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Searches for CP violation in two-body charm decays

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The LHCb experiment recorded data corresponding to an integrated luminosity of 3.0 fb^{-1} during its first run of data taking. These data yield the largest samples of charmed hadrons in the world and are used to search for *CP* violation in the D^0 system. Among the many measurements performed at LHCb, a measurement of the direct *CP* asymmetry in $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ decays is presented and is found to be

$$A_{CP}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-2.9 \pm 5.2 \pm 2.2)\,\%,$$

where the first uncertainty is statistical and the second systematic. This represents a significant improvement in precision over the previous measurement of this parameter. Measurements of the parameter A_Γ, defined as the *CP* asymmetry of the D^0 effective lifetime when decaying to a *CP* eigenstate, are also presented. Using semi-leptonic b-hadron decays to tag the flavour of the D^0 meson at production with the $\mathrm{K}^+\mathrm{K}^-$ and $\pi^+\pi^-$ final states yields

$$A_\Gamma(\mathrm{K}^+\mathrm{K}^-) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\,\%,$$
$$A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\,\%.$$

Thus no evidence of direct or indirect *CP* violation in the D^0 system is found, though it is tightly constrained.

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1. Introduction

The D^0 meson is the only heavy, neutral meson comprised from up-type quarks in the Standard Model (SM) making it a unique system in which to study *CP* violation. Due to the form of the CKM matrix *CP* violation in interactions involving charm quarks is strongly suppressed. For a final state f, defining the amplitudes $A_f = \langle f|\mathscr{H}|\mathrm{D}^0\rangle$, $A_{\bar{f}} = \langle \bar{f}|\mathscr{H}|\mathrm{D}^0\rangle$, $\bar{A}_f = \langle f|\mathscr{H}|\bar{\mathrm{D}}^0\rangle$, and $\bar{A}_{\bar{f}} = \langle \bar{f}|\mathscr{H}|\bar{\mathrm{D}}^0\rangle$, with $\mathscr{H}$ the Hamiltonian, direct *CP* violation is quantified by

$$A_{CP}^{dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}. \tag{1.1}$$

In the SM direct *CP* violation in the decays $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$ is predicted to be up to $\mathscr{O}(10^{-3})$ [1].

As the D^0 meson is neutral it can oscillate into a $\bar{\mathrm{D}}^0$ meson, and vice-versa. Consequently, the mass eigenstates in which the D^0 and $\bar{\mathrm{D}}^0$ mesons propagate are superpositions of the flavour eigenstates, defined by

$$|\mathrm{D}_{L,H}\rangle = p|\mathrm{D}^0\rangle \pm q|\bar{\mathrm{D}}^0\rangle, \tag{1.2}$$

with masses $m_{H,L}$ and widths $\Gamma_{H,L}$. Here p and q are complex, satisfying $|p|^2 + |q|^2 = 1$. The rate of mixing is quantified by

$$x = \frac{2(m_H - m_L)}{\Gamma_H + \Gamma_L}, \text{ and } y = \frac{\Gamma_H - \Gamma_L}{\Gamma_H + \Gamma_L}. \tag{1.3}$$

D^0 mixing is now firmly established experimentally though uncertainties are still relatively large [2]. *CP* violation in mixing is quantified (following the conventions of [3]) by

$$A_{CP}^{mix} = \left|\frac{q}{p}\right|^2 - 1. \tag{1.4}$$

For a final state accessible to both D^0 and $\bar{\mathrm{D}}^0$ mesons *CP* violation can arise from interference between mixing and decay, which is quantified by

$$\lambda_f \equiv \frac{qA_f}{p\bar{A}_f} = \left|\frac{qA_f}{p\bar{A}_f}\right| e^{i\phi}. \tag{1.5}$$

Such indirect *CP* violation is predicted to be up to $\mathscr{O}(10^{-4})$ in the SM [4]. Observation of larger direct or indirect *CP* violation than SM predictions would be a strong indication of new physics.

The LHCb detector at the LHC, CERN, is a forward arm spectrometer covering the high pseudo-rapidity region $2 < \eta < 5$ and is specifically designed to perform high precision measurements of decays involving b and c quarks [5]. Key components of the detector are: the Vertex Locator (VELO), which provides fine tracking around the interaction point and achieves impact parameter resolutions of ∼20 µm for tracks with $p_T > 1$ GeV [6]; two Ring Imaging Cherenkov detectors providing particle identification with excellent separation of π and K mesons across a wide momentum range [7]; and the tracking stations, positioned before and after the dipole magnet, which achieve momentum resolutions of ∼0.5-0.8 % [8].

During its first data-taking run the LHCb experiment recorded data corresponding to integrated luminosities of 1.0 fb^{-1} at $\sqrt{s} = 7\,\mathrm{TeV}$ in 2011 and 2.0 fb^{-1} at $\sqrt{s} = 8\,\mathrm{TeV}$ in 2012. As the $c\bar{c}$ production cross section in the pp collisions provided by the LHC is very large [9] this has yielded the largest data sets of charm meson decays in the world. This has allowed the LHCb experiment to perform many of the highest precision measurements of *CP* violation in the D^0 system to date. Among these are the measurement of direct *CP* violation in $\mathrm{D}^0 \to \mathrm{K^0_S K^0_S}$ decays [10], presented in Sec. 2, and the measurements of indirect *CP* violation in $\mathrm{D}^0 \to \mathrm{K^+K^-}$ and $\mathrm{D}^0 \to \pi^+\pi^-$ [11], presented in Sec. 3.

2. Direct *CP* violation in $\mathrm{D}^0 \to \mathrm{K^0_S K^0_S}$

The dominant, tree-level amplitudes in $\mathrm{D}^0 \to \mathrm{K^0_S K^0_S}$ decays largely cancel, meaning the $\mathrm{K^0_S K^0_S}$ final state is predominantly reached through final state scattering $\mathrm{D}^0 \to \pi^+\pi^- \to \mathrm{K^0_S K^0_S}$ and $\mathrm{D}^0 \to \mathrm{K^+K^-} \to \mathrm{K^0_S K^0_S}$. The additional interference introduced by this re-scattering can enhance direct *CP* violation to $\mathscr{O}(10^{-2})$. The only previous measurement of this found $A_{CP}(\mathrm{D}^0 \to \mathrm{K^0_S K^0_S}) = (23 \pm 19)\%$ [12].

To determine $A_{CP}(\mathrm{D}^0 \to \mathrm{K^0_S K^0_S})$, firstly $\mathrm{K^0_S} \to \pi^+\pi^-$ candidates are reconstructed and combined to form the D^0 candidates. These are required to have invariant mass within ±20 MeV of the known D^0 mass [13]. As this is a *CP* eigenstate final state there is no detection asymmetry. The flavour of the D^0 candidates at production is determined using $\mathrm{D}^{*+} \to \mathrm{D}^0\pi_s^+$ decays, where the charge of the “soft pion”, π_s^+, determines the D^0 flavour. Decays of $\mathrm{D}^{*+} \to \mathrm{D}^0\pi_s^+$ with $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ are used to determine the D^{*+} production and π_s^+ detection asymmetries. The background from $\mathrm{D}^0 \to \mathrm{K^0_S}\pi^+\pi^-$ decays is removed using a minimum flight distance cut on the $\mathrm{K^0_S}$ candidates. The remaining background is combinatorial which is minimised via a multi-variate selection using candidate kinematics, decay times, geometry and decay-tree fit quality variables.

Candidates are accepted if any track in the event, excluding that of the π_s^+ candidate, has triggered the event. As $\mathrm{K^0_S}$ mesons are relatively long lived slightly more than half of their decays occur outside the acceptance of the VELO. Those which decay outside the VELO but before the tracking station in front of the dipole magnet (known as downstream candidates) are still reconstructed but with worse momentum and vertex resolution than those which decay within the VELO (known as long candidates). Consequently the D^0 candidates are divided into subsets where: both $\mathrm{K^0_S}$ candidates are long (LL); one $\mathrm{K^0_S}$ candidate is long and the other downstream (LD); both $\mathrm{K^0_S}$ candidates are downstream (DD). Additionally, a dedicated trigger for LL candidates was implemented for 2012 data taking giving a much cleaner data sample, so candidates satisfying this trigger (labelled LLtrig) are separated from other LL candidates.

To improve the D^0 and D^{*+} mass resolutions the mass of the $\mathrm{K^0_S}$ candidates is constrained to the known $\mathrm{K^0_S}$ mass and the trajectory of the D^0 candidate is constrained to originate from primary interaction point. The yields of D^0 and $\overline{\mathrm{D}}{}^0$ signal are then determined via fits to the distribution of $\Delta m \equiv m(\mathrm{D}^{*+}) - m(\mathrm{D}^0)$. The signal is modelled using a sum of three Gaussians and the combinatorial background with an empirical threshold function. The four subsets (LLtrig, LL, LD, DD) are fitted independently. For each fit the shape parameters for signal and background are shared between D^0 and $\overline{\mathrm{D}}{}^0$ candidates. Fig. 1 shows the Δm fits for LL candidates. In total, approximately 650 signal decays are found.

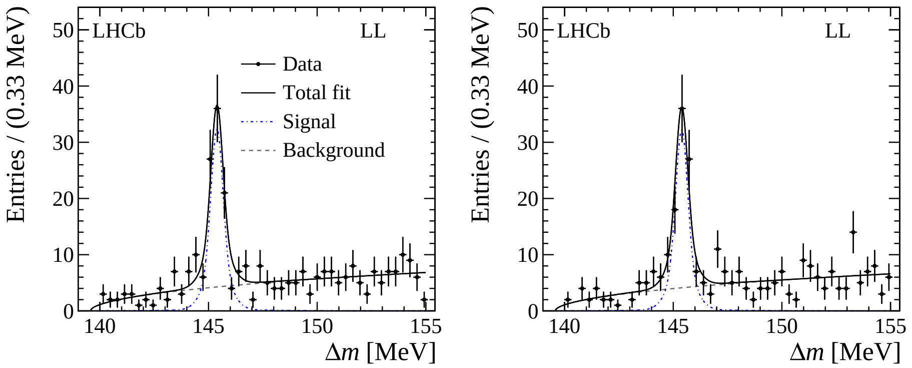

Figure 1: Fits to the distribution of Δm for (left) D^0 and (right) $\bar{\mathrm{D}}^0$ LL candidates.

The final result is obtained by taking a simple weighted average of the asymmetries of each subset and is found to be

$$A_{CP}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-2.9 \pm 5.2 \pm 2.2)\,\%, \tag{2.1}$$

where the first uncertainty is statistical and the second systematic. The dominant systematic uncertainties arise from the accuracy of the fit model and the D^{*+} production and π^+_s detection asymmetries (determined from the control channel). This represents a significant improvement in precision over the previous measurement, but shows no indication of *CP* violation. For the second data taking run the precision achieved is expected to improve significantly due to the implementation of dedicated triggers for LD and DD candidates.

3. Indirect *CP* violation in semi-leptonic-tagged $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$

The *CP* asymmetry of the effective lifetime of the D^0 meson decaying to a *CP* eigenstate final state, f, is primarily sensitive to indirect *CP* violation as [14]

$$A_\Gamma \equiv \frac{\hat{\Gamma}(\mathrm{D}^0 \to f) - \hat{\Gamma}(\bar{\mathrm{D}}^0 \to f)}{\hat{\Gamma}(\mathrm{D}^0 \to f) + \hat{\Gamma}(\bar{\mathrm{D}}^0 \to f)} \approx \eta_{CP}\left[\left(A^{mix}_{CP}/2 - A^{dir}_{CP}\right) y\cos\phi - x\sin\phi\right], \tag{3.1}$$

where $\hat{\Gamma}$ is the inverse of the effective lifetime and η_{CP} is the *CP* eigenvalue of f. For $\mathrm{D}^0 \to \pi^+\pi^-$ and $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ decays $\eta_{CP} = 1$. Previous measurements of A_Γ using D^{*+} tagged D^0 decays have found no evidence of *CP* violation [15].

A complementary flavour tagging technique is to use $\mathrm{B} \to \mathrm{D}^0\mu^- X$ decays, where the charge of the μ^- gives the flavour of the D^0 at production and X denotes any other decay products of the B that aren't considered. To measure A_Γ, combinatorial backgrounds are firstly minimised by applying cuts to kinematic and decay-tree fit quality variables. The yields of D^0 and $\bar{\mathrm{D}}^0$ are obtained from fits to the distributions $m(\mathrm{D}^0)$ in bins of D^0 decay time in order to calculate

$$A_{CP}(t) \simeq A^{dir}_{CP} - A_\Gamma \frac{t}{\tau}, \tag{3.2}$$

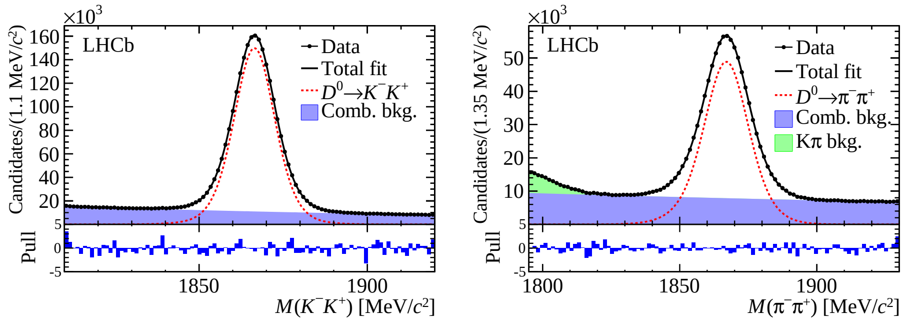

Figure 2: Decay-time integrated fits to the $m(\mathrm{D}^0)$ distributions for (left) $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and (right) $\mathrm{D}^0 \to \pi^+\pi^-$ candidates.

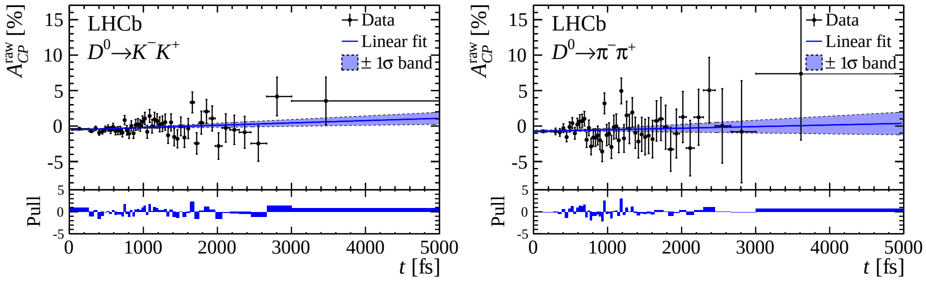

Figure 3: *CP* asymmetry as a function of decay time for (left) $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and (right) $\mathrm{D}^0 \to \pi^+\pi^-$ candidates.

where τ is the world average of the effective lifetime of the D^0 meson in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$ decays. The measured value of A_{CP}^{dir} includes the B production and μ^- detection asymmetries. The reconstruction efficiency as a function of decay time cancels in the asymmetry calculation and, assuming no asymmetry in the mistag rate, any mistagging only reduces the sensitivity to A_Γ without introducing a bias.

Fig. 2 shows the decay-time integrated fits to the $m(\mathrm{D}^0)$ distributions for $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and $\mathrm{D}^0 \to \pi^+\pi^-$ candidates. The shape parameters are fixed from these fits for the fits in bins of decay time. D^0 and $\overline{\mathrm{D}}^0$ candidates are fitted simultaneously in order to determine the asymmetry directly. Approximately 2.34×10^6 $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ and 0.79×10^6 $\mathrm{D}^0 \to \pi^+\pi^-$ signal decays are found. Fig. 3 shows the fits to the *CP* asymmetries as a function of decay time, which find

$$\begin{aligned} A_\Gamma(\mathrm{K}^+\mathrm{K}^-) &= (-0.134 \pm 0.077^{+0.026}_{-0.034})\,\%, \\ A_\Gamma(\pi^+\pi^-) &= (-0.092 \pm 0.145^{+0.025}_{-0.033})\,\%, \end{aligned} \tag{3.3}$$

where the first uncertainty is statistical and the second systematic. The sources of systematics are well understood from the $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ control channel and are expected to scale with statistics for the second data taking run.

These measurements show no indication of *CP* violation. Including them in the world average gives a result of $-A_\Gamma \simeq a_{CP}^{ind} = (0.058 \pm 0.040)\,\%$ [3]. Combining this with measurements of direct *CP* violation in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$ decays in a global fit yields a p-value for *CP* conservation of 1.8 %.

4. Conclusions

During the first data taking run the LHCb experiment recorded data corresponding to an integrated luminosity of 3.0 fb^{-1}. These data have been used to measure the direct *CP* asymmetry in $\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}$ decays, finding $A_{CP}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S}) = (-2.9 \pm 5.2 \pm 2.2)\,\%$. This represents a significant improvement over the previous measurement. Indirect *CP* asymmetries in $\mathrm{D}^0 \to \mathrm{h}^+\mathrm{h}^-$ decays have also been measured using semi-leptonic B decays to tag the D^0 flavour at production, finding $A_\Gamma(\mathrm{K}^+\mathrm{K}^-) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\,\%$ and $A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\,\%$. Thus *CP* violation in the D^0 system remains consistent with zero, though it is tightly constrained. For the second data taking run the precision on $A_{CP}(\mathrm{D}^0 \to \mathrm{K}^0_\mathrm{S}\mathrm{K}^0_\mathrm{S})$ is expected to improve considerably due to the use of additional dedicated trigger lines. Measurements of A_Γ will also benefit from improvements in triggering in addition to increased production cross sections at $\sqrt{s} = 13$ TeV. The third data taking run, following the LHCb detector upgrade, will yield another order of magnitude in statistics. Thus the potential is high for the discovery of *CP* violation in the D^0 system, and perhaps new physics, at the LHCb experiment in the coming years.

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