Track reconstruction in the LHCb experiment
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Chapter 1

Theoretical context

In this thesis a study of the track reconstruction in the LHCb detector is described. The LHCb detector is optimised for the measurement of $B$ meson production and decay at the LHC, in particular the observation and measurement of $CP$ asymmetries in specific $B$ meson decays. In this chapter the theoretical context for these measurements is discussed. It is, however, not intended to give a full theoretical description of $CP$ violation in neutral $B$ meson decays. For more detailed descriptions the reader is referred to excellent publications and textbooks[7, 8, 9, 10].

Section 1.1 describes the concept of $CP$ violation. Section 1.2 explains how $CP$ violation is incorporated in the Standard Model. Section 1.3 describes the neutral $B$ meson system. Section 1.4 discusses two $B$ decay channels which for the LHCb experiment are used as benchmark channels for track reconstruction. Section 1.5 describes production characteristics of $B$ mesons at the LHC.

1.1 $CP$ violation

The violation of $CP$ symmetry implies that the laws of nature are not invariant under the combined Charge and Parity transformation. Parity $P$ is the inversion of space coordinates (exchange of left and right handedness). Charge conjugation $C$ changes the sign of the “internal” quantum numbers such as charge and baryon number.

For a long time physics was assumed to be invariant under the parity transformation, i.e. the mirror image of any physical process obeys the same physical laws as the original process. However, in 1957 an experiment[11] showed that the electrons emitted in the beta decay of $^{60}Co$ are predominantly produced in the direction opposite to the spin of the cobalt nucleus. The mirror image of an electron decay opposite to the spin direction is a decay along the spin direction. After the alignment of the spins the observation of a top/down asymmetry in the experiment immediately implies the violation of parity.

Later, it was observed that in the decay $\pi^+ \rightarrow \mu^+\nu_\mu$ the neutrino always emerges left handed. Again, parity is violated as the mirror process, i.e. with the neutrino right handed, does not occur. However, the charge conjugate of the mirror process, i.e. $\pi^- \rightarrow \mu^-\bar{\nu}_\mu$ with the anti-neutrino right handed, was observed. Therefore, it seemed that the symmetry is restored under the combined operation of $C$ and $P$. 
### Table 1.1: The three families of elementary fermions in the Standard Model, i.e. the leptons and quarks.

<table>
<thead>
<tr>
<th>fermion</th>
<th>family</th>
<th>$q/e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton</td>
<td>I</td>
<td>$e$</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>$\mu$</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$\tau$</td>
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<tr>
<td></td>
<td>$\nu_e$</td>
<td>0</td>
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<td></td>
<td>$\nu_\mu$</td>
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<td></td>
<td>$\nu_\tau$</td>
<td></td>
</tr>
<tr>
<td>quark</td>
<td>I</td>
<td>$u$</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>$c$</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>$t$</td>
</tr>
<tr>
<td></td>
<td>$d$</td>
<td>$2/3$</td>
</tr>
<tr>
<td></td>
<td>$s$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b$</td>
<td>$-1/3$</td>
</tr>
</tbody>
</table>

However, in 1964 also $CP$ symmetry was demonstrated to be violated in the decay of neutral kaons\[^3\]. An interesting aspect of neutral kaons is the ability for a $K^0$ to transform into the anti-particle $\bar{K}^0$ and vice versa (see section 1.3 for the similar underlying mechanism for neutral $B$ mesons in the Standard Model). It turned out that the particles observed in nature (the mass eigenstates) are not $K^0$ and $\bar{K}^0$, but linear combinations of these states. Two states are observed with quite distinct lifetimes: $K_S$ with $\tau = 0.89 \times 10^{-10} \text{ s}$ and $K_L$ with $\tau = 5.2 \times 10^{-8} \text{ s}$. The experiment in 1964 showed the $K_L$ to be composed of the $CP = -1$ eigenstate $K_2$ with a small admixture of the $CP = +1$ eigenstate $K_1$, i.e.

$$|K_L| = \frac{1}{\sqrt{1+|\epsilon|^2}} (|K_1| + \epsilon |K_2|). \quad (1.1)$$

Experimentally $\epsilon$ is found to be $(2.271 \pm 0.017) \times 10^{-3}[4]$ demonstrating violation of $CP$ symmetry in the mixing of $K^0$ and $\bar{K}^0$. The next section shows how $CP$ violation is incorporated in the standard model.

### 1.2 $CP$ violation in the Standard Model

The Standard Model provides an accurate theoretical framework for the description of the interactions between the fundamental constituents of matter. Matter is thought to be made out of two types of fundamental fermions (spin $\frac{1}{2}$ particles): quarks and leptons. Interactions are described by the exchange of spin 1 bosons. The interactions described by the Standard Model are the electromagnetic-, weak- and strong-force. Gravitation, the fourth fundamental interaction, is not incorporated in the model.

The fundamental fermions of the Standard Model are divided into three families with similar properties but increasing mass. Each family contains a lepton with an associated lepton-neutrino as well as an up- and down- type quark (see table 1.1). Together with the corresponding anti-particles the Standard Model incorporates 24 fundamental fermions\(^1\). With the recent\[^{12}\] direct observation of the tau neutrino all fermions of the Standard Model are experimentally observed.

Quantum Electro Dynamics (QED) gives the quantum field description of electromagnetic interactions between charged fermions. The corresponding electromagnetic

\[^1\]Each quark can in addition occur in three colour states.
current is mediated by the exchange of photons. In the sixties Glashow, Weinberg and Salam [13, 14, 15] developed a theory combining the electromagnetic and weak interactions. They predicted the existence of three mediators of the weak interaction, i.e. the $Z$, $W^+$ and $W^-$. These massive bosons were found in 1983[16, 17]. The theory of the strong interactions, Quantum Chromo Dynamics (QCD), describes an interaction that acts only between quarks. The strong interaction is mediated by 8 gauge bosons collectively called gluons.

The charged current weak interaction (mediated by the exchange of $W^\pm$ bosons) is known to maximally violate $P$. The violation is explained by the sum of a vector and axial-vector in the hadronic charged current of this interaction\footnote{A vector changes sign under the parity operation whereas an axial vector does not.}, i.e. it has the form:

$$j_{ud}^{cc} = (\bar{u}, c, t) \gamma_u (1 - \gamma_5) V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix},$$

where $\gamma_u$ are the Dirac matrices, $1 - \gamma_5$ the projection operator to left handed states and $V_{CKM}$ the $3 \times 3$ unitary Cabibbo-Kobayashi-Maskawa matrix\[18, 19\]

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \quad (1.3)$$

The CKM matrix relates the flavour eigenstates of the down type quarks ($d, s, b$) to the weak interaction eigenstates ($d', s', b'$), i.e.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.4)$$

The elements of $V_{CKM}$ express the relative strength of the couplings between the up and down type quarks. The requirement of unitarity of the matrix, i.e. $V_{CKM}^* V_{CKM} = 1$, introduces constraints between the elements. In general three real parameters and six phases can be defined for a unitary $3 \times 3$ matrix. Five can however be removed by appropriate re-phasing of the quark fields without changing the physically observable quantities. A popular parametrisation is due to Wolfenstein\[20\] expressed in powers of the sine of the Cabibbo angle\[18\] $\lambda = 0.222 \pm 0.002[4]$:

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4), \quad (1.5)$$

with $A, \rho$ and $\eta$ real numbers. The phase, i.e. the imaginary component $i\eta$, is the source of $CP$ violation in the Standard Model.

The unitarity relation of the CKM matrix that is most relevant for $B$ mesons decays is:

$$\sum_i V_{id}^* V_{ib} = V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0, \quad (1.6)$$
The three complex quantities $V_{ud}V_{ub}^*$ form a triangle in the complex plane as shown in figure 1.1. The angles of this unitarity triangle are defined by:

$$
\alpha = \arg \left( \frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right)
$$

$$
\beta = \arg \left( \frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right)
$$

$$
\gamma = \arg \left( \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)
$$

Recently, the experiments BaBar and Belle made direct measurements of the angle $\beta$ using $B_d$ meson decays. The BaBar result is[5]:

$$
\sin 2\beta = 0.75 \pm 0.09\text{(stat)} \pm 0.04\text{(syst)} \quad .
$$

The Belle result is[6]:

$$
\sin 2\beta = 0.82 \pm 0.12\text{(stat)} \pm 0.05\text{(syst)} \quad .
$$

The area of the unitarity triangle is a measure of the amount of $CP$ violation, i.e. in case no $CP$ violation would exist the triangle would collapse into a line[21]. The BaBar and Belle results thus show the existence of $CP$ violation in $B$ meson decays.

In order to test if the Standard Model provides the full explanation of the observed $CP$ violation additional measurements are required. If the sides and angles of the unitarity triangle(s) are independently measured the triangle becomes over-constrained. LHCb aims to test the internal consistency of the Standard Model by making precision measurements on many different $B$ meson decay channels.
1.3 Neutral $B$ mesons

Neutral $B$ meson decays are interesting to study $CP$ violation for several reasons:

- Due to the large $b$ quark mass, Heavy Quark Effective Theory (HQET)[22] provides a framework to calculate hadronic effects. Hence the theoretical uncertainties in these calculations are much smaller than for the kaon system.

- Due to the existence of $B^0 - ar{B}^0$ oscillations, two interfering amplitudes (i.e. the direct decay $B^0 \rightarrow f$ and the decay via mixing $B^0 \rightarrow ar{B}^0 \rightarrow f$) with possibly different phases contribute to the decay of a neutral $B$ meson. Because these amplitudes are expected to be of the same order the $CP$ asymmetry is expected to be large.

In this section the physics of the neutral $B$ meson system is described. The symbols $B^0$ and $\bar{B}^0$ are used to represent the particle and anti-particle states of both $B^0_d$ as $B^0_s$.

$B^0 - \bar{B}^0$ oscillations (mixing) occur in the Standard Model through the exchange of two $W$ bosons via the box diagrams shown in figure 1.2. The dominant diagrams are the ones that exchange two top quarks (i.e. $i = t$). This is due to the high top quark mass (compared to charm and up quarks) and because the diagrams are Cabibbo favoured[23].

The time dependent wave function for neutral $B$ mesons can be written as the superposition:

$$\Psi(t) = a(t) \left| B^0 \right> + b(t) \left| \bar{B}^0 \right> \tag{1.10}$$

The time evolution of this system is described by the Schrödinger equation:

$$i\hbar \frac{\partial \Psi}{\partial t} = H\Psi = \left( M - i \frac{\Gamma}{2} \right) \Psi \tag{1.11}$$

with $M$ and $\Gamma$ the $2 \times 2$ mass and decay matrices. Normalising and diagonalising $H$ results in the two mass eigenstates $B_L$ and $B_H$ expressed in terms of the flavour
eigenstates $B^0$ and $\bar{B}^0$:

$$
|B_L\rangle = \frac{1}{\sqrt{p^2 + q^2}} (p |B^0\rangle + q |\bar{B}^0\rangle),
$$

$$
|B_H\rangle = \frac{1}{\sqrt{p^2 + q^2}} (p |B^0\rangle - q |\bar{B}^0\rangle).
$$

(1.12)

They have a simple exponential evolution in time, i.e.

$$
|B_L(t)\rangle = e^{-\left(\Gamma_L/2 + iM_L\right)t} |B_L(0)\rangle,
$$

$$
|B_H(t)\rangle = e^{-\left(\Gamma_H/2 + iM_H\right)t} |B_H(0)\rangle.
$$

(1.13)

It then follows that the evolution of an initially $(t = 0)$ pure $B^0$ (or $\bar{B}^0$) is given by:

$$
|B^0_{\text{phys}}(t)\rangle = g_+(t) |B^0\rangle + (q/p) g_-(t) |\bar{B}^0\rangle,
$$

$$
|\bar{B}^0_{\text{phys}}(t)\rangle = (p/q) g_-(t) |B^0\rangle + g_+(t) |\bar{B}^0\rangle.
$$

(1.14)

with

$$
g_\pm(t) = \frac{1}{2} \left( e^{-\left(\Gamma_L/2 + iM_L\right)t} \pm e^{-\left(\Gamma_H/2 + iM_H\right)t} \right).
$$

(1.15)

What is measured experimentally are the decay rates of particles into final states. The time-dependent rates for initially pure $B^0$ and $\bar{B}^0$ states decaying into final state $f$ at time $t$ are given by:

$$
R_f(t) \equiv |\langle f | B^0_{\text{phys}}(t) \rangle|^2 = \frac{|A_f|^2}{2} e^{-\Gamma t} (I_+(t) + I_-(t))
$$

$$
\tilde{R}_f(t) \equiv |\langle f | \bar{B}^0_{\text{phys}}(t) \rangle|^2 = \frac{|\bar{A}_f|^2}{2} \left| \frac{p}{q} \right|^2 e^{-\Gamma t} (I_+(t) - I_-(t)),
$$

(1.16)

where $\Gamma$ is the average decay width of the two mass eigenstates, and with $A_f \equiv \langle f | B^0 \rangle$, i.e. the instantaneous decay amplitude for a flavour eigenstate $B^0$ into final state $f$. The functions $I_+(t)$ and $I_-(t)$ are given by:

$$
I_+(t) = (1 + |\lambda|^2) \cosh \frac{\Delta \Gamma}{2} t - 2 \text{Re}(\lambda) \sinh \frac{\Delta \Gamma}{2} t
$$

$$
I_-(t) = (1 - |\lambda|^2) \cos \Delta m t - 2 \text{Im}(\lambda) \sin \Delta m t,
$$

(1.17)

with $\Delta \Gamma$ and $\Delta m$ the mass and decay width differences of the mass eigenstates. The complex parameter $\lambda$ is given by:

$$
\lambda = \frac{q A_f}{p \bar{A}_f},
$$

(1.18)

with $\bar{A}_f \equiv \langle f | \bar{B}^0 \rangle$, i.e. the instantaneous decay amplitude $\bar{B}^0 \to f$.

The above equations hold in general for all neutral $B$ decays. The components of the decay rate formulae express the time dependence due to the oscillations. The specifics for a certain decay, i.e. the difference in decay amplitudes, is expressed in the single
parameter $\lambda$. A similar set of equations for the time-dependent rates $R_f(t)$ and $\bar{R}_f(t)$ of the $B^0$ and $\bar{B}^0$ states decaying into final state $f$ is obtained by replacing $A_f \rightarrow \bar{A}_f$, $\bar{A}_f \rightarrow A_f$ and interchanging $p$ and $q$ in equations 1.16-1.18. The parameter $\lambda$ then transforms into $\bar{\lambda} = \frac{p A_f}{q A_f}$.

$CP$ violation is studied by measuring the decay-rate asymmetry between particles and anti-particles. In the time dependent decay-rate asymmetries

$$A_f(t) = \frac{R_f(t) - \bar{R}_f(t)}{R_f(t) + \bar{R}_f(t)}$$

$$A_{\bar{f}}(t) = \frac{R_{\bar{f}}(t) - \bar{R}_{\bar{f}}(t)}{R_{\bar{f}}(t) + \bar{R}_{\bar{f}}(t)}$$

(1.19)

acceptance effects of the detector are cancelled since the asymmetries are built from identical particles. In case the final state is a $CP$ eigenstate $f = \bar{f}$ and the rate asymmetries $A_f(t)$ and $A_{\bar{f}}(t)$ are identical. This asymmetry is a $CP$ asymmetry and can directly be used to demonstrate $CP$ violation. If in addition the decay is dominated by a single CKM phase and under the assumption\(^3\) $|q/p| = 1$ the parameter $|\lambda| = 1$. Combining equation 1.16 and 1.17 into equation 1.19, and assuming $\Delta \Gamma \approx 0$, the $CP$ asymmetry simplifies to:

$$A_{\text{CP}}(t) = -\text{Im}(\lambda) \sin \Delta mt .$$

(1.20)

The term $\sin(\Delta mt)$ expresses the $B^0-\bar{B}^0$ oscillations, the amplitude $\text{Im}(\lambda)$ is the amount of $CP$ violation.

$\Delta \Gamma \approx 0$

### 1.4 $B$ decays in LHCb

Many different decay modes of the $B_d$ and $B_s$ exist. However, most of the decay modes interesting for the study of $CP$ violation have small branching ratios. Therefore, an efficient reconstruction of these decays is essential. As is discussed in section 2.4 the selection of generic $B$ decay events in LHCb is done at trigger level 1. To select the interesting $B$ meson decays from the large $B$ sample, the full $B$ decay needs to be reconstructed. Hence, all stable decay products need to be efficiently and precisely reconstructed by the tracking system. In this thesis the reconstruction of two benchmark decay modes is investigated. Selected are a decay into two final state particles, i.e. $B_d \rightarrow \pi^+\pi^-$ and a decay into four particles, i.e. $B_s \rightarrow D_s^+K^-$ followed by $D_s^+ \rightarrow K^+K^-\pi^\pm$.

#### 1.4.1 $B_d \rightarrow \pi^+\pi^-$

The decay $B_d \rightarrow \pi^+\pi^-$ is interesting because the final state is a $CP$ eigenstate. The decay rate asymmetries $A_f(t)$ and $A_{\bar{f}}(t)$ in equation 1.19 are therefore $CP$ asymmetries. Assuming the $\bar{b} \rightarrow \bar{u} + W(ud)$ tree diagram in figure 1.3 (left) is the dominant Feynman

\(^3\)This is expected to be a very good approximation for neutral $B$ mesons.
Figure 1.3: The tree(left) and penguin(right) Feynman diagrams for the decay $B_d \rightarrow \pi^+\pi^-$. The index $i$ represents one of the up-type quarks $u, c, t$.

diagram contributing to this decay and using $\lambda = |\lambda|e^{i\phi}$ it can be shown that $\phi = 2\alpha$ and hence $\text{Im}(\lambda) = \sin 2\alpha$. Therefore (using equation 1.20), the CP asymmetry is given by:

$$A_{\pi\pi} = -\sin 2\alpha \sin \Delta mt$$  \hspace{1cm} (1.21)

This channel can thus be used to measure the angle $\alpha$ of the unitarity triangle.$^4$

The $B_d$ meson has an average lifetime of $1.56 \times 10^{-12}$ s. It will travel on average about one cm (seen from the LHCb lab-frame) before it decays (see figure 1.4). The decay is therefore characterised by a displaced vertex made up by two oppositely charged tracks (pions). The resulting momentum vector points to the primary vertex. The existence of a $B$ meson decay vertex a few mm apart from the primary interaction vertex is a general characteristic of $B$ events. The LHCb experiment relies on the existence of these secondary vertices to trigger on $B$ events (see trigger section 2.4).

1.4.2 $B_s \rightarrow D_s^\pm K^\mp$

Another relevant channel is the decay of a $B_s$ meson into a $D_s$ meson and a kaon. Both decays $B_s \rightarrow D_s^- K^+$ and that of $B_s \rightarrow D_s^+ K^-$ are possible. The leading order Feynman diagram for the channel $B_s \rightarrow D_s^- K^+$ is indicated in the left plot of figure 1.5. The decay is determined by the $\bar{b} \rightarrow \bar{c} + W(us)$ transition. The channel $B_s \rightarrow D_s^+ K^-$ proceeds through the right diagram in figure 1.5, i.e. via a $\bar{b} \rightarrow \bar{u} + W(cs)$ transition. The conjugate diagrams hold for the decay of the $B_s$.

The rate asymmetries $A_{D_s^- K^+}(t)$ and $A_{D_s^+ K^-}(t)$ are expected to be large. From these

$^4$In case the penguin diagram of figure 1.3 (right) contributes significantly (which seems to be the case[24]) the approximation leading to equation 1.20 does not hold. It can be shown that the CP asymmetry is then given by:

$$A_{\pi\pi} = a \cos \Delta mt + b \sin \Delta mt$$  \hspace{1cm} (1.22)

where $a$ and $b$ depend on the ratio of the contribution of the penguin and tree diagrams and on the strong phase difference between these diagrams[7].
1.4. $B$ decays in LHCb

**Figure 1.4:** The simulated decay length of the $B_d$ meson in $B_d \rightarrow \pi^+\pi^-$ events.

**Figure 1.5:** Feynman diagrams of the decay of a $B_s$ into a $D_s^-K^+$ and into a $D_s^+K^-$ pair.
rate asymmetries $|\lambda|$ and $\phi$ can be extracted. It can be shown\cite{ref7} that:

$$\phi = \arg \lambda = -\gamma' + \Delta$$

$$\bar{\phi} = \arg \bar{\lambda} = \gamma' + \Delta$$,

(1.23)

where the weak angle $\gamma' = \gamma - 2\delta \gamma$. The angle $\delta \gamma$ is a small phase in the $B_s$ mixing and $\gamma$ is defined in equation 1.7. $\Delta$ is the strong-phase difference between the $b \to c + W(\bar{u}s)$ and $b \to u + W(\bar{c}s)$ transition diagrams. By measuring both time dependent decay asymmetries the angle $\gamma'$ can thus be extracted.

$B_s$ mesons have an average lifetime of $1.6 \times 10^{-12}$ s, and will, similarly to $B_d$, travel in the LHCb lab-frame typically 1 cm. The $D_s$ has a lifetime ($0.46 \times 10^{-12}$ s) and will travel a few mm. In this thesis the decay of the $D_s$ into $KK\pi$ is discussed\footnote{The branching ratio for the $D_s$ decay into these particles is about 5 %. Most other decays can not be fully reconstructed because they contain neutrinos and neutral particles.}. The decay is kinematically characterised by two oppositely charged kaons with an additional pion forming a vertex displaced from the primary vertex. The resulting momentum vector points to the $B_s$ decay vertex, which is made of this $D_s$ together with an additional kaon (see figure 1.6).

### 1.5 $B$ meson production

The calculation of the $B$ meson production cross sections in proton-proton collisions at the LHC are complicated due to non perturbative QCD effects as well as the fact that protons are composite particles. Heavy flavour production in a hadron collider is
usually described by splitting the interaction in a hard (high momentum transfer) part and in a soft part. The hard part describes the strong interaction of constituent partons forming heavy flavour quarks in terms of elementary processes such as the diagrams shown in figure 1.7. Calculations of the cross section for heavy flavour production have been performed to next-to-leading order precision (see e.g. [8] and references therein). The calculations are quantitatively in good agreement with experimental data for $t$ quarks. However, for the lighter $b$ quarks large discrepancies between calculations and measurements are observed. Large uncertainties exist due to higher order effects. As in reference[7] it is assumed that the cross section for inelastic proton-proton collisions is 80 mb, the $b\bar{b}$ cross section is taken to be 0.5 mb.

In the strong interaction $b$ quarks will always be produced in $b\bar{b}$—pairs. Figure 1.8 shows the relation between the polar angle (i.e. the angle with respect to the beam axis) of a $B$ meson and $\bar{B}$ meson produced in the same $B$ event as obtained with the event generator PYTHIA[25]. The figure shows that the polar angle of the $b$ quark and that of the $\bar{b}$ quark have a strong positive correlation. In addition, the figure shows that the $B$ meson production is peaked at small ($\sim O$ rad) and high($\sim \pi$ rad) $\theta$, i.e. along the beam. The fact that both $B$ mesons are produced in the same forward region has led to the single arm forward geometry of the LHCb detector (see section 2.2). As can be seen from figure 1.9 the LHCb angular acceptance of 10 mrad to 250 mrad covers a large fraction of the phase-space of produced $B$ mesons.

In LHCb we are interested in studying specific $B$ meson decays and hence in the efficient reconstruction of the stable decay products of these mesons. In addition to the $B$ mesons many other particles are produced in the proton-proton collision. The tracks from the underlying event, i.e. all produced particles not directly associated with the $B$, need in principle$^6$ not to be reconstructed. Figure 1.10 shows the primary charged particle multiplicity within the LHCb acceptance for $B \rightarrow \pi^+\pi^-$ events. In addition, the figure shows the primary particle multiplicity for minimum bias$^7$ inelastic interactions.

$^6$The current RICH (global) pattern recognition algorithm assumes most particles traversing the detector volume to be efficiently reconstructed.

$^7$A minimum bias event is an event obtained with a random trigger, i.e. no selection(bias) on the type of interaction is applied.
**Figure 1.8:** Simulated correlation between the polar angle $\theta$ of a $B$ meson and of a $B$ meson simultaneously produced in a single event.

**Figure 1.9:** Simulated pseudo-rapidity distribution ($\eta = -\log(\tan(\theta/2))$) for $B$ mesons produced at the LHC. The lines indicate the LHCb detector geometrical acceptance.
1.5. $B$ meson production

Figure 1.10: The simulated primary charged particle multiplicity in the LHCb geometric acceptance for $B \rightarrow \pi^+\pi^-$ events and inelastic interactions.

These distributions show that the particle multiplicities for $B$ events are expected to be higher than for minimum bias inelastic interactions.