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Charm mixing and CP violation at the LHCb experiment

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In pp collisions at the LHC, the LHCb experiment has collected the world's largest sample of beauty and charmed hadrons. Very precise measurements obtained from these data provide tests of the Standard Model, which can be interpreted as indirect searches for new physics. Using data corresponding to an integrated luminosity of 3.0 fb^{-1} recorded in 2011 and 2012, measurements of direct and indirect CP violation in the charm sector and of D^0 mixing parameters were performed. Results from several decay modes are presented with complementary time-dependent and time-integrated analyses.

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1. Introduction

The Standard Model (SM) describes the fundamental particles interactions via the strong, electromagnetic and weak forces. It provides precise predictions for measurable quantities that can be tested experimentally. It is widely considered that the SM is not final since many phenomena in this model are not well understood. For this reason, today, one of the main goal of particle physics is to search for physics beyond the SM.

In the LHCb experiment [1], the experimenters are testing the SM in precise measurements of known processes. If the disagreement between the experiment and the SM prediction is found, it will be indication for the existence of the new physics effects. The promising areas in these searches are the measurements of CP symmetry violation. The CP asymmetry has been observed in $K-$ and $B-$ meson systems [2, 3, 4, 5, 6]. However, no CPV has been observed in the charm sector, despite the experimental progress seen in charm physics in the last decade.

The CPV in the charm sector is expected to be very small in the SM [7]. Since evidence of $D^0-\bar{D}^0$ oscillations was first reported [8, 9, 10] there is growing interest in this subject. Details of the measurement of $D^0-\bar{D}^0$ oscillations achieved recently at the LHCb are discussed in Sec. 3. CPV arises when two or more amplitudes with different weak and strong phases contribute to the same final state. This is possible in the singly Cabibbo-suppressed (SCS) D decays, where significant tree and penguin contributions can be expected. The time-integrated CP asymmetry measurements in two-body SCS D^0 decays are discussed in Secs 4 and 5. Conclusions are presented in Sec. 6.

2. LHCb detector

The LHCb detector [1] is a single-arm forward spectrometer covering pseudorapidity range from 2 up to 5. The detector was designed for study of particles containing b or c quarks. Displaced vertices of b and c-hadron decays can be measured with 20 μm resolution. The decay time resolution of 10% of the D meson lifetime is achieved using a silicon vertex locator. The tracking system measures the charged particles with a momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV to 0.6% at 100 GeV, corresponding to a typical mass resolution of approximately a few MeV for a two-body charm meson decay. The $b\bar{b}$ cross-section in 4π in pp collisions of 284 ± 53 μb is measured with the LHCb detector at $\sqrt{s} = 7$ TeV [11]. The measured $c\bar{c}$ cross-section is about 20 times larger than the $b\bar{b}$ cross-section [12].

3. Observation of $D^0-\bar{D}^0$ oscillation in $D^0 \to K^+\pi^-\pi^+\pi^-$

Until now, all observations of charm oscillations have been made in the decay mode $D^0 \to K^+\pi^-$ [13, 14, 15]. The first such observation in a different decay channel, $D^0 \to K^+\pi^-\pi^+\pi^-$ is performed by the LHCb experiment [16]. This measurement is made by measuring the time-dependent ratio of $D^0 \to K^+\pi^-\pi^+\pi^-$ to $D^0 \to K^-\pi^+\pi^-\pi^+$ decay rates. The $D^0 \to K^+\pi^-\pi^+\pi^-$ decays are called wrong-sign (WS) decays. The $D^0 \to K^-\pi^+\pi^-\pi^+$ decays are called right-sign (RS) decays. The WS amplitude includes dominant contributions from both the doubly Cabibbo-suppressed (DCS) decay, and a $D^0-\bar{D}^0$ oscillation followed by a Cabibbo-favoured (CF) decay.

The RS decays are dominated by the CF amplitude, and has negligible contributions from $D^0-\bar{D}^0$ oscillations. The D^0 flavour has to be identified at both the production and decay. The flavour of the D^0 meson at the production time is identified by the charge of the slow pion (π_s) from $D^{*+}\to D^0\pi_s^+$ and $D^{*-}\to\bar{D}^0\pi_s^-$ decays. The flavour at the time of decay is identified using the almost flavour-specific final state.

Assuming negligible CPV, to second order in t/τ, the time-dependence of the phase space ratio $R(t)$ of WS to RS integrated decay rates is approximated by [7]

$$R(t)=(r_D)^2-r_DR_Dy'\frac{t}{\tau}+\frac{x^2+y^2}{4}(\frac{t}{\tau})^2, \tag{3.1}$$

where t/τ is the decay time expressed in units of the average D^0 lifetime (τ), r_D gives the phase space averaged ratio of DCS to CF amplitudes. The dimensionless parameters x and y describe mixing in the D^0 meson system, with x proportional to the mass difference of the two mass eigenstates, ΔM ($x=\Delta M/\Gamma$), and y proportional to the width difference, $\Delta\Gamma$ ($y=\Delta\Gamma/2\Gamma$). The Γ is the average D^0 decay width. The y' is defined by $y'\equiv y\cos\delta_D-x\sin\delta_D$, where δ_D is the average strong phase difference. The coherence factor, R_D, and δ_D are defined by $R_De^{-i\delta_D}\equiv\langle\cos\delta\rangle+i\langle\sin\delta\rangle$, where $\langle\cos\delta\rangle$ and $\langle\sin\delta\rangle$ are the cosine and sine of the phase difference between CF and DCS amplitudes averaged over a phase space.

The measurement of the time-dependent WS/RS ratio is performed with 3 fb^{-1} in ten independent bins of D^0 decay time, chosen to have a similar number of candidates in each bin. The number of RS and WS decays are determined using fits to the invariant mass difference $\Delta m\equiv m(K^+\pi^-\pi^+\pi^-\pi_s^\pm)-m(K^+\pi^-\pi^+\pi^-)$ distributions in each bin. The Δm distribution of WS and RS signal candidates with the results of a binned likelihood fit superimposed in shown in Fig. 1. The RS (WS) yield estimated from the fit corresponds to 11.4×10^6 (42500) events.

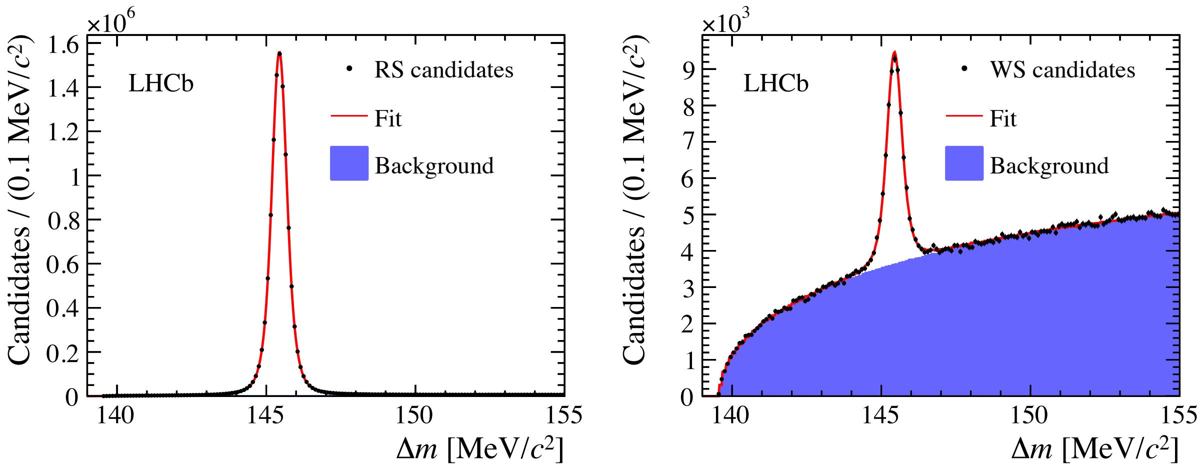

Figure 1: Decay time integrated Δm distributions for RS (left) and WS (right) candidates with the fit result superimposed.

To study the time dependence of the WS/RS ratio, the two fits are performed to the data: the unconstrained and no-mixing fit configurations. In no-mixing fit configuration the parameters $R_D y'$ and $\frac{1}{4}(x^2+y^2)$ are fixed to zero. Fig. 2 shows the decay time-dependent fits to the WS/RS ratio. The no-mixing hypothesis is excluded at a significance level of 8.2 standard deviations. In the unconstrained fit the obtained parameters are $r_D = (5.67 \pm 0.12) \times 10^{-2}$, $R_D y' = (0.3 \pm 1.8) \times 10^{-3}$ and $\frac{1}{4}(x^2+y^2) = (4.8 \pm 1.8) \times 10^{-5}$. In comparison, in the mixing-constrained fit the parameters are $r_D = (5.50 \pm 0.07) \times 10^{-2}$, $R_D y' = (-3.0 \pm 0.7) \times 10^{-3}$, $x = (4.1 \pm 1.7) \times 10^{-3}$ and $y = (6.7 \pm 0.8) \times 10^{-3}$.

The decay time-integrated WS/RS ratio, $R = (r_D)^2 - r_D R_D y' + \frac{1}{2}(x^2+y^2)$, is calculated to be $(3.29 \pm 0.08) \times 10^{-3}$ for the unconstrained result and $(3.22 \pm 0.05) \times 10^{-3}$ for the mixing-constrained result.

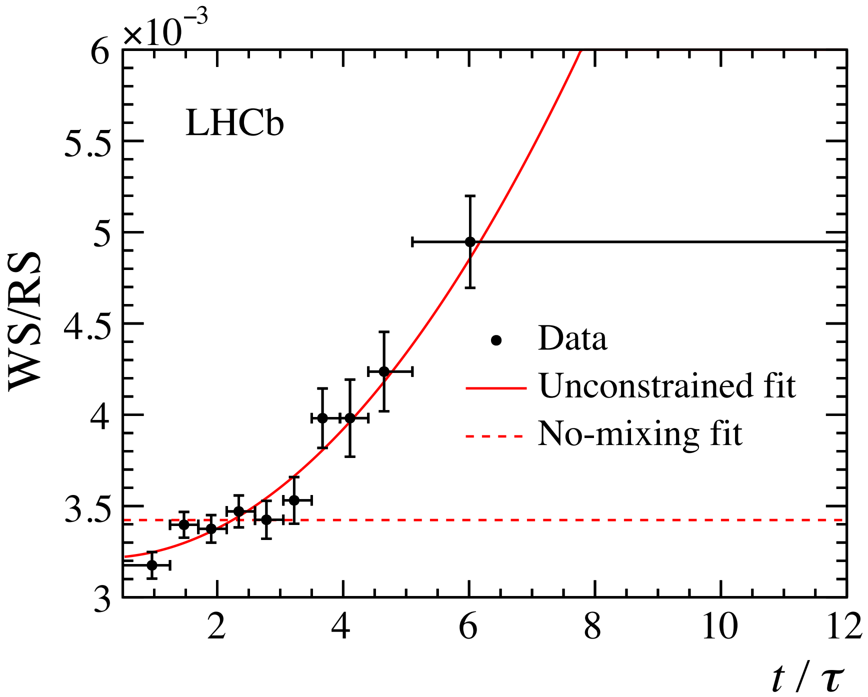

Figure 2: Decay time evolution of the background-subtracted and efficiency correlated WS/RS ratio (points) with the results of the unconstrained (solid line) and no-mixing (dashed line) fits superimposed.

4. The difference of time-integrated *CP* asymmetries in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ decays

The *CP* asymmetry of a decay of a D^0 meson to a *CP* eigenstate, $A_{CP}(f)$, can be expressed in terms of two contributions: a direct component associated with CPV in the decay amplitudes and an indirect component associated with CPV in the mixing or in the interference between mixing and decay. It can be written to the first order as [17, 18]

$$A_{CP}(f) = a_{CP}^{\mathrm{dir}}(f)\left(1 + \frac{\langle t(f)\rangle}{\tau} y_{CP}\right) + \frac{\langle t(f)\rangle}{\tau} a_{CP}^{\mathrm{ind}}, \tag{4.1}$$

where $\langle t(f) \rangle$ denotes the mean decay time of $D^0 \to f$ decays in the reconstructed sample, $a_{CP}^{\text{dir}}(f)$ is the direct CPV, τ the D^0 lifetime, a_{CP}^{ind} the indirect CPV and y_{CP} is the deviation from unity of the ratio of the effective lifetimes of decays to flavour specific and CP-even final states. The indirect component is universal for CP eigenstates in the SM, whilst the direct component depends in general on the final state.

The time-integrated CP asymmetry measurement of difference between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$, ΔA_{CP}, is performed with 3 fb^{-1} [19]. The flavour of the D^0 meson at the production state is identified in the same way as in the measurement of observation of $D^0 - \bar{D}^0$ oscillation (see Sec. 3).

The measured raw time-integrated asymmetry is a sum of physics and detector asymmetries,

$$A_{\text{Raw}}(f) = A_{CP}(f) + A_{\text{D}}(f) + A_{\text{D}}(\pi_s^+) + A_{\text{P}}(D^{*+}), \tag{4.2}$$

where $A_{\text{D}}(f)$ and $A_{\text{D}}(\pi_s^+)$ are the asymmetries in the reconstruction efficiencies of the D^0 final state and of the soft pion, $A_{\text{P}}(D^{*+})$ is the production asymmetry for D^{*+} mesons, arising from the hadronisation of charm quarks in pp collisions. The magnitudes of $A_{\text{D}}(\pi_s^+)$ and $A_{\text{P}}(D^{*+})$ are both about 1%. Since both K^-K^+ and $\pi^-\pi^+$ final states are self-conjugate, $A_{\text{D}}(K^-K^+)$ and $A_{\text{D}}(\pi^-\pi^+)$ are identically zero. To a good approximation $A_{\text{D}}(\pi_s^+)$ and $A_{\text{P}}(D^{*+})$ are independent of the final state f in any given kinematic region, and thus cancel in the difference, giving

$$\Delta A_{CP} = A_{\text{Raw}}(K^-K^+) - A_{\text{Raw}}(\pi^-\pi^+). \tag{4.3}$$

A binned minimum χ^2 fits to the mass difference δm distributions, $\delta m \equiv m(h^-h^+\pi_s^+) - m(h^-h^+) - m(\pi^+)$ for $h = K, \pi$, are performed to determine the signal yields. The δm distributions of the $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ are shown in Fig. 3. The D^{*+} signal yields are 7.7×10^6 for $D^0 \to K^-K^+$ decays and 2.5×10^6 for $D^0 \to \pi^-\pi^+$ decays.

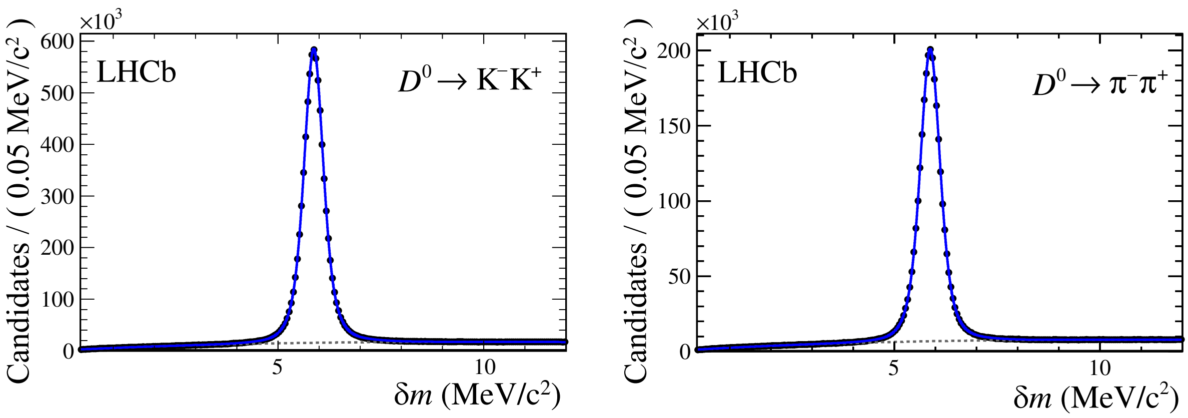

Figure 3: Fit to the δm spectra, where the D^0 is reconstructed in the final state K^-K^+ (left) and $\pi^-\pi^+$ (right). The dashed line corresponds to the background component in the fit.

The data samples are split into eight mutually exclusive subsamples. The value of ΔA_{CP} is determined in each subsample. Testing the eight independent measurements for mutual consistency gives $\chi^2/ndf = 6.2/7$, corresponding to a p-value of 0.52, where the ndf is the number degree of freedom. The weighted average of the values corresponding to all subsamples is calculated as

$$\Delta A_{CP} = (-0.10 \pm 0.08(stat) \pm 0.03(syst))\%.$$

The difference in CP asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ can be written as [19]

$$\Delta A_{CP} = \Delta a_{CP}^{\text{dir}}(1 + \frac{\langle \bar{t} \rangle}{\tau} y_{CP}) + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\text{ind}}, \tag{4.4}$$

where $\langle \bar{t} \rangle$ is the arithmetic average of $\langle t(K^-K^+) \rangle$ and $\langle t(\pi^-\pi^+) \rangle$.

The difference and the average of the mean decay times relative to the D^0 lifetime are measured as

$$\Delta \langle t \rangle / \tau(D^0) = 0.1153 \pm 0.0007(stat) \pm 0.0018(syst)$$

and

$$\langle \bar{t} \rangle / \tau(D^0) = 2.0949 \pm 0.0004(stat) \pm 0.0159(syst).$$

Given the dependence of ΔA_{CP} on the direct and indirect CP asymmetries and the measured value of $\Delta \langle t \rangle / \tau$, the contribution from indirect CPV is suppressed and ΔA_{CP} is primarily sensitive to direct CPV.

The flavour of the D^0 meson at the production point can also identified using the other independent method, in which the D^0 mesons are produced in inclusive semileptonic B meson decays to the $D^0\mu^-\bar{\nu}_\mu X$ final state, where X means other possible particles [20]. The charge of the accompanying muon in this case used to identify the flavour of the D^0 meson ($\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ or $B \to \bar{D}^0\mu^+\nu_\mu X$). For these decays, the ΔA_{CP} between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ is measured as

$$\Delta A_{CP} = (0.14 \pm 0.16(stat) \pm 0.08(syst))\%.$$

The above value agrees with the value obtained in the method, in which the D^0 meson is produced in D^{*+} decay.

5. Measurement of indirect CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays

The singly Cabibbo-suppressed (SCS) decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ also are used to measure indirect CPV from the asymmetry between the effective D^0 and $\bar{D}^0$ lifetimes, A_Γ. The effective lifetime is the lifetime obtained from a single exponential fit to the decay time distribution.

The time-dependent CP asymmetry can be written, to the first order, as [17]

$$A_{CP}(t) = a_{CP}^{\text{dir}} - A_\Gamma \frac{t}{\tau}. \tag{5.1}$$

Furthermore, A_Γ can be approximated in terms of the $D^0-\bar{D}^0$ mixing parameters x and y, as [18]

$$A_\Gamma = (a_{CP}^{\rm mix}/2 - a_{CP}^{\rm dir})y\cos\phi - x\sin\phi, \tag{5.2}$$

where $a_{CP}^{\rm mix}$ describes CPV in $D^0-\bar{D}^0$ mixing, the weak phase ϕ describes CPV in the interference between mixing and decay.

As well as in the measurements of the ΔA_{CP}, the initial flavour of the D^0 is determined by the charge of the accompanying muon in semileptonic b-hadron decays [21]. The initial flavour of the D^0 can be determined by the charge of the pion in the $D^{*+} \to D^0\pi^+$ decays [22].

The mass distributions for the selected $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$, tagged using the charge of the accompanying muon in semileptonic b-hadron decays, are shown in Fig. 4. The number of signal candidates obtained from the fits are 2.34×10^6 for $D^0 \to K^-K^+$ and 0.79×10^6 for $D^0 \to \pi^-\pi^+$.

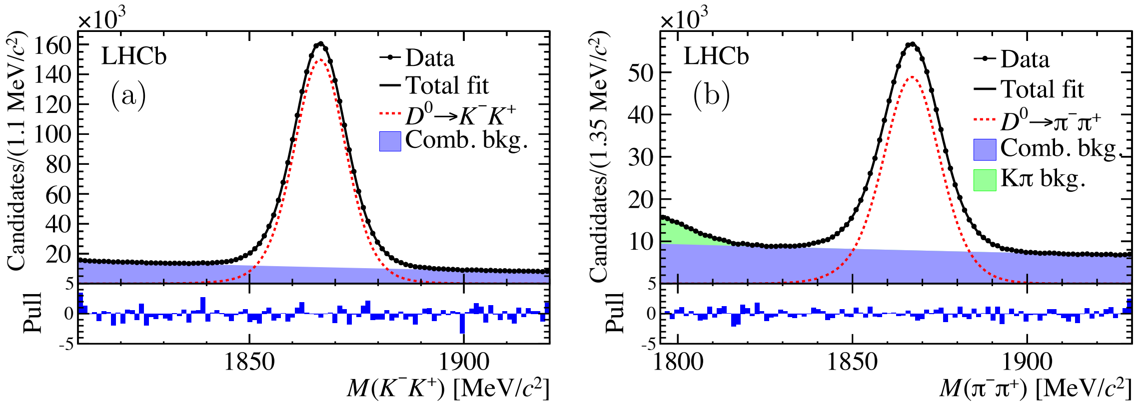

Figure 4: Invariant mass distributions for (a) $D^0 \to K^-K^+$ and (b) $D^0 \to \pi^-\pi^+$ candidates. The results of the fits are overlaid. Underneath each plot the pull in each mass bin is shown, where the pull is defined as the difference between the data point and total fit, divided by the corresponding uncertainty.

The raw CP asymmetry is determined from fits to the mass distributions in 50 bins of the D^0 decay time. The fits are performed simultaneously for D^0 and $\bar{D}^0$ candidates and the asymmetry is determined for each decay time bin. The measured asymmetries in bins of decay time are shown in Fig. 5. From a χ^2 fit to these distributions, the values of A_Γ are determined as

$$A_\Gamma(K^-K^+) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%,$$

$$A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%.$$

The values for A_Γ are compatible with the assumption of no indirect CPV. The fits have good p-values of 54.3% ($D^0 \to K^-K^+$) and 30.8% ($D^0 \to \pi^-\pi^+$). The above measured values are sensitive to direct CPV and they agree with those measured in second method, when the initial flavour of the D^0 is determined by the charge of the pion in a $D^{*+} \to D^0\pi^+$ decays:

$$A_\Gamma(K^-K^+) = (-0.035 \pm 0.062 \pm 0.012)\%,$$

$$A_\Gamma(\pi^-\pi^+) = (-0.033 \pm 0.106 \pm 0.014)\%.$$

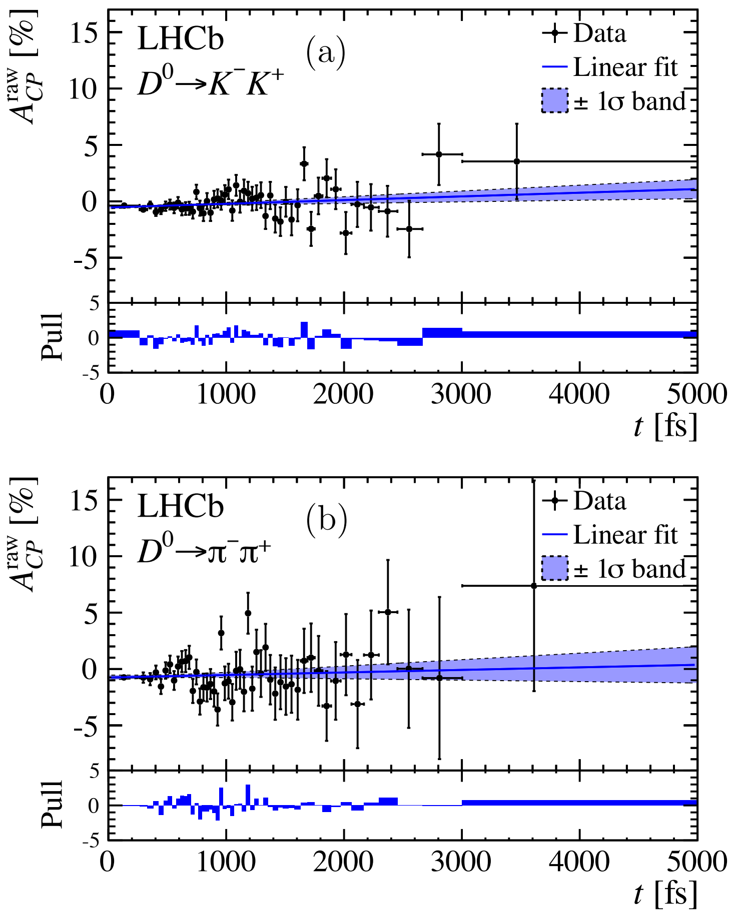

Figure 5: Raw *CP* asymmetry as fuction of D^0 decay time for (a) $D^0 \to K^-K^+$ and (b) $D^0 \to \pi^-\pi^+$ candidates. The results of the χ^2 fits are shown as blue, solid lines with the ± 1 standard deviation (σ) bands indicated by the dashed lines. Underneath each plot the pull in each time bin is shown.

6. Summary

The data, corresponding to an integrated luminosity of 3 fb^{-1}, recorded using the LHCb detector in 2011 and 2012, are used to precisely test the SM predictions. The decay time dependence of the ratio $D^0 \to K^+\pi^-\pi^+\pi^-$ to $D^0 \to K^-\pi^+\pi^-\pi^+$ decay rates is observed and no-mixing hypothesis is excluded at a significance level of 8.2 standard deviations. Study of time-integrated difference in *CP* asymmetry between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, as well as time-dependent asymmetries in the effective lifetimes of the same decays, are consistent with the hypothesis of no *CP* violation in charm sector. There are the most precise measurements of *CP* asymmetry in charm sector from a single experiment.

Assuming that indirect *CP* violation is independent of the D^0 final state, and combining all LHCb measurements on *CP* violation in charm sector, the values of the direct and indirect *CP* asymmetries are found to be $\Delta a_{CP}^{\rm dir} = (-0.061 \pm 0.076)\%$ and $a_{CP}^{\rm ind} = (0.058 \pm 0.044)\%$ [19]. Results are summarized in the ($\Delta a_{CP}^{\rm dir}$,$a_{CP}^{\rm ind}$) plane shown in Fig. 6. The result is consistent with the hypothesis of *CP* symmetry with a *p*-value of 0.32.

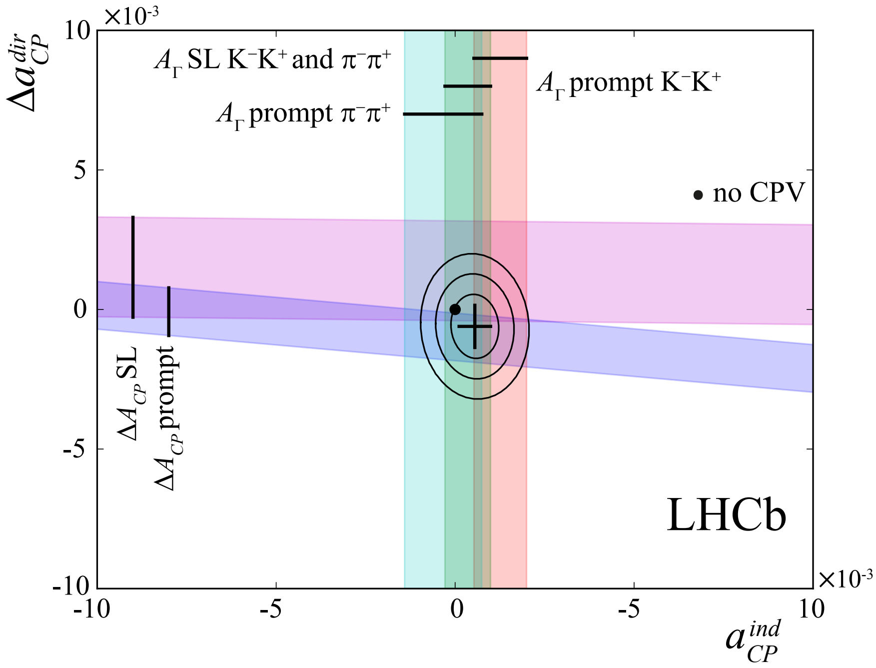

Figure 6: Contour plot of $\Delta a_{CP}^{\rm dir}$ versus $a_{CP}^{\rm ind}$. The point $(0,0)$ denotes the hypothesis of no *CP* violation. The solid bands represent the measurements in Refs. [19, 20, 21, 23]. The contour lines show the 68%, 95% and 99% confidence-level intervals from the combination.

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