiasedMBNB” and appears under the version “Stripping12c”. The selection requirements are listed in Table 3.14 where t is proper decay time.

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h^-}) > 750 \text{ MeV}/c$ $\max((\text{Track } \chi^2/\text{nDOF})^{h^+}, (\text{Track } \chi^2/\text{nDOF})^{h^-}) < 3$
PID $K^\pm$	$\Delta\log\mathcal{L}_{K-\pi} > 5$
PID $\pi^\pm$	$\Delta\log\mathcal{L}_{K-\pi} < 5$
Combination	$\text{DOCA} < 0.1 \text{ mm}$ $p_T > 2500 \text{ MeV}/c$ $p > 5000 \text{ MeV}/c$
Mother	$\text{Vertex } \chi^2/\text{nDOF} < 10$ $t > 0.15 \text{ ps}$ $1815 \text{ MeV}/c^2 < m_D < 1915 \text{ MeV}/c^2$

Table 3.14: Criteria for candidates passing the “D2hhLTUnbiasedMBNB” stripping lines for untagged $D \rightarrow h^+h^-$ decays. D candidates are reconstructed assuming K^+K^- , $K^\pm\pi^\mp$ and $\pi^+\pi^-$ decay hypotheses and the corresponding PID requirements are applied.

Unfortunately, despite the favourable selection power of the proper time unbiased approach it proved impossible to develop a proper time unbiased HLT1 line. The extremely large number of tracks in each event during 2010 made imposing impact parameter requirements in HLT1 a necessity in order to allow the trigger to run within timing restrictions. A unbiased HLT1 would require vertex and proper time fits to be performed

for each candidate and this was deemed too computationally demanding without first rejecting the majority of tracks using impact parameter requirements.

However, working with others it was possible to “tie” the stripping line to the minimum-bias and no-bias trigger lines, such that their outputs were passed directly to the stripping algorithm. These lines trigger either randomly on the bunch crossing or on other effects not correlated with the underlying event and so are completely free of proper time bias. However, these lines are heavily prescaled and so the amount of statistics delivered in 2010 was limited. Nonetheless, the data delivered by this combination of proper time unbiased stripping and trigger is extremely useful in studying the effect of impact parameter selections and other aspects of the $D \rightarrow h^+h^-$ analysis. However, the level of available statistics is too low to make a competitive measurement of y_{CP} .

Figures 3.15 and 3.16 show the K^+K^- and $\pi^\pm K^\mp$ mass and proper time distributions from the unbiased stripping line. The background levels are significantly higher than for the proper time biased selections since the relatively low statistics made it possible to make much looser requirements to achieve maximum signal statistics. A sharp proper time cut-off is visible in the proper time plots due to the simple proper time cut used in the selection; there is no sign of a proper time turn-on curve due to proper time biasing requirements.

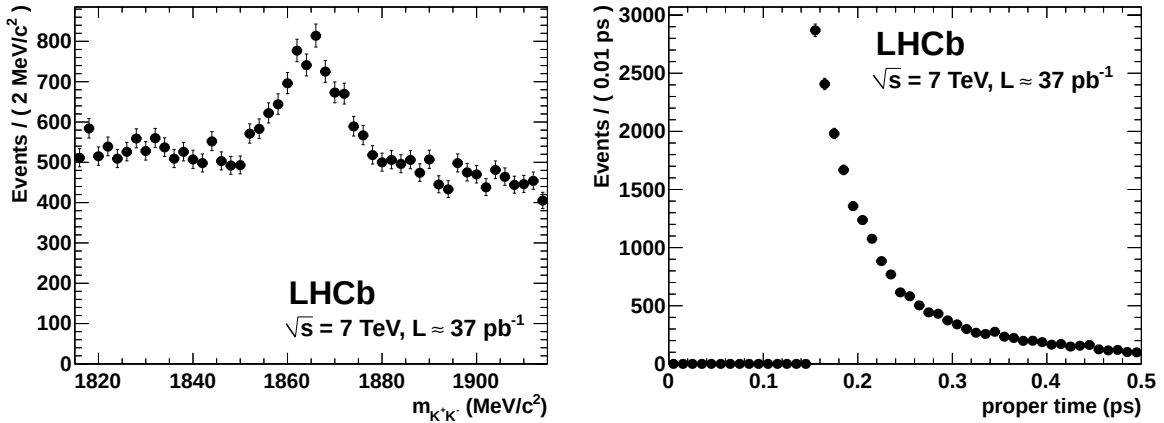


Figure 3.15: The K^+K^- mass distribution with a clear $D^0 \rightarrow K^+K^-$ mass peak (left) and proper time distribution (right) from the 2010 minimum-bias and no-bias triggered LHCb dataset, stripped by the D2hhLTUnbiasedMNNB stripping line.

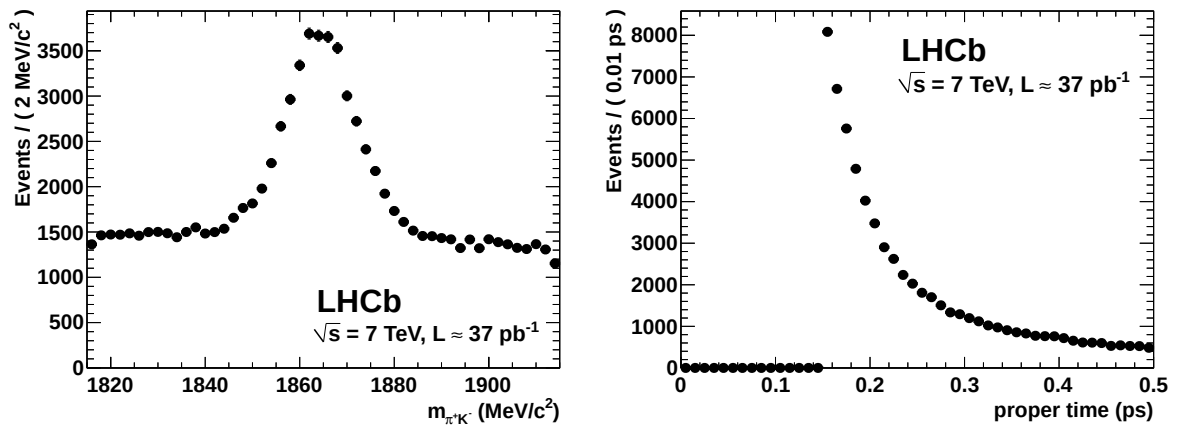


Figure 3.16: The $\pi^\pm K^\mp$ mass distribution with a clear $D^0 \rightarrow \pi^+ K^-$ mass peak (left) and proper time distribution (right) from the 2010 minimum-bias and no-bias triggered LHCb dataset, stripped by the D2hhLTUnbiasedMNNB stripping line.

Chapter 4

Simulation

“If you don’t know anything about computers, just remember that they are machines that do exactly what you tell them but often surprise you in the result.”

— Richard Dawkins

This chapter describes the simulated data used to perform studies for the lifetime measurements presented in this dissertation. Simulated data is extremely useful in validating many aspects of the analysis as well as for the evaluation of systematic uncertainties. Two simulation programs are described. The first is the *full* LHCb Monte Carlo simulation which includes a physics-based description of the proton-proton collision, hadronization and particle decay as well as a simulation of the response of the LHCb detector. The second is a simplified “toy” simulation written specifically to study $B \rightarrow h^+h^-$ and $D \rightarrow h^+h^-$ decays with very high statistics not achievable with the full LHCb simulation.

4.1 LHCb Monte Carlo Simulation

The simulation software used at LHCb is described in Section 2.2.5. The simulated events for $B \rightarrow h^+h^-$ and $D \rightarrow h^+h^-$ decays were produced using the “MC10” settings with a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$ and a mean number of proton-proton collisions per event $\nu = 2.5$. All candidates were simulated so that their tracks fall within the LHCb geometrical acceptance. Each event was passed through the trigger software with

TCK 0x002e002a and flagged as passed or rejected (though all events were written to disk). This TCK was chosen as it is a good representation of the settings under which the majority of the 2010 dataset was collected.

4.1.1 $B \rightarrow h^+ h^-$ Simulation Sample

The types of decays simulated for the $B \rightarrow h^+ h^-$ Monte Carlo data sample are listed in Table 4.1.

Decay Mode	Magnet Up	Magnet Down
$B_s^0 \rightarrow K^+ K^-$	484,796	516,295
$B^0 \rightarrow K^+ \pi^-$	502,492	509,393

Table 4.1: Number of signal events simulated and reconstructed for different $B \rightarrow h^+ h^-$ decays at $\sqrt{s} = 7 \text{ TeV}$, $\nu = 2.5$, TCK 0x002e002a for each magnet polarity.

4.1.2 $D \rightarrow h^+ h^-$ Simulation Sample

The types of decays simulated for the $D \rightarrow h^+ h^-$ Monte Carlo data sample are listed in Table 4.2. Only $D \rightarrow h^+ h^-$ candidates were selected.

Decay Mode	Magnet Up	Magnet Down
$D^{*+} \rightarrow \pi^+ D^0(K^+ K^-)$	2,038,185	1,998,795
$D^{*+} \rightarrow \pi^+ D^0(\pi^+ K^-)$	2,239,092	2,187,302

Table 4.2: Number of signal events simulated and reconstructed for different $D \rightarrow h^+ h^-$ decays at $\sqrt{s} = 7 \text{ TeV}$, $\nu = 2.5$, TCK 0x002e002a for each magnet polarity.

4.2 Toy Monte Carlo Simulation

This section describes a simplified “toy” Monte Carlo simulation algorithm written to simulate two body decays at LHCb. The model includes the effects of the detector’s geometrical acceptance, momentum and vertex resolutions and uses relativistic kinematics to realistically describe the flights and decays of particles. This simplified model is a very useful tool for validation of the methods presented later and is also employed for the study of proper time acceptance effects.

4.2.1 Generation

The mother particle is generated with four properties: momentum p , polar angle θ , azimuthal angle ϕ and proper decay time t . The user must specify the mean lifetime τ and rest mass m of the particle to be generated along with the masses of the two decay products (m_a, m_b).

The momentum of the mother is generated by randomly sampling a template histogram. In the case of $B \rightarrow h^+h^-$ and $D \rightarrow h^+h^-$ decays this is taken from 2010 LHCb Monte Carlo simulated events. The polar angle is generated from a Gaussian distribution fitted to 2010 LHCb $B \rightarrow h^+h^-$ Monte Carlo and the particle is required to be produced within the 10-250 mrad geometrical acceptance of LHCb. The azimuthal angle is generated from a uniform distribution. The distributions of the generated quantities are shown in Figure 4.1.

The primary vertex (origin of the mother) is always set at $\vec{r}_{PV}(x, y, z) = (0, 0, 0)$ and the location of the decay vertex is determined by the mother’s momentum, flight direction and proper decay time. The two body decay is performed in the rest frame of the mother where the two daughters are generated back to back with an isotropic flight direction. The momenta of the daughters in the rest frame (p'_a, p'_b) are determined by the masses of the mother and the decay products according to

$$p'_a = p'_b = \sqrt{\left(\frac{m^2 + m_b^2 - m_a^2}{2m}\right)^2 - m_b^2}. \quad (4.1)$$

A transformation to the lab frame is performed and the lab four-momenta of the

daughters calculated.

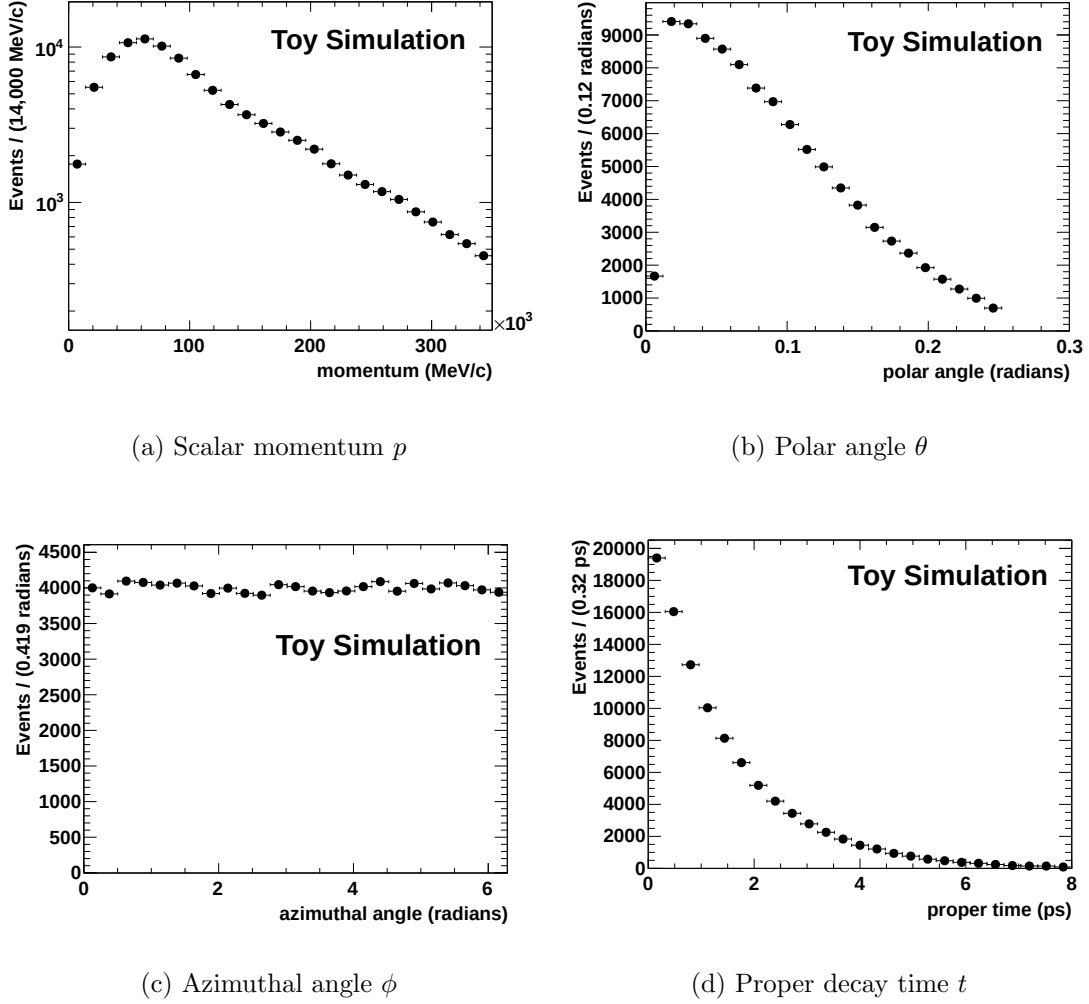


Figure 4.1: Generated quantities for $B_s^0 \rightarrow K^+ K^-$ candidates from the toy model.

4.2.2 Resolution and Reconstruction

Four pieces of information are taken from the generation and used to reconstruct the decay candidate: the location of the primary vertex $\vec{r}_{PV}$, the location of the decay vertex $\vec{r}_{SV}$ and the three-momenta of the two daughters $\vec{p}_a$ and $\vec{p}_b$. The “measured” values of these quantities are calculated by smearing the generated values using appropriate resolution functions.

The primary and decay vertices’ (x, y, z) coordinates are smeared using resolution

histograms taken from simulated $B \rightarrow h^+h^-$ candidates from the 2010 LHCb Monte Carlo simulation. As discussed in Chapter 2 the LHCb experiment has different spatial resolutions in the x , y , and z directions and different spatial resolutions for primary and secondary vertices due to the number of tracks involved in the vertex fit. The toy model therefore uses six different histograms, one for each spatial coordinate and vertex type. The momenta of the daughters are also smeared using resolution histograms taken from 2010 LHCb Monte Carlo and different resolution histograms are used for pions and kaons. At present a momentum resolution scale factor is added which has been tuned so that the mass resolution observed for B and D candidates is the same as for 2010 data.

Using these measured vertex positions and momenta the program calculates all dependent variables of interest: proper decay time, momentum of the mother, distance of flight, impact parameters and so on. The mass of the mother is calculated using a hypothesis for the masses of the daughters supplied by the user. Since all these quantities are derived in a similar fashion to the LHCb reconstruction, this toy may be used to make detailed studies of proper time acceptance, fit stability and validity which would be otherwise impossible with the comparatively limited quantity of full LHCb Monte Carlo simulated events. The current limitations of the toy simulation are that it is unable to calculate χ^2 quantities as it does not perform track or vertex fits and that it does not include PID information.

4.2.3 Combinatorial Background Model

In order to study the stability and validity of the lifetime fit it is necessary to include combinatorial background candidates. At LHCb combinatorial candidates arise from the random combination of tracks (both real and ghosts) to form a candidate that never existed in reality. In the case of the toy simulation the masses and proper decay times of background candidates are generated directly from probability distribution functions (PDFs) fitted to LHCb data rather than by designing a more realistic model. However, this simplification is appropriate for the $B_s^0 \rightarrow K^+K^-$ lifetime analysis as the toy model is not employed in detailed studies of the combinatorial background.

The masses of the combinatorial candidates are generated from a first order polynomial PDF fitted to data:

$$PDF_{Comb}(m) = 1.0 - \nabla^{bkg} \times m. \quad (4.2)$$

where ∇^{bkg} is the fitted gradient of the polynomial. The proper time t , distribution is generated from the PDF:

$$PDF_{Comb}(t) = [1.0 - \text{erf}((A^{bkg} - t)/B^{bkg})] \times [f_L^{bkg} e^{-t/\tau_L^{bkg}} + (1 - f_L^{bkg}) e^{-t/\tau_S^{bkg}}] \quad (4.3)$$

where the first term containing the error function (erf) describes the proper time acceptance and the two exponential distributions to simulate short-lived and long-lived backgrounds. The parameters A^{bkg} and B^{bkg} , the fraction f_L^{bkg} and the lifetimes τ_L^{bkg} and τ_S^{bkg} are determined from fits to 2010 LHCb data.

4.2.4 $B \rightarrow h^+ h^-$ Candidates Generated Using the Model

Using the signal model described above and the combinatorial background model described in Section 4.2.3 it is possible to generate simulated candidates which closely resemble those from LHCb data. This is illustrated in Figures 4.2 and 4.3 which show the $K^+ K^-$ and $K^\pm \pi^\mp$ $B \rightarrow h^+ h^-$ mass spectra generated using this toy model. The signal peaks are fitted with Gaussian distributions and the combinatorial background with first order polynomials.

4.3 Conclusion

This chapter has outlined two different ways of generating Monte Carlo simulated events. The first is the full LHCb simulation which includes a detailed description of the detector response and is useful for testing detailed aspects of both the $B \rightarrow h^+ h^-$ and $D \rightarrow h^+ h^-$ analyses. The second is a simplified “toy” Monte Carlo simulation algorithm which has a realistic physics simulation with the detector response modelled using resolution histograms taken from the full LHCb simulation. This toy model is useful for high statistics tests of general principles and performance of the analysis which would not be possible using the processor-intensive full simulation algorithms.

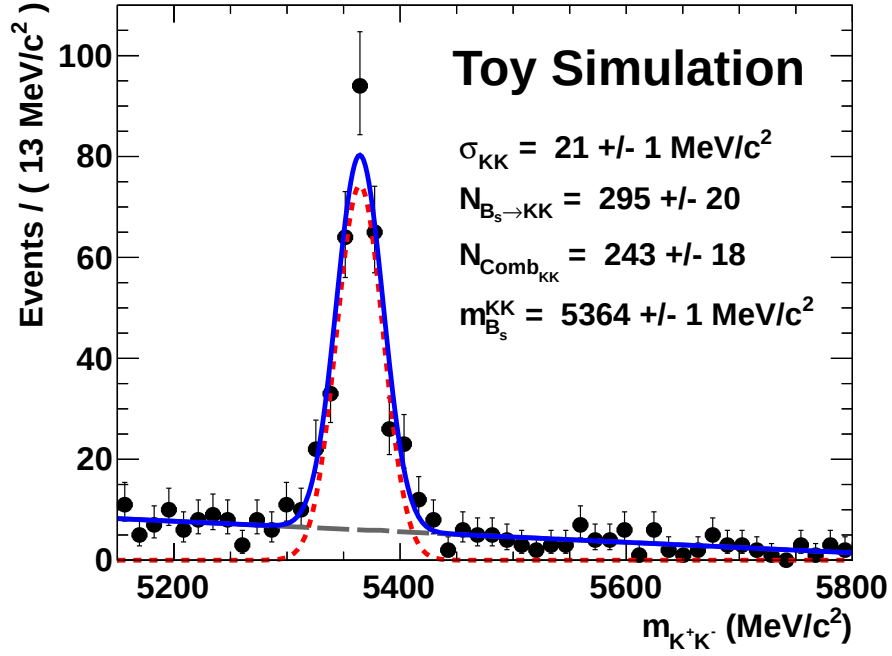


Figure 4.2: Fit to the K^+K^- mass spectrum for toy Monte Carlo data tuned to 2010 LHCb data. The total PDF (blue solid line) is composed of the $B_s^0 \rightarrow K^+K^-$ (red medium-dashed line) and combinatorial background (grey long-dashed line) PDFs.

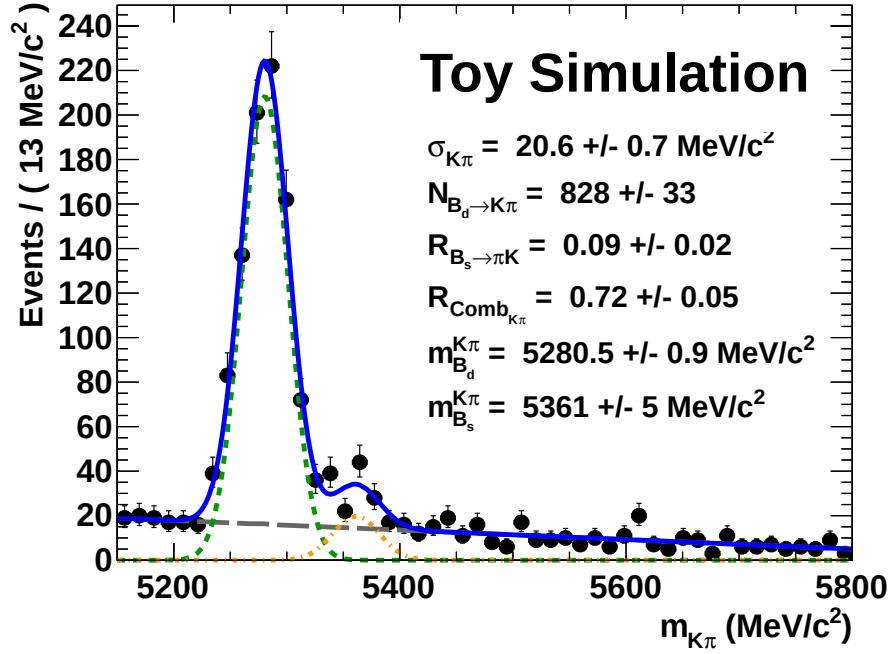


Figure 4.3: Fit to the $K^\pm\pi^\mp$ mass spectrum for toy Monte Carlo data tuned to 2010 LHCb data. The total PDF (blue solid line) is composed of the $B^0 \rightarrow K^+\pi^-$ (green medium-dashed line), $B_s^0 \rightarrow \pi^+K^-$ (orange short-dashed line) and combinatorial background (grey long-dashed line) PDFs.

Chapter 5

Proper Decay Time Acceptance Correction

“Observe a method in the distribution of your time. Every hour will then know its proper employment, and no time will be lost.”

— Bishop George Horne

The proper decay time t' of an unstable particle is the amount of time that the particle lives for in its rest frame. At LHCb the proper decay time is calculated from the distance between the production and decay vertices L , the momentum of the particle p and the measured mass of the particle m :

$$t = \frac{Lm}{p}. \quad (5.1)$$

where t is the *measured* proper decay time. If the particle has a mean lifetime of τ then a sample of these decays will have a proper decay time distribution that follows a simple exponential distribution

$$T(t') = T(0)e^{-\frac{t'}{\tau}} \quad (5.2)$$

where $t' \geq 0$. The proper time resolution of the LHCb detector depends upon the spatial resolution for the location of interaction and decay vertices and the momentum resolution of the detector (which in turn determines the mass resolution). If the proper time resolution is modelled as a simple Gaussian distribution with mean μ_t and width

σ_t then the resolution at LHCb is measured as $\sigma_t \simeq 50$ fs as discussed in Section 2.2.2.4. The measured proper time distribution then follows

$$T_{meas}(t) = \frac{1}{\sqrt{2\pi\sigma_t^2}} \int_0^\infty T(0) e^{-\frac{t'}{\tau}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'. \quad (5.3)$$

As described in Chapter 2 the trigger and offline selections impose minimum requirements on the impact parameters of the B daughter tracks with respect to the interaction vertex and also on the distance of flight of the B candidate. These requirements tend to reject candidates with shorter proper decay times and spoil the simple form of the distribution described above. In general the selection efficiency ϵ is a function of proper time and enters the measured proper decay time distribution according to

$$T_{meas}(t) = \frac{\epsilon(t)}{\sqrt{2\pi\sigma_t^2}} \int_0^\infty T(0) e^{-\frac{t'}{\tau}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'. \quad (5.4)$$

This effect is referred to as “proper decay time acceptance” and must be corrected for if an unbiased measurement of the mean lifetime is to be made. Figure 5.1 shows the proper time distributions of simulated $B_s^0 \rightarrow K^+K^-$ decays from the full LHCb Monte Carlo simulation identified using generator information. The effect of detector resolution is clear from the “measured” distribution where a tail extending into negative values of proper time is observed. The effect of trigger acceptance is also seen in the sculpting of the distribution at low proper time for triggered candidates. Figure 5.2 shows the selection efficiency of the trigger settings used in Figure 5.1 as a function of proper time.

In Sections 5.1 and 5.2 two data-driven methods for correcting the effect of proper decay time acceptance are described and their validity as applied to $B \rightarrow h^+h^-$ and $D \rightarrow h^+h^-$ decays is explored.

5.1 The Ratio Method

The simplest way to correct for the effect of the selection acceptance is to remove regions of proper time where the efficiency curve has non-zero gradient. However, in most cases there is no point at which the efficiency curve becomes flat and so this approach will fail to correct for the acceptance bias. Furthermore, this approach will reject a large fraction of the recorded events and therefore severely restrict the statistical precision of the measurement. In the case of the $B_s^0 \rightarrow K^+K^-$ lifetime measurement the proper

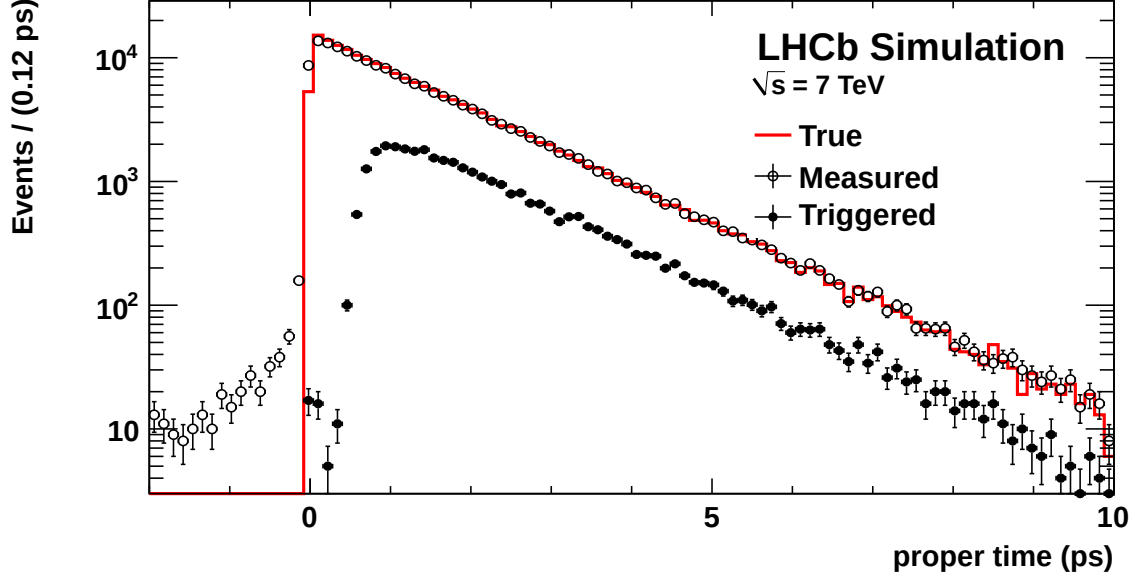


Figure 5.1: Proper decay time distributions of $B_s^0 \rightarrow K^+ K^-$ candidates from the full LHCb simulation identified using generator information. The red line shows the distribution of the generated or “true” proper time, the open circles show the measured proper time and the solid circles show the measured proper time for candidates TOS with respect to the L0 Hadron, HLT1 single track and HLT2 “B2HH” trigger lines.

time acceptance bias may be eliminated by taking a ratio of the $B_s^0 \rightarrow K^+ K^-$ decay time distribution with that of $B^0 \rightarrow K^+ \pi^-$.

The channels $B_s^0 \rightarrow K^+ K^-$ and $B^0 \rightarrow K^+ \pi^-$ have the same decay topology and very similar kinematics and as such most resolution and acceptance effects should be the same for both. The ratio of the proper time distributions of $B_s^0 \rightarrow K^+ K^-$ and $B^0 \rightarrow K^+ \pi^-$ may be expressed as

$$R(t) \equiv \frac{T_{meas}^{B_s \rightarrow KK}(t)}{T_{meas}^{B \rightarrow K\pi}(t)} \quad (5.5)$$

$$= \frac{\epsilon^{B_s \rightarrow KK}(t) \int_0^\infty T^{B_s \rightarrow KK}(0) e^{-\frac{t'}{\tau_{K^+ K^-}}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'}{\epsilon^{B \rightarrow K\pi}(t) \int_0^\infty T^{B \rightarrow K\pi}(0) e^{-\frac{t'}{\tau_{B \rightarrow K\pi}}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'} \quad (5.6)$$

where the proper time resolutions for $K^+ K^-$ and $K^\pm \pi^\mp$ final states are assumed to be the same^a. If the two acceptance functions are the same to within a multiplicative

^aIn principle the momentum resolutions for pions and kaons may be different and so the proper time resolutions for the $K^+ K^-$ and $K^\pm \pi^\mp$ final states may also differ. However, this is predicted to be a

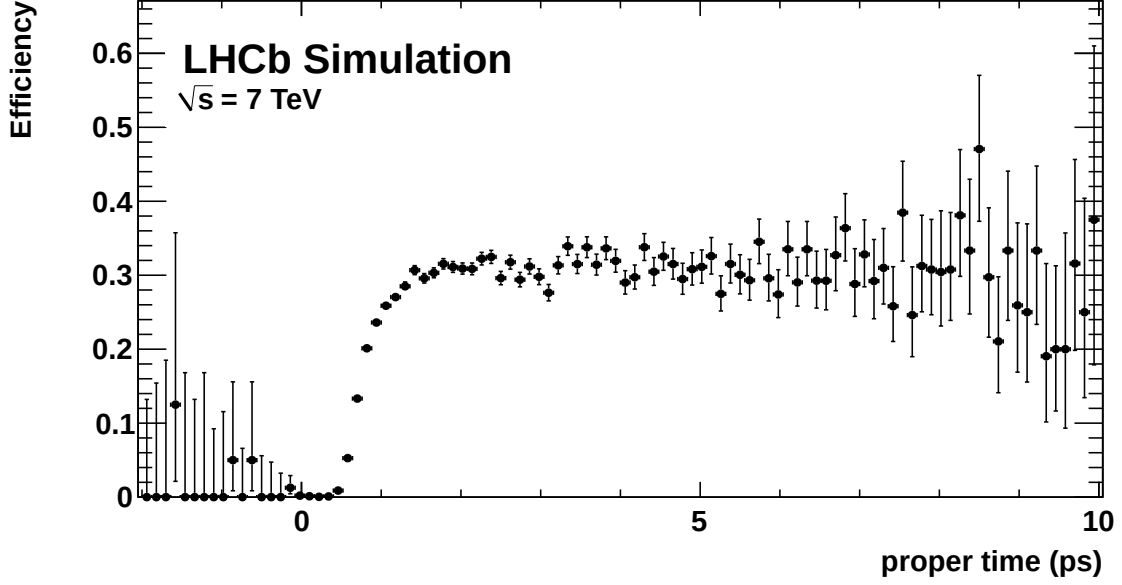


Figure 5.2: The efficiency of the combined L0 Hadron, HLT1 single track and HLT2 “B2HH” trigger lines for $B_s^0 \rightarrow K^+K^-$ candidates from the full LHCb simulation identified using generator information. Candidates are triggered on signal.

constant then the ratio becomes

$$R(t) = R(0) \frac{\int_0^\infty e^{-\frac{t'}{\tau_{K^+K^-}}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'}{\int_0^\infty e^{-\frac{t'}{\tau_{B \rightarrow K\pi}}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'} \quad (5.7)$$

where the constant factor is defined by

$$R(0) \equiv \frac{\epsilon^{B_s \rightarrow KK}(t) T^{B_s \rightarrow KK}(0)}{\epsilon^{B \rightarrow K\pi}(t) T^{B \rightarrow K\pi}(0)}. \quad (5.8)$$

There is no analytical description of the convolution of an exponential with zero cut-off and a Gaussian distribution. However, to a good approximation the resolution effects cancel between the two channels and the ratio reduces to

$$R(t) \simeq R(0) e^{-t(\tau_{K^+K^-}^{-1} - \tau_{B \rightarrow K\pi}^{-1})}. \quad (5.9)$$

The $B_s^0 \rightarrow K^+K^-$ lifetime $\tau_{K^+K^-}$ can then be extracted using an external measurement of the $B^0 \rightarrow K^+\pi^-$ lifetime. The key assumption of this approach, that the proper

tiny effect and is neglected for the remainder of the discussion.

time acceptance functions for $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ are the same to within a multiplicative constant, needs to be tested. This is explored in the following section.

5.1.1 Validation of the Ratio Method for $B_s^0 \rightarrow K^+K^-$

5.1.1.1 Tests on LHCb Monte Carlo Simulated Events

The studies described here were performed using the simulated $B \rightarrow h^+h^-$ dataset described in Section 4.1. The acceptance cancellation is studied by calculating the selection efficiency as a function of proper time for $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ and then taking a ratio of the two distributions. The resulting ratio is then fitted with a first order polynomial of the form $y = a + bx$ to verify that the gradient b is consistent with zero. The intercept, a need not be equal to one as the $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ acceptance functions may differ by a multiplicative constant without biasing the measured lifetime.

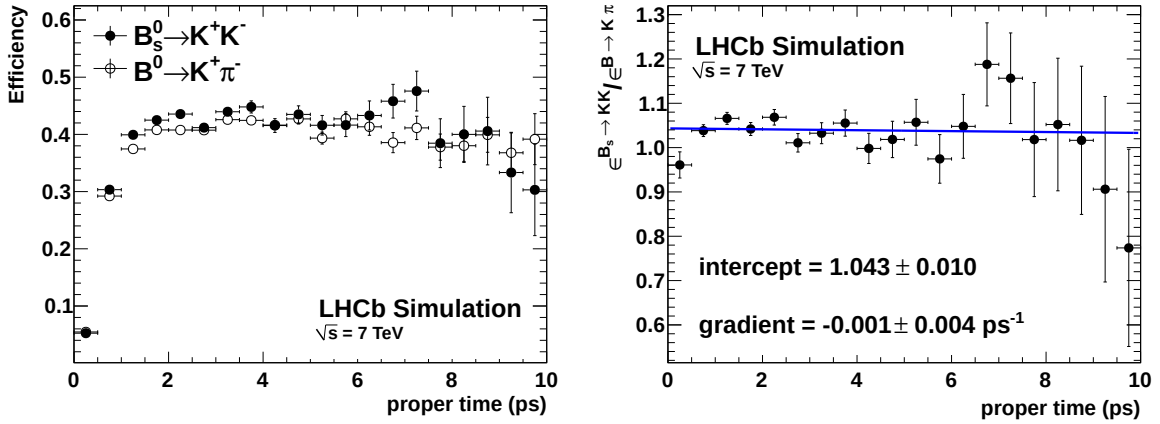


Figure 5.3: Left: the efficiency of the full LHCb trigger with TCK 0x002e002a as a function of proper decay time for $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ candidates identified using generator information from the full LHCb simulation. Candidates are TOS and/or TIS with respect to each trigger level. Right: the ratio of the $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ proper decay time acceptance functions for simulated candidates with a first order polynomial fit.

Figure 5.3 shows the proper time acceptance functions and acceptance ratio due to the LHCb trigger with TCK 0x002e002a. The candidates are required to pass each level of the trigger (L0, HLT1, HLT2) as either TIS or TOS^b with respect to the sum

^bDue to an error in the production of the Monte Carlo simulated events it was not possible to include TUS candidates.

of all trigger lines. Of the 93,650 $B_s^0 \rightarrow K^+K^-$ candidates in the simulated dataset 26,680 passed this requirement, giving an overall trigger efficiency of $(28.49 \pm 0.15)\%$. For $B^0 \rightarrow K^+\pi^-$ 66,378 out of 241,176 candidates were triggered giving an efficiency of $(27.52 \pm 0.09)\%$.

We see that the gradient of the fit to the ratio in Figure 5.3 (right) is consistent with zero, demonstrating that the proper time acceptance due to the trigger cancels in the ratio between $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$. The number of triggered $B_s^0 \rightarrow K^+K^-$ candidates in this simulated dataset is approximately 90 times larger than the total number of offline selected $B_s^0 \rightarrow K^+K^-$ candidates in the real 2010 dataset and this result therefore gives a high level of confidence that any non-cancelling trigger bias will be negligible for the 2010 LHCb dataset.

Figure 5.4 shows the proper time acceptance functions and acceptance ratio due to the combination of the LHCb trigger, stripping, offline and PID selections described in Chapter 3. Of the 93,650 $B_s^0 \rightarrow K^+K^-$ candidates in the simulated dataset 8,376 passed the full trigger and selection, giving an overall selection efficiency of $(8.94 \pm 0.09)\%$. For $B^0 \rightarrow K^+\pi^-$ 18,642 out of 241,176 candidates were selected giving an efficiency of $(7.73 \pm 0.05)\%$. Again we see that the gradient of the fit is consistent with zero demonstrating that the proper time acceptance cancels in the ratio to within statistical precision. Approximately 30 times more simulated $B_s^0 \rightarrow K^+K^-$ candidates passed the full trigger and selection compared to 2010 data, once again giving a high level of confidence that the effect of acceptance bias will be negligible for this analysis in 2010.

5.1.1.2 Tests on Toy Monte Carlo Simulated Events

The quantity of full LHCb simulated events is limited by the availability of disk space and processing power and as such very high statistics studies of the acceptance cancellation can only be made using the toy Monte Carlo simulation described in Section 4.2. As discussed previously a limitation of the toy simulation is that no track or vertex fits are performed and as a result χ^2 -type criteria imposed in the offline and trigger selections (see Tables 3.2 and 3.6.) are not reproducible.

In order to test proper decay time acceptance effects using the toy simulation it was necessary to design selections based on purely kinematical quantities that gave the same acceptance effects as the full selection for real data. The approach was to replace

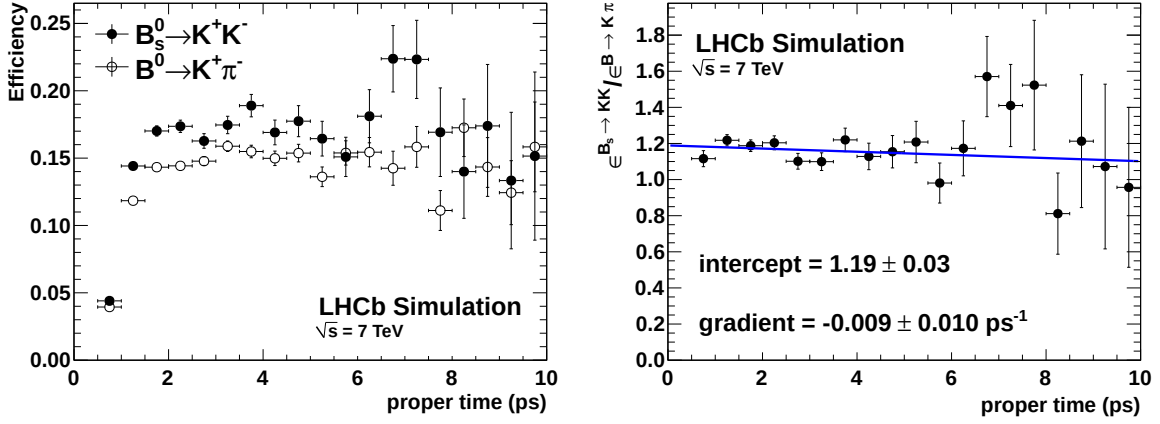


Figure 5.4: Left: the efficiency of the combination of the full LHCb trigger, stripping selection, offline selection and PID selection as a function of proper decay time for $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ candidates identified using generator information from the full LHCb simulation. Candidates are TOS and/or TIS with respect to each trigger level. Right: the ratio of the $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ proper decay time acceptance functions for simulated candidates with a first order polynomial fit.

requirements on χ^2 -type variables with cuts on their non- χ^2 analogues; for example, requirements on impact parameter χ^2 are replaced by requirements on impact parameter directly. The choice of criteria was tuned to give the same efficiency with respect to simulated candidates as the equivalent criteria in the full selection.

There are two elements to the selection. The first is an emulation of the HLT1 single track trigger line that ran in 2010. The criteria imposed are summarised in Table 5.1. The second element is an emulation of the logical AND of the HLT2 “B2HH” trigger, the stripping selection and the offline selection. The criteria used in this case are listed in Table 5.2.

One daughter must satisfy all of the following requirements
$p > 13,000$ MeV/ c $p_T > 1850$ MeV/ c $IP > 0.11$ mm

Table 5.1: Selection criteria for the toy emulation of the HLT1 single track trigger.

Criterion Type	Criterion
Daughter	$\min(p_T^{h^+}, p_T^{h'^-}) > 700 \text{ MeV}/c$ $\max(p_T^{h^+}, p_T^{h'^-}) > 2400 \text{ MeV}/c$ $\min(IP^{h^+}, IP^{h'^-}) > 0.08 \text{ mm}$ $\max(IP^{h^+}, IP^{h'^-}) > 0.2 \text{ mm}$
Mother	$4800 \text{ MeV}/c^2 < m_B < 5800 \text{ MeV}/c^2$ $IP^B < 0.07 \text{ mm}$ $FD^B > 2.2 \text{ mm}$

Table 5.2: Selection criteria for the toy emulation of the HLT2 “B2HH” trigger, stripping and offline selections.

Approximately 255,000 $B_s^0 \rightarrow K^+K^-$ candidates and 677,000 $B^0 \rightarrow K^+\pi^-$ toy simulated candidates passing the emulated selection are used in this study. Figure 5.5 shows the ratio of the proper time acceptance functions for the two decay modes. The ratio is fitted with a straight line and the gradient is found to be consistent with zero within statistical uncertainty. This toy offline selected sample is 850 times larger than the 2010 LHCb dataset and this very precise cancellation indicates that the analysis will be insensitive to any non-cancelling bias for the lifetime of the LHCb experiment.

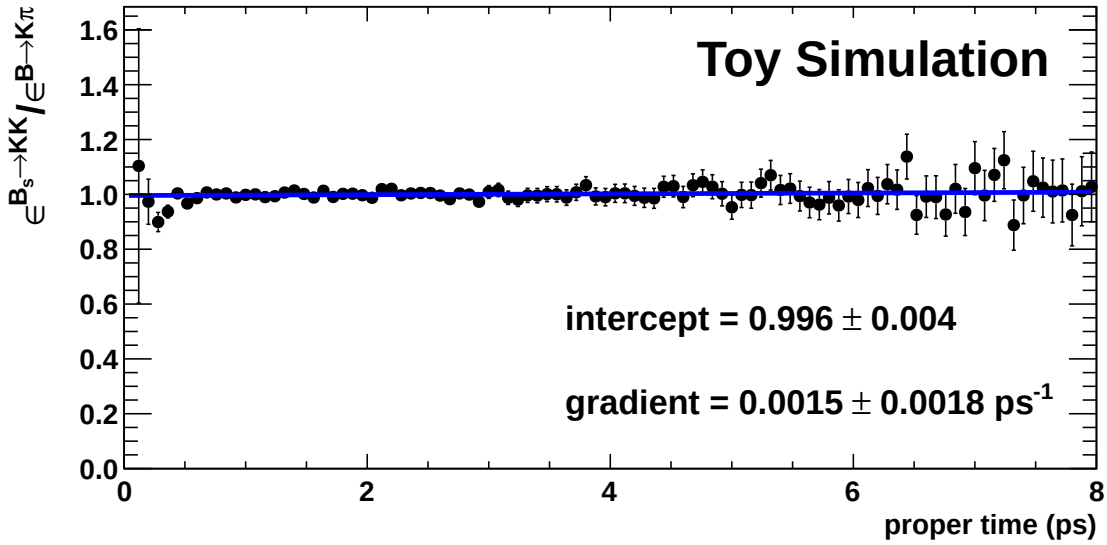


Figure 5.5: The ratio of the proper time acceptance functions from the emulated toy selection for true $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ candidates from a toy Monte Carlo simulation with a first order polynomial fit.

5.2 The Relative Acceptance Correction Method

Several challenges not faced when measuring the $B_s^0 \rightarrow K^+ K^-$ lifetime must be overcome in order to make measurements of the $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$ lifetimes. First, the level of precision required is much greater; only a few hundred $B \rightarrow h^+ h^-$ candidates were collected during the 2010 run whereas many millions of $D \rightarrow h^+ h^-$ candidates were obtained. Consequently, the statistical uncertainty on $D \rightarrow h^+ h^-$ lifetime measurements will be of the order of a few femtoseconds compared to around a hundred femtoseconds for $B_s^0 \rightarrow K^+ K^-$. This much greater statistical precision means that systematic effects must be understood and controlled to a far greater degree and this is especially true for the proper time acceptance correction.

Second, the presence of secondary D decays (discussed in Section 3.4) requires that prompt and secondary decays be separated in order to make unbiased lifetime measurements. Finally, the smaller D^0 mass (1864.80 ± 0.14 MeV/ c^2 [11]) means that exchanging a kaon for a pion in the final state has a much greater effect on the kinematic profile of the candidate which has a corresponding effect on the proper time acceptance. As a direct result of this, the Ratio Method described in Section 5.1 is insufficient to properly account for the effects of proper time acceptance on $D \rightarrow h^+ h^-$ decays.

This section describes a novel approach that has been developed in order to overcome this problem. Section 5.2.1 discusses the above challenges in more detail and outlines how and why the Ratio Method fails in this case, Section 5.2.3 describes the statistical framework of the new approach, tests to validate the new approach are presented in Section 5.2.4 and the conclusions and further work required are discussed in Section 5.3.

5.2.1 Motivation

Extensive studies using simulated data have demonstrated that taking a ratio of the $B_s^0 \rightarrow K^+ K^-$ and $B^0 \rightarrow K^+ \pi^-$ proper time distributions cancels the effects of selection induced proper time acceptance to a degree of precision that far outstrips the statistical uncertainty on the $B_s^0 \rightarrow K^+ K^-$ lifetime from the 2010 dataset. This point was discussed in Section 5.1.1. However, taking a ratio of the $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$ proper time distributions does not fully cancel the acceptance effects to the degree of precision required for a y_{CP} measurement.

Figure 5.6 shows the ratio of selection efficiencies

$$R_\epsilon(t) \equiv \frac{\epsilon^{D \rightarrow KK}(t)}{\epsilon^{D \rightarrow \pi K}(t)} \quad (5.10)$$

as a function of proper decay time where ϵ is the efficiency of the Hlt1TrackAllL0 trigger (TOS), Hlt2CharmOSTF2Body trigger (TOS) and the D2hhPrompt stripping line for full LHCb simulated $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+K^-$ candidates. It can be seen from the figure that the acceptance functions of the two modes are not equal and their ratio follows a non-trivial distribution. Evidently the ratio method as applied to the $B_s^0 \rightarrow K^+K^-$ mode will not remove all acceptance effects in the case of $D^0 \rightarrow K^+K^-$.

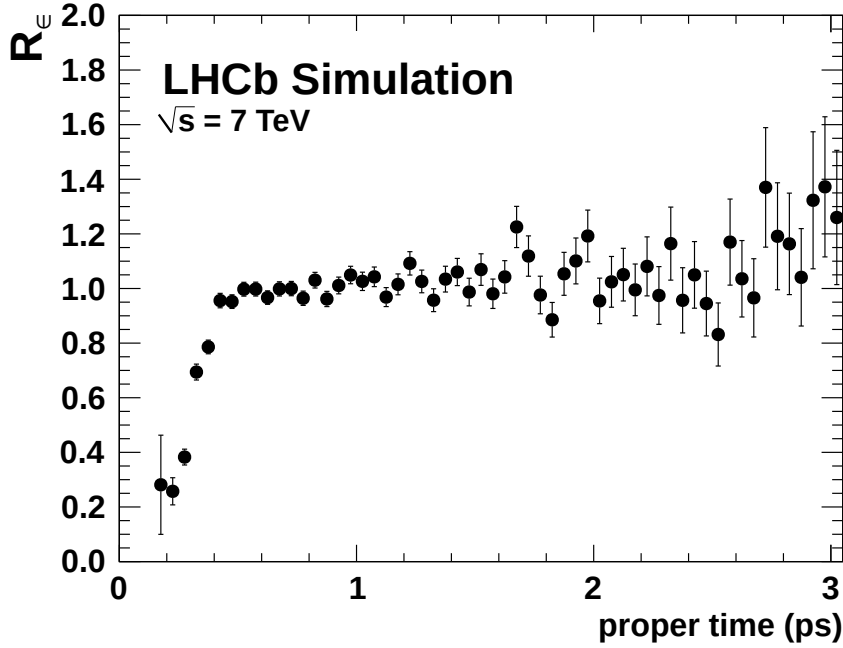


Figure 5.6: The ratio of the proper time acceptance functions of $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+K^-$ candidates identified from generator information from full LHCb simulated events. Candidates are required to be TOS with respect to the Hlt1TrackAllL0 trigger, TOS with respect to the Hlt2CharmOSTF2Body trigger and to pass the D2hhPrompt stripping line, excluding the PID requirements.

The reasons why the ratio method works well for $B_s^0 \rightarrow K^+K^-/B^0 \rightarrow K^+\pi^-$ and poorly for $D^0 \rightarrow K^+K^-/D^0 \rightarrow \pi^+K^-$ are twofold. Firstly, the low statistics available in the $B_s^0 \rightarrow K^+K^-$ mode makes the measurement in 2010 data relatively insensitive to any non-cancelling bias. More significant however, is the difference between the $B_{(s)}^0$ and D^0 masses. In both cases, the final states of the signal mode (K^+K^-) and control mode ($K^\pm\pi^\mp$) differ by exchanging a kaon for a pion. The difference between the kaon

and pion masses $m_K - m_\pi = 493.677 \text{ MeV}/c^2 - 139.57018 \text{ MeV}/c^2 = 354.10682 \text{ MeV}/c^2$ [11] is only 6.6% of the B_s^0 mass but 19.0% of the D^0 mass. As a result the difference between the K^+K^- and $K^\pm\pi^\mp$ final states has a much more pronounced effect on the kinematics of a D^0 decay than it does on a $B_{(s)}^0$ decay.

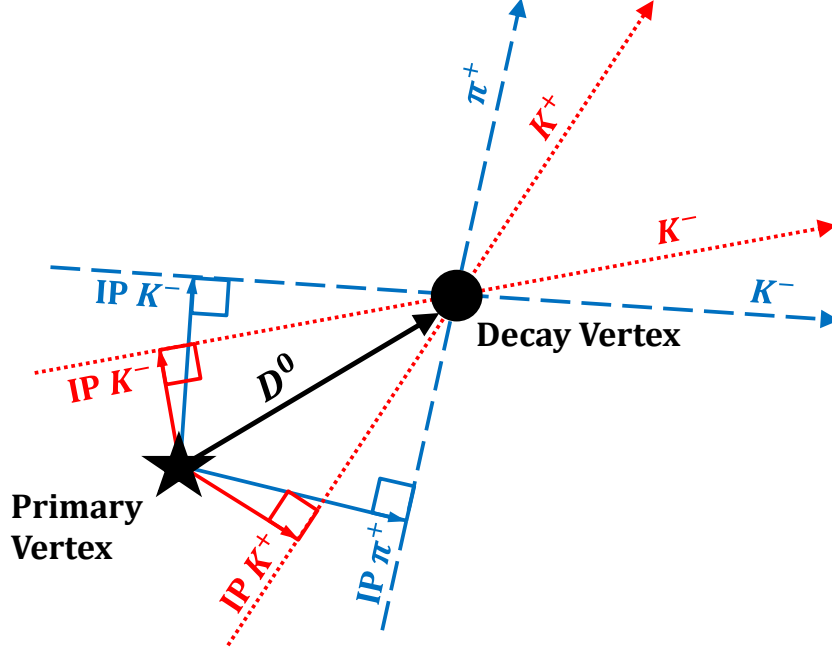


Figure 5.7: Cartoon illustrating how different opening angles due to different decay products leads to different impact parameters with respect to the primary vertex in the case of a $D^0 \rightarrow K^+K^-$ or $D^0 \rightarrow \pi^+K^-$ decay.

This can be understood intuitively as follows. When a D^0 meson decays its rest mass is used to produce the rest masses of its daughters and the remainder is carried away by the daughters in the form of momentum. In a $D^0 \rightarrow K^+K^-$ decay, less energy is available in the D^0 rest frame to be converted into momentum than in a $D^0 \rightarrow \pi^+K^-$ decay, since more of the available energy must be used to make an extra, heavier kaon. As a result, in the lab frame, the opening angle between the daughters of a $D^0 \rightarrow K^+K^-$ decay is smaller on average than for $D^0 \rightarrow \pi^+K^-$ decays and as a result the impact parameter (IP) with respect to the primary vertex is on average smaller for $D^0 \rightarrow K^+K^-$. This point is illustrated in Figure 5.7 where the π^+K^- decay daughters have larger impact parameters than the K^+K^- daughters thanks to increased momentum in the D^0 rest frame. Since the trigger and stripping selections make minimum requirements on impact parameters, $D^0 \rightarrow K^+K^-$ decays are more likely to be rejected by these requirements than $D^0 \rightarrow \pi^+K^-$ decays and this leads to a different acceptance between the two channels and an inexact cancellation.

Furthermore, a combination of requirements on the distance of flight of the D^0 and the momenta of the daughters can lead to a bias in the proper time ratio. This is a consequence of the daughters in $D^0 \rightarrow K^+K^-$ decays having smaller momenta in the D^0 rest frame compared to $D^0 \rightarrow \pi^+K^-$. Viewed in the lab frame, this has the effect of increasing the minimum momentum of the pair of daughters while simultaneously reducing the maximum momentum of the two daughters. As a result $D^0 \rightarrow K^+K^-$ candidates are more likely to pass a minimum momentum requirement (i.e. requiring that both daughters have momentum larger than some threshold) but less likely to pass a maximum momentum requirement (where one of the daughters must have a momentum above some threshold). Therefore, if, for instance, both daughters are required to have momenta greater than 1 GeV/c this imposes a harsher constraint on the mothers momentum for $D^0 \rightarrow \pi^+K^-$ than for $D^0 \rightarrow K^+K^-$. Since the D^0 distance of flight is determined by both proper time and D^0 momentum this effectively requires that a given D^0 meson, living for some proper time, must have higher momentum to pass as $D^0 \rightarrow \pi^+K^-$ than as $D^0 \rightarrow K^+K^-$. As a result, the proper time acceptance functions for the two channels are, once again, different.

Since the y_{CP} measurement must be made at a precision of 0.1% it is necessary to either cancel or understand the acceptance to a very high degree. In Section 5.2.2 the canonical TIS/TOS approach to calculating acceptance functions is shown to be unsuitable for $D \rightarrow h^+h^-$ decays and a new data-driven Bayesian approach to overcome the problem of non-cancelling acceptance bias is described in Section 5.2.3.

5.2.2 Failure of the TIS/TOS Approach for $D \rightarrow h^+h^-$

For relatively abundant decay modes such as $D^0 \rightarrow \pi^+K^-$ and $D^0 \rightarrow K^+K^-$, a significant number of candidates will be triggered independently of signal (TIS). In theory, it is possible to evaluate the proper time acceptance of a trigger by calculating a ratio of proper time distributions according to

$$\epsilon(t) = \frac{T_{meas}^{TOSTIS}(t)}{T_{meas}^{TIS}(t)} \quad (5.11)$$

where $T_{meas}^{TOSTIS}(t)$ is the proper time distribution of candidates that are both TOS and TIS with respect to the trigger and $T_{meas}^{TIS}(t)$ is the proper time distribution of candidates that are TIS with respect to the trigger. Figure 5.8 shows the TIS efficiency of the Hlt1TrackAllL0 trigger for D^0 candidates that are TOS with respect to

the Hlt1TrackAllL0 trigger as a function of proper time:

$$\epsilon(t) = \frac{T_{meas}^{\text{TOSTIS}}(t)}{T_{meas}^{\text{TOS}}(t)}. \quad (5.12)$$

This function should be constant in proper time since the TIS efficiency should be completely uncorrelated with the properties of the D^0 . However, it can be seen in the right-hand plot of Figure 5.8 that the TIS efficiency increases dramatically as a function of proper decay time, demonstrating that TIS is not really independent of signal.

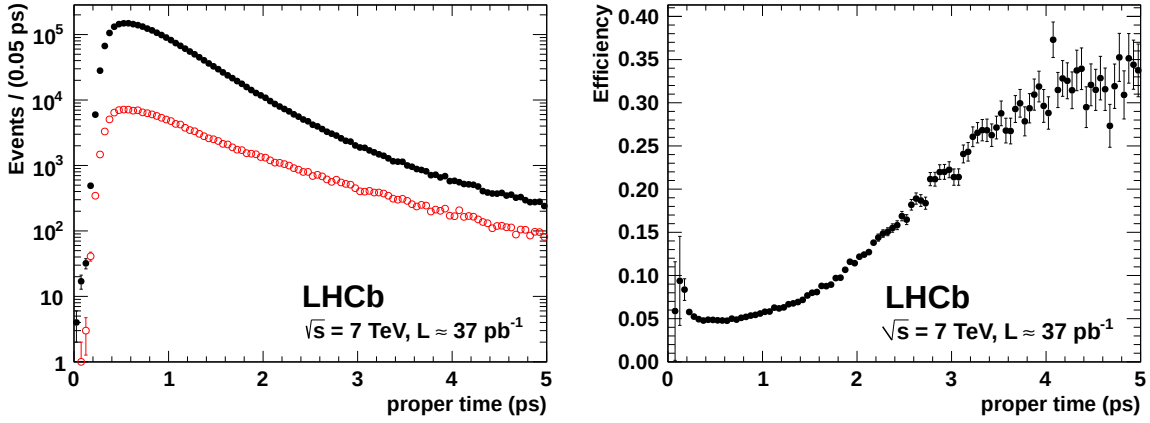


Figure 5.8: Left: the proper time distributions of $D^0 \rightarrow \pi^+ K^-$ candidates TOS with respect to the Hlt1TrackAllL0 trigger (black dots) and TIS+TOS with respect to the Hlt1TrackAllL0 trigger (red open circles). Right: the Hlt1TrackAllL0 trigger TIS efficiency for $D^0 \rightarrow \pi^+ K^-$ candidates that are TOS with respect to the Hlt1TrackAllL0 trigger. Taken from 2010 LHCb data.

As discussed previously this effect arises from the fact that a large fraction of TIS candidates are in fact secondary D decays coming from decays of the form $B \rightarrow D^0 X$ where the trigger fires on the X . This is confirmed by examining the impact parameter χ^2 ($IP\chi^2$) distributions of TIS candidates. Prompt D^0 mesons originating at the interaction vertex should have zero impact parameter with respect to that vertex, although in practice this is smeared by resolution effects. Secondary D^0 mesons will tend to have large impact parameters since the B meson has a long lifetime and hence the D^0 production vertex will be significantly displaced from the primary vertex. This point is illustrated in Figure 5.9.

Figure 5.10 compares the $\log(IP\chi^2)$ distributions of Hlt1TrackAllL0 TOS and TIS+TOS candidates; $\log(IP\chi^2)$ is plotted as this distribution is more easily interpreted visually than $IP\chi^2$. Both distributions have a larger Gaussian-like shape on the left due to

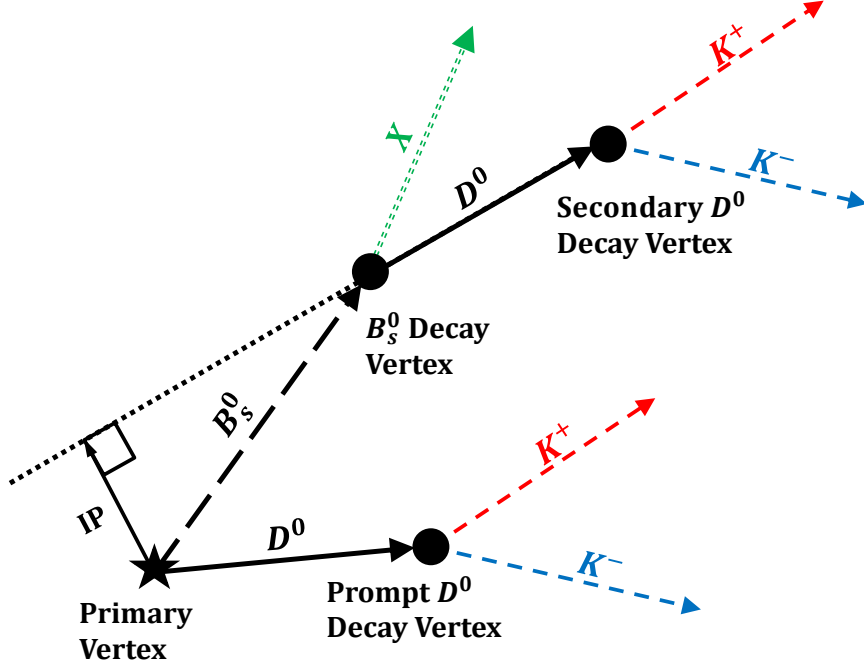


Figure 5.9: Cartoon illustrating prompt and secondary $D^0 \rightarrow K^+ K^-$ decays. Note that the D^0 meson arising from the decay of the B_s^0 meson has a large impact parameter with respect to the primary vertex.

prompt D^0 candidates and a smaller Gaussian-like shoulder on the right due to secondary D^0 candidates. It is clear that the secondary contribution is greatly enhanced for Hlt1TrackAllL0 TIS+TOS candidates demonstrating that in a large fraction of cases TIS trigger decisions are caused by the unreconstructed X particle from the B decay. As a result TIS candidates cannot be used to accurately evaluate the proper decay time acceptance of the trigger.

5.2.3 A Data-Driven Bayesian Approach to Calculate the Relative Proper Time Acceptance

As discussed in Section 5.1 the ratio of the proper time distributions of two decay modes (i.e. $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$) may be expressed as

$$R(t) \equiv \frac{T_{meas}^{D \rightarrow KK}(t)}{T_{meas}^{D \rightarrow \pi K}(t)} \quad (5.13)$$

$$= \frac{\epsilon^{D \rightarrow KK}(t) \int_0^\infty T^{D \rightarrow KK}(0) e^{-\frac{t'}{\tau_{D \rightarrow KK}}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'}{\epsilon^{D \rightarrow \pi K}(t) \int_0^\infty T^{D \rightarrow \pi K}(0) e^{-\frac{t'}{\tau_{D \rightarrow \pi K}}} e^{-\frac{(t-t'-\mu_t)^2}{2\sigma_t^2}} dt'}. \quad (5.14)$$

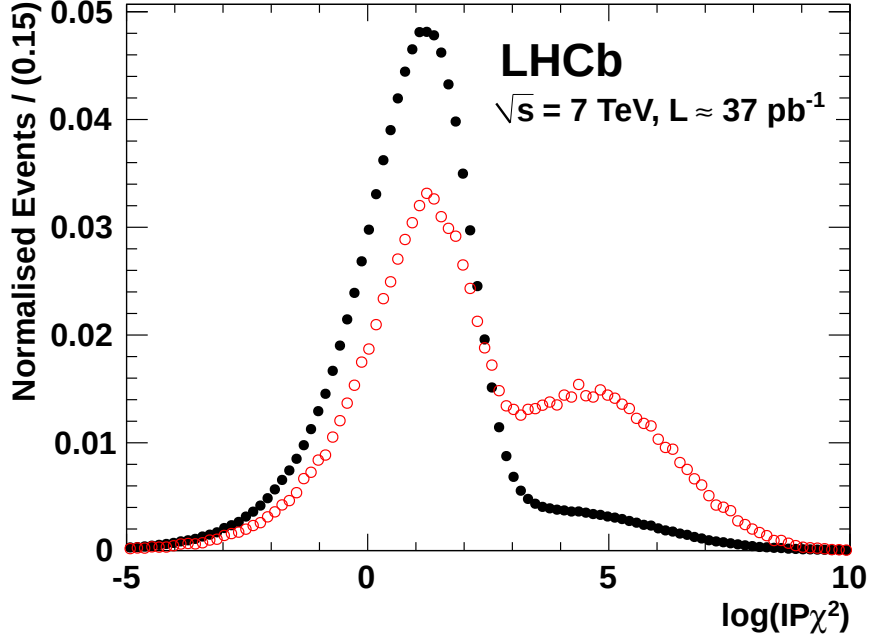


Figure 5.10: The $\log(IP\chi^2)$ of $D^0 \rightarrow \pi^+K^-$ candidates TOS with respect to the Hlt1TrackAllL0 trigger (black dots) and TIS+TOS with respect to the Hlt1TrackAllL0 trigger (red open circles). Both plots are normalised to have unit area. Taken from 2010 LHCb data.

As demonstrated by Figure 5.6 the ratio of proper decay time acceptances

$$R_\epsilon(t) \equiv \frac{\epsilon^{D \rightarrow KK}(t)}{\epsilon^{D \rightarrow \pi K}(t)} \quad (5.15)$$

is not constant in proper time and must be evaluated in order to make an unbiased measurement of the relative $D^0 \rightarrow K^+K^-$ lifetime. The selection efficiency $\epsilon(t)$ is essentially a time-dependent probability for a candidate to pass the trigger and selection. In more familiar statistics notation $\epsilon^{D \rightarrow KK}(t)$ could be written as $P(K^+K^- \text{ acc.})[t]$; i.e. the probability that the $D^0 \rightarrow K^+K^-$ candidate is accepted for a given value of proper time t .

Bayes' theorem [70] states that

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad (5.16)$$

where $P(A)$ denotes the probability of event A occurring and $P(A|B)$ denotes the probability of event A occurring given that event B has occurred.

Consider a D^0 meson with momentum p that decays after proper time t . Assume for simplicity that at the point of decay the D^0 will decay either into a K^+K^- or π^+K^- final state. As discussed previously, the probability of passing the selection is dependent which of the two final states it decays into. Using Bayes' theorem the conditional probability of the candidate being accepted when it decays to K^+K^- can be related to the probability of being accepted when it decays to π^+K^- . Taking event A as the D^0 decaying to the K^+K^- final state and being accepted and event B as the D^0 decaying into the π^+K^- final state and being accepted the conditional probability is

$$P(K^+K^- \text{ acc.} | \pi^+K^- \text{ acc.}) = \frac{P(\pi^+K^- \text{ acc.} | K^+K^- \text{ acc.})P(K^+K^- \text{ acc.})}{P(\pi^+K^- \text{ acc.})}. \quad (5.17)$$

Rearranging this equation gives

$$\frac{P(K^+K^- \text{ acc.})}{P(\pi^+K^- \text{ acc.})} = \frac{P(K^+K^- \text{ acc.} | \pi^+K^- \text{ acc.})}{P(\pi^+K^- \text{ acc.} | K^+K^- \text{ acc.})} \quad (5.18)$$

which is equal to the relative acceptance

$$R_\epsilon = \frac{\epsilon^{D \rightarrow KK}}{\epsilon^{D \rightarrow \pi K}} = \frac{P(K^+K^- \text{ acc.})}{P(\pi^+K^- \text{ acc.})}. \quad (5.19)$$

Therefore, if the conditional probabilities $P(K^+K^- \text{ acc.} | \pi^+K^- \text{ acc.})$ and $P(\pi^+K^- \text{ acc.} | K^+K^- \text{ acc.})$ can be evaluated as a function of proper time it will be possible to calculate the relative acceptance function $R_\epsilon(t)$ which can then in turn be used to correct the ratio of proper time distributions and make an unbiased relative measurement of the $D^0 \rightarrow K^+K^-$ lifetime.

5.2.3.1 Details of the Calculation

It turns out that it is indeed possible to evaluate these conditional probabilities from data alone. The procedure is essentially to recalculate the decay of the D^0 candidates as if they had decayed to the opposite final state (i.e. $D^0 \rightarrow K^+K^-$ candidates are converted to $D^0 \rightarrow \pi^+K^-$ and vice versa) and re-evaluate the trigger and selection decisions for the altered decay. The details of the calculation are as follows:

1. Take each $D^0 \rightarrow K^+K^-$ candidate that has passed the selection.
2. Boost into the D^0 rest frame.

3. Calculate the invariant mass of the sum of the daughters 4-momenta, m_D , (the measured mass of the mother).
4. Since this is a two body decay, the daughters are produced back-to-back with momenta of equal magnitude. Record the angle of flight of the daughters with respect to direction of flight of the D^0 .
5. Calculate what the magnitude of the daughters' momenta would have been had the mother instead decayed as $D^0 \rightarrow \pi^+ K^-$.
6. Recalculate the 4-momenta of the daughters in the case of a $D^0 \rightarrow \pi^+ K^-$ using the original flight direction in the D^0 rest frame, the newly calculated magnitude and the new mass hypothesis of the daughters.
7. Boost back into the lab frame. The direction and magnitude of the momentum vectors of the daughters will have changed but the momentum and mass of the mother will not.
8. Recalculate selection quantities such as impact parameter and transverse momentum of the daughters.
9. Re-apply the selection to the newly calculated hypothetical quantities and flag the candidate as passed or failed as $D^0 \rightarrow \pi^+ K^-$.
10. Taking a ratio of the proper time distribution of candidates that pass the selection both as $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ K^-$ with the original proper time distribution of the $D^0 \rightarrow K^+ K^-$ candidates gives $P(\pi^+ K^- \text{ acc.} | K^+ K^- \text{ acc.})$.
11. Repeat for all selected $D^0 \rightarrow \pi^+ K^-$ candidates, recalculating the decay as $D^0 \rightarrow K^+ K^-$ to evaluate $P(K^+ K^- \text{ acc.} | \pi^+ K^- \text{ acc.})$.

This procedure is referred to as the ReLative Acceptance Correction (RLAC).

5.2.4 Validation of the Relative Acceptance Correction Method for $D^0 \rightarrow K^+ K^-$

This section describes tests performed using both toy and full LHCb Monte Carlo simulated events to test the efficacy of the RLAC procedure.

5.2.4.1 Tests on Toy Monte Carlo Simulated Events

Tests have been performed using the toy Monte Carlo simulation described in Section 4.2. 10 million $D^0 \rightarrow K^+K^-$ and 10 million $D^0 \rightarrow \pi^+K^-$ candidates were generated and passed through an emulation of the Hlt1TrackAllL0 trigger, Hlt2CharmOSTF2Body trigger and the D2hhPrompt stripping selection and the RLAC algorithm described above was applied. Figure 5.11 shows the resulting relative acceptance function R_ϵ with the actual in black and the calculated in red. It is clear from this plot that the RLAC procedure is working very well, with the calculated points closely tracking the actual data points.

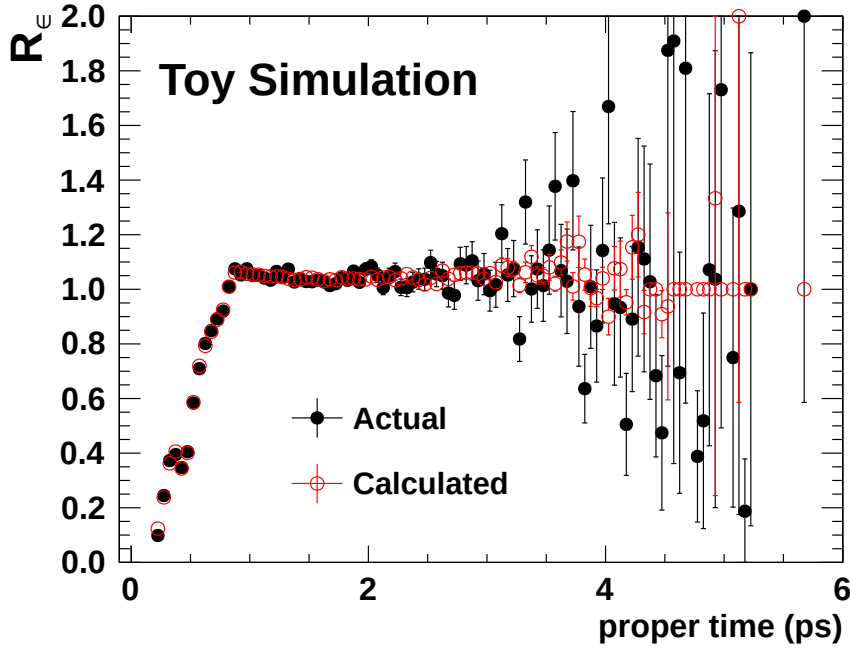


Figure 5.11: The relative proper time acceptance function R_ϵ for 10 million $D^0 \rightarrow K^+K^-$ and 10 million $D^0 \rightarrow \pi^+K^-$ toy Monte Carlo simulated candidates with an emulation of Hlt1TrackAllL0 trigger, Hlt2CharmOSTF2Body trigger and the D2hhPrompt stripping selection applied. The actual relative acceptance is marked by black dots and the RLAC calculation of the relative acceptance is marked by red open circles.

Figure 5.12 shows the ratio of the calculated relative acceptance to the actual fitted with a first order polynomial. The ratio is flat and the fit intercept and gradient consistent with one and zero respectively, demonstrating clearly that the RLAC procedure works extremely well for toy Monte Carlo simulated events.

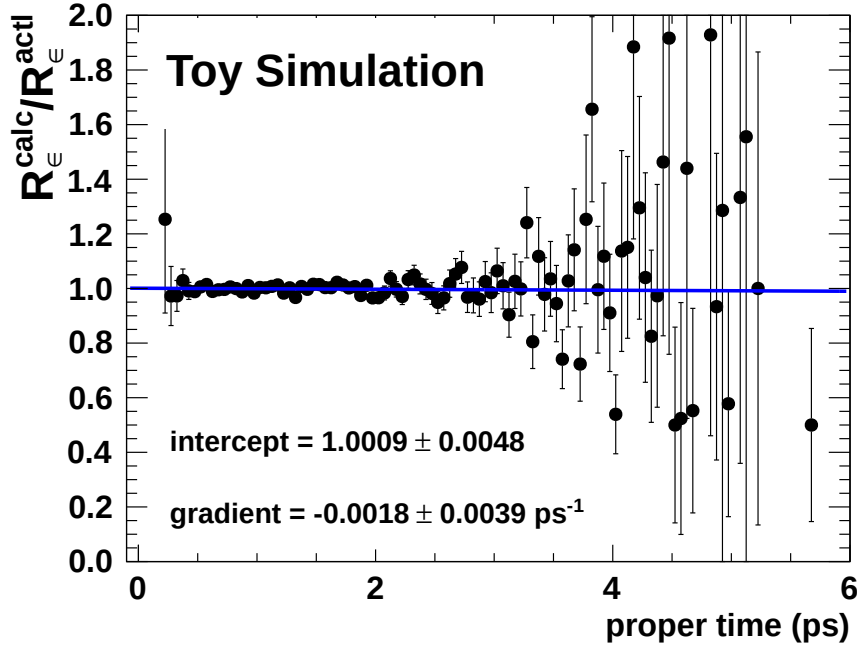


Figure 5.12: The ratio of the RLAC calculated to actual relative acceptance functions with first order polynomial fit.

5.2.4.2 Tests on LHCb Monte Carlo Simulated Events

The RLAC procedure has also been adapted to work with the full LHCb software suite in order that it can be applied to both LHCb Monte Carlo simulated events and real LHCb data. The algorithm was implemented using the DaVinci v26r4 [60] analysis software and the details of the implementation are described in Appendix A.

Stripping Selection and Emulated Trigger The first tests performed applied the D2hhPrompt stripping selection (excluding the PID requirements) along with emulations of the Hlt1TrackAllL0 and Hlt2CharmOSTF2Body triggers where requirements were made on offline quantities. The emulations were based on the requirements used in Tables 3.2 and 3.10. However, the requirements on the number of track and VELO hits made in the Hlt1TrackAllL0 trigger were not imposed as these quantities were not available in the offline data sample.

Figure 5.13 compares the actual and the RLAC calculation of the relative proper time acceptance and Figure 5.14 shows the ratio of the RLAC calculation and the actual relative acceptance functions fitted with a first order polynomial. It can be seen from

both these plots that for the emulated trigger the procedure again works well with the intercept and gradient of the ratio of calculated to actual consistent with one and zero respectively. However, it should be noted that the available LHCb Monte Carlo $D^0 \rightarrow K^+K^-$ statistics are about 10 times smaller than those available in data in 2010 data and so much higher statistics of LHCb Monte Carlo simulation are required for validation in order to be confident when making a 0.1% measurement of y_{CP} .

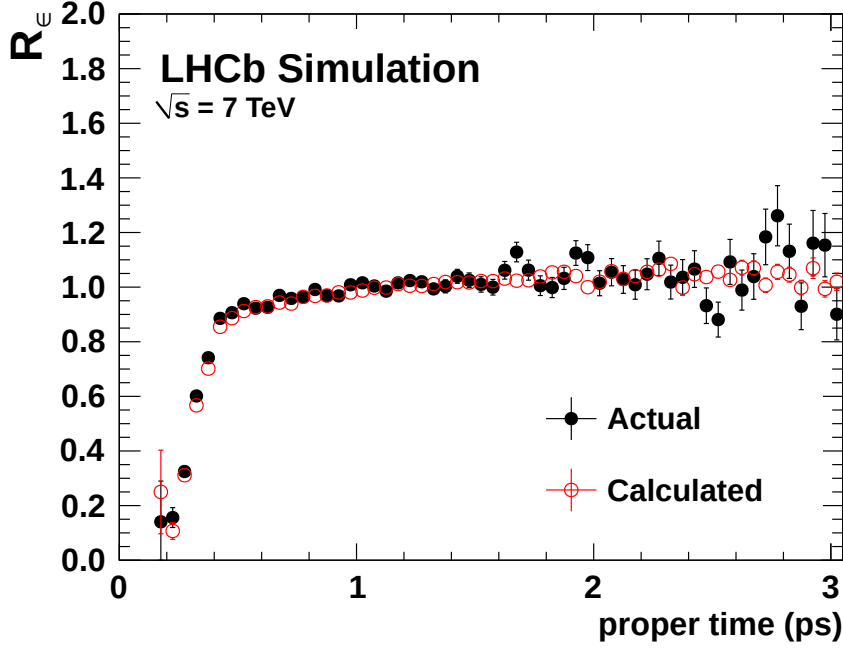


Figure 5.13: The relative proper time acceptance function R_e for 3.9 million $D^0 \rightarrow K^+K^-$ and 4.3 million $D^0 \rightarrow \pi^+K^-$ full LHCb Monte Carlo simulated candidates with an emulation of the Hlt1TrackAllL0 trigger, the Hlt2CharmOSTF2Body trigger and the full D2hhPrompt stripping selection applied. The actual relative acceptance is marked by black dots and the RLAC calculation of the relative acceptance is marked by red open circles.

Stripping Selection and Full Trigger Finally, the RLAC procedure is tested by applying the full trigger to LHCb Monte Carlo simulated events. The TCK used is 0x002e002a. Candidates are required to be TOS with respect to both the Hlt1TrackAllL0 trigger and the Hlt2CharmOSTF2Body trigger but no requirement is made on L0 decision. A complication arises when applying the full trigger as the RLAC procedure requires the trigger and selection to be re-applied after the decay has been changed between K^+K^- and π^+K^- . At present, it is not technically possible to re-run the full trigger in this way as it would require moving trigger objects such as particle tracks which

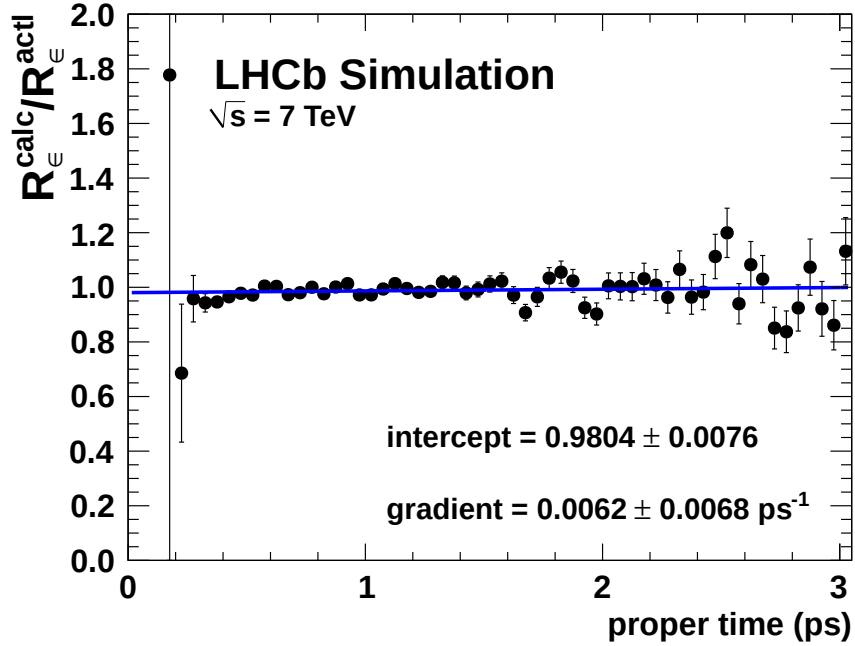


Figure 5.14: The ratio of the RLAC calculated to actual relative acceptance functions due to an emulation of the Hlt1TrackAllL0 trigger, the Hlt2CharmOSTF2Body trigger and the full D2hhPrompt stripping selection with first order polynomial fit. Full LHCb simulated candidates are used.

is beyond the scope of this dissertation. As a result, the selection is re-applied using the offline emulation of the triggers described in the previous section. If the emulation is not accurate then this may introduce a bias into the correction.

Figures 5.15 and 5.16 compare the RLAC calculation of the relative acceptance with that obtained from the full trigger. Overall, the correction still appears to perform well, however there is evidence of a non-zero slope on the ratio of calculated to actual at the 1.3σ level. Unfortunately, it is not currently possible to test the RLAC calculation any further due to limited LHCb Monte Carlo statistics. However, in the following section the further work required to accurately verify this approach for use on data is discussed along with the key challenges.

5.3 Conclusions

In Section 5.1 it was seen that the proper time acceptance bias due to selection may be cancelled by taking a ratio of the proper time distributions of the $B_s^0 \rightarrow K^+ K^-$

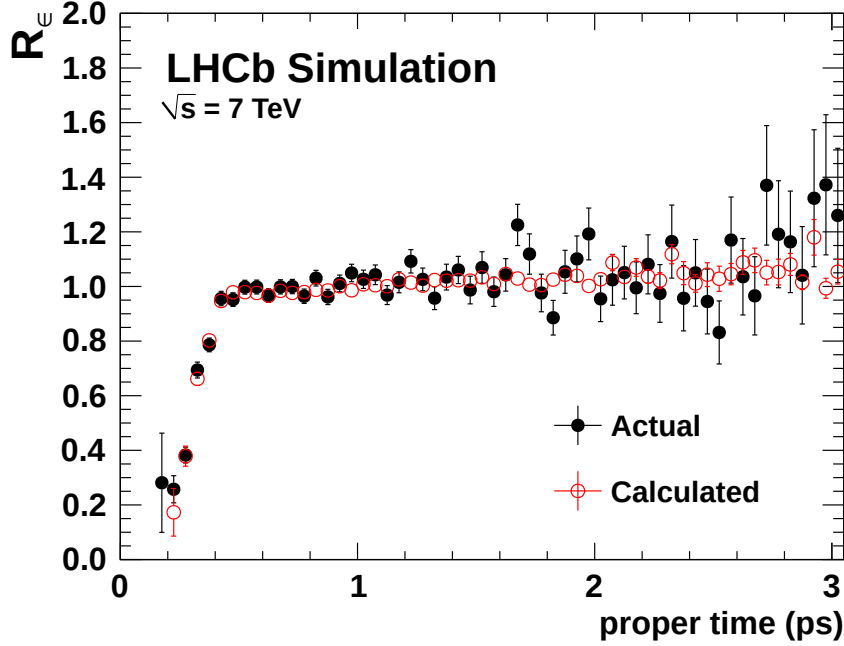


Figure 5.15: The relative proper time acceptance function R_ϵ for 3.9 million $D^0 \rightarrow K^+ K^-$ and 4.3 million $D^0 \rightarrow \pi^+ K^-$ full LHCb Monte Carlo simulated candidates with the full Hlt1TrackAllL0 trigger, the full Hlt2CharmOSTF2Body trigger and the full D2hhPrompt stripping selection applied. The actual relative acceptance is marked by black dots and the RLAC calculation of the relative acceptance is marked by red open circles. The RLAC calculation is performed using an emulation of the trigger.

and $B^0 \rightarrow K^+ \pi^-$ decay modes. This allows the $B_s^0 \rightarrow K^+ K^-$ effective lifetime to be measured relative to the better constrained B^0 lifetime. However, this approach fails in the case of $D^0 \rightarrow K^+ K^- / D^0 \rightarrow \pi^+ K^-$ due to significant differences between the kinematics of the two decay modes.

The relative acceptance correction described in Section 5.2 method looks extremely promising as a technique for making an unbiased relative measurement of y_{CP} . High statistics toy Monte Carlo studies have demonstrated that the method works to a high degree of precision and further studies using LHCb simulations have shown that the method also performs well within the available statistics.

However, there are a number of systematic effects which require investigation before the technique can be applied to data. The most challenging issue is dealing with the LHCb trigger acceptance. At present, the trigger must be emulated using offline quantities and this throws up a number of potential problems. The first comes from the

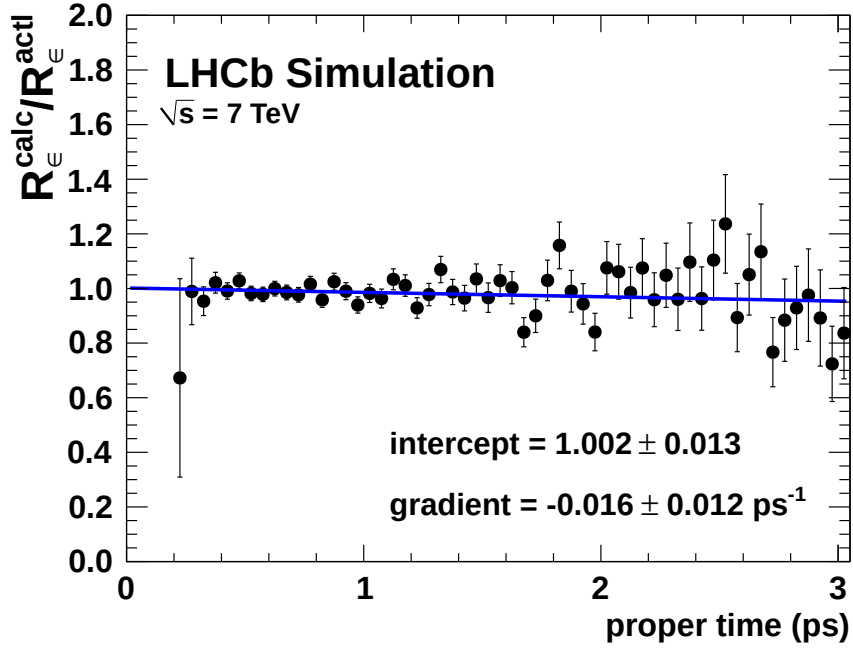


Figure 5.16: The ratio of the RLAC calculated to actual relative acceptance functions due to the full Hlt1TrackAllL0 trigger, the full Hlt2CharmOSTF2Body trigger and the full D2hhPrompt stripping selection with first order polynomial fit. Full LHCb simulated candidates are used. The RLAC calculation is performed using an emulation of the trigger.

difference in resolutions on momentum and impact parameter between the trigger and offline. As a result, requirements made offline may not reflect those made in the trigger. Second, requirements made in the trigger on the number of track and VELO hits will require some modelling of the LHCb detector offline in order to evaluate the effect of changing the decay type on these quantities. Finally, an emulation of the L0 trigger may prove very challenging as it operates in a very different way from both the HLT and the offline analysis.

Ideally in future it will be possible to re-run the full LHCb trigger directly in order to circumvent these issues. This will require work using the trigger software in order to alter the angles and momenta of trigger tracks so that the trigger decision can be evaluated accurately. This is a complex task beyond the scope of this dissertation.

The other main challenge arises in validating the method to the required precision. While high statistics toy Monte Carlo studies can give confidence in the underlying premise of the approach one must also be convinced that the method works in the context of the LHCb experiment where many complex and interconnected factors are at

play. One approach would be to generate very high statistics LHCb Monte Carlo samples of the order of hundreds of millions of $D \rightarrow h^+ h^-$ candidates. It may also be possible to test the method using data only by performing the procedure for $D^0 \rightarrow \pi^+ K^-$ versus $\bar{D}^0 \rightarrow \pi^- K^+$. The relative proper time acceptance between these two modes should be completely flat and this fact could be used to verify the RLAC technique by making the switch $K \leftrightarrow \pi$.

Chapter 6

Measuring the $B_s^0 \rightarrow K^+ K^-$ Lifetime

“There is no excellent beauty that hath not some strangeness in the proportion.”

— Francis Bacon, *Of Beauty*

This chapter describes the method used to make a measurement of the $B_s^0 \rightarrow K^+ K^-$ lifetime relative to the $B^0 \rightarrow K^+ \pi^-$ lifetime. The approach described has evolved from the one presented in [71] which was written before the first LHC collisions. This measurement is also presented in [72]. Section 6.1 describes the fit used to extract the effective $B_s^0 \rightarrow K^+ K^-$ lifetime and Section 6.2 describes the validation of the fitting procedure using both full LHCb and toy Monte Carlo simulations. The resulting fits and the measured lifetime are presented in Section 6.3. The systematic uncertainties associated with this measurement are explored in Chapter 7.

6.1 Fitting Procedure

The fit used to extract the $B_s^0 \rightarrow K^+ K^-$ lifetime is implemented using the RooFit package [73] which is based on the ROOT environment [74]. The MINUIT package [75] performs the function minimisation. All fits presented are un-binned extended maximum likelihood fits.

6.1.1 Mass Fits

The proper decay time distributions are extracted by fits to the invariant mass spectrum of each final state in bins of proper decay time. As described in Section 3.3.3.2 the PID capability of the LHCb experiment is used to split the data into the two final states, K^+K^- and $K^\pm\pi^\mp$.

6.1.1.1 K^+K^- Mass Fit

The only signal channel decaying to this final state is $B_s^0 \rightarrow K^+K^-$ ($B^0 \rightarrow K^+K^-$ is yet to be observed). A single Gaussian function is used to fit for $B_s^0 \rightarrow K^+K^-$ candidates and a first order polynomial distribution is used to model the combinatorial background. Although fits to LHCb Monte Carlo simulated data indicate that a single Gaussian distribution is insufficient to model signal decay modes completely, at the current level of statistics the fit is insensitive to anything more complex. A validation of this choice of probability distribution function (PDF) is described in Section 6.2.1. The PDF for the K^+K^- mass (m_{KK}) spectrum is then given by

$$PDF_{KK}(m_{KK}) = N_{B_s \rightarrow KK} A e^{-(m_{KK} - m_{B_s}^{KK})^2 / 2\sigma_{KK}^2} + N_{Comb_{KK}} B (c_0^{KK} + c_1^{KK} m_{KK}) \quad (6.1)$$

where $N_{B_s \rightarrow KK}$ is the yield of $B_s^0 \rightarrow K^+K^-$ decays, $N_{Comb_{KK}}$ the yield of combinatorial background, $m_{B_s}^{KK}$ the B_s^0 mass in the K^+K^- mass spectrum, σ_{KK} the K^+K^- mass resolution, A the normalisation coefficient of the Gaussian, B the normalisation coefficient of the polynomial, and c_0^{KK} and c_1^{KK} are the polynomial coefficients (c_0 is always chosen as equal to one by RooFit due to the extra degree of freedom associated with the normalisation). The fit range is $5150.0 \text{ MeV}/c^2 < m_{KK} < 5800.0 \text{ MeV}/c^2$.

6.1.1.2 $K^\pm\pi^\mp$ Mass Fit

The fit to the $K^\pm\pi^\mp$ mass spectrum must account for both $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow \pi^+K^-$ decay modes. These signal modes are modelled using single Gaussian distributions with a common resolution $\sigma_{K\pi}$ and the combinatorial background is modelled using a first order polynomial. The total $K^\pm\pi^\mp$ PDF is then

$$\begin{aligned} PDF_{K\pi}(m_{K\pi}) &= N_{B \rightarrow K\pi} C e^{-(m_{K\pi} - m_B^{K\pi})^2 / 2\sigma_{K\pi}^2} + N_{B_s \rightarrow \pi K} D e^{-(m_{K\pi} - m_{B_s}^{\pi K})^2 / 2\sigma_{K\pi}^2} \\ &+ N_{Comb_{K\pi}} E (c_0^{K\pi} + c_1^{K\pi} m_{K\pi}) \end{aligned} \quad (6.2)$$

where $m_{K\pi}$ is the candidate mass under the $K^\pm\pi^\mp$ hypothesis, $m_{B(s)}^{K\pi}$ is the $B_{(s)}$ mass under the $K^\pm\pi^\mp$ hypothesis, $N_{B\rightarrow K\pi}$, $N_{B_s\rightarrow\pi K}$ and $N_{Comb_{K\pi}}$ are the yields of $B^0 \rightarrow K^+\pi^-$, $B_s^0 \rightarrow \pi^+K^-$ and combinatorial background and C , D and E are normalisation factors. However, it should be noted that the yields of $B_s^0 \rightarrow \pi^+K^-$ and the backgrounds are not fitted directly but rather the ratio of their yields to that of $B^0 \rightarrow K^+\pi^-$ such that

$$N_{B_s\rightarrow\pi K} = R_{B_s\rightarrow\pi K} \times N_{B\rightarrow K\pi} \quad (6.3)$$

$$N_{Comb_{K\pi}} = R_{Comb_{K\pi}} \times N_{B\rightarrow K\pi} \quad (6.4)$$

As for the K^+K^- spectrum, the fit range is $5150.0 \text{ MeV}/c^2 < m_{K\pi} < 5800.0 \text{ MeV}/c^2$.

6.1.2 Lifetime Fit

As described in Chapter 5 the ratio of the $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$ proper time distributions may be expressed as:

$$R^{B_s\rightarrow KK}(t) = R^{B_s\rightarrow KK}(0)e^{-t(\tau_{K^+K^-}^{-1} - \tau_{B\rightarrow K\pi}^{-1})}. \quad (6.5)$$

As with $B_s^0 \rightarrow K^+K^-$, the $B_s^0 \rightarrow \pi^+K^-$ decay mode is almost kinematically identical to $B^0 \rightarrow K^+\pi^-$ and the acceptance cancellation between the two modes is therefore also very precise. The ratio of the $B_s^0 \rightarrow \pi^+K^-$ and $B^0 \rightarrow K^+\pi^-$ proper time distributions may therefore be expressed as:

$$R^{B_s\rightarrow\pi K}(t) = R^{B_s\rightarrow\pi K}(0)e^{-t(\tau_{B_s\rightarrow\pi K}^{-1} - \tau_{B\rightarrow K\pi}^{-1})}. \quad (6.6)$$

At this point it is helpful to define the quantities

$$\Delta\Gamma_{K^+K^-} \equiv \tau_{K^+K^-}^{-1} - \tau_{B\rightarrow K\pi}^{-1} \quad (6.7)$$

$$\Delta\Gamma_{\pi^+K^-} \equiv \tau_{B_s\rightarrow\pi K}^{-1} - \tau_{B\rightarrow K\pi}^{-1} \quad (6.8)$$

such that

$$R^{B_s\rightarrow KK}(t) = R^{B_s\rightarrow KK}(0)e^{-t\Delta\Gamma_{K^+K^-}} \quad (6.9)$$

$$R^{B_s\rightarrow\pi K}(t) = R^{B_s\rightarrow\pi K}(0)e^{-t\Delta\Gamma_{\pi^+K^-}}. \quad (6.10)$$

The lifetime fit is performed so that the quantities $\Delta\Gamma_{K^+K^-}$ and $\Delta\Gamma_{\pi^+K^-}$ are extracted directly, rather than the lifetimes $\tau_{K^+K^-}$ and $\tau_{B_s \rightarrow \pi K}$ themselves. This is done so that no external measurement of the $B^0 \rightarrow K^+\pi^-$ lifetime is required as input to the fit. Since the $B^0 \rightarrow K^+\pi^-$ lifetime is equal to the mean B^0 lifetime τ_B , $\tau_{K^+K^-}$ may be extracted from $\Delta\Gamma_{K^+K^-}$ using τ_B as input, where $\tau_B = 1.519 \pm 0.007$ ps [11].

The difference of inverse lifetimes $\Delta\Gamma_{K^+K^-}$ is extracted using the mass fits described in Section 6.1.1 performed in bins of proper time. The dataset is split into 30 proper time bins which are chosen so that each contains approximately the same number of candidates. The optimum number of bins depends upon the available statistics. In principle the larger the number of bins used the better as by binning the data one throws away the information about how the proper decay time varies across the bin. However, this must be balanced against the need for a minimum number of candidates in a given bin so that the mass fit converges. The maximum number of bins for which the fit converged reliably in toy simulations corresponding to the available statistics in data was found to be 30.

$\Delta\Gamma_{K^+K^-}$ is fitted for directly by means of a simultaneous fit of both final states and proper time bins. A simultaneous PDF is constructed that spans the entire dataset. In each proper time bin mass fits of the form described above are performed but only the yields of $B^0 \rightarrow K^+\pi^-$ and the backgrounds are allowed to float completely freely. The parameters of the signal and background PDFs are fixed from fits to the time-integrated dataset. In each case the limits on the yields are set to ± 10 times the total number of candidates in the bin. The yields of the two other signal modes are expressed in terms of the ratios to the yield of $B^0 \rightarrow K^+\pi^-$:

$$N_{B_s \rightarrow KK}(\bar{t}_i) = R_{B_s \rightarrow KK}(\bar{t}_i) N_{B \rightarrow K\pi}(\bar{t}_i) \quad (6.11)$$

$$N_{B_s \rightarrow \pi K}(\bar{t}_i) = R_{B_s \rightarrow \pi K}(\bar{t}_i) N_{B \rightarrow K\pi}(\bar{t}_i) \quad (6.12)$$

where $\bar{t}_i$ is the mean value of t in the i^{th} bin. The ratios are then given in turn by:

$$R_{B_s \rightarrow KK}(\bar{t}_i) = R^{B_s \rightarrow KK}(0) e^{-\bar{t}_i \Delta\Gamma_{K^+K^-}} \quad (6.13)$$

$$R_{B_s \rightarrow \pi K}(\bar{t}_i) = R^{B_s \rightarrow \pi K}(0) e^{-\bar{t}_i \Delta\Gamma_{\pi^+K^-}}. \quad (6.14)$$

The background yields are similarly expressed in terms of the ratio to the $B^0 \rightarrow K^+\pi^-$

yield

$$N_{Comb_{KK}}(\bar{t}_i) = R_{Comb_{KK}}(\bar{t}_i)N_{B \rightarrow K\pi}(\bar{t}_i) \quad (6.15)$$

$$N_{Comb_{K\pi}}(\bar{t}_i) = R_{Comb_{K\pi}}(\bar{t}_i)N_{B \rightarrow K\pi}(\bar{t}_i) \quad (6.16)$$

with the ratios $R_{Comb_{KK}}(\bar{t}_i)$ and $R_{Comb_{K\pi}}(\bar{t}_i)$ each allowed to float freely. The PDFs for each final state in each proper time bin are then

$$\begin{aligned} PDF_{KK}(m_{KK}, \bar{t}_i) = & N_{B_s \rightarrow KK}(\bar{t}_i) A e^{-(m_{KK} - m_{B_s}^{KK})^2 / 2\sigma_{KK}^2} \\ & + N_{Comb_{KK}}(\bar{t}_i) B (c_0^{KK} + c_1^{KK} m_{KK}) \end{aligned} \quad (6.17)$$

$$\begin{aligned} PDF_{K\pi}(m_{K\pi}, \bar{t}_i) = & N_{B \rightarrow K\pi}(\bar{t}_i) C e^{-(m_{K\pi} - m_B^{K\pi})^2 / 2\sigma_{K\pi}^2} \\ & + N_{B_s \rightarrow \pi K}(\bar{t}_i) D e^{-(m_{K\pi} - m_{B_s}^{\pi K})^2 / 2\sigma_{K\pi}^2} \\ & + N_{Comb_{K\pi}}(\bar{t}_i) E (c_0^{K\pi} + c_1^{K\pi} m_{K\pi}) \end{aligned} \quad (6.18)$$

and a simultaneous fit is performed across all final states and proper time bins. The free parameters of the simultaneous fit are listed in Table 6.1. The parameters fixed in the time-integrated mass fits are listed in Table 6.2. The fit is performed in the range $-1.0 \text{ ps} < t < 35.0 \text{ ps}$.

Parameter Category	Parameter
$K^+ K^-$ final state	$R^{B_s \rightarrow KK}(0)$
	$R_{Comb_{KK}}(\bar{t}_i) \ (i = 0, 1, \dots, 29)$
$K^\pm \pi^\mp$ final state	$N_{B \rightarrow K\pi}(\bar{t}_i) \ (i = 0, 1, \dots, 29)$
	$R^{B_s \rightarrow \pi K}(0)$
	$R_{Comb_{K\pi}}(\bar{t}_i) \ (i = 0, 1, \dots, 29)$
Ratio decay constants	$\Delta\Gamma_{K^+ K^-}$
	$\Delta\Gamma_{\pi^+ K^-}$

Table 6.1: Free parameters of the simultaneous lifetime fit.

Parameter Category	Parameter
K^+K^- final state	$m_{B_s}^{KK}$
	σ_{KK}
	c_1^{KK}
$K^\pm\pi^\mp$ final state	$m_B^{K\pi}$
	$m_{B_s}^{K\pi}$
	$\sigma_{K\pi}$
	c_1^{KK}

Table 6.2: Fixed parameters of the simultaneous lifetime fits. Their values are fixed to the results obtained from time-integrated mass fits to the K^+K^- and $K^\pm\pi^\mp$ spectra.

6.2 Validation of the Fitting Procedure

6.2.1 $B \rightarrow h^+h^-$ Mass PDFs

As stated in Section 6.1.1 a single Gaussian distribution is not sufficient to parametrise the invariant mass distribution of a $B \rightarrow h^+h^-$ decay mode. However, at the level of statistics currently available the fit is not sensitive to a more complex shape. Studies have been performed using LHCb 2010 Monte Carlo to validate this approach. Different PDFs are fitted to true $B_s^0 \rightarrow K^+K^-$ candidates that have passed the stripping and offline selections and the χ^2 per degree of freedom of the fit is used as a measure of fit quality.

Three functions of increasing complexity are chosen: a single Gaussian distribution, the sum of two Gaussian distributions and a “Double Crystal Ball” distribution (a function with a central Gaussian core and polynomial tails on the high and low sides). The fits are performed at three levels of statistics: 300 candidates, 1000 candidates and 15,000 candidates. The fits are shown in Figures 6.1, 6.2 and 6.3 and the fit χ^2 values are listed in Table 6.3. It is observed that the χ^2 per degree of freedom remains less than or close to 1 for all functions up to 1000 candidates; it is only at very high statistics that there is a noticeable improvement in fit quality from using a more complex parametrisation. The use of single Gaussian PDF to fit $B \rightarrow h^+h^-$ signals is therefore justified and sufficient.

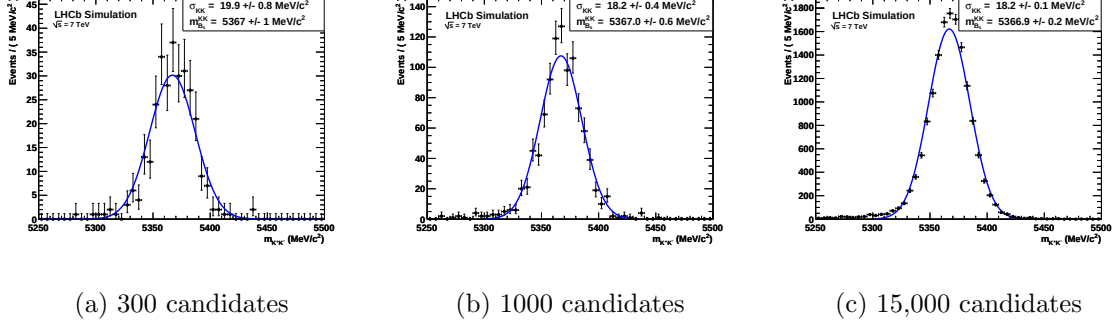


Figure 6.1: Fits to offline selected 2010 LHCb simulation $B_s^0 \rightarrow K^+ K^-$ candidates using Gaussian distributions.

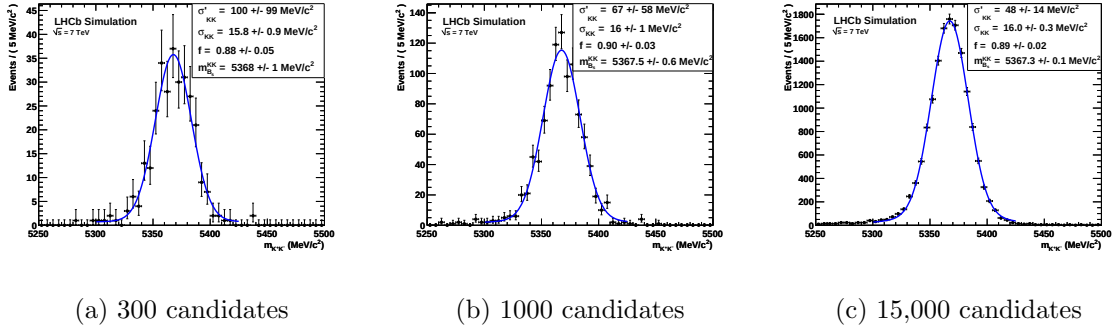


Figure 6.2: Fits to offline selected 2010 LHCb simulation $B_s^0 \rightarrow K^+ K^-$ candidates using the sum of two Gaussian distributions.

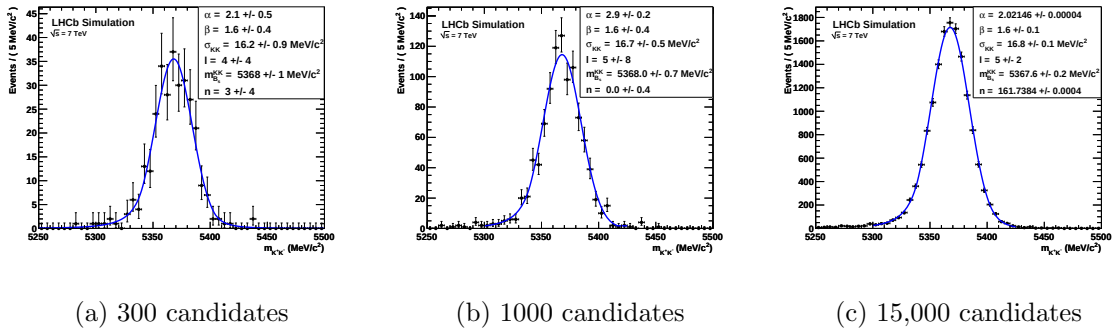


Figure 6.3: Fits to offline selected 2010 LHCb simulation $B_s^0 \rightarrow K^+ K^-$ candidates using “Double Crystal Ball” distributions.

Number of candidates	χ^2 per degree of freedom		
	Gaussian	Sum of two Gaussians	“Double Crystal Ball”
300	0.366	0.511	0.294
1000	0.992	0.722	0.751
15,000	5.227	1.468	0.996

Table 6.3: Fit χ^2 per degree of freedom for different choices of $B \rightarrow h^+h^-$ mass PDFs for different levels of statistics.

6.2.2 The Lifetime Fit

The toy simulation (see Section 4.2) has been used to investigate the accuracy and precision of the lifetime fit described in Section 6.1.2. In each experiment 910 $B_s^0 \rightarrow K^+K^-$ candidates, 212 $B_s^0 \rightarrow \pi^+K^-$ candidates and 2,400 $B^0 \rightarrow K^+\pi^-$ candidates are generated along with 221 K^+K^- combinatorial background candidates and 564 $K^\pm\pi^\mp$ combinatorial background candidates. These numbers are chosen so that the same number of candidates are selected as for real data. The model used to generate combinatorial background is described in Section 4.2.3 and the input parameters of the model are listed in Table 6.4.

In this case the $B_s^0 \rightarrow K^+K^-$ channel is simulated as having a single mean lifetime, rather than the double exponential distribution predicted by Equation 1.57. This in effect assumes that $\mathcal{A}_{\Delta\Gamma} = -1.0$. The effect of a different value of $\mathcal{A}_{\Delta\Gamma}$ is explored in Chapter 7. The input values to the toy simulation are listed in Table 6.4.

The selection described in Tables 5.1 and 5.2 is applied to the simulated data. This reduces the number of candidates to the same level as seen in the 2010 LHCb dataset.

The full fit is then performed and $\Delta\Gamma_{K^+K^-}$ evaluated. 10,000 experiments are performed and the “pull” ([measured value - true value] / statistical uncertainty) of $\Delta\Gamma_{K^+K^-}$ is fitted with a Gaussian distribution as illustrated in Figure 6.4. The mean is consistent with zero and the width is consistent with one, demonstrating that the lifetime fit is unbiased and estimates the uncertainties accurately. Furthermore, this demonstrates that the proper time acceptance cancels to a very high precision.

Parameter	Default value	Comment
m_{B^0}	5279.53 MeV/ c^2	B^0 mass
$m_{B_s^0}$	5366.3 MeV/ c^2	B_s^0 mass
$m_{K^\pm}$	493.677 MeV/ c^2	kaon mass
$m_{\pi^\pm}$	139.57018 MeV/ c^2	pion mass
τ_{B^0}	1.525 ps	B^0 mean lifetime
$\tau_{B_s^0}$	1.472 ps	B_s^0 mean lifetime
$\tau_{K^+K^-}$	1.472 ps	Effective $B_s^0 \rightarrow K^+K^-$ lifetime
∇^{bkg}	0.165 (GeV/ c^2) $^{-1}$	Combinatorial background mass PDF gradient
A^{bkg}	0.7 ps	Combinatorial background acceptance turn-on
B^{bkg}	0.08 ps	Combinatorial background acceptance width
f_L^{bkg}	0.2	Combinatorial background long-lived fraction
τ_L^{bkg}	1.3 ps	Combinatorial background long-lived lifetime
τ_S^{bkg}	0.6 ps	Combinatorial background short-lived lifetime

Table 6.4: Default values of the input parameters of the toy Monte Carlo generator used for validating the lifetime fit. The values are from the PDG [11] or taken from fits to LHCb data.

6.3 Results and Extraction of the Effective $B_s^0 \rightarrow K^+K^-$ Lifetime

The results of the fit described in Section 6.1 applied to the data described in Section 3.3 are presented in this section. The time-integrated mass fits to the $K^\pm\pi^\mp$ and K^+K^- mass spectra are shown in Figures 6.5 and 6.7 respectively. The yields of each mode extracted from the fit are listed in Table 6.5.

The proper time distributions extracted from the simultaneous proper time fit described in Section 6.1.2 are shown in Figures 6.6 and 6.8. These plots show the proper time distributions for $B_s^0 \rightarrow K^+K^-$, $B_s^0 \rightarrow \pi^+K^-$, $B^0 \rightarrow K^+\pi^-$ and combinatorial background. The fits to the K^+K^- and $K^\pm\pi^\mp$ invariant spectra in bins of proper time are shown in Figures B.1 to B.8 in Appendix B.

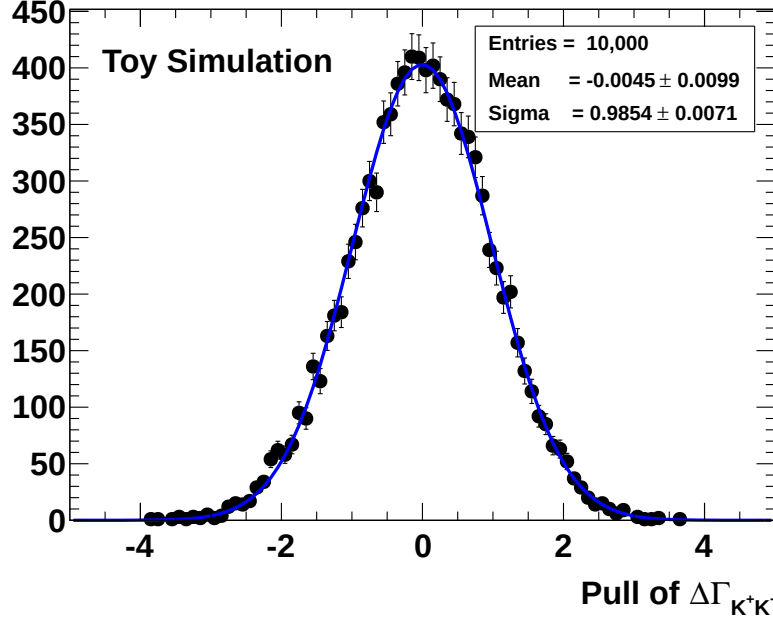


Figure 6.4: The pull of $\Delta\Gamma_{K^+K^-}$ from 10,000 toy Monte Carlo experiments with Gaussian fit.

Decay mode	Yield
$B_s^0 \rightarrow K^+K^-$	300 ± 19
$B_s^0 \rightarrow \pi^+K^-$	71 ± 16
$B^0 \rightarrow K^+\pi^-$	793 ± 33

Table 6.5: The yields of the $B \rightarrow h^+h^-$ decay modes extracted from the time-integrated mass fits.

The fitted value of $\Delta\Gamma_{K^+K^-}$ is

$$\Delta\Gamma_{K^+K^-} = 0.013 \pm 0.045(\text{stat}) \text{ ps}^{-1} \quad (6.19)$$

where $\Delta\Gamma_{K^+K^-}$ is the difference of inverse lifetimes $\Delta\Gamma_{K^+K^-} \equiv 1/\tau_{K^+K^-} - 1/\tau_{B \rightarrow K\pi}$. The systematic uncertainties associated with this measurement are evaluated in Chapter 7 and a calculation of the effective $B_s^0 \rightarrow K^+K^-$ lifetime $\tau_{K^+K^-}$ using external input is performed in Chapter 8.

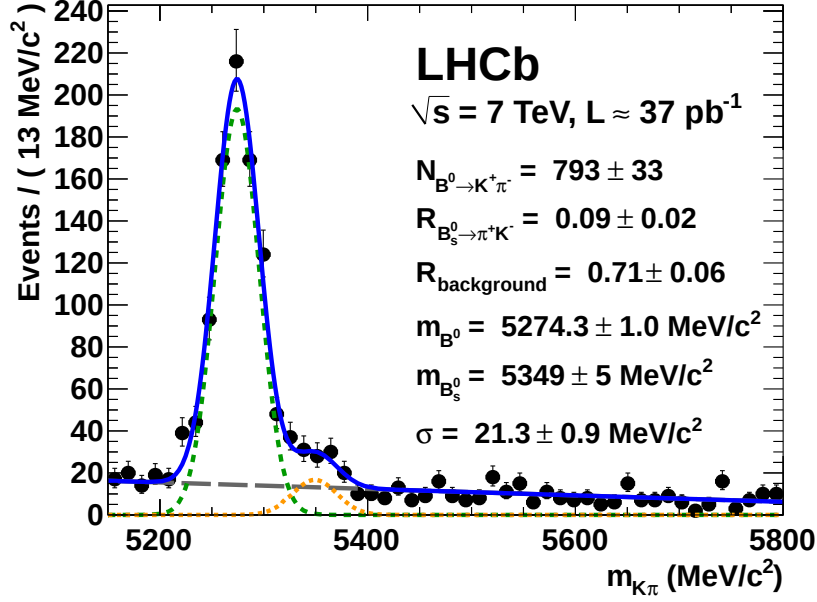


Figure 6.5: Fit to the $K^\pm\pi^\mp$ mass spectrum for 2010 LHCb data. The total PDF (blue solid line) is composed of the $B^0 \rightarrow K^+\pi^-$ (green medium-dashed line), $B_s^0 \rightarrow \pi^+K^-$ (orange short-dashed line) and combinatorial background (grey long-dashed line) PDFs.

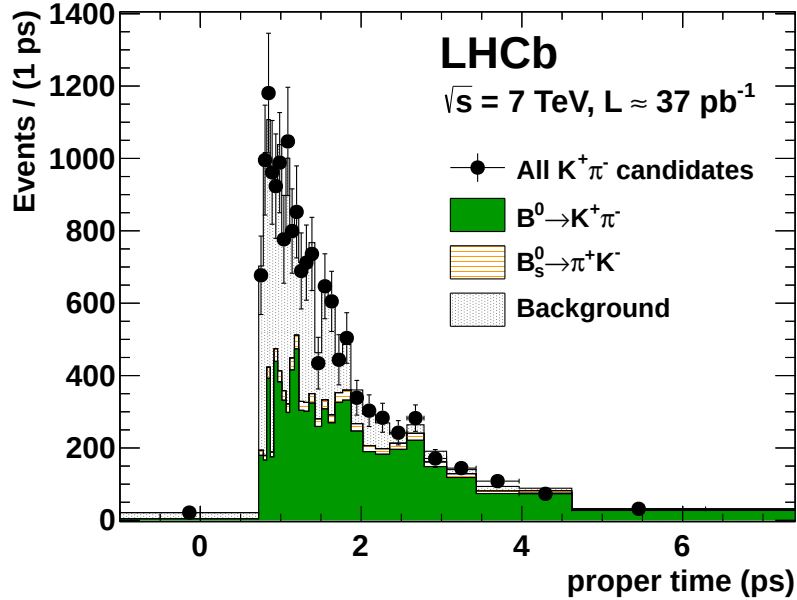


Figure 6.6: The fitted proper time distributions for $B \rightarrow K\pi$ candidates. The black points are the total number of $K^\pm\pi^\mp$ candidates. The stacked histogram contains $B^0 \rightarrow K^+\pi^-$ in green (solid fill), $B_s^0 \rightarrow \pi^+K^-$ in orange (horizontal hatching) and combinatorial background (dotted fill) in grey.

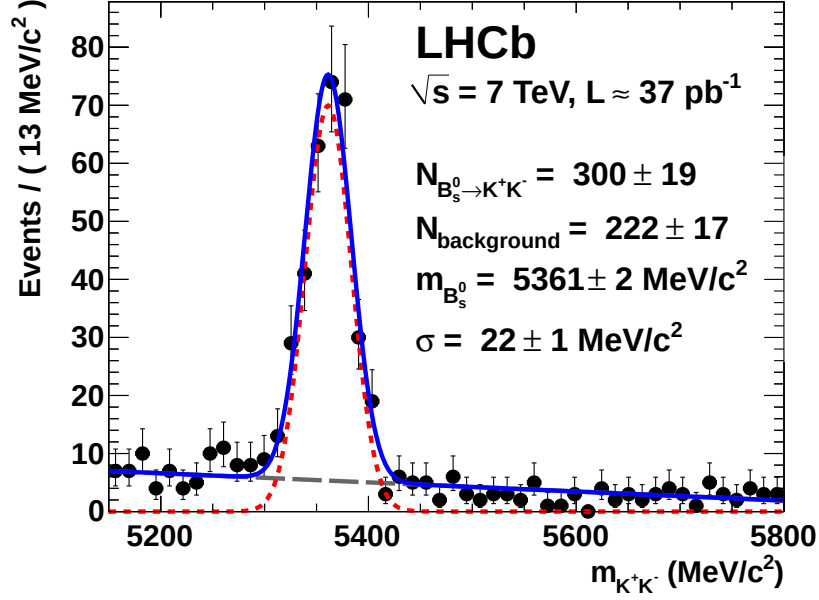


Figure 6.7: Fit to the K^+K^- mass spectrum for 2010 LHCb data. The total PDF (blue solid line) is composed of the $B_s^0 \rightarrow K^+K^-$ (red medium-dashed line) and combinatorial background (grey long-dashed line) PDFs.

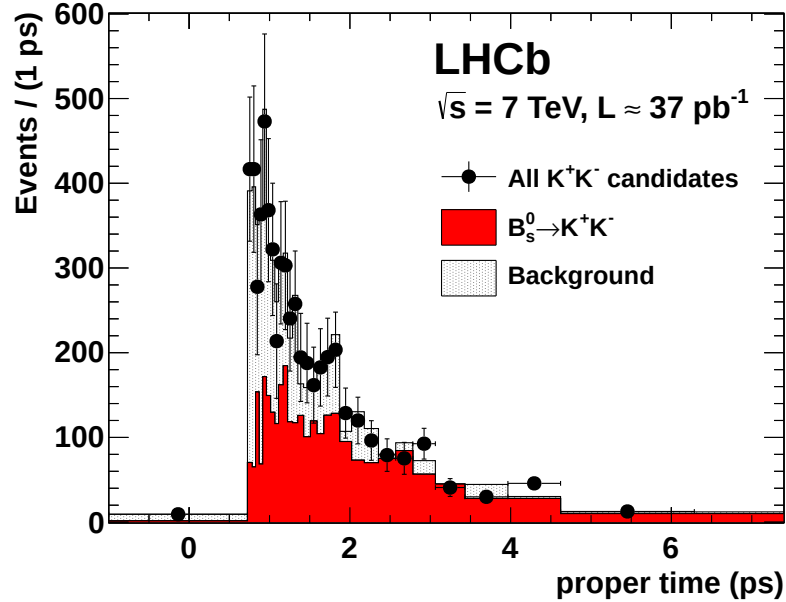


Figure 6.8: The fitted proper time distributions for $B \rightarrow KK$ candidates. The black points are the total number of K^+K^- candidates. The stacked histogram contains $B_s^0 \rightarrow K^+K^-$ in red (solid fill) and combinatorial background in grey (dotted fill).

Chapter 7

Systematic Uncertainties

“To believe with certainty we must begin with doubting.”

— Stanisław Leszczyński, King of Poland

In this chapter the systematic uncertainties associated with the measurement of $\Delta\Gamma_{K^+K^-}$ and the effective $B_s^0 \rightarrow K^+K^-$ lifetime are evaluated. A portion of the work described was performed in collaboration with researchers from CERN and University of Glasgow who were engaged in an absolute measurement of the $B_s^0 \rightarrow K^+K^-$ lifetime [76, 77]. In particular, Sections 7.2.1, 7.5, 7.6 and 7.7 received substantial contributions from our collaborators. The remaining sections are the result of independent work.

7.1 Fit Method and Acceptance Cancellation

As described in Section 6.2.2 extensive toy Monte Carlo simulation studies have demonstrated that the fit method is unbiased and that the proper time acceptance cancels to a high precision between $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow K^+\pi^-$. The mean of the pull of $\Delta\Gamma_{K^+K^-}$ from 10,000 toy experiments was found to be -0.0045 ± 0.0099 . The mean statistical uncertainty on $\Delta\Gamma_{K^+K^-}$ from these toys is 0.048 ps^{-1} and so a bias due to the fit and acceptance cancellation is excluded down to a level of $0.0099 \times 0.048 \text{ ps}^{-1} = 0.00048 \text{ ps}^{-1}$. Therefore, the combined systematic uncertainty for the fit and acceptance cancellation is 0.00048 ps^{-1} .

7.2 Contamination from $B \rightarrow h^+h^-$ Modes

Despite strong PID requirements being imposed in the selection there will inevitably be some level of contamination of $K^\pm\pi^\mp$ decay modes in the K^+K^- final state dataset and vice versa since no selection can be 100% efficient for rejecting background. Significant cross-contamination may alter the measured value of $\Delta\Gamma_{K^+K^-}$ and so it is important to evaluate the scale of any such contamination. Since Monte Carlo simulation of PID quantities does not currently agree with data, the data-driven approach described in [78] and [79] is used to estimate the $K - \pi$ mis-identification efficiency for $B \rightarrow h^+h^-$ decays (see Section 7.2.1). In Section 7.2.2 this result is used to estimate the level of contamination in the K^+K^- and $K^\pm\pi^\mp$ final states along with the resulting bias on the measured value of $\Delta\Gamma_{K^+K^-}$.

7.2.1 Estimation of $K - \pi$ Misidentification Efficiency

The PID selections described in Section 3.3.3.2 make requirements designed to reject kaons, pions, protons, muons and electrons. The most significant contamination from $B \rightarrow h^+h^-$ modes in the K^+K^- final state is likely to come from $B^0 \rightarrow K^+\pi^-$, $B^0 \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow K^+K^-$ (so far not observed) while contamination in the $K^\pm\pi^\mp$ final state will be dominated by $B_s^0 \rightarrow K^+K^-$ and $B^0 \rightarrow \pi^+\pi^-$. The level of contamination depends chiefly upon the $K - \pi$ separation power of the selection, specifically the requirements that kaon candidates have $\Delta\log\mathcal{L}_{K-\pi} > 8$ and pion candidates have $\Delta\log\mathcal{L}_{K-\pi} < -5$. It is therefore necessary to evaluate the efficiencies of these requirements for both kaons and pions in order to estimate the total level of cross-contamination.

To achieve this, pure samples of kaons and pions are required. These “calibration samples” are obtained from 2010 LHCb data. The pion calibration sample is a combination of pions from the decays of K_S^0 , D^* and Λ particles while kaons are obtained from ϕ and D^* decays. The $\Delta\log\mathcal{L}_{K-\pi}$ and momentum distributions of the kaon and pion calibration samples are shown in Figures 7.1 and 7.2 respectively.

The PID separation power for a given track is dependent upon its kinematical properties, particularly momentum, as well as on the number of interaction vertices in the event. Since the momentum distributions of the calibration samples differ from those of pions and kaons from B decays their $\Delta\log\mathcal{L}$ distributions are also different. As a result the calibration samples cannot be used to estimate the efficiency of the selection

for $B \rightarrow h^+h^-$ modes directly.

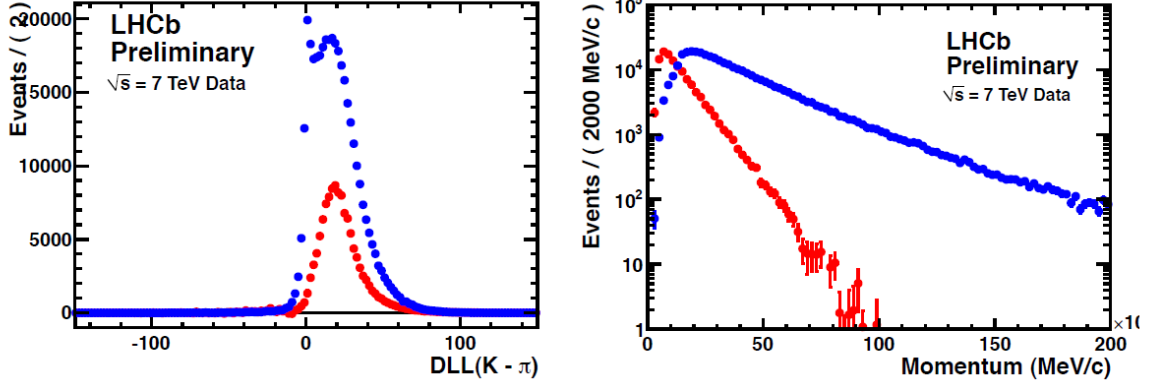


Figure 7.1: The $\Delta\log\mathcal{L}_{K-\pi}$ (left) and momentum (right) distributions for calibration sample kaons obtained from 2010 LHCb data [79]. Kaons from D decays are shown in blue and kaons from ϕ decays are shown in red.

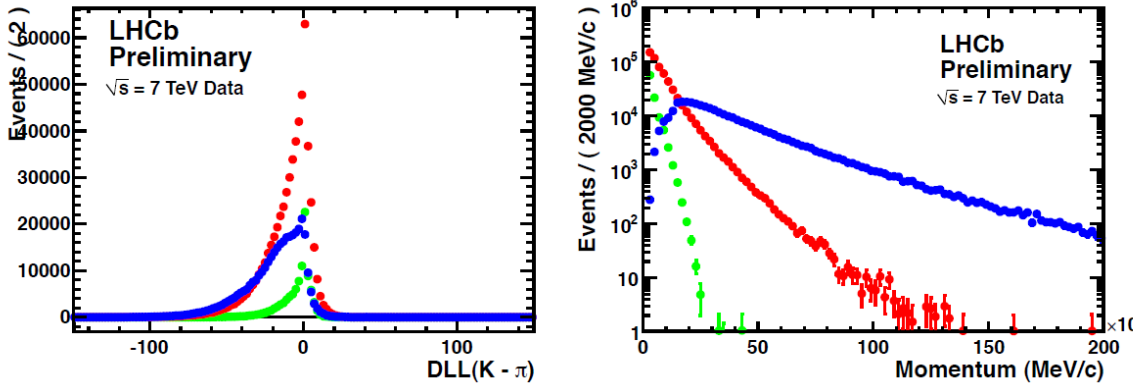


Figure 7.2: The $\Delta\log\mathcal{L}_{K-\pi}$ (left) and momentum (right) distributions for calibration sample pions obtained from 2010 LHCb data [79]. Pions from D decays are shown in blue, pions from K_S^0 decays are shown in red and pions from Λ decays are shown in green.

However, if the data is split into small regions of kinematic phase space, the $\Delta\log\mathcal{L}$ distributions for the calibration and $B \rightarrow h^+h^-$ samples will be the same. Using this fact, the $\Delta\log\mathcal{L}$ distributions for kaons and pions from $B \rightarrow h^+h^-$ decays can be reconstructed by re-weighting the calibration samples' $\Delta\log\mathcal{L}$ distributions. The procedure adopted is as follows:

1. The calibration samples are binned in momentum p , transverse momentum p_T and the number of interaction vertices in the event n_{PV} to produce an array of $\Delta\log\mathcal{L}$ distributions, one for each bin.

2. For a given bin the fraction of offline selected $B \rightarrow h^+h^-$ daughters (kaons or pions) that fall within that bin is calculated.
3. The binned $\Delta\log\mathcal{L}$ distributions from the calibration samples are weighted by these fractions and summed to produce a total $\Delta\log\mathcal{L}$ distribution that reflects the true form of $B \rightarrow h^+h^-$ $\Delta\log\mathcal{L}$ distribution.

This approach is illustrated by Figure 7.3 which shows how the $\Delta\log\mathcal{L}_{K-\pi}$ distribution for Monte Carlo calibration tracks changes after reweighting using $B^0 \rightarrow \pi^+\pi^-$ Monte Carlo simulated events. After the reweighting procedure the calibration distribution is in good agreement with that of the $B^0 \rightarrow \pi^+\pi^-$ events.

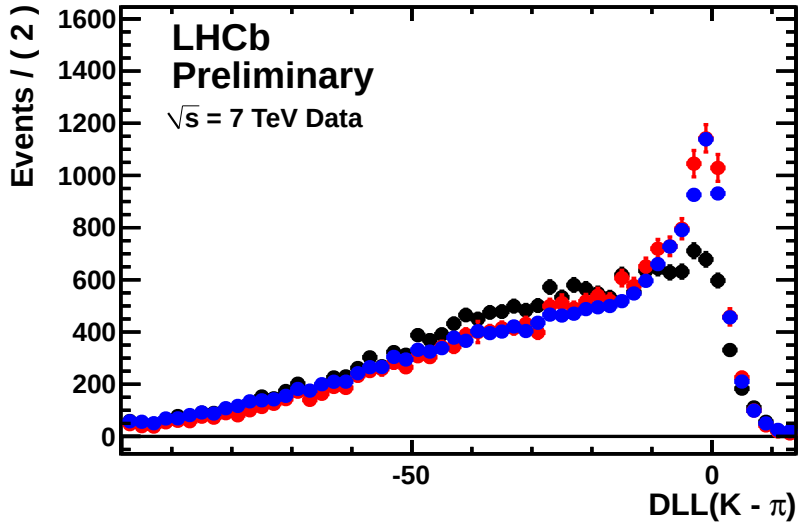


Figure 7.3: Comparison of the $\Delta\log\mathcal{L}_{K-\pi}$ distribution for simulated calibration tracks before re-weighting (black) and after re-weighting (red) [76]. The distribution for $B^0 \rightarrow \pi^+\pi^-$ simulation tracks is also shown (blue).

For this approach to be effective in data a suitable binning scheme must be found. This was done using the $B \rightarrow h^+h^-$ offline selected data and choosing bins such that there were approximately equal numbers of candidates in each bin. This was done to ensure a minimum number of candidates in each bin so that the reweighting procedure could give meaningful results. The binning scheme used had 8 p bins, 9 p_T bins and 4 n_{PV} bins.

The offline selected $B \rightarrow h^+h^-$ data sample was then used to re-weight the 2010 LHCb data calibration samples using this binning scheme. This produced estimates of

the $\Delta\log\mathcal{L}_{K-\pi}$ distributions for kaons and pions from $B \rightarrow h^+h^-$ decays. The efficiencies of the PID selection requirements for kaons and pions have been evaluated and are listed in Table 7.1.

PID Cut	Efficiency for kaons %	Efficiency for pions %
$\Delta\log\mathcal{L}_{K-\pi} > 8$	68.79 ± 0.18	1.472 ± 0.021
$\Delta\log\mathcal{L}_{K-\pi} < -5$	1.539 ± 0.021	69.56 ± 0.19

Table 7.1: Efficiency of the $\Delta\log\mathcal{L}_{K-\pi}$ cuts on pure samples of kaons and pions from data re-weighted to the $B \rightarrow h^+h^-$ dataset.

7.2.2 Effect of Contamination on the Measured Lifetime

Using the efficiencies for pions and kaons obtained from the re-weighting procedure, the selection efficiencies for K^+K^- , $K^\pm\pi^\mp$ and $\pi^+\pi^-$ final states can be determined. It is assumed that the value of $\Delta\log\mathcal{L}_{K-\pi}$ for one daughter is independent of the value for the other. In practice this is an approximation as the momenta of the two daughters are correlated and so the values of PID will also be related. The sample average efficiencies in Table 7.1 are then used to calculate the efficiencies for each final state and these are listed in Table 7.2.

	Efficiency %		
Final State	$B_{(s)}^0 \rightarrow K^\pm K^\mp$	$B_{(s)}^0 \rightarrow K^\pm \pi^\mp$	$B_{(s)}^0 \rightarrow \pi^\pm \pi^\mp$
K^+K^-	47.32 ± 0.25	1.013 ± 0.015	0.0217 ± 0.0006
$K^\pm\pi^\mp$	1.059 ± 0.015	47.85 ± 0.18	1.024 ± 0.015

Table 7.2: Efficiency of the K^+K^- and $K^\pm\pi^\mp$ final state PID requirements for all $B \rightarrow h^+h^-$ decay modes. A particle is identified as a kaon if $\Delta\log\mathcal{L}_{K-\pi} > 8$ and as a pion if $\Delta\log\mathcal{L}_{K-\pi} < -5$.

In order to estimate the levels of contamination the relative abundance of each $B \rightarrow h^+h^-$ mode must be determined. These are calculated from the hadronization fractions for $b \rightarrow B_{(s)}$ and the branching ratios of each decay from [11] and are listed in Table 3.7. Combining this information with the results of the time-integrated mass fits in Section

6.3 and the selection efficiencies the expected yields of each $B \rightarrow h^+h^-$ mode in each final state selection can be calculated. The estimated yields of each $B \rightarrow h^+h^-$ mode in each final state selected data sample are listed in Table 7.3.

Final State	Number of Candidates	
	K^+K^-	$K^\pm\pi^\mp$
$B_s^0 \rightarrow K^+K^-$	276	6
$B_s^0 \rightarrow \pi^+K^-$	1	53
$B^0 \rightarrow K^+\pi^-$	17	800
$B^0 \rightarrow \pi^+\pi^-$	0	5
$B^0 \rightarrow K^+K^-$	6	0
Total	300	864

Table 7.3: Estimated yields for each $B \rightarrow h^+h^-$ decay mode in each final state dataset.

The impact of this level of contamination on the measured value of $\Delta\Gamma_{K^+K^-}$ can now be assessed using the toy Monte Carlo model. The only significant contamination comes from the channels $B^0 \rightarrow K^+\pi^-$ and $B^0 \rightarrow K^+K^-$ in the K^+K^- final state. In principle the bias due to contamination will vary depending upon the measured value of $\Delta\Gamma_{K^+K^-}$. A larger value of $|\Delta\Gamma_{K^+K^-}|$ should produce a larger bias as the proper time distribution of the contamination will differ more significantly from that of $B_s^0 \rightarrow K^+K^-$. The bias is evaluated for three choices of the effective $B_s^0 \rightarrow K^+K^-$ lifetime: 1.372 ps, 1.472 ps and 1.572 ps. These correspond to values of $\Delta\Gamma_{K^+K^-}$ of approximately 0.0731, 0.0236 and -0.0196 respectively. 1.472 ps is close to the value measured in data and the high and low values are chosen to be 1σ from the central value.

Using the same configuration of the toy model described in Section 6.2.2, the selection described in Tables 5.1 and 5.2 and fit procedure described in Section 6.1.2, 5,000 experiments are performed with the level of $B^0 \rightarrow K^+\pi^-$ and $B^0 \rightarrow K^+K^-$ contamination listed in Table 7.3 for each value of $\tau_{K^+K^-}$.

The pull distributions for the measured value of $\Delta\Gamma_{K^+K^-}$ are shown in Figure 7.4 and the mean of the pull distributions are listed in Table 7.4. The maximum observed bias in the pull mean is 0.097 which is interpreted as a systematic uncertainty on the measured value of $\Delta\Gamma_{K^+K^-}$ of 0.0049 ps^{-1} .

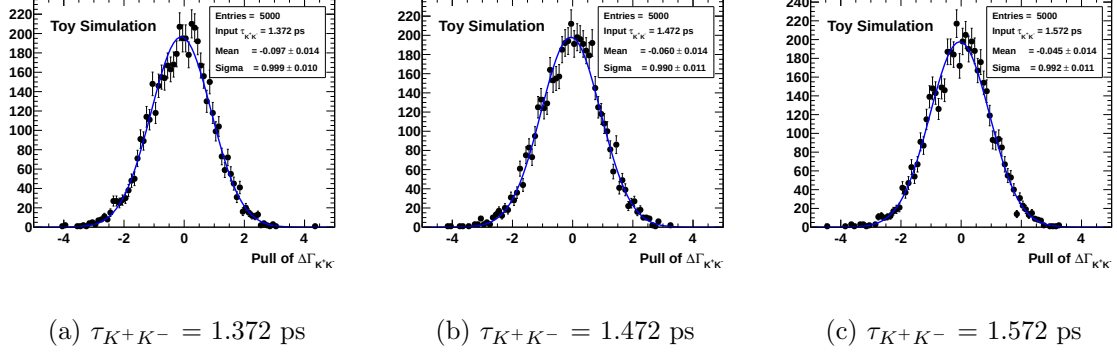


Figure 7.4: Pull distributions of $\Delta\Gamma_{K+K^-}$ from toy studies including contamination from $B \rightarrow h^+h^-$ modes.

τ_{K+K^-} / ps	$\Delta\Gamma_{K+K^-} / \text{ps}^{-1}$	Pull mean	Pull width
1.372	0.0731	-0.097 ± 0.014	0.999 ± 0.010
1.472	0.0236	-0.060 ± 0.014	0.990 ± 0.011
1.572	-0.0196	-0.045 ± 0.014	0.992 ± 0.011

Table 7.4: Means and widths of the pulls of $\Delta\Gamma_{K+K^-}$ from toy Monte Carlo experiments performed for different values of $\Delta\Gamma_{K+K^-}$ with contamination from $B \rightarrow h^+h^-$ modes.

7.3 Contamination from Partially Reconstructed Background

There is a possibility that partially reconstructed decay modes may form a component of the background on the low-mass side of the K^+K^- and $K^\pm\pi^\mp$ invariant mass distributions. Since $\Delta\Gamma_{K+K^-}$ is extracted using mass fits in bins of proper time, this contamination may alter the measured value. The most significant partially reconstructed backgrounds arise from three body decays of B mesons such as $B_s^0 \rightarrow K^- \rho^+ (\pi^+ \pi^0)$ or $B^+ \rightarrow \pi^+ \pi^+ \pi^-$ where only two of the daughters are used to reconstruct the B candidate.

A minimum mass cut of 5,150 MeV/ c^2 is applied in the fit specifically with the intention of excluding this kind of background. However, there is the potential that a small level of contamination may leak under the B peak due to the high-mass tail of the partially reconstructed invariant mass spectrum. The presence of significant partially reconstructed background is determined by extending the range of the mass fit in data

from 5150 MeV/c^2 to 5,000 MeV/c^2 for both K^+K^- and $K^\pm\pi^\mp$. A significant change in the fitted gradient of the combinatorial background PDF indicates a significant level of partially reconstructed background.

The fitted gradients before and after the relaxation of the minimum mass cut are listed in Table 7.5. No change in the gradient of the K^+K^- combinatorial background mass PDF is observed, demonstrating that there is no significant partially reconstructed background in the K^+K^- spectrum. This conclusion is confirmed upon inspection of Figure 7.5 which shows the K^+K^- mass fit extended down to 5,000 MeV/c^2 , where no low-mass shoulder due to partially reconstructed background is observed. However, in the $K^\pm\pi^\mp$ case a 2σ change in the gradient is observed, indicating the presence of such a background.

Gradient	mass > 5,150 MeV/c^2	mass > 5,000 MeV/c^2
$c_1^{K\pi}$	$(-1.61 \pm 0.03) \times 10^{-4} (\text{MeV}/c^2)^{-1}$	$(-1.68 \pm 0.01) \times 10^{-4} (\text{MeV}/c^2)^{-1}$
c_1^{KK}	$(-1.66 \pm 0.03) \times 10^{-4} (\text{MeV}/c^2)^{-1}$	$(-1.66 \pm 0.02) \times 10^{-4} (\text{MeV}/c^2)^{-1}$

Table 7.5: The fitted gradient of the combinatorial background PDF for K^+K^- and $K^\pm\pi^\mp$ final states before and after the relaxation of the minimum mass cut.

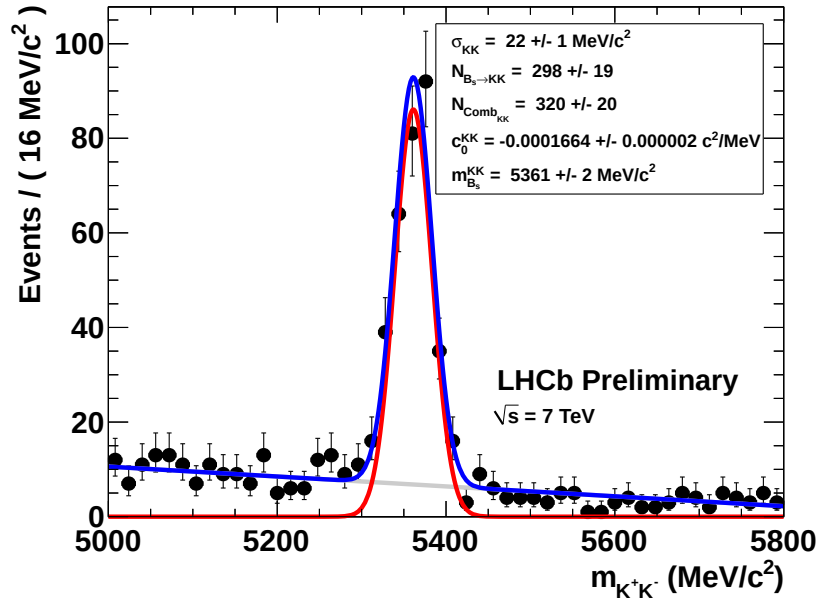


Figure 7.5: Fit to the K^+K^- mass spectrum for 2010 LHCb data with a minimum accepted mass of 5,000 MeV/c^2 .

In order to estimate the effect of such contamination on $\Delta\Gamma_{K^+K^-}$ a model for the partially reconstructed background must be established to be used in toy Monte Carlo studies. A realistic toy model (such as the one used to generate $B \rightarrow h^+h^-$ candidates) is not appropriate in this case as the background is comprised of a large number of overlapping modes which would be impractical to simulate fully. Instead the approach used in the toy studies to simulate combinatorial background (see Section 4.2.3) is adopted and the partially reconstructed background candidates are generated from data-driven mass and proper time PDFs.

The PDF used to fit the partially reconstructed mass distribution is a “Double Crystal Ball”. This is composed of a Gaussian core with polynomial tails on the low and high sides. The parameters of this function are fixed to those obtained in a fit to partially reconstructed 2010 LHCb Monte Carlo $B_s^0 \rightarrow K^- \rho^+ (\pi^+ \pi^0)$ candidates. This function is then added to the $K^\pm \pi^\mp$ mass fit to the 2010 data set and the mean of the Double Crystal Ball allowed to float freely. The resulting fit is shown in Figure 7.6 where the partially reconstructed background is visible as a bump on the lower side of the B peak with an estimated yield of 146 ± 29 candidates. The fit results in a value of $c_1^{K\pi} = (-1.61 \pm 0.03) \times 10^{-4} (\text{MeV}/c^2)^{-1}$ which is consistent with the value obtained before the relaxation of the minimum mass cut. This demonstrates that the partially reconstructed background has been accounted for in the fit.

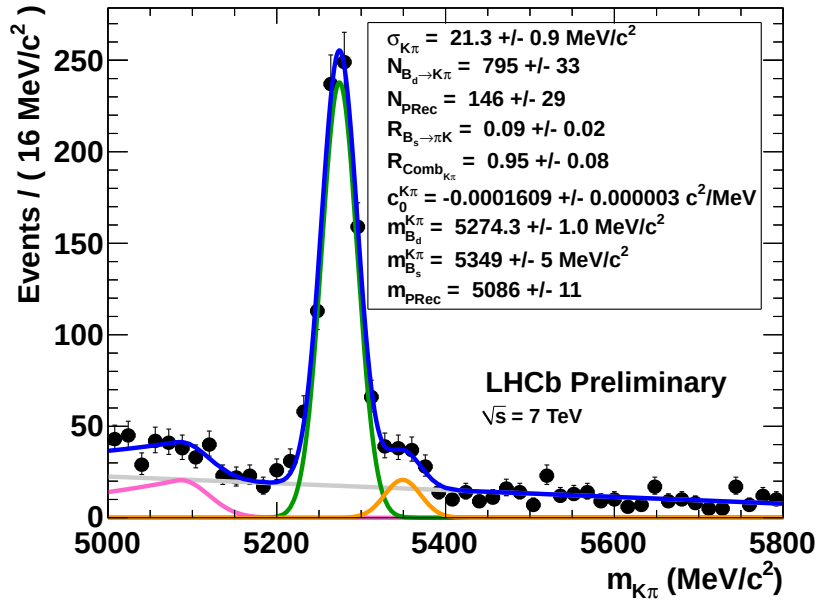


Figure 7.6: Fit to the $K^\pm \pi^\mp$ mass spectrum for 2010 LHCb data including partially reconstructed background.

The proper time distribution used is similar to that of the combinatorial background proper time distribution:

$$PDF_{Comb}(t) = [1.0 - \text{erf}((A - t)/B)] \times [f_1 e^{-t/\tau_1} + f_2 e^{-t/\tau_2} + (1 - f_1 - f_2) e^{-t/\tau_3}] \quad (7.1)$$

where $[1.0 - \text{erf}((A - t)/B)]$ is the acceptance function and the three exponential functions simulate different possible contributions to the background from B_s^0 , B^0 and $B^\pm$ mesons. The values of the parameters used are listed in Table 7.6.

Parameter	Default value	Comment
A	0.7 ps	Acceptance turn-on
B	0.08 ps	Acceptance width
f_1	1/3	Mode 1 fraction
f_2	1/3	Mode 2 fraction
τ_1	1.4 ps	Mode 1 lifetime
τ_2	1.5 ps	Mode 2 lifetime
τ_3	1.6 ps	Mode 3 lifetime

Table 7.6: Default values of the parameters used in the toy Monte Carlo generator for partially reconstructed background.

Taking the above proper time distribution and the mass distribution fitted to data 10,000 experiments were performed using exactly the same arrangement as described in Section 6.2.2 but with an additional 146 partially reconstructed candidates per experiment. The resulting pull distribution of $\Delta\Gamma_{K^+K^-}$ is then fitted with a Gaussian distribution in order to evaluate the size of any bias. This is shown in Figure 7.7 where there is evidence of a bias to the pull mean of -0.023 ± 0.010 which translates to a bias of $\Delta\Gamma_{K^+K^-}$ of 0.0011 ps^{-1} which is taken as the systematic uncertainty due to partially reconstructed background.

7.4 Combinatorial Background

A priori there is no analytical function which describes the mass distribution of the combinatorial background. For this analysis a first order polynomial was chosen as the

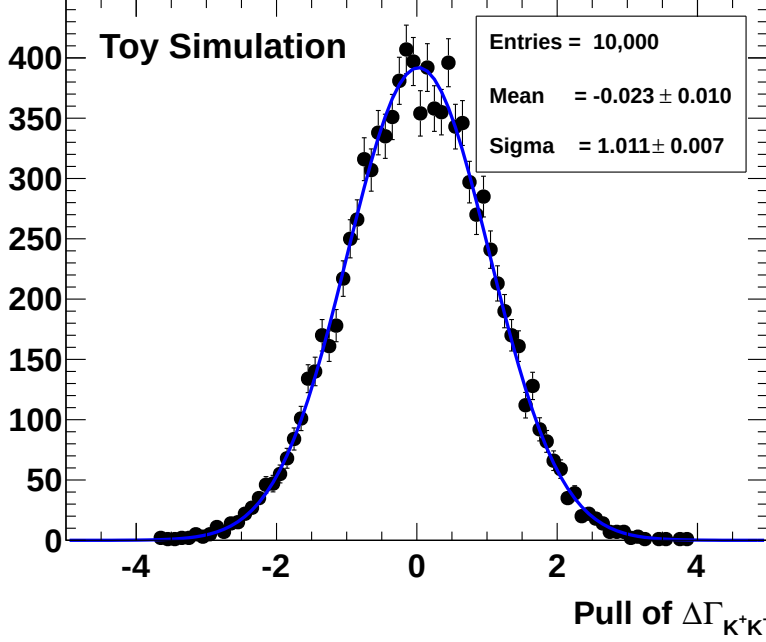


Figure 7.7: The pull of $\Delta\Gamma_{K^+K^-}$ from 10,000 toy Monte Carlo experiments with Gaussian fit including the effect of partially reconstructed background.

simplest function that provided a good fit. The systematic uncertainty on $\Delta\Gamma_{K^+K^-}$ due to this choice is assessed in this section. The toy Monte Carlo model uses the same function to generate combinatorial background as the one fitted to data. To estimate the size of the systematic uncertainty, combinatorial background candidates are generated using an exponential function but the fit is performed with a first order polynomial. The mass PDF used to generate the combinatorial background is then

$$PDF_{bkg}^{gen}(m) = Ne^{km} \quad (7.2)$$

where N is the normalisation, k is the decay constant and m is the invariant mass. Fits to 2010 data give $k = -0.00209 \text{ (MeV}/c^2)^{-1}$ for K^+K^- background and $k = -0.00155 \text{ (MeV}/c^2)^{-1}$ for $K^\pm\pi^\mp$ background.

10,000 toy experiments are performed using the same setup as described in Section 6.2.2 except generating the combinatorial background using the above exponential mass PDF. The fit is still performed using a first order polynomial. The resulting pull distribution along with Gaussian fit is shown Figure 7.8 where a bias on the mean of -0.034 ± 0.010 is observed. This translates to a systematic uncertainty on $\Delta\Gamma_{K^+K^-}$ of 0.0016 ps^{-1} .

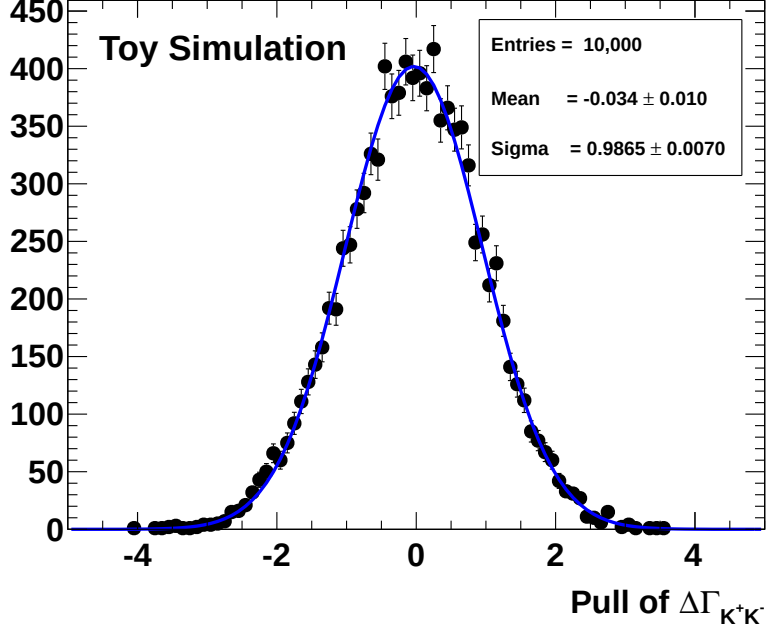


Figure 7.8: The pull of $\Delta\Gamma_{K^+K^-}$ from 10,000 toy Monte Carlo experiments with Gaussian fit including the effect of mis-modelling the combinatorial background.

7.5 Primary Vertex Association

In events with multiple primary interaction vertices there is the potential for the B^0 candidate to be associated with the wrong primary vertex and consequently the proper decay time to be mismeasured. A high precision evaluation of this effect has been performed using $D \rightarrow h^+h^-$ decays. The D^0 and $\bar{D}^0$ lifetimes are measured for events containing one, two and three primary vertices from LHCb data following the method described in [69]. Figure 7.9 shows the measured lifetimes as a function of the number of primary vertices.

The difference between the measured D^0 ($\bar{D}^0$) lifetime for one primary vertex and the full dataset is approximately 0.8 fs. Any effect is likely to be due to an absolute scaling of the measured distance of flight. Hence this value should be scaled by a factor of $\frac{m_B}{\langle p_B \rangle} / \frac{m_D}{\langle p_D \rangle} \approx 1.5$ to give a systematic uncertainty of 1.2 fs on $\tau_{K^+K^-}$. This translates to a systematic uncertainty of 0.00054 ps^{-1} on $\Delta\Gamma_{K^+K^-}$.

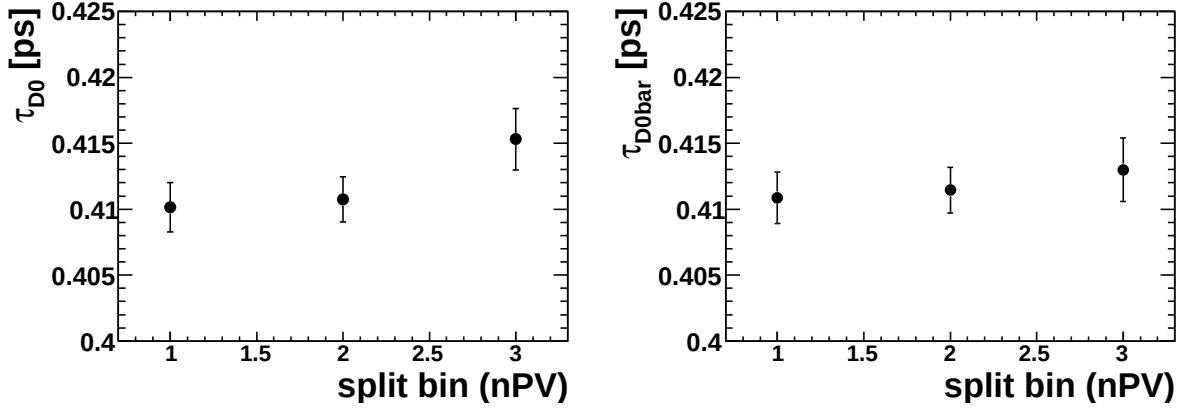


Figure 7.9: The fitted lifetime (τ_{D^0}) for D^0 (left) and $\bar{D}^0$ (right) as a function of the number of primary vertices (nPV) [80].

7.6 Uncertainty on Length Scale

The effect of misalignments in the vertex detector on measured lifetimes has been studied in [71]. A sample of 20,000 LHCb Monte Carlo simulated $B_s^0 \rightarrow K^+ K^-$ candidates was reconstructed using a description of the VELO detectors in which the positions of the modules were misaligned by distances sampled randomly from a Gaussian distribution with a width equal to the uncertainty on the measured positions of the VELO modules. It was found that random VELO misalignments have a negligible effect on the measured $B_s^0 \rightarrow K^+ K^-$ lifetime. Furthermore, in [81] the uncertainty on the z -positions of the VELO modules was found to have a maximum effect of 0.04% on B lifetime measurements.

However, in [82] it was found that if misalignments conspired to modify the VELO z -scale this could have a measurable effect on B lifetimes. This is since the measured proper decay time is calculated from the distance between primary and secondary vertices which are found by the VELO. In [81] this effect is limited to be less than 5×10^{-5} which has a negligible effect on B lifetime measurements.

A further bias may arise due to the uncertainty on the distance between the VELO and the tracking stations. Momentum and mass measurements are affected by a mis-measurement of this distance and so, therefore, are proper time measurements. A 2 mm discrepancy has been found in [83] between the position of the TT from the survey and extrapolated VELO tracks. This difference is conservatively assigned to the effect that would produce the largest systematic shift: a change in the VELO z -scale. This gives

rise to a 0.1% bias on measured B lifetimes which translates to systematic uncertainties of 1.5 fs on $\tau_{K^+K^-}$ and 0.00068 ps^{-1} on $\Delta\Gamma_{K^+K^-}$.

7.7 The Effect of a $B_s^0 - \bar{B}_s^0$ Production Asymmetry

Equation 1.51 in Section 1.2.1 assumes that B_s^0 and $\bar{B}_s^0$ mesons are produced in equal quantities at LHCb. However, since the LHC collides protons the production of hadrons versus anti-hadrons may be asymmetric. The production asymmetry is defined as

$$A_p \equiv \frac{R_{B_s^0} - R_{\bar{B}_s^0}}{R_{B_s^0} + R_{\bar{B}_s^0}} \quad (7.3)$$

where $R_{B_s^0}$ and $R_{\bar{B}_s^0}$ are the rates of B_s^0 and $\bar{B}_s^0$ production. The production asymmetry for B_s^0 mesons has yet to be measured at LHCb however the scale may be inferred from the B^0 production asymmetry which is measured as $0.024 \pm 0.013 \text{ (stat)} \pm 0.010 \text{ (syst)}$ as described in [64]. Naïvely the B_s^0 production asymmetry should be smaller since while the B^0 shares a valence d quark with the proton and the $\bar{B}^0$ does not, neither the B_s^0 or $\bar{B}_s^0$ share valence quarks with the proton. However, this is not necessarily a safe assumption since flavour conservation demands that b and $\bar{b}$ quarks be produced in equal quantities and the preponderance of $\bar{b}$ over b quarks in the B^0 system must be accounted for by opposite sign production asymmetries in other particles.

However, in the absence of a direct measurement a reasonable assumption is to take the B_s^0 production asymmetry as equal in magnitude to the B^0 asymmetry. The presence of such an asymmetry will alter the measured proper decay time distribution of $B_s^0 \rightarrow K^+K^-$ and have an effect on the measurement of the effective lifetime $\tau_{K^+K^-}$. The effect of A_p is calculated in what follows. Starting from Equations 1.49 and 1.50

$$\begin{aligned} \Gamma(B_s^0(t) \rightarrow f) &= \frac{1}{2} N_f |A_f|^2 (1 + |\lambda_f|^2) e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta\Gamma_s t}{2} + \mathcal{A}_{CP}^{dir} \cos(\Delta m_s t) \right. \\ &\quad \left. + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_s t}{2} + \mathcal{A}_{CP}^{mix} \sin(\Delta m_s t) \right\}, \end{aligned} \quad (7.4)$$

$$\begin{aligned} \Gamma(\bar{B}_s^0(t) \rightarrow f) &= \frac{1}{2} N_f |A_f|^2 (1 + a)(1 + |\lambda_f|^2) e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta\Gamma_s t}{2} - \mathcal{A}_{CP}^{dir} \cos(\Delta m_s t) \right. \\ &\quad \left. + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_s t}{2} - \mathcal{A}_{CP}^{mix} \sin(\Delta m_s t) \right\} \end{aligned} \quad (7.5)$$

the total decay rate including the effect of production asymmetry is

$$\begin{aligned}
\Gamma[f, t] &= \left(\frac{1 + A_p}{2} \right) \Gamma(B_s^0(t) \rightarrow f) + \left(\frac{1 - A_p}{2} \right) \Gamma(\bar{B}_s^0(t) \rightarrow f) \\
&= \frac{1}{2} N_f |A_f|^2 (1 + |\lambda_f|^2) e^{-\Gamma_s t} \left\{ \cosh \frac{\Delta\Gamma_s t}{2} + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_s t}{2} \right. \\
&\quad \left. + A_p [\mathcal{A}_{CP}^{dir} \cos(\Delta m_s t) + \mathcal{A}_{CP}^{mix} \sin(\Delta m_s t)] \right\} + \mathcal{O}(a). \tag{7.6}
\end{aligned}$$

Using $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ and neglecting terms of order a , this becomes

$$\begin{aligned}
\Gamma[f, t] &\simeq \frac{1}{4} N_f |A_f|^2 (1 + |\lambda_f|^2) \left\{ (1 - \mathcal{A}_{\Delta\Gamma}) e^{-\Gamma_L t} + (1 + \mathcal{A}_{\Delta\Gamma}) e^{-\Gamma_H t} \right. \\
&\quad \left. + 2A_p e^{-\Gamma_s t} [\mathcal{A}_{CP}^{dir} \cos(\Delta m_s t) + \mathcal{A}_{CP}^{mix} \sin(\Delta m_s t)] \right\}. \tag{7.7}
\end{aligned}$$

Inspecting Equation 7.7 the production asymmetry introduces an extra oscillatory term and by setting $A_p = 0$ the usual double exponential form of the proper decay time distribution is recovered.

The effect of this extra production asymmetry term on the measured effective lifetime can now be calculated. Ignoring the effects of proper time resolution and acceptance the effective lifetime is simply

$$\tau_{K^+K^-} = \frac{\int_0^\infty t \cdot \Gamma[KK, t] dt}{\int_0^\infty \Gamma[KK, t] dt}. \tag{7.8}$$

Using the results from integration by parts

$$\int_0^\infty e^{-\Gamma_s t} \cos(\Delta m_s t) dt = \frac{\Gamma_s}{\Delta m_s^2 + \Gamma_s^2} \tag{7.9}$$

$$\int_0^\infty e^{-\Gamma_s t} \sin(\Delta m_s t) dt = \frac{\Delta m_s}{\Delta m_s^2 + \Gamma_s^2} \tag{7.10}$$

$$\int_0^\infty t \cdot e^{-\Gamma_s t} dt = \frac{1}{\Gamma_s^2} \tag{7.11}$$

$$\int_0^\infty t \cdot e^{-\Gamma_s t} \cos(\Delta m_s t) dt = \frac{\Gamma_s^2 - \Delta m_s^2}{(\Delta m_s^2 + \Gamma_s^2)^2} \tag{7.12}$$

$$\int_0^\infty t \cdot e^{-\Gamma_s t} \sin(\Delta m_s t) dt = \frac{2\Gamma_s \Delta m_s}{(\Delta m_s^2 + \Gamma_s^2)^2} \tag{7.13}$$

and defining $N' \equiv \frac{1}{4}N_f|A_f|^2(1 + |\lambda_f|^2)$ it can be shown that

$$\int_0^\infty t \cdot \Gamma[f, t] dt = N' \left\{ \frac{1 - \mathcal{A}_{\Delta\Gamma}}{\Gamma_L^2} + \frac{1 + \mathcal{A}_{\Delta\Gamma}}{\Gamma_H^2} + 2A_p \left[\mathcal{A}_{CP}^{dir} \frac{\Gamma_s^2 - \Delta m_s^2}{(\Delta m_s^2 + \Gamma_s^2)^2} + \mathcal{A}_{CP}^{mix} \frac{2\Gamma_s \Delta m_s}{(\Delta m_s^2 + \Gamma_s^2)^2} \right] \right\} \quad (7.14)$$

and

$$\int_0^\infty \Gamma[f, t] dt = N' \left\{ \frac{1 - \mathcal{A}_{\Delta\Gamma}}{\Gamma_L} + \frac{1 + \mathcal{A}_{\Delta\Gamma}}{\Gamma_H} + 2A_p \left[\mathcal{A}_{CP}^{dir} \frac{\Gamma_s}{\Delta m_s^2 + \Gamma_s^2} + \mathcal{A}_{CP}^{mix} \frac{\Delta m_s}{\Delta m_s^2 + \Gamma_s^2} \right] \right\}. \quad (7.15)$$

The effective lifetime in the presence of a production asymmetry may now be calculated. In order to obtain an upper limit on the size of any such effect we choose $A_p = 0.040$ (1σ larger the measured value at LHCb) and the extreme value $\mathcal{A}_{\Delta\Gamma} = -0.6$. Since $(\mathcal{A}_{\Delta\Gamma})^2 + (\mathcal{A}_{CP}^{dir})^2 + (\mathcal{A}_{CP}^{mix})^2 = 1$ this choice requires that $(\mathcal{A}_{CP}^{dir})^2 + (\mathcal{A}_{CP}^{mix})^2 = 0.64$. It is assumed that $\mathcal{A}_{CP}^{dir} = \mathcal{A}_{CP}^{mix} = 0.57$. Finally the PDG [11] values of $\Gamma_s = 0.702 \text{ ps}^{-1}$, $\Delta\Gamma_s = 0.062 \text{ ps}^{-1}$ and $\Delta m_s = 17.77 \text{ ps}^{-1}$ are used.

The effective lifetime in the presence of a production asymmetry is found to be 1.38992 ps. Setting $A_p = 0$ this becomes 1.39130 ps. The difference is 0.0014 ps and this is assigned as the systematic uncertainty on the measured lifetime. This corresponds to a systematic uncertainty on $\Delta\Gamma_{K^+K^-}$ of 0.00063 ps^{-1} .

7.8 The Effect of Proper Time Acceptance on the Mix of Light and Heavy Mass Eigenstates

While the $B_s^0 \rightarrow K^+K^-$ lifetime is expected to be dominated by the decay of the light mass eigenstate there may also be a contribution from the heavy mass eigenstate:

$$\Gamma[f, t] = N_f \frac{|A_f|^2}{2} (1 + |\lambda_f|^2) \left[(1 - \mathcal{A}_{\Delta\Gamma}) e^{-\Gamma_L t} + (1 + \mathcal{A}_{\Delta\Gamma}) e^{-\Gamma_H t} \right]. \quad (7.16)$$

As discussed in Section 1.3 when fitted with a single exponential we obtain the effective lifetime

$$\tau_{K^+K^-}^{-1} = \frac{A/\Gamma_L + B/\Gamma_H}{A/\Gamma_L^2 + B/\Gamma_H^2}. \quad (7.17)$$

Since the trigger and offline selections tend to reject short-lived particles the light mass component will be diminished in the data compared to the heavy mass component. This may produce a small bias in the measurement of $\Delta\Gamma_{K^+K^-}$ and hence the effective $B_s^0 \rightarrow K^+K^-$ lifetime. In order to estimate the size of such an effect, a check has been performed using a toy Monte Carlo simulation where a single $B_s^0 \rightarrow K^+K^-$ decay mode is replaced with the light and heavy decay modes.

The values $\Delta\Gamma_s = 0.1 \text{ ps}^{-1}$ and $A_{\Delta\Gamma_s} = -0.6$ are used for this test. This is a very conservative choice as the Standard Model predicts a value for $A_{\Delta\Gamma_s}$ of -0.97. The relative fractions of the light and heavy eigenstates are then $(1 - \mathcal{A}_{\Delta\Gamma})/2 = 0.8$ and $(1 + \mathcal{A}_{\Delta\Gamma})/2 = 0.2$ respectively and the light and heavy lifetimes equal to $1/\Gamma_L$ and $1/\Gamma_H$. 10,000 toy experiments were performed, generating the same number of candidates as observed in data and imposing the selection. The resulting pull of $\Delta\Gamma_{K^+K^-}$ is shown in Figure 7.10.

The bias in the mean of the pull distribution is seen to be 0.023 ± 0.010 and so an uncertainty of 0.0011 ps^{-1} on the interpretation of $\Delta\Gamma_{K^+K^-}$ is ascribed. This corresponds to an uncertainty of 0.0024 ps on $\tau_{K^+K^-}$. This is described as a “model interpretation” uncertainty as it does not represent a failure of the acceptance correction and is important only when interpreting $\tau_{K^+K^-}$ in terms of Equation 7.17.

7.9 Combined Systematic Uncertainty

Each source of systematic uncertainty is listed in Table 7.7. Assuming independence and adding in quadrature the total systematic uncertainty on $\Delta\Gamma_{K^+K^-}$ is found to be $\sigma(\text{syst}) = \pm 0.0054 \text{ ps}^{-1}$. The table also lists the systematic uncertainties on the effective $B_s^0 \rightarrow K^+K^-$ lifetime $\tau_{K^+K^-}$ if $\Delta\Gamma_{K^+K^-}$ is interpreted using the PDG [11] value of the mean B^0 lifetime, $\tau_B = 1.519 \pm 0.007 \text{ ps}$. These uncertainties were calculated using the

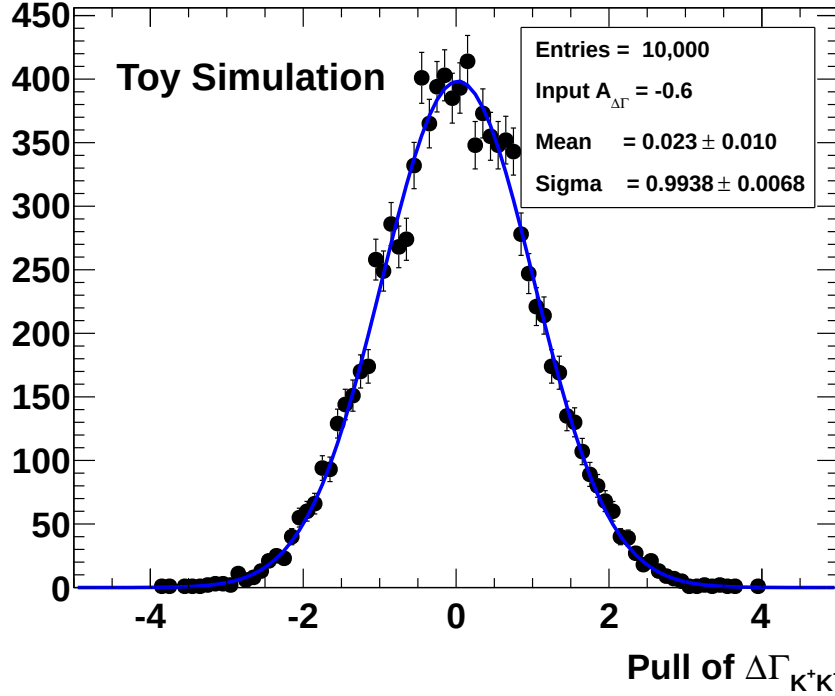


Figure 7.10: Pull of $\Delta\Gamma_{K^+K^-}$ fitted with a Gaussian function from 10,000 toy Monte Carlo experiments performed with $\mathcal{A}_{\Delta\Gamma} = -0.6$.

propagation of uncertainty formula:

$$\sigma_f^2 = \left(\frac{\partial f}{\partial X} \right)^2 \sigma_X^2 + \left(\frac{\partial f}{\partial Y} \right)^2 \sigma_Y^2 + \dots \quad (7.18)$$

such that

$$\sigma_{\tau_{K^+K^-}} = \sigma_{\Delta\Gamma_{K^+K^-}} \tau_{K^+K^-}^2. \quad (7.19)$$

The “model interpretation bias” is the effect due to the unknown mix of light and heavy mass eigenstates described in Section 7.8. The “ B^0 Lifetime Uncertainty”, the systematic uncertainty on $\tau_{K^+K^-}$ due to the statistical uncertainty on the mean B^0 lifetime, is also included where the uncertainties are related by

$$\sigma_{\tau_{K^+K^-}} = \frac{\tau_{K^+K^-}}{\tau_B} \sigma_{\tau_B}. \quad (7.20)$$

The dominant sources of systematic uncertainty are due to contamination from $B \rightarrow h^+h^-$ modes in the K^+K^- mass window, uncertainty in the modelling of the combinatorial background and contamination from partially reconstructed background. However,

the overall systematic uncertainty on $\Delta\Gamma_{K^+K^-}$ is well below the level of statistical uncertainty on the measurement. Many of these systematic uncertainties will be reduced with the larger 2011 dataset accompanied by more detailed studies of these effects.

Source of uncertainty	$\Delta\Gamma_{K^+K^-}$ Uncertainty / ps^{-1}	$\tau_{K^+K^-}$ Uncertainty / ps
Fit and Acceptance	0.00048	0.0011
$B \rightarrow h^+h^-$ Contamination	0.0049	0.011
Partially Reco. Background	0.0011	0.0024
Combinatorial Background	0.0016	0.0035
Primary Vertex Association	0.00054	0.0012
Length Scale	0.00068	0.0015
Production Asymmetry	0.00061	0.0014
Total (added in quadrature)	0.0054	0.012
Model Interpretation Bias	0.0011	0.0024
B^0 Lifetime Uncertainty	-	0.0069

Table 7.7: Sources of systematic uncertainty on the measurements of $\Delta\Gamma_{K^+K^-}$ and $\tau_{K^+K^-}$.

Chapter 8

Conclusions

“Q: How do you know that an elephant has been in your fridge?”

“A: Footprints in the butter.”

The field of particle physics is at a crossroads in its development. The Standard Model, the bedrock of particle theory for nearly half a century, is under assault from a new generation of experiments at the Large Hadron Collider. Though arguably the most successful theoretical framework ever developed, few believe that the Standard Model is the final word. The Higgs has yet to make itself known to experimenters, and without it the Standard Model cannot continue in its current form. Theoretical calculations at high energy and observations from astronomers leave questions that the theory fails to answer and the long search for a quantum theory of gravity goes on.

The new theories devised to address the Standard Model’s apparent shortcomings predict new phenomena and fundamental particles at an energy range above the reach of previous experiments. The LHC was constructed to find the Higgs and to seek out evidence of this “new physics”. So far the Standard Model has stood firm and to date there is no convincing evidence of new physics effects. More troubling perhaps, there is no convincing evidence of the Higgs either.

There are two approaches to find new physics if it is out there to be discovered. “How do you know that an elephant has been in your fridge?” Well, either you find the elephant, or as the punchline goes, you look for footprints in the butter. The LHCb experiment is designed to do the latter; to look for footprints left by new particles on Standard Model processes, in particular in the decays of B mesons.

The $B_s^0 \rightarrow K^+K^-$ decay is one of a number of promising channels in which to find these signatures. New physics is predicted to alter the $B_s^0 \rightarrow K^+K^-$ lifetime from the Standard Model prediction. In this dissertation a measurement of the $B_s^0 \rightarrow K^+K^-$ lifetime relative to the better known B^0 lifetime was presented and found to be

$$\Delta\Gamma_{K^+K^-} = 0.013 \pm 0.045(\text{stat}) \pm 0.005(\text{syst}) \pm 0.001(\text{model}) \text{ ps}^{-1} \quad (8.1)$$

where $\Delta\Gamma_{K^+K^-} \equiv 1/\tau_{K^+K^-} - 1/\tau_{B \rightarrow K\pi}$, $\tau_{K^+K^-}$ is the effective $B_s^0 \rightarrow K^+K^-$ lifetime and $\tau_{B \rightarrow K\pi}$ is the $B^0 \rightarrow K^+\pi^-$ lifetime. Taking the $B^0 \rightarrow K^+\pi^-$ lifetime as equal to the mean B^0 lifetime which is measured as [11]

$$\tau_B = 1.519 \pm 0.007 \text{ ps} \quad (8.2)$$

the effective $B_s^0 \rightarrow K^+K^-$ lifetime is measured as

$$\tau_{K^+K^-} = 1.490 \pm 0.100(\text{stat}) \pm 0.012(\text{syst}) \pm 0.002(\text{model}) \pm 0.007(\text{input}) \text{ ps.} \quad (8.3)$$

This is in agreement with the CDF measurement [18, 19]

$$\tau_{K^+K^-} = 1.53 \pm 0.18(\text{stat}) \pm 0.02(\text{syst})\text{ps.} \quad (8.4)$$

It also agrees with the absolute measurement of the effective lifetime made at LHCb using the 2010 dataset [76, 77]

$$\tau_{K^+K^-} = 1.440 \pm 0.096(\text{stat}) \pm 0.008(\text{syst}) \pm 0.003(\text{model}) \text{ ps.} \quad (8.5)$$

The statistical uncertainties of these two measurements are correlated as they share a significant proportion of events. The result is also in agreement with the Standard Model prediction [15]

$$\tau_{K^+K^-}|_{SM} = (1.390 \pm 0.032)\text{ps.} \quad (8.6)$$

Taken together these two LHCb results are currently the world's most precise measurements of the effective $B_s^0 \rightarrow K^+K^-$ lifetime.

So far this measurement is in agreement with the Standard Model prediction but is statistically limited. However, a more precise evaluation of the effective $B_s^0 \rightarrow K^+K^-$ lifetime will be made using the estimated 1 fb^{-1} of data which will have been collected by LHCb at the end of 2011. This will reduce the statistical uncertainty to around 0.02

ps, providing an exciting opportunity to test the Standard Model at high precision.

A Bayesian technique to account for proper time acceptance effects when making relative lifetime measurements, applied to the decays of D^0 mesons, was also presented. A measurement of the $D^0 \rightarrow K^+K^-/D^0 \rightarrow \pi^+K^-$ lifetime ratio y_{CP} is another avenue through which new physics could be discovered and a high precision measurement of this quantity will also be possible with the 2011 LHCb dataset.

This is an exciting time to be involved in particle physics research. The next few years, or maybe even months, could see a paradigm shift in our thinking about matter at the smallest scales. The LHCb experiment is at the leading edge of the search to find signatures of new physical phenomena which the Standard Model cannot explain and is continuously pushing back the frontiers of our understanding of CP violation. With some luck and a great deal of work we may soon know whether or not there really are elephants in the fridge.

Appendix A

Implementation of the Relative Acceptance Correction in DaVinci

Implementing the RLAC procedure using the DaVinci software package is somewhat more complex than in the case of the toy Monte Carlo simulation. For the toy simulation no track fits or vertex fits are performed; the only relevant objects are vectors containing the momenta of particles and the positions of vertices. However, for full LHCb simulations and real data the algorithm must handle tracks and vertices. The algorithm developed operates as follows:

1. Take a D candidate.
2. Clone its daughters to produce new particle objects.
3. Use the DaVinci function “ParticleTransporter” to evaluate the daughters 4-momenta at the z -coordinate of the decay vertex.
4. Sum the 4-momenta of the daughters to find a boost vector to the zero momentum frame. The subtlety is that the vertex fit works in a way that means that the 4-momentum of the mother is not equal to the sum of the 4-momenta of its daughters.
5. Boost to the zero momentum frame, evaluate the invariant mass of the mother by taking the square of the summed 4-momenta, recalculate the momenta of the daughters given the new decay daughters masses, boost back to the lab frame and calculate the new 4-momenta of the daughters.

6. Assign these new 4-momenta to the cloned daughters, along with new measured masses and new particle IDs.
7. Give the cloned daughters a vector of dummy particles using the “setDaughters” method. This “hack” is required since the function used to evaluate distances in DaVinci (“IDistanceCalculator”) always uses the track of a basic particle to evaluate impact parameters. The function must be fooled into thinking that the new daughters are not basic particles so that it uses their new momenta to calculate new impact parameters from the reference point of the decay vertex.
8. Give the new, modified daughters to IDistanceCalculator and calculate the new impact parameters and impact parameter χ^2 s.
9. Write the new variables to a ROOT ntuple.

A number of internal checks are performed by the algorithm to give confidence that the method is working as expected:

1. The original particles are cloned to produce new particle objects.
2. These are propagated them to the decay vertex using “ParticleTransporter”. This is necessary since the reference location of particles where their momenta are calculated are not necessarily at their production vertex.
3. The cloned daughters are given them dummy daughters to fool “IDistanceCalculator” into using their momenta rather than track information.
4. Momenta and impact parameters are then measured. They agree to within 1 part in 100,000 with the original values of the unmodified daughters.
5. These cloned daughters are also put through the boost, decay, boost calculation but without changing their masses. Again this leads to no observable change on the calculated quantities.

These internal checks give confidence that the DaVinci specific steps that are required to implement the relative acceptance correction do not introduce any additional errors or biases to the results.

Appendix B

Additional Figures

B.1 Invariant Mass Fits in Bins of Proper Time

Figures B.1 to B.8 show the K^+K^- and $K^\pm\pi^\mp$ mass fits in bins of proper time used for the extraction of $\Delta\Gamma_{K^+K^-}$. The plots appear in order of increasing proper time.

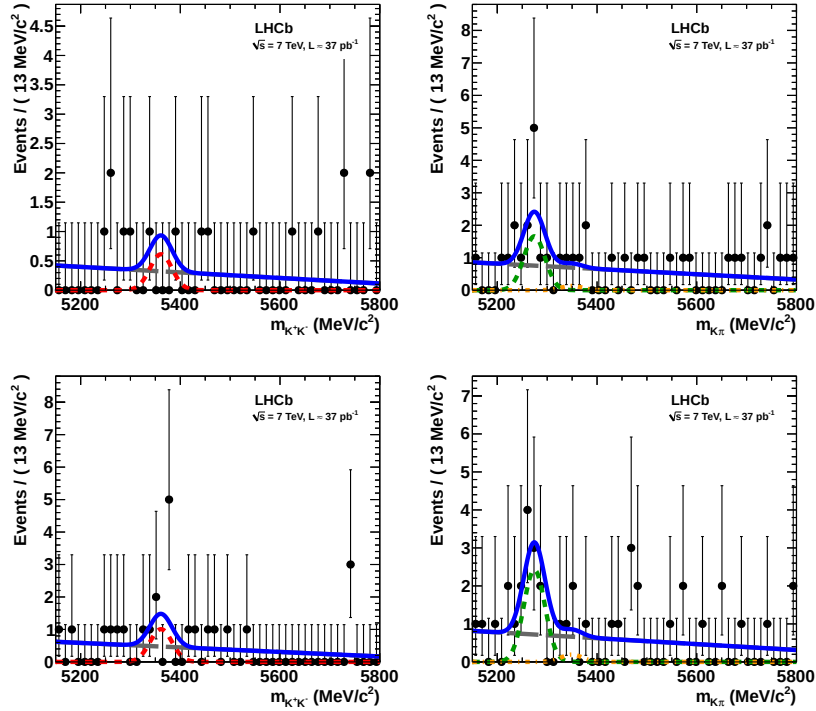


Figure B.1: Fits to the K^+K^- (left) and $K^\pm\pi^\mp$ (right) mass spectra in bins of proper time.

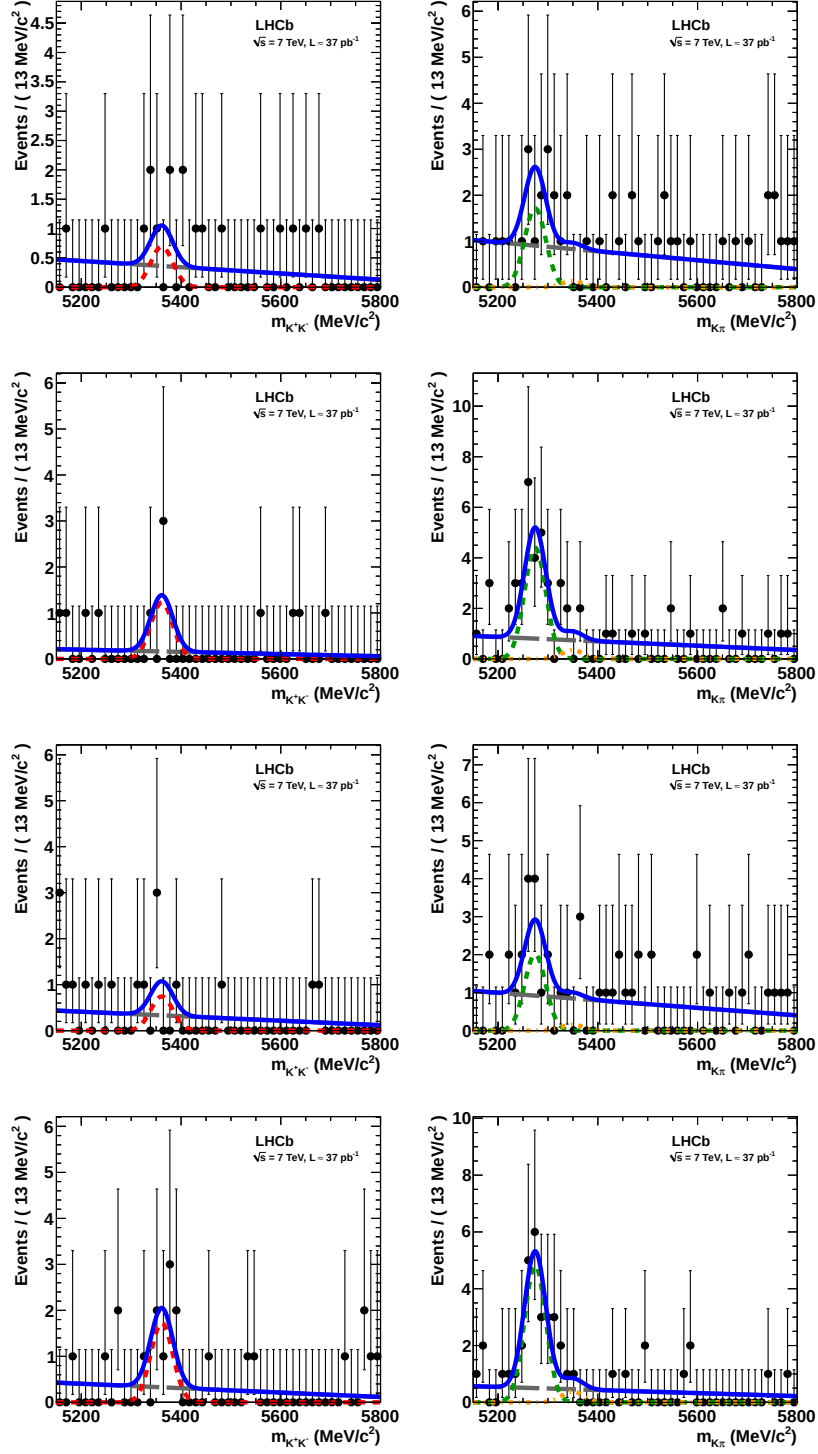


Figure B.2: Fits to the K^+K^- (left) and $K^\pm\pi^\mp$ (right) mass spectra in bins of proper time.

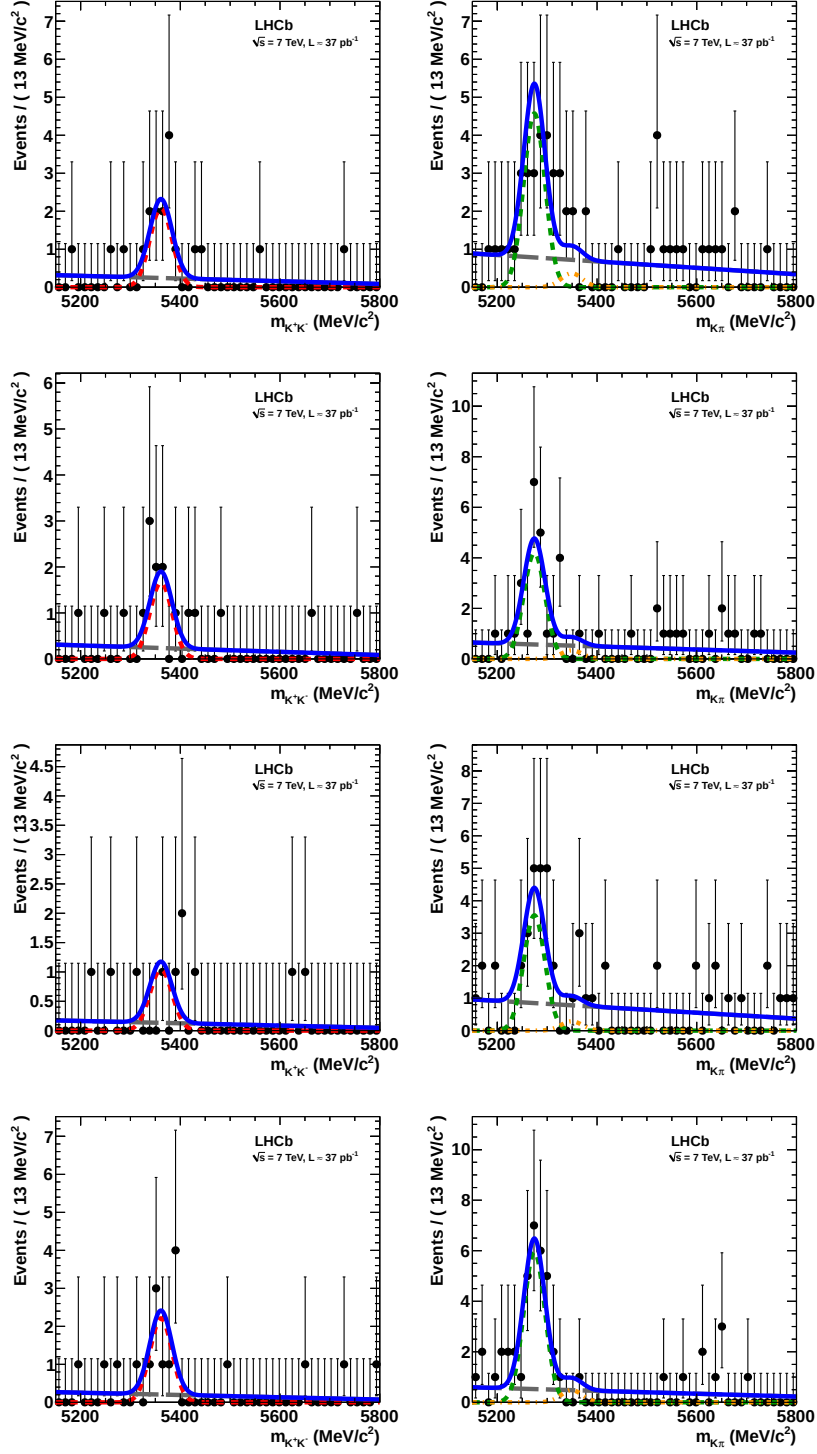


Figure B.3: Fits to the K^+K^- (left) and $K^\pm\pi^\mp$ (right) mass spectra in bins of proper time.

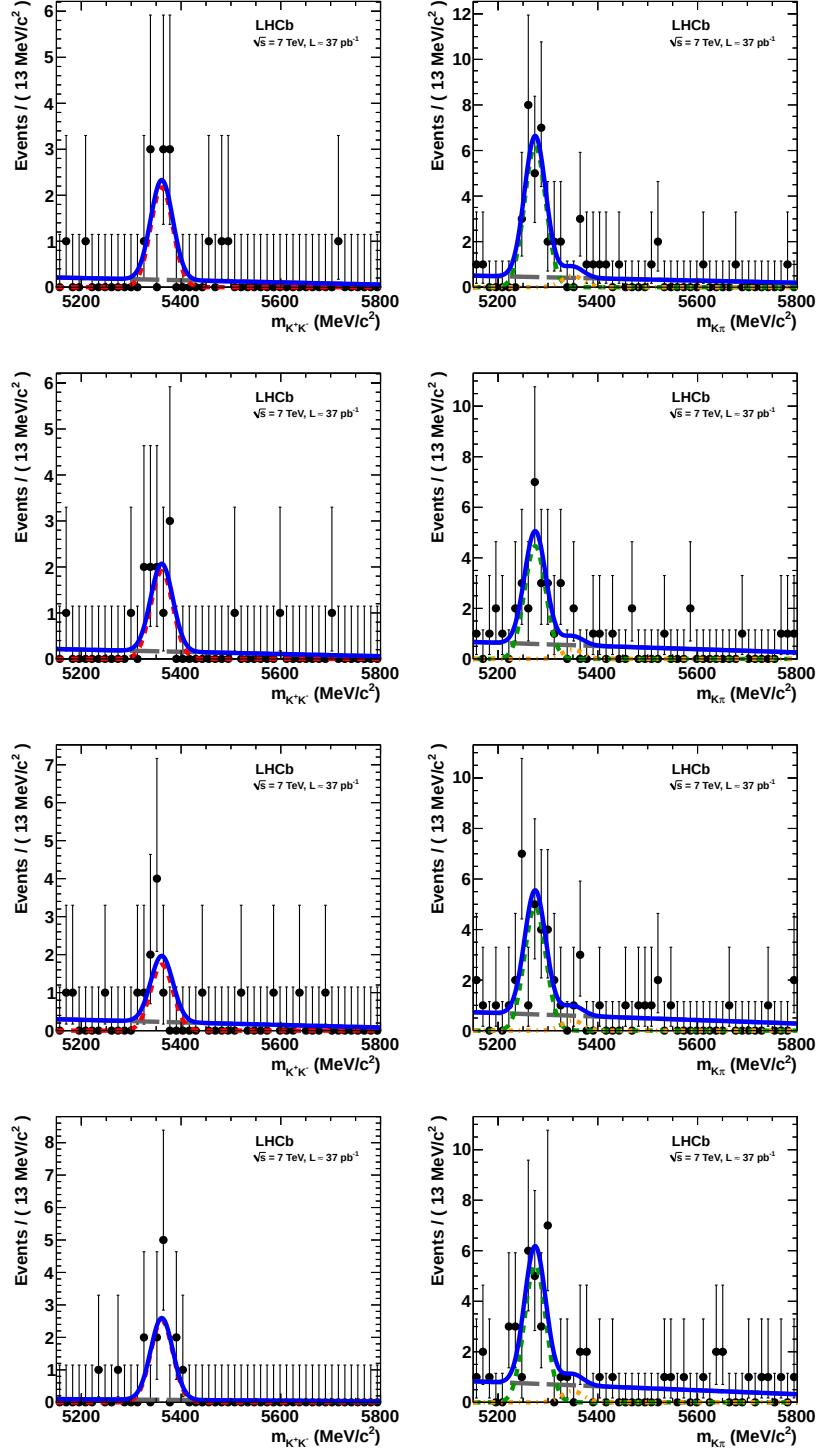


Figure B.4: Fits to the K^+K^- (left) and $K^\pm\pi^\mp$ (right) mass spectra in bins of proper time.

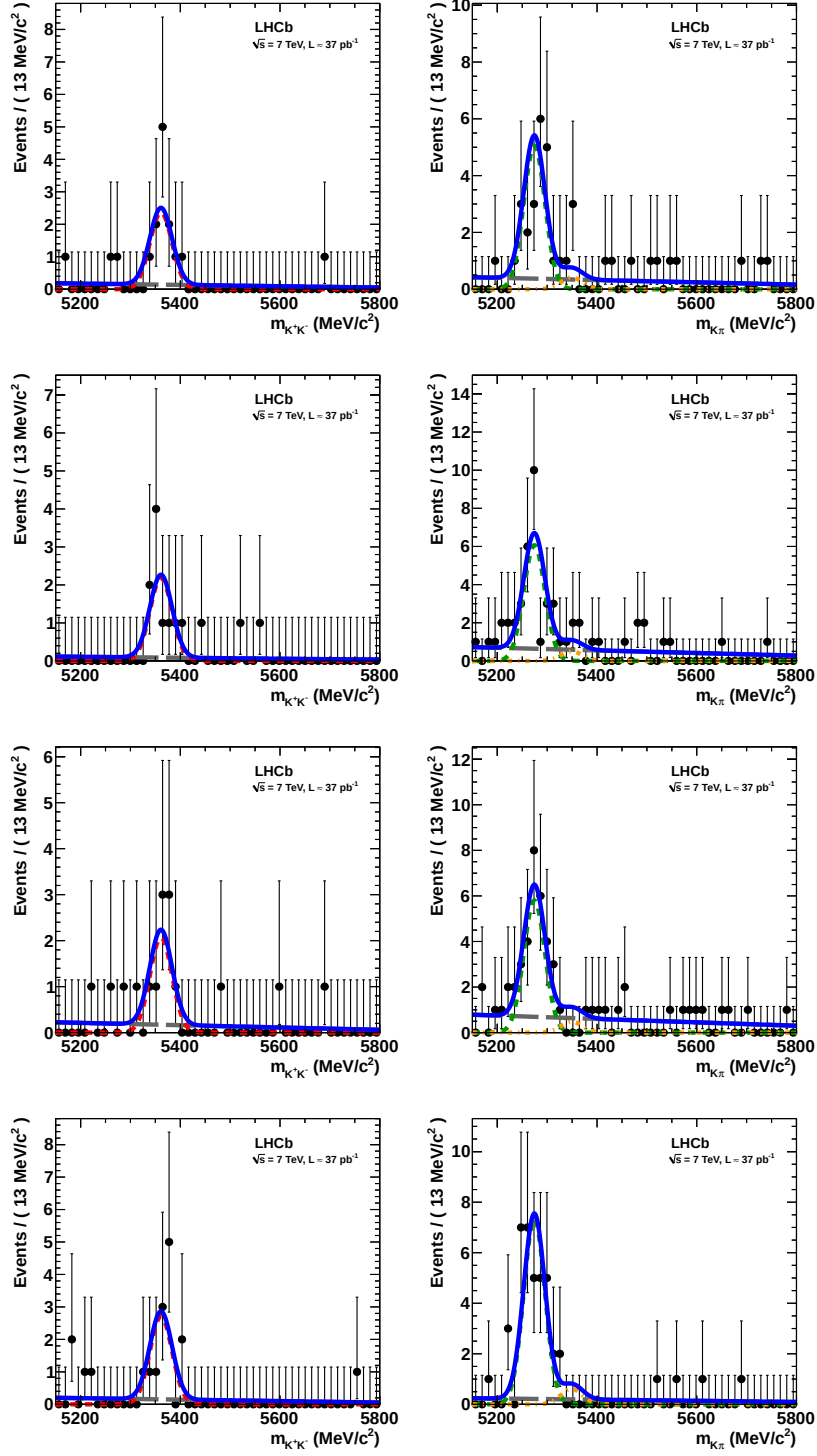


Figure B.5: Fits to the K^+K^- (left) and $K^\pm\pi^\mp$ (right) mass spectra in bins of proper time.

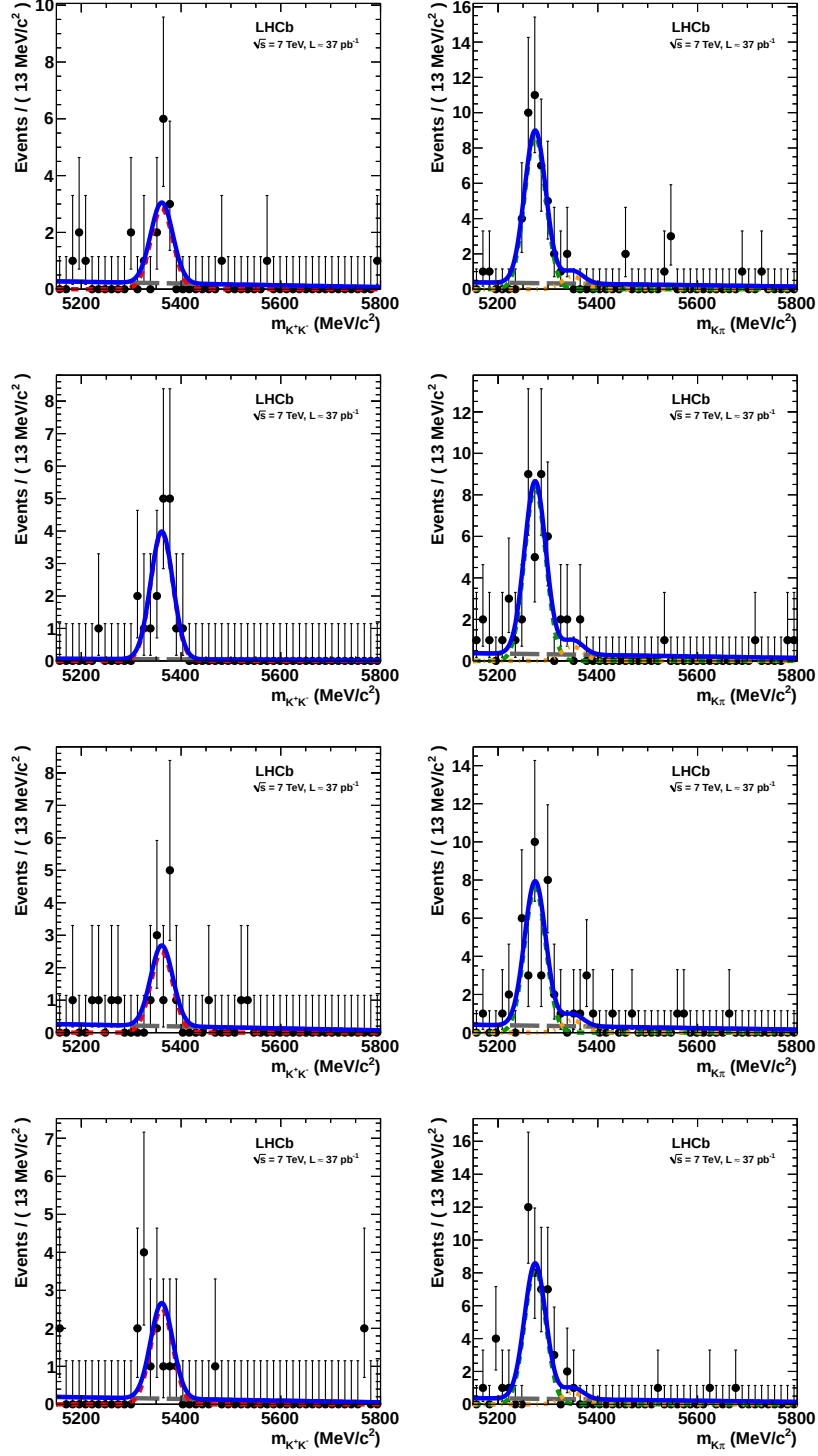


Figure B.6: Fits to the K^+K^- (left) and $K^\pm\pi^\mp$ (right) mass spectra in bins of proper time.

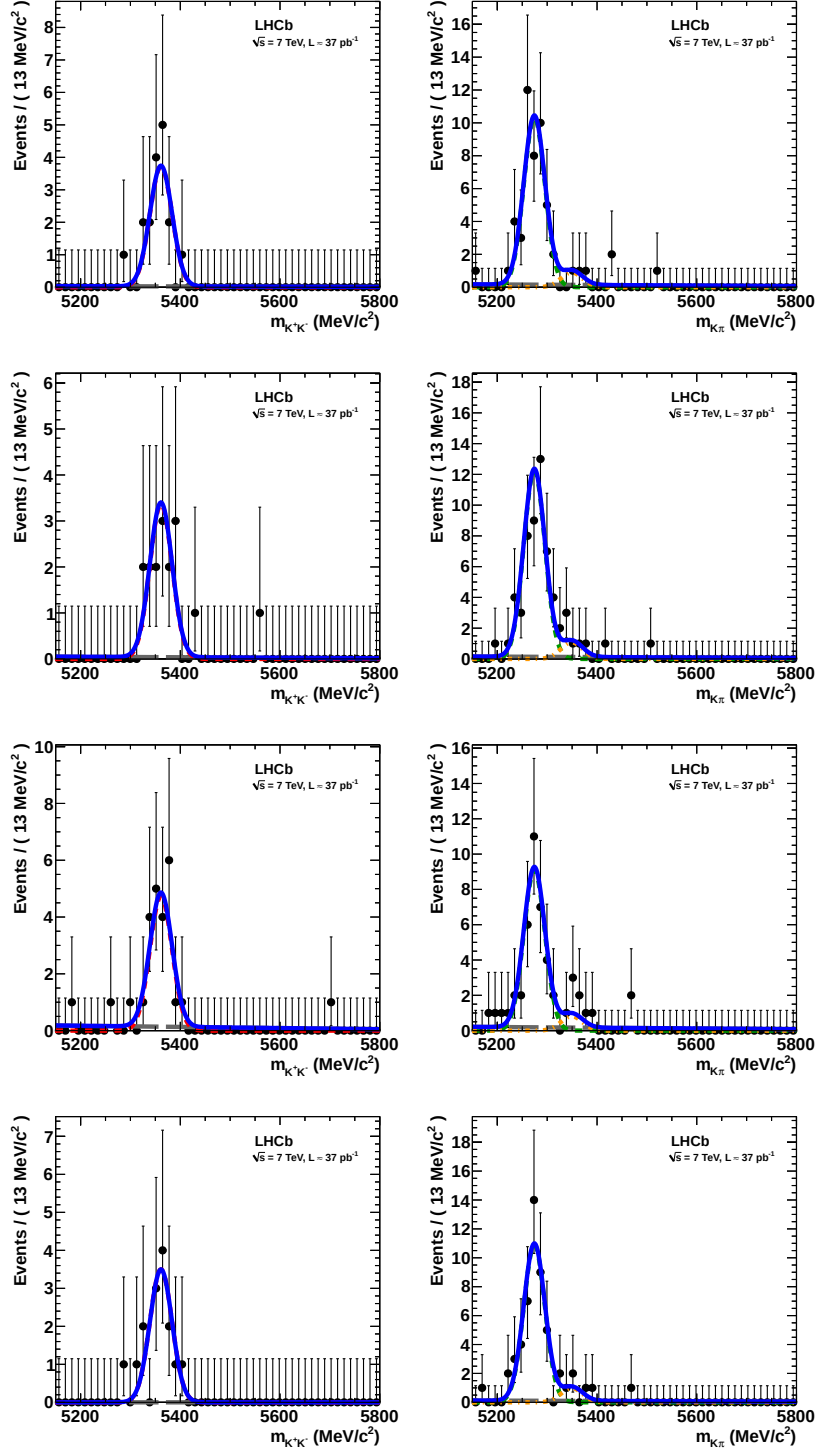


Figure B.7: Fits to the K^+K^- (left) and $K^\pm\pi^\mp$ (right) mass spectra in bins of proper time.

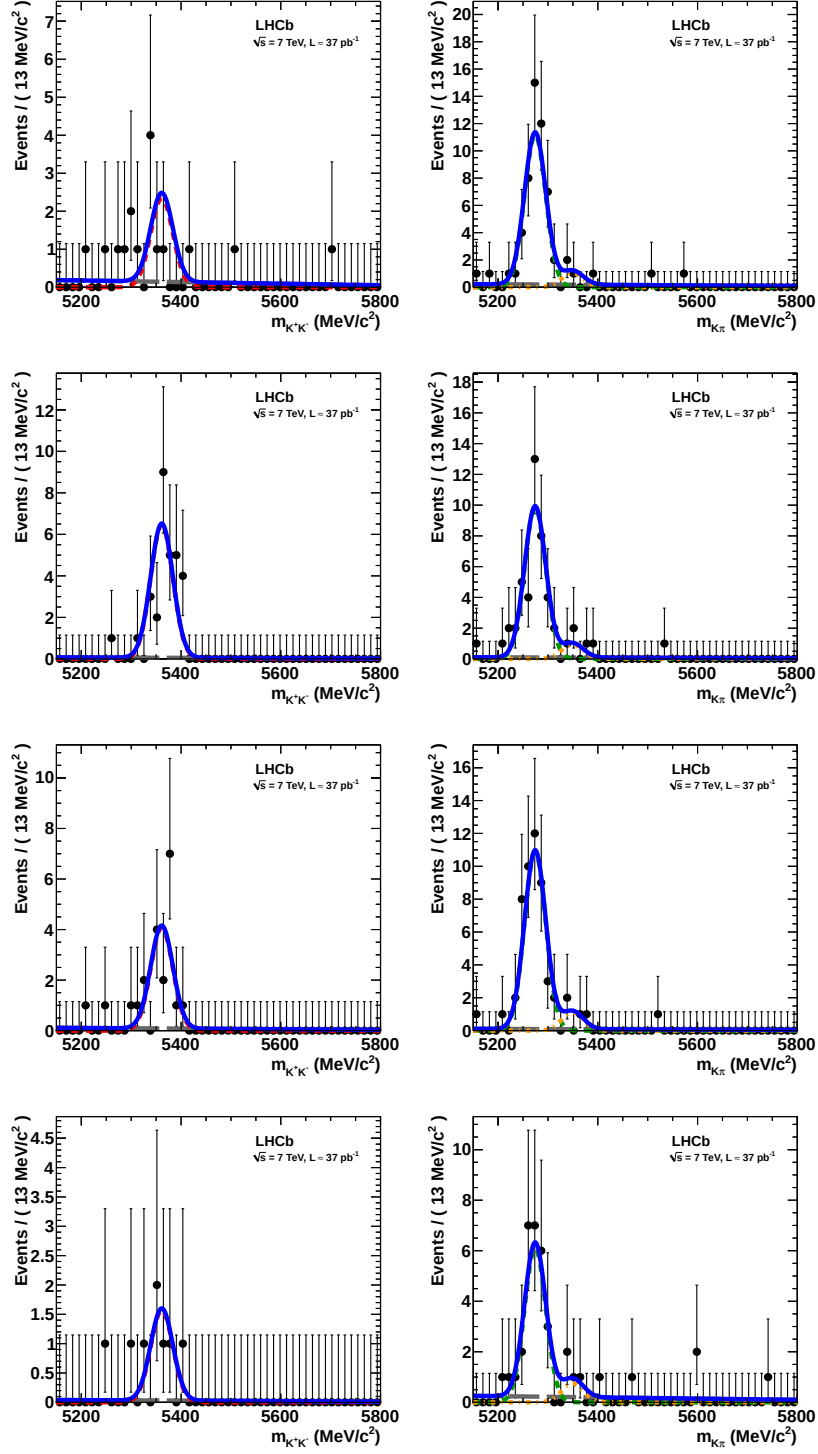


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