Recent results from the LHCb experiment

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Abstract. The LHCb experiment was presented with emphasis on the performance during the 2010 and 2011 runs. In addition, a selection of the first few competitive physics results were presented.

1. Introduction
The LHCb experiment is dedicated to the study of heavy flavour physics at the Large Hadron Collider (LHC), being designed to perform precision measurements of charge-parity (CP) violation and rare decays involving transitions of the b and c quarks. The violation of the CP symmetry is one of the ingredients necessary for the generation of the baryon asymmetry observed in the universe [1]. Within the Standard Model (SM), CP is only violated in the flavor changing processes and all the CP violation observables can be written in terms of only 4 parameters, the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, making the model highly predictive. However, the amount of CP violation provided by the CKM mechanism is much too tiny to explain the observed baryon asymmetry [2], therefore new sources of CP violation are needed and might show up in flavor changing processes. These indirect searches for new physics are complementary to the direct searches performed at the general purpose experiments and are sensitive to higher energy scales.

In order to identify these new sources of CP violation, an excellent control of the SM contributions is needed. In the last decade, huge progress has been achieved on this field by the B factories and the Tevatron experiments CDF and D0 and also by lattice QCD calculations. This progress can be illustrated by the evolution of the constraints imposed by measurements to the sides and angles of one of the CKM unitarity triangles, from 2001 to 2011, shown in Fig. 1 [4], which also show constraints due to observations in the kaon system. The agreement and consistency of the SM predictions with measurements is remarkable. Nevertheless, it is still possible that new physics (NP) phenomenae contribute to $b \rightarrow s$ transitions, predicted to be small in the SM, and experimentally not probed with the same precision as the $b \rightarrow d$ transitions. Thanks to the large b and c cross-sections in high energy proton collisions and a dedicated trigger, LHCb will make important contributions to this sector.

With the first data collected at a centre-of-mass energy of 7 TeV at the LHC, LHCb published many results on heavy flavor production, including some first observations. The focus of this presentation was on the detector performance and on a few of the first competitive results on CP violation and rare decays.
2. LHCb detector and performance

The LHCb detector [3] is a single-arm forward spectrometer (see Fig. 2) covering the region \((1.9 \leq \eta \leq 4.9)\) where the \(b\bar{b}\) (and \(c\bar{c}\)) production is peaked. It incorporates precision vertexing and tracking systems, particle identification over a wide momentum spectrum and relies on relatively soft transverse momentum triggers, efficient for both leptonic and purely hadronic decays of the B and D mesons.

In 2011, the LHC machine provided proton-proton collisions at a center-of-mass energy of 7 TeV and increasing luminosity. LHCb can work at constant luminosity independently from the other intersections, thus optimizing the number of interactions per bunch crossing for collecting clean events. In spite of running at an instantaneous luminosity of about \(3.5 \times 10^{32} \text{ cm}^2 \text{s}^{-1}\) and an average number of interactions per crossing of \(\mu \sim 1.5\), about twice the original planned instantaneous luminosity and four times the expected \(\mu\), the experiment performed very well during this period.

A very high precision measurement of the primary and secondary vertices is essential for the determination of the B or D meson decays and to resolve the fast \(B_s\) oscillations. A very good momentum resolution is also crucial to the obtention of good mass resolutions and background discrimination. These measurements are performed by the micro-strip silicon vertex detector (VELO) and the tracking system. The latter consists of one silicon micro- strip detector, named the Tracker Turicensis (TT), located in front of the spectrometer magnet and three tracking stations downstream of the magnet. The stations are composed of a silicon micro- strip detector in the inner parts (IT) and of straw-tubes in the less occupied outer parts (OT).

The VELO, the highest resolution vertex detector at the LHC, is a retractible device that surrounds the collision region and is closed at every beam injection. The VELO sensors achieve a single hit resolution of 4 \(\mu\)m in the direction transverse to the beam for the smallest pitch region and optimal angle. A primary vertex resolution of about 16 \(\mu\)m in X/Y and 76 \(\mu\)m in Z has been obtained for 25 track vertices, see plot of Fig. 3(a). The corresponding proper-time resolution of about 50 fs allows for an accurate determination of the B-lifetimes (of about 1500 fs). Another important performance figure for a B-physics experiment is the impact parameter resolution which is found to be \(14.4 \mu\text{m} + 19.5/\text{p}_{T} \mu\text{m}\) (preliminary determination).
The tracking system together with the 4 Tm magnet provide a momentum resolution of 0.3\% to 0.5\%. Continuous improvements in the alignment of the tracking stations during the 2010 data taking have resulted in significant improvements in the mass resolution, resulting in for example a $J/\psi$ mass resolution of 13 MeV/$c^2$.

Another important requirement for LHCb analyses is the particle identification, which is provided by the Ring Imaging CHERENKOV (RICH), the calorimeters and the muon sub-detectors. Hadron identification, provided by the RICH system, in particular the ability to distinguish kaons and pions, is crucial to many LHCb analyses, particularly where the final states of interest are purely hadronic. The calorimeters provide identification of electrons, photons and hadrons in addition to the measurement of their energies and positions. As well as being part of the
LHCb trigger, the muon system provides identification of muons to a very high level of purity, fundamental for many CP-sensitive measurements that have $J/\Psi$ in their final states and also for those involving rare leptonic or semileptonic decays.

In order to achieve $\pi/K$ separation over the extensive momentum range of $\sim 1$ to 100 GeV/c, two separate RICH detectors are employed, using three separate radiators: aerogel, $C_4F_{10}$ and CF$_4$. The aerogel radiator of RICH-1, located upstream of the LHCb dipole magnet, is composed of 5 cm thick tiles arranged around the LHC beam pipe. Located directly behind the aerogel is $\sim 1$ m of $C_4F_{10}$. Together, the radiators of RICH-1 provide PID for tracks from 1 to approximately 60 GeV/c. RICH-2, located downstream of the magnet, contains the CF$_4$ gas radiator and provides PID over the momentum range of approximately 50 to 100 GeV/c.

The arrangement of optics is similar in both sub-detectors; spherical focusing mirrors project the Cherenkov photons onto a series of flat mirrors which then reflect them onto a set of photon detector arrays, located outside the detector acceptance. The photon detector used is the Hybrid Photon Detector (HPD). Angular resolutions of 1.62 and 0.62 mrad have been achieved for the RICH1 and RICH2, respectively. These numbers are very close the values obtained from Monte Carlo simulations. The efficiency and purity of $\pi/K$ identification over the entire momentum range is shown in Fig. 3(b), which are also in good agreement with simulation.

The LHCb Calorimetry system (CALO) takes the classical form of an electromagnetic calorimeter (ECAL) followed by a hadron calorimeter (HCAL) and is located downstream of RICH-2. To help in the distinction of $e^\pm$ from the overwhelming background of $\pi^0$ and $\pi^\pm$ mesons, longitudinal separation of the EM showers is needed. This is achieved by using two additional detectors in front of the ECAL: a Scintillator Pad (SPD) and Pre-Shower (PS) detector. The ECAL is a shashlik type sampling calorimeter of thickness 25 $X_0$, composed of 66 alternating layers of lead absorber and scintillator, achieving an energy resolution of $\sigma_E / E = 9\% \pm 0.8\%$. The HCAL, also a sampling type detector, is composed of alternating layers of iron and scintillator with a resolution of $\sigma_E / E = 69\% \pm 9\%$. Thanks to the good performance of the CALO system, LHCb has reconstructed 1599 $B \to K^{*0}\gamma$ decays and 210 $B_s^0 \to \phi\gamma$ decays in the first 340 pb$^{-1}$ of pp collisions recorded in 2011 (see Fig. 4), allowing the measurement of the ratio of the branching fractions, found to be

$$\frac{B(B\to K^{*0}\gamma)}{B(B_s^0\to\phi\gamma)} = 1.52 \pm 0.14(stat) \pm 0.10(syst) \pm 0.12(fs/fd) \ [5].$$

This measurement is in good agreement with previous measurements and show the potential of the experiment to make important contributions to the study of these radiative $b \to s\gamma$ transitions, which may have its dynamics modified by new virtual heavy particles propagating within the loop.

![Figure 4](image-url)  

**Figure 4.** Invariant mass of $B \to K^{*0}\gamma$ (a) and $B_s^0 \to \phi\gamma$ (b) candidates.
The muon system is composed of five stations of Multi-Wire Proportional Chambers (MWPCs), labelled M1-M5, positioned around the beam axis. Stations M2 to M5 are located downstream of the calorimeters, with 80 cm thick iron plates interspersed between each. These iron plates act as absorbers to reduce any hadronic background that survives past the calorimeters. The first station, M1, sits immediately in front of the calorimeters. Due to the high particle fluxes experienced around the inner region of this upstream station, a technology with extended longevity is used: triple-GEM (Gas Electron Multiplier) detectors. Based on a sample of \( J/\psi \rightarrow \mu^+\mu^- \) decays the efficiency has been determined at 97.3 ± 1.2% which is in close agreement with the MC expectations. Incorrect identification rates of kaons and pions as muons are at the level of 1% and below that for particles with momentum above 10 GeV/c. An illustration of the muon identification performance is given by the clear peaks corresponding to the different di-muon resonances \( J/\psi, \psi(2S), \Upsilon(1S) \) and \( \Upsilon(1S) \) shown in the mass spectra of Fig. 5.

Figure 5. Di-muon invariant mass spectrum in the ranges (2.9 - 3.9) GeV/c\(^2\) (left) and (9-11) GeV/c\(^2\) (right).

3. Search for the rare decays \( B^0_{d,s} \rightarrow \mu^+\mu^- \)

The search for the rare decays \( B^0_{d,s} \rightarrow \mu^+\mu^- \) is one of the most promising ways to test the SM. Within this model, the branching ratios of these flavour changing neutral current transitions, which occur only at loop level, are helicity suppressed and are computed with good precision: \( \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9} \) and \( \mathcal{B}(B^0_d \rightarrow \mu^+\mu^-) = (0.010 \pm 0.001) \times 10^{-9} \) [6]. Large enhancements are possible in many variants of SuperSymmetry and alternative new physics models.

Before the 2011 summer, the best published limits from the Tevatron at 95% CL were obtained using 6.1 fb\(^{-1}\) by the D0 collaboration [7], and using 2 fb\(^{-1}\) by the CDF collaboration[8]. The CDF collaboration had also presented a preliminary result[9] with 6.9 fb\(^{-1}\) in which an excess of \( B^0_s \rightarrow \mu^+\mu^- \) candidates was reported, compatible with \( \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8} \). The LHCb Collaboration had obtained the limits \( \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) < 5.4 \times 10^{-8} \) and \( \mathcal{B}(B^0_d \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8} \) at 95% CL based on 37 pb\(^{-1}\) of luminosity collected in the 2010 run [10]. At the summer conferences, LHCb presented a measurement based on 300 pb\(^{-1}\) of integrated luminosity collected between March and June 2011 [11] (accepted for publication in Physics Letters B).

The LHCb analysis is done by classifying selected candidates in bins of a 2D parameter space made by the invariant mass and a multivariate classifier (Boosted Decision Tree - BDT) which
gives rise to time-dependent CP violation, a difference in the proper decay time distribution of $B_s$ of decay via mixing in the process $B_s \rightarrow J/\psi \phi$ is one of the key measurements for LHCb. It is shown on Figure 7 the constraints imposed by upper limits down to $2 \times$ SM level in the region around the current NUHM1 best fit point [14]. In this figure, tan$\beta$ is the ratio of the vacuum expectation values of the two neutral CP-even Higgs fields and $M_A$ is the pseudoscalar Higgs mass.

The signal and background expectations are compared with the distribution of observed events, and the limits are set using the CL$_s$ method [12]. The number of observed events for the $B_s^0 \rightarrow \mu^+\mu^-$ decay is in good agreement with the background expectation and the SM signal branching fraction. The upper limits obtained after combination with the results obtained in 2010 are [11]

$$B(B_s^0 \rightarrow \mu^+\mu^-) < 1.2(1.4) \times 10^{-8} \text{ at } 90\% (95\%) \text{ CL},$$

$$B(B_d^0 \rightarrow \mu^+\mu^-) < 2.6(3.2) \times 10^{-9} \text{ at } 90\% (95\%) \text{ CL}.$$ 

In Fig. 6 the luminosity needed for a 3$\sigma$ evidence as a function of the $B(B_s^0 \rightarrow \mu^+\mu^-)$ is shown. Approximately 2 fb$^{-1}$ are needed to reach the SM prediction [13]. As an example of how the upper limits on $B(B_s^0 \rightarrow \mu^+\mu^-)$ impose constraints on extensions of the SM, it is shown in Fig. 7 the constraints imposed by upper limits down to $2 \times$ SM level in the region around the current NUHM1 best fit point [14]. In this figure, tan$\beta$ is the ratio of the vacuum expectation values of the two neutral CP-even Higgs fields and $M_A$ is the pseudoscalar Higgs mass.

### Figure 6.
Luminosity needed in order to get a $B_s^0 \rightarrow \mu^+\mu^-$ 3$\sigma$ evidence.

### Figure 7.
Constraints imposed by upper limits on $B(B_s^0 \rightarrow \mu^+\mu^-)$ at the $10^6$ level on the region around the minimum of the NUHM1 fit (from [14]).
B and $\bar{B}$ decays. In the SM, it is predicted to be $\phi_s = -2\beta_s = \text{arg}(\overline{V}_{ts}V_{td}^*/V_{us}V_{ud}^*)$, neglecting penguin contributions. Global fits to experimental data give a small and precise value $2\beta_s = (0.0363 \pm 0.0017)$ rad [4]. New particles could contribute to the mixing box diagram modifying the SM prediction, by adding a new phase. Before the 2011 summer conferences, the results from the experiments at Tevatron were both above the SM prediction [15, 7], although not with enough precision to rule out the SM value. The values were compatible with the 68% confidence intervals obtained by LHCb with the first 36 pb$^{-1}$ of data collected in 2010 and, when combined with the semi-leptonic asymmetry measurement by D0 [17] could be considered as a possible hint for NP.

The latest results reported by LHCb [18] were obtained with $\sim$340 pb$^{-1}$, from which $\sim$8300 candidates are selected. The fit to the decay time distributions provide a simultaneous measurement of the phase $\phi_s$, of the average lifetime $\Gamma_s$ and of $\Delta \Gamma_s$, the difference between the decay widths of the mass eigenstates. The measurement requires several inputs. The oscillation frequency $\Delta m_s$ is obtained from an unbinned likelihood fit to the mass and proper time distribution of about 9200 $B^0_s \rightarrow D_\gamma^0 \pi^+$ candidates [19], $\Delta m_s = (17.725 \pm 0.041 \pm 0.026)$ ps$^{-1}$. The proper time resolution is measured by using $J/\psi$ originated directly from the interaction point and the acceptance is determined from the relative efficiency of events passing a lifetime unbiased selection and a lifetime biased selection. Since the final state of the decay $B^0_s \rightarrow J/\psi \phi$ of a pseudo-scalar to two vector mesons is not a CP eigenstate, an angular analysis is needed to disentangle the CP odd and even states. The angular acceptances for the three transversity angles $\phi, \theta$ and $\psi$ are determined from simulation and cross-checked in the decay $B^0_s \rightarrow J/\psi K^*$. The flavour of the $B^0_s$ meson is determined by algorithms exploiting several properties of each event. In order to enhance the tagging power $\epsilon(1-2\omega)^2$, where $\epsilon$ is the tagging efficiency and $\omega$ is the probability of incorrect tagging (mistag), a per-event mistag probability is used in the fits. This mistag probability is calibrated on data, using $B^+ \rightarrow J/\psi K^+$ events and validated on $B^0 \rightarrow J/\psi K^*$. The results from the unbinned maximum likelihood fit of the mass, proper time and angular distributions are given in Fig. 8. The signal sample contains a 4% contribution from non-resonant $s$-wave decays, which is also taken into account in the fit.

The $\phi_s$ and $\Delta \Gamma_s$ values extracted from the fit are $\phi_s = (0.13 \pm 0.18 \pm 0.07)$ rad, $\Gamma_s = (0.656 \pm 0.009 \pm 0.008)$ ps$^{-1}$ and $\Delta \Gamma_s = (0.123 \pm 0.029 \pm 0.011)$ ps$^{-1}$. The dominant sources of systematic uncertainties are the background description and the angular acceptances. These are the most precise measurements of $\phi_s$ and $\gamma_s$ and the first significant measurement of a non-zero $\Delta \Gamma_s$ value, all compatible with SM predictions, as can be seen from Fig. 9.

The decay $B^0_s \rightarrow J/\psi f_0$, first observed by LHCb, is also sensitive to the phase $\phi_s$. Since the final state is a pure CP odd state, no angular analysis is needed. The value of $\Gamma_s$ is given as input to the unbinned maximum likelihood fit to the mass and proper time distributions, which provides $\phi_s = (-0.44 \pm 0.44 \pm 0.02)$ rad [21]. A first naive combination of this result with the $\phi_s$ obtained from the $B^0_s \rightarrow J/\psi \phi$, assuming Gaussian errors, yields $\phi_s = (0.03 \pm 0.16 \pm 0.07)$ rad [22].

5. **Search for direct CP violation in the decay $D^+ \rightarrow K^- K^+ \pi^+$**

Within the SM, hadronic charm decays occur dominantly via tree level amplitudes. Since all quarks building up initial and final states belong to the first two generations, the transitions are governed by a $2 \times 2$ Cabibbo quark mixing matrix, which is real. CP violating penguin contributions are strongly suppressed and therefore, CP violation is expected to be very small [23]. For $D^+$ decays, CP asymmetries predictions are maximal for singly cabibbo suppressed modes and are of the order of $10^{-5}$ [24]. Any observation larger than this would be an unambiguous sign for new physics.

LHCb performed a model independent search for local CP asymmetries across the Dalitz Plot (DP), based on the work in [25], using a sample that corresponds to about 35 pb$^{-1}$ collected in
Figure 8. Fit projections to invariant mass (top left), proper time (top right) and angular distributions.

2010 [26]. Approximately 400,000 $D^\pm \to K^\mp K^\pm \pi^\pm$ decays have been selected for this analysis. The basic strategy is to divide the $D^+$ and $D^-$ Dalitz plots into bins and for each bin compute the anisotropy variable $S_{CP}^i = \frac{N_+^i - N_-^i}{\sqrt{N_+^i + N_-^i}}$, where $N_+^i$ and $N_-^i$ are the number of $D^+$ and $D^-$ in bin $i$. The DP are normalized to the same number of entries to eliminate global asymmetries. In the absence of local asymmetries, the distribution of the $S_{CP}^i$ is a Gaussian centered at zero and with width $\sigma = 1$. Deviations from this distribution would be the evidence for CP violation. A $\chi^2$ test is also used to evaluate the compatibility with the hypothesis of null local asymmetry, where $\chi^2 = \sum_i (S_{CP}^i)^2$. The number of degrees of freedom is the number of bins minus one, due to the normalisation. The p-value calculated from this gives the probability of observing a $\chi^2$ greater than or equal to that observed under the hypothesis of no CP-violation. Several arrangements of bins are tested, uniform and adaptative, determined from pseudo-experiments in order to optimize the sensitivity to different sources of CP violation. The main advantage
of this method is to draw a map of the regions in the Dalitz plot in which CPV occurs. The method, however, is not capable to quantify the strength of CPV. For that one needs to perform a full Dalitz plot analysis.

The technique relies on careful accounting for local asymmetries that could be induced by sources such as the different production mechanisms for \( D^+ \) and \( D^- \), differences in the K-nucleon inelastic cross-section, differences in the reconstruction or trigger efficiencies, left-right detector asymmetries, etc. The existence of these local asymmetries are investigated using the Cabibbo favoured control channels \( D_s \to K^-K^+\pi^+ \) and \( D^+ \to K^-\pi^+\pi^+ \). The 3-hadron invariant mass distributions for both signal and control channel candidates is shown in Fig. 10. The method is also applied to the events in the side bands shown in Fig. 10 to investigate possible asymmetries that could arise due to the background contamination. All these tests are fully consistent with no asymmetry, thus the method is determined to be very robust against systematic effects. No evidence for CP violation was found in the decay \( D^+ \to K^-K^+\pi^+ \) and p-values ranging from 4% to 99% have been observed for the different binning schemes tested. In particular, for a uniform grid of 530 equally sized bins and an adaptative configuration of 106 bins of sizes optimized to have about the same number of events, the p-values obtained are 10.6% and 65%. The \( S_{CP} \) values across the DP are shown in Fig. 11. The corresponding \( S_{CP} \) distributions are shown in Fig. 12, with a behavior perfectly compatible to normal Gaussians.

This analysis will be performed with the 1 fb\(^{-1} \) dataset collected in 2011, from which up to 10 M \( D \to K^\pm K^\mp \pi^\pm \) are expected to be selected. Moreover, additional singly and doubly Cabibbo suppressed modes will be available which might be sensitive to different NP effects.

6. Conclusions

Thanks to the large \( b \) and \( c \) cross-sections at the LHC and to the excellent performance of the machine and the experiment itself, LHCb could already perform competitive measurements involving rare decays and CP violation. No deviation from the SM was observed, but there is still room for NP observations, since the precision is still dominated by statistical uncertainties. Moreover, the experiment has many other studies on the physics programme, several of them under preparation with the whole data collected in 2011.
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