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Physics and recent results from LHCb

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Abstract. The LHCb experiment has collected more than 1 fb^{-1} of integrated luminosity in 2010 and 2011 and is producing a large amount of results in beauty and charmed meson physics. An overview of the most recent results on rare B decays, CP violation, and charmless B meson decays will be given along with an outlook to the physics perspectives and to the LHCb upgrade.

1 Introduction

The LHCb experiment at the CERN Large Hadron Collider (LHC), has been designed to search for potential effects of physics beyond the Standard Model (SM) in CP violation and rare decays using charm and beauty hadrons. Flavour physics observables have sensitivity to new particles via their indirect effects in loop diagrams and allow to probe a mass scale far beyond that accessible in direct searches. Of particular interest are processes that are strongly suppressed in the SM, such as flavour–changing neutral current $b \to s$ transitions where the expected very small branching ratios can be strongly enhanced by additional amplitudes involving new heavy particles. In a complementary way, any deviation observed comparing precision measurements of Cabibbo-Kobayashi-Maskawa matrix elements obtained from decays which are not sensitive to new physics and from decays where physics beyond the SM can contribute to the decay amplitudes, would be an evidence of new physics effects. LHCb is optimized to exploit the large $b\bar{b}$ production cross section at LHC energies which has been measured to be $(288 \pm 4 \pm 48)$ μb at $\sqrt{s} = 7$ TeV [1]. The large $c\bar{c}$ production cross–section allows also a very rich charm physics program at LHCb. In 2010 and 2011 LHCb collected a total integrated luminosity of 1.1 fb^{-1} allowing the collaboration to provide very important results on some of the key measurement of the experiment's physics program [2]. In these proceedings some of the most important results are reviewed.

2 The LHCb Detector

Due to the strongly forward peaked $b\bar{b}$ production cross–section at the LHC, the LHCb detector is designed as a single-arm forward spectrometer with an angular acceptance of $2 < \eta < 5$ where η is the pseudorapidity. LHCb captures almost 40% of the $b\bar{b}$ production cross–section at the LHC while covering only about 4% of the solid angle. The detector consists of: a silicon micro-strip vertex detector (Vertex Locator) around the interaction region; a tracking system comprising a tracking station equipped with silicon strip detectors (TT) upstream of the about 4 Tm dipole magnet and three tracking stations (T1-T3) downstream of the magnet; two RICH detectors (RICH1 just downstream of the VELO and RICH2, placed downstream of T3); an electromagnetic and a hadronic calorimeter; a muon system made of five stations equipped with multiwire proportional chambers and Gas Electron Multipliers (GEM) detectors. Key performance parameters are an excellent vertex resolution resulting in a proper time resolution of about 50 fs; a momentum resolution for charged particles better than 0.6%

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up to above 100 GeV/c; good kaon/pion separation in the momentum range 2 GeV/c up to 100 GeV/c; muon identification efficiency of 97% with a misidentification rate of 0.7%. A key element of the experiment is the trigger system which features two levels to reduce the 40 MHz input rate to the 3–4 kHz output rate to the storage system. The first level, called L0 (Level 0), is implemented in custom electronic boards working in a fully synchronous architecture with a fixed latency of 4 μs and a maximal output rate of 1 MHz. The L0 trigger selects high transverse momentum muons, photons, electrons and charged hadrons. The second level, called HLT (High Level Trigger), is a fully software trigger running on a dedicated farm of about 2000 CPUs. The HLT first reduces the rate to about 30 kHz using the tracking information to confirm the L0 candidates, adding, if required, an impact parameter (IP) cut. Then, inclusive and exclusive selections are applied using the full event reconstruction. In 2010 and 2011 LHCb has collected 1.1 fb^{-1} with an efficiency exceeding 90%. In 2011 a luminosity leveling procedure allowed the experiment to run at constant luminosity throughout the fill. The luminosity was gradually increased up to 4×10^{32} cm^{-2}s^{-1} which is twice the design LHCb luminosity and is the value chosen for the 2012 run.

3 Search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

The decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ are very rare flavour–changing neutral current processes whose branching ratios, within the SM, are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.1 \pm 0.01) \times 10^{-9}$ respectively [3, 4]. The branching ratios can be strongly enhanced in many models beyond the SM. For example, in the framework of the Minimal Supersymmetric Standard Model (MSSM) the branching ratio is proportional to $(\tan\beta)^6$ [5], so that it can be larger than the SM value by more than one order of magnitude. LHCb has already published an upper limit based on 0.37 fb^{-1} [6]. The results discussed here are an update with based on 1.0 fb^{-1} of pp collisions. While $B_s^0 \to \mu^+\mu^-$ or $B^0 \to \mu^+\mu^-$ signal is relatively easy to trigger and reconstruct, the background rejection requires a quite complex analysis. After simple selection of opposite charge muon pairs with a common vertex, the analysis relies on two variables: the invariant mass of the selected muon pairs $M_{\mu\mu}$ and a discriminant built on the output of a Boosted Decision Tree (BDT) [7], based on kinematical and topological variables. The events are categorized in a bidimensional distribution in $M_{\mu\mu}$ and BDT. The mass distributions are calibrated directly with data, taking the central values from $B_s^0 \to K^+K^-$ and $B^0 \to K^+\pi^-$ samples respectively, while the mass resolutions are obtained with a power-law interpolation between the measured resolutions of charmonium and bottomonium resonances decaying into two muons. The results of the interpolation are $\sigma(m_{B_s^0}) = (24.8 \pm 0.8)$ MeV/c^2 and $\sigma(m_{B^0}) = (24.3 \pm 0.7)$ MeV/c^2 cross checked also with $B_{(s)}^0 \to h^+h'^-$ control channels. The BDT is trained with simulated events but the probability to have a given BDT output is calibrated on data using

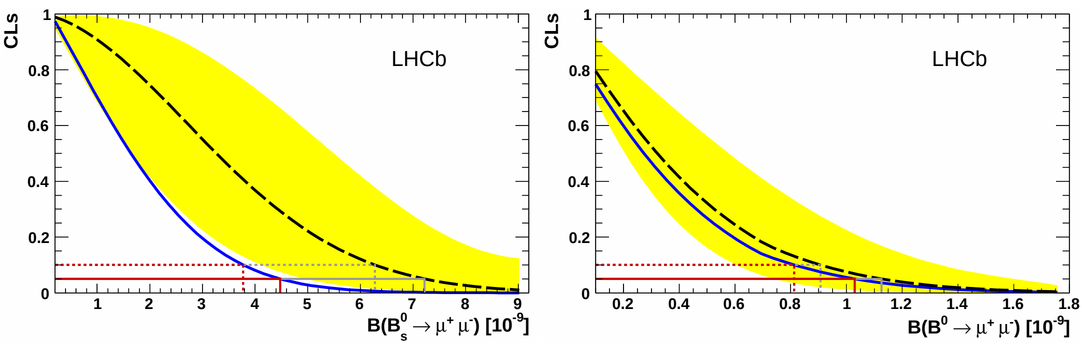

Fig. 1. CLs as a function of $\mathcal{B}$ for (left) B_s^0 and (right) B^0 decays in $\mu^+\mu^-$. The long–dashed lines are the expected CLs distributions (background + SM signal for B_s^0 and background only for B^0) while the yellow areas represent the expected $\pm 1\sigma$ variation. The solid lines are the observed CLs. The dotted (solid) horizontal lines show the upper limits at 90% (95%) C.L.

$B^0_{(s)} \to h^+h'^-$ events selected without particle identification requirements and candidates in $B_{(s)}$ mass sidebands for signal and background respectively. The branching fractions are measured relative to three different normalization decays: $B^+ \to J/\psi K^+$, $B^0_s \to J/\psi\phi$ and $B^0 \to K^+\pi^-$ (including the charge conjugated processes), giving consistent normalization factors which are averaged to a single event sensitivity of $(0.319 \pm 0.028) \times 10^{-9}$. The ratio of production fractions used in the normalization is measured directly by LHCb: $f_s/f_d = 0.27^{+0.21}_{-0.20}$ [8]. The number of candidates and expected signal and background events is extracted from the bidimensional distribution of $M_{\mu\mu}$ and BDT and the compatibility of the observed distribution of events with that expected for a given branching fraction hypothesis is computed using the CLs method [9]. The results obtained are shown in Figure 1. From these curves, the upper limits on the branching ratios for the two decays can be derived: $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.3 \times 10^{-9}$ at 95% CL, which are the most stringent upper limits to date. The $B^0_s \to \mu^+\mu^-$ branching ratio has also been directly measured: $\mathcal{B}(B^0_s \to \mu^+\mu^-) = 0.8^{+1.8}_{-1.3} \times 10^{-9}$.

4 Measurement of the CP-violating phase ϕ_s in B^0_s decays

In B^0_s decays, CP violation can arise from the interference between B^0_s mixing and decay to the same final state, like for example in the decays $B^0_s \to J/\psi\phi$ or $B^0_s \to J/\psi f_0$ [10]. In these decays the time dependent CP violation asymmetry can be expressed in terms of $\Delta\Gamma_s$, the decay width difference between the B^0_s mass eigenstates, and a single phase ϕ_s [11]. In the SM, ϕ_s is predicted, with good precision, to be small: $\phi_s^{SM} = (0.036 \pm 0.002)$ rad [12]. This quantity, therefore is very sensitive to contributions from physics beyond the SM that could lead to much larger values [13]. LHCb has published results with the 2010 data [14]; in these proceedings recent measurements of ϕ_s by LHCb in the decay modes $B^0_s \to J/\psi\phi$ and $B^0_s \to J/\psi\pi^+\pi^-$ with a data sample corresponding to 1.0 fb^{-1} are presented. Since the $J/\psi\phi$ final state is not a pure CP eigenstate, a full angular analysis is needed to extract ϕ_s from $B^0_s \to J/\psi\phi$. On the contrary, the final state for $B^0_s \to J/\psi\pi^+\pi^-$ is almost purely CP odd and no angular analysis needed. In the measurement of all the time dependent amplitudes, the value of Δm_s is taken from LHCb measurements based on 2010 and 2011 data: $\Delta m_s = (17.63 \pm 0.11 \pm 0.02)$ ps^{-1} [15] and $\Delta m_s = (17.725 \pm 0.041 \pm 0.026)$ ps^{-1} [16]. The remaining nine parameters: $\Gamma_s, \Delta\Gamma_s, \phi_s$, three amplitude ratios and three strong phase differences, are extracted from fits to the experimental distributions, including a K^+K^- S–wave component. The effective tagging power is found to be $\varepsilon_{tag}D^2 = (2.43 \pm 0.08 \pm 0.26)\%$ and the time resolution measured from the $B^0_s \to J/\psi\phi$ decay time distribution is 45 fs. From the analysis of $B^0_s \to J/\psi\phi$ decays, the measured values of ϕ_s, Γ_s and $\Delta\Gamma_s$ are: $\phi_s = (-0.001 \pm 0.101 \pm 0.027)$ rad, $\Gamma_s = (0.6580 \pm 0.0054 \pm 0.0066)$ ps^{-1}, $\Delta\Gamma_s = (0.116 \pm 0.018 \pm 0.006)$ ps^{-1}. The last result is the first observation at more than 5σ level of $\Delta\Gamma_s \neq 0$. With a simultaneous fit

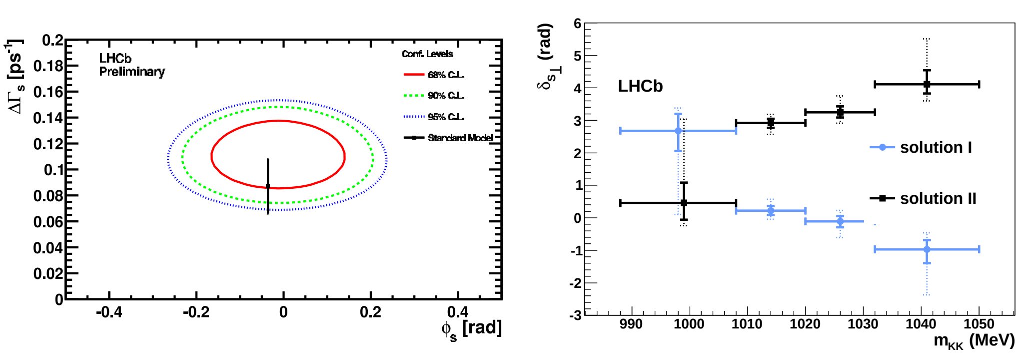

Fig. 2. Left: measured $\Delta\Gamma_s$ versus ϕ_s 68%, 90% and 95% C.L. contours. The ful square with error bars represent the SM prediction. Right: measured phase differences between S–wave and perpendicular P–wave amplitudes in four intervals of m_{KK} for solution I (full circles) and solution II (full squares).

with the channel $B_s^0 \to J/\psi\pi^+\pi^-$, LHCb obtains $\phi_s = (-0.002 \pm 0.083 \pm 0.027)$ rad which is the most precise measurement of ϕ_s to date. Details of this analysis can be found in [17]. These preliminary results are summarized in Figure 2 (left plot). Since the time dependent differential decay rates are invariant under the transformation $(\phi_s, \Delta\Gamma_s) \to (\pi - \phi_s, -\Delta\Gamma_s)$ the above analysis (Solution I, $\Delta\Gamma_s > 0$) allows for a complementary solution with $\Delta\Gamma_s < 0$ (Solution II). From an analysis of the decays $B_s^0 \to J/\psi K^+K^-$, LHCb has determined the sign of $\Delta\Gamma_s$ by measuring the phase difference between the S–wave amplitude and the perpendicular P–wave amplitude $\delta_\perp$ which is expected to decrease as a function of the invariant mass of the K^+K^- system m_{KK}. From this measurement it was found that $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H > 0$ at 4.7σ level [18]. The result is shown in Figure 2 (right plot).

5 Charmless b decays

Decays of B mesons into charmless final states are very interesting from the flavour physics point of view. In particular, they can provide important measurements of direct as well as indirect CP violation and, assuming U-spin symmetry, they provide a way to measure the angle γ. At LHCb they are selected by the hadronic trigger and by exploiting the excellent $\pi/K/p$ identification power of the experiment's RICH system. Some of these decays have very small branching ratios like the decay $B_s^0 \to \pi^+\pi^-$ observed for the first time by LHCb with a branching fraction of $\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (0.98^{+0.23}_{-0.19} \pm 0.11) \times 10^{-6}$ [19]. Direct CP violation effects can be studied in a straightforward way by looking for asymmetries between flavour specific $B_{(s)} \to K\pi$ decays and their charge conjugated. Direct CP violation is clearly visible, as shown in Figure 3. The measured asymmetries are $A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011 \pm 0.008$ and $A_{CP}(B_s^0 \to K\pi) = +0.27 \pm 0.08 \pm 0.02$. The first measurement is the first observation of direct CP violation in B decays at a hadron collider and the most precise measurement to date while the second constitutes the first evidence of direct CP violation in B_s^0 decays [20].

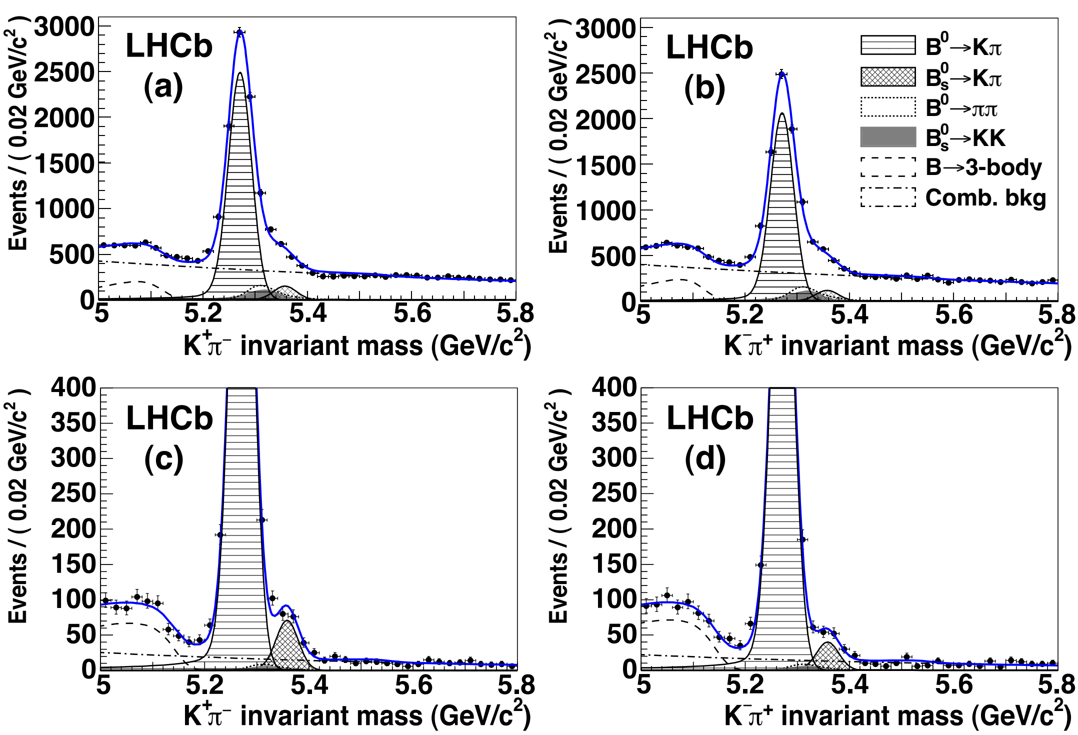

Fig. 3. Invariant mass distributions of the selected $\overset{(-)}{B}{}^0_{(s)} \to K^\pm\pi^\mp$ decays. The asymmetry between charge conjugated modes is clearly visible.

By studying the decays $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$, the results shown above can be extended to the measurement of time dependent CP asymmetries defined as:

$$A_{CP}(t) = \frac{A_f^{dir}\cos(\Delta mt) + A_f^{mix}\sin(\Delta mt)}{\cosh(\frac{\Delta\Gamma}{2}t) - A_f^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma}{2}t)}, \quad (1)$$

where f is the K^+K^- or $\pi^+\pi^-$ final state. These measurements allow to extract gamma in loop processes, a key test of the SM consistency. The analysis can provide also a test of U-spin symmetry ($d \leftrightarrow s$) since, in the case of negligible annihilation contributions for $K\pi$ modes we have: $A_{CP}(B^0 \to K\pi) \approx A_{KK}^{dir}$ and $A_{CP}(B_s^0 \to K\pi) \approx A_{\pi\pi}^{dir}$ [21]. The measurement of time dependent asymmetries requires the flavour tagging of the neutral B mesons, whose performance is studied directly on data using the flavour specific $K\pi$ final states described above. From these measurements LHCb has obtained the following values for $A_{\pi\pi}^{dir}$, $A_{\pi\pi}^{mix}$ (first measurements at a hadron collider), A_{KK}^{dir} and A_{KK}^{mix} (first measurements): $A_{\pi\pi}^{dir} = 0.11 \pm 0.2 \pm 0.03$, $A_{\pi\pi}^{mix} = -0.56 \pm 0.17 \pm 0.03$, $A_{KK}^{dir} = 0.02 \pm 0.18 \pm 0.04$ and $A_{KK}^{mix} = 0.17 \pm 0.18 \pm 0.05$.

6 The LHCb upgrade

The excellent results reviewed in the previous sections along with many others not included in these proceedings demonstrate that LHCb is able to cover a vast program of flavour physics both with beauty and charmed hadrons. However, even if LHCb is presently running at twice the design luminosity, there are many important channels sensitive to physics beyond the SM where the current experimental sensitivity can not reach the theoretical uncertainties. To bring the statistical and systematic errors at the level or below the theoretical errors for these decay channels, the LHCb collaboration is designing an upgraded detector that should increase the annual yield by a factor 10 for leptonic channels and by a factor 20 for hadronic ones and should collect 50 fb^{-1} at a constant luminosity of about 10^{33} $\text{cm}^{-2}\text{s}^{-1}$ with 25 ns bunch spacing. The sub–systems under study should sustain a peak luminosity of 2×10^{33} $\text{cm}^{-2}\text{s}^{-1}$. The key element of the upgrade is a fully software trigger (the so called Event Filter Farm) able to process data at an input rate of 40 MHz. The upgraded LHCb should start taking data in 2018 after the second long shutdown of the LHC. Details of the project can be found in the Letter of Intent of the LHCb upgrade [22].

7 Conclusion

Some of the most important LHCb results obtained with a data sample corresponding to about 1 fb^{-1} of pp collisions have been briefly reviewed. These results are a sample of a large amount of measurements provided by LHCb covering a vast program in flavour physics. In 2012 LHCb is taking data at an instantaneous luminosity which is twice the design value and is expected to provide a large number of results in beauty and charm physics in the near future. An upgraded detector is currently under design to fully exploit the experiment's discovery potential in very rare meson decays.

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