STATUS AND RESULTS OF THE LHCb EXPERIMENT*

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The LHCb experiment at the LHC has collected more than $1\,\mathrm{fb}^{-1}$ of physics data during the first two years of operation at the LHC, reaching one of its most important milestones. This has allowed the experiment to already perform extensive world-class measurements in b and c-physics, in order to probe New Physics Beyond the Standard Model. In this paper, the status and excellent performance of the LHCb experiment are reviewed, focusing the attention on the most important aspects of the operation of the experiment. Moreover, several important physics results are highlighted together with their impact for the full physics program at the LHC. Finally, a description of the upgrade of the detector to collect more than $50\,\mathrm{fb}^{-1}$ starting in 2018 will be also given.

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1. Introduction

The LHCb experiment [1] is a dedicated heavy flavor physics precision experiment whose main aim is to probe Physics Beyond the Standard Model, by studying the very rare decays of beauty and charm-flavored hadrons and by measuring CP-violating observables precisely. In the past years, the B factories have confirmed that the mechanism proposed by Kobayashi and Maskawa is the major source of CP violation observed so far. The SM description has been confirmed at the level of 10–20% accuracy in the $b \to d$ transitions, while NP effects can still be large in $b \to s$ transitions. For example, by modifying the B_s mixing phase ϕ_s, measured from $B_s^0 \to J/\psi\phi$ decays, or in channels dominated by other loop diagrams, such as the very rare decay $B_s^0 \to \mu^+\mu^-$.

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The LHCb physics program is inserted in the broader physics program of the other experiments at the LHC accelerator, which is designed and built to achieve the highest energy collisions available at accelerators ($\sqrt{s} = 7$ TeV in 2010 and 2011). In such an environment, high precision measurements can reveal New Physics phenomena as differences with Standard Model predictions. Flavor physics can then provide hints of new phenomenology before the direct discoveries of new particles as performed by the two LHC general-purpose detectors ATLAS and CMS. LHCb will extend the b-physics results from the B factories by studying decays of heavier b hadrons, such as B_s or B_c. LHCb will tackle the challenge of current and future b-physics experiment to widen the range of measured decays, reaching channels that are strongly suppressed in the SM and to improve the precision of the measurements to achieve the necessary sensitivity to NP effects in loops.

2. The LHCb detector

As shown in figure 1, the LHCb detector is a single-arm spectrometer with a forward angular coverage from approximately 10 mrad to 300 mrad. The choice of the detector geometry [2] is motivated by the fact that at high energies both the $b/\bar{b}$ mesons are predominantly produced in the same forward (or backward) cone and that b-production at the LHC has large cross sections as compared to the B factories and to the Tevatron. It is, in fact, measured to be about 300 $\mu\mathrm{b}^{-1}$ at $\sqrt{s} = 7$ TeV [3], which is three times larger than at Tevatron. A sample of about 10^{12} b mesons can be produced

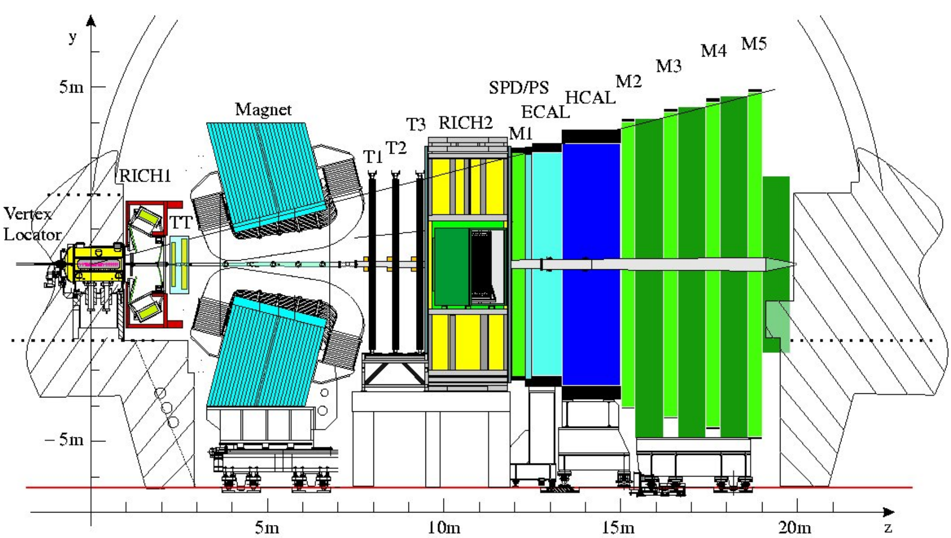

Fig. 1. The layout of the LHCb detector.

at LHCb during a nominal year with all b-hadron species present. For these reasons, the LHCb detector is equipped with a vertex locator (VELO), a charged-particle tracking system with a warm magnet of about 4 Tm integrated field, two aerogel and gas Ring Imaging Cherenkov counters (RICH), electromagnetic (ECAL) and hadronic (HCAL) calorimeters and muon systems. Moreover, due to a large minimum-bias cross section equal to $65\,\mathrm{mb}^{-1}$ in the LHCb acceptance, only 1 out of about 200 pp interactions contains b quarks. Therefore, a very selective and efficient trigger is also needed, based on the efficient event reconstruction and particle identification. It is important to note here that the charm production cross section is about 20 times larger [4] than the b quark one and therefore LHCb has a great potential for charm studies too.

2.1. The LHCb tracking system

The LHCb tracking system consists of a warm dipole magnet, which generates a magnetic field integral of about 4 Tm, four tracking stations and the VELO.

The first tracking station located upstream of the magnet consists of four layers of silicon strip detectors. The remaining three stations downstream of the magnet are each constructed from four double-layers of straw tubes in the outer region, covering most (98%) of the tracker area, and silicon strips in the area closer to the beam pipe (2%) as about 20% of the charged particles traversing the detector go through the silicon inner tracker, due to the forward-peaked multiplicity distribution. The measured impact-parameter resolution is $14\,\mu$m in the highest p_{T} bin, in good agreement with Monte Carlo expectations.

The VELO consists of 21 stations, each made of two silicon half disks and variable pitch size, which measure the radial and azimuthal coordinates. The VELO has the unique feature of being located at a very close distance from the beam line (8 mm), inside a vacuum vessel, separated from the beam vacuum by a thin aluminum foil. The VELO closes around the beam line whenever all the safety conditions are met and this allows an impressive vertex resolution to be achieved. For instance, a proper time resolution of about 50 fs for the decay $B_s^0 \to J/\psi\phi$ was achieved, which is about a factor of seven smaller than the B_s oscillation period. For a typical primary vertex producing 25 tracks, the resolution is $16\,\mu$m in x and y, and $76\,\mu$m in z as shown in figure 2.

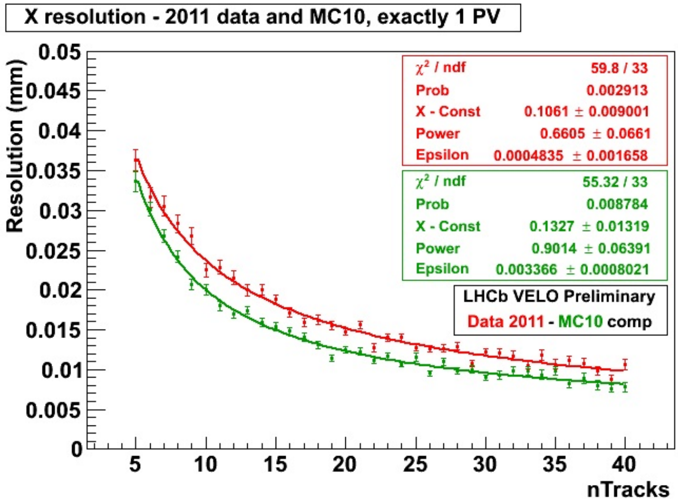

Fig. 2. VELO resolution of primary vertex location as a function of the number of tracks.

2.2. The LHCb particle identification

Particle identification is provided by the two RICH detectors and the calorimeter and muon systems.

The RICH system is one of the crucial components of the LHCb detector. The first RICH, located upstream of the magnet, employs two radiators, C_4F_{10} gas and aerogel, ensuring good separation between kaons and pions in the momentum range from 2 to 60 GeV/c. A second RICH in front of the calorimeters uses a gas radiator, CF_4, and extends the momentum coverage up to about 100 GeV/c. The calorimeter system comprises a pre-shower detector (PS-SPD) consisting of 2.5 radiation lengths of lead sheet sandwiched between two scintillator plates, a 25 radiation lengths lead-scintillator electromagnetic calorimeter (ECAL) of the *shashlik* type and a 5.6 interaction lengths iron-scintillator hadron calorimeter (HCAL). The muon detector consists of five muon stations equipped with multi-wire proportional chambers, with the exception of the center of the first station, which uses triple-GEM detectors.

The two RICH detectors allow charged kaon identification with an efficiency of about 96% while the fake rate from pions as kaons is about 7% in the momentum range of 3–100 GeV/c. The average electron identification efficiency extracted from electrons produced in photon conversions is about 90% with a misidentification rate of about 3–5% for electrons with momentum above 10 GeV/c. Identification of muons is done by the muon system with an efficiency which reaches 97% and just 1–2% misidentification rate.

2.3. The LHCb trigger system

As mentioned earlier, the challenge of a b-physics experiment in a hadron collider is due to the very high cross sections of minimum-bias events. Moreover, as hints of New Physics may be found in very rare decays in the B system, it is clear that a very efficient and selective trigger must be in place in order to record only the interesting events.

The LHCb trigger system is one of the most critical systems of the LHCb detector. It consists of two levels (figure 3): a first-level hardware-based trigger (Level-0) and a second-level software-based trigger (High Level Trigger). The Level-0 trigger is implemented on custom electronics boards and it is designed to reduce the input rate to about 1.1 MHz, reducing by a factor 30 the nominal bunch–bunch rate from the LHC accelerator. The Level-0 trigger decision is based on calorimeter and muon chamber information and selects muons, electrons, photons or hadrons above a given p_{T} or E_{T} threshold, typically in the range 1 to 4 GeV. A fixed latency ensures that the trigger decision reaches all the sub-detector electronics synchronously.

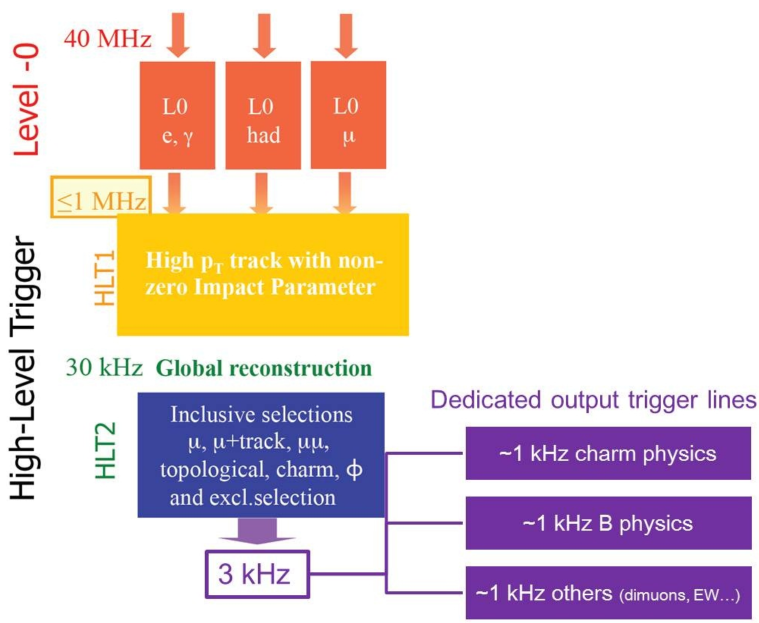

Fig. 3. Schematic drawing of the LHCb trigger system.

Selected events are then sent to a processing farm, composed of more than 1000 multi-core processors adding up to about 15000 CPU cores. Each processing core runs an HLT software algorithm which analyzes the received event and selects it if within the criteria. The final output rate is about

3 kHz for an event size of about 65 kB. The HLT algorithms are designed to be simple, inclusive and fast. This is realized by performing at the first stage of the HLT, called HLT1, a partial reconstruction to select a single, good-quality track with high momentum and large impact parameter, as well as lifetime-unbiased muons and electrons. The second stage of the HLT, called HLT2, processes few enough events that it is possible to perform a reconstruction very similar to that used offline. The average HLT execution time is O (20 ms) per event. It is worth noting here that in 2011 the 3 kHz output of physics data was divided into three dedicated main output trigger lines, where 1 kHz of events were dedicated to charm physics, 1 kHz to hadron and the rest to other decays (mostly di-muons).

Finally, in order to allow for more flexibility and full control of the readout system, an intelligent centralized timing, trigger and readout control system was also developed with the main task of distributing timing and trigger information to the whole readout system and managing the synchronization of each element in the readout system. Having a centralized, control of the readout system allowed implementing new techniques and improvements as the requirements changed due to new running conditions and new physics objectives.

3. Operational aspects of the LHCb detector

In order to increase the efficiency of the trigger, LHCb was designed to record physics data at an average instantaneous luminosity of $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, therefore allowing for a small number of interactions per bunch–bunch collisions — this quantity is usually referred to as *pileup* and the design pileup value at LHCb was 1. However, during the 2011 data taking period, the LHCb experiment collected data at twice the design luminosity thanks to numerous operational aspects.

One of the major breakthrough of the data taking period in 2011 was the so-called *luminosity leveling*. In practice, the luminosity delivered to LHCb by the LHC accelerator was kept constant throughout the entire length of a physics fill, by gradually separating the beams in the vertical plane at the LHCb interaction point. This is graphically shown in figure 4, where the LHCb luminosity trend for Fill 2195 is shown as compared to the luminosity of ATLAS and CMS. While the luminosity delivered in ATLAS and CMS falls exponentially, the luminosity delivered in LHCb remains constant. With this novel technique, excellent operational stability is achieved as the whole detector and readout system will perform consistently throughout an entire fill, by having constant occupancies, constant trigger rates and constant event processing times. Moreover, as the luminosity leveling is an automatic procedure established between the LHC accelerator and the

LHCb experiment, it is possible to choose the operational point according to the desired running conditions. This can be seen in figure 5, where the peak of instantaneous luminosity is trended over time during the 2011 data taking period. Three major periods of running at three different values of instantaneous luminosity are clearly visible.

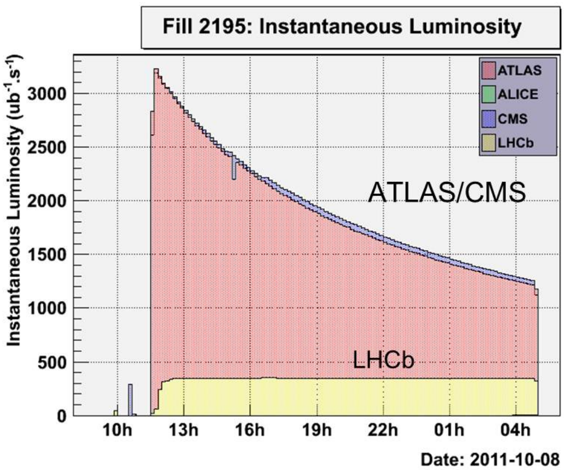

Fig. 4. Example of luminosity leveling throughout a physics fill. The LHCb delivered luminosity is kept constant as opposed to the delivered luminosity in ATLAS and CMS.

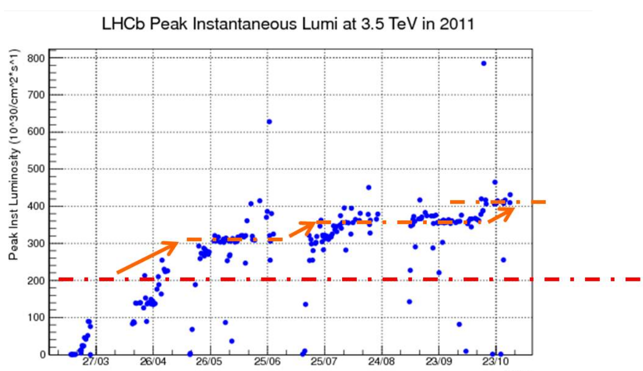

Fig. 5. Peak of instantaneous luminosity over time during the 2011 data taking period. Different periods of running at different selected luminosity allowed the LHCb experiment to record physics data with very high operational efficiency and stability. Ultimately, more than 50% of the recorded physics data was recorded at an instantaneous luminosity of about $4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which is twice the design luminosity (dashed/red line).

With this procedure in place, the LHCb experiment recorded more than 50% of the data by running at a constant luminosity of $4 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is twice the design value. This excellent operational stability allowed the LHCb readout system to push about 3 kHz of triggered physics data to tape, accumulating about 630 TB of data which corresponds to about 11 billion physics events.

4. Performance of the LHCb detector

The LHCb detector had excellent performance throughout the entire 2011 data taking period which is added to the already excellent performance of the 2010 data taking period, where world-class measurements were already performed with only $37\,\mathrm{pb}^{-1}$ of luminosity recorded [5].

As shown in figure 6, the LHCb experiment recorded more than $1\,\mathrm{fb}^{-1}$ of useful physics data in 2011, with a global operational efficiency of more than 90%. There are four main sources of inefficiency during physics data taking in LHCb:

- the high voltages of each sub-detector in physics configuration which should be at nominal values;
- the VELO safety closing procedure which moves the VELO towards the beam line up to 5 mm of distance;
- the availability of the data acquisition system;
- the running dead time coming from the network back pressure or events processing.

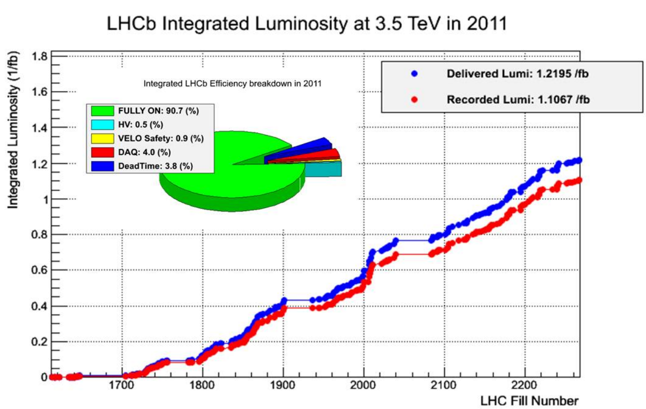

Fig. 6. The LHCb detector recorded more than $1\,\mathrm{fb}^{-1}$ of useful physics data with a global efficiency above 90%.

As the detector operated throughout the year with more than 99% of active and working channels, almost the entire collected dataset was already good for physics analysis. Therefore, the reprocessing of the data had an efficiency above 99%.

With such excellent detector and operational performance, the LHCb experiment could start its physics program early on in the period of data taking. Already throughout the year, world-best measurements were performed and more will come with the entire collected dataset. It is foreseen to, at least, double the LHCb dataset by the end of 2012, setting most of the world-best limits in flavor physics.

5. Selected physics results

The very first physics results from LHCb were various production and spectroscopy measurements. The b-hadron production cross section in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ 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 $5.2\,\mathrm{pb}^{-1}$ gives $\sigma(pp \to b\bar{b}X) = 288 \pm 4(\mathrm{stat.}) \pm 48(\mathrm{syst.})\mu\mathrm{b}$ [6]. 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. It gives $\sigma(b\bar{b}) = 284 \pm 20 \pm 49\mu\mathrm{b}$ [3], which is fully compatible with the first method.

The precise determination of the angle γ of the B_d CKM Unitarity Triangle is one of the major goals of the LHCb physics program. The comparison of its measurements in tree-level decays, such as $B \to DK$ and in loop-mediated processes, such as $B^0 \to \pi^+\pi^-$ can provide signs of New Physics. With only $320\,\mathrm{pb}^{-1}$ (one third of the full 2011 dataset), LHCb was able to already report the most precise single measurement of direct CPV in $B_d^0 \to K\pi$ and the first evidence of CPV in $B_s^0 \to K\pi$ decays [9] (figure 7). Another important search for the open-charm $B^\pm \to (K^\mp\pi^\pm)_D K^\pm$ decay with $343\,\mathrm{pb}^{-1}$ of data has been reported by LHCb [10]. With about $2\,\mathrm{fb}^{-1}$ of recorded data in 2012, the LHCb experiment expects to measure the angle γ with a precision of about 5°.

Another important contribution by the LHCb experiment is the measurement of CPV in the B_s^0 system. LHCb discovered a new channel, $B_s^0 \to J/\psi f_0(980)$ [11], which together with the decay $B_s^0 \to J/\psi\phi$ allows measurement of the B_s^0 phase, which is responsible for mixing-induced CP violation. Any significant enhancement in this CP violating phase above the small value predicted by the Standard Model would be a clear sign of New Physics. Critical to the measurement is the ability to resolve fast $B_s^0 - \bar{B}_s^0$ oscillations. This has been demonstrated by LHCb's

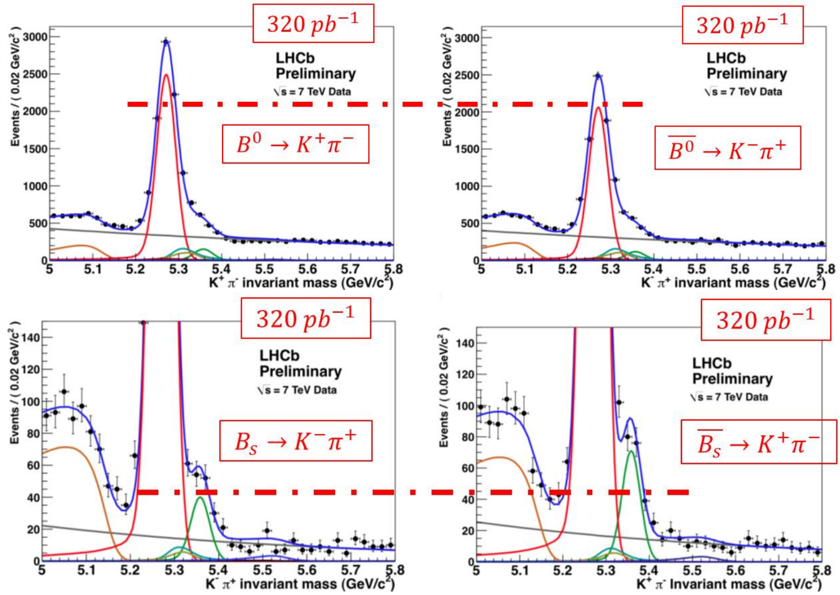

Fig. 7. LHCb already performed world-class measurements of direct CPV. Comparisons of measurements in $B^0_{s,d} \to K\pi$ allow determinations of CPV in the B system.

world best measurement (with about 0.3 fb^{-1}) of the oscillation parameter $\Delta m_s = 17.725 \pm 0.041(\text{stat.}) \pm 0.025(\text{syst.})\,\text{ps}^{-1}$ [12]. Moreover, LHCb extracted a measurement of $\phi_s = 0.03 \pm 0.16(\text{stat.}) \pm 0.07(\text{syst.})$ based on the analysis of the best of the width decays difference in the B_s system, $\Delta\Gamma_s$. Contours of the value of ϕ_s in the $\Delta\Gamma_s$ plane can be found in figure 8 and in [12], where it is shown that the LHCb measurement is consistent with the SM prediction.

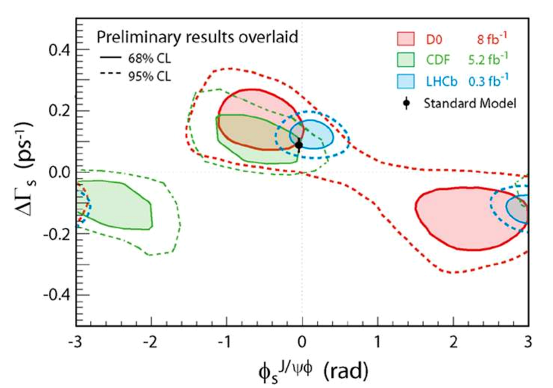

Fig. 8. Comparison of LHCb, CDF and D0 measurements in the $\phi_s - \Delta\Gamma_s$ plane.

As mentioned before, the LHCb detector has also great potential in studying CPV in the charm sector, thanks to the very large statistics available and to the dedicated 1 kHz trigger line. The first evidence of CPV in the charm sector was found at LHCb by measuring the difference ($\Delta A_{\rm CP}$) in CP asymmetries for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. A significance of 3.5σ was found for the measurement of $\Delta A_{\rm CP} = (-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}))\%$ [13].

Another very promising way to look for New Physics is to search for very rare decays such as $B^0_{s,d} \to \mu^+\mu^-$. The branching ratios (BR) of these rare decays are predicted with high precision in the SM, $\text{BR}(B^0_s \to \mu^+\mu^-) = (0.32 \pm 0.02) \times 10^{-8}$ and $\text{BR}(B^0_d \to \mu^+\mu^-) = (1.0 \pm 0.5) \times 10^{-10}$. LHCb set new limits with only 0.3 fb^{-1} for these decays thanks to an analysis based on multivariate estimators combining vertex and geometrical information: $\text{BR}(B^0_s \to \mu^+\mu^-) < 1.6 \times 10^{-8}$(95% C.L.) and $\text{BR}(B^0_d \to \mu^+\mu^-) < 3.6 \times 10^{-9}$(95% C.L.) [14]. A combined analysis with CMS (with 0.3 fb^{-1} from LHCb and 1.1 fb^{-1} from CMS [15]) allowed set the limit $\text{BR}(B^0_s \to \mu^+\mu^-) < 1.6 \times 10^{-8}$(95% C.L.). Also, predictions on the amount of data needed for possible 3σ evidence or 5σ discovery on the decay were made, as shown in figure 9.

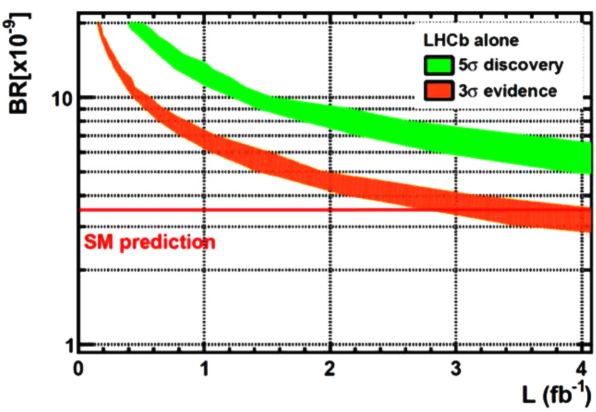

Fig. 9. Estimation of the $\text{BR}(B^0_s \to \mu^+\mu^-)$ limits over integrated luminosity. At about 2.5 fb^{-1} of integrated luminosity at LHCb, there is room for a 3σ evidence already at the end of 2012.

6. The LHCb upgrade

The LHCb experiment was designed to complete its physics program after collecting about 5 fb^{-1} of integrated luminosity in about five years of data taking at an average instantaneous luminosity of $2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$. As shown in the previous sections, the excellent performance of the detector enlarged the initial physics program and operational goals. However, in order to go further, an upgrade of the detector is required to collect the necessary data in a manageable amount of time. This upgrade is intended to allow the detector to operate at between five and ten times higher average instantaneous luminosity, having a fully flexible trigger architecture. The aim is to collect about $50\,\mathrm{fb}^{-1}$ after ten years of operation.

In [16], the LHCb Collaboration presented a first proposal for a possible upgrade in a shutdown period currently scheduled in 2018. The target luminosity is $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is ten times the original design specifications. To achieve this, the LHCb experiment is considering an upgrade towards a *trigger-free 40 MHz complete event readout* in which the event selection will only be performed on a processing farm by a high-level software trigger with an access to all detector information (figure 10) and which profits from the ability to distinguish displaced vertices in the VELO. The main reason for choosing a trigger-less architecture is due to the current

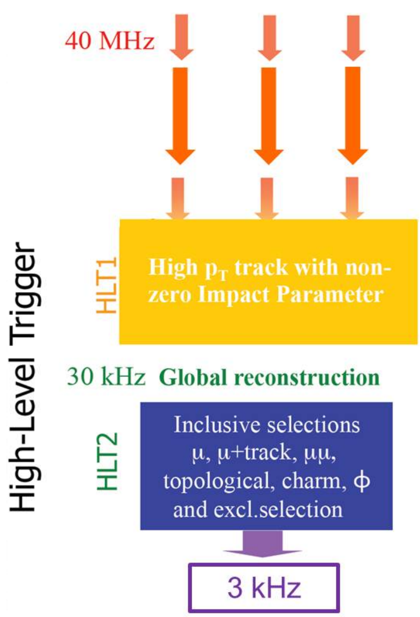

Fig. 10. Schematic drawing of the upgraded trigger architecture as compared to figure 3. The first-level trigger is suppressed and the full set of events is available to the farm to be analyzed and processed. In reality, a *Low Level Trigger* will still be present between the Front–End electronics and the Back–End electronics in order to allow for a staged upgraded readout architecture and also for rate regulation of the system in case needed.

trigger architecture which enriches the sample of di-muons events, but has a low efficiency for fully hadronic channels. This is because the selection of events is based on the transverse energy deposition of several GeV particles in the calorimeter sub-detector. Any increase in luminosity would require applying harder cuts reducing even more the efficiency of the hadron channels. The best way to overcome this limitation is to have the full event available at a software level. If considerable changes in the detector performance are achieved by having the full event information available, then the LHCb experiment can profit from an increase in luminosity exploiting the higher-pileup events.

In order to be compatible with a trigger-less readout architecture, many LHCb sub-detectors will have to be replaced and studies are ongoing to define the technologies to be used. Also a completely new approach based on the ATCA technology is being considered as the main technology of the readout system. Moreover, studies are ongoing in order to also evaluate the impact of the LHCb upgrade in the global LHC physics program.

7. Conclusion

The LHCb experiment had a successful and fruitful 2011 year of data taking at the LHC. The superb detector performance and operation allowed first world-class measurements in flavor physics at the LHC. The 2012 year of data taking will allow the LHCb experiment to at least double its current dataset. Moreover, the work for a new upgraded detector is already ongoing in order to be ready for operation around 2018. This will allow the experiment to increase its dataset by a factor 10.

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