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Mixing and CP violation in the beauty and charm sectors at LHCb

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Abstract. The LHCb detector is a dedicated heavy flavour experiment operating at the Large Hadron Collider designed to pursue an extensive study of CP violation in the beauty and charm sectors. In the first part of this contribution, important milestones towards the measurement of CP violation in the beauty sector using $B^{\pm}$ and B^0_s decays are presented. In the second part, highlights of the searches of CP violation in the charm sector are reported.

1 Introduction

The LHCb detector is a single-arm spectrometer designed to test the CKM paradigm of flavour structure and CP violation. In this document six LHCb measurements of CP violation in the beauty and charm sectors are reviewed. A detailed analysis of the $B^{\pm} \to DK^{\pm}$ decay, sensitive to the CKM angle γ, is presented in Sec.2. The analysis of $B^0_s \to J/\psi\phi$ and $B^0_s \to J/\psi\pi^+\pi^-$ is reported for the measurement of the CP violating phase ϕ_s in Sec. 3. Finally, in Sec.4 three measurements of charm hadron decays are presented, including a first observation of CP violation in the charm sector.

2 Towards a measurement of the CKM angle γ

The angle γ is defined as $\gamma = arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$, where V_{ij} are elements of the CKM matrix. It is the least accurately known phase of the CKM unitary triangle. The particularity of the angle γ is that it can be measured using only tree-level decays through the interference between the favoured $B^- \to D^0K^-$ and the suppressed $B^- \to \bar{D}^0K^-$ amplitudes. Therefore, it becomes a crucial reference measurement for constraining physics beyond the Standard Model when compared with other measurements from decays involving penguin diagrams.

Here, the analysis of $B^{\pm}$ decays in the CP modes $[K^+K^-]_D h^{\pm}$ and $[\pi^+\pi^-]_D h^{\pm}$ and the favoured $[K^{\pm}\pi^{\mp}]_D h^{\pm}$ where $h = \pi, K$ is presented. The sensitivity is greater in $B^- \to DK^-$ than in $B^- \to D\pi^-$ decays (where D refers to both D^0 and $\overline{D}^0$), which are used as a high-statistics control sample to extract probability density functions.

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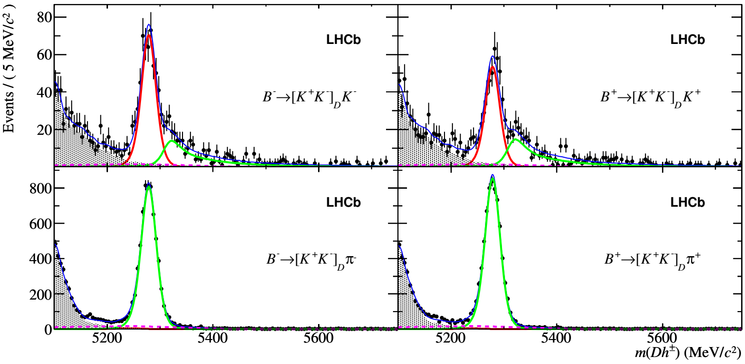

Figure 1. Invariant mass distributions of the selected $B^\pm \to [K^+K^-]_D h^\pm$ candidates. The left plots are B^- candidates, B^+ are on the right. In the top plots the bachelor track is assigned to be a kaon while in the bottom plots the bachelor track is a pion. The solid red curve represents the $B \to DK$ events, the solid green curve is $B \to D\pi$. The shaded contributions are partially reconstruced events and the total PDF includes the combinatorial component. The contributions from $\Lambda_b \to \Lambda_c^\pm h^\mp$ decays is indicated by the dashed line.

For the CP-even eigenstates (f_{CP+}) the branching ratios and the asymmetry are defined as

$$\begin{aligned} R_{CP\pm} &= \frac{[\Gamma(B^-\to D_{CP\pm}K^-)+\Gamma(B^+\to D_{CP\pm}K^+)]}{2\Gamma(B^-\to DK^-)} = 1 + r_B^2 \pm 2r_B\cos\delta_B\cos\gamma\,, \\ A_{CP\pm} &= \frac{\Gamma(B^-\to D_{CP\pm}K^-)-\Gamma(B^+\to D_{CP\pm}K^+)}{\Gamma(B^-\to D_{CP\pm}K^-)+\Gamma(B^+\to D_{CP\pm}K^+)} = \frac{\pm 2r_B\sin\delta_B\sin\gamma}{R_{CP\pm}}\,, \end{aligned} \tag{1}$$

where r_B is the relative magnitude of the suppressed amplitude $r_B = |A(b\to u)/A(b\to c)|$, δ_B is the strong phase and γ is the weak phase. This method is theoretically clean to determine γ and was proposed by Gronau, London and Wyler (GLW) [1].

For the $D^0 \to K^\pm\pi^\mp$ decays the ratio of branching ratios and the asymmetry are defined as

$$\begin{aligned} R_{ADS} &= \frac{\Gamma(B^-\to[K^+\pi^-]_DK^-)+\Gamma(B^+\to[K^-\pi^+]_DK^+)}{\Gamma(B^-\to[K^-\pi^+]_DK^-)+\Gamma(B^+\to[K^+\pi^-]_DK^+)} = r_B^2 + r_D^2 + 2r_B\,r_D\cos\gamma\cos(\delta_B+\delta_D), \\ A_{ADS} &= \frac{\Gamma(B^-\to[K^+\pi^-]_DK^-)-\Gamma(B^+\to[K^-\pi^+]_DK^+)}{\Gamma(B^-\to[K^+\pi^-]_DK^-)+\Gamma(B^+\to[K^-\pi^+]_DK^+)} = 2r_B\,r_D\sin\gamma\sin(\delta_B+\delta_D)/R_{ADS}\,. \end{aligned} \tag{2}$$

This method was proposed by Atwood, Dunietz and Soni (ADS) [2] to overcome the fact that in the GLW method the two amplitudes that interfere are not of the same magnitude. In $D \to K^+\pi^-$ decays, the favoured transition $b \to c$ is followed by the double CKM-suppressed D decay interfering with the supressed $b \to u$ transition followed by the CKM-favoured D decay. The amplitudes of such combinations are of similar total magnitude and hence large interference can occur.

A sample of 1.0 fb^{-1} of data collected by the LHCb experiment was used to extract the asymetries and branching ratios with a binned maximum-likelihood fit to the invariant mass distributions of the selected B candidates. Figures 1 and 2 show the invariant mass distributions for the $B^\pm \to [K^+K^-]_D h^\pm$ and $B^\pm \to [K^\pm\pi^\mp]_D h^\pm$ decays, respectively.

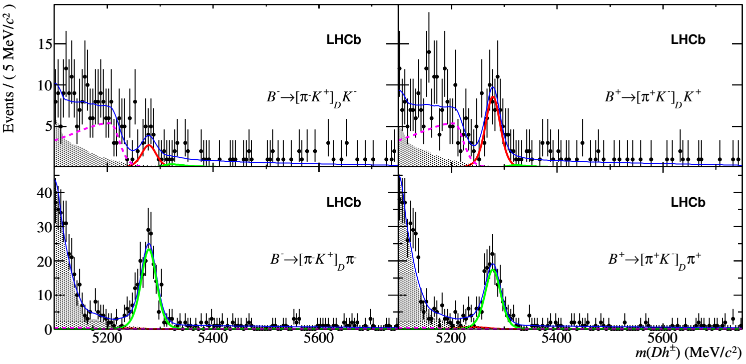

Figure 2. Invariant mass distibutions of the $B^\pm \to [K^\pm\pi^\mp]_D h^\pm$ decay. See caption of Fig. 1 for a full description. The dashed line here represents the partially reconstructed $B_s^0 \to \bar{D}^0K^-\pi^+$ and $\bar{B}_s^0 \to D^0K^+\pi^+$ decays where the pions are lost.

The results are the following

$$\begin{aligned}
A_{CP+} &= 0.145 \pm 0.032 \pm 0.010\,, & R_{CP+} &= 1.007 \pm 0.038 \pm 0.012\\
A_{ADS(K)} &= -0.52 \pm 0.15 \pm 0.02\,, & R_{ADS(K)} &= 0.0152 \pm 0.0020 \pm 0.0004\\
A_{ADS(\pi)} &= 0.143 \pm 0.062 \pm 0.011\,, & R_{ADS(\pi)} &= 0.00410 \pm 0.00025 \pm 0.00005
\end{aligned}$$

where the first error is statistical and the second is the systematic. The ADS $B^\pm \to DK^\pm$ mode is observed with 10σ statistical significance when comparing the maximum likelihood to that of the null hypothesis. This mode shows evidence of a large ($4\ \sigma$) negative asymmetry as seen in previous measurements [3–5]. The $B^\pm \to D\pi^\pm$ ADS modes shows a hint of a positive asymmetry with $2.4\ \sigma$ significance. The CP-even eigenstates modes K^+K^- and $\pi^+\pi^-$ both show a positive asymmetry. These measurements are the most precise and in good agreement with the B factories [6] and will contribute for a future extraction of the angle γ.

3 The CP violating phase ϕ_s

The CP violating phase ϕ_s can be measured through the interference between the direct decay of $B_s^0 \to J/\psi\phi$ and the decay via $B_s^0 - \bar{B}_s^0$ oscillation. In the Standard Model this CP violating phase is predicted to be $\phi_s^{SM} \simeq -2\beta_s$, where $\beta_s = \arg\,(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ [7, 8]. The indirect determination via global fits to experimental data gives $2\beta_s = 0.036 \pm 0.002$ rad [1, 9]. However, contributions from physics beyond the Standard Model may affect this value of ϕ_s [1, 1, 1].

3.1 The $B_s^0 \to J/\psi\phi$ analysis

In order to measure the CP violating phase ϕ_s three basic ingredients are needed. First, as the $B_s^0 \to J/\psi\phi$ final state is a mixture of CP-odd and CP-even states which contribute with different signs to the CP asymmetry, an angular analysis is needed. As the CP asymmetry is proper lifetime dependent and the oscillations of the B_s^0 meson occur with high frequency (Δm = 17.63 ± 0.11 ps^{-1} [1]) the decay

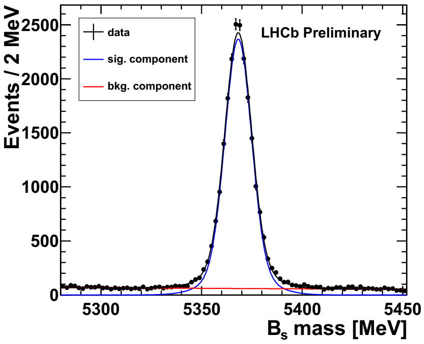

Figure 3. Reconstructed invariant mass distribution of selected $B_s^0 \to J/\psi\phi$ candidates.

time needs to be determined with high precision. Finally, in order to have the maximum sensitivity to ϕ_s, the initial flavour of the B_s^0 meson needs to be determined.

A first measurement was performed using a sample of 0.4 fb^{-1}[1]. Here we present an update using 1 fb^{-1} of data [1], where aproximately 21200 $B_s \to J/\psi\phi$ events were selected as shown in Fig. 3.

The physical parameters are extracted from a maximum likelihood fit to the mass, the proper lifetime, the initial flavour of the B_s^0 and the 4-body decay angles as shown in Fig. 4. Besides ϕ_s, additional physics observables are extracted: the average decay width (Γ_s), the difference between the heavy and light B_s^0 mass eigenstates ($\Delta\Gamma_s$) and the polarization amplitudes A_0, $A_\perp$, $A_\parallel$ and A_S of the P- and S-wave components of the K^+K^- spectrum. The results obtained for the CP violating phase ϕ_s, the decay width Γ_s and the mean decay width difference $\Delta\Gamma_s$ are

$$\begin{aligned}
\phi_s &= -0.001 \pm 0.101\,(\text{stat}) \pm 0.027\,(\text{syst})\,\text{rad},\\
\Gamma_s &= 0.6580 \pm 0.0054\,(\text{stat}) \pm 0.0066\,(\text{syst})\,\text{ps}^{-1},\\
\Delta\Gamma_s &= 0.116 \pm 0.018\,(\text{stat}) \pm 0.006\,(\text{syst})\,\text{ps}^{-1}.
\end{aligned}$$

This is the world's most precise meaurement of ϕ_s and the first direct observation for a non-zero value for $\Delta\Gamma_s$. The results are in good agreement with the Standard Model predictions [1]. This analysis results in a two-fold ambiguity in the plane ($\Delta\Gamma_s, \phi_s$) due to the invariance of the differential decay rate under the transformation ($\phi_s \leftrightarrow \pi - \phi_s$; $\Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s$). The LHCb experiment has recently solved this ambiguity [1] by studying the difference in the strong phase between the K^+K^- S-wave and P-wave in the $B_s^0 \to J/\psi K^+K^-$ decay as a function of the K^+K^- invariant mass. The conclusion is that values of ϕ_s close to zero and positive $\Delta\Gamma_s$ are preferred. Therefore, the mass eigenstate that is almost CP-even is lighter and decays faster than the state that is almost CP-odd.

3.2 The $B_s^0 \to J/\psi\pi^+\pi^-$ analysis

In this section, the measurement of ϕ_s in $B_s^0 \to J/\psi\pi^+\pi^-$ decays using 1 fb^{-1} of data [1] is reported. The main difference with the previous published result [2] is that the $\pi\pi$ spectrum was extended to [775-1550] MeV/c^2. The resonance structure of the $B_s^0 \to J/\psi\pi^+\pi^-$ decays was studied using a modified Dalitz plot and it was found that the spectrum is dominated by a CP-odd component via the $f_0(980)$ meson decay. Aproximately 7400 signal events are selected. An unbinned maximum

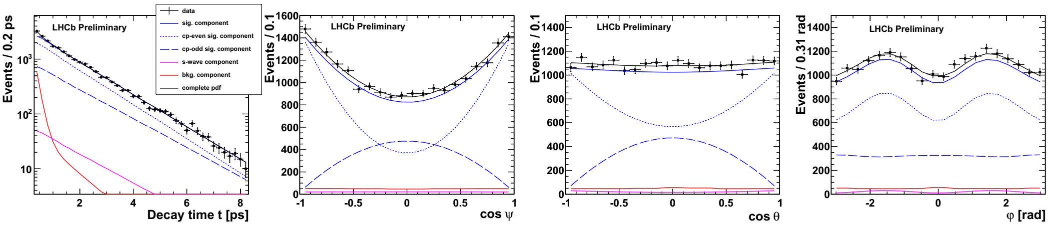

Figure 4. Data points overlaid with fit projections for the decay time (top-left) and tranversity angle distributions. The total fit result is represented by the black line. The signal component is represented by the solid blue line; the dashed and dotted blue lines show the CP-odd and CP-even signal components respectively. The S-wave component is represented by the solid pink line. The background component is given by the red line.

likelihood fit to the mass, the decay time and the initial flavour of the B_s^0 yields a value of $\phi = -0.019^{+0.173+0.004}_{-0.174-0.003}$ rad, where the first error is statistical and the second is systematic. No evidence of CP violation is found. Both measurements using $B_s^0 \to J/\psi\pi^+\pi^-$ and $B_s^0 \to J/\psi\phi$ decays are compatible with each other within uncertainties. A combined simultaneous fit to both decays gives $\phi_s = -0.002 \pm 0.083 \pm 0.027$ rad.

4 CP violation in charm

The interest of studying CP violation in the charm sector is the fact that it is predicted to be very small in the Standard Model [2] and could be enhanced by New Physics [2]. Three different measurements are presented here: a time-integrated CP violation measurement in two body D^0 decays, a search for time-integrated CP violation in the three-body decays of the $D^\pm$ mesons and measurements of time-dependent CP violation and mixing in two body D^0 decays.

4.1 Time-integrated CP asymmetries in D^0 decays

The LHCb experiment has measured the difference in time-integrated CP asymmetries between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays using 0.6 pb^{-1} of data collected in 2011 [2] . The initial flavour of the D^0 is tagged using $D^{*+} \to D^0\pi^+$ decays, where the charge of the π tags the produced flavour of the D^0. The raw asymmetry for the tagged D^0 decays to a final state f is defined as:

$$A_{raw}(f) \equiv \frac{N\left(D^{*+} \to D^0(f)\pi^+\right) - N\left(D^{*-} \to \bar{D}^0(f)\pi^-\right)}{N\left(D^{*+} \to D^0(f)\pi^+\right) + N\left(D^{*-} \to \bar{D}^0(f)\pi^-\right)}, \tag{3}$$

where $N(X)$ is the number of the reconstructed X decays after background subtraction. This raw asymmetry is made up of a sum of various contributions

$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi^+) + A_P(D^{*+}), \tag{4}$$

where $A_D(f)$ is the asymmetry in selecting the D^0 decay, $A_D(\pi^+)$ is the asymmetry in selecting the soft pion, and $A_P(D^{*+})$ is the production asymmetry for D^{*+} mesons. Considering that $A_D(\pi^+)$ and A_P are independent of the D^0 decay (f) and that no D^0 asymmetry $A_D(K^+K^-) = A_D(\pi^+\pi^-) = 0$ can be detected for a spin-0 particle decaying into a two-body self-conjugate final state, the difference in raw asymmetries between the KK and $\pi\pi$ modes is

$$\Delta \mathrm{A}_{\mathrm{CP}}(\mathrm{f}) = \mathrm{A}_{\mathrm{raw}}(\mathrm{K}^+\mathrm{K}^-) - \mathrm{A}_{\mathrm{raw}}(\pi^+\pi^-). \tag{5}$$

In order to reduce any residual production and detection asymmetry, the measurement of $A_{CP}(f)$ is obtained by fitting the mass difference spectra ($\delta m \equiv m(h^+h^-\pi^+) - m(h^+h^-) - m(\pi^+)$ for $h = K, \pi$) of the selected candidates in 54 kinematic bins of the transverse momentum p_T and pseudorapidity η of the D^{*+} candidates, the momentum of the slow pion, and the sign of the momentum component on the horizontal plane p_x of the slow pion at the D^{*+} vertex. From the measurement of $\Delta \mathrm{A}_{\mathrm{CP}}(\mathrm{f})$ in each bin, a weighted average is performed to give the result

$$\Delta \mathrm{A}_{\mathrm{CP}}(\mathrm{f}) = [-0.82 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})] \times 10^{-2}. \tag{6}$$

This measurement represents the first evidence for CP violation in the charm sector. To establish whether this result is consistent with the SM direct and indirect CP violation measurements in other channels as more precise $\Delta \mathrm{A}_{\mathrm{CP}}$ measurements and advances in theory are needed but likely won't be sufficient to resolve the puzzle.

4.2 Time-integrated CP asymmetries in $D^\pm \to K^+K^-\pi^\pm$ decays

A model-independent analysis of the Dalitz plot of $D^\pm \to K^+K^-\pi^\pm$ decays is performed in order to search for direct CP violation effects. For each bin in the Dalitz plot, a local CP asymmetry variable is defined [2]

$$S^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}, \tag{7}$$

where $N^i(D^\pm)$ is the number of $D^\pm$ candidates in the i^{th} bin and α is the ratio between the D^+ and D^- yields, which accounts for an overall asymmetry. The variable S^i_{CP} is measured in individual bins of the Dalitz plot, and the overall distribution of the measured S^i_{CP} values is compared to the distribution expected in the case of zero CP violation, which corresponds to a Gaussian distribution with zero mean and unit width. At the LHCb experiment this is studied using a data sample correspondig to 35 pb^{-1} of integrated luminosity [2]. The signal $D^\pm \to K^+K^-\pi^\pm$ sample consists of aproximately 403,000 selected candidates. The normalized distributions for D^+ and D^- are compared using four different binning schemes. Figure 5 shows the distribution of S^i_{CP} in the Dalitz plot for one of the schemes and the distribution of S^i_{CP} fitted with a Gaussian function. In all cases, the p-values are consistent with no CP violation, with values ranging from 4% to 99%.

4.3 Mixing and time-dependent CP asymmetries in D^0 decays

The neutral D meson mass eigenstates $D_{1,2}$ with masses $m_{1,2}$ and widths $\Gamma_{1,2}$, can be expressed as linear combination of the flavour eigenstates as $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ with complex coefficients satisfying $|p|^2 + |q|^2 = 1$. The average mass and width are defined as $m \equiv (m_1 + m_2)/2$ and $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$. The mixing parameters are defined as $x \equiv (m_2 - m_1)/\Gamma$ and $y \equiv (\Gamma_2 - \Gamma_1)/(2\Gamma)$. The LHCb analysis consists in the measurement of the CP violation parameters y_{CP} and A_Γ [2]. Both quantities are measured here for the first time at a hadron collider. The observable y_{CP} is the deviation from unity of the ratio of effective lifetimes in the decay modes $D^0 \to K^+\pi^+$ and $D^0 \to K^+K^-$,

$$y_{CP} \equiv \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1. \tag{8}$$

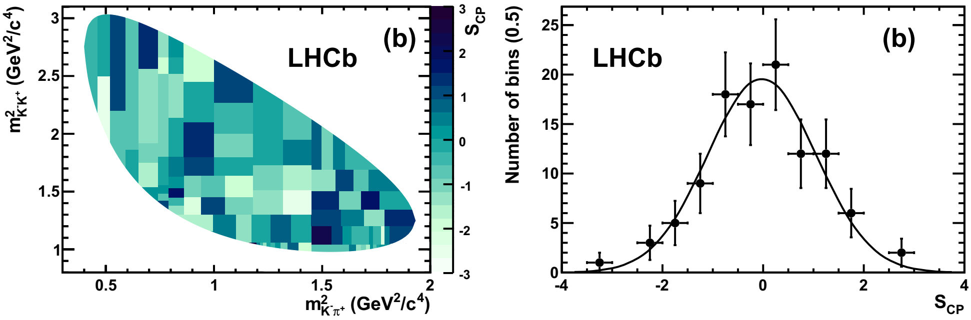

Figure 5. Distribution of S^i_{CP} in the Dalitz plot for the scheme with 106 bins (right figure). Distribution of S^i_{CP} fitted to a Gaussian function.

Similarly, A_Γ is given by the asymmetry of the effective lifetimes as

$$A_\Gamma \equiv \frac{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)}. \tag{9}$$

In the limit of no CP violation y_{CP} is equal to y. Therefore, any difference between y and y_{CP} would be a sign of CP violation. The measurements presented here are based on a data sample corresponding to an integrated luminosity of 29 pb^{-1} [2]. The candidates are tagged by reconstructing the $D^{*+} \to D^0\pi^+$ decay, where the charge of the slow pion determines the flavour of the D meson at production. The number of selected candidates is aproximately 280,000 for $D \to K^+\pi^+$ and 40,000 for $D \to K^+K^-$. Figure 6 shows the invariant mass difference Δm of the D^{*+} and the D candidate. The measurement of y_{CP} and A_Γ is based on absolute lifetime measurements which have to be corrected for lifetime biasing effects. The analysis uses a data-driven approach to measure the decay-time acceptance on an event-by-event basis. More details of this procedure can be found in [2]. The results are

$$y_{CP} = (5.5 \pm 6.3(\text{stat}) \pm 4.1(\text{syst})) \times 10^{-3} \tag{10}$$

and

$$A_\Gamma = (-5.9 \pm 5.9(\text{stat}) \pm 2.1(\text{syst})) \times 10^{-3}, \tag{11}$$

which are in agreement with previous measurements [2, 2, 2].

5 Conclusion

This contribution has reviewed three measurements in the beauty sector and three in the charm sector. In the beauty sector, important milestones towards the measurement of γ with the determination of R_{CP}, A_{CP}, R_{ADS} and A_{ADS} have been presented. In the B^0_s system the combined analysis of the decays $B^0_s \to J/\psi\phi$ and $B^0_s \to J/\psi\pi^+\pi^-$ give the most precise measurement of CP violating phase $\phi_s = -0.002 \pm 0.083 \pm 0.027$. In the charm sector three measurements of time-integrated and time-dependent CP asymetries in the decays of D^0 and D^+, including a first observation of CP violation in the charm sector are reported.

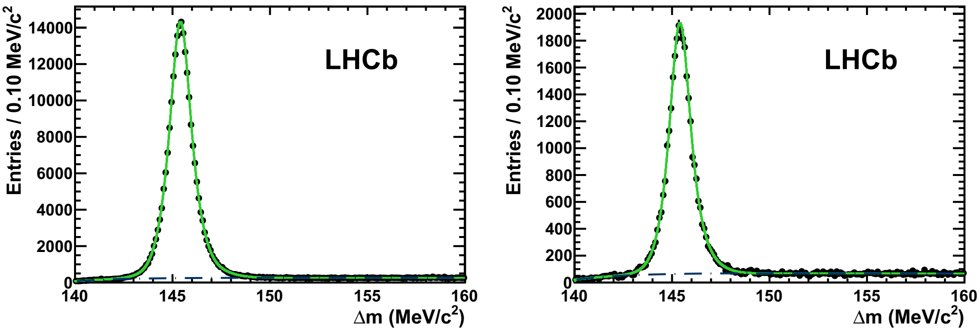

Figure 6. Δm fit projections of (left) $D^0 \to K^-\pi^+$ and (right) $D^0 \to K^-K^+$ candidates. Shown are data (points), the total fit (green, solid) and the background component (blue, dot-dashed).

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