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Status and Physics Prospects of the LHCb experiment

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LHCb is an experiment dedicated to the study of B physics and CP violation. At the dawn of the first proton beams at the LHC, we review the status of the apparatus and discuss the physics prospects.

1. Introduction

The beauty sector is a promising place for the study of CP violation effects, and to search for seeds of new physics. The BABAR, BELLE and TEVATRON experiments have strongly contributed to this field by constraining B oscillation and the CKM parameters. A new step will taken by LHCb which will make use of the unprecedented number of B hadrons produced at the LHC collider. While the study of the electroweak interaction is our primary interest, QCD considerations are important for the performance of measurements with hadrons.

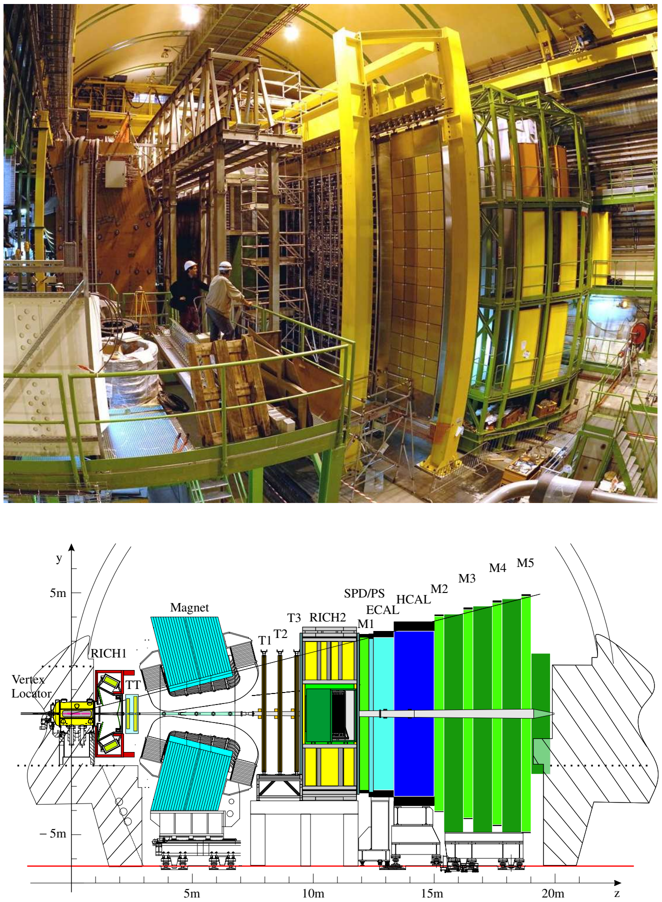

Figure 1. Overview of the LHCb detector with its different elements: *above* photograph taken in 2008; *below* schematic of the detector.

2. LHCb requirements and performance

2.1. Detector design

In the LHC context b quarks are produced in pairs, with a sharply peaked forward-backward distribution. This configuration motivated the design of the LHCb detector [1] as a single-arm forward spectrometer (figure 1), with a fiducial acceptance covering a pseudo-rapidity of $\eta \in [1.9, 4.9]$. As beauty production suffers from a large uncertainty, the $pp \rightarrow b\bar{b}$ cross-section is taken conventionally to be 230 μb in the LHCb acceptance, and will be measured precisely.

The luminosity is limited at LHCb to a few 10^{32} cm^{-2}s^{-1} by ensuring that the LHC beams are less strongly focussed than for the general-purpose detectors. Indeed, the design luminosity is chosen to maximize the probability of a single interaction per bunch crossing.

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2.2. Subdetectors

B hadron signatures used in LHCb include the detection of particles with high p_T (a few GeV/c) coming from a displaced vertex (typically 1 cm from the primary vertex). The subdetectors are designed to achieve this aim.

Tracker stations (**TT** & **T1-T3**), the vertex locator (**VELO**) and the dipole **magnet** allow tracks coming from B decay to be reconstructed with a good efficiency (95%, for 4% of ghost tracks) and a momentum resolution $\delta p/p$ of 0.4%. The 5 μm hit resolution of the VELO supplies an impact parameter resolution of 30 μm. A calorimetry system (scintillating pad detector **SPD**, preshower **PS**, electromagnetic **ECAL** & hadronic **HCAL** calorimeters) completes the kinematics determination. To reject background, excellent particle identification is based on calorimeters, muon chambers (**M1-M5**) and especially Cherenkov detectors (**RICH**) for discriminating protons, kaons and pions. Signal selection based on these elements leads to a B mass resolution of $15-20$ MeV/c^2.

The measurement of oscillations imposes further requirements. The VELO is designed to ensure a good proper time resolution, 40 fs, for resolving B_s^0 oscillations. Tagging the quark flavour at production is crucial. From the combination of several methods, the effective tagging power is estimated to 4-5% for B_d^0 and 7-9% for B_s^0.

2.3. Two-level trigger

As the beauty production in the LHCb acceptance represents less than 1% of the total cross-section, a trigger selects, online, the events relevant for physics analysis. The data rate is consequently reduced from 40 MHz to 2 kHz. The trigger architecture is made up of two levels:

1. The L0 trigger is a hardware level reducing the data rate to 1 MHz. Its decision is based on global cuts (pile-up, global energy, etc) and on the reconstruction of calorimeter and muon candidates with the highest transverse momentum.

2. The HLT is a software trigger level using almost all detector information. 200 Hz of the output data rate is dedicated to the B physics program; other components are reserved for calibration and additional physics topics.

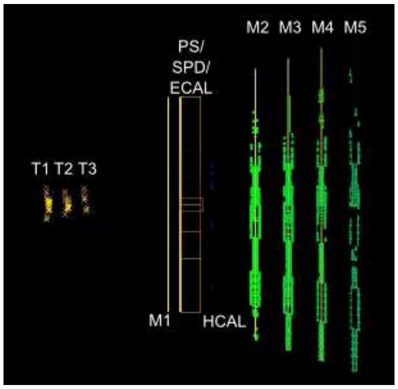

Figure 2. First beam particles through the LHCb subdetectors lying after the magnet (M1 & ECAL were not read out for this event).

3. First beams and LHCb schedule

At the time of this writing, apart from the **M1** station, all subdetectors are installed and cabled. Calibration and time-alignment of the different elements have been performed with cosmic particles and continue with the first LHC beams. Figure 2 shows reconstructed tracks of an event taken on the official LHC start-up day, 10 September 2008. While 2008 runs will be dedicated to commissioning, an early physics program will use 0.5 fb^{-1} in 2009 with the design luminosity of 2×10^{32} cm^{-2}s^{-1}. The luminosity is planned to be gradually increased up to 5×10^{32} cm^{-2}s^{-1} for a total statistics of 10 fb^{-1} by about 2013. The option to subsequently upgrade LHCb detector is also being investigated.

4. LHCb physics program

CP violation and rare decays are the main research fields of the LHCb experiment. Some of the most promising analyses are discussed in this paper.

4.1. CP violation in the B sector

LHCb will contribute to the search for new physics by constraining CP violation parameters, especially the mixing phase ϕ_s of B_s^0 oscillations

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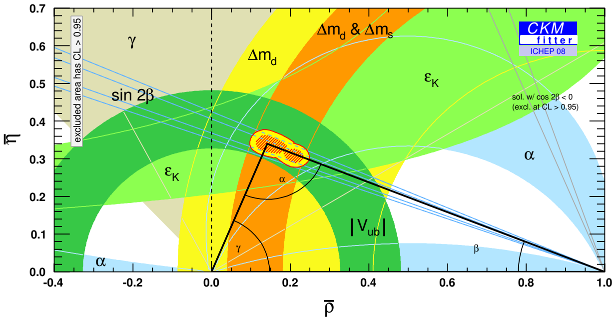

Figure 3. Constraint on the CKM matrix parameters in the $\bar{\rho} - \bar{\eta}$ plane.

and the angle γ of the Unitarity Triangle. Expected results are given for 2 fb^{-1}.

4.1.1. B_s^0 mixing phase ϕ_s

The phase ϕ_s is predicted very small in the Standard Model (SM), (-0.0368 ± 0.0017) rad, and could be much larger if new physics contributes. Improving the precision of the current measurements, for example (-0.79 ± 0.57) rad from D0 [2], is a key point of the LHCb program. ϕ_s can be extracted from the time-dependent CP asymmetry in decay rates and two sets of signal events can be studied for this goal [3]. The first one contains pure CP eigenstates such as $B_s^0 \to J/\Psi\eta$, $B_s^0 \to J/\Psi\eta'$, $B_s^0 \to \eta_c\phi$ or $B_d^0 \to D_s^+ D_s^-$. However, these channels have a low yield (2-8k/channel); a resolution of 0.046 rad on ϕ_s can be reached. The second set gathers the admixture of CP eigenstates. The golden channel is $B_s^0 \to J/\psi\phi$ which has a large yield (130k) and a clean signature. On the other hand, an angular analysis is required in order to disentangle even and odd eigenstates. This analysis leads to the better resolution of 0.023 rad.

4.1.2. CKM angle γ

Figure 3 shows the different experimental constraints on the Unitary Triangle. The average of its angles from direct measurements are (from CKMfitter [4]):

$$\alpha = 88.3^{\circ}{}^{+5.7^{\circ}}_{-4.8^{\circ}}, \ \beta = 21.15^{\circ}{}^{+0.90^{\circ}}_{-0.88^{\circ}}, \ \gamma = 67^{\circ}{}^{+32^{\circ}}_{-25^{\circ}}.$$

Unlike the other angles, γ is poorly constrained and a strong LHCb contribution to this measurement is expected. Three independent approaches [5] can be followed to extract this parameter:

1. From tree amplitudes like $B_{s,d}^0 \to D_{s,d}^{\pm} K^{\mp}$, the two transitions $b \to c$ and $b \to u$ interfere via B_s^0 mixing and allow to access in a very clean way $\gamma + \phi_{s,d}$. In principle, this measurement suffers from an eightfold ambiguity which can be solved by invoking U-spin symmetry. A resolution of $\sim 10^{\circ}$ on γ is expected.

2. From tree amplitudes like $B^{\pm} \to D^0 K^{\pm}$, the two transitions $b \to c$ and $b \to u$ interfere to a common D^0 and $\bar{D}^0$ final state. The analysis strategy (GLW, ADS, GGSZ Dalitz) depends on the nature of this common final state. For some channels, the expected result depends heavily on the strong phase values (like $B^0 \to D^0(K\pi/hh)K^{*0}$) or on background assumptions (like $B^{\pm} \to D^0(K_s^0\pi^+\pi^-)K^{\pm}$). Combining all analyses leads to a resolution of $\sim 5^{\circ}$ on γ.

3. From penguin amplitudes $B_{s,d}^0 \to hh$, the $b \to u$ tree interferes with the $b \to d(s)$ penguin transition. γ can be extracted from the CP asymmetry in the $B_s^0 \to KK$ and $B_d^0 \to \pi\pi$ decays by assuming U-spin symmetry. The precision on γ is about 10° with this method. Futhermore, these modes are also potentially sensitive to new physics.

4.2. Rare B decays

Rare B decays provide opportunities to constrain new physics contributions in transitions such as $b \to l^+l^-$, $b \to sl^-l^+$ or $b \to s\gamma$. This purpose is illustrated in the present paper with two relevant examples.

4.2.1. $B_s^0 \to \mu^+\mu^-$ branching ratio

The braching ratio of this channel is sensitive to new physics, in particular SUSY (MSSM enhancement or suppression by $\tan^6\beta/M_A^4$ term). CDF has constrained the branching ratio to be less than 4.7×10^{-8} (90% CL) [6]. As the SM prediction is $(3.35 \pm 0.32) \times 10^{-9}$, new physics could still contribute an order of magnitude. In the

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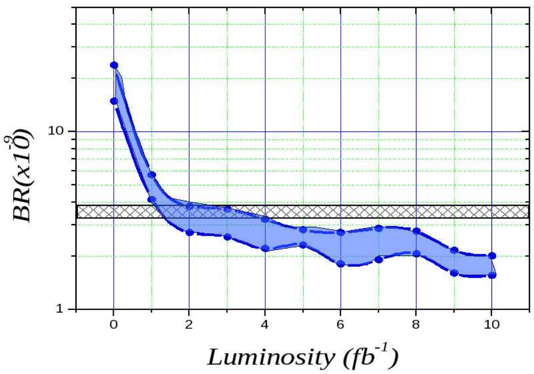

Figure 4. $B_s^0 \to \mu^+\mu^-$ branching ratio as a function of the integrated luminosity (for 3σ measurement).

LHCb context, the analysis [7] profits from the excellent reconstruction, identification and trigger efficiencies for muons. As shown in figure 4, the limit on the branching ratio is a function of the integrated luminosity. Assuming the SM branching ratio, evidence for the channel (at 3σ) can be achieved with 2 fb^{-1} and it can be observed (5σ) with 6 fb^{-1}.

4.2.2. $B_d^0 \to K^{*0}\mu^+\mu^-$ asymmetry A_{FB}

New physics can affect $B_d^0 \to K^{*0}\mu^+\mu^-$ dynamics and a promising observable for studying its effects is the muon forward-backward asymmetry $A_{FB}(s)$ with $s = m^2_{\mu^+\mu^-}$ in the $\mu^+\mu^-$ rest frame. This asymmetry can be expressed as:

$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

with θ an angle defined by figure 5.

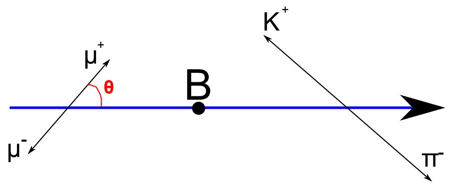

Figure 5. The angle θ between the μ^+ and the z-axis in the $\mu^+\mu^-$ rest frame. The z-axis is the direction in which the B meson flies in the rest frame of the $\mu^+\mu^-$.

A first measurement of this asymmetry will be the zero point crossing (s_0, such that $A_{FB}(s_0) = 0$). Predicted to be $4.39^{+0.38}_{-0.35}$ GeV^2/c^4 in the SM, s_0 can differ according to the considered SUSY model. In the LHCb context, the s_0 resolution [8] can reach 0.5 GeV^2/c^4 with 2 fb^{-1} and 0.3 GeV^2/c^4 with 6 fb^{-1}, allowing supersymmetric models to be discriminated.

4.3. Other physics

The LHCb physics program is completed by additional analyses such as the $b\bar{b}$ cross-section measurement, charm physics (especially D^0 mixing and CP violation), the mass and lifetime of B_c^+ and Λ_b^0, spectroscopy of heavy-flavoured hadrons, and the potential to observe new physics processes with b-jets.

5. Summary

With the LHC start-up, LHCb is now ready to explore B physics and to extend the B factory results. In 2009, the early physics program with 0.5 fb^{-1} will allows first measurements to be performed (such as ϕ_s from $B_s^0 \to J/\psi\phi$, BR($B_s^0 \to \mu^+\mu^-$) limit and the s_0 parameter from $B_d^0 \to K^{*0}\mu^+\mu^-$). According to analysis expectations with a higher integrated luminosity, LHCb has great potential for the discovery of new physics.

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