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Recent results from LHCb

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The LHCb detector at LHC is designed for searches of New Physics in CP violation and rare decays. Since the LHC startup, LHCb accumulated a large sample of beauty and charm hadron decay events. Here the status of the LHCb experiment and its latest physics results are reviewed. The strategy of its upgrade for higher luminosity is also discussed.

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1. Introduction

LHCb [1] is an LHC experiment dedicated to flavour physics studies. The main physics goal of LHCb is to search for New Physics phenomena in flavour physics processes. These studies can impose important constraints on the parameters of physics beyond the Standard Model, because New Physics objects can essentially modify parameters of flavour decays. Exploiting the copious production of charm and beauty hadrons at LHC, LHCb is intended to perform precision measurements of CP violation observables and studies of rare decays.

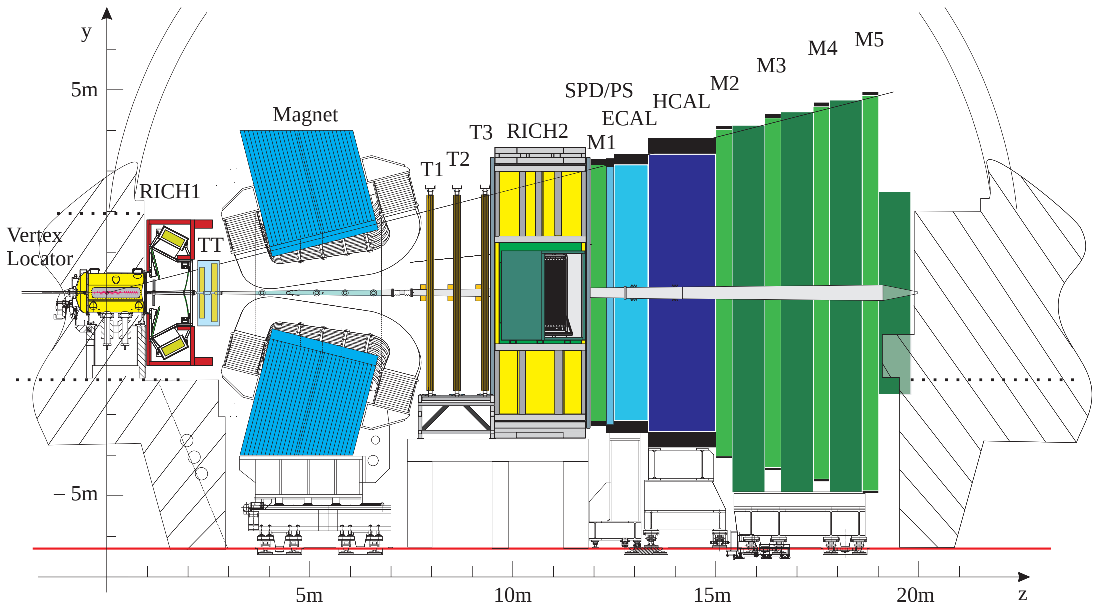

Figure 1: Overview of the LHCb detector.

2. The LHCb experiment

At LHC the $b\bar{b}$ quark pairs are produced with significant boost in the forward or backward direction. This determines the design of the LHCb detector, which is a single-arm forward spectrometer (Fig.1) covering the pseudo-rapidity range of $2 < \eta < 5$.

Due to the boost, the B hadrons have significant decay path, typically ~1 cm; their high mass leads to decay products with high p_T. The signature of the b event in LHCb is therefore particles with high p_T (few GeV) coming from a displaced vertex. The LHCb detector is optimised for such events.

The LHCb layout is shown in Fig.1. The tracking system consists of a silicon strip vertex detector (Vertex Locator, VELO) around the interaction point, a warm magnet ($4T \cdot m$ field) and four tracking stations: one (TT) upstream and three (T1–T3) downstream of the magnet.

The VELO detector is placed surrounding the interaction point. It measures the track coordinates with few μm accuracies, which allows to determine the primary vertices of pp interactions (40 tracks on average) and identify secondary vertices of B decays. The detector consists of two retractable halves. During the "Stable Beam" LHC mode they are moved towards each other such that the sensitive area starts at ∼7.5 mm from the beam. During injection and beam adjustments the detector is kept open by $\approx \pm 30$ mm, for safety reasons.

The TT tracking station is made of silicon strip detectors, while T1–T3 consists of straw tube planes on the periphery (Outer Tracker) and silicon strip detectors around the beam pipe (Inner Tracker).

The $\pi/K/p$ separation in wide momentum range, up to 100 GeV/c, is performed by the system of two Ring Image Cherenkov detectors, RICH1 and RICH2.

The calorimetry system provides precision measurements of γ, e energy, $\gamma/e/h$ separation and Level 0 trigger for high p_T particles. It consists of a preshower detector (PS/SPD), an Electromagnetic Calorimeter (ECAL) and a Hadron Calorimeter (HCAL).

The detector is completed by the Muon system consisting of iron filters interlaced by four tracking stations (M2–M5); the Muon tracking station M1 is placed in front of the calorimetry system. The Muon system provides Level 0 trigger for the high p_T muons and information for the offline muon identification.

The LHCb trigger system [1] consists of purely hardware Level 0 (L0) and software implemented High Level Trigger (HLT) running on the Event Filter Farm composed of about 1300 nodes.

The L0 decision is based on fast hardware reconstruction of highest p_T hadron, electron, photon and muon candidates. L0 reduces the event rate (the clock runs at 40 MHz but the beam crossing rate is about 14 MHz) to ∼1 MHz. Selected events are then read out and sent to the HLT for further selection.

The HLT selection proceeds in two steps. At the first step it searches for a high p_T track with a significant impact parameter with respect to the primary vertex. For muon triggers, the track has also to be validated by the muon detector. A rejection factor of about 20 is obtained at this step. At the second step, the retained events are fully reconstructed, then selections are made for particular processes. The HLT output rate is about 3 kHz, and includes some fraction of randomly selected events, which are used for monitoring purposes.

In 2010 LHCb was running at low luminosity and collected 37 pb^{-1}. The first data were taken at low trigger thresholds, which was very important for understanding the detector operation. In 2011 LHCb is running at its full design luminosity (and above), the core physics programme [3] is started. More than 1 fb^{-1} is expected by the end of 2011.

Unlike ATLAS and CMS, LHCb is not designed to run at the full LHC luminosity. The strongest limitation comes from the event pile-up: the quality of event reconstruction deteriorates with the number of primary pp vertices in one event. For this reason, a levelling system has been developed in LHC, which keeps the LHCb luminosity constant by adjusting the vertical separation of the beams.

It turned out that the LHCb detector, event reconstruction and analysis are able to work well in heavier conditions than designed. At the moment of the conference, in September 2011, LHC was running at $\sqrt{s} = 7$ TeV with ∼1400 bunches in each beam, and peak luminosity $\mathcal{L} = 2 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$ in ATLAS and CMS. At the same time, LHCb was running at $\mathcal{L} = 3.5 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$, with average number of pp interactions per event (μ) of ≈1.4. This significantly exceeds the original design parameters [1]: $\mathcal{L} = 2 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$ and μ=0.4 for LHC running at $\sqrt{s} = 14$ TeV and 2622 bunches per beam.

Several benchmark plots for the detector performance are shown in Fig.2.

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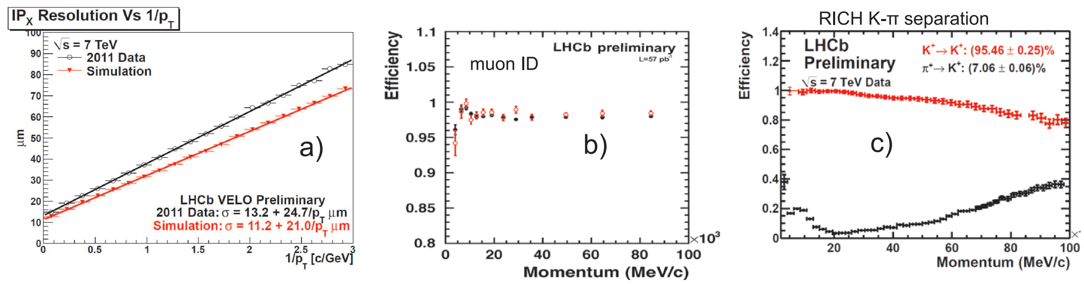

Figure 2: LHCb performance: track impact parameter resolution with VELO (a); muon ID efficiency (b); K/π separation with RICH (c).

The VELO performance [2] is illustrated in Fig.2a by the $1/p_T$ dependence of resolution on IP_x, the x projection of track impact paramter (IP), is given. It is found to be 13.2μm for high p_T tracks. It is slightly worse than expected from simulation, which could come from under-estimation of the VELO material budget in the detector model.

The muon identification efficiency as a function of track momentum is shown in Fig.2b. It is better than 97% for particles with $p > 4$ GeV, with misidentification probability of $\sim$2.5%. The RICH $K-\pi$ separation efficiency and purity as a function of track momentum are shown in Fig.2c. The performance of both RICH and MUON systems agrees well with simulation.

The accuracy of the tracking and calorimetric systems results in effective mass resolution of $\sim$15 MeV for $J/\psi \to \mu\mu$ and 8-10 MeV for $\pi^0 \to \gamma\gamma$. The typical proper time resolution for B decays is $\sim$ 50 fs.

3. Selected physics results

The very first physics results from LHCb were various production and spectroscopy measurements. The world most accurate b-hadron mass measurements were performed on the first 37 pb^{-1} of data taken in 2010 [4]. The momentum scale was calibrated using a large sample of $J/\psi \to \mu^+\mu^-$ decays to better than 0.1 per mill accuracy. The b-hadron production cross section in pp collisions at $\sqrt{s} = 7$ TeV was measured in LHCb with two methods. The first method is based on the 4π extrapolation of the production cross-section of "J/ψ from b", *i.e.* those coming from detached decay vertices. The analysis using the data sample of 5.2 pb^{-1} gives $\sigma(pp \to b\bar{b}X = 288 \pm 4(stat) \pm 48(syst)$ μb [5]. Another method is based on the measurement of $b \to D^0 X \mu^- \nu_\mu$ (+cc) inclusive yields via counting of right-sign $D^0\mu$ combinations coming from detached decay vertices [6]. It gives 284$\pm$20$\pm$49 μb, which is fully compatible with the first method.

The B_s oscillation frequency, Δm_s, was measured using 340 pb^{-1} [7]. The $B_s \to D_s\pi$ decay was used for the measurements, with D_s decaying into $K^+K^-\pi$. The three D_s decay modes into the $K^+K^-\pi$ final state, $\phi\pi$, K^*K and $(K^+K^-\pi)_{nonresonant}$, were analyzed separately, taking into account individual features of each mode to obtain the best background rejection. A total of 9181 B_s decay candidates were selected in these three modes. The world's most accurate result was obtained: $\Delta m_s = 17.725 \pm 0.041$(stat.)$\pm 0.026$(syst.) ps^{-1}. The result was obtained from an unbinned maximum likelihood fit; however with the statistics used in this analysis, the oscillation pattern is

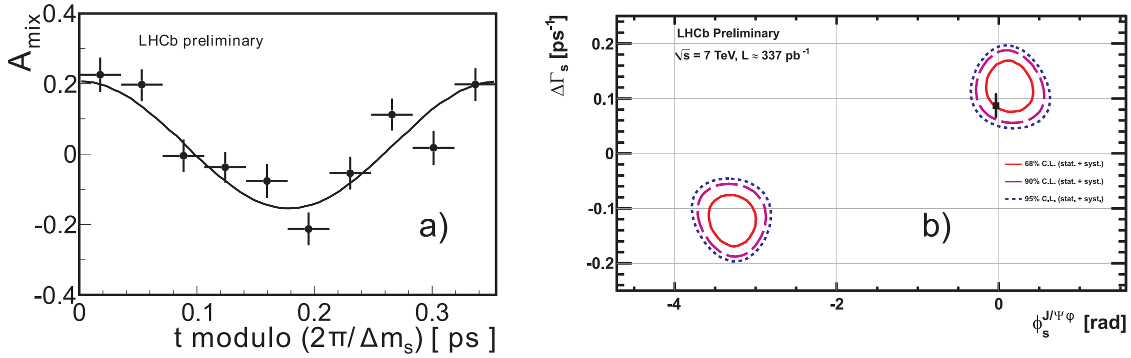

Figure 3: Mixing asymmetry for signal B_s candidates as function of proper time modulo $2\pi/\Delta m_s$ (a); 2D likelihood confidence region in the $\varphi_s^{J/\psi\phi}$ - $\Delta\Gamma_s$ plane, the black square corresponds to the SM predicted value (b).

directly observable in the plot of asymmetry as a function of the proper time modulo $2\pi/\Delta m_s$ (see Fig.3a).

Measurement of φ_s, the B_s mixing phase, in the decay $B_s \to J/\psi\phi$ is one of the key goals of the LHCb experiment [3]. In SM this phase is very small: $\varphi_s = 2\arg(V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$; the indirect determination via global fit to experimental data gives $\varphi_s \approx 0.03648^{+0.00080}_{-0.00075}$ [8]. The actual value of φ_s may be modified by a contribution of New Physics particles to the box diagram determining the $B_s - \overline{B_s}$ oscillation. The direct measurement of φ_s is a powerful test of New Physics models.

The decay $B_s \to J/\psi(\mu\mu)\phi(KK)$ is the most suitable one due to its relatively large branching fraction and clearly reconstructable final state. The decay is dominated by tree diagrams and is well described by Standard Model.

Both CP-odd and CP-even B_s states may decay into $J/\psi\phi$. As they differ in orientation of spin of J/ψ and ϕ and their relative angular momentum, they can be separated via angular analysis of the $(\mu\mu)(KK)$ final state. The direct measurement of φ_s is performed by analyzing the time-dependent decay rate of the two B_s CP states. This allows to determine not only the oscillation phase φ_s but also the lifetime difference of the two B_s states, $\Delta\Gamma_s$, in the same analysis. Such studies have previously been performed by the Tevatron experiments [9, 10].

The world's most accurate result was obtained by LHCb using 340 pb^{-1} [11]. The Δm_s value from [7] is used as an input for this analysis. The result is:

$$\begin{aligned}
\phi_s &= 0.13 \pm 0.18(\text{stat}) \pm 0.07(\text{syst})\ \text{rad} \\
\Delta\Gamma_s &= 0.123 \pm 0.029(\text{stat}) \pm 0.008(\text{syst})\ \text{ps}^{-1} \\
\Gamma_s &= 0.656 \pm 0.009(\text{stat}) \pm 0.008(\text{syst})\ \text{ps}^{-1}
\end{aligned}$$

Its graphical representation as a likelihood contour plot at the $\varphi_s^{J/\psi\phi}$ - $\Delta\Gamma_s$ plane is shown in Fig.3b. It is in a good agreement with Standard Model predictions.

Study of the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ can provide an indirect constraint on the masses of New Physics particles. These are Flavor Changing Neutral Current decays which are in addition helicity suppressed; the SM predicts $\mathcal{B}(B_s^0 \to \mu\mu) = (3.2 \pm 0.2) \cdot 10^{-9}$ and $\mathcal{B}(B^0 \to$

$\mu\mu) = (0.10 \pm 0.01) \cdot 10^{-9}$. However New Physics contributions can significantly enhance these values.

The best upper limits prior to LHCb on the probability of these decays were obtained by the Tevatron experiments. The D0 analysis of 6.1 fb^{-1} of data gives $\mathcal{B}(B_s^0 \to \mu\mu) < 5.1 \cdot 10^{-8}$ at 95% CL [13]. The CDF collaboration has obtained using 6.9 fb^{-1} upper limits of $\mathcal{B}(B_s^0 \to \mu\mu) < 4.0 \cdot 10^{-8}$ and $\mathcal{B}(B^0 \to \mu\mu) < 6.0 \cdot 10^{-9}$ at 95% CL [14]. In the CDF data set an excess of candidates is observed, and a measurement of branching fraction is provided: $\mathcal{B}(B_s^0 \to \mu\mu) = 1.8^{+1.1}_{-0.9} \cdot 10^{-8}$.

The LHCb collaboration had obtained the world's best upper limit for $B_s^0 \to \mu^+\mu^-$ using 300 pb^{-1} of 2011 data [15]: $\mathcal{B}(B_s^0 \to \mu\mu) < 1.3(1.6) \cdot 10^{-8}$ at 90%(95%) CL. Combined with the LHCb 2010 result [16] and recent CMS result [17], the limit becomes $\mathcal{B}(B_s^0 \to \mu\mu) < 1.3(1.6) \cdot 10^{-8}$ at 90%(95%) CL [18], which, in particular, does not confirm the excess seen by CDF.

4. LHCb Upgrade

Starting from 2011, LHCb is running at its design luminosity, and is expected to take 1–2 fb^{-1} of physics data per year. By 2017, before the second long LHC shutdown, LHCb will collect 5–10 fb^{-1}. With these data, LHCb will obtain results that will extensively test the SM in the flavour sector. It will improve the precision of many key parameters in B and D physics, in particular, the B_s system will be studied with accuracy which is difficult to achieve at B-factories. This will significantly restrict the parameter space of New Physics. The hope is to observe phenomena beyond Standard Model.

It is clear however that after that point, to further improve the precision of the measurements of key flavour physics parameters, LHCb has to substantially increase its running luminosity. The goal is to make LHCb able to run at $2 \cdot 10^{33}$cm^{-2}s^{-1}. The only way to overcome the limit of 1–2 fb^{-1} per year is to upgrade the detector.

A detailed discussion of the physics case for LHCb upgrade, as well as analysis of limitations of the present setup and overview of upgraded detector, are given in the Letter of Intent for the LHCb Upgrade published in March 2011 [19].

The most painful limiting factor of the present detector is due to the LHCb trigger architecture which is described above. Namely, the criteria for the L0 trigger decision are based on the presence of a high E_T object. While this provides high efficiencies on (di)muon events, fully hadronic decays typically have efficiencies less than 50%. In these hadronic decays the E_T threshold required to reduce the event rate to an acceptable level is already a substantial fraction of the B meson mass. Any increase in luminosity requires an increase of this threshold, which then further reduces the efficiency. The trigger yield for hadronic processes saturates with increasing luminosity.

To overcome this situation it is essential to remove the 1 MHz L0 limitation and to have a trigger decision based on information that is more discriminating than E_T, *e.g.* the presence of a displaced secondary vertex. The natural solution is to remove the L0 stage and supply the events at full beam crossing frequency to a software implemented trigger system. As a consequence, this will require replacement of the front end electronics of almost all the LHCb subdetectors. Moreover, as in many subdetectors the front end electronics is integrated with the sensitive elements, those will have to be replaced too.

The physics programme of the LHCb upgrade requires an extremely performant vertex detector with fast pattern recognition capabilities, very good vertex resolution, good track separation, low occupancy close to the interaction point. Its radiation hardness should be sufficient to stand the increased luminosity. A completely new VELO detector with appropriate electronics is going to be constructed. A silicon pixel detector is an attractive option due to the high granularity and the relative ease of pattern recognition. The alternative is a silicon strip detector similar to the current VELO design, but with improved cooling and a new readout ASIC.

The tracking system of LHCb also has to be redesigned, in order to be able to work at luminosities up to $2 \cdot 10^{33}$ cm^{-2}s^{-1}. Two options are being considered for the tracker upgrade, one is a scintillating fibre detector with SiPM readout, the other is a silicon strip detector.

The particle identification (PID) system is a vital component of the upgraded detector. Several key physics channels which involve kaons rely on RICH PID to reject copious backgrounds from multiple-track combinatorics and events with similar decay topologies. The current RICH system employs custom-built Hybrid Photon Detectors (HPD) [1]. They cannot be re-used in the upgraded RICH detector, since the HPDs contain integrated readout electronics which is incompatible with the readout rate of 40MHz. It is therefore proposed to replace the HPDs with Multi-anode Photomultipliers (MaPMTs) with external 40MHz readout electronics.

The aerogel system in RICH1 will be eliminated. Instead, one option is to integrate another particle ID detector based on time of flight that uses Cherenkov light in quartz (TORCH), complementing the RICH detectors in the low momentum particle ID. The TORCH is a challenging project, and its installation may come later, without compromising the initial operation of the upgraded detector.

The luminosity of 10^{33} cm^{-2}s^{-1} does not require substantial rebuilds of the Calorimeter and Muon systems. It is planned to remove the preshower detector, while keeping the present ECAL and HCAL calorimeter modules, their photomultipliers and HV system. To prevent fast wearing of PMTs at the higher luminosity, their gain will be decreased by factor of $\sim$5, and the gain of the preamplifiers in the new Front End boards will be increased accordingly. The muon system Front-End electronics is already able to run at 40 MHz. Only small modifications are needed to have the system fully integrated with the rest of the upgraded DAQ.

A bigger CPU farm and more powerful DAQ infrastructure will be needed to cope with a factor 10 higher event flow.

The installation of the upgraded detector is proposed for the 2018 LHC shutdown. This is not connected to the LHC luminosity upgrade, as the required LHC luminosity is already available. The detector will collect at least 50 fb^{-1} of data integrated over around ten years of operation. Taking into account the increase in trigger efficiency for the hadronic channels, this will result in a yield of events at least ten times greater than the present experiment.

5. Conclusion

LHCb is running successfully at its design parameters (and beyond!), demonstrating very good detector performance, and collected by now 800 pb^{-1} of physics data. It is expected to collect $\sim$ 1 fb^{-1} by the end of 2011 and the same amount or more in 2012. Already now, using only 1/3 of the 2011 statistics, LHCb obtained world class measurements in many areas. By now, no significant deviation from the SM has been observed. In particular, the hints observed by Tevatron experiments in $B_s \to \mu\mu$ and φ_s were not confirmed. More precise measurements will be obtained with the full 2011 and then with 2012 data.

An upgrade of LHCb to work at high luminosity is foreseen, with much detector R&D ongoing.

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