LHCb experiment : Physics Programme and Status of Detector

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LHCb is a dedicated experiment at the CERN LHC proton-proton collider designed to search for **CP** violation in the B meson system. A general review of the B decay channels is given. Emphasis is put on the precision measurements of the CKM matrix elements and the performances of the different subdetectors. Special importance is given to the trigger system made out from *four levels*.

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] has not been completely tested 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, which is roughly 4×10^5 greater than the $Y(4S)$ cross-section at the e^+e^- collider. On the other hand, in one year data taking ($\approx 10^7$ s/y) with an average luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, the expected number of $(b\bar{b})$ pairs is $N_{b\bar{b}} = 10^{12}$. The production of B-hadrons is expected to be roughly :

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

According to the many open channels arising in the final states, a wide physics programme can

be performed :

Standard B physics

It consists essentially in performing high precision measurements of the Unitarity Triangle parameters : angles through CP violation and sides through decay rates. Another subject is an exhaustive study of the $B_s^0 - \bar{B}_s^0$ system, essentially their mixing and oscillation parameters x_s and y_s .

New 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 $B_s^0 \rightarrow \mu^+\mu^-$, $B^0 \rightarrow \ell^+\ell^-X$ ($Br \sim 10^{-7} - 10^{-9}$) and (iii) search for forbidden channels like $B_{d,s}^0 \rightarrow e^\pm\mu^\mp$.

The above channels offer the opportunity to look for Flavour Changing Neutral Currents (FCNC) and for Supersymmetric processes.

Special 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 rate predicted by the SM. In the special case of two neutral vector mesons with $J^{PC} = 1^{--}$ (charmed or charmless ones), the CP value is

$(-1)^\ell$ where ℓ is the orbital angular momentum; a *mixing of eigenstates* arises with $\ell = 0, 1, 2$. So, very detailed angular analysis can be performed in a model independent way [4] leading to important tests to the heavy quark effective theory.

2. Detector for B physics at proton collider : LHCb

According to the gluon-gluon fusion mechanism, the resulting B mesons are very peaked in the forward direction with an angle $\Theta_B \leq 200 \text{ mrad}$ and a mean momentum $\langle P_B \rangle = 80 \text{ GeV}/c$. Thus, the particles coming from B decays must be detected at *very small angles* with respect to the beam axis : $15 \text{ mrad} \leq \theta_i \leq 300 \text{ mrad}$.

It follows that the LHCb detector must be very similar to a fixed target experiment and the chosen 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 $\approx 7 \text{ mm}$ 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, $\sigma_z = 42 \pm 1 \text{ } \mu\text{m}$
- Perpendicular to the beam, $\sigma_\perp = 10 \pm 1 \text{ } \mu\text{m}$
- And for the special reaction $B_s \rightarrow D_s \pi$, time resolution is : $\sigma_t = 42 \text{ fs}$.

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 : $\epsilon_{\text{tracking}} = 96\% \pm 1\%$ and the momentum resolution is well approximated by the relation :

$$\sigma_p/p = 0.4\%$$

In the Technical Proposal, 11 stations were foreseen. At the present time and in the framework of "LHCb-light", 4 stations are sufficient to provide the same resolutions.

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 from $B_d^0 \rightarrow \pi^+\pi^-$ 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 in order to cover all the photo-detector area ($2.6 m^2$). Following figures 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).

- 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 $2X_0$.

- 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 $4 \times 4 cm^2$ sizes, middle one with $6 \times 6 cm^2$ sizes and outer section with $12 \times 12 cm^2$ sizes. Each subdetector has ~ 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.

- 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, $13 \times 13 cm^2$ and $26 \times 26 cm^2$, and ~ 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 $p_T \geq 1 \text{ GeV}/c$ 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.
- 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 : $E_T(\gamma) \geq 4 \text{ GeV}$, $E_T(h) \geq 2.4 \text{ GeV}$, $E_T(e) \geq 2.4 \text{ GeV}$, $P_T(\mu) \geq 1 \text{ GeV}$.

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 $E_{T1} + E_{T2} \geq 3 \text{ GeV}$. 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 :

(i) The first 25 *mrad* cone of the beam pipe will be made out of Beryllium. (ii) Minor change will affect the VELO because the 25 stations of the T.P. will be replaced by 21.

(iii) Tracking system : An important reduction of the number of stations has been studied; 4 stations instead of 11 (as mentioned in the T.P.) can provide the same resolution for track reconstruction.

tion. 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 : the B track efficiency is nearly 90% in a wide momentum range while the ghost rate is $\leq 10\%$.

(iv) 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.

(v) 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 while 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

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

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

Angle α

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

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

$B_d \rightarrow \pi^0\pi^0 \Rightarrow \text{Channel under study}$

Angle γ

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

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

(1) $\approx 340\text{K ev/y}$, the angle γ being deduced from the measurement of $(\gamma + 2\beta)$ with an ex-

pected error $\sigma(\gamma) = 10^\circ$

(2) $\approx 2.5\text{K ev/y} \Rightarrow \text{measurement of } (\gamma - 2\delta\gamma)$, 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 :

$$B_d \rightarrow \pi^+\pi^- \quad \text{and} \quad B_s \rightarrow K^+K^-$$

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

Angle $\delta\gamma$

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

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 in order to search for New Physics.

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