Status and expected performance of the LHCb experiment

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Abstract

LHCb is a dedicated $b$-physics experiment at the future LHC collider. Its construction has started and it will be ready to take data from the start of LHC operation, scheduled in 2007, and directly at its full physics potential. LHCb will benefit from an unprecedented source of $b$-hadrons, provided by LHC, to improve substantially precision measurements of CP violation parameters in many different and complementary channels. The detector provides good particle identification, vertexing and has an efficient and flexible trigger. Its status and expected performance are reviewed.

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1. INTRODUCTION

On one hand the Standard Model (SM) predicts large CP violating asymmetries for $B$ mesons, in many but often rare decays. On another hand the LHC collider will provide an unprecedented source of $b$-hadrons. Benefit will be taken from that by constructing the LHCb experiment [1]. It has been conceived to study CP violation and other rare phenomena in $b$-hadron decays with very high precision. This should provide a profound understanding of quark flavour physics in the framework of the Standard Model, and may reveal a sign of physics beyond.

At LHC energies not only are huge numbers of $B$ mesons produced, but there are also produced a large variety of final states involving a $b$-hadron ($B_d, B_u, B_s, B_c, \Lambda_b, \ldots$). In particular, LHCb will be also capable of measuring CP violation effects for the first time in decay modes involving $B_s$ mesons. The LHCb experiment, thanks to robust and efficient triggering and particle identification systems, will be able to exploit this large production to detect and measure pure hadronic and multi-body final states, and also to constrain the unitarity triangles of the CKM [2] matrix (Figure 1).

Thanks to the large $b\bar{b}$ production yield, LHCb will also have the opportunity to investigate very rare decays of $b$-mesons [1,4,5], for example, $B^0 \to K^{*0}\gamma$, $B^0 \to K^{*0}\mu\mu$, $B^0_d \to \mu\mu$, etc.

Complementary measurements will be made of the parameters in different channels, giving additional cross checks. If new physics is present, over-constraining the CKM unitarity triangle will be very important in order to disentangle the SM components from the New Physics.

![Figure 1. The two non-squashed unitarity triangles in the Wolfenstein’s parametrization [3].](image-url)
2. LHC

The Large Hadron Collider (LHC) at CERN, Geneva, will collide protons at a centre-of-mass energy of 14 TeV with a frequency of 40 MHz. The accelerator will be housed in the 27 km tunnel that has been built for the LEP collider. LHC is scheduled to start data taking in 2007. The clear objective is to get the luminosity to $10^{33}$ cm$^{-2}$s$^{-1}$ during 2007 operation. Then the luminosity will be increased to $10^{34}$ cm$^{-2}$s$^{-1}$, its nominal one, in the next few years. The construction of the accelerator is progressing well. For instance, already more than 300 dipoles are delivered of a total of 1200. The transfer line is installed, which represents 2.6 km, and first beam is expected in October 2004.

The total cross section at LHC energy is conservatively assumed to be $\sim 100$ mb and the $b\bar{b}$ total cross section to be $\sim 500$ µb. Furthermore $b$ and $\bar{b}$ pairs production are correlated. They are predominantly produced in the same forward or backward cone, so that a forward spectrometer like LHCb will have an acceptance similar to the one of a central detector like ATLAS or CMS to capture both produced $b$-hadrons.

3. Satus of LHCb

LHCb will run at a reduced luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, obtained by controlling the focus of the beam at the LHCb interaction point. This has been chosen to optimise the number of single interactions per crossing to produce clean events and also to facilitate the triggering and reconstruction. This permits also to make radiation damage in the forward region more manageable.

With this luminosity, LHCb expects about $10^{12}$ $b\bar{b}$ events per year ($10^{7}$s). This luminosity is quite moderate compare to the LHC design one, so it is expected to obtain it from the LHC start-up.

LHCb is a single arm spectrometer covering the range $1.9 < \eta < 4.9$ (Figure 2). It consists of a silicon vertex detector (VELO) which includes a pile-up system surrounding a beam pipe, a magnet and a tracking system, two RICH counters, a calorimeter system and a muon detector. All detector subsystems, except for RICH1, are split into two halves that can be separated horizontally for maintenance and access to the beam pipe.

LHCb has recently undergone a major re-optimisation [4], which led to a substantially reduced material budget and improved performances. Its construction has started and is progressing well.

Among the most important features of the LHCb detector are: an efficient trigger for many $b$ decay topologies; an efficient particle identification; an excellent proper time resolution; a good mass resolution.

3.1. The vertex locator

The vertex locator (VELO) is installed inside the vacuum tank at the interaction region [6]. It is made of series of 21 detector stations placed along the beam line covering a distance of about 1 m. It represents 0.23 m$^2$ of silicon, read-out in 170k channels. Each station consists of two pairs of half-circular Si microstrip detectors; one with sensors with strips at constant radius ($r$-sensors) and one with sensors with quasi radial strips ($\phi$-sensors). The sensors are made from 220 µm thin silicon. The strip pitch and length varies as a function of the radial position of the
3.2. The tracking system

In addition to the VELO, the LHCb tracking system consists of one tracking station before the magnet (TT) and three tracking stations behind the magnet (T1–T3). It is used to measure angles and momenta and provides a momentum resolution of $\frac{\Delta p}{p} \simeq 0.37\%$. For example the mass resolution is about 14 MeV for $B_s \rightarrow D_s^-\pi^+$ decays. The track finding efficiency is $\sim 94\%$ for tracks with hits in all tracking stations (for $p > 10$ GeV/c).

3.2.1. The magnet

To achieve a precision on momentum measurements of better than half a percent for momenta up to 200 GeV/c, the LHC dipole provides an integrated field of 4 Tm [7]. The warm magnet has an aluminium conductor and is centred at $z \sim 5$ m. Its weight is 1600 tons and its power consumption is 4.2 MW. Magnetic field has been introduced between the VELO and the magnet, i.e. in the region of RICH1 and TT, for Level-1 trigger improvement. The magnetic field will be regularly reversed to reduce experimental systematic errors in CP violation measurements.

The iron yoke plates and Al coils have been delivered and their assembly is finished in the LHCb pit. The magnet is moving into its final position in July 2004 and its commissioning is in Autumn 2004. Field map measurements will be performed in 2004–2005.

3.2.2. The tracking chambers

Each tracking station consists of 4 layers. The outer layers (1 and 4) have vertical readout strips ($x$–layers) to measure the track coordinates in the bending plane. The inner layers (2 and 3) are rotated by a stereo angle of $+5^\circ$ and $-5^\circ$ respectively. The first station is the Trigger Tracker [4]. It consists of four planes of silicon microstrip detectors with a pitch of 198 $\mu$m. Strips have lengths of up to 33 cm with a thickness of 500 $\mu$m. They amount to a total surface of approximately 8.3 m$^2$ of silicon and to 180k readout channels. The four layers are arranged in two pairs, with a gap of 30 cm between second and third detection layers.

The three remaining stations are placed behind the magnet with equal spacing. Each station consists of an Inner Tracker (IT) [8] close to the beam pipe and an Outer tracker (OT) [9] surrounding the IT. The IT uses silicon microstrip detectors with a pitch of 198 $\mu$m. Strips have lengths of up to 11–22 cm with a thickness of 320–410 $\mu$m depending on the location. They amount to a total surface of approximately 4.2 m$^2$ of silicon and to 130k readout channels. The OT is made of 5 mm $\times$ 4.7 m straw tubes, with a fast drift gas, allowing signal collection in less than 50 ns. It consists of about 50k readout channels. The serial production has started in 4 different sites.

3.3. The RICH

Two Ring Imaging Cherenkov detectors (RICH1&2) are used for charged hadron identification [10]. They are made with three radiators: Aerogel and C$_4$F$_{10}$ for RICH1, sited upstream of the magnet, which has an angular coverage 25–300 mrad and CF$_4$ for RICH2 which has an angular coverage 15-120 mrad. They provide greater than $3 \sigma \pi/K$ separation over the momentum interval $3 < p < 80$ GeV/c.

The photodetectors used are 1024-pixel LHC-speed Hybrid Photodiodes (HPD) developed by LHCb and currently under fabrication. The con-
struction of RICH2 is advancing. The space frame, the exit/entrance windows, the mirror support are ready.

3.4. The calorimeter system

The calorimeter system consists of 4 subdetectors [11]. A Scintillating Pad Detector (SPD) to distinguish charged particles from photons is followed by a 15 mm lead wall (2.5 X₀) and a Preshower (PS) made with the same technology. The detector elements are 15 mm thick scintillator pads. A groove in the scintillator holds the helicoidal WLS fiber which collects the scintillation light. The light from both WLS fiber ends is sent by long clear fibers to 64-anode photomultipliers tubes that are located above or below the detector. Just after is the Electromagnetic Calorimeter (ECAL) based on the Pb/scintillator Shashlik type (25 X₀, 1.1 λ₁), followed by the Hadronic Calorimeter (HCAL) based on the iron/scintillator tile type (5.6 λ₁). SPD, PS and ECAL are made of 5962 channels while HCAL has 1468 channels.

They provide electron, photon and hadron (including π⁰) identification and play a central role in the Level-0 trigger. Their readout is performed every 25 ns. The efficiency to identify an electron is expected to be ε(e → e) = 95% for a misidentification rate ε(π → e) = 0.7%. In a testbeam, an energy resolution of σ_E/E = 8.3% ⊕ 1.5% for the ECAL and σ_E/E = 75% ⊕ 15% for the HCAL has been measured.

The construction is progressing well. 30% of the PS/SPD modules is completed and the assembly of the supermodules starts in September. All the ECAL modules are ready and the installation in the pit will start in November 2004, while 70% of the HCAL modules is also completed and the installation will start by end of 2004.

3.5. The muon system

The muon system consists of 5 stations of 1380 Multi Wire Proportional Chambers [12]. M1 in front of the calorimeter system and M2–M5 behind it, interleaved with iron shielding plates. M1 is used mainly to improve the momentum resolution in the first trigger level. It consists of two layers of MWPC, while the other four stations are made from four layers. This represents a total surface of approximately 435 m², readout in 26k channels and a hadron absorber thickness of 20 λ₁.

The system provides efficient muon identification, typically 94% for a pion misidentification rate below 1%. Highest p_T muons are selected and used for Level-0 trigger. The production has started in various sites, and the muon filter chariot (2000 tons Fe) is being delivered.

3.6. The trigger

The LHCb trigger is dedicated to select b decays of interest. It is subdivided in three trigger levels, called Level-0, Level-1 and HLT [13]. The aim of Level-0 is to reduce the LHC beam crossing rate of 40 MHz which contains about 10 MHz of crossings with visible pp interactions at the LHCb luminosity, to a rate of about 1 MHz at which in principle all sub-systems could be used for deriving a trigger decision. It preselects the “highest p_T” (>1–2 GeV/c) muon tracks and highest E_T calorimeter clusters (e, γ, π⁰ and hadrons) which information is collected by the Level-0 Decision Unit (L0DU) to select events. With simple arithmetic, L0DU combines all signatures into one decision per crossing. Events can be rejected based on global event variables such as the total transverse energy deposited in HCAL, the charged track multiplicities, or the number of interactions as reconstructed by the Pile-Up system. To be fast it is implemented on hardware.

The Level-1 algorithm will be implemented on a commodity processor farm, which is shared between Level-1, HLT and offline reconstruction algorithms. The Level-1 algorithm uses the information from Level-0, VELO and TT and its implementation is easily scalable to include other parts of the detector. Events are selected based on tracks with a large p_T and a significant impact parameter to the primary vertex. The maximum Level-1 output rate has been fixed to 40 kHz, at which rate full event building is performed.

The HLT algorithm starts with a pre-trigger which aims at confirming the Level-1 decision with better resolution, followed by selection algorithms dedicated to either select specific final states, or generic cuts to enrich the b-content of
the events written to storage at a target rate of about 200 Hz.

The efficiency achieved by the Level-0 and Level-1 triggers varies between 30% and 60% depending on the final states, while the HLT efficiency will reach nearly 100%.

4. EXPECTED PERFORMANCE

4.1. Simulation

The LHCb collaboration uses the PYTHIA 6.2 physics generator in conjunction with QQ and GEANT3. The track multiplicity has been tuned to reproduced CDF and UA5 data and the model includes the description of multiple parton-parton interaction with varying impact parameter. Multiple \( pp \) interactions in the same bunch crossing are also included. The response of the detector is simulated in a realistic way including noise and spill-over effects. A complete description of material from TDRs is used and individual detector responses are tuned on test beam results. A complete pattern reconstruction in reconstruction is performed. Reconstruction and selection algorithms do not make use of the true Monte Carlo information at any stage.

In 2004, EvtGen and GEANT4 are used to generate events. About 180 million events are being simulated and analysed in a distributed way (GRID).

4.2. Physics

About 67 million events were produced in 2003 with about 10 million \( bb \) events, and they are used to evaluate the expected physics performance quoted here [4]. CKM angles are defined on Figure 1. Results are given for one year of LHCb data taking \( i.e. \) 2 \( fb^{-1} \).

4.2.1. Flavour tagging

The identification of the initial flavour of reconstructed \( B_{d}^0 \) and \( B_{s}^0 \) mesons is often necessary. Different algorithms have been developed using same-side kaon tag, opposite-side kaon tag, lepton tag or vertex charge. Combining them, they typically provide an effective tagging efficiency of around 4% for \( B_{d}^0 \) and 6% for \( B_{s}^0 \) channels.

4.2.2. \( \beta \) from \( B_{d}^0 \rightarrow J/\psi K_{S}^0 \)

The \( B_{d}^0 \rightarrow J/\psi K_{S}^0 \) mode is the “gold-plated” channel explored at \( B \)-factories. Precision measurement of this parameter is very important. The CKM angle \( \beta \) is extracted from a fit to the time dependent asymmetry:

\[
A^{\mathrm{CP}} = A^{\mathrm{dir}} \cos(\Delta m t) + A^{\mathrm{mix}} \sin(\Delta m t)
\]

where \( A^{\mathrm{dir}} \) is expected to be equal to 0 and \( A^{\mathrm{mix}} \) to \( \sin 2 \beta \) in the SM. LHCb data will bring a lot of statistics to this channel, which can be used to look into higher order effects and also to fit \( A^{\mathrm{dir}} \). LHCb will collect 240k events in one year, which will obtain a statistical precision on \( \sin 2 \beta \) of around 0.02.

4.2.3. \( \Delta m_{s} \) from \( B_{s}^0 \rightarrow D_{s}^- (K K \pi) \pi^+ \)

LHCb will fully reconstruct this decay to measure the \( B_{s}^0 \) oscillation frequency. It will benefit from excellent momentum resolution (a mass resolution \( < 14 \) MeV/\( c^2 \)), decay length resolution (\( \sim 200 \) \( \mu m \)), proper time resolution (\( \sim 40 \) fs) and an effective tagging efficiency close to 9%. In one year, LHCb will collect 80k events and will be able to observe greater than 5\( \sigma \) oscillation signal if \( \Delta m_{s} < 68 \) \( ps^{-1} \), which is well beyond the SM expectation (14.8-26 \( ps^{-1} \)). Once a \( B_{s} \overline{B}_{s} \) oscillation signal is seen, its frequency is precisely determined, about \( \pm 0.01 \) \( ps^{-1} \).

4.2.4. \( \chi \) from \( B_{s} \rightarrow J/\psi \phi \)

The decay \( B_{s} \rightarrow J/\psi \phi \) is the \( B_{s} \) counterpart of the “golden” mode \( B_{d} \rightarrow J/\psi K_{S} \) and is particularly interesting as it gives access to the weak mixing phase of the \( B_{s} \). This analysis is complicated by the fact that the final state is made by two vector mesons and so two orbital momentum states can occur. Therefore an angular analysis of the decay final states is needed to separate \( CP \)-even and \( CP \)-odd contributions. Experimentally, good proper-time resolution is essential. This is the case in LHCb (<38 fs) and feasible thanks to the large sample collected by reconstructing \( \phi \) in \( K^+ K^- \) and \( J/\psi \) in \( e^+ e^- \) or in \( \mu^+ \mu^- \), 120k events in one year. The attainable precision for \( \sin 2 \chi \) is of the order of \( \pm 0.06 \) and for \( \Delta \Gamma_{s} / \Gamma_{s} \) is \( \pm 0.02 \) (for \( \Delta m_{s} = 20 \) \( ps^{-1} \)).

In the SM, the expected asymmetry is very small (\( \sin 2 \chi \sim 0.04 \)), so it offers a sensitive probe.
for CP violating contributions beyond the SM.

4.2.5. $\gamma$ from $B^0_d \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$

In both decays, large $b \to d(s)$ penguin contributions are present in addition to the $b \to u$ tree transition. The time-dependent decay asymmetries $A_{\text{CP}}^\gamma = A^\text{dir}\cos(\Delta m_d t) + A^\text{mix}\sin(\Delta m_d t)$ can be measured in both channels; this provides four observables which can be parametrized with seven parameters. By exploiting the U-spin symmetry of the strong interaction to relate observables in both decays [14] and measurements of $\chi$ from $B_s \to J/\psi\phi$ and of $\beta$ from $B_d \to J/\psi K^0_S$, these can be reduced to three parameters and $\gamma$ can easily be extracted. Particle identification and good mass resolution are vital for this measurement. In one year, LHCb will collect around 26k of $B^0_d \to \pi^+\pi^-$ and 37k of $B^0_s \to K^+K^-$ and will have a sensitivity to the $\gamma$ angle of 4–6 degrees.

4.2.6. $\gamma$ from $B^0 \to \overline{D}^0 K^{*0}$, $D^0 K^{*0}$

The simultaneous measurement of the rates for the decays $B^0 \to \overline{D}^0(K^+\pi^-)K^{*0}$, $B^0 \to \overline{D}^0(K^+\pi^-)K^{*0}$, $B^0 \to D^0(K^+\pi^-)K^{*0}$, and their CP conjugates, where $K^{*0} \to K^+\pi^-$, allows the CKM angle $\gamma$ to be extracted without the need of flavour tagging or proper-time determination [15]. Since branching ratios are very small, high statistics and good particle identification are necessary for this measurement. The LHCb sensitivity to the $\gamma$ angle is of 7–8 degrees in one year of data taking.

4.2.7. $\gamma$ from $B^+_s \to D^+_s K^+$

The decay $B^+_s \to D^+_s K^+$ and its charge conjugate can proceed through two tree decay diagrams, the interference of which gives access to the phase $\gamma - 2\chi$, and hence to the CKM angle $\gamma$ if $2\chi$ is determined otherwise (e.g. with $B_s \to J/\psi\phi$). Four time-dependent decay rates are measured. Particle identification and good mass resolution are very important; the signal is dominated by background from the $B^0_s \to D^+_s \pi^+$ decays, which has a branching fraction 12 times higher than the signal channel. LHCb will record about 5.4k events in one year, giving a sensitivity of 14–15 degrees in $\gamma$.

5. CONCLUSION

LHCb will perform a study of CP violation with unprecedented precision in many different and complementary channels, having access to all $b$-hadron species. Some of the measurements will be more and some less sensitive to new physics contributions allowing us to disentangle the effects and to have a comprehensive understanding.

The detector provides excellent particle identification, vertex, momentum and proper decay time resolution and has an efficient, flexible and robust trigger. Construction has started and is progressing well. LHCb will be ready for data-taking at the LHC start-up in 2007 with its nominal luminosity. It will provide a sensitive test of the Standard Model and physics beyond.

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