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Commissioning and Early Physics at LHCb

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Abstract. The LHCb experiment has been designed to perform precision measurements on CP asymmetries and rare decay searches of B mesons. The LHCb construction and installation has been finished early summer last year. The experiment is ready to exploit first data from CERN's Large Hadron Collider (LHC). The very first data collected with a minimal interaction trigger should allow the space alignment of the detector to be performed. Then, when energy and momentum scales have been calibrated, the particle identification will be commissioned. The trigger will also be commissioned ready for data-taking in 2010, when LHCb's nominal luminosity should be reached and the full physics programme deployed. First measurements comprise inclusive particle production, where final states containing a pair of oppositely charged muons (e.g. J/ψ production) will be isolated. We will report on the commissioning of the different subsystems performed with cosmic data and the few particle beams delivered by the accelerator last year and the progress made toward the first physics measurements.

1. Introduction

LHCb is the experiment dedicated to heavy flavour physics at the LHC [1, 2]. Its primary goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons. So far, B-factories and the Tevatron's experimental programs have taught us that heavy flavor physics is fully consistent with the CKM mechanism. On the other hand, the level of CP violation in the Standard Model weak interactions cannot explain the amount of matter in the universe. Hence, we need a new source of CP violation beyond the Standard Model to solve this puzzle. The effect of such a new source might be seen in heavy flavour physics, given the fact of the much improved precision in the experimental program expected in the future. There are many models of new physics which produce contributions that change the expectations of for instance CP violation phases, rare decay branching fractions, and may even generate decay modes forbidden in the Standard Model.

To examine the aforementioned possibilities, the LHCb experiment will study CP asymmetries and rare decays of B_d, B_s and D mesons with high statistics and using many different decay modes. A large $b\bar{b}$ production cross section of about 500 μb is expected at an energy of 14 TeV, and will make the LHC the most copious source of B mesons in the world. In addition, B_c and b-baryons like Λ_b will be produced in a numerous manner. Running at a reduced luminosity of $\mathcal{L} = 2 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by locally defocusing the beams at LHCb interaction point, 10^{12} $b\bar{b}$ pairs would be produced in 10^7s, corresponding to one year of data (2 fb^{-1}). The reason to run at a lower luminosity than the other LHC experiments is that in this case the events will be dominated by a single proton-proton interaction per bunch crossing. These are much simpler to analyze than those with multiple primary proton-proton interactions. Furthermore, the occupancy in the detector remains low and the radiation damage reduced.

The LHCb detector has been designed and constructed to exploit this large number of b hadrons. First of all, the trigger is efficient, robust and flexible enough to handle the harsh hadronic environment ($\sigma_{inel} \sim 80$ mb), and sensitive to many different final states. Superb vertex and momentum resolution are key prerequisites for the good proper-time resolution needed to study the rapidly oscillating $B_s - \overline{B_s}$ meson system and for good invariant mass resolution, required to reduce the huge combinatorial background. In addition to electron, muon, γ, π^0 and η detection, identification of protons, kaons and pions is vital in order to reconstruct many hadronic B meson decay final states such as $B^0 \to \pi^+\pi^-$, $B \to DK(^*)$ and $B_s \to D_s^{\pm}K(^{\pm})$, that are key decays for the physics goals of the experiment. Finally, a data acquisition system with a high bandwidth and a powerful online data processing optimize the data taking.

2. Detector overview and Performance

LHCb is a single-arm spectrometer with a forward angular coverage from approximately 15 mrad to 300 (250) mrad in the bending (non-bending) plane. The choice of the detector geometry is motivated by the fact that at high energies both the b and $\bar{b}$-hadrons are predominantly produced in the same forward or backward cone. The layout of the LHCb spectrometer is shown in figure 1. A modification to the LHC optics, displacing the interaction point by 11.25 m from the centre, has permitted maximum use to be made of the existing cavern for the LHCb detector components. In the following we described very briefly the LHCb experimental setup, a detailed description can be found in [3].

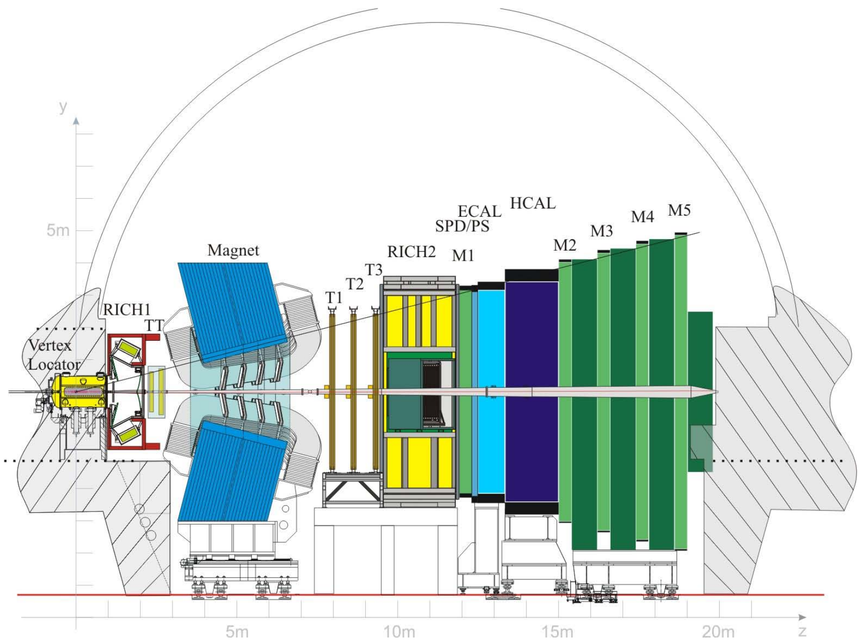

Figure 1. Side view of the *LHCb* detector. The interaction point is at the left. The following components are indicated: the Vertex Locator (VELO), the dipole magnet, the two RICH detectors, the four tracking stations TT and T1-T3, the Scintillating Pad Detector (SPD), Preshower (PS), Electromagnetic (ECAL) and Hadronic (HCAL) calorimeters, and the five muon stations M1-M5.

2.1. Tracking system

The tracking system consists of the vertex locator system (VELO) and four planar tracking stations: the Tracker Turicensis (TT) upstream of the dipole magnet and T1-T3 downstream of the magnet. VELO and TT use silicon microstrip detectors. In T1-T3, silicon microstrips are used in the region close to the beam pipe (Inner Tracker, IT) whereas straw-tubes are employed in the outer region of the stations (Outer Tracker, OT).

The VErtex LOcator (VELO) provides precise measurements of track coordinates close to the interaction region, which are used to identify the displaced secondary vertices which are a distinctive feature of b and c-hadron decays. The VELO consists of a series of silicon modules, half moon shaped, each providing a measure of the r and ϕ coordinates, arranged along the beam direction. The VELO modules are placed at a radial distance from the beam which is smaller than the aperture required by the LHC during injection and must therefore be retractable. The detectors are mounted in a vessel that maintains vacuum around the sensors and is separated from the machine vacuum by a thin walled corrugated aluminum sheet. This is done to minimize the material traversed by a charged particle before it crosses the sensors and the geometry is such that it allows the two halves of the VELO to overlap when in the closed position.

2.2. Particle Identification

Particle identification (PID) is a fundamental requirement for LHCb. It is essential for the goals of the experiment to separate pions from kaons in selected B hadron decays. At large polar angles the momentum spectrum is softer while at small polar angles the momentum spectrum is harder; hence the particle identification system consistes of two RICH detectors to cover the full momentum range. The upstream detector, RICH 1, covers the low momentum charged particle range ~1-60 GeV/c using aerogel and C_4F_{10} radiators, while the downstream detector, RICH 2, covers the high momentum range from ~15 GeV/c up to and beyond 100 GeV/c using a CF_4 radiator. RICH 1 covers the full LHCb acceptance and is located upstream of the magnet to detect the low momentum particles. RICH 2 is located downstream of the magnet and has a limited angular acceptance of $\sim \pm 15$ mrad to $\pm$ 120 mrad (horizontal) and ± 100 mrad (vertical), but covers the region where high momentum particles are produced.

The LHCb calorimeter system performs several functions. It selects transverse energy hadron, electron and photon candidates for the first trigger level (L0), which makes a decision 4 μs after the interaction. It provides the identification of electrons, photons and hadrons as well as the measurement of their energies and positions. The reconstruction with good accuracy of π^0 and prompt photons is essential for flavour tagging and for the study of B-meson decays. A classical arrangement of an electromagnetic calorimeter (ECAL) followed by a hadron calorimeter (HCAL) has been followed. A preshower detector (PS), a thin lead converter, and a scintillator pad detector (SPD) plane used to detect charge particles, are positioned before the ECAL. They are used in the rejection of the high background of charged pions (PS), and π^0's (SPD).

Muon triggering and offline muon identification are fundamental requirements of the LHC experiment, since they are present in the final states of many CP-sensitive B decays [2], the CP asymmetry and oscillation measurements as well as in flavor-changing neutral current decays that may reveal new Physics Beyond the Standard Model [4] . The muon system provides fast information for the high p_T muon trigger at the first trigger level (L0) and muon identification for the high-level trigger (HLT) and offline analysis. The muon system, shown in figure 1, is composed of five stations (M1-M5), with a projective geometry, placed along the beam axis.

2.3. Trigger system

As a result of the LHC bunch structure and low luminosity at LHCb, the crossing frequency with interactions visible by the spectrometer is about 10 MHz. An interaction is visible if it produces at least two charged particles that can be reconstructed using the information from the VELO and the stations T1-T3. This rate has to be reduced by the trigger to about 2 kHz, at which rate the events are written to storage for further offline analysis. This reduction is organized in two trigger layers: Level-0 (L0) and the High Level Trigger (HLT) [5].

The L0 trigger is a hardware trigger implemented on custom-made electronics, operating synchronously with the 40 MHz bunch crossing frequency. It has a fixed latency of 4 μs, and reduces the LHC beam crossing rate of 40 MHz to the rate of 1 MHz at which the entire detector can be read out. The Level-0 trigger selects events with high p_T particles in the final state, detected in the calorimeters and muon detectors.

The High Level Trigger selects exclusive B decay modes as well as auxiliary signals for systematic studies, such as inclusive B decays. HLT is a software trigger, implemented as selection algorithms running on a computing farm using commercially available equipment, and runs asynchronously. The HLT starts with confirming the high p_T L0-candidates, after which it selects events with fully or partially reconstructed B-decay modes.

The data acquisition rate after the HLT is 2 kHz and the event size $\sim$ 35 kB. Therefore minimum bias (MB) data can be recorded at a maximum rate of 2 kHz and MB physics can be performed on early data with large data samples.

2.4. Performance

The momentum resolution of the spectrometer varies from 0.3 to 0.5% depending on the momentum, see figure 2. The mass resolution is very good, at the level of $10 \div 4.9$ MeV/c^2. The efficiency for tracking reconstruction is high of about 95% with a small ghost fraction, $\sim$ 4% for tracks with $p_T > 0.5$ GeV/c, see figure 3. The resolution in the impact parameter is better than 30 μm and the proper time resolution is of the order of 40 fs.

Particle identification (PID)is crucial in many decay channels. Figure 4 shows how the mass spectra looks like in the case of B charmless decays with and without PID to discriminate kaons from pions. Kaon PID efficiency is expected to be at the level of 88% while contamination stays at the level of 3%, figure 5.

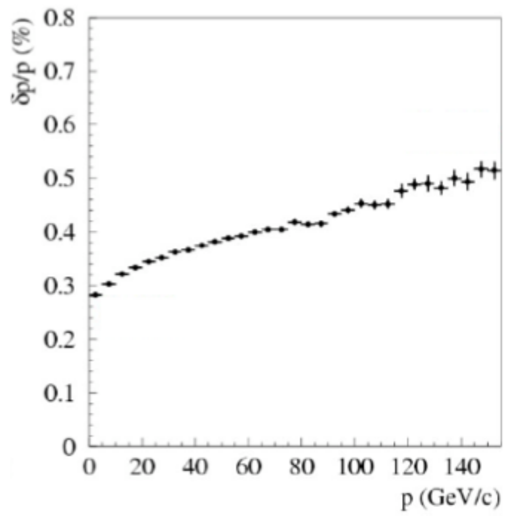

Figure 2. LHCb momentum resolution as a function of momentum.

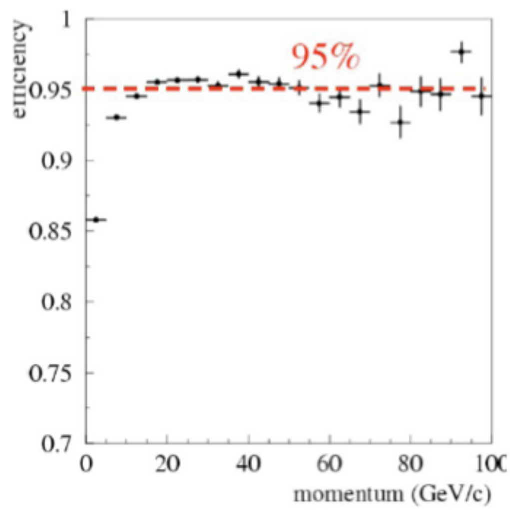

Figure 3. Efficiency of track reconstruction versus momentum.

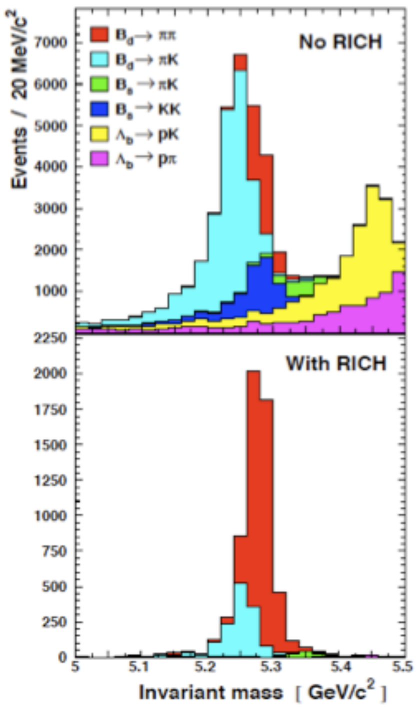

Figure 4. LHCb momentum resolution as a function of momentum.

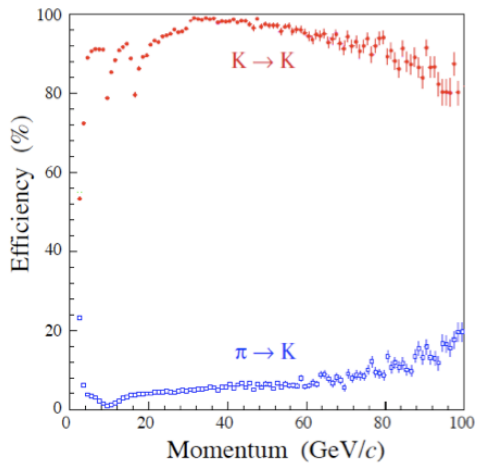

Figure 5. Kaon identification efficiency (solid points) and pion misidentification rate (open points).

3. Commissioning

Commissioning for LHCb started in 2007. The strategy can be summarized in three steps. First of all, each sub-detector was commissioned individually, second LHCb was commissioned as a whole without particle beams, and finally the commissioning with particle beams happened in 2008. In the first step, each sub-detector was commissioned independently. The safety issues were checked and hardware operations controls and monitoring have been tested. Initial settings of time and space alignment have been set to reasonable values leading to the coherency of the data produced by each sub-detector. Signal, trigger and control cables were tested. Calibration pulses have been employed to test the response of the hardware, to find dead or noisy electronic channels and to check the channel mapping. Once all the sub-systems finished their commissioning, the system was exercised as a whole with all the sub-detectors integrated. The whole experiment has been read out to maximum hardware trigger rate of 100 kHz due to the limited capacity of the network and the event filter farm. The designed hardware trigger rate of 1 MHz will be reached in 2009, since buying late the commercial components gives you more for your money. Data storage at 2 kHz was already exercised in 2008. Although the configuration of the LHCb experiment is not well suited for cosmic runs, accepting tracks within ± 250 mrad from horizontal with a rate well below 1 Hz, cosmic data have been very useful for the internal time and space alignment of one detector or a few neighbors in which more vertical cosmic tracks can be used. Finally, commissioning with particle beams was performed during summer 2008 to ensure proper readout and trigger. We started with single beams at the injection energy. Injections were performed from the SPS into the LHC to test the new injection lines and their optics. At the beginning the beam was blocked in a stopper (TED) about 340 m behind the LHCb experiment. Particles were coming in the wrong direction, from the muon chambers towards the VELO detector see figure 1. The fluence in this case was 10 cm^{-2}. In a

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second step, the beam was stopped 50 m from the LHCb detector in a collimator/beam stopper (TDI) just after the kicker injection magnet, in this case the fluence was 100 times higher. Finally particles beams were injected and passed through the LHCb experiment. In the case of the injection at point 8 (LHCb) most of the time the sub-detectors have been off to avoid damage. While in the case of beam in the opposite direction, injected at point 2 which is far away, the environment is cleaner hence the sub-detectors could stay on and register single shots to a collimator in front of the experiment, beam-gas events or beam splashes, see figures 6, 7. All this wealth of cosmic and particle beams data have been used to perform a first time and space alignment. As soon as we have particle beams in the accelerator again we will perform the final alignment in time and space. Time alignment will be the first task, a specific trigger and readout mode already use this year has been designed for that purpose. The trigger will be accepting only HCAL decisions. The DAQ in this mode can acquire up to fifteen successive clock cycles, that corresponds to fifteen bunch crossings, seven before the actual trigger given by HCAL and another seven after. At low luminosity, the central sample should be the only one to have any activity in the detector. This is true for the HCAL by construction. The time settings and delays of the rest of the sub-detectors will be adjusted so they are synchronized with the HCAL and have activity in the same central clock beat out of the fifteen consecutive.

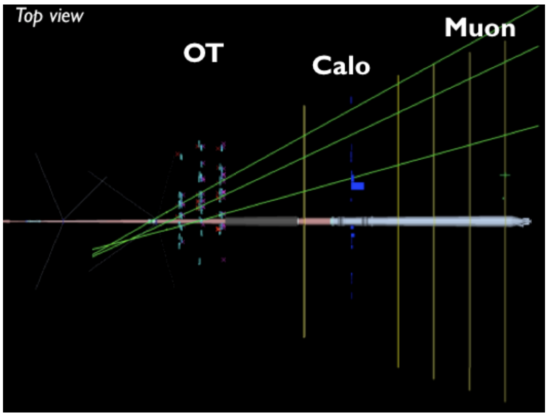

Figure 6. Low multiplicity event recorded with the LHCb detector during injection test at point 2 on September 10th of 2008.

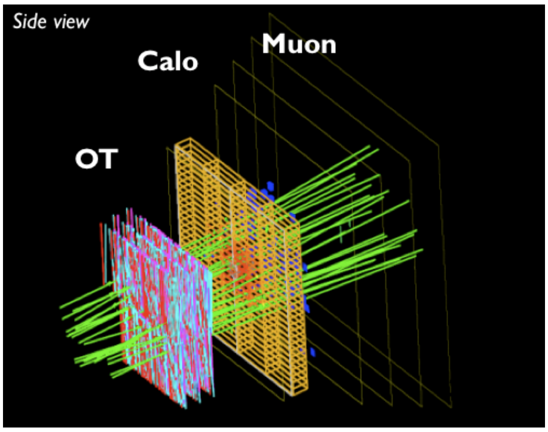

Figure 7. High multiplicity event seen in the LHCb detector on September 10th of 2008.

Space alignment of the detector has an crucial impact on the physics analysis to be performed and on the High Level Trigger that relies on the tracking. During the installation of the tracking system, the position of the different tracking sub-detectors is surveyed and monitored constantly with a precision of few hundreds of μm. During the TED runs last year the VELO sub-detector has been aligned to 10 μm for the Rϕ modules. It was proved that during installation the modules did not move, since a geometrical survey was done before installation with a precision of 20 μm. The final expected space alignment precision for the VELO with the first particles is 2 μm. This has been validated during several *Alignment Challenge and Detector Commissioning* test-beams performed in 2007.

The VELO, TT and T-stations will be aligned altogether by connecting track segments produced by charged particles. Finally, the other sub-detectors will be aligned with respect to the tracking system. The ECAL, HCAL and muon system are positioned with a precision better than 1 mm. Electron and muon samples will be used to improve their alignments.

Apart from the alignment of the tracking system, the momentum resolution depends on the magnetic field uncertainties. The B field will be flipped regularly to understand detector asymmetries, its components have been measured with a precision better than 0.03%. The total effect is intended to contribute less than 10% to the momentum resolution uncertainty. The momentum scale can be corrected by measuring the mass of reconstructed $K^0_S, \Lambda, J/\psi, \Upsilon, Z^0, etc\ldots$

The ECAL modules have been calibrated before the installation with cosmic rays with a precision of about 10%. There are different techniques under consideration to calibrate the ECAL, and they lead to different precisions. Energy flow methods should permit to reduce the uncertainty down to 1%. More sophisticated iterative methods based on the reconstruction of the π^0 mass may improved the precision up to less than 1%.

4. Early Physics at LHCb

The Physics scope of the LHCb experiment can be summarized in the following topics:

- CP-violation [6].
- Rare decays [7].
- Soft QCD physics, first physics with minimum bias data.
- Quarkonia and B physics, first physics with J/ψ.
- Electroweak physics.
- Higgs and exotica [8].
- Charm physics.

Due to space limitations, we will only focus here on the observable processes with the first Minimum Bias data sample to be collected, see figure 8, and with a simple muon trigger.

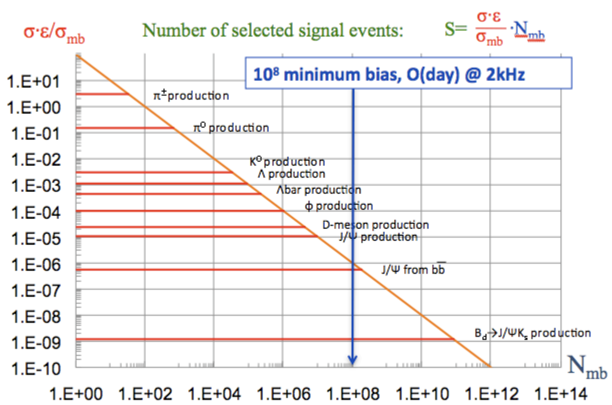

Figure 8. In this graph, the observable processes as a function of the size of the Minimum Bias samples collected are shown. 10^8 events can be recorded in one day at 2kHz.

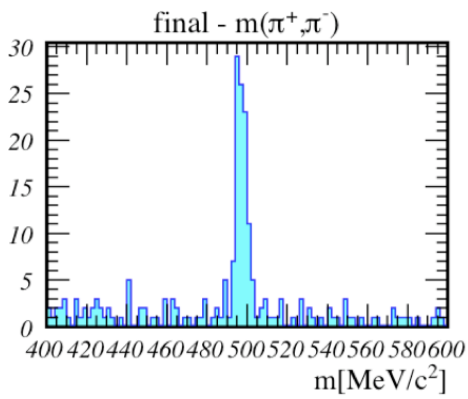

Figure 9. K^0_S signal out of 10k minimum bias events.

Collecting 10^8 minimum bias events, with a small HCAL $E_{\rm T}$ cut at L0 trigger to reject empty events, will give access to large samples of V^0s $(K^0_s, \Lambda, \overline{\Lambda})$ and will allow to measure differential production distributions with respect to (η, p_T). Analysis of Monte Carlo data have demonstrated that with a few kinematical and vertex cuts we can obtain signal from K^0_S like the one shown in figure 9, similarly using as well the Armenteros-Podolanski plot we can select pure (96%) $\Lambda/\overline{\Lambda}$ samples of O(100k) in 10^8 minimum bias events. Apart from the fact that these clean and unbiased samples can be used for PID studies, they can allow us to perform strangeness studies in a unique η range ($1.9 \div 4.9$). Since strange quarks are necessarily the result of the hadronization they can probe the fragmentation field in a unique way. The Λ hyperon can give insights on beam remnant fragmentation issues. We can obtain input to the different hadronization/fragmentation models from inclusive distributions of strange particles. Baryon to meson ratios (Λ/K^0_S vs $\mathrm{p_T}$), $\mathrm{m_T}$ distributions, $\mathrm{p_T}$ spectra for different species of strange particles will help distinguishing between the different theoretical models available.

If we collect 10^9 events passing passing single muon trigger, L0 with a small cut on the $\mathrm{p_T}$ of the muon (< 1 GeV/c) no impact parameter cut and the corresponding HLT, we can study dimuon physics: $J/\psi \to \mu\mu$, $\psi(2S) \to \mu\mu$, and other quarkonia production (ratios) and spectroscopy ($\chi_c \to J/\psi\gamma$, Υ(1S) $\to \mu\mu$, $X(3872) \to J/\psi\gamma\pi\pi$, $Z^+ \to \psi(2S)\pi^+, \ldots$).

J/ψ production is an important building block for many CP and rare decays analyses. In an early stage we can separate prompt J/ψ from $b \to J/\psi$ (detached) and measure their differential cross sections although for that we will need luminosity measurements that might not be available in the beginning. The important point here is to measure at the same time the J/ψ polarization since its acceptance depends on it. Monte Carlo simulations have shown that we will reconstruct 300K $J/\psi \to \mu\mu$ in this early 0.5 fb^{-1} sample of 10^9 single muon triggers. The prompt component will be used to study the proper time resolution of the experiment. In the case of the decay $\psi(2S) \to \mu\mu$, once reconstructed we can measure easily the $\psi(2S)$ to J/ψ production ratio since no luminosity measurement needed.

Finally, although this cannot be considered as early physics, B_c mass and lifetime measurements should be straight forward at LHCb. The strategy will be to use the $B_c^+ \to J\psi\pi^+$ decay mode. We expect ~ 311 for 1 fb^{-1} with a noise to signal ratio $1.15 < B/S < 2.15$. For that $1fb^{-1}$ we expect in the mass measurement $\pm$ 1.4 (stat) $\pm$ 1.5 (syst) MeV/c^2 improving on the best measurement from CDF $\pm 2.9(stat) \pm 2.5(syst) MeV/c^2$[9]. For the lifetime measurement with this data sample we foresee $\pm 0.029(stat) \pm 0.016(syst)ps$ while the best measurement from D0 experiment has $\pm 0.038(stat) \pm 0.032(syst)ps$ [10].

5. Conclusions

The LHCb experiment has been commissioned actively with cosmic and beam data during last year. Large Minimum Bias data samples will be collected in the forward region at a rate of 2 kHz, as soon as the LHC delivers proton-proton collisions. At the beginning, the efforts of the collaboration will be devoted to the Minimum Bias event analysis, to calibrate the detector, and the tuning of the Monte Carlo parameters, followed by the production of results with early data.

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