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Measurement of instrumental asymmetries of kaons and pions

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Abstract

We measure instrumental asymmetries of kaons and pions using $D^0 \to K^-\pi^+$ and $D^- \to K^0_S\pi^-$ decays. We use the data collected by Belle II at the $\Upsilon(4S)$ energy during 2019, 2020 and the first half of 2021 which correspond to $189\,\mathrm{fb}^{-1}$ of integrated luminosity. We study the dependence of the instrumental asymmetries on the momentum and polar angle of the particle and on the number of drift-chamber hits of its track.

1. INTRODUCTION

Measurements of charge-parity-violating decay-rate asymmetries ($\mathcal{A}_{CP}$) are a fundamental goal of the Belle II physics program. Decay-rate asymmetries are derived from charge-dependent signal yields of reconstructed decays candidates. Such yield-asymmetries might be affected by biases due to charge-dependent reconstruction efficiencies of final state particles. These biases are the detection asymmetries ($\mathcal{A}_{\rm det}$). They originate from different sources. For instance, when charge kaons are reconstructed, a detection asymmetry is expected from the known difference of K^+ and K^- interaction probabilities with matter. Other source of $\mathcal{A}_{\rm det}$ might come from tracking or particle-identification algorithms.
Simulation might not model perfectly all these effects (*e.g.* because of a approximated description of detector material budget). It is pivotal to carry out auxiliary measurements on abundant samples of control data to determine detection asymmetries, so that measured charge-yields asymmetries can be corrected for to measure genuine *CP* asymmetries. In this document, we report a measurement of detection asymmetries of kaons and pions using control samples of $D^0 \to K^-\pi^+$ and $D^- \to K^0_S\pi^-$ decays. We use data collected by Belle II at the $\Upsilon(4S)$ energy during 2019, 2020 and the first half of 2021 which correspond to $189\,\mathrm{fb}^{-1}$ of integrated luminosity. We study the dependence of the instrumental asymmetries on the momentum and polar angle of the particle and on the number of drift-chamber hits of its track.

2. $\mathcal{A}_{\rm det}$ FROM D CONTROL DECAYS

To determine $\mathcal{A}_{\rm det}$ from the D control decays, we measure signal-yield asymmetries $\mathcal{A}_{\rm raw}$ from a fit of the D mass distribution of the reconstructed candidates. The yields asymmetry can be decomposed in three contributions, as

$$\mathcal{A}_{\rm raw} = \frac{N - \overline{N}}{N + \overline{N}} = \mathcal{A}_{CP} + \mathcal{A}_{\rm det} + \mathcal{A}_{\rm FB}, \tag{1}$$

where N is the measured signal yield for a charge-specific decay (*i.e.*, number of $D^0 \to K^-\pi^+$ or $D^- \to K^0_{\rm S}\pi^-$ decays) and $\overline{N}$ for its *CP* conjugate. The term $\mathcal{A}_{\rm FB}$ is the forward-backward asymmetry, a known asymmetry in the production of D and $\overline{D}$ mesons due to the γ^*-Z^0 interference in $e^+e^- \to c\bar{c}$ processes [1].

We choose D decays with null or very-well known values of $\mathcal{A}_{CP}$. The $D^0 \to K^-\pi^+$ decays is governed solely by a Cabibbo-favored tree amplitude to a very good approximation. The expected $\mathcal{A}_{CP}$, if any, is smaller than 0.1%, as confirmed by measurements; so we assume $\mathcal{A}_{CP}(D^0 \to K^-\pi^+) = 0$. Decays $D^- \to K^0_{\rm S}\pi^-$ are also expected to exhibit a small *CP* asymmetry. The measured value, $\mathcal{A}_{CP}(D^- \to K^0_{\rm S}\pi^-) = (0.41 \pm 0.09)\%$ [2], differs from zero; in the following, we subtract this value from the measured $\mathcal{A}_{\rm raw}$.

Knowing the values of $\mathcal{A}_{CP}$ for our control decays, we need to subtract $\mathcal{A}_{\rm FB}$ from $\mathcal{A}_{\rm raw}$ to determine $\mathcal{A}_{\rm det}$. The asymmetry $\mathcal{A}_{\rm FB}$ is known to be anti-symmetric as a function of $\cos\theta^*_D$, *i.e.* the cosine of the D meson polar angle in centre-of-mass system [1]. Assuming that $\mathcal{A}_{\rm det}$ is not anti-symmetric in $\cos\theta^*_D$, $\mathcal{A}_{\rm FB}$ can be cancelled by measuring $\mathcal{A}_{\rm raw}$ in bins of $\cos\theta^*_D$ and averaging the values obtained in bins of opposite sign of $\cos\theta^*_D$:

$$\mathcal{A}_{\rm det} = \frac{\mathcal{A}'_{\rm raw}(\cos\theta^*_D) + \mathcal{A}'_{\rm raw}(-\cos\theta^*_D)}{2}. \tag{2}$$

where $\mathcal{A}'_{\rm raw}$ is the charge-yield asymmetries corrected for $\mathcal{A}_{CP}$. We perform the measurement in four bins of $\cos\theta^*_D$: [-1,-0.50],[-0.50,0],[0,0.50],[0.50,1] obtaining two values of $\mathcal{A}_{\rm det}$ which are averaged to a single final result. In the following, we subtract the contribution of $\mathcal{A}_{\rm FB}$ using this method.

Using the $D^0 \to K^-\pi^+$ sample, we measure the detection asymmetry $\mathcal{A}_{\rm det}(K^-\pi^+)$, *i.e.* that for the particle pair $K^-\pi^+$. With the $D^- \to K^0_{\rm S}\pi^-$ decays, we access the asymmetry of the $K^0_S\pi^-$ pair. Assuming that particle-pair detection asymmetry is the sum of the individual detection asymmetry of each particle, we derive the detection asymmetry of pions and kaons as

$$\mathcal{A}_{\rm det}(\pi^-) \simeq \mathcal{A}_{\rm det}(D^- \to K^0_{\rm S}\pi^-) \tag{3}$$

$$\mathcal{A}_{\rm det}(K^-) \simeq \mathcal{A}_{\rm det}(D^0 \to K^-\pi^+) - \mathcal{A}_{\rm det}(\pi^+). \tag{4}$$

We neglect tiny contribution from *CP* violation in neutral kaons and consider $\mathcal{A}_{\rm det}(K^0_{\rm S}) = 0$. The subtraction of $\mathcal{A}_{\rm det}(\pi^+)$ $(= -\mathcal{A}_{\rm det}(\pi^-))$ in Eq. 4 is valid as long as pion kinematic is similar in the $D^0 \to K^-\pi^+$ and $D^- \to K^0_{\rm S}\pi^-$ samples, a fair assumption for these decays.

3. SELECTION

Events enriched in signal D decays are first selected by requiring the presence of at least three tracks with transverse momentum $p_T > 0.2$ GeV/c and originating from the interaction region (IR), and by vetoing events consistent with Bhabha scattering. The tracks are required to be in the central drift-chamber (CDC) angular acceptance, to have at least 1 hit in the CDC, and to have converged track fit.

For $D^0 \to K^-\pi^+$ candidates, we require a threshold for particle-identification of the kaon candidate from a variable that combine information provided by the CDC, the TOP and the ARICH detectors. The invariant mass of the $K\pi$ system must be $1.80 < m(K\pi) < 1.95\,{\rm GeV/c^2}$, and the momentum of D^0 candidate in the centre-of-mass frame $p(D^0) > 2.5\,{\rm GeV/c}$ to select $e^+e^- \to c\bar{c}$ events.

For $D^- \to K^0_{\rm S}\pi^-$ candidates, we require the $K^0_{\rm S}$ significance of distance to be larger than 44.5, and the $K^0_{\rm S}$ mass to be in the range $0.4942 < m(K^0_S) < 0.5014\,{\rm GeV}/c^2$. The invariant mass of $K^0_{\rm S}\pi$ candidate must be in the range $1.82 < m(K^0_S\pi) < 1.93\,{\rm GeV}/c^2$ and the D^- momentum in the center-of-mass $p(D^-) > 2.5\,{\rm GeV/c}$ to select $e^+e^- \to c\bar{c}$ events.

4. ASYMMETRY DETERMINATION

To determine $\mathcal{A}_{\rm det}$, we fit simultaneously the binned distributions of the D and $\overline{D}$ candidate masses. The mass distributions with fit projections overlaid are presented in Fig. 1.

For the $D^0 \to K^-\pi^+$ decays, $\mathcal{P}_{\rm sig}$ (signal PDF) is a sum of a Johnson and a Gaussian function, and $\mathcal{P}_{\rm bkg}$ (background PDF) is an exponential function. The parameters of $\mathcal{P}_{\rm sig}$ are fixed from the fit using the simulation; we add as free parameters a shift on the mean and a scale factor for the width of the peak. The slope parameter of $\mathcal{P}_{\rm bkg}$ is free.

For the $D^- \to K^0_{\rm S}\pi^-$ decays, $\mathcal{P}_{\rm sig}$ is a sum of a Johnson and a Gaussian function; $\mathcal{P}_{\rm bkg}$ is the sum of an exponential function, to model a smooth component dominated by combinatorial background, and a Crystal-Ball function, to model a D^-_s background peaking around $1.89\,{\rm Gev}/c^2$. The parameters of $\mathcal{P}_{\rm sig}$ and those of the Crystal-Ball component of $\mathcal{P}_{\rm bkg}$ are

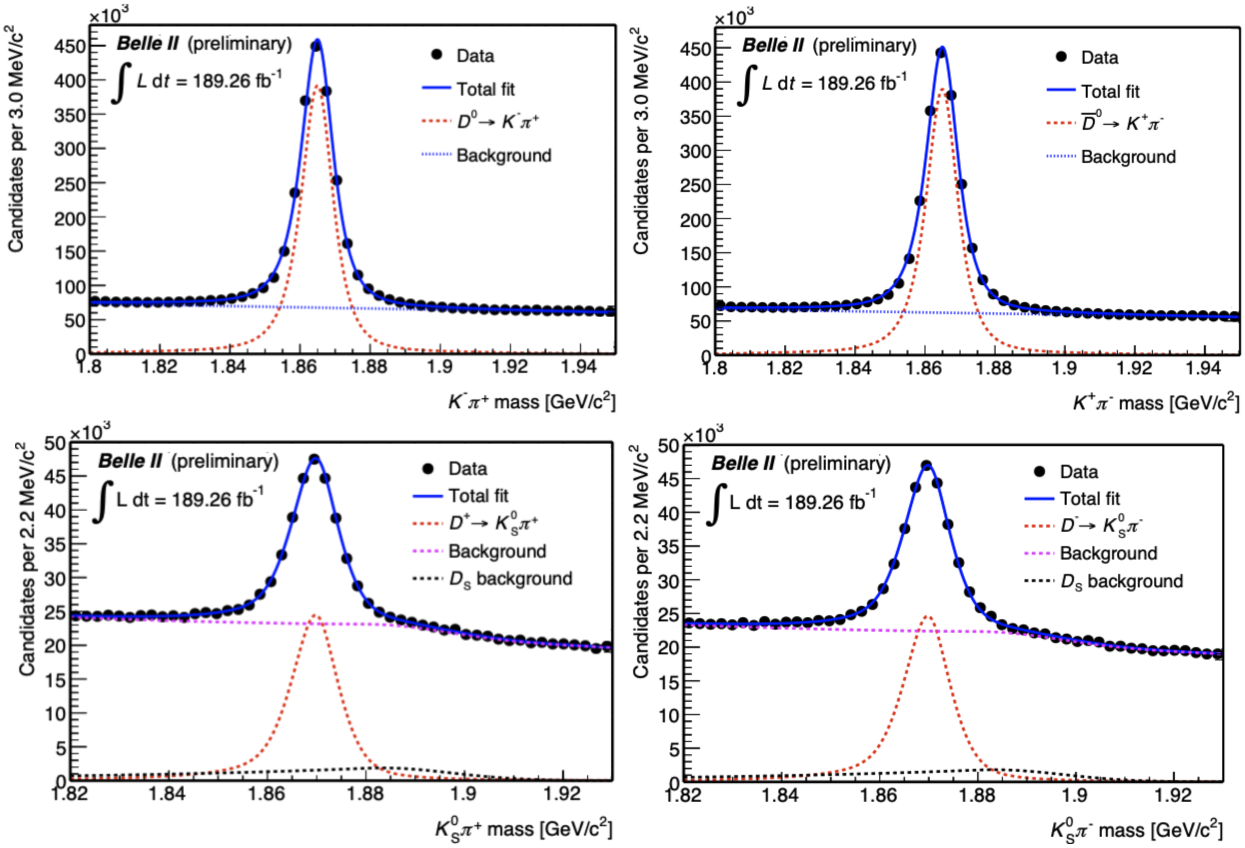

FIG. 1. (Top) Mass distributions for (left) $D^0 \to K^-\pi^+$ candidates and (right) $\overline{D}^0 \to K^+\pi^-$ candidates. (Bottom) Mass distributions for (left) $D^+ \to K^0_S\pi^+$ candidates and (right) $D^- \to K^0_S\pi^-$ candidates. Fit projections are overlaid.

fixed from the fit using the simulation; we add as free parameters a common shift on the mean and a common scale factor for the width of the peaks. The slope of the exponential and the fraction of the D_s^- background of $\mathcal{P}_{\rm bkg}$ are free parameters.
We measure:

$$\mathcal{A}_{\rm det}(K^-\pi^+) = (0.43 \pm 0.06)\% \,, \tag{5}$$

$$\mathcal{A}_{\rm det}(\pi^-) = (-0.10 \pm 0.34)\% \tag{6}$$

$$\mathcal{A}_{\rm det}(K^-) = (0.33 \pm 0.34)\% \,. \tag{7}$$

5. DEPENDENCIES OF $\mathcal{A}_{\rm det}$

We investigate possible dependencies of $\mathcal{A}_{\rm det}$ on the particle momentum (p), the cosine of polar angle ($\cos\theta$), and the number of CDC hits. Dependence of $\mathcal{A}_{\rm det}$ on p and $\cos\theta$ can be expected because interaction cross-sections depend on particle momentum and because particle traverse different material budget according to its direction. In addition, asymmetries intrinsic in tracking algorithms might also depend on particle kinematic. The average number of CDC hits varies for tracks of opposite curvature, and this might induce also a charge asymmetry as a function of CDC hits.
We show the dependence on each single variable marginalising over the distribution of the

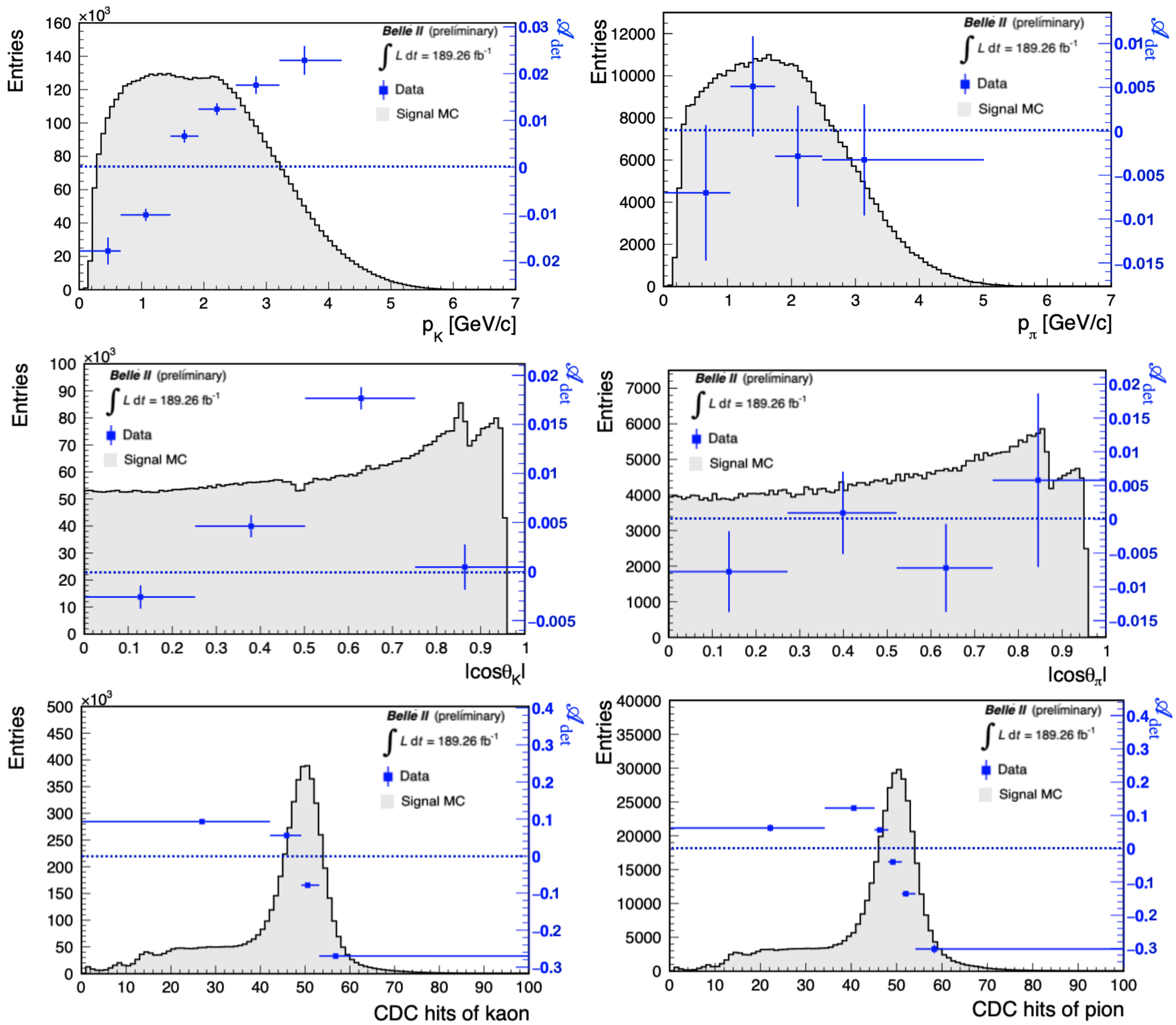

FIG. 2. (left column) Measurement of $\mathcal{A}_{\mathrm{det}}(K^-\pi^+)$ as a function of kaon (top) momentum $p(K)$, (middle) cosine of polar angle $\cos\theta(K)$, (bottom) track CDC hits. (right column) Measurement of $\mathcal{A}_{\mathrm{det}}(\pi^-)$ as a function of pion (top) momentum $p(\pi)$, (middle) cosine of polar angle $\cos\theta(\pi)$, (bottom) track CDC hits. Blue markers show measured values in data. The point are placed at the average of the values in the considered bin. The distributions of the variables for signal decays in simulation are also drawn as grey histograms.

others, although the three variables are not independent of each other. As example, we report plots of $\mathcal{A}_{\mathrm{det}}$ as a function of the three variables in Fig. 2 for both channels. We observe a variation of $\mathcal{A}_{\mathrm{det}}(K^-\pi^+)$ of about 4% and 2% as a function of $p(K)$ and $|\cos\theta(K)|$, respectively. The largest dependence of $\mathcal{A}_{\mathrm{det}}(K^-\pi^+)$ is observed as a function of CDC hits, where the asymmetry spans a range of about 40%. We observe a uniform values of $\mathcal{A}_{\mathrm{det}}(\pi^-)$, with deviations of about 1%, as a function of $p(\pi)$ or $|\cos\theta(\pi)|$. But, similarly to what observed for $D^0 \to K^-\pi^+$, a large dependence is observed as a function of CDC hits, where $\mathcal{A}_{\mathrm{det}}$ spans a range of about 40%.

6. $\mathcal{A}_{\text{det}}$ FOR $B^+ \to h^+\pi^0$ DECAYS

The measurement of $\mathcal{A}_{\text{det}}(\pi^-)$ and $\mathcal{A}_{\text{det}}(K^+)$ are used to subtract instrumental asymmetry for the measurement of CP asymmetries in $B^+ \to h^+\pi^0$ decays reported in Ref. [3]. Given the observed dependencies of $\mathcal{A}_{\text{det}}$, the distributions of momentum, cosine of polar angle, and CDC hits of pions and kaons of D and B decays are compared. We attempted a simultaneously weighting of D-decays distributions to mirror those of the target B decays. A closure test on simulation showed that residual discrepancy remains between the value of $\mathcal{A}_{\text{det}}$ measured in the D and B decays after this reweighting, and a systematic uncertainty of about 1% for both $\mathcal{A}_{\text{det}}(\pi^+)$ and $\mathcal{A}_{\text{det}}(K^+)$ has been assigned based on the observed differences. This suggests that further dependencies must be considered to improve the determination of $\mathcal{A}_{\text{det}}$ from D control channels. The final values obtained for $B^+ \to h^+\pi^0$ decays are:

$$\mathcal{A}_{\text{det}}(\pi^-) = (-0.5 \pm 1.0)\% \tag{8}$$
$$\mathcal{A}_{\text{det}}(K^-) = (-1.1 \pm 1.0)\% \,. \tag{9}$$

[1] A. J. Bevan et al., *The Physics of the B Factories*, 2014. `https://arxiv.org/abs/1406.6311`.

[2] P. Zyla and others (Particle Data Group), *The review of particle physics*, 2020. Prog. Theor. Exp. Phys. 083C01 (2020) .

[3] (Belle II collaboration), J. Skorupa et al., *Measurement of the Branching Ratio and Direct CP Asymmetry of $B^+ \to \pi^+\pi^0$ and $B^+ \to K^+\pi^0$ using the ICHEP 2022 Dataset*, 2022. `https://docs.belle2.org/record/2999/files/BELLE2-NOTE-PH-2022-024_v2.pdf`.