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CP violation in the B and D systems at LHCb

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Summary. — This review presents some of the latest measurements on CP violation in the B and D meson systems performed by the LHCb experiment with data collected at LHC in pp collisions at 7 and 8 TeV.

PACS 13.25.Hw – Decays of bottom mesons.
PACS 13.25.Ft – Decays of charmed mesons.
PACS 29.20.db – Storage rings and colliders.

The B and D systems provide an ideal laboratory to test the predictions on CP violation of the Standard Model (SM) and to search for violations beyond the SM. Large samples of B and D mesons have been produced at LHC in pp collisions at 7 and 8 TeV. The results presented here refer mainly to the analysis of the first $1\,\text{fb}^{-1}$ of collected data, but in some cases the full $3\,\text{fb}^{-1}$ data sample is used.

1. – CP violation in $B^0_s \to J/\psi K^+K^-$ and $B^0_s \to J/\psi\pi^+\pi^-$ decays

In a B^0_s decay to a final state which is a CP eigenstate a CP-violating phase can arise in the interference between decays with or without B^0_s-$\overline{B}^0_s$ oscillations. The $B^0_s \to J/\psi\phi$ decay([1]) is considered the golden mode for measuring this type of CP violation. Within the SM this decay is dominated by $b \to c\bar{c}s$ quark level transitions, the weak phase is given by $\phi_s^{\rm SM} = -2\arg(-V_{\rm ts}V^*_{\rm tb}/V_{\rm cs}V^*_{\rm cb})$, neglecting QCD penguin contributions. Global fits to experimental data give a small and precise value (-0.0363 ± 0.0016) rad [1]. A precise measurement of ϕ_s is a sensitive test on the presence of new particles contributing in the mixing box diagram which could modify the SM prediction, adding a new phase.

The world most precise measurement of ϕ_s is performed by LHCb with $1\,\text{fb}^{-1}$ of data using $B^0_s \to J/\psi K^+K^-$ decays [2]. The $B^0_s \to J/\psi K^+K^-$ decay proceeds predominantly

([1]) Charge conjugate states are always included unless explicity indicated differently.

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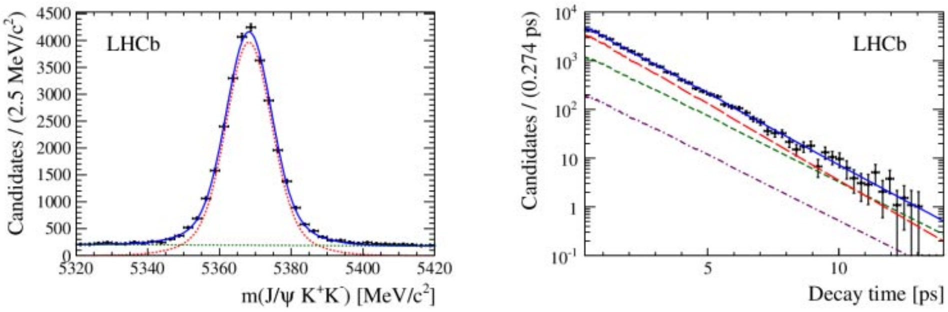

Fig. 1. – Data distributions for $B_s^0 \to J/\psi K^+K^-$ candidates. Left: invariant-mass distribution. Curves for the fitted contributions from signal (dotted red), background (dotted green) and their combination (solid blue) are overlaid. Right: decay time distribution. The solid blue line shows the total signal contribution, which is composed of CP-even (long-dashed red), CP-odd (short-dashed green) and S-wave (dotted-dashed purple) contributions.

via $B_s^0 \to J/\psi\phi$ with the ϕ meson subsequently decaying to K^+K^-, in a P-wave configuration. The final is a superposition of CP-even and CP-odd states, depending upon the relative orbital angular momentum of the J/ψ and ϕ mesons. The same final state can also be produced with K^+K^- pairs in an S-wave configuration; this final state being CP-odd. In order to achieve sensitivity to the two CP components the distribution of the final-state decay angles is analyzed. A maximum-likelihood fit is performed to the mass, decay time and angular distributions of the events. The initial flavour of the B_s^0 is defined by a combination of various flavour tagging algorithms. The invariant mass and the decay time distributions of the $B_s^0 \to J/\psi K^+K^-$ candidates, together with the projection of the fitted PDF are shown in fig. 1.

A similar analysis is performed in the $B_s^0 \to J/\psi\pi^+\pi^-$ decay mode. The region of $\pi^+\pi^-$ mass in the (775–1550) MeV/c^2 range is found to be 97.7% CP-odd, at 95% CL [3,4], as a consequence no angular analysis is required to measure the phase ϕ_s in this case. A likelihood fit is performed to the mass and time distributions of flavour-tagged data. The mixing phase is found to be $\phi_\mathrm{s} = -0.014^{+0.17}_{-0.16} \pm 0.01\,\mathrm{rad}$, using $1\,\mathrm{fb}^{-1}$ of data [5].

A global result is obtained from a simultaneous fit performed to both the $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ data sets [2], the main parameters extracted are

$$\begin{aligned}\phi_\mathrm{s} &= 0.01 \pm 0.07 \pm 0.01\,\mathrm{rad},\\ \Gamma_\mathrm{s} &= 0.661 \pm 0.004 \pm 0.006\,\mathrm{ps}^{-1},\\ \Delta\Gamma_\mathrm{s} &= 0.106 \pm 0.011 \pm 0.007\,\mathrm{ps}^{-1}.\end{aligned}$$

The measurements of ϕ_s, $\Delta\Gamma_\mathrm{s}$ and Γ_s are in agreement with the SM prediction. A constraint to possible new physics (NP) contributions to the B_s^0 mixing has been derived from these result to be below 30% at 3σ [6].

As a first step to the upcoming new results with $3\,\mathrm{fb}^{-1}$ of data an amplitude analysis is performed for a precise study of the CP content of the $B_s^0 \to J/\psi\pi^+\pi^-$ decay [4]. The best description of the decay is obtained considering five interfering states $f_0(980)$, $f_0(1500)$, $f_0(1790)$, $f_2(1270)$ and $f_2'(1525)$. The mass distribution of the $\pi^+\pi^-$ pairs for events in the B_s^0 signal region is shown in fig. 2.

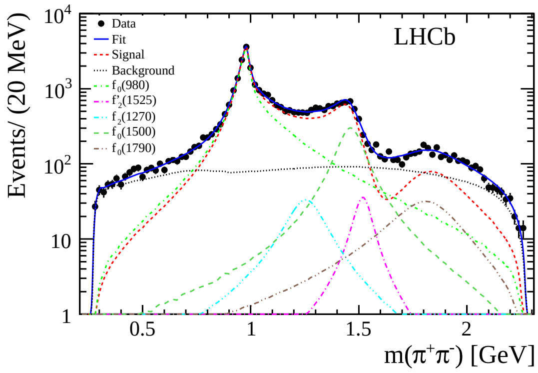

Fig. 2. – Mass distribution of selected $\pi^+\pi^-$ combinations, the contributing components are indicated in the figure.

2. – Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^{*0}$

The $B^0 \to \phi K^{*0}$ decay is a flavour changing neutral current decay which is described in the SM by a gluonic penguin diagram. It is sensitive to possible NP contributions in the loop. The new LHCb analysis of this mode uses $1\,\mathrm{fb}^{-1}$ of data and selects 1655 ± 42 signal candidates [7]. An angular analysis of time-integrated decay rates is performed to disantangle the helicity structure of the decay. For the P-wave the longitudinal (L), parallel ($\|$) and perpendicular ($\perp$) components are included, with the constraint on the fractions $f_\| = 1 - f_L - f_\perp$. For the S-wave, contributions for the $B^0 \to \phi K^+\pi^-$ and $B^0 \to K^*(892)^0 K^+ K^-$ are considered. The mass distribution of the intermediate resonances and the angular distributions are shown in fig. 3. The resulting parameters

$$\begin{aligned} f_L &= 0.497 \pm 0.019 \pm 0.015, \\ f_\perp &= 0.221 \pm 0.016 \pm 0.013, \\ f_S(K\pi) &= 0.143 \pm 0.013 \pm 0.012, \\ f_S(KK) &= 0.122 \pm 0.013 \pm 0.008 \end{aligned}$$

show a large component of longitudinal polarization, in agreement with previous measurements performed by BaBar [8] and Belle [9], and a significant S-wave contribution. The CP raw asymmetry is measured from fits to the $KKK\pi$ mass distribution performed separately for B^0 and $\bar{B}^0$ decays, identified using the charge of the final state kaon in the $K^{*0} \to K^+\pi^-$ decay.

$$A_{CP}^{\mathrm{raw}} = \frac{N(\bar{B}^0 \to \phi \bar{K}^{*0}) - N(B^0 \to \phi K^{*0})}{N(\bar{B}^0 \to \phi \bar{K}^{*0}) + N(B^0 \to \phi K^{*0})}\,.$$

The CP asymmetry is obtained correcting the raw asymmetry for the asymmetry in the detection of $K^+\pi^-$ with respect to $K^-\pi^+$, and for $\bar{B}^0/B^0$ production asymmetry. The latter is determined using the $B^0 \to J\psi K^{*0}$ control channel, where the CP asymmetry is assumed to be negligible. No evidence of CP asymmetry is found, the result $A_{CP}(B^0 \to$

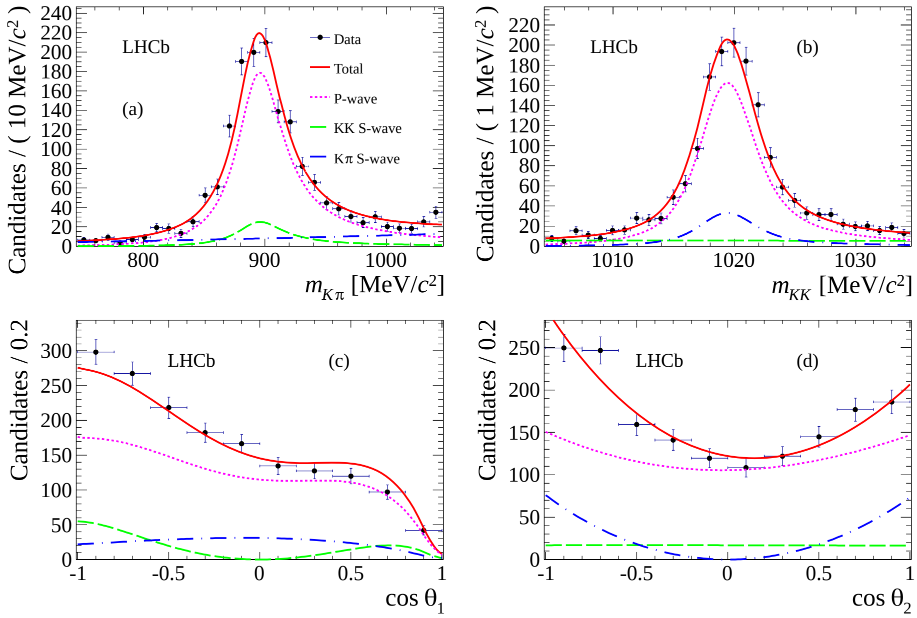

Fig. 3. – Distributions for the intermediate resonances and for two helicity angles of the $B^0 \to \phi K^{*0}$ decays. (a) mass($K\pi$) (b) mass(KK) (c) cos(θ_1) (d) cos(θ_2) The background is subtracted and the results of the fit are superimposed.

$\phi K^{*0}) = (+1.5 \pm 3.2(\text{stat}) \pm 0.5(\text{syst}))\%$ is in agreement with, and a factor two more precise than the previous BaBar and Belle results.

3. – Direct CP violation in charmless B decays

Evidence of direct CP violation was measured by LHCb in two body charmless decays of B^0 and B_s^0 mesons, with a significance of more than 10.5 and 6.5 σ, respectively [10]

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst}),$$
$$A_{CP}(B_s^0 \to \pi^+K^-) = 0.27 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}).$$

Charge asymmetries are measured also in charmless three bodies decays of $B^\pm$ mesons. Four final states are analyzed $B^\pm \to K^+K^-K^\pm$, $B^\pm \to \pi^+\pi^-K^\pm$, $B^\pm \to \pi^+\pi^-\pi^\pm$ and $B^\pm \to K^+K^-\pi^\pm$ [11, 12]. As an example, the $B^\pm$ mass distributions for the $B^\pm \to \pi^+\pi^-\pi^\pm$ and $B^\pm \to K^+K^-\pi^\pm$ decays are shown in fig. 4. The inclusive CP asymmetries are measured as

$$A_{CP}(B^\pm \to \pi^+\pi^-K^\pm) = 0.032 \pm 0.008 \pm 0.004 \pm 0.007,$$
$$A_{CP}(B^\pm \to K^+K^-K^\pm) = -0.043 \pm 0.009 \pm 0.003 \pm 0.007,$$
$$A_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm) = 0.117 \pm 0.021 \pm 0.009 \pm 0.007,$$
$$A_{CP}(B^\pm \to K^+K^-\pi^\pm) = -0.141 \pm 0.040 \pm 0.018 \pm 0.007,$$

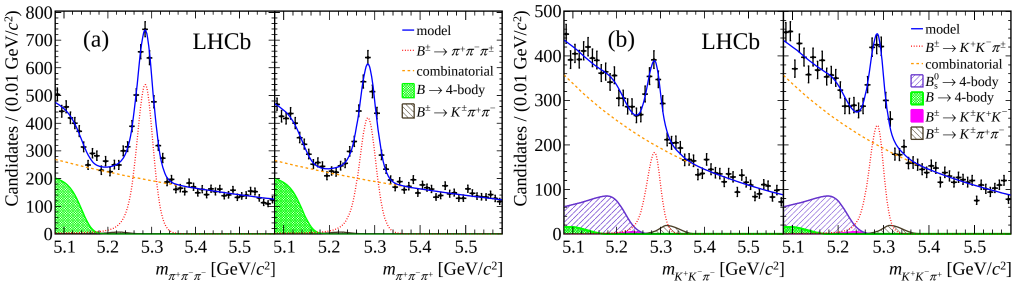

Fig. 4. – Mass distribution of (a) $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ and (b) $B^{\pm} \to K^+K^-\pi^{\pm}$ decays. The left-hand panel in each figure shows the B^- modes and the right-hand panel shows the B^+ modes. The results of an unbind maximum likelihood fit are overlaid, the main fit contributions are also shown.

where the first uncertainty is statistical, the second is the experimental systematic and the third is due to the CP asymmetry of the $B^{\pm} \to J/\psi K^{\pm}$ reference mode which is used to correct for detection and production effects. These results provides the first evidence of inclusive CP asymmetries in charmless three body decays, with a significance ranging from 3 to 5 σ. They are useful inputs for studies on the origin of these large asymmetries which could be related to large strong phase space differences between intermediate states or to final-state re-scattering effects [13]. These asymmetries are not uniformly distributed in phase space. The study of the Dalitz plot distributions shows that large asymmetries are present in localized regions of the phase space, outside known resonance regions. The distribution of the asymmetry across the phase space is shown in fig. 5 for two decays modes. Restricting to the region defined by $m^2_{\pi^+\pi^- high} > 15\,\text{GeV}^2/c^4$ and $m^2_{\pi^+\pi^- low} < 0.4\,\text{GeV}^2/c^4$ or $m^2_{K^+K^-} < 1.5\,\text{GeV}^2/c^4$, the asymmetries are measured to be

$$A^{reg}_{CP}(B^{\pm} \to \pi^+\pi^-\pi^{\pm}) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007,$$
$$A^{reg}_{CP}(B^{\pm} \to K^+K^-\pi^{\pm}) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007.$$

4. – Mixing and CP violation studies with $D^0 \to K\pi$ decays

Charm is the only up-type quark allowing mixing studies. Small CP violation is expected in the SM and the studies provide good probe for possible NP contributions. LHCb was the first experiment to observe D^0 oscillations with an evidence of more than 5σ, with $1\,\text{fb}^{-1}$ of pp data [14].

In the update of the analysis with $3\,\text{fb}^{-1}$ of data a search for CP violation is also performed [15]. A sample of prompt $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays is used, where the D^0 flavour is tagged by the charge of the slow pion emitted in the D^{*+} decay. The sample is divided into right sign decays (RS = $D^0 \to K^-\pi^+$) which are dominated by Cabibbo favoured decays, and wrong sign decays (WS = $D^0 \to K^+\pi^-$) which contain double Cabibbo-suppressed decays and decays after D^0 mixing. About 5.4×10^6 and 2.3×10^5 signal events are selected in the two samples, the mass distribution of the $D^0\pi$ combination is shown in fig. 6. The ratio of the time-dependent decay rate of WS to RS

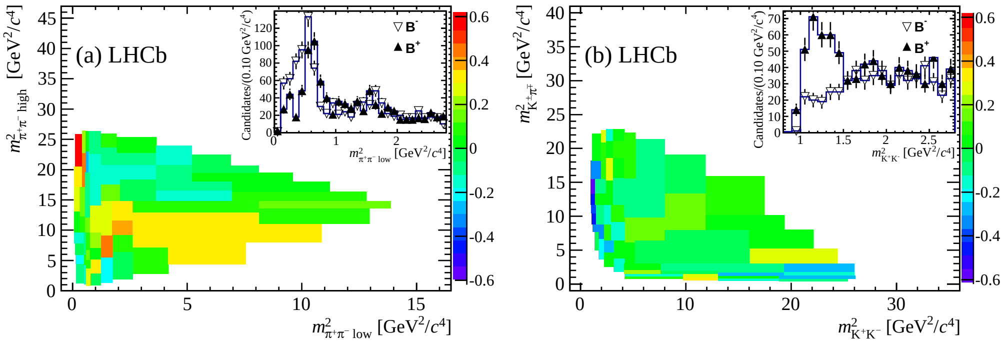

Fig. 5. – Asymmetries of the number of events in bins of the Dalitz plot, for the (a) $B^\pm \to \pi^+\pi^-\pi^\pm$ and (b) $B^\pm \to K^+K^-\pi^\pm$ decays. The inset figures show the projection of the number of events in bins of the (a) $m^2_{\pi^+\pi^- low}$ variable, for $m^2_{\pi^+\pi^- high} > 15\,\mathrm{GeV}^2/c^4$ and (b) of the $m^2_{K^+K^-}$ variable.

can be expressed as

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

where R_D is the ratio of the suppressed to favoured decay rates, x and y are the parameters characterizing the oscillations $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$, Δm is the mass difference between the two mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$ and $1/\Gamma$ is the average of the lifetimes of the two eigenstates. The relations $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$ involve the strong phase difference δ between the suppressed and favoured amplitudes. τ is the D^0 lifetime. In order to search for possible direct or indirect CP violation, separate ratios are measured for initially produced D^0 and $\bar{D}^0$ mesons, as tagged from the D^{*+} de-

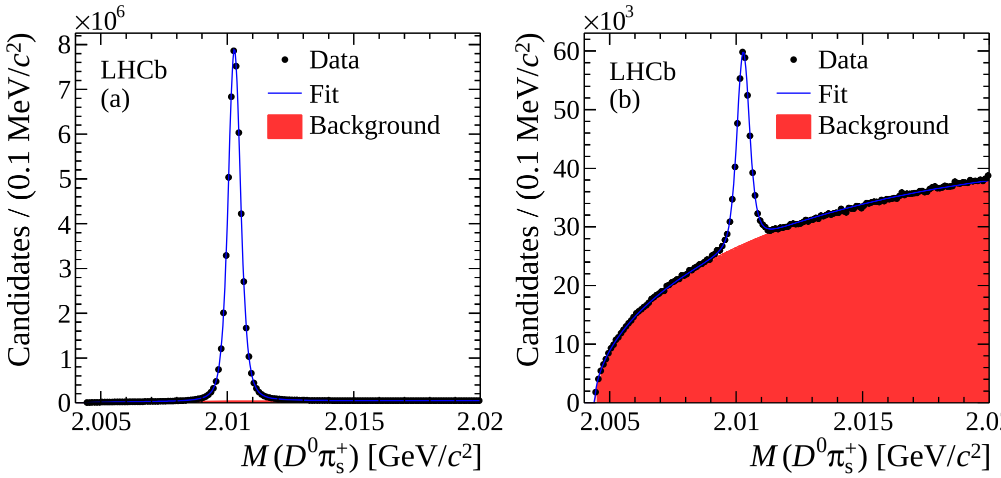

Fig. 6. – Mass distribution of the $D^0\pi$ candidates in the (a) right sign and (b) wrong sign samples.

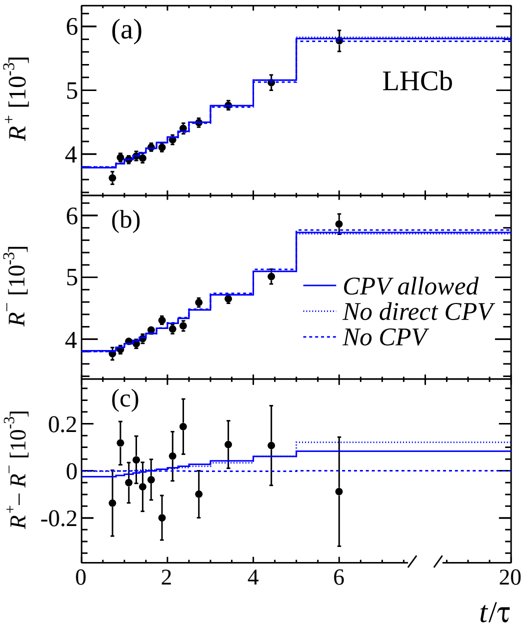

Fig. 7. – Ratios of WS-to-RS event yields for (a) D^{*+} decays (b) D^{*-} decays (c) their difference as a function of the decay time, in units of D^0 lifetime. Projections of the fits allowing for (dashed line) no CP violation, (dotted line) no direct CP violation, and (solid line) full CP violation are overlaid.

cay. Two sets of parameters are used in the two cases, indicated with the superscript "+" and "−", respectively. Three fits are performed to the data, the first allows for direct and indirect CP violation, the second allows only indirect CP violation, constraining $R_D^{\pm}$ to a common value, while the third constraints all parameters to be the same in the D^0 and $\bar{D^0}$ samples. The decay ratios, efficiency corrected, their difference and the fitted functions are shown in fig. 7. The data are compatible with CP symmetry. Direct CP violation is parametrized by the asymmetry, measured to be $(R_D^+ - R_D^-)/(R_D^+ + R_D^-) = (-0.7 \pm 1.9)\%$. Indirect CP violation would manifest itself in a time dependence of the difference of the yield ratios, but the slope in fig. 7(c) is compatible with zero. From the first fit, the magnitude $|q/p|$ is derived as $0.75 < |q/p| < 1.2$ at 68% CL, providing no evidence of CP violation in mixing. In the CP-conserving hypothesis, the world best determination of the mixing parameters is obtained as $R_D = (3.568 \pm 0.058 \pm 0.033) \times 10^{-3}$, $y' = (4.8 \pm 0.08 \pm 0.5) \times 10^{-3}$, $x'^2 = (5.5 \pm 4.2 \pm 2.6) \times 10^{-5}$, where the first uncertainty is statistical and the second is the experimental systematic.

5. – Effective lifetimes in $D^0 \to KK, \pi\pi$

The measurement of effective lifetimes of D^0 decays into CP-even eigenstates $D^0 \to K^+K^-$ or $D^0 \to \pi^+\pi^-$ provides a test of the presence of indirect CP violation [16]. The asymmetry of the effective lifetimes is

$$A_\Gamma = \frac{\hat{\tau}(\bar{D^0}) - \hat{\tau}(D^0)}{\hat{\tau}(\bar{D^0}) + \hat{\tau}(D^0)} \approx \left(\frac{A_M + A_d}{2} y \cos\phi - x \sin\phi\right),$$

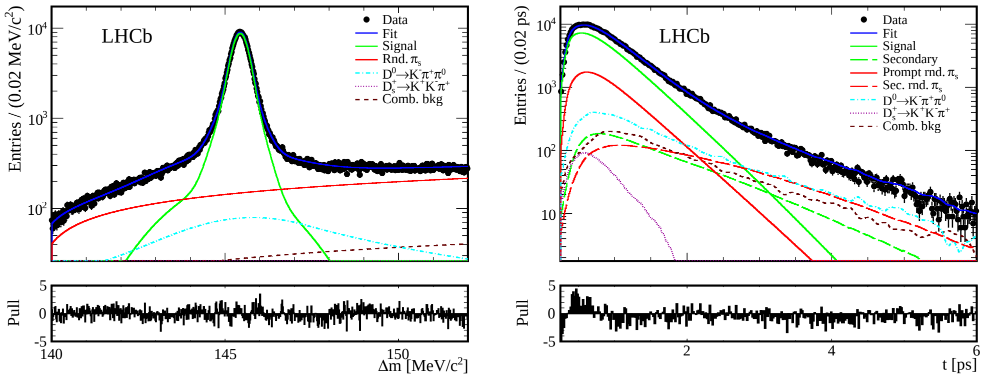

Fig. 8. – Distributions of (left) $D^* - D^0$ mass difference and (right) decay time for a sample of $\bar{D}^0 \to K^+K^-$ candidates, the fit projections are overlaid.

where x, y have been defined before, $A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$, $A_d = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$, being A_f ($\bar{A}_f$) the amplitude for the D^0 ($\bar{D}^0$) decay into the final state f, and ϕ is the mixing phase. A_Γ is sensitive to CP violation in mixing, as the contribution from direct CP violation is expected to be negligible compared to the current precision of measurements. In the SM the phase is independent on the final state and is zero if CP is conserved. The measurement is performed by LHCb using $1\,\text{fb}^{-1}$ of data, 3.1×10^6 $D^0 \to K^+K^-$, 1.03×10^6 and $D^0 \to \pi^+\pi^-$ signal candidates are found, flavour tagged by the charge of the slow pion emitted in D^{*+} decays. Two-stage unbinned maximum likelihood fits are performed. First the mass of the $KK(\pi\pi)$ pair and the D^*-D^0 mass difference are fitted, in order to discriminate signal from background and to determine the yield of D^0 and $\bar{D}^0$. Then a fit is performed to the D^0 decay time and to the D^0 pointing in order to determine the D^0 lifetime, discriminating from the small component of non-prompt D^0 events. The data are divided into eight samples according to the LHCb magnet polarity and the running period. In fig. 8 the mass and decay time distributions are shown for one sample of $\bar{D}^0 \to K^+K^-$ candidates. The decay time acceptance is measured on data. The asymmetries are determined as

$$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}, \qquad A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$$

showing no evidence of CP violation and no significant difference between the two final states.

6. – Search for direct CP violation in $D^+ \to \pi^+\pi^-\pi^+$ decays

The asymmetry between time-integrated decay rates of $D^+ \to \pi^+\pi^-\pi^+$ and $D^- \to \pi^-\pi^+\pi^-$ decays has been measured by LHCb with $1\,\text{fb}^{-1}$ of data [17]. The decay is a Cabibbo-suppressed decay sensitive to possible NP contributions. The analysis exploits multi-body dynamics to search for charge asymmetries localized in phase space regions using a strategy similar to the one used in the study of four-bodies decays of charmed mesons in ref. [18]. In order to control possible asymmetries related to production or detection effects, the Cabibbo favoured decays $D_s^- \to \pi^-\pi^+\pi^-$ are used. The signal and the control decay modes contain about 2.7×10^6 events each. The Dalitz plot distributions of the D^+ and D^- samples are compared using a model-independent technique. A χ^2 test is performed on a statistics constructed from the ratios of D^+ and D^- events in each bin. Different binning strategies are tried and all p-values for the null hypothesis of no CP violation are found to be above 50%, thus giving no evidence of CP violation in the three-body $D^\pm$ decay.

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