Characterization of Silica Aerogel for the LHCb RICH Detector and Measurement of the Oscillation Parameter $\Delta m_s$

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Se si riuscisse a trovare un altro modo più conforme alle regole del gioco, sarebbe molto bello...

Ma intanto ti ho fregato!!!
LHCb is the Large Hadron Collider experiment dedicated to precise measurements of CP violation and rare decays in the $B$ meson sector. It is presently under construction at CERN, and it will start operations in 2007.

In the Standard Model picture, CP violation naturally arises by the complex phase in the unitary $3 \times 3$ Cabibbo–Kobayashi–Maskawa (CKM) matrix which accounts for the quark mixing. Thanks both to the high $b\bar{b}$ cross section and to the high luminosity, the LHC collider will be by far the most copious source of $B$ mesons. A large amount of data will be available and the consistency of the Standard Model will be definitively tested by measuring in several ways all the angles and all the sides of the Unitarity Triangle. These measurements will over-constrain the model and look for inconsistencies due to New Physics.

The design of the detector has been optimized to match the kinematical structure of $b\bar{b}$ events produced in a proton–proton collision. One of the key aspects of LHCb is the identification of the particles produced in $b$–hadron decays. This tool is used to enhance the signal to background ratio in the selection channels and to provide an efficient kaon tag; it will be achieved using Ring Imaging CHerenkov (RICH) detectors. In particular, LHCb will use two RICH detectors, one covering the charged particle momentum range $1 - 65$ GeV/$c$ using both solid silica aerogel and gaseous $C_4F_{10}$ radiators, and the other covering up to 100 GeV/$c$ using gaseous $CF_4$. Pixel Hybrid Photon Detectors (HPDs) have been developed to detect Cherenkov light in the wavelength range $200 - 600$ nm.

The thesis is structured into six chapters:

**Chapter 1** is a general introduction to the “CP violation” problem and to the “Beauty Physics”. The experimental status of the CKM matrix will be given;

**Chapter 2** describes the Large Hadron Collider machine and the general lay–out of the LHCb experiment;

**Chapter 3** is devoted to RICH detectors. Some basic operating principles are given and the experimental challenges together with the factors limiting the particle identification power are discussed. In the second part of the chapter, the design and the performances of the LHCb RICH detectors will be presented;
Chapter 4 introduces solid silica aerogel. This chapter describes the characterization of the optical properties of silica aerogel and all the tests performed during the R&D activity. Results of these tests are discussed;

Chapter 5 shows a possible approach to extract the unmeasured oscillation frequency $\Delta m_s$ from fully reconstructed $B^0_s \rightarrow D^-\pi^+$ events. The measurement of this parameter is part of the wide physics program of the LHCb collaboration. In the Standard Model picture, the value of $\Delta m_s$ is expected to be $\sim 20\,\text{ps}^{-1}$, and its measurement is quite challenging. Deviation from the expected value would suggest New Physics beyond the Standard Model;

Chapter 6 presents the Level–0 Muon Trigger. A fast and efficient trigger system is required by the detector to reduce the large amounts of uninteresting processes, such as minimum bias events. Muons with high transverse momentum $p_T$ will be used by the trigger system. An introduction to the stand–alone application currently used to optimize and to test the performances of the Level–0 Muon Trigger will be given.
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Chapter 1

Beauty physics and CP violation

The Standard Model of electroweak and strong interactions has been deeply experimentally tested to be the most successful description of all observed phenomena in particle physics up to the energies presently explored. There are several reasons to consider it as an effective low–energy model of a more fundamental theory like the “Grand Unified Theory”, but up to now no experimental evidence of physics beyond the Standard Model has been found.

The violation of the CP symmetry is one of the most interesting topics in high energy particle physics. This chapter presents the introductory theoretical issues about CP violation and Beauty Physics in order to understand the design of a $B$ physics dedicated experiment as LHCb.

1.1 Matter–antimatter asymmetry

There is experimental evidence that the universe is composed of matter particles (protons, neutrons and electrons) rather than their antimatter partners (antiprotons, antineutrons and positrons). If the moon were composed of antimatter, then lunar probes and astronauts would have vanished in a fireball of energy as soon as they touched the lunar surface. The solar wind and cosmic rays do not destroy us, implying that the sun and the Milky Way are also made of matter.

The existence (or absence) of antimatter nuclei in space is closely connected with the foundation of the theories of elementary particle physics. Up to the scale currently accessible, experiments have shown that the abundance of baryons in the universe is at least six orders of magnitude higher than that of antibaryons [1]. The Big Bang should have created equal amounts of matter and antimatter. The Cosmic Microwave Background (CMB) radiation shows that in the early days of the cosmos particles and antiparticles were populating it on equal basis. On one side particles and antiparticles were continuously annihilating each other, while on the other the abundance of high energy photons was keeping on creating them. The expansion and the consequent cooling down of the universe made the high
energy photons rarer and rarer, the annihilation process was no longer balanced by pair creation. Since then all antibaryons disappeared, while one baryon in ten billions survived building the universe.

In 1967 A. D. Sakharov outlined three conditions for the matter–antimatter imbalance to arise: the first one concerned the proton decay (baryon number non–conservation), the second one was related to the cooling rate of the universe (lack of thermal equilibrium), and the third one predicted a measurable difference between matter and antimatter due to CP violation during the baryogenesis \[2\] \[3\]. Although the Standard Model incorporates CP violation, its level is too small to explain the observed asymmetry \[4\].

### 1.2 CP violation

Symmetries and conservation laws are a constant theme in particle physics. Two kinds of symmetry operations exist, continuous or discrete. Rotations, space or time translations are examples of continuous symmetries and are associated to angular momentum, linear momentum and energy conservation laws respectively.

Charge conjugation (C), parity (P) and time reversal (T) are three discrete symmetries important in the field of particle physics. The parity operator performs a space inversion reversing the handedness; it reverses the momentum of a particle, but it does not change its angular momentum nor its spin, transforming a left–handed particle into a right–handed one. Time reversal interchanges the forward and backward light cones. The charge conjugation operator interchanges a particle with its antiparticle without affecting its spin nor its momentum.

Experiments showed that fundamental interactions are not invariant under C, P and T transformations and neither under any pair of them as CP, PT or CT in any order. However, the CPT combination is an exact symmetry in any local field theory and its universal invariance has been mathematically demonstrated in a theorem by R. Jost and up to date it has passed all verification tests \[5\]. It has been observed that electromagnetic and strong interactions are invariant under C, P and T transformations. The weak interaction violates C and P separately, but it preserves CP and T to a good approximation. Only certain rare processes have been observed to exhibit CP violation.

In 1957 it was discovered that $\beta$–decay of $^{60}$Co nuclei violated the parity transformation P \[6\]; subsequently it was shown how the production of neutrinos is also a parity violating process. At that time, although parity was accepted to be violated, the combination CP was considered as a universal invariance. This perception changed in 1964. J. W. Cronin, V. L. Fitch and collaborators discovered that CP symmetry is violated by neutral $K$ meson rare decays \[7\]. In 1980 J. W. Cronin and V. L. Fitch were jointly awarded the Nobel Prize in Physics “for the discovery of violations of fundamental symmetry principles in the decay of neutral $K$ mesons” \[8\].
Since its discovery, CP violation has been deeply studied for many years in the $K$ meson sector. Recently, the BaBar and BELLE experiments observed CP violation also in $B$ meson decays \[9, 10\]. Other results are expected in the next years. The study of $B$ meson physics becomes the ideal tool to further confirm the Standard Model and search for hints of New Physics. Last but not least, it might explain the unanswered matter–antimatter asymmetry.

### 1.3 The Standard Model

The Standard Model with three quark families naturally allows for CP violation in weak interaction. Flavour changing processes between quarks are due only to charged current interactions with couplings given by a mixing matrix. In 1963 N. Cabibbo introduced a mixing angle between $d$ and $s$ quarks to save universality in some hadronic weak decays \[11\]. In 1973, one year before the $c$ quark discovery, M. Kobayashi and T. Maskawa proposed a model for the quark mixing assuming three generations of quarks \[12\].

The Lagrangian function of charged current weak interaction, which describes the transitions between different quark flavours, is:

$$
\mathcal{L}_{W^\pm} = G_F \left( \bar{u} \gamma^\mu (1 - \gamma^5) \bar{t} \right) \gamma^\mu \left( \begin{array}{c} d \\ s \\ b \end{array} \right) W^\mu + h.c.
$$

(1.1)

where $\gamma^\mu$ are the Dirac matrices, $(1 - \gamma^5)$ the operator projecting all states to their left–handed component and $W^\mu$ the $W$–boson exchange operator. The $(u, c, t)$ and $(d, s, b)$ states represent the mass eigenstates of quarks.

The unitary $3 \times 3$ Cabibbo–Kobayashi–Maskawa (CKM) matrix\[ connects the weak eigenstates (primed) to the corresponding mass eigenstates (unprimed):

$$
\left( \begin{array}{c} d' \\ s' \\ b' \end{array} \right) = \hat{V} \left( \begin{array}{c} d \\ s \\ b \end{array} \right) = \left( \begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{array} \right) \left( \begin{array}{c} d \\ s \\ b \end{array} \right)
$$

(1.2)

\[1\]Universality of the weak interactions, which is required in a gauge theory such as the Standard Model, requires the mixing matrix to be unitary. Unitarity of the CKM matrix assures the absence of flavour changing neutral current transitions at the tree level. This means that the elementary vertices involving neutral gauge bosons and the neutral Higgs boson are flavour conserving. This property is known under the name of Glashow–Iliopoulos–Maiani (GIM) mechanism.
In general, the $V_{ij}$'s are complex numbers. A unitary $n \times n$ matrix can be parameterized by $n^2$ independent real quantities ($2n^2$ real parameters minus $n^2$ unitarity conditions). Of these, $n(n-1)/2$ are the Euler angles associated with rotations in a $n$–dimensional space. The remaining $n(n+1)/2$ are called phases, not all of which have physical meaning as some may be removed by a new definition of the quark fields forming the basis of the matrix representation. Of these $2n$ field phases ($n$ from the up–type quarks and another $n$ from the down–type quarks), $(2n-1)$ are arbitrary. Thus, the number of measurable phases in the CKM matrix is $(n-1)(n-2)/2$. In the Standard Model with $n = 3$ quark families, the $V$ matrix has three angles and one phase. This phase introduces CP violation in the Standard Model. No CP violation is expected if only two generations of quarks are considered.

1.3.1 Parameterization of the CKM matrix

Several parameterizations of the CKM matrix are available in the literature. All of them are based on its unitarity. The first parameterization of the CKM matrix was put forward by M. Kobayashi and T. Maskawa \cite{12}. L. L. Chau and W. Y. Keung have introduced a different parameterization \cite{13}. With $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$ ($i, j = 1, 2, 3$), the standard parameterization is given by:

\[
\hat{V} = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\] (1.3)

where $\delta$ is the phase necessary for CP violation; both $c_{ij}$ and $s_{ij}$ can be chosen to be positive and $\delta$ may vary in the range $(0, 2\pi)$. From measurements of CP violation in the $K$ sector, $\delta$ is forced to be in the range $(0, \pi)$.

Dedicated phenomenological studies indicate that $s_{13}$ and $s_{23}$ are small numbers, $O(10^{-3})$ and $O(10^{-2})$ respectively; to a good accuracy, the four independent parameters can be chosen as:

\[
s_{12} = |V_{us}|, \quad s_{13} = |V_{ub}|, \quad s_{23} = |V_{cb}|, \quad \delta
\] (1.4)

The first three parameters can be extracted from tree level decays mediated by the transitions $s \rightarrow u$, $b \rightarrow u$ and $b \rightarrow c$, respectively. The phase $\delta$ can be extracted from CP violating transitions or loop processes sensitive to $|V_{td}|$.

Experimentally a hierarchical pattern of the absolute values of the elements of the matrix has been found, the diagonal elements being close to unity, the elements $|V_{us}|$ and $|V_{cd}|$ being of the order of $0.2$, the elements $|V_{cb}|$ and $|V_{ts}|$ of the order of $4 \times 10^{-2}$, whereas $|V_{ub}|$ and $|V_{td}|$ are of the order $5 \times 10^{-3}$ \cite{14}. In 1983
it was realized that the bottom quark decays predominantly to the charm quark ($|V_{cb}| \gg |V_{ub}|$). L. Wolfenstein introduced a new parameterization which enhances the measured hierarchy of those elements, even if it is only an approximation of the CKM matrix \[15\]. His parameterization has become very popular. Each element is expanded as a power series in the small parameter $\lambda = |V_{us}| \approx 0.22$:

$$
\hat{V} = \left( \begin{array}{ccc}
1 - \frac{1}{2} \lambda^2 & \lambda & A \lambda^3 (\rho - i \eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\
A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{array} \right) + \mathcal{O}(\lambda^4) \quad (1.5)
$$

and the set of parameters in Eq. \[1.4\] are replaced by the new ones:

$$
\lambda, \ A, \ \rho, \ \eta \quad (1.6)
$$

Thanks to the smallness of $\lambda$ and to the fact that for each element the power expansion parameter is actually $\lambda^2$, Eq. \[1.5\] is a good approximation of the standard parameterization Eq. \[1.3\].

The Wolfenstein parameterization is more transparent than the standard one. If a highest level of accuracy is required, the terms $\mathcal{O}(\lambda^4)$ and $\mathcal{O}(\lambda^5)$ must be included. This can be done in several ways, because the exact definition of the parameters in Eq. \[1.6\] is not unique in terms of the neglected order $\mathcal{O}(\lambda^4)$. A useful definition worldwide adopted defines the Wolfenstein parameters through:

$$
s_{12} = \lambda, \ s_{23} = A \lambda^2, \ s_{13} e^{-i \delta} = A \lambda^3 (\rho - i \eta) \quad (1.7)
$$

to all orders in $\lambda$. It follows that:

$$
\rho = \frac{s_{13}}{s_{12} s_{23}} \cos \delta, \quad \eta = \frac{s_{13}}{s_{12} s_{23}} \sin \delta \quad (1.8)
$$

The change of variables shown in Eq. \[1.7, 1.8\] guarantees a perfect correspondence between the standard and the Wolfenstein parameterizations, and also that the latter satisfies unitarity exactly. Expanding each element in powers of $\lambda$, the matrix in Eq. \[1.5\] is recovered and in addition explicit corrections of $\mathcal{O}(\lambda^4)$ and higher order terms are found:
\[ V_{ud} = 1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 + \mathcal{O} (\lambda^6) \]
\[ V_{us} = \lambda + \mathcal{O} (\lambda^7) \]
\[ V_{ub} = A \lambda^3 (\rho - i \eta) \] (1.9)

\[ V_{cd} = -\lambda + \frac{1}{2} A^2 \lambda^5 [1 - 2 (\rho + i \eta)] + \mathcal{O} (\lambda^7) \]
\[ V_{cs} = 1 - \frac{1}{2} \lambda^2 - \frac{1}{8} \lambda^4 (1 + 4A^2) + \mathcal{O} (\lambda^6) \]
\[ V_{cb} = A \lambda^2 + \mathcal{O} (\lambda^8) \] (1.10)

\[ V_{td} = A \lambda^3 (1 - \overline{\rho} - i \overline{\eta}) + \mathcal{O} (\lambda^7) \]
\[ V_{ts} = -A \lambda^2 + \frac{1}{2} A^4 \lambda^4 [1 - 2 (\rho + i \eta)] + \mathcal{O} (\lambda^6) \]
\[ V_{tb} = 1 - \frac{1}{2} A^2 \lambda^4 + \mathcal{O} (\lambda^6) \] (1.11)

where:

\[ \overline{\rho} = \rho \left( 1 - \frac{1}{2} \lambda^2 \right), \quad \overline{\eta} = \eta \left( 1 - \frac{1}{2} \lambda^2 \right) \] (1.12)

By definition the expression of \( V_{ub} \) is unchanged relative to the original Wolfenstein parameterization and the corrections to \( V_{us} \) and \( V_{cb} \) appear only at \( \mathcal{O} (\lambda^7) \) and \( \mathcal{O} (\lambda^8) \) respectively. The advantage of this generalization is the absence of relevant corrections to \( V_{us}, V_{cd} \) and \( V_{ub} \); the elegant change in \( V_{td} \) allows a simple generalization of the Unitarity Triangle to higher orders in \( \lambda \).

The Standard Model prediction of the CKM matrix unitarity must be experimentally tested. Non-fulfilment of the unitarity constraints would signal New Physics beyond the Standard Model.

### 1.3.2 The Unitarity Triangle

The unitarity of the CKM matrix allows to construct six orthogonality relationships. The orthogonality condition between the first and the third columns of the \( \hat{V} \) matrix:

\[ \sum_{i=1}^{3} V_{ui} V_{uj}^{\ast} = 1 
\]
The Standard Model

1.3 The Standard Model

\[ \eta \pm \rho \equiv (\rho, \eta) \]
\[ B \equiv (1, 0) \]
\[ C \equiv (0, 0) \]

Since its sides have been normalized by \(|V_{cd}V_{cb}^*|\), this is also the so-called Unitarity Triangle.

Figure 1.1: Representation of Eq. (1.13) as a triangle in the \((\rho, \eta)\) complex plane. Since its sides have been normalized by \(|V_{cd}V_{cb}^*|\), this is also the so-called Unitarity Triangle.

\[
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
\]

is very interesting because it involves simultaneously the elements \(V_{ub}, V_{cb}\) and \(V_{td}\) which are under extensive discussion at present.

All the six orthogonality relations can be represented in the \((\rho, \eta)\) complex plane as triangles, but the one usually considered is the relation in Eq. (1.13) because its angles are all relatively large. This is referred to as the “Unitarity Triangle”; the other five triangles should be useful when data on rare and CP violating decays improve. All the triangles have equal area \(A\) related to the measure of the strength of CP violation, well described by the Jarlskog parameter \(|J_{CP}| = 2A|\).

Thanks to the invariance of Eq. (1.13) under any transformation of phases, the corresponding triangle is rotated in the \((\rho, \eta)\) plane under such transformations. Since angles and sides do not change, they are phase independent and physical observables, so they can be directly measured in suitable experiments.

The construction of the Unitarity Triangle proceeds as follows: to an excellent degree of accuracy the term \(V_{cd}V_{cb}^*\) is real with \(|V_{cd}V_{cb}^*| = A\lambda^3 + O(\lambda^7)\). Keeping all the \(O(\lambda^5)\) corrections and normalizing to unity the \(V_{cd}V_{cb}^*\) side, Eq. (1.13) can be represented as the triangle shown in Fig. (1.1) in the \((\rho, \eta)\) plane.

The useful formulæ related to this triangle are summarized in the following:

– the quantities \(\sin(2\alpha), \sin(2\beta)\) and \(\sin(2\gamma)\) can be expressed as a function of the complex variables \((\rho, \eta)\):
\[
\sin(2\alpha) = \frac{2\eta (\eta^2 + \rho^2 - \bar{\rho})}{(\bar{\rho}^2 + \eta^2) \left[(1 - \bar{\rho})^2 + \eta^2\right]} \tag{1.14}
\]

\[
\sin(2\beta) = \frac{2\eta (1 - \bar{\rho})}{(1 - \bar{\rho})^2 + \eta^2} \tag{1.15}
\]

\[
\sin(2\gamma) = \frac{2\rho\eta}{\rho^2 + \eta^2} \tag{1.16}
\]

– the two sides $\overline{CA}$ and $\overline{BA}$ are usually denoted by $R_b$ and $R_t$ respectively and are given by:

\[
R_b = \frac{|V_{cd}V_{ub}^*|}{|V_{cd}V_{cb}^*|} = \sqrt{\rho^2 + \eta^2} = \left(1 - \frac{1}{2}\lambda^2\right) \frac{1}{\lambda} |V_{ub}| |V_{cb}|\]

\[
R_t = \frac{|V_{td}V_{tb}^*|}{|V_{cd}V_{cb}^*|} = \sqrt{(1 - \rho)^2 + \eta^2} = \frac{1}{\lambda} |V_{td}| |V_{cb}| \tag{1.17}
\]

– the angle $\beta$ and $\gamma = \delta$ are directly related to the complex phases of the CKM matrix elements $V_{td}$ and $V_{ub}$ respectively, through:

\[
V_{td} = |V_{td}|e^{-i\beta}, \quad V_{ub} = |V_{ub}|e^{-i\gamma} \tag{1.18}
\]

– the unitarity relation Eq. (1.13) can be written as:

\[
R_b e^{i\gamma} + R_t e^{-i\beta} = 1 \tag{1.19}
\]

– the angle $\alpha$ can be extracted through the relation:

\[
\alpha + \beta + \gamma = \pi \mod 2\pi \tag{1.20}
\]

It can be demonstrated that Eq. (1.20) holds even if Eq. (1.13) is not valid. In this case there would be deviations from $3 \times 3$ unitarity of the CKM matrix and the Unitarity Triangle is not closed [17].
Eq. (1.19) clearly shows that the knowledge of \((R_t, \beta)\) allows to determine \((R_b, \gamma)\) through:

\[
R_b = \sqrt{1 + R_t^2 - 2R_t \cos \beta}, \quad \cot \gamma = \frac{1 - R_t \cos \beta}{R_t \sin \beta}
\] (1.21)

and similarly \((R_t, \beta)\) can be expressed through \((R_b, \gamma)\):

\[
R_t = \sqrt{1 + R_b^2 - 2R_b \cos \gamma}, \quad \cot \beta = \frac{1 - R_b \cos \gamma}{R_b \sin \gamma}
\] (1.22)

The triangle shown in Fig. (1.1), \(|V_{us}|\) and \(|V_{cb}|\) give the full description of the CKM matrix. Looking at the expressions for \(R_b\) and \(R_t\), within the Standard Model the measurements of four CP conserving decays sensitive to \(|V_{us}|, |V_{ub}|, |V_{cb}|\) and \(|V_{td}|\) can tell whether CP violation \((\eta \neq 0 \text{ or } \gamma \neq 0, \pi)\) is correctly predicted in the Standard Model itself.

While the \(\lambda\) and \(A\) variables of the Wolfenstein parameterization are relatively well known, the parameters \(\rho\) and \(\eta\) or equivalently the angles \(\alpha, \beta,\) and \(\gamma\) are much more uncertain. The main goal of the next CP violation experiments is to over-constrain these parameters and, possibly, to find inconsistencies suggesting the existence of New Physics beyond the Standard Model.

### 1.4 Experimental status of the CKM matrix

During the last two decades several strategies have been proposed to determine the CKM matrix and the related Unitarity Triangle. The LEP and SLD era of precision electroweak physics has left a legacy of beautiful measurements that strongly constrain extensions of the Standard Model \[18\]. On the other hand \(B\) factories have thoroughly developed the study of precision \(b\) physics and, after the great achievement of the \(A_{CP} (B^0_d \rightarrow J/\Psi K^0_s)\) measurement, a new era has started with many analyses aimed at constraining angles and sides of the Unitarity Triangle in several processes.

The standard analysis relies on the following measurements: \(|V_{ub}|/|V_{cb}|\), \(\Delta m_d\), the lower limit of \(\Delta m_s\) and the measurements of a pair of CP violating quantities, \(\epsilon_K\) and \(\sin (2\beta)\). These five measurements restrict, at present, the possible range of variation of the \(\rho\) and \(\eta\) parameters:

- \(B\) hadrons can decay through the \(b \rightarrow c\) and \(b \rightarrow u\) transitions. Semileptonic decays have a relatively large branching fraction \((\sim 10\%)\) and the corresponding measurements can be interpreted using a well established theoretical framework. The relative charmless to charmed \(b\)-hadron semileptonic decay rate is proportional to the square of the ratio:
\[ \left| \frac{V_{ub}}{V_{cb}} \right| = \frac{\lambda}{1 - \lambda^2/2} \sqrt{\bar{\rho}^2 + \eta^2} \]  

(1.23)

allowing the measurement of the length of the $\overline{CA}$ side of the Unitarity Triangle.

- $B_d^0 - \overline{B_d^0}$ oscillations occur, in the Standard Model, through a second order process (box diagram) with a loop containing $W^\pm$ bosons and up–type quarks. The top quark exchanging box diagram is the dominant one. The time oscillation frequency $\Delta m_d$ is expressed, in the Standard Model, as:

\[ \Delta m_d \propto A^2 \lambda^6 \left[ (1 - \bar{\rho})^2 + \eta^2 \right] \]  

(1.24)

The measurement of $\Delta m_d$ gives a constraint on the length of the $\overline{BA}$ side.

- the $B_s^0 - \overline{B_s^0}$ time oscillation frequency is proportional to the square of $|V_{ts}|$ element. The measurement of $\Delta m_s$ would give a strong constraint on some non–perturbative QCD quantities in the relation linking $\Delta m_s$ to the $\bar{\rho}$ and $\eta$ parameters. In any case, the ratio between the values of the mass difference between the mass eigenstates measured in the $B_d^0$ and in the $B_s^0$ systems can be used:

\[ \frac{\Delta m_d}{\Delta m_s} \propto \left( \frac{\lambda}{1 - \lambda^2/2} \right)^2 \cdot \frac{(1 - \bar{\rho})^2 + \eta^2}{\left(1 + \frac{\lambda^2}{1 - \lambda^2/2} \bar{\rho} \right)^2 + \lambda^4 \eta^2} \]  

(1.25)

The measurement of the ratio $\Delta m_d/\Delta m_s$ also constrains the length of the $\overline{BA}$ side of the Unitarity Triangle.

- indirect CP violation in the $K^0 - \overline{K^0}$ system is usually expressed in terms of the $\epsilon_K$ parameter, which is the fraction of the CP violating component in the mass eigenstates. The constraint brought by the measurement of $\epsilon_K$ corresponds to an hyperbola in the $(\bar{\rho}, \eta)$ plane.

- the mixing induced CP asymmetry in $B_d^0 \to J/\Psi K^0_s$ decays allows to determine the angle $\beta$ of the Unitarity Triangle essentially without any hadronic uncertainties. A possible manifestation of the CP asymmetry could appear in the interference between amplitudes describing decays with and without mixing. The process $B_d^0 \to J/\Psi K^0_s$ is dominated by a tree diagram and the asymmetry:
Figure 1.2: Allowed regions for $\rho$ and $\eta$. The closed contours at 68% and 95% probability are shown. The full lines correspond to 95% probability regions for the constraints, given by the measurements of $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $\epsilon_K$, $\sin(2\beta)$, $\gamma$ and $\alpha$. The dotted curve corresponds to the 95% upper limit obtained from the experimental study of $B^0_s - \bar{B}^0_s$ oscillations [19, 20].

\[ A_{CP} (B^0_d \rightarrow J/\Psi K^0_s) = -2\sin(2\beta) \sin(\Delta m_d) \Delta t \quad (1.26) \]

gives a constraint on $\sin(2\beta)$ in the complex plane.

The standard fit of the above measurements gives a clear picture of the success of the Standard Model; a crucial test of the model itself in the quark sector consists in establishing CP violation by using sides of the Unitarity Triangle. This is achieved by measuring CP conserving processes such as semileptonic $B$ decays and $B^0_q - \bar{B}^0_q$ oscillations ($q = d, s$). The comparison of the region selected by these constraints and the one selected by direct measurements of CP violating quantities $\epsilon_K$ and $\sin(2\beta)$ gives an additional picture of the success of the Standard Model in flavour physics.

Thanks to the huge statistics collected at the $B$ factories, new CP violating parameters have been recently determined allowing for the direct determination of the angles $\alpha$, $\gamma$, $(2\beta + \gamma)$ and $\cos(2\beta)$. Results from these new constraints on the Unitarity Triangle can improve the standard analysis; Tab. 1.1 lists a summary of all the parameters; Fig. 1.2 shows the corresponding allowed regions in the $(\rho, \eta)$ plane [19, 20].
Table 1.1: Values and probability ranges for the Unitarity Triangle parameters obtained from the fit using all the available constraints: $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $\epsilon_K$, $\sin(2\beta)$, $\gamma$, $\alpha$ and $\cos(2\beta)$ [19, 20].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>68%</th>
<th>95%</th>
<th>99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>$0.216 \pm 0.036$</td>
<td>$(0.143, 0.288)$</td>
<td>$(0.118, 0.309)$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$0.342 \pm 0.022$</td>
<td>$(0.300, 0.385)$</td>
<td>$(0.286, 0.398)$</td>
</tr>
<tr>
<td>$\alpha$ [^{\circ}]</td>
<td>$98.5 \pm 5.7$</td>
<td>$(87.1, 109.8)$</td>
<td>$(83.5, 113.3)$</td>
</tr>
<tr>
<td>$\beta$ [^{\circ}]</td>
<td>$23.8 \pm 1.5$</td>
<td>$(21.3, 26.2)$</td>
<td>$(20.8, 27.1)$</td>
</tr>
<tr>
<td>$\gamma$ [^{\circ}]</td>
<td>$57.6 \pm 5.5$</td>
<td>$(46.8, 68.7)$</td>
<td>$(43.5, 72.4)$</td>
</tr>
<tr>
<td>$\sin 2\alpha$</td>
<td>$-0.29 \pm 0.19$</td>
<td>$(-0.64, 0.09)$</td>
<td>$(-0.73, 0.22)$</td>
</tr>
<tr>
<td>$\sin 2\beta$</td>
<td>$0.735 \pm 0.024$</td>
<td>$(0.688, 0.781)$</td>
<td>$(0.673, 0.794)$</td>
</tr>
<tr>
<td>$\sin (2\beta + \gamma)$</td>
<td>$0.959 \pm 0.028$</td>
<td>$(0.890, 0.996)$</td>
<td>$(0.859, 0.998)$</td>
</tr>
</tbody>
</table>

1.5 The future of the CKM matrix

The Standard Model picture of quark mixing survived the first major test: the constraints from the lengths of the sides and those from $\sin(2\beta)$ and $\epsilon_K$ point to the same region of the apex of the Unitarity Triangle. Now the task is to look for corrections to the standard picture. This can be achieved studying in more detail the $B$ meson system where there are many decays modes available.

At present time, the experimental challenge is dominated by the BaBar and BELLE experiments which are collecting data at $e^+e^-$ colliders [9, 10]. Following the cancellation of BTeV and the foreseen closure of BaBar, LHCb may become the only running $B$ physics experiment (unless SUPER–BELLE is approved) [21, 22]. Advantages of a hadron collider environment like LHC include the availability of $B_s^0$ mesons and huge $b\bar{b}$ cross section; from the enormous amount of data, several precision measurements will be done to extract the angles of the Unitarity Triangle in order to test the consistency of the Standard Model.
Chapter 2

The LHCb experiment

The frontier research in high energy particle physics requires large centre of mass energies and high luminosities. Both features will be met by the Large Hadron Collider (LHC) under construction at CERN. LHC will be a copious source of $b$–hadrons, and it will be the optimal environment to host LHCb, the Large Hadron Collider Beauty experiment dedicated to precise measurements of CP violation phenomena and to study rare decays.

In this chapter the LHC machine, its main experimental challenges and the LHCb experiment are briefly presented.

2.1 The Large Hadron Collider

The CERN Large Hadron Collider, LHC, is presently under construction and will start operating in 2007 [23]. This machine is being installed in the already existing LEP tunnel and will provide proton–proton ($pp$) and heavy ion (up to Pb–Pb) collisions. A $pp$ collider is adopted instead of an electron–positron ($e^+e^-$) circular machine in order to limit the synchrotron radiation, and therefore to accelerate particles to a larger energy

1 The choice of a $pp$ instead of a proton–antiproton ($p\bar{p}$) collider is motivated by the requirement of a very high luminosity which can not be reached with $\bar{p}$, and also by the fact that at high energy the charge independent gluon–gluon interaction gives the dominant contribution to the production of new particles.

When running in $pp$ mode, the centre of mass energy will be $\sqrt{s} = 14$ TeV, a factor seven larger than the current world record (Tevatron at Fermilab, $p\bar{p}$ at $\sqrt{s} = 2$ TeV), and the design luminosity will be $10^{34} \text{cm}^{-2}\text{s}^{-1}$, two orders of magnitude larger than the LEP and Tevatron ones. Such luminosity and centre of mass energy will allow searches for new particles up to masses of about 5 TeV.

1High energy electrons can be produced at linear accelerators; projects of linear $e^+e^-$ colliders are on the way, but the timescales for their construction are much larger than the LHC one.
The LHCb experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum at collision</td>
<td>7 TeV/c</td>
</tr>
<tr>
<td>Momentum at injection</td>
<td>450 GeV/c</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Bunch crossing frequency</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2835</td>
</tr>
<tr>
<td>Number of protons per bunch</td>
<td>$\sim 10^{11}$</td>
</tr>
<tr>
<td>Beam crossing angle</td>
<td>300 $\mu$m</td>
</tr>
<tr>
<td>Bunch length</td>
<td>7.7 cm</td>
</tr>
<tr>
<td>Beam radius at the interaction point</td>
<td>16.7 $\mu$m</td>
</tr>
<tr>
<td>Ring circumference</td>
<td>26659 m</td>
</tr>
<tr>
<td>Number of bending dipoles</td>
<td>1232</td>
</tr>
<tr>
<td>Field of bending dipoles</td>
<td>8.386 T</td>
</tr>
<tr>
<td>Temperature of magnets</td>
<td>1.9 K</td>
</tr>
</tbody>
</table>

Table 2.1: Main design parameters of the Large Hadron Collider.

The limiting factor to the achievable centre of mass energy is the bending power needed to keep the beams circulating in the $\sim 27$ km circumference of the LEP tunnel. From the Lorentz force law:

$$p = \frac{e}{c} BR \simeq 0.3 BR$$  \quad (2.1)$$

where $p$ is the beam momentum in TeV/c, $B$ the provided magnetic field in tesla and $R \sim 4.3$ km is the radius of the LEP ring, the bending power needed to achieve the design beam momentum is 5.4 T. In practice, since the machine can not be completely filled with magnets, the needed bending power is obtained with about 1200 superconducting 14.2 m long dipole magnets providing a field of 8.4 T, which represents a very ambitious technological challenge. The superconducting magnets use a Nb–Ti conductor cooled down to 1.9 K by means of superfluid helium. The main LHC design parameters are listed in Tab. 2.1.

Two phases are foreseen for the LHC operation: during the first three years the instantaneous luminosity will start with $10^{33}$ cm$^{-2}$s$^{-1}$ (“low luminosity” phase) and will reach $10^{34}$ cm$^{-2}$s$^{-1}$, the design luminosity of the machine, afterwards (“high luminosity” phase). However, the luminosity at the LHCb will be locally controlled by defocusing the beams at the LHCb interaction point such that it will have a mean value$^{2}$ $L_{av} = 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$. The choice of this value as the LHCb design luminosity will be motivated in Section 2.1.1.

---

$^{2}$The luminosity $L$ is assumed to decrease exponentially with a 10 hour luminosity lifetime during the course of 7 hour fills with an average value of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, which implies that a luminosity $\sim 2.8 \times 10^{32}$ cm$^{-2}$s$^{-1}$ at the start and $\sim 1.4 \times 10^{32}$ cm$^{-2}$s$^{-1}$ at the end of the fill.
All the available CERN accelerators will be used in the injection chain, as shown in Fig. [2.1]: the proton beam exiting the LINAC will be injected in the PS via the PSB, then in the SPS and finally in the LHC ring.

Four detectors will take data at LHC. ATLAS and CMS are general purpose experiments with a broad physics program, including both searches for new particles and precision measurements [24, 25]; LHCb is the experiment dedicated to the physics of $b$-hadrons and to CP violation [22]. ALICE is the heavy ion experiment which will study the behaviour of the nuclear matter at very high energies and densities, and the formation of the quark–gluon plasma [26].
2.1.1 The luminosity

In a collider machine, the rate $\mathcal{R}$ of occurrence of a given process is proportional to its cross section, $\sigma$, and to a factor of proportionality called luminosity, $\mathcal{L}$. The $b\bar{b}$ pairs production rate is:

$$\mathcal{R}_{b\bar{b}} = \sigma_{b\bar{b}} \mathcal{L}$$  \hspace{1cm} (2.2)

where $\sigma_{b\bar{b}}$ is the $b\bar{b}$ cross section. The number $n$ of proton–proton interactions occurring in a given bunch crossing follows a Poisson distribution:

$$P(\mu, n) = \frac{\mu^n}{n!} e^{-\mu}$$  \hspace{1cm} (2.3)

Here, $\mu$ denotes the average number of proton–proton interactions (known as collisions) per bunch crossing, and it is related to the luminosity and the total inelastic $pp$ cross section:

$$\mu = \frac{\sigma_{\text{inel}}}{f_{\text{LHC}} \varepsilon_{\text{filled}}}$$  \hspace{1cm} (2.4)

where $\sigma_{\text{inel}}$ denotes the total inelastic $pp$ cross section, $\mathcal{L}$ is the luminosity, $f_{\text{LHC}}$ is the 40 MHz LHC bunch crossing frequency and $\varepsilon_{\text{filled}} = 0.744$ is the fraction of non–empty bunch crossings. Fig. (2.2) shows the probability for observing $n \leq 4$ inelastic $pp$ interactions as a function of the luminosity. A higher luminosity results in a smaller number of bunch crossings with no interaction ($n = 0$), while the fraction of multiple interactions ($n > 1$) rapidly increases.

In order for the decay distances of $B$ mesons to be measured accurately, the primary vertex has to be determined with high precision. Single interactions (with $n = 1$) are most suitable for this purpose. As shown in Fig. (2.2), assuming $\sigma_{\text{inel}} = 80$ mb, the probability of having a single interaction reaches its maximum when the luminosity is about $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$. However, running at this luminosity, the probability of multiple interactions ($n > 1$) is rather high. The base–line solution is to run at $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ (“optimal” luminosity), so that the detector occupancies in the tracking systems will be lower and the radiation damage (particularly in the vertex detector) will be reduced. However, the subdetectors and the data acquisition system have been designed to cope with luminosities up to $5 \times 10^{32}$ cm$^{-2}$s$^{-1}$ (“maximal” luminosity).
2.2 Phenomenology of proton–proton collisions

Since the total inelastic $pp$ cross section is about 80 mb at $\sqrt{s} = 14$ TeV, when running at high luminosity the number of events produced per second by $pp$ interactions is expected to be $R = \sigma \times L \sim 10^9$ Hz. All these events fit in one of the following two classes:

- most events are due to large distance collisions between the incoming protons. Protons interact as a whole, so the momentum transfer is small ("soft collisions"). Therefore, particle scattering at large angles is suppressed; final state particles have large longitudinal momentum but small transverse momentum relative to the beam line ($p_T \sim 500$ MeV/c). Most of the collision energy escapes along the beam pipe. Final states arising from these soft interactions are called "minimum bias" events, and even if they represent by far the majority of the $pp$ collisions, they are not interesting for the physics program of the experiment but they need to be studied carefully because they constitute a potential source of background;

- monochromatic proton beams can be seen as beams of partons (quarks and gluons) with a wide energy band. Fig. 2.3 shows a diagram of this model.
Occasionally, head–on collisions occur between two partons of the incoming protons. These interactions are at small distance, so they are characterized by large momentum transfer ("hard collisions"). Final state particles can be produced at large angles with respect to the beam line (high $p_T$), and massive particles can be created.

These are the interesting physics events at LHC, but they are rare compared to the soft interactions.

In the hard scattering of quarks and gluons, the effective centre of mass energy of the interaction, $\sqrt{\hat{s}}$, is, unlike at $e^+e^-$ collider, smaller than the centre of mass energy of the machine, $\sqrt{s}$, and it is given by:

$$\sqrt{\hat{s}} = \sqrt{x_a x_b s}$$

where $x_a$ and $x_b$ are the fractions of the proton momenta carried by the two colliding partons, as shown in Fig. 2.3. If $x_a \approx x_b \equiv x$, then the above relation becomes:

$$\sqrt{\hat{s}} \simeq x \sqrt{s}$$

Therefore, in order to produce a particle of mass 100 GeV/$c^2$, two quarks (or gluons) carrying only 1% of the proton momentum are needed ($x \sim 0.01$), whereas a particle of mass 5 TeV/$c^2$ can only be produced if two partons with $x \sim 0.35$

---

3For instance, the production of a $W$ boson through the $q\bar{q}$ annihilation has a cross section of the order of 150 nb, i.e. $10^5$ times smaller than the total inelastic $pp$ cross section.
interact. The momentum distributions of quarks and gluons inside the proton are called parton distribution functions. Up and down quarks contribute to the quantum numbers of the protons ("valence quarks") and therefore carry a large fraction of the proton momentum. The proton contains also gluons and other quarks, which give rise to the so-called "sea quarks" and which exhibit much smaller momenta. They are mainly produced by gluon radiation from the valence quarks, and by subsequent gluon splitting into $q\bar{q}$ pairs.

The parton momentum distributions depend on the momentum exchanged in the interaction, $Q^2$. At large $Q^2$, the interacting particles see the short-distance structure of the protons, and hence have access to the sea. Therefore the parton distribution functions are shifted towards small $x$ values. For small $Q^2$, on the other hand, only the valence quarks are visible and the parton distribution functions peak at large $x$ values.

The cross section of a generic hard scattering interaction is given by:

$$\sigma = \sum_{a,b} \int dxa db f_a (x_a, Q^2) f_b (x_b, Q^2) \hat{\sigma}_{ab} (x_a, x_b)$$

where $\hat{\sigma}_{ab} (x_a, x_b)$ is the cross section of the elementary interaction between the two partons, and the parton distribution functions $f_a (x_a, Q^2)$ and $f_b (x_b, Q^2)$ give the probability of finding a parton carrying a fraction $x_{a,b}$ of the proton momentum.

### 2.2.1 The experimental challenges

The experimental conditions at LHC will be very challenging for the experiments which will have to face two main difficulties. The first one (the pile–up) is related to the machine luminosity, the second one (the QCD background) to the physics of proton–proton collisions.

#### Pile–up

Inside the beams, protons are grouped in bunches of $\sim 10^{11}$ particles each, colliding at a given interaction point every 25 ns. Since the expected interaction rate is $\sim 10^9$ events per second when running at high luminosity, on average 25 soft interactions (minimum bias events) occur simultaneously at each crossing. These give rise, every 25 ns, to about 1000 charged particles in the detector over the pseudorapidity region $|\eta| < 2.5$.

As a consequence, when a high $p_T$ event is produced in a bunch crossing, this event is overlapped, on average, with 25 additional soft events, which are therefore called "pile–up" events.

---

4 The pseudorapidity is defined as $\eta = -\ln [\cot (\theta/2)]$, being $\theta$ the polar angle of a produced particle with respect to the beam–line.
The pile-up is one of the most serious experimental difficulties at LHC, carrying a large impact on the detector design. In fact, the LHC detectors must have a fast response time, otherwise the signal from the detector would be integrated over many bunch crossings and the pile-up would be too large. Typical response times required by the LHC detectors are in the range 20 – 50 ns, which corresponds to integrating over 1 – 2 bunch crossings and therefore summing 25 – 50 minimum bias events on average. Furthermore, the LHC detectors must have a fine read-out granularity, in order to minimize the probability that particles from the pile-up traverse the same detector element as an interesting object. This implies a large number of read-out channels. Finally, the LHC detectors

Figure 2.4: *Cross section for several processes as a function of the centre of mass energy in a proton–proton collision.*
must be radiation resistant, because of the high flux of particles coming from the pp collisions. This flux, integrated over ten years of operation, amounts to up to $10^{17}$ neutrons/cm$^2$ and up to $10^7$ Gy in the forward calorimeters.

**QCD background**

The rate of high transverse momentum events at a hadron collider is dominated by QCD jet production. Jets arise from the fragmentation of quarks and gluons in the final state, which are produced through a variety of Feynman diagrams. Jet production is a strong process and therefore has a large cross section. Furthermore many decay channels contribute to this final state (e.g. $qq \rightarrow qq$, $gg \rightarrow qq$, $qg \rightarrow qg$). On the other hand, the most interesting physics processes at the LHC are rare processes, either because they involve the production of heavy particles, or because they have weak cross sections.

The production cross sections for several channels at hadron colliders are shown in Fig. (2.4) as a function of the centre of mass energy. It can be seen, for example, that at the LHC energy the production cross section for jets with $E_{t}^{jet} > 0.25$ TeV is four orders of magnitude larger than the cross section for a Higgs boson of mass 100 GeV/c$^2$. Therefore, there is no hope to detect a Higgs boson decaying into jets, since such final states are swamped by the much larger jet rate (referred as “QCD background”), and decays to leptons and photons have to be used instead. Since decays into leptons or photons have usually a smaller branching ratio than decays into quarks, the price to pay to get rid of the QCD background is a smaller event rate.

**2.3 Bottom production at LHC**

The dominant first order mechanisms for heavy quarks production at LHC are believed to be the gluon–gluon and parton–parton fusions ($gg$ and $q\bar{q}$). In particular, in proton–proton collisions, $b\bar{b}$ pairs are produced by the following hard processes:

- pair creation: the hard process produces two heavy quarks in the final state through the reactions $gg \rightarrow q\bar{q}$ and $q\bar{q} \rightarrow q\bar{q}$;

- flavour excitation: a heavy quark in one incoming hadron is put on mass shell by scattering off a parton from the opposite hadron, $qq \rightarrow qq$ or $qg \rightarrow qg$. The incoming heavy quark is assumed to come from a $g \rightarrow q\bar{q}$ splitting in the initial state shower. This hard process is characterized by one heavy quark in the final state;

- gluon splitting: no heavy quark is involved in the hard scattering. Instead a $q\bar{q}$ pair is produced in the initial or final state shower from a $g \rightarrow q\bar{q}$ branching.
Fig. 2.5: Feynman diagrams of the dominant $b\bar{b}$ production mechanisms at lowest order in $\alpha_s^2$. Light partons within the incoming protons collide and produce the heavy $b\bar{b}$ pair via elementary strong interaction vertices.

Fig. (2.5) shows some topologies belonging to the processes specified above. The production cross sections for heavy flavour pairs have been calculated up to next–to–leading order. However, theoretical predictions and experimental measurements have large discrepancies. Also the calculated and measured kinematical distributions are different. It is therefore expected that higher order corrections give a significant contribution.

At LHC energies, the parton distribution functions of the proton (both quark and gluon) are such that it is most likely that partons with very different momenta interact. As a consequence, the centre of mass energy of the produced $b\bar{b}$ pair is boosted along the direction of the higher momentum gluon, and this results in both the $b$ and the $\bar{b}$ being predominantly produced in the same forward cone. Thus, LHC is an intrinsically asymmetric high energy gluon–gluon collider.

In Fig. (2.6) the simulated polar angle distribution of $b$– and $\bar{b}$–hadrons produced by $pp$ interactions is plotted. This forward correlation motivates the design of the LHCb detector. The expected cross section for the production of $b\bar{b}$ pairs at LHC is $\sigma_{b\bar{b}} = 500 \, \mu b$, providing about $10^{12}$ $b\bar{b}$ pairs per year ($10^7$ s) of running at the LHCb mean luminosity $L_{av}$. The LHC collider will be a full spectrum source of $b$–hadrons: $B_{d}^{\pm}$, $B_{s}^{0}$, $B_{s}^{0}$, $B_{c}^{\pm}$, $\Lambda_b$ and many others, enabling LHCb to measure CP violation phenomena with high statistics in many different decay channels.
2.4 The LHCb experiment

Based on the expected properties of $b\bar{b}$ pair production at the LHC collider explained in Section 2.3 and taking into account the available budget and the limited space for the detector, the Large Hadron Collider beauty experiment for precise measurements of CP violation and rare decays (LHCb) design consists of a single-arm spectrometer with a forward coverage from 10 mrad to 300 (250) mrad in the bending (non–bending) plane [22].

Selection and reconstruction of rare $B$ decays in an environment with high background rates implies the following experimental requirements for the detector:

- a fast and efficient triggering scheme to reduce the large amounts of uninteresting processes, such as minimum bias events. This is achieved by triggering on particles with large transverse momentum $p_T$ and displaced decay vertices;

- a precise invariant mass reconstruction needed to reject backgrounds due to random combinations of tracks. This implies a high momentum resolution;

- an excellent vertex and decay time resolution required to study the rapidly oscillating $B^0_s$ mesons, as well as the time–dependent CP asymmetries.
Good vertex reconstruction is a fundamental requirement since displaced secondary vertices are a distinctive feature of $b$–hadron decays;

- a powerful particle identification. In particular, lepton ($e$, $\mu$) identification is required for trigger purposes and for tagging with semileptonic decays; hadron ($K$, $\pi$) identification is needed for kaon tagging and used for selecting high purity final states relevant for CP violation studies. For example:

1. $B_{d}^{0} \rightarrow \pi^{\pm}\pi^{\mp}$ decays, which can be used to extract the angle $\alpha$, are heavily contaminated by $B_{d}^{0} \rightarrow K^{\pm}\pi^{\mp}$, $B_{s}^{0} \rightarrow K^{\pm}\pi^{\mp}$ and $B_{s}^{0} \rightarrow K^{\pm}K^{\mp}$ decays;

2. $B_{s}^{0} \rightarrow D_{s}^{-}\pi^{+}$ contaminates the selection of $B_{s}^{0} \rightarrow D_{s}^{+}K^{\mp}$ used for the measurement of the angle ($\gamma - 2\delta_{\gamma}$).

The detector is currently under construction; the LHC Intersection Point 8, which hosted DELPHI in the LEP era, has been allocated to the experiment. A modification of the LHC optics, displacing the interaction point by 11.25 m from the centre of the experimental hall, has permitted to maximize the use of the existing cavern freeing 19.7 m for the LHCb detector components. A right–handed coordinate system is defined on the interaction point, with $z$ along the beam–line axis, $y$ pointing upwards and $x$ pointing toward the centre of the LHC ring.

**Forward versus central geometry**

The relatively low luminosity of the first phase of LHC will allow the ATLAS and CMS experiments to carry out most of their $b$ physics program. While ATLAS and CMS are central detectors, LHCb has a forward geometry. There are several issues for which either forward or central geometry has an advantage. The forward geometry is able to utilize the correlated $b\bar{b}$ pairs shown in Fig. 2.6. However, the minimum bias events will also peak in the same forward cone and a dedicated high $p_T$ trigger will try to minimize their presence in the collected data.

Fig. 2.7 shows $b$–hadrons transverse momentum $p_T$ as a function of their pseudorapidity $\eta$: ATLAS and CMS cover the pseudorapidity range $|\eta| \leq 2.5$, whereas LHCb covers the region $1.9 \leq \eta \leq 4.9$.

The forward geometry is open, simplifying the mechanical design, the installation and the maintenance requirements. LHCb will be able to obtain much better vertex resolution than the central experiments since the forward geometry allows the vertex detector to be placed much closer to the interaction point than it would in a central geometry configuration. Neither ATLAS nor CMS have dedicated detectors for hadron identification.
2.4 The LHCb experiment

2.4.1 Detector reoptimization

The LHCb detector underwent an extensive reoptimization phase during the period 2001 – 2003 \cite{28}. There were two objectives in reoptimizing the LHCb detector since the Technical Proposal \cite{22}: reduce the amount of material in the detector and improve the trigger performance.

Material budget\footnote{The amount of material traversed by particles is parameterized in terms of radiation length \(X_0\) (the scaling variable for the probability of occurrence of bremsstrahlung, pair production, and for the variance of the angle of multiple scattering) and nuclear interaction length \(\lambda_I\) (the mean free path of a particle before undergoing an inelastic nuclear interaction).} is an issue, due to problems arising from multiple scattering and high energy \(\gamma\) emission inside the detectors along the trajectory of a particle. This lead to a big effort towards the optimization of the detector, including the removal of a certain number of tracking stations, without losing in performance of the tracking and momentum resolution while minimizing the material along the particle trajectories.

It was also realized that the performance of the trigger could be made more robust by adding \(p_T\) information to tracks with a large impact parameter. This could be achieved by associating the high \(p_T\) calorimeter clusters and muons found at Level–0 Trigger to the tracks found in the vertex detector.

Figure 2.7: \(b\)-hadrons transverse momentum \(p_T\) as a function of their pseudorapidity \(\eta\), showing the \((\eta, p_T)\) regions covered by ATLAS and CMS experiments compared to that covered by LHCb.
The layout of the detector after the reoptimization is shown in Fig. (2.8). In the following sections a brief description of the subdetectors as well as the trigger strategy will be given.

### 2.4.2 Beam pipe

The beam pipe consists of a thin exit window sealed to the vertex detector vacuum tank followed by two conical parts with apertures of 25 mrad and 10 mrad respectively [22, 28]. The first section of 1840 mm length is made of 1 mm thick beryllium and consists of a 25 mrad cone followed by a 10 mrad cone. The two cones are connected by a thin window followed by a short cylindrical section (250 mm in length) that constitutes the narrowest aperture of the beam pipe, with an inner diameter of 50 mm.

The second and the third sections are long sections of 10 mrad aluminium–beryllium alloy cones with a length of 3876 mm and 6000 mm respectively. They are formed from several pieces of increasing thickness (1.0 mm to 2.4 mm) welded together. The two conical sections are connected by optimized flanges located at 7100 mm from the interaction point.

A second transition connects this part with the last section of the beam pipe. It consists of a 10 mrad cone connecting two standard stainless–steel bellows, and has stainless–steel flanges.

The choice of the material is a compromise between price and the need to
minimize the interaction of particles with the beam pipe which constitutes a major source of background in the detector. In particular, stainless–steel is used in correspondence of the calorimetric and muon systems, where the total particle flux shows little dependence on the beam pipe material.

2.4.3 Magnet

The spectrometer dipole is placed close to the interaction region, in order to keep its size small. Since the tracking detectors have to provide a momentum measurement for charged particles with a precision of 0.4% for momenta up to 200 GeV/c, a warm magnet is chosen to obtain a high field integral of 4 Tm with a short length [22, 29]. The field is vertically oriented and its polarity can be changed to reduce systematic errors in the CP violation measurements that could result from a left–right asymmetry of the detector. The aperture of the magnet is $4.3 \times 3.6$ m$^2$. The coil is designed to maximize the field homogeneity.

Champagne bottles were opened in the underground control room of Point 8 during the night of November, 9th 2004 to celebrate reaching the full magnetic field of the magnet successfully. The commissioning had just started to confirm that the almost 60-tonne coils, along with the 1500-tonne iron yoke, perform in the expected way, and that the power, cooling, and control systems work properly.
Figure 2.10: The VELO vacuum vessel with the silicon sensors. The main components are the silicon sensor stations, the corrugated RF foils, the RF box, the wakefield guides and the thin exit window. The LHC beam pipe is also shown.

A photograph of the magnet is shown in Fig. (2.9).

2.4.4 Vertex detector system

The vertex detector has to provide precise measurements of track coordinates close to the interaction region [22, 28, 30]. These are used to reconstruct production and decay vertices of $B$ mesons, to provide an accurate measurement of their flight time, and to measure the impact parameter of particles used to tag the $b$ flavour. The vertex detector also provides information to the Level–0 and Level–1 Trigger systems.

The vertex detector uses silicon strip detectors positioned perpendicular to the beam direction. To get the highest primary and secondary vertex resolution, the detector must be positioned as close to the interaction point as possible. In addition, the material budget between the interaction point and the detector should be as small as possible to avoid multiple scattering. This is done by positioning the whole system inside a secondary beam vacuum chamber, allowing to get the sensitive area at a distance of 8 mm from the beam–line axis.

The system consists of two components, the VErtex LOcator (VELO) and the pile–up veto counter. The VELO is shown in Fig. (2.10), and consists of 21 stations with radial or azimuthal strip sensors, interspersed over one metre
parallel to the beam direction. The lay–out is shown in Fig. 2.11. The stations closest to the interaction point are required to reconstruct tracks with angle up to 390 mrad. The most downstream stations are required to reconstruct low angle tracks down to 15 mrad. Each station consists of two planes of 220 $\mu$m thick silicon strips as illustrated in Fig. 2.11. One plane is designed to measure the radial position coordinates, and the other to measure the azimuthal ones.

The two planes placed upstream of the main VELO act as a pile–up veto counter. This is used in the Level–0 Trigger to suppress events with multiple proton–proton interaction in a single bunch crossing. By counting the number of primary vertices, the pile–up veto counter will be able to reject 80% of multiple interactions while retaining 95% of single interactions.

In a typical event, the primary vertex resolution is 42 $\mu$m in the $z$ direction and 10 $\mu$m in the perpendicular plane. The precision on the decay length is decay channel dependent, and ranges from 220 $\mu$m to 370 $\mu$m. A lifetime resolution of 35 – 40 fs is achieved for $B^0_s \rightarrow D_s^- \pi^+$ events, allowing a measurement of the $\Delta m_s$ parameter up to 68 ps$^{-1}$ after one year of data taking and with a statistical significance of at least five standard deviations [28].
The main task of the tracking system is to provide efficient reconstruction of charged particle tracks and precise measurements of their momenta. It has to provide measurements of track directions for the reconstruction of Cherenkov rings in the RICH detectors. Also, tracking hits are used for trigger purposes.

The tracking system consists of the VELO and the pile–up veto counter, the Trigger Tracker (TT) located before the magnet and three stations (T1, T2 and T3) located after the magnet. Each of T1, T2 and T3 are divided into two components known as the Inner Tracker (IT) and the Outer Tracker (OT) [22, 28, 30, 31, 32].

The measurement of charged particle momenta is based on the bending of the trajectory by a magnetic field. The motion of a particle with momentum $p$ and electrical charge $ze$ in a uniform magnetic field $B$ is described by an helix with a radius of curvature $R$ and pitch angle $\lambda$. The radius of curvature and the momentum perpendicular to $B$, $p_T$, are related by:

$$p_T = p \cos \lambda = 0.3zeBR$$ \hspace{1cm} (2.8)

where $p$ is measured in GeV/c, $B$ in tesla and the radius $R$ in metres. At first order, the main contributions to momentum resolution are random change of track direction due to multiple scattering along the particle trajectory, spatial resolution to the measurements, misalignment of tracking detectors and imperfect knowledge of the magnetic field map.

**Trigger Tracker (TT)**

The Trigger Tracker (TT) is located after the RICH 1 detector and in front of the entrance of the magnet. Its purpose is twofold. Firstly, it will be used in the Level–1 Trigger to assign $p_T$ information to large impact parameter tracks; secondly, it will be used in the offline analysis to reconstruct the trajectories of the long–lived neutral particles that decay outside of the fiducial volume of the vertex detector and of low momentum particles that are bent out of the detector acceptance before reaching the tracking stations T1–T3.

The Trigger Tracker active area will be covered entirely by silicon microstrip detectors with a strip pitch of 198 $\mu$m and strip lengths of up to 33 cm. Four detection layers amount to a total surface of approximately 8.3 $m^2$ of silicon and to about 180k read–out channels. The first and the fourth layers have vertical read–out strips, the second and the third layers have read–out strips rotated by a stereo angle of +5° and −5° respectively.

The four layers are arranged in two pairs, with a gap of approximately 30 cm between the second and the third detection layer: the first two layers (TTa) are...
centred around \( z = 232 \text{ cm} \), the last two (TTb) around \( z = 262 \text{ cm} \). The active area of the Trigger Tracker covers the nominal acceptance of the spectrometer, as shown in Fig. 2.12.

**Tracking stations (T1–T3)**

Owing to the variation in particle flux with respect to the polar angle, different detector granularities are needed for the low and the high flux regions. Therefore, each of the stations T1, T2 and T3 are split into two systems, the Inner Tracker (IT) and the Outer Tracker (OT). Each of them uses a different technology.

The Inner Tracker covers a cross-shaped area around the beam pipe, approximately \( 120 \times 40 \text{ cm}^2 \), where particle densities are highest (charged particle fluxes of up to \( 5 \times 10^5 \text{ cm}^{-2}\text{s}^{-1} \) are expected in the innermost region of the Inner Tracker). The technology used is the same as that used in the Trigger Tracker, namely single-sided silicon strip detectors. Each station consists of four detection layers, with two \( \pm 5^\circ \) stereo views sandwiched in between two layers with vertical strips. The overall sensitive surface of the three Inner Tracker stations amounts to approximately \( 4.2 \text{ m}^2 \). Large strip pitches of about 200 \( \mu \text{m} \) arranged in read-out strips of up to 22 cm length will be employed in order to minimize the number of read-out channels.

The Outer Tracker will cover the remaining area of the stations T1–T3, where the expected charged particle fluxes are less than \( 10^5 \text{ cm}^{-2}\text{s}^{-1} \), low enough to use straw tube drift chambers with an inner diameter of 5 mm. Each tracking station consists in a stack of four layers of modules. Emphasis is on tracking precision in the bending plane: drift cells have their wires running vertically and along two stereo planes which are tilted by \( \pm 5^\circ \) with respect to the vertical direction.

The gas mixture must have high amplification power and high drift velocity.
A maximum drift time of 50 ns is mandatory to keep the number of overlapping events low. A gas mixture with 75/15/10 of Ar/CF$_4$/CO$_2$ was found to satisfy this requirement.

2.4.6 RICH detectors

Particle identification over a large momentum range is a fundamental requirement of the LHCb experiment. Leptons are identified for both trigger and tagging purposes, photons must be identified both for $B$ decays with prompt photons as well as for $B$ decays with $\pi^0$ particles, while in hadronic $B$ decays a powerful $\pi/K$ separation is required.

Hadronic particle identification for $\pi$, $K$ and $p$ is performed by Ring Imaging CHerenkov (RICH) detectors. The momentum upper limit required for $\pi/K$ separation is determined by tracks from a low multiplicity decay channels, e.g. $B^0_d \rightarrow \pi^+\pi^-$: 90% of the tracks have a momentum less than 150 GeV/c. Identification of tagging kaons and tracks from high multiplicity decays define the lower momentum limit required: a momentum greater than 1 GeV/c is necessary.

The most suitable technique to cover the required momentum range is the use of Ring Imaging CHerenkov (RICH) detectors with various radiators [22, 28, 33]. Three radiators are foreseen: solid silica aerogel and two fluorocarbon gases,
Table 2.2: Parameters of the Cherenkov radiators foreseen in the RICH detectors. The refractive index $n$ for visible light at STP conditions, the maximum Cherenkov angle $\theta_{\text{max}}$, and the momentum thresholds for $\pi$ and $K$ are listed.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\text{CF}_4$</th>
<th>$\text{C}<em>4\text{F}</em>{10}$</th>
<th>Aerogel</th>
</tr>
</thead>
<tbody>
<tr>
<td>refractive index</td>
<td>1.0005</td>
<td>1.0014</td>
<td>1.03</td>
</tr>
<tr>
<td>$\theta_{\text{max}}$ (mrad)</td>
<td>32</td>
<td>53</td>
<td>242</td>
</tr>
<tr>
<td>$p_{th}(\pi)$ (GeV/c)</td>
<td>4.4</td>
<td>2.6</td>
<td>0.6</td>
</tr>
<tr>
<td>$p_{th}(K)$ (GeV/c)</td>
<td>15.6</td>
<td>9.3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

$\text{C}_4\text{F}_{10}$ and $\text{CF}_4$; some details concerning these materials are given in Tab. (2.2).

Fig. (2.13) shows the polar angle $\theta$ as a function of momentum for all tracks in simulated $B_s^0 \rightarrow D_s^- \pi^+$ events. There is a clear correlation, with tracks at large angles having a softer momentum spectrum. The detector intended for the identification of low momentum particles, RICH 1, is therefore designed to cover polar angles out to the full spectrometer acceptance. It is located between the VELO and the Trigger Tracker systems to identify low momentum tracks that will be swept out of the acceptance. It combines both solid silica aerogel and gaseous $\text{C}_4\text{F}_{10}$ radiators. The detector for the identification of high momentum particles, RICH 2, is placed between the tracking stations and the muon detector, and it uses gaseous $\text{CF}_4$ radiator. A detailed description of the RICH detectors will be given in Chapter 3.

2.4.7 Calorimeters

The calorimeter system of LHCb is placed in the middle of the detector, sandwiched between the M1 and M2 muon chambers, and it consists of an Electromagnetic (ECAL) and a Hadronic (HCAL) Calorimeters [22, 34]. Two additional detection layers, a Scintillator Pad Detector (SPD) and a PreShower (PS) are placed just in front of the ECAL. Each detector is divided into regions with different granularity. This lateral segmentation, as illustrated in Fig. (2.14), increases in number (decreases in cell size) closer to the beam–line corresponding to the expected increase in particle flux in this region.

The purpose of the calorimeters is the identification of hadrons, photons and electrons and the measurement of their energies and positions. This information is used in the Level–0 Trigger, offline analysis and also for the reconstruction of electrons, $\pi^0$ and photons. This task is important to enable the identification of decay channels containing a prompt $\gamma$ or $\pi^0$, such as $B_d^0 \rightarrow \rho^0\pi^0$, sensitive to the angle $\gamma$ of the Unitarity Triangle.

The different detection layers are arranged such that there is an optimal particle identification with minimal loss of energy resolution. A particle entering the calorimeter first traverses the SPD which registers only charged particles.
Electromagnetic particles (electrons and photons) start to shower when crossing the PS detector. This detector consists of $2X_0$ (12 mm) thick lead wall, together with another SPD detector behind it. This second SPD detects a possible shower development. Wavelength shifting fibres (WLS) transport the photons from the scintillator to the photon detectors. The main task of the PS detector is the rejection of π background for the electron trigger. In the ECAL detector the electromagnetic particles develop a full shower, while hadrons ($\pi$, $p$ and $n$) will shower mainly inside the HCAL sector. The detection of the full shower provides a measurement of the total energy of the particle.

The ECAL is constructed with a “shashlik” technology\textsuperscript{6} with a sampling structure. It is built up from 66 alternating layers of 2 mm thick lead sheets and 4 mm thick scintillator plates. The total radiation thickness of this detector is $25X_0$. The HCAL is an iron–scintillating tile calorimeter, read–out by Multi–Anode PhotoMultiplier Tubes (MAPMT). The 4 mm thick scintillator and the 16 mm thick iron plates are parallel to the beam axis. With a total thickness of 1.2 m, the HCAL amounts to $5.6\lambda_I$.

The ECAL granularity is chosen high enough to separate two individual showers from two collinear photons originating from a high energy $\pi^0 \rightarrow \gamma\gamma$. The expected energy resolution of the ECAL up to 200 GeV is:

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

(2.9)

where the first term ($E$ in GeV) is a statistical term describing possible fluctuations in the shower creation process, and the second term is systematic in origin. The expected energy resolution of the HCAL is:

\textsuperscript{6}So named because the scintillator tiles are pierced by the WLS fibres as on a skewer.
\[
\frac{\sigma(E)}{E} = \frac{80\%}{\sqrt{E}} \pm 10\% \quad (2.10)
\]

2.4.8 Muon detector

The LHCb muon detector is used to provide muon identification in event reconstruction, muon information for the high \(p_T\) Level–0 Trigger and the suppression of the muon background in many interesting \(B\) decays. In fact, muons are present in many exclusive final states such as the two benchmark decay channels, \(B^0_d \rightarrow J/\Psi(\mu^+\mu^-)K_{s}\) and \(B^0_s \rightarrow J/\Psi(\mu^+\mu^-)\phi\) and in rare decays such as \(B^0_s \rightarrow \mu^+\mu^-\). In addition, the reconstructed muons from semileptonic decays can be used for the flavour tagging.

The muon detector uses the high interaction length of muons to provide a robust muon trigger. The heavy flavour content of triggered events is enhanced by requiring the candidate muons to have high transverse momentum \(p_T\). The same unique properties are utilized offline to accurately identify muons reconstructed in the tracking system and to provide flavour tagging.

The system consists of five stations, labelled M1 to M5, equipped with Multi–Wire Proportional Chamber (MWPC) and sampled with 80 cm thick steel plates in between, positioned at the most downstream side of the detector [22, 35, 36, 37]. Station M1 is placed in front of the SPD and PS, and it is important for the transverse momentum measurement of the candidate muon track used in the Level–0 Trigger. The other stations are used as validation planes to reject the large amounts of background. Including the calorimeters, the total absorber length of the muon system is 20\(\lambda_I\).

In a similar way as in the calorimeters, there are different regions in the stations, each with a different granularity. All the sensitive planes of the muon detector are using the MWPC technology apart from the innermost part of M1, where the track density is as large as \(4 \times 10^5 \text{ cm}^{-2}\text{s}^{-1}\), and the standard MWPC chamber will have ageing problems. Triple Gas Electron Multiplier detectors (GEM) will be used in this region.

The polar angle and the momentum of particles are correlated such that high momentum tracks are closer to the beam–line axis. Multiple scattering in the absorber increases with the radial distance from the beam–line, limiting the spatial resolution of the detector. The granularity of the detector varies such that its contribution to the \(p_T\) resolution is approximately equal to the multiple scattering contribution. The total resolution on the \(p_T\) measurement is about 20\%.
Figure 2.15: Overview of the three trigger levels. Muon stations M1–M5 are used to reconstruct two muons per quadrant. The SPD, PS, ECAL and HCAL are used to reconstruct hadrons, electrons, $\gamma$ and $\pi^0$ with the largest transverse energy, the charged particle multiplicity, and the total energy. The pile-up veto counter is used to recognize multiple interactions per bunch crossing. Level–1 Trigger uses the information from VELO, TT, and Level–0 Trigger to reduce the rate to 40 kHz. T1–T3 and M2–M4 could be included in Level–1 Trigger. The High Level Trigger uses all data in the event apart from the RICH to reduce the rate to 200 Hz.

2.5 Trigger

The LHCb experiment plans to operate at the fixed luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ so that the majority of bunch crossing results in single interactions, which are easier to process for triggering and reconstruction due to lower channel occupancy. Due to the LHC bunch structure and low luminosity the frequency of crossings
with interactions visible \(^7\) by the spectrometer is about 10 MHz, which has to be reduced by the trigger to a few hundred Hz, at which rate the events are written to storage for further offline analysis. This reduction is achieved by three levels: Level–0 Trigger (L0), Level–1 Trigger (L1) and the High Level Trigger (HLT) \(^{22, 28, 38}\). L0 is implemented in custom electronics, while L1 and HLT are executed on a computing farm (about 1800 CPUs). Fig. (2.15) shows an overview of all the subdetectors participating in the three trigger levels.

**Level–0 Trigger**

The task of Level–0 Trigger is to reduce the event rate from 40 MHz to 1 MHz, rate at which in principle all the subdetectors could contribute to a trigger decision. Due to their large boost and mass, \(b\)-hadron decays contain large \(E_T\) lepton, hadron or photon in the final state, so that Level–0 Trigger reconstructs the highest \(E_T\) hadron, electron and photon clusters in the calorimeter and the two highest \(p_T\) muons in the muon system.

Events can be rejected based on global event variables such as charged track multiplicities and the number of interactions, as reconstructed by the pile-up veto counter, to assure that the selection is based on \(b\) signatures rather than large combinatorics, and that these events will not occupy a disproportional fraction of the data–flow bandwidth or available processing power in subsequent trigger levels. All L0 triggers are fully synchronous and their latency does not depend upon occupancy nor on history; all the electronics is implemented in full custom boards. The Level–0 Decision Unit (L0DU) collects information from all the components to form the Level–0 Trigger. The L0DU performs simple arithmetics to combine all signatures into one decision per crossing.

A more detailed description of the Level–0 Muon Trigger will be given in Chapter 6.

**Level–1 Trigger**

The Level–1 Trigger operates to identify events with a secondary vertex. At the 1 MHz output rate of Level–0 Trigger, analogue data are digitized and stored for the time needed to process the Level–1 Trigger algorithm. This algorithm uses the information from Level–0 Trigger, the VELO and the Trigger Tracker systems, and reconstructs tracks in the VELO, and matches these tracks to L0 muons or calorimeter clusters to identify them and to measure their momenta. The fringe field of the magnet between the VELO and the Trigger Tracker is used to determine the momenta of particles with a resolution of 20% – 40%. Events are selected on the basis of the presence of tracks with large \(p_T\) and significant impact parameter with respect to the primary vertex.

---

\(^7\)An interaction is defined to be visible if it produces at least two charged particles with sufficient hits in the VELO and T1–T3 systems to allow them to be reconstructible.
The total output rate of Level–1 Trigger is 40 kHz, with a maximum latency of the algorithm of 1.7 ms.

**High Level Trigger**

The High Level Trigger uses information from all the subdetectors and perform partial or full event reconstruction, selecting events which are associated with specific $b$–hadrons decay modes. The High Level Trigger and Level–1 Trigger algorithms run currently on the same CPU nodes, with Level–1 taking priority due to its limited latency budget. The HLT algorithm starts with the reconstruction of the VELO tracks and the primary vertex, rather than having this information transmitted from Level–1 algorithm. A fast pattern recognition program links the VELO tracks to the tracking stations T1–T3, after which a set of selection cuts dedicated to specific final states is applied.

The High Level Trigger has a latency of 200 ms. While the maximum output rates of the first two levels are dictated by the implementation of the front–end hardware, the output rate of the High Level Trigger is kept more flexible. At an output rate of 200 Hz, events are fully reconstructed and particle identification applied before being written to storage. The possibility of including RICH information in the High Level Trigger algorithm is presently under study.
Chapter 3

RICH detectors for LHCb

The LHCb fundamental requirement of particle identification is achieved by the use of Ring Imaging CHeRenkov (RICH) detectors. The ability to distinguish between $\pi$ and $K$ mesons in a variety of final states is essential for the physics program of the LHCb experiment. This tool highly improves the performances of flavour tagging and the purity of the data samples collected for the different event signatures of interest for the physics analysis.

In the first part of this chapter, the basic principles of such detectors are given, the issues of designing devices based on such a technique and the factors limiting the particle identification power are discussed. A review of the design and performance of the RICH detectors of LHCb are then presented.

3.1 Particle identification

A particle is univocally identified by its rest mass and electrical charge. The electric charge is determined by the bending of the trajectory in a suitable static magnetic field. Much more challenging is the precise measurement of the rest mass of particles whose momentum spans a wide range. As already shown in Section 2.4.6, at LHCb the momentum covers the range $2 - 100$ GeV/$c$. The mass of the particle is provided by measuring at least two of the three correlated quantities: momentum, kinetic energy and velocity. The choice is usually restricted to the momentum and velocity which are related by $p = mc\gamma/\beta$. While the momentum is relatively well measured by the tracking system, the velocity can be determined by one of the following methods: energy loss, time of flight, detection of Cherenkov or transition radiation.

As will be explained in Section 3.3.1, the velocity resolution $\sigma_\beta/\beta$ is momentum dependent. Fig. (3.1) shows that in order to separate $\pi$ from $K$ mesons already in the momentum range of a few GeV/$c$, the velocity resolution must be better than a few percent. Such a precision can be achieved in this momentum range only by Cherenkov detectors. The capability of using the Cherenkov
Figure 3.1: Velocity resolution required to particle identification as a function of their momentum, as expressed in Eq. (3.27).

radiation for particle identification was clear since its discovery in 1937 \[39\].

### 3.2 The Cherenkov radiation

Almost fifty years before the experimental achievements of P. A. Cherenkov, O. Heaviside showed that charged particles moving faster than light in vacuum emit electromagnetic radiation whose wavefront propagates at a fixed angle with respect to the particle direction \[40\]. Although he made a wrong starting hypothesis since the condition of superluminality is not achievable in vacuum, his result was correct because the speed of the charged particle moving in a dielectric medium with a refractive index larger than unity can exceed the local phase velocity of light.

In 1910 M. and P. Curie observed a faint blue light coming from the neighbourhood of a strong radioactive source of radium in water, but this phenomenon was not studied deeply.

The first deliberate attempt to study this light was made by M. L. Mallet, who firstly noticed the differences with respect to fluorescence and other known forms of luminescence, and also photographed the light spectrum \[41, 42, 43\]. In 1934, P. A. Cherenkov under the supervision of S. Vavilov, trying to understand
3.2 The Cherenkov radiation

the origin of the weak luminescence that salt solutions emit when struck by γ rays, published a paper proving that the light emission was caused by Compton electrons moving quickly through the liquid and showing the relationship between the emission angle and the refractive index of the same medium [44, 45, 46, 47, 48]. In 1937, I. M. Frank and I. Y. Tamm formulated the theory of the Cherenkov effect and predicted the radiation spectrum by applying the equations of classical electrodynamics [49]. The quantum formulation of the phenomenon was elaborated by V. L. Ginzburg a few years later [50, 51].

In 1958 P. A. Cherenkov, I. M. Frank and I. Y. Tamm were jointly awarded the Nobel Prize in Physics “for the discovery and the interpretation of the Cherenkov effect” [52].

3.2.1 Properties of Cherenkov radiation

The Maxwell equations [1] for electromagnetic waves travelling in a medium with refractive index \( n \) can be written in terms of the scalar potential \( \Phi \) and the vector potential \( A \) [53]:

\[
\nabla^2 A - n^2 \frac{\partial^2 A}{\partial t^2} = 0
\]
\[
\nabla^2 \Phi - n^2 \frac{\partial^2 \Phi}{\partial t^2} = 0
\]

having imposed the generalized Lorenz gauge condition:

\[
\nabla \cdot A + n^2 \frac{\partial \Phi}{\partial t} = 0
\]

A monochromatic photon with given momentum \( \mathbf{k} \), moving in a medium with refractive index \( n = n(\omega) \), is described by the wave function \( A_\mu(x, t) \):

\[
A_\mu(x, t) = \varepsilon_\mu e^{i(k \cdot x - \omega t)}
\]

being \( \omega \) the frequency of the photon, \( \varepsilon_\mu \) the polarization vector and \( \mu = 0, 1, 2, 3 \). The dispersion law and gauge condition have the form:

\footnote{The quantum theoretical approach to the physics of the Cherenkov effect can be simplified by the convention \( \hbar = 1 \) and \( c = 1 \).}
Figure 3.2: Feynman diagram of the photon emission by Cherenkov effect. A particle of momentum $p$ emits a photon with momentum $k$.

$$|k| = n(\omega)\omega$$

$$k \cdot \varepsilon - n^2(\omega)\varepsilon_0 = 0$$

The classical wave function defined in Eq. (3.3) may be considered as an effective quantum wave function for a photon with energy $\omega$ travelling inside matter. According to Eq. (3.4), the corresponding momentum has modulus $n(\omega)\omega$.

In order to calculate the probability per unit time for a particle with charge $e$ and relative velocity $\beta = v/c$ travelling in a dispersive medium to emit a photon with energy in the interval $(\omega, \omega + d\omega)$, one can use of the standard vertex of photon emission [54]. The phase space term will be modified by the substitution of the momentum of the photon with the effective momentum:

$$k^\mu \equiv (\omega, k(\omega))$$

$$|k(\omega)| = n(\omega)\omega$$

Fig. (3.2) shows the Feynman diagram of the photon emission at the tree level. The emission probability per unit time is given by:

$$d\Gamma = \frac{1}{2E} |\mathcal{M}_{fi}|^2 d\Phi^{(2)}$$

being $E$ the energy of the incoming charged particle with momentum $p$, $|\mathcal{M}_{fi}|$ the transition amplitude for the photon emission and $d\Phi^{(2)}$ the two-body phase space defined as:
3.2 The Cherenkov radiation

\[ d\Phi^{(2)} = \frac{d^3p'}{2p'_0(2\pi)^3} \frac{d^4k}{(2\pi)^4} 2\pi \delta \left( k^2 - n^2\omega^2 \right) (2\pi)^3 \delta^{(3)} \left( p' + k - p \right) 2\pi \delta \left( \omega + E' - E \right) \]

where \((E', p')\) is the momentum of the outgoing charged particle.

Experimentally, the energy loss due to the Cherenkov radiation is lower than the one due to ionization of the molecules of the traversed medium\(^2\). Since the energy loss in single photon emission is small with respect to the energy of the charged particle, the following approximation can be used:

\[ E - E' \simeq \frac{\partial E}{\partial p} \cdot k = \beta \cdot k \]  

(3.8)

This approximation allows to express the phase space factor in Eq. (3.7) as:

\[ d\Phi^{(2)} \simeq \frac{1}{2p'_0} \frac{d\omega \, d^3k}{(2\pi)^2} \delta \left( k^2 - n^2\omega^2 \right) \delta \left( \omega - \beta \cdot k \right) \]  

(3.9)

The last factor in Eq. (3.9) sets a relation between the frequency of the photon and its emission angle with respect to the direction of the charged particle. Comparing the identity \( \omega = k \cdot \beta = \beta k \cos \theta \) with Eq. (3.4), the result is:

\[ \cos \theta = \frac{1}{n(\omega)} \beta \]  

(3.10)

In the following, the symbol \( \theta_C \) will be used to refer to the Cherenkov angle satisfying this relation. Three outstanding features of the Cherenkov radiation arise from Eq. (3.10):

- since \(| \cos (\theta_C) | \leq 1\), there exists a threshold velocity \( \beta_{th} = 1/n\); the emission takes place only if the velocity of the particle is higher than \( \beta_{th}\). The Lorentz boost factor related to this condition is \( \gamma_{th} = 1/\sqrt{(1 - 1/n^2)}\);

- all the photons with the same frequency are emitted at a well defined angle;

- when the speed of the particle approaches the velocity of light in vacuum (\( \beta \to 1\)), then \( \theta_C \) takes the maximum value \( \theta_{max} = \arccos (1/n)\). This condition is referred to as saturated Cherenkov effect.

\(^2\)Considering an electron moving with \( \beta \sim 1\) across a 1 cm thick of water \((n = 1.33)\), in the spectral range 400 – 700 nm the electron loses about 500 eV by the Cherenkov effect, whilst its energy loss by ionization is 2 MeV. Eq. (3.19) describes the energy loss by Cherenkov effect.
The transition amplitude for the emission process is given by:

\[ M_{fi} = e \varepsilon^* \mu_j \tag{3.11} \]

If the momentum transfer is small compared to the momentum of the charged particle, the current factor \( j^\mu \) can be approximated to:

\[ j^\mu = \bar{u}(p') \gamma^\mu u(p) \simeq \bar{u}(p') \gamma^\mu u(p) = 2p^\mu \tag{3.12} \]

Eq. (3.13) allows us to express \( \varepsilon_0 \) in terms of \( \varepsilon \), with the result:

\[ M_{fi} = 2e \varepsilon \cdot \left[ \frac{k_0^0}{n^2(\omega)\omega} - p \right] \tag{3.13} \]

Summing over all the polarization states:

\[ \langle |M_{fi}|^2 \rangle = 4e^2 \left[ \frac{k_i E}{n^2(\omega)\omega} - p_i \right] \left[ \frac{k_j E}{n^2(\omega)\omega} - p_j \right] \left( \delta_{ij} - \frac{k_i k_j}{k^2} \right) \tag{3.14} \]

This expression is further simplified through the relations:

\[ p \cdot k = \frac{p}{\beta} \omega \]
\[ k^2 = n^2(\omega)\omega^2 \tag{3.15} \]

leading to:

\[ \langle |M_{fi}|^2 \rangle = 4e^2 p^2 \left( 1 - \frac{1}{n^2(\omega)\beta^2} \right) \tag{3.16} \]

Finally, the frequency spectrum is:

\[ d\Gamma = \frac{1}{2E} 4e p^2 \left( 1 - \frac{1}{n^2(\omega)\beta^2} \right) \frac{1}{8\pi} \frac{d\omega}{p} = \alpha \beta \left( 1 - \frac{1}{n^2(\omega)\beta^2} \right) d\omega \tag{3.17} \]

where \( \alpha \) is the fine–structure constant. Equivalently:

\[ \frac{d\Gamma}{d\omega} = \alpha \beta \sin^2 \theta_C \tag{3.18} \]
being \( \theta_C \) the angle between the particle direction and the Cherenkov photon momentum. The energy loss of the particle equals to:

\[
\frac{dE}{dx} = \frac{1}{\beta} \frac{dE}{dt} = \frac{1}{\beta} \int \omega d\Gamma = \alpha \int \left(1 - \frac{1}{n^2(\omega)\beta^2}\right) \omega d\omega
\]

the above integral ranging over those frequencies for which \( n(\omega) > 1 \) and emission can take place. For all dielectric media, there is a natural cut-off defined by the plasma frequency \( \omega_p \), so that the refractive index can be written as [53]:

\[
n(\omega) = \left(1 - \frac{\omega_p^2}{\omega^2}\right)
\]

For frequencies larger than \( \omega_p \), the refractive index is always lower than unity and the Cherenkov threshold condition can not be satisfied by any physical particle.

### 3.3 Cherenkov detectors

The use of Cherenkov radiation for particle identification started immediately after its discovery [39]. At the beginning, distilled water was used as radiator and photographic emulsions or researcher eyes as photon detector.

An important improvement in the use of this radiation for particle physics experiments had to await the end of World War II, thanks to the development of the vacuum PhotoMultiplier Tubes (PMT) which allowed the detection of such a feeble light with high efficiency and fast response. It was J. V. Jelley who first in 1951 employed photomultiplier tubes to detect single fast particles with high efficiency [55].

The idea to discriminate particles by measuring the emission angle \( \theta_C \) was conceived by A. Roberts in 1960 and proved to be an extremely powerful method for identification of particles [50]. In 1977, T. Ypsilantis and J. Seguinot used gaseous photon detector to detect Cherenkov photons [57]. This technique was named RICH, an acronym for “Ring Imaging CHerenkov” coined by T. Ekelof as a good omen for the funding situation of the experimental group involved in the R&D program. In 1982 the first RICH detector was successfully installed at a high energy physics experiment (E605 at Fermilab [58]), and many others have been designed and built since then, thanks to the considerable advances in the technologies associated with photon detectors.

A full detailed review about Cherenkov detectors can be found elsewhere [59, 60].
3.3.1 Operating principles of RICH counters

The use of Cherenkov effect to measure the velocity of charged particles over a wide momentum spectrum requires the detection of as many photons as possible conserving the emission angle information. In a RICH detector, photons emitted from several particles in the same event are focused by spherical (or parabolic) mirrors onto a photon detection system that converts photons into electrons with high spatial and temporal resolutions.

Photon detectors are placed on the focal surface of the mirror; several photon detection approaches are possible. Generally the photo–electric effect is exploited to convert the impinging photons into electrons which are accelerated and then detected. The choice of the photoelectron detection technique is related to the speed and resolution requirements and the energy range of the photons.

Spherical mirrors play an important role: parallel rays are focused on the same point in the focal plane, so the image of the Cherenkov cone of photons emitted along the trajectory of the particle becomes a ring and the radiator thickness effect disappears. The refractive index of the transparent dielectric medium, referred to as the radiator, is appropriate for the range of particle momentum being specifically studied and for the photon detection system.

The design of a Cherenkov detector relies on Eq. (3.10) and (3.19) and on the knowledge of the optical properties of the radiator. The number $N$ of detected photoelectrons for a charged particle crossing a radiator with length $L$ is:

$$N = \left(\frac{\alpha}{\hbar c}\right) L \varepsilon_A \int TRQ \sin^2 \theta_C dE = N_0 L \sin^2 \theta_C$$

being $\varepsilon_A$ the fraction of the photon detector active area, $T$ the transparency of the radiator and windows, $R$ the mirror reflectivity and $Q$ the quantum efficiency of the photon detectors. The proportionality factor $N_0$ is referred to as the figure of merit of the detector, and the larger is the $N_0$, the better is the detector.

The number of detected photoelectrons given by Eq. (3.21) is the expected value of a Poisson distribution. For saturated charged particles, the Cherenkov angle asymptotically tends to $\theta_{max}$ which is related to the threshold Lorentz factor $\gamma_{th}$ as:

$$\sin^2 \theta_{max} = \frac{1}{\gamma_{th}^2}$$

with a maximum expected number of detected Cherenkov photons:

\footnote{RICH detectors without a focusing system (proximity focusing detectors) are also used.}
\[ N_{\text{max}} = \frac{N_0 L}{\gamma_{\text{th}}^2} \]  

(3.23)

The fraction of Cherenkov photons at a given angle with respect to the maximum yield is expressed by:

\[ \frac{N}{N_{\text{max}}} = \frac{\sin^2 \theta_C}{\sin^2 \theta_{\text{max}}} \]  

(3.24)

From Eq. (3.10), the resolution on the velocity measurement of the charged particle for a single detected photon is:

\[ \frac{\sigma_\beta}{\beta} = \sigma_{\theta_C} \tan (\theta_C) \]  

(3.25)

where \( \sigma_{\theta_C} \) is the uncertainty on the emission angle for a single detected photon. Several factors contribute to the total uncertainty on the measurement of \( \theta_C \):

- since all media are dispersive, the chromatic aberration of the radiating medium, \( \Delta n/n \), contribute to the resolution \( \sigma_\beta/\beta \) by a spread in the emission angle for Cherenkov photons with different energies. The related uncertainty is referred to as the chromatic error;

- spherical aberrations, misalignment of all the optical components and imperfections on the reflecting surfaces and windows contribute to the uncertainty on the Cherenkov angle with an optical error term;

- the finite granularity of the photon detectors introduces an uncertainty;

- spread in the particle direction due to multiple scattering in the radiator and errors in the reconstructed track parameters introduce an additional tracking error.

All these contributions are independent and add in quadrature; since each detected photoelectron gives a separate measurement, for \( N \) photoelectrons the Cherenkov angle resolution is improved, so that the resolution on the velocity of the charged particle becomes:

\[ \frac{\sigma_\beta}{\beta} = \frac{\sigma_{\theta_C}}{\sqrt{N}} \tan (\theta_C) \]  

(3.26)
Figure 3.3: Cherenkov angle $\theta_C$ distributions for each of the three radiators to be used in LHCb as a function of charged particle momentum and mass.

The particle identification performance of a RICH detector is usually expressed in terms of the separating power between different particles. For two particles with masses $m_1$ and $m_2$ and momentum $p$:

$$\frac{\Delta \beta}{\beta} \approx \frac{m_1^2 - m_2^2}{2p^2}$$

(3.27)

Consequently:

$$\frac{m_1^2 - m_2^2}{2p^2} = \frac{\beta n}{\sqrt{N}} \sigma_{\theta_C}$$

(3.28)

For those two charged particles, a RICH detector with a figure of merit $N_0$ measures the Cherenkov angle $\theta_1$ and $\theta_2$ with an accuracy described by the number of standard deviations $n_\sigma$ such that $(\theta_1 - \theta_2) = n_\sigma \sigma_{\theta_C}$. From Eq. (3.27), the corresponding upper momentum limit $p_{m_1,m_2}$ for $n_\sigma$ standard deviation separation is given by [60]:


\[ p_{m_1,m_2} = \sqrt{\frac{m_1^2 - m_2^2}{2n_\beta n_\sigma} \sqrt{N_0L}} = \sqrt{\frac{m_1^2 - m_2^2}{2n_\sigma} \frac{\sqrt{N}}{\sigma_{\theta_C} \tan \theta_C}} \]  

(3.29)

A good RICH design allows the value \( p_{m_1,m_2} \) to be extended as far as possible once \( n_\sigma \) has been fixed by physics requirements on the desired particle identification efficiency and the allowed contamination. Eq. (3.29) entails that the largest momentum limit is achievable by increasing the figure of merit \( N_0 \) and decreasing the single detected photon uncertainty \( \sigma_{\theta_C} \).

### 3.4 The RICH system in LHCb

As mentioned in the Section 2.4.6, particle identification is crucial for the physics program of LHCb. Separation between particles, and especially between \( \pi \) and \( K \), is essential to correctly tag CP violating and rare decays of \( B \) mesons. From Fig. (2.13) the correlation between the distributions of the polar angle \( \theta \) and the particle momentum \( p \) for all the tracks in simulated \( B_0^0 \rightarrow D^- \pi^+ \) events is clearly evident. In order to cover the wide momentum (2 – 100 GeV/c) and polar angle (10 – 300 mrad) ranges, two RICH detectors, RICH 1 and RICH 2, have been designed.

Three radiators are implemented, with different refractive indices. Solid silica aerogel is suitable for the lowest momentum tracks, while the intermediate region of the spectrum is well matched to gaseous \( C_4F_{10} \). For the highest momentum tracks, gaseous \( CF_4 \) is used. Fig. (3.3) plots the distribution of the Cherenkov angle \( \theta_C \) for each of the three radiators as a function of the momentum and the mass of several charged particles.

#### 3.4.1 RICH 1

RICH 1 [22, 28, 33, 61] is designed to provide particle identification over the momentum range 2 – 60 GeV/c. It combines solid silica aerogel and gaseous \( C_4F_{10} \) radiators to cover the full outer acceptance of the detector up to 300 (250) mrad in the horizontal (vertical) plane. It is hosted between the VELO system and the Trigger Tracker, before the magnet and close to the interaction region. The inner acceptance of 25 mrad is defined by the beam pipe. The lay-out of the detector and a cut-away 3D model of the detector are shown in Fig. (3.4).

Particles traverse 5 cm thick silica aerogel radiator before crossing 85 cm long \( C_4F_{10} \) gas radiator filling the gas enclosure. Cherenkov photons are focused onto the photon detector planes using tilted spherical mirrors and a secondary plane of flat mirrors, as shown in Fig. (3.4). The mirror surface is segmented into four rectangular quadrants with a footprint in the \((x,y)\) plane projection of the
Figure 3.4: General lay-out and cut-away 3D model of the vertical RICH 1 detector, here shown attached by its gas-tight seal to the VELO tank.

detector system of $795 \times 600 \text{ mm}^2$. Each quadrant is further segmented and consists of two mirrors; each of the eight mirrors can be individually adjusted in angle so that the upper and lower segments share a common centre of curvature.

The spherical mirrors have a radius of curvature 2700 mm and the axes of each spherical mirror quadrants are tilted by 316 mrad vertically with respect to the beam-line; they are hosted inside the LHCb acceptance. Since the overall reoptimization of the LHCb detector, beryllium–glass spherical mirrors are foreseen. The beryllium substrate is 3 mm thick and the glass coating is 0.3 mm, so that such items would contribute to the material budget of the experiment with 0.8% of a radiation length $X_0$ and 0.7% of a nuclear interaction length $\lambda_I$.

To cover the flat mirror surface, 16 rectangular mirrors will be used. All the 16 individual mirrors have the same nominal dimensions, $370 \times 387 \text{ mm}^2$, and consist of 6 mm thick glass; they are located outside the detector acceptance and tilted at an angle 250 mrad with respect to the $y$ axis.

As shown in Fig. (3.4), two photon detector planes are housed in the top and bottom magnetic shielding boxes, and they are tilted at an angle 1.091 rad with respect to the $y$ axis.

The emission point error is an acceptable value of 0.80 mrad for the gas radiator, and negligible compared with other sources of uncertainty for the aerogel. A typical track and its generated photons is displayed in Fig. (3.5).
3.4 The RICH system in LHCb

3.4.2 RICH 2

RICH 2 [22, 28, 33, 02] is placed between the last tracking station and the first muon station and it employs low refractive index gaseous CF$_4$ as Cherenkov radiator. This detector is suitable for high momentum particle identification. The average particle track length inside the gas radiator is 167 cm. Within the reduced angular acceptance limited to 120 mrad and to 100 mrad in the horizontal and vertical plane respectively, particle identification is extended beyond 100 GeV/c. A sketch of the RICH 2 lay-out is shown in Fig. (3.6).

The optical geometry configuration of RICH 2 is similar to the one adopted in RICH 1, but it is horizontally symmetric. On each side of the detector there is a spherical mirror surface of 4.1 m$^2$ and a flat mirror surface of 3.1 m$^2$. Spherical mirrors are inside the detector acceptance and focus the Cherenkov light; flat mirrors are used to reflect the ring images onto the photon detector planes housed outside the LHCb acceptance. The reflective surfaces are made up by matrices of mirror segments, each of which is fixed on an independent high precision adjustment support.

Each of the spherical mirror matrices is composed by 21 hexagonal and 7 half hexagonal 6 mm thick glass mirrors, and it is tilted by 390 mrad horizontally with respect to the beam–line. The radius of curvature is 8600 mm. To cover one
half of the flat mirror surface, 20 rectangular 6 mm thick glass mirror segments of $410 \times 380 \text{ mm}^2$ will be used. Each array is tilted by 185 mrad horizontally. The two photon detector matrices are placed inside the magnetic shielding boxes.

The overall emission point error is expected to be 0.33 mrad. The construction of the RICH 2 detector is at an advanced stage. The installation in the pit and the commissioning will start soon.

### 3.4.3 Radiators

Solid silica aerogel and gaseous C$_4$F$_{10}$ and CF$_4$ are the Cherenkov radiators. The main properties of these three materials are summarized in Tab. (3.1).

The variation of the refractive index as a function of the photon energy is the source of the chromatic error which constitutes the predominant contribution to the overall uncertainty $\sigma_{\theta}^{\text{total}}$ on the measured Cherenkov angle.

For aerogel, the Rayleigh scattering limits the performances of the Cherenkov angle reconstruction [53]. To reduce the background due to the UV photons which are the most scattered, a 100 $\mu$m thick glass filter is foreseen downstream of the aerogel. A more detailed discussion of the properties of silica aerogel will be given in Chapter [4].

Both the C$_4$F$_{10}$ and CF$_4$ gas volumes will be at room temperature and atmospheric pressure, and monitored during the data taking for ensuring the required level of impurities (water vapour and oxygen).

As mentioned in Tab. (3.1), the emission point error is related to the fact that with tilted focusing mirrors the image of each Cherenkov photon depends

$^4$D 263 T borosilicate glass by SCHOTT Guinchard SA.
Material | Aerogel | C₄F₁₀ | CF₄
---|---|---|---
$L$ cm | 5 | 85 | 167
$n$ | 1.03 | 1.0014 | 1.0005
$\theta_{max}^C$ mrad | 242 | 53 | 32
$p_{th}(\pi)$ GeV/c | 0.6 | 2.6 | 4.4
$p_{th}(K)$ GeV/c | 2.0 | 9.3 | 15.6
$\sigma_{\theta_{emission}}$ mrad | 0.34 | 0.80 | 0.33
$\sigma_{\theta_{chromatic}}$ mrad | 2.07 | 0.80 | 0.47
$\sigma_{\theta_{pixel}}$ mrad | 0.57 | 0.57 | 0.16
$\sigma_{\theta_{total}}$ (RICH only) mrad | 2.19 | 1.29 | 0.60
$\sigma_{\theta_{total}}$ (RICH+Tracks) mrad | 2.60 | 1.60 | 0.61
$N$ | 6.8 | 31.0 | 23.0

Table 3.1: Parameters of the radiators to be used in the RICH systems and contributions to the resolution as determined from the simulation. The total resolution per photoelectron and the mean number of detected photoelectrons in the ring image are also reported.

on its emission point on the track. In the reconstruction algorithm, all photons are treated as if they were emitted at the mid–point of the track through the radiator, leading to some smearing of the reconstructed angle.

### 3.4.4 The LHCb Hybrid Photon Detector

The photon detector planes of both RICH detectors cover a total area of 2.6 m² over which it is necessary to detect single photons with a high efficiency and high spatial granularity. A spatial resolution of 2.5 × 2.5 mm² has been chosen as the best compromise between cost considerations and the requirement that the uncertainty due to the finite pixel size of the detector does not dominate the total uncertainty in the measurement of the Cherenkov angle. Photon detectors need to be sensitive to Cherenkov photons both in the visible and in the UV ranges of the electromagnetic spectrum. The read–out must be fast, compatible with the 25 ns time between bunch crossings. The pixel Hybrid Photon Detector (HPD) solution has been selected after a very intense R&D activity [63].

A schematic drawing of the HPD and a photograph of a small array are shown in Fig. (3.7). Pixel HPDs have been developed in collaboration with industry. They consist of a cylindrical vacuum tube with an overall diameter of 83 mm; the base of the tube houses the silicon sensor equipped with 1024 pixels of 0.5 × 0.625 mm² in size grouped in 0.5 × 0.5 mm² super–pixel which, thanks to the electrostatic image demagnification factor of five, corresponds to the nominal 2.5 × 2.5 mm² granularity of the HPD photocathode.

On the inner surface of the 7 mm thick quartz spherical entrance window a S20
Figure 3.7: Left: schematic drawing of a pixel Hybrid Photon Detector, illustrating photoelectron trajectories. Right: photograph of the first six hexagonally packed photon detectors successfully tested in a recent beam test (November 2004).

Figure 3.8: Measured quantum efficiency as a function of incident photon energy of a typical pre-production pixel Hybrid Photon Detector.

multi–alkali photocathode is deposited; a typical quantum efficiency distribution of the window–photocathode system is plotted in Fig. (3.8). Photoelectrons created by incident Cherenkov photons are accelerated and cross–focused onto the silicon sensor by the potential difference between the grounded anode and the photocathode at $-20$ kV. Two intermediate electrodes define the focusing shape of the electrical field and the demagnification factor. The impact of the photoelectrons on the sensor generates a signal of about 5000 electrons. The 1024 channels, radiation tolerant CMOS front–end chip is encapsulated inside.
3.4 The RICH system in LHCb

The RICH system in LHCb

Figure 3.9: HPDs detector assembly designed for RICH 2.

each HPD. It accepts input data at 40 MHz and provides discriminated binary signals with 4 µs latency.

A detailed design of the HPDs assembly has been developed. Fig. (3.9) shows the assembly: 7 columns of 14 HPDs and 9 columns of 16 HPDs per side (top–bottom and left–right) are foreseen for RICH 1 and RICH 2 respectively. Every column carries also the Level–0 electronics (Interface Module), the Low Voltage (LV) and High Voltage (HV) distribution boards. The HPDs are hexagonally packed, with a pitch of 91.5 mm for RICH 1 and 89.5 mm for RICH 2.

The residual magnetic field in both RICH regions degrade the imaging performances of the HPDs. Dedicated studies have been done to parameterize the image deformation. The external magnetic field causes the photoelectron trajectory to be bent, resulting in a non–trivial correspondence between the position of the impinging photon on the photocathode and the pixel hit on the anode. Fig. (3.10) shows an example of such distortions. An HPD tube without a dedicated shielding is magnetic tolerant up to approximately 10 gauss. A single tube with a 1 mm thick Mumetal® shield can tolerate a magnetic field in the order of 30 gauss. Despite the overall iron shielding boxes, all tubes will be housed in Mumetal cylinders. Residual distortions will be regularly monitored during data taking and corrected for in the offline analysis [64].

5Mumetal®–Magnetic Shielding Alloy is a proprietary name for a high permeability, magnetically soft alloy.
Figure 3.10: Left: test pattern with no magnetic field applied as recorded by an HPD tube with an individual magnetic shielding. Middle: distortion of the previous pattern with a 50 gauss longitudinal magnetic field applied. Right: the same as before, but with a 50 gauss transverse magnetic field [64].

Figure 3.11: Event display of detected photoelectrons for a typical event in RICH 1 and RICH 2. All the background sources and detailed photon detector response are included. The two detector plane halves are plotted next to each other; fitted rings are also superimposed, indicated by solid lines for rings from long tracks and dashed lines for other tracks.

3.5 Pattern recognition and performances

Fig. (3.11) shows an event display of the photon detector hits in a typical event for both the RICH detectors: for RICH 1, densely populated small diameter rings can be seen from the C_4F_{10} gas radiator, as well as the more sparsely populated large diameter rings from silica aerogel.

Particle identification by RICH detectors is performed by the following pattern
recognition tool. The pattern of hit pixels of HPDs is compared to the pattern that would be expected under a given mass hypothesis for the reconstructed tracks crossing the detectors, using the knowledge of their optics. A likelihood is determined from this comparison and then maximized varying the track mass hypothesis. Due to the high track multiplicity environment typical of LHCb events, the main source of background photons is from neighbouring tracks; by maximizing the global likelihood function for all the found tracks, this background can be optimally controlled [22, 28, 33, 65].

To study the performance of the RICH system, long tracks from several decay channels have been simulated. The ratio of log–likelihoods between assuming pion and kaon mass hypothesis in the analysis is determined:

$$\Delta \ln \mathcal{L}_{K\pi} = \ln \mathcal{L}(K) - \ln \mathcal{L}(\pi) = \ln \left[ \frac{\mathcal{L}(K)}{\mathcal{L}(\pi)} \right]$$

(3.30)

This log–likelihood difference can be converted into the number of standard deviations describing the significance of $\pi/K$ separation, as already explained in Section 3.3.1, according to the relation:

$$n_\sigma = \sqrt{2|\Delta \ln \mathcal{L}|}$$

(3.31)

The distribution of the significance is shown in Fig. (3.12) as a function of momentum for all the tracks matched to true pions in $B^0_d \rightarrow \pi^\pm \pi^{\mp}$ events. The few negative significance entries correspond to tracks for which the kaon mass hypothesis was preferred over the pion one. The superimposed average illustrates that $\pi/K$ separation can be successfully achieved over most of the momentum range between 2 GeV/c and 100 GeV/c.

Since the significance shown in Fig. (3.12) has not a Gaussian shape for a fixed momentum of the particle, more relevant is the performance expressed as the efficiency for the reconstructing $K$ mesons viewed in conjunction with the misidentification rate for $\pi$ mesons. The typical average efficiency for $K$ meson identification is 88% over the momentum range of interest, and the average $\pi$ meson misidentification rate is $3-6\%$. By varying the $\Delta \ln \mathcal{L}$ cut used to $\pi/K$ separation, the misidentification rate of $\pi$ can be reduced improving the purity of the selected sample at the cost of reduction of the $K$ identification efficiency. Of course, the trade–off between efficiency and purity can be adjusted offline according to the needs of the physics analysis [28].

As an example, with a cut $\Delta \ln \mathcal{L}_{K\pi} > 2$ to the long tracks from $B^0_s \rightarrow D^\pm_s K^\mp$ events, the selected sample comprises 62% kaons, 10% pions and 22% protons.

6Tracks traversing the full detector from the VELO to the tracking stations are classified as “long tracks”; they are the most important set of tracks for $B$ decay reconstruction.
Figure 3.12: Left: significance of $\pi/K$ separation as defined in Eq. (3.30) as a function of momentum for true pions, for each track in a sample of $B^0_d \rightarrow \pi^\pm \pi^\mp$ events. The average separation is superimposed as a line. Right: $K$ meson identification efficiency (solid points) and $\pi$ meson misidentification rate (open points) as a function of momentum. The effect of crossing the thresholds for Cherenkov light production in the three radiators is visible.

(the remainder 6% being leptons and ghosts); the proton background can be furthermore suppressed applying a cut on $\Delta \ln L_{Kp}$. Requiring $\Delta \ln L_{Kp} > -2$, the proton contamination is reduced by a factor two with a loss of kaon efficiency of only 3%.
Chapter 4
Silica aerogel

Silica aerogel is a solid material made of SiO$_2$ with a very low density. Thanks to its transparency and its refractive index which can be tuned within a wide range to match the physical requirements, silica aerogel is an appealing material for Cherenkov detectors.

This chapter is mainly devoted to a detailed presentation of the R&D activity carried out on samples from different manufacturers, providing feedback to the production lines in the attempt to achieve optimal quality aerogel to be used in LHCb RICH 1 detector.

4.1 Introduction to silica aerogel

The first attempts to use silica aerogel as radiator in Cherenkov detectors were made in mid 1970s when samples with high transparency started to be available [66]. Then, in the early 1980s, two large Cherenkov detectors were designed: one using 1700 litres of silica aerogel in the TASSO detector at DESY and another with 1000 litres in the EHS experiment at CERN [67, 68].

Since then, many threshold and RICH counters adopted aerogel to identify charged particles with momentum ranging from a few hundred MeV/c to a few GeV/c. In 1998 a RICH detector with silica aerogel as radiator has been constructed and implemented in the HERMES detector [69, 70]. Other experiments like LHCb, AMS and BELLE plan to use silica aerogel [10, 22, 71, 72].

Silica aerogels are not recent products of modern technology; the first aerogels were prepared in 1931. At that time, S. S. Kistler discovered the key aspects of aerogel production and published the first paper on aerogels [73]. Kistler’s silica aerogels were very similar to the ones prepared today: they were transparent, low density, and highly porous materials that stimulated considerable academic interest. A few years later, Kistler took a position with the Monsanto Corporation. Shortly thereafter, Monsanto began marketing a product known simply as “aerogel”. Monsanto’s aerogel was used as an additive or a thixotropic
agent in cosmetics and tooth–pastes. Very little new work on aerogels occurred throughout the next three decades.

Aerogels had been largely forgotten when, in the late 1970s, the French government approached S. Teichner seeking a method for storing oxygen and rocket fuels in porous materials in a practical and safe way. This R&D activity lead to improve the manufacturing technique of aerogel in terms of homogeneity of the product and time efficiency.

After that, new developments in aerogels science and technology occurred rapidly as an increasing number of researchers joined the field. Industrial plants as well as research centres were pushed toward the production of samples with as high transparency as possible, isotropic as far as the optical properties are concerned, and with customized refractive index.

In 2002 S. Jones of NASA’s Jet Propulsion Laboratory (USA), a scientist who produced the aerogel used by STARDUST device to capture both cometary and interstellar material samples, also created the lightest version ever with a density of only 3 mg/cm$^3$ [74]. The team was awarded the Guinness World Record Official Certificate. Further information about recent applications of silica aerogels can be found elsewhere [75].

### 4.1.1 Synthesis of silica aerogel

The production of silica aerogels involves two steps, the formation of a wet gel, and its drying. In the early days wet gels were made by the aqueous condensation of sodium silicate. While this process worked well, the reaction formed salts within the gel, so their removing was needed by many repetitive washings (a time–consuming and laborious procedure). Since mid 1970s, with the rapid development of sol–gel chemistry, the production of all silica aerogels utilizes silicon alkoxide as precursors in the metabolic pathway, such as tetramethyl orthosilicate Si(OCH$_3$)$_4$ (TMOS), and tetraethyl orthosilicate Si(OCH$_2$CH$_3$)$_4$ (TEOS). However, since there is not a unique recipe for manufacturing aerogel, final products can also have different properties.

#### Sol–gel chemistry

The chemical equation for the formation of a silica gel from TEOS is:

$$\text{Si(OCH}_2\text{CH}_3\text{)}_4 + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 4\text{HOCH}_2\text{CH}_3$$

(4.1)

$^1$Thixotropy is the property of certain gels of becoming fluid when agitated and of reverting back to a gel when left to stand.
This reaction is typically performed in an ethanol environment. The density of the final product depends on the concentration of silicon alkoxide monomers in the solution.

**Catalysts**

Since the kinetics of the above reaction is slow at room temperature, often requiring several days to reach completion, acid or base catalysts are usually added to the mixture to speed up the reaction. The type and amount of catalysts used play key roles in the microstructural, physical and optical properties of the final product.

As condensation reactions progress, the liquid solution will set into a much more dense material. At this point, the gel is usually removed from its mould, but it must be kept covered by alcohol to prevent evaporation of the liquid contained in the pores of the gel. Evaporation causes severe damage to the gel and will lead to poor quality aerogels.

**Ageing and soaking**

When a sol reaches the gel point, it is often assumed that the hydrolysis and condensation reactions of the silicon alkoxide reactant are complete. This is far from being the case. The gel point simply represents the time when the polymerizing silica species span the container containing the sol. At this point the silica backbone of the gel contains a significant number of unreacted alkoxide groups: hydrolysis and condensation can continue for several times the time needed for a complete gelation. Sufficient time must be given for the strengthening of the silica network. This can be enhanced by controlling both the pH and water content of the covering solution. The gels are best left undisturbed in this solution for up to 48 hours.

This and all the subsequent processing steps are diffusion controlled. That is, transport of material into and out of the gel is unaffected by convection or mixing (due to the solid silica network). Diffusion, in turn, is affected by the thickness of the gel. In short, the time required for each processing step increases dramatically as the thickness of the gel increases.

Once the gel is formed, all the water still contained within its pores must be removed prior to drying. This is simply accomplished by soaking the gel in pure alcohol several times until all the water is removed. Again, the time required for this step is thickness dependent. Any water left in the gel will not be removed by supercritical drying and will lead to an opaque, white, and very dense aerogel.

**Supercritical drying**

The last and most important step in silica aerogel production is the supercritical drying. This is where the liquid within the gel is removed, leaving only the linked
silica network. The process can be performed by venting the ethanol above its critical point (high temperature: very dangerous) or by prior solvent exchange with CO$_2$ followed by supercritical venting (low temperature: less dangerous). For this last procedure, the use of an autoclave specially designed for that purpose is mandatory.

4.1.2 Chemical and physical properties of silica aerogels

As shown in Fig. (4.1), the final product consists of a linked network of particles of 2 – 5 nm in diameter, and pores whose average radius is about 20 nm. Silica particles of such a small size have an extraordinarily large surface to volume ratio, approximately $2 \times 10^9$ m$^{-1}$, and a corresponding high specific surface area, $\sim 1000$ m$^2$/g. In Appendix A, typical values of some physical properties of silica aerogel are given.

The density is calibrated by choosing the appropriate TEOS to ethanol ratio during the gel formation process; typically it lies in the range 0.003 – 0.35 g/cm$^3$.

The nature of the surface groups of a silica aerogel is strongly dependent on the conditions used in its preparation. For aerogel prepared using the supercritical alcohol drying process, the surface consists of alkoxy (–OR) groups. On the other hand, with the carbon dioxide drying process, the surface is almost covered with hydroxyl (–OH) groups. A more striking effect of the hydroxyl surface is seen in the physical behavior of silica aerogels.

As with most hydroxyl surfaces, the surface of silica aerogels can show strong hydrogen–bonding effects. Because of this, aerogels with hydroxyl surface are extremely hygroscopic. Dry aerogels will absorb water directly from air, with mass increases of up to 20%. This absorption has no visible effect on the aerogel,
While the adsorption of water vapor does not harm silica aerogels, contact with liquid water has disastrous results: the net effect is a complete collapse of the aerogel monolith. The material changes from a transparent solid with a definite shape to a fine white powder. This powder has the same mass and total surface area as the original aerogel, but it has lost its solid integrity. Silica aerogels with fully hydroxylated surfaces are, therefore, classified as hydrophilic or hygroscopic. This problem can be circumvented by converting the surface hydroxyl (–OH) groups to a non-polar (–OR) group. This completely protects the aerogel from damage by liquid water. Silica aerogels produced in this way are classified as hydrophobic. Fig. (4.2) shows how the interaction of water with the pore structure and solid backbone of silica aerogels works.

Silica aerogels have a very low thermal conductivity which decreases even further under vacuum; for this reason, they are an attractive alternative to traditional insulation thanks to their high insulating power and very small weight.

4.1.3 Optical properties of silica aerogel

The good reason which makes silica aerogel an appealing material for Cherenkov detectors is that its refractive index $n$ can be easily tuned. The refractive index $n$ and the aerogel density $\rho$ are related according to the formula:

$$n(\lambda) = 1 + k(\lambda)\rho$$

(4.2)

which is an approximation of the general Clausius–Mossotti relation for values of the refractive index very close to unity [53].
Typically, if the density \( \rho \) is expressed in g/cm\(^3\), at \( \lambda = 400 \) nm the wavelength dependent coefficient \( k \) is about 0.21 \( i.e. \); the knowledge of this coefficient is necessary for a fast and simple refractive index control during the production. As a result, the refractive index can be selected according to the experimental and physical requirements in the wide range between 1.01 and 1.1 (at \( \lambda = 600 \) nm), lower than any liquid at STP conditions and higher than all gases at pressures up to 10 bar. This makes silica aerogel a suitable Cherenkov radiator for a detector designed to identify charged particles in the low momentum range \( 1 - 10 \) GeV/c.

Aerogel is transparent, a compulsory property for a Cherenkov radiator. The light diffusion within the aerogel is usually the factor limiting the performance of this material as Cherenkov radiator for a RICH detector. The pore structure of aerogel acts as a network of scattering centres. The dominant contribution to the total diffusion probability comes from the Rayleigh scattering mechanism. The scattering cross section for a photon of wavelength \( \lambda \) is proportional to \( \lambda^{-4} \). As shown in Fig. (4.3), the material displays a slight bluish haze when an illuminated piece is viewed against a dark background.

The absorption cross section is, within a wide range, wavelength independent and can be neglected when considering samples a few centimetres thick. The transparency \( T \) of the aerogel is well parameterized by the Hunt formula:

\[
T(\lambda) = \frac{I}{I_0} = A e^{-Ct/\lambda^4}
\]

where \( I_0 \) and \( I \) are the incident and the transmitted wavelength dependent intensities of the light beam through the sample. \( A \) is the surface scattering coefficient,
4.2 Optical characterization of silica aerogel

Several properties and behaviours of aerogel can be tested [78]. In view of the particular LHCb application, the transparency $T$, the refractive index $n$ and the

$t$ the thickness of the aerogel block, and $\lambda$ the wavelength of the impinging light beam. $C$ is the clarity factor and it is used to specify the optical quality of a sample together with $A$. They are usually referred to as the “Hunt parameters”. An ideal aerogel would have $A$ and $C$ close to 1 and 0 respectively.

Independent laboratory and beam tests have been carried out in order to evaluate the performances of a variety of aerogels. In particular, hygroscopic aerogel produced at the Boreskov Institute of Catalysis in collaboration with the Budker Institute of Nuclear Physics in Novosibirsk (Russia) and hydrophobic aerogel from the Matsushita Electric Works Ltd. (Japan) have been considered.

A big effort in the R&D activity has been put during the last few years in order to obtain large size with high clarity silica aerogel. Thanks to our russian colleagues, LHCb will use hygroscopic aerogel, $200 \times 200 \times 50 \text{ mm}^3$ wide, the largest size ever.

Figure 4.4: Example of a transmittance measurement fitted with Eq. (4.3). The result of the fit, shown as the black dotted line, is hardly visible because superimposed to the measurement. It gives $A = (98.45 \pm 0.05)\%$ and $C = (0.00585 \pm 0.00001) \mu\text{m}^4/\text{cm}$. 

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.4.png}
\caption{Example of a transmittance measurement fitted with Eq. (4.3). The result of the fit, shown as the black dotted line, is hardly visible because superimposed to the measurement. It gives $A = (98.45 \pm 0.05)\%$ and $C = (0.00585 \pm 0.00001) \mu\text{m}^4/\text{cm}$.}
\end{figure}
uniformity of the refractive index within a tile have been measured for many tiles. Ageing effects due to irradiation and absorption of humidity as well as compatibility with $\text{C}_4\text{F}_{10}$ (the gas radiator of RICH 1) and natural ageing affects have been investigated.

### 4.2.1 Transmittance measurements

The transmittance $T$ is measured by means of a double beam spectrophotometer. A scan in the wavelength range between 200 nm and 800 nm is performed in steps of 1 nm. An example of such a spectrum is shown in Fig. 4.4 for a hygroscopic aerogel monolith from the first batch of $200 \times 200 \times 50 \text{ mm}^3$ blocks delivered. The curve has been fitted with Eq. 4.3 in order to determine both the parameters $A$ and $C$.

To estimate the point to point variation of the Hunt parameters $A$ and $C$, several measurements have been performed with the spectrophotometer beam entrance point scanning the two wider surfaces of a $50 \times 50 \times 20 \text{ mm}^3$ tile. The measured dispersion can be assumed as systematic error on $A$ and $C$ for the whole tile. For hygroscopic aerogel the transmittance at $\lambda = 400 \text{ nm}$ is uniform in the tile at the level of $3\% - 4\%$. The dispersion of the clarity factor $C$ is about $2\%$. In the case of hydrophobic aerogel, these dispersions are about $1\% - 2\%$ for the transmittance at $\lambda = 400 \text{ nm}$ and $7\%$ for the clarity $C$ respectively.

### 4.2.2 Measuring the refractive index

The refractive index $n$ of aerogel is measured using both green ($\lambda = 543.5 \text{ nm}$) and red ($\lambda = 632.8 \text{ nm}$) He–Ne laser sources. The measurements are performed
4.3 Behaviour with irradiation

using the prism method. Fig. (4.5) shows the block positioned in front of the laser beam on a turning table. The sample is rotated until the deflection angle $\theta_{\text{out}}$ reaches its minimum. In that condition the index of refraction is given by:

$$n = \frac{\sin \left( \frac{\Phi + \theta_{\text{out}}}{2} \right)}{\sin \left( \frac{\Phi}{2} \right)}$$  \hspace{2cm} (4.4)

where $\Phi$ is the angle between the two adjacent sides of the block ($\Phi \simeq 90^\circ$); $\theta_{\text{out}}$, the deflection angle, is determined by measuring the displacement $x$ with a CCD camera$^2$ located at a distance $L$ from the aerogel.

4.3 Behaviour with irradiation

Due to the LHC hot environment, the aerogel radiator will be exposed to very intense irradiation; possible deterioration of its optical properties can reduce the particle identification performances.

The aerogel radiator wall will be positioned close to the beam pipe, approximately one metre downstream of the interaction point, so it will be exposed to a significant particle flux, up to $3.5 \times 10^{12} \text{ particles/cm}^2/\text{per year}$. In order to investigate possible deteriorations, samples of aerogel have been exposed to different sources of particles and their optical parameters monitored at different steps of the irradiation process.

4.3.1 Sources of irradiation

One hygroscopic, $50 \times 50 \times 23 \text{ mm}^3$ tile has been exposed to a proton source (IRRAD–1$^7$) using the CERN PS T7 East Hall beam. The primary proton beam had a momentum of 24 GeV/$c$, the spot was $2 \times 2 \text{ cm}^2$ wide with fluxes in the range $1 - 3 \times 10^{13} \text{ p/cm}^2/\text{h}$. Because of the small size of the beam, irradiation was concentrated only in the centre of the tile.

The proton exposure was made in six steps, as summarized in Tab. (4.1). The total fluence amounts to $51.525 \times 10^{12} \text{ p/cm}^2$. The first three irradiation steps correspond each to about one year of operation of the aerogel at LHCb, the last ones to larger doses that will not be reached in the lifetime of the detector, according to accurate simulations.

Another tile was exposed to neutrons, this time irradiating uniformly the whole tile. Neutrons were obtained using the CERN PS T8 proton beam with

$^2$SONY® XC–ST70CE with 768 × 512 pixels and a sensitive area of $1.025 \times 0.850 \text{ cm}^2$. 
Table 4.1: Fluence in number of protons per square centimetre traversing the central part of the aerogel sample. For each irradiation step, the fitted values of $A$ and $C$ are shown. The quoted errors are those determined by the fit.

<table>
<thead>
<tr>
<th>Fluence $(10^{12} , \text{p/cm}^2)$</th>
<th>$A$ (%)</th>
<th>$C$ $(10^{-4} , \text{µm}^4/\text{cm})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>83.13 ± 0.04</td>
<td>53.8 ± 0.1</td>
</tr>
<tr>
<td>3.545</td>
<td>86.45 ± 0.04</td>
<td>54.5 ± 0.1</td>
</tr>
<tr>
<td>7.045</td>
<td>91.55 ± 0.04</td>
<td>55.2 ± 0.1</td>
</tr>
<tr>
<td>9.725</td>
<td>91.00 ± 0.04</td>
<td>55.8 ± 0.1</td>
</tr>
<tr>
<td>19.445</td>
<td>86.18 ± 0.04</td>
<td>56.9 ± 0.1</td>
</tr>
<tr>
<td>35.645</td>
<td>88.23 ± 0.04</td>
<td>54.6 ± 0.1</td>
</tr>
<tr>
<td>51.525</td>
<td>85.22 ± 0.04</td>
<td>54.5 ± 0.1</td>
</tr>
</tbody>
</table>

Table 4.2: Fluence in units of 1 MeV equivalent neutrons per square centimetre absorbed by the aerogel sample irradiated with the mixed beam ($n, p, \pi^\pm, \gamma$). For each irradiation step, the fitted values of $A$ and $C$ are shown. The quoted errors are those determined by the fit.

<table>
<thead>
<tr>
<th>Fluence $(10^{12} , \text{n/cm}^2)$</th>
<th>$A$ (%)</th>
<th>$C$ $(10^{-4} , \text{µm}^4/\text{cm})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>81.47 ± 0.04</td>
<td>57.0 ± 0.1</td>
</tr>
<tr>
<td>6.79</td>
<td>80.10 ± 0.04</td>
<td>62.3 ± 0.1</td>
</tr>
<tr>
<td>9.95</td>
<td>79.26 ± 0.04</td>
<td>64.2 ± 0.1</td>
</tr>
<tr>
<td>21.25</td>
<td>79.34 ± 0.04</td>
<td>64.7 ± 0.1</td>
</tr>
<tr>
<td>38.35</td>
<td>83.72 ± 0.04</td>
<td>67.3 ± 0.1</td>
</tr>
<tr>
<td>55.15</td>
<td>85.42 ± 0.04</td>
<td>68.3 ± 0.1</td>
</tr>
</tbody>
</table>

momentum of 24 GeV/c interacting on lead and carbon targets (IRRAD–2 [80]). Secondary particles were neutrons (energy range: 50 KeV – 1 GeV), protons, $\pi^+$, $\pi^–$ (energy range: 0.3 – 4 GeV) and $\gamma$ (energy range: 100 KeV – 100 MeV). An energy cut on the spectrum (energy higher than 100 KeV) was applied to calculate the dose of neutrons.

With this selection, 1 MeV equivalent neutron flux is $5.59 \times 10^{11} \, \text{n/cm}^2/\text{h}$ at 50 cm from the flux axis, $1.11 \times 10^{12} \, \text{n/cm}^2/\text{h}$ at 10 cm. The total accumulated fluence was $55.15 \times 10^{12} \, \text{n/cm}^2$, corresponding approximately to 15 years of LHCb data taking. Tab. (4.2) summarizes the measurements at each irradiation step.

Finally, tiles of both hygroscopic and hydrophobic aerogel were irradiated with $\gamma$ from a radioactive $^{60}\text{Co}$ source used in a Gammacell® 220 unit [81] located at

$^3$Gammacell® 220 is a proprietary name of the Atomic Energy of Canada Limited (AECL) and MDS Nordion International.
### 4.3 Behaviour with irradiation

#### Table 4.3: Dose absorbed by the hygroscopic and hydrophobic aerogel samples irradiated with $\gamma$ rays from $^{60}$Co. For each irradiation step, the fitted values of $A$ and $C$ are shown. The quoted errors are those determined by the fit. The absorbed dose is the equivalent dose calculated for SiO$_2$.

<table>
<thead>
<tr>
<th>Dose (Gy)</th>
<th>$A$ (%)</th>
<th>$C$ ($10^{-4}$ $\mu$m$^4$/cm)</th>
<th>Dose (Gy)</th>
<th>$A$ (%)</th>
<th>$C$ ($10^{-4}$ $\mu$m$^4$/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>97.09 ± 0.04</td>
<td>44.4 ± 0.1</td>
<td>0</td>
<td>94.33 ± 0.3</td>
<td>78.9 ± 0.2</td>
</tr>
<tr>
<td>38296</td>
<td>97.38 ± 0.04</td>
<td>44.0 ± 0.1</td>
<td>37305</td>
<td>96.59 ± 0.3</td>
<td>77.0 ± 0.2</td>
</tr>
<tr>
<td>73364</td>
<td>93.37 ± 0.04</td>
<td>39.0 ± 0.1</td>
<td>72373</td>
<td>98.18 ± 0.5</td>
<td>61.3 ± 0.2</td>
</tr>
<tr>
<td>115654</td>
<td>98.24 ± 0.04</td>
<td>41.5 ± 0.1</td>
<td>114663</td>
<td>97.99 ± 0.5</td>
<td>79.4 ± 0.2</td>
</tr>
<tr>
<td>229081</td>
<td>98.28 ± 0.04</td>
<td>41.0 ± 0.1</td>
<td>228090</td>
<td>98.36 ± 0.3</td>
<td>71.0 ± 0.2</td>
</tr>
</tbody>
</table>

the Istituto Superiore di Sanità in Rome (Italy). The source provides an uniform irradiation by $\gamma$ rays with an energy of 1.3 and 1.7 MeV. Also in this case, the transmittance was monitored as an ageing indicator after every irradiation period. Five irradiation steps provided a total dose of $\sim 230$ kGy, corresponding to the dose absorbed by the innermost region of the aerogel radiator in about 30 years of operation of LHCb. Tab. (4.3) summarizes the measurements with both hygroscopic and hydrophobic aerogel. The results with $\gamma$ irradiation on hydrophobic aerogel are in agreement with previous tests [82].

#### 4.3.2 Measurements and results

The transmittance of the irradiated tiles was measured before and after each irradiation step, and the curves were then fitted with Eq. (4.3) to determine the Hunt parameters $A$ and $C$. During irradiation, the hygroscopic tiles were sealed in a polyethylene bag filled with nitrogen to ensure isolation from humid air. Each time the transmittance was measured, the aerogel block was exposed to air for about one hour.

In order to disentangle effects due to the handling of the tiles from the irradiation ones, measurements were made systematically also on a reference tile, with optical parameters $A$ and $C$ very close to those of the irradiated ones. The comparison of the two samples was then made to account for the effects due to handling in the irradiation measurements. The ratio of the transmittances of the irradiated and the reference samples is plotted in Fig. (4.6) for different wavelengths as a function of the absorbed dose. Fig. (4.7) presents the ratios for the clarity factor. For proton irradiation, no evidence of degradation of the optical parameters is detectable for both the parameters $A$ and $C$.

The results from the neutron exposure show a more complex response. While $T$ does not change for wavelengths above $\lambda = 400$ nm, the value of the clarity...
Figure 4.6: Transmittance ratios $T_{irr}/T_{ref}$ as a function of the absorbed dose at different wavelengths for proton (left) and neutron (right) irradiation. A linear fit has been superimposed.

Figure 4.7: Clarity ratios $C_{irr}/C_{ref}$ as a function of the absorbed dose for proton (left) and neutron (right) irradiation. A linear fit has been superimposed.
factor $C$ presents an increasing trend, as if the structure of the silica aggregates and empty bubbles inside the tile were modified by the high flux of particles traversing the aerogel sample. The worsening in the clarity is mainly determined by the behaviour at small values of wavelength as shown in Fig. (4.6).

No detectable decrease of the aerogel optical quality has been found with $\gamma$ irradiation, as shown in Fig. (4.8): the transmittance $T$ is unchanged within the experimental uncertainties. For this kind of irradiation, the index of refraction was measured before starting the test and after $\sim$ 20 kGy; no detectable variations have been observed, as shown in Tab. (4.4). No comparison with reference tiles is available in the case of $\gamma$ irradiation.

### Table 4.4: Index of refraction for hygroscopic and hydrophobic aerogel samples as a function of the absorbed dose during $\gamma$ irradiation at $\lambda=632.8$ nm. Errors are explained in Section 4.4.2

<table>
<thead>
<tr>
<th>Absorbed dose (Gy)</th>
<th>Hygroscopic</th>
<th>Hydrophobic</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0336 ± 0.0003</td>
<td>1.0297 ± 0.0003</td>
</tr>
<tr>
<td>18797.0</td>
<td>1.0326 ± 0.0003</td>
<td>−</td>
</tr>
<tr>
<td>19788.0</td>
<td>−</td>
<td>1.0304 ± 0.0003</td>
</tr>
</tbody>
</table>

Figure 4.8: Transmittance as a function of the absorbed dose during $\gamma$ irradiation at different wavelengths (left) and clarity as a function of the absorbed dose (right). A linear fit has been superimposed.
4.4 Behaviour with humidity

As explained in Section 4.1.2, hygroscopic aerogel absorbs water from humid air. Water molecules can be eliminated by baking the aerogel at high temperatures. The humidity test was performed using the following procedure. The aerogel tile was baked at a temperature of \( \sim 500 ^\circ C \) for four hours. That temperature was reached in five hours in order to avoid possible cracks due to thermal stress. At the end of this first baking process, the index of refraction and transmittance were measured and \( A \) and \( C \) were determined. The aerogel block was then exposed to humid air for about one week; the optical parameters were monitored. Finally, a new baking cycle was done in order to find out if it was possible to restore the initial values.

4.4.1 The experimental set–up

Fig. 4.9 shows the set–up used to expose aerogel to humid air, very similar to a green–house. The aerogel tile was placed on a high precision balance; glasses of water were placed near the tile, inside the transparent box, creating a humid environment. The temperature of the room was about \( 24 ^\circ C \), and the variations of
Figure 4.10: Temperature and relative humidity of the room and weight variation of the aerogel tile as a function of time; vertical lines indicate intervals of 24 hours.
the aerogel weight caused by the absorption of water were recorded by the balance as a function of temperature and of relative humidity which were continuously monitored during all the test and are shown in Fig. (4.10). This figure shows also the variation of the aerogel weight as a function of time. The steep rise indicates that at the beginning the aerogel can absorb a large amount of water vapour, then the absorption of water slows down. Oscillations are due to a day–night effect in the temperature of the room.

The refractive index \( n \) and light transmission \( T \) of the hygroscopic aerogel were measured as a function of the humidity absorbed. If the relative humidity of the optical laboratory (where measurements are done) is different from the one of the aerogel environment inside the box, the aerogel can absorb or expel some water to reach equilibrium. This is a quite fast process, so in order to keep the aerogel under uniform conditions and thus minimize variations of weight, measurements were made turning off the air conditioning system of the room, inducing a relative humidity between 60% and 70%.

### 4.4.2 Measurements and results

The prism method, as described in Section [4.2.2](#), provides an accurate measurement of the refractive index. The uncertainty on \( n \) is related to that of the two angles \( \Phi \) and \( \theta_{out} \); the latter is determined by the two distances \( x \) and \( L \), as shown in Fig. (4.5). From Eq. (4.4), the error on \( n \) is given by:
4.4 Behaviour with humidity

<table>
<thead>
<tr>
<th>$m$ (g)</th>
<th>$n$</th>
<th>8.06</th>
<th>8.35</th>
<th>8.63</th>
<th>8.09</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0335 ± 0.0005</td>
<td>1.0345 ± 0.0012</td>
<td>1.0363 ± 0.0029</td>
<td>1.0331 ± 0.0009</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5: *Index of refraction measured with the green laser source as a function of mass variations during the humidity test. The refractive index after the second baking process is shown in the last column.*

\[
\sigma_n^2 = \left( \frac{\partial n}{\partial \Phi} \right)^2 \sigma^2_{\Phi} + \left( \frac{\partial n}{\partial x} \right)^2 \left[ \sigma^2_X + \frac{x^2}{L^2} \sigma^2_L \right] \quad (4.5)
\]

The laser spot on the CCD display presents a central region approximately 2 mm wide with halos around it, as shown in Fig. (4.11). The centre of gravity of the image was used to measure the $x$ displacement on the screen. The precision on $x$ and $L$ are $\sigma_x = 0.5$ mm and $\sigma_L = 5$ mm respectively. The uncertainty on the angle $\Phi$ is essentially determined by the small deviation from $\Phi = 90^\circ$ due to local imperfections on the surfaces of the tiles crossed by the laser beam. Assuming $\sigma_{\Phi} = 0$, the uncertainty on $n$ is $\sigma_n \sim 0.0003$. The contribution to $\sigma_n$ due to the uncertainty on the angle $\Phi$ is plotted in Fig. (4.11). The contribution to $\sigma_n$ due to the definition of the minimum displacement condition is negligible ($\sigma_n < 7 \times 10^{-5}$).

The refractive index was then determined from several measurements corresponding to different entrance points on the aerogel. The mean value was taken as the final measurement. Table (4.5) lists the values of $n$ as a function of the absorbed humidity reflected in the increase of the aerogel weight. The spreads of each set of measurements are reported as the errors. These spreads are related to local non–homogeneities of the tiles, but they are also connected to the fast variation of the aerogel weight during the measurement procedure, as explained in Section 4.4.1. The index of refraction increases with the amount of absorbed water. The maximum variation $\Delta n/n_0$ (corresponding to $\Delta m/m_0 = 7.1\%$) was 0.3% for the green laser source. Such variation would largely affect the particle identification performances.

Fig. (4.12) shows the results for the transmittance $T$ at different wavelengths and for the clarity factor $C$ measured at different steps of water absorption. A linear fit has been superimposed. For $C$ an increase as a function of the absorbed humidity has been detected. Tab. (4.6) summarizes the results of the humidity test.

The humidity test revealed that a prolonged exposure to humid air does not irreversibly degrade the optical properties of aerogel, which are completely restored by baking the exposed sample at $\sim 500^\circ$C for several hours, as shown in Fig. (4.12) and Tab. (4.6).
Figure 4.12: Left: transmittance as a function of $\Delta m / m_0$ at different wavelengths. Right: clarity as a function of $\Delta m / m_0$.

<table>
<thead>
<tr>
<th>$m$</th>
<th>8.06 g</th>
<th>8.35 g</th>
<th>8.61 g</th>
<th>8.07 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$ (%)</td>
<td>82.49 ± 0.04</td>
<td>82.54 ± 0.04</td>
<td>81.35 ± 0.04</td>
<td>81.94 ± 0.04</td>
</tr>
<tr>
<td>$C$ ($10^{-4} \mu m^4/cm$)</td>
<td>55.1 ± 0.1</td>
<td>61.9 ± 0.1</td>
<td>69.1 ± 0.1</td>
<td>57.3 ± 0.1</td>
</tr>
</tbody>
</table>

Table 4.6: Values of the parameters $A$ and $C$ as a function of mass for different steps in the humidity test. Results after the second baking process are listed in the last column.

### 4.5 Refractive index uniformity studies

The refractive index of aerogel is determined during production by tuning the density according to Eq. (4.2) [83]. Local density inhomogeneities lead to point to point variations of the refractive index within the monoliths. These variations contribute to the Cherenkov angle $\theta_C$ uncertainty in RICH detectors. In order for the contribution to the total resolution on $\theta_C$ due to inhomogeneities not to be the dominant one, the maximum allowed refractive index variation $\sigma(n - 1)/(n - 1)$ for LHCb aerogel is 1%, corresponding to an uncertainty $\sigma(\theta_C) \simeq 1.17$ mrad if $n = 1.030$.

A method to study possible refractive index variations uses a laser beam directed perpendicular to the aerogel surface in order to measure deviations from the straight optical path [84, 85]. Assuming a refractive index gradient within a monolith as the one shown in Fig. (4.13), the deviation angle $\delta$ can be determined as follows. The velocities of laser rays impinging on the two entrance points A and B separated by $dy$ are:
4.5 Refractive index uniformity studies

Figure 4.13: Diagram used to determine the deviation angle $\delta$ for an aerogel block with a refractive index gradient in the $y$ direction.

$$v_A = \frac{c}{n + dn}, \quad v_B = \frac{c}{n} > v_A \quad (4.6)$$

so, the time needed to travel the same infinitesimal distance $dt$ inside the block is given by:

$$\tau_A = \frac{dt}{v_A} = \frac{dt}{c (n + dn)}, \quad \tau_B = \frac{dt}{v_B} = \frac{dt}{c n} \quad (4.7)$$

The infinitesimal space difference travelled in the same time interval is:

$$dx = (\tau_A - \tau_B) \times c = \frac{dt}{n} \frac{dn}{n} \quad (4.8)$$

Simple geometrical considerations allow to write:

$$dx = \tan \delta(y) \ dy \simeq \delta(y) \ dy \quad (4.9)$$

being $\delta = \delta(y)$ the angle which is small if the refractive index difference $(n_A - n_B)$ is also small. As a consequence:
Figure 4.14: Experimental set-up used to study the refractive index uniformity with the laser beam method.

\[ d\delta(y)dy = \frac{dt}{n} \frac{dn}{dy} \]  

(4.10)

or:

\[ \frac{dn}{dy} = n \frac{d\delta(y)}{dt} \]  

(4.11)

The deviation angle \( \delta(y) \) is proportional to the refractive index gradient:

\[ d\delta(y) = \frac{dn}{dy} \times \frac{dt}{n} \]  

(4.12)

The last step consists in integrating Eq. (4.12): assuming both the refractive index \( n \) and its gradient in the \( y \) direction to be constant along the \( x \) axis, the integration over the whole thickness \( t \) of the aerogel block gives:

\[ \frac{dn}{dy} = n \frac{\delta(y)}{t} \]  

(4.13)

where \( t \) is the thickness of the aerogel tile. Scanning \( \delta(y) \) along the \( y \) direction, the integrated variation can be easily determined:

\[ \Delta n(y) = \frac{n}{t} \int_{y_0}^{y} \delta(y) \, dy \]  

(4.14)
4.5 Refractive index uniformity studies

Figure 4.15: Result from the scan of an aerogel block. The green solid line shows the maximum $\sigma(n)$ allowed by LHCb specifications; the blue dotted line shows the measured value of $\sigma(n)$ combining the two data series corresponding to scans along orthogonal directions on a $100 \times 100 \times 41$ mm$^3$ tile.

Fig. (4.14) shows the set–up arranged for the laser beam method. Results from one tested tile are plotted in Fig. (4.15). The limitation of this method is that only one wavelength at a time is used, and there is a certain arbitrariness in extrapolating the result to the wavelength range relevant for the Cherenkov effect. In any case a limited number of wavelength can be used.

An alternative method was therefore developed, based on the use of a charged particle beam with velocity $\beta = 1$. This method exploits the Cherenkov effect itself, and it is therefore appropriate to study the influence of refractive index variations convoluted with the emission spectrum on the Cherenkov angle reconstruction performance.

A set–up has been installed at the 500 MeV electron beam of the DAΦNE Beam Test Facility (BTF) at the “Laboratori Nazionali di Frascati” (Italy). The electron beam, producing saturated Cherenkov rings in the aerogel, is used to scan the index of refraction varying the entrance point of the beam in the aerogel block. Black & white, $8'' \times 10''$ wide photographic films$^4$ have been used as photon detectors. The exposed films have been processed by a professional photographic

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$^4$Kodak® Professional TRI-X 400 Film/400TX and ILFORD® HP5 Plus 400.
laboratory and then scanned and digitized for data analysis. The idea underlying these tests is that, by letting the beam enter the aerogel surface in different points, any local change in the refractive index reflects in a different distribution of the Cherenkov photons on the film. Two table–top Cherenkov counters have been designed and built, under the acronym “APACHE” for “Aerogel Photographic Analysis by Cherenkov Emission”.

4.5.1 The Beam Test Facility at DAΦNE

As shown in Fig. 4.16, the Beam Test Facility (BTF) is part of the DAΦNE complex. It includes a high current electron and positron LINAC machine, a 510 MeV electron and positron accumulator and two storage rings. The $e^-$ and $e^+$ beams from the LINAC are stacked and dumped in the accumulator ring for being subsequently extracted and injected into the main DAΦNE rings. When the injector system is not delivering beams to the accumulator, the beam can be transported into the beam test area by a dedicated transfer line.

The BTF facility has been designed and commissioned to provide a defined number of particles in a wide range of multiplicities and energies, mainly for detector calibration purposes.

4.5.2 APACHE I

A first configuration was chosen as a proximity focusing to simplify both installation and data analysis, in order to get a quick feed–back on the potential of the
method. Fig. (4.17) shows the layout of the set-up used for APACHE I.

On top of a 25 mm thick polymethyl–metacrylate (PMMA) plate, a dark–room was mounted to prevent spurious light in the hall to interfere with the experiment. Everything inside the dark–room was painted black to avoid reflection of scattered Cherenkov photons. The $100 \times 100 \times 41 \text{ mm}^3$ hygroscopic aerogel tile to be tested was placed on a platform with the wide faces perpendicular to the beam axis. The photographic film is mounted downstream and parallel to the aerogel, on a frame with blinds at a distance of 30 cm, such that the ring size is the maximum that the film can fully contain. The photons emitted by electrons going through the aerogel are collected onto the film. The dark–room volume is flushed with nitrogen to avoid as much as possible a variation of the optical properties of the aerogel due to the absorption of humidity [87]. A black paper screen is used to absorb the photons produced in nitrogen between the entrance window of the dark–room and the aerogel block, as shown in Fig. (4.17).

Since the Rayleigh scattering is the dominant contribution to the total diffusion probability inside the aerogel, runs have been taken with and without a UV filter at the exit surface of the aerogel to investigate possible advantages of absorbing the highest energy photons.

Fig. (4.18) shows how the film looks like after developing and scanning. The large ring contains Cherenkov photons emitted inside the aerogel; the small full circle in the centre of the film contains the photons emitted in nitrogen between the aerogel and the film itself.

The analysis of each film starts determining the centre of gravity of the distribution of nitrogen photons, which is used as the intersection point of the electron beam trajectory and the film surface. Centring on this point, the integrated light intensity in circles of increasing radius is calculated and the differential radial distribution of photons is built for each image. To first approximation, relative

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5D 263 T borosilicate glass by SCHOTT Guinchard SA.
Figure 4.18: Left: a GEANT4 simulation of the photon distribution on a film in a typical APACHE I run. Superimposed to the scatter plot, two circles show the edges of the distribution foreseen in the absence of Rayleigh scattering, the width being due to the aerogel thickness only. Right: scanned image of a data film. Part of the aerogel ring fell outside the acceptance due to misalignment.

variations of the refractive index from point to point inside an aerogel monolith reflect in shifts of the radial position of the peaks of those differential distributions.

The GEANT4 simulation tool–kit has been used to study the systematics involved in data processing and analysis [88]. Apart from the refractive index, many parameters influence the light distribution on the film, such as the direction of the electrons, the scattering probability, the aerogel thickness, the distance between the aerogel and the film and the detection efficiency curve of the film itself. All the details of the APACHE I configuration have been implemented in a dedicated complete simulation, used also to investigate the relation between the refractive index inhomogeneities and the measurable shifts of the radial intensity peak. A sample plot of the simulated distribution is shown in Fig. (4.18).

To limit spurious shifts of the light distribution due to film processing, the average light intensity in a small region close to the side of the film, blinded by the film holder (and therefore not exposed to Cherenkov light) has been determined as background. The resulting distribution, after background subtraction, is fitted with a Gaussian function modulated by the detection efficiency of the film, which has been estimated on the basis of the technical specifications of the film manufacturer and general considerations on the photographic process. A
4.5 Refractive index uniformity studies

Figure 4.19: Left: the radial, peak normalized light intensity distribution from a typical APACHE I run. In blue, the distribution is fitted with a Gaussian modulated by the film response function. Right: summary scatter plot of the measurements of all the APACHE I runs. The blue dashed lines bound the one standard deviation region around the average value for $R$.

A grain in the film is about $1 \mu m^2$ in size and it turns to a black point after development only if at least three photons impinge on it. The simulated photon distribution gives the probability per electron that a single grain is hit by three or more photons as a function of the radial distance of the grain from the centre of the inner ring. The quantum efficiency of the film is taken to be 100% and wavelength independent. The fit function has four free parameters: the peak position and height, the Gaussian spread and the integrated electron flux. Due to the relatively poor detection efficiency of the film, a rather high integrated fluence was needed; on average, 350 bunches of approximately $3 \times 10^7$ electrons were shot on the aerogel for each run. The fitted integrated electron flux agrees with the beam line measurements.

An example of one such fit is shown in Fig. (4.19). Runs were taken varying the position of the aerogel block with respect to the electron beam. With this configuration, the simulation shows that a point to point refractive index variation $\sigma(n - 1)/(n - 1)$ of 1% corresponds to $\Delta R = 0.4$ mm, where $R$ is the peak position in the radial distribution plot. The expected resolution is 0.25 mm and it is dominated by the thickness of the block. Results summarized in Fig. (4.19) give $\sigma(R) = 0.37$ mm. With the APACHE I resolution, the tested tile is within LHCb specifications.
4.5.3 APACHE II

In order to improve the precision in the mean Cherenkov angle measurement and therefore to have a higher resolving power in terms of refractive index inhomogeneities, a set of measurements with a focusing configuration was performed. A light–tight anodized aluminium vessel provides the housing for all the components. A sketch of the APACHE II set–up is shown in Fig. (4.20). The $100 \times 100 \times 41$ mm$^3$, hygroscopic aerogel tile is placed on a variable–height platform with the wide faces perpendicular to the beam–line axis; all the volume is flushed with dry nitrogen and a spherical mirror with a radius of curvature $R = 949$ mm is mounted downstream of the aerogel, vertically tilted with respect to the beam line. The vertical tilt moves the focal surface of the mirror where the film is placed to collect the focused Cherenkov photons, safely out of the electron beam path.

After a few preliminary runs, data have always been taken with the same UV filter used in APACHE I runs to kill the most energetic photons; a black paper screen is used to stop the Cherenkov photons produced by nitrogen upstream of the aerogel.

A new GEANT4 simulation has been implemented according to the new set–up, as shown in Fig. (4.21). An example of a simulated run and a scanned image of the film used with the new geometry is given in Fig. (4.22). With respect to APACHE I, the two rings are neater, but non–trivially distorted by spherical aberrations.

Data analysis has been performed on the digitized images, after the background has been subtracted as described in Section 4.5.2. From the actual position in space of a photon hit, it is possible to determine its Cherenkov emission.
4.5 Refractive index uniformity studies

Figure 4.21: A full detailed GEANT4 event display of a typical APACHE II event.

Figure 4.22: Left: a GEANT4 simulation of the photon distribution on the film in a typical APACHE II run. Right: scanned image of a data film. Part of the aerogel ring fell outside the acceptance due to limited size of the film plates.

angle. The direction of the electron beam, the photon emission point, the position in space of the centre of curvature of the mirror and its radius must be known.
Figure 4.23: Left: the Cherenkov angle distribution. The two peaks refer to photons emitted in nitrogen (low angles) and in aerogel (large angles). The light intensity is expressed in terms of the 8-bit value of the scan. Right: summary scatter plot of the results of all APACHE II runs. Blue and red data points belong to the horizontal and vertical scans respectively. The green solid line is the mean value of the average Cherenkov angle from all the films; the purple dashed lines bound the one standard deviation region around the mean value: \( \sigma(\theta_C) = 1.14 \text{ mrad} \).

The beam direction has been extracted from data. The centre of gravity of the nitrogen Cherenkov ring has been retracked considering it as the hit point of a photon in the same fashion as for the actual Cherenkov photons, assuming a beam direction along the reference line in the experimental hall. The direction determined by this retracking procedure has then been used as the real beam direction for the following film analysis. An average deviation of 24 mrad from the reference line has been measured and corrected for.

The hit by hit retracking algorithm allows to build the distribution of the reconstructed Cherenkov emission angle [65]. In Fig. (4.23) such distribution is plotted. From these plots the average shift of the mean Cherenkov angle from film to film is extracted, and therefore the point to point refractive index variation within the aerogel tile. The parameter which best suits for comparison among runs is the angle for which the distribution of Cherenkov photons from aerogel has a maximum. Simulation shows a strong correlation between a refractive index change and the corresponding shift in the reconstructed Cherenkov angle peak.

To study the uncertainties associated to this configuration the simulation was run in order to estimate the effect of small changes in the set-up geometry or beam conditions. The beam direction has been varied both as parallel displacement and as a tilt with respect to the nominal beam axis. The film position in space has
4.5 Refractive index uniformity studies

been varied in order to check the effect of systematic shifts in the reconstruction parameters in the analysis. Since the aim of the experiment is a scan of relative variations of $n$, it has been found out that small misalignments do not contribute substantially to the accuracy, as long as the conditions are stable from run to run.

The distribution of the Cherenkov angle of photons produced in the nitrogen volume between the aerogel and the spherical mirror is a good indicator to monitor the run conditions stability. The value of the angle for which the nitrogen ring has a maximum is independent of the aerogel, and it is expected to be constant from run to run, apart for tiny refractive index variations due to temperature and pressure changes. Any significant displacement of the nitrogen Cherenkov peak is then to be ascribed to uncontrolled variations of the beam conditions. It has been verified that the precision in the peak position is 0.3 mrad. All the contributions to the systematic uncertainties are listed in Tab. 4.7.

The scan performed on the block consisted in 15 points distributed on the surface at which the beam was shot. The variance $\sigma(\theta_C)$ of the angular peak positions in all the films is $\sigma(\theta_C) = 1.14$ mrad and it is shown in Fig. (4.23). This specific tile complies with the requested specifications $\sigma(\theta_C) \leq 1.17$ mrad.

### LHCb silica aerogel

A first batch of aerogel blocks complying the LHCb request on large thickness and transverse dimensions has been produced and delivered. One of these tiles has been tested with the APACHE II set-up. This tile is $200 \times 200 \times 50$ mm$^3$ wide and its Hunt parameters are $A = 98\%$ and $C = 0.0058$ µm$^4$/cm. A scan across the whole surface has been performed, 25 points in total.

The analysis followed the procedure explained in Section 4.5.3. A summary of these measurements is shown in Fig. (4.24): the deviation of the mean Cherenkov angle measured at each run with respect to the average of all measurements is plotted as a function of the coordinates of the electron beam entrance point on the aerogel surface. The interpolated colour map stops 2 cm from the sides, since no data have been taken with the beam nominal entrance point in that region. The plot suggests a refractive index gradient from the centre of the tile towards

<table>
<thead>
<tr>
<th>Source</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam divergence</td>
<td>0.1 mrad</td>
</tr>
<tr>
<td>Beam shift</td>
<td>0.1 mrad</td>
</tr>
<tr>
<td>Beam tilt</td>
<td>0.2 mrad</td>
</tr>
<tr>
<td>Film position</td>
<td>0.2 mrad</td>
</tr>
<tr>
<td>Total resolution</td>
<td>0.3 mrad</td>
</tr>
</tbody>
</table>

Table 4.7: Systematic contributions to the angular peak resolution in APACHE II.
the sides, particularly marked on the right hand side. This can be explained in terms of the average 24 mrad horizontal deviation of the beam path with respect to the theoretical direction. In fact, since the aerogel is placed approximately at 60 cm from the end of the vacuum pipe, this implies that on average the runs taken on the right hand side of the block have traversed the surface only 6 mm from the block side; considering a beam spread $\sigma_x = \sigma_y \simeq 5$ mm, the whole tile has been scanned. The mean deviation from the average value of the Cherenkov angle is 0.9 mrad, corresponding to a variation of the refractive index within the tile $\sigma(n - 1)/(n - 1) = 0.76\%$, well within the specifications.

### 4.6 Compatibility of silica aerogel with $C_4F_{10}$

The aerogel radiator wall will not be hermetically sealed inside the RICH 1 detector. As a consequence, it will be in contact with the gaseous $C_4F_{10}$ radiator. Generally air fills the porous structure of this solid, and in RICH 1 a replacement of air with $C_4F_{10}$ is expected. From gas diffusion calculation and assuming only the two largest surfaces exposed to $C_4F_{10}$, the time to accomplish this replacement is about half an hour, changing slightly the index of refraction. Possible effects have been investigated and results are presented in the following.
4.6 Compatibility of silica aerogel with $C_4F_{10}$

Figure 4.25: Clarity as a function of elapsed time in the $C_4F_{10}$ compatibility gas test. Blue stars refer to the final LHCb silica aerogel; red dots and green triangles show the behaviour of the clarity for a hydrophobic (“MAT03”) and hygroscopic (“710–8”) old tiles respectively for comparison purposes only. For the hydrophobic block, the initial value of $C$ was not measured at the time the sample was put in $C_4F_{10}$–filled box.

4.6.1 $C_4F_{10}$ effect on the clarity factor

A $100 \times 100 \times 50$ mm$^3$ hygroscopic block of the pre–production aerogel batch is kept in a $C_4F_{10}$–filled box. The clarity factor $C$ is periodically monitored to evaluate possible effects due to the gas. The trend of the clarity factor is shown in Fig. (4.25) as a function of time. After the initial steep rise, the degradation of the clarity slows down. This test is going on.

Several simulation studies and beam tests showed that a worsening in the clarity factor of $\approx 20\%$ does not dramatically change the number of detected photoelectrons, and it has minor effects both on the resolution, on the amount of the scattered background and ultimately on the particle identification performances [89].

4.6.2 $C_4F_{10}$ effect on the refractive index

All the refractive index measurements have been performed in the optical laboratory at standard environmental conditions. The effects of the replacement of air by $C_4F_{10}$ have been investigated.
Table 4.8: Typical values of the refractive index and density for the materials used in the production of silica aerogel. Values for the aerogel are from the manufacturer data sheets.

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive Index</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>1.4584</td>
<td>2.65</td>
</tr>
<tr>
<td>C₄F₁₀</td>
<td>1.0014</td>
<td>0.01006</td>
</tr>
<tr>
<td>Air (STP)</td>
<td>1.00029</td>
<td>0.001293</td>
</tr>
<tr>
<td>Aerogel</td>
<td>1.030</td>
<td>0.154</td>
</tr>
</tbody>
</table>

The structure of the aerogel can be interpreted by the two phase media model [90]. In this model, the aerogel is assumed to consist of two phases with constant mass density: the silica solid phase with a mass density $ρ_s$ and the void (gas) phase with $ρ_g = ρ_{air}$. The two phases occupy volume fractions $Φ_s$ and $Φ_g$ respectively ($Φ_s + Φ_g = 1$). According to the Clausius–Mossotti relation [53], the effective refractive index $n$ can be obtained averaging over both the solid and void phases:

$$\left(\frac{n^2 - 1}{n^2 + 2}\right) = Φ_s \left(\frac{n_s^2 - 1}{n_s^2 + 2}\right) + Φ_g \left(\frac{n_g^2 - 1}{n_g^2 + 2}\right)$$

(4.15)

where $n_s$ is the refractive index of the solid phase and $n_g$ of the gas one. If $ρ$ is the macroscopic density of the aerogel block, then $Φ_s = ρ/ρ_s$ and Eq. (4.15) becomes:

$$\left(\frac{n^2 - 1}{n^2 + 2}\right) = \frac{ρ}{ρ_s} \left(\frac{n_s^2 - 1}{n_s^2 + 2}\right) + \left(1 - \frac{ρ}{ρ_s}\right) \left(\frac{n_g^2 - 1}{n_g^2 + 2}\right)$$

(4.16)

which reduces to Eq. (4.2) when $n ≃ 1$ and $n_g = 1$.

Typical values of the variables needed in Eq. (4.16) are listed in Tab. (4.8). Assuming for the aerogel a refractive index $n_{air} = 1.0279$ when the structure is filled with air, the corresponding density ratio is $ρ/ρ_s = 0.07$, so the refractive index $n_{C₄F₁₀} = 1.0289$ when filled with $C₄F₁₀$. The corresponding variation of $(n - 1)$ from an air–filled to a $C₄F₁₀$–filled aerogel is 3.6%. The replacement of air with $C₄F₁₀$ does not constitute a danger for the particle identification performances because all the tile changes its refractive index of the same amount.

### 4.7 Natural ageing of silica aerogel

In the framework of the study of all possible ageing effects acting on the aerogel, one 100 × 100 × 41 mm³ hygroscopic tile is currently kept sealed from the atmosphere and its optical parameters are periodically measured. Possible natural
ageing effects can be unveiled by monitoring the refractive index $n$ and the clarity factor $C$.

Results are plotted in Fig. (4.26): after almost two years of monitoring, no significant degradation of the optical properties have been observed. The visible small variations of $n$ and $C$ can be ascribed to uncontrolled absorption or rejection of humidity during measurements [87].

### 4.8 Tests of silica aerogel as RICH radiator

Several beam tests have been performed in the last years to evaluate the performances of silica aerogel as Cherenkov radiator [91, 92, 93]. The last one (October 2003) had a twofold purpose: to evaluate the performances of large thickness and transverse dimensions aerogel bricks, characterizing the photon yield and the Cherenkov angle resolution, and to test the latest pixel Hybrid Photon Detectors (HPD) prototypes [63].

#### 4.8.1 The experimental set–up

Four aerogel blocks as Cherenkov radiator, a tilted spherical mirror and three HPDs were housed inside a light–tight anodized aluminium vessel, as shown in Fig. (4.27). Nitrogen was flushed through the vessel to prevent the hygroscopic aerogel to absorb humidity [87]. The set–up was located in the CERN PS T9
Figure 4.27: Photograph of the set–up used in the October 2003 beam test. All the components are clearly visible. From the left: the aerogel $2 \times 2$ tiles wall (bottom), the three HPDs with the read–out cards (top) and the spherical mirror.

East Hall area. From the primary proton beam with a momentum of 24 GeV/c, the secondary beams can be selected in momentum and charge. The beam–line can yield both a pure $\pi^-$ and a mixture of $\pi^+$ and $p$ beams; the beams used in data taking had momentum of 10 GeV/c.

The Cherenkov photons generated inside the aerogel were reflected by the tilted spherical mirror and focused onto the photon detectors placed outside the acceptance. The Cherenkov light from the nitrogen volume downstream of the aerogel was focused in the insensitive region between the three HPDs. Data using only nitrogen as radiator medium were recorded for calibration purposes. In these cases, the mirror was realigned to focus the Cherenkov rings on each photon detector in turn: the nitrogen rings could be fully contained on a single HPD. Thanks to the adjustable support, the whole set–up could be moved in all directions, allowing the scanning of several different aerogel regions, with the particle beam crossing the tiles at various positions.

The trigger signal was provided by the coincidence of a set of scintillators located on the beam–line. Two smaller scintillators covering an area of $1 \text{ cm}^2$ located at about 8 m apart limited the beam divergence to $\sim 1.5$ mrad. Three pixel silicon detectors have been also installed for tracking. Data from this tracking
4.8 Tests of silica aerogel as RICH radiator

detector have been used for determining the event by event particle trajectory.

4.8.2 The photon detectors

Three pixel Hybrid Photon Detectors, named in the following HPD0, HPD1 and HPD2, were used to detect Cherenkov photons. They were located on the upper side of the vessel, at the vertices of an equilateral triangle, with HPD0 and HPD1 located symmetrically with respect to the middle vertical plane, on which the third detector, HPD2, was placed.

Their quantum efficiency curves showed maxima in the range $23\% - 29\%$ for wavelengths around $\lambda = 270$ nm, and a second peak at $\lambda = 440$ nm, where values around $19\%$ have been measured. For this beam test, each HPD was read out without the eightfold grouping explained in Section 3.4.4 but with total of 8192 channels per HPD. Due to limitations of the high voltage (HV) insulation in the set–up, the HPDs were powered at $-18$ kV and not at the design value $-20$ kV. The demagnification law, defined as the radial distance of the photoelectron hit on the anode as a function of the radial distance of the emission point on the cathode, has been determined by numerical simulation and confirmed later by measurements.

The three HPDs showed an excellent signal to noise ratio performance. Even well above the HV threshold, the detection efficiency of photoelectrons by the anode is less than 100% because of inefficiencies in charge generation and collection, due to back scattering of photoelectrons and charge sharing among adjacent pixels. Dedicated measurements allowed to estimate a detection efficiency around 82% operating at $-18$ kV and at the chosen threshold.

4.8.3 The beam monitoring system

The event by event tracking for the Cherenkov angle reconstruction and the measurement of the beam divergence was provided by a silicon telescope. It consisted of three layers of silicon detectors, each equipped by $22 \times 22$ pixels, $1.3 \times 1.3$ mm$^2$ wide. Two planes were placed upstream of the vessel, the third downstream; the distance between the first and the third layers was about 4.8 m.

For each event the hits in the telescope were fitted with a least squares linear fit in the horizontal and vertical planes independently. The residues between the fitted coordinate and the actual hit coordinate was minimized to find the best alignment. The central position determined in each silicon telescope plane defines the nominal beam direction. The beam divergence for the $\pi^-$ beam was found to be 1.6 mrad in the horizontal plane and 0.7 mrad in the vertical one. The uncertainty on the track direction due to the finite pixel size is 0.05 mrad.
<table>
<thead>
<tr>
<th>Thickness</th>
<th>Tile I</th>
<th>Tile II</th>
<th>Tile III</th>
<th>Tile IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>1.0286</td>
<td>1.0292</td>
<td>1.0272</td>
<td>1.0307</td>
</tr>
<tr>
<td>A (%)</td>
<td>86</td>
<td>88</td>
<td>87</td>
<td>96</td>
</tr>
<tr>
<td>C (µm²/cm)</td>
<td>0.0052</td>
<td>0.0056</td>
<td>0.0054</td>
<td>0.0061</td>
</tr>
</tbody>
</table>

Table 4.9: Mechanical and optical properties of the four aerogel blocks used in the beam test, as measured before the test. The refractive index refers to $\lambda = 543.5$ nm.

4.8.4 The Cherenkov radiator

The Cherenkov radiator consisted of four 100 $\times$ 100 $\times$ 40 mm³ hygroscopic aerogel tiles closely packed in a 2 $\times$ 2 matrix wall. Their optical properties are listed in Tab. 4.9. In some runs, a 100 µm thick UV filter was added to kill photons with energy above 3 eV which are Rayleigh scattered, potentially degrading the resolution of the system.

4.8.5 Simulation of the beam test

A detailed simulation of the beam test including all the physical processes concerning the set-up has been developed with the GEANT4 software tool–kit. Both a pure $\pi^-$ and mixed $\pi^+$/p beams have been used to create Cherenkov photons uniformly in energy and with the corresponding Cherenkov angles along the trajectory crossing the aerogel and nitrogen.

Two parameterizations of the refractive index dispersion law have been used. The first one is based on the Lorentz–Lorenz relation between the refractive index $n$ and energy $E$ of the incident photon:

$$n^2(E) = \frac{1 + 2cf(E)}{1 - 2cf(E)}$$  \hspace{1cm} (4.17)

where:

$$c = \frac{4\pi a\rho N_A}{2M}$$  \hspace{1cm} (4.18)

$$f(E) = \frac{F_1}{G_1^2 - E^2} + \frac{F_2}{G_2^2 - E^2}$$  \hspace{1cm} (4.19)

---

*D 263 T borosilicate glass by SCHOTT Guinchard SA.*
4.8 Tests of silica aerogel as RICH radiator

Figure 4.28: Top: hits on the silicon anode on each HPD. Bottom: the reconstructed Cherenkov ring as seen by the three HPDs in a typical run with $\pi^-$ beam. Red hits fall in the $\pm 2$ mrad band around the expected Cherenkov ring. Spots visible in HPD0 and HPD2 are due to reflections of photoelectrons inside HPDs.

being $\rho$ the density of the medium, $M$ its molecular weight, $a$ the Bohr radius and $N_A$ the Avogadro constant. The parameters $F_{1,2}$ and $G_{1,2}$ are extracted from fused quartz data, and then the whole curve is scaled to match the measured refractive index at the wavelength $\lambda = 543.5$ nm at which a measurement is available.

In the second approach the aerogel is considered as a binary mixture of solid SiO$_2$ and gas as it has been explained in Section 4.6.2

\[
n = 1 + \frac{3}{2} \frac{\rho_s (n_s^2 - 1)}{\rho_s (n_s^2 + 2)} \tag{4.20}
\]
where \( \rho \) is the macroscopic density of the aerogel block, \( \rho_s \) and \( n_s \) are the density and the refractive index of the silica solid phase respectively.

It must be stressed out that the dispersion curve obtained with this method neglects the presence of residues in the aerogel, such as water or ethanol and consequently it could be under-estimated by roughly 10%. Also for this parameterization, the density \( \rho \) was tuned to match the measured refractive index value, assuming that the residues do not modify the shape of the dispersion curve.

Mirror reflectivity and quantum efficiencies of HPDs were measured in the laboratory in order to get the simulation as realistic as possible.

4.8.6 Experimental results

In Fig. (4.28) the photoelectron hits on the silicon anode of the three HPDs are shown for a typical \( \pi^- \) run. Data have been used to study the photoelectron yield and the angular resolution for the aerogel. Details about results from the analysis of the calibration runs with nitrogen can be found elsewhere [94].

Photoelectron yield

The photoelectron yield is defined as the average number of detected photoelectrons per charged particle crossing the Cherenkov radiator. In each HPD a clustering algorithm has been applied to hits in adjacent pixels to include charge sharing effects. On average, 8.5%, 14.7% and 9.6% of two-pixels clusters were found in HPD0, HPD1 and HPD2 respectively. Each cluster was considered as corresponding to one photoelectron. Possible under-estimation of the number of photons due to the probability of two photoelectrons hitting neighbour pixels has been determined by simulation and found to be of the order of 0.01 photoelectrons per HPD per event.

A signal region was defined as the band \( \pm 3 \) standard deviation wide around the average angle \( \theta_C \) which has been reconstructed as described in the following Section. The number of hits per event is counted in this band. Few pixels were masked or inefficient for a total of 0.13% of the pixels in the signal band for the three HPDs. As shown in Fig. (4.28), some spots due to reflections are visible. The regions containing these spots were removed both in data and in simulation.

Dark count background was studied by counting hits in runs taken triggering outside beam spills. The average number of fired pixels per trigger per HPD has been found to be 1.6, corresponding to less than \( 2 \times 10^{-4} \) of the pixels per event. From a random trigger run with masked aerogel, the average number of hits within the signal region band was found to be 0.012 per event. This numbers has been subtracted from the number of photoelectrons in signal data.

The average number of photoelectrons per event has been determined fitting data with a Poisson distribution. The photoelectron yield for each HPD is given in Tab. (4.10), both for run with and without the UV filter. Corrections accounting
Tests of silica aerogel as RICH radiator

<table>
<thead>
<tr>
<th></th>
<th>HPD0</th>
<th>HPD1</th>
<th>HPD2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>With UV Filter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>1.19 ± 0.01</td>
<td>1.00 ± 0.01</td>
<td>0.86 ± 0.01</td>
</tr>
<tr>
<td>2π geometry</td>
<td>11.7 ± 0.2</td>
<td>9.3 ± 0.2</td>
<td>9.1 ± 0.2</td>
</tr>
<tr>
<td><strong>MC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2π geometry</td>
<td>1.22 ± 0.08</td>
<td>1.09 ± 0.07</td>
<td>1.21 ± 0.08</td>
</tr>
<tr>
<td><strong>Without UV Filter</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>1.60 ± 0.01</td>
<td>1.41 ± 0.01</td>
<td>1.21 ± 0.01</td>
</tr>
<tr>
<td>2π geometry</td>
<td>15.7 ± 0.3</td>
<td>13.2 ± 0.3</td>
<td>12.7 ± 0.3</td>
</tr>
<tr>
<td><strong>MC</strong></td>
<td>1.62 ± 0.10</td>
<td>1.47 ± 0.09</td>
<td>1.59 ± 0.10</td>
</tr>
<tr>
<td>2π geometry</td>
<td>15.9 ± 1.0</td>
<td>13.7 ± 0.8</td>
<td>16.7 ± 1.1</td>
</tr>
</tbody>
</table>

Table 4.10: Number of photoelectrons per event per HPD in the signal region defined. Errors on data are statistical only, while those on Monte–Carlo include the systematic uncertainties. The photoelectron yield extrapolated to a full 2π geometry is also reported.

classing effect and missing pixels are included. Data and Monte–Carlo agree for HPD0 and HPD1, while for HPD2 the simulation is slightly above the observed signal. Since the same effect has been observed also for the nitrogen rings, this mismatch can be ascribed to the quantum efficiency curve used in the simulation. Systematic uncertainty is related to mirror reflectivity (2%) and photocathode quantum efficiencies (6%) used in the simulation.

The number of photoelectrons extrapolated to the full ring (2π geometry) for the runs with and without the UV filter have been determined and are listed in Tab. (4.10). The variations in the photoelectron yield among the HPDs are mainly due to their different quantum efficiencies.

Other effects related to photoelectron yield and scattered contributions in the signal band are under study. In particular, the dependence of the photoelectron yield as a function of the applied HV has been considered: a progressive increase of the yield is found. The reduction of the photoelectron yield by the UV filter has been measured to be 27% on average.

**Resolution on Cherenkov angle**

The Cherenkov angle has been reconstructed for all the photoelectron hits by a retracking procedure, using as particle direction the one determined by the three layers of the silicon telescope and assuming the mid–point of aerogel as emission point of Cherenkov photons [65].

The angular distributions from each HPD are fitted with a Gaussian function determining the average angle \( \theta_C \) and the resolution \( \sigma_{\theta_C} \). Effects due to refraction at the HPD quartz window has not been considered in the reconstruction of
From Monte–Carlo studies, a positive shift of the average Cherenkov angle of 1.0 mrad is expected in HPD2, which has a higher average angle of photon incidence than the other photon detectors; no shifts are seen for HPD0 and HPD1.

Results are listed in Tab. 4.11. For simulation, the distributions are poorly fitted by a Gaussian function. Since resolutions in data are worse than in Monte–Carlo, several specific studies have been performed to better understand the differences. The effect of the refractive index chromaticity on the angular resolution has been estimated to be 2.3 mrad; using the second parameterization of the refractive index, this contribution would be of the order of 1.7 mrad. All the contributions to the angular resolution are listed in Tab. 4.12.

An additional contribution to the resolution observed in the data, not included in the simulation, is related to possible non–homogeneity of the refractive index of a block. For one of the tiles in the test, a spread $\sigma (n - 1) / (n - 1) = 1.0\%$ was measured over the whole monolith, corresponding to a 1.1 mrad spread in the Cherenkov angle [95].

Other contributions to the Cherenkov angle resolution were considered [94].

---

Table 4.11: Cherenkov angle resolutions in millirad for single photons for each HPD.

<table>
<thead>
<tr>
<th></th>
<th>With Filter</th>
<th>Without Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromaticity</td>
<td>2.3 mrad</td>
<td>2.7 mrad</td>
</tr>
<tr>
<td>Emission point</td>
<td>0.7 mrad</td>
<td>0.7 mrad</td>
</tr>
<tr>
<td>Pixel</td>
<td>0.5 mrad</td>
<td>0.5 mrad</td>
</tr>
<tr>
<td>Quartz window refraction</td>
<td>0.15 mrad</td>
<td>0.2 mrad</td>
</tr>
<tr>
<td>Total resolution</td>
<td>2.5 mrad</td>
<td>2.8 mrad</td>
</tr>
</tbody>
</table>

Table 4.12: List of contributions to the angular resolution for runs with and without the UV filter. Values are averaged on the three HPDs.

The refractive index dispersion law in the wavelength range 350–825 nm is presently under study by dedicated measurements.
Figure 4.29: Cherenkov rings in a run with mixed 10 GeV/c $\pi^+$ and $p$ beam, without the UV filter. In red, hits falling in the $\pm 2$ mrad band around the expected Cherenkov ring for saturated $\pi^+$.

Pion/proton separation

Data from runs with mixed 10 GeV/c $\pi^+$ and $p$ beam show two Cherenkov rings\(^8\). A fit of the reconstructed Cherenkov distributions with two Gaussian functions gives $\theta_{\pi} = 238.4$ mrad and $\theta_p = 221.4$ mrad with a single photon resolution of 5 mrad. The resolution is degraded by the superposition of the two rings generated by $\pi^+$ and $p$. From the distance between the two peaks and the single photon resolution previously determined with the UV filter, the pion/proton separation significance at 10 GeV/c is $5.2\sigma \sqrt{N}$, being $N$ the average number of photoelectrons. Extrapolating to a pion/kaon separation efficiency, the measured resolution would allow a 3.8 standard deviation separation in the same experimental conditions, at 10 GeV/c.

Scan across aerogel tiles

A study of the effects due to the packaging of the blocks of aerogel has been done. All the results presented in the previous sections are from data taken with the beam crossing only one of the four aerogel blocks (Tile I). Other runs have been done moving laterally the aerogel matrix inside the vessel or moving the vessel

\(^8\)No UV filter was used during runs with mixed positive beam.
itself with respect to the beam, in order to scan different regions of the tile close to the borders.

Steps of 5 mm were done. Since in the horizontal plane the beam profile had a Gaussian spread of the order of 2.5 mm, all the intermediate positions have been covered. The silicon telescope planes have been used to determine the event by event particle position; no UV filter was used. The number of hits in each HPDs have been measured, summing over the whole detector, as a function of the particle entrance point in the aerogel. A loss of photons has been observed when the beam enters the gap between two adjacent tiles, and the Cherenkov light crosses the tile border. A gap of 0.1 mm between the tiles has been considered in the simulation. The agreement of data with Monte–Carlo is satisfactory.

It must be noticed that in the test, the beam direction was almost parallel to the tile lateral surfaces, while the angular incidence in the aerogel wall inside the RICH 1 detector will be always of several degrees.
Chapter 5

\( B_s^0 \rightarrow D_s^- \pi^+ \) and \( \Delta m_s \) sensitivity

The \( B_s^0 - \overline{B_s^0} \) time oscillation frequency, related to the mass difference between the light and heavy mass eigenstates of the \( B_s^0 \) system, is proportional to the square of the \( |V_{ts}| \) element in the CKM matrix. The measurement of \( \Delta m_s \), together with \( \Delta m_d \), gives a strong constraint on the length of the side \( BA \) of the Unitarity Triangle.

In this chapter, after a short review about the oscillation phenomenology in the Standard Model, a method to study the sensitivity of the \( \Delta m_s \) measurement from \( B_s^0 \rightarrow D_s^- \pi^+ \) events will be described. Preliminary results will be given.

5.1 Oscillation phenomenology

The formalism used to describe the time evolution and decay of the neutral mesons is valid for \( B_d^0 (\bar{d}d) \) and \( B_s^0 (\bar{s}s) \), but also for \( K^0 (\bar{s}d) \) and \( D^0 (\bar{c}c) \); since this chapter is devoted to the measurement of the mixing parameter in the \( B_s^0 \) system, only the notation \( B_s^0 \) will be used in the following sections. Very detailed explanations about the oscillation phenomenology within and beyond the Standard Model can be found elsewhere [14, 17, 96].

If only the strong and the electromagnetic interactions existed, \( B_s^0 \) and \( \overline{B_s^0} \) would be stable particles with the same mass \( m \). Because of the weak interaction, they decay. Neither electric charge conservation nor any other conservation law with respect to the electromagnetic interaction prevent \( B_s^0 \) and \( \overline{B_s^0} \) from having both real and virtual transitions to a common state. The consequence is that they mix between themselves before decaying. The leading Feynman diagrams contributing to this process involve two \( W \) bosons and two up–type quarks and are depicted in Fig. (5.1).

An unstable meson can be described by the non–relativistic Schrödinger equation \( i \partial_t \psi = (m - \frac{i}{2} \Gamma) \psi \) with the solution:

\[
|\psi\rangle = |\psi_0\rangle e^{-imt} e^{-\frac{i}{2} \Gamma t}
\] (5.1)
Figure 5.1: Dominant box diagrams for the $B_q^0 - \overline{B_q^0}$ transitions ($q = d, s$).

giving the typical exponential law of radioactive decay, since $|\langle \psi_0 | \psi \rangle|^2 = e^{-\Gamma t}$.

The $B_s^0$ and $\overline{B_s^0}$ pair can be described as a two component quantum state obeying the time–dependent Schrödinger equation:

$$i\partial_t \psi = H \psi$$  \hspace{1cm} (5.2)

where the most general Hamiltonian operator is:

$$H = M - \frac{i}{2} \Gamma = \begin{pmatrix}
    m_{11} - \frac{i}{2} \Gamma_{11} & m_{12} - \frac{i}{2} \Gamma_{12} \\
    m_{12}^* - \frac{i}{2} \Gamma_{12}^* & m_{22} - \frac{i}{2} \Gamma_{22}
\end{pmatrix}$$  \hspace{1cm} (5.3)

$M$ and $\Gamma$ are Hermitian but $H$ is not; the indices 1 and 2 correspond to the base vectors $|B_s^0\rangle$ and $|\overline{B_s^0}\rangle$ respectively. These states are assumed to be correctly normalized, $|\langle B_s^0 | B_s^0 \rangle| = |\langle \overline{B_s^0} | \overline{B_s^0} \rangle| = 1$. The matrices $M$ and $\Gamma$ calculated in second–order perturbation theory are sums over some intermediate states. The states contributing to $M$ are virtual, while the ones contributing to $\Gamma$ are physical states to which both $B_s^0$ and $\overline{B_s^0}$ decay.

The CPT invariance\footnote{The combination CPT is an exact symmetry in any field theory.} requires $m_{11} = m_{22} \equiv m$ and $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$, so the number of real parameters of Eq. (5.3) reduces to six:

$$H = \begin{pmatrix}
    H & H_{12} \\
    H_{21} & H
\end{pmatrix} = \begin{pmatrix}
    m - \frac{i}{2} \Gamma & m_{12} - \frac{i}{2} \Gamma_{12} \\
    m_{12}^* - \frac{i}{2} \Gamma_{12}^* & m - \frac{i}{2} \Gamma
\end{pmatrix}$$  \hspace{1cm} (5.4)

The generalized phenomenology including CPT violation is not considered here.
5.1 Oscillation phenomenology

The Hamiltonian operator is responsible for the propagation of the states, for their mixing and for their decays. Because of the non-Hermitian feature, the eigenvalues of Eq. (5.3) are not real. The eigenvalues corresponding to the two eigenvectors are \( \mu = H \pm \sqrt{H_{12}H_{21}} \), or explicitly:

\[
\begin{align*}
\mu_L &= m_L - \frac{i}{2} \Gamma_L = m - \frac{i}{2} \Gamma - \sqrt{(m_{12} - \frac{i}{2} \Gamma_{12}) (m_{12}^* - \frac{i}{2} \Gamma_{12}^*)} \\
\mu_H &= m_H - \frac{i}{2} \Gamma_H = m - \frac{i}{2} \Gamma + \sqrt{(m_{12} - \frac{i}{2} \Gamma_{12}) (m_{12}^* - \frac{i}{2} \Gamma_{12}^*)} 
\end{align*}
\]

(5.5)

where the indices \( L, H \) are for the light and the heavy states respectively; \( m \) and \( \Gamma \) are the average mass and width:

\[
m = \frac{m_L + m_H}{2}, \quad \Gamma = \frac{\Gamma_L + \Gamma_H}{2}
\]

(5.6)

The differences are:

\[
\frac{\Delta m}{2} = \frac{m_H - m_L}{2} = \Re \sqrt{(m_{12} - \frac{i}{2} \Gamma_{12}) (m_{12}^* - \frac{i}{2} \Gamma_{12}^*)} \quad \text{(5.7)}
\]

\[
\frac{\Delta \Gamma}{2} = \frac{\Gamma_H - \Gamma_L}{2} = -2 \Im \sqrt{(m_{12} - \frac{i}{2} \Gamma_{12}) (m_{12}^* - \frac{i}{2} \Gamma_{12}^*)} \quad \text{(5.8)}
\]

\[
\frac{\Delta \mu}{2} = \frac{\mu_H - \mu_L}{2} = \sqrt{|m_{12}|^2 - \frac{1}{4} |\Gamma_{12}|^2 - i \Re (m_{12} \Gamma_{12}^*)} \quad \text{(5.9)}
\]

The connection between the mass and lifetime (width) differences and the off-diagonal elements in the mass matrix are shown in Eq. (5.7–5.9); in particular, \( \Delta m = 0 \) if \( m_{12} = 0 \) and \( \Delta \Gamma = 0 \) if \( \Gamma_{12} = 0 \). Squaring Eq. (5.9) and separating the real and the imaginary parts, the useful relations:

\[
(\Delta m)^2 - \frac{1}{4} (\Delta \Gamma)^2 = 4|m_{12}|^2 - |\Gamma_{12}|^2 \\
\Delta m \Delta \Gamma = 4 \Re (m_{12} \Gamma_{12}^*)
\]

(5.10)
connect the $\Delta m$ and $\Delta \Gamma$ parameters with the off–diagonal elements $m_{12}$ and $\Gamma_{12}$. From Eq. (5.7), the mass difference $\Delta m$ is positive by definition; the sign of $\Delta \Gamma$ is physically meaningful. In the different neutral meson systems ($B_0^0$, $B_s^0$, $K^0$ and $D^0$) these observables have different orders of magnitude and, therefore, different approximations can be used. It is then convenient to introduce the dimensionless parameters:

$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L} = \frac{\tau_L - \tau_H}{\tau_L + \tau_H}$$ (5.11)

where $x$ is a non–negative real number and $|y| < 1$, approaching the limiting values when one decay width is much larger than the other one, as in the $K^0$ system; it is an asymmetry parameter in the widths or, equivalently, in the lifetimes $\tau_L$ and $\tau_H$.

Contrary to what happens with $B_s^0$ and $\bar{B}_s^0$, $B_L$ and $B_H$ have exponential evolution laws with well–defined masses and decay widths. Thus:

$$|B_L(t)\rangle = e^{-i\mu_L t}|B_L\rangle = e^{-i\mu_L t}e^{-\Gamma_L t/2}|B_L\rangle$$
$$|B_H(t)\rangle = e^{-i\mu_H t}|B_H\rangle = e^{-i\mu_H t}e^{-\Gamma_H t/2}|B_H\rangle$$ (5.12)

where the symbol $t$ always refers to the time measured in the rest frame of the decaying particle. From Eq. (5.12):

$$|\langle B_s^0|B_H(t)\rangle|^2 = e^{-\Gamma_H t}|\langle B_s^0|B_H\rangle|^2$$
$$|\langle B_s^0|B_H(t)\rangle|^2 = e^{-\Gamma_H t}|\langle B_s^0|B_H\rangle|^2$$ (5.13)

which displays the typical exponential damping in the probabilities to observe a $B_s^0$ or a $\bar{B}_s^0$, identifying $\Gamma_H$ as the decay width of $B_H$; similarly, $\Gamma_L$ is the decay width of $B_L$.

Assuming from now on CPT not to be violated, the two mass eigenstates $|B_L\rangle$ and $|B_H\rangle$ are related to the flavour ones $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ by the linear combination:

$$|B_L\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$
$$|B_H\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$ (5.14)
or equivalently:

\[ |B_s^0\rangle = \frac{|B_H\rangle + |B_L\rangle}{2p} \]
\[ |\overline{B}_s^0\rangle = \frac{|B_H\rangle - |B_L\rangle}{2q} \] (5.15)

where the complex coefficient \( p \) and \( q \) obey the normalization condition:

\[ |p|^2 + |q|^2 = 1 \] (5.16)

The \( q/p \) ratio can be calculated:

\[ \frac{q}{p} = \frac{\Delta \mu}{2m_{12} - i\Gamma_{12}} = \frac{2m_{12}^* - i\Gamma_{12}^*}{\Delta \mu} = \sqrt{\frac{2m_{12}^* - i\Gamma_{12}^*}{2m_{12}^* - i\Gamma_{12}}} \] (5.17)

Since \( q \), \( p \) and \( q/p \) are not invariant under rephasing, their phases can not be measured. The condition \( |q/p| \neq 1 \) implies CP violation, which results from the fact that the flavour eigenstates are different from the CP eigenstates. Assuming CP conservation, \( \Delta m_s = 2|m_{12}| \) and \( \Delta \Gamma_s = 2|\Gamma_{12}| \).

### 5.1.1 \( B_s^0 - \overline{B}_s^0 \) mixing

Suppose that a \( B_s^0 \) (\( \overline{B}_s^0 \)) is created at time \( t = 0 \), and denote by \( B_s^0(t) \) (\( \overline{B}_s^0(t) \)) the state that it evolves into after a time interval \( t \), measured in its rest frame. Using Eq. (5.12, 5.14, 5.15), their time evolution can be written as:

\[ |B_s^0(t)\rangle = g_+(t)|B_s^0\rangle + \frac{q}{p}g_-(t)|\overline{B}_s^0\rangle \]
\[ |\overline{B}_s^0(t)\rangle = \frac{p}{q}g_-(t)|B_s^0\rangle + g_+(t)|\overline{B}_s^0\rangle \] (5.18)

where:

\[ g_{\pm}(t) = \frac{1}{2} [e^{-i\mu_{s}\Delta t} \pm e^{-i\mu_{L}t}] \] (5.19)
$B^0_s \rightarrow D_s^- \pi^+$ and $\Delta m_s$ sensitivity

![Graph showing $B^0_s - B^0_s$ mixing](image1)

![Graph showing $B^0_d - B^0_d$ mixing](image2)

**Figure 5.2:** Left: probability for a pure $|B^0_s\rangle$ at production to decay as a $|B^0_s\rangle$ (blue line) or as a $|B^0_d\rangle$ (red line). Right: the same as before, but for the $B^0_d$ system. Published values of lifetimes $\tau_s$, $\tau_d$ and mass difference $\Delta m_s$, $\Delta m_d$ have been used [14]. Both the $\Delta \Gamma_q/\Gamma_q$ ($q = s, d$) quantities are set to zero.

The following formulæ are also useful

\[ |g_{\pm}(t)|^2 = \frac{1}{4} \left[ e^{-\Gamma_H t} + e^{-\Gamma_L t} \pm 2 e^{-\Gamma_s t} \cos(\Delta m_s t) \right] \]
\[ = \frac{e^{-\Gamma_s t}}{2} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) \pm \cos(\Delta m_s t) \right] \]  
\[ (5.20) \]

\[ g_+^*(t)g_-(t) = \frac{1}{4} \left[ e^{-\Gamma_H t} - e^{-\Gamma_L t} - 2 i e^{-\Gamma_s t} \sin(\Delta m_s t) \right] \]
\[ = -\frac{e^{-\Gamma_s t}}{2} \left[ \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) + i \sin(\Delta m_s t) \right] \]  
\[ (5.21) \]

From Eq. (5.18), the probability that a particle initially identified\footnote{A specific notation $\Gamma_s$, $\Delta m_s$ and $\Delta \Gamma_s$ according to the $B^0_s - \overline{B^0_s}$ system will be used.} as a $B^0_s$ is again identified as a $B^0_s$ at time $t$, is equal to the probability that a particle which was $\overline{B^0_s}$ at time $t = 0$ is again a $\overline{B^0_s}$ at time $t$:

\footnote{Generally, experiments on heavy neutral meson systems involve determining the flavour of a neutral meson at its production time and when it decays. The flavour of the meson at the decay time may be found by looking the flavour–specific decays; the determination of the initial
\[ \text{Prob} \left[ B_s^0(t) = B_s^0 \right] = \text{Prob} \left[ \overline{B_s^0}(t) = \overline{B_s^0} \right] = |g_+(t)|^2 \]  

(5.22)

and on the other hand, the probabilities that a particle identified as a $B_s^0$ at time $t = 0$ becomes $\overline{B_s^0}$ at time $t$, and that a particle identified as a $\overline{B_s^0}$ at time $t = 0$ becomes a $B_s^0$ at time $t$, are only equal if CP is conserved in the mixing:

\[ \text{Prob} \left[ \overline{B_s^0}(t) = B_s^0 \right] = \left| \frac{p}{q} \right|^2 |g_-(t)|^2 \]

\[ \text{Prob} \left[ B_s^0(t) = \overline{B_s^0} \right] = \left| \frac{q}{p} \right|^2 |g_-(t)|^2 \]  

(5.23)

It follows that if the ratio of $q$ and $p$ is not equal to unity, there would be an asymmetry between a particle and its antiparticle, implying CP violation. The oscillatory behaviour is graphically illustrated in Fig. (5.2) for both the $B_s^0$ and the $B_d^0$ systems. Considering the $\lambda$ dependence of the ratio $\Delta m_s/\Delta m_s$, shown in Eq. (1.25), the expected value of the $\Delta m_s$ parameter in the Standard Model framework would be around 20 ps$^{-1}$. The experimental challenges arising from a so high $\Delta m_s$ mixing frequency with respect to the small $\Delta m_d$ are clearly evident.

Using Eq. (5.18), the probabilities per unit time $dt$ that the initially produced $B_s^0$ or $\overline{B_s^0}$ decays to the final state $f$ or $\overline{f}$ during the time interval $[t, t + dt]$ are:

\[ \Gamma \left[ B_s^0(t) \rightarrow f \right] = |A_f|^2 \left\{ |g_+(t)|^2 + |\lambda_f|^2 |g_-(t)|^2 + 2 \Re \left[ \lambda_f g_+(t) g_-(t) \right] \right\} \]

\[ \Gamma \left[ B_s^0(t) \rightarrow \overline{f} \right] = |A_f|^2 \left\{ \left| \frac{p}{q} \right|^2 |g_-(t)|^2 + |\lambda_f|^2 |g_+(t)|^2 + 2 \Re \left[ \lambda_f g_+(t) g_-(t) \right] \right\} \]

\[ \Gamma \left[ \overline{B_s^0}(t) \rightarrow f \right] = |\overline{A_f}|^2 \left\{ |g_-(t)|^2 + |\lambda_f|^2 |g_+(t)|^2 + 2 \Re \left[ \overline{\lambda_f} g_+(t) g_-(t) \right] \right\} \]

\[ \Gamma \left[ \overline{B_s^0}(t) \rightarrow \overline{f} \right] = |\overline{A_f}|^2 \left\{ \left| \frac{q}{p} \right|^2 |g_+(t)|^2 + |\lambda_f|^2 |g_-(t)|^2 + 2 \Re \left[ \overline{\lambda_f} g_+(t) g_-(t) \right] \right\} \]  

(5.24)

flavour is usually called “tagging” and is done using the rule of associated production: both the strong and the electromagnetic interactions conserve flavour, and therefore a quark $q$ is always produced in association with its antiquark $\bar{q}$. Thus, the reasoning behind the tagging strategy is if a quark $q$ has been detected in one side of the detector, the quark in the opposite side must be a $\bar{q}$. Neutral meson flavour tagging is complicated by the fact that the mesons can mix into each other before decaying.
$B_0^s \rightarrow D^- \pi^+$ and $\Delta m_s$ sensitivity

where $A_f \equiv \langle f|H|B_0^s \rangle$ and $\overline{A}_f \equiv \langle f|H|\overline{B}_0^s \rangle$ are the decay amplitudes of the $B_0^s \rightarrow f$ and $\overline{B}_0^s \rightarrow f$ processes; the CP conjugated decay amplitudes $A_f$ and $\overline{A}_f$ can be defined in an analogous way. The complex parameter $\lambda_f$ is:

$$\lambda_f = \frac{q}{p} \frac{\overline{A}_f}{A_f} = \frac{1}{\overline{A}_f}$$

(5.25)

Experimentally it may be impossible to measure the time dependence; in that case the total numbers of events are usually measured [17, 96].

Using Eq. (5.20, 5.21), the relations in Eq. (5.24) may be written in the form:

$$\Gamma \left[ B_0^s(t) \rightarrow f \right] = |A_f|^2 \frac{e^{-\Gamma_s t}}{2} [H + I]$$

$$\Gamma \left[ \overline{B}_0^s(t) \rightarrow f \right] = |A_f|^2 \frac{e^{-\Gamma_s t}}{2} \left[ \frac{p}{q} \right]^2 [H - I]$$

(5.26)

where $H$ and $I$ are defined to be:

$$H = \left( 1 + |\lambda_f|^2 \right) \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - 2 \Re \left[ \lambda_f \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right]$$

$$I = \left( 1 - |\lambda_f|^2 \right) \cos (\Delta m_s t) + 2 \Im \left[ \lambda_f \sin (\Delta m_s t) \right]$$

(5.27)

The function $H$ depends on exponentials and on $\Delta \Gamma_s$ and it is the decay dependent term; the function $I$ describes the oscillatory component and it depends on $\Delta m_s$. If the final state $f$ is a CP eigenstate, then $H$ is CP conserving, while $I$ is CP violating because CP conservation imposes $\lambda_f = \pm 1$.

The experimental challenge is to measure the unknown parameters $\Delta m_s$, $\Delta \Gamma_s$, $|q/p|$, $|A_f/\overline{A}_f|$, $\lambda_f$ and $\lambda_f$ using $B$ mesons decaying into several final states $f$ and $\overline{f}$. The time–dependent decay rate asymmetries, $A_f(t)$ and $A_{\overline{f}}(t)$ allow the extraction of these parameters. Two time–dependent decay rate asymmetries are possible:

$$A_f(t) = \frac{\Gamma \left[ B_0^0(t) \rightarrow f \right] - \Gamma \left[ \overline{B}_0^0(t) \rightarrow f \right]}{\Gamma \left[ B_0^0(t) \rightarrow f \right] + \Gamma \left[ \overline{B}_0^0(t) \rightarrow f \right]}$$

$$A_{\overline{f}}(t) = \frac{\Gamma \left[ B_0^0(t) \rightarrow \overline{f} \right] - \Gamma \left[ \overline{B}_0^0(t) \rightarrow \overline{f} \right]}{\Gamma \left[ B_0^0(t) \rightarrow \overline{f} \right] + \Gamma \left[ \overline{B}_0^0(t) \rightarrow \overline{f} \right]}$$

(5.28)
5.1 Oscillation phenomenology

The advantage of using such asymmetries is that some systematic uncertainties like the detector acceptance cancel out.

5.1.2 Flavour–specific decays

The frequency of $B_s^0 - \bar{B}_s^0$ mixing is fixed by the value of the $\Delta m_s$ parameter. A decay into a flavour–specific final state (as for example $B_s^0 \to D_s^- \pi^+$) is well suited for the oscillation frequency measurement. Fig. (5.3) displays the flavour–specific decay diagrams of the $B_s^0 \to D_s^- \pi^+$ process.

In a flavour–specific process, only $B_s^0 \to f$ and $\bar{B}_s^0 \to \bar{f}$ are allowed, while $B_s^0 \to \bar{f}$ and $\bar{B}_s^0 \to f$ events are forbidden. This corresponds to $A_f = \bar{A}_f = 0$, and $\lambda_f = \bar{\lambda}_f = 0$, and Eq. (5.24) become:

\[
\begin{align*}
\Gamma [B_s^0(t) \to f] &= |A_f|^2 |g_+(t)|^2 \\
\Gamma [\bar{B}_s^0(t) \to \bar{f}] &= |\bar{A}_f|^2 \left| \frac{q}{p} \right|^2 |g_-(t)|^2 \\
\Gamma [\bar{B}_s^0(t) \to f] &= |A_f|^2 \left| \frac{p}{q} \right|^2 |g_-(t)|^2 \\
\Gamma [B_s^0(t) \to \bar{f}] &= |\bar{A}_f|^2 |g_+(t)|^2
\end{align*}
\] (5.29)

Clearly, the probabilities per unit time of the $B_s^0(t) \to \bar{f}$ and $\bar{B}_s^0(t) \to f$ processes vanish at $t = 0$, but they are non–zero for a generic $t$ due to the mixing of the

![Diagram](image-url)
neutral mesons. It is also due to mixing that one can find two states $f$ or $\bar{f}$ as the result of the decay of a state which initially was a $B_s^0 - B_s^0$ pair.

Substituting these decay rates into the time–dependent asymmetry Eq. (5.28), the following relation is obtained:

$$A_{\text{mix}}(t) = \frac{\cos(\Delta m_s t)}{\cosh\left(\frac{\Delta \Gamma_s}{2} t\right)}$$  \hspace{1cm} (5.30)

In the case of heavy neutral mesons, it is usually assumed that mixing CP violation $|q/p|$ is small and can be neglected\footnote{In the Standard Model, the deviation of the CP violating parameter $|q/p|$ in the $B_s^0 - B_s^0$ system is expected to be very small, $\lesssim O(10^{-4})$.}. From Eq. (5.30), both $\Delta m_s$ and $\Delta \Gamma_s$ can be extracted.

### 5.2 Current experimental status on $\Delta m_s$

Up to now, $B_s^0 - \bar{B}_s^0$ oscillations have been studied by several experiments, such as ALEPH \cite{97}, CDF \cite{98}, DELPHI \cite{99, 100, 101, 102}, DO \cite{103}, OPAL \cite{104, 105} and SLD \cite{106, 107}. Unfortunately, no evidence of an oscillating signal has been found, mainly because the expected period of these oscillations turns out to be so small that it can not be resolved with proper time resolutions and statistics achieved so far. The analyses based on inclusive lepton samples collected at LEP appear to be the most sensitive ones, thanks to the better proper time resolution as well as the few fully reconstructed $B_s^0$ events.

The amplitude fit method has been introduced to extract a lower limit on the $\Delta m_s$ mixing parameter \cite{108}. This method\footnote{The amplitude fit method was developed to overcome the difficulties related to the combination of different likelihood functions; results from different experiments can be easily combined using an average weighted by the amplitude $A$.}, which combines the advantages of a Fourier transform analysis with the power and simplicity of a maximum likelihood fit, consists of measuring a $B_s^0 - \bar{B}_s^0$ oscillation amplitude $A$ at several different test values of $\Delta m_s$, maximizing a likelihood function based on the decay rates of Eq. (5.26) where the cosine terms have been multiplied by a weight $A$. One expects $A = 1$ at the true value of $\Delta m_s$ and $A = 0$ at a test value of $\Delta m_s$ (far) below the true value.

All the results are limited by the small available statistics; the world average spectrum determined with the amplitude fit method is displayed in Fig. (5.4), including all results published by March 2005. The combined sensitivity for 95% CL exclusion of $\Delta m_s$ values is found to be 18.5 ps$^{-1}$ \cite{20}. The present limit is:

\[\text{In the Standard Model, the deviation of the CP violating parameter } |q/p| \text{ in the } B_s^0 - \bar{B}_s^0 \text{ system is expected to be very small, } \lesssim O(10^{-4}).\]
5.2 Current experimental status on $\Delta m_s$

![Diagram of combined measurements of the $B_0^s$ oscillation amplitude as a function of $\Delta m_s$, including all results published by March 2005 [20]. The measurements are dominated by statistical uncertainties. Neighbouring points are statistically correlated.](image)

Figure 5.4: Combined measurements of the $B_0^s$ oscillation amplitude as a function of $\Delta m_s$, including all results published by March 2005 [20]. The measurements are dominated by statistical uncertainties. Neighbouring points are statistically correlated.

$$\Delta m_s > 14.5 \text{ ps}^{-1} \text{ at 95\% CL}$$

(5.31)

The values between $14.5 \text{ ps}^{-1}$ and $21.7 \text{ ps}^{-1}$ cannot be excluded because in that region data and signal are compatible. However, no deviation from $A = 0$ is seen in Fig. 5.4 that would indicate the observation of a signal.

It should be noted that most $\Delta m_s$ analyses assume no decay width difference in the $B_0^s$ system. Due to the presence of the hyperbolic cosine terms, a non-zero value of $\Delta \Gamma_s$ would reduce the oscillation amplitude with a small time-dependent damping factor that would be very difficult to distinguish from time resolution effects.

The measurement of both the $\Delta m_s$ and the $\Delta \Gamma_s$ parameters, planned in the LHCb physics program, will be done with high precision, thanks to the superior experimental performances (in terms of proper time resolution and flavour tagging issues) and to the huge statistics available. An estimation of the LHCb sensitivity to $\Delta m_s$ has been done by simulation. An observation of $\Delta m_s$ with a statistical significance of at least five standard deviations is possible up to $68 \text{ ps}^{-1}$. From Standard Model calculations, $\Delta m_s \simeq 20 \text{ ps}^{-1}$ is expected. A larger value of this parameter will indicate New Physics contributions beyond the Standard Model,
and LHCb should be sensitive also to that.

In the following an example of such a measurement will be presented. The $B_s^0 \rightarrow D^- \pi^+$ flavour–specific decay channel will be used.

### 5.3 $B_s^0 \rightarrow D_s^- \pi^+$ selection and reconstruction

Since the $B_s^0 \rightarrow D^- \pi^+$ and $B_s^0 \rightarrow D^\pm K^\mp$ decays have similar topological properties, the selection criteria for both decays are almost identical. A dedicated algorithm has been implemented and tested on Monte–Carlo samples in order to optimize the signal to background ratios [109, 110]. All the LHCb software applications use the Object–Oriented technology; the standard TDRselBs2DsPi v3r4 running within the DaVinci v12r11 physics analysis software has been used [111]. A custom code has been also written to save the selected events and to fill ntuples for the subsequent offline analysis.

#### 5.3.1 Event topology

The typical $B_s^0 \rightarrow D^- \pi^+$ ($B_s^0 \rightarrow D^\pm K^\mp$) event topology is shown in Fig. (5.5). Thanks to the relatively high lifetime, $\tau_{B_s^0} = (1.461 \pm 0.057)$ ps, at LHC energies the $B_s^0$ can fly a few centimetres before decaying, and a secondary vertex can be observed [112]. The $\pi^+$ ($K^\mp$) that accompanies the $D^-_s$ ($D^\pm_s$) is usually referred to as the bachelor $\pi^+$ ($K^\mp$); it has a relatively high transverse momentum.

The $D^\pm_s$ meson has a lifetime $\tau_{D^\pm_s} = (0.490 \pm 0.009)$ ps, and therefore a de-
Table 5.1: Processes considered in this analysis. The related visible branching ratios are the ones used for the 2004 Data Challenge production and they might differ from the values published [14]. All the $D_s^\pm$ mesons have been forced to decay as $D_s^- \rightarrow K^- K^+ \pi^-$. The detached vertex can be observed [14]. The $D_s^- \rightarrow K^- K^+ \pi^-$ decay has been selected for its significant branching ratio. The three body final state is produced through resonances, but the selection algorithm is much more general and could be applied to all $D_s^- \rightarrow K^- K^+ \pi^-$ final states.

### 5.3.2 Monte–Carlo event samples

The analysis presented in this chapter has been done processing Monte–Carlo data produced during the 2004 Data Challenge (DC04). The $B_s^0 \rightarrow D_s^- \pi^+$ channel is the signal of the analysis. Two classes of background from $b\bar{b}$ can be distinguished: one consists of four body $b$–hadron decays, and the other of combinatorics.

In the first class there are exclusively reconstructed $B$ meson decays with a similar topology of the signal and with a significant branching ratio. For example, a mistake in the particle identification of a bachelor $K^\pm$ as a $\pi^\pm$ can result in the selection of the background event $B_s^0 \rightarrow D_s^\pm K^\mp$ as a signal event. Since the $B_s^0 \rightarrow D_s^- \pi^+$ branching ratio is a factor $\sim 15$ larger than the $B_s^0 \rightarrow D_s^\pm K^\mp$, the $B_s^0 \rightarrow D_s^\pm K^\mp$ background can be safely neglected [14]. Other four body decay channels are $B_d^0 \rightarrow D_d^- \pi^+$ and $B_d^0 \rightarrow D_d^\pm \pi^+$ and $\Lambda_b^0 \rightarrow \Lambda^+ \pi^-$. Tab. (5.1) lists the
processes considered in this work together with their visible branching ratio. They have been selected because in their final states there are several $\pi^\pm$ and $K^\pm$ which could give rise to false signal events.

The second class consists of pure combinatorial background: random combinations of tracks can lead to a $B^0_s$ meson candidate. This type of background can in principle occur in any interaction (also in minimum bias events), but since both the trigger strategy and the event selection require the presence of a detached secondary vertex and high $p_T$ tracks, it is assumed here that only $b\bar{b}$-inclusive events can produce combinatorial background.

Also combinatorics from $c\bar{c}$-inclusive events could be a danger at LHCb. At LHC energies the $c\bar{c}$ cross section is roughly 10 times the $b\bar{b}$ one, but the trigger system should be able to reject most of the events coming from $c\bar{c}$ fragmentation. A specific study will be presented in Section 5.4.2 and 5.6.4.

### 5.3.3 The event selection

The algorithm starts with some loose preselection criteria in order to select all possible $B^0_s$ candidates. Both an unconstrained vertex fit and a vertex fit with the $D_s^-$ mass constraint is applied for the $D_s^-$ candidates; the unconstrained $D_s^-$ vertex is then used to create the $B^0_s$ vertex. In addition to $B^0_s$ and $D_s^-$ vertices, also a primary vertex is reconstructed. In case of multiple interactions, more than one primary vertex can be reconstructed, and it is assumed that the $B^0_s$ candidate originates from the vertex with the highest track multiplicity.

Although events are highly boosted in the forward direction, the reconstruction of primary vertex has good resolution along the $z$ axis, thanks to the fact that the reconstructed vertex contains many tracks, typically 60, including tracks with a large opening angle in the laboratory frame.

Some kinematical cuts are then applied to select a clean sample of $B^0_s \rightarrow D_s^- \pi^+$ events. Three steps are foreseen: firstly well reconstructed tracks are required, then the candidates forming a $D_s^-$ vertex are selected and in the end the bachelor particle is found to fully reconstruct the $B^0_s$ vertex.

### 5.4 Event yield calculation

Dedicated studies of the trigger and total offline selection efficiencies have been done to estimate the expected annual event yield of $B^0_s \rightarrow D_s^- \pi^+$ events. This

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6 Other channels could be considered, but they were not available at the time of this analysis or their statistics was too small.

7 The visible branching ratio includes the branching ratio of the decay and of the sub-decay.

8 This assumption leads sometimes to select the wrong primary vertex. Further improvements are foreseen in the next releases of the selection algorithm.
5.4 Event yield calculation

<table>
<thead>
<tr>
<th>Process</th>
<th>Assumption/measured</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_s^0 \rightarrow D^- \pi^+ )</td>
<td>( BR_{vis}(B_d^0 \rightarrow D^\pm \pi^\mp) ) measured</td>
<td>((2.76 \pm 0.25) \times 10^{-3})</td>
</tr>
<tr>
<td>( D_s^- \rightarrow K^- K^+ \pi^- )</td>
<td></td>
<td>((4.40 \pm 1.20) \times 10^{-2})</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow D^- (\rightarrow K^- K^+ \pi^-) \pi^+ )</td>
<td></td>
<td>((1.21 \pm 0.35) \times 10^{-4})</td>
</tr>
</tbody>
</table>

Table 5.2: Visible branching ratios for \( B_s^0 \rightarrow D^- \pi^+ \), with \( D_s^- \rightarrow K^- K^+ \pi^- \). [14]

The calculation uses the total number of produced events and the total efficiency. The number of produced events (both \( B_s^0 \) and \( B_s^0 \)) in one year of data taking is:

\[
N_{\text{prod}} = \mathcal{L} \times \Delta t_{\text{LHC}} \times \sigma_{\bar{b}b} \times \left[ 1 - \left( 1 - \text{Prob} [\bar{b} \rightarrow B_s^0] \right)^2 \right] \times BR_{\text{vis}} \tag{5.32}
\]

where \( \mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) is the luminosity at which LHCb will operate, \( \Delta t_{\text{LHC}} = 10^{7} \text{ s} \) the annual data taking time interval, \( \sigma_{\bar{b}b} \simeq 500 \mu\text{b} \) the \( \bar{b}b \) production cross section extrapolated to the LHC energy, \( \text{Prob} [\bar{b} \rightarrow B_s^0] \simeq 10\% \) the fraction of the \( \bar{b} \) quark to produce a \( B_s^0 \) meson. The last factor is the visible branching ratio to the selected final state.

Substituting the visible branching ratio value listed in Tab. (5.2), the number of \( B_s^0 \rightarrow D^- \pi^+ \) events produced in one year of data taking is:

\[
N_{\text{prod}} = (2.4 \pm 0.7) \times 10^7 \tag{5.33}
\]

Unfortunately this is not the number of events available for the \( \Delta m_s \) measurements. In fact trigger, reconstruction and selection efficiencies must be considered together with a detection efficiency factor (including the geometrical acceptance in \( 4\pi \)) and all the material effects in the detector. The annual yield of offline triggered, reconstructed and selected events can calculated by:

\[
N_{\text{phys}} = N_{\text{prod}} \times \epsilon_{\text{tot}} \tag{5.34}
\]

The total efficiency \( \epsilon_{\text{tot}} \) is factorized into several contributions [110]. Considering a typical value \( \epsilon_{\text{tot}} = (0.337 \pm 0.008)\% \), for the offline analysis a total number \( N_{\text{phys}} = (8.1 \pm 2.4) \times 10^4 \) events per year are expected [28].

9The probabilities of a \( b \) or \( \bar{b} \) quark to hadronize into a \( B_s^0 \) or \( B_s^0 \) meson are assumed to be the same.

10Improvements in the selection algorithm leading to a better efficiency \( \epsilon_{\text{tot}} \) are presently under study. The consequence is that also the annual signal yield improves.
5.4.1 The $b\bar{b}$–inclusive sample

A large number of $b\bar{b}$–inclusive events was generated in the 2004 Data Challenge production with the constraint that at least one the two $b$–hadron was inside the 400 mrad angular acceptance. In this sample all the possible decays of $b$–hadrons can be found in the proportion of their visible branching ratios.

About $4.4 \times 10^7$ $b\bar{b}$–inclusive events have been analysed. This would correspond roughly to the number of events produced in about $10^3$ s of data taking, or, equivalently, to an integrated luminosity $L_{int} \simeq 0.2$ pb$^{-1}$. In this data sample, $(1.6 \pm 0.4)$ signal events are expected.

5.4.2 The $D_s^\pm$–inclusive sample

Recently a limited amount of $D_s^\pm$–inclusive events has been made available for the analysis. Producing these data, several cuts and specific requirements have been applied to speed up their generation. This data sample includes $D_s^\pm$ from $c\bar{c}$ and from $b\bar{b}$ fragmentation and decays. The $D_s^\pm$ meson is then forced to decay into the three body final state $K^\pm K^\mp \pi^\pm$.

Unfortunately, only part of this sample is useful to investigate the impact of possible background originating from $c\bar{c}$ pairs in the selection of $B_0^s \rightarrow D_s^- \pi^+$. In principle this source of background should be reduced by the trigger system, but some events can satisfy all the triggering criteria and are written on tape. Because of the presence of prompt $D_s^\mp$, false signal events can be reconstructed and selected. Additional information about such a source of background will be given in Section 5.6.4. A massive production of more specific $D_s^\pm$–inclusive coming only from $c\bar{c}$ pairs has been planned and will start soon.

5.5 Selected events

Tab. (5.3) lists the number of triggered, reconstructed and selected events with respect to the number of read events: the statistics of the signal corresponds to an integrated luminosity $L_{int} \simeq 0.88$ fb$^{-1}$. The same selection algorithm has been applied to all the channels. The distribution of the invariant mass of the $B_0^s$ candidates is shown in Fig. (5.6). The histograms are normalized to compensate for the different branching ratios. Clearly an invariant mass cut could reject most of the survived background events. It must be noticed that, due to the presence of

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$^{11}$Due to a random seed bug found in the simulation, many events have been generated with the same seed. The consequence is that in $4.4 \times 10^7$ events, only about $1.55 \times 10^7$ events are actually independent. A correction factor must then be applied. $^{12}$There is another $D$ meson in the event, but it can be a $D^0$, $D^\pm$, $D^{*0}$, $D^{*\pm}$ and so on. It can also be another $D_s^\pm$, but in this case it is not forced to decay into $K^\pm K^\mp \pi^\pm$. This sample is usually referred to as “$D_s^\pm$–inclusive” or “$D_s^\pm$ cocktail”.

---
5.5 Selected events

<table>
<thead>
<tr>
<th>Process</th>
<th>Monte–Carlo events</th>
<th>Selected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow D^+ \pi^+$</td>
<td>3,728,500</td>
<td>36,605</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^+_s \pi^+$</td>
<td>4,515,000</td>
<td>10,596</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^- \pi^+$</td>
<td>82,000</td>
<td>486</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^+_s K^+$</td>
<td>13,000</td>
<td>21</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^0 \pi^+$</td>
<td>273,500</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^+_s K^-$</td>
<td>100,000</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \eta_c(1S)\phi(1020)$</td>
<td>450,000</td>
<td>1</td>
</tr>
<tr>
<td>$B^0_s \rightarrow K^+ K^+$</td>
<td>40,500</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \pi^+ \pi^+$</td>
<td>52,000</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_s \rightarrow K^0 K^+$</td>
<td>63,500</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi(1020)\phi(1020)$</td>
<td>69,000</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^- \rho(770)^+$</td>
<td>476,000</td>
<td>852</td>
</tr>
<tr>
<td>$B^0_d \rightarrow D^+ \pi^+$</td>
<td>70,000</td>
<td>9</td>
</tr>
<tr>
<td>$B^0_d \rightarrow D^+_s \pi^+$</td>
<td>95,500</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_d \rightarrow D^0 \pi^+$</td>
<td>326,500</td>
<td>0</td>
</tr>
<tr>
<td>$B^0_d \rightarrow D^- a_1(1260)^+$</td>
<td>203,000</td>
<td>0</td>
</tr>
<tr>
<td>$b\bar{b}$–inclusive</td>
<td>44,016,000</td>
<td>69</td>
</tr>
<tr>
<td>$D^\pm$–inclusive</td>
<td>992,000</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 5.3: Monte–Carlo event samples used in this analysis. Numbers of read and selected are shown.

A $D^\pm$ or a prompt $D^\pm$ mesons, both $B^0_s \rightarrow D^- \pi^+$ and $B^0_s \rightarrow D^- \rho(770)^+$ events are frequently selected by the algorithm. The $\gamma$ or $\pi^0$ from the $D^\pm_s$ and $\rho(770)^+$ decays are not reconstructed, so the $B^0_s$ invariant mass is under–estimated and these events are positioned on the left side with respect to the peak of the $B^0_s$ invariant mass from the signal.

About the more general $b\bar{b}$–inclusive sample, the invariant mass distribution is illustrated in Fig. 5.7. The origin of the 69 selected events has been inspected in more detail, event by event, and only two of them are true $B^0_s \rightarrow D^- \pi^+$ events; this number is in agreement with the calculation reported in Section 5.4.1. The others are a mixture of incompletely reconstructed $b$ decays ($\gamma$, $\pi^0$ missing), real $b$ events with $K^\pm$ and $\pi^\pm$ misidentification and pure combinatorial background.

In the $D^\pm_s$–inclusive data sample described in Section 5.4.2, 10 events have been selected. They have been found to originate from $B^0_s$ or $B^0_d$. Even if in the simulation the ratio $\sigma_{c\bar{c}}/\sigma_{b\bar{b}} \sim 6.6$ was used ($\sigma_{b\bar{b}} = 0.627$ mb and $\sigma_{c\bar{c}} = 4.112$ mb) and roughly two $D^\pm_s$ from $c\bar{c}$ for one from $b\bar{b}$ are expected, the $b$ quark origin of all the selected events can be explained in terms of the trigger selection and of a tight invariant mass cut implemented in the algorithm. No events from $c\bar{c}$ have been found, but this is mainly due to the limited number of generated data. Of course, a much larger statistics must be considered to investigate the event yield.
Figure 5.6: Invariant mass distribution for the triggered, selected and reconstructed $B^0_s$ candidates from $B^0_s \rightarrow D^- \pi^+$ (signal) and from several background processes considered. The histograms are correctly normalized to compensate for the different branching ratios. The blue vertical hatched line shows the cut on the $B^0_s$ invariant mass applied in this analysis. Red dots indicate the sum of all the contributions. The statistics corresponds to an integrated luminosity $L_{\text{int}} \simeq 0.88 \, \text{fb}^{-1}$.

efficiency, the shape of the invariant mass distribution and the impact of such events in the $\Delta m_s$ measurement.

5.5.1 Flavour tagging

As mentioned in Section 5.1.1, the event reconstruction specifies if the final state is $f$ or $\bar{f}$, but in order to extract CP violating parameters the knowledge of the flavour of $B$ meson at production is required to classify the event in one of the four classes as in Eq. (5.24). The task of determining the initial flavour is the so-called “flavour tagging”. Specific algorithms have been developed to tag the flavour of each neutral $B$ meson candidate [113]. The information coming from the rest of the event is used, particularly from the decay of the other $b$–hadron produced in the same collision.

For a given neutral $B$ meson, three tagging outcomes are possible, either the meson has been tagged correctly, either wrongly or it has not been tagged. The tagging efficiency $\epsilon_{\text{tag}}$ and the wrong tag fraction $\omega_{\text{tag}}$ define the flavour tagging
performances. Defining \( r \) the number of events where a correct tag has been assigned, \( w \) the number of wrong tag and \( u \) the events with no tag at all, the tagging efficiency, the wrong tag fraction and the effective efficiency are given by:

\[
\begin{align*}
\epsilon_{\text{tag}} &= \frac{r + w}{r + w + u} \\
\omega_{\text{tag}} &= \frac{w}{r + w} \\
\epsilon_{\text{eff}} &= \epsilon_{\text{tag}} (1 - 2\omega_{\text{tag}})^2
\end{align*}
\]  

The performances of standard flavour tagging algorithm applied to the signal are listed in Tab. (5.4).

### 5.5.2 Proper time reconstruction

The proper decay time \( \tau \) of each reconstructed event is used to extract the \( \Delta m_s \) mixing parameter. The decay time is determined by:
Figure 5.8: Left: proper time resolution for all the selected $B^0_s \rightarrow D^- s \pi^+$ events. Right: pull distribution fitted with a normal Gaussian distribution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{\text{tag}}$</td>
<td>$(57.8 \pm 0.3)%$</td>
</tr>
<tr>
<td>$\omega_{\text{tag}}$</td>
<td>$(32.5 \pm 0.3)%$</td>
</tr>
<tr>
<td>$\epsilon_{\text{eff}}$</td>
<td>$(7.1 \pm 0.3)%$</td>
</tr>
</tbody>
</table>

Table 5.4: Tagging efficiency $\epsilon_{\text{tag}}$, wrong tag fraction $\omega_{\text{tag}}$ and effective tagging efficiency $\epsilon_{\text{eff}}$ for triggered, selected and reconstructed $B^0_s \rightarrow D^- s \pi^+$ signal events.

$$\tau = \frac{mL}{p}$$ (5.36)

where $m$, $L$ and $p$ are the mass, the decay distance and the momentum of the $B^0_s$ particle. The error on the proper time is given by:

$$\sigma_{\tau} = \sqrt{\frac{m^2}{p^2} \sigma^2_L + \frac{\tau^2}{p^2} \sigma^2_p}$$ (5.37)

Fig. 5.8 shows the proper time resolution for the selected $B^0_s \rightarrow D^- s \pi^+$ events. The distribution is fitted with a pair of Gaussian functions, with the same mean value. The first Gaussian has a width $\sigma_1 = (30 \pm 1)\text{fs}$ and describes 69% of the entries, while the remaining of the events are described by a second Gaussian.
Figure 5.9: Proper time distribution of $B_0^s \rightarrow D_s^- \pi^+$ events tagged as unoscillated (left) or oscillated (right). The fast oscillatory pattern is clearly visible.

with $\sigma_2 = (57 \pm 2)$ fs. The average resolution is of the order of 40 fs, good enough to detect the fast $B_0^s - \overline{B}_0^s$ oscillations. The pull of the proper time is described by a normal Gaussian and it is shown in Fig. (5.8): the small deviation of its width from unity indicates that errors are under-estimated. There is a bias, approximately 3 fs and 0.08 for the proper time resolution and the pull respectively. The origin of such bias is presently under investigation.

The selection efficiency of $B_0^s \rightarrow D_s^- \pi^+$ candidates is not constant with respect to the proper time. The ratio between selected and generated events describes the acceptance function $A(t)$ of the detector. The efficiency is relatively small for proper time smaller than 2 ps, then it becomes approximately flat. Several analytical formulae have been tried to describe this behaviour; this acceptance function introduces a bias in selecting events, but if time-dependent asymmetries are used, it safely cancels out.

The proper time distributions of selected $B_0^s \rightarrow D_s^- \pi^+$ events tagged as un-oscillated or oscillated are shown in Fig. (5.9). The fast oscillatory pattern is clearly visible, with an input value $\Delta m_s = 20 \text{ ps}^{-1}$. Comparing with the distributions from theory shown in Fig. (5.2), these reconstructed ones are modulated by the acceptance function (cut-off at small proper time values), the wrong tag fraction (reduction of the amplitude of oscillations) and the experimental resolutions (enlargement of the oscillatory peaks). Since the tagging efficiency is $\epsilon_{\text{tag}} = 57.8\%$, part of the selected events can not be tagged, and their proper time distribution will not be used.
5.6 A method to extract $\Delta m_s$

The challenging measurement of the $\Delta m_s$ mixing frequency can be performed in several ways. The maximum likelihood fit approach is the favourite one, but a perfect parameterization of both the signal and all the background sources together with the correct description of all the experimental parameters make it difficult to implement. Also, the normalization of the probability distribution functions is difficult to perform and it requires high computing power \[109]\.

The amplitude fit method was introduced and developed in order to set a lower limit of $\Delta m_s$ with a limited statistics and to solve the critical problem of combining limits from different experiments \[108]\.

An alternative approach will be presented and used. It is based on the fact that $\Delta m_s$ is a frequency and uses the spectral analysis technology to extract it. A similar approach has been already used in the past to study the sensitivity to $\Delta m_s$ by several collaborations \[114, 115, 116, 117]\.

5.6.1 The time–dependent asymmetry

Before extracting CP violating parameters from the time–dependent asymmetries listed in Eq. (5.28) or Eq. (5.30), some effects affecting differently $B_s^0$ and $\bar{B}_s^0$ production and identification should be considered. Difference in the flavour tagging efficiencies can be reduced by regularly switching the polarity of the magnetic field. Wrong tags dilute the magnitude of the time–dependent asymmetry.

For flavour–specific decays, the measured asymmetry is:

$$A(t) = D \times A_{mix}(t) = D \times \frac{\cos(\Delta m_s t)}{\cosh\left(\frac{\Delta \Gamma_s}{2} t\right)}$$

where $D = (1 - 2\omega_{tag})$ is the dilution factor. Its value is channel dependent. In this analysis, the value listed in Tab. (5.4) will be used. The time–dependent asymmetry for the selected $B_s^0 \to D^-\pi^+$ events is plotted in Fig. (5.10).

5.6.2 Sensitivity to $\Delta m_s$

The method used in this analysis is alternative to the Fourier transform and it was introduced in the 1960s by F. J. M. Barning and P. Vanček, and additionally elaborated by J. D. Scargle and finally developed by N. R. Lomb \[118]\.

Some details about the mathematics of the so–called “Lomb method” are reported in Appendix \[15\].
5.6 A method to extract $\Delta m_s$

The time-dependent asymmetry shown in Fig. (5.10) is sampled\(^{13}\) at equidistant time intervals $\Delta t$. Fig. (5.11) shows the result of applying the Lomb algorithm. The position of the peaks in the periodogram indicates the angular frequencies of all the harmonic components of the oscillating signal. In this exercise, the oscillatory component clearly presents an angular frequency close to $\omega = 20.0 \text{ ps}^{-1}$ with a significance level bigger than 99.9%; other peaks approach, but their significance do not exceed the 50.0% level, so they can be considered as spurious frequencies due to the finite experimental resolutions which introduce random noise in the time-dependent asymmetry, as shown in Fig. (5.10).

As a starting point, the spectral analysis of pure $B_s^0 \to D_s^- \pi^+$ events has been done. The result found is $\Delta m_s = (20.109 \pm 0.033) \text{ ps}^{-1}$, which is in agreement with the input value ($\Delta m_s = 20 \text{ ps}^{-1}$) of the simulation. The origin of the three standard deviations of discrepancy has been investigated and will be explained later in Section 5.6.3.

When the background sources listed in Tab. (5.3) are added to the selected data sample\(^{14}\), the result changes to $\Delta m_s = (20.100 \pm 0.037) \text{ ps}^{-1}$. If an ad-

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\(^{13}\)The sampling frequency of the signal must satisfy the Nyquist’s theorem.

\(^{14}\)All the selected events from different channels have been normalized to the statistics of the
Figure 5.11: Normalized power spectrum of the time–dependent asymmetry reconstructed with selected $B^0_s \rightarrow D^-\pi^+$ events. Horizontal lines indicate the significance levels related to the peaks found in the spectral analysis. The result found is $\Delta m_s = (20.109 \pm 0.033) \, \text{ps}^{-1}$.

ditional cut on the reconstructed $B^0_s$ invariant mass is applied to reject all the events with a mass less than 5.3327 GeV/$c^2$, then $\Delta m_s = (20.102 \pm 0.033) \, \text{ps}^{-1}$ is obtained. With this selection, most of the $B^0_s \rightarrow D^*_\pi^+$ and $B^0_d \rightarrow D^- \rho(770)^+$ events are not included in the time–dependence asymmetry. The related periodograms are shown in Fig. (5.12).

The three measurements of $\Delta m_s$ are similar for a couple of reasons. First, the amount of background is small compared to the statistics of the signal. Second, no other mixing frequencies are introduced in the time–dependent asymmetry; in fact all the events added as background are from $B^0_s$ decay, they degrade only the invariant mass and proper time resolutions, but do not change the frequency content of the asymmetry. The presence of $B^0_d \rightarrow D^\pm \pi^\mp$ events should introduce a second peak located near $\Delta m_d = (0.502 \pm 0.007) \, \text{ps}^{-1}$ [14]. The corresponding peak has a small significance level because of the limited statistics of this channel.

signal before constructing the time–dependent asymmetry.
5.6 A method to extract $\Delta m_s$

5.6.3 Systematics of the spectral analysis approach

Some issues related to the implemented Lomb method have been also investigated. All these tests have been performed using a stand–alone simulation package\(^{15}\) which allows to fix some physical parameters like the mixing frequency $\Delta m_s$, the $\Delta \Gamma_s/\Gamma_s$ ratio, the tagging performances and many others; the experimental resolutions are simulated by Gaussian smearing. For the presented tests, only $B^0_s \to D^-\pi^+$ events were simulated with $\Delta \Gamma_s/\Gamma_s$ fixed to 10%, and the wrong tag fraction to $\omega_{\text{tag}} = 32.5\%$.

The goal of the first test was to study the average precision of the Lomb method. As shown in Tab. (5.5), for some fixed value of the mixing frequencies, 100 “Monte–Carlo experiments” were performed, each of which correspond to five years of data taking. For each experiment, the spectral analysis algorithm was applied to determine $\Delta m_s$ and its uncertainty. The average precisions of these experiments are listed in Tab. (5.5): the method does not present biases, and the input values can be measured with an uncertainty up to $0.3\%$. The scatter plot for the $\Delta m_s = 20.0\, \text{ps}^{-1}$ case is shown in Fig. (5.13).

The relevant quantity to investigate was therefore the maximum value of time oscillation frequency $\Delta m_s$ measurable in the experiment. This is the sensitivity limit of the spectral analysis approach. To evaluate this limit, samples of data with $\Delta m_s$ in the range between $5.0\, \text{ps}^{-1}$ and $60.0\, \text{ps}^{-1}$ were simulated, with a

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\(^{15}\)The BMasterFit package available from the NIKHEF LHCb group has been used.
Figure 5.13: Left: scatter plot of the results from the 100 experiment performed to test the statistical precision of the Lomb method. The blue line indicate the most probable value from the distribution, and the green hatched ones limit the FWHM asymmetric error region around it. Right: spectra for the sensitivity limit search. The blue horizontal hatched line indicate the 90% significance level.

<table>
<thead>
<tr>
<th>True $\Delta m_s$ (ps$^{-1}$)</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_s$ (ps$^{-1}$)</td>
<td>15.000$^{+0.024}_{-0.040}$</td>
<td>20.000$^{+0.016}_{-0.040}$</td>
<td>25.000$^{+0.016}_{-0.016}$</td>
<td>30.000$^{+0.053}_{-0.053}$</td>
</tr>
</tbody>
</table>

Table 5.5: Statistical precision on $\Delta m_s$ with the Lomb spectral analysis. The statistics used in these exercises correspond to five years of LHCb data taking.

statistics corresponding to five years of data taking. The Lomb method was then applied; the resulting spectra are shown in Fig. (5.13). The sensitivity found is $\Delta m_s \simeq 50.0$ ps$^{-1}$ with 90% significance level.

The effect of the data taking time has been checked for a couple of values of the mixing frequency, $\Delta m_s = 20.0$ ps$^{-1}$ and $\Delta m_s = 30.0$ ps$^{-1}$. The results obtained are shown in Fig. (5.14): increasing the statistics, the residues between the true value and the measured one decrease to zero. Small discrepancies are visible in the first years of data taking. This is due to statistical fluctuations both in the simulation and in the spectral analysis.

The last source of systematics considered is related to experimental issues. Dedicated studies with the stand–alone simulation package showed that the acceptance function $A (t)$ of the detector is not a concern in the measurement of $\Delta m_s$ with the Lomb method. This is because in the time–dependent asymmetry this acceptance cancels out. If the proper time resolution gets worse, the
discrepancy between the true value of $\Delta m_s$ and the measured one increases.

The impact of the flavour tagging performances on the spectral analysis has also been studied. The value of the wrong tag fraction is the most critical parameter in the analysis: it determines the dilution factor $D$ which controls the amplitude of the time–dependent asymmetry in Eq. (5.38). If $\omega_{\text{tag}}$ approaches to zero, no wrong tags are assigned, the dilution factor comes near to unity and the asymmetry has the maximum amplitude. This is the optimal situation to measure a fast oscillation frequency because higher amplitude constrains it in a better way than smaller amplitudes. On the other hand, when the wrong tag fraction approaches its maximum, $\omega_{\text{tag}} = 0.5$, events are randomly tagged and the amplitude of the time–dependent asymmetry is smeared, making difficult the extraction of the mixing frequency. This behaviour has been successfully confirmed by the analysis of data produced with the stand–alone Monte–Carlo package.

5.6.4 The $b\bar{b}$– and $D_s^\pm$–inclusive analyses

Due to the limited size of the available statistics, neither $b\bar{b}$– nor $D_s^\pm$–inclusive events have been used to extract $\Delta m_s$. More events are needed to apply the spec-
tral method, because the oscillatory pattern of the time-dependent asymmetry is not well defined.

However, from the number of true signal events in the $b\bar{b}$-inclusive sample, it is clear that a narrow mass window cut will be important to enhance the signal to background ratio. Also the background from $D_s^{±}$-inclusive events can be a danger in the $\Delta m_s$ measurement with the $B_s^0 \rightarrow D_s^-\pi^+$ decay channel. More specific studies about the impact of such backgrounds are foreseen with a larger statistics.

5.6.5 Preliminary conclusions

The mass difference in the $B_s^0 - \bar{B}_s^0$ system is much larger than the one in the $B_d^0 - \bar{B}_d^0$ case, and it is still not measured. Only lower limits on $\Delta m_s$ are available, but to get a significant constraint on the CKM matrix in the Standard Model framework, a precise measurement of it is needed.

In the near future, Tevatron and LHC experiments will measure $\Delta m_s$ together with the $\Delta \Gamma_s$ parameter, thanks to a large statistics and to excellent experimental conditions. In particular, at LHC, it will be possible to test if the $\Delta m_s$ parameter is consistent with the Standard Model predictions. In the first year of good data, the expectations are to measure $\Delta m_s$ with a statistical precision of the order of $0.030 \text{ ps}^{-1}$ if $\Delta m_s = 20 \text{ ps}^{-1}$.

The analysis presented here shows that the LHCb experiment will be ready to measure the mixing frequency $\Delta m_s$ from the very beginning of LHC operations. The high sensitivity of the experiment allows the measurement of high $\Delta m_s$ values compatible with extensions of the Standard Model picture. The spectral analysis used can be useful during the first trials of this measurement, when all the backgrounds sources and flavour tagging performances will not be completely understood. If fact the ingredients of the Lomb method are only the two proper time distributions for oscillated and unoscillated events to build the time-dependent asymmetry and the wrong tag fraction $\omega_{\text{tag}}$. The latter parameter can be estimated from Monte-Carlo or from other control channels. In this way a narrow range can be fixed in which measure $\Delta m_s$ with the maximum likelihood fit method in order to get a better measurement and to reduce the uncertainty.
Chapter 6

The Level–0 Muon Trigger

The online muon triggering and offline muon identification are essential tools for the challenging physics program of the LHCb experiment. The muon detector is also part of the trigger system and it provides a robust and reliable trigger signal thanks to the high penetrative power of muons. The heavy flavour content of triggered events is enhanced by requiring the candidate muons to have high transverse momentum $p_T$.

In this chapter a brief description of the Level–0 Muon Trigger (L0 Muon Trigger) is given.

6.1 Lay–out of the muon system

The muon detector has been introduced in Section 2.4.8. It consists of five stations interleaved with muon filters [22, 28, 35, 36, 37]. While stations M2–M3 are devoted to the muon track finding, stations M4 and M5 are used to confirm the muon identification. The M1 station is placed before the calorimeter and plays an important role for the transverse momentum measurement of each muon track, improving the resolution by 30%.

Each station has two sensitive layers with independent read–out. The system has about 120,000 physical channels, logically grouped into 25,920 channels. As shown in Fig. (6.1), each station is subdivided into four regions with different logical pad dimensions. Region and pad sizes scale by a factor two from one region to the adjacent one. The logical lay–out in all the stations is projective in the vertical direction to the interaction point. It is projective also in the horizontal direction if the bending due to the magnetic field in the horizontal plane is ignored.

The logical pad dimensions have been optimized; compared to M1, the pad size along the $x$ axis is twice smaller for M2–M3 and coarser for M4–M5. Pads are obtained by the crossing of horizontal and vertical strips whenever possible. Strips are employed in stations M2–M5, while M1 and region R1 of both M4
and M5 are equipped with pads. Each region is subdivided into sectors, defined by the size of the horizontal and vertical strips and match the dimension of the underlying chambers.

To provide a trigger signal, the Level–0 Muon Trigger looks for muon tracks with high transverse momentum, $p_T$. The track finding is performed on the logical pad lay–out: it searches for hits defining a straight line through the M1–M5 stations and pointing towards the interaction point. The position of a track in M1 and M2 allows to determine the $p_T$ of the candidate muon. Fig. (6.2) schematically shows how the track finding works with a pair of muons.

In order to hide the complex structure of the stations and to simplify the processing, the muon detector is subdivided into 192 towers pointing to the interaction point as shown in Fig. (6.3). A tower contains logical pads with the same lay–out: 48 pads from M1, $2 \times 96$ pads from M2 and M3, $2 \times 24$ pads
Figure 6.2: Track finding by the Level–0 Muon Trigger. For each logical pad hit in M3, hits are sought in M4, M5 and M2, in a field of interest (highlighted) around a line projecting to the interaction region. When hits are found in the M2–M5 stations, an extrapolation to M1 is done from hits in M2 and M3, and the closest M1 hit to this extrapolation is selected. The track direction determined by M1 and M2 hits is used in the $p_T$ measurement, assuming a particle from the interaction point and a single kick from the magnetic field. In this example, $\mu^+$ and $\mu^-$ cross the same pad in M3.

from M4 and M5. As a consequence, the same algorithm can be executed in each tower, which is the key element of the trigger processor. Each tower is connected to a Processing Unit (PU). The Level–0 Muon Trigger is implemented with the four quadrants of the muon system treated independently.

The signals coming from all the logical channels belonging to a tower are sent to a PU using six high–speed optical links. The intersection between a tower and a station defines a sector. The corresponding logical channels are transported on a dedicated optical link to ease the connectivity between the muon detector and the trigger and the data distribution within a processor.

For regions R1 and R2 of the M2 and M3 stations, the data flow is more complex. In fact, in region R1 a sector is shared by two towers while in region R2 a tower maps to two sectors. The first case requires additional exchange of logical channels between PUs while the second one requires eight optical links instead of six. A unique processing board containing four PUs deals with all cases by programming differently the FPGAs\(^1\) and by grouping two interconnected PUs

\(^1\)FPGAs, namely “Field–Programmable Gate Arrays”, are part of the electronic boards to be used in the Level–0 Muon Trigger.
6.2 Level–0 Muon Trigger implementation

In each region of a quadrant the track finder algorithm is performed by 12 PUs arranged on processing boards grouped with a fourfold scheme for regions R1, R3 and R4, and a twofold one for region R2 [119, 120 121]. A PU collects data from the five muon stations for pads and strips forming a tower, and also information from neighbouring towers to avoid inefficiency on boundaries of the regions. Logical channels are merged when they are transferred from region $R_i$ to region $R_{i+1}$; in the opposite transfer direction, logical channels are replicated in four channels to match the granularity of the receiving PU. All the data collected in each tower have the same granularity.

6.2.1 Search algorithm in M3, M4, M5 and M2

The track finding is performed in parallel for all pads. For each logical pad in M3 (track seed), the straight line passing through the hit and the interaction point is extrapolated to M4, M5 and M2. Hits are looked for in these stations in
search windows referred to as Fields Of Interest (FOI), approximately centered on the straight line extrapolation. FOIs are open along the $x$ axis for all stations and along the $y$ axis only for M4 and M5. The size of the FOIs depends on the station considered, the level of background, and the minimum bias retention level required. The size of the FOIs can be defined before executing the algorithm. When at least one hit is found inside the FOIs for each of the stations M4, M5 and M2, a muon track is flagged and the pad hit in M2 closest to the extrapolation from M3 is selected for subsequent use.

A muon candidate is thus determined by the address of the seed in M3 and the address of the pad hit in M2.

6.2.2 Extrapolation to M1 and $p_T$ computation

The track position in M1 is determined by the straight line passing through the selected M2 pad and the M3 seed, extrapolating to M1, and identifying in the FOIs the pad hit closest to the extrapolation point. Once the track finding is completed, the evaluation of the transverse momentum $p_T$ can start.

In this computation, the transverse momentum $p_T$ of each muon candidate is determined from the track hits in M1 and M2, using look–up tables. The $p_T$ is encoded on a 8 bit word: 7 bits plus 1 for the sign, corresponding to a precision of 40 MeV/c between 0 and 5.08 GeV/c.

6.2.3 Candidates selection

The number of candidate muons per PU is limited to two; if additional candidates are found, they are discarded and the PU signals an overflow. The two highest $p_T$ muon tracks are selected first for each processor board and then for each quadrant. The pad hit addresses in M3 and M2 and the computed $p_T$ for up to eight candidates are transferred to the Level–0 Decision Unit (L0DU); if no candidates are found, the addresses are set to 0 and the status word signals the absence of candidates.

6.3 Level–0 Decision Unit

The L0DU receives data from the calorimeter, the muon and the pile–up veto counter at 40 MHz, arriving at different fixed times. The L0DU latency budget is 500 ns, counted from the last arrival of data. The computation of the decision can start with a set of information coming from a Level–0 sub–trigger, after which all the information is time aligned.

An algorithm is executed to determine the trigger decision and a summary bank is constructed. The decision is sent to the Read–out Supervisor which has
The Level–0 Muon Trigger

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>$\pm 3$</td>
<td>$\pm 5$</td>
<td>$\pm 3$</td>
<td>$\pm 3$</td>
</tr>
<tr>
<td>$y$</td>
<td>$-$</td>
<td>$-$</td>
<td>$\pm 1$</td>
<td>$\pm 1$</td>
</tr>
</tbody>
</table>

Table 6.1: Maximum size of the FOIs along the $x$ and $y$ coordinates, expressed in terms of pads with respect to the pad lying on the straight line passing through the hit in M3 and the interaction point. A FOI of $\pm 3$ corresponds to a total width of 7 pads.

<table>
<thead>
<tr>
<th>Candidate’s origin</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$–hadron</td>
<td>2.2</td>
</tr>
<tr>
<td>$c$–hadron</td>
<td>3.3</td>
</tr>
<tr>
<td>$\pi$</td>
<td>63.2</td>
</tr>
<tr>
<td>$K$</td>
<td>28.5</td>
</tr>
<tr>
<td>other particles ($p$, $n$, $\tau$, . . .)</td>
<td>1.1</td>
</tr>
<tr>
<td>ghost tracks</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 6.2: Origin of candidate triggering minimum bias events for a fixed output rate of 125 kHz. The table includes hadron punch–through.

the ultimate decision about whether to accept an event or not [122]. The output rate is 1 MHz.

### 6.4 Level–0 Muon Trigger performances

The performances of the Level–0 Muon Trigger have been tested in order to optimize several parameters of the previously described algorithm. The system has been designed to work with a minimum bias output rate of 200 kHz; several combinations of the sizes of the FOIs and cut values on $p_T$ have been tested; decreasing the dimensions of the FOIs and increasing the cut on $p_T$, the output rate reduces. The actual largest FOIs optimized considering the trigger efficiency with respect to the size of the FOIs are listed in Tab. (6.1).

The transverse momentum $p_T$ determined for the muon candidates found in minimum bias and $B^0_s \rightarrow J/\Psi(\mu^+\mu^-)\phi$ samples can be compared in Fig. (6.4), with optimized FOI sizes and with an output rate of 125 kHz (single muon trigger). The corresponding trigger efficiency is also shown as a function of the cut of $p_T$.

Tab. (6.2) lists the origin of each candidate within the minimum bias event sample. They mainly come from $\pi$ and $K$ decaying in flight. The resolution on the transverse momentum $p_T$ for muons from $b$ quark is of the order of 20%.

---

2Single muon and di–muon triggers share this output rate with ratios 2/3 and 1/3 respectively.
6.5 The L0mAnalysis package

In order to study and optimize the performances of the Level–0 Muon Trigger, a dedicated package has been developed since the beginning of the project. The L0mAnalysis package is an Object–Oriented software based on Gaudi and running within the DaVinci physics analysis software developed for the physics analysis of the experiment [111].

Since all the computing utilities are continuously developing, part of the work in the Level–0 Muon Trigger project was to maintain the code of the L0mAnalysis package up to date. The previous release, used to perform detailed studies of the Level–0 Muon Trigger and in particular to optimize the sizes of the FOIs, was running within the DaVinci v12v3 environment. It could read data produced during the 2004 Data Challenge (DC04). A new version of the software framework...
has been recently released and many changes have been introduced. Since it is based on a new architecture of the computing project, it is incompatible with DC04 data. A new release of the L0mAnalysis package was needed.

The current release of the application is labelled as v4r4 and it runs within DaVinci v14r4. It can read the Real Time Trigger Challenge (RTTC) and the foreseeable 2006 Data Challenge (DC06) simulated events.

To study the performance of the Level–0 Muon Trigger, the first step is to read data and to fill ntuples. Typically, minimum bias and $B^0 \rightarrow J/\Psi(\mu^+\mu^-)\phi$ events are considered. The created ntuples can be then analysed in order to optimize the sizes of the FOIs, to study the signal efficiency as a function of the $p_T$ as well as its output rate, but also the origin of the selected candidates and of the backgrounds.

Since no simulated data were available at the time the L0mAnalysis v4r4 was released, a small amount of both minimum bias and $B^0 \rightarrow J/\Psi(\mu^+\mu^-)\phi$ events have been produced for debugging purposes. Of course, due to the limited statistics available, no performance studies could be done.

---

3Some changes to the code might be needed.
4For this stand-alone simulation, Gauss v19r4, Boole v9r0 and Brunel v27r0 standard versions have been used.
Appendix A

Physical properties of aerogel

Typical value of some physical properties of aerogel are listed in Table (A.1). Note that most of the properties listed are significantly affected by the conditions used to prepare the aerogel and any subsequent post-processing. Low thermal conductivity and high fracture toughness are nicely shown in Fig. (A.1).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>0.003 – 0.35 g/cm³</td>
<td>typical density ~ 0.1 g/cm³</td>
</tr>
<tr>
<td>internal surface area</td>
<td>600 – 1000 m²/g</td>
<td></td>
</tr>
<tr>
<td>SiO₂ volume fraction</td>
<td>0.13% – 15%</td>
<td>typically 5% (95% free space)</td>
</tr>
<tr>
<td>mean pore diameter</td>
<td>~ 20 nm</td>
<td>varies with density</td>
</tr>
<tr>
<td>particle diameter</td>
<td>2 – 5 nm</td>
<td></td>
</tr>
<tr>
<td>refractive index</td>
<td>1.0 – 1.05</td>
<td></td>
</tr>
<tr>
<td>thermal tolerance</td>
<td>up to 500 °C</td>
<td>shrinkage begins at ~ 500 °C</td>
</tr>
<tr>
<td>melting point</td>
<td>&gt; 1200 °C</td>
<td></td>
</tr>
<tr>
<td>thermal conductivity</td>
<td>~ 0.017 W/mK</td>
<td>very low thermal conductivity</td>
</tr>
<tr>
<td>thermal expansion coeff.</td>
<td>2.0 – 4.0 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
<td>independent of density</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>10⁶ – 10⁷ N/m²</td>
<td>very small</td>
</tr>
<tr>
<td>tensile strength</td>
<td>16 kPa</td>
<td>for density 0.1 g/cm³</td>
</tr>
<tr>
<td>fracture toughness</td>
<td>~ 0.8 kPa m¹/²</td>
<td>for density 0.1 g/cm³</td>
</tr>
<tr>
<td>dielectric constant</td>
<td>~ 1.1</td>
<td>for density 0.1 g/cm³</td>
</tr>
<tr>
<td>sound velocity</td>
<td>100 m/s</td>
<td>for density 0.07 g/cm³</td>
</tr>
</tbody>
</table>

Table A.1: Some physical properties of silica aerogels.
Figure A.1: The silica aerogel photo gallery.
Appendix B

The Lomb method

Time series and spectral analysis have long been used in several fields, in astronomy, geophysics, oceanography and many other experimental sciences to find the unknown frequencies of some oscillatory signals. D. Bernoulli first proposed the main tool used in timing analysis; he postulated that a time–dependent function could be expressed as an infinite sum of sines and cosines. J. B. J. Fourier later expressed this more formally. If the function is a periodic time signal, then the Fourier transform describes the frequency content of that signal in the frequency domain.

All the classical methods used in the spectral analysis are based on evenly sampled data. Considering a time–dependent physical variable $h$, it can be sampled as:

$$h_n = h(n\Delta t) \quad n = \ldots, -3, -2, -1, 0, 1, 2, 3, \ldots$$  \hspace{1cm} (B.1)

where $\Delta t$ is the sampling time interval. The Nyquist sampling theorem ensures that the data set in Eq. (B.1) contains complete information about all spectral components of the signal $h(t)$ up to the critical frequency $f_c = 1/(2\Delta t)$, and aliased information about any signal components at frequencies larger than $f_c$.

Sometimes evenly spaced data can not be recorded because of several reasons. For examples, in most ground–based astronomical work, uniform spacing is impossible to achieve. Interpolation of missing data or rebinning the unevenly sampled data could be the way out to get to evenly spaced ones, but such techniques perform poorly. Long gaps in the data, for example, often produce a spurious bulge of power at low frequencies.

A specific method for the spectral analysis of unevenly sampled data was initially proposed by F. J. M. Barning, P. Vaníček and J. D. Scargle and then developed by N. R. Lomb. Today it is known as “Lomb method” and it evaluates data only at times $t_i$ that are actually measured \[123, 124, 125, 126, 127\].

The algorithm of the Lomb method is easy to implement \[118\]. Some details of the mathematics will be given in the following sections.
B.1 Calculating the Lomb periodogram

Suppose for a physical variable there are \( N \) data points \( h_i = h(t_i) \) with the index \( i = 1, 2, 3, \ldots, N \); the mean and variance of the data set are defined by the usual formulæ:

\[
\bar{h} = \frac{1}{N} \sum_{i=1}^{N} h_i \quad \sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (h_i - \bar{h})^2 \quad (B.2)
\]

The Lomb periodogram as a function of the angular frequency \( \omega = 2\pi f > 0 \) is defined as:

\[
P_N^*(\omega) = \frac{1}{2} \left\{ \frac{\sum_{j=1}^{N} (h_j - \bar{h}) \cos(\omega(t_j - \tau))}{\sum_{j=1}^{N} \cos^2 \omega(t_j - \tau)} \right\}^2 + \left\{ \frac{\sum_{j=1}^{N} (h_j - \bar{h}) \sin(\omega(t_j - \tau))}{\sum_{j=1}^{N} \sin^2 \omega(t_j - \tau)} \right\}^2
\]

(B.3)

where \( \tau \) is defined by the following equation:

\[
\tan(2\omega\tau) = \frac{\sum_{j=1}^{N} \sin 2\omega t_j}{\sum_{j=1}^{N} \cos 2\omega t_j} \quad (B.4)
\]

When \( P_N^*(\omega) \) is defined as in Eq. (B.3), it has several useful properties which the usual discrete Fourier transform does not have. First, the inclusion of the \( \tau \) term makes the Lomb periodogram invariant to a shift of the origin of time by any constant. Second, this form makes the spectral analysis exactly equivalent to the equation that one would obtain if one estimated the harmonic content of a given data set, at a given angular frequency \( \omega \), by linear least-squares fitting to the model:

\[
h(t) = A \cos \omega t + B \sin \omega t \quad (B.5)
\]

This fact gives some insight into why the method can give results superior to discrete Fourier transform methods: it weights the sampled data on a “per point” basis instead of on a “per time interval” basis, when uneven sampling can render the latter seriously in error.
Another useful property of the Lomb method defined in Eq. (B.3) is that if the signal \( h_i = h(t_i) \) is purely noise, then the power in \( P_N^*(\omega) \) follows an exponential probability distribution which provides a convenient estimate of the probability that a given peak is a true signal or whether it is the result of randomly distributed noise.

It can be shown that the correct normalization factor for \( P_N^*(\omega) \) is the total variance of the data:

\[
P_N(\omega) = \frac{1}{\sigma^2} \times P_N^*(\omega)
\]  

(B.6)

and with this normalization the periodogram has the mentioned exponential probability distribution.

### B.2 The false alarm probability

The exponential distribution can be very useful. For any angular frequency \( \omega_0 \), the probability that \( P_N(\omega) \) is of height \( z \) or higher is:

\[
\Pr \left[ P_N(\omega_0) > z \right] = e^{-z}
\]  

(B.7)

If \( z \) is the highest peak in the periodogram and \( M \) is the number of the scanned independent angular frequencies, the probability that at each independent frequency the peak is smaller than \( z \) is \( (1 - e^{-z}) \), so the probability that at every frequency the height is lower than \( z \) is:

\[
\Pr \left[ P_N(\omega) < z \right] = (1 - e^{-z})^M
\]  

(B.8)

Thus, the probability that some peak is of height \( z \) or higher defines the false alarm probability:

\[
F = 1 - (1 - e^{-z})^M
\]  

(B.9)

The false alarm probability tells the probability that a peak with height \( z \) or higher will occur, with the assumption that data are pure noise. As a consequence, the quantity \( (1 - F) \) describes the probability that the data contain a signal. The false alarm probability described is the significance level of any peak in the Lomb periodogram: a small value for it indicates a highly significant periodic signal.

To evaluate this significance, the number \( M \) of independent angular frequencies is needed. Since the interesting region in the spectrum is where the significance is a small number, \( \ll 1 \), then Eq. (B.9) can be expanded to give:
Specific studies with Monte–Carlo experiments showed that in general $M$ depends on the number of frequencies scanned, the number of data point $N$ and their detailed spacing [128]. It turns out that $M$ is very close to $N$ when data points are approximately equally spaced and when the sampled frequencies fill the frequency range from zero to the critical frequency $f_c$. The value of $M$ is not importantly different from random spacing than for equal spacing of the data points.

### B.3 Uncertainty of the frequency

The uncertainty in the determination of a frequency in the Lomb periodogram can be determined [128] [129]. The standard deviation of the frequency is:

$$
\sigma_\omega = \frac{3\pi \sigma_N}{2AT\sqrt{N}}
$$

where $A$ is the amplitude of the signal, $\sigma_N$ the square root of the variance of the noise after the signal has been subtracted and $T$ the total time length of the data set. The derivation of such an uncertainty assumes a single signal with Gaussian noise, and even data spacing. Uneven data spacing does not seem to degrade the uncertainty to any noticeable degree. The presence of more than one signal, on the other hand, can cause further shifts in detected frequencies if they are closely spaced.
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Se si riuscisse a trovare un altro modo più conforme alle regole del gioco, sarebbe molto bello...
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1 Tack vare henne pratar jag nu även svenska! Hej Då.
Thank you!
Riassunto in lingua italiana

LHCb è un esperimento dedicato allo studio della violazione della simmetria CP e di alcuni decadimenti rari nel settore dei mesoni B. Raccoglierà dati presso il Large Hadron Collider (LHC) in costruzione al CERN.

La violazione di CP è prevista già nel Modello Standard con tre famiglie di quark e, per quanto riguarda le interazioni deboli, essa è generata dalla matrice unitaria complessa detta di Cabibbo–Kobayashi–Maskawa (matrice CKM). Fenomeni che violano CP osservati nel settore dei mesoni K neutri confermano questo meccanismo. Recentemente processi che violano CP sono stati evidenziati dagli esperimenti BaBar e BELLE con decadimenti dei mesoni B prodotti presso le B Factory (PEP–II e KEKB, rispettivamente).

La violazione di CP riveste un ruolo importante nel campo della cosmologia. Infatti costituisce uno degli ingredienti necessari per spiegare l’eccesso di materia rispetto all’antimateria osservabile nell’universo. Tuttavia l’asimmetria generata nel Modello Standard dal meccanismo CKM non è sufficiente per spiegare l’entità di questo eccesso, e ciò suggerisce l’esistenza di altri contributi che estendono il Modello Standard stesso.

A partire dalla sua scoperta (1964), la violazione di CP è stata ampiamente studiata nel sistema dei mesoni K. La fisica del quark b permette di completarne lo studio, anche grazie al maggior numero di decadimenti disponibili per la determinazione dei parametri che descrivono la matrice CKM. L’obiettivo di LHCb è quello di misurare, in maniera ridondante, lati ed angoli del triangolo unitario collegato alla stessa matrice CKM.

Ad LHC, grazie alla grande sezione d’urto di produzione, $\sigma_{\text{tot}} \approx 500 \mu b$, nelle interazioni protone–protone ($pp$) con energia nel centro di massa di 14 TeV ci sarà un’abbondante produzione di adroni $B$ di diversa tipologia ($B_u, B_d, B_s, B_c, \Lambda_b$ e altri). L’elevata luminosità della macchina metterà a disposizione dell’analisi una statistica considerevole per i diversi canali.

Nella progettazione dell’esperimento si è tenuto conto della particolare distribuzione angolare delle coppie $b\bar{b}$ che sono prodotte entro due coni molto stretti lungo l’asse di scorrimento dei fasci (uno in avanti, l’altro all’indietro). Questo giustifica l’accettanza angolare del rivelatore limitata a 300 mrad e 250 mrad nei piani orizzontale e verticale, e la disposizione dei diversi rivelatori che compongono l’esperimento, dal rivelatore di vertice, ai sistemi di tracciamento e di
identificazione delle particelle, ai calorimetri e alle camere per i muoni. Un efficiente sistema di trigger permette di scartare buona parte degli eventi di fondo, non interessanti nel programma di fisica di LHCb.

L’identificazione delle particelle costituisce uno strumento indispensabile per le successive analisi dei dati raccolti. Gli stati finali dei decadimenti interessanti sono caratterizzati dalla presenza di $K$, $\pi$, $e$, $\mu$, per cui una precisa identificazione di tali particelle permette di ricostruire e selezionare correttamente i processi con cui sono state prodotte, aumentando di conseguenza il rapporto segnale–fondo; inoltre l’informazione relativa all’identificazione viene impiegata anche per il flavour tagging, ossia per riconoscere la presenza, alla produzione, del quark $b$ oppure $\bar{b}$ del mesone $B$ ricostruito.

Per questo, LHCb è equipaggiato con due rivelatori Ring Imaging CHERENkov (RICH) che coprono l’intervallo di momento $1 – 100$ GeV/$c$ e l’intera accettanza angolare. In particolare, il RICH 1 è ottimizzato per identificare particelle con momento nell’intervallo $1 – 65$ GeV/$c$ e con angolo polare fino a 300 mrad; esso utilizza due radiatori Cherenkov, uno solido (silica aerogel) e uno gassoso ($C_4F_{10}$). Il RICH 2 identificherà particelle con momento fino a $100$ GeV/$c$ e con angolo polare fino a 120 mrad, impiegando un solo radiatore gassoso ($CF_4$). I fotoni prodotti per effetto Cherenkov verranno rivelati tramite pixel Hybrid Photon Detectors (HPDs) ottimizzati per essere sensibili nell’intervallo di lunghezze d’onda 200 – 600 nm.

La presente tesi è strutturata come segue:

Capitolo 1 – si introducono il problema della violazione di CP e la sua connessione con la fisica del quark $b$ (Beauty Physics). Il capitolo si conclude con la presentazione dello stato sperimentale della matrice CKM;

Capitolo 2 – si descrivono brevemente il Large Hadron Collider e lo schema generale di LHCb;

Capitolo 3 – vengono presentati i principi di funzionamento dei rivelatori RICH, le problematiche sperimentali, i fattori che limitano le prestazioni ed il potere discriminante nell’identificazione delle particelle. Nella seconda parte del capitolo si descrivono brevemente i due rivelatori RICH di LHCb, mettendo in risalto sia gli aspetti tecnologici di avanguardia (come ad esempio l’impiego di pixel HPDs), sia le prestazioni e le risoluzioni attese;

Capitolo 4 – si descrive l’aerogel, il radiatore (solido) di luce Cherenkov che verrà impiegato nel RICH 1. In questo capitolo, dopo un’introduzione generale, si presentano una serie di test condotti per studiare il comportamento di tale materiale in presenza di radiazioni e di assorbimento di umidità (infatti l’aerogel di LHCb è igroscopico), la sua compatibilità con il $C_4F_{10}$ (l’aerogel sarà a contatto con questo gas all’interno RICH 1) ed eventuali effetti legati all’invecchiamento naturale. Tutti questi test hanno confermato
la possibilità di utilizzare l’aerogel in LHCb. Inoltre si è anche provveduto a misurare il grado di uniformità dell’indice di rifrazione all’interno di singole mattonelle, utilizzando due differenti metodi. In particolare, nel primo si stimano variazioni di indice di rifrazione misurando le deflessioni di luce laser che attraversa la mattonella. Il secondo metodo vede l’impiego di un fascio di elettroni con cui si studia l’omogeneità dell’indice di rifrazione utilizzando direttamente l’effetto Cherenkov. Anche sotto questo aspetto, l’aerogel considerato soddisfa pienamente le specifiche di uniformità;

**Capitolo 5** – nel vasto programma di fisica cui si dedicherà LHCb, la misura del parametro $\Delta m_s$ legato alle oscillazioni $B^0_s \rightarrow \bar{B}^0_s$ è di fondamentale importanza. Da alcune considerazioni, nel Modello Standard ci si attende $\Delta m_s \sim 20 \text{ ps}^{-1}$, per cui la sua misura risulta particolarmente difficile data la rapidità delle oscillazioni. In questo capitolo si presenta uno studio sulla sensibilità nella misura di $\Delta m_s$ da eventi $B^0_s \rightarrow D^- \pi^+$ completamente ricostruiti. Il lavoro qui presentato prevede l’utilizzo dell’analisi spettrale della asimmetria dipendente dal tempo proprio per ricavare la frequenza di oscillazione. Si conclude il capitolo con uno studio relativo alle possibili sorgenti di fondo potenzialmente pericolose per questa misura;

**Capitolo 6** – si illustrano i principi di funzionamento del Level-0 Muon Trigger e dell’algoritmo implementato per la ricerca della coppia di candidati $\mu^\pm$ con cui si costruisce un segnale di trigger. Nella seconda parte del capitolo viene descritta l’applicazione software utilizzata per l’ottimizzazione e lo studio delle prestazioni del Level-0 Muon Trigger.