LHCb Physics, Performance, Prospects

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The LHCb experiment at CERNs Large Hadron Collider (LHC) performs precision measurements of processes involving B mesons and other hadrons containing b or c quarks. Of particular interest are observables that exhibit high sensitivity to possible contributions from New Physics. LHCb has seen a rapid and very successful startup during the first year of physics at the LHC. About 37 pb^{-1} of pp collisions at a center of mass energy of 7 TeV were collected in 2010 and first competitive results from the analysis of these data were presented at the 2011 winter conferences. Analyses based on an almost ten times larger data set collected in spring 2011 are being prepared for the summer conferences. About 1 fb^{-1} are going to be collected by the end of 2011. These data will enable LHCb to perform sensitive searches for New Physics in many analyses.

1 The LHCb experiment

The main goal of the LHCb experiment [1] is to search for signatures of New Physics beyond the Standard Model of particle physics. LHCb does this by performing precision measurements of the mixing and decay of hadrons that contain a b or c quark. Of particular interest are processes that involve loop diagrams and that are suppressed in the Standard Model. Most New Physics models predict heavy, new particles that can appear in the loops and affect the magnitudes or phases of observables. The sensitivity to these possible contributions from New Physics is particularly large, if the predicted Standard Model value of the observable is small. A prominent example is the $B_s^0-\overline{B}_s^0$ mixing phase, ϕ_s. In the Standard Model, $B_s^0-\overline{B}_s^0$ mixing proceeds through box diagrams involving a double $W^\pm$ exchange. The phase of this process is predicted to be close to zero with small uncertainty. The observation of a significantly larger mixing phase would be a clear hint for contributions from New Physics. A precise measurement of ϕ_s involves many of the key features of the LHCb experiment: large samples of reconstructed B_s^0 and $\overline{B}_s^0$ decays, an excellent decay time resolution to resolve the rapid $B_s^0-\overline{B}_s^0$ flavour oscillations, and an efficient kaon identification for tagging the flavour of the B_s^0 meson at production.

The $b\bar{b}$ production cross section at the LHC is strongly peaked towards small polar angles with respect to the beam axis. The LHCb detector is therefore laid out as a forward spectrometer, as illustrated in Fig. 1. Excellent vertex and momentum resolution is provided by the vertex locator (VELO) and four tracking stations (TT,T1-T3) surrounding a dipole magnet with an integrated field of about 4 Tm. To achieve the best possible resolution on production and decay vertices and the decay length of the short-lived and rapidly oscillating B mesons, the VELO is installed inside the LHC vacuum vessel. Only a 300 μm thin aluminium foil separates the detectors from the LHC beams. During data taking, the detectors approach the beams to

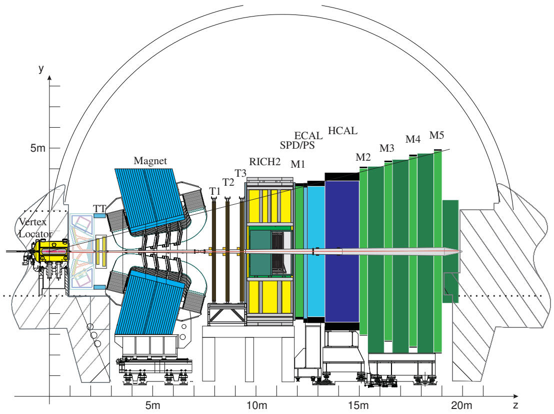

Figure 1: Vertical cross section through the LHCb detector. The LHC proton beams collide inside the Vertex Locator on the left.

as little as 8 mm. Excellent kaon/pion separation over a wide momentum range from 2 GeV/c to above 100 GeV/c is provided by two RICH detectors using a combination of three different radiators. The detector is completed by a calorimeter system (PRS, SPD, ECAL, HCAL) and a muon system (M1-M5). The calorimeter and muon systems provide the input for the first level trigger. This trigger level is implemented in hardware and searches for muon and hadron candidates with transverse momenta above a few GeV/c. It reduces the event rate from the 40 MHz bunch crossing frequency of the LHC to about 1 MHz. The higher level triggers have access to the full detector information and are implemented in software running on a multi-processor computer farm. They make use of generic features of B decays, such as displaced decay vertices as well as large impact parameters and high transverse momenta of decay products to reduce the rate to about 30 kHz and then perform exclusive event selections for specific decay channels. Events are saved to disk at a rate of a few kHz. The flexibility of the trigger scheme proved very useful during the first year of LHC operation as it allowed to adjust selection criteria to the rapidly changing running conditions.

LHCb was designed to operate at an instantaneous luminosity of 2×10^{32} cm^{-2}s^{-1}. Towards the end of the 2010 data taking period, this luminosity was reached although the number of proton bunches circulating in the LHC was still significantly smaller than nominal. This was made possible by operating the experiment at significantly higher number of proton-proton interactions per LHC bunch crossing than originally foreseen. Even under these harsher than foreseen running conditions, the LHCb experiment performed extremely well. Significantly more than 90% of all detector channels were fully operational and about 37 pb^{-1} of data were collected in 2010 with a data taking efficiency in excess of 90%. Key performance parameters, such as decay time and invariant mass resolutions were close to expectation from Monte Carlo simulations. Small remaining differences are attributed to the not yet perfect spatial alignment of the detector and calibration of the magnetic field strength. In 2011, the number of proton bunches in the LHC has been increased to half its nominal value and LHCb is operating at up to a factor of two higher instantaneous luminosity than originally foreseen.

2 Selected results from the 2010 data taking

The data collected in 2010 were successfully employed not only to verify the detector performance and commission analyses but also to produce first competitive physics results. An example of this is the first LHCb measurement of the $B_s^0 - \overline{B}_s^0$ oscillation frequency, Δm_s. This quantity has been previously measured at the Tevatron and the most precise result, $\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}^{-1}$ [2], has been published by the CDF collaboration. For LHCb, the ability to resolve the rapid $B_s^0 - \overline{B}_s^0$ oscillations is a prerequisite for several key analyses, most notably the measurement of the $B_s^0 - \overline{B}_s^0$ mixing phase, ϕ_s, mentioned above. A first measurement of Δm_shas been performed using a sample of 1800 $B_s^0 \to D_s^\pm \pi^\mp$ and $B_s^0 \to D_s^\pm 3\pi$ decays collected in 2010. The measurement essentially requires three ingredients from each event: the decay time of the B_s^0 meson, its flavour at production, and its flavour at decay. The decay time is determined from the measured positions of the production and decay vertices and the reconstructed momentum of the B_s^0 meson. The flavour at decay is given by the charge of the $D_s^\pm$ meson. The determination of the flavour at production relies on the fact that a b quark is usually produced in association with an $\overline{b}$ quark and vice-versa. The flavour of the B_s^0 under investigation can therefore be implied by looking at flavour-specific signatures from the decay of the accompanying opposite-flavour b hadron. In particular, the charge of a decay lepton or kaon or the sum of charges of particles from the decay vertex of the accompanying b hadron are used. The preliminary result of this first LHCb measurement, $\Delta m_s = 17.63 \pm 0.11(\text{stat}) \pm 0.04(\text{syst})\ \text{ps}^{-1}$ [3], is compatible with the published CDF measurement and already has a comparable statistical error and a significantly smaller systematic error. This result reflects the excellent vertex and momentum resolution of the detector. A measurement of Δm_s with reduced statistical uncertainty, using a ten times larger data sample collected in spring 2011, will be shown at the summer conferences.

The particle identification capability of the experiment is illustrated by the observation of a clear signal for direct CP violation in $B^0 \to K^\pm \pi^\mp$ decays. Excellent kaon/pion separation is required, first to separate the $B^0 \to K^\pm \pi^\mp$ signal from other two-body B meson decays such as $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$, and then to distinguish between $B^0 \to K^+\pi^-$ decays and $\overline{B}^0 \to K^-\pi^+$ decays. The resulting invariant mass distributions for the two charge conjugated final states are shown in Fig. 2. The asymmetry due to direct CP violation in this decay is clearly visible in the raw event yields. Production and detection asymmetries are small and after correcting for these, a preliminary result for the CP asymmetry of $A_{\text{CP}} = \left[\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)\right] / \left[\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)\right] = 0.074 \pm 0.033(\text{stat}) \pm 0.008(\text{syst})$ is found [4]. This result is in good agreement with the current world average of $A_{\text{CP}} = -0.098^{+0.012}_{-0.011}$ [5]. Note that the precision of the LHCb result is again limited by its statistical uncertainty. A significantly more precise result is expected from the 2011 data.

Another early benchmark analysis is the search for the very rare decay $B_s^0 \to \mu^+\mu^-$. This decay is strongly suppressed in the Standard Model, which predicts a branching fraction of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ [6]. The branching fraction can be significantly enhanced in many extensions of the Standard Model. Searches for $B_s^0 \to \mu^+\mu^-$ have been performed at the Tevatron but the decay has not been observed yet. The best upper limit on the branching fraction so far has been reported by the CDF collaboration, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.6 \times 10^{-8}$ at 90% CL [7]. Based on a search for this decay in the 2010 data, LHCb has published an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.3 \times 10^{-8}$ at 90% CL [8], which already approaches the best Tevatron result. A significantly improved LHCb result, based on the data sample collected in

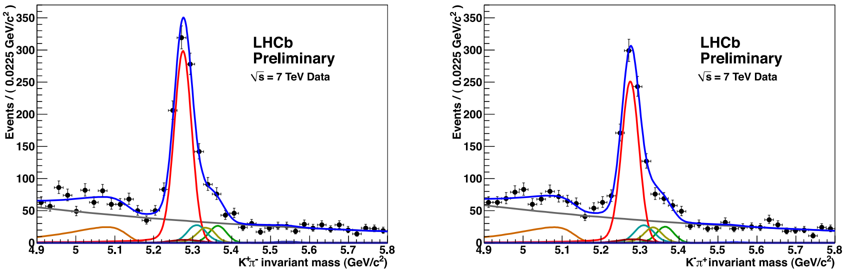

Figure 2: Invariant mass distributions for $K^+\pi^-$ (left) and for $K^-\pi^+$ (right).

spring 2011, will be shown at the summer conferences.

Both Tevatron experiments, CDF and D0, have reported measurements of the $B_s^0 - \overline{B}_s^0$ mixing phase, ϕ_s, which might hint at a possible discrepancy with the Standard Model prediction [9]. The statistical precision of these measurements is, however, still rather limited. The size of the LHCb data set collected in 2010 does not yet suffice to perform a competitive measurement of ϕ_s. As a proof of principle of the measurement, an analysis has nevertheless been performed with encouraging results [10]. A competitive ϕ_s measurement based on the data sample collected in spring 2011 will be shown at the summer conferences.

3 Physics potential

A few measurements with good sensitivity to possible contributions from New Physics have already been mentioned above. Another key measurement for LHCb is the precise determination of the CKM angle $\gamma = \arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$. Various methods have been proposed that would allow a theoretically clean determination of γ, but they all require large samples of B meson decays to kaons and pions. Therefore γ is so far not well constrained by direct measurements. Using the 2011/2012 data samples, LHCb expects to determine γ to a precision of about 5° from pure tree decays such as $B^\pm \to D^0 K^\pm$ as well as from loop-induced Penguin decays such as $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$. As New Physics is not expected to affect tree decays at a significant level, a comparison of the results obtained in these two approaches will provide a sensitive test for possible New Physics contributions in the loops. Moreover, a comparison of the measured value of γ with the value of γ obtained from Standard Model fits will test the CKM picture of CP violation in the b sector.

LHCb also has a strong and interesting physics programme in the charm sector. In particular, CP violation in $D^0 - \overline{D}^0$ mixing is predicted to be very small in the Standard Model. Experimentally, this field is not well explored so far and therefore provides excellent discovery potential.

Finally, the unique forward acceptance of the LHCb detector also provides for interesting measurements in other fields, such as electroweak physics, where the measurement of differential cross sections for $W^\pm$ and Z^0 production and Drell-Yan processes can constrain the parton density functions of the proton. These measurements provide important input for example for the estimation of backgrounds in SUSY searches at ATLAS and CMS.

LHCb will collect a data sample of about 1 fb^{-1} by the end of 2011 and can expect up to

3 fb^{-1} by the end of 2012. These data sets will permit LHCb to perform sensitive searches for New Physics contributions in many analyses. These searches will either lead to the indirect discovery of New Physics beyond the Standard Model or permit to severly constrain the parameter space of New Physics models.

I would like to thank the organizers of the 7th Patras Workshop on Axions, WIMPs and WISPs for having given me the opportunity to present the beauty-ful physics of the LHCb experiment in the beautiful setting of the greek island of Mykonos.

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