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The role of neutral kaons in the high-precision measurements of *CP* violation in the charm sector

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The measurement of the asymmetry in detecting neutral kaons, K^0 and $\overline{K}^0$, produced in charm hadron decays and propagating through detector material is crucial for the search for *CP* violation in the charm sector. This asymmetry is precisely modeled and measured in the $D^+ \to K^0_S\pi^+ \to [\pi^+\pi^-]\pi^+$ and $D^+ \to \phi\pi^+ \to [K^+K^-]\pi^+$ decay channels. The analysis is based on data collected with the LHCb experiment during Run 2 (2016–2018), corresponding to an integrated luminosity of $5.4\,\mathrm{fb}^{-1}$ of pp collisions at a center-of-mass energy of 13 TeV. For the first time, the model describing the time-dependent neutral kaon detection asymmetry, $A_D(K^0_S, t_{K^0_S})$, incorporates an additional source of *CP* violation arising from the interference between the Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) amplitudes in the $D^+ \to K^0_S\pi^+$ decay. These interference effects are parameterized by the modulus of the ratio and the relative strong phase of the DCS to CF amplitudes, r_π and δ_π, which are directly measured from data for the first time via a fit to the time dependence of $A_D(K^0_S, t_{K^0_S})$. As an application of this study, the *CP* asymmetry in the $D^+ \to \phi\pi^+$ channel is measured using the full Run 2 data sample, with the $D^+ \to K^0_S\pi^+$ decay serving as a calibration mode.

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1. Introduction

High-precision measurements of *CP* violation in charm decays are of paramount importance, as physical *CP*-violating asymmetries are highly suppressed in the Standard Model, at the level of $10^{-3} - 10^{-4}$, and even lower for time-dependent observables. The first observation of *CP* violation in the charm sector [1], through the well-known ΔA_{CP} observable,

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}, \tag{1}$$

remains a topic of intense debate, as it is not yet clear whether its origin is entirely within the Standard Model or hints at new physics. Any additional observation of *CP* violation in charm decays would provide valuable theoretical insights to help resolve this puzzle. These high-precision measurements demand extreme care, as even tiny experimental biases, such as charge-asymmetric effects in particle production and detection, must be accounted for with high accuracy. This experimental challenge, already extremely difficult and complex with current datasets, will become even more critical with the significantly larger data samples being collected by the LHCb Upgrade I experiment during LHC Runs 3 and 4. It will be particularly challenging during its second upgrade phase, at very high instantaneous luminosity in LHC Run 5 and beyond, where an unprecedented data sample of heavy-flavour decays, amounting to approximately 300 fb^{-1} of integrated luminosity, will be collected.

The most reliable approaches for constraining or measuring such biases rely on fully data-driven methods, typically utilizing one or more calibration channels where *CP* violation is expected to be much smaller than the associated experimental uncertainties. Among the most promising decay modes for use as reference channels in the high-precision regime are the $D^0 \to K^0_S\pi^+\pi^-$ and $D^+ \to K^0_S\pi^+$ decays. The particle-antiparticle asymmetry in these channels is significantly influenced by the time evolution of neutral kaons, which can travel several meters in the detector before decaying. The $K^0 - \overline{K}^0$ mixing and interactions of neutral kaons with the detector induce an asymmetry in the detection of K^0_S mesons produced in D or $\overline{D}$ decays, which must be carefully modeled and precisely measured using the abundant samples of neutral and charged D mesons available. These proceedings present an extension of the current methods used to determine the neutral kaon detection asymmetry in the high-precision regime, along with its application to ongoing and future searches for *CP* violation in the charm sector at the LHCb experiment.

2. Precision measurements of *CP* violation in the charm sector at LHCb

The asymmetry in a generic $D \to f$ decay can be estimated directly from the number of reconstructed events with a D or $\overline{D}$ meson:

$$A_{\mathrm{raw}}(D \to f) = \frac{N(D \to f) - N(\overline{D} \to \overline{f})}{N(D \to f) + N(\overline{D} \to \overline{f})}. \tag{2}$$

However, the raw asymmetry defined in this way does not solely depend on the *CP* asymmetry of the decay. In particular, since the initial state (pp) is not *CP*-invariant, the production cross sections of D and $\overline{D}$ mesons are different, leading to a production asymmetry of the initial D meson, denoted as

$A_P(D)$. Additionally, since the detector is composed of matter, there may be a detection asymmetry between the final state f and its *CP*-conjugate $\overline{f}$, represented by $A_D(f)$. If all these contributions are small (of the order of 1% or less), the total raw asymmetry can be approximated as:

$$A_{\text{raw}}(D \to f) \approx A_P(D) + A_D(f) + A_{CP}(D \to f). \quad (3)$$

To extract the *CP* asymmetries, it is necessary to use one or more calibration channels that share the same nuisance asymmetries as the channel of interest. In this way, by subtracting from $A_{\text{raw}}(D \to f)$ a properly constructed combination of the raw asymmetries in the calibration channels, the only remaining term is the desired *CP* asymmetry: $A_{CP}(D \to f)$. This procedure, however, is non-trivial, as the *CP* asymmetries we seek to measure are of the order of $10^{-3} - 10^{-4}$, while nuisance asymmetries and detection effects are typically an order of magnitude larger, around 10^{-2}. Moreover, calibration channels with neutral kaons in the final state—widely used due to their high statistics—introduce an additional challenge: the need to determine and subtract the detection asymmetry of neutral kaons, $A_D(K^0_\text{S})$. This is achieved by employing models that describe the time evolution of neutral kaons in matter.

3. Neutral kaon detection asymmetry

Experimentally, a neutral kaon is produced as a flavor eigenstate, either as a K^0 or a $\overline{K}^0$, but it oscillates and interacts with the detector material as it propagates. At LHCb, neutral kaons are reconstructed through their decay $K^0_\text{S} \to \pi^+\pi^-$. Although neutral kaons are electrically neutral, they are not *CP*-invariant, meaning their time evolution and decay width depend on their initial flavor, leading to an asymmetry in their detection. The two main sources of this asymmetry considered so far are *CP* violation in $K^0 - \overline{K}^0$ mixing, where the oscillation probabilities differ for K^0 and $\overline{K}^0$, and differences in K^0 and $\overline{K}^0$ interactions with matter, which affect how they propagate through the detector. This work introduces a third source of neutral kaon detection asymmetry, first parametrized in Ref. [2, 3], arising in hadronic D-meson decays with a neutral kaon in the final state. Specifically, a D meson can produce a $K^0_\text{S} f$ final state via two interfering amplitudes:

- the Cabibbo Favoured (CF) $D \to \overline{K}^0 f$, in which the $c \to s\bar{d}u$ transition occurs;
- the Doubly Cabibbo Suppressed (DCS) $D \to K^0 f$, in which the $c \to d\bar{s}u$ transition occurs.

Since both K^0 and $\overline{K}^0$ can reach the $\pi^+\pi^-$ final state through mixing, their interference introduces a new source of *CP* asymmetry. This effect must be incorporated into neutral kaon asymmetry models, as it may significantly impact commonly used calibration channels, such as:

- Two-body decays like $D^+ \to K^0_\text{S}\pi^+$, where two interfering amplitudes contribute.
- Three-body decays like $D^0 \to K^0_\text{S}\pi^+\pi^-$, which involve multiple CF and DCS amplitudes.

The extension of the neutral kaon asymmetry model to incorporate this new interference effect has been validated using the $D^+ \to K^0_\text{S}\pi^+$ decay channel. This channel provides an ideal testing ground due to its high statistical precision and the presence of only two interfering amplitudes. The interference between Cabibbo-Favoured (CF) and Doubly Cabibbo-Suppressed (DCS) charm decays is characterized by two real parameters: the magnitude of the ratio between the CF and DCS amplitudes, r_π, and their relative strong phase, δ_π. These parameters are defined as:

$$\frac{\mathcal{A}(D^+ \to K^0\pi^+)}{\mathcal{A}(D^+ \to \overline{K}^0\pi^+)} \equiv r_\pi\, e^{i\delta_\pi}. \tag{4}$$

Theoretical predictions for these parameters have been obtained using the Factorisation-Assisted Topological Amplitudes (FAT) method to model strong amplitudes, as reported in Ref. [2]: $r_\pi = -0.073 \pm 0.004$ and $\delta_\pi = -1.39 \pm 0.05$. Thanks to detailed models describing the time evolution of neutral kaons in matter, combined with precise knowledge of the LHCb detector material distribution, it is possible to compute the detection asymmetry for each neutral kaon as a function of its decay time. This asymmetry is defined as

$$A_D(K^0_\mathrm{S}, t) \equiv \frac{\Gamma\left[\psi_K^{(+)}(t) \to \pi^+\pi^-\right] - \Gamma\left[\psi_K^{(-)}(t) \to \pi^+\pi^-\right]}{\Gamma\left[\psi_K^{(+)}(t) \to \pi^+\pi^-\right] + \Gamma\left[\psi_K^{(-)}(t) \to \pi^+\pi^-\right]}, \tag{5}$$

where $\psi_K^{(+)}(t)$ and $\psi_K^{(-)}(t)$ represent the state of a neutral kaon initially produced in a D^+ or D^- decay, respectively, after evolving inside the detector. This detection asymmetry depends on the parameters r_π and δ_π, which characterize the initial state of neutral kaons in the $D^\pm \to K^0_\mathrm{S}\pi^\pm$ decay. The dependence of $A_D(K^0_\mathrm{S}, t)$ on the K^0_S decay time is shown in Fig. 1.

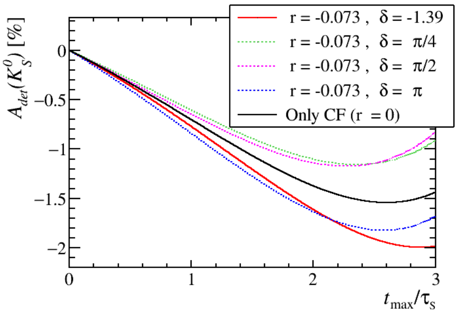

Figure 1: Neutral kaon detection asymmetry as a function of the K^0_S decay time for different values of r_π and δ_π. It is important to note that $A_D(K^0_\mathrm{S}, t = 0) = 0$ for any (r_π, δ_π) choice.

4. Measurement of $A_D(K^0_\mathrm{S})$ in the $D^+ \to K^0_\mathrm{S}\pi^+$ channel

The goal of this analysis is to measure the time-dependent neutral kaon detection asymmetry in $D^+ \to K^0_\mathrm{S}\pi^+$ decays and compare it with the presented model to test its accuracy. The data sample used for this study was collected by the LHCb detector during Run 2 (2016-2018), corresponding to a total integrated luminosity of 5.4 fb^{-1}. In addition to the signal channel, the $D^+ \to \phi\pi^+$ decay is used as a control sample to cancel nuisance asymmetries arising from D^+ meson production and π^+ detection. The total yields of signal events amount to 50 million $D^+ \to K^0_\mathrm{S}\pi^+$ and 30 million $D^+ \to \phi\pi^+$. The key observable in this analysis is the difference between the raw asymmetries of the $D^+ \to K^0_S\pi^+$ and $D^+ \to \phi\pi^+$ channels, defined as

$$\begin{aligned}\Delta A(K^0_S) &\equiv A_{raw}(D^+ \to K^0_S\pi^+) - A_{raw}(D^+ \to \phi\pi^+)\\ &= A_D(K^0_S) - A_{CP}(D^+ \to \phi\pi^+),\end{aligned} \tag{6}$$

where the last term acts as an overall offset independent of the K^0_S decay time and does not affect the time dependence of $A_D(K^0_S)$. To study the time dependence of this asymmetry, the $D^+ \to K^0_S\pi^+$ sample is divided into several K^0_S decay time bins. To cancel nuisance asymmetries in each bin, the control sample is similarly divided into corresponding subsamples. Using this approach, $\Delta A(K^0_S)$ is measured as a function of $t/\tau_{K^0_S}$ and compared with the model predictions for the time dependence of neutral kaon detection asymmetry. The left panel of Fig. 2 shows that the measured $\Delta A_{K^0_S}(t)$ is well described by the $A_D(K^0_S, t)$ model using the theoretical predictions for r_π and δ_π. By testing the agreement between the measured and predicted time-dependent neutral kaon detection asymmetry, confidence intervals for r_π and δ_π are derived. These intervals are obtained using the *Plugin* method [4], which is fully data-driven and relies only on well-known physical observables governing the time evolution of neutral kaons in vacuum and matter. The confidence regions are determined through a Goodness-of-Fit statistic that quantifies the agreement between the measured $\Delta A(K^0_S)$ time dependence and model predictions generated for different values of r_π and δ_π.

As an application of the extended $A_D(K^0_S, t)$ model, the *CP* asymmetry $A_{CP}(D^+ \to \phi\pi^+)$ is measured using the full Run2 dataset, extracted from the best-fit offset of the $\Delta A(K^0_S)$ observable. The best-fit offset is determined using the *Profile Likelihood* method, which optimizes r_π and δ_π as nuisance parameters directly from the data. This measurement achieves a statistical and systematic uncertainty of approximately 5×10^{-4}, improving upon the previous LHCb result [5], which was based on 2016 and 2017 data and assumed the studied interference effect to be negligible.

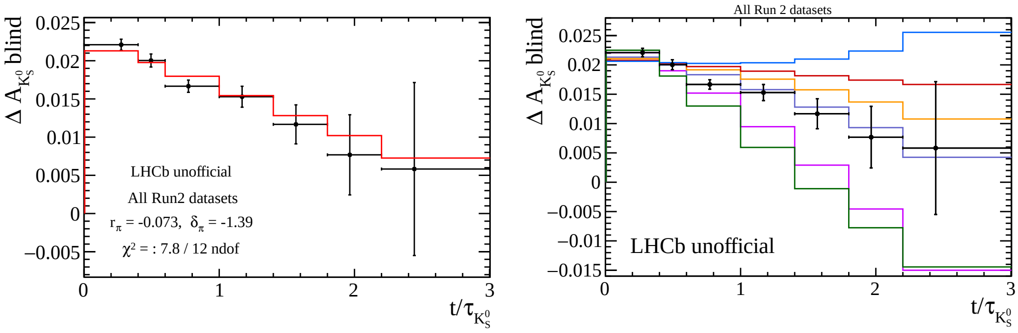

Figure 2: Left: $\Delta A_{K^0_S}(t)$ observable and $A_D(K^0_S, t)$ model for the FAT prediction of r_π and δ_π. Right: $\Delta A_{K^0_S}(t)$ observable and $A_D(K^0_S, t)$ models built for different r_π and δ_π values.

5. Conclusions and future perspectives

Precision measurements of *CP* violation in the charm sector at LHCb require stringent control of detector-induced biases. With the larger data samples expected in future runs, improving the accuracy in determining and subtracting such nuisance effects will be crucial. The use of calibration channels with neutral kaons in the final state demands a thorough understanding and modeling of all sources of neutral kaon detection asymmetry.

These proceedings present the incorporation of a new asymmetric effect in neutral kaon detection in D meson decays: the interference between Cabibbo-Favoured (CF) and Doubly Cabibbo-Suppressed (DCS) charm amplitudes, combined with $K^0 - \overline{K}^0$ mixing. The study is conducted using the $D^+ \to K^0_S\pi^+$ channel, where this interference is parametrized by two real quantities: the magnitude ratio of the DCS to CF amplitudes, r_π, and their relative strong phase, δ_π. Thanks to the large dataset collected by the LHCb experiment during Run 2 (2015-2018), these parameters are measured using a fully data-driven method, independent of any assumptions about the strong amplitudes. Looking ahead, the LHCb collaboration is working on a new measurement of the time-integrated *CP* asymmetry, $A_{CP}(D^0 \to K^+K^-)$, using Run 2 data with a novel approach based on a single calibration channel, $D^0 \to K^0_S\pi^+\pi^-$ [6]. This method will provide a measurement largely independent of previous ones [7], offering a crucial test of our current understanding of *CP* violation in charm decays. This is particularly promising for the future, as precision approaches the 10^{-4} level. In general, the neutral kaon detection asymmetry model presented in these proceedings is a key component to precisely determine $A_D(K^0_S)$ directly from data. This is especially important because $A_D(K^0_S)$ is not removed in the difference between the two raw asymmetries, making its accurate modeling essential for future high-precision charm *CP* violation measurements.

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