LHCb experiment : physics programme and status of detector

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LHCb is a dedicated experiment designed to search for **CP** violation in both neutral and charged B meson decays at the LHC proton-proton collider. A general review of the main B decay channels is given by stressing on the physical parameters which can be measured and interpreted in the framework of the standard CKM matrix. On the experimental side, emphasis will be put on the different subdetectors which enter the whole detector, the main role of the trigger system made out from *four levels* and finally the global performance of the LHCb detector.

Introduction

CP symmetry is both a fundamental and approximate symmetry in Nature. The main dynamics explaining its violation in $K^0\bar{K}^0$ system [1] and recently in $B^0\bar{B}^0$ system [2], [3] is still unknown and represents a crucial challenge in Particle Physics for the next decades.

Understanding the dynamical process underlying CP violation (CPV) requires very high statistics in the field of B mesons which decay channels will be thoroughly studied at future experiments like **LHCb** at CERN.

1. Motivations for B physics at proton collider

At the LHC proton collider foreseen for the year 2007, the energy in the centre of mass will be $\sqrt{s}\ =\ 14$ TeV. At this energy, the $b\bar{b}$ production process is dominated by the *gluon-gluon fusion* and the expected cross-section is $\sigma(pp \rightarrow b\bar{b} + X)\ =\ 0.5\ mb$. Compared to the $Y(4S)$ one at e^+e^- collider ($\sigma = 1.15\ nb$), the ratio of the two cross-sections is greater than $4{\times}10^5$

On the other hand, in one year data taking ($\approx\ 10^7$s/y) with an average luminosity of $2 \times 10^{32} cm^{-2}s^{-1}$, the expected number of $(b\bar{b})$ pairs is roughly $N_{b\bar{b}}\ =\ 10^{12}$, which leads to the production of several hadronic flavours associated with the b quark like :

$B_d^0(40\%),\ B_s^0(10\%),\ B_u^{\pm}(40\%),\ B_c^{\pm},\ \Lambda_b, ...(10\%)$

According to the many open channels which arise in the final states, a thorough study of CPV can thus be performed with a wide physics programme which can be divided into three main parts:

Standard B physics

It consists essentially in performing high precision measurements of the Unitarity Triangle (UT) angles $\alpha,\ \beta,\ \gamma,\ \delta\gamma$; triangles deduced from the unitarity of the CKM flavour matrix and which side lengths are of order $O(\lambda^3)$ where $\lambda =\ \sin\theta_C =$ 0.22.

Another subject is an exhaustive study of $B_s^0 - \bar{B}_s^0$ system, essentially their mixing and oscillation parameters x_s and y_s.

Modern B physics

This item includes different reactions which can reveal new physics beyond the Standard Model (SM) : (i) the radiative B decays $b\ \rightarrow\ s(d)\gamma$ which proceed via *electroweak penguin diagrams* and which provide, too, a precise measurement of some poorly known CKM matrix elements like $|V_{td}|$ *and* $|V_{ts}|$; (ii) search for *rare decays* like ${B_s}^0\ \rightarrow\ \mu^+\mu^-$, $B^0\ \rightarrow\ \ell^+\ell^-X$ which SM branching ratios are predicted to be very small $(10^{-7} - 10^{-9})$ and (iii) search for forbidden channels like ${B^0}_{d,s} \rightarrow e^{\pm}\mu^{\mp}$.

The above channels offer the opportunity to look for processes *beyond the SM* which can mix with the SM ones, especially the Flavour Changing Neutral Currents (FCNC) and the Supersymmetric processes.

New-Old items with B physics

(i) According to the high statistics expected with LHCb, search for *direct CPV* with charged $B^{\pm}$ mesons can be done. Despite the small asymmetry predicted by the SM, direct CPV is an important ingredient in the understanding of the approximate CP symmetry.

(ii) Final states with *vector mesons* (charmed or charmless mesons) coming from B decays have non negligeable branching ratios ($10^{-4} - 10^{-6}$). In the special case of neutral vector mesons with $J^{PC} = 1^{--}$, $B^0_{d,s} \to V^0_1 V^0_2 \ \Rightarrow CP = (-1)^{\ell}$, a *mixing of eigenstates* arise with $\ell = 0, 1, 2$. So, very detailed angular analysis can be performed in a model independent way [4] and tests of heavy quark effective theories can be performed.

2. Detector for B physics at proton collider : LHCb

The main production mechanism of b quarks being the gluon-gluon fusion, the resulting B mesons are very peaked in the forward direction with an angle $\Theta_B \leq 200\ mrad$ and a mean momentum $< P_B > = \ 80\ GeV/c$. Thus, the particles coming from B decays must be detected at *very small angles* with respect to the beam axis : $15\ mrad \leq \theta_i \leq 300\ mrad$.

It follows that the LHCb detector must be very similar to a fixed target experiment and the choosen option is that of an *open detector* because of easiness of installing different subdetectors and ensuring their maintenance.

Other physical parameters enter in the conception of a dedicated detector : (i) the mean path length of a B meson is $\approx 7\ mm$ and (ii) the inelastic pp cross-section is $80\ mb$. Thus, the main requirements for a performing beauty meson detector must be :

- Vertex detector.
- Particle Identification system in order to separate between $\gamma/e/\mu/\pi/K/p$, complemented by a very accurate track reconstruction and momentum resolution.
- High selective and fast trigger system in order to select both *(semi-)leptonic* and *purely hadronic* channels.

In figure 1 is displayed the "classic" LHCB detector as proposed in 1998 for the T.P. [5] : the main subdetectors are respectively the Vertex Locator (VELO), two Ring Imaging Cherenkovs, a Tracker system (Inner and Outer), a Calorimetric system followed by the Muon detector and a magnet providing a good uniformity and a maximum field of 1.1 Tesla. In the next section, the main characteristics and performance of each subdetector are discussed.

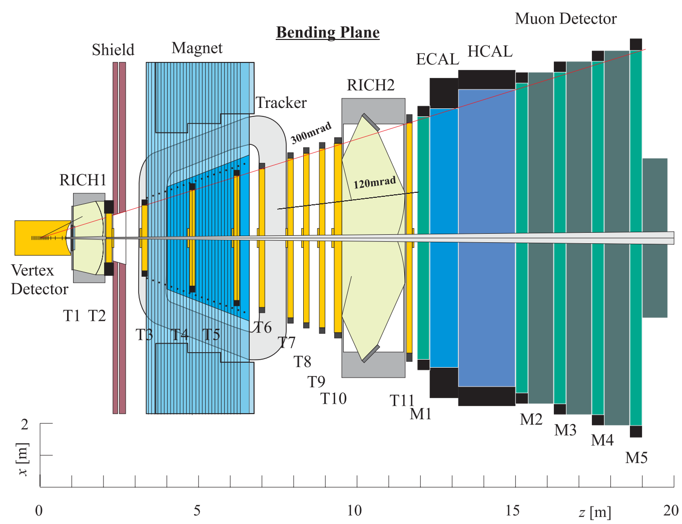


Figure 1. Classic LHCb detector

VErtex LOcator (VELO)

VELO [6] is a silicon vertex detector made out of 21 stations. Each station contains 2 discs divided into sectors : one disc with *radial strips* for measuring the Φ angle, the other disc with *circular strips* for r coordinate measurement. With more than $200,000$ electronic channels and a total silicon area of $0.32\ m^2$, good resolutions on the primary vertex are obtained :

- In the beam direction, $\sigma_z = 42 \pm 1\ \ \mu m$
- Perpendicular to the beam, $\sigma_{\perp} = 10 \pm 1\ \ \mu m$
- And for the special reaction $B_s \to D_s \pi$, time

resolution is : $\sigma_t = 42\ fs$.

Tracking system

The tracking system [7]is a set of several stations made out of *Inner* and *Outer* trackers which involve two different technologies : the Inner tracker, which represents almost 2% of the total area, is a set of silicon sensors, while the Outer tracker ($\approx$ 98% of the active area) is composed of *straw tubes* of 5 mm diameter operating as drift cells. The average reconstruction efficiency for an individual track coming from B decays is : $\epsilon_{tracking} = \quad 96\% \pm 1\%$ and the momentum resolution is well approximated by the relation : $\sigma_p/p \quad = \quad 0.4\%$

In the Technical Proposal, 11 stations were foreseen. Then this number evolved to 9 and at the present time, in the framework of "LHCb-light", 4 stations are sufficient to provide the same resolutions than those mentionned above.

RICH detectors

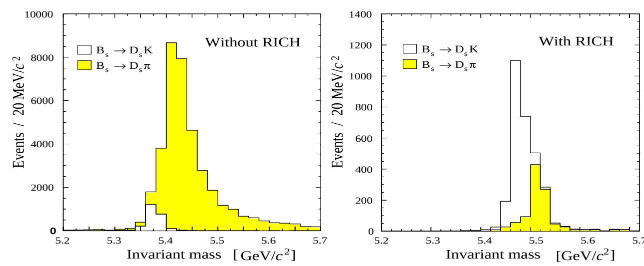
The Ring Imaging CHerenkovs represent the milestone of the LHCb detector [8]; the main purpose being the separation between π and K mesons in a wide momentum range : $1 - 150\ GeV/c$. A simple examination of $\pi^{\pm}$ momentum spectrum coming form $B_d^0 \rightarrow \pi^+\pi^-$ shows that $\approx$ 90% of the pions have a momentum $\leq 150\ GeV/c$; while kaons coming from high multiplicity B decays have momentum down to 1 GeV/c . To fulfill these conditions, *two* RICH detectors are necessary with *three kinds of radiators* of different indices :

Radiator	Index	Momentum range
Silica aerogel	1.03	low
Gaseous C_4F_{10}	1.0014	intermediate
Gaseous CF_4	1.0005	high

• RICH1 of volume $2.4 \times 2.4 \times 1\ m^3$ is very close to the VELO; its angular acceptances are respectively $\Theta_H \leq 300$ mrad and $\Theta_V \leq 200$ mrad and the corresponding momentum range for π/K separation lies between 1 and 100 GeV/c .

• RICH2 with a much bigger volume, $7 \times 7 \times 2.45\ m^3$, is placed downstream and has smaller angular acceptances : $\Theta_H \leq 120$ mrad , $\Theta_V \leq 100$ mrad. The radiator is CF_4 and the corresponding momentum range for π/K separation is $100 - 150\ GeV/c$.

For both the two RICHs, the electronic readout will be achieved by Hybrid PhotoDetectors (HPD) which number is close to 450 to cover all the photo-detector area (2.6 m^2). Figures below show the performance of the RICH detectors in identifying pions and kaons in the special case of channels $B_s \rightarrow D_s K$ and $B_d \rightarrow \pi^+\pi^-$.



Calorimetric system

It is another milestone of LHCb [9]. It is made out from 4 subdetectors : a scintillator pad detector (SPD), a preshower (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL). On the trigger side, the calorimetric system plays an important role for the $L0$ level trigger (see next paragraph).

SPD and Preshower

After the RICH2 a lead wall of 12 mm thickness is installed and it is sandwiched by two scintillator planes : The first plane or SPD signals the passage of charged particles and it discriminates between photons and electrons. The second one, the PreShower, located after the lead discriminates between $e^{\pm}$ and $\pi^{\pm}$. Its total radiation length is $2X_0$.

ECAL

The ECAL has a *shashlik technology* : 2mm lead $\oplus$ 4mm scintillator plates. Its thickness of $25X_0$ is optimised in order to get the best energy resolution for electrons and photons. Its energy resolution is given by the relation : $\sigma_E/E = 10\%/\sqrt{E} \oplus 1.5\%$ (GeV).

Both SPD, PS and ECAL possess the same cellular structure. The cell sizes are variable according to their proximity to the beam axis : inner section with 4x4 cm^2 sizes, middle one with 6x6 cm^2 sizes and outer section with 12x12 cm^2 sizes. Each subdetector has $\sim$ 6000 electronic channels and the readout system consists of wavelength shifting fibers (WLS) which transmit light to photomultipliers(PMT). Monoanode PMT for the ECAL and multianode PMT with 64 anodes are foreseen for the SPD and the PS.

HCAL

The HCAL sampling structure is a set of Iron/Scintillator tiles of 16mm iron $\oplus$ 4 mm scintillator; its total thickness being approximately $5.6\lambda_I$. It has only two cell sizes, 13x13 cm^2 and 26x26 cm^2, and $\sim$ 1500 electronic channels readout by WLS and monoanode PMT. Its energy resolution is given by : $\sigma_E/E = 80\%/\sqrt{E} \oplus 10\%$ (GeV)

Muon system

LHCb detector includes five muon stations, one station located just after the RICH2 and the other four stations after the HCAL. Two kinds of technology are used : (i) multiwire proportionnal chambers (MWPC) for the inner detector and (ii) resistive plate chamber (RPC) for the outer one [10].

The muon system provides an input signal for the L0 level trigger if the condition $p_T \geq 1\ GeV/c$ is fulfilled.

3. Trigger system for LHCb

Looking for exclusive B decay channels requires a highly selective and performing trigger system : It must reject the huge background coming from inelastic proton-proton scattering, $\sigma(b\bar{b})/\sigma_{Inelastic} \approx 0.006$, select the different signals and reconstruct the B mesons online.

A careful study leads to the conception of a trigger with *four levels* in order to reduce the incident beam rate from **40 MHz** to **200 Hz** :

• L0 level based on the transverse energy of a photon or a charged particle.
• L1 level related to the Vertex detector informations.
• L2 and L3 levels are rather software triggers related to the event reconstruction.

L0 trigger

Its aim is to detect high transverse momentum hadron, electron or photon with the calorimetric system and muon with the muon subdetector : $E_T(\gamma) \geq 4\ GeV, \quad E_T(h) \geq 2.4\ GeV, \quad E_T(e) \geq 2.4\ GeV, \quad P_T(\mu) \geq 1\ GeV.$

The L0 output rate is then reduced to 1 MHz.

Since the Technical Proposal, important improvement has been done, especially the conception and realization of a π^0 trigger which is essential for channels like : $B_d^0 \rightarrow \pi^0\pi^0$, $B_d^0 \rightarrow \rho^{\pm}\pi^{\mp}$, $B_d^0 \rightarrow \rho^+\rho^-$

The π^0 trigger [11] concerns 15% to 45% of the unconverted photon pairs. A very elaborated algorithm studying the cluster topology in the ECAL has been put on by imposing that the transverse energy of the two main neutral clusters must verify $E_{T1} + E_{T2} \geq 3$ GeV. Its result is the improvement of the L0 trigger performance : the efficiency of channels with at least one π^0 increases from 10% to 20%.

L1 trigger

The L1 trigger is based on informations coming from the vertex detector and from hits in the different stations in order to reconstruct the primary and secondary vertices. Its input rate is 1 MHz (L0 output) and its output rate is 40 kHz, the output informations are then driven towards the Data Acquisition system (DAQ).

L2 and L3 triggers

The L2 trigger refines the vertex positions and the track reconstruction by using partial informations from different subdetectors; its output rate is 5 kHz.
The L3 trigger uses complete data for B meson reconstruction. Its output rate is **200 Hz**.

The global trigger efficiency has an average value around 30% and it depends usually on the studied channel. Since the Technical Proposal important improvements have been made, especially for hadronic channels which efficiency increases notably [12].

4. Reoptimization of LHCb detector : LHCb-light

An important ingredient in LHCb experiment is the global resolution of the detector. By examining the material up to the RICH2 (according to the classic version), its thickness is roughly equivalent to 60% X_0 and 20% Λ_I. It is mandatory to reduce this thickness for obvious reasons :

• Reducing the hadron absorption (serious inconvenient for the hadronic trigger).

• Maintaining a good momentum resolution and a good efficiency for γ and $e^{\pm}$ detection.

The beam pipe and some subdetectors have to be upgraded :

Beam pipe : The first 25 *mrad* cone is made out of Beryllium.

VELO : Minor change because the 25 stations of the T.P. are replaced by 21.

Tracking system : An important reduction of the number of stations has been studied; **4** stations instead of 11 (as mentionned in the T.P.) can provide the same resolution for track reconstruction. This can be achieved by removing the stations in the magnet and performing a new tracking algorithm based on a modified configuration of the tracking stations : Two half-stations TTa and TTb will be located after the RICH1, while **3** stations ST1-ST3 of identical height will be put after the magnet.

The results are very promising because the B track efficiency is nearly 90% in a wide momentum range while the ghost rate is $\leq$ 10%.

RICH system : The shielding plate after RICH1 (and before the magnet) will be removed. A new configuration and design of the RICH1 spherical mirrors are under study.

Level L1 trigger : Performance of level L1 will be increased by making entirely the half stations TTa and TTb with silicium.

LHCb-light final TDR is in progress and will be submitted to the LHCC in Autumn 2002 and Trigger TDR will be submitted early 2003.

5. Physics performance with LHCb

The existence of high statistics and diversified channels leads to different ways for measuring the UT angles. Apart some "golden" and standard channels, many other channels contribute to the determination of angles α, β and γ. In the following are the main reactions with the expected number of reconstructed events during one year data taking.

Angle β

$B_d \rightarrow J\Psi K_s^0 \Rightarrow$ 100K events/year, the statistical error being $\sigma(\sin 2\beta) \;=\; 0.02$

$B_d \rightarrow \Phi K_s^0 \Rightarrow$ Channel under study

Angle α

$B_d \rightarrow \pi^+\pi^- \Rightarrow$ 5K ev/y, $\sigma(\sin 2\alpha) \;=\; 0.05$

$B_d \rightarrow \rho\pi \Rightarrow$ 1.3K ev/y, $\sigma(\alpha) \;=\; 2.5^\circ - 5^\circ$

$B_d \rightarrow \pi^0\pi^0 \Rightarrow$ Channel under study

Angle γ

• There exist several channels which help to estimate the angle γ. The most important ones are :

$B_d \rightarrow D^{*\pm}\pi^{\mp}$ (1) and $B_s \rightarrow {D_s}^{\pm}K^{\mp}$ (2)

(1) $\approx 340K$ ev/y, the angle γ being deduced from the measurement of $(\gamma + 2\beta)$ with an expected error $\sigma(\gamma) \;=\; 10^\circ$

(2) $\approx 2.5K$ ev/y $\Rightarrow$ measurement of $(\gamma - 2\delta\gamma)$, with an error $\sigma(\gamma - 2\delta\gamma) = 6^\circ - 13^\circ$

• *"Fleischer method"* :

$SU(3)_f$ symmetry is used for the two conjugate channels :

$B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

It will allow the determination of both the two angles β and γ. This method will be investigated.

Angle $\delta\gamma$

• $B_s^0 \rightarrow J/\Psi\Phi \Rightarrow$ 80K ev/y, $\sigma(\delta\gamma) \;=\; 2^\circ$.

It is one of the "golden channels" where *New Physics* could be looked for.

Conclusion

LHCb provides a clean identification of the main B decay exclusive channels. Its four level trigger helps to reject the backgrounds and to perform online the reconstruction of B mesons.

By disposing of many methods of measuring the **UT angles**, opportunity is offered to over-constrain the **CKM** matrix elements. This technique is essential to look for *substantial deviations* from the SM predictions and to answer two crucial questions in modern Particle Physics :

Does New Physics exist and what is the dynamical origin of CP Violation ?

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