

**A Study of the RICH Detector Performance and
Search for New Physics in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ Decays
with the LHCb Experiment**

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Abstract

The LHCb experiment will make precision $\mathcal{CP}$ -violation and rare decay measurements at the Large Hadron Collider which is due to start running in 2008. These will provide an indirect window onto new physics beyond the Standard Model (SM). The Ring Imaging Cherenkov (RICH) sub-detectors provide essential particle identification for many LHCb physics analyses. A system test of the RICH photon detectors and electronics has been successfully performed at CERN. The reconstructed mean Cherenkov angle and photon yields are in good agreement with expectations. The Cherenkov angle resolution of the RICH Hybrid Photon Detectors (HPDs) is measured to be 1.66 ± 0.03 mrad where the quoted error is the systematic error and the statistical error is negligible. The resolution is in good agreement with the Monte Carlo (MC) simulation.

The rare decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$ provides a sensitive test of the SM. The reconstruction and selection of these events has been studied using the full LHCb MC simulation. With a 2 fb^{-1} data set, $7200 \pm 180 \pm_{1900}^{2200}$ signal events are expected where the first error is the statistical error from the MC event sample and the second error is from the measured branching ratio. A total background of 1770 ± 310 events is expected excluding a potential background of 1730 events from non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ decays. The background is expected to be dominated by events with muons from real b-decays.

The forward-backward asymmetry (A_{FB}) in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ events is sensitive to new physics. The large number of signal events expected means that the A_{FB} distribution can be measured as a function of the invariant mass of the muon pair. The sensitivity to the zero-crossing point of A_{FB} , i.e. the expected statistical precision, is estimated to be $0.60 \text{ GeV}^2/c^4$ with 2 fb^{-1} and $0.29 \text{ GeV}^2/c^4$ with 10 fb^{-1} of data and corresponds to approximately 1 and 5 years of data taking respectively.

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.

Jeremy Dickens

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Preface

The Standard Model (SM) has been at the heart of particle physics for the past 30 years. Although the SM describes all current experimental data it is expected to fail at the energies of the Large-Hadron-Collider (LHC), currently under final commissioning at CERN. The spontaneous symmetry breaking of the Higgs field in the SM provides a mechanism for the generation of masses for fermions and bosons. Direct searches for the Higgs-boson have, so far, constrained its mass to be greater than $114.4 \text{ GeV}/c^2$ [1]. At the LHC energy scale ($\mathcal{O}(1 \text{ TeV})$) unitarity for the scattering $e^+e^- \rightarrow W^+W^-$ is violated in the SM in the absence of a Higgs-boson with a mass less than $\mathcal{O}(1 \text{ TeV}/c^2)$. However, the loop interactions of the Higgs field with fermions causes the mass of the Higgs-boson to diverge to an arbitrarily large value, typically the Planck mass scale. This divergence is naturally cancelled by imposing a new symmetry on the theory, such as SuperSymmetry, introducing a new set of particles and interactions. Other theories, such as extra-spatial dimensions, can also, in principle, account for the Higgs mass. There is therefore a good motivation for new physics, of some type, beyond the SM.

The LHC is the highest energy collider ever built. Of the four main experiments that will run as part of the LHC two, ATLAS [2] and CMS [3], are general purpose detectors. These experiments are designed to detect generic new physics signatures – in particular the Higgs-boson and SuperSymmetry – through direct methods, for example the production of new particles. The ALICE [4] experiment is a heavy-ion experiment which will investigate the physics of the quark-gluon plasma that arises through strongly interacting matter at high energy densities. The LHCb [5] experiment is a dedicated B-physics experiment designed to test the SM through precision measurements of $\mathcal{CP}$ -violation and rare B-decay processes.

The LHCb experiment provides a complementary approach to the direct searches of the general purpose detectors by searching for new physics signatures indirectly, as devi-

ations from the SM. The physics program of LHCb is largely divided into two sections: $\mathcal{CP}$ -violation measurements and rare decay measurements. $\mathcal{CP}$ -violation is accommodated naturally in the SM through the Cabbibo-Kobayashi-Maskawa (CKM) matrix with an imaginary phase. Currently, all $\mathcal{CP}$ -violation measurements are consistent with the SM expectations. The $\mathcal{CP}$ -violation measurements at LHCb will over-constrain the elements of the CKM matrix (or, equivalently, the sides and angles of the Unitarity Triangle) and therefore test the SM description.

Measurements of rare decay processes also provide a window to detecting the presence of new physics. Here, a rare decay is one which has no possible tree-level Feynman diagram so the leading order process occurs at the one-loop level or beyond, rather than any absolute constraint on the branching ratio. New physics processes (e.g. new Super-Symmetric particles) can be present in the virtual loops and, although never detected directly, can affect the decay distributions changing them from their SM expectations. Since the loops contain only virtual particles this approach can probe higher mass scales than is possible by the direct production of new particles.

The LHCb experiment is currently in the final stages of detector commissioning in preparation for the start of data-taking. This thesis describes work on two aspects of the LHCb experiment:

- The LHCb-UK collaboration is largely responsible for the design and manufacture of the particle identification sub-detectors (RICH) for the experiment. A major part of this thesis is based on the analysis of data from the RICH testbeams in 2004. An overview of the RICH system is given in Chapter 2. A description of the testbeam apparatus, electronics and data analysis is given in Chapter 3.
- The decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$ is a key rare decay measurement for LHCb. The huge numbers of B-particles produced at LHCb ($\mathcal{O}(10^{12})$ per nominal physics year) means that even rare processes with branching ratios of order 10^{-6} can be studied very precisely. As described in Chapter 1, the $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decay is sensitive to new physics processes, particularly in the zero-crossing point of the forward-backward asymmetry (A_{FB}). The criteria to select these events from the background are presented in Chapter 4. A description of the level and type of background expected is given in Chapter 5 and the resulting statistical sensitivity to the zero-crossing point of A_{FB} is presented in Chapter 6.

Finally, the conclusions of this work are presented in Chapter 7.

The author's contribution to this work is described in the text and reference made the work of others as necessary. In particular, I performed the Cherenkov angle analysis for the RICH testbeam in 2004 (Chapter 3). I was responsible for writing the reconstruction software, modifying parts of the simulation software and the subsequent Cherenkov angle analysis, including measuring the contributions to the resolution and the systematic uncertainty studies. The photon yield studies are the work of others and are presented for completeness. For the testbeam in 2006 in Italy, I was responsible for writing the data acquisition software to read out the off-detector electronics. For the $B_d^0 \rightarrow K^* \mu^+ \mu^-$ analysis I performed the selection criteria optimisation, using the standard LHCb software tools (Chapter 4). I also carried out the work on identifying, estimating and classifying the backgrounds in the analysis (Chapter 5) and estimating the statistical sensitivity of LHCb to the zero-crossing point (Chapter 6).

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Chapter 1

Theory of the Rare Decay

$$B_d^0 \rightarrow K^* \mu^+ \mu^-$$

This chapter describes the theory of rare B-decays. An overview of the $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decay is presented in Section 1.2 with a discussion of the relevant Wilson operators and coefficients and the effective Hamiltonian. The theory of the forward-backward asymmetry in the decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$ in the Standard Model (SM) is presented in Section 1.3. A discussion of other angular correlations in the decay is given in Section 1.4. Finally, the forward-backward asymmetry in some New Physics scenarios is given in Section 1.5.

1.1 Introduction to the Standard Model

The SM has been at the heart of particle physics for nearly three decades. It describes the interactions of the fundamental particles through three of the four known forces: the strong interaction (through the $SU(3)_C$ group), the weak interaction ($SU(2)_L$ group) and the electromagnetic interaction ($U(1)$ group). Although the SM is very successful and describes the wealth of current experimental evidence, it is not a complete theory – not least because gravity is not included. There is, therefore, good motivation to search for physics beyond the SM. Two general, complementary approaches exist – direct searches, where new particles are produced directly in high energy collisions, and indirect searches, where new particles or interactions are produced in virtual states (for example in loop-diagrams) and their effect is observed indirectly as deviations from the

SM predictions.

Quark mixing in the SM is incorporated via the Cabibbo-Kobayashi-Maskawa (CKM) mechanism. In general, the flavour eigenstates (of the $SU(2)_L$ group) are not necessarily the same as the mass eigenstates because of possible Yukawa interaction terms between different generations. It is usual to construct the SM with the physical quarks (i.e. the mass eigenstates) which diagonalise the mass matrix. In this case inter-generation interactions are present, mediated by the charged W-bosons. The flavour eigenstates (d, s and b) are then related to the mass eigenstates ($\tilde{d}$, $\tilde{s}$ and $\tilde{b}$) by

$$\begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} = \mathbf{V}_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad (1.1)$$

where $\mathbf{V}_{CKM}$ is the unitary CKM matrix [6, 7]

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

and V_{ij} represent the matrix coupling elements between up-type quarks (i) and down-type quarks (j).

The weak charged current

$$J^\mu = \bar{q}_j V_{ij}^* \gamma^\mu (1 - \gamma^5) q_i \quad (1.3)$$

is therefore only conserved under the combined operation of $\mathcal{CP}$, ($q_i \rightarrow i\gamma^0\gamma^2 q_i$ and $\bar{q}_j \rightarrow \bar{q}_j i\gamma^2\gamma^0$) if $V_{ij} = V_{ij}^*$, i.e. if $\mathbf{V}_{CKM}$ is not complex.

A general (3×3) complex matrix has 18 free, real parameters. In this case, nine of these degrees of freedom are removed because of the constraint of unitarity and a further five degrees of freedom are removed by absorbing them into the relative phases between the six quark fields. This therefore leaves four independent parameters, usually described as three angles and one complex phase. $\mathbf{V}_{CKM}$ can then be written as

$$\mathbf{V}_{CKM} = R_{23} \times R_{13} \times R_{12}, \quad (1.4)$$

where

$$R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \quad R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.5)$$

and $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$ and i, j represent the generation labels.

It is observed experimentally that there is a hierarchy in the mixing of the quarks. The mixing within a generation (i.e. the diagonal elements of the CKM matrix) is much larger than the mixing between the first and second generations and between the second and third generations. The mixing between the first and third generations is smaller again. The Wolfenstein parameterisation [8] is an expansion which reflects this hierarchy, where the CKM matrix is expanded in powers of λ (which describes the mixing between the first and second generations), to give

$$\mathbf{V}_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \quad (1.6)$$

In this parameterisation, the four parameters (A , λ , ρ and η) replace the three rotation angles and complex phase of Equation 1.5.

The LHCb experiment will be sensitive to higher orders of the CKM matrix than is given in Equation 1.6. The correction, to include the fifth order terms in λ , is given by

$$\delta V = \begin{pmatrix} -\frac{1}{8}\lambda^4 & 0 & 0 \\ \frac{1}{2}A^2\lambda^5(1 - 2(\rho + i\eta)) & -\frac{1}{8}\lambda^4(1 + 4A^2) & 0 \\ \frac{1}{2}A\lambda^5(\rho + i\eta) & \frac{1}{2}A\lambda^4(1 - 2(\rho + i\eta)) & -\frac{1}{2}A^2\lambda^4 \end{pmatrix}. \quad (1.7)$$

The unitarity of $\mathbf{V}_{CKM}$ produces six orthogonality conditions between its rows and columns. These relations can be represented as triangles in the complex plane. The condition

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (1.8)$$

can be represented by the Unitarity Triangle, shown in Figure 1.1(a), where the phase of $V_{cd}V_{cb}^*$ is chosen to be real and the sides are scaled by a factor $1 / A\lambda^3$ i.e. the length of the side $|V_{cd}V_{cb}^*|$.

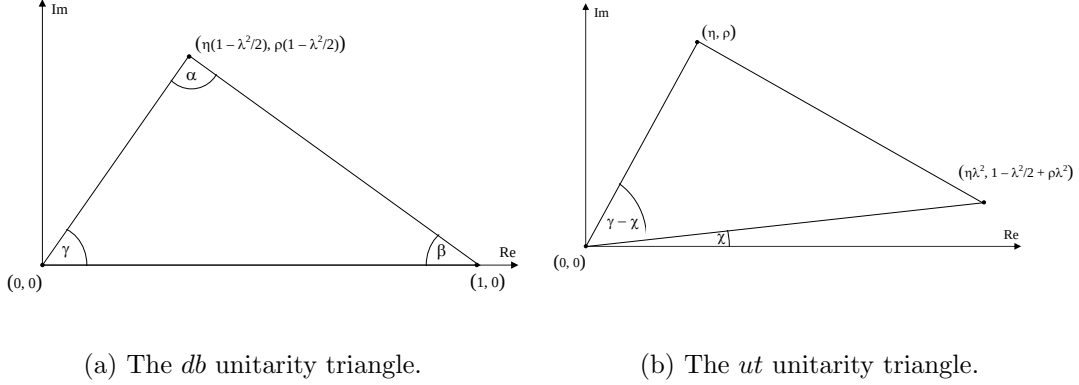


Figure 1.1: The unitarity triangles.

The three angles, α , β and γ (Figure 1.1(a)), in the db triangle and the B_s mixing phase, $\phi_s = 2\chi$ (Figure 1.1(b)), will be measured to high precision by LHCb. The current status of the Unitarity Triangle is shown in Figure 1.2. The impact of LHCb on these measurements is shown in Figure 1.3, where the relevant errors are reduced to those expected from LHCb with 10 fb^{-1} of data, equivalent to approximately five years of running.

1.2 Theory of the Decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$

The decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$ is a flavour-changing-neutral current which proceeds via a $b \rightarrow s$ transition through penguin diagrams, as shown in Figure 1.4. No tree-level SM diagrams exist for these decay types and so the leading order processes occur at the one loop-level; new physics processes can therefore enter at the same level as the SM processes. Additional contributions to the decay rate from new particles (for example SuperSymmetric charginos) could exist and provide a route to observe new physics indirectly [10]. This also means that the decay distributions could be significantly modified. One such distribution is the forward-backward asymmetry (defined in Section 1.3), which, as a function of the di-muon mass ($M_{\mu\mu}$), provides a sensitive test of the SM [11, 12].

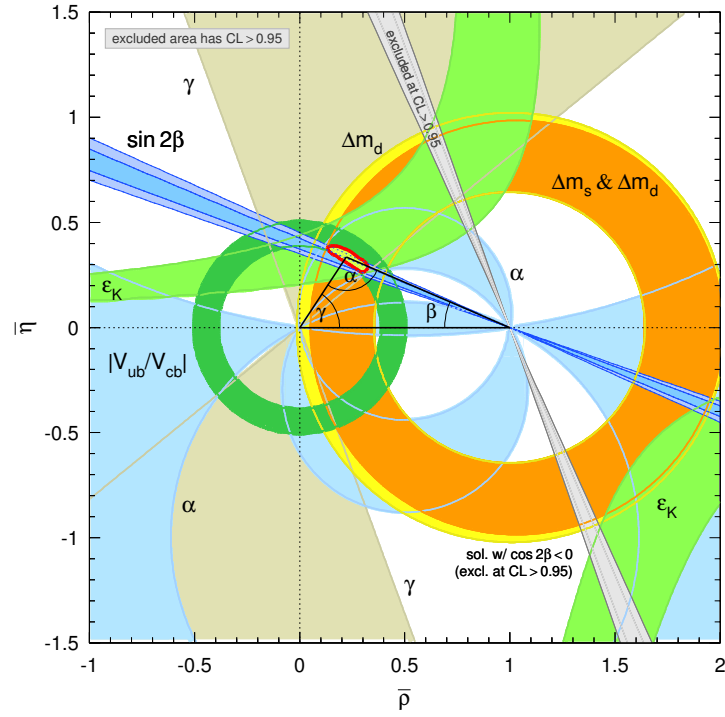


Figure 1.2: The current status of the Unitarity Triangle [1].

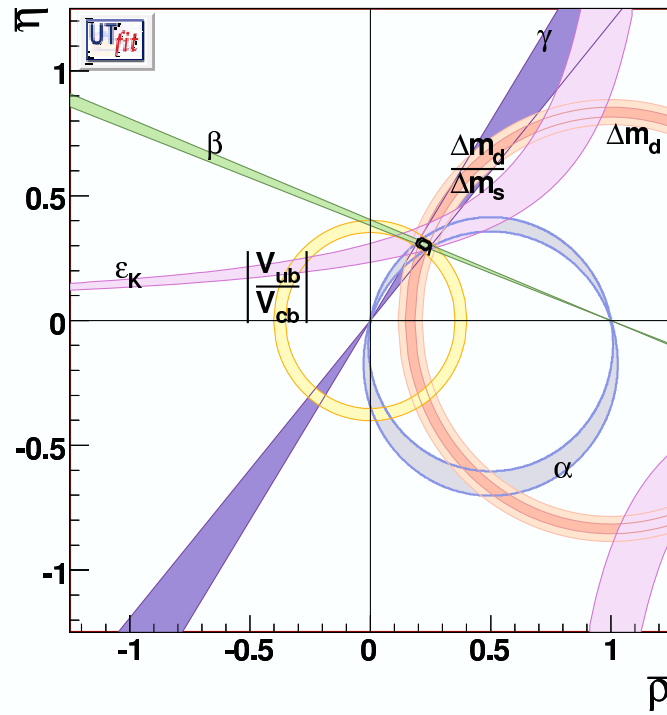
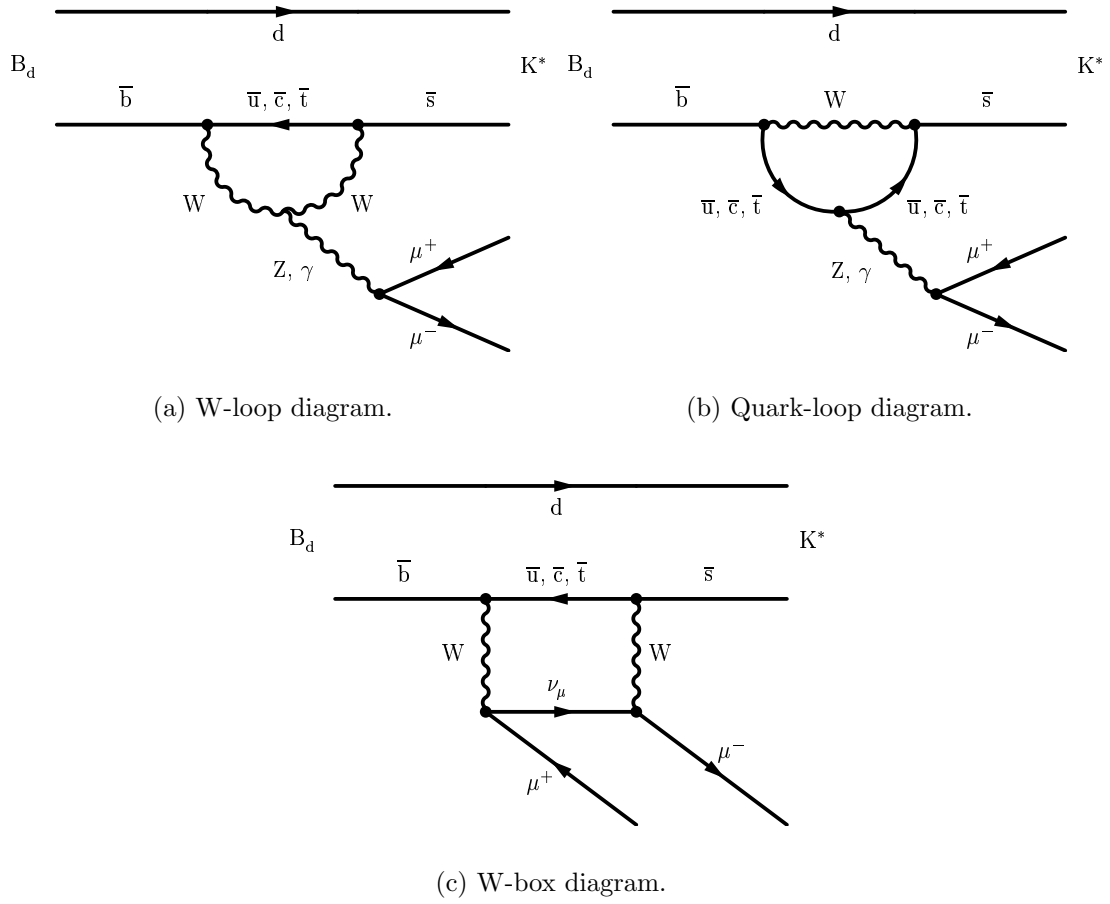


Figure 1.3: The Unitarity Triangle projection with 10 fb^{-1} of LHCb data [9].

**Figure 1.4:** $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays within the SM.

1.2.1 The Wilson Coefficients and Operators

In the quark sector of the SM, the effects of Quantum-Chromodynamics (QCD) and the weak interaction are inextricably linked because quarks are bound in hadron states. It is therefore necessary to understand the effects of the weak and strong interactions together. The Operator Product Expansion (OPE) [13, 14] was proposed to allow this. The OPE factorises the long- and short-distance physics of an interaction into local operators and their respective coefficients. For example, the amplitude for a process from an initial state I to a final state F can be written as

$$A(I \rightarrow F) = \langle F | \mathcal{H}_{eff} | I \rangle = \sum_i C_i(\mu) \langle F | \mathcal{O}_i(\mu) | I \rangle, \quad (1.9)$$

where the effective Hamiltonian ($\mathcal{H}_{eff}$) is factorised into the sum of local operators, $\mathcal{O}_i(\mu)$, multiplied by some coefficients, $C_i(\mu)$, evaluated at some factorisation scale μ . Typically, for B-decays, μ is taken to be $\mathcal{O}(1 \text{ GeV})$.

The two parts of the OPE are:

- **Wilson coefficients** C_i : encode the short-distance part of the interaction. Any degrees of freedom in the gauge boson, fermion or scalar fields with a mass greater than the factorisation scale are integrated out. Their effects are therefore accounted for in the Wilson coefficients. In the limit that the mass scale of the field is much greater than the factorisation scale (e.g. $M_W \gg \mu$), the interaction appears to be point like. The Wilson coefficients can then be calculated perturbatively and the coefficients relevant to this study have now been calculated to Next-to-Next-to-Leading-Order [15–17].
- **Wilson operators** $\mathcal{O}_i$: encode the long-distance part of the interaction (i.e. the non-perturbative QCD effects). These therefore include the non-perturbative effects of quarks bound in hadrons. Various techniques, such as Heavy-Quark-Effective-Theory (HQET) and Large-Energy-Effective-Theory (LEET) have been developed for these calculations [10, 18–20].

The standard Wilson operators and corresponding Feynman diagrams relevant to B-decays are given in Equations 1.10 – 1.14 and Figure 1.5. For completeness, the remaining operators are also given [15, 21–26]:

- **Current-Current operators :**

$$\begin{aligned}\mathcal{O}_1 &= (\bar{s}_\alpha \gamma_\mu P_L c_\beta)(\bar{c}_\beta \gamma^\mu P_L b_\alpha) & \mathcal{O}_1^{(u)} &= (\bar{s}_\alpha \gamma_\mu P_L u_\beta)(\bar{u}_\beta \gamma^\mu P_L b_\alpha) \\ \mathcal{O}_2 &= (\bar{s}_\alpha \gamma_\mu P_L c_\alpha)(\bar{c}_\beta \gamma^\mu P_L b_\beta) & \mathcal{O}_2^{(u)} &= (\bar{s}_\alpha \gamma_\mu P_L u_\alpha)(\bar{u}_\beta \gamma^\mu P_L b_\beta),\end{aligned}\tag{1.10}$$

for the example of $b \rightarrow c \bar{c} s$ and $b \rightarrow u \bar{u} s$ transitions, where, in these and the following equations, $P_{L,R}$ are the chiral projection operators $(\frac{1}{2}(1 \mp \gamma_5))$ and α, β denote the quark colour indices.

- ***QCD* penguin operators :**

$$\begin{aligned}\mathcal{O}_3 &= (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_L q_\beta) \\ \mathcal{O}_4 &= (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_L q_\alpha) \\ \mathcal{O}_5 &= (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_R q_\beta) \\ \mathcal{O}_6 &= (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} (\bar{q}_\beta \gamma^\mu P_R q_\alpha),\end{aligned}\tag{1.11}$$

where the quark current from the gluon has been decomposed into a $(V - A)$ part and a $(V + A)$ part.

- **Electroweak penguin operators :**

$$\begin{aligned}\mathcal{O}_7 &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} e_q (\bar{q}_\beta \gamma^\mu P_R q_\beta) \\ \mathcal{O}_8 &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} e_q (\bar{q}_\beta \gamma^\mu P_R q_\alpha) \\ \mathcal{O}_9 &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=d,u,s,c} e_q (\bar{q}_\beta \gamma^\mu P_L q_\beta) \\ \mathcal{O}_{10} &= \frac{3}{2}(\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=d,u,s,c} e_q (\bar{q}_\beta \gamma^\mu P_L q_\alpha)\end{aligned}\tag{1.12}$$

- **Magnetic penguin operators :**

$$\begin{aligned}\mathcal{O}_{7\gamma} &= \frac{e}{16\pi^2} \bar{s}_\alpha \sigma_{\mu\nu} (m_b P_R) b_\alpha F^{\mu\nu} \\ \mathcal{O}_{8g} &= \frac{g_s}{16\pi^2} \bar{s}_\alpha T_{\alpha\beta}^a \sigma_{\mu\nu} (m_b P_R) b_\beta G^{a\mu\nu},\end{aligned}\tag{1.13}$$

where the mass of the s-quark has been neglected in comparison with the mass of b-quark [27, 28].

- **Semi-leptonic operators :**

$$\begin{aligned}\mathcal{O}_{9V} &= \frac{e}{16\pi^2} (\bar{s}_\alpha \gamma^\mu P_L b_\alpha) (\bar{\ell} \gamma_\mu \ell) \\ \mathcal{O}_{10A} &= \frac{e}{16\pi^2} (\bar{s}_\alpha \gamma^\mu P_L b_\alpha) (\bar{\ell} \gamma_\mu \gamma_5 \ell),\end{aligned}\tag{1.14}$$

where the lepton pair are produced in a vector and axial-vector state respectively.

The Wilson coefficients and operators are evaluated at some factorisation scale (μ), which separates the contributions into the short- and long-distance components. The value of μ can be chosen arbitrarily since the final result must be independent of it, i.e. the μ dependence of the Wilson coefficients must cancel the dependence of the operators. In practice the factorisation scale is chosen to be of order of the mass of the decaying hadron i.e. $\mathcal{O}(m_b)$ for B-decays. Because of higher order corrections and the running of α_s with the energy scale, the coefficients are actually calculated at a scale $\mathcal{O}(M_W)$. The coefficients are then evolved down to the hadron mass scale ($\mathcal{O}(1 \text{ GeV})$) using the Renormalisation Group Equations (RGE) [29]. However, this process introduces large logarithms to the expressions for the Wilson coefficients such that terms like $(\alpha_s \ln(M_W / \mu))$ appear and are $\mathcal{O}(1)$. This means that the series cannot be truncated and should be resummed – in the Leading-Logarithm approximation all terms like $(\alpha_s \ln(M_W / \mu))^n$ are summed [23, 24]. In general, as higher order terms are included (for example in the Next-to-Leading-Logarithm approximation, where terms like $\alpha_s(\alpha_s \ln(M_W / \mu))^n$ are summed) the Wilson operators mix. Physically this corresponds to adding extra gluons or virtual quark lines to the diagrams.

The Wilson operators relevant to the $b \rightarrow s \ell^+ \ell^-$ transition are: $\mathcal{O}_{7\gamma}$, where the lepton pair is produced from a virtual photon, and $\mathcal{O}_{9V}$ ($\mathcal{O}_{10A}$), where the lepton pair is produced in a vector (axial-vector) state from a Z-boson. However, because the perturbation series in $(\alpha_s \ln(M_W / \mu))$ must be resummed to all orders, higher order processes must be considered. This therefore allows mixing of the Wilson operators $\mathcal{O}_1 - \mathcal{O}_6$ into $\mathcal{O}_{7\gamma}$ and $\mathcal{O}_{9V}$ [30–32]. There is no mixing of these operators into $\mathcal{O}_{10A}$ because the lepton pair is produced in an axial-vector state [30].

For the specific case of the decays $b \rightarrow s \gamma$ and $b \rightarrow s \ell^+ \ell^-$, the mixing between the pure QCD operators ($\mathcal{O}_1 - \mathcal{O}_6$) and the penguin operators ($\mathcal{O}_7 - \mathcal{O}_{10}$) vanishes at the one-loop level, though not at higher orders. It is therefore useful to introduce the

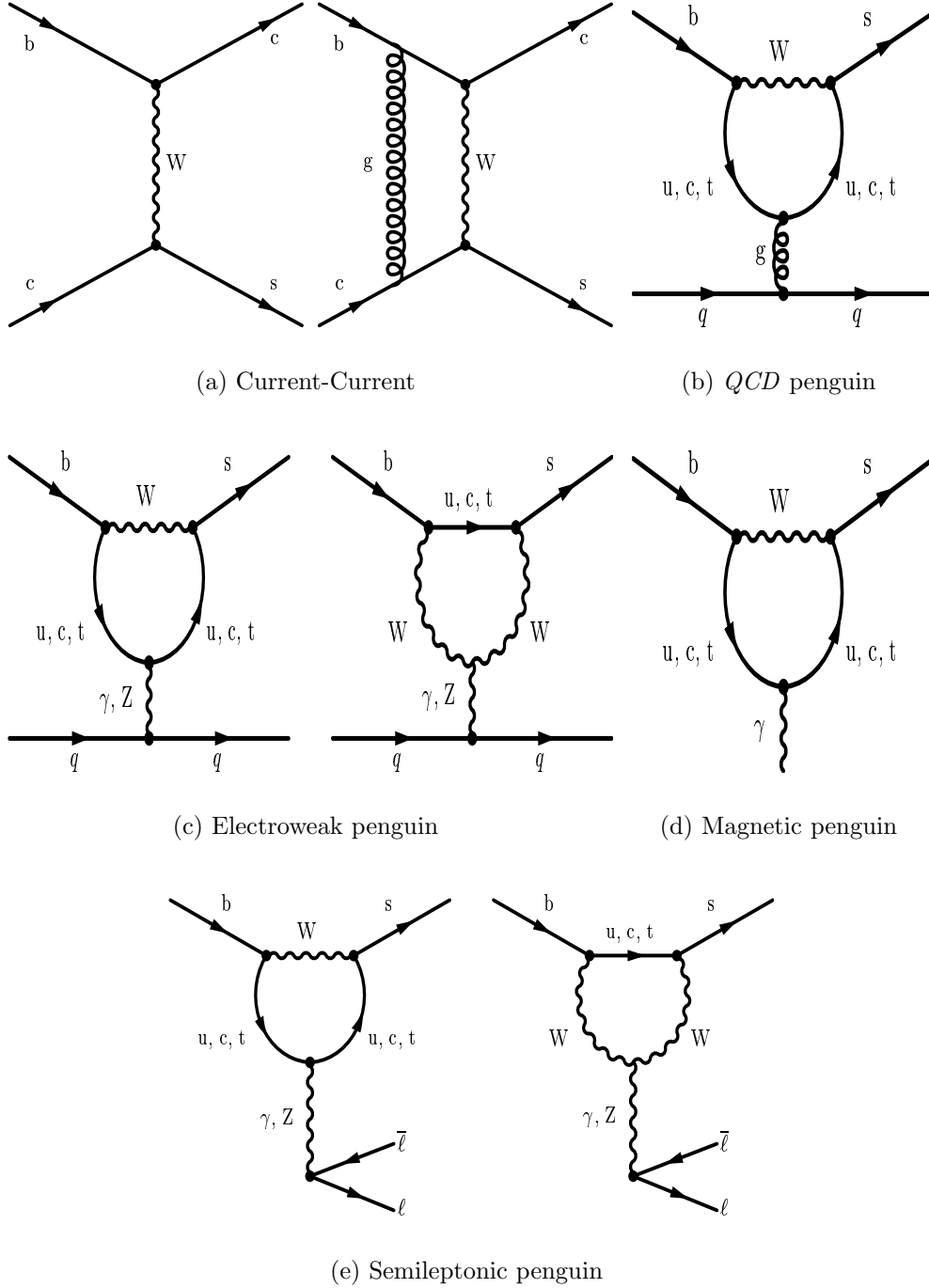


Figure 1.5: The leading order Feynman diagrams for the Wilson operators.

effective Wilson coefficients, C_7^{eff} and C_9^{eff} , to account for this mixing. In the standard basis they are defined as linear combinations of the original coefficients and, to leading order, are given by [29, 33, 34]:

$$C_7^{eff} = C_7 - C_3/3 - 4C_4/9 - 20C_5/3 - 80C_6/9 \quad (1.15)$$

$$C_9^{eff}(q^2) = C_9 + Y(q^2), \quad (1.16)$$

where $Y(q^2)$ represents the perturbative $\mathcal{O}(\alpha_s)$ corrections to the four-quark Wilson operators, $\mathcal{O}_1 - \mathcal{O}_6$, and is given by [33, 35]

$$\begin{aligned} Y(q^2) = & h(s, m_c) (4C_1/3 + C_2 + 6C_3 + 60C_5) \\ & - \frac{1}{2} h(s, m_b) (7C_3 + 4C_4/3 + 76C_5 + 64C_6/3) \\ & - \frac{1}{2} h(s, 0) (C_3 + 4C_4/3 + 16C_5 + 64C_6/3) \\ & + \frac{2}{9} (6C_3 + 32C_5 + 32C_6/3), \end{aligned} \quad (1.17)$$

and the function $h(s, m_q)$ is given by

$$h(s, m_q) = -\frac{4}{9} \left(\ln \frac{m_q^2}{\mu^2} - \frac{2}{3} - z \right) - \frac{4}{9} (2+z) \sqrt{|z-1|} \begin{cases} \arctan \frac{1}{\sqrt{z-1}} & z > 1 \\ \ln \frac{1+\sqrt{1-z}}{\sqrt{z}} - \frac{i\pi}{2} & z \leq 1 \end{cases}, \quad (1.18)$$

where $z = 4m_q^2/s$.

1.2.2 The Effective Hamiltonian

From the Wilson operators given in Equations 1.10 – 1.14, the effective Hamiltonian for the $b \rightarrow s \ell^+ \ell^-$ transition is given by [26, 33]

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i \mathcal{O}_i + \frac{4G_F}{\sqrt{2}} V_{us}^* V_{ub} \left[C_1 (\mathcal{O}_1^{(u)} - \mathcal{O}_1) + C_2 (\mathcal{O}_2^{(u)} - \mathcal{O}_2) \right], \quad (1.19)$$

where the unitarity of the CKM matrix has been used in writing the flavour structure of the Wilson operators $\mathcal{O}_1$ and $\mathcal{O}_2$ in the second term. The matrix element for the

decay is therefore given by [26]

$$\begin{aligned} \mathcal{M}(b \rightarrow s \ell^+ \ell^-) = & \frac{G_F \alpha}{\sqrt{2} \pi} V_{ts}^* V_{tb} \left[\left(C_9^{eff} - C_{10} \right) (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu P_L \ell) + \right. \\ & \left(C_9^{eff} + C_{10} \right) (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu P_R \ell) - \\ & \left. 2 C_7^{eff} \left(\bar{s} i \sigma_{\mu\nu} \frac{q^\nu}{q^2} m_b P_R b \right) (\bar{\ell} \gamma^\mu \ell) \right], \end{aligned} \quad (1.20)$$

where q^ν is the four momentum of the di-lepton system and C_7^{eff} and C_9^{eff} are given in Equations 1.15 and 1.16. In the kinematic region below the $c\bar{c}$ pair threshold ($q^2 \lesssim 7 \text{ GeV}^2$), the double differential decay spectrum is given by [33]

$$\begin{aligned} \frac{d^2 \Gamma}{dq^2 d \cos \theta_{FB}} = & \frac{G_F^2 |V_{ts}^* V_{tb}|^2}{128 \pi^3} M_{B_d}^3 \lambda(q^2, M_{K^*}^2)^3 \left(\frac{\alpha_{EM}}{4\pi} \right)^2 \\ & \left[(1 + \cos^2 \theta_{FB}) \frac{2q^2}{M_{B_d}^2} \xi_\perp(q^2)^2 \left(|C_{9,\perp}(q^2)|^2 + C_{10}^2 \right) \right. \\ & + (1 - \cos^2 \theta_{FB}) \left(\frac{E \xi_\parallel(q^2)^2}{M_{K^*}} \right)^2 \left(|C_{9,\parallel}(q^2)|^2 + C_{10}^2 \Delta_\parallel(q^2)^2 \right) \\ & \left. - \cos \theta_{FB} \frac{8q^2}{M_{B_d}^2} \xi_\perp(q^2)^2 \Re \{ C_{9,\perp}(q^2) \} C_{10} \right], \end{aligned} \quad (1.21)$$

where θ_{FB} is the lepton angle used to construct the forward-backward asymmetry (defined in Section 1.3) and

$$\lambda(q^2, M_{K^*}^2) = \left[\left(1 - \frac{q^2}{M_{B_d}^2} \right)^2 - \frac{2M_{K^*}^2}{M_{B_d}^2} \left(1 + \frac{q^2}{M_{B_d}^2} \right) + \frac{M_{K^*}^4}{M_{B_d}^4} \right]^{1/2}. \quad (1.22)$$

The functions $\xi_\perp(q^2)$ and $\xi_\parallel(q^2)$ are given in reference [33] and describe the form factors for the $B_d \rightarrow K^*$ in the heavy (b) quark and high energy limits. The expressions for the effective Wilson coefficients $C_{9,\perp}$ and $C_{9,\parallel}$ are also given in reference [33]. The coefficient $C_{9,\perp}$ is important for the forward-backward asymmetry and is given by

$$C_{9,\perp}(q^2) \equiv C_9 + Y(q^2) + \frac{2m_b M_{B_d}}{q^2} C_7^{eff} + \dots \quad (1.23)$$

In order to calculate the branching ratio for this decay it is necessary to know the form factors for the $B_d \rightarrow K^*$ transition. These can be estimated using a variety of techniques

which factorise the momentum scales. These include HQET, where the velocity of the heavy quark bound in a meson is assumed to be constant in a fixed momentum scattering, and Soft-Collinear-Effective-Theory (SCET), where the light hadronic decay products have large energy, $\mathcal{O}(m_b)$ [36]. A number of SM predictions for the branching ratio are given in Table 1.1, together with the most recent experimental measurements.

Reference	Branching ratio ($\times 10^{-6}$)
Ali et al. (1999) [27]	1.9 ± 0.5
Lunghi et al. (2002) [37, 38]	1.19 ± 0.39
Ali (2002) [39]	1.2 ± 0.4
Zhong (2003) [40]	$1.78^{+0.49}_{-0.70}$
Belle (2003) [41]	$1.33^{+0.42}_{-0.37} \pm 0.1 \pm 0.05$
BaBar (2006) [42]	$0.87^{+0.38}_{-0.33} \pm 0.12$
PDG average (2006) [1]	$1.22^{+0.38}_{-0.32}$

Table 1.1: A summary of the SM branching ratio predictions and experimental results for $B_d^0 \rightarrow K^* \mu^+ \mu^-$.

1.3 The Forward-Backward Asymmetry

The forward-backward asymmetry (A_{FB}) is constructed from the lepton angle (θ_{FB} in Equation 1.21) which is defined as the angle between the positive (negative) muon and the B_d -meson ($\bar{B}_d^0$ -meson), in the di-muon rest frame. The asymmetry is then the difference between the number of forward-going events ($\theta_{FB} < \pi/2$) and backward-going events ($\theta_{FB} > \pi/2$) divided by the total number of events:

$$A_{FB}(q^2) = \frac{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_{FB}} d\cos\theta_{FB} - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_{FB}} d\cos\theta_{FB}}{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta_{FB}} d\cos\theta_{FB} + \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta_{FB}} d\cos\theta_{FB}}. \quad (1.24)$$

With this definition, the first two terms in Equation 1.21 with $(1 \pm \cos^2\theta_{FB})$ dependence produce no A_{FB} and it is therefore only the third term which generates a non-zero asymmetry. This term arises from the interference between the vector and axial-vector lepton currents and is related to the different left- and right-handed chiral couplings of the leptons to the Z and $W^+ W^-$ bosons from the penguin loop [43]. The asymmetry,

as a function of the di-muon mass, is therefore proportional to $\xi_\perp(q^2)^2 \Re\{C_{9,\perp}(q^2)\}$ and has a zero point if $\Re\{C_{9,\perp}(q^2)\} = 0$. At leading order this requires [33]

$$\Re\{C_9^{eff}\} = C_9 + \Re\{Y(q_0^2)\} = -\frac{2\hat{m}_b}{\hat{s}_0} C_7^{eff}, \quad (1.25)$$

where $\hat{s}_0 = q_0^2 / M_{B_d}^2$ and $\hat{m}_b = m_b / M_{B_d}$.

At the Leading-Log approximation and within the Large-Energy-Effective-Theory the prediction for the zero-crossing point is [11, 27]

$$\Re\{C_9^{eff}\} = -\frac{2\hat{m}_b}{\hat{s}_0} C_7^{eff} \frac{1 - \hat{s}_0}{1 + M_{K^*}^2 - \hat{s}_0}. \quad (1.26)$$

The value of $\hat{s}_0$ is nearly independent of the form factor models because the relevant ratios are free from hadronic uncertainties in the combined heavy quark and large energy limit. The measurement of the zero-crossing point of the forward-backward asymmetry therefore provides a clean measurement of the relevant Wilson coefficients C_9 and C_7^{eff} . The absolute value of C_7^{eff} can be determined from $B \rightarrow X_s \gamma$ decays [27] – the experimentally measured value for this branching ratio is $(3.54 \pm 0.26) \times 10^{-4}$ [1], in good agreement with the SM prediction of $(3.28 \pm 0.33) \times 10^{-4}$ [29]. This measurement gives $C_7^{eff}(M_{B_d}) = 0.37 \pm 0.01$ for the Wilson Coefficient [27]. From Equation 1.25 it can be seen that the forward-backward asymmetry only has zero-crossing point if $\text{Sign}(\Re\{C_9^{eff}\}C_7^{eff}) = -1$. Combined with the sign of the A_{FB} distribution and data from $B \rightarrow X_s \gamma$ this allows the dominant Wilson coefficients to be unambiguously determined [44]. Deviations from the SM predictions would therefore be a sign of new physics. A number of SM predictions for the A_{FB} zero-crossing point are given in Table 1.2. The A_{FB} distribution, calculated in the SM, is shown in Figure 1.6, taken from reference [33].

The current experimental measurements of the forward-backward asymmetry, from the B-factory experiments (BaBar and Belle) are shown in Figures 1.7 and 1.8 [42, 50, 51]. Both experiments have collected ~ 100 $B_d^0 \rightarrow K^* \ell^+ \ell^-$ events [42, 50] and the CDF experiment has collected ~ 35 $B_d^0 \rightarrow K^* \mu^+ \mu^-$ events [52]. With the projected total data sets for these experiments (~ 500 , ~ 750 and ~ 8 fb^{-1} for BaBar, Belle and CDF respectively [53, 54]) a total of ~ 600 events should be observed.

Reference	Zero-crossing point (GeV^2/c^4)
Burdman (1998) [45]	3.9
Ali et al. (1999) [27]	$2.88^{+0.44}_{-0.28}$
Beneke et al. (2001) [33]	4.2 ± 0.6
Hurth et al. (2004) [46]	3.9 ± 0.25
Beneke et al. (2005) [47]	$4.36^{+0.33}_{-0.31}$
Ali et al. (2006) [48]	$4.07^{+0.16}_{-0.13}$
Hurth et al. (2007) [49]	3.5 ± 0.12

Table 1.2: A summary of the SM predictions for the A_{FB} zero-crossing point in the decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$.

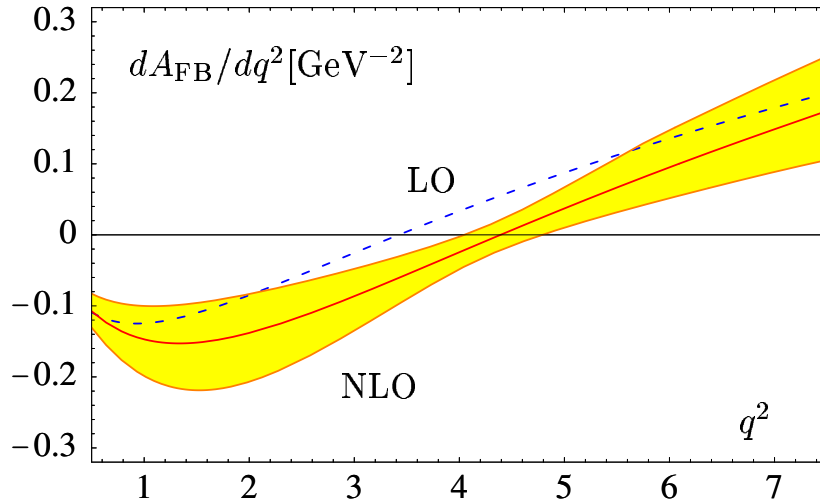


Figure 1.6: The A_{FB} distribution at NLO in the SM [33].

1.3.1 The Effect of Non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ Decays

The non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ decay is potentially a dangerous background for the analysis of the $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decay because of the common final state, since the K^* is observed through its decay to $K^+ \pi^-$. This decay mode has not been experimentally observed [1] and furthermore is not considered to be a significant background to the $K^* \mu^+ \mu^-$ analyses at BaBar or Belle [41, 42]. However, with the large statistics of the LHC experiments this mode may become significant.

The effect of the non-resonant events on A_{FB} depends on the kinematics of the

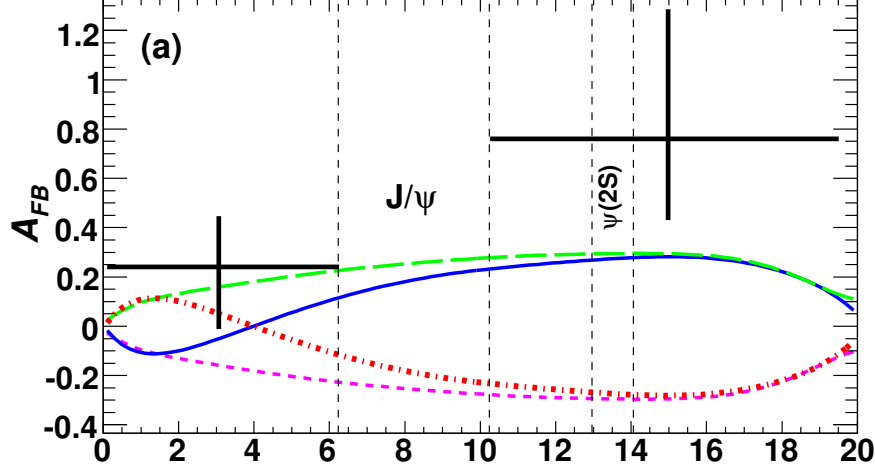


Figure 1.7: The measured forward-backward asymmetry distribution from 384M $B\bar{B}$ events with the BaBar experiment [55]. The solid, long-dashed, short-dashed and dot-dashed lines show the predictions of the SM, the case with $C_7 = -C_7(\text{SM})$, the case with $C_9C_{10} = -C_9C_{10}(\text{SM})$ and the case with $C_7 = -C_7(\text{SM})$ and $C_9C_{10} = -C_9C_{10}(\text{SM})$ respectively.

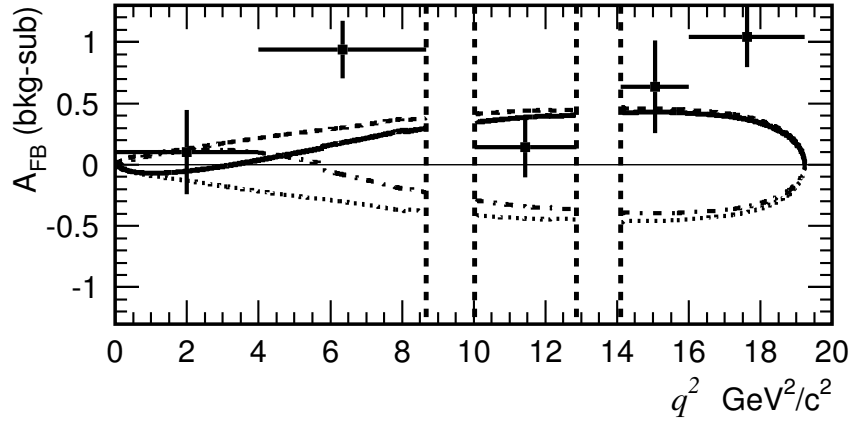


Figure 1.8: The measured forward-backward asymmetry distribution from 386M $B\bar{B}$ events with the Belle experiment [50]. The solid line shows the fit result for $C_7 < 0$. The dashed (dot-dashed) line shows the prediction with C_7 (C_{10}) > 0 . The dotted line shows the prediction for the case C_7 and $C_{10} > 0$.

decay [56]. The authors of reference [56] divide the phase space into three regions, as shown in Figure 1.9:

- **Region I** : soft pion and energetic kaon ($E_\pi \lesssim 1$ GeV and $E_K \gtrsim 1$ GeV)
- **Region II** : collinear pion and kaon ($E_\pi \gtrsim 1$ GeV and $E_K \gtrsim 1$ GeV)
- **Region III** : soft kaon ($E_K \lesssim 1$ GeV)

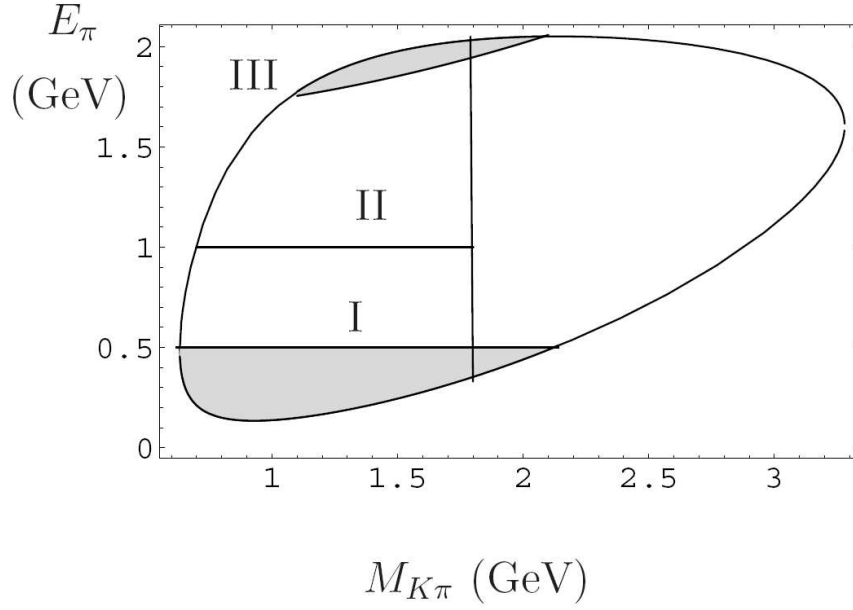


Figure 1.9: The phase space of the decay $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ at $q^2 = 4 \text{ GeV}^2$, in variables E_π and $M_{K\pi}$ [56]. The regions I, II and III are defined in the text. Region I is the area below the $E_\pi = 1$ GeV line. Region III is shown as the upper shaded area. Region II covers the remaining area of the allowed phase space, above the $E_\pi = 1$ GeV line and below region III. The lower shaded area shows the region of applicability of chiral perturbation theory.

In general, the non-resonant events produce a forward-backward asymmetry with a zero-crossing point which depends on the mass of the hadronic system and the energy of the pion: $q_0^2 = q_0^2(M_{K\pi}, E_\pi)$. In principle this is also true for the resonant K^* events since they are experimentally observed through the decay $K^* \rightarrow K^+ \pi^-$ and so could introduce a shift in the zero-crossing point. In Region II, where the kaon and pion are collinear, the non-resonant events behave like the resonant events and there is not expected to be any relative shift in the zero-crossing point. However, in Region I, the correction from the non-resonant amplitude becomes significant and introduces a shift in the zero-crossing point of A_{FB} with respect to the resonant events and with respect

to the zero-crossing point in Region II. The amplitude in Region III is suppressed and this region is not considered in reference [56].

The plot in Figure 1.10, taken from reference [56], shows the effect of including these contributions to the A_{FB} zero-crossing point for a variety of different E_π cuts used to separate the two regions. The difference in these curves is a measure of the uncertainty in the procedure. The dotted line shows the prediction for the zero-crossing point without these corrections.

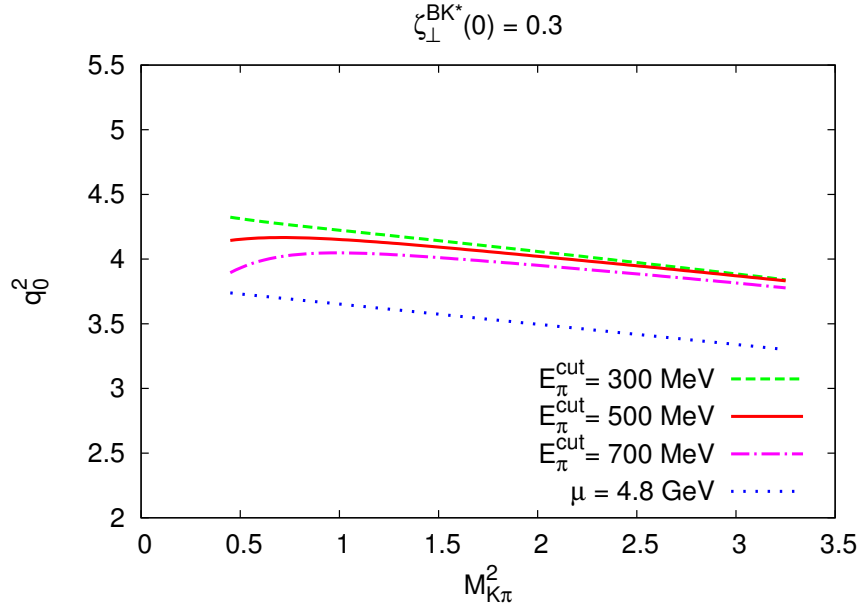


Figure 1.10: The A_{FB} zero-crossing points (q_0^2) as a function of the invariant mass of the $K^\pm \pi^\mp$ system [56].

1.4 Other Angular Correlations

In addition to θ_{FB} , used to construct A_{FB} as described above, other angular correlations exist in the decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$. Assuming the K^* to be on mass-shell, the decay kinematics are completely described by four variables: the $\mu\mu$ -mass and the three decay angles (θ_{FB} , θ_K and ϕ) shown in Figure 1.11.

In the limit where the initial hadron is heavy and the final meson has large energy, the $B_d^0 \rightarrow K^*$ transition can be described by two universal form factors [57]. It is useful to rewrite the helicity amplitudes H_{+1} , H_{-1} , H_0 and H_t , in terms of the transversity

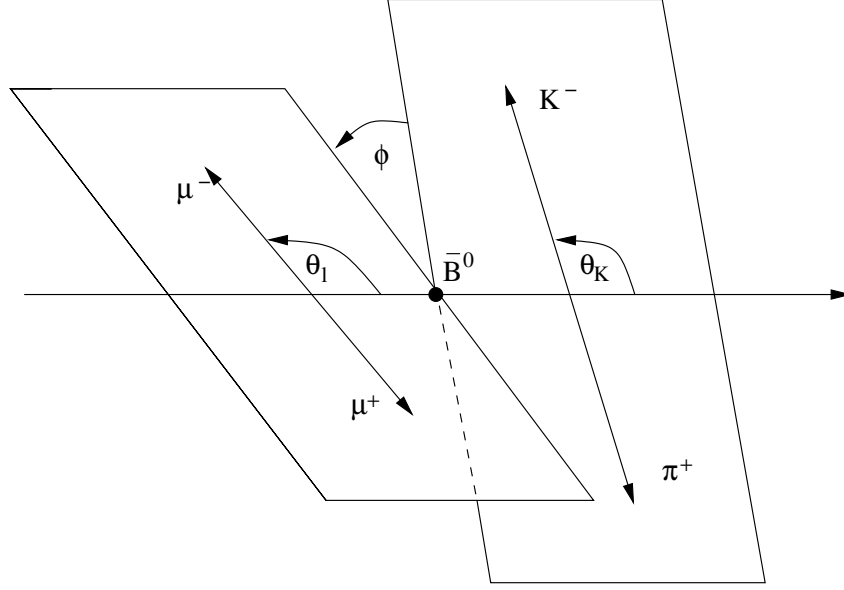


Figure 1.11: The angles used to describe the $\bar{B}_d^0 \rightarrow \bar{K}^* \mu^+ \mu^-$ decay, measured in the $\mu\mu$ rest frame. The z-axis is the direction of the B-meson in this frame. θ_{FB} (θ_l in the diagram) is the angle between the μ^- and the z-axis. θ_K is the angle between the K^- and z-axis. ϕ is the angle between the planes defined by the $\mu\mu$ system and K^* decay products.

amplitudes $A_\perp$, $A_\parallel$, A_0 and A_t , where [57, 58]

$$A_{\perp,\parallel} = (H_{+1} \mp H_{-1}) / \sqrt{2}; \quad A_0 = H_0; \quad A_t = H_t. \quad (1.27)$$

New transversity variables can then be defined (as in Equation 1.28), as ratios of the transversity amplitudes in which the theoretical uncertainties largely cancel

$$\begin{aligned} A_T^{(1)}(s) &= \frac{-2\Re\{A_\parallel A_\perp^*\}}{|A_\perp|^2 + |A_\parallel|^2}; \\ A_T^{(2)}(s) &= \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}; \\ \alpha_{K^*}(s) &= \frac{2|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} - 1; \\ F_L(s) &= \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}; \\ F_T(s) &= \frac{|A_\perp|^2 + |A_\parallel|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}. \end{aligned} \quad (1.28)$$

The SM predictions for these variables are shown in Figure 1.12.

Experimentally, these variables can be extracted by simultaneously fitting the angular distributions θ_{FB} , θ_K and ϕ , as a function of q^2 [59].

1.5 $B_d^0 \rightarrow K^* \mu^+ \mu^-$ in New Physics Scenarios

Although the SM currently describes the wealth of experimental evidence, there are good reasons to believe that it is not a complete theory. As it stands the SM provides no description of the origin of mass; however, the Higgs mechanism, proposed in reference [60, 61], can solve this. The proposed Higgs field has a broken symmetry which generates mass terms for the gauge bosons and predicts the existence of a new particle – the Higgs-boson. The search for this boson has been a major theme in particle physics for the past decade and it should be discovered or ruled out by the general purpose detectors at the LHC. In calculating the Higgs-boson mass the one-loop corrections involve a sum over all fermions, as in Figure 1.13(a). This introduces a term in the Higgs mass which depends on the cut-off scale in the integral over the fermion momenta (typically assumed to be $\mathcal{O}(M_{Planck})$). Therefore, in order to reduce the Higgs mass to the TeV scale, either some unnatural cancelling of the divergent terms is needed or a further symmetry must be imposed. The most popular theory for this is SuperSymmetry (SUSY) [62], in which each SM fermion has a SUSY scalar partner. The couplings of the SUSY scalars (see Figure 1.13(b)) to the Higgs produce terms in the mass calculation with the opposite sign to their SM partners, thus naturally cancelling the leading divergent terms.

All the angular distributions in the decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$ can be modified in new physics scenarios [58]. The existence of physics beyond the SM could therefore be discovered by measuring the properties of rare B-decays. Although new particles are unlikely to be observed directly (any new particles should have masses greater than the B-mass), their effect in the virtual loops of flavour-changing-neutral currents could strongly affect the decay properties. For example, new particles could affect the values of the Wilson coefficients, as new heavy degrees of freedom are integrated out in the *OPE*. Alternatively, new interactions, for example new effective flavour-changing-neutral-currents, could introduce new Wilson operators to the basis [63].

The effect of a number of SUSY models on the forward-backward asymmetry has been studied in reference [27]. These include:

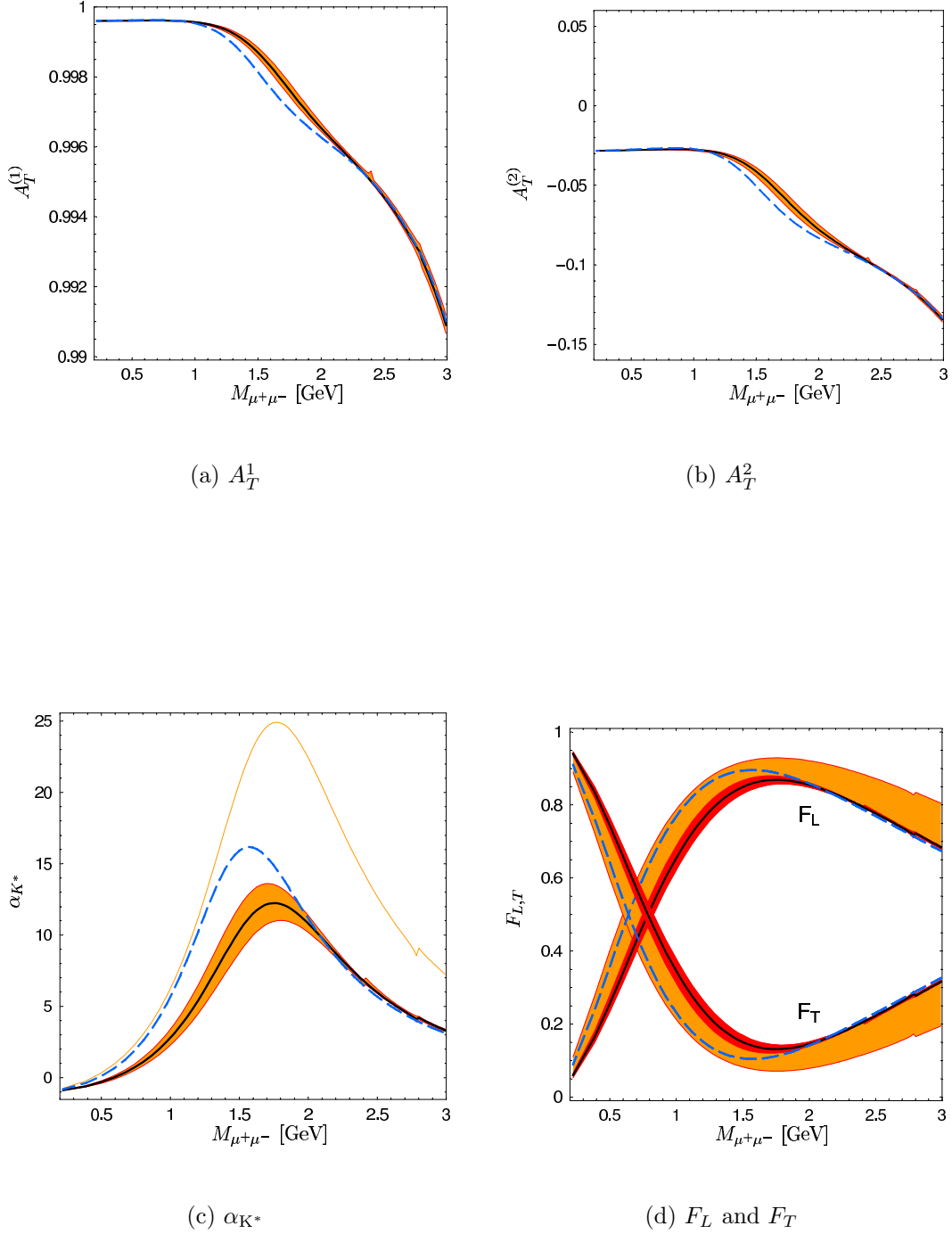


Figure 1.12: The SM predictions for the transversity amplitudes [57]. The dashed (solid) lines show the LL (NLL) calculations. The shaded areas show the changes from varying the input parameters.

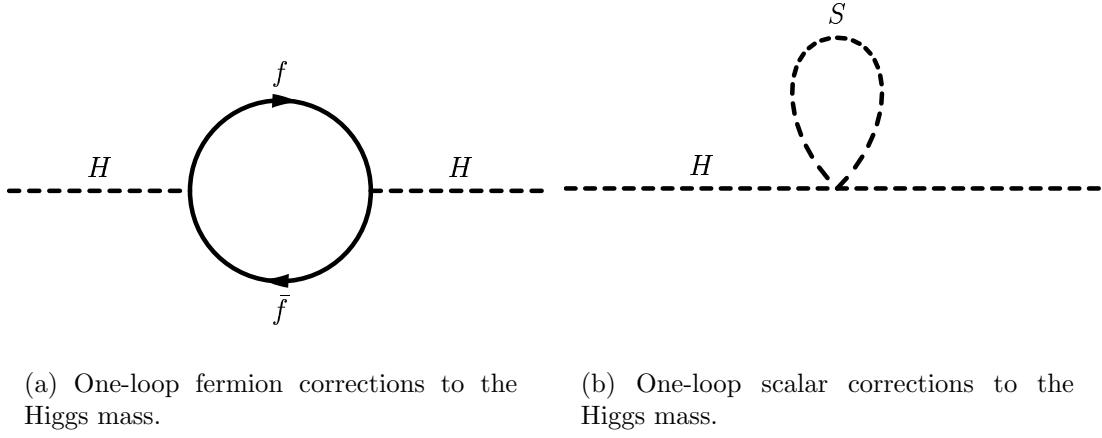


Figure 1.13: The one-loop corrections to the Higgs-boson mass.

- **Supergravity (SUGRA)** : a model where SUSY breaking occurs through a flavour blind gravity-like interaction;
- **Minimal flavour-violating (MFV)** : a SuperSymmetric extension to the SM, where flavour violation is assumed to be solely caused by the charged current sector;
- **Mass insertion approximation (MIA)** : a generic SuperSymmetric extension with non- CKM flavour violations.

The forward-backward asymmetry in these models, and the SM, is shown in Figure 1.14 taken from reference [27]. The asymmetry in a SM extension with four generations is shown in Figure 1.15, taken from reference [64].

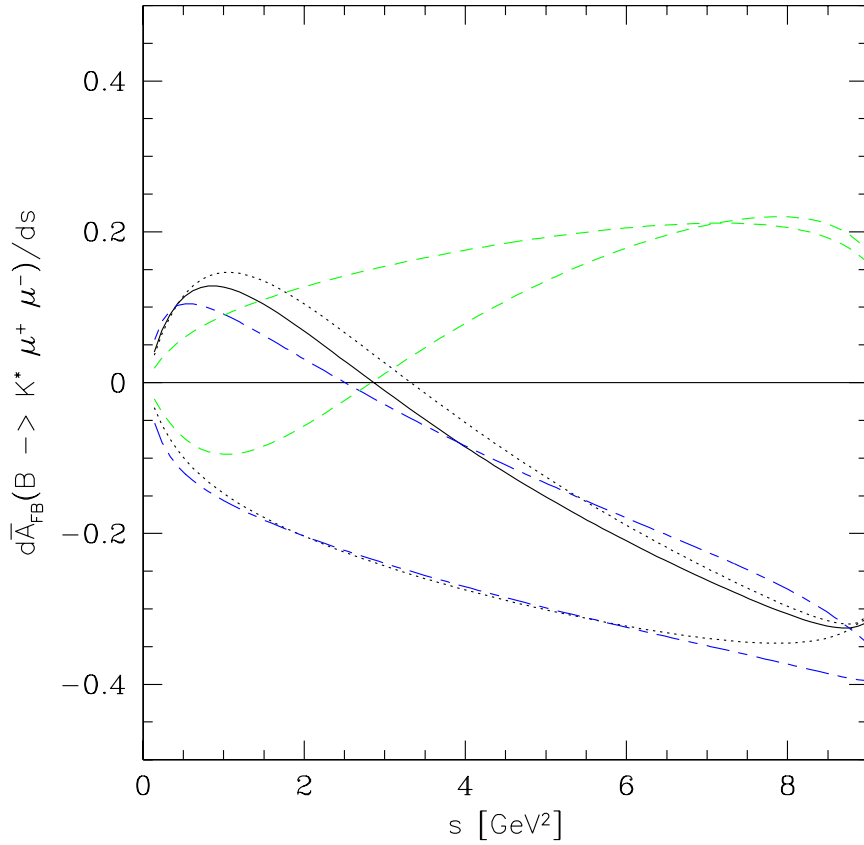


Figure 1.14: The forward-backward asymmetry in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays as a function of the $\mu\mu$ -mass squared (s) [27]. The solid line gives the SM prediction. The dotted (long-short dashed) lines correspond to the SUGRA (MIA-SUSY) models with the upper and lower curves representing $C_7^{eff} < 0$ and $C_7^{eff} > 0$ respectively. The dashed curves (with positive asymmetry for large s) correspond to the MIA-SUSY models in the “best-depression scenario” [65].

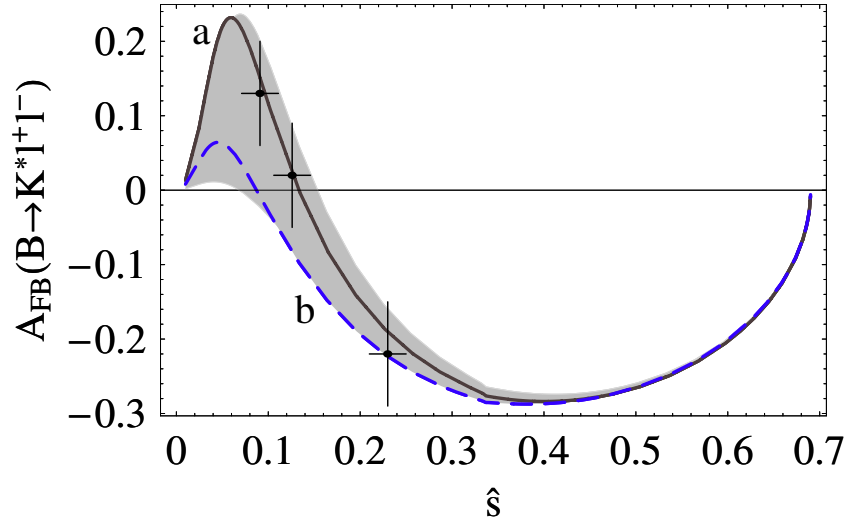


Figure 1.15: The forward-backward asymmetry in $B_d^0 \rightarrow K^* \ell^+ \ell^-$ decays as a function of the $\mu\mu$ -mass squared, normalised to $M_{B_d}^2$ ($\hat{s}$) for the SM (solid) and 4th generation model [64]. The points show a possible 2 fb⁻¹ measurement from LHCb.

Chapter 2

The LHCb Experiment at the LHC

The LHCb experiment is the only dedicated b-physics experiment at the Large Hadron Collider (LHC) at CERN. The accelerator and detectors are constructed and are now being commissioned before initial running. This chapter gives a brief description of the LHC accelerator and heavy flavour production at the LHC before presenting the details of the LHCb detector.

2.1 The Large Hadron Collider

The LHC will accelerate protons in two counter-rotating beams around a 27 km circular ring [66, 67]. The accelerator has been constructed in the tunnel previously used to house the Large Electron and Positron (LEP) collider [68]. The installation of the LHC is nearing completion [69], with all magnets now installed. The ~ 1200 superconducting dipole magnets produce a magnetic field strength of ~ 8 T to bend the protons round the ring. The dipole magnets will operate at a temperature of 1.9 K, cooled by a large bath of liquid helium [67]. A photograph of one of the LHC dipole magnets is shown in Figure 2.1.

The LHC beam acceleration and injection scheme is shown schematically in Figure 2.2 [70]. Protons are created from a hydrogen duoplasmatron source and accelerated to an energy of 50 MeV in linear accelerators [71, 72]. The protons are then injected into the Proton-Synchrotron-Booster (PSB) complex consisting of four rings, each one quarter of the size of the Proton-Synchrotron (PS) ring. The PSB rings, each containing one bunch, accelerate the protons to 1.4 GeV for injection into the PS. The bunches



Figure 2.1: An LHC dipole magnet.

injected from the PSB are split, accelerated to 25 GeV and then further split to create the 25 ns bunch train necessary for LHC operation. This process also creates the necessary gaps in the beam structure to allow time for the extraction magnets to be ramped up. The beam is then extracted into the Super-Proton-Synchrotron (SPS), where it is accelerated to 450 GeV and finally injected into the LHC ring. The time to completely fill both LHC rings will be ~ 10 min [73].

The protons in each beam will be grouped in ~ 2800 bunches, each containing $\sim 10^{11}$ protons, spaced at 25 ns intervals. This is less than the maximum number of possible bunches (~ 3600) because empty bunch buckets are inserted as the beam is injected into the SPS. The average rate of crossings, where both beam buckets are filled, is therefore 30 MHz. The beams will be brought together to collide at four points around the ring, in the ATLAS, CMS, ALICE and LHCb detectors, at a centre-of-mass energy of 14 TeV. The LHC will operate at a nominal luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which will produce an average of ~ 37 proton-proton collisions per bunch crossing, where both bunch buckets are filled [74]. For LHCb this would result in too high a detector occupancy for precision b-physics and the luminosity at the LHCb interaction point is therefore reduced by locally de-focussing the beams by a factor of ~ 50 , to a luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ [5]. A diagram of the LHC ring and the four main interaction points is shown in Figure 2.3.

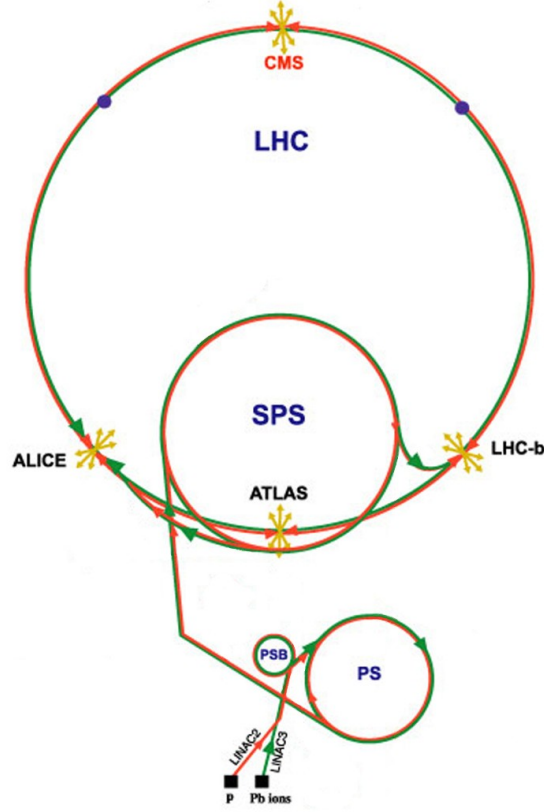


Figure 2.2: The LHC injector complex.

2.2 The LHCb Experiment

The LHCb detector is largely constructed and installed at CERN [75]. The experiment is optimised for measuring charge-parity violation ($\mathcal{CP}$ -violation) and rare phenomena in the decays of heavy flavours (including B-mesons, Λ_b and D-mesons) [5, 76]. The physics of the production and decay of b-hadrons and the consequences for the detector design are described in the following sections.

2.2.1 Heavy Flavour Production at the LHC

The LHC will be the most intense source of b-hadrons at any collider in the world. At the baseline LHCb luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and assuming an inclusive $b\bar{b}$ cross-section of 500 pb, LHCb is expected to produce 10^{12} $b\bar{b}$ pairs per year (10^7 s). This corresponds

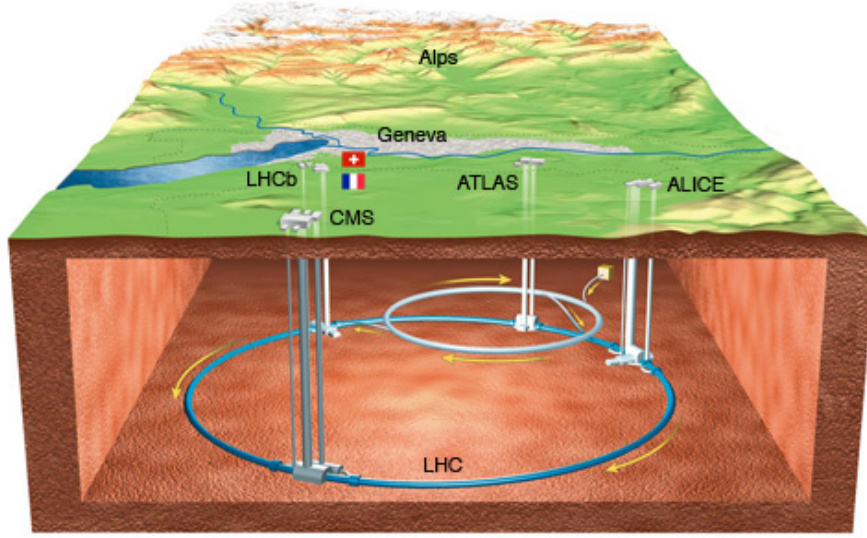


Figure 2.3: The LHC ring and the main experimental interaction site.

to a b -production rate of 100 kHz. Unlike at the PEP-II and KEK accelerators (for the BaBar and Belle experiments) which collide e^+e^- , with a fixed centre-of-mass energy, at a hadron collider the partons involved in the interactions have a range of energies. This means the whole spectrum of b -hadrons will be produced, in approximately the following ratios: B_d (40%), B_u (40%), B_s (10%) and b -baryons (10%) [1].

The cross-section for b -quark production at the LHC can be calculated using perturbative QCD because of the large b -quark mass in comparison to the QCD scale (~ 1 GeV) [77]. At leading-order (LO) two processes are allowed: gluon-gluon fusion (gg -fusion), shown in Figure 2.4(a), and quark-antiquark annihilation ($q\bar{q}$ -annihilation), shown in Figure 2.4(b). At next-to-leading-order (NLO) the flavour excitation process, where the heavy quark is assumed to be already present in the colliding hadron, is allowed. The Feynman diagrams for this process are a sub-set of the NLO gg -fusion virtual emission diagrams and are therefore not included explicitly in the cross-section calculations [78]. The gg -fusion process is expected to be dominant [79, 80]. Using predictions of the proton parton distribution functions (for example, from reference [81]) and the LO matrix elements for b -quark production, it is expected that the gg -fusion process will produce $b\bar{b}$ pairs with higher transverse momentum than the $q\bar{q}$ -annihilation process. Given the forward rapidity range of the LHCb detector ($1.8 < \eta < 4.9$), the $q\bar{q}$ -annihilation process is therefore expected to be enhanced with respect to the central ATLAS and CMS detectors.

The $b\bar{b}$ production cross-section is suppressed as the rapidity difference between the

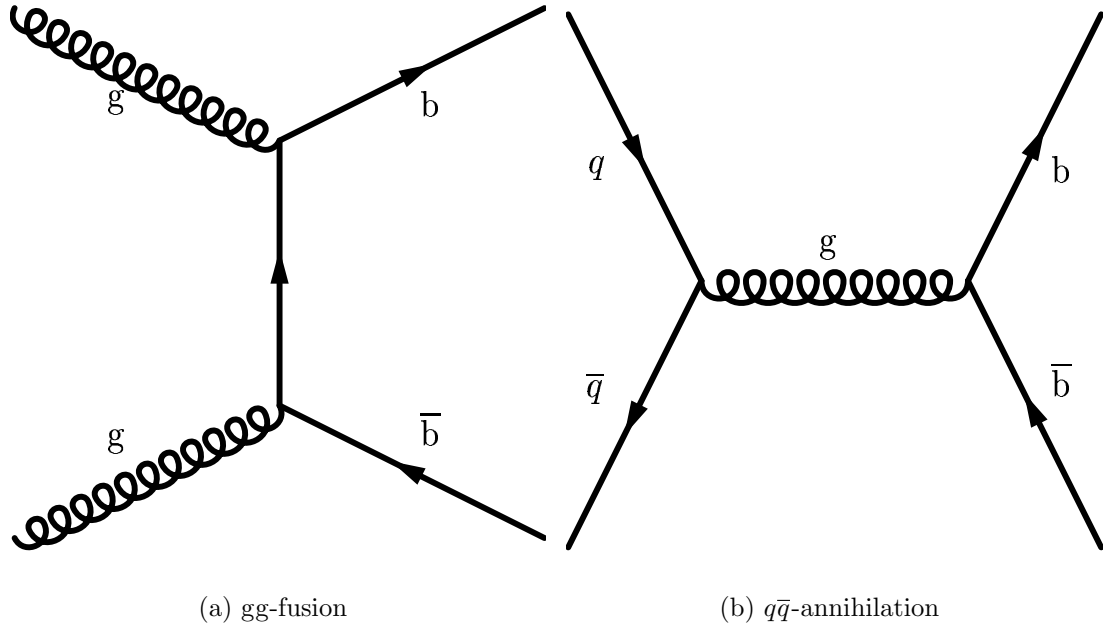


Figure 2.4: Leading order Feynman diagrams for heavy quark production.

b -quark and $\bar{b}$ -antiquark increases [80]. The polar angles of the b - and $\bar{b}$ -quarks will therefore be highly correlated. The cross-section is also suppressed as the transverse mass (defined as the sum in quadrature of the b -quark mass and the transverse momentum with respect to the beam-line, p_T) of the system increases. These two effects mean that the b - and $\bar{b}$ -quarks are expected to be produced with a small rapidity difference and small p_T , i.e. the quarks will predominately be produced both in the forward- or both in the backward-directions, as shown in Figure 2.5. This has consequences for the design of the LHCb detector since if the b -quark is produced within the detector acceptance it is likely that the $\bar{b}$ -antiquark will also be produced within the acceptance.

A single-arm forward spectrometer design was chosen for the LHCb detector because of space constraints in the cavern and budget considerations. The extra precision gained from using all the available space for a forward spectrometer out-weighs the loss in statistics from a detector with full angular coverage. In fact, the loss in statistics from the reduced coverage is only a factor of two because of the correlation between the production angles of the b -quark and $\bar{b}$ -antiquark. This is particularly important for b -tagging studies, where the flavour of the B -particle of interest is determined at production by a measurement of the flavour of the other B -particle in the event, requiring both particles to be in the detector acceptance. The LHCb detector is therefore a single-arm forward spectrometer, with a maximum angular acceptance of 300 mrad in the

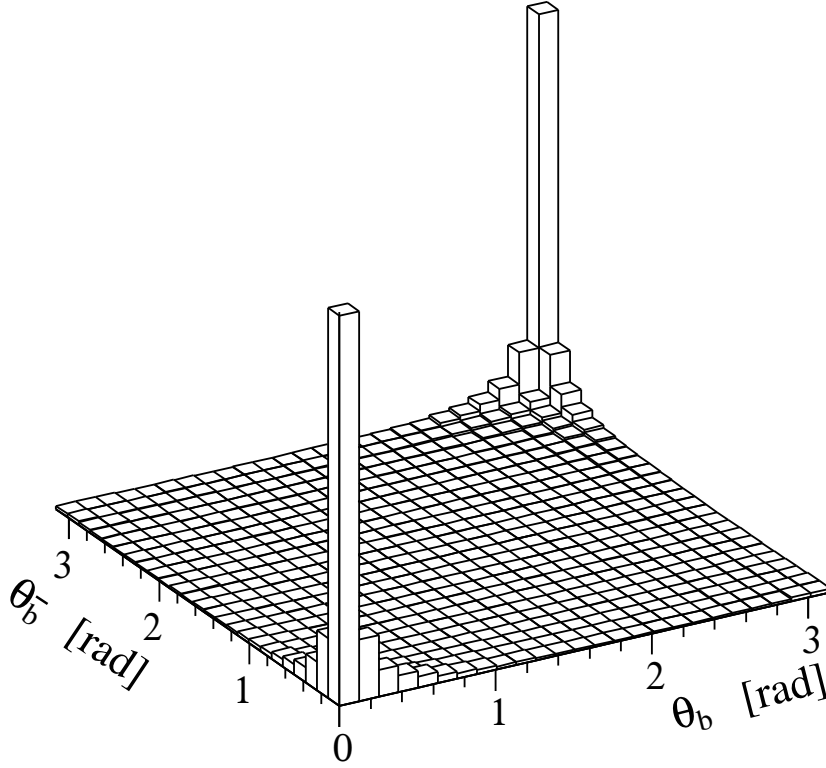


Figure 2.5: The polar production angle with respect to the beam line (θ_b and $\theta_{\bar{b}}$) of b-hadrons at the LHC [5].

bending (horizontal) plane and 250 mrad in the non-bending (vertical) plane. The inner acceptance, 10 mrad, is defined by the beam pipe. The LHCb detector is shown in Figure 2.6 and a photograph of the experimental cavern is shown in Figure 2.7.

2.2.2 b-Hadron Decays

The tree-level weak decays of b-hadrons proceed through the *CKM*-suppressed $b \rightarrow c$ and $b \rightarrow u$ transitions because the *CKM*-favoured $b \rightarrow t$ transition is kinematically forbidden owing to the large top-quark mass, $m_t \sim 175 \text{ GeV}/c^2$ [1].

The small values of the inter-generation *CKM*-factors ($|V_{ub}| = (4.31 \pm 0.30) \times 10^{-3}$ and $|V_{cb}| = (41.6 \pm 0.6) \times 10^{-3}$ [1]) results in a long B-meson proper lifetime, $\tau_b \sim \mathcal{O}(1) \text{ ps}$ [82]. At LHCb the typical b-hadron momentum is $\sim 80 \text{ GeV}/c$ giving a typical decay length of $\sim 1 \text{ cm}$ [5]. These displaced decay vertices are an excellent signature of b-hadron decays and the LHCb detector must be able to detect them and

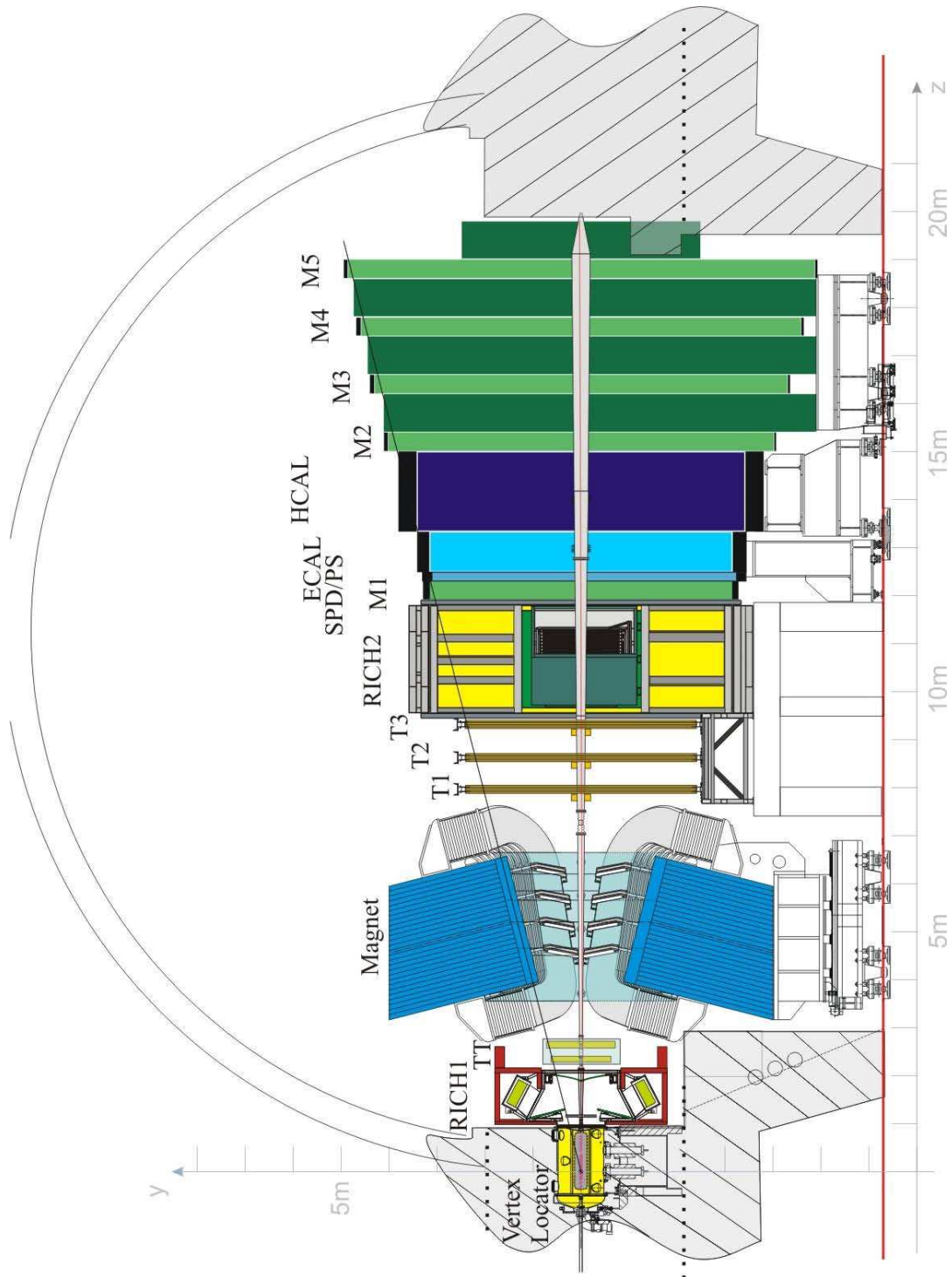


Figure 2.6: The LHCb detector. The downstream direction is defined as the direction of increasing z . The vertex locator is shown at $z = 0$, followed by the first particle identification (pID) detector (RICH1) and the first tracking station (TT). Downstream of the magnet are the three tracking stations (T1 – T3), the second pID detector (RICH2), the first muon station (M1), the calorimetry system (SPD/PS/ECAL/HCAL) and the other muon stations (M2 – M5).

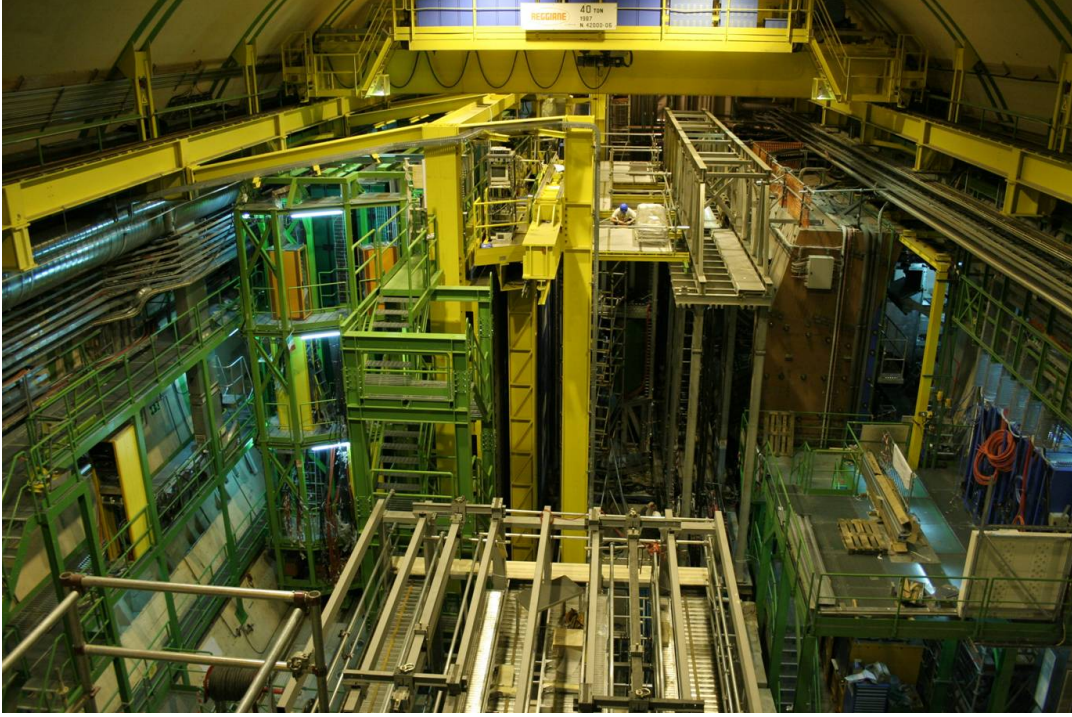


Figure 2.7: A photograph of the LHCb cavern with the detector installed.

distinguish them from the primary interaction vertex (PV). The Vertex Locator (VELO) sub-detector, described in Section 2.2.6 was designed for this purpose. Precise vertexing in the VELO is also necessary to measure B-meson lifetimes.

To make precise $\mathcal{CP}$ -violation and rare B-decay measurements, the LHCb detector must be capable of reconstructing charged particle tracks with high efficiency, up to $\sim 150 \text{ GeV}/c$, for example in the decays $B_s^0 \rightarrow K^+ K^-$ and $B_d^0 \rightarrow \pi^+ \pi^-$. Many of the other decay modes under study at LHCb also have charged hadrons in the final state. Good particle identification is therefore essential and the Ring Imaging Cherenkov (RICH) sub-detectors, described in Section 2.2.7, provide crucial information for this purpose. The calorimeter sub-detectors, described in Section 2.2.9, provide particle identification information for neutral particles and electrons. The muon sub-detectors, described in Section 2.2.10, provide information for muon identification.

Good mass resolution is required to reduce the background in the reconstructed mass signal region. For example in the $B_d^0 \rightarrow \pi^+ \pi^-$ analysis the expected mass resolution of $17 \text{ MeV}/c^2$ will allow a tight mass window to be applied which will suppress the backgrounds from other two-body modes by a factor three [5]. To achieve a mass resolution of $\sim 20 \text{ MeV}/c^2$ requires a momentum resolution of at least $\delta p/p \sim 0.4\%$. Assuming

equal contributions from resolution and multiple scattering effects, this requires that the track resolution per measured point is $\sim 200 \mu\text{m}$. The LHCb tracking system, designed to achieve this resolution, is described in Section 2.2.8.

Many $\mathcal{CP}$ -violation measurements, for example in the decay $B_d^0 \rightarrow J/\psi K_S^0$, and rare decay measurements, for example in the decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$, require efficient $\mu^\pm$ identification. High p_T muons, above $\sim 2 \text{ GeV}/c$, can provide a clean signal for the trigger system because of their penetrating power. The muon sub-detector system is described in Section 2.2.10.

An efficient trigger system is essential to select those decays of interest to be recorded. Approximately 0.25% of bunch-crossings at the LHC produce b-quark pairs and, of those, the decays of interest typically have branching ratios $\mathcal{O}(10^{-4})$. The trigger system takes advantage of the long B-meson lifetime and high mass to select events with displaced secondary vertices and high- p_T tracks.

In summary, the main components of the LHCb detector are: the vertex locator (VELO), the ring imaging Cherenkov (RICH) detectors, the tracking system, the calorimeter system, the muon detector and the trigger system. These various sub-detectors, designed to meet the physics requirements, are described in the following sections. A large portion of the work described in this thesis is related to the RICH system, which is described in Section 2.2.7.

2.2.3 LHCb Nominal Luminosity

The number of pp interactions per bunch crossing is described by a Poisson distribution with mean

$$\mu = \frac{\mathcal{L} \sigma}{f}, \quad (2.1)$$

where $\mathcal{L}$ is the luminosity, σ is the pp interaction cross-section and f is the bunch crossing frequency (30 MHz). The pp inelastic scattering cross-section is expected to be $(111.5 \pm 1.2^{+4.1}_{-2.1}) \text{ mb}$ at the LHC [83] and will be measured by the TOTEM experiment [84]. The probability of a given number of interactions per bunch crossing is shown in Figure 2.8, as a function of luminosity. At the nominal luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, LHCb would expect an average of 37 inelastic pp interactions per bunch crossing. This would result in detector occupancies, particularly in the tracking stations, far above the

acceptable levels imposed by budgetary and technological constraints. Bunch crossings with multiple interactions are also less useful for b-tagging and lifetime studies because of the ambiguities arising from possible multiple primary vertices.

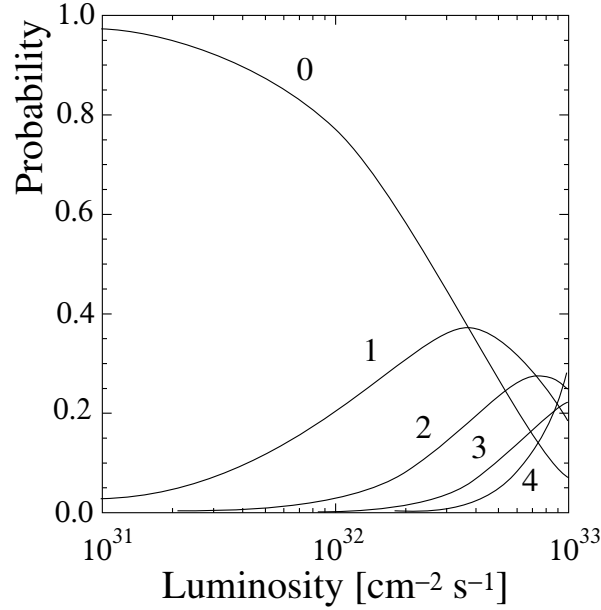


Figure 2.8: The pp interaction probability as a function of luminosity, assuming a cross-section of 80 mb [5]. The curves for zero, one, two, three and four interactions per bunch crossing are shown.

In order to reduce the number of crossings with multiple interactions and maximise the number of single interaction crossings, LHCb will run at a reduced luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ [76]. This will be achieved by defocussing the proton beams at the interaction point. The reduced luminosity means that an average of 0.74 pp interactions per bunch crossing is expected. The rate of single (multiple) interaction crossings will be therefore be 10.6 (5.1) MHz. Including the effect of the empty beam buckets, the rate of crossings with no interactions is expected to be 24.2 MHz.

2.2.4 Beam pipe

The LHCb beam pipe passes through the centre of the detector and maintains the vacuum needed for the beam. Because it is in the high rapidity region of the detector it is important to minimise the interaction length of the material in order to reduce the number of secondary particles.

The beam pipe is divided into four sections along its length. The first runs from

the upstream seal to the LHC beam pipe to the downstream edge of the VELO detector; the second runs to the downstream edge of the first RICH (RICH1) detector; the third extends to the upstream edge of the calorimeter system and the final section seals downstream back to the LHC beam pipe [85]. The first section of the beam pipe has a diameter of ~ 1.2 m to accommodate the retractable VELO. The second section, sealed to the VELO exit window, is made of 1 mm thick beryllium. Beryllium was chosen because this section is in a region where it is important to minimise the number of secondary particles from particle–material interactions which would particularly affect the RICH1 and trigger-tracker (TT) station occupancies. The relatively short length, 1.8 m, of this section allowed this choice. The third section consists of two mechanical sections also made from beryllium, between 1.0 and 2.4 mm thick. The two sections have a 10 mrad aperture. The final section is surrounded by the calorimeter and muon systems and is made of ~ 3 mm thick stainless steel.

2.2.5 Magnet

The LHCb dipole magnet is required to have an aperture of at least ± 300 mrad in the horizontal plane and ± 250 mrad in the vertical plane to match the detector acceptance. RICH1 must be in a region of low magnetic field to reduce the bending of charged particle tracks in the gas radiator and to prevent distortions in the photon-detectors. The VELO must also be in a low field region to allow a fast track finding algorithm to be used in the trigger. A small fringe field upstream of the magnet has, however, been introduced to allow for an approximate p_T measurement in the trigger. The magnet is required to provide sufficient field integral for tracks originating near the primary vertex to achieve the required momentum resolution.

The magnet is located downstream of RICH1 [86], which has magnetic shielding to reduce the local field in the region of the photon detectors. A photograph of the magnet is shown in Figure 2.9, viewed from the downstream edge. The coils of the magnet are tilted and offset to follow the detector acceptance. The inner faces of the magnet are placed 100 mm outside the acceptance.

A warm magnet design has been chosen in preference to a superconducting design. This is for two main reasons, the first being that the increased cost of building a superconducting magnet is not compensated for in lower running costs within the expected lifetime of the experiment. The second reason is that a warm magnet allows rapid ramping which in turn means the field polarity can be switched at regular intervals to

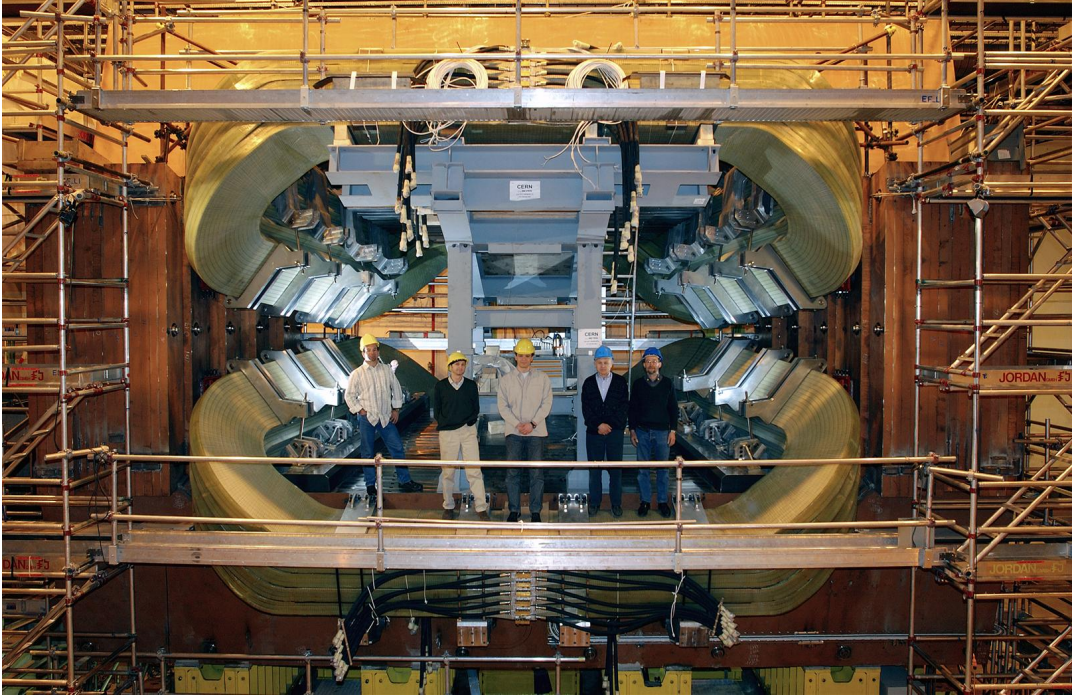


Figure 2.9: The LHCb dipole magnet.

reduce the systematic effect of any left-right detector asymmetries. A vertical field with peak strength of 1.1 T is used. This gives a 4 Tm integrated field, sufficient to measure charged particle momenta with a resolution of $\delta p/p \sim 0.4\%$ [86]. The deflection of particles in the upstream fringe field of the magnet is used to provide an approximate momentum measurement in the trigger [87, 88]. A map of the magnetic field is shown in Figure 2.10.

2.2.6 Vertex Locator Detector

The LHCb Vertex Locator (VELO) is a crucial part of the LHCb tracking system [89]. A schematic of the VELO is shown in Figure 2.11. In order to reconstruct B-decays with a good signal-to-background ratio and perform b-tagging studies, it is necessary to be able to resolve the displaced secondary vertices which are typical of these decays. Since B-mesons at LHC energies fly $\mathcal{O}(1\text{ cm})$ before decaying, the VELO must provide $\mathcal{O}(1\text{ mm})$ resolution on the position of these vertices. Tracks from B-meson decays typically have a large impact-parameter with respect to the PV. The impact-parameter is therefore a useful criterion to distinguish between tracks from B-decays and those from the rest of the event. Mistaking tracks from the PV, for example, for tracks from B-decays will

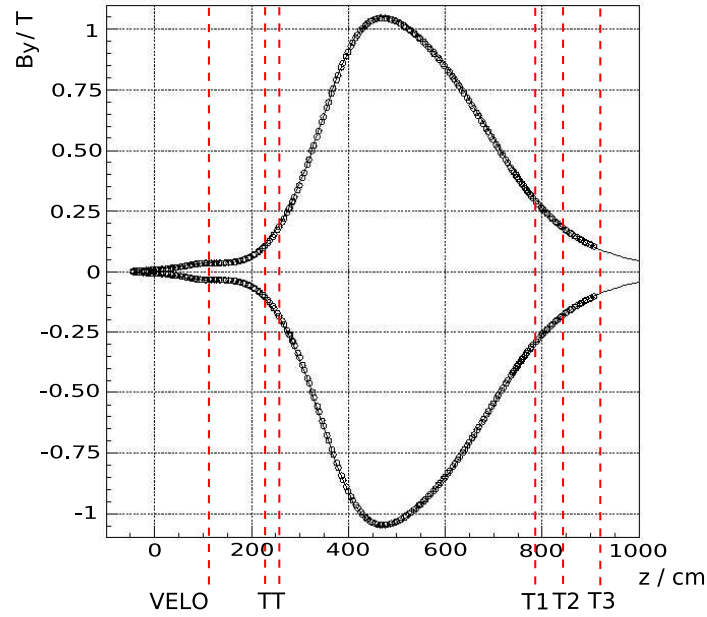


Figure 2.10: The measured on-axis field of the LHCb magnet (i.e. along the beam line). The positions of the tracking stations are also shown.

be a source of combinatorial background, where B-decays are incorrectly reconstructed from other tracks in an event. To determine the impact-parameter requires the position of the PV to be reconstructed and the VELO is therefore the only detector which is, in part, upstream of the nominal interaction point. A pair of dedicated tracking stations, are also placed upstream of the nominal interaction point to provide information for the pile-up veto trigger, as described in Section 2.3.1. The VELO also provides information that is used in a fast tracking algorithm for the trigger.

The VELO comprises 21 tracking stations (modules) divided in two halves. Each station has two silicon sensors (to measure radial and azimuthal positions) and employs a Roman-Pot design to protect the sensors during LHC beam injection. A short track extrapolation distance from the first station to the PV leads to a better impact-parameter resolution and the inner active radius of the VELO sensors should therefore be as small as possible. This is limited by the LHC beam size which during stable running should be less than $100\text{ }\mu\text{m}$ [67], although for safety reasons the distance of closest approach allowed is 5 mm [89]. During injection the *RMS* beam spot size will be $\sim 280\text{ }\mu\text{m}$, approximately four times larger than during stable running. This requires that the silicon modules can be retracted by a distance of 3 cm .

The physical dimensions of the VELO are set by the requirement that any track

within the LHCb angular acceptance of $250 \text{ mrad} \times 300 \text{ mrad}$ should pass through at least three stations. The outer radius of the VELO modules means that the distance between modules must be $\sim 3 \text{ cm}$ in the central region. The position of the last downstream module is defined by the inner angular acceptance (15 mrad) and the minimum distance of the sensors to the beam line.

To enable the VELO sensors to be as close as possible to the beam and with minimal material in the LHCb detector acceptance, the silicon detectors will be operated in a vacuum. The VELO detector therefore effectively acts as an expanded section of the LHC beam pipe. To protect the LHC vacuum from out-gassing, the silicon sensors are placed in a thin aluminium box which forms a secondary vacuum box. The aluminium box also acts as a shield to protect the detector from RF pickup of the wake-fields generated by the LHC beams. The arrangement of the VELO modules and the RF foil is shown in Figure 2.11. The RF foil is corrugated along the beam line in order to allow the two halves of the detector to overlap slightly for alignment.

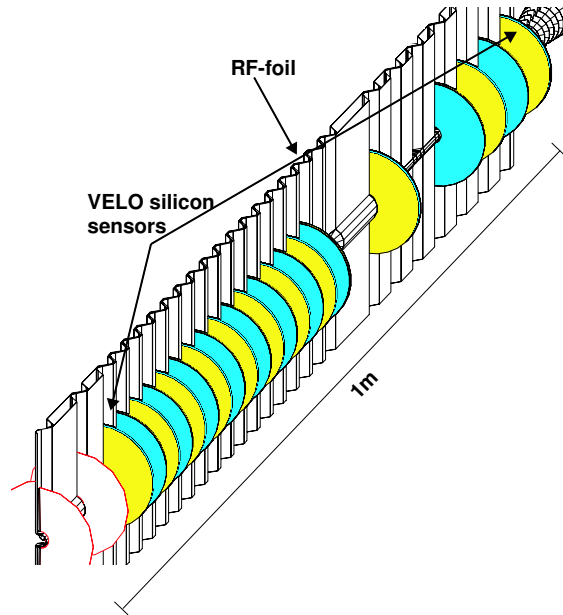


Figure 2.11: The arrangement of the VELO modules and the RF foil.

The VELO sensors have been designed to meet the above requirements [89]. Each sensor is an approximate semi-circular annulus with an outer radius of 42 mm and an opening angle of 182° , to allow some overlap between the two detector halves for alignment. The overall size of the sensor is restricted by the 100 mm wafers used in the production. The inner radius of the active area of the sensors is $\sim 8 \text{ mm}$. This is determined by the safe distance from the LHC beam line (5 mm), the clearances necessary for

the aluminium RF foil and the 1 mm thick guard structures on the silicon. The sensors are populated with silicon strips in radial and azimuthal patterns. The strip layout for the two sensor designs is shown in Figure 2.12. For practical readout reasons the number of channels per sensor is limited to 2048. The radius measuring sensors (R-sensors) are divided into four sectors, each with 512 strips running in concentric circles. The pitch of the silicon strips varies linearly from $40\text{ }\mu\text{m}$ at the inner edge to $101.6\text{ }\mu\text{m}$ at the outer edge. This variation is intended to keep the strip occupancy approximately constant across the detector. The segmentation of the strips in the R-sensors into 45° sections is sufficient to allow the position of the PV to be determined from these sensors alone in the second level of the trigger [89]. The azimuthal angle measuring sensors (ϕ -sensors) are divided into two sections: the inner radius section with 682 strips and the outer radius section with 1366 strips. The strips have a stereo angle of 20° in the inner region and -10° in the outer region. The ϕ -sensors therefore mainly provide information on the azimuthal angle of the detected hit but also some radial information.

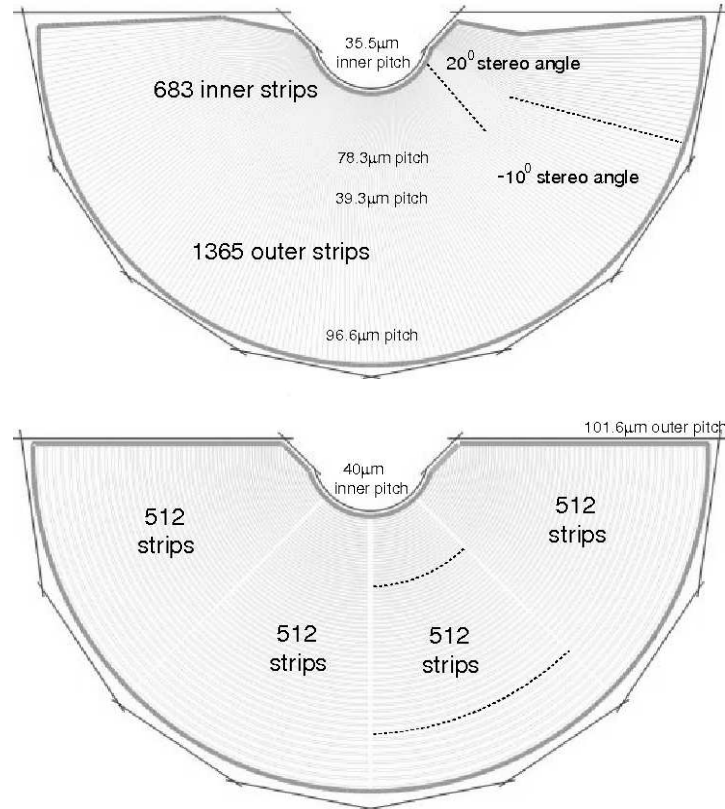


Figure 2.12: The VELO strip layout for R-sensors and ϕ -sensors.

The silicon sensors are mounted on supporting structures which, together with the readout electronic chips, are called modules. Each module holds two sensors (one R- and

one ϕ -) and provides the base for the readout electronics to be mounted. The type of sensor in the upstream position is alternated in consecutive modules so the stereo angle of the ϕ -sensors is reversed from module to module.

The VELO has 21 modules, six of which are upstream of the nominal interaction point. This was chosen as a balance between the tracking resolution and the amount of material in the detector. The upstream modules are used to improve the resolution on the location of the PV. Two extra modules which have only R-sensors, and are also placed upstream of the nominal interaction point, are used in the first level trigger to veto multiple interaction events [87]. The layout of the modules is shown in Figure 2.13 and a photograph of the modules, before installation in the detector, is shown in Figure 2.14.

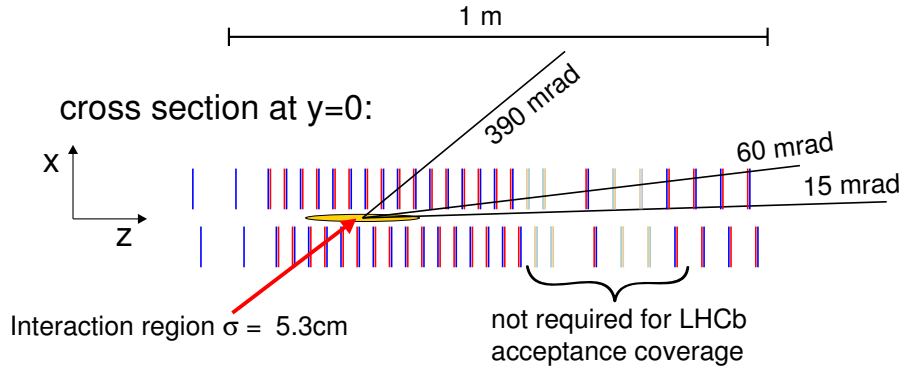


Figure 2.13: The LHCb VELO module layout.

As described above, the VELO design meets all the requirements for LHCb. Assuming a flat track distribution in the rapidity range $2.0 < \eta < 4.2$, the VELO presents an average of 15.7% of a radiation length. Considering only the material before the first hit, the VELO presents 2.7% of a radiation length, dominated by the RF foil. The expected resolution on the position of the PV, from Monte-Carlo simulations, is $\sim 50\text{ }\mu\text{m}$ in the direction parallel to the beam line (z -direction) and $\sim 13\text{ }\mu\text{m}$ in the transverse direction (xy -direction) [90]. The VELO is expected to give a proper time resolution of 40 fs [76], sufficient to resolve B_s oscillations [91].

2.2.7 Ring Imaging Cherenkov Detectors

There is a strong correlation between the polar angle and momentum of tracks in LHCb, as seen in Figure 2.15. LHCb therefore employs two Ring Imaging Cherenkov (RICH) detectors for particle identification over the momentum range $2 - 150\text{ GeV}/c$. The first

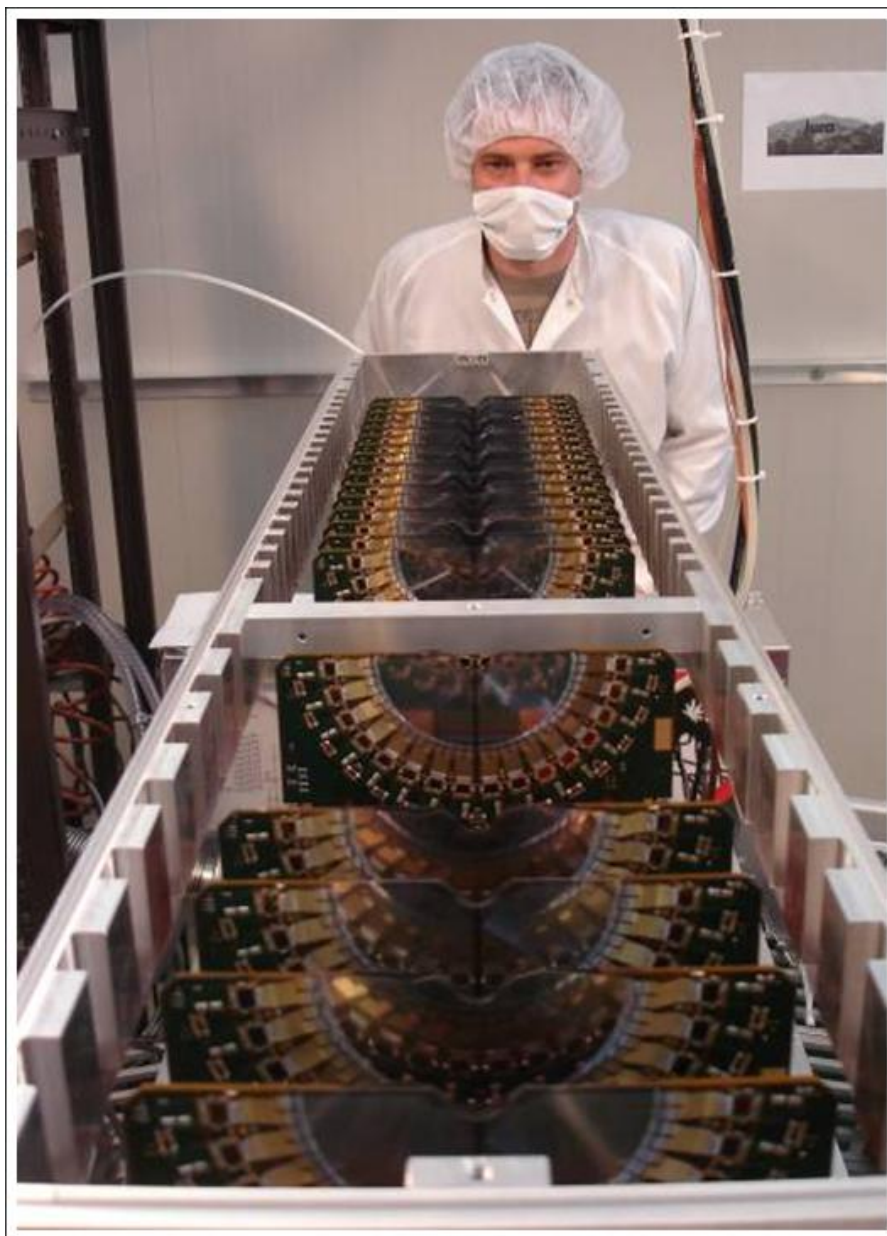


Figure 2.14: A photograph of the VELO modules seen from the beam line.

of these detectors, RICH1 (sited immediately upstream of the magnet) covers the lower momentum range $2 - 70 \text{ GeV}/c$ out to polar angles of 300 mrad , while the downstream detector, RICH2 (sited downstream of the tracking detectors), covers the higher momentum range, up to $\sim 150 \text{ GeV}/c$. Three radiators are used to cover the whole momentum range – C_4F_{10} and aerogel in RICH1 and CF_4 in RICH2. These are described in more details in Section 2.2.7.2.

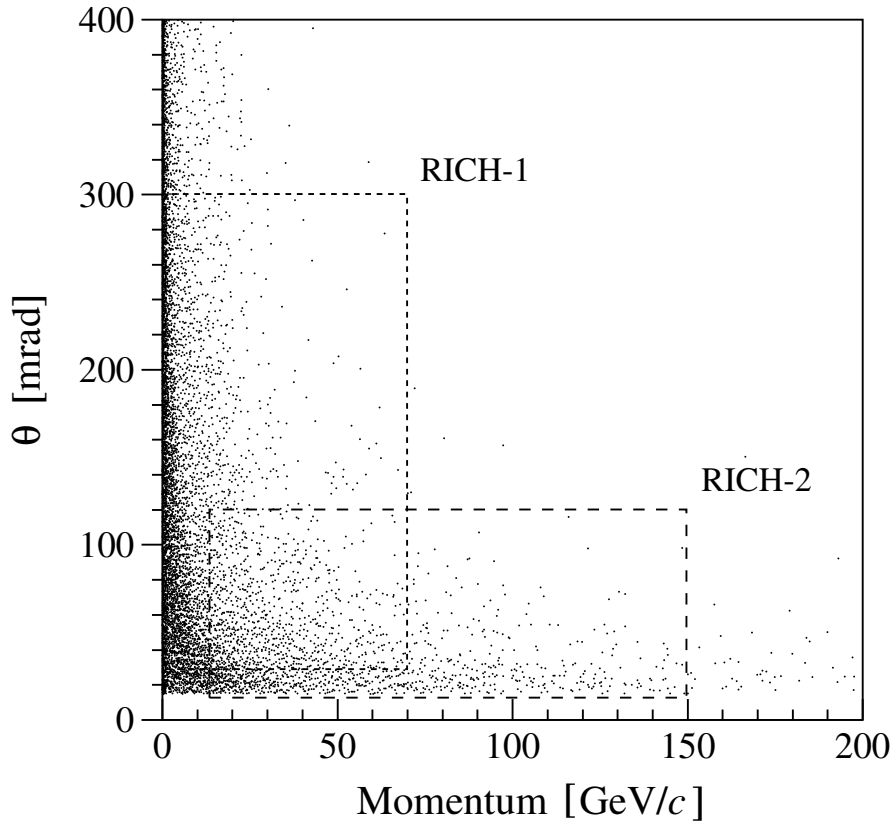


Figure 2.15: The polar angle and momentum coverage of the RICH detectors. The plot uses all tracks from $B_d^0 \rightarrow \pi^+ \pi^-$ events.

In order to detect low momentum particles which may be bent out of the detector acceptance and to minimise the necessary active area, RICH1 is located upstream of the magnet, close to the interaction point. This means it must operate in the small fringe magnetic field, needed to measure track momenta for the early stages of the trigger. To reduce the material within the LHCb detector acceptance which would degrade the tracking resolution, a series of mirrors reflect the Cherenkov photons to bring them out of the detector acceptance. The photon detectors are then located above and below the beam line. A diagram of the RICH1 detector layout is shown in Figure 2.16.

The second RICH detector, RICH2, is located downstream of the magnet, after the

last tracking station. It has a lower angular acceptance than RICH1 (~ 120 mrad) and covers the high momentum range up to ~ 150 GeV/ c . It is similar in design to RICH1, except for the overall scale. The Cherenkov photons are reflected by a set of flat mirrors to bring them out of the detector acceptance^a and then a set of focussing spherical mirrors. In this way, the length of RICH2 is kept within the space available between the tracking stations and the calorimeters. Photographs of the RICH2 detector in transport and under installation in the detector cavern are shown in Figures 2.17 and 2.18.

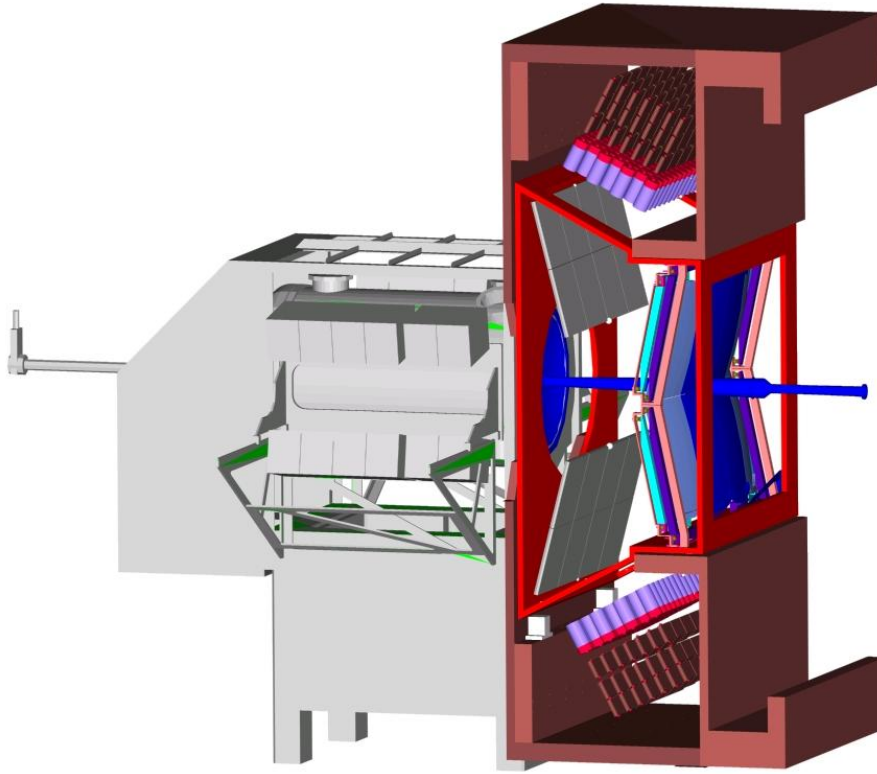


Figure 2.16: A schematic of the RICH1 detector. The grey shaded region shows the VELO.

The RICH detectors are necessary for the majority of physics analyses, particularly to distinguish between $\pi^\pm$ and $K^\pm$, though they also provide information for $\mu^\pm$, $e^\pm$ and proton identification. The identification of charged kaons also provides a useful flavour tag. For example, efficient separation between $\pi^\pm$ and $K^\pm$ is essential in the analysis of the two-body decay $B_d^0 \rightarrow \pi^+ \pi^-$, where good rejection of other two-body decays such as $B_s^0 \rightarrow K^+ K^-$ is required. The reconstructed B_d -mass distribution for $B_d^0 \rightarrow \pi^+ \pi^-$

^aActually, these flat mirrors are spherical, with a radius of curvature of ~ 90 m. The effect of using non-flat mirrors can be corrected for in the reconstruction, with a small loss in Cherenkov angle resolution.



Figure 2.17: A photograph of the RICH2 detector in transport to the detector cavern.

candidates is shown in Figures 2.19(a) and 2.19(b), before and after using the RICH information to veto $K^\pm$ tracks respectively.

2.2.7.1 Cherenkov Effect

A summary of the main results is presented in this section – a more detailed description of the Cherenkov effect is given in Appendix A. Cherenkov radiation, produced by a charged particle travelling through a medium faster than the local speed of light, is emitted at a constant angle, the Cherenkov angle, to the direction of motion of the particle. The Cherenkov angle depends only on the speed of the particle and is given by

$$\cos \theta_C \simeq \frac{1}{\beta_0 n}, \quad (2.2)$$

where n is the refractive index of the medium. A measurement of the Cherenkov angle and momentum of a particle therefore allows the mass to be calculated.

Cherenkov radiation is emitted randomly along the charged particle's path through the medium, which requires the use of focussing mirrors in the LHCb RICH detectors, as discussed elsewhere. The frequency spectrum of the emitted radiation, in the far-visible and near-UV, has implications for the design of the photon detectors, discussed below.



Figure 2.18: A photograph of the RICH2 detector under installation in the detector cavern.

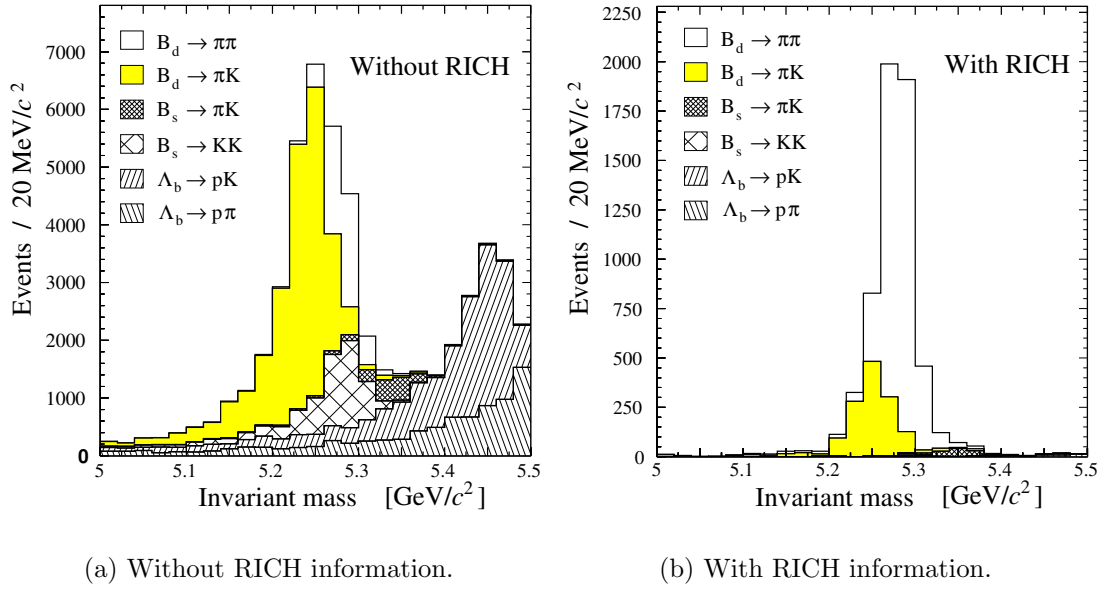


Figure 2.19: The reconstructed B_d -mass distribution for $B_d^0 \rightarrow \pi^+ \pi^-$ candidates without and with RICH information [92].

2.2.7.2 Radiators

The LHCb RICH detectors use three radiators with different refractive indices to cover the required momentum range. RICH1 has one gas radiator (C_4F_{10}) and an aerogel radiator. Aerogel is a transparent SiO_2 material with refractive index $n = 1.03$ [93]. The aerogel is arranged in 5 cm thick tiles, forming a single panel. The high refractive index provides coverage down to low momenta – the $K^\pm$ threshold for Cherenkov photon production in aerogel is ~ 2 GeV/c. The Cherenkov rings from the aerogel typically have five or six photons. Since the particle identification algorithm does not use a ring-finding based approach, but rather maximises a global likelihood based on a given photon's distance from a track, the relatively small number of photons from an aerogel ring still provide useful information. The RICH1 gas radiator (C_4F_{10}) fills the volume between the aerogel panel and the spherical mirrors and has a path length of 85 cm. The gas has a refractive index of $n = 1.0014$ at $\lambda = 260$ nm and so provides 3σ separation between $\pi^\pm$ and $K^\pm$ up to ~ 50 GeV/c. The RICH2 detector has only one radiator, CF_4 gas, with refractive index $n = 1.0005$ at $\lambda = 260$ nm, which provides separation between $\pi^\pm$ and $K^\pm$ in the range 20 – 150 GeV/c. A summary of the radiator properties is given in Table 2.1, where σ_θ is the Cherenkov angle resolution for a single photon and Δ_θ ($\pi - K$) is the difference in the Cherenkov angle for pions and kaons.

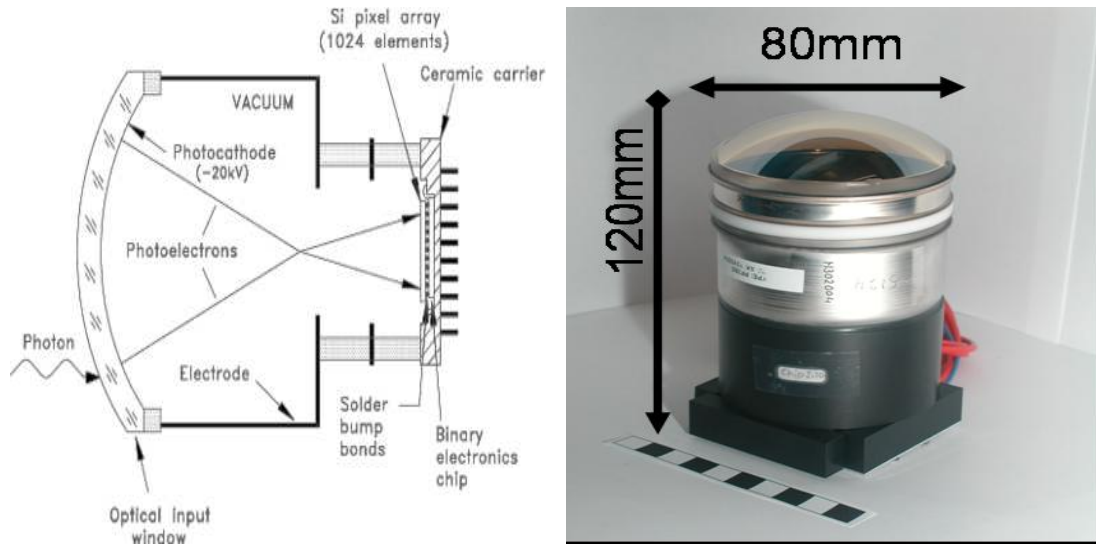
Characteristic	Radiator		
	Aerogel	C ₄ F ₁₀	CF ₄
Path length / cm	5	85	167
Refractive index	1.03	1.0014	1.0005
$p_{\text{threshold}}(\pi)$ / GeV/ c	0.6	2.6	4.4
$p_{\text{threshold}}(\text{K})$ / GeV/ c	2.1	9.3	15.6
σ_{θ} / mrad	2.00	1.45	0.58
$\Delta_{\theta}(\pi - \text{K})$ / mrad	2.1 (at 15 GeV/ c)	0.8 (at 50 GeV/ c)	0.4 (at 100 GeV/ c)

Table 2.1: A summary of the characteristics of the radiators used in RICH1 and RICH2 [92].

2.2.7.3 The Hybrid Photon Detector

LHCb utilizes the Hybrid Photon Detector (HPD), developed in close collaboration with industry, as the photo-detector in both RICH sub-detectors [94–96]. The HPD is a single photon detector which operates at the LHC bunch crossing frequency of 40 MHz and has a spatial resolution of $2.5 \text{ mm} \times 2.5 \text{ mm}$. A schematic diagram is shown in Figure 2.20(a) and a photograph of a prototype HPD is shown in Figure 2.20(b). The HPD consists of an $\sim 80 \text{ mm}$ diameter vacuum tube with a quartz entrance window and an encapsulated silicon anode. The quartz entrance window is a 7 mm thick spherical surface coated with an S20 multi-alkali photocathode.

Incident photons are converted to photoelectrons with a typical peak quantum efficiency of $\sim 25\%$ at a wavelength of 270 nm. The photoelectrons are accelerated across a potential difference of 20 kV onto the silicon anode. The optics of the accelerating electric fields also cross-focus and demagnify the image by a factor of ~ 5.5 . Accelerated photoelectrons incident on the anode typically produce ~ 5000 electron-hole pairs in the silicon. The anode is divided into 256×32 pixels, each of area $62.5 \mu\text{m} \times 500 \mu\text{m}$. Each pixel is bump-bonded to a single channel of the LHCbPIX1 binary readout chip [97]. In the LHCb readout scheme, eight pixels are OR-ed together to form 32×32 “super-pixels” of size $500 \mu\text{m} \times 500 \mu\text{m}$. A summary of laboratory measurements performed on pre-production HPDs is given in Table 2.2 and a plot of nine typical HPD quantum efficiencies for photoelectron production is shown in Figure 2.21. The dark count rate is the rate of photoelectrons which are produced by thermal emission from the photocathode and then strike the anode. The resulting hits form a background to the hits caused by Cherenkov photons. Ion feedback occurs when a photoelectron interacts with a residual



(a) A schematic of the HPD, showing an example photoelectron trajectory.

(b) A photograph of a prototype HPD.

Figure 2.20: The HPD for the RICH detectors.

gas molecule in the HPD vacuum, creating an electron and ion pair. The ion drifts back to the cathode where it can cause a bunch of electrons to be released which are then detected as a large cluster of hits.

	Specification	Laboratory test result
Pixel response	$> 95\%$	$> 99\%$
Minimum threshold	$< 2000 e^-$	Typical $1200 e^-$
Noise	$< 250 e^-$	Typical $160 e^-$
Leakage current	Typical $1 \mu A$ at 80 V bias	$< 1 \mu A$
Dark count rate	$< 5 \text{ kHz} / \text{cm}^2$	$0.03 - 3 \text{ kHz} / \text{cm}^2$
Ion feedback rate	$< 10^{-2}$ relative to signal	$< 10^{-3}$
Anode detection efficiency	Typical 85%	$78 - 89\%$

Table 2.2: A summary of HPD laboratory measurements.

In RICH1, an iron structure is used to funnel the fringe field from the magnet, decreasing the field in the photon detector regions while maintaining sufficient field integral to estimate track momenta to $\sim 30\%$ for the trigger. With no further shielding, the magnetic field in the region of the photon detectors would be $\mathcal{O}(10 \text{ G})$, which would

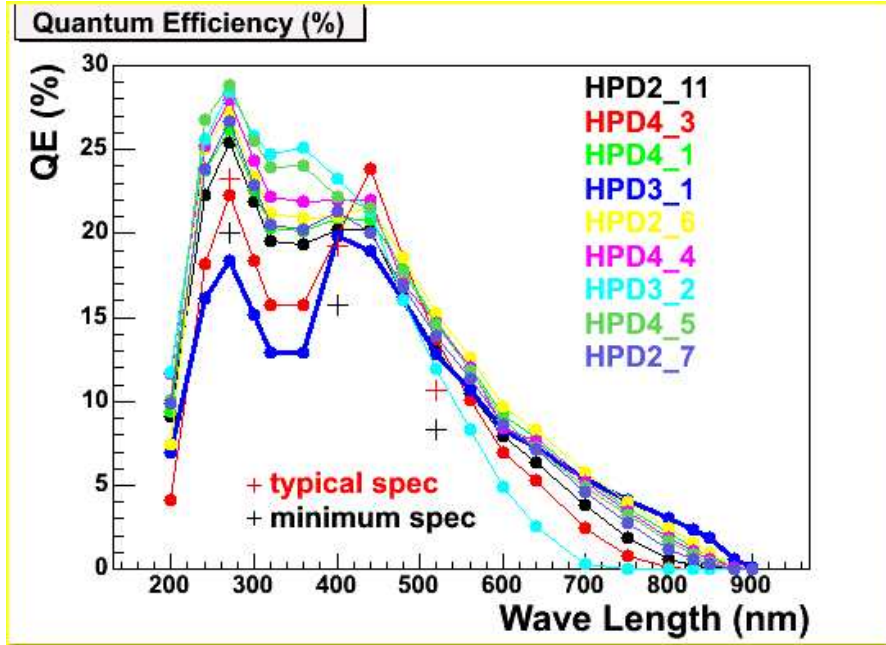


Figure 2.21: Typical HPD quantum efficiencies for photoelectron production as a function of the incident photon wavelength [98].

degrade the performance of the HPDs [99]. The photon detectors are therefore further shielded from the magnetic field by individual μ -metal shields.

The HPDs are arranged in a close-packed array to give maximum coverage. Accounting for the active area of the HPD ($\sim 74\%$) and the efficiency of this close-packing, this arrangement gives an active area of 2.6 m^2 and a geometric efficiency of $\sim 67\%$. The detectors are mounted in columns which hold the HPDs and their associated on-detector electronics. The columns can be removed from the detector housing for maintenance if necessary. The mechanics for mounting HPDs in RICH1 and RICH2 are very similar and only the scheme for RICH2 is described here.

Each column in RICH1 (RICH2) has 14 (16) HPDs, connected via Zero-Insertion-Force sockets and kapton cables to the on-detector readout electronics. Dedicated low-voltage (LV) boards, providing $\sim 5 \text{ V}$, are used to power the readout electronics (L0-boards) and pixel-chips. The high-voltage (HV), nominally 20 kV , for the electric fields used to accelerate and cross-focus the photoelectrons in the HPD is also provided by custom boards. The on- and off-detector electronics are kept in synchronisation with each other and the rest of the LHCb detector via the Trigger and Timing Control (TTC) system [100]. A photograph of a fully assembled production column is shown in Figure 2.22. In total, 484 HPDs are needed for the LHCb experiment – 196 for RICH1

(14 columns) and 288 for RICH2 (18 columns) [94].

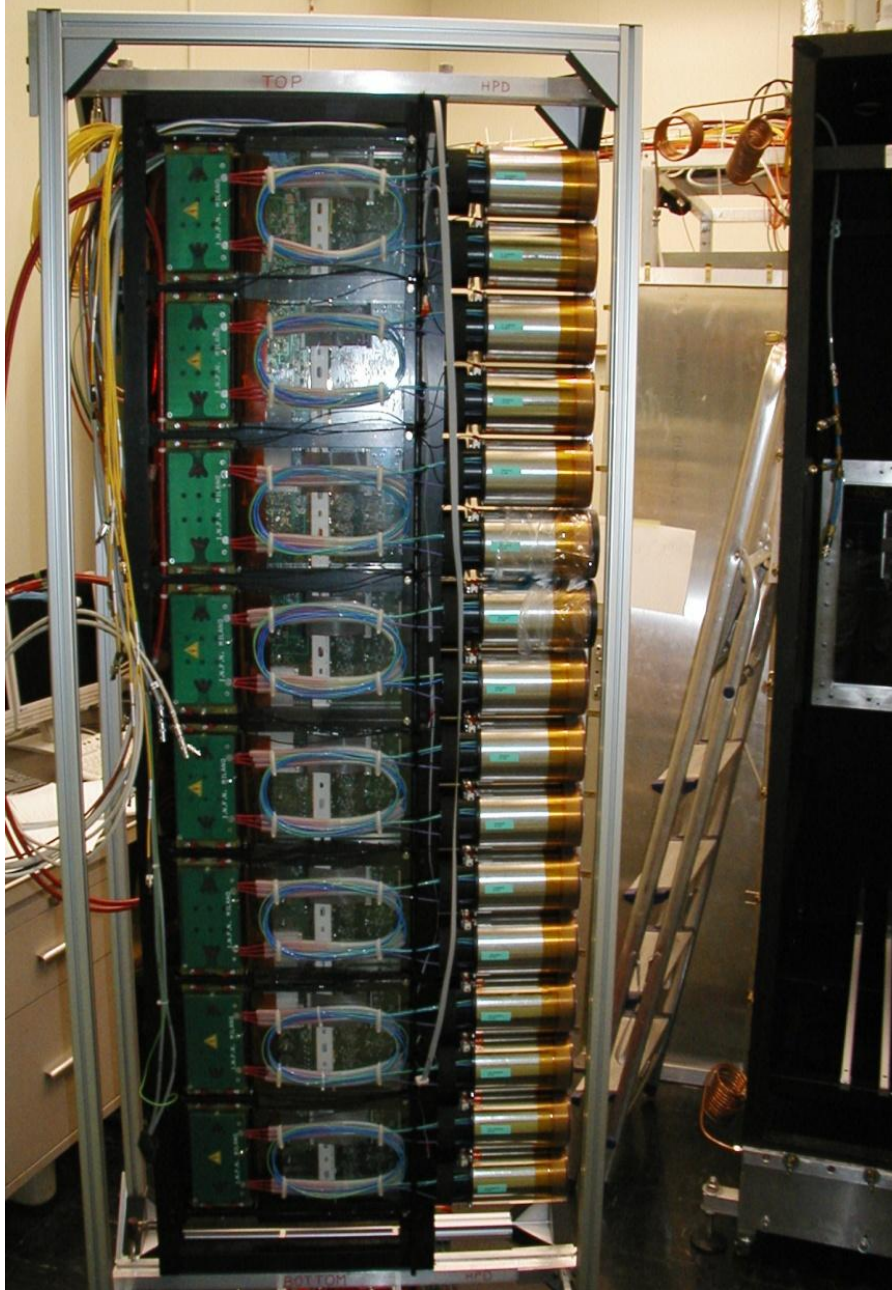


Figure 2.22: A RICH2 column with 16 HPDs and the respective L0-, LV- and HV-boards.

2.2.7.4 Readout Electronics

The readout chain for the RICH detectors consists of the front-end pixel-chip (LHCbPIX1) within the HPDs, the on-detector electronics (L0-board [101]) and the off-detector electronics (L1-board [102]). The entire system is driven at the LHC bunch crossing frequency of 40 MHz.

The pixel-chip is designed to be tolerant to ionising radiation and single event upset. The chip has a front-end amplifier and discriminator to give binary readout at 40 MHz. The discriminator has a threshold of $\sim 1500 e^-$ and a pixel-to-pixel RMS of $\sim 200 e^-$, allowing single photoelectron detection including those where the charge is shared between neighbouring pixels.

The HPDs are connected via kapton cable to the L0-boards which multiplex the data to be passed to the off-detector L1-boards. Each L0-board takes data from two HPDs. The data are stored as 32-bit words in First-In-First-Out (FIFO) memory buffers for up to 4 μs to await the L0-trigger decision [103]. Functionality is provided by the “PINT” chip, a radiation-tolerant fuse-link Field-Programmable-Gate-Array (FPGA).

The data are driven via gigabit optical links to the L1-boards. Synchronisation of the front-end electronics to the off-detector electronics is achieved via the Timing, Trigger and Control Receiver ASIC (TTCvi) [100]. The L1-boards further format the data, perform some error checking and zero-suppress the data words if needed. Data are then sent via gigabit Ethernet to the readout supervisor for distribution to the trigger computer farms and storage.

2.2.7.5 RICH Reconstruction Software

The LHCb RICH reconstruction procedure is based on a maximal likelihood approach, in Cherenkov angle space [5]. A ring on the photo-detector planes from a given charged track will be approximately elliptical, with a degree of distortion that depends on the track position and direction. A typical event display of the rings in RICH1 from a $B_d^0 \rightarrow \pi^+ \pi^-$ event is shown in Figure 2.23.

The particle identification algorithm assigns a particle type to each track in such a way as to maximise the likelihood that the observed photons were produced by those tracks based on the expected Cherenkov angles. Initially all tracks are assumed to be pions, the most common particle type. The assumption for each track is then changed

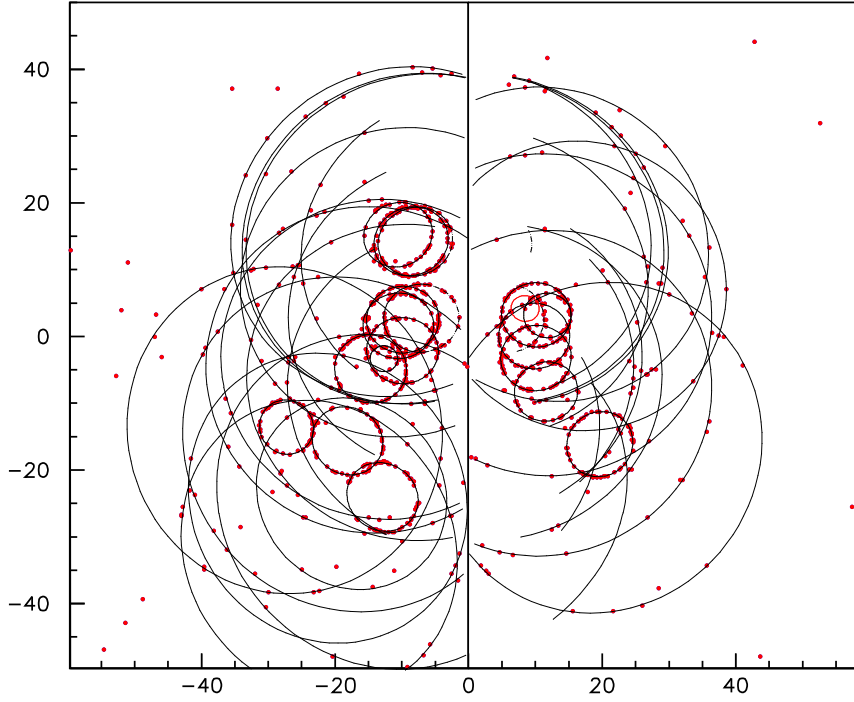


Figure 2.23: An event display of Cherenkov rings in RICH1 [5].

in turn and the likelihood recalculated – the change with the largest increase in the likelihood is kept. This procedure is repeated until no further improvements are seen. A plot of the RICH detector performance for identifying kaons is shown in Figure 2.24.

2.2.8 Tracking System

The LHCb tracking system [76] consists of three sub-detectors: the VELO, the Trigger-Tracker (TT) station and the main tracking stations, labelled T1-T3 in Figure 2.6. The purpose of the tracking is to provide spatial measurements of charged particles passing through the detector volume. This allows properties such as the particle impact-parameter and momentum to be calculated. The tracking stations (TT and T1-T3) therefore provide excellent resolution in the horizontal (bending) plane. Some information of the track position in the vertical (non-bending) plane is necessary for ring-finding in the RICH detectors. A typical $b\bar{b}$ event, shown in Figure 2.25, has ~ 72 reconstructed tracks.

The TT station is located directly downstream of the RICH1 detector and upstream of the magnet. It is used to reconstruct low momentum particles which are swept out of

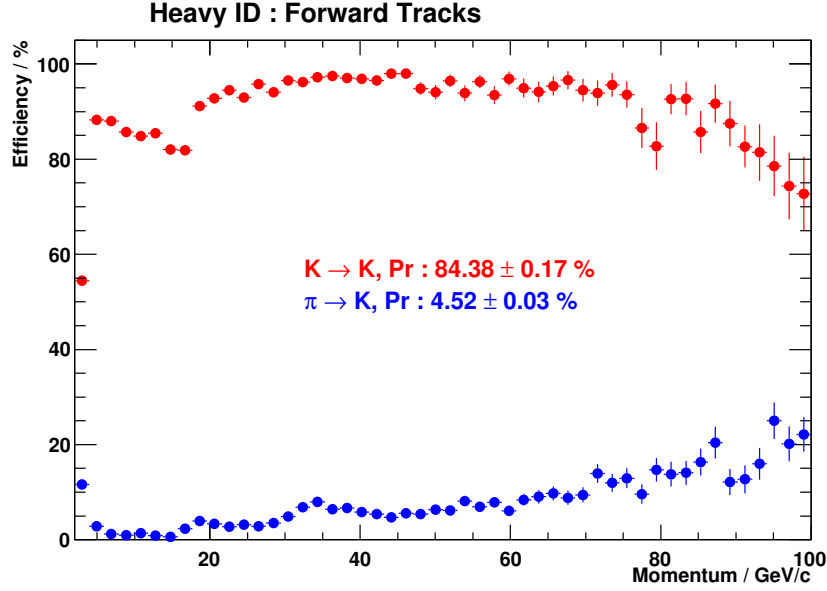


Figure 2.24: The RICH detector performance for identifying kaons as a function of the track momentum [104]. The mis-identification rate is also shown.

the detector acceptance by the magnet as well as in the tracking of the decay products from long-lived neutral particles such as the K_S^0 . The TT station is based entirely on silicon-strip sensor technology. The design of the sensors and their layout are identical in design to the Inner Tracker sensors, described below.

The main tracking stations (T1-T3) are divided into two regions: the Inner Tracker (IT) and the Outer Tracker (OT). The IT provides tracking in the central region of the detector around the beam pipe where the particle fluxes are highest [105]. The IT therefore uses silicon-strip sensors which provide the necessary resolution and have a granularity such that high occupancy is not a problem. Each sensor is $\sim 8 \text{ cm} \times 11 \text{ cm}$ and has 384 silicon strips with a pitch of $198 \mu\text{m}$. Ladders of 11 or 12 mechanically joined sensors are used to cover the necessary area. The IT is assembled in a cross-shape around the beam pipe, extending $\sim 120 \text{ cm}$ in the horizontal-direction and $\sim 40 \text{ cm}$ in the vertical-direction. Although it only covers approximately 2% of the acceptance (the rest being covered by the OT), it receives approximately 20% of the charged particle flux.

To instrument the whole tracking area with silicon detectors would be prohibitively expensive. The OT is therefore based on the cheaper drift-cells with straw-tube technology [106]. Kapton tubes are filled with a mixture of Ar(75%) / CO_2 (10%) / CF_4 (15%)

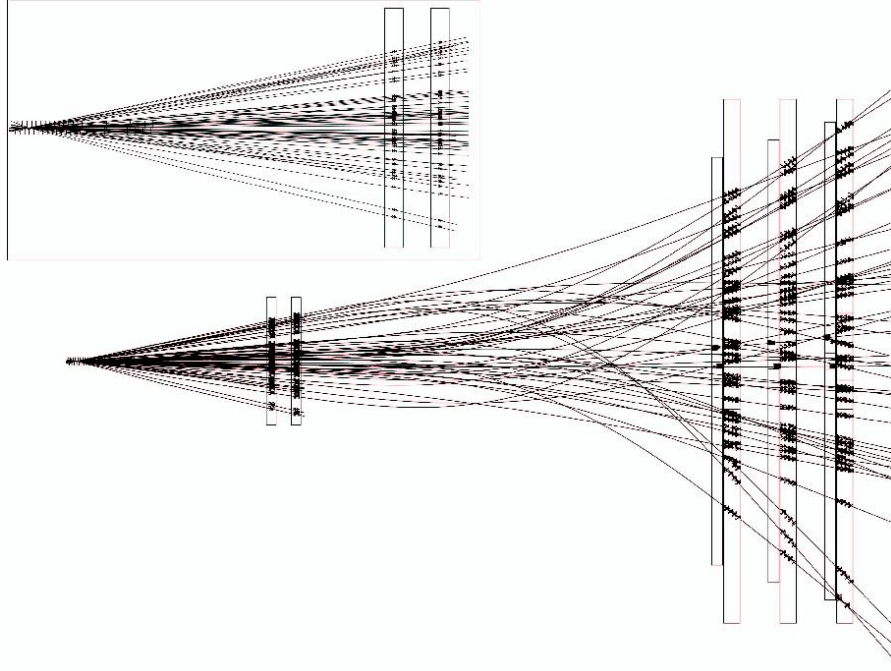


Figure 2.25: A display of reconstructed tracks from a typical $b\bar{b}$ event passing through the tracking detectors [76]. The upper (lower) display shows tracks in the non-bending (bending) plane.

gases with a thin gold-tungsten wire down the centre. The concentration of CF_4 gas can be varied to ensure the maximum drift time across the 5 mm tube is below 50 ns (two LHC bunch crossings).

The four tracking stations (TT and T1-T3) are each divided into four detector layers. In the TT these layers are spaced by approximately 30 cm in the z -direction; the layers in the T1-T3 stations have the minimum separation allowed by the detector mechanics. In all the stations, the most upstream and downstream layers have vertically orientated strips or tubes, providing position information in the bending plane only. The inner layers (u , v) are rotated by $\pm 5^\circ$ to provide two stereo views, sufficient for pattern recognition in the non-bending plane. In the OT, each layer consists of two planes of straw-tubes, overlapped by half a tube.

The track reconstruction algorithm is based on track seeds, built from hits in the VELO (VELO-seed) or hits in the T-stations (T-seed). From these seeds, the full tracks are reconstructed, adding in the information from the other tracking detectors. Three main track types, shown in Figure 2.26, are reconstructed:

- **Long tracks** : traverse all the tracking detectors. A VELO-seed is matched to

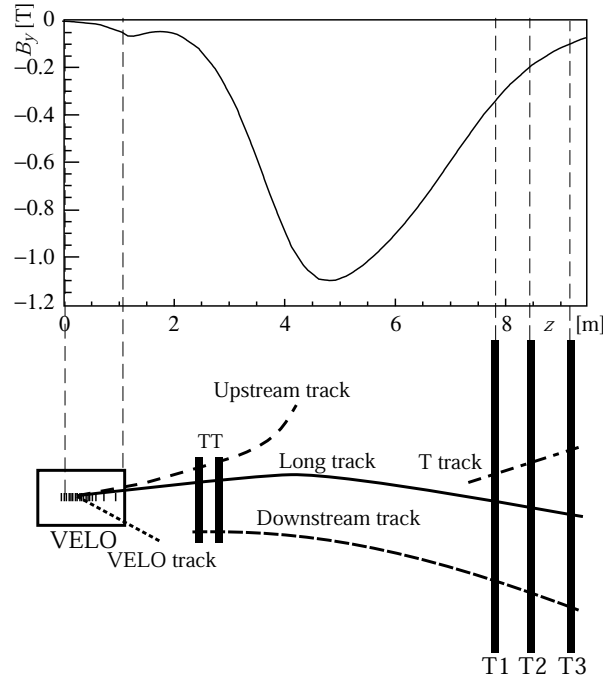


Figure 2.26: An illustration of track types and their corresponding sub-detector information [76]. The upper plot shows the magnetic field component in the vertical direction (B_y) as a function of the z -coordinate.

hits in the T-stations and TT station.

- **Upstream tracks :** traverse only the VELO and TT station. These are typically low momentum tracks which are swept out of the detector acceptance by the magnet.
- **Downstream tracks :** traverse only the TT station and the T-stations. These are typically particles from the decay of long-lived neutrals, such as K_S^0 .

The long tracks have the best performance: $\sim 96\%$ efficiency and $\sim 3\%$ ghost rate. The momentum resolution ($\delta p/p$) of these tracks is in the range 0.35% at low momentum, below approximately $10 \text{ GeV}/c$, to 0.55% at high momentum, above approximately $100 \text{ GeV}/c$. The upstream tracks have a worse resolution, $\delta p/p \sim 15\%$ for tracks in the range $1 - 5 \text{ GeV}/c$, because of the small field integral between the VELO and TT station. Downstream tracks have a resolution of $\delta p/p \sim 0.4\%$ for charged pions above $5 \text{ GeV}/c$ from K_S^0 decays [76].

2.2.9 Calorimeter System

The LHCb calorimeter system consists of four parts: a scintillating pad detector (SPD), a pre-shower detector (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL) [107]. The purpose of the calorimeter system is to provide information for the L0-trigger and to measure particle energies and positions for charged and neutral particles such as photons or π^0 . Since neutral particles leave no information elsewhere in the detector, the calorimeter system is essential for the reconstruction of B-decays involving these particles. The calorimeter system is located directly downstream of the first muon station and covers the complete LHCb acceptance of $250 \text{ mrad} \times 300 \text{ mrad}$. A $30 \text{ mrad} \times 30 \text{ mrad}$ central hole allows the beam pipe to pass through the detector and prevents severe radiation damage.

The SPD is a 15 mm thick scintillating pad placed at the most upstream edge of the calorimeter. Electrons but not photons will interact in the scintillator, providing extra information to distinguish between them, which is not possible after showering has begun. This is crucial for reducing the background in the first level electron trigger caused by photons from π^0 decays with high transverse energy, E_T , defined as the sum in quadrature of the particle's mass and p_T . The PS detector is a 12 mm thick lead wall followed by another layer of scintillating tiles. The lead wall presents $\sim 2 X_0$ for electrons but is insignificant in terms of the radiation length for pions and therefore allows the rejection of the large background from charged pions.

The ECAL has a depth of 25 radiation lengths. It is a sampling calorimeter, with 2 mm thick lead sheets interspersed with 4 mm thick scintillator tiles. Three tile sizes are used to approximately match the detector occupancy. The tile sizes used in the SPD and PS are scaled according to their z-position to present the same solid angle. This allows for faster and simpler energy reconstruction in the trigger electronics [108]. The ECAL is readout using Shaslik technology, where wavelength shifting (WLS) fibres are embedded in the scintillating tiles. Scintillation light, produced by charged particles in the tiles, is absorbed and re-emitted as green light by the WLS fibres and transmitted to photon detectors outside the detector acceptance. Using this technology the following resolution is expected and has been achieved in testbeams [109]:

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 1.5\%. \quad (2.3)$$

The HCAL is based on a similar design to the ECAL: scintillating tiles are sandwiched

between steel absorber plates, with some layers consisting of only steel plates, as shown in Figure 2.27. The tiles in the HCAL have one edge parallel to the beam direction and the scintillation light is transmitted by WLS fibres, attached to the tile edge, to the photon detectors. In total the HCAL is 5.6 interaction lengths deep, sufficient for the first level hadron trigger requirements [110], and gives an energy resolution of

$$\frac{\sigma(E)}{E} = \frac{80\%}{\sqrt{E}} \oplus 10.0\%. \quad (2.4)$$

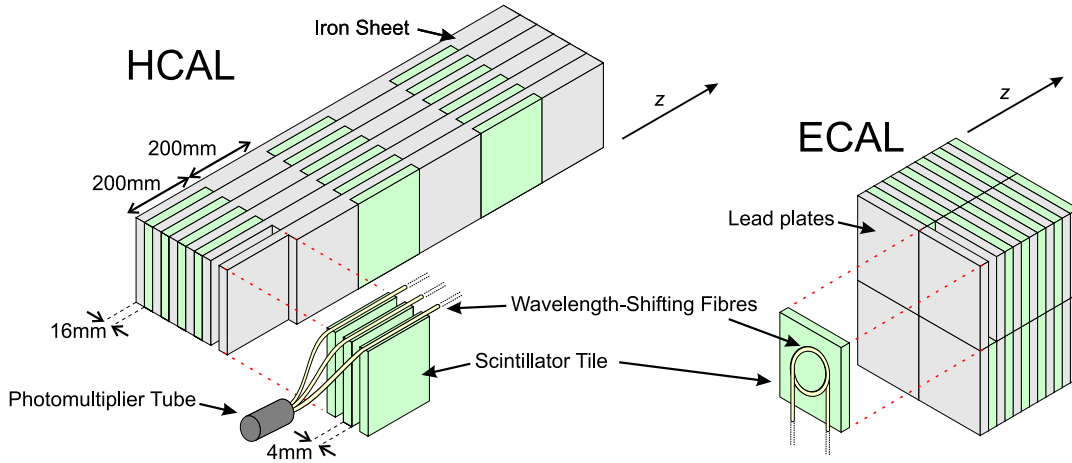


Figure 2.27: The structure of the LHCb calorimeter scintillator tiles and absorber plates.

2.2.10 Muon System

The LHCb muon sub-detector is designed to provide a robust trigger for penetrating muons from B-decays, as well as information for their offline identification. Muons are present in many $\mathcal{CP}$ -sensitive and rare-decay modes and the muon trigger is a crucial part of the LHCb trigger scheme, providing approximately 25% of the Level-0 rate [111]. The muon detector is matched to the acceptance of the rest of the detector. The inner acceptance is 20 (16) mrad in the bending (non-bending) plane and it extends to 306 (258) mrad. This gives approximately a 20% acceptance for muons from b-decays.

The muon system is comprised of five stations, labelled M1-M5. Station M1 is placed upstream of the calorimeter system and is used primarily to provide an improved p_T measurement for muons that reach the other stations. Stations M2-M5 are the most downstream components of the LHCb detector. These stations are interleaved with 80 cm thick iron absorbers to select penetrating muons. The physical size of each

station is matched to the angular acceptance and thus increases with distance from the interaction point. Each station in the muon system consists of two detector planes, logically OR-ed together, necessary for the system to reach the required efficiency of 90% for identifying muons above $3 \text{ GeV}/c$. Each plane is further subdivided into four regions (R1 – R4), centred on the beam-pipe. The granularity of the regions increases with distance from the beam-pipe, such that its contribution to the p_T resolution is comparable to the contribution from multiple-scattering.

Two detector technologies are employed in the muon system: multi-wire-proportional-chambers (MWPC) [112] and Triple Gas-Electron-Multiplier (GEM) [113] detectors. The MWPC are used everywhere except the innermost region of M1, where the high particle flux necessitates a different technology choice and the Triple-GEM detectors are used. The MWPC consist of a 5 mm gap filled with an Ar / CO₂ / CF₄ gas mixture [114], with the anode wires placed in the centre of the gap and a 3 kV potential applied. A muon traversing the gap produces ~ 50 electrons which are accelerated toward the wires and undergo gas amplification near the anodes. Three readout schemes are used for the MWPC depending on their location with the detector. In the outer region (R4) of the stations the chambers are readout via the anode wires. This is the simplest and safest readout scheme for these detectors but the resolution is limited by the anode wire spacing (2.5 mm) in one direction (horizontal) and the chamber size in the perpendicular (vertical) direction (20 – 30 cm). The resolution needed in the inner regions of the detector (regions R1-R2 in stations M2-M3) cannot be achieved by simple wire readout because the necessary chamber size would be impractically small. Instead, a combination of anode wire and cathode pad readout is employed. Cathode pads are etched onto the cathode planes. The resolution is then defined by the wire strip in the horizontal direction and the cathode pad size in the vertical direction. Cathode pad readout is used in the remaining MWPC regions. In some regions of the detector the constraints on the noise level and dead-time of the system limit the size of the physical chambers to be less than the required spatial resolution. In this case, in order to reduce the number of readout channels, up to four adjacent physical channels are logically OR-ed together.

The L0-muon trigger uses an independent muon track reconstruction, searching for hits in a straight line in all five stations. A p_T estimate for the muon candidate is obtained from the position of the track in the first two stations. The offline muon reconstruction is based on a field-of-interest (FOI) search [115]. Tracks from the tracking stations are projected to the muon stations and required to be in the M1 – M5 acceptances. In each region of each station a FOI is defined, based on the logical pad size and the distribution

of tracks from $J/\psi \rightarrow \mu^- \mu^+$ decays. A muon is identified if it leaves at least one hit in the FOI in each of the following stations:

- M2 and M3, for tracks where $p < 6 \text{ GeV}/c$;
- M2 and M3 and (M4 or M5), for tracks where $6 < p < 10 \text{ GeV}/c$;
- M2 and M3 and M4 and M5, for tracks where $p > 10 \text{ GeV}/c$.

This gives an efficiency of $(94.30 \pm 0.07)\%$ for identifying muons, with a pion contamination of $(1.05 \pm 0.01)\%$ [116].

2.3 LHCb Trigger System

The LHCb trigger is essential to the operation of the detector because the fraction of bunch crossings that produce a $b\bar{b}$ pair is $\mathcal{O}(0.01)$. The typical branching ratios of decays of interest are $\mathcal{O}(10^{-4})$ and the fraction of these events with all their decay products within the detector acceptance is ~ 0.3 . The huge reduction in event rate from the LHC bunch-crossing frequency is achieved by a two level trigger scheme.

The LHCb trigger is based on a two level scheme [117, 118]: Level 0 (L0) and the High-Level-Trigger (HLT). The trigger exploits the large lifetime of B-particles, which produce displaced secondary vertices, and their large invariant mass, which results in decay products with high p_T [75]. The L0 trigger is a hardware trigger implemented in custom electronics and uses partial information from the detector. Events which pass the L0 trigger are fully read out and passed to the HLT software trigger, running on a dedicated computing farm, for further processing. A more detailed description of the L0 and HLT triggers is given in the following sub-sections. The requirement of the trigger is to have the maximum efficiency for passing events that are selected offline. The trigger system should also be flexible to allow overlapping triggers which are useful for trigger efficiency studies [87].

2.3.1 Level-0 Trigger

The L0 trigger runs at the LHC frequency of 40 MHz, with an output rate of 1 MHz. The trigger is implemented in four discrete hardware units, processing information from

the muon, calorimeter and pile-up veto systems. This information is combined and a decision made by the Level-Zero-Decision-Unit (L0DU). Because the full detector information is not read out from the front-end electronics until a L0-accept is received, the data from the sub-detectors must be stored in memory buffers for the duration of the L0 latency [119]. This is fixed in LHCb to be 4 μ s which includes time-of-flight, cable delays and delays in the front-end electronics, leaving 2 μ s for the trigger processing [87].

The L0 muon trigger is designed to select high p_T muon candidates [120, 121]. The four quadrants of the detector are treated independently and the detector is divided into 192 towers which point to the interaction point. Because the granularity of the muon detector pads in each station is projective to the interaction point, each tower has a fixed number of pads enabling the same algorithm to be run everywhere. For each hit in station M3, a straight line extrapolation from the interaction point is performed to search for hits in stations M2, M4, and M5 within a field of interest. A track is flagged if a hit is found in all four stations and the p_T of this track is computed by extrapolating back to the M1 station. Again, because the muon stations are projective, a lot of this processing can be performed using look-up tables instead of recomputing the information for every event. The two highest p_T muon candidates from each quadrant are transmitted to the L0DU.

The L0 calorimeter trigger is designed to select particles with high E_T deposits in the calorimeters. The aim is to identify and select the highest E_T electron, photon, π^0 and hadron candidates. The total E_T in the calorimeter system and the total multiplicity in the SPD detector is also passed to the L0DU. First, a sum of the energy deposits in each cluster of 2×2 cells is performed. The cluster size is chosen as a balance between containing all the energy from a particle and avoiding an overlap between neighbouring particles. Information from the PS and SPD detectors is added to identify the type of candidate. A similar procedure is performed to search for the highest E_T hadron candidate, although here a correction for the corresponding E_T deposit in the ECAL is made to improve the estimate. The calorimeter system also passes a measure of the event multiplicity from the SPD and the total E_T in the HCAL to the decision unit. This information can be used to reject events with little activity in the detector and busy events from pile-up interactions.

The L0 pile-up system consists of two VELO planes, upstream of the interaction point. The modules are equipped with R-sensors which allows a simple vertex finding algorithm to be run. For every pair of hits, a linear extrapolation is made to calculate the z-position of the track candidate at the beam line, with a resolution of ~ 3 mm, sufficient

to separate different interaction vertices [122]. This information is histogrammed and a peak search performed. Hits from the primary peak are masked and the procedure repeated to search for other interaction vertices. The pile-up system sends information to the L0DU about the number of tracks from the zero, one or two primary interaction vertices. The pile-up veto can be used to enhance the yield of offline selected events because it allows other trigger requirements to be relaxed within the 1 MHz limit [123].

The L0DU processes the information from the three input systems, to apply p_T , E_T or multiplicity criteria as necessary. The L0DU is reprogrammable to allow the trigger thresholds to be changed once real data arrives [124]. Typical L0 efficiencies for hadronic, muon and electromagnetic channels are approximately 50%, 90% and 70% respectively [117]. The final decision about whether to broadcast a L0-accept or L0-reject is taken by the Readout Supervisor (RS). The RS can override the L0DU, to insert random triggers for data-mining and calibration triggers. It can also throttle the L0-accept rate to prevent buffer overflows in the front-end electronics.

2.3.2 High-Level-Trigger

The High-Level-Trigger (HLT) is a software trigger which will run on a dedicated computing farm consisting of approximately 1800 nodes [125, 126]. The trigger is based on an alley scheme which tries to confirm the decision made at L0 [127, 128] – for example, the muon-alley is only run if the L0 trigger reconstructed a muon candidate. A schematic of the HLT data flow is shown in Figure 2.28 – where HLT1 represents the alleys part of the HLT and HLT2 represents the inclusive and exclusive selections, described below. This approach leads to a simple trigger with greater correlations between the stages. A small number of paths by which an event can be triggered makes any trigger bias easier to isolate. The average rate of events selected by the HLT to be written to disk will be 2 kHz.

The HLT runs three alleys (muon, hadron and ECAL) before running the inclusive and exclusive selections. An overview of the three alleys is presented below [128]:

- **Muon alleys** : the single- or di-muon alleys are run if the L0 trigger selected a muon candidate. The L0 muon candidate tracks from the muon stations are matched to VELO tracks and then hits in the T-stations, which improves the momentum estimate to $\sim 1\%$ [117]. Impact parameter and p_T cuts are applied to select single-muon events [130]. A di-muon selection is made for events with two

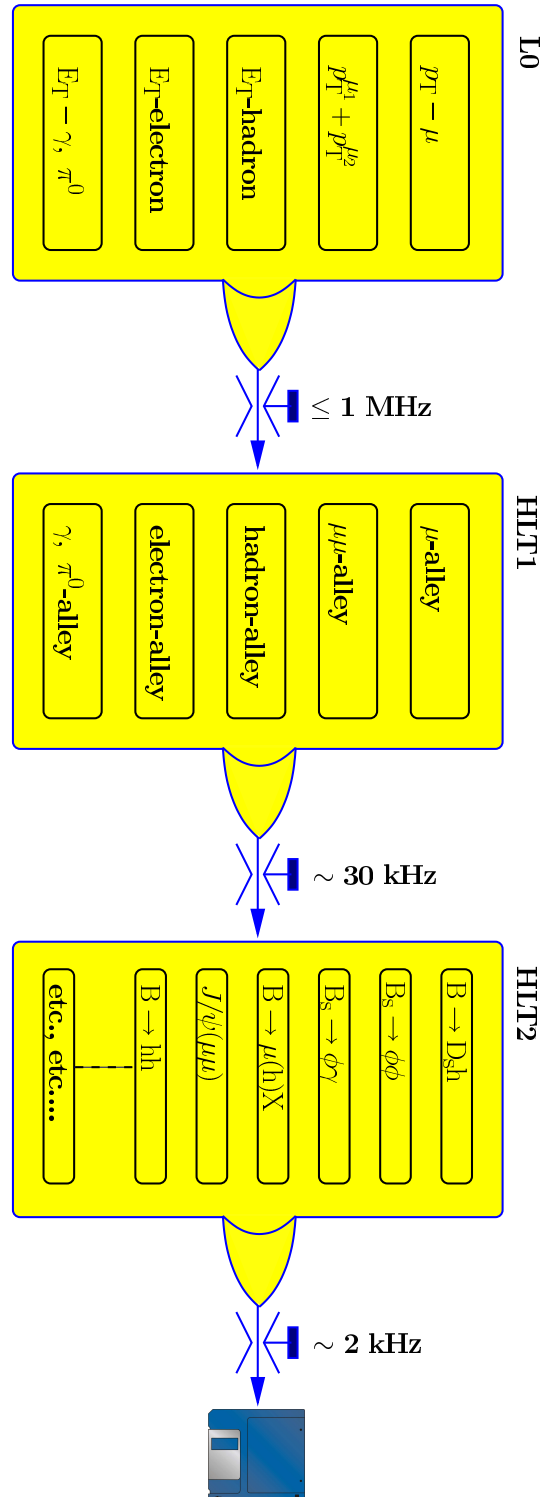


Figure 2.28: A schematic of the LHCb trigger data flow [129].

muon candidates, requiring an invariant mass greater than $2.5 \text{ GeV}/c^2$, or with a high impact-parameter. The output rate of the muon alleys is expected to be $\sim 10 \text{ kHz}$, with an efficiency of greater than 90% on L0-muon triggered events [131].

- **Hadron alley** : the hadron alley is run if a L0 calorimeter candidate is found. The calorimeter cluster is matched to a VELO track with high impact-parameter and then matched to a track segment in the TT-station [132]. This process allows events to be rejected as soon as possible if no matching track can be found. A search is then performed to find a companion track with high impact-parameter and p_T to make a secondary vertex. The output rate of the hadron alley is expected to be $\sim 5 \text{ kHz}$.
- **ECAL alleys** : the ECAL alleys (sub-divided into the electron alley and the photon or π^0 alley) are run if a L0 electron or photon candidate is found. In the electron alley, the L0 electron candidate is confirmed by matching the position of the ECAL cluster to tracks in the T-stations and VELO and a p_T cut applied [133]. A reduced p_T cut is made for events where a second confirmed L0 electron candidate is found. The procedure for the photon alley is currently under investigation, where it is planned to require the presence of a high- p_T hadron in addition to the photon. The output rate from the ECAL alleys is expected to be $\sim 8 \text{ kHz}$.

An event is rejected at this stage if all of the alleys that were executed returned a negative result. Following the alleys, the inclusive and exclusive selections are run [129] and any remaining tracks in the event, not already considered in the alleys, are reconstructed. The full detector information is then available to the selections. The information from the RICH detectors is not currently used in the HLT because the time taken to run the full particle identification algorithms is too long. The full likelihood approach (global algorithm) requires $\sim 550 \text{ ms}$ on a 2.8 GHz Xeon processor which is an order of magnitude slower than is necessary for use in the HLT [134]. A simplified global algorithm is being developed that can in principle meet the speed requirements. A more local approach, which considers tracks independently rather than simultaneously is also being developed.

The inclusive selections reconstruct intermediate particle states, without requiring the explicit reconstruction of a B-meson. For example, a $D^*(2010)^\pm \rightarrow D^0 \pi^\pm$ (where $D^0 \rightarrow K^- \pi^+$) selection is foreseen, to be used to calibrate the RICH particle identification performance. The exclusive selections are designed to have maximum efficiency with respect to the events selected offline in the core LHCb physics channels. The output

rate of the alleys stage of the HLT will be ~ 30 kHz, to be reduced to 2 kHz of events written to storage. A summary of the bandwidth division for the different triggers is given in Table 2.3.

Trigger	Allowed output rate
L0	1 MHz
HLT alleys	30 kHz
Single muon inclusive	900 Hz
Di-muon inclusive	600 Hz
D* inclusive	300 Hz
Exclusive selections	200 Hz

Table 2.3: A summary of the trigger output rates.

For the $B_d^0 \rightarrow K^* \mu^+ \mu^-$ channel, the majority of events are expected to be triggered by the di-muon alley. The current implementation of this selection imposes a di-muon mass cut, $M_{\mu\mu} > 2.5 \text{ GeV}/c^2$. Because the forward-backward asymmetry in this channel will be measured as a function of the di-muon mass, this cut must be removed or the low di-muon mass events triggered through an exclusive selection. The exclusive selection must also select any necessary control channels and events in the B-mass sidebands.

2.4 Data Handling and Monitoring

The Experiment Control System (ECS) will control the configuration, operation and monitoring of the detector. To ensure a reliable system, which can be recovered from system errors without physical intervention to the hardware, the control and data paths have been strictly separated [125]. The ECS has been designed with a simple tree-like hierarchical architecture. This will allow the system to be partitioned and therefore the various sub-detectors can be operated independently for commissioning or calibration tests.

Both stages of the HLT will be run on the online computing farm. The entire detector information is passed to the online farm at the L0 accept rate of 1 MHz, with an average event size of ~ 50 kByte. This corresponds to a data rate of ~ 50 GByte/s from the detector to the online farm [135]. The single-level software trigger system allows for a

simplified data flow system to be implemented. The full detector data from an event is passed to a single node in the online farm which performs the event building and then runs the trigger algorithms [136]. The system has been designed to also handle events with significantly larger data sizes for calibration or sub-detector tests.

The Readout Supervisor is responsible for ensuring the data are kept synchronous. It monitors the status of the data buffers in the front-end electronics and can override the L0 trigger decision in the case of a possible buffer overflow. Congestion or overflows in the online farm processing can also be prevented by the Readout Supervisor.

The RAW data from the full HLT output at ~ 2 kHz are passed from the online farm to the CERN permanent storage facility [126], together with a reduced reconstructed data summary (rDST) from the events that pass the exclusive b-selections in the HLT at ~ 200 Hz. Given an estimated event size of ~ 25 kByte, this corresponds to a data transfer rate of ~ 55 MByte/s. A 40 TByte buffer (equivalent to ~ 8 days of data) will be installed at the experiment site in case the connection to the central storage is lost. A complete copy of the data will be stored at CERN and a second copy will be distributed over six Tier-1 sites across Europe. The RAW data will then be fully reconstructed, using the full detector calibration and alignment parameters, and a number of physics selections applied. This will be performed at CERN and the Tier 1 sites. Reprocessing of the data will occur periodically during the year, as more accurate alignment parameters become available and the physics selections are refined.

Chapter 3

Performance of a Prototype RICH Detector in a Charged Particle Beam

In this chapter the performance of six pre-production HPDs in a charged particle beam is described. The purpose of the testbeam, carried out at CERN in 2004, was to provide a rigorous test of the full pre-production on-detector electronics for the RICH system and to verify the performance of the HPDs. The testbeam environment exposes the system to more realistic conditions than laboratory tests and the Cherenkov radiation provides a standard candle to measure the detector resolution and efficiency. In Sections 3.2 – 3.4 the readout electronics and the testbeam setup are described. In Section 3.5 the analysis techniques and results from the testbeam are presented. Finally, in Section 3.6, a summary of follow-up studies, including later testbeams in 2005 and 2006, is described.

3.1 Introduction

In order to measure the performance of the six pre-production HPDs, developed for the LHCb RICH detectors, tests were carried out at the CERN-PS T9 beam line. The accelerator provided a 10 GeV/ c mixed π^- and e^- beam. The trigger was provided by two 2 cm $\times$ 2 cm scintillators placed either side of the detector housing. Particles arrived randomly in continuous spills of 2.2 s – typically 10^3 particles were triggered per spill. The low intensity gave a negligible probability for events with multiple particles.

Unlike in LHCb, the trigger signal was asynchronous to the 25 ns readout clock. Because of the finite time taken for the level of charge to cross the threshold in the pixel-chip of the HPD, this gave a non-uniform efficiency for reading out the data which depended on the arrival time of the particle within the 25 ns trigger window. This effect was corrected for in the photon yield studies described in Section 3.5.5.

3.2 The Prototype RICH Detector

A prototype RICH detector with a parabolic focussing mirror was placed in the beam. A threshold Cherenkov counter, placed upstream of the detector housing, was used to veto (or select) the electrons to reduce the beam contamination. In veto mode, the counter was used to select π^- with an electron contamination of $\sim 5\%$. A schematic of the testbeam setup is shown in Figure 3.1 and a photograph of the experimental area in Figure 3.2.

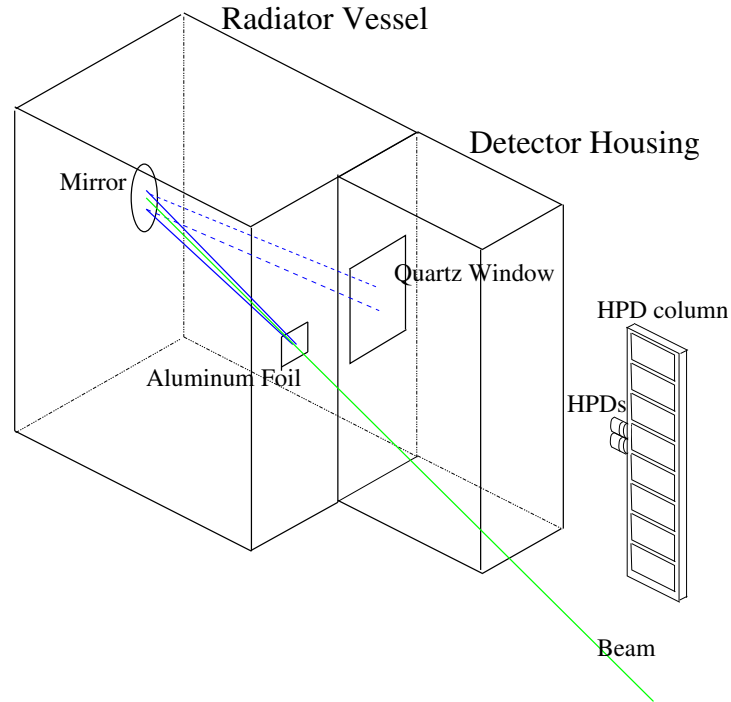


Figure 3.1: Schematic of the prototype RICH detector used in the testbeam, showing the beam and Cherenkov light trajectory.

Charged particles entered through the aluminium foil window and passed through the centre of the mirror. The detector housing was filled with N_2 gas, which acted as a Cherenkov radiator. Photons, emitted at an angle of ~ 23 mrad to the beam direction,



Figure 3.2: Photograph of the testbeam experimental area, showing the beam line and prototype RICH detector.

were reflected by the parabolic mirror and passed through the quartz window into the detector housing and onto the detector plane. The image of the Cherenkov photons, emitted randomly along a given particle's track, formed a solid disc on the mirror. The parabolic mirror, which had a focal length of 1024 mm, focused the photons into a ring on the focal plane.

The six HPDs were arranged in a close-packed array, across three columns, as shown in Figure 3.3. The HPD labelled as C1 was positioned on the focal plane of the mirror. This HPD was in the same horizontal plane as the beam direction and was therefore on-axis in the vertical direction. This means photons emitted in the vertical plane were focussed perfectly and there was no dependence on the photon emission-point along the particle's track. For photons emitted in the horizontal plane, there was a weak dependence on the emission-point; however, this was shown to be a small effect, as described in Table 3.4.

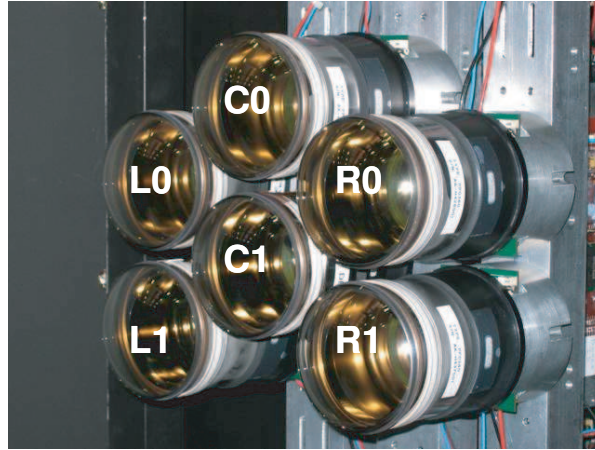


Figure 3.3: The arrangement of the six pre-production HPDs mounted onto columns in a close-packed array. The labelling scheme is also shown.

The N_2 gas radiator and mirror focal length were chosen to give a ring that could be fully contained in one HPD. The mirror was tilted to focus the ring onto each of the six HPDs in turn. Approximately 30k events were collected on each HPD in this configuration. A C_4F_{10} radiator was also used for some runs. This gas has a higher refractive index compared to N_2 , so the Cherenkov angle was correspondingly larger, producing rings spread across three or four HPDs.

3.2.1 Alignment of the Detector Housing

The alignment of the detector housing was performed with a laser system. First, the two trigger scintillators were positioned in the beam line to maximise the trigger rate. The line between the two scintillators was then assumed to be the line of the beam and a laser was aligned to shine along this line. The detector housing was then positioned so that the laser light fell on the centre of the mirror and was reflected to the centre of HPD C1 to within ± 1 mm. The mirror position was adjusted by three screw gauges. In order to determine the necessary screw positions, the mirror was tilted to reflect the laser light onto the centres of the other five HPDs in turn.

3.3 The Readout Electronics

The electronics used in the testbeam differed slightly from those that are used in LHCb. Three pre-production L0-boards were used to control and read out the HPDs – these boards were identical to the production boards used in LHCb, except for minor changes in the firmware of the PINT chips. Pre-production LV and HV boards were mounted on the columns to provide the necessary voltages to the HPD. The L0-boards passed the data via the optical links to prototype L1-boards connected to custom receiver cards. The L1-boards stored the data until the end of the spill, to then be transferred to disk via a PCI interface.

Later testbeams used pre-production 6-channel L1-boards in place of the prototype 4-channel boards and custom receiver cards. The changes in the readout and DAQ software necessary to use the L1-boards are described in Section 3.6.

3.4 Simulation of the Testbeam Setup

The testbeam setup was simulated using a Monte Carlo (MC) model based on the GEANT4 software framework [137]. The MC was configured to simulate the experimental setup of the testbeam geometry as well as a number of physics processes. For the beam particles this accounted for the beam divergence and any scattering processes or decays in flight.

The refractive index of the N₂ gas was parameterised using the two-pole Sellmeier

equation described in Equation 3.2. The refractive index is therefore given by [138]

$$n(E) = \sqrt{\frac{1+2x}{1-x}}, \quad (3.1)$$

where n is the refractive index, and x is given by

$$x = 0.3738 \times \rho_{(STP)} \times \frac{T_{(STP)}}{T} \times \frac{P}{P_{(STP)}} \times \frac{1}{m} \left(\frac{F_1}{E_1^2 - E^2} + \frac{F_2}{E_2^2 - E^2} \right), \quad (3.2)$$

where $P_{(STP)}$ is the gas pressure at Standard Temperature and Pressure (STP), $T_{(STP)}$ is the gas temperature at STP, ρ_{STP} is the gas density at STP, m is the gas molecular weight, E is the photon energy and F_1 , F_2 , E_1 and E_2 are the Sellmeier parameters [139, 140].

Cherenkov photon production was simulated randomly along the radiator length, in the energy range 1.3 – 6.5 eV. The photons were traced through the experimental setup to the HPD photocathode. The reflectivity and transmission characteristics of the mirror and quartz windows were simulated according to laboratory measurements. In the MC, the photons were reflected specularly. A modification to implement the effect of the mirror surface roughness (D_0)^a was made for the systematic error studies described in Section 3.5.4.1. In this case the mirror normal was rotated by an angle sampled from a Gaussian with $\mu = 0$ and $\sigma = D_0 / 8R$ where R is the mirror radius of curvature. From the definition of the mirror D_0 , the intensity distribution of the measured spot size has a characteristic width $\sigma_{spot} = D_0 / 4$. Given that the mirror focal point is at a distance $R / 2$ from the centre of the mirror surface the Gaussian describing the angular smearing must therefore have a width $\sigma_{angle} = D_0 / 8R$.

The HPD quantum efficiency for photoelectron production (QE) was implemented in the simulation using values measured in the laboratory for the six HPDs. For HPD C1, the QE curve is shown in Figure 3.4 as a function of photon wavelength. The effect of the electron optics of the HPD (the demagnification law) was implemented using a parameterisation i.e. the photoelectrons were not traced through simulated electric fields. Photoelectrons were assigned an energy of 20 keV, corresponding to the electric potential between the cathode and anode. A linear parameterisation of the demagnification law was used with a constant factor of 5.64, chosen so the simulated rings in the MC matched the rings in the data. This value was confirmed by laboratory

^aThis is defined as the diameter of the image measured at the focal point within which 95% of the intensity of light ($\pm 4\sigma$) from a source at infinity falls.

measurements. A two-dimensional Gaussian smearing of the photoelectron direction was implemented to simulate the HPD Point-Spread-Function (PSF). The PSF is defined as the *RMS* of the photoelectron distribution at the anode resulting from a point source of photoelectrons at the cathode. This arises because some component of the initial velocity of the photoelectrons at emission is perpendicular to the electric field.

When a photoelectron strikes the anode there is a probability that it will back-scatter. A backscattered photon deposits some energy in one pixel but then scatters from the surface and strikes the anode elsewhere on the chip, or on the anode carrier. There is an $\sim 18\%$ probability of a given photoelectron undergoing back-scattering. The anode detection efficiency was therefore taken to be 82% to account for this probability. This detection efficiency is modified in the testbeam because of the asynchronous beam. The efficiency of the HPD to read-out a given pixel hit within the 25 ns trigger clock depends on the arrival time of the photoelectron within that clock. The relative readout efficiency of HPD C1, normalised to the anode detection efficiency, is shown in Figure 3.5. The calculation of the efficiency curve for detecting pixel hits as a function of the arrival time within the trigger clock window is described in Section 3.5.5. In the MC, each event was assigned an arrival time randomly in the range 0 – 25 ns. The anode detection efficiency was then varied according to the arrival time and the efficiency curve.

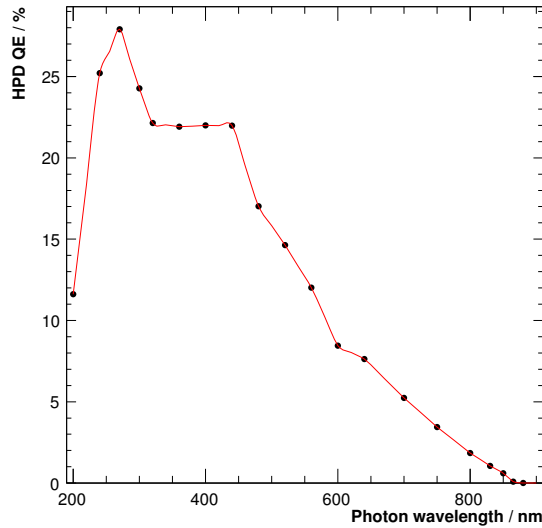


Figure 3.4: The measured quantum efficiency curve for HPD C1 as function of wavelength.

A simple charge-sharing model was also added to the MC. As the charge in the anode from a photoelectron hit is amplified, it can diffuse to an adjacent pixel. If sufficient

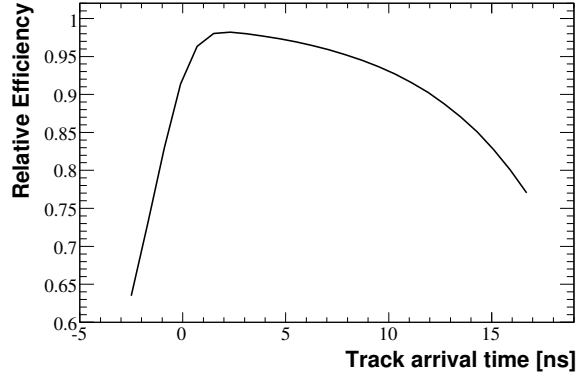


Figure 3.5: The readout efficiency curve as function of track arrival time for HPD C1, relative to the intrinsic anode detection efficiency of $\sim 82\%$ [140].

charge diffuses both pixels can cross the threshold and therefore be read out. The charge sharing effect was added to the MC, with a 3% probability per pixel, measured from the data [140]. The position of the extra hit was chosen randomly from the four direct neighbours of this pixel.

When simulating the N_2 runs, the MC geometry was adjusted so that the Cherenkov rings were centred on the outside of the HPD for that run. The pixel chip in the HPD is positioned so that the HPD-axis (which defines the cylindrical symmetry of the HPD) passes through the centre of the chip. The manufacturing process which positions the pixel chip produces a variation in the pixel position $\mathcal{O}(2)$ pixels). The pixel chip offsets in the MC were chosen so the simulated rings overlaid the data rings on the pixel chip. The pixel chip offsets used in the MC are given in Table 3.1.

HPD	HPD-axis	
	Col / pixels	Row / pixels
L0	15.07	15.83
L1	12.82	15.28
C0	13.53	13.96
C1	13.36	14.78
R0	13.58	18.32
R1	13.77	14.63

Table 3.1: A summary of the pixel-chip offsets used in the MC.

A display of the testbeam MC setup is shown in Figure 3.6. The display shows a single charged pion track (red) passing through the detector with the generated Cherenkov photons (green) emitted randomly along the radiator length. As the photons strike the photocathode, the path of any resulting photoelectrons is shown in red. A full display of the HPDs is not shown here – only the photocathode and the pixel chips.

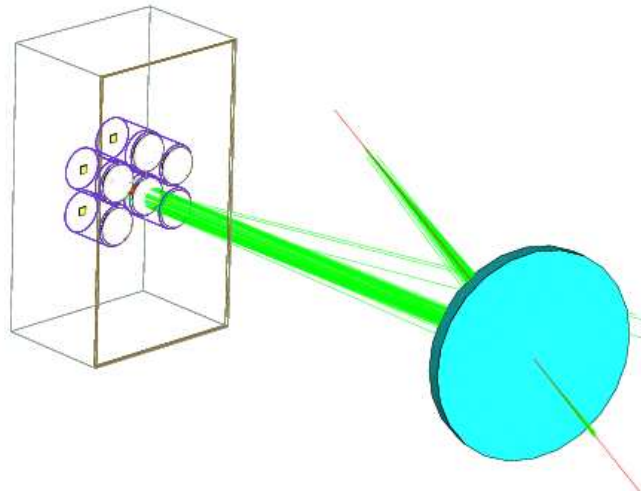


Figure 3.6: A single event display from the testbeam MC. A single charged pion (red) is shown entering the detector. Cherenkov photons (green) are emitted randomly along the particle’s path through the radiator and are reflected by the mirror (blue). Photoelectrons produced at the photocathodes (blank purple circles) are shown in red but are largely obscured by other the HPDs in the display.

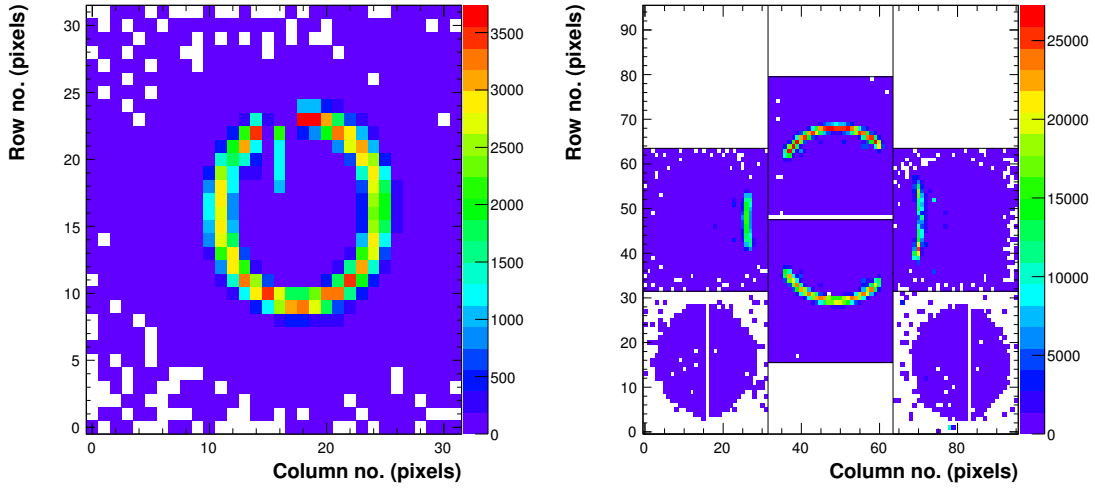
3.5 Data Analysis

The analysis of the data is divided into two main sections: photon counting and Cherenkov angle resolution studies. The testbeam environment provided a standard candle with which to measure the HPD efficiency. The results of this analysis are presented in Section 3.5.5.

The data analysis was restricted to N_2 -pion runs, taken with the N_2 radiator, where the rings were fully contained in one HPD and with the beam threshold Cherenkov counter used to veto electrons – the beam was therefore dominated by pions. For the Cherenkov angle resolution studies the analysis focussed on HPD C1, which was on-axis in the vertical direction. Data sets where the beam threshold Cherenkov counter

was used to select electron events (N_2 -electron runs) were used to evaluate some of the systematic effects. In these runs the beam contained approximately equal numbers of electrons and pions. For the rest of this chapter, unless specifically stated otherwise, the data presented are from N_2 -pion runs, with the mirror tilted to focus the ring on HPD C1.

A nitrogen ring image on HPD C1, integrated over $\sim 30k$ events is shown in Figure 3.7(a). The integrated ring is well defined, indicating that the spread of ring centres from event-to-event is small. The ring has a radius of ~ 7 pixels on the pixel chip, corresponding to a radius of ~ 20 mm on the photocathode. A readout problem affected some of the columns on this HPD. The hits in columns 15, 16 and 17 with row numbers greater than 16 (i.e. the upper halves of the columns) were therefore not considered in the analysis. A C_4F_{10} ring image spread over four HPDs, integrated over $\sim 100k$ events is shown in Figure 3.7(b). The background level on the HPDs which contain part of the ring is higher than the two HPDs without the ring because of back-scattered photoelectrons.



(a) A N_2 ring on HPD C1.

(b) A C_4F_{10} ring on four HPDs.

Figure 3.7: Accumulated Cherenkov ring images, integrated over $\sim 30k$ events (a) and $\sim 100k$ events (b).

3.5.1 Pixel-chip Offsets and the HPD Active Area

The HPD-axis is the axis of symmetry of the HPD electron optics. The demagnification of the pixel hits in the reconstruction is performed with respect to this axis. The HPD-axis nominally passes through the centre of the pixel chip; however, for the pre-production HPDs, the pixel chip was placed in the HPD with a mechanical precision of ~ 2 mm. Failing to account for this offset in the reconstruction would produce a distorted ring and would therefore affect the measured Cherenkov angle. The edge of the active area of the HPD is defined by a kovar ring glued to the inside of the HPD quartz window. The photocathode is deposited inside this ring and so defines the area over which photons are detected. Since the demagnified image of the photocathode on the anode is smaller than the size of the pixel chip, pixel hits recorded outside this active area cannot come from direct photoelectrons.

The pixel-chip offsets and active area were determined from data taken using a low-intensity LED. Integrated over a large number of events, the LED illuminated the whole tube with approximately uniform intensity. This produced a solid disc of pixel hits, centred on the HPD axis and with radius defined by the active area of the HPD. The pixel-hit image of an LED-run with 100k events is shown in Figure 3.8(a). The pixels within the active area have an average of ~ 750 hits integrated over the run. An edge finding algorithm was used to find the edge of the active area – any pixel with occupancy greater than half the average occupancy and with at least three neighbours with less than half the average occupancy was defined as an edge hit. The resulting ring of edge-hits was fitted with a circle. To reduce the effect of any noisy or dead pixels which could be identified as edge pixels, any edge hit more than two pixels from the fitted circle was removed and the circle re-fitted. The remaining edge hits are shown in Figure 3.8(b), with the refitted circle also shown.

The parameters of the circles fitted to the edge-hits from LED runs on the six HPDs are shown in Table 3.2. The active radius measurements were used in the reconstruction to select hits of interest.

To ensure the simulated Cherenkov rings overlapped the data rings, the offsets in the MC were calculated assuming the beam was centred on the outside of the HPD. The difference between the offsets used in the MC and those measured from the LED data could arise if the photocathode was not centred on the HPD axis. The systematic difference in the column direction may be due to an offset in the beam position by

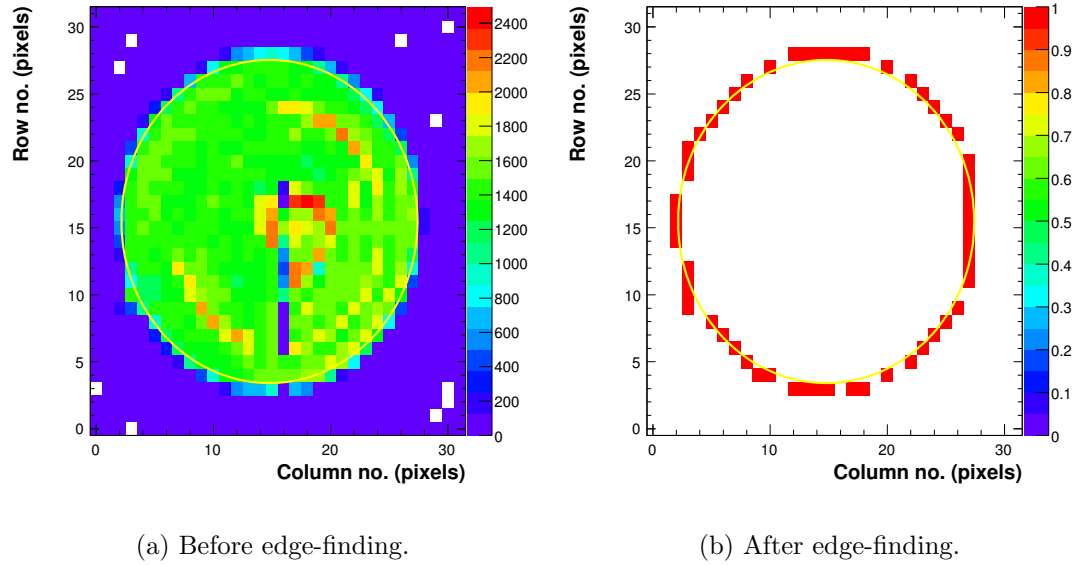


Figure 3.8: The pixel-chip images for an LED run on HPD C1 with $\sim 100\text{k}$ events, before and after applying the edge-finding algorithm. The fitted circle is shown in both images.

HPD	HPD-axis		Active area radius / pixels
	Col / pixels	Row / pixels	
L0	16.5 ± 0.7	15.7 ± 0.7	12.7 ± 0.5
L1	14.1 ± 0.7	15.6 ± 0.7	12.3 ± 0.5
C0	15.1 ± 0.7	14.0 ± 0.7	12.2 ± 0.5
C1	14.8 ± 0.7	15.5 ± 0.7	12.6 ± 0.5
R0	15.6 ± 0.7	15.7 ± 0.7	12.1 ± 0.5
R1	15.8 ± 0.7	15.0 ± 0.7	12.1 ± 0.5

Table 3.2: The measurements of the HPD pixel-chip offsets.

$\sim 1\text{ mm}$. This would systematically shift the Cherenkov ring by $\sim 4\text{ mm}$ on the HPD quartz window or 1.5 pixels. No difference was observed between the Cherenkov angle resolution using these pixel-chip offsets and those in the MC. The offsets in the MC, described in Section 3.4, were therefore used in the reconstruction.

3.5.2 Event Selection

A non-negligible beam contamination from electrons was observed in the reconstructed data and a small contribution from negatively charged kaons was also seen. In N_2 , however, kaons are below threshold for producing Cherenkov light and so, although triggered by the scintillators, produce no hits in the HPDs. The event selection described below was designed to reject the electron events while retaining a high fraction of the pion events.

Some preliminary hit selection was performed, to remove hits that could not have come from Cherenkov photons:

- Only hits on the signal HPD, onto which the ring was focussed for that run, were considered.
- Hits outside the active area of the HPD, as measured in Section 3.5.1, were excluded. These hits were largely from back-scattered photoelectrons.

To reduce the effect of the beam contamination, some further cuts were applied to the data. To ensure that a well defined Cherenkov ring could be reconstructed, only events with at least four pixel hits were considered. To reduce the background from electron events, a cut was applied to select events with hits in a region of interest. After accounting for the demagnification law (see Section 3.5.3.1), a circle was fitted to the demagnified pixel hits for all events in a given run passing the requirements above. The average of the fitted ring centres was used to define the centre of an annulus. The region of interest was then defined as: $r_1 < r < r_2$, where r is the radius of a hit from the centre of the annulus and r_1 and r_2 are the radii of the inner and outer edges of the annulus respectively. The values of r_1 and r_2 were chosen so that all hits from the pion rings within $\sim 3\sigma$ (defined below as the width of the radius distribution of the hits) were contained in the annulus, while selecting only a small fraction of the electron events. An event was used in the analysis if it had at least four hits in the annulus and no more than three hits outside it. For the Cherenkov angle resolution studies, only those hits that were in the region of interest were used in the photon and beam reconstruction. This cut removed one or more hits in $\sim 6\%$ of data events and $\sim 4\%$ of MC events. This difference arises because there is a small probability for back-scattered photoelectrons to be detected, which is not modelled in the MC.

The hit-radius is defined as the radius of a given pixel hit with respect to the fitted

ring centre for that event. The distribution of hit-radii is shown in Figure 3.9. The distribution was fitted with two Gaussians to account for pion events and background events. The Gaussian for the pion peak had a mean of 19.5 mm and a width of 1.3 mm. The values of r_1 and r_2 were chosen to be 15.8 mm and 23.0 mm ($\pm 2.7\sigma$). The MC showed that this gave a 91% efficiency for selecting pion events and a 99% efficiency for rejecting electron events. In the data, these criteria gave an overall probability of selecting an event of 85%, from which the original electron contamination was estimated to be 7%. The distribution of circle-radii from an electron run is shown in Figure 3.10, where a circle is fitted to all selected hits in an event. Three Gaussians were used to fit the electron data – the electron peak is well described by a Gaussian with mean 24.1 mm and width 0.5 mm.

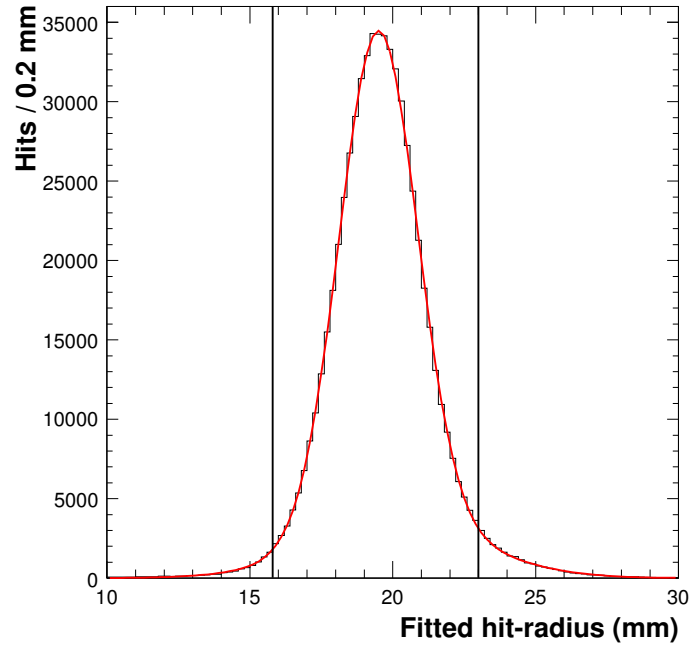


Figure 3.9: The distribution of fitted hit-radii to define the region of interest (black bars) with a fitted double Gaussian (red curve).

3.5.3 Cherenkov Angle Reconstruction

The Cherenkov angle is calculated as the angle between the reconstructed photon and beam directions. Only events passing the selection criteria defined in Section 3.5.2 were considered.

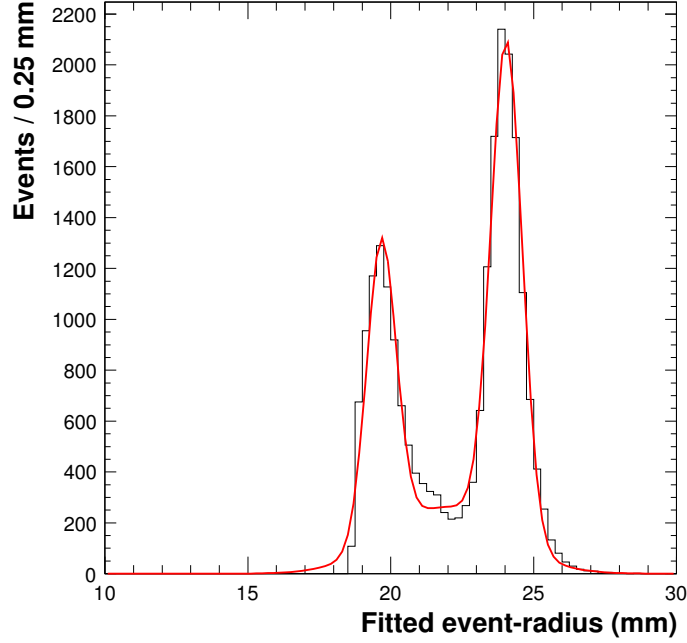


Figure 3.10: The distribution of fitted circle-radii from an N₂–electron run, with a fitted triple Gaussian (red curve). There is one entry per event.

The reconstruction procedure is divided into five main parts: hit selection, demagnification of the selected hits, correction for refraction effects in the HPD quartz window, reconstruction of the photon direction and reconstruction of the beam direction. The hit selection is described above and the other parts are described in the following subsections.

3.5.3.1 Image Demagnification

A linear demagnification law was used to map a pixel position to its corresponding coordinate on the photocathode (the origin of the photoelectron)

$$x_{\text{photocathode}} = -5.64 \times 0.5 \times (x_{\text{pixel}} - x_0) \quad (3.3)$$

$$y_{\text{photocathode}} = -5.64 \times 0.5 \times (y_{\text{pixel}} - y_0) \quad (3.4)$$

where x_{pixel} (y_{pixel}) is the row (column) number, in the range $[0, 31]$, and x_0 (y_0) is the row (column) number of the HPD-axis on the pixel chip. The spherical shape of the

HPD quartz entrance window was accounted for in the calculation of $z_{\text{photocathode}}$

$$z_{\text{photocathode}} = R_{\text{photocathode}} - \sqrt{R_{\text{photocathode}}^2 - x_{\text{photocathode}}^2 - y_{\text{photocathode}}^2}, \quad (3.5)$$

where $R_{\text{photocathode}}$ is the inner radius of the HPD quartz entrance window. This procedure gave a one-to-one mapping of the pixel hits to the photocathode surface.

3.5.3.2 Photon Refraction in the HPD Quartz Window

The effect of photon refraction in the HPD quartz entrance window could not be accounted for analytically because the incident direction of the photon was a-priori unknown. An iterative fit procedure was therefore used to establish the photon impact point on the outside of the HPD quartz window ($\mathbf{r}_{\text{HPD}}$) for each photoelectron-origin ($\mathbf{r}_{\text{photocathode}}$). In each iteration, a candidate $\mathbf{r}_{\text{HPD}}$ was considered: using a knowledge of the mirror optics (described in Section 3.5.3.3) and assuming the photon emission-point to be half-way along the radiator length, the incident photon direction on the HPD was then calculated. The resulting candidate photoelectron-origin was then calculated and compared to $\mathbf{r}_{\text{photocathode}}$. The distance between the candidate photoelectron-origin and $\mathbf{r}_{\text{photocathode}}$ was subsequently minimised. The MC simulation indicated that this procedure reconstructed $\mathbf{r}_{\text{HPD}}$ to an accuracy of ~ 0.1 mm.

3.5.3.3 Reconstruction of the Photon Direction

A parabolic mirror was used in the testbeam to focus the Cherenkov light onto the HPDs (with a diameter of ~ 200 mm and a radius of curvature of ~ 2047 mm). The small size of the mirror, in comparison to its radius of curvature, meant that to a good approximation it could be treated as a spherical segment. The MC showed that the difference between a parabolic and spherical mirror with these dimensions was negligible in the testbeam setup.

An outline of the mirror optics is shown in Figure 3.11. For a spherical mirror, the optics are described by a quartic equation with coefficients which depend on: the photon emission-point (E), the mirror centre-of-curvature (C) and the photon detection-point (D). The point C was calculated from the alignment of the mirror and the point E was assumed to be half-way along the length of the nominal beam line through the radiator. The point D was taken to be the position of the photon impact point on the HPD quartz

window, i.e. the output of the iterative fit described above. This allowed the position of the photon impact point on the mirror (M) to be found. The photon direction was then taken to be the unit vector along the line joining E to M.

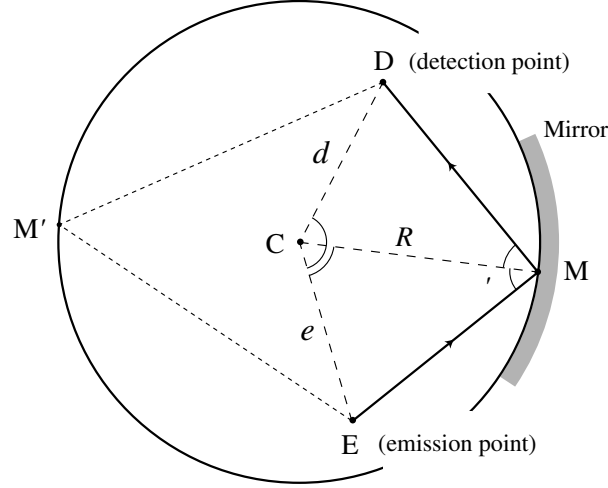


Figure 3.11: A schematic of the testbeam mirror optics [141]. The solid black line with the arrow shows the path of the photon – E is the emission point; M is the reflection point on the mirror and D is the detection point. The distance R is the mirror radius of curvature and the point C is the centre of curvature.

The photon emission-point (E) was taken to be half-way along the length of the nominal beam line through the radiator. An improved estimate of the emission-point was calculated using a knowledge of the reconstructed beam direction on an event-by-event basis, instead of the nominal beam direction. This was shown to give no significant improvement in the Cherenkov angle resolution because the focussing property of the mirror produces a very weak dependence on the emission-point.

For the default geometric setup, the mirror centre of curvature (C) was calculated in the reconstruction so that the reflection of the nominal beam direction in the mirror would impact on the centre of HPD C1. The centre of curvature for other setups (e.g. to focus the ring on a different HPD) was calculated in a similar way, to ensure that if the nominal beam direction were reflected, that reflection would pass through the centre of the HPD.

3.5.3.4 Reconstruction of the Beam Direction

No tracking information was available in the testbeam setup. The beam direction was therefore reconstructed from the pixel-hit data. In order to decouple the photon and

beam reconstruction uncertainties, the beam reconstruction was done for every selected hit, using the information of the other hits in the event. For a given hit, a circle was fitted to the ring produced by the other Cherenkov photons. The fit was performed using the reconstructed photon positions on the HPD quartz window, i.e. having already accounted for the demagnification and refraction effects. The centre of the fitted circle was assumed to be the point that the beam particle would have passed through had it been reflected by the mirror. The point where the beam particle hit the mirror could therefore be found using a knowledge of the mirror optics, in a similar way to the photon reconstruction. The detection-point was taken to be the centre of the fitted circle and the emission-point was assumed to be 2 m upstream of the detector housing. This choice for the emission-point is arbitrary – the exit of the beam from the beam-line was therefore chosen. A small change was seen in the reconstructed beam directions as this assumption was changed between 1 m and 10 m upstream of the detector.

The distributions of reconstructed ring centres in the Y- and Z-projections (corresponding to the row and column directions of the pixel chip) are shown in Figures 3.12(a) and 3.12(b). The resolution on the position of the centres, from the MC simulation, was shown to be ~ 0.5 mm, consistent with the pixelisation error on the individual hits used in the circle fit. This gave an error on the reconstructed beam direction of ~ 1 mrad.

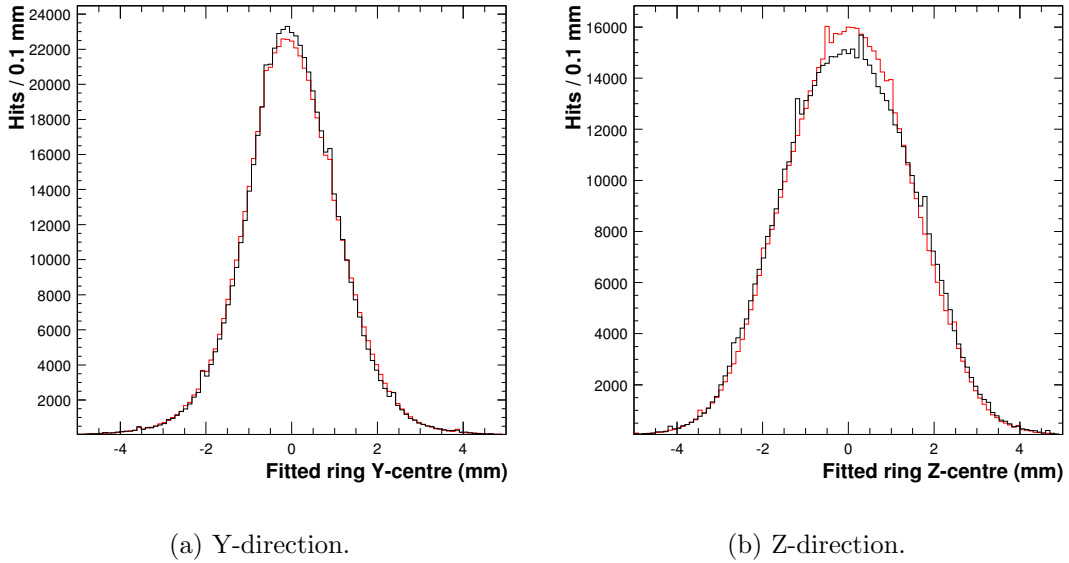


Figure 3.12: The distribution of fitted circle centres from the data (black) and the MC (red).

In each event, a circle was also fitted to all the selected hits in the event, with centre $\mathbf{C}_{evt}$ and radius R_{evt} . This event-circle was compared to the fitted circle used in the beam reconstruction (the hit-circle), with centre $\mathbf{C}_{hit}$ and radius R_{hit} . To ensure the hit-circle was similar to the event-circle, the following three cuts were applied:

- the centres were required to be less than 4 mm apart ($|\mathbf{C}_{evt} - \mathbf{C}_{hit}| < 4 \text{ mm}$);
- the radii were required to be less than 4 mm different ($|R_{evt} - R_{hit}| < 4 \text{ mm}$) and
- the reconstructed positions of the beam impact on the mirror were required to be less than 4 mm apart ($|M_{evt} - M_{hit}| < 4 \text{ mm}$).

These cuts were effective against events where there were relatively few selected hits and at least one of the hits lay a long way from the ring. In this case the background hit could pull the fitted circle and so affect the Cherenkov angle distribution. The combination of these cuts removed $\sim 3\%$ of hits from the tails of the respective distributions.

3.5.4 Cherenkov Angle Resolution Studies

The Cherenkov angle distribution for a N₂-pion run on HPD C1 (black line) is shown in Figure 3.13. Also shown in Figure 3.13 is the MC distribution for this setup. Only those hits which were inside the region of interest were used in the reconstruction. The data and MC distributions are in good agreement, with a mean 19.64 (19.63) mrad in the data (MC) and an *RMS* of 1.66 (1.64) mrad. The statistical errors on the mean and *RMS* values are negligible. The systematic uncertainties are described in Section 3.5.4.1.

A summary of the Cherenkov angle resolutions for the six HPDs is given in Table 3.3. The variation in the mean Cherenkov angle arises because a common demagnification law was assumed for the six HPDs. As can be seen from Table 3.2, the radius of the demagnified image of the photocathode (which is a measure of the HPD demagnification factor) varies by $\sim 2\%$, consistent with the variation in mean Cherenkov angle. There is a small variation in the Cherenkov angle resolution across the six HPDs. This may be due to changes in the HPD PSF which is affected by the demagnification factor.

The Cherenkov angle resolution can be expressed in terms of four contributions: the chromatic effect, photon reconstruction, beam reconstruction and charge sharing. The photon reconstruction can be further separated into contributions from HPD pixelisation, HPD PSF and the photon emission-point. The beam direction was reconstructed

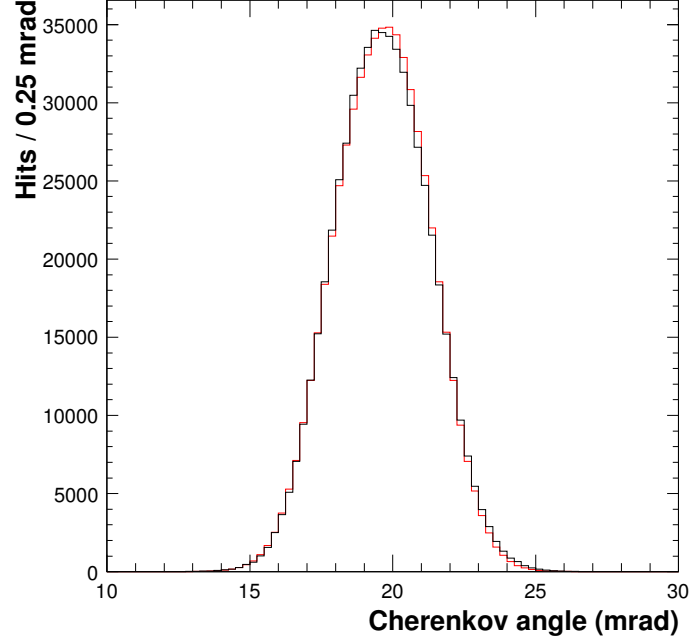


Figure 3.13: The reconstructed Cherenkov angle for data (black line) and MC (red line) for a N_2 -pion run on HPD C1. There is one entry per selected photoelectron hit.

HPD	mean θ_C / mrad	θ_C resolution / mrad
L0	19.83	1.67
L1	19.23	1.67
C0	19.51	1.61
C1	19.64	1.66
R0	19.13	1.69
R1	19.50	1.68

Table 3.3: A summary of the Cherenkov angle measurements. The statistical errors on the mean (RMS) values are 0.02 mrad (0.001 mrad).

by fitting circles to the Cherenkov ring and so receives contributions to the error from the HPD pixelisation, PSF and emission-point effects, in addition to the beam divergence and any circle fitting errors. The contributions from these effects were estimated from the MC and are described below.

The contribution from the chromatic effect arises because the Cherenkov photons are emitted with a distribution of energies and the refractive index of the N_2 gas has

a wavelength dependence. The distribution of generated Cherenkov angles for those photons in the MC which reach an HPD is shown in Figure 3.14. The double peak structure arises from the combination of the chromatic effect and the HPD quantum efficiency which is not uniform as a function of wavelength. The contribution to the Cherenkov angle resolution from this effect was determined to be 0.41 mrad, equal to the *RMS* of this distribution.

The contribution inherent to the reconstruction geometry (i.e. the procedures to account for the refraction in the HPD quartz and reflection from the mirror) was estimated, from the MC, to be 0.03 mrad. This was estimated using the true beam direction, the true photoelectron-origin and the true emission-point to reconstruct the photon direction, thus removing any contribution from the pixelisation, PSF or emission-point assumptions. The difference between the true and reconstructed^b Cherenkov angles is shown in Figure 3.15; the contribution assigned to the reconstruction is the *RMS* of this distribution. In comparison to the overall resolution of 1.66 mrad, this is a negligible contribution and is ignored for the remaining discussion. In order to isolate the various contributions charge-sharing in the pixel-chip was turned off in the MC in the following discussion.

The overall contribution from the photon reconstruction procedure was estimated to be 1.28 mrad. This was determined from the MC using the true beam direction in the reconstruction instead of the standard circle-fitting procedure. This was further divided into the contributions from the pixelisation (0.78 mrad), HPD PSF (1.00 mrad) and emission-point effects (0.19 mrad). The contribution from the HPD PSF effect was determined using the true beam direction, the true photon emission-point and the true hit coordinate on the pixel-chip, i.e. after the MC has simulated the PSF effect but before pixelisation. The combined contribution from the PSF and pixelisation was determined in a similar manner, using the pixelised coordinate on the pixel-chip instead of the true coordinate (1.27 mrad). The contribution from pixelisation alone (0.78 mrad) was then calculated as the difference in quadrature between the combined contribution and the PSF contribution alone. This is consistent with the value determined directly from a MC simulation with the HPD PSF set to zero (0.79 mrad). The final contribution to the photon reconstruction, from the emission-point assumption, was determined using the true beam direction and the true photon-impact point on the HPD quartz window but assuming the emission-point to be half-way along the radiator length.

^bFor this section reconstructed means using the reconstruction procedures but with some MC truth information used as input in place of pixel-hit data.

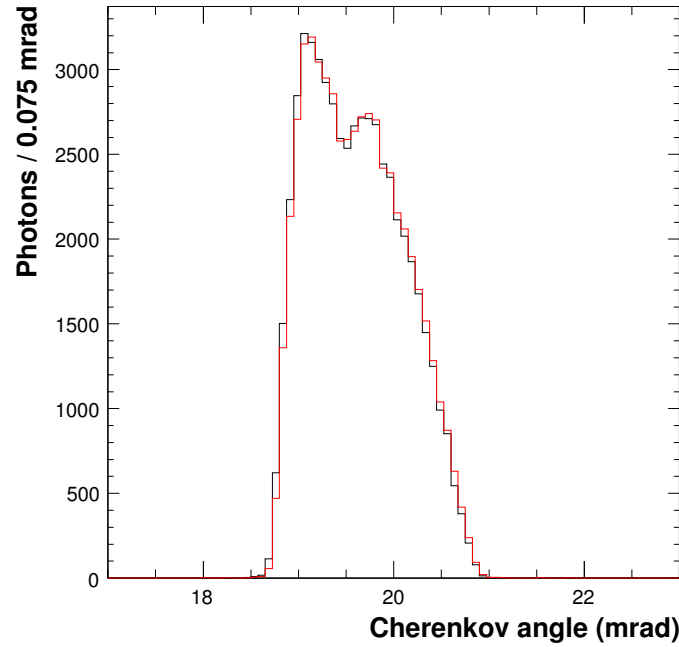


Figure 3.14: The distribution of Cherenkov angles generated in the MC.

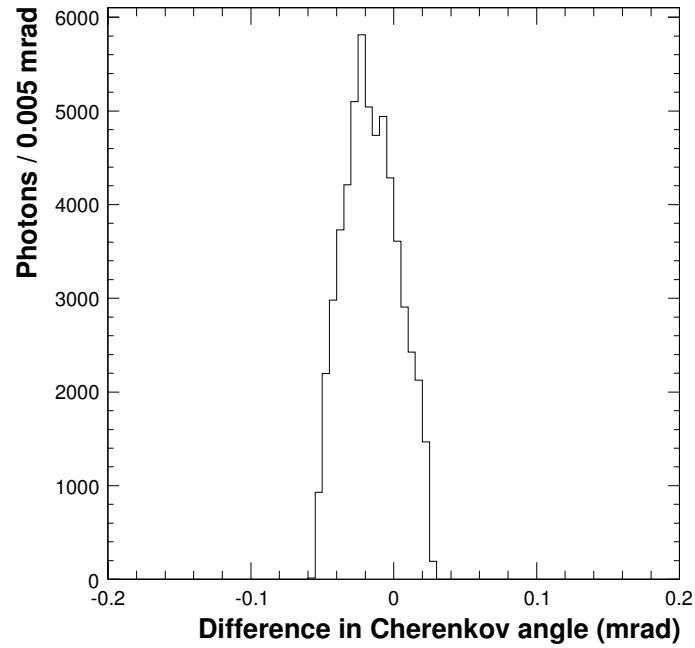


Figure 3.15: The difference between the generated and reconstructed Cherenkov angles from the MC, using the true photon-impact position and the true beam direction.

The contribution from the beam reconstruction (0.95 mrad) was determined using the true photon direction in the reconstruction. Because the beam was reconstructed from the pixel hits, this has contributions from the same effects as the photon reconstruction, in addition to the beam divergence and circle fitting. The contributions from the beam divergence, circle-fitting procedure and the emission-point effects were combined into an intrinsic-beam contribution; this would be present even if the HPDs detected the photons with infinite accuracy. The intrinsic-beam contribution (0.52 mrad) was estimated using the true photon direction in the photon reconstruction and the true photon impact coordinate on the HPD quartz window in the beam reconstruction. The other contributions to the beam reconstruction, from the pixelisation (0.49 mrad) and HPD PSF (0.63 mrad), were estimated in similar way.

The final contribution, from charge-sharing, was determined by turning on the charge-sharing routine in the MC. Other studies in the testbeam analysis measured the charge-sharing to be at the 3% level^c. The charge-sharing hits have no true Cherenkov angle and therefore it was not possible to evaluate the contribution from the distribution of the difference between true and reconstructed Cherenkov angles. The contribution was determined as the difference in quadrature between the *RMS* of the reconstructed Cherenkov angle distribution with and without charge-sharing turned on in the MC.

A summary of the contributions to the Cherenkov angle resolution is given in Table 3.4. The pixelisation and HPD-PSF effects dominate the resolution owing to the geometry of the testbeam detector. In LHCb the Cherenkov rings are much larger and spread over multiple HPDs so the pixelisation and HPD-PSF effects are expected to be much smaller – at a similar level to the emission-point and chromatic effects. Also, in LHCb, the equivalent of the beam reconstruction is not necessary because the tracking detectors will provide information on a particle’s direction. The contribution from the beam reconstruction will therefore be replaced by the tracking errors.

The contributions to the Cherenkov angle resolution are largely uncorrelated. The sum in quadrature of the intrinsic-beam (0.52 mrad), beam pixelisation (0.49 mrad) and beam HPD-PSF (0.63 mrad) contributions is 0.95 mrad, equal to the total contribution determined directly using the MC. Similarly, the sum in quadrature of the contributions to the photon reconstruction (1.28 mrad) is equal to the total contribution evaluated directly from the MC. Finally, the sum in quadrature of all the contributions (chro-

^cIn this definition of charge-sharing, each pixel-hit has a 3% chance to charge-share into an adjacent pixel and produce an extra hit.

Effect	Contribution / mrad
Data	1.66
MC	1.64
Chromatic	0.41
Beam reconstruction	0.95
– Intrinsic-beam	0.52
– Pixelisation	0.49
– HPD-PSF	0.63
Photon reconstruction	1.28
– Pixelisation	0.78
– HPD-PSF	1.00
– Emission-point	0.19
Charge sharing	0.12
Combination in quadrature	1.65

Table 3.4: The contributions to the Cherenkov angle resolution. The statistical errors on the *RMS* values are $\mathcal{O}(10^{-3} \text{ mrad})$.

matic effect, beam reconstruction, photon reconstruction and charge-sharing) is in good agreement with both the resolution from the full MC and from the data.

3.5.4.1 Systematic Uncertainties

The systematic errors on the Cherenkov angle resolution from a number of components in the testbeam setup were evaluated from the MC. A variety of parameters were changed in the simulation one-by-one, in each case by an amount equivalent to the estimated error on that parameter. The full reconstruction was run on the modified MC samples and the *RMS* of the Cherenkov angle distribution was compared to the nominal MC. The systematic error assigned to the parameter under investigation was then the difference in the *RMS* of the nominal and modified MC Cherenkov angle distributions.

- **Pixel-chip offset :** the error on the HPD-axis measurements, described in Section 3.5.1, was estimated to be ± 0.7 pixels in both the row and column directions. The pixel chip offset was therefore changed by this amount in both directions in the MC – a small change of $\sim 0.01 \text{ mrad}$, was seen in the resolution. This was a

small effect because the beam direction was determined from the ring data and so the Cherenkov angle is largely insensitive to the absolute position of the ring.

- **Beam energy** : the spread of beam energies provided by the accelerator was checked to be small by analysing the electron data. In these runs, a Cherenkov threshold counter was used to trigger electrons with $\sim 50\%$ purity. The saturated electrons were unaffected by the small changes in the beam energy from the accelerator. A comparison between the Cherenkov angle resolution from the pion and from the electron data showed that the effect of the beam energy distribution was negligible.
- **Beam divergence** : the beam divergence was measured to be 1.4 mrad and 0.6 mrad in the x- and y-directions respectively by matching the data and MC distributions of the fitted circle centres, as shown in Figure 3.12. The error on the beam divergence was conservatively estimated to be 50% and the corresponding systematic error on the resolution was determined to be ~ 0.02 mrad. Again, because the beam direction was determined on an event-by-event basis, the beam divergence has a small effect on the resolution.
- **Mean beam direction** : the average beam direction, about which the beam diverged, was varied in the MC by an amount equivalent to the beam divergence, i.e. by 1.4 mrad and 0.6 mrad in the x- and y-directions respectively. The systematic error from this source was determined to be ~ 0.01 mrad.
- **Mean beam position** : the beam position was fixed by the two scintillators used as a trigger. The mean beam position was therefore moved in each direction in the MC by half the size of the scintillators, i.e. by ± 1 cm. The change in the resolution was measured to be ~ 0.01 mrad.
- **Mirror tilt angle** : the mirror tilt angle was changed by an amount sufficient to move the mean position of the Cherenkov rings by ± 1 mm on the surface of the HPD, estimated to be the error on the laser alignment procedure described in Section 3.2.1. The systematic error was measured to be ~ 0.01 mrad. Because the adjusted mirror tilt moves the position of the ring on the HPD, the shape of the ring can be affected by different distortions or refraction effects owing to it being off centre.
- **Mirror position along the beam line** : the mirror was moved in the MC by ± 2 mm, again representing the estimated error on the geometry measurements.

This gave a change in the resolution of ~ 0.001 mrad. Moving the mirror along the beam line changed the radiator length and hence the number of photons emitted. This change, however, was undetectable because the radiator length was only changed by $\sim 0.1\%$, which would give rise to a change in the mean number of detected photoelectrons per event of ~ 0.01 . A shift in the mirror position in the MC also changed the distance between the mirror and the HPDs and therefore affected the focus of the rings.

- **Mirror radius of curvature :** changing the mirror radius of curvature affects the focus of the rings on the HPD in a similar way to moving in the mirror along the beam line. The radius of curvature was changed in the simulation by ± 15 mm, equal to the difference between the measured and nominal values. A change of ~ 0.01 mrad, was seen in the Cherenkov angle resolution.
- **Mirror focussing quality :** in the standard MC, the mirror was assumed to give perfect specular reflections. The surface roughness of the mirror results in a smearing of the reflected angle and thus the reconstructed photon direction. The mirror used in the testbeam had a D_0 of 0.3 mm. The effect of the surface roughness of the mirror was added to the MC as a Gaussian smearing of the reflected angle with sigma equal to $D_0 / 8R$. The systematic error from the mirror D_0 was found to be ~ 0.01 mrad.

A toy model simulation was used to check the correlation between the mirror position along the beam line (mirror Z-position) and mirror radius of curvature. As described above, these two effects are expected to be correlated since they both change the focal plane of the mirror. The toy model geometry was setup to be the same as the full MC geometry. Photons were emitted with constant Cherenkov angle at random intervals along a nominal particle track. The photons were ray traced to the mirror, specularly reflected and traced to the HPD quartz window. The radius of the photon impact on the HPD was calculated with respect to the centre of the ring, defined by the impact position of a photon emitted with zero Cherenkov angle, i.e. parallel to the particle track. A measure of how well the photons are focussed at the HPD was obtained from the *RMS* of the radius distribution. The *RMS* of the radius distribution is shown in Figure 3.16 as the mirror Z-position and radius of curvature were changed in the toy model. The mirror does not perfectly focus the photons for any combination of Z-position and radius because the testbeam geometry is off-axis in the horizontal plane. The *RMS* of the radius distribution for the default setup is ~ 0.7 mm. The increase

in the RMS of the radius distribution at the extremes of Figure 3.16(b) translates to an increase in the Cherenkov angle resolution of ~ 0.02 mrad, as expected from the studies using the full MC. The correlation between the two parameters can be seen in Figures 3.16(a) and 3.16(b). As the two parameters are changed, by amounts equivalent to their respective errors, the resultant change in the Cherenkov angle resolution is small and this correlation was therefore ignored.

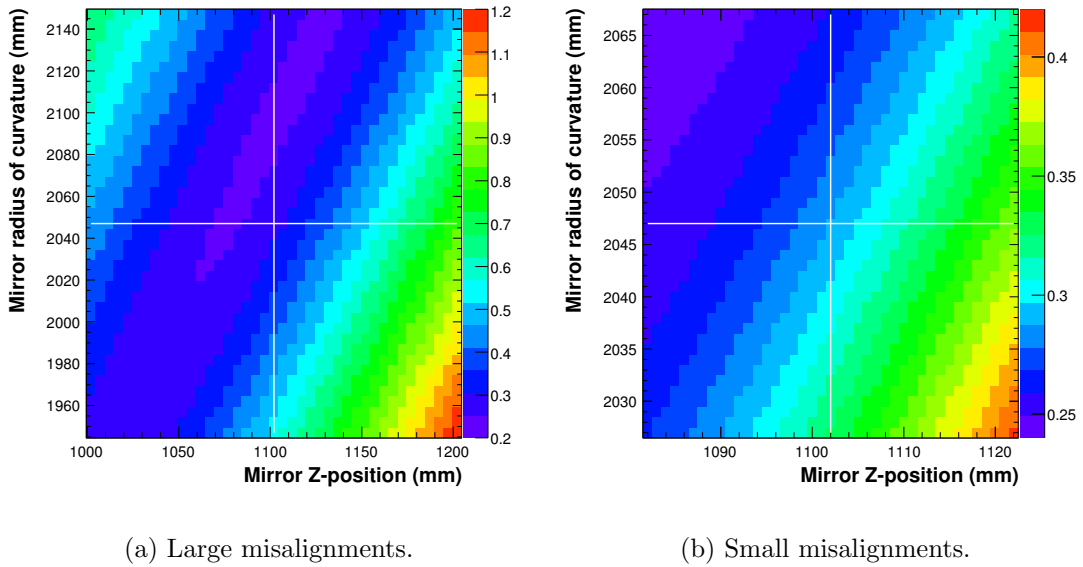


Figure 3.16: The variation in the RMS of the radius distribution for simulated photons in the toy model, as the mirror Z-position and radius of curvature are changed.

A toy model was also used to check the validity of the assumption that the parabolic mirror used in the testbeam could be treated as a spherical mirror for the reconstruction. In a similar way to the toy model described above, photons emitted along the radiator length were ray traced to the HPD quartz window surface. For each photon this was done once using the parabolic mirror and once using a spherical mirror with similar properties. A negligible difference (~ 0.006 mm) was seen in the photon impact positions using the two mirror setups. This difference was therefore ignored for the systematic error studies.

A summary of the systematic errors is shown in Table 3.5. The total systematic error is calculated as the sum in quadrature of the individual components. The Cherenkov

angle was therefore measured to be

$$\begin{aligned}\theta_C &= 19.64 \text{ mrad}, \\ \sigma_{\theta_C} &= 1.66 \pm 0.03 \text{ mrad},\end{aligned}$$

where the quoted error is the total systematic error and the statistical error is an order of magnitude smaller. This is in good agreement with the MC values

$$\begin{aligned}\theta_C &= 19.63 \text{ mrad}, \\ \sigma_{\theta_C} &= 1.64 \pm 0.03 \text{ mrad}.\end{aligned}$$

Mis-alignment	Change in θ_C / mrad
Pixel-chip offset	0.008
Beam divergence	0.019
Mean beam direction	0.006
Mean beam position	0.016
Mirror tilt angle	0.007
Mirror position	0.001
Mirror radius of curvature	0.008
Mirror D_0	0.007
Combination in quadrature	0.030

Table 3.5: Summary of systematic errors on the Cherenkov angle resolution.

3.5.5 Photoelectron Yield Results

A summary of the photoelectron yield analysis is presented in this section [140]. The analysis is concentrated on the N₂-pion runs where the rings are focussed on single HPDs. Results are presented for four of the six HPDs – a known timing problem affected HPDs C0 and R0 and they were not included in the analysis.

The number of photons emitted by a charged particle travelling through a medium

is given by

$$dN = \frac{2\pi\alpha L}{\lambda^2} \left(1 - \frac{1}{n(\lambda)^2 \beta^2} \right) d\lambda, \quad (3.6)$$

where L is the radiator length (1102 mm), λ is the photon wavelength and n is the gas refractive index. The reflectivity of the mirror (R_M), transmission of the quartz windows (T_{quartz}) and HPD quantum efficiency (QE) reduce this yield, hence the number of detected pixel-hits is given by

$$dN = \frac{2\pi\alpha L}{\lambda^2} \left(1 - \frac{1}{n(\lambda)^2 \beta^2} \right) \cdot R_M(\lambda) \cdot T_{quartz}(\lambda) \cdot QE(\lambda) \cdot \epsilon_{det} d\lambda, \quad (3.7)$$

where ϵ_{det} is the pixel-chip detection efficiency. For the testbeam the mirror reflectivity was typically greater than $\sim 80\%$ and the quartz transmission greater than $\sim 90\%$. The HPD quantum efficiency varied in the range $10\% - 20\%$ as a function of photon wavelength (for example Figure 3.4). For a nominal pixel-chip detection efficiency of 85% , ~ 8 hits were therefore expected per event.

A resolution model to account for the asynchronous beam effect and also for time jitter in the system was used to calculate ϵ_{det} for each HPD. The Poisson distribution of the number of photons is further modified by effects of the binary readout, which include charge sharing and double-hits. Charge sharing results in an extra hit being read out whereas double-hits (where two genuine photoelectrons land in the same pixel) results in one less hit being read out. The charge sharing is measured from the data using dark-count runs where no light source was present and was found to be in the range $2\% - 4\%$. The double hit probability was also measured from the data as a function of the number of hits in the event. A correction was also made for any dead pixels on each of the pixel chips. The distribution of the number of selected hits per event for HPD C1 is shown in Figure 3.17 [140]. Also shown in Figure 3.17 is the fit to the number of hits accounting for all the timing and readout effects which is in good agreement with the data.

A summary of measurements for the four HPDs is shown in Table 3.6. The measured values are all in good agreement with the expectations.

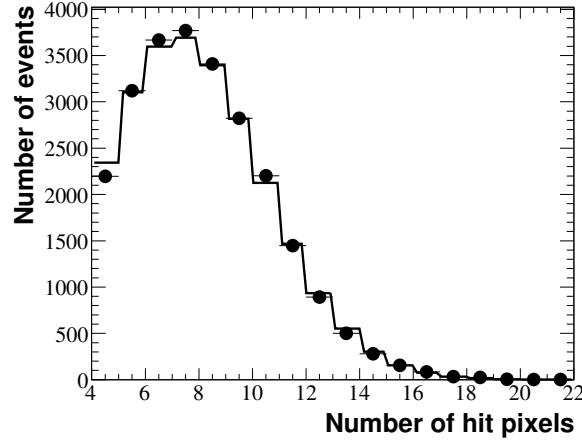


Figure 3.17: The number of pixel-hits per event (points) on HPD C1, with the corresponding fit (line) overlaid [140].

HPD	χ^2/ndf	μ_{fit}	μ_{exp}	Ratio
L0	21/14	8.7 ± 0.2	8.9 ± 0.6	0.98 ± 0.10
L1	12/16	10.1 ± 0.1	10.7 ± 0.7	0.94 ± 0.07
C1	30/16	11.5 ± 0.3	11.2 ± 0.6	1.03 ± 0.08
R1	37/16	10.2 ± 0.1	10.0 ± 0.4	1.02 ± 0.06

Table 3.6: Summary of the photoelectron yield measurements.

3.6 Summary of Follow-up Studies

A subsequent testbeam was carried out at the INFN laboratory in Frascati, Italy, in 2006. To test the on-detector system integration, 36 production HPDs were mounted on three columns with the final L0, LV and HV-boards. Four pre-production 12-channel L1-boards were used to read out the data. The accelerator provided 500 MeV electrons, again at random intervals with respect to the 40 MHz readout clock.

A new data acquisition system (DAQ) was written for this testbeam in the LabView framework [142] to allow the readout of all 36 HPDs simultaneously. The L1-boards were configured via a USB interface from the DAQ computer. This allowed the full features of the L1-board to be used, including the blocking of individual input channels or memory banks. Each of the three L1-boards used to read out the HPDs received data via a 12-way optical fibre. To increase the rate of data taking, any unused links were blocked. Unstable optical links which would cause problems in the automatic error

checking routines could also be blocked. The 12-channel L1-boards each had six memory banks so data from two optical channels, corresponding to two HPDs, were multiplexed into one memory bank. Any memory bank that had both its input optical links blocked was not read-out. Groups of events, typically 1000 at a time, were stored in the on-board memory chips. These were then passed via Ethernet to a DAQ computer, to be written to disk. Some basic error checking was implemented in the DAQ. This checked that the number of events received by the L1-board matched the number of triggers and that the correct amount of data was stored in the memory chips. Monitoring of the pixel-chip hits and the average number of hits per event was implemented to allow basic data quality checks.

Data were taken in similar configurations to the previous testbeam. The majority of the runs were taken with an N_2 radiator with the ring fully contained on one HPD. Some runs were taken with the ring split over two HPDs. In this testbeam the beam had no pion contamination, so in principle the event selection procedure using the region of interest was not needed in the analysis. During the testbeam an unknown background, seen on all HPDs and in time with the beam, was observed. This was significantly reduced with a lead shielding wall placed round the detector housing. However, it was still necessary to apply the event selection, with the region of interest modified to account for the larger electron rings, to reduce the effect of this background. The Cherenkov angle distribution is shown in Figure 3.18, fitted with a Gaussian with mean 24.5 mrad and width 1.75 mrad. The mean of the distribution is consistent with the expected Cherenkov angle. The resolution is also in agreement with the measurements from the previous testbeam.

A final testbeam in September 2006 was carried out at the CERN-SPS accelerator. The on-detector (L0) and off-detector (L1) electronics used in this testbeam were identical to those that will be used in LHCb. The full suite of LHCb readout software was also used from the online readout-supervisor and event builder to the offline analysis framework. This testbeam was the first opportunity to operate the RICH electronics in a beam with a 25 ns structure.

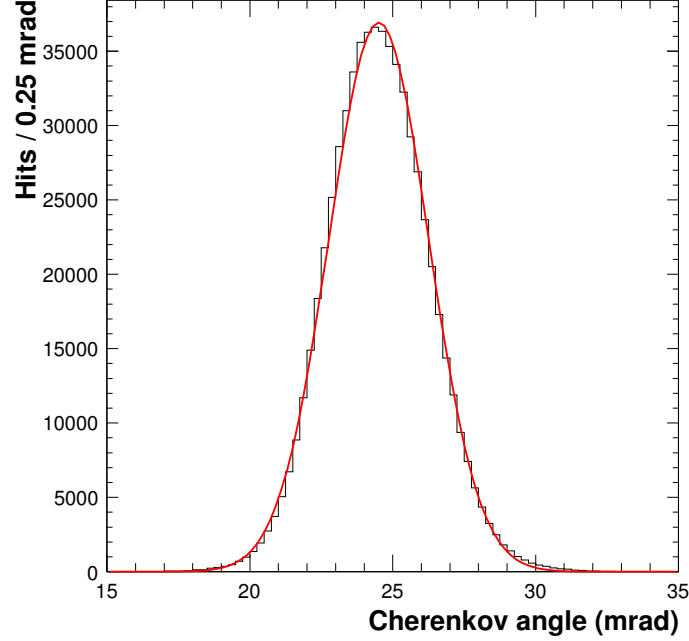


Figure 3.18: The Cherenkov angle distribution (black) for an N₂ ring from the Frascati testbeam. The fitted Gaussian is shown in red.

3.7 Summary of Cherenkov Angle and Photoelectron Yield Results

The majority of the analysis presented in this chapter is based on the data from the CERN-2004 testbeam. The Cherenkov angle was found to be

$$\theta_C = 19.64 \text{ mrad},$$

with a resolution of

$$\sigma_{\theta_C} = 1.66 \pm 0.03 \text{ mrad},$$

in good agreement with the MC simulation. The error quoted on the resolution is the total systematic error and the statistical error is an order of magnitude smaller. The resolution is dominated by the HPD pixelisation effect (0.78 mrad) and HPD-PSF effect (1.00 mrad). The photoelectron yield for HPD C1 was found to be 8.7 ± 0.2 , in good agreement with the expected value. The results of the analyses from subsequent testbeams, at Frascati and CERN in 2006, confirmed these results.

Chapter 4

Reconstruction and Selection of $B_d^0 \rightarrow K^* \mu^+ \mu^-$ Decays

This chapter presents an overview of the LHCb software used for the simulation and reconstruction of B-decay events. The LHCb DaVinci application, described below, was used to implement the initial selection of the decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$. The remainder of the analysis was performed using the ROOT framework [143]. The offline selection cuts are described and the resulting annual signal yield estimate is presented.

4.1 Overview of LHCb Software

The LHCb software is based on the object-orientated Gaudi C++ architecture [144]. The architecture differs slightly from a standard C++ philosophy in that structures to store data (data-objects) and to process data (algorithms) are implemented separately. This allows for a longer stability of the data objects (e.g. the LHCb Event Model) while the algorithms evolve more rapidly. It also means that alternative algorithms can be implemented more easily without repeating the data storage. Gaudi applications and algorithms are configured via custom job-options files [145].

The LHCb computing model is well suited for distributive computing because all applications run as part of the same Gaudi framework. The LHCb DIRAC project [146] provides the necessary workload management tools and the GANGA project [147] provides the job submission interface. These allow simulation and reconstruction jobs to

be run as part of the LCG Grid [148] which provides significant computing power and storage resources. The system is based on a job-pilot scheme that searches for suitable computing resources (e.g. to ensure the relevant data is stored at a given site) before sending the necessary files for that job.

In the following sections, an overview of the Monte-Carlo simulation (Gauss and Boole) and the reconstruction (Brunel and DaVinci) applications is given.

4.1.1 Monte-Carlo Event Simulation

The MC simulation is divided into three main steps: the event generation, detector simulation and detector digitisation [126]. Practically, these are grouped as two applications: Gauss [149, 150] and Boole [151].

- **Event generation (Gauss)** : performs the simulation of the underlying proton-proton interaction and scattering processes using the Pythia package [152]. This has been tuned to reproduce multiplicities at lower energies [153, 154] and accounts for LHC beam effects such as the transverse or longitudinal beam sizes and the reducing luminosity during a run. The simulation of B-decays is done using the EvtGen package [155, 156] developed for the BaBar experiment and modified for LHCb.
- **Detector simulation (Gauss)** : simulates the interaction of the particles in the event as they pass through the detector. This includes, for example, energy deposits in the silicon detectors and the production of Cherenkov photons in the RICH detectors. This step is handled by the GEANT4 toolkit [137] with parameters tuned where possible using information from testbeam or laboratory data. For example, the size of the HPD PSF was tuned from RICH testbeam data (see Section 3.5). The resulting energy deposits (hits) are passed to the Boole application.
- **Detector digitisation (Boole)** : models the response of the detector to the particle interactions. The Boole application applies the detector response to the hits generated previously and simulates the effect of the readout electronics and the L0-trigger hardware. To account for any overspill from other bunch crossings, three minimum bias events (corresponding to the subsequent and two previous bunch crossings) are superimposed on the in-time signal event being simulated. The

effect of electronics noise and cross-talk between channels is also included. The final stage is a simulation of the readout process including the zero-suppression routines of the electronics. The output format of this stage is then identical to the real data format.

4.1.2 Event Reconstruction

The event reconstruction is designed to run identically on both real and simulated data. Any MC information from simulated events is processed in separate algorithms and links made to associate reconstructed quantities to MC-truth quantities. This ensures that the reconstruction will not technically break when presented with real data.

The reconstruction procedure is divided in two parts: track reconstruction (performed by the Brunel [157] application) and decay reconstruction (performed by the DaVinci [158] application). The input to Brunel is the Raw Buffer object, produced by either the LHCb data-acquisition system or the Boole application. The Brunel application decodes the Raw Buffer object and runs the pattern recognition routines to produce a precise set of tracks with the minimum number of false tracks. False tracks are classified as either ghosts, where the reconstructed track is not associated to any MC particle, or clones, where the reconstructed track is associated to more than one MC particle. The set of reconstructed tracks is then passed as inputs to the calorimeter, RICH and muon sub-detector particle identification routines.

The DaVinci application assigns particle identification hypotheses to the reconstructed tracks to form reconstructed particles. It also reconstructs the primary interaction vertex (PV) position. Standard extrapolation and vertexing routines are used to reconstruct unstable particles which decayed within the experiment and dedicated algorithms are then run to select particles and decays of interest.

4.2 Signal and Background Samples

Events generated using the full LHCb GEANT4-based MC simulation were used to optimise the signal selection criteria. These events were generated as part of the LHCb Data-Challenge-2004 (DC04). The dominant background in LHCb after the trigger is expected to be from events containing real b-decays [76, 87]. These events typically have

high p_T and high impact-parameter tracks which can be incorrectly combined to mimic a signal decay. The background sample of 24M $b\bar{b}$ -inclusive events, generated as part of DC04, reflected this expectation.

The selection criteria were chosen to maximise the signal-to-background significance, defined as $S / \sqrt{S + B}$ [159], using a sample of 52.5k signal events and 24M $b\bar{b}$ -inclusive events. This definition of the significance was chosen to minimise the relative error on the estimate of the number of true signal events in the presence of background and is therefore equivalent to minimising the error on the branching ratio estimate. Because of the limited background MC statistics (described below) a full, simultaneous optimisation of all the selection cuts was not possible.

In order to avoid using the same sample to measure the background level and to place the cuts and because of the limited statistical significance of the $b\bar{b}$ -inclusive sample, the background was evaluated using a number of specific samples. These samples were chosen to reflect the major background sources identified from the $b\bar{b}$ -inclusive sample. This procedure also guards against any biases introduced when fine-tuning the cuts with only a small number of surviving MC events. The event samples used are described below and summarised in Table 4.1.

A sample of 52.5k $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays was generated with the requirement that the B_d decayed within 400 mrad of the beamline. This requirement increases the number of useful events generated (i.e. removing those that could not possibly be detected by LHCb) and is motivated by the geometric acceptance of the LHCb detector. This requirement has an efficiency of 0.349 for B_d events [160] – the 52.5k signal events generated are therefore equivalent to $52.5k / 0.349 = 150k$ events without the geometric cuts in the event generator. This sample therefore represents $\sim 0.5 \text{ fb}^{-1}$ or ~ 3 months of data-taking.

The cuts were chosen using a sample of $b\bar{b}$ -inclusive decays as a typical background. Again motivated by the LHCb geometric acceptance, the $b\bar{b}$ events were generated with the requirement that one of the b - or $\bar{b}$ -quarks decayed within 400 mrad of the beamline with an efficiency of 0.434 [160]. The total of 24M events generated is therefore equivalent to $24M / 0.434 = 55M$ events without this requirement. This sample represents ~ 25 minutes of data-taking and is therefore much less statistically significant than the signal sample.

Given the small statistical significance of the $b\bar{b}$ -inclusive sample with respect to the signal sample, higher significance samples were used to evaluate the level of the

background. The justification for using these samples is given in Chapter 5. A list of the samples used and their significances^a with respect to the $b\bar{b}$ sample, is given in Table 4.1. The signal branching ratios used in the simulation are also given. In the first two samples in Table 4.1, the b - and $\bar{b}$ -quarks were decayed according to the b -hadron production fractions given in Table 4.2. The requirement that only one of the b - or $\bar{b}$ -quarks be within 400 mrad of the beam line means these two samples have a higher value of ε_{gen} . The remaining samples required that the signal b -hadron be within 400 mrad of the beam line. The slight variation in the values of ε_{gen} for these samples arises because of the different momentum spectra of the b -hadron types.

Sample	Branching ratio	No. of events generated	ε_{gen}	No. of events in 4π	Significance w.r.t $b\bar{b}$
$b\bar{b}$ -inclusive	—	24×10^6	0.434	55×10^6	1
$b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$	0.012	8.9×10^6	0.434	20×10^6	31
$B_d^0 \rightarrow s \mu^+ \mu^-$	4×10^{-6}	136500	0.349	390000	1900
$B_u^+ \rightarrow s \mu^+ \mu^-$	4×10^{-6}	157000	0.349	450000	2100
$B_d^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$	0.9894%	3.9×10^6	0.349	11×10^6	21
$B_u^+ \rightarrow \mu^+ c (\rightarrow \mu^-)$	0.7328%	3.9×10^6	0.349	11×10^6	29
$B_s^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$	0.6122%	1.0×10^6	0.348	3.0×10^6	32
$\Lambda_b \rightarrow \mu^- c (\rightarrow \mu^+)$	0.3464%	1.0×10^6	0.347	3.0×10^6	51
$B_d^0 \rightarrow K^* \mu^+ \mu^-$	1.22×10^{-6}	52500	0.349	150000	—
$K^* \rightarrow K^+ \pi^-$	0.67	—	—	—	—

Table 4.1: The significance of the specific background event samples with respect to the $b\bar{b}$ -inclusive sample.

The $b\bar{b}$ -inclusive cross-section was assumed to be 500 μb . In a nominal LHCb year (10^7 s) at the nominal luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, 10^{12} $b\bar{b}$ pairs will be produced. The production fractions assumed for the B -mesons and Λ_b are given in Table 4.2 [1]. These production fractions and branching ratios were used throughout the calculations in this document. Approximately 650k $B_d^0 \rightarrow K^* \mu^+ \mu^-$ events are expected to be produced per nominal physics year in LHCb, where

$$N_{B_d^0 \rightarrow K^* \mu^+ \mu^-} = 10^{12} \times 2 \times 0.398 \times (1.22 \times 10^{-6}) \times 0.67, \quad (4.1)$$

^aThe significance of a sample is calculated according to the equivalent integrated luminosity with respect to the $b\bar{b}$ sample.

assuming 10^{12} $b\bar{b}$ pairs are produced per year.

B-particle	Production fraction
B_d	0.398
B_u	0.398
B_s	0.103
Λ_b	0.100

Table 4.2: B-particle production fractions [1].

4.3 Event Reconstruction and Selection

The general procedure for reconstructing $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays is described below. The event reconstruction can be divided into two parts: track reconstruction and track combination, as described in Section 4.1.2. In this analysis the reconstructed $K^\pm$ and $\pi^\pm$ are combined to form K^* candidates. The K^* candidates are then combined with two $\mu^\pm$ tracks to form B_d candidates. Since this is a rare decay it is safe to assume there is a maximum of one true signal decay per event and the selection efficiencies can be safely calculated at the event level rather than candidate level. In practice, after the full selection cuts are applied, the number of signal or background events with multiple candidates is negligible ($< 1\%$).

4.3.1 Charged Particle Identification

The LHCb global particle identification information was used to identify the type of charged particle track. The information from the different sub-detectors is combined into an overall log-likelihood ($\ln\mathcal{L}$) value for a given particle hypothesis. This value is compared to the $\ln\mathcal{L}$ for the π hypothesis, to produce a $\Delta\ln\mathcal{L}$ value. For muons the $\Delta\ln\mathcal{L}$ is dominated by the muon sub-detector information. To identify a track as a $\mu^\pm$, the muon detectors must have returned a positive muon identification which means a minimum number of hits were required in the muon detector stations^b, as described in Section 2.2.10. In practice, this requirement has good efficiency for identifying true

^bTechnically, this means the DET='Muon' flag must be set true.

muons so only a loose $\Delta \ln \mathcal{L}$ cut was then imposed

$$\Delta \ln \mathcal{L}_{\mu\pi} = \ln \mathcal{L}_\mu - \ln \mathcal{L}_\pi > -15,$$

as shown in Figure 4.1(a). These requirements gave an efficiency of $> 99\%$ for selecting true muons from $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays. For the charged kaon and pion identification the majority of the information comes from the RICH detectors. For the offline selection, the RICH detectors were required to have contributed to the global $\Delta \ln \mathcal{L}$ value which means at least one detected Cherenkov photon must be assigned to the track^c. For the $\pi^\pm$ the cut was placed at

$$\Delta \ln \mathcal{L}_{\pi K} > -5,$$

with an efficiency of $\sim 98\%$ for selecting true $\pi^\pm$ from $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays, as shown in Figure 4.1(b). For the $K^\pm$ identification, two $\Delta \ln \mathcal{L}$ cuts, shown in Figures 4.1(c) and 4.1(d), were used

$$\Delta \ln \mathcal{L}_{K\pi} > -5$$

$$\Delta \ln \mathcal{L}_{Kp} > -5.$$

Together, these cuts had an efficiency of $\sim 95\%$ for selecting true $K^\pm$ from $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays.

4.3.2 $K^\pm$, $\pi^\pm$ and $\mu^\pm$ Track Selection

Tracks from true b-decays typically have high p_T and impact-parameter because of the large B-mass and long B-lifetime respectively. The charged track selection therefore reflected this, cutting on the track p_T and Impact Parameter Significance (IPS , defined below). A cut on the track momentum (p) was imposed at the preselection stage. The preselection is a loose set of cuts, designed to have high efficiency on signal, with a moderate background rejection. Because the preselection was applied to the $b\bar{b}$ -inclusive sample before the final cuts were optimised, these preselection cuts form the minimal set of cuts that must be applied. To maximise the efficiency for selecting events, as opposed to selecting tracks, only those tracks which were used to reconstruct the B_d candidate were used in the optimisation process. Unless specifically mentioned otherwise, in all

^cTechnically, this means the DET='RICH' flag must be set true.

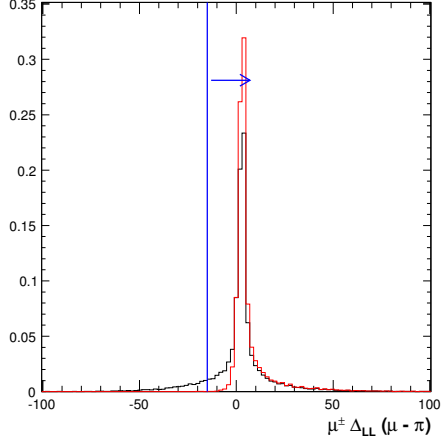
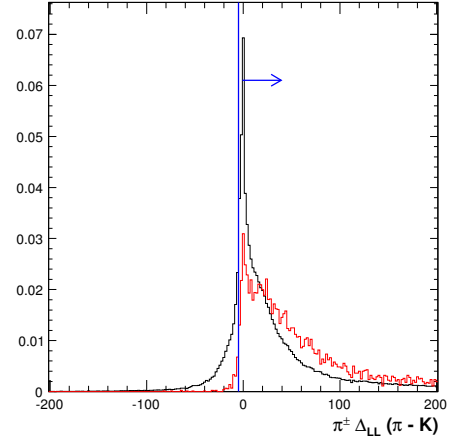
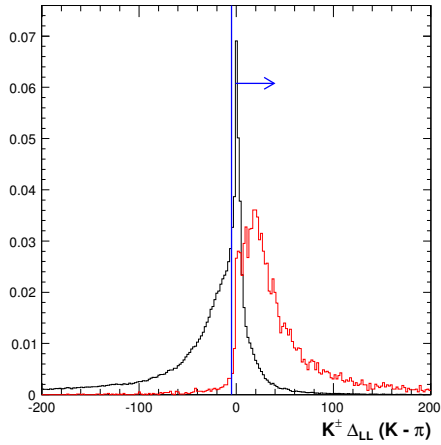
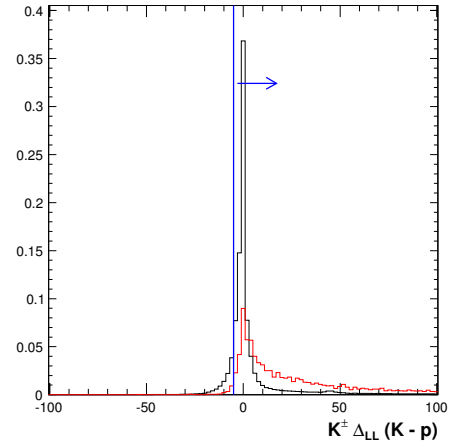
(a) Muon $\Delta \ln \mathcal{L}_{\mu\pi}$ distribution.(b) Pion $\Delta \ln \mathcal{L}_{\pi K}$ distribution.(c) Kaon $\Delta \ln \mathcal{L}_{K\pi}$ distribution.(d) Kaon $\Delta \ln \mathcal{L}_{Kp}$ distribution.

Figure 4.1: The reconstructed $\mu^\pm$ (a), $\pi^\pm$ (b) and $K^\pm$ (c and d) $\Delta \ln \mathcal{L}$ distributions for tracks in signal events. The black lines show the distributions for all charged tracks in the event before applying any $\Delta \ln \mathcal{L}$ cuts. The red lines show the distributions for just tracks coming from signal $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays.

plots in the remainder of this chapter the red (black) line represents the signal ($b\bar{b}$ -inclusive) distribution.

The IPS is defined as the impact parameter of a track with respect to a PV divided by its error. Since many events have more than one PV, the cut is made on the smallest IPS ($sIPS$). The momentum vectors of the $K^\pm$, $\pi^\pm$ and $\mu^\pm$ in candidate signal decays are required to not point back to any PV, i.e. to have a large $sIPS$. The requirement for the B_d is that the momentum vector does point back to at least one of the PVs in the event. The $sIPS$ (p_T) distributions for the $K^\pm$, $\pi^\pm$ and $\mu^\pm$ candidates are shown in Figures 4.2(a), 4.3(a) and 4.4(a) (4.2(b), 4.3(b) and 4.4(b)) respectively. In each figure, the plot shows the signal and $b\bar{b}$ -inclusive distributions, normalised to unit area. The blue lines and arrows show the positions and directions of the cuts. The events in the plots have the preselection cuts applied (the criteria for which are summarised in Table 4.3). The $K^\pm$, $\pi^\pm$ and $\mu^\pm$ $sIPS$ and p_T cuts were required to be

$$\begin{aligned} K^\pm \quad sIPS &> 3, \quad p_T > 400 \text{ MeV}/c \\ \pi^\pm \quad sIPS &> 3, \quad p_T > 250 \text{ MeV}/c \\ \mu^\pm \quad sIPS &> 2, \quad p_T > 500 \text{ MeV}/c. \end{aligned}$$

For the rest of this chapter, the set of cuts applied to the $K^\pm$, $\pi^\pm$ and $\mu^\pm$ are called the track-selection.

4.3.3 K^* and $\mu\mu$ Selection

The selection of the intermediate states in the decay was applied to those tracks selected by the track selection described above. Although the two muons do not actually form an intermediate resonance (the J/ψ resonance regions are removed by a mass-veto cut, described below), they were technically treated as forming an intermediate state to investigate cuts on the $\mu\mu$ vertex. This was because a large component of the background contained muons from different b -decays which are therefore less likely to form a good vertex.

The p_T , vertex- χ^2 and $sIPS$ cuts for the K^* selection were unchanged from their respective preselection values. The plots in Figure 4.5 show the signal and $b\bar{b}$ -inclusive distributions for these variables with the preselection cuts applied.

With the track selection cuts described above applied, a K^* flight-significance cut

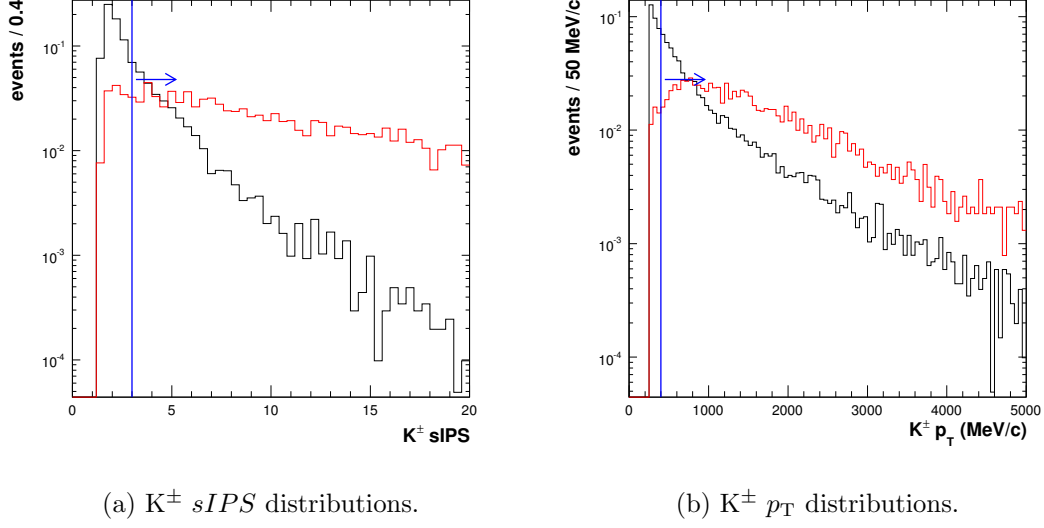


Figure 4.2: The reconstructed $K^\pm$ $sIPS$ (a) and p_T (b) distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection cuts with arbitrary normalisation. The lines and arrows show the positions and directions of the cuts.

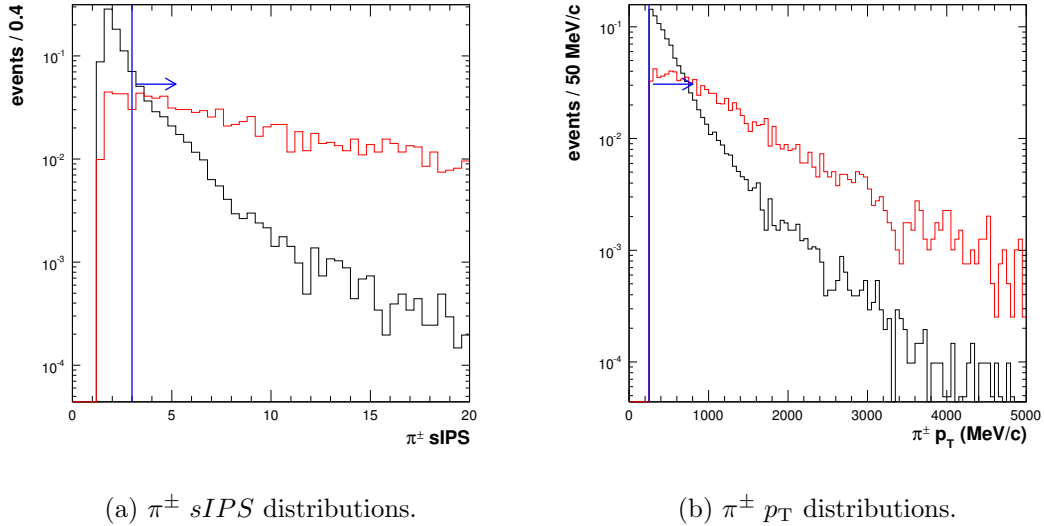


Figure 4.3: The reconstructed $\pi^\pm$ $sIPS$ (a) and p_T (b) distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection cuts with arbitrary normalisation. The lines and arrows show the positions and directions of the cuts.

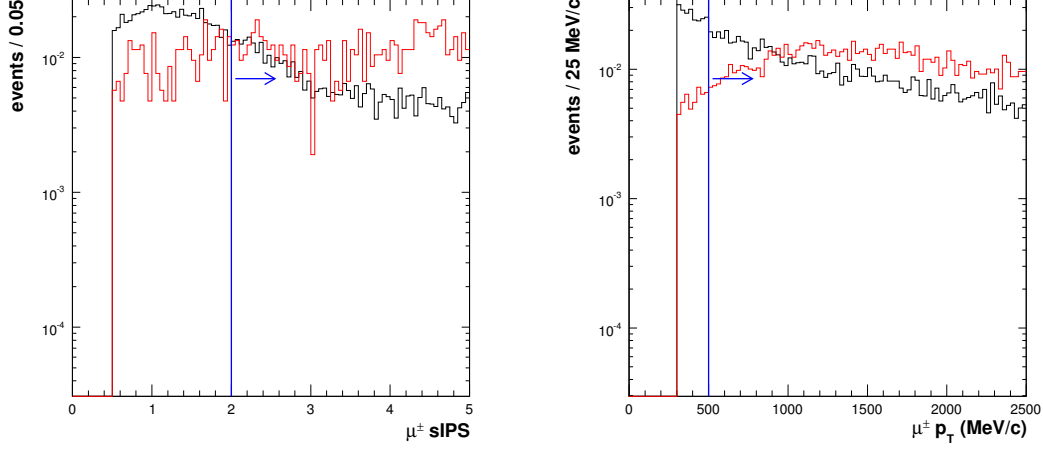
(a) $\mu^\pm$ $sIPS$ distributions.(b) $\mu^\pm$ p_T distributions.

Figure 4.4: The reconstructed $\mu^\pm$ $sIPS$ (a) and p_T (b) distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection cuts with arbitrary normalisation. The lines and arrows show the positions and directions of the cuts.

was investigated. The flight-significance is defined as the distance between the PV and the K^* decay vertex divided by its respective error. The plot in Figure 4.6 shows the distribution of the K^* flight-significance for signal and $b\bar{b}$ -inclusive background. The cut required

$$K^* \text{ flight-significance} > 1.$$

A mass veto was applied to the $\mu\mu$ invariant-mass to remove the J/ψ ($1S$) and J/ψ ($2S$) resonances. The branching ratio and A_{FB} measurements should be made in the region where short distance physics dominates [161], i.e. away from the $c\bar{c}$ -resonances. Candidates with $\mu\mu$ -mass around the J/ψ ($1S$) or J/ψ ($2S$) resonances are therefore rejected in the range

$$\begin{aligned} 2900 < M_{\mu\mu} < 3200 \text{ MeV}/c^2 \\ 3650 < M_{\mu\mu} < 3725 \text{ MeV}/c^2. \end{aligned}$$

The $\mu\mu$ vertex- χ^2 and flight-distance cuts were applied to the candidates selected by the preselection and track-selection criteria. The plots in Figure 4.7 show the signal

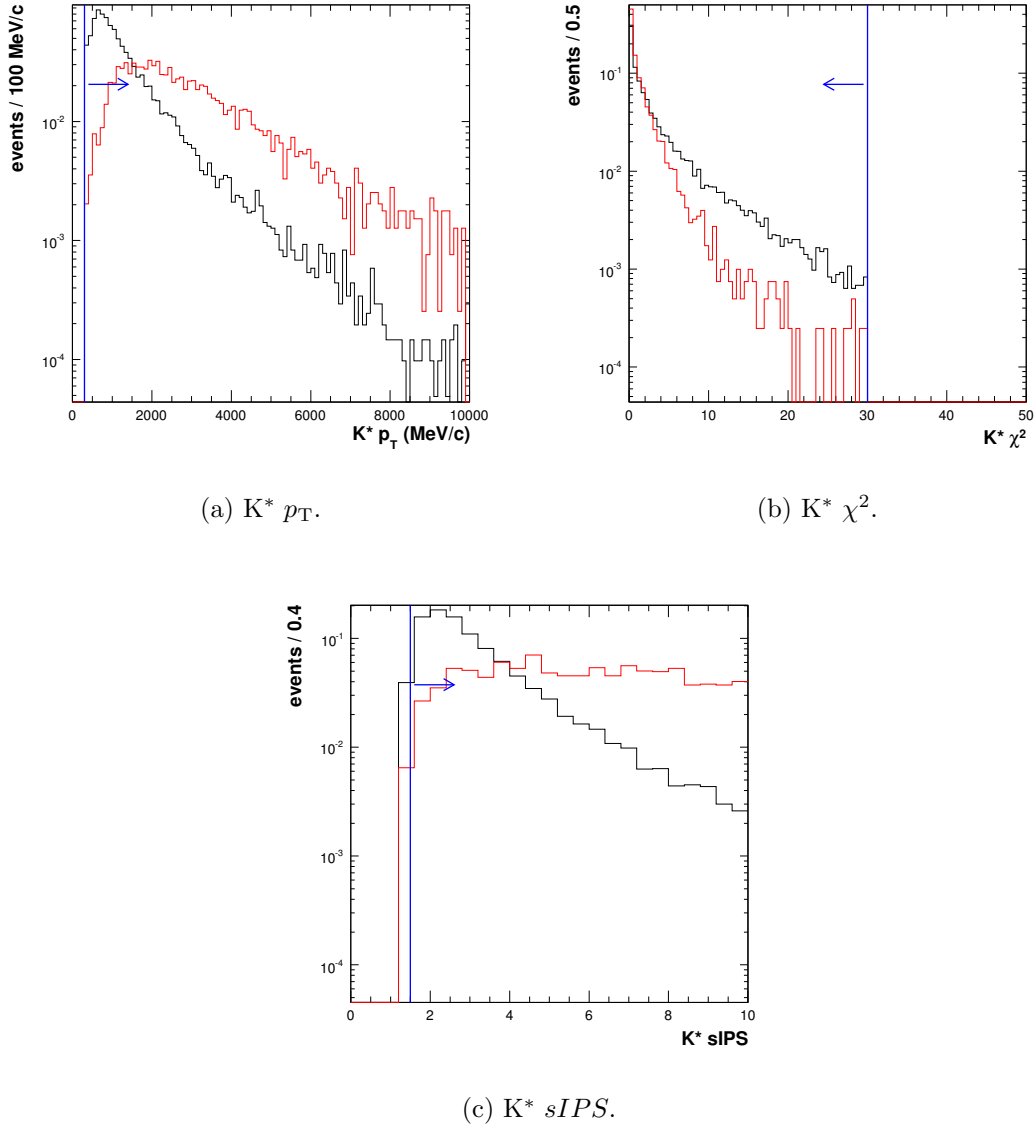


Figure 4.5: The reconstructed $K^* p_T$ (a), vertex- χ^2 (b) and $sIPS$ (c) distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection cuts with arbitrary normalisation. The lines and arrows show the positions and directions of the cuts.

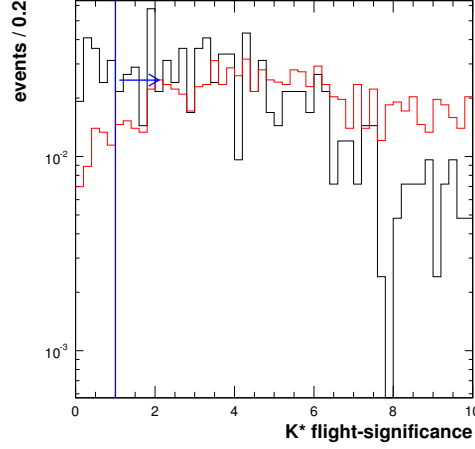


Figure 4.6: The reconstructed K^* flight-significance distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection and track-selection cuts with arbitrary normalisation. The line and arrow show the position and direction of the cut.

and $b\bar{b}$ -inclusive background distributions for the vertex- χ^2 and flight-distance variables. The cuts required

$$\begin{aligned} \mu\mu \text{ vertex-}\chi^2 &< 15 \\ \mu\mu \text{ flight-distance} &> 1 \text{ mm.} \end{aligned}$$

4.3.4 B_d Selection

The selection for the reconstructed B_d candidate was applied to those K^* and $\mu\mu$ candidates selected by the criteria described above (intermediate-selection). The p_T cut for the B_d selection was unchanged from its preselection value – the signal and $b\bar{b}$ -inclusive distributions are shown in Figure 4.8 with the preselection cuts applied.

Five further cuts were applied to the surviving B_d candidates to reduce the remaining background. The vertex- χ^2 , flight-significance and $sIPS$ distributions for the B_d candidates selected by the preselection and intermediate-selection described above are

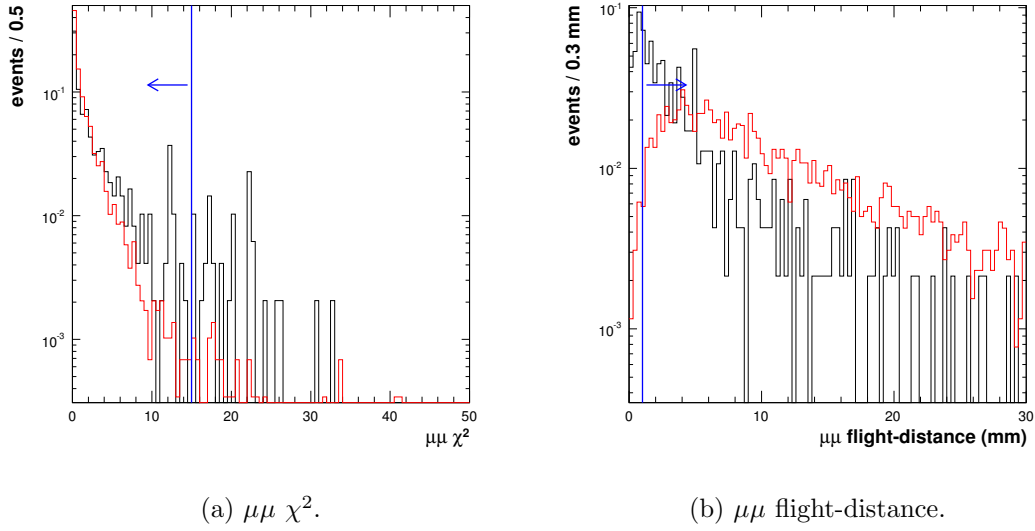


Figure 4.7: The reconstructed $\mu\mu \chi^2$ (a) and flight-distance (b) distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection and track-selection cuts with arbitrary normalisation. The lines and arrows show the positions and directions of the cuts.

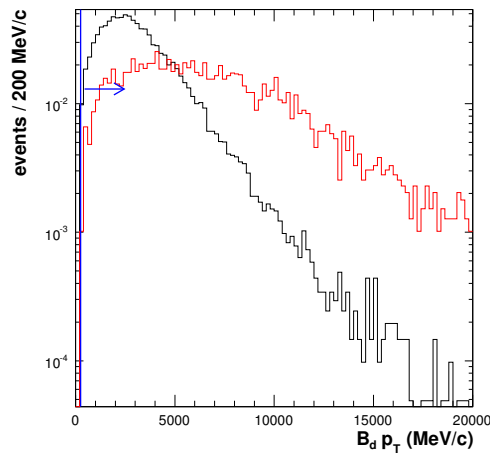


Figure 4.8: The reconstructed $B_d p_T$ distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection cuts with arbitrary normalisation. The line and arrow shows the position and direction of the cut.

shown in Figure 4.9. The cuts required

$$\begin{aligned} B_d \text{ vertex-}\chi^2 &< 20 \\ B_d \text{ flight-significance} &> 6 \\ B_d \text{ } sIPS &< 5. \end{aligned}$$

The B_d pointing-angle (θ) is the angle between the flight direction (the line joining the primary and reconstructed decay vertices) and the momentum vector direction. For a true, fully reconstructed B_d particle, these vectors are parallel (within the detector resolution) but for a fake B_d particle, including a true B_d particle where at least one decay product is not considered or is missing, the θ values have a large spread. Figure 4.10 shows the $\cos(\theta)$ distribution for signal and $b\bar{b}$ -inclusive candidates selected by the preselection and intermediate-selection described above with arbitrary normalisation. The cut was chosen to require

$$\cos(\theta) > 0.99975.$$

A vertex-isolation cut was placed on the number of tracks within 3σ of the reconstructed B_d vertex and is designed to remove candidates where a track from a PV is used to reconstruct the B_d . This can occur if a track is mis-reconstructed, for example if the charged particle interacts with material in the detector and is deflected, or if a PV is mis-reconstructed or not reconstructed at all. The latter cases can lead to a large number of tracks which pass the necessary $sIPS$ cut. The distribution of the number of tracks within 3σ of the B_d vertex is shown in Figure 4.11 for candidates which pass all the criteria described above. The red line shows the distribution of the number of tracks in signal candidates; the black shows the distribution of the number of tracks in background candidates, evaluated from a number of specific background samples described in Chapter 5. The final cut required that fewer than 11 tracks were within 3σ of the B_d vertex.

4.3.5 Summary of Selection Cuts

A summary of the selection cuts is given in Table 4.3. These were found to give an efficiency of $(20.6 \pm 0.5)\%$ for reconstructed $B_d^0 \rightarrow K^* \mu^+ \mu^-$ signal events.

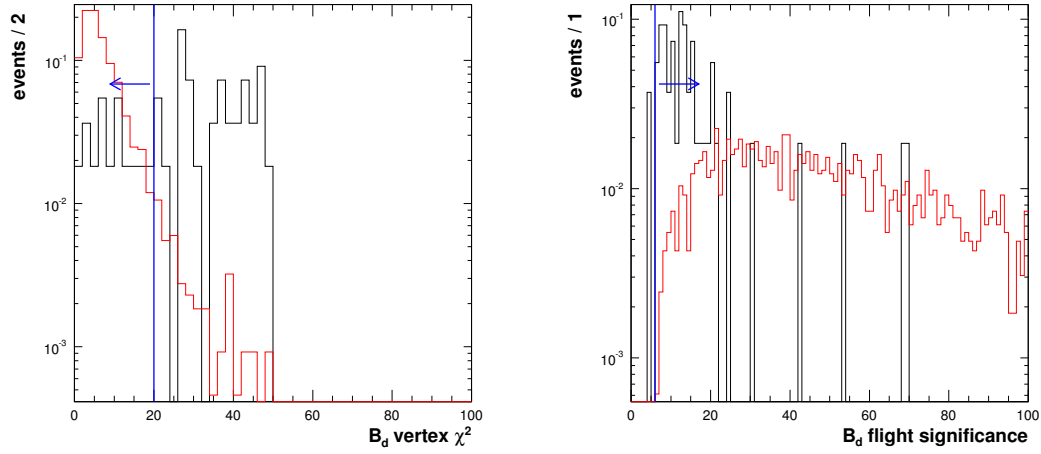
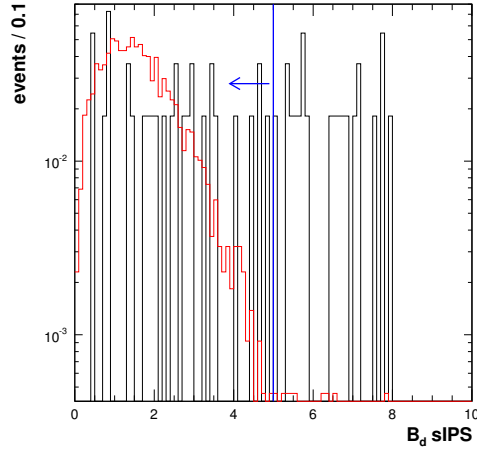
(a) B_d vertex- χ^2 .(b) B_d flight-significance.(c) B_d $sIPS$.

Figure 4.9: The reconstructed B_d vertex- χ^2 (a), flight-significance (b) and $sIPS$ (c) distributions for signal (red) and bb -inclusive (black) candidates passing the preselection and intermediate-selection cuts with arbitrary normalisation. The lines and arrows show the positions and directions of the cuts.

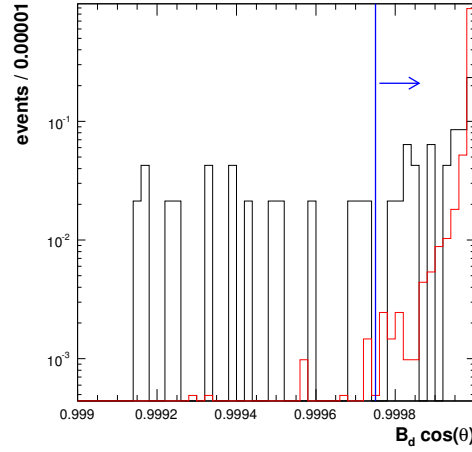


Figure 4.10: The reconstructed $B_d \cos(\theta)$ distributions for signal (red) and $b\bar{b}$ -inclusive (black) candidates passing the preselection and intermediate-selection cuts with arbitrary normalisation. The line and arrow shows the position and direction of the cut.

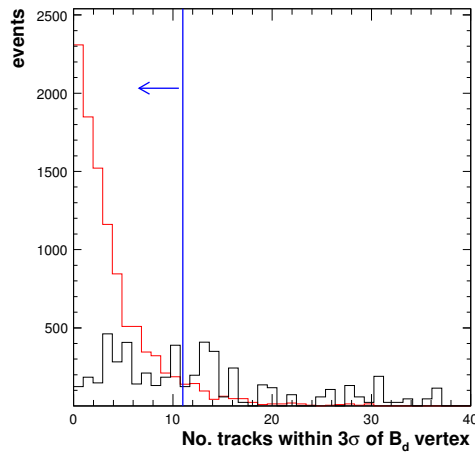


Figure 4.11: The number of tracks within 3σ of the reconstructed B_d vertex for signal (red) and background (black) samples.

Particle	Cut variable	Selection cut value	Preselection cut value
B_d	Mass window	$\pm 50 \text{ MeV}/c^2 (3.6\sigma)^d$	$\pm 500 \text{ MeV}/c^2$
	p_T	$> 250 \text{ MeV}/c$	$> 250 \text{ MeV}/c$
	vertex- χ^2	< 20	< 50
	$\cos(\theta)$	> 0.99975	> 0.99
	flight-significance	> 6	–
	$sIPS$	< 5	< 8
	Vertex Isolation ^e	< 11	–
K^*	mass window	$\pm 100 \text{ MeV}/c^2 (2 \times FWHM)^f$	$\pm 300 \text{ MeV}/c^2$
	p_T	$> 300 \text{ MeV}/c$	$> 300 \text{ MeV}/c$
	vertex- χ^2	< 30	< 30
	flight-significance	> 1	–
	$sIPS$	> 1.5	> 1.5
$K^\pm$	p	$> 2000 \text{ MeV}/c$	$> 2000 \text{ MeV}/c$
	p_T	$> 400 \text{ MeV}/c$	$> 250 \text{ MeV}/c$
	$sIPS$	> 3.0	> 1.5
$\pi^\pm$	p	$> 2000 \text{ MeV}/c$	$> 2000 \text{ MeV}/c$
	p_T	$> 250 \text{ MeV}/c$	$> 250 \text{ MeV}/c$
	$sIPS$	> 3.0	> 1.5
$\mu\mu$	J/ Ψ (1S, 2S) veto	$2900 - 3200 \text{ MeV}/c^2$	–
		$3650 - 3725 \text{ MeV}/c^2$	–
	vertex- χ^2	< 15	–
	flight-distance	$> 1 \text{ mm}$	–
$\mu^\pm$	p	$> 4000 \text{ MeV}/c$	$> 4000 \text{ MeV}/c$
	p_T	$> 500 \text{ MeV}/c$	$> 300 \text{ MeV}/c$
	$sIPS$	> 2.0	> 0.5

Table 4.3: Summary of the selection and preselection cuts.^dMeasured by fitting a Gaussian shape to the reconstructed B_d -mass distribution.^eCounted as the number of tracks within 3- IPS of the B_d vertex.^fFull-Width-Half-Maximum ($FWHM$) measured by fitting a Breit-Wigner shape to the reconstructed K^* mass distribution.

The invariant mass distributions of the reconstructed B_d and K^* candidates for selected events are shown in Figures 4.12 and 4.13 where the full selection criteria have been applied. The K^* -mass cut has been removed in Figure 4.12 and the B_d -mass cut in Figure 4.13.

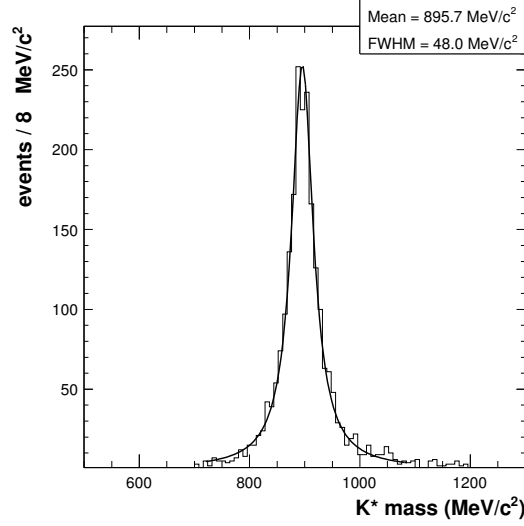


Figure 4.12: Reconstructed K^* mass distribution for signal candidates passing the selection criteria. The signal distribution has a Breit-Wigner shape fitted.

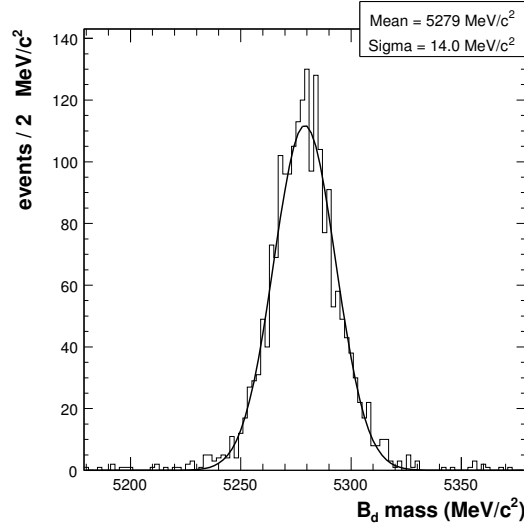


Figure 4.13: Reconstructed B_d mass distribution for signal candidates passing the selection criteria. The signal distribution has a Gaussian shape fitted.

A Breit-Wigner shape was fitted to the K^* -mass distribution. The best fit mean (full-width-half-maximum, $FWHM$) from the fit is 895.7 (48.0) MeV/c^2 , in good agreement with the Particle Data Group values [1]. The χ^2 per degree of freedom of this fit was

86 / 61. The K^* -mass window was placed at

$$M_{K^*} \pm 100 \text{ MeV}/c^2,$$

approximately twice the $FWHM$. A Gaussian was fitted to the B_d -mass distribution in Figure 4.13. The best fit Gaussian has a mean (width) of 5279 (14.0) MeV/c^2 with a χ^2 per degree of freedom of 101 / 67.

The generated^g $\mu\mu$ -mass distribution from 6.5M events is shown in Figure 4.14(a). The $\mu\mu$ -mass distribution of the selected events is shown in Figure 4.14(b). The black (red) line in shows the distribution before (after) all the selection cuts were applied. The shaded boxes show the J/ψ mass vetoes. The ratio of the $\mu\mu$ -mass distributions in Figure 4.14(b), plotted in Figure 4.15, shows that the efficiency of the cuts does not depend on $M_{\mu\mu}$ up to $\sim 3500 \text{ MeV}/c^2$. Above this mass the efficiency decreases with $M_{\mu\mu}$. This loss of efficiency is caused by the $K^\pm$ and $\pi^\pm$ $sIPS$ requirements. The $\mu\mu$ -mass depends on the angle between the B_d and the K^* lines of flight – a small angle giving a large $M_{\mu\mu}$. A small opening angle makes it more likely that the line of flight of the K^* points back to the B_d production vertex and hence less likely that both the $K^\pm$ and $\pi^\pm$ will have $sIPS > 3$.

4.4 Signal Event Yields

The reconstruction efficiency (ε_{rec}) is given by the number of events reconstructed (9150) divided by the number generated, having removed the effect of the event generator cut. Therefore, $\varepsilon_{rec} = 9150 / 150k = (6.10 \pm 0.06)\%$. Of the 9150 events, 1889 pass the selection criteria giving a selection efficiency ($\varepsilon_{sel/rec}$) of $(20.6 \pm 0.5)\%$. The overall selection efficiency (ε_{sel}) is therefore $1889 / 150k = (1.26 \pm 0.03)\%$.

4.4.1 Trigger Efficiency

Events passing the requirements in Table 4.3 were passed through a simulation of LHCb's trigger. LHCb has recently changed from a 3-level to a 2-level trigger scheme. At the time of this analysis the trigger simulation was only available using the 3-level scheme,

^gThese events were simulated using the full LHCb simulation software but without the detector simulation.

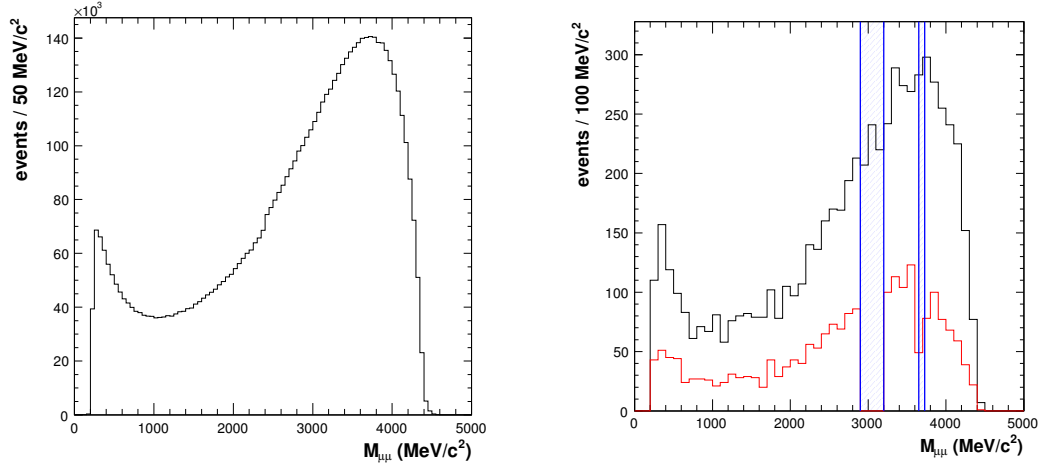
(a) The generated $\mu\mu$ -mass distribution.(b) The reconstructed $\mu\mu$ -mass distribution before (black) and after (red) applying the selection criteria.

Figure 4.14: The di-muon invariant mass distributions. The blue boxes show the mass-veto regions.

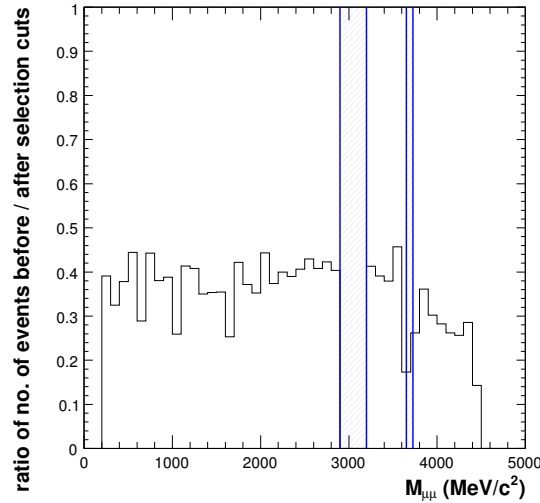


Figure 4.15: Ratio of reconstructed $\mu\mu$ -mass distributions for signal candidates before and after applying the selection criteria. The blue boxes show the mass-veto regions.

so efficiencies will be presented for the old scheme. No major changes in the trigger efficiencies are expected with the new scheme.

The 3-level system consisted of a hardware trigger – Level-0 (L0) – and two software triggers – Level-1 (L1) and the High-Level-Trigger (HLT). The L0 trigger is unchanged between the two schemes, and is described in Section 2.3.1. The alleys stage of the HLT in the 2-level scheme (described in Section 2.3.2) performs a similar function to the L1 trigger in the 3-level scheme. In the design of the L1 trigger, the trigger processors had access to only a subset of the detector information whereas, due to an enhanced detector readout system, the HLT alleys in principle have access to the complete detector information. The L1 trigger was designed to reduce the rate of accepted events from the L0 trigger output rate of 1 MHz to ~ 40 kHz using digitized information from the L0 trigger, VELO and TT stations. Tracks in the VELO and TT were reconstructed and matched to L0-muons or calorimeter clusters to give momentum information. The fringe magnetic field between the VELO and TT stations was used to calculate the momentum with a resolution of $\sim 30\%$ [87]. The L1 trigger then selected events with high p_T and large impact-parameter tracks. For the MC used in this study, the cuts shown in Table 4.4 were applied in the L0 and L1 muon triggers.

Trigger	Type	Cut
L0	Single muon	$p_T(\mu) > 1.3 \text{ GeV}/c$
	Di-muon	$\Sigma p_T(\mu) > 1.5 \text{ GeV}/c$ $\Sigma E_{T(CALO)} > 5 \text{ GeV}$
L1	Single muon	$p_T(\mu) > 2.3 \text{ GeV}/c$
	Di-muon	$M_{\mu\mu} > 500 \text{ MeV}/c^2$ $IP_{\mu\mu} > 0.075$

Table 4.4: The L0 and L1 trigger requirements.

The combined L0 and L1 trigger efficiency on offline selected $B_d^0 \rightarrow K^* \mu^+ \mu^-$ events was found to be $(89 \pm 3)\%$ ($= 93\% \times 95\%$ for the L0 and L1 triggers respectively).

4.4.2 Annual Yield Estimate

In a nominal physics year LHCb will collect 2 fb^{-1} of data [76]. Taking the $b\bar{b}$ -inclusive cross-section as $500 \text{ } \mu\text{b}$, this will give 10^{12} $b\bar{b}$ pairs per year. The combined annual signal yield (S) for B_d and $\bar{B}_d^0$ is therefore given by

$$S = N_{b\bar{b}} \times 2 \times f(\bar{b} \rightarrow B_d) \times \mathcal{B}(B_d^0 \rightarrow K^* \mu^+ \mu^-) \times \mathcal{B}(K^* \rightarrow K^+ \pi^-) \times \varepsilon_{TOT}, \quad (4.2)$$

where $N_{b\bar{b}}$ is the number of $b\bar{b}$ pairs per year (10^{12}), $f(\bar{b} \rightarrow B_d)$ is the B_d production fraction (0.398) and ε_{TOT} is the combined trigger, reconstruction and selection efficiency: $(1.11 \pm 0.03)\%$. The branching ratios ($\mathcal{B}$) for $B_d^0 \rightarrow K^* \mu^+ \mu^-$ and $K^* \rightarrow K^+ \pi^-$ were taken from Table 4.1. The annual yield for $B_d^0 \rightarrow K^* \mu^+ \mu^-$ is then $7200 \pm 180 \pm_{1900}^{2200}$, where the first error is the statistical error on the number of selected events and the second error is the measured uncertainty on the branching ratio for this decay [1].

Chapter 5

Background Studies in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ Decays

This chapter presents a study of the expected backgrounds in the $B_d^0 \rightarrow K^* \mu^+ \mu^-$ analysis. The background categories are classified in Section 5.1. The background from the sample of $b\bar{b}$ -inclusive events used to optimise the selection criteria is discussed in Section 5.2. The background from a number of specific samples is studied in Sections 5.3–5.5 and the total expected background is presented in Section 5.6. Finally, early plans to measure the background from real data are discussed in Section 5.7. In this analysis, unless specifically mentioned, the L0 and L1 trigger simulations were not run on the background samples.

5.1 Background Classification

In order to understand the nature and common features of the background, a dedicated background classification tool was used [162, 163]. If possible, for each reconstructed particle in the potentially dangerous background categories, a match to a corresponding MC-particle was found based on the track momentum and position. This allowed the major sources of the background events to be identified. The background events were classified into eight categories:

- **Common-final-state :** the MC B-decay produces the same final state particles as the signal decay. This category includes non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events;

- **Low-mass** : the MC B-decay has at least one extra final state particle, that is not used in the reconstruction e.g. $B_d^0 \rightarrow K^* \mu^+ \mu^- \pi^0$;
- **Reflection** : the MC B-decay is the same as the signal decay, but with at least one particle mis-identified e.g. $B_d^0 \rightarrow K^* \mu^+ \mu^-$ with the K^+ and π^- swapped;
- **Part-reco-phys** : the MC B-decay meets the criteria to be classified as Low-mass and in addition has a mis-identified particle e.g. $B_d \rightarrow K^{*-} (\rightarrow K^0 \pi^-) \pi^+ \mu^- \mu^+$ where one pion is mis-identified as a kaon;
- **Ghost** : the MC B-decay has at least one reconstructed track with no corresponding MC track;
- **From-PV** : the reconstructed B_d candidate has at least one particle which comes directly from the same PV as the MC B-decay;
- **Different-PV** : the reconstructed B_d candidate has at least one particle which comes directly from a different PV to the MC B-decay;
- **Combinatoric** : the particles used to reconstruct the B_d candidate come from multiple MC B-decays.

Any background sources which peak at the B_d -mass were considered in the same (tight) mass window as for the signal sample ($\pm 50 \text{ MeV}/c^2$).

The Ghost, From-PV, Different-PV and Combinatoric categories have at least one reconstructed particle which originate from somewhere other than the true B-decay. They can therefore in general produce a range of reconstructed B_d -masses. To increase the statistical significance of the background samples, events passing the cuts were considered in a loose B_d -mass window ($\pm 500 \text{ MeV}/c^2$). For the purposes of the yield calculations presented in the following sections, the events were assumed to have a flat distribution in B_d -mass and were extrapolated linearly into the tight mass window. Events in the Low-mass category which were far below the tight mass window and, given the measured mass resolutions, could not enter the tight mass window were not included in the yield calculation.

5.2 Background from $b\bar{b}$ -inclusive Events

Four events from the 24M simulated events in the $b\bar{b}$ -inclusive sample survived the offline selection described in Chapter 4, with a loosened B_d -mass window of $\pm 500 \text{ MeV}/c^2$. These events are classified in Table 5.1, in which the particles used to reconstruct the B_d candidate are shown in red. Samples with higher statistical significances were used to evaluate the level of the background. The final column in Table 5.1 shows the relevant sample for each of the surviving events.

Event description	Classification	Higher significance sample
$B_d^0 \rightarrow K^* (K^+ \pi^-) J/\psi (\mu^- \mu^+ \gamma)$	Low-mass	–
$B_u^- \rightarrow \bar{K}^* (K^- \pi^+) \mu^- \mu^+ \pi^-$	Low-mass	–
$\bar{B}_d^0 \rightarrow K^- \pi^+ \mu^- \mu^+$	Common-final-state	$B_d^0 \rightarrow s \mu^+ \mu^-$
$B_d^0 \rightarrow D^{*0} (D^0 (K^{*+} (K^+ \pi^0) \rho^- (\pi^- \pi^0)) \pi^0) \pi^- \mu^+ \nu$ $\bar{B}_d^0 \rightarrow D^{*+} \mu^- \nu$	Combinatoric	$b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$

Table 5.1: A description of the events from the $b\bar{b}$ -inclusive sample which survive the selection criteria. The particles indicated indicated in red are those used to reconstruct the B_d candidate.

The two Low-mass events have a missing photon and pion respectively. The first of these events has a missing photon from a $J/\psi \rightarrow \mu^- \mu^+ \gamma$ decay. Although in principle the photon could carry an arbitrarily small amount of energy, here it has sufficient energy such that the event survives the J/ψ -mass veto used in the analysis. The mass of the B_d candidate should therefore fall outside the tight B_d -mass window. The missing π^- in the second event means that this event type will also be outside the tight B_d -mass window. The reconstructed masses of the B_d candidates in the two Low-mass events are $5061 \text{ MeV}/c^2$ and $4798 \text{ MeV}/c^2$ respectively and are at least 12σ below the tight B_d -mass window. Given the MC statistics, the small tail of events of these types which could enter the tight B_d -mass window cannot be estimated.

The non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events, classified as Common-final-state are potentially a dangerous source of background. These events peak at the B_d -mass and are different from the resonant signal events only in that the invariant mass of the $K^\pm \pi^\mp$ pair is not necessarily the mass of the K^* . The Standard Model branching ratio for the

decay $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ has not yet been directly measured [1]. The LHCb simulation uses a branching ratio for the decay $B_d^0 \rightarrow s \mu^+ \mu^-$ of 4×10^{-6} , of which the non-resonant events form a subset with a branching ratio in the MC of 1×10^{-6} . However, an approximate upper limit for this branching ratio of 4×10^{-7} can be extracted from reference [42]. This was done by comparing the number of events in the B_d -mass and the K^* -mass peaks; any non-resonant events should appear as an excess in the B_d -mass peak. No evidence was found for the non-resonant events and an upper limit was set based on an estimate of the accuracy of the procedure. The yield estimates for the non-resonant events in the following sections are calculated using a branching ratio of 4×10^{-7} . The $B_d^0 \rightarrow s \mu^+ \mu^-$ MC sample is a factor 1900 more significant than the $b\bar{b}$ -inclusive sample and is therefore used to give a better precision estimate of the background level from the non-resonant events. For all other event types, the event yields quoted in this chapter use the branching ratios as in the LHCb simulation and as presented in Table 4.1.

The final event from the $b\bar{b}$ -inclusive sample is classified as Combinatoric. This event type is present in the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ sample which has a higher statistical significance. In this event, the reconstructed muons come from different B-decays. In general, the muons in the four surviving events from the $b\bar{b}$ -inclusive sample were taken from B-decays – either as di-muons from the same B-meson or as two single muons from different B-decays. The higher statistical significance background samples studied therefore reflected this: two di-muon samples ($b \rightarrow s \mu^+ \mu^-$ and $b \rightarrow \mu^- c (\rightarrow \mu^+)$) and the pair of single muons sample ($b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$). The background estimate from all the higher statistical significance samples is presented in the following sections. The potential background from Drell-Yan processes is not considered here but is expected to be a small fraction of the overall background.

5.3 Background from $b \rightarrow s \mu^+ \mu^-$ Events

The background from the $B_d^0 \rightarrow s \mu^+ \mu^-$ and $B_u^+ \rightarrow s \mu^+ \mu^-$ samples is evaluated in this section. The non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events comprise approximately 25% of the B_d sample and a further 8% of the events decay via a K^* (dominated by the type $B_d^0 \rightarrow K^* \mu^+ \mu^- \pi^0$), although there are no signal events. The remaining events were dominated by decays of the type $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^- X$. Of the 390k B_d (450k B_u) events from these samples 804 (241) pass all the selection criteria. The B_d (B_u) sample has a factor 1900 (2100) higher significance than the $b\bar{b}$ -inclusive sample. Therefore, for

the B_d case, 0.4 events ($= 804 / 1900$) should have been seen in the $b\bar{b}$ sample. This is consistent with the one event actually seen. For the B_u case, 0.11 events ($= 241 / 2100$) should have been seen in the $b\bar{b}$ sample, consistent with the zero events observed.

Details of the surviving events and corresponding annual yields are given in Sections 5.3.1 and 5.3.2.

5.3.1 Background from $B_d^0 \rightarrow s \mu^+ \mu^-$ Events

The classification of the 804 events passing the selection criteria is shown in Table 5.2. The branching ratio for this sample is 4×10^{-6} . The annual yield is therefore given by

$$\begin{aligned} Yield &= N_{b\bar{b}} \times 2 \times f(\bar{b} \rightarrow B_d) \times \mathcal{B}(B_d^0 \rightarrow s \mu^+ \mu^-) \times (Sel / Gen), \\ &= 10^{12} \times 2 \times 0.398 \times 4 \times 10^{-6} \times (Sel / 390000), \end{aligned} \quad (5.1)$$

where $N_{b\bar{b}}$ is the number of $b\bar{b}$ pairs per nominal physics year (2 fb^{-1}), f is the production fraction of the B_d , Sel is the number of events selected extrapolated to the tight B_d -mass window, and Gen is the size of the sample.

Classification	No. of candidates	Annual yield
Common-final-state	620	2019
Low-mass	162	–
Reflection	5	16
Part-reco-phys	8	–
Ghost	2	2
From-PV	2	2
Combinatoric	5	4
Total	804	2043

Table 5.2: The classification of the surviving candidates from the $B_d^0 \rightarrow s \mu^+ \mu^-$ sample. The yield for the non-resonant events (Common-final-state category) is calculated using $\mathcal{B} = 4 \times 10^{-7}$.

The events classified as Common-final-state are all non-resonant events of the type $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$. These events have the same kinematics as the signal events, except that the invariant mass of the $K^\pm \pi^\mp$ is not necessarily the mass of the K^* . In the 620

events that pass the selection, the $K^\pm \pi^\mp$ invariant mass is within $2 FWHM$ of the K^* mass. The K^* mass cut selects $\sim 30\%$ of the events which pass the other criteria.

All five events in the Reflection category were non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events, with the $K^\pm$ mis-identified as a $\pi^\pm$ and the $\pi^\pm$ mis-identified as a $K^\pm$. To first order, these events therefore peak at the B_d -mass. However, because the charge of the $K^\pm$ is used to determine whether the decaying B-particle was a B_d or $\bar{B}_d^0$, the mis-identification results in the wrong flavour being associated to the B-meson. As the B_d and $\bar{B}_d^0$ have an opposite forward-backward asymmetry (A_{FB}), these events therefore dilute A_{FB} and are counted as background.

The Low-mass category events were typically $B_d^0 \rightarrow K^* \mu^+ \mu^- \pi^0$, $B_d^0 \rightarrow K \rho \mu^+ \mu^-$ and $B_d^0 \rightarrow K^\pm \pi^\pm \mu^+ \mu^- \pi^0$ decays. The mass distribution of the Low-mass events is shown in Figure 5.1(a). All the events lie more than 6σ from the tight B_d -mass window and so were neglected for the yield calculations.

Of the eight Part-reco-phys events, seven came from $B_d^0 \rightarrow K^{*-} (\rightarrow K^0 \pi^-) \pi^+ \mu^+ \mu^-$ decays, with one of the $\pi^\pm$ mis-identified as a $K^\pm$. These events were at least $110 \text{ MeV}/c^2$ below the B_d -mass and were therefore neglected for the yield calculation. The remaining event in this category had a π^- which was not reconstructed. This event could therefore be classified as an effective Low-mass and so was also neglected for the yield calculation.

The nine events in the other categories (Ghost, From-PV and Combinatoric) all came from event types that do not peak at the B_d -mass. The background was therefore evaluated in the loose B_d -mass window ($\pm 500 \text{ MeV}/c^2$) and extrapolated into the tight B_d -mass window ($\pm 50 \text{ MeV}/c^2$). The reconstructed B_d -mass distribution of these events is shown in Figure 5.1(b).

5.3.2 Background from $B_u^+ \rightarrow s \mu^+ \mu^-$ Events

The classification of the 241 events (from 450k) passing the selection criteria in the $B_u^+ \rightarrow s \mu^+ \mu^-$ sample is shown in Table 5.3. This sample has the same branching ratio as the corresponding B_d sample, so the annual yield is given by

$$\begin{aligned} Yield &= N_{b\bar{b}} \times 2 \times f(\bar{b} \rightarrow B_u) \times \mathcal{B}(B_u^+ \rightarrow s \mu^+ \mu^-) \times (Sel / Gen), \\ &= 10^{12} \times 2 \times 0.398 \times 4 \times 10^{-6} \times (Sel / 450000), \end{aligned} \quad (5.2)$$

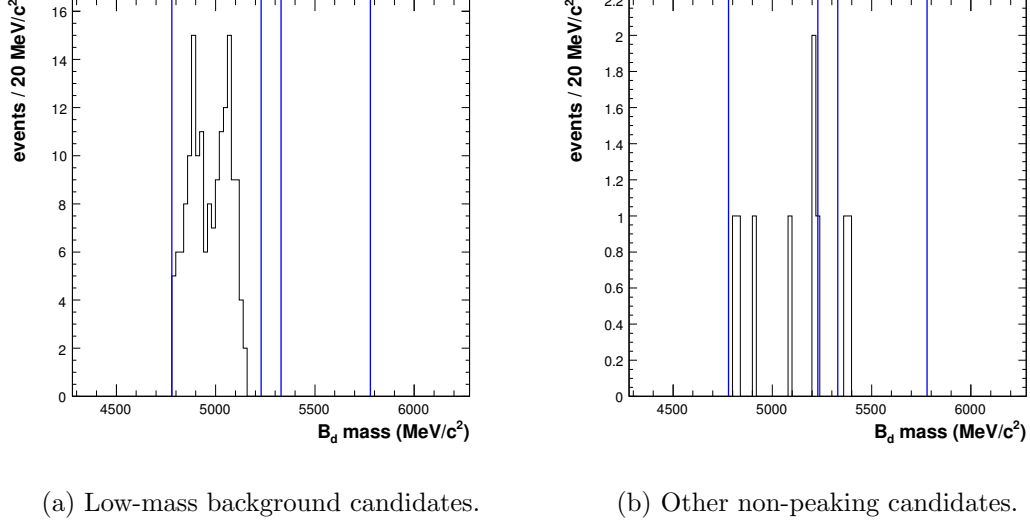


Figure 5.1: The reconstructed B_d -mass distribution for the selected candidates in the $B_d^0 \rightarrow s \mu^+ \mu^-$ sample. The outer (inner) bars show the loose (tight) mass window.

where $N_{b\bar{b}}$ is the number of $b\bar{b}$ pairs per nominal physics year (2 fb^{-1}), f is the production fraction of the B_u , Sel is the number of events selected extrapolated to the tight B_d -mass window and Gen is the size of the sample.

Classification	No. of candidates	Annual yield
Low-mass	228	—
Part-reco-phys	5	4
Ghost	2	1
From-PV	4	3
Combinatoric	4	3
Total	243	11

Table 5.3: The classification of the surviving candidates from the $B_u^+ \rightarrow s \mu^+ \mu^-$ sample. The total number of candidates classified does not equal the number of events (241) because two of the events have multiple candidates.

The 228 Low-mass candidates mainly came from decays of the type $B_u^\pm \rightarrow K^* \pi^\pm \mu^+ \mu^-$ and $B_u^\pm \rightarrow K^\pm \rho \mu^+ \mu^-$. The reconstructed B_d -mass distribution of these events is shown in Figure 5.2(a). The events lie at least 5σ below the tight B_d -mass window and so were

neglected for the yield calculations.

The five Part-reco-phys candidates were all from $B_u^\pm \rightarrow K^\pm \pi^0 (\rightarrow \gamma \gamma (e^- e^+)) \mu^+ \mu^-$ decays with one of the conversion electrons mis-identified as a $\pi^\pm$. The reconstructed B_d -masses for these five events are: 5099, 5014, 4963, 5261 and 5132 MeV/c^2 respectively. The non-reconstructed particles (photon and electron) in these decays are light in comparison to the B_d -mass resolution ($\sim 18 \text{ MeV}/c^2$) and therefore the reconstructed B_d -mass will not necessarily always be outside the tight mass window of $\pm 50 \text{ MeV}/c^2$. These events were therefore included in the yield calculation.

The ten events in the other categories (Ghost, From-PV and Combinatoric) were all from sources that do not peak at the B_d -mass. The reconstructed B_d -mass distribution of these events and the five Part-reco-phys events is shown in Figure 5.2(b). The rate from this background was therefore evaluated using events in the loose B_d -mass window ($\pm 500 \text{ MeV}/c^2$) and extrapolated into the tight B_d -mass window, scaling by a factor of ten. Although there are limited statistics, there is evidence of more background below the tight B_d -mass window than above it; however, there is no evidence that the events below the tight B_d -mass window contribute only at low mass and therefore all events were considered when extrapolating the rate.

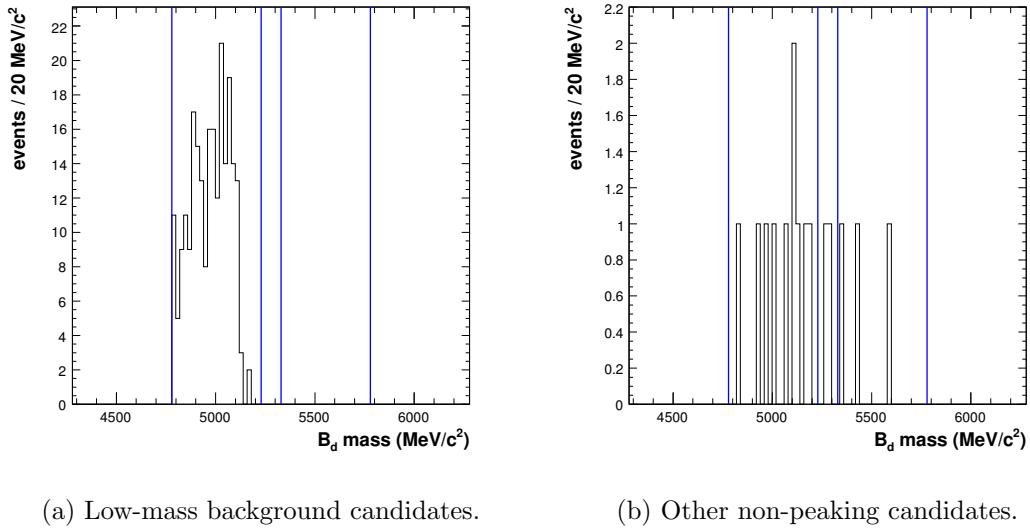


Figure 5.2: The reconstructed B_d -mass distribution for the selected candidates in the $B_d^0 \rightarrow s \mu^+ \mu^-$ sample. The outer (inner) bars show the loose (tight) mass window.

5.4 Background from $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ Events

A total of 21 events (from 20M) $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ events pass the selection cuts. In the majority of the events, the two reconstructed muons were taken from different B-decays. This sample has a factor 31 higher significance than the $b\bar{b}$ -inclusive sample. Therefore, 0.7 events ($= 21 / 31$) should have been seen in the $b\bar{b}$ sample, consistent with the one event actually seen. The classification and corresponding annual yield of these events is shown in Table 5.4.

The branching ratio for the inclusive muon decay, $\mathcal{B}(b \rightarrow \mu^-)$, is 10.95% [1], so $\mathcal{B}(b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+) = 0.012 (= 0.1095^2)$. The annual yield is therefore given by

$$\begin{aligned} Yield &= N_{b\bar{b}} \times \mathcal{B}(b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+) \times (Sel / Gen), \\ &= 10^{12} \times 0.012 \times (Sel / 20 \times 10^6), \end{aligned} \quad (5.3)$$

where $N_{b\bar{b}}$ is the number of $b\bar{b}$ pairs per nominal physics year (2 fb^{-1}), Sel is the number of events selected extrapolated to the tight B_d -mass window and Gen is the size of the sample.

Classification	No. of candidates	Annual yield
Low-mass	2	118
Combinatoric	19	1112
Total	21	1230

Table 5.4: The classification of the candidates from the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ sample surviving the selection cuts.

The two Low-mass events have reconstructed B_d -masses of 5516 and 4872 MeV/c^2 . In both events a neutrino was missing and the first event also had a K^- mis-identified as a μ^- . This type of Low-mass event could potentially have a reconstructed B_d -mass that falls in the tight B_d -mass window. The events were therefore included in the yield calculation and the rate extrapolated into the tight B_d -mass window, scaling by a factor of ten as for the Combinatoric category. The reconstructed B_d -mass distribution for all 21 background events is shown in Figure 5.3.

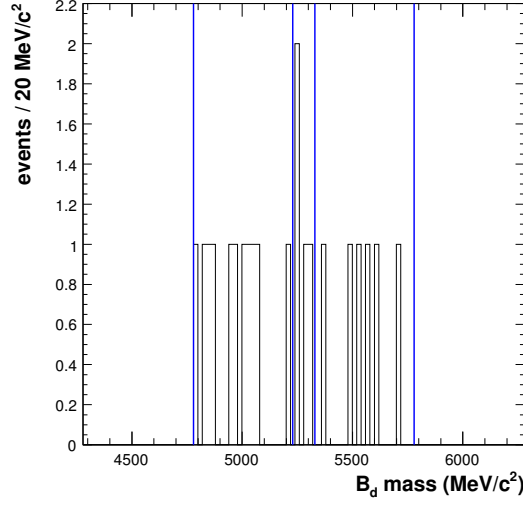


Figure 5.3: The reconstructed B_d -mass distribution for the surviving events in the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ sample. The outer (inner) bars show the loose (tight) mass window.

5.5 Background from $b \rightarrow \mu^- c (\rightarrow \mu^+)$ Events

This section presents a summary of the backgrounds from the four samples: B_d , B_u , B_s and $\Lambda_b \rightarrow \mu^- c (\rightarrow \mu^+)$, in which the B-particle decays into a state containing a μ^- and a charm particle; the charm particle then decays into a final state containing a μ^+ . In these samples, the events are split approximately equally between three-, four- and five-prong topologies. The number of candidates surviving the selection criteria and their classification is shown in Table 5.5. No events from the B_s sample passed the selection criteria.

To avoid double counting, events which also fall in the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ sample, which has a higher significance than any of these samples, were excluded. This removed one event from the Combinatoric category in the B_u sample, already accounted for in Table 5.5. No such events were found in the B_d or Λ_b samples. The four Low-mass events in the B_d sample were all of the type $B_d \rightarrow D^- (K^* (K^+ \pi^-) \mu^- \bar{\nu}) \mu^+ \nu$. These events have reconstructed B_d -masses (4786, 4787, 4878 and 4819 MeV/c^2), at least 400 MeV/c^2 below the nominal B_d -mass, and were therefore excluded from the yield calculation. The reconstructed B_d -mass distribution of the remaining 20 candidates from the four samples is shown in Figure 5.4.

Each of the samples has a significance of ~ 30 times higher than the $b\bar{b}$ -inclusive

Classification	B_d	B_u	Λ_b
Low-mass	4	0	0
Part-reco-phys	0	0	4
From-PV	1	2	0
Combinatoric	2	10	1
Total	7	12	5
Annual yield	211	626	120

Table 5.5: The classification of the surviving candidates from the $b \rightarrow \mu^- c (\rightarrow \mu^+)$ samples. No events survived from the $B_s^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$ sample.

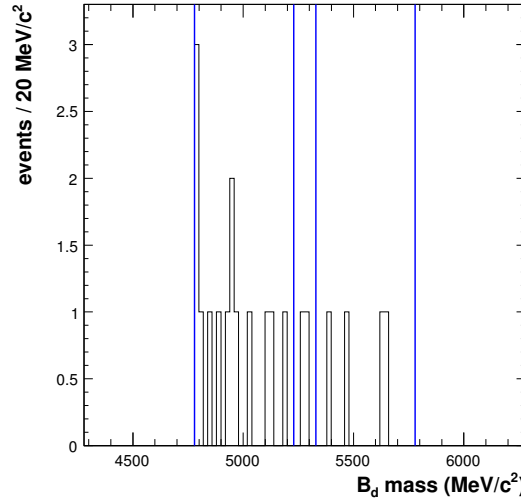


Figure 5.4: The reconstructed B_d -mass distribution for the surviving events in the B_d , B_u and $\Lambda_b \rightarrow \mu^- c (\rightarrow \mu^+)$ samples. The outer (inner) bars show the loose (tight) mass window.

sample. The annual yields are shown in Table 5.5 and were calculated using the branching ratios for these samples given in Table 4.1. The rates from the three, twelve and five events from the B_d , B_u and Λ_b samples respectively were extrapolated into the tight B_d -mass window, scaling by a factor of ten. As in Section 5.3.2, there is evidence of more background below the tight B_d -mass window than above it. Again, there is no evidence that the events below the tight B_d -mass window contribute only at low mass and therefore all events were considered when extrapolating the rate.

5.6 Total Background

A summary of the overall background rates is shown in Table 5.6. The numbers presented exclude events from double counting between samples and any events that could not fall in the tight B_d -mass window. The table also shows the combined L0 and L1 trigger efficiencies. The total annual background expected (including the non-resonant events) is 4200 ± 350 events with background over signal ratio (B/S) of 0.5 ± 0.2 , before applying the L0 and L1 triggers^a. After applying the triggers the rate drops to 3500 ± 320 with a background over signal ratio $B/S = 0.5 \pm 0.2$. Excluding the non-resonant events, the annual background annual rate estimate is 1770 ± 310 after the L0 and L1 triggers, giving $B/S = 0.2 \pm 0.1$.

Sample		Annual yield		Trigger efficiency
		Before L0 and L1	After L0 and L1	
$B_d^0 \rightarrow s \mu^+ \mu^-$	Non-resonant	2020 ± 80	1730 ± 75	86%
	All other	24 ± 10	20 ± 7	83%
$B_u^+ \rightarrow s \mu^+ \mu^-$		11 ± 3	9 ± 3	81%
$b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$		1230 ± 270	1050 ± 250	85%
$B_d^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$		210 ± 120	70 ± 70	33%
$B_u^+ \rightarrow \mu^+ c (\rightarrow \mu^-)$		630 ± 180	470 ± 160	75%
$B_s^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$		< 110 @ 90% C.L.	–	–
$\Lambda_b \rightarrow \mu^- c (\rightarrow \mu^+)$		120 ± 50	100 ± 50	83%
Total background		4200 ± 350	3500 ± 320	83%
Signal		8130 ± 2300	7200 ± 2100	89%
B/S		0.5 ± 0.2	0.5 ± 0.2	

Table 5.6: A summary of the background estimates and corresponding annual yields. The limit from $B_s^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$ decays is not included in the total background estimate.

As described in Section 1.3.1, recent theoretical work suggests that the non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events can, under certain kinematic conditions, be treated as signal [56, 164]. In events where the $K^\pm$ and $\pi^\pm$ can be treated as collinear, the A_{FB} of

^aFor the background, only the statistical error from the number of selected events is considered. For the signal estimates the measured error on the branching ratio is also included.

the non-resonant events is calculated to be the same as for the signal events. The non-resonant events could therefore be moved from the background estimate and included in the signal estimate. If the branching ratio of the non-resonant events is 4×10^{-7} (as discussed in Section 5.2), the number of events expected in the required kinematic region, where the $K^\pm$ and $\pi^\pm$ are collinear, is ~ 800 per 2 fb^{-1} . However, since the theoretical prediction of the rate of these events is very uncertain and this event type has not been experimentally observed [42], for the purposes of this analysis the rate will be removed from the background estimate and not included in the signal estimate. The total background estimate from 2 fb^{-1} is therefore 1770 ± 310 , after the L0 and L1 triggers, with $B/S = 0.2 \pm 0.1$.

5.7 Background Measurements with Data

As described in Chapter 6, in order to measure the zero-crossing point of A_{FB} , it is necessary to know the type of background. Both the rate and the shape of the lepton angle $(\theta_{FB})^b$ distribution of the background will need to be measured. Two mass constraints (the B_d and K^*) are applied in the analysis and in principle both sets of sidebands could be used to measure the background in regions where the signal events will not contribute. Strategies to measure the background directly from the data are presented in this section.

5.7.1 Non-resonant Background Events

The expected rate and A_{FB} of the non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events is currently uncertain. No evidence for this event type is seen in the $K^\pm \pi^\mp$ mass distribution in reference [42]. Further theoretical work may show that these events could be used as signal events in the A_{FB} measurement [165], although this may reduce the kinematic region within which it is safe to make the measurement. These events peak at the B_d -mass and not at the K^* -mass. The rate of these events could therefore be measured from the K^* sideband region in the B_d signal region. Until the first data from LHCb is collected, the rate and effect on the A_{FB} distribution of these events cannot be precisely determined.

^bThe lepton angle is defined as the angle between the μ^- (μ^+) and B_d ($\bar{B}_d^0$), measured in the $\mu\mu$ rest frame.

5.7.2 Semi-leptonic Backgrounds

The two dominant background sources are expected to be from $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ decays and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ decays (respectively 1050 and 640 events per 2 fb^{-1} after applying the L0 and L1 triggers). It is more useful for the A_{FB} study to classify the background in terms of its shape in θ_{FB} , as described in Chapter 6. All of the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ events and approximately half of the $b \rightarrow \mu^- c (\rightarrow \mu^+)$ events are expected to be symmetric about $\pi/2$ in θ_{FB} . This is because either the muons come from different b-decays or there is no correlation between the charges of the $K^\pm$ and the forward-going $\mu^\pm$. The remaining events in the $b \rightarrow \mu^- c (\rightarrow \mu^+)$ sample, where the charges of the $K^\pm$ and the forward-going $\mu^\pm$ (usually the $\mu^\pm$ directly from the b-decay, rather than from the c-decay) are correlated, are expected to be asymmetric in θ_{FB} . In order to subtract the background for the A_{FB} measurement it is necessary to know both the rate and the shape of the θ_{FB} distribution of this background in the signal region. The surviving events from the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ MC background samples were classified as either symmetric or asymmetric in θ_{FB} using the truth information. With a 2 fb^{-1} data sample, 820 symmetric background events and 280 asymmetric background events are expected in the range $(2m_\mu)^2 < q^2 < 9 \text{ GeV}^2/c^4$ where q^2 is the $\mu\mu$ invariant mass. Further details are given in Chapter 6.

The level of the background could be extracted from the B_d -mass sidebands provided there are no sources that peak in the signal region and that any Low-mass events are below the lower sideband region, i.e. that the background composition is the same in the signal and sideband regions. Depending on the level of the background, it may be that the shape of the θ_{FB} distribution is not a significant effect (see Section 6.2.5). If the ratio of symmetric to asymmetric background types in the sideband region is different to the ratio in the signal region, the two background types must be extracted separately. If the two ratios are the same, it is possible that the backgrounds could be extracted together.

The strategy to measure the background cannot be finalised until the first data is collected and the relevant distributions can be checked. However, some checks can be made using the MC simulation – if the distributions in the sidebands are different in the MC then the procedure will almost certainly be unsuitable to apply to data.

In order to maximise the MC statistics, this study was performed at the MC truth level (i.e. before reconstruction effects and efficiencies) and without the selection criteria applied. The $\mu\mu$ - and B_d -mass resolutions ($\sim 8 \text{ MeV}/c^2$ and $\sim 14 \text{ MeV}/c^2$ respectively)

are significantly smaller than the corresponding relevant scales in the A_{FB} analysis (see Chapter 6). This means the MC truth information is a good approximation to the reconstructed quantities. The $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ ($b \rightarrow \mu^- c (\rightarrow \mu^+)$) MC sample therefore contains approximately 4M (6M) events, equivalent to many years of nominal LHCb data taking.

Within a given event, for example a $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ event, there are typically many charged particles that could be used to reconstruct a B-candidate. In each event only one set of final state particles was used to create a potential B-candidate. These particles were chosen using the information about the structure of the background events expected from the studies presented above.

- $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$: in the majority of the surviving events from this sample, the two $\mu^\pm$ used to reconstruct the B_d candidate were those which came from the two b-quark decays. In this study therefore, the two $\mu^\pm$ which came from the b-quark decays were used to construct a B_d candidate. The $K^\pm$ ($\pi^\pm$) was picked randomly from the list of $K^\pm$ ($\pi^\pm$) from the decays of the two b-quarks.
- $b \rightarrow \mu^- c (\rightarrow \mu^+)$: for this event type the two $\mu^\pm$ from the b-decay were used to construct the B-candidate. If possible, the $K^\pm$ and $\pi^\pm$ were picked from the decay products of different b-quarks, with the $K^\pm$ preferentially taken from the same decay as produced the $\mu^\pm$; otherwise they were chosen randomly from the two b-quark decays.

Figure 5.5 shows the mass of the reconstructed B_d candidate plotted against the mass of the reconstructed K^* candidate for the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ (red dots in Figure 5.5(a)) and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ (blue dots in Figure 5.5(b)) event types. In both cases, the signal events are also plotted and are shown in black. The plots contain statistics equivalent to eight years of LHCb running (i.e. the signal region around the B_d - and K^* -masses contain eight times the expected annual yields of the signal, $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ event types). These plots show an approximately uniform distribution of background events across the phase space. Figure 5.6 shows the reconstructed B_d candidate mass for those events within the K^* -mass window. With $\pm 50 \text{ MeV}/c^2$ sidebands, there are approximately equal numbers of events within the sideband and signal regions.

If the nature of the background in the sideband regions is the same as in the signal region (for example, the Low-mass events are avoided) the background θ_{FB} dis-

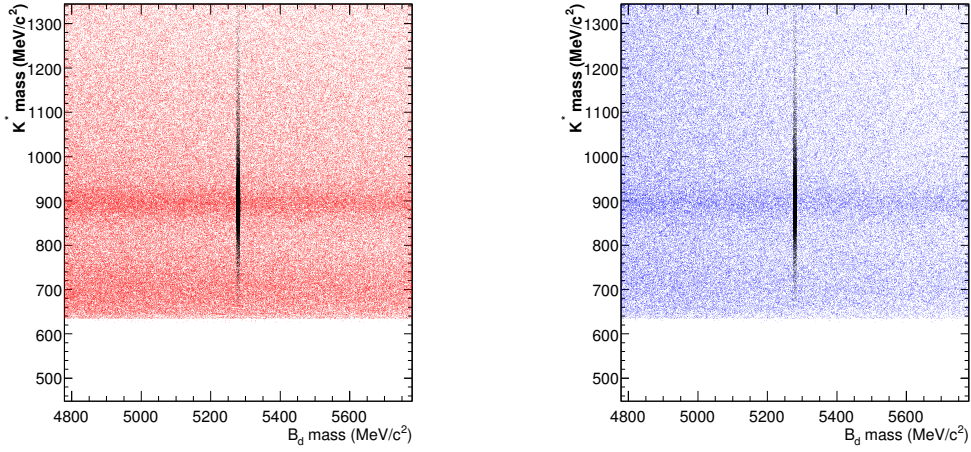
(a) The $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ sample (red).(b) The $b \rightarrow \mu^- c (\rightarrow \mu^+)$ sample (blue).

Figure 5.5: The $B_d : K^*$ mass distributions for generator level events in the background samples. The signal (black) distribution is also shown.

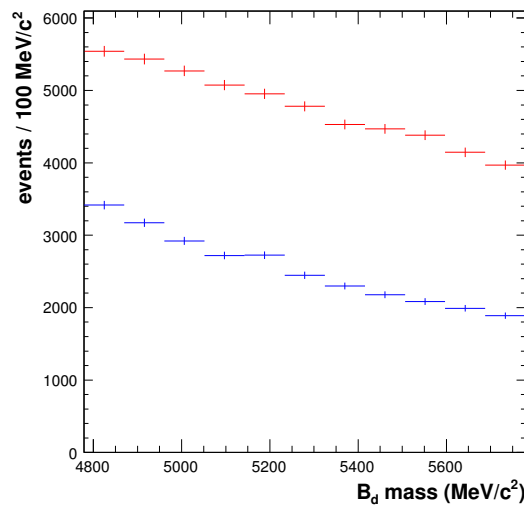


Figure 5.6: The B_d -mass distribution for generator level events from the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ MC event samples.

tribution could be measured from the events in the sidebands. However, because the $b \rightarrow \mu^-$, $\bar{b} \rightarrow \mu^+$ and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ event types have different θ_{FB} distributions, the total background rate could only be extracted if the ratio of the two event types is the same in the sideband and signal regions. As shown in Figure 5.6, the rates of the two background types reduce approximately linearly with increasing B-mass. To maintain a constant ratio of the two event types between the signal and sideband regions, this therefore requires that the upper and lower sidebands are the same size.

In order to measure the θ_{FB} distribution from the sidebands, it is necessary that the distributions in the signal and sideband regions are the same. The θ_{FB} distributions for events in the sideband and signal regions are shown in Figure 5.7: $b \rightarrow \mu^-$, $\bar{b} \rightarrow \mu^+$ in red (Figure 5.7(a)) and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ in blue (Figure 5.7(b)). In both plots, the solid (dashed) line shows the distribution for those events in the signal (B_d -sideband) region. Within the statistical errors of the event samples, the two signal and sideband distributions match well with differences of 1.2σ and 0.40σ respectively.

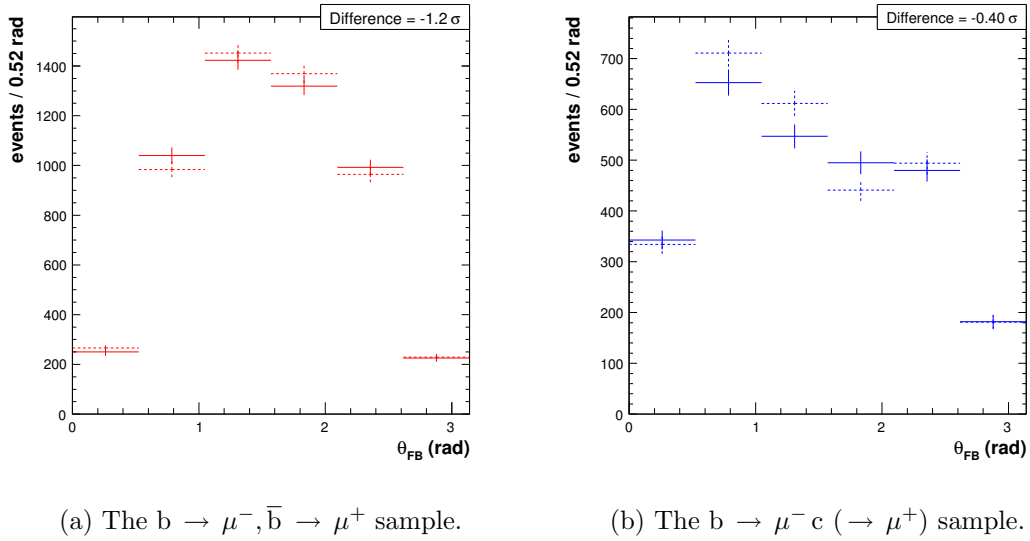


Figure 5.7: The θ_{FB} distributions for generator level events from the background samples. The solid (dashed) lines show the distributions of events in the signal (sideband) regions.

The MC therefore indicates that both the rate and the θ_{FB} distribution of the background in the signal region could be measured from the events in the sideband regions. Furthermore the distinction between symmetric and asymmetric events can be ignored for these purposes because the ratio of the two event types is the same in the signal and

sideband regions. If these features in the MC are also present in the data, it is possible that the θ_{FB} distributions for both event types could be measured simultaneously. This distribution, normalised to the expected number of background events, could then be subtracted from the distribution measured in the signal region to allow the background subtracted A_{FB} distribution (i.e. in principle for signal only) to be measured.

If the rate of the semi-leptonic background or its θ_{FB} distribution cannot be reliably extracted from the sideband region, other methods could be employed. For example, the rate of background events, and possibly the θ_{FB} distribution, could be measured by reconstructing events of the type $B_d^0 \rightarrow K^* \mu^+ \mu^+$ and its charge conjugate (i.e. where the two muons have the same charge). These events could arise in the $b \rightarrow \mu^-$, $\bar{b} \rightarrow \mu^+$ sample when one of the B-mesons formed in the hadronisation oscillates before decay. Assuming a knowledge of the hadron production fractions and the oscillation probabilities for the B_d and B_s mesons, the rate of opposite-sign muon events of the type $b \rightarrow \mu^-$, $\bar{b} \rightarrow \mu^+$ could be estimated from the number of same-sign muon events. This event sample should be free from contamination from $b \rightarrow \mu^- c$ ($\rightarrow \mu^+$) events because in the latter case the muons come from the same b-decay and therefore cannot be of the same charge. A similar procedure using same-sign $B_d^0 \rightarrow K^* (\rightarrow K^+ \pi^+) \mu^+ \mu^-$ events may be useful to measure the rate of the $b \rightarrow \mu^- c$ ($\rightarrow \mu^+$) events, although there will be some contamination from the $b \rightarrow \mu^-$, $\bar{b} \rightarrow \mu^+$ events, which could also contain same-sign $K^+ \pi^+$ events.

Chapter 6

Sensitivity to A_{FB} in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ Decays

In this chapter, the statistical precision with which LHCb will be able to measure the forward-backward asymmetry is presented. As described in Chapter 1, the zero-crossing point is particularly sensitive to New Physics because the form factor ratio used in the calculation is almost free of hadronic uncertainties. The LHCb selection and resulting backgrounds were presented in Chapters 4 and 5. A brief summary of the results relevant to the study of the sensitivity are briefly summarised in Section 6.1. Then, in Section 6.2, the measurement of forward-backward asymmetry and the determination of the zero-crossing point are discussed. Potential systematic effects are discussed in Section 6.3. Finally, in Section 6.4, the conclusions are presented.

6.1 LHCb Signal Yield and Background Estimate

After the application of the selection cuts described in Chapter 4 and accounting for the relevant trigger efficiency, the signal yield and background expected from a 2 fb^{-1} data set are summarised in Table 6.1. The numbers are shown after applying the L0 and L1 triggers. The efficiency of the High-Level-Trigger (HLT) is not accounted for, however it is expected to be greater than 80%.

The background samples denoted $B_d, B_u^+ \rightarrow s \mu^+ \mu^-$ were generated with the requirement that the B-meson decays to a final state containing two muons and a strange

Sample		2 fb ⁻¹ Yield	
		Full q^2 range	$(2m_\mu)^2 < q^2 < 9 \text{ GeV}^2/c^4$
$B_d^0 \rightarrow s \mu^+ \mu^-$	Non-resonant	1730 ± 75	1040 ± 50
	All other	20 ± 7	11 ± 4
$B_u^+ \rightarrow s \mu^+ \mu^-$		9 ± 3	4 ± 2
$b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$		1050 ± 250	550 ± 170
$B_d^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$		70 ± 70	50 ± 50
$B_u^+ \rightarrow \mu^+ c (\rightarrow \mu^-)$		470 ± 160	470 ± 160
$\Lambda_b \rightarrow \mu^- c (\rightarrow \mu^+)$		100 ± 50	40 ± 30
Total background		3500 ± 320	2200 ± 250
Signal		7200 ± 180	3700 ± 130

Table 6.1: A summary of the background estimates and corresponding yields for a 2 fb⁻¹ data set, with L0 and L1 triggers applied. Only the statistical errors are quoted.

particle (for example $\bar{B}_u^- \rightarrow K^- \pi^0 \mu^- \mu^+$). The non-resonant decay $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$, which forms part of the B_d sample, has not yet been observed and the rate of this irreducible background is calculated using a branching ratio of 4×10^{-7} , extracted as an approximate upper limit from reference [42], as discussed in Section 5.2. Since this rate is a limit and, under certain kinematic conditions, these non-resonant events are expected to have a signal-like A_{FB} [56], this background source is neglected for the present study. In the remaining events that pass the selection criteria from either sample, the K and the two muons are typically taken from the B-decay; the π is usually taken from elsewhere in the event. Having excluded the non-resonant events, these sources are expected to form a negligible part of the total background (total of ~ 30 events per 2 fb⁻¹) and they are also neglected for this study. The 3700 signal events expected in the range $(2m_\mu)^2 < q^2 < 9 \text{ GeV}^2/c^4$ from a nominal year of data then have a background-over-signal ratio (B/S) of 0.3 ± 0.1 .

Neglecting the non-resonant events, the background sources denoted $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ and $b \rightarrow \mu^- c (\rightarrow \mu^+)$ are expected to dominate. In the $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ decays the B-particles were forced to decay directly to muons. In these events, the two reconstructed muons were taken from different b-decays; the K and π were also typically taken from the b-decay products. The other major source of background ($b \rightarrow \mu^- c (\rightarrow \mu^+)$) comes from cascade decays, in which the B-particle decays to a state containing a muon and

a charm particle and the charm particle then decays into a final state containing another muon. A typical event type in this sample is $B_u^+ \rightarrow \mu^+ \nu_\mu D^0 (\rightarrow K^+ \mu^- \bar{\nu}_\mu)$. The muon direct from the b-decay typically has higher momentum than the muon from the c-decay. The background from these $b \rightarrow \mu^- c (\rightarrow \mu^+)$ samples is shown in Table 6.1 – no events from the B_s sample survived.

The q^2 distribution of the 41 background events surviving the selection is shown in Figure 6.1. As discussed in Chapter 4, the regions around the $J/\psi(1S)$ and $J/\psi(2S)$ resonances have been removed by selection cuts. With the limited Monte Carlo statistics available it is difficult to assess how the background will affect the q^2 distribution measurement. In Figure 6.2 the statistical errors on the q^2 distribution are shown having added the (statistically fluctuated) background expected with a flat $M_{\mu\mu}$ distribution.

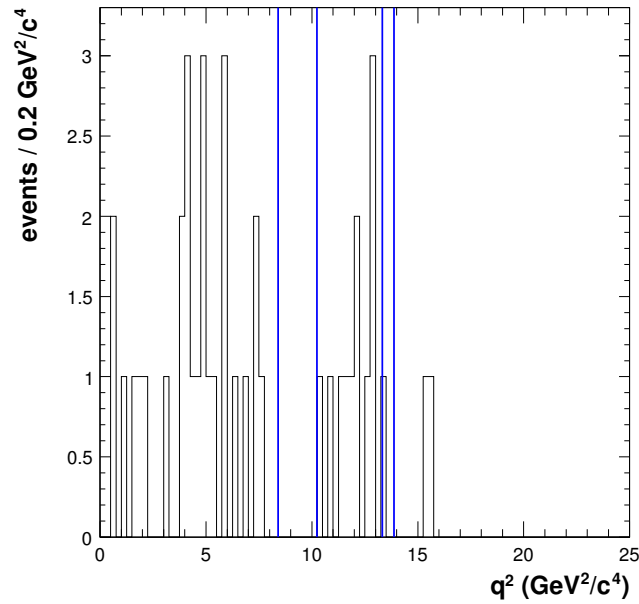


Figure 6.1: The q^2 distribution for surviving background events.

6.2 The Forward-Backward Asymmetry and its Zero Point

The following sub-sections describe the toy Monte-Carlo model used to measure the statistical precision with which LHCb will be able to measure the zero-crossing point of

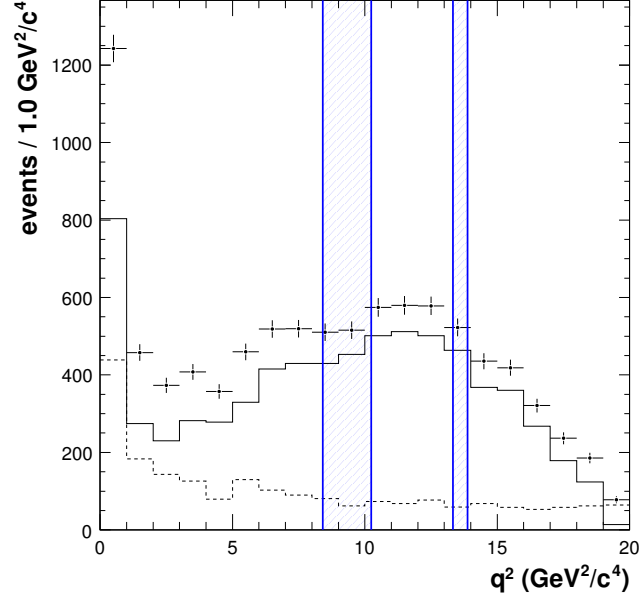


Figure 6.2: A possible q^2 distribution for a 2 fb^{-1} data sample (solid line – expected signal distribution; dashed line – fluctuated background distribution, added at the expected level with a flat $M_{\mu\mu}$ distribution; points – sum of the solid and dashed lines).

the A_{FB} distribution. The following assumptions are made:

- the effect of the detector acceptance and the selection criteria (the “acceptance function”) on the q^2 and θ_{FB} distributions is known without error;
- the size of the backgrounds, and their q^2 and θ_{FB} distributions, in the signal region can be determined from the side-bands of the reconstructed B_d -mass and K^* -mass distributions and from control channels and
- the size of the non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ background can be well measured and its effect on A_{FB} understood.

6.2.1 The Forward-Backward Asymmetry

In a given q^2 bin, the forward-backward asymmetry is calculated from the distribution of the angle, θ_{FB} , between the μ^+ (μ^-) and the reconstructed B_d ($\bar{B}_d^0$), measured in the di-muon rest frame. The charge of the $K^\pm$ from the K^* decay is used to determine the flavour of the B-meson. For $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays, the K^* decays to $K^+ \pi^-$ whereas,

in the conjugate case, the $\bar{B}_d^0$ decays to $\bar{K}^*$ which results in $K^- \pi^+$ in the final state. The conjugate decay has the opposite asymmetry [63]. Events with a reconstructed K^+ are therefore assumed to have come from a B_d decay and the angle is made with the μ^+ . Conversely, events with a reconstructed K^- are assumed to have come from a $\bar{B}_d^0$ decay and the angle is made with μ^- . A_{FB} is then the difference between the number of forward-going events ($\theta_{FB} < \pi/2$) and the number of backward-going events ($\theta_{FB} > \pi/2$) divided by the sum of the number of forward- and backward-going events. In this analysis $\mathcal{CP}$ -conservation is assumed and the asymmetries from B_d and $\bar{B}_d^0$ decays are combined. Since the SM predictions are restricted to the kinematic region below the $c\bar{c}$ -resonances [33, 166, 167], the analysis is performed in the range $(2m_\mu)^2 < q^2 < 9 \text{ GeV}^2/c^4$.

The θ_{FB} distribution from 6.5M events produced using the LHCb Monte Carlo event generator [76] is shown in Figure 6.3. The corresponding A_{FB} distribution is shown in Figure 6.4. The event generator uses the BTOSLLBALL model [27, 168] which uses Wilson Coefficients (below $q^2 \sim 5.75 \text{ GeV}^2/c^4$) calculated at NLO. The discontinuity at $q^2 \sim 5.75 \text{ GeV}^2/c^4$ is due to a change in the order to which the Wilson Coefficients are calculated. The distribution is fitted with a straight line in the range $3.8 - 4.1 \text{ GeV}^2/c^4$ and the zero point is found to be $(4.03 \pm 0.1) \text{ GeV}^2/c^4$.

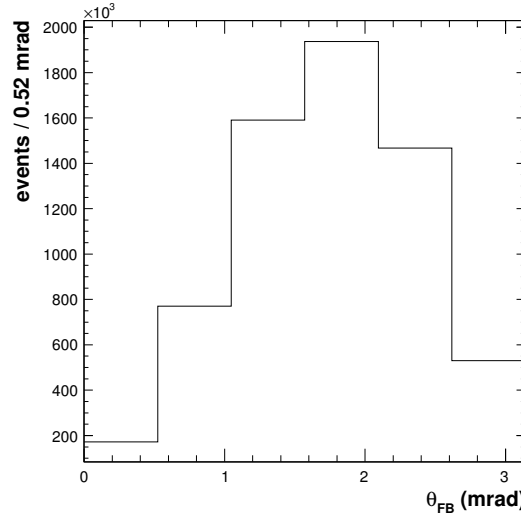


Figure 6.3: The θ_{FB} distribution from the 6.5M generator level signal events, using the BTOSLLBALL model in the event generator (EvtGen).

To extract the shape of the A_{FB} distribution and hence the zero-crossing point, it is necessary to determine the θ_{FB} distribution as a function of q^2 . As can be seen from Equation 1.24, for a given q^2 , only the transition of events across the $\theta_{FB} = \pi/2$ radians

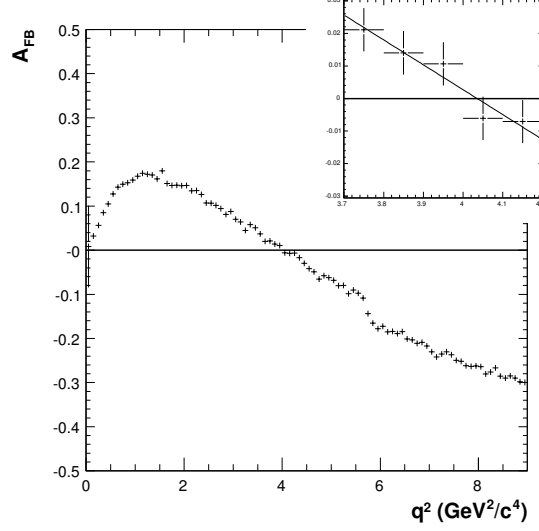


Figure 6.4: The A_{FB} distribution from the 6.5M generator level signal events, using the BTOSLLBALL model in the event generator (EvtGen).

boundary affects the A_{FB} value measured.

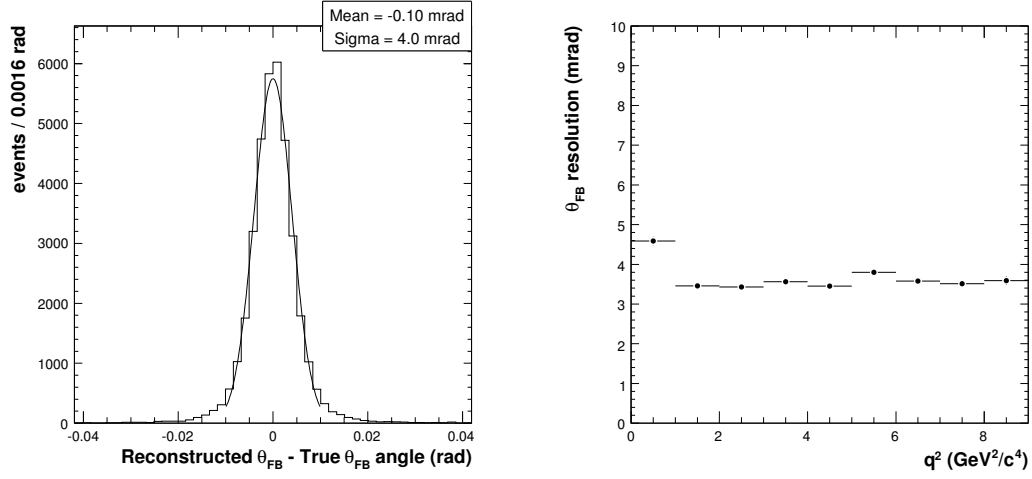
In order to extract the precision with which A_{FB} could be determined, it was necessary to produce a large number of simulated 2 fb^{-1} data sets. This allowed the zero-crossing point to be extracted for each 2 fb^{-1} data set and therefore gave an estimate of the statistical variation expected on this measurement. The method used to simulate these experiments is described in the next sub-sections.

6.2.2 Determining the Acceptance Function

The LHCb GEANT4 based Monte Carlo simulation [76] was used to simulate 1M signal events. The same settings were used as in Chapter 4 and are also described in reference [169]. The θ_{FB} resolution for all events passing the selection criteria is shown in Figure 6.5(a) and Figure 6.5(b) shows this resolution as a function of q^2 . The simulation indicates that the resolution on θ_{FB} is $\sim 4 \text{ mrad}$ and is not a strong function of q^2 or θ_{FB} .

The q^2 resolution for all events passing the selection criteria is shown in Figure 6.6. The RMS of the distribution is $\sim 0.07 \text{ GeV}^2/c^4$ and is approximately flat as a function of θ_{FB} and q^2 .

The 1M simulated events were used to determine the acceptance function – defined as the ratio of the number of events that pass the selection criteria and the L0 and L1



(a) The difference between the measured- and generated θ_{FB} for signal events which pass the selection criteria. The curve is a Gaussian fit.

(b) The resolution of θ_{FB} for signal events which pass the selection criteria, as a function of q^2 .

Figure 6.5: The θ_{FB} resolution.

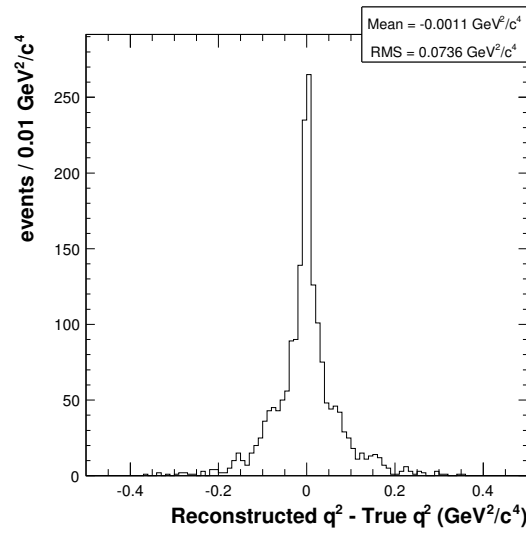


Figure 6.6: The difference between the measured- and true- q^2 for signal events which pass the selection criteria.

triggers to the number generated. The effect of the geometry of the detector and the selection cuts means that the acceptance function is not flat in either q^2 or θ_{FB} . The acceptance distribution, as a function of q^2 and θ_{FB} is shown in Figures 6.7(a) and 6.7(b) respectively. Given their shapes, good approximations to the acceptance functions are obtained with bins of 1 GeV^2 in q^2 and of $\pi/6$ rad in θ_{FB} . Coarse binning is required to reduce the statistical errors on the acceptance.

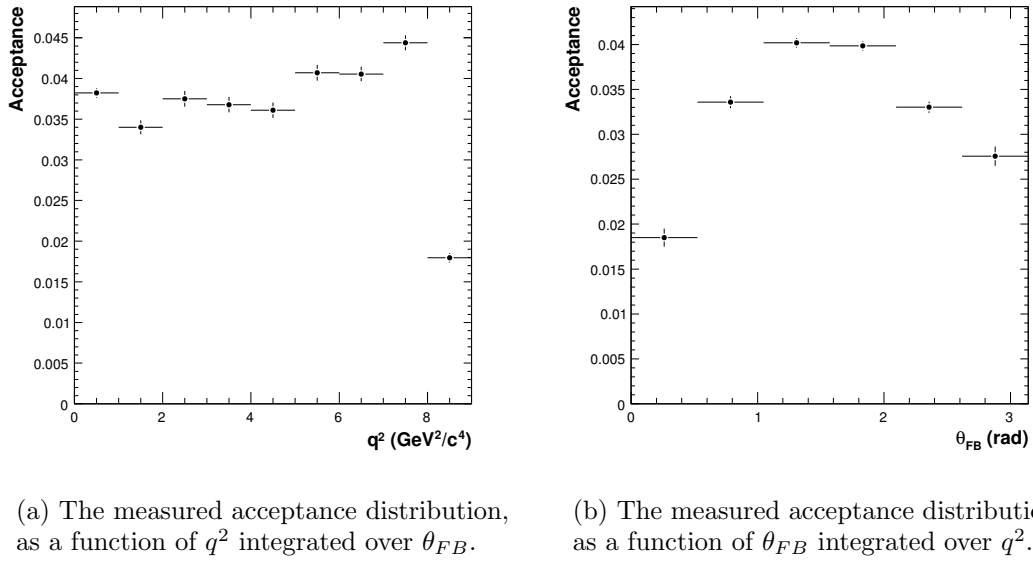


Figure 6.7: The measured acceptance distributions.

If the generated θ_{FB} distribution was symmetric or the associated acceptance function was flat, then the acceptance would have no effect on the A_{FB} value measured. However, given an asymmetric θ_{FB} distribution, the value of the measured A_{FB} is potentially affected, even in the case of a symmetric acceptance function. The effect of the acceptance function must therefore be corrected for before measuring A_{FB} .

The measured resolutions are negligible compared to the respective q^2 and θ_{FB} bin widths. Given that the resolutions are such small fractions of the bin widths and that the generated distributions and relevant acceptance functions vary slowly over the corresponding ranges, the effect of the detector resolution on the binned quantities is small.

6.2.3 Simulating the Measured A_{FB} Distribution

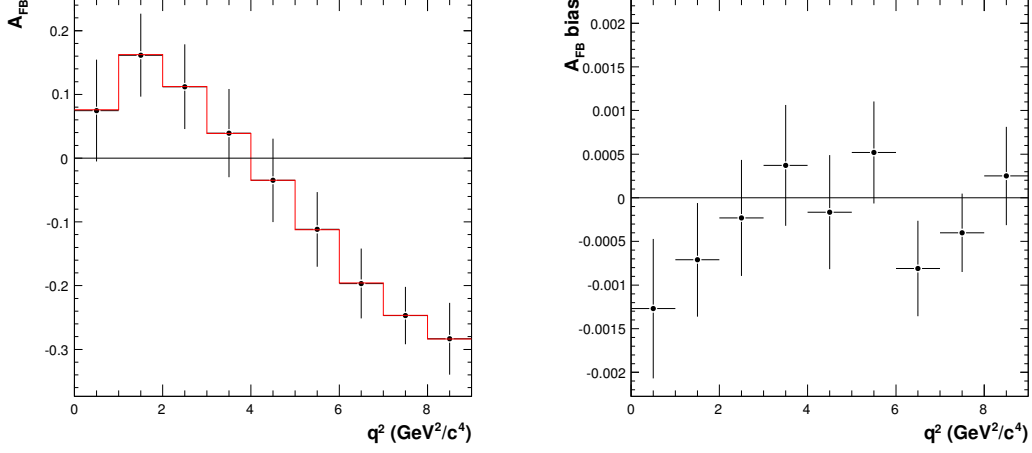
Owing to the limited statistics available, it was not possible to use the full LHCb Monte Carlo to simulate multiple 2 fb^{-1} data sets. However, it was possible to generate a large number of events using the standard LHCb Monte Carlo, without the detector simulation. A toy MC model was written in the ROOT framework [143] to simulate a large number of statistically independent LHCb experiments. For a given 2 fb^{-1} experiment, in each bin of q^2 , the generated θ_{FB} distribution was therefore taken from this sample and multiplied by the (binomially fluctuated) θ_{FB} acceptance function for this value of q^2 which was determined from the full simulation. In this way, a full 2-dimensional acceptance function was applied in bins of $\theta_{FB} \times q^2$. This gave the “expected signal distribution”. The expected signal distribution was then sampled according to the (Poisson fluctuated) expected number of events in the relevant q^2 bin to give a fluctuated “experimental signal distribution” i.e. a possible measurement with a 2 fb^{-1} data set. The unfluctuated acceptance distribution was then used to unfold the effect of the detector and selection criteria in each $\theta_{FB} \times q^2$ bin and A_{FB} was then computed.

6.2.4 The A_{FB} Precision in the Absence of Background

The A_{FB} distribution as a function of q^2 is shown in Figure 6.8(a): the solid line is the generated distribution and the points are the means of the A_{FB} measurements in each bin from 10000 toy 2 fb^{-1} experiments. The difference between the generated A_{FB} and the means of the measured values from the toy experiments is shown in Figure 6.8(b) – no significant bias is seen in any q^2 bin.

For each toy experiment, the A_{FB} distribution was fitted with a linear parameterisation in the region around the zero point, $2 < q^2 < 6 \text{ GeV}^2/c^4$. The zero-crossing point was then calculated from the result of the fit. The A_{FB} distribution from an example 2 fb^{-1} toy experiment is shown in Figure 6.9 with the fitted line superimposed. The distribution of measured zero-crossing points from 10000 such 2 fb^{-1} experiments is shown in Figure 6.10. The *RMS* of this distribution is $0.52 \text{ GeV}^2/c^4$. In the absence of background the sensitivity to the zero-crossing point is therefore

$$\sigma_{q_0^2} = (0.52 \pm 0.01) \text{ GeV}^2/c^4,$$



(a) The generated A_{FB} distribution (red line) and the mean experimental A_{FB} from 10000 toy 2 fb^{-1} experiments (black points).

(b) The difference between the generated A_{FB} values and the means of the measured values, from 10000 toy 2 fb^{-1} experiments.

Figure 6.8: A comparison of A_{FB} in the toy model and generator events.

with 2 fb^{-1} of data. With 10 fb^{-1} of data, this reduces to

$$\sigma_{q_0^2} = (0.26 \pm 0.005) \text{ GeV}^2/\text{c}^4.$$

The simulation of the background and its effect on the statistical precision of the zero-crossing point are discussed in the following sub-sections.

6.2.5 The A_{FB} Precision in the Presence of Background

In the background events seen in Chapter 5 the reconstructed muons were typically taken from b-decays, either from different b-decays, or one muon from a b-decay and the other muon from a subsequent c-decay. These events were split into two classes, symmetric and asymmetric, according to their distribution in θ_{FB} . As described in Section 6.2.1, the θ_{FB} angle is made with the μ^+ for B_d events (which contain a K^+) and with the μ^- for $\bar{B}_d^0$ events (which contain a K^-). Background events where there is no correlation either between the angular distribution of the two muons or between the charges of the reconstructed K and of the forward-going μ will therefore be symmetric in θ_{FB} .

In events where the two reconstructed muons are taken from different b-decays, there

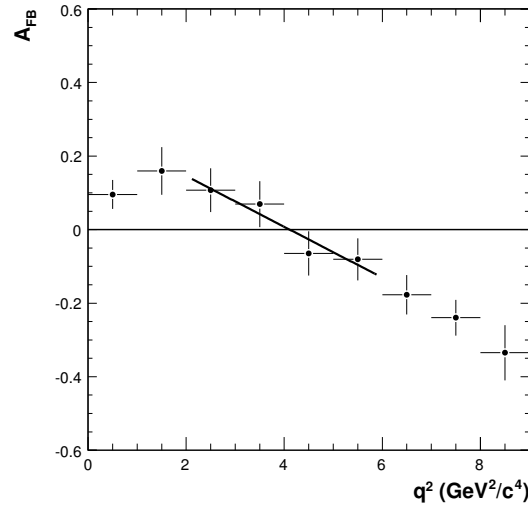


Figure 6.9: The A_{FB} distribution from an example 2 fb^{-1} toy experiment. The solid line shows the fit result.

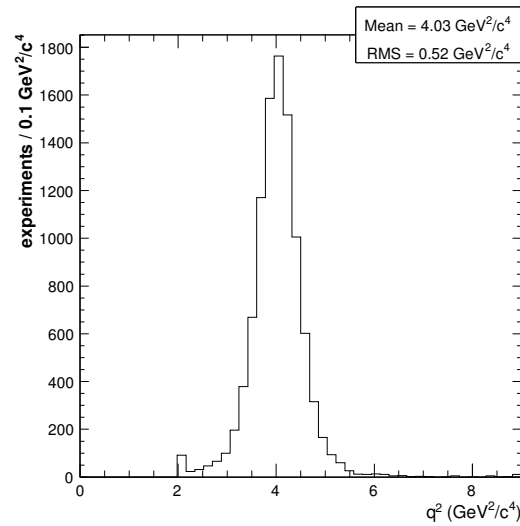


Figure 6.10: The distribution of measured zero-crossing points, from 10000 2 fb^{-1} toy experiments, with no background added.

is no correlation between the momenta of the two muons. There is therefore no angular correlation between them and the θ_{FB} angle distribution is expected to be symmetric about $\pi/2$. All the background events of the type $b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ are of this type.

An asymmetric θ_{FB} distribution can be generated if the two muons and the kaon (or pion) used to reconstruct the B-candidate are taken from the same b-decay. In this case, a correlation between the muons and also between the charges of the K and the forward-going μ can be present. For example, when the K^+ , μ^+ and μ^- are selected from the decay $B_u^+ \rightarrow \mu^+ \nu_\mu D^0 (\rightarrow K^+ \mu^- \bar{\nu}_\mu)$, (and the π^- is selected from the other b-decay in the event or taken as a mis-reconstructed primary particle) the K^+ results in the event being treated as a B_d decay and so the angle is made with the μ^+ . This μ^+ comes directly from the b-decay (as opposed to from the D^0 -decay). In the charge conjugate of this mode, the angle is calculated using the μ^- which is still the muon directly from the b-decay. This muon has, on average, higher momentum than the muon from the c-decay and is therefore more likely to be in the forward direction than the background direction in the $\mu^+ \mu^-$ rest-frame. This means θ_{FB} is likely to be greater than $\pi/2$ because the B_d is more likely to be in the backward direction in this frame i.e. the muon is likely to be backward-going. The distribution in A_{FB} is therefore asymmetric. By analogous reasoning events of the type $B_u^- \rightarrow \mu^- \bar{\nu}_\mu D^0 (\rightarrow \mu^+ \nu_\mu \rho^- (\rightarrow \pi^- \pi^0))$ – distinguished because of the $c \rightarrow d$ quark transition rather than a $c \rightarrow s$ quark transition – have the opposite asymmetry in A_{FB} because the charge of the K is required to have the opposite charge of the π .

Barring initial state asymmetries, $b \rightarrow \mu^- c (\rightarrow \mu^+)$ background events where the charge of the reconstructed K is uncorrelated to the charge of the forward-going μ will have no asymmetry. This occurs if, for example, the K and π are taken from the PV. Approximately half of the background events from the $b \rightarrow \mu^- c (\rightarrow \mu^+)$ samples are of this type and are symmetric in θ_{FB} .

The background events that survive the selection were divided into the categories symmetric, asymmetric-(b) – where the angle is made with the muon from the b-quark decay and hence are more likely to be backward-going – and asymmetric-(c) – where the angle is made with the muon from the c-decay and hence are more likely to be forward-going. The expected 2 fb^{-1} yields in the required q^2 range, and after applying the L0 and L1 triggers, are shown in Table 6.2.

In the following sub-sections the background is treated as a function of $M_{\mu\mu}$ (rather

Sample	Symmetric	Asymmetric-(b)	Asymmetric-(c)
$b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$	552 ± 174	–	–
$B_d^0 \rightarrow \mu^+ c (\rightarrow \mu^-)$	31 ± 31	16 ± 16	–
$B_u^+ \rightarrow \mu^+ c (\rightarrow \mu^-)$	236 ± 104	197 ± 94	39 ± 39
$\Lambda_b \rightarrow \mu^- c (\rightarrow \mu^+)$	8 ± 8	–	31 ± 24
Total	827 ± 205	213 ± 95	70 ± 46

Table 6.2: The breakdown of the expected background from a 2 fb^{-1} data sample, into symmetric and asymmetric categories.

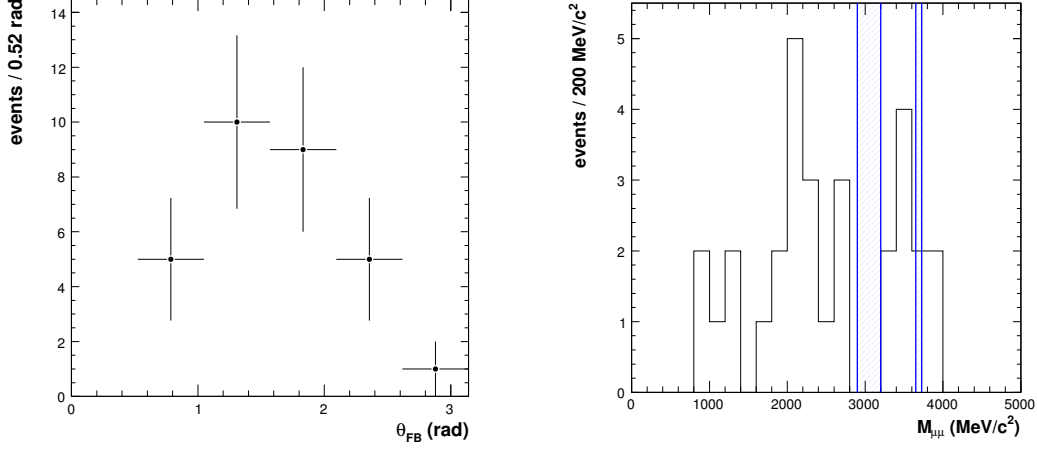
than q^2) and θ_{FB} . This is because the parameterisations are made in terms of $M_{\mu\mu}$ (flat in $M_{\mu\mu}$ for the symmetric background and as a Gaussian in $M_{\mu\mu}$ for the asymmetric background). When the background is added in the toy MC model, the $M_{\mu\mu}$ distributions are transformed to the corresponding q^2 distributions.

6.2.5.1 Symmetric Background Events

The θ_{FB} distribution for the events from the MC background samples passing the selection criteria and categorised as symmetric is shown in Figure 6.11(a). Given the limited MC statistics the distribution is consistent with being symmetric.

If the background is known perfectly then after subtraction it will have no effect on the A_{FB} distribution. However, fluctuations in the background level will affect A_{FB} . In the required q^2 range, after applying the L0 and L1 triggers, 3700 signal and ~ 820 symmetric background events are expected per 2 fb^{-1} of data. Assuming the symmetric background has flat $M_{\mu\mu}$ and θ_{FB} distributions, it is expected to contribute ~ 15 events in each bin. A typical signal bin is expected to contain ~ 70 events. After subtraction, the fluctuations in the symmetric background are therefore expected to have a small effect.

A flat distribution for θ_{FB} was assumed – as long as the distribution used is symmetric, the actual distribution has no effect because the number of events is integrated in θ_{FB} . The $M_{\mu\mu}$ distribution of the events categorised as symmetric background is shown in Figure 6.11(b). Owing to the small statistics, the true underlying distribution is poorly known. For the remainder of this chapter, the $M_{\mu\mu}$ distribution was therefore assumed to be flat. Other $M_{\mu\mu}$ parameterisations, such as a cubic and triangular parameterisations, were tried and were seen to give no effect.



(a) The θ_{FB} distribution for the background events classified as symmetric, as seen in Table 6.2.

(b) The $M_{\mu\mu}$ distribution for the background events classified as symmetric, as seen in Table 6.2.

Figure 6.11: The distribution of the symmetric background.

The background added in each $q^2 \times \theta_{FB}$ bin was calculated from the respective $M_{\mu\mu}$ (q^2) and θ_{FB} distributions and then Poisson fluctuated. The background was assumed to be perfectly known and so the calculated level (unfluctuated) was then removed. The residual background remaining in each bin is therefore the Poisson fluctuations of the level in that bin.

The distribution of fitted zero points from 10000 toy 2 fb^{-1} experiments is shown in Figure 6.12. The distribution has mean (*RMS*) $4.01 \text{ GeV}^2/c^4$ ($0.58 \text{ GeV}^2/c^4$). In this example, a flat distribution in $M_{\mu\mu}$ was used. The small peaks at $2 \text{ GeV}^2/c^4$ and $9 \text{ GeV}^2/c^4$ are due to experiments where the fit converged to a zero point outside this range.

In summary, given the level of symmetric background expected, the effect of adding the background is the same for any shape of q^2 ($M_{\mu\mu}$) distribution assumed. The measured mean zero-crossing point is not changed by this background; however, the precision with which the zero-crossing point can be determined is reduced to $0.58 \text{ GeV}^2/c^4$. For the rest of this chapter, a flat distribution in both $M_{\mu\mu}$ and θ_{FB} is used for this background type. The effect of mis-measuring this background and subtracting only part of it is evaluated in Section 6.3.2.

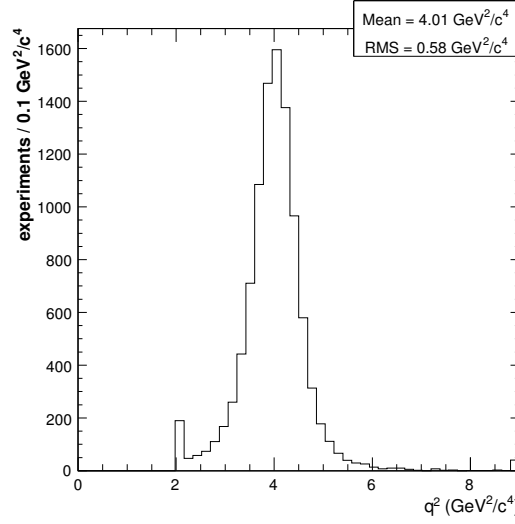


Figure 6.12: The distribution of fitted zero points from 10000 toy 2 fb^{-1} experiments, with the symmetric background added at the expected level with a flat distribution in $M_{\mu\mu}$.

6.2.5.2 Asymmetric Background Events

The asymmetric background forms the smaller part of the overall background. Approximately half of the events in the $b \rightarrow \mu^- c (\rightarrow \mu^+)$ samples fall in this category. The details of the classification of these events into the asymmetric-(b) and -(c) categories are given above. For these events, it is necessary to know the shape in both $M_{\mu\mu} (q^2)$ and θ_{FB} . The θ_{FB} and $M_{\mu\mu}$ distributions of the events passing the selection criteria and classified as asymmetric-(b) are shown in Figures 6.13(a) and 6.13(b) respectively. The equivalent distributions for the events in the asymmetric-(c) category are shown in Figures 6.14(a) and 6.14(b). The θ_{FB} distributions are asymmetric but the statistics are insufficient to parameterise the distributions in $M_{\mu\mu}$ or θ_{FB} .

Events in the asymmetric-(b) category which pass the selection criteria are typically of the type $B_u^- \rightarrow \mu^- \bar{\nu}_\mu D^* (\rightarrow D^0 \pi^0)$, where the D^0 decays $D^0 \rightarrow K^- \mu^+ \nu_\mu$. The two muons and the K^- from this decay are used, with a pion from elsewhere in the event, to build the candidate signal- B_d .

In the asymmetric-(c) category one of the five selected events is similar to the events in the -(b) category but with the K^- from the D^0 decay replaced with a π^- . The π^- (and the two muons) from the B_u^- decay were selected, together with a K^+ from elsewhere in the event, therefore giving the opposite asymmetry. The remaining four events are of the type $\Lambda_b \rightarrow \mu^- \bar{\nu}_\mu \Lambda_c^+ (\rightarrow p^+ \pi^- \mu^+ \nu_\mu)$, with the p^+ mis-identified as a K^+ . Although

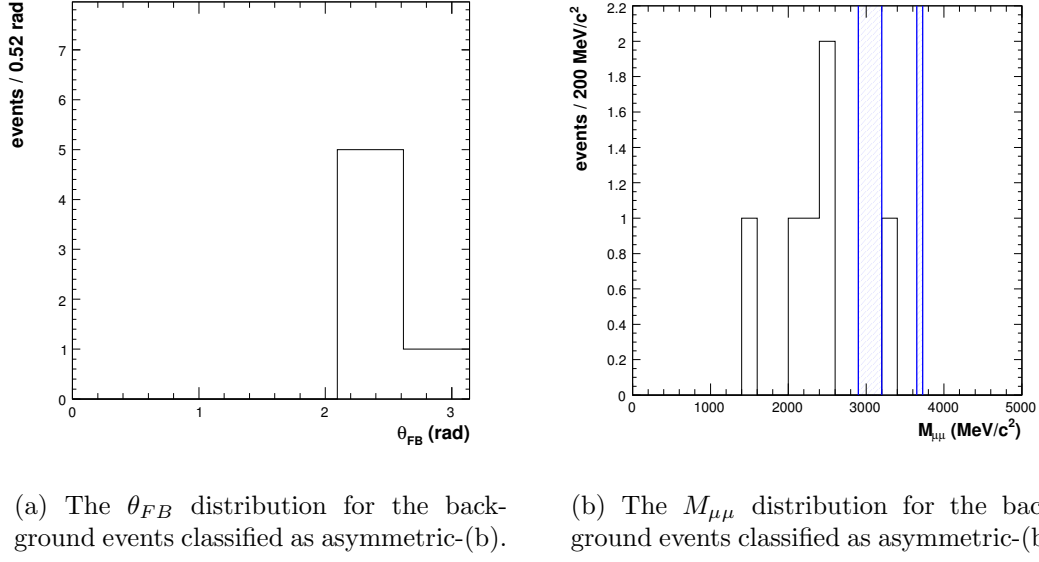


Figure 6.13: The distribution of the asymmetric-(b) background.

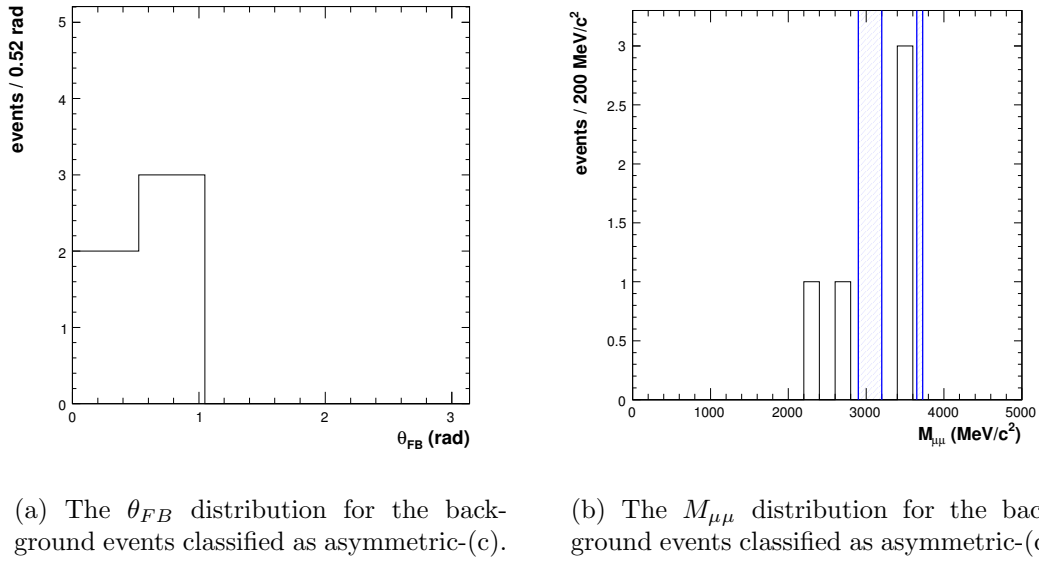


Figure 6.14: The distribution of the asymmetric-(c) background.

the Λ_b mass is higher than the B_d mass, these events could be considered as low-mass because of the proton mis-identification. Due to the low statistics, the tail of events of this type which might enter the tight B_d -mass window cannot be estimated. A cut on the kaon-proton log-likelihood difference from the RICH detectors could also potentially be used to reduce the background from these events; however, again owing to small statistics, the effect of this is hard to measure. In order to be conservative, the rate from these events was therefore extrapolated into the tight B_d -mass window and treated as background.

The background studies showed that in the events which passed the selection criteria from the $b \rightarrow \mu^- c$ ($\rightarrow \mu^+$) samples, the reconstructed muons were the true muons from the b - and subsequent c -decay. Given the excellent $M_{\mu\mu}$ resolution ($\sim 10 \text{ MeV}/c^2$), a sample of generator level events (which use the LHCb event generator but without the detector simulation) was therefore used to determine the $M_{\mu\mu}$ distribution of the asymmetric background with good statistics. It was not possible to extract the θ_{FB} distribution from these events because this requires the momentum of the reconstructed B_d . Not all the particles needed to fully reconstruct the B_d could be identified at the generator level because typically at least one of the K or π was not taken from the signal b -decay. Therefore, as with the symmetric background, it was necessary to make an assumption about the θ_{FB} distribution. A number of different assumptions and their effect on the zero-crossing point sensitivity are described below.

The θ_{FB} distributions shown in Figures 6.13(a) and 6.14(a) suggest that some cancellation might be expected i.e. that the net negative asymmetry of the 70 forward-going events from the -(c)category would cancel the net positive asymmetry of 70 of the backward-going events from the -(b) category and these could then collectively be treated as symmetric background. However, this cancellation cannot be accurately estimated and so it was conservatively assumed that there is no cancellation between the two categories. Four input θ_{FB} distributions were tried:

- **a** : all events in one forward-going bin;
- **b** : all events in one backward-going bin;
- **c** : all events distributed flat across the three forward-going bins;
- **d** : all events distributed flat across the three backward-going bins.

The $M_{\mu\mu}$ distribution was extracted from the sample of generator level events of

the type $b \rightarrow \mu^- c (\rightarrow \mu^+)$, with the di-muon invariant mass formed using the two muons from the b-decay. The distribution is strongly affected by the momentum (p) and transverse momentum (p_T) of the muons. The selection cut values, as in Chapter 4, were therefore applied (4000 and 500 MeV/ c respectively) to these variables at the generator level. As expected, the effect comes mainly from the cuts applied to the muons from the c-decay which typically have lower momentum and p_T than the muons from the b-decay. Other cuts, such as the muon impact-parameter with respect to the PV and the di-muon distance of closest approach (chosen to mimic the $\mu\mu$ -vertex χ^2) were found to have a small effect on the shape of the $M_{\mu\mu}$ distribution. The $M_{\mu\mu}$ distribution is shown in Figure 6.15, before (black) and after (red) the momentum cuts. Two $M_{\mu\mu}$ distributions were tried: the red distribution from Figure 6.15 normalised to a 2 fb $^{-1}$ data set and a Gaussian parameterisation, with mean (sigma) 1.7 (0.5) GeV/ c^2 . No difference was observed in the sensitivity to the zero-crossing point between the two $M_{\mu\mu}$ parameterisations.

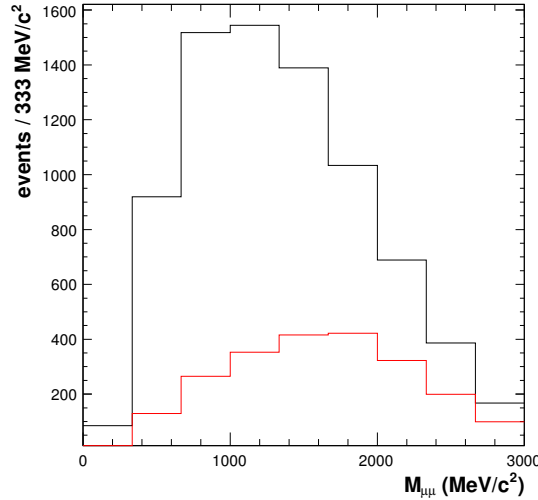


Figure 6.15: The generator level $M_{\mu\mu}$ distribution for a sample of the $b \rightarrow \mu^- c (\rightarrow \mu^+)$ events. The black (red) curve is before (after) the p and p_T cuts were applied. The overall normalisation of the curves is arbitrary.

For the four θ_{FB} parameterisations described above, the sensitivity to the zero-crossing point varied over a small range and was independent of the $M_{\mu\mu}$ parameterisation used. These different parameterisations therefore had little effect on the sensitivity to the zero-crossing point.

For the asymmetric background in the rest of this study, the θ_{FB} distribution was taken as in case (a) above and the $M_{\mu\mu}$ distribution was taken from a Gaussian with

mean (sigma) $1.7 (0.5) \text{ GeV}/c^2$. The effect of the asymmetric background on the sensitivity to the zero point is similar to the symmetric background. The distribution of fitted zero points is shown in Figure 6.16 – from 10000 toy 2 fb^{-1} experiments, the zero-crossing point was measured to be

$$q_0^2 = 4.03 \pm 0.53 \text{ GeV}^2/c^4.$$

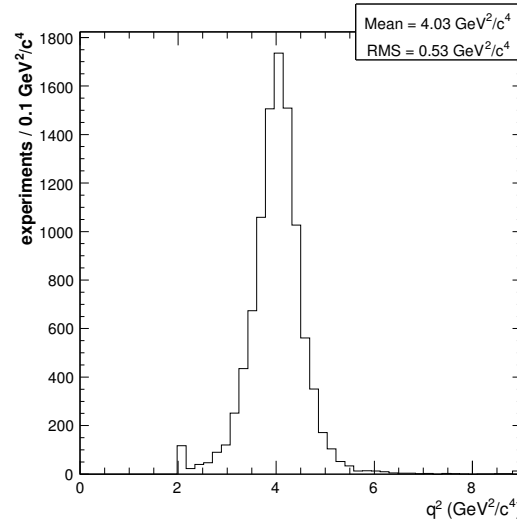


Figure 6.16: The distribution of fitted zero points from 10000 toy 2 fb^{-1} experiments, with the asymmetric background added at the expected level. The small peaks at 2 and $9 \text{ GeV}^2/c^4$ correspond to toy experiments where the fit was outside this region.

6.2.5.3 Both Symmetric and Asymmetric Background Events

The effect of adding both the symmetric and asymmetric backgrounds is shown in Figures 6.17(a) and 6.17(b) for 2 fb^{-1} and 10 fb^{-1} data sets respectively. From 10000 toy 2 fb^{-1} experiments, the zero point is determined to be $4.02 \pm 0.60 \text{ GeV}^2/c^4$. With 10 fb^{-1} of data the precision with which the zero-crossing point can be extracted improves to $0.29 \text{ GeV}^2/c^4$.

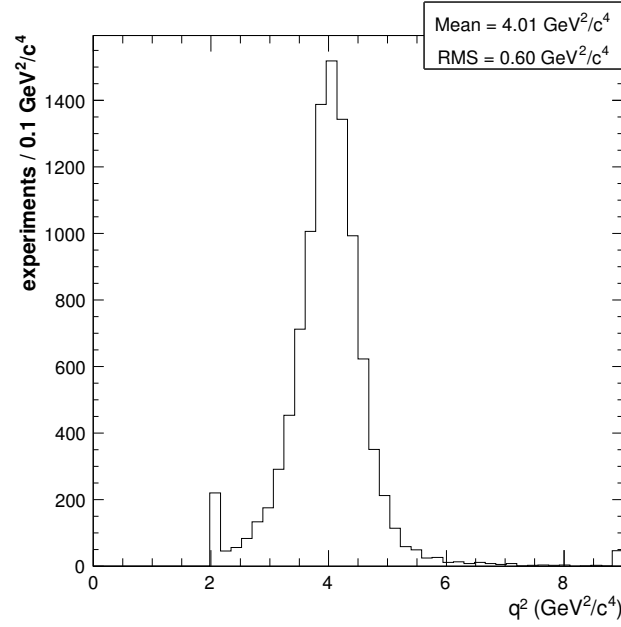
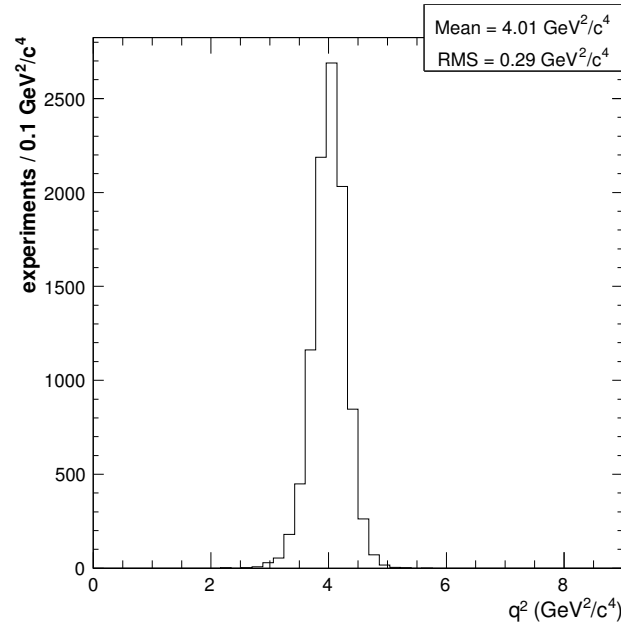
(a) 2 fb⁻¹ data sets.(b) 10 fb⁻¹ data sets.

Figure 6.17: The distribution of fitted zero points from 10000 toy experiments for a 2 fb⁻¹ (a) and 10 fb⁻¹ (b) data set. Both symmetric and asymmetric backgrounds have been added at the expected levels. The small peaks at 2 and 9 GeV²/c⁴ correspond to toy experiments where the fit was outside this region.

6.3 Systematic Effects

The toy model described in the previous sections was used to extract the statistical variation across many repeat experiments. The systematic errors are harder to evaluate. Three main systematic effects have been identified for the analysis of the zero-crossing point of A_{FB} .

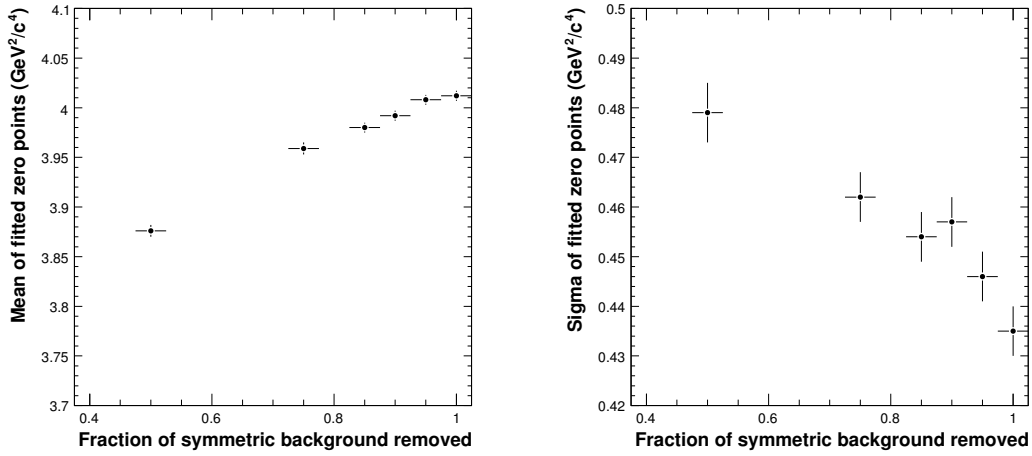
6.3.1 Detector Resolution

A poor detector resolution in either $M_{\mu\mu}$ or θ_{FB} could affect the measured zero-crossing point. The q^2 resolution, from the MC, is expected to be $\sim 0.07 \text{ GeV}^2/c^4$. Given the size of the q^2 bins ($1 \text{ GeV}^2/c^4$), any effect from this resolution will in practice be small. Similarly, the effect of a non-zero θ_{FB} resolution is also expected to be small. The resolution from the MC is expected to be $\sim 4 \text{ mrad}$, to be compared to θ_{FB} bins of $\pi/6 \text{ rad}$. Only events which cross the $\theta_{FB} = \pi/2$ boundary affect the measured A_{FB} value because events are classified as either forward- or backward-going. If the θ_{FB} distribution were flat at around $\pi/2$, the resolution would have no effect because the same number of events would move across the boundary in both directions. The size of the effect of a non-zero θ_{FB} resolution therefore depends on the slope of the θ_{FB} distribution at around $\pi/2$. As shown in Figure 6.3, the distribution is approximately flat around $\pi/2$ and this is expected to be a small effect. Increasing the size of the θ_{FB} resolution by even a factor of 10 in the toy model, in the absence of background, has no effect on the sensitivity to the zero-crossing point.

6.3.2 Mis-measurement of the Background

A mis-measurement of either the background level or distribution will affect the measured A_{FB} distribution. The effect of subtracting only part of the symmetric background was also studied. A flat distribution in $M_{\mu\mu}$ was used and only a fraction (f) of the expected background was removed from each bin. For example, if 15 events were expected in a given bin, the background added would be sampled from a Poisson with mean 15 and the amount removed in this bin would be $f \times 15$. The fitted mean of the measured zero-crossing points from the toy model, for different values of f in the range $1.0 - 0.5$, is shown in Figure 6.18(a). The effect on the precision with which the zero-crossing point can be extracted is shown in Figure 6.18(b). There is an approximately linear increase in

the bias of the fitted means as the efficiency for removing the background is decreased. A similar effect is seen in the sensitivity – the precision with which the zero-crossing point can be extracted decreases as the efficiency for removing the background drops. Given the precision expected for a single measurement ($\sim 0.5 \text{ GeV}^2/c^4$), any bias in the mean should be a small effect. Even for a systematic mis-measurement of half the background level, the sensitivity only increases from $\sim 0.58 \text{ GeV}^2/c^4$ to $\sim 0.48 \text{ GeV}^2/c^4$.



(a) The fitted mean of the measured zero-crossing points, as a function of the efficiency for removing the background. The errors shown are from the distribution of zero points.

(b) The fitted sigma of the measured zero-crossing points, as a function of the efficiency for removing the background. The errors shown are from the distribution of zero points.

Figure 6.18: The effect of mis-measuring the symmetric background.

The level of the background, including any non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events, can be found using the B_d and K^* sidebands, as discussed in Section 5.7. A procedure to understand the effect of the non-resonant events, if present at a significant level, is under study.

6.3.3 Determination of the Acceptance Function

A non-flat acceptance function, as shown in Figure 6.7(b), distorts the measured A_{FB} distribution and it is therefore necessary to correct for this effect. The plot in Figure 6.19 shows the effect of applying the expected acceptance function in the toy model but unfolding a flat acceptance function – the measured A_{FB} values are changed significantly.

The acceptance function can be divided into several components: the effect of the re-

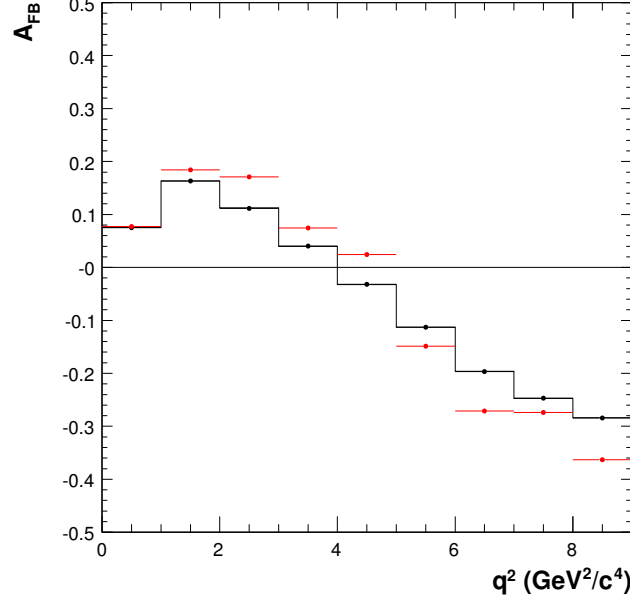


Figure 6.19: The A_{FB} distribution in the standard toy model (black points) and from not unfolding the acceptance function (red points). The black curve shows the A_{FB} distribution from the generator level events.

construction and detector geometry; the effect of the muon particle ID; the effect of the RICH particle ID and the effect of the selection cuts. The acceptance function, for the lowest q^2 bin, is shown in Figure 6.20 divided into these components.

The effects of the reconstruction and detector geometry (black points in Figure 6.21) and requiring the RICH particle ID (pink points in Figure 6.21) produce a relatively flat acceptance function. The dominant components of the acceptance function warping are the muon particle ID and the selection criteria (dominated by the muon p_T cut). As described in Section 2.2.10, the muon particle ID requires muons to have momentum greater than $3 \text{ GeV}/c$. The fraction of muons satisfying this requirement changes as a function of θ_{FB} , warping the acceptance function. After removing the effect of this implicit $3 \text{ GeV}/c$ momentum cut, the warping of the acceptance function as function of θ_{FB} is much less, as shown in Table 6.3. Because the muon ID efficiency is a function of q^2 , even after removing the effect of the $3 \text{ GeV}/c$ momentum cut, it is not possible to use the $B_d^0 \rightarrow J/\psi K^*$ decay to measure it. The efficiency will therefore be measured using the full LHCb MC and checked with the $B_d^0 \rightarrow J/\psi K^*$ decay, i.e. at one value of q^2 .

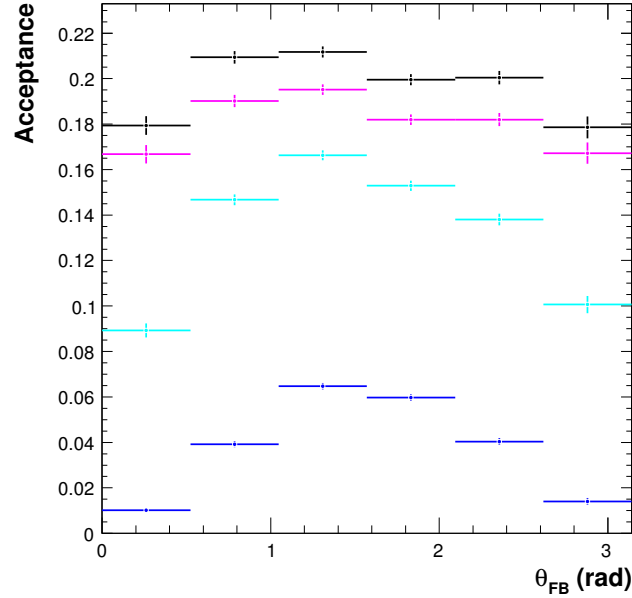


Figure 6.20: The acceptance function stages, for the lowest q^2 bin. The black points show the acceptance from the reconstruction and detector geometry alone. The pink points include the effect of the additionally requiring the RICH particle ID for the K and π . The turquoise points show the effect of then also requiring the muon particle ID and the dark blue points show the full acceptance function including all these components and the selection criteria.

q^2 bin (GeV^2/c^4)	$0 < q^2 < 1$			$4 < q^2 < 5$			$8 < q^2 < 9$		
Angle bins	0 & 5	1 & 4	2 & 3	0 & 5	1 & 4	2 & 3	0 & 5	1 & 4	2 & 3
fraction with $p > 3 \text{ GeV}/c$	76%	91%	98%	93%	95%	97%	98%	98%	99%
μ -rec efficiency	53%	70%	77%	66%	73%	77%	77%	79%	80%
μ -rec efficiency after $p > 3 \text{ GeV}/c$	78%	79%	80%	74%	78%	80%	79%	81%	82%

Table 6.3: The effect on the acceptance function of the muon particle ID $3 \text{ GeV}/c$ momentum cut.

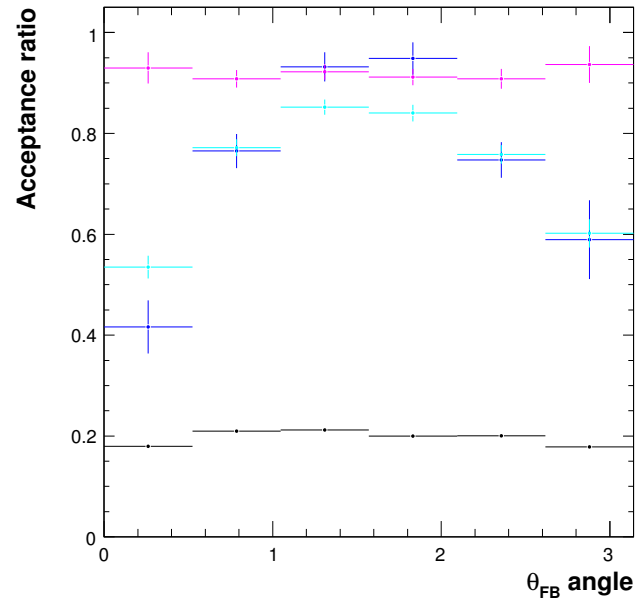


Figure 6.21: The acceptance function components, for the lowest q^2 bin. The black points show the acceptance from the reconstruction and geometry. The pink points show the effect of just the RICH particle ID (pink divided by black in Figure 6.20). The turquoise points show the effect of just the muon particle ID (turquoise divided by pink in Figure 6.20). The blue points show the effect of the selection cuts (blue divided by turquoise in Figure 6.20).

6.3.4 Other Systematic Effects

Other possible systematic effects which will need to be considered include:

- any detector asymmetry;
- the effect of the selection cuts;
- the effect of the trigger requirements;
- the method used to extract the zero-crossing point from the A_{FB} distribution and
- any change in the θ_{FB} distribution between the backgrounds in the sideband and signal regions.

6.4 Conclusions

Taking the signal yields and background estimates as given in Chapters 4 and 5, for a 2 fb^{-1} data set, 3700 ± 130 signal events are expected after the L0 and L1 triggers in the required q^2 range $(2m_\mu)^2 < q^2 < 9 \text{ GeV}^2/c^4$. Ignoring the potential background from non-resonant events, 1100 ± 250 background events are expected.

The backgrounds were divided into two categories: symmetric and asymmetric in θ_{FB} . The symmetric class (820 ± 200 events per 2 fb^{-1}) dominates the background and was parameterised as a flat distribution in both $M_{\mu\mu}$ and θ_{FB} . Given the level of the background, the exact choice of parameterisation had little effect on the sensitivity. The $M_{\mu\mu}$ distribution of the asymmetric class (280 ± 110 events per 2 fb^{-1}) was taken from a Gaussian parameterisation with $\mu = 1.7 \text{ GeV}/c^2$ and $\sigma = 0.5 \text{ GeV}/c^2$. No cancellation was assumed between the opposite asymmetries that arise in this category and the events were assumed to all lie in one θ_{FB} bin.

With no background added, the statistical sensitivity to the zero-crossing point was estimated to be

$$\sigma_{q_0^2} = (0.52 \pm 0.01) \text{ GeV}^2/c^4.$$

Adding the background at the expected level, with no cancellation, the zero-crossing

point was measured from the toy model, with a precision of

$$\sigma_{q_0^2} = (0.60 \pm 0.01) \text{ GeV}^2/c^4.$$

The expected sensitivity is therefore smaller than the error on the current theoretical prediction in the SM ($\pm 0.6 \text{ GeV}^2/c^4$). With 10 fb^{-1} the precision with which the zero-crossing point can be extracted is expected to improve to

$$\sigma_{q_0^2} = (0.29 \pm 0.003) \text{ GeV}^2/c^4.$$

In all cases, no bias in the mean of the measured zero-crossing point was observed.

The above signal and background yields can be compared with the expectations from ATLAS and CMS. With three years of data (30 fb^{-1}) ATLAS expect 2500 signal events, with an upper limit of 12000 background events [161, 170]. The resulting statistical precision on the A_{FB} distribution is $\sim 4\%$, ignoring detector and background effects. The CMS experiment has equivalent potential to ATLAS in this decay [170]. The expected sensitivity of LHCb to the A_{FB} distribution and its zero-crossing point with 2 fb^{-1} of data should be sufficient to detect or constrain some of the proposed new physics models described in Chapter 1.

Chapter 7

Conclusions

This thesis has presented two bodies of research as part of the LHCb experiment: the analysis of the Cherenkov angle resolution of the HPDs for the RICH detectors and the analysis of the rare decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$.

The prototype RICH detector with six pre-production HPDs was placed in a charged π^- / e^- beam at CERN. The work described in Chapter 3 presents the analysis of the Cherenkov angle resolution of these HPDs. With some simple cuts to select Cherenkov rings produced by single pions, the Cherenkov angle was measured to be 19.64 mrad in good agreement with expectations. The Cherenkov angle resolution for HPD-C1 was found to be

$$\sigma_{\theta_C} = 1.66 \pm 0.03 \text{ mrad},$$

where the quoted error refers to the systematic error from mis-alignments and the statistical error is negligible. The resolution is in good agreement with the resolution expected from the MC-simulation, 1.64 mrad. The dominant components of the resolution were found to be from the HPD pixelisation effect (0.78 mrad) and the HPD point-spread-function (1.00 mrad). The photoelectron yield was also found to be in good agreement with expectations. The results from later testbeams at the CERN and Frascati facilities were consistent with these measurements.

The rare decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$ provides a sensitive test of the SM, particularly in the zero-crossing point of the forward-backward asymmetry. The reconstruction and selection of these decays has been demonstrated using the full LHCb MC-simulation, including a detailed description of the material and response of the detector. The se-

lection criteria presented in Chapter 4 give an overall efficiency of $(1.11 \pm 0.03)\%$ which includes the reconstruction (6.10%), selection (20.6%) and trigger efficiencies (89%). This gives a signal yield of $7200 \pm 180 \pm_{1900}^{2200}$ per 2 fb^{-1} of data (one physics year of 10^7 s at a nominal luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$), where the first error is the statistical error from the number of events in the MC sample and the second error is from the branching ratio measurement. The background was investigated using a sample of 24M $b\bar{b}$ -inclusive events and was found to be dominated by events with real muons from b -decays, as presented in Chapter 5. The statistical significance of the $b\bar{b}$ -inclusive sample, however, was insufficient to estimate the level of this background precisely. Dedicated background samples, chosen to reflect the expected backgrounds, were therefore used to evaluate the level of the background. The total background was estimated to be 1770 ± 310 , excluding the non-resonant $B_d^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ events (a further 1730 ± 75 events) which are currently experimentally unobserved and may possibly be counted as signal under certain circumstances. The background is dominated by events of the type $b \rightarrow \mu^-$, $\bar{b} \rightarrow \mu^+$ where the two reconstructed muons come from true b -decays and the K and π are taken from the other decay products of the b -quark.

The sensitivity to the zero-crossing point of the forward-backward asymmetry was investigated using a toy-MC model. Assuming the only errors on the background q^2 and θ_{FB} distributions arise from statistical fluctuations in the number of events and that the detector acceptance function is known to within the statistical errors, the zero-crossing point was, on average, found to be $4.02 \text{ GeV}^2/c^4$, in good agreement with the input value to the simulation of $(4.03 \pm 0.1) \text{ GeV}^2/c^4$. The sensitivity of a single measurement was found to be

$$q_0^2 = 4.02 \pm 0.60 \text{ GeV}^2/c^4 \quad (2 \text{ fb}^{-1} \text{ data sample})$$

$$q_0^2 = 4.02 \pm 0.29 \text{ GeV}^2/c^4 \quad (10 \text{ fb}^{-1} \text{ data sample}).$$

With a 2 fb^{-1} data set the error on the zero-crossing point is expected to be less than the error on the SM theoretical prediction and LHCb will therefore be sensitive to new physics in $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays with the first year of data at the LHC.

Appendix A

The Cherenkov Effect

The Cherenkov effect was first discovered in 1934 by P. A. Cherenkov and explained by I. M. Frank and I. E. Tamm [171, 172]. Cherenkov radiation is emitted when charged particles travel through a dielectric medium with refractive index n at a speed (v) greater than the local speed of light (c/n). Under these conditions the induced dipole arrangement, due to the polarisation of the surrounding medium, is asymmetric along the particle track and results in spontaneous radiation emission. Cherenkov radiation is emitted at a characteristic angle that, in all practical cases, depends only on the refractive index of the medium and the speed of the particle. This property is essential to the principle of the RICH detectors – a momentum measurement from the tracking detectors combined with a speed measurement from the Cherenkov angle allows the particle to be identified.

The Cherenkov angle can be derived by considering the relativistic emission of a photon from a charged particle. Consider a charged particle with initial energy, E_0 , and momentum, p_0 , travelling through a medium with refractive index, n . The photon is emitted with energy E , and momentum^a $p = nE/c$, at an angle θ_C , to the incident particle direction. The particle is scattered through an angle ϕ , with energy E_1 and momentum p_1 . Applying energy and momentum conservation, the 4-momentum equation is then

$$(E_0, p_0, 0, 0) = (E, p \cos \theta_C, p \sin \theta_C, 0) + (E_1, p_1 \cos \phi, -p_1 \sin \phi, 0). \quad (\text{A.1})$$

Re-arranging the three simultaneous equations from the non-zero components of Equa-

^aThis comes from the group velocity equation $v_g = \frac{\partial E}{\partial p} = \frac{c}{n}$.

tion A.1 to eliminate the dependence on ϕ and E_1 gives an expression for $\cos \theta_C$

$$\cos \theta_C = \frac{1}{\beta_0 n} + \frac{\hbar k}{2p_0} \left(1 - \frac{1}{n^2} \right), \quad (\text{A.2})$$

where $\beta_0 = v/c$ is the initial velocity fraction of the radiating particle and k is the wavenumber of the photon. The second term accounts for the recoil of the radiating particle and can be neglected in all practical cases, resulting in the usual Cherenkov angle formula

$$\cos \theta_C \simeq \frac{1}{\beta_0 n}. \quad (\text{A.3})$$

Classically, this can be thought of in a Huygens construction in terms of spherical waves which interfere. This is illustrated in Figure A.1. The secondary wavefronts constructively interfere along a line at an angle $\cos \theta_C = 1/\beta n$ to the particle line of flight [173]. Since Cherenkov emission only occurs when the speed of the charged particle is greater than the local speed of light ($\beta > 1/n$), the refractive index of the medium must be greater than one. At the threshold for Cherenkov emission ($v = c/n$), the radiation is emitted in the forward cone i.e. $\theta_C = 0$. At the other extreme ($\beta = 1$), the Cherenkov angle saturates so that $\theta_C = \arccos(1/n)$.

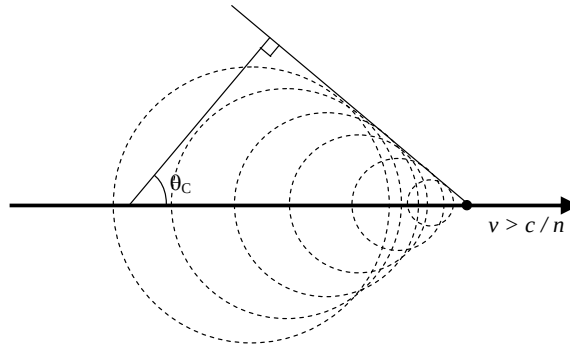


Figure A.1: A Huygens construction for Cherenkov radiation.

The energy loss per unit length by a charged particle travelling through a dielectric medium is given by the Frank-Tamm relation [174]

$$\left(\frac{dE}{dx} \right)_{rad} = \frac{Z^2 e^2}{4\pi \epsilon_0 c^2} \int_{\epsilon(\omega) \beta^2 > 1} \omega \left(1 - \frac{1}{\beta^2 n^2} \right) d\omega, \quad (\text{A.4})$$

where Ze is the charge of the radiating particle and $\sqrt{\epsilon(\omega)}$ is the refractive index. Assuming that the refractive index (n) is independent of the photon frequency, this can be re-arranged to give the expected number of photons emitted from a particle travelling through a radiator of length L in a given energy range

$$\frac{dN}{dE} = LZ^2 \left(\frac{\alpha}{c\hbar} \right) \sin^2 \theta_C \quad (\text{A.5})$$

The energy spectrum of Cherenkov radiation is therefore flat in energy. A high frequency cut-off, when the refractive index of the medium falls below unity, prevents the divergence of the total energy emitted [172]. In the LHCb RICH detectors, photons are detected over the approximate wavelength range 200 – 700 nm.

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