B decays, CKM, spectroscopy and charm at LHCb

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1 Introduction

Precise measurements of CP violation and searches for rare decays have a high potential for discovering effects of New Physics. They are a specific task of the LHCb experiment and are complementary to direct searches performed by general purpose LHC experiments (ATLAS and CMS). In this review only part of the broad physics program of LHCb can be covered, additional information can be found in other contributions to this Conference [1].

LHCb is a single arm forward detector at the LHC which covers the region of pseudo-rapidity $2 < \eta < 5$ where the production of $b\overline{b}$ and $c\overline{c}$ pairs from pp collisions at $\sqrt{s} = 7$ TeV is copious. A full description of the LHCb detector and main performance can be found in [2, 3].

During the run of LHC at $\sqrt{s} = 7$ TeV in 2010 LHCb collected about 36 pb^{-1} of data, while an integrated luminosity of about 1 fb^{-1} is expected by the end of 2011. The preliminary results of the analysis of the 2010 data are presented in the following.

2 Heavy flavour production and spectroscopy

The inclusive production of beauty and charm hadrons in pp collisions has been measured by LHCb. In particular using semi-leptonic decays $b \to D^0(K\pi)\mu\overline{\nu}_\mu X$ the cross section $\sigma(pp \to bbX) = 284 \pm 20 \pm 49\ \mu b$ is obtained [4], extrapolating to the full phase space.

All species of beauty hadrons can be produced in pp collisions, including B_c^+. This is a particularly interesting state, being composed of a heavy quark and a heavy antiquark of different flavours: $\overline{b}$ and c. LHCb has observed a signal of $\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+$ events and has measured the ratio of $\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+$ to $\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}$ decay yields, in the fiducial region $p_\mathrm{T} > 4\,\mathrm{GeV}/c$ and $2.5 < \eta < 4.5$, to be equal to

$$R_{c+} = \frac{\sigma\left(B_c^+\right) \times \mathcal{B}\left(\mathrm{B_c^+} \to \mathrm{J}/\psi\pi^+\right)}{\sigma\left(B^+\right) \times \mathcal{B}\left(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}\right)} = (2.2 \pm 0.8 \pm 0.2)\% \tag{1}$$

where the first uncertainty is statistical and the second systematic [5]. This is the first step of a promising rich program of studies of B_c^+ properties at LHCb.

The production rates of different b hadrons are measured by the fragmentation functions f_u, f_d, f_s, f_Λ, which describe the probability that a b quark will hadronize into a $\mathrm{B_q}$ meson (where q=u, d, s) or a Λ_b baryon, respectively. Knowledge on these quantities is needed for example for the determination of exclusive branching fractions of $\mathrm{B_s^0}$, like the rare $\mathrm{B_s^0} \rightarrow \mu^+\mu^-$. Two measurements have been performed at LHCb using hadronic and semi-leptonic b decays, respectively [6]. In the first one the relative yields of the $\mathrm{B_s^0} \rightarrow \mathrm{D_s^-}\pi^+$ to $\mathrm{B^0} \rightarrow \mathrm{D^-}\pi^+$ or $\mathrm{B^0} \rightarrow \mathrm{D^-K^+}$ decays are used to obtain: $f_s/f_d = 0.245 \pm 0.017 \pm 0.018 \pm 0.018$, where the first uncertainty is statistical, the second systematic and the third is a theoretical uncertainty dominated by the uncertainty on the form factor ratio. The fragmentation function measurements performed with $b \rightarrow (D^0, D^+, D_s, \Lambda_b)\mu\overline{\nu}_\mu X$ events give results compatible with the hadronic one. A p_T dependence is observed in the case of the Λ_b fragmentation fraction, with higher values at small p_T.

3 Search for New Physics in CPV and CKM precision measurements

In the Standard Model (SM) the mixing of quarks is described by the CKM matrix which also accounts for CP violation through an irreducible complex phase. Accurate measurements exist for most of the matrix parameters [7], however experimental uncertainties are still large in same cases as for the angle $\gamma = \arg\left(-V_{\mathrm{ud}}V_{\mathrm{ub}}^*/V_{\mathrm{cd}}V_{\mathrm{cb}}^*\right)$ and for quantities related to the $\mathrm{B_s^0}$ mixing.

For a self-conjugate final state ($f = \overline{f}$), a CP violating phase arises from the interference between $\mathrm{B_s^0}$ decay to f either directly or via $\mathrm{B_s^0}$–$\overline{\mathrm{B}}{}_\mathrm{s}^0$ oscillation, producing a difference in the decay time distributions of $\mathrm{B_s^0}$ mesons and $\overline{\mathrm{B}}{}_\mathrm{s}^0$ mesons. The $\mathrm{B_s^0} \rightarrow \mathrm{J}/\psi(\mu\mu)\phi(\mathrm{KK})$ decay is considered the golden mode for measuring this type of CP violation. Within the SM this decay is dominated by $\overline{\mathrm{b}} \rightarrow \overline{\mathrm{c}}\mathrm{c}\overline{\mathrm{s}}$ quark level transitions. Neglecting QCD penguin contribution the phase is: $\phi_\mathrm{s}^\mathrm{SM} = -2\beta_\mathrm{s}$, where $\beta_\mathrm{s} = \arg\left(-V_{\mathrm{ts}}V_{\mathrm{tb}}^*/V_{\mathrm{cs}}V_{\mathrm{cb}}^*\right)$. Global fits to experimental data give a small and precise value $2\beta_\mathrm{s} = (-0.0363 \pm 0.0017)$ rad [8]. New particles could contribute to the mixing box diagram modifying the SM prediction, adding a new phase. Recent results from experiment at Tevatron give hints of deviations of ϕ_s from the SM predicted value [9], with an uncertainty on ϕ_s of about 0.5 rad.

The precise determination of ϕ_s is one of the key goals of the LHCb experiment. This measurement has been carefully prepared with a series of intermediate studies performed on 2010 data which prove the capability of LHCb to perform a clean signal selection for $\mathrm{B} \rightarrow \mathrm{J}/\psi\mathrm{X}$ channels, to control the decay time and the angular acceptance and resolutions and to have a correct determination of the flavour of the B mesons at production. Events of several $B \rightarrow J/\psi X$ decay modes have been selected is a similar way with a decay time unbiased di-muon trigger. Low background remains after the additional requirements on the decay time $t > 0.3$ ps, which removes mainly events with a prompt J/ψ. As an example the invariant mass distribution of the selected $B_s^0 \rightarrow J/\psi\phi$ events is shown in Fig. 1, the mass resolution is about 8 MeV/c^2. An average decay time resolution of about 50 ps is determined on data, using prompt J/ψ events.

The $B_s^0 \rightarrow J/\psi\phi$ decay proceeds via a vector-vector intermediate state with contributions from both CP-even and CP-odd amplitudes. In order to achieve good sensitivity to the two components the distribution of the final state decay angles in the transversity basis is analysed. The decay angular acceptance is determined using simulated events, it varies by less than 5% over the full range for all three angles. First an un-tagged analysis is performed, which does not separate the flavour of the initial mesons (flavour tagging), in this case CP violation is ignored. Results of the likelihood fit to the mass, proper-time and angular distributions are shown in Table 1.

Table 1: Parameters extracted from the fit to the $B_s^0 \rightarrow J/\psi\phi$ events in the untagged analysis. The first uncertainty is statistical and the second is systematic. LHCb preliminary results from 36 pb^{-1}.

Parameter	Result
Γ_s [ps^{-1}]	$0.680 \pm 0.034 \pm 0.027$
$\Delta\Gamma_s$ [ps^{-1}]	$0.084 \pm 0.112 \pm 0.021$
$\lvert A_\perp \rvert^2$	$0.279 \pm 0.057 \pm 0.014$
$\lvert A_0 \rvert^2$	$0.532 \pm 0.040 \pm 0.028$
$\cos\delta_\parallel$	$-1.24 \pm 0.27 \pm 0.09$

The flavour of the B meson at production is determined by algorithms exploiting several properties of each event. The algorithms have been optimized on data for the maximum tagging power $\epsilon(1-2\omega)^2$, where ϵ is the tagging efficiency and ω is the mistag. The tagging power is enhanced by using in the fits a per-event mistag probability, which is calibrated on data, using $B^+ \rightarrow J/\psi K^+$ events, and validated on $B^0 \rightarrow J/\psi K^{*0}$ [10]. The tagging power for $B_s^0 \rightarrow J/\psi\phi$ events is found to be $\epsilon(1-2\omega)^2 = 2.2 \pm 0.5$ %, where the uncertainty is dominated by the statistical fluctuations in the control channel.

For the tagged analysis events selected by a displaced track trigger have been also used, for a total sample of 757±28 signal events ($t > 0.3$ ps) [11]. The result of the fit is presented as two-dimensional confidence level regions in the $\Delta\Gamma_s$ -ϕ_s plane obtained using a likelihood ratio ordering, following the prescription of Feldman and Cousins [12]. Fig. 1 shows the 68.3%, 90% and 95% confidence level contours in the

$\Delta\Gamma_s$ -ϕ_s plane. With current event yields systematic uncertainties were found to have only a small effect on the contours. When projecting the confidence level contours onto one dimension it results $-2.7 < \phi_s < 0.5$ rad at 68% CL. Substantial improvements are expected in the determination of ϕ_s with the larger 2011 data sample and the use of additional tagging algorithms.

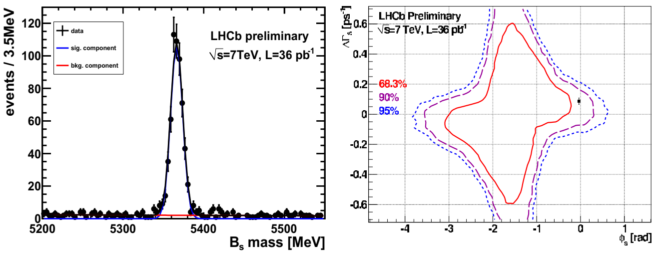

Figure 1: Left: invariant mass distribution of selected $B_s^0 \to J/\psi\phi$ events. Right: Feldman and Cousins regions in the $\Delta\Gamma_s$ -ϕ_s plane. The CL at the SM point (black square) is 0.785 which corresponds to a deviation of 1.2 σ.

LHCb has also performed the first observation of $B_s^0 \to J/\psi f_0$ events, measuring the ratio:

$$\frac{\Gamma\left(B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-\right)}{\Gamma\left(B_s^0 \to J/\psi\phi, \phi \to K^+K^-\right)} = 0.252^{+0.046+0.027}_{-0.032-0.033} \tag{2}$$

This decay mode will allow another measurement of ϕ_s to be performed with 2011 data. In this case there is no need for an angular analysis, as the final state has a defined CP.

For the measurement of the B_s^0 oscillation frequency a total of 1350 B_s^0 candidates are reconstructed in $B_s^0 \to D_s^-\pi^+$ ($D_s^- \to \phi\pi^-, K^{0*}\pi^-, K^+K^-\pi^-$) and $B_s^0 \to D_s^-(\phi\pi^-)\pi^+\pi^-\pi^+$ decay modes [13]. The four modes are analysed individually but a single set of physical parameters, namely B_s^0 mass, lifetime and mixing frequency, is determined in a common fit to mass and decay time distributions of all modes. Good decay time resolution is crucial for resolving fast B_s^0 oscillations. In this analysis the event-per-event resolution σ_t is used, it is calibrated on data using B_s^0 candidates formed by a prompt D_s^- and a pion, obtaining an average decay time resolutions of 44 and 36 fs, for $B_s^0 \to D_s^-\pi^+$ and $B_s^0 \to D_s^-(\phi\pi^-)\pi^+\pi^-\pi^+$ decays, respectively. The mixing frequency is measured as $\Delta m_s = 17.63 \pm 0.11 \pm 0.04$ ps $^{-1}$ with a 4.2 σ significance. Fig. 2 shows the likelihood profile as a function of Δm_s and the mixing asymmetry for signal candidates as a function of decay time.

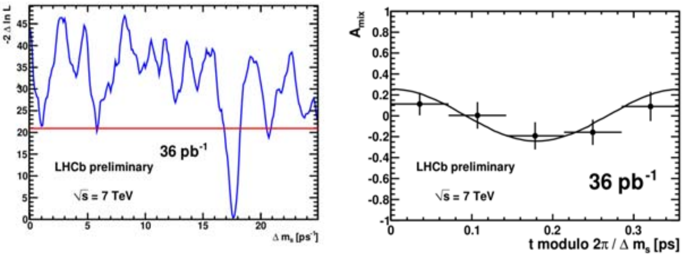

Figure 2: Left: likelihood scan for $\Delta m_{\rm s}$ the line indicates the likelihood value evaluated in the limit of infinite mixing frequency. Right: mixing asymmetry for signal $\mathrm{B_s^0}$ candidates as a function of decay time modulo $2\pi/\Delta m_{\rm s}$.

Several different approaches will be pursued at LHCb to measure γ exploiting the interference between $b \to u$ and $b \to c$ transitions.

A clean determination from tree level processes can be performed with $\mathrm{B} \to \mathrm{DK}$ decays, using final states accessible to both $\mathrm{D^0}$ and $\overline{\mathrm{D}}^0$. As a first step, clean samples of $\mathrm{B^+} \to \mathrm{D^0K^-}$ and $\mathrm{B^+} \to \mathrm{D^0}\pi^-$ events have been selected with yields comparable to those collected by CDF in 1 $\mathrm{fb^{-1}}$. LHCb has studied also decay modes with three charged hadrons $\mathrm{B} \to \mathrm{D3h}$ which give additional opportunities for the measurement of γ [14].

Two-body charmless B decays offer a rich phenomenology to explore the phase structure of the CKM matrix and to search for manifestations of New Physics beyond the SM. These decays can proceed through penguins diagrams, which in some cases are the dominant ones. Direct CP asymmetries in $\mathrm{B_q} \to \mathrm{K}\pi$ decays and the $\mathrm{B_s^0} \to \mathrm{K^+K^-}$ lifetime have been measured with the first LHCb data. A variety of other measurements are foreseen with forthcoming larger data sample, including the measurement of the γ angle. The excellent performance of LHCb in separating the different hadronic final states with particle identification in the RICH detector and the good mass resolution are crucial in these studies. In Fig. 3 the invariant mass distribution of $\mathrm{B^0} \to \mathrm{K^+}\pi^-$ and $\mathrm{B_s^0} \to \pi^+\mathrm{K^-}$ events are shown [15].

The measured raw CP asymmetries are corrected for possible detector asymmetry effects and production asymmetries to give:

$$A_{CP}(\mathrm{B^0} \to \mathrm{K^+}\pi^-) = -0.074 \pm 0.033 \pm 0.008, \tag{3}$$

$$A_{CP}(\mathrm{B_s^0} \to \pi^+\mathrm{K^-}) = 0.15 \pm 0.19 \pm 0.02 \tag{4}$$

The results are in agreement with the current HFAG value [16] and with the previous CDF measurement [17] of these quantities, respectively.

The decay time distribution of the untagged $B_s^0 \to K^+K^-$decay is given by

$$\hat{\Gamma}(B_s^0 \to K^+K^-) \equiv R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t}, \tag{5}$$

where R_H and R_L are the fractions of the heavy (Γ_H) and light (Γ_L) states contributing to the $B_s^0 \to K^+K^-$decay. It is primarily sensitive to the width of the short-lived light state of the B_s^0. The selection procedure of the sample of B mesons decaying into two hadrons makes minimum requirements on the flight distance of the B meson, as a consequence it tends to reject candidates which decay after a short decay time. Two independent data-driven approaches have been developed to compensate for the resulting bias. The results of the two measurements are in good agreement and are combined obtaining for the lifetime: $\tau_{B_s} = 1.440 \pm 0.096 \pm 0.010$ ps where the first uncertainty is statistical and the second is systematic [18]. It represents the world best precision on this quantity.

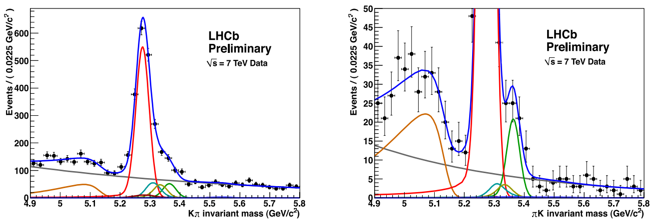

Figure 3: Invariant mass distribution of $B^0 \to K^+\pi^-$ (left) and $B_s^0 \to \pi^+K^-$ (right).

4 CPV in charm

Mixing of neutral charm mesons hmv as been recently established but no evidence of CP violation has been found so far [7]. The LHCb experiment is especially well suited for time dependent measurements which allow mixing and indirect CP asymmetry determinations, as presented in [1]. Flavour tagging of D^0 decays is obtained from the decay chain $D^{*+} \to D^0\pi^+$. Prompt charm production is used, to exploit the higher yield. The contribution from secondary charm produced in B decays is separated in a fit to the distribution of the D^0 impact parameter with respect to the primary vertex.

First time-integrated direct CP asymmetry measurements have also been performed with 2010 data. The asymmetries are determined in the two decay modes $D^0 \to K^+K^-$and $D^0 \to \pi^+\pi^-$and the difference is taken in order to subtract the contribution of any production asymmetry. Effects of detection asymmetries cancel in the decays to self-conjugate final states. The final result is [19]:

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.28 \pm 0.70 \pm 0.25)\% \qquad (6)$$

A statistical sensitivity of about 0.1 % is expected with 1 fb^{-1}.

5 Search for New Physics in rare decays

The branching fractions of the rare decays $\mathrm{B}^0_{\mathrm{s,d}} \to \mu^+\mu^-$ are precisely predicted in the SM as: $\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-)^{SM} = (0.32 \pm 0.02) \times 10^{-8}$ and $\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-)^{SM} = (0.010 \pm 0.001) \times 10^{-8}$, respectively. New Physics models, especially those with an extended Higgs sector, can significantly enhance these branching fractions. The best limits at 95 % C.L. published so far have been achieved at the Tevatron and are more than ten times above the SM.

After a loose cut-based pre-selection 343 (342) events are selected in the $\mathrm{B}^0_\mathrm{s}(\mathrm{B}^0)$ ± 60 MeV/c^2 signal mass windows, with less than 1 (0.1) events expected, assuming the SM branching fraction. The additional signal from background separation is achieved by means of a geometrical likelihood (GL) which combines several topological variables describing the decay and is calibrated on data, using inclusive $B \to h^+h^{'-}$ events. The final analysis is performed in two-dimensional bins of the di-muon invariant mass and the GL. Three control channels are used for normalizing the event yields and calculate the branching fractions, namely $\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+$, $\mathrm{B}^0_\mathrm{s} \to \mathrm{J}/\psi\phi$ and $\mathrm{B}^0 \to \mathrm{K}^+\pi^-$, they all give consistent results. No significant deviation from the background-only hypothesis is found and the upper limits result [20]:

$$\mathcal{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) < 4.3(5.6) \times 10^{-8} \qquad (7)$$

$$\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 1.2(1.5) \times 10^{-8} \qquad (8)$$

at 90% (95%) C.L. In the B^0_s case the observed limits are similar to the best published one, in the B^0 case they are more restrictive.

Good prospects for upcoming measurements in the $\mathrm{B}^0 \to \mu^+\mu^-\mathrm{K}^{*0}$ channels and in radiative B decays have been presented in [1].

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