Charm mixing and CP violation at LHCb

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LHCb has collected the world's largest sample of charmed hadrons. This sample is used to search for direct CP violation in the multibody prompt charm decays $D^0 \to \pi^-\pi^+\pi^0$. The search employs an unbinned model independent method known as the energy test. Using the data collected by LHCb at centre-of-mass energy of 8 TeV, the world's best sensitivity to CP violation in this decay is achieved. The data are found to be consistent with the hypothesis of CP symmetry with a p-value of $(2.6 \pm 0.5)\%$. In addition, new measurements of indirect CP violation in muon-tagged D^0 decays to two-body CP even final states are presented. The time dependent CP asymmetries in the decay rates of the singly Cabibbo-suppressed decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays using the full LHCb run 1 data set are determined to be $A_\Gamma(K^-K^+) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%$ and $A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%$. These results are compatible with the hypothesis of no indirect CPV and with previous LHCb measurements.

1 Introduction

The excellent performance of the LHC and the LHCb experiment, along with large production $c\bar{c}$ cross sections for pp collisions at $\sqrt{s}$ of 7 and 8 TeV has enabled unprecedentedly large samples of charm decays to be recorded during 2011 and 2012, corresponding to 3 fb^{-1} of integrated luminosity.

The mass eigenstates of the neutral charm mesons are are a linear combination of the flavour eigenstates D^0 and $\bar{D^0}$, $|D_{1,2}\rangle = p\,|D^0\rangle \pm q\left|\bar{D^0}\right\rangle$ where the complex coefficients p, q satisfy $|p|^2 + |q|^2 = 1$. This results in D^0 and $\bar{D^0}$ oscillations. The mixing parameters are defined as $x = (m_1 - m_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/2\Gamma$, where m_1, m_2, Γ_1 and Γ_2 are the masses and the decay widths for D_1 and D_2, respectively, and $(\Gamma_1 + \Gamma_2)/2 = \Gamma$. The phase convention is chosen such that $CP\,|D^0\rangle = -\left|\bar{D^0}\right\rangle$. The first evidence of D^0 and $\bar{D^0}$ oscillation was reported in 2007 by BaBar [1] and Belle [2] . Now the mixing in the charm sector is well established and it has been measured with a very large significance at the LHCb experiment [3].

The large samples of collected and reconstructed charm meson decays allow the study of CP violation (CPV) effects at a precision not achieved before in charm decays. The data was taken with a regular swap of the polarity of the spectrometer dipole magnet which can compensate for the left-right detector asymmetries to a first order. Both types of charm decays, originating from the primary vertex, and coming from a parent beauty hadron are exploited at LHCb; this is indicated for each of the presented analyses.

2 Search for CPV in $D^0 \to \pi^-\pi^+\pi^0$ decays with the energy test

Asymmetries in the Dalitz plot substructure can be measured using an amplitude model or using model independent statistical analysis. The latter methods allow the discovery of CP violation without identifying its source. The model independent analysis can be done using binned and unbinned techiques. At LHCb, both types of model independent analyses are widely explored [4], [5], [6].

The energy test [7] is an unbinned model-independent statistical method to search for time-integrated CP violation in $D^0 \to \pi^-\pi^+\pi^0$ decays. The method relies on the comparison of two D^0 and $\bar{D}^0$ flavour samples and is sensitive to CPV localised in the phase-space of the multi body final state. This is the first application of the method for a CPV search.

The final state $\pi^-\pi^+\pi^0$ is a self-conjugate state. The flavour of the prompt D^0 is tagged by the charge of the slow pion, π_s, in the strong decay $D^* \to D^0\pi_s$. The total sample used consists of about 660 thousand $D^0 \to \pi^-\pi^+\pi^0$ decays corresponding to about 2fb^{-1} collected during 2012.

In this analysis two categories of neutral pions are used - resolved, for which the two final photons are reconstructed separately, and merged, which are detected as one merged cluster in the detector. The resolved neutral pions have a lower transverse energy, E_T, while the merged ones have a higher E_T. The decay $D^0 \to \pi^-\pi^+\pi^0$ is dominated by the $\rho(770)$ resonances with the ρ meson decaying into a pair of pions which can be seen in the enhanced event density regions on the Dalitz plot (see Fig. 1). By using both merged and resolved neutral pions for the reconstruction of the D^0 mesons, the coverage of the Dalitz plot is improved.

At LHCb, the energy test is used to assign a p-value for a non-zero CPV hypothesis [6]. In this method, a test statistic T is used to compare the average distances based on the metric function ψ. It is defined as

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\overline{n}} \frac{\psi_{ij}}{\overline{n}(\overline{n}-1)} - \sum_{i,j}^{n,\overline{n}} \frac{\psi_{ij}}{n\overline{n}}, \tag{1}$$

and the metric function $\psi_{ij} \equiv \psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$ is chosen as a Gaussian function with a tunable parameter σ as it should be a falling function with increasing the distance between events. T compares the average distances of pairs of events belonging to two samples of opposite flavour. The normalisation factor removes the impact of global asymmetries. The distance between two points in phase space is given by $d_{ij} = (m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})$, where the $1, 2, 3$ subscripts indicate the final-state particles. For no-CPV, T is expected to be zero, and larger than zero in case of the CPV. This unbinned technique calculates a p-value under the hypothesis of CP symmetry by comparing the nominal T value observed in data to a distribution of T values obtained from permutation samples, where the flavour of the D^0 is randomly reassigned to simulate samples without CP violation. The p-value for the no CPV hypothesis is obtained as the fraction of permutation T values greater than the nominal T value.

LHCb has the best sensitivity to local CPV in this decay (to few degrees of CPV in the phase, and to few percent CPV in the amplitude) in general. Only in the case of CPV in the ρ^0 amplitude the LHCb sensitivity is similar to the previous most sensitive study of this decay done by the BaBar collaboration [8].

By counting the fraction of permutations with a T value above the nominal T value in the data, a p-value of $(2.6 \pm 0.5) \times 10^{-2}$ is extracted. This result is based on 1000 permutations. A small phase-space region dominated by the ρ^+ resonance contains candidates with a local positive asymmetry exceeding 1σ significance. The result is consistent with CP conservation at the current level of precision.

The data sample has been split according to various criteria to test the stability of the results. Analyses of sub-samples with opposite magnet polarity, with different trigger configurations, and with fiducial selection requirements removing areas of high local asymmetry of the tagging soft pion from the D^*+ decay all provide consistent results. Various checks have been performed to ensure there are no asymmetries arising form background events or detector related asymmetries. No indication of background or detector related asymmetries was found.

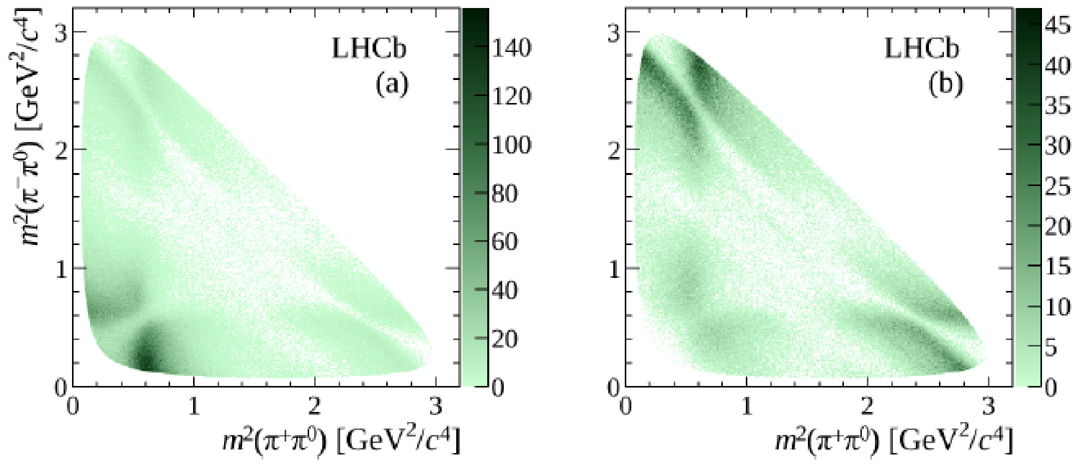

Figure 1 – The Dalitz plot of the $D^0 \to \pi^-\pi^+\pi^0$ decay with merged (a) and resolved (b) neutral pions.

3 Search for indirect CPV in the muon-tagged singly Cabibbo suppressed $D^0 \to h^-h^+$ decays

The indirect CPV is measured through, A_Γ, the asymmetry the effective lifetimes of decays to CP eigenstates

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to h^-h^+) - \tau(D^0 \to h^-h^+)}{\tau(\bar{D}^0 \to h^-h^+) + \tau(D^0 \to h^-h^+)} \tag{2}$$

A_Γ is equivalent to the indirect CPV asymmetry with a good approximation (neglecting the direct CPV term $A_d\ y\ \cos\phi$)

$$A_\Gamma \approx \frac{1}{2} A_M\ y\ \cos\phi + x\ \sin\phi = -a_{CP}^{ind}. \tag{3}$$

The indirect CPV comprises a non-zero asymmetry in the mixing,

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}, \tag{4}$$

and CPV through a non-zero phase ϕ. A large value of A_Γ or a final state dependence can indicate new physics.

For this analysis, the flavour of the D^0 mesons at production is determined by the charge of the muon in the semileptonic decays $B \to D^0\mu\nu X$.

To extract A_Γ, the CP asymmetries

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f;t) - \Gamma(\bar{D}^0 \to f;t)}{\Gamma(D^0 \to f;t) + \Gamma(\bar{D}^0 \to f;t)} \tag{5}$$

in the decay rates of D^0 and $\bar{D}^0$ are measured in 50 bins of the decay times by fits to the D^0 invariant mass. The asymmetry measured in each bin is plotted as a function of the decay time in Fig. 2. A_Γ is given by the slope of the linear fit of this distribution

$$A_{CP}(t) = A_{CP}^{dir} - A_\Gamma \frac{t}{\tau}. \tag{6}$$

The results obtained with the full sample of muon-tagged D^0 decays corresponding to 3 fb^{-1} are [9]

$$\begin{aligned} A_\Gamma(K^-K^+) &= (-0.134 \pm 0.077^{+0.026}_{-0.034})\%; \\ A_\Gamma(\pi^-\pi^+) &= (-0.092 \pm 0.145^{+0.025}_{-0.033})\%. \end{aligned} \tag{7}$$

The results for both decay modes are consistent with each other. These measurements are statistically dominated, and the largest systematic contribution arises from the mistag asymmetry. The results are compatible with the Standard model expectations [10], [11] of $A_\Gamma < 10^{-4}$, and they agree with the current most precise measurements of A_Γ done at LHCb by using the 2011 data sample of the prompt tagged $D^0 \to h^-h^+$ decays [12]

$$A_\Gamma(K^-K^+) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3};$$
$$A_\Gamma(\pi^-\pi^+) = (0.33 \pm 1.06 \pm 0.14) \times 10^{-3}. \quad (8)$$

The prompt and the muon-tagged results are uncorrelated, and by studying both, a larger decay time range is covered.

4 Summary of the CP violation searches in charm

The current status of the CPV searches in charm is summarised in Fig. 3 [13] combining the most recent A_Γ (including the muon-tagged A_Γ results) and ΔA_{CP} measurements [14], [15]. On the x-axis the indirect CPV asymmetry, a_{CP}^{ind}, is plotted, and on the y-axis the direct CPV asymmetry, Δa_{CP}^{dir}, is shown. The best fit values

$$a_{CP}^{ind} = (0.06 \pm 0.04)\%;$$
$$\Delta a_{CP}^{dir} = (-0.26 \pm 0.10)\%, \quad (9)$$

are compatible with the hypothesis of no-CPV in the charm sector at 1.8% CL.

5 Conclusions

LHCb has performed world leading measurements in the charm sector. The $D^0 - \bar{D}^0$ mixing is well established. The searches for indirect and direct CPV in two- and multi body decays are consistent with CP conservation, in agreement with the SM at the current level of precision.

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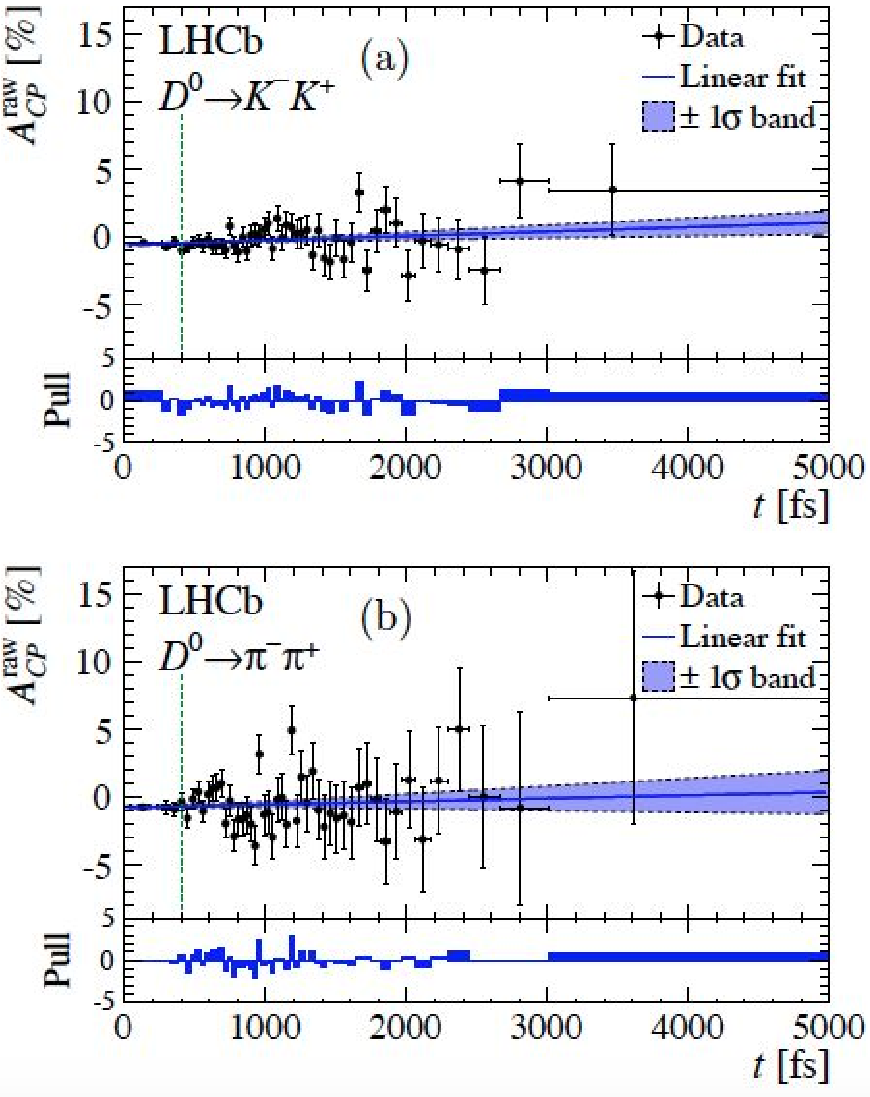

Figure 2 – The asymmetry $A_{CP}(f;t)$ in 50 bins of the decay time for (a) $D^0 \to K^+K^-$ and for (b) $D^0 \to \pi^+\pi^-$ decays.

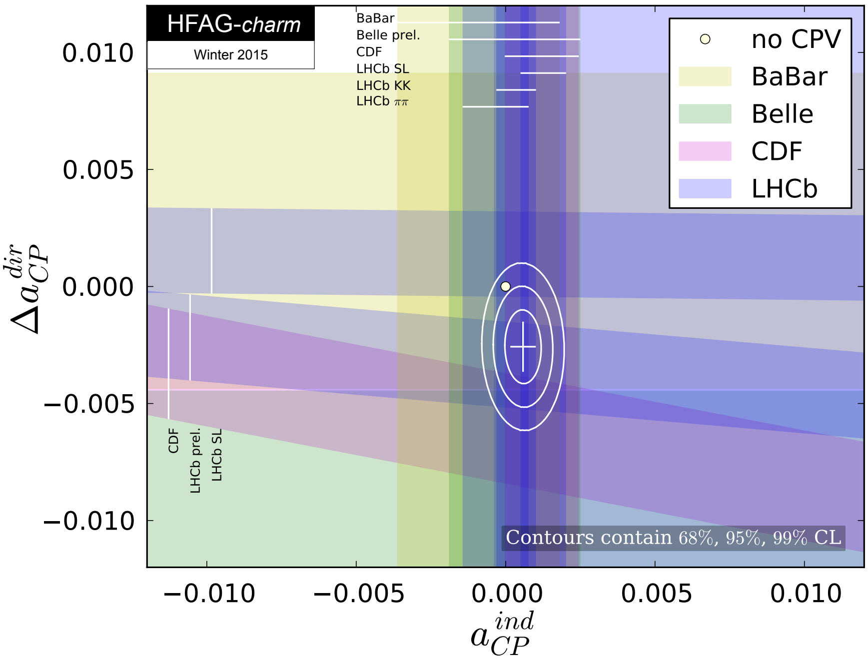

Figure 3 – Direct CP asymmetry versus indirect CPV asymmetry in the charm sector.

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