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CP violation in the B and D systems at LHCb

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The large samples of mesons containing a b or a c quark colleted by the LHCb experiment in 2011 and 2012, corresponding to an integrated luminosity of $3 fb^{-1}$, provide an unprecedent framework to perform high precision measurements of CP violation. A comparison of measurements of CP violating observables with the Standard Model predictions can reveal contributions from physics beyond the Standard Model. Studies of B and D meson decays at LHCb are presented in this document.

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1. Introduction

Measurements of CP violation and branching ratios of rare decays of B and D mesons probe the flavour structure of the Standard Model (SM). These measurements can be significantly enhanced if new heavy particles from physics beyond the SM play a significant role in these decays. Precision measurements of CP violating observables in these decays can thus provide evidence for, or put limits on, contributions from physics beyond the SM. Studies of B and D meson decays at LHCb are shown in this document.

2. CP violation in the B system

Measurements of CP violating observables in B decays are shown in this section for final states containing 2, 3 and 4 particles.

2.1 Two-body decays: CP violation in $B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays

The most straightforward effect of CP violation is the direct CP violation in the decay. This is the case of $B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays. Direct CP asymmetries arise when at least two amplitudes with different strong and weak phases contribute to the decay. Strong (weak) phases are phases that do not change (do change) sign under a CP transformation.

$B_s^0 \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays proceed through tree and penguin amplitudes, and the interference between them gives rise to a direct CP asymmetry sensitive to the CKM angle γ. The direct CP asymmetry A_{CP} is defined as

$$A_{CP}(B_s^0 \to K^-\pi^+) = \frac{\Gamma(\bar{B}_s^0 \to K^+\pi^-) - \Gamma(B_s^0 \to K^-\pi^+)}{\Gamma(\bar{B}_s^0 \to K^+\pi^-) + \Gamma(B_s^0 \to K^-\pi^+)}, \tag{2.1}$$

similarly for $B^0 \to K^+\pi^-$ decays. LHCb has reported the first observation of CP violation in B_s^0 decays using $1 fb^{-1}$ of data collected in 2011, with the result $A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\ (stat) \pm 0.01\ (syst)$, with significance exceeding 5 standard deviations.. The most precise mesurement of $A_{CP}(B^0 \to K^+\pi^-)$ was also performed, finding $A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\ (stat) \pm 0.003\ (syst)$ [2]. The results of the fit to the two-body invariant mass of these decays is shown in figure 1.

These measurements can be combined to provide a consistency check of the SM. The observable

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathscr{B}(B_s^0 \to K^-\pi^+)}{\mathscr{B}(B^0 \to K^+\pi^-)} \frac{\tau_d}{\tau_s} \tag{2.2}$$

is expected to vanish in the SM. Here, $\mathscr{B}$ represents the branching ratio, and τ_d (τ_s) is the lifetime of the B^0 (B_s^0) meson. With the LHCb results above, and the B^0 and B_s^0 lifetimes taken from [3] , $\Delta = -0.02 \pm 0.05\ (stat) \pm 0.04\ (syst)$ is found to be compatible with the SM.

2.2 Three-body decays: CP violation in $B^\pm \to h^+h^-h'^\pm$ decays

The effect of a CP asymmetry as a consequence of at least two interfering amplitudes with different strong and weak phases shows up in a clear way in $B^\pm \to h^+h^-h'^\pm$ decays, where h and

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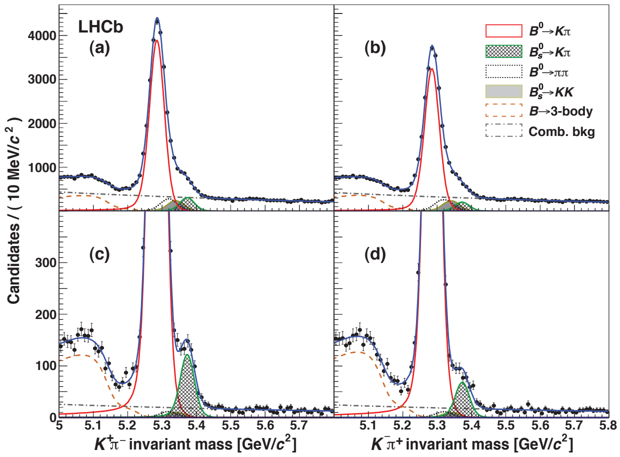

Figure 1: Invariant mass spectra of $K^+\pi^-$, (a) and (c), and $K^-\pi^+$, (b) and (d) pairs. Top and bottom plots correspond to two different event selections optimized for the best sensitivity on $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to K^-\pi^+)$. The results of an unbinned maximum likelihood fits to a mass model and its main components are overlaid.

h' represent either a pion or a kaon. There are theoretical interpretation for phase space $B^\pm \to h^+h^-h'^\pm$ decays. Final state interaction ocurring between two or more decay channels with the same flavour quantum numbers is a possible explanation. A Dalitz analysis of $B^\pm$ to three-body decays can help to understand the interplay between the weak and strong interaction.

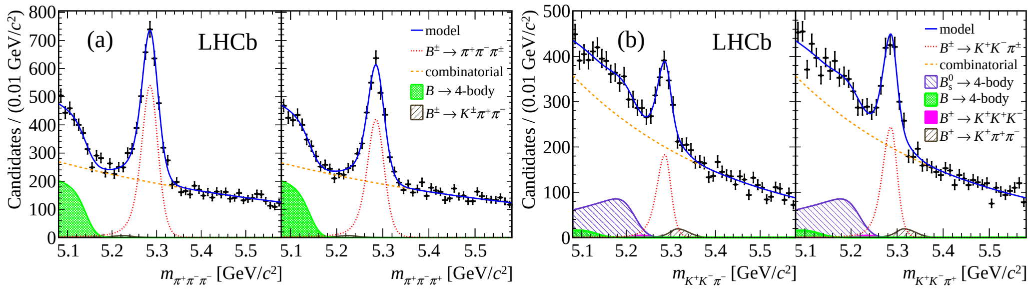

Figure 2: Invariant mass spectra of (a) $B^\pm \to \pi^+\pi^-\pi^\pm$ decays and (b) $B^\pm \to K^+K^-\pi^\pm$ decays. The left panel in each figure shows the B^- modes and the right panel shows the B^+ modes. The results of the unbinned maximum likelihood fits are overlaid. The main components of the fits are also shown.

Four different decay modes, and their respective CP conjugated modes, were analyzed by the LHCb experiment using $1 fb^{-1}$ of 2011 data: $B^\pm \to \pi^+\pi^-\pi^\pm$, $B^\pm \to K^+K^-\pi^\pm$ [4], $B^\pm \to \pi^+\pi^-K^\pm$ and $B^\pm \to K^+K^-K^\pm$ [5]. Three-body invariant mass distributions for $B^\pm \to \pi^+\pi^-\pi^\pm$ and $B^\pm \to K^+K^-\pi^\pm$ are shown in figure 2. The results for the inclusive CP asymmetries are:

$$\begin{aligned}
A_{CP}(B^+ \to K^+K^-\pi^+) &= -0.141 \pm 0.040\,(stat) \pm 0.018\,(syst) \pm 0.007\,(J/\psi K^+),\\
A_{CP}(B^+ \to \pi^+\pi^-\pi^+) &= 0.117 \pm 0.021\,(stat) \pm 0.009\,(syst) \pm 0.007\,(J/\psi K^+),\\
A_{CP}(B^+ \to \pi^+\pi^-K^+) &= 0.032 \pm 0.008\,(stat) \pm 0.004\,(syst) \pm 0.007\,(J/\psi K^+),\\
A_{CP}(B^+ \to K^+K^-K^+) &= -0.043 \pm 0.009\,(stat) \pm 0.003\,(syst) \pm 0.007\,(J/\psi K^+),
\end{aligned}$$

where the first error is statistical, the second systematic and the last one is due to the uncertainty on the branching ratio of the $B^+ \to J/\psi K^+$ decay used as a control channel to have under control the production and detection asymmetries.

In addition to the inclusive asymmetries, CP asymmetries in the two-dimensional phase space of two-body invariant masses were also studied. For $B^\pm \to K^\pm\pi^+\pi^-$, a positive asymmetry around the $\rho(770)^0$ and above the $f_0(980)$ resonances is identified. No asymmetry is present in the low-mass region of the $K^\pm\pi^\mp$ invariant mass projection. For $B^\pm \to K^\pm K^+K^-$, an asymmetry is concentrated at low values of the two-body invariant masses. This asymmetry is found to be not related to the $\phi(1020)$ resonance. For $B^\pm \to \pi^\pm K^+K^-$ and $B^\pm \to \pi^\pm\pi^+\pi^-$ decay modes, the positive asymmetries are at low $\pi^+\pi^-$ masses and the negative at low K^+K^- masses, both not clearly associated to intermediate resonance states. Moreover, the absolute values for the inclusive asymmetries in $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+K^-$ are found to be very similar. This apparent correlation, together with the inhomogeneous CP asymmetry distribution in the Dalitz plot, could be related to compound CP violation. In order to quantify a possible compound CP asymmetry, the introduction of new amplitude analysis techniques is necessary.

2.3 Measurement of the weak phase ϕ_s in $B_s^0 \to J/\psi h^+h^-$ decays

The decay of a B_s^0 meson into a $J/\psi h^+h^-$ final state, where h can be either a kaon or a pion is a combination of CP eigenstates. In the case of the $B_s^0 \to J/\psi K^+K^-$, the final state is a combination of two CP-even and one CP-odd CP eigenstates, corresponding to three different polarization states. For $B_s^0 \to J/\psi\pi^+\pi^-$ decays, the final state is a CP-odd eigenstate. The decay can be produced directly or via $B_s^0 - \bar{B}_s^0$ oscillation (*mixing*). The interference between these two processes gives rise to a CP violating weak phase, ϕ_s, that can be determined by using these decay modes. For $B_s^0 \to J/\psi h^+h^-$ decays, in the SM, neglecting sub-leading penguin contributions, ϕ_s is predicted to be $-2\beta_s$, with $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ and V_{ij} the elements of the CKM matrix [1]. The SM predicts $2\beta_s = 0.0364 \pm 0.0016$ rad. This value can be significantly modified in the presence of New Physics contributions in the $B_s^0 - \bar{B}_s^0$ mixing box diagram.

To extract the weak phase ϕ_s, a time-dependent analysis is needed. In the case of the $B_s^0 \to J/\psi K^+K^-$, the K^+K^- pair comes from a (spin-1) $\phi(1020)$ meson, and as a consequence, an angular analysis is needed to separate the two CP-even and one CP-odd components (in addition a S–wave contribution is taken into account). In the case of $B_s^0 \to J/\psi\pi^+\pi^-$ decays, the $\pi^+\pi^-$ pair comes mainly from the $f_0(980)$ and $f_0(1370)$ spin-0 resonances, and no angular analysis is needed.

In figure 3, the results of the time-dependent angular analysis to $B_s^0 \to J/\psi K^+K^-$ decays is shown. The combined result of the $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ analyses is

$$\phi_s \;=\; 0.01 \pm 0.07\;(stat) \pm 0.01\;(syst)\;rad,$$

being the most precise measurement at the present [6]. The result is compatible with the SM so far, and put strong constraints on New Physics models. However, there is still place for New Physics. The precision in ϕ_s by the end of the LHCb upgrade is expected to be about 0.008 rad.

2.4 Measurement of the ϕ_s weak phase in penguin decays

The SM predicts a small CP violating weak phase ϕ_s for loop mediated $b \to s$ transitions to

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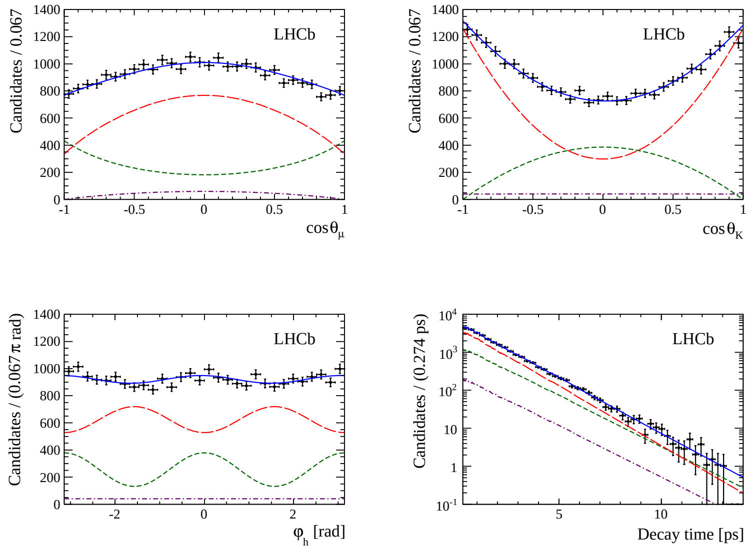

Figure 3: Helicity angles and decay time distributions for $B_s^0 \to J/\psi K^+K^-$ decays. Points correspond to experimental data. The projection of the total (blue), CP-even (long-dashed red), CP-odd (short-dashed gree) and S–wave (dotted-dashed purple) probability density functions from the unbinned maximum likelihood fit are overlaid.

CP eigenstates, so any observed deviation could be a signal of physics beyond the SM. For $b \to d$ transitions, the SM branching ratios are an order of magnitude ($\sim |V_{td}|^2/|V_{ts}|^2$) smaller.

LHCb has observed for the first time the two vector-vector B_s^0 decays $B_s^0 \to \phi \bar{K}^{*0}$ [1] [7], corresponding to a $b \to d$ transition, and $B_s^0 \to K^{*0}\bar{K}^{*0}$[8], corresponding to a $b \to s$ transition. In addition to these discoveries, a first measurement of the CP violating weak phase ϕ_s has been performed using $B_s^0 \to \phi\phi$ decays [9].

The measurement of ϕ_s using tree dominated decays, as the $B_s^0 \to J/\psi K^+K^-$, has already been described above. In the case of $B_s^0 \to \phi\phi$ decays, the SM predicts ϕ_s to be close to zero.

LHCb has performed a time-dependent angular analysis of $B_s^0 \to \phi\phi$ decays using $1 fb^{-1}$ of data collected in 2011. The analysis involves three helicity angles and the decay time. The angles are defined in figure 4. The model describing the $B_s^0 \to \phi\phi$ decay depends on six parameters: three polarization fractions $|A_0|^2$, $|A_\parallel|^2$ and $|A_\perp|^2$ ($|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$), two strong phases, $\delta_\parallel$ and $\delta_\perp$, and the CP violating phase ϕ_s. Additionally, an S–wave contribution from a non-resonant state or from the $f_0(980)$ resonance is included with amplitude $|A_S|^2$ and strong phase δ_S.

An interval of $[-2.46, -0.76]$ rad at 68% confidence level is obtained for ϕ_s, including systematic uncertainties. The results of the analysis are shown in table 1, where $|A_0|^2$ and $|A_\perp|^2$ are the fractions of longitudinal and perpendicular polarizations; and δ_0, $\delta_\parallel$ and $\delta_\perp$ are the phases of the longitudinal, parallel and perpendicular amplitudes. $|A_S|^2$ and δ_S are the amplitude and phase of the S–wave contributions, coming from a non-resonant state or from the $f_0(980)$ spin-0 resonance. The results of the unbinned maximum likelihood fit are shown in figure 5.

[1] The final state in $B_s^0 \to \phi \bar{K}^{*0}$ decays is a combination of CP eigenstates only if the $\bar{K}^{*0}$ decays into a neutral kaon

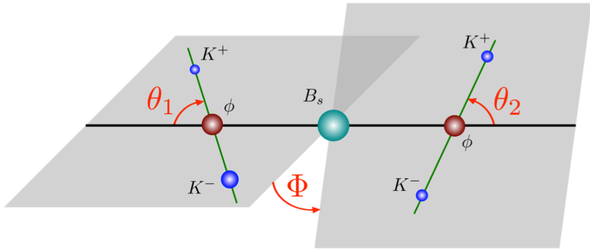

Figure 4: Angles definition for the analysis of $B_s^0 \to \phi\phi$ decays.

Parameter	Value	σ_{stat}	σ_{syst}
ϕ_s[rad] (68% CL)		$[-2.37, -0.92]$	0.22
$\lvert A_0\rvert^2$	0.329	0.033	0.017
$\lvert A_\perp\rvert^2$	0.358	0.046	0.018
$\lvert A_S\rvert^2$	0.016	$^{+0.024}_{-0.012}$	0.009
$\delta_\perp - \delta_\parallel$ [rad]	2.19	0.44	0.12
$\delta_\perp - \delta_0$ [rad]	-1.47	0.48	0.10
δ_S [rad]	0.65	$^{+0.89}_{-1.65}$	0.33

Table 1: Fit results with statistical and systematic uncertainties. A 68% statistical confidence interval is quoted for ϕ_s. Amplitudes are defined at time $t = 0$.

The limited amount of statistics does not allow to provide a value for ϕ_s, and a confidence interval is given. The analysis of the full data set, including the additional $2fb^{-1}$ collected in 2012 is on-going, and will provide a strong test of the SM, since a deviation of ϕ_s from zero would be a signal of physics beyond the SM.

3. CP violation in the D system

Branching ratios and CP violating observables of rare decays in charm systems can be significantly enhanced if they recieve contributions from physics beyond the SM. The study of D^0 decays into a pair of charged hadrons are presented in the next sections.

3.1 CP violation in $D^0 \to K^\pm\pi^\mp$ decays

Mass eigenstates of neutral charm mesons are linear combinations of the flavour eigenstates $|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, where p and q are complex numbers. This results in $D^0 - \bar{D}^0$ oscillations as a function of the decay time, if the eigenstates have different masses. The oscillation is characterized by the difference in mass $\Delta m = m_2 - m_1$ and decay width $\Delta\Gamma = \Gamma_2 - \Gamma_1$ between the D mass eigenstates. These differences are usually expressed in terms of the mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, where Γ is the average decay width of neutral D mesons. The study of CP violation in D^0 oscillation may point to contributions from physics beyond the SM. In this section, the decay-time-dependent ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ rates is studied, with the corresponding ratio for the charge-conjugate processes.

and a neutral pion

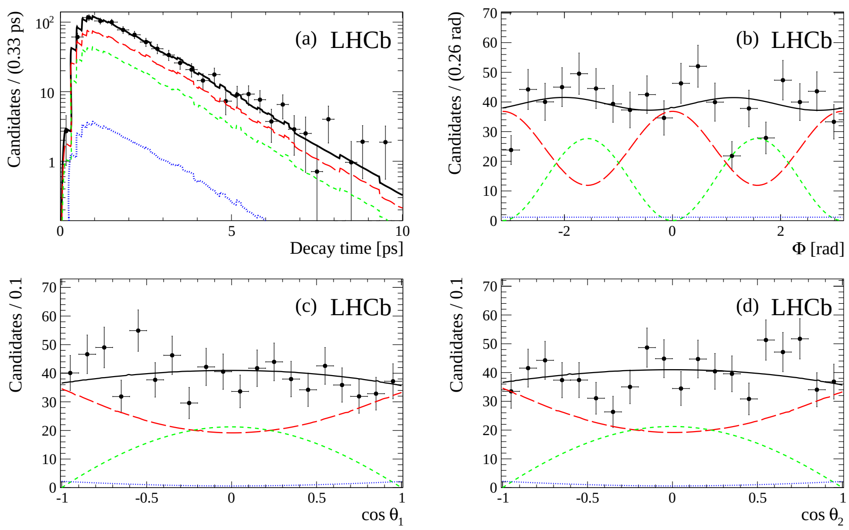

Figure 5: One-dimensional projections of the $B_s^0 \to \phi\phi$ fit for (a) the B_s^0 decay time, (b) helicity angle Φ and the cosine of the helicity angles (c) θ_1 and (d) θ_2. The data are marked as points, while the solid lines represent the projections of the best fit. The CP even P-wave, the CP-odd P-wave and S-wave components are shown by the long dashed, short dashed and dotted lines, respectively.

The *right-sign* (RS) decay $D^0 \to K^-\pi^+$ proceeds dominantly via a Cabibbo-favored (CF) process in which no $D^0-\bar{D}^0$ mixing occurs. The *wrong-sign* (WS) $D^0 \to K^+\pi^-$ decay proceeds through a double-Cabibbo-suppressed (DCS) amplitude and a process in which the D^0 first mixes and then decays via a CF process. In the limit of $|x|,|y| << 1$, and assuming negligible CP violation, the time-dependent ratio of WS-to-RS decay rates is given by

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2+y'^2}{4}\left(\frac{t}{\tau}\right)^2, \tag{3.1}$$

where t is the decay time, τ is the average D^0 lifetime, and R_D is the ratio of suppressed-to-favored decay rates. The parameters x' and y' depend linearly on the mixing parameters as $x' \equiv x\cos\delta + y\sin\delta$ and $y' \equiv y\cos\delta - x\sin\delta$, where δ is the strong-phase difference between the suppressed and favored amplitudes $\mathscr{A}(D^0 \to K^+\pi^-)/\mathscr{A}(\bar{D}^0 \to K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}$. Allowing for CP violation, the rates $R^+(t)$ and $R^-(t)$ of initially produced D^0 and $\bar{D}^0$ mesons are functions of independent sets of mixing parameters $(R_D^{\pm}, x'^{2\pm}, y'^{\pm})$. A difference between R_D^+ and R_D^- arises if the ratio between the magnitudes of suppressed and favored decay amplitudes is not CP symmetric (direct CP violation). Violation of CP symmetry either in mixing $|q/p| \neq 1$ or in the interference between mixing and decay amplitudes $\phi \equiv \arg\left[q\mathscr{A}(\bar{D}^0 \to K^+\pi^-)/p\mathscr{A}(D^0 \to K^+\pi^-)\right] - \delta \neq 0$ are usually referred to as indirect CP violation and would result in differences between (x'^{2+}, y'^+) and (x'^{2-}, y'^-).

In this analysis, $D^{*+} \to D^0\pi_s^+$ decays are used [10]. The charge of the soft momentum pion π_s^+ determines the flavour of the D meson. The invariant mass of the $D^0\pi_s^+$ system (and charge conjugated) is shown in figure 6. RS and WS candidates are then divided in bins of the D^0 decay time and the $D^0\pi_s^+$ invariant mass distribution is fitted in each bin to obtain the yields. The

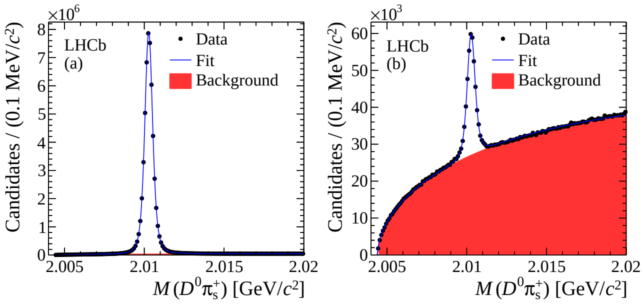

Figure 6: $D^0\pi_s^+$ invariant mass for RS (left) and WS (right) candidates.

ratios $R^{\pm}(t)$, shown in figure 7, are fitted using equation 3.1. Three hypotheses are tested: no CP violation, direct CP violation allowed, and both direct and indirect CP violation allowed.

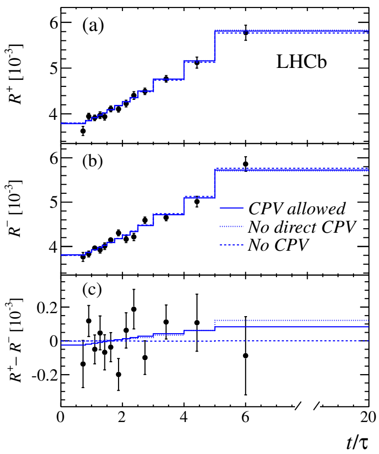

Figure 7: Efficiency corrected ratio of RS over WS candidates for initial D^0 (top) and $\bar{D}^0$ (middle) candidates. The difference between both ratios is showed on the bottom. Three hypothesis of CP violation are shown.

The results, using the full $3 fb^{-1}$ of data, in the case of CP conservation hypothesis are

$$R_D = (3.568 \pm 0.066) \times 10^{-3},\ x'^2 = (5.5 \pm 4.9) \times 10^{-5},\ y' = (4.8 \pm 1.0) \times 10^{-3}, \tag{3.2}$$

which excludes the no mixing hypothesis at more than 10σ significance. The results in which CP violation is allowed give $A_D = (R_D^+ - R_D^-)/(R_D^+ + R_D^-) = (-0.7 \pm 1.9)\%$ and $0.75 < |q/p| < 1.25$ and $0.67 < |q/p| < 1.25$ at 68.5% and 95.5% confidence level, respectively, where the relations $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\phi \pm y' \sin\phi)$ and $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\phi \mp x' \sin\phi)$ were used. Confidence regions in the (x'^2, y') plane are shown in figure 8.

The observed parameters studying D^0 and $\bar{D}^0$ decays separately show no evidence for CP violation. They provide the most stringent bounds on A_D and $|q/p|$ from a single experiment.

3.2 Measurements of indirect CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

Measurements of indirect CP violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays can be per-

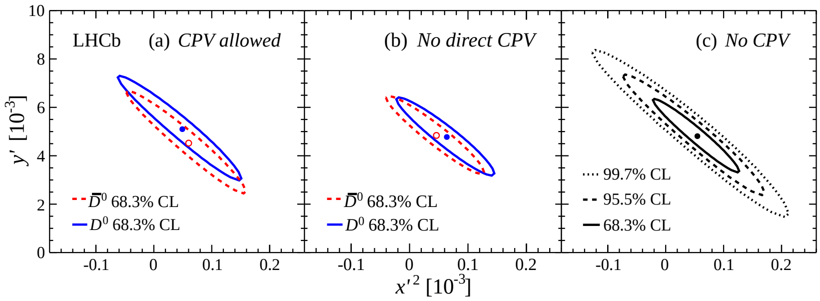

Figure 8: Confidence regions in the (x'^2, y') plane obtained (a) without any restriction on CP violation, (b) asumming no direct CP violation, and (c) asumming CP conservation.

formed through the observable

$$A_\Gamma = \frac{\hat{\Gamma} - \hat{\bar{\Gamma}}}{\hat{\Gamma} + \hat{\bar{\Gamma}}} \simeq \eta_{CP} \left(\frac{A_m + A_d}{2} y \cos\phi - x \sin\phi \right),$$

where $\hat{\Gamma}$ and $\hat{\bar{\Gamma}}$ are the inverse of the effective lifetimes in decays of D^0 and $\bar{D}^0$ mesons into a CP eigenstate with eigenvalue η_{CP}; x and y are the mixing parameters, previously defined, and

$$A_m = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2},\; A_d = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2},\; \phi = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right),$$

where A_f ($\bar{A}_f$) is the amplitude for a D^0 ($\bar{D}^0$) meson decaying into the given final CP eigenstate f.

As in the previous section, the decay chain $D^{*+} \to D^0 \pi_s^+$ is used to obtain the flavour of the D^0 candidate at production. Both the K^+K^- and $\pi^+\pi^-$ final states are analyzed. The effective lifetime is obtained by performing an unbinned maximum likelihood fit to the decay-time distribution [11], as shown in figure 9.

The analysis of $1 fb^{-1}$ data collected in 2011 gives

$$\begin{aligned} A_\Gamma^{KK} &= (-0.35 \pm 0.62\,(stat) \pm 0.12\,(syst)) \times 10^{-3} \\ A_\Gamma^{\pi\pi} &= (\;\;\,0.33 \pm 1.03\,(stat) \pm 0.14\,(syst)) \times 10^{-3} \end{aligned}$$

where the dominant systematic uncertainties arise from the knowledge of the acceptance correction and the modeling of the backgrounds. These results are compatible with no indirect CP violation.

4. Summary and conclusions

Measurements of CP violating observables in the B and D systems at LHCb have been presented. CP violation in the B_s^0 system has been observed for the first time in $B_s^0 \to K^-\pi^+$ decays. Direct CP violation in the phase space of the three-body decays of charged B mesons are also reported. The mixing induced weak phase ϕ_s has been measured in tree dominated $B_s^0 \to J/\psi K^+K^-$ and penguin $B_s^0 \to \phi\phi$ decays. In the D system, measurement of direct and indirect CP violation has been presented in $D^0 \to K^\pm\pi^\mp$, $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. Results of CP violation measurements in the D system are so far compatible with no CP violation.

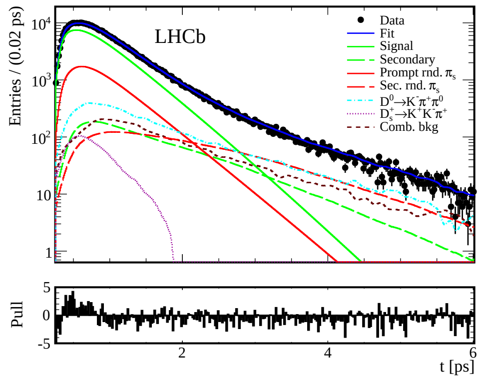

Figure 9: Fit to the decay time of $\bar{D}^0 \to K^- K^+$ and corresponding pull distribution for candidates with magnet polarity down.

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