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Status of LHCb

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Summary. — The present report describes the status of the LHCb experiment at the start-up of the LHC data taking at the center-of-mass energy of $\sqrt{s} = 7$ TeV.

PACS 13.20.He – Decays of bottom mesons.
PACS 29.40.-n – Radiation detectors.

1. – Heavy flavour physics at LHC

In the last ten-fifteen years experiments have been successful in demonstrating the effectiveness of the Standard Model (SM) in describing heavy quark phenomenology. Most notably, the measurements of CP violation in B-decays, across a wide range of decay modes, have been found to be consistent with the CKM mechanism describing the quark mixing.

Experiments of the LHC collider, which are now starting their data taking, will be collecting unprecedented statistics of both rare and extremely rare processes, and hopefully will reveal discrepancies of measurement results with respect to SM predictions.

The LHCb experiment in particular focuses on using precision heavy flavour physics with the main goal of looking for indirect evidence of New Physics in CP violation and rare decays of beauty and charm hadrons. To perform its research program LHCb will exploit the large proton-proton beauty cross section of LHC (expected to be of the order of 500 μb at the beam energy of 14 TeV), to collect large data sample of B^0, B_s, B_c and b-baryons (such as the Λ_b) decays.

LHCb aims to test the SM in five main areas:

– Measuring the size of CP violation in $B_s^0 \leftrightarrow \overline{B}_s^0$ mixing.

– Measuring branching fractions and kinematic properties of several dimuon B-decays, which have been identified as having high sensitivity to NP contributions in loop diagrams. The most promising of these modes being $B_s^0 \to \mu^+\mu^-$ and $B^0 \to K^*\mu^+\mu^-$.

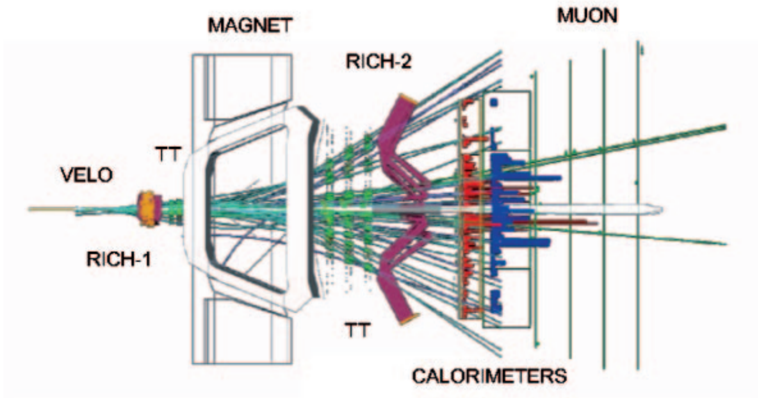

Fig. 1. – LHCb event display. First event recorded at $\sqrt{s} = 7$ TeV.

– In precision measurements of the CKM parameter γ, where tree processes will yield results independent of New-Physics couplings, while loop processes will prove sensitive to them.

– Sensitivity to anomolous right-handed currents can be tested by measuring the polarization of photons produced in radiative B-decays, as in the Penguin processes $B_s^0 \to \phi\gamma$ and $B^0 \to K^*\gamma$.

– LHCb has a rich charm programme, which includes a measurement of CP violation in D mixing and searches for rare muonic D decays.

With respect to the other LHC experiments LHCb requires a modest instantaneous luminosity of 2–5 $\times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which favours events dominated by single interaction per bunch crossing, thus easing reconstruction and analysis(1). The integrated luminosity is expected to be of the order of 2 fb^{-1} per nominal year of data taking.

According to plans, the LHC experiments will collect 1 fb^{-1} before the foreseen LHC long term shutdown. Feasibility studies on key measurements, relying on Monte Carlo simulated events, indicate that LHCb will already provide interesting results with 1 fb^{-1} integrated luminosity. For instance, LHCb is expected to be competitive in measuring the weak phase ϕ_s of the $B_s^0 \leftrightarrow \overline{B}_s^0$ oscillation, in the $B_s^0 \to J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$ golden mode, with an order of 200 pb^{-1} exploiting its high resolution vertex detector and a larger boost compared to previous experiments.

A detailed review of the LHCb physics programme and performance on key channels can be found in [1].

2. – Detector overview

The LHCb detector (visible in fig. 1) is a single arm spectrometer with detector elements placed along one of the proton beam lines of the LHC, covering the forward region

(1) Luminosity can be tuned at the LHCb interaction point IP8, independently of the other experiments.

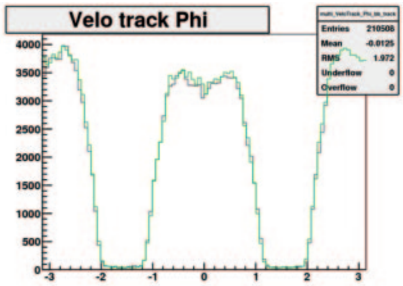

Fig. 2. – ϕ coordinates of tracks matching vertex segments. Vertex detector in open position.

within 10 mrad to 300 (250) mrad in the bending (non-bending) plane, corresponding to the pseudo-rapidity range $1.9 < \eta < 4.9$ [2]. Detector geometry optimally contains b- and $\overline{\text{b}}$-hadrons, which at LHC are predominantly produced in the same forward (or backward) cone(²).

The tracking system of LHCb is comprised of: the vertex detector (VELO), a silicon strip device that surrounds the proton-proton interaction region; a silicon strip tracking station, located before the magnet; and three tracking stations, located behind the magnet, each one equipped with silicon strips in the regions close to the beam-pipe (Internal Tracking, IT, to cope with the high particle current density), and with drift-time detectors in the external regions (Outer Tracker, OT) further from the beam-pipe.

VELO provides precise measurements of the track coordinates close to the interaction region(³), for precise lifetime determination, with an expected resolution on proper time measurements of about 30 fs. Relative momentum resolution in the foreseen momentum range 5–100 GeV/c is expected to be in average of the order of $\delta p/p \sim 0.4\%$, resulting in an invariant mass resolution of about 20 MeV/c^2 on the reconstructed B mass.

Particle identification to separate pions from kaons is ensured by two RICH detectors. Due to the use of three radiators, the RICH detectors can resolve similar hadronic final states over the whole momentum range. The upstream RICH1 uses C_4F_{10} and Aerogel to cover the lower momentum range, and RICH2, downstream of the spectrometer magnet, contains CF_4 to provide particle ID for higher momentum tracks. LHCb is also equipped with a calorimeter system, consisting of a Scintillator Pad Detector (SPD), a Pre-Shower (PS), a sampling Electromagnet Calorimeter (ECAL) and a Hadronic Calorimeter (HCAL) (used only for triggering on hadronic B-decay modes). Identification of muons is provided by a dedicated MUON system built using MWPC, and triple-GEM detectors in a region close to the beam-pipe.

In order to cope with the high rate production of b-hadrons in the harsh LHC environment, the LHCb detector requires a selective and flexible trigger system which is sensitive

(²) $\text{b}\overline{\text{b}}$ pairs are produced in gluon-gluon fusion by strongly asymmetric colliding partons. As a consequence pairs are boosted along the direction of the higher momentum gluon and both the b-hadrons are produced in the same forward (or backward) direction.
(³) Module halves have to be retracted from the data taking working positions during the LHC beams injection phase for safety reasons.

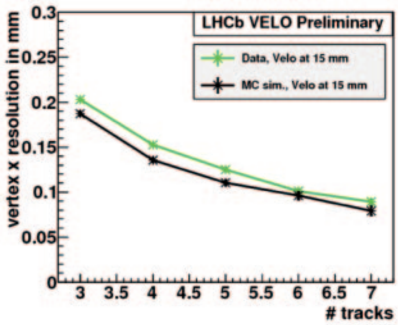

Fig. 3. – X coordinate of primary vertices *vs.* number of tracks.

to many different final states and a data acquisition system with a high bandwidth and powerful online data processing capability. The trigger system has been structured into two layers which are designed to achieve the reduction of the bunch crossing frequency of 40 MHz to the frequency of 2 kHz, at which events are recorded. The first level trigger (L0) reduces the bunch crossing rate to 1 MHz, selecting high-p_T objects using the calorimeter and muon systems, operating on custom electronics with a constant latency of 4 μs. The second level trigger (HLT) is a software trigger, based on selection algorithms running on the online cluster, which is highly adaptable and which increases with knowledge. The first task of the HLT is to confirm L0-objects before using the vertex detector to search for a displaced vertex. The trigger then uses the full spectrometer information to accept decay modes of interest at the foreseen write-to-tape frequency. An HLT mean processing time of the order of 10 ms, at the input rate of 1 MHz, sets the size of the computing cluster to the order of 10^4 CPU cores.

3. – Commissioning and first signals

The horizontal layout of the LHCb detector is not well suited to detect cosmic rays. Nevertheless, by relaxing the trigger thresholds on p_T and E_T a data rate of about 1 Hz has been achieved, allowing to collect several million useful cosmic events in a couple of years. Cosmic-ray sample permitted to perform time and spatial alignment of the large sub-detectors. Later commissioning with beams dumped on TED (Transfer-line External Dump), located 340 m behind LHCb, were used to improve the alignment of sub-detectors, especially smaller ones. The resulting showers (of approximately

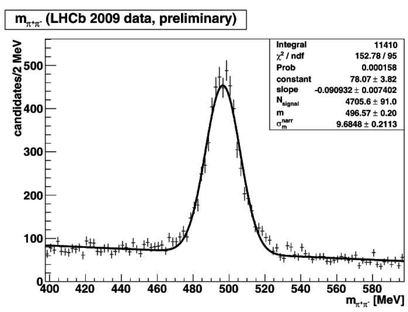

Fig. 4. – Invariant mass of track pairs reconstructed downstream.

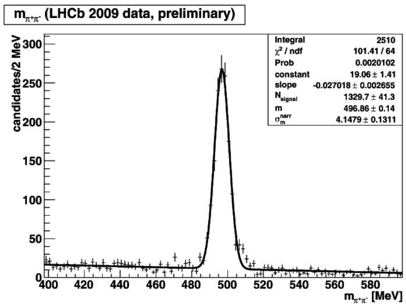

Fig. 5. – Tracks matching segments reconstructed by the vertex detector

10 particle/cm^2) were used to test the VELO and silicon tracker data-acquisitions systems for the first time. Over 99% of the detector channels have been seen to be functioning correctly. The alignment procedure performed using tracks from the TED showed sensors were displaced by less than 10 μm with respect to their surveyed positions. The hit resolutions after alignment for VELO sensors showed very good agreement with a binary performance.

Data collected at the proton beam energy of 450 GeV with a minimum bias trigger based on the calorimeters and muon system was then used to complete the commissioning of the sub-detectors and of the trigger. Tracking efficiency above 95% has been measured for particles traversing the entire detector, with momenta greater than 5 GeV/c, with a contamination of ghost tracks at the level of 10%.

In order to avoid possible damages to the vertex detector during the early commissioning of the accelerator, module halves have been kept in safe position at ± 15 mm from the beam line. The distribution of the ϕ coordinates of tracks matched to vertex segments is visible in fig. 2. Resolution in the primary vertex reconstruction as a function of the number of tracks attached to the vertex is shown in fig. 3. In this configuration vertex resolution in the transverse plane is above 100 μm, in reasonable agreement (within 10%) with the results of Monte Carlo simulations. This resolution is five to ten times worse than the foreseen design performance, when the detector halves are closer to the beam at ± 8 mm, in the configuration foreseen to run at higher energies.

With protons colliding at the energy of 900 GeV LHCb observed the first signals of K^0_s and ϕ. The mass spectra of the reconstructed $\mathrm{K}^0_s \to \pi^+\pi^-$ are presented in fig. 4 and fig. 5. The two distributions show how the mass resolution improves when the tracks are required to match the vertex segments. Figure 6 shows the two-body invariant mass

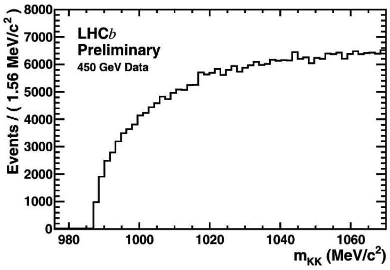

Fig. 6. – $\mathrm{K}^+\mathrm{K}^-$ invariant mass without RICH particle ID.

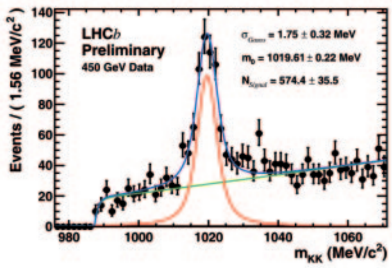

Fig. 7. – K^+K^- invariant mass distribution requiring the RICH particle ID.

assuming the kaon hypothesis for both tracks. In order to observe the ϕ signal we need the RICH particle ID to reject the background as shown in fig. 7. The invariant mass distribution of the muon pairs is shown in fig. 8. One can notice here the strong agreement between the observed distribution and the Monte Carlo simulations. Figure 9 shows the efficiency of the L0 muon trigger as a function of the p_T compared to the Monte Carlo. The agreement between the two distributions again is quite remarkable.

During data taking the spectrometer is monitored with a fast reconstruction of the reference signal $J/\Psi \to \mu^+\mu^-$, together with $K^0_s \to \pi^+\pi^-$ and $\Lambda^0 \to p\,\pi^-$. In order to provide the calibration samples of pions and kaons for the RICH system the decay chain $D^{*+} \to D^0(K^-\pi^+)\,\pi^+$ is reconstructed, where a selection based on the mass difference between D^{*+} and D^0 leaves a clean sample of D^0. The kaons and pions from the D^0 are used to calibrate the ring size and number of photons per track observed in each RICH detector, while Λ^0 decays provide a clean set of both protons and pions. Muons are identified by hits in a window around the extrapolated track direction in the muon sub-detector. Window sizes are tuned on data using samples from $J/\Psi \to \mu^+\mu^-$ decays, while $\Lambda^0 \to p\,\pi^-$ decays provide backgrounds of both pions and protons to evaluate misidentification probabilities.

In the next two years LHC will provide proton-proton collisions at a center-of-mass energy of 7 TeV. For this reason the beauty quark production cross section, which linearly depends on $\sqrt{s}$, is expected to be reduced by 50% with respect to the LHC design operating conditions. On the other hand, the instantaneous luminosity is foreseen to increase to $10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$ as the number of circulating bunches increases approaching the preferred LHCb luminosity range. In this scenario LHCb should operate without

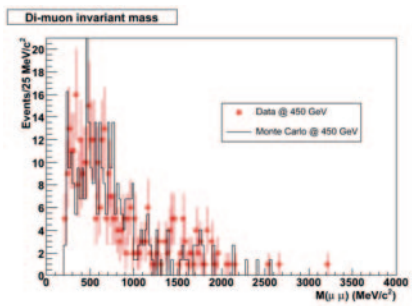

Fig. 8. – Muon pairs invariant mass.

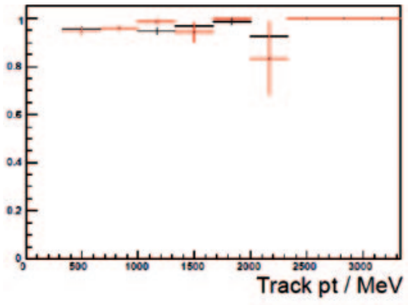

Fig. 9. – The L0 trigger efficiency as a function of p_T.

severe limitations. In particular the physics program can be enriched by collecting large samples of charmed mesons operating with low p_T and E_T trigger thresholds, until the interaction rate remains well below the L0 maximum output frequency of 1 MHz.

One of the important goals of the program is to measure the beauty quark production cross section at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. This should already be possible with the first 10 nb^{-1} using the $J/\Psi \to \mu^+\mu^-$ sample. J/Ψ from b-hadron decays can be separated from prompt J/Ψ using the J/Ψ proper time. From a fit to the proper time distribution it is possible to determine the total cross sections for all J/Ψ and for the delayed $b \to J/\Psi$ in the p_T acceptance 0.5–10 GeV/c and rapidity range $2.5 < y < 5.0$. Measurement precision is expected to be limited by systematic error on the luminosity measurement and on tracking efficiency. Luminosity can be determined using Van der Meer scan and with the beam gas interaction events (only possible at LHCb) with an expected precision at the level of 10%.

REFERENCES

[1] Adeva B. *et al.* (LHCb Collaboration), *Roadmap for selected key measurements of LHCb*, arXiv:0912.4179.

[2] Adeva B. *et al.* (LHCb Collaboration), *JINST*, **3** (2008) S08005.