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LHCb: Status and Prospects

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The huge $b\bar{b}$ cross section at the LHC makes it possible to collect large samples of B hadrons. This allows for the detailed study of CP violating asymmetries, and hunt for rare decays. The LHCb detector is a dedicated B-physics experiment aimed at meeting the challenges involved. After introducing the experiment and the status of its construction, an overview of the expected performance is given, highlighting a few physics modes.

1. INTRODUCTION

The LHCb experiment is designed to take advantage of the huge $\mathrm{b\bar{b}}$ production rate at the Large Hadron Collider (LHC). This rate is the product of a cross-section of approximately 500 mb for $\mathrm{b\bar{b}}$ production in pp collisions at 14 TeV, and a modest luminosity of $2 \times 10^{32}\,\mathrm{cm^{-2}\,s^{-1}}$. Assuming an integrated luminosity of $2\,\mathrm{fb^{-1}}$ for a nominal running year, this corresponds to the production of 10^{12} $\mathrm{b\bar{b}}$ pairs.

This large production rate offers the opportunity to study in detail rare b hadron decays, including $\mathrm{B_s^0}$ and Λ_b decays. However, there is a price one has to pay for this large b rate: the presence of an even larger inelastic rate. The $\mathrm{b\bar{b}}$ cross section is only $\approx 0.5\%$ of the total cross section; as a result the challenge for the experiment is not just to retrieve the decays of interest from the huge $\mathrm{b\bar{b}}$ sample, but to do this in the presence of a huge non-b background.

One of the important selection criteria to reject the large amount of background is to require the presence of charged tracks which are not consistent with the hypothesis that they are produced at the primary interaction vertex. However, in the case that multiple events pile-up in a single crossing, background events can fake such a signature if one of the primary vertices is not recognized as such. The pile-up probability is shown in Fig. 1 as a function of luminosity. The nominal luminosity is chosen to be at values around $2 \times 10^{32}\,\mathrm{cm^2\,s^{-1}}$ as the majority of bunch crossings have only one interaction, limiting this effect. In addition, the radiation dose to which the detector is exposed is reduced at this relatively low luminosity.

The expected angular distribution of b quarks produced in LHC collisions is shown in Fig. 1. Because a large fraction of the $\mathrm{b\bar{b}}$ pairs is produced in the (same) forward direction, the experiment is designed as a single-arm forward dipole spectrometer, with an angular coverage of approximately 15 mrad to 300 (250) mrad in the bending (non-bending) plane. To fit the experiment into the experimental area in point 8 of the LHC ring the collision point is offset from the center of the cavern. The cavern is split in two zones by a concrete shielding wall, which allows much of the read-out electronics to be in a low radiation region.

2. DETECTOR STATUS

The global detector layout is shown in Fig. 2.

The tracking system of LHCb can globally be divided into three sub-systems. First, around the interaction point, a silicon Vertex Locator (Velo) is placed. This detector provides precision measurements of the track orbit close to the interaction region. For this purpose, the Velo features a series of disk-shaped silicon sensors perpendicular to the the beam direction. The inner most radius of the sensors is at a distance of only 8 mm from the LHC beams. Second, downstream of the interaction point, but still in front of the magnet, the so-called Trigger Tracker (TT), instrumented with silicon strip sensors, is located.

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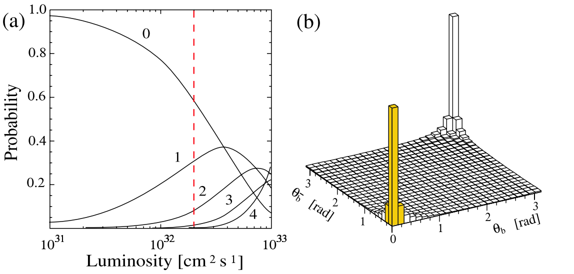

Figure 1. (a) Probability of the number of pp interactions per bunch crossing as a function of luminosity. The dashed line indicates the nominal LHCb luminosity. (b) The polar angle distribution of the b and $\bar{\mathrm{b}}$ hadrons produced at the LHC. The shaded region is the one selected by the LHCb experiment.

This detector covers the full acceptance and has a surface area of 8 m^2. Together with the VELO, this detector provides an initial momentum measurement for the trigger. This detector is followed by a large dipole magnet, with an analyzing power of 4 Tm. Behind this magnet, three tracking stations, T1, T2 and T3, can be found. These three stations are constructed utilizing two different detector technologies; The interior part, close to the beam line, consists of silicon strip detectors whereas the exterior part is made from straw tube drift cells. This division is driven by the observation that, even though the former has an area only 2% of the latter, about 20% of the tracks will pass through it.

The ring-imaging Cherencov system consists of two detectors, and utilizes three different radiators: silica areogel, C_4F_{10} and CF_4 gas, to provide $K-\pi$ separation in the momentum range between 2 and 100 GeV/c. The first detector, just downstream of the vertex detector, provides coverage for low and intermediate momentum tracks over the full acceptance. A second detector, downstream of the tracking system, covers the high-momentum tracks at polar angles below 120 mrad. This two detectors allows both the use of kaon identification for flavor tagging as well as for disentangling various hadronic B decays modes.

The calorimeter system consists of a pre-shower with scintilating pad detectors on either side of a $2X_0$ sheet of lead, followed by a $25X_0$ electromagnetic calorimeter, constructed as a lead-scintillator Shashlik combination. This is completed with a $5.6\lambda_I$ hadronic calorimeter consisting of iron-scintillator tiles. Both calorimeters have been installed, and the six meter high construction is clearly visible in Fig. 3.

The detector is completed by a muon system, made up of five stations, separated by iron. Expect for the inner most part of the first station, which uses triple-GEM detectors, multi-wire proportional chambers are used.

The status of installation is reflected in Fig. 3, which shows the LHCb cavern in May 2006. The magnet, RICH2, and both electromagnetic and hadronic calorimeters are already clearly recognizable.

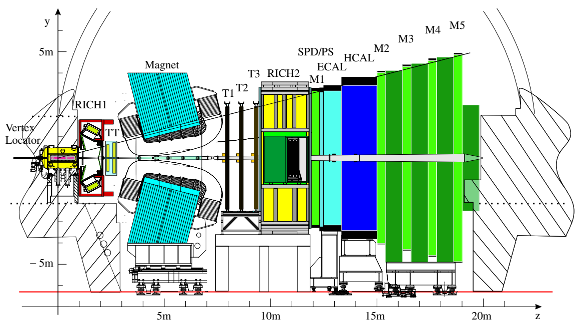

Figure 2. Layout of the LHCb spectrometer.

3. EVENT GENERATION AND SIMULATION

The expected performance of the experiment is studied on fully-simulated events, generated using PYTHIA (together with EvtGen for the B hadron decays), and simulated with GEANT4. The geometry and material of the detectors are

Figure 3. View of the LHCb experimental area in May 2006. From left to right, one sees the scaffolding of the muon system, the hadronic and electromagnetic calorimeters, the second RICH, and finally the magnet. Note that this view of the detector is from the opposite side compared to the drawing of the layout in Fig. 2.

described in detail, using the the results of the various sub-detector TDRs. The detector response is simulated using the results obtained from beam tests of prototypes, eg. detection efficiencies and resolutions. Electronic noise and cross-talk effects are also included. The detector response is simulated taking into account the arrival time of each particle, which, depending on the detection technology and electronics, may span several consecutive bunch crossings. This effect is referred to as spill-over. To take it into account not only particles produced in a specific bunch-crossing are considered, but also those in previous and subsequent crossings. The probability that one of these crossings produces particles is determined as a function of the instantaneous luminosity.

4. TRIGGER STRATEGY

One of the largest challenges of the LHCb experiment is the trigger. It is designed to distinguish minimum-bias events from events containing B hadrons by looking for the presence of particles with large transverse momentum, and for evidence of the existence of secondary vertices. To cope with the data rate within the allotted time budget, the trigger is split into two parts. The first trigger, called Level-0, is based on dedicated custom hardware and runs synchronous with the LHC beam crossings at 40 MHz, with a fixed latency of 4 μs. This trigger requires the presence of at least one lepton or hadron with a p_T exceeding 1 to 3 GeV/c. This should reduce the rate down to 1 MHz. At this point the entire detector is read out, and the data is shipped to a farm of dedicated PCs, consisting of about 2000 CPUs. As a result, the main limitation of this system is the CPU capacity available. Currently this stage of processing is split into two stage. The first stage starts with a confirmation and refinement of the Level-0 decision with the additional information now available. For example, at this stage it becomes possible to determine a first momentum estimate for those tracks which seem inconsistent with the primary vertex. This makes it possible to distinguish between high p_T charged tracks from secondary vertices, and low momentum tracks which have scattered whilst traversing the detector material, and which, without knowledge of their momentum, were initially considered to be inconsistent with the primary vertex. This processing stage takes about 1 ms, and reduces the rate down to approximately 40 kHz. At this point it becomes feasible to fully reconstruct the events, and select them into several separate output streams, which are written to mass storage at a rate of up to 2 kHz.

The output rate is currently split between several samples. First, there are the fully reconstructed candidates. These are expected to consume a rate of about 200 Hz. Next, three inclusive streams are foreseen: one which selects dimuons with a mass consistent with a J/ψ (or larger), and is expected to use up to 600 Hz. The events in this stream do not rely on the displaced vertex signature to be selected, and could thus be used to (amongst other uses) commission and calibrate those trigger channels which do require this signature. Next a rate of 300 Hz is reserved for events containing reconstructed D^{*0} mesons. These D^{*0} mesons provide, through the charge correlation between the D^0 decay products and the charge of the low-momentum pion, a means to select samples of kaons and pions without the use of the RICH detectors. This makes this sample a good candidate for their calibration. Finally, the remaining rate is used to select B hadrons which decay semileptonically in an inclusive way, triggered by the presence of the muon.

5. EXPECTED PERFORMANCE

In a typical $b\bar{b}$ event, approximately 30 charged particles traverse the whole spectrometer. The current pattern recognition and track reconstruction is capable of reconstructing more than 95% of these tracks in case they originate from the decay of B hadrons. In case of the decay of long lived particles, such as $K^0_S \to \pi^+\pi^-$, they can be reconstructed with an efficiency of 75% when they decay inside the vertex detector.

One of the advantages of the spectrometer setup is given by the large analyzing power of the magnet of about 4 Tm. This results in an excellent momentum resolution, shown in Fig. 4, which in turn translates into an excellent invariant mass resolution for fully reconstructed B

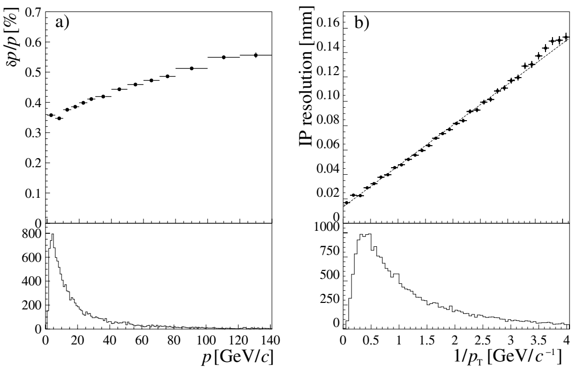

Figure 4. Resolution on the reconstructed track parameters at their production vertex:(a) momentum resolution as a function of momentum, (b) impact parameter resolution as a function of $1/p_T$. The momentum and transverse momentum spectra of B decay daughters are shown in the lower parts of the plots.

hadron decays. A few examples are shown in Table 1.

Due to the combination of the large boost and the fact that the innermost point of the vertex detector is at a distance of only 8 mm from the LHC beams, the proper time resolution is also expect to be significantly better than what has been achieved so far. In case of the decay $B^0_s \to D^-_s\pi^+$, the average resolution is expected to be around 40 fs, which should be compared to values around 100 fs reached by CDF, and which are also expected for Atlas and CMS.

The two RICH detectors provide for dedicated Kaon identification. Not only does this provide a powerful means to separate eg. kaons from pions in two-body B decays, but it also insures that kaons can be used for flavor tagging. The combined tagging power for B^0 decays is expected to be between 4% and 5%, whereas the same-side kaon tagging should increase the power for B^0_s decays to values between 7% and 9%.

Table 1
Invariant mass resolution in MeV/c^2 for several fully reconstructed B hadron decays

	Atlas	CMS	LHCb
$B_s^0 \to \mu^+\mu^-$	80	46	18
$B_s^0 \to D_s^-\pi^+$	46	??	14
$B_s^0 \to J/\psi\phi$	38	32	16
$B_s^0 \to J/\psi\phi$ (with J/ψ mass constraint)	17	13	8

6. PHYSICS PROSPECTS

One of the first LHCb measurements will be the determination of the B_s^0 mixing frequency. Even though its value is now well know[1], this measurement perform an important role to demonstrate the calibration and performance of the displaced track trigger, the proper time resolution and the flavor tagging. The expected yield of reconstructed $B_s^0 \to D_s^-\pi^+$ in a nominal year is 80k, which a signal-over-background ratio of approximately three. Another important aspect of this mode is that it is a stepping stone towards the selection of $B_s^0 \to D_s^\mp K^\pm$. This particular decay is the B_s^0 equivalent of the $B^0 \to D^{(*)-}\pi^+$, and measures the sum of the weak phase from the $B_s^0\bar{B}_s^0$ mixing amplitude, ϕ_s, and the relative phase of V_{ub} with respect to V_{cb}, i.e. γ. Unlike the decay $B^0 \to D^{(*)-}\pi^+$, the two decay amplitudes are similar (both $\mathcal{O}(\lambda^3)$), and thus their ratio can be extracted directly from the data. With an expected number of events around 5.4K, and a signal-over-background better than unity, it is expected that from a simultaneous fit to the four time-dependent rates one can extract the angle γ with a precision of 14° in a nominal year. Note that a priori there is an eight-fold ambiguity which can be reduced to a two-fold ambiguity for sufficiently large values of $\Delta\Gamma$, the width difference between the CP-even and CP-odd combinations of B_s^0 and $\bar{B}_s^0$, or by using U-spin symmetry and the decay $B^0 \to D^-\pi^+$.

The above mentioned measurement relies on knowledge of both the $B_s^0\bar{B}_s^0$ mixing phase ϕ_s, and the value of $\Delta\Gamma$. These quantities can be measured using the decay $B_s^0 \to J/\psi\phi$. This decay is the B_s^0 version of the golden B-factory mode $B^0 \to J/\psi K_S^0$. The fact that the decay contains a J/ψ makes triggering on this channel relatively easy and robust. In combination with the relatively large branching ratio, one expects a reconstructed yield of about 125k events, with a signal-over-background of at least three. Compared to $B^0 \to J/\psi K_S^0$ there is one additional complication: the final state contains two vector mesons. This implies that one needs separate the CP-even and CP-odd contributions to this decay. Using a single-angle transversity analysis, the expected precision on ϕ_s is 0.03 for a nominal year. In addition to measuring ϕ_s, this mode thus also offers the opportunity to measure the (relative) width difference $\Delta\Gamma/\Gamma$ This is quantity is expected to be measured with an accuracy of around 1%.

Another example of a channel were LHCb can be expected to perform very well is the exclusive decay $B^0 \to \mu^+\mu^- K^{*0}$. This is currently the mode with the smallest measured branching ratio. Even so, the large production rate is expected to result in a sample of approximately 4.4k events per nominal year, with background-over-signal ratios somewhere between 0.2 and 2.6. The forward-backward asymmetry of this decay as a function of s is a sensitive probe of the contribution of new particles to this decay. With the sample LHCb should collect in a year, one should be able to determine the zero-crossing of the forward-backward asymmetry as a function of s to an accuracy of 1.2 GeV^2.

As is well known[2], the branching ratio for the very rare process $B_s^0 \to \mu^+\mu^-$ could be enhanced significantly by the contribution of new particles to the loop diagram. In the absence of new physics, the Standard Model branching ratio is 3.5×10^{-9}, whereas the current 90% CL limit from the Tevatron experiments is 1.5×10^{-7}. For the Standard Model branching ratio, LHCb could expect to collect a signal of seventeen events per nominal year. Even though Atlas and CMS will run at higher instantaneous luminosity than LHCb, and hence could in principle collect larger samples, one can expect LHCb to make good use its excellent momentum resolution to reject backgrounds (see 1). At present it is assumed that the main background will be from B hadrons decaying semileptonically. The estimate of the size of this background is is limited by the size of the simulated sample. From the non-observation of any selected background within the simulated sample, only limit on the amount of background can be set such that B/S should be less than 6 at 90%CL.

For a review of other physics goals and performance studies of the LHCb experiment, see [3]

7. CONCLUSION

The LHCb spectrometer provides excellent tracking, combined with dedicated particle identification, and a flexible trigger. Thanks to the large $b\bar{b}$ production rate available, it is expected to improve upon the results from current B factories in several exclusive modes, and to extend the search for the effects of new, heavy particles to the B^0_s system. The construction of the experiment is on target for initial collisions in the second half of 2007. Given the modest luminosity requirements, the experiment has the possibility of producing competitive physics results soon after the initial startup of the LHC.

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