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Measurement of the time-integrated CP asymmetry in $D^0 \to K^0_S K^0_S$ decays with LHCb

Giulia Tuci[*] , on behalf of the LHCb collaboration
Universitá di Pisa and INFN Pisa
E-mail: `giulia.tuci@pi.infn.it`

CP violation in charm has not yet been observed, although measurements of time-integrated CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays have reached a precision of $\mathcal{O}(10^{-3})$. The $D^0 \to K^0_S K^0_S$ decay is a promising discovery channel for CP violation in charm. A prediction based on the Standard Model gives an upper limit for the CP asymmetry of about 1% and further enhancements could result from contributions from physics beyond the Standard Model. A preliminary measurement of the time-integrated CP asymmetry in prompt $D^0 \to K^0_S K^0_S$ decays is presented, performed using data collected with the LHCb experiment in 2015 and 2016 at a 13 TeV pp center-of-mass energy (Run 2). The CP asymmetry is measured to be

$$A^{CP}(D^0 \to K^0_S K^0_S) = (0.042 \pm 0.034 \pm 0.010),$$

where the first uncertainty is statistical and the second is systematic. This result represents a significant improvement with respect to the previous LHCb Run 1 measurement.

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[*] Speaker.

1. Motivations

CP violation has not yet been observed in the charm sector, although measurements of time-integrated *CP* asymmetry in Cabibbo-suppressed $D^0 \to h^+h^-$ $(h = \pi, K)$ decays have reached the remarkable precision of $\mathscr{O}(10^{-3})$ [1]. A complementary approach is to search for *CP* violation in decay channels with a lower branching ratio and with suppressed amplitudes, but where the *CP* asymmetry could be enhanced to an observable level. For this reason $D^0 \to K^0_S K^0_S$ is a promising discovery channel. In fact only loop-suppressed and exchange diagrams, where the latter vanish in the SU(3) flavour limit, contribute to this decays. These contributions are of similar size and therefore A^{CP} could reach the level of $\sim 1\%$ [2] and be observed. The *CP* asymmetry is defined as

$$A^{CP}(K^0_S K^0_S) \equiv \frac{\Gamma(D^0 \to K^0_S K^0_S) - \Gamma(\bar{D}^0 \to K^0_S K^0_S)}{\Gamma(D^0 \to K^0_S K^0_S) + \Gamma(\bar{D}^0 \to K^0_S K^0_S)}, \tag{1.1}$$

where Γ is the decay rate of D^0 $(\bar{D}^0)$ in the final state $K^0_S K^0_S$. This quantity has already been measured by the CLEO collaboration [3], by the Belle collaboration [4], and by the LHCb collaboration [5] using Run 1 data. All the measurements are compatible with zero and the world's best measurement has been performed by Belle, who measured $A^{CP}(K^0_S K^0_S) = (-0.02 \pm 1.53 \pm 0.17)\%$, where the first uncertainty is statistical and the second is systematic. Here a new LHCb measurement, performed using data collected in the first two years of Run 2 ($\sqrt{s} = 13$TeV, integrated luminosity $\sim 2\text{fb}^{-1}$), is presented.

2. Detector and signal samples

The LHCb detector [6] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The silicon-strip vertex detector surrounding the pp interaction region allows c and b hadrons to be identified from their characteristically long flight distance and the tracking system provides the precise measurement of momentum of charged particles ($\sigma_p/p \sim 0.5\% - 1\%$).

In LHCb tracks are classified according to the subdetectors crossed. In particular particles traversing the full tracking system are called "long" tracks, while tracks reconstructed in all the tracking stations but not in the vertex-detector are called "downstream" tracks. In this analysis two samples are used: the LL sample, with both K^0_S reconstructed from long tracks, and the LD sample, with one K^0_S reconstructed from long tracks and the other one reconstructed from downstream tracks. The two samples are analysed separately because of the different mass resolution.

3. Analysis strategy and main background sources

A sample of flavour-tagged $D^0 \to K^0_S K^0_S$ decays has been obtained by selecting prompt D^{*+} candidates, with subsequent decay $D^{*+} \to D^0\pi^+$ (charge conjugate decays are implied throughout this document, unless explicitly specified). The sign of the pion in this decay gives the flavour of the accompanying D^0, and $D^0 - \bar{D}^0$ mixing is negligible at this level of precision. K^0_S candidates are reconstructed in the $\pi^+\pi^-$ decay channel.

The quantity measured in LHCb is $A^\mathrm{raw} = \dfrac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}$, where N_{D^0} is the measured yield of $D^{*+} \to D^0\pi^+$ and $N_{\bar{D}^0}$ is the measured yield of $D^{*-} \to \bar{D}^0\pi^-$ decays. This observable is related to the *CP* asymmetry by the expression, valid to first order, $A^\mathrm{raw} \approx A^{CP} + A^\mathrm{prod} + A^\mathrm{det}$, where A^prod is the production asymmetry of the $D^{*\pm}$ and A^det is the detection asymmetry of the tag pion. The production asymmetry arises from the fact that the initial state pp is not *CP*-symmetric, and therefore the production cross section of D^{*+} is different from the production cross section of D^{*-}. The detection asymmetry depends both on the magnet polarity (left-right detector asymmetry) and on different detection efficiencies for opposite charged tracks (particles and antiparticles have different interaction cross sections with detector material). To remove these two asymmetries $D^0 \to K^+K^-$ is used as a calibration channel. In fact these asymmetries cancel out in the difference $\Delta A^{CP} = A^\mathrm{raw}(K^0_\mathrm{S}K^0_\mathrm{S}) - A^\mathrm{raw}(K^+K^-)$ if the kinematics of the D^{*+} and tag pion are equal. Then the *CP* asymmetry in the $K^0_\mathrm{S}K^0_\mathrm{S}$ decay channel can be determined by computing

$$A^{CP}(K^0_\mathrm{S}K^0_\mathrm{S}) = \Delta A^{CP} + A^{CP}(K^+K^-). \tag{3.1}$$

The value of $A^{CP}(K^+K^-)$ has been independently measured by LHCb with an uncertainty of $\sim 0.2\%$ [1], which is an order of magnitude smaller than the sensitivity on the $D^0 \to K^0_\mathrm{S}K^0_\mathrm{S}$ decay channel. The imperfect cancellation of production and detection asymmetries due to differences in D^{*+} and tag pion kinematics is taken into account as a systematic uncertainty.

The raw asymmetry is extracted by fitting the $\Delta m = m(D^{*+}) - m(D^0)$ distribution. Some sources of background could peak in this mass distribution and this could lead to a bias in the final measurement. The two main sources of this peaking background are: $D^0 \to K^0_\mathrm{S}\pi^+\pi^-$ decays, in which the $\pi^+\pi^-$ pair is wrongly assigned to come from a K^0_S decay, and secondary decays, in which the D^{*+} is not coming from the primary interaction, but from a b-hadron decay. The $D^0 \to K^0_\mathrm{S}\pi^+\pi^-$ background, which in principle could have a different A^{CP} with respect to the signal, can be reduced using information on the K^0_S mass and K^0_S flight distance. In particular a real K^0_S should have a flight distance significantly different from zero, while a fake K^0_S, which in reality is a pair of pions coming directly from the D^0 decay, should have a flight distance compatible with zero. In Fig. 1 a two-dimensional plot of the value of the quantity $\log(\chi^2_\mathrm{FD})$ for K^0_S pairs in the LL sample is shown. The quantity χ^2_FD is the square of the measured K^0_S flight distance divided by the square of its uncertainty. A requirement on χ^2_FD is only necessary for long K^0_S candidates, since downstream K^0_S candidates decay far from the primary vertex by construction. Secondary decays are characterised by the same *CP* asymmetry, but by a different production asymmetry due to the presence of the b-hadron. This background can be reduced using information on vertex displacement. In fact a D^0 coming from a secondary decay will decay further from the primary vertex than a D^0 coming from a prompt decay. After applying cuts to reduce the peaking backgrounds, a selection on the output of a k-Nearest-Neighbors classifier is applied to reduce the combinatorial background. For the $D^0 \to K^+K^-$ control channel, an attempt is made to keep the selection similar to the $D^0 \to K^0_\mathrm{S}K^0_\mathrm{S}$ channel, to improve cancellation of detector and production asymmetries.

The signal yields in the selected sample are 759 ± 32 LL candidates and 308 ± 26 LD candidates. We note that, although only 40% of the K^0_S with the two daughter tracks inside the LHCb acceptance decay inside the vertex detector [7], the yield for LL candidates is more than twice the yield for LD candidates. This is partly due to the selection strategy adopted in the first stage of the

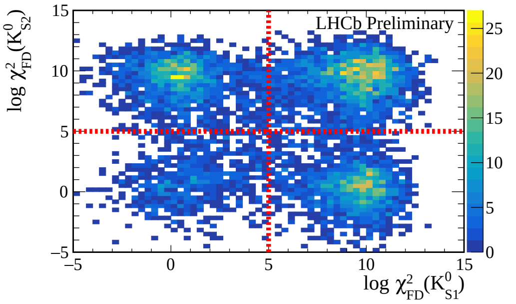

Figure 1: Two-dimensional distribution of the logarithm of the K^0_S flight distance significance ($\log(\chi^2_{FD})$) for the two K^0_S candidates in the LL subsample of $D^0 \to K^0_S K^0_S$ decays. The upper right part of the plot, where both K^0_S candidates have significant flight distances, is the $D^0 \to K^0_S K^0_S$ signal, while the upper left and lower right regions correspond to $D^0 \to K^0_S \pi^+\pi^-$ decays. In the lower left part, $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays and combinatorial background are present.

LHCb software trigger, that due to CPU time constraints relies only on the reconstruction of long tracks, thus reducing the efficiency for LD candidates.

4. Results and outlook

The result, obtained by performing a simultaneous maximum likelihood fit to the separate D^{*+} and D^{*-} unbinned Δm distributions, is [8]

$$A^{CP}(K^0_S K^0_S) = (0.042 \pm 0.034 \pm 0.010),$$

where the first uncertainty is statistical and the second is systematic. The raw asymmetry A^{raw} is a free and shared parameter in the fit. The fitted Δm distributions, obtained for the "magnet up" polarity, are shown in Fig. 2.

Results obtained on LL and LD samples and on the two separate magnet polarities are compatible within 2σ. The main systematic uncertainty arises from the possible bias introduced by the fitting procedure for the determination of A^{raw} on the $D^0 \to K^0_S K^0_S$ signal sample (5×10^{-3} for LL and 10×10^{-3} for LD). Combining these results with the previous LHCb measurement on the Run 1 dataset, the asymmetry value obtained is

$$A^{CP}(K^0_S K^0_S) = (0.020 \pm 0.029 \pm 0.010),$$

therefore no evidence of *CP* violation is found.

Using the full Run 2 dataset collected by LHCb, the statistical uncertainty on this measurement will approach the precision reached by Belle, and further improvements are expected from the LHCb Upgrade. For the recently proposed Phase-II LHCb Upgrade, the LHCb collaboration is actively considering the deployment of dedicated accelerators in the trigger and data-processing chain to find tracks downstream of the magnet and present these tracks to the earliest stage of the software trigger [9]. This would allow to significantly increase the efficiency for these decay modes and thus offer the opportunity to probe the Standard Model predictions on these channels with significantly better precision, at the 10^{-3} level.

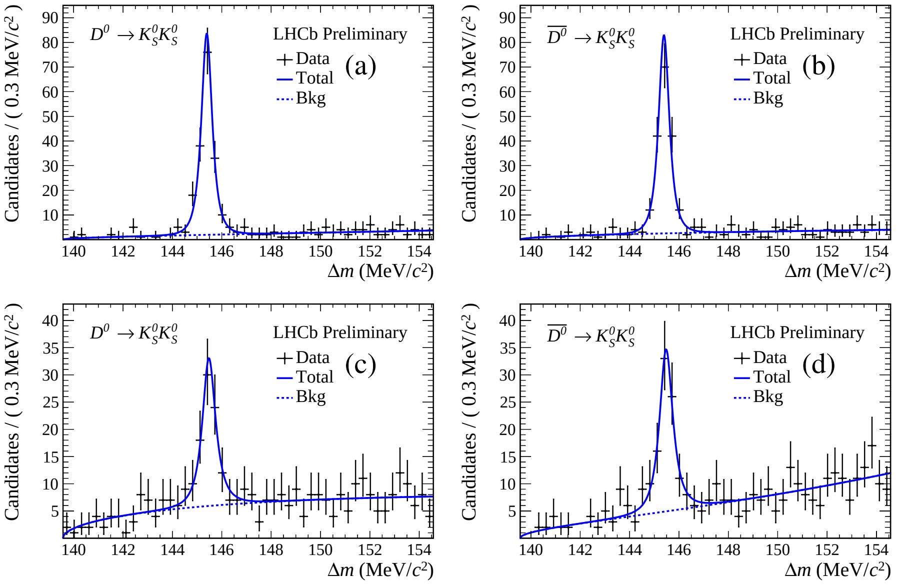

Figure 2: Preliminary fits to Δm distributions of $D^0 \to K^0_S K^0_S$ candidates for the "magnet up" polarity. The fit to (a) $D^{*+} \to D^0\pi^+$ and (b) $D^{*-} \to \bar{D}^0\pi^-$ candidates for the LL sample and the fit to (c) $D^{*+} \to D^0\pi^+$ and (d) $D^{*-} \to \bar{D}^0\pi^-$ candidates for the LD sample are shown. The black crosses represent the data points, the solid blue curve is the total fit function, and the dashed blue curve is the background component of the fit.

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