THE LHCb PROJECT*

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The LHCb experiment at the Large Hadron Collider (LHC) at CERN is designed to study CP-violation and rare decays in the B-meson system. A general overview of the project is given, including the physics motivation, the design of the detector and the expected LHCb performance.

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1. Physics motivation

CP-violation is now well established in the neutral kaon system, but its origin is not yet understood. The Standard Model with three quark families can accommodate CP-violation through a complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) matrix. In the minimal Standard Model the CKM matrix is unitary. This property can be expressed geometrically by a set of triangles in the complex plane of which only two are non-degenerate. These triangles are shown in Fig. 1 in the Wolfenstein parameterization of the CKM matrix, developed up to the fifth power of the sine of the Cabibbo angle λ.

Before the start of the LHC, many different experiments, both at e^+e^- B-factories as well as at hadron machines, will perform measurements in the B-meson system that can be related to the angles and sides of the unitarity triangles. The length of the side opposite to the angle β, proportional to $|V_{ub}|$, will be known from $b \to u + W$ measurements, and the length of the side opposite to the angle γ, proportional to $|V_{td}|$, will be known from B-mixing measurements, although both with some non-negligible hadronic uncertainties. The third side of the first unitarity triangle of Fig. 1 has a unit length normalized to $|V_{cb}|$. Thus the knowledge of $|V_{cb}|$, $|V_{ub}|$ and

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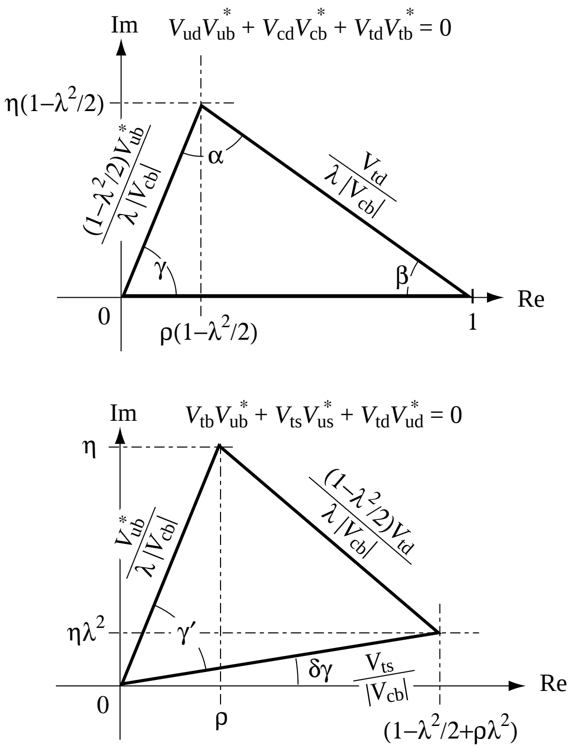

Fig. 1. Unitarity triangles obtained with the Wolfenstein parameterization of the CKM matrix, developed up to the fifth power of the sine of the Cabibbo angle λ.

$|V_{td}|$ allows for an indirect determination of the angles β and γ. In addition, the angle β will also be directly measured from the CP-asymmetry in $B_d^0 \to J/\psi K_S^0$ decays, and $\sin(2\beta)$ will probably be known with a precision below 0.05 by the time the LHC becomes operational. However, due to the limited statistics together with theoretical uncertainties for decay channels like $B_d^0 \to \pi^+\pi^-$ and $B_d^0 \to \pi^+\pi^-\pi^0$, the angle $\alpha = \pi - (\beta + \gamma)$ will only be known with a very limited precision. Neither a direct measurement of γ can be expected, nor the determination of $\delta\gamma$ that will require high statistic B_s^0 decays at hadron machines.

Although CP-violation will be established by the start of LHC, more effort will be required to over constrain the unitarity triangles in order to fully investigate CP-violation and possibly reveal new physics beyond the Standard Model. The aim of the LHCb experiment is to measure precisely CP-violation effects in both the $B_d^0 - \overline{B_d^0}$ and the $B_s^0 - \overline{B_s^0}$ systems, and to determine the phases of the CKM elements that enter in the two unitarity triangles in as many different ways as possible.

2. The LHCb detector

The principle of the LHCb experiment is discussed in the Technical Proposal (TP) [1] that was approved by CERN in 1998. The experiment will profit from the very large b-quarks production cross section in the 14 TeV proton–proton collisions of 0.5 mb, about 1 % of the total visible cross section in LHCb. In order to reduce the number of multiple interactions per bunch crossing, and to limit the radiation dose to the detectors, LHCb will run at an average luminosity of $2 \times 10^{32}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is much lower than the nominal luminosity of LHC at the ATLAS and CMS interaction points. This value is expected from the start-up of the accelerator and can be kept with increasing LHC luminosity by a local de-tuning of the beams at the LHCb interaction point.

The requirements to the detector are an efficient trigger for many B-decay topologies, an excellent particle identification for π–K separation in a wide momentum range, a good decay-time resolution in particular to resolve fast B_s oscillations, and a good mass resolution to efficiently suppress background.

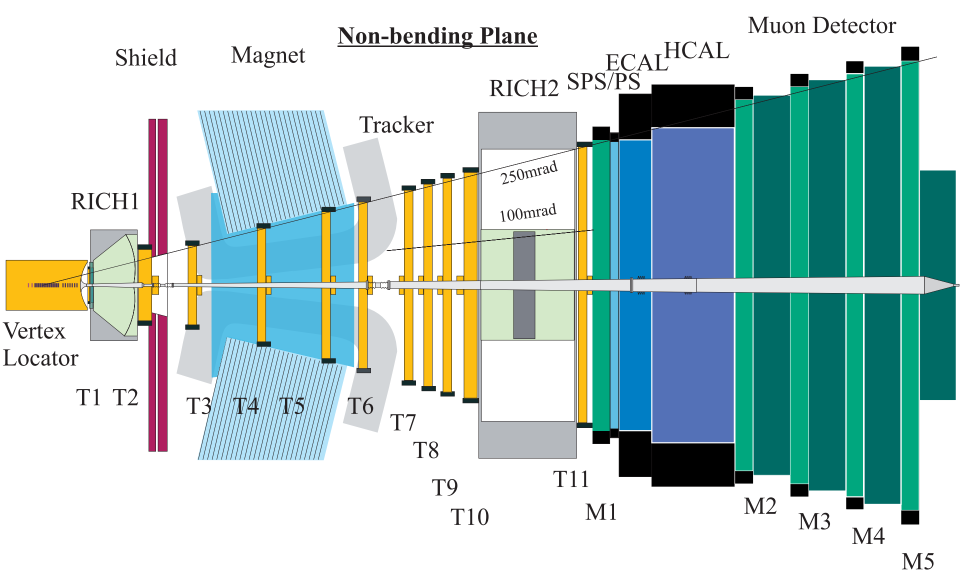

Fig. 2. Side view of the LHCb detector.

An overview of the LHCb detector is shown in Fig. 2. The single-arm forward geometry of the spectrometer with a maximum angular coverage of about 15 to 300 mrad has been chosen to match the correlated $b\bar{b}$ production with predominantly low polar angles.

A stand-alone reconstruction of secondary vertices produced by B-meson decays is performed by the Vertex Locator (VELO) [2] that surrounds the interaction point. It consists of 25 r- and ϕ-measuring stations that are made from half circular 200 μm silicon sensors disposed orthogonally to the beam. The sensors have an active radius from 8 to 40 mm. They will be hosted in Roman pots inside the vacuum tank and are retractable from the beams during injection. The system will provide a 40 μm resolution on the reconstructed primary vertex along the beam axis. The proper time resolution for $B_s^0 \to D_s^- \pi^+$ is estimated to be 43 fs, which would allow to measure B_s^0 oscillations up to $x_s = 75$ in one year of data taking with a significance of better than $5\,\sigma$.

The main tracking system consists of 11 stations (T1–T11) and a warm dipole magnet producing a vertical field with a bending power of 4 Tm [3]. In view of the high particle density close to the beam axis the stations are split into outer and inner subsystems at at radius of about 0.5 m. The baseline technologies that are being investigated are drift chambers with straw-tube geometry for the outer tracker, and possibly a combination of micro-pattern gas chambers and silicon detector technologies for the inner part. This system will form a magnetic spectrometer with a momentum resolution of 0.3 % up to 200 GeV/c. An average mass resolution of 17 MeV/c^2 is expected for $B_d^0 \to \pi^+\pi^-$ decays, and of 11 MeV/c^2 for $B_s^0 \to D_s^- K$ decays.

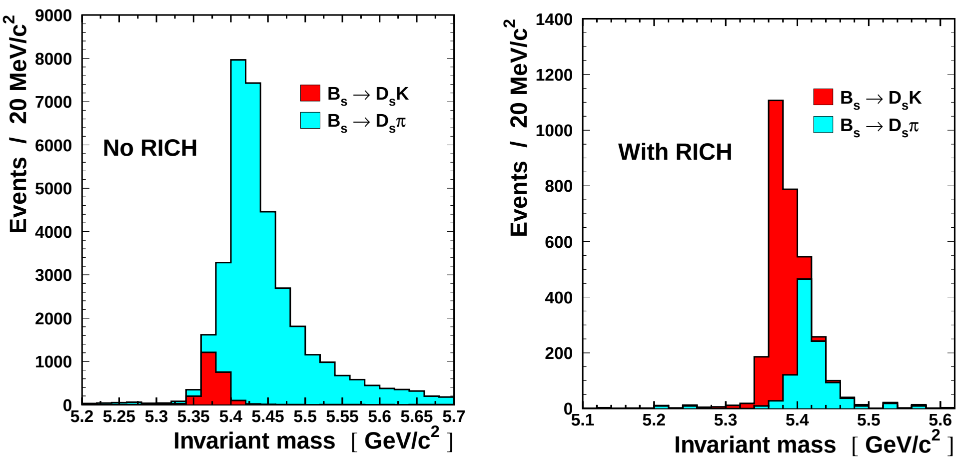

Fig. 3. Invariant mass spectrum for $B_s^0 \to D_s^- K$ decays before and after particle identification with the RICH detectors.

Two RICH detectors [4] with complementary but significantly overlapping momentum ranges have been designed, in order to obtain a π/K separation in the range from approximately 1 to 100 GeV. Particle identification in the high momentum region is important to suppress background in two-body

B decays, whereas identification of low momentum hadrons is needed for b-flavor tagging. The RICH1 detector has aero-gel and C_4F_{10} radiators, while RICH2 employs CF_4. In both detectors the Cherenkov light is observed by pixel HPDs with single photoelectron sensitivity. The performance of the RICH system is illustrated in Fig. 3, showing the invariant mass spectrum for $B_s^0 \to D_s^- K$ decays before and after the particle identification is applied. It is clearly seen that the RICH system efficiently rejects events from $B_s^0 \to D_s^- \pi$ decays that have similar topology to the $B_s^0 \to D_s^- K$ decays.

In order to identify photons, electrons, π^0's and hadrons, the LHCb calorimeter system [5] consists of three sub-detector components, the scintillator-lead pre-shower (PS) detector, the "shashlik"-type Electromagnetic Calorimeter (ECAL), and the scintillating tile Hadron Calorimeter (HCAL). All sub-detectors have a similar technology with scintillating tiles as active material that are readout via wavelength-shifting fibers, and using lead or steel plates as absorber material. Since all sub-detectors have to provide information to the L0 trigger, the optics are optimized for fast signal transmission and are readout in one bunch crossing of 25 ns. The ECAL and HCAL provide an energy resolution of $\sigma_E/E = 10\,\%/\sqrt{E} \oplus 1.5\,\%$ (E in GeV) and $\sigma_E/E = 80\,\%/\sqrt{E} \oplus 10\,\%$ (E in GeV), respectively. A π^0 mass resolution of 6 MeV/c^2 is expected for *e.g.* $B_d^0 \to \rho + \pi$ decays.

The muon system [6] is composed of five stations that are sandwiched between iron filters, except for the first part where ECAL and HCAL play the role of filters. Resistive Plate Chambers (RPC) are planned for the moderate flux regions while Multi Wire Proportional Chambers (MWPC) with anode and/or cathode readout will be used for the high flux regions. The system is optimized to trigger efficiently at L0 on muons from B-meson decays such as $B_d^0 \to J/\Psi(\mu^+\mu^-)K_S^0$, $B_s^0 \to J/\Psi(\mu^+\mu^-)\Phi$, and $B_s^0 \to \mu^+\mu^-$.

The trigger system is designed to be very flexible and robust, consisting of four levels. The first level (L0) runs at 40 MHz input rate using information of the calorimeter and muon systems to select events with hadrons, leptons or photons with high transverse energy in the range of 1 to 3.5 GeV depending on the type of particle. A pile-up veto rejects events with multiple interactions in one bunch crossing. The second trigger level (L1) runs at 1 MHz input rate and uses information of the Vertex Locator to identify displaced vertices, a signature of b-hadron decays. This requires stand-alone three-dimensional pattern recognition to reject minimum bias events that have passed the L0 trigger. The other two trigger levels start with an input rate of 40 KHz and further reduce this rate to 200 Hz. Having access to the full event information the secondary vertices can be further refined by adding momentum information from the tracker (L2), and a complete final state reconstruction can be performed using the offline algorithms (L3).

3. Expected LHCb performance

For many CP-violation studies it is essential to tag the flavor of a B hadron at production. LHCb considers to tag with leptons from $b \to l$ and with charged kaons from $b \to c \to s$ decays. The expected overall tagging efficiency is 40 % with a mistag rate of 30 %.

For most of the important decay channels the dedicated LHCb trigger has an overall efficiency of about 30 % for reconstructed and tagged events. In the leptonic channels for example, $B_d^0 \to J/\Psi(e^+e^-)K_S^0$ and $B_d^0 \to J/\Psi(\mu^+\mu^-)K_S^0$ decays have efficiencies of 24 % and 36 %, respectively. For the hadronic decays of $B_d^0 \to \pi^+\pi^-$ we expect a total efficiency of 30 %.

In order to over-constrain the unitarity triangles and to reveal possible new physics beyond the Standard Model, LHCb will determine the angles α, β and γ, as well as $\delta\gamma$, in as many different ways as possible. The physics performances are described in the Technical Proposal [1] and in a CERN Yellow Report [7]. In one year of nominal LHCb luminosity ≈ 50 k useful events will be collected in the $B_d^0 \to J/\Psi K_S^0$ decay channel, which leads to a precision of 0.02 on the determination of $\sin(2\beta)$. Approximately 30 k events are expected in the $B_s^0 \to J/\Psi\Phi$ decay allowing a measurement of $\delta\gamma$ within $0.6°$ to $1.4°$, depending on the value of $\delta\gamma$ and of the strong interaction phases. Again, depending on the central value and the final state strong interactions, a precision of $4°$ to $19°$ per year of running is expected on γ from $B_d^0 \to DK^{0*}$ decays, and of $6°$ to $14°$ on $\gamma - 2\delta\gamma$ from $B_s^0 \to D_SK$ decays. Furthermore one expects an error of $2.5°$ to $5°$ on α from about 1300 $B_d^0 \to \rho + \pi$ events per year.

Also part of the LHCb program is the study of rare B-decays such as the FCNC channels $B_s^0 \to \mu^+\mu^-$ with an expected 10 events per year and $B_d^0 \to K^{0*}\gamma$ with 26 k events per year.

4. Conclusion

LHCb will take full profit from the very large b-quarks production cross section at LHC, from its start-up in 2006. With an efficient trigger for many B-decay topologies, an excellent particle identification for π–K separation in a wide momentum range, a good decay-time resolution to resolve fast B_s oscillations, and a good mass resolution for charged as well as neutral decay modes, the LHCb experiment is well suited to examine the consistency of the CKM description for CP-violation, and to search for new physics.

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