Indirect $CP$ Violation in $D^0 \rightarrow h^+ h^-$ Decays at LHCb

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Indirect $CP$ violation in the $D^0$ system can be probed by measuring the parameter $A_Γ$, defined as the $CP$ asymmetry of the effective lifetime of the $D^0$ meson decaying to a $CP$ eigenstate. This can be significantly enhanced beyond Standard Model predictions by new physics. Measurements of $A_Γ$ using $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays reconstructed from $pp$ collisions collected by the LHCb experiment, corresponding to an integrated luminosity of $1.0 \, fb^{-1}$, are presented. The results are

\[
A_Γ(\pi\pi) = (+0.33 \pm 1.06 \pm 0.14) \times 10^{-3},
\]

\[
A_Γ(KK) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3},
\]

where the uncertainties are statistical and systematic, respectively. These are the most precise measurements of their kind to date, and show no evidence of $CP$ violation.

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Figure 1: Fits to (left) the $D^0$ invariant mass distribution and (right) the $\Delta m \equiv m(D^{+}) - m(D^0)$ distribution for $D^0 \rightarrow K^+K^-$ candidates from the data subset with magnet polarity down, recorded in the earlier of the two running periods.

1. Introduction

Similarly to the $B^0$ and $B_s^0$ systems, the mass eigenstates of the $D^0$ system, $|D_{1,2}\rangle$, with masses $m_{1,2}$ and widths $\Gamma_{1,2}$, are superpositions of the flavour eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, where $p$ and $q$ are complex and satisfy $|p|^2 + |q|^2 = 1$. This causes mixing between the $|D^0\rangle$ and $|\bar{D}^0\rangle$ states, and allows for “indirect” $CP$ violation in mixing, and in interference between mixing and decay, when decaying to a $CP$ eigenstate. Indirect $CP$ asymmetries in the $D^0$ system can be significantly enhanced beyond Standard Model (SM) predictions by new physics [1]. In decays of $D^0$ mesons to a $CP$ eigenstate $f$, indirect $CP$ violation can be probed using [2]

$$A_\Gamma \equiv \frac{\Gamma(D^0 \rightarrow f) - \hat{\Gamma}(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \hat{\Gamma}(\bar{D}^0 \rightarrow f)} \approx \eta_{CP} \left\{ \frac{1}{2} (A_m + A_d) y \cos \phi - x \sin \phi \right\},$$

where $\hat{\Gamma}$ is the inverse of the effective lifetime of the decay, $\eta_{CP}$ is the $CP$ eigenvalue of $f$, $x \equiv 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2)$, $y \equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$, $A_m \equiv (|q/p|^2 - |p/q|^2)/(|q/p|^2 + |p/q|^2)$, $A_d \equiv (|A_f|^2 - |\bar{A}_f|^2)/(|A_f|^2 + |\bar{A}_f|^2)$, with $A_f$ the decay amplitude, and $\phi \equiv \arg(q\bar{A}_f/pA_f)$. The effective lifetime is defined as the average decay time of a particle with an initial state of $|D^0\rangle$ or $|\bar{D}^0\rangle$, $i.e.$ that obtained by fitting the decay-time distribution of signal with a single exponential.

The LHCb detector at the LHC, CERN, is a forward-arm spectrometer, specifically designed for high precision measurements of decays of $b$ and $c$ hadrons [3]. During 2011 the experiment collected $pp$ collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of $1.0$ $fb^{-1}$. Due to the large $c\bar{c}$ production cross section [4], the decay-time resolution of approximately 50 fs for $D^0$ decays [5] and the excellent separation of $\pi$ and $K$ achieved by the detector [6], it is very well suited to measure $A_\Gamma$ with high precision.

2. Methodology

The decay chain $D^{*+} \rightarrow D^0\pi^+_s$ is used to determine the flavour of the $D^0$ candidates at production, via the charge of the $\pi_s$ meson. The $CP$-even $K^+K^-$ and $\pi^+\pi^-$ final states are used to calculate $A_\Gamma$ [7]. The predominant candidate selection criteria require the $K^+K^-$ or $\pi^+\pi^-$ tracks to have large impact parameter (IP), large transverse momentum ($p_T$), invariant mass within 50 MeV
of the world average $D^0$ mass, and for the vector sum of their momenta to point closely back to the position of the pp collision. Using data corresponding to an integrated luminosity of $1.0 \text{ fb}^{-1}$, 4.8M $D^0 \rightarrow K^+ K^-$ candidates and 1.5M $D^0 \rightarrow \pi^+ \pi^-$ candidates are selected. The data are divided by $D^0$ flavour, the polarity of the LHCb dipole magnet, and two separate running periods. Combinatorial and partially reconstructed backgrounds are discriminated using a simultaneous fit to the distributions of $D^0$ mass and $\Delta m \equiv m(D^{*+}) - m(D^0)$. Examples of these fits are shown in Fig. 1 for $D^0 \rightarrow K^+ K^-$ candidates, for data recorded with the magnet polarity down during the earlier of the two running periods.

A fit to the decay-time distribution of the candidates is then used to determine the effective lifetimes of the $D^0$ and $\bar{D}^0$ signal. Only candidates for which the $D^{*+}$ is produced directly at the pp collision are considered as signal. The background from $B \rightarrow D^{*+}X$ decays is discriminated by simultaneously fitting the distributions of the decay time and the natural logarithm of the hypothesis that the $D^0$ candidate originates directly from the pp collision ($\ln(\chi^2_{IP})$). The selection efficiency as a function of decay time is obtained from data using per-candidate acceptance functions, as described in detail in Ref. [8]. The decay-time and $\ln(\chi^2_{IP})$ distributions for combinatorial and specific backgrounds are obtained from the data using the discrimination provided by the mass and $\Delta m$ fits to employ the "Weights technique" [9] with kernel density estimation [10]. Figure 2 shows fits to the distributions of decay time and $\ln(\chi^2_{IP})$ for $D^0 \rightarrow K^+ K^-$ candidates, using the same data subset as Fig. 1. Inaccuracies in the fit model are examined as a source of systematic uncertainty, as discussed in the following section.

3. Results and systematics

The fits detailed in the previous section find

$$A_T(\pi\pi) = (0.33 \pm 0.14) \times 10^{-3},$$
$$A_T(KK) = (-0.35 \pm 0.12) \times 10^{-3},$$

where the uncertainties are statistical and systematic, respectively. These are the most precise measurements of their kind to date, and show no evidence of CP violation. The dominant systematic uncertainties arise from the modelling of the selection efficiency as a function of decay time, and
the modelling of the background from $B \to D^{*+} X$ decays. Figure 3 (left) shows the world average of $A_\Gamma$, which is dominated by these measurements and is consistent with zero. Figure 3 (right) shows the combined fit to measurements of direct and indirect $CP$ violation in $D^0 \to h^+ h^-$ decays, which yields a p-value for zero $CP$ violation of 5.1 % [11].

The precision of these measurements will be improved by the addition of 2.1 fb$^{-1}$ of data already collected during 2012. Together with data to be recorded in run II, and, in time, following the LHCb upgrade, measurements with precisions of approximately $1 \times 10^{-4}$ are possible, giving great potential for the discovery of indirect $CP$ violation in the $D^0$ system.

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