Search for CP violation in $D^0 \to \pi^+\pi^-\pi^0$ decays at Belle II

L. Massaccesi(1)(2)(*) on behalf of the Belle II italian collaboration

(1) *Dipartimento di Fisica, Università di Pisa - 56127 Pisa, Italy*
(2) *INFN, Sezione di Pisa - 56127 Pisa, Italy*

Summary. — The Belle II experiment has a sample of $424\,\mathrm{fb}^{-1}$ of data from e^+e^- collisions with center-of-mass energy close to the mass of the $\Upsilon(4S)$ resonance, corresponding to approximately 550 million $e^+e^- \to c\bar{c}$ events, which can be used for precision measurements in the charm sector. The standard model predictions of CP violation in this sector are typically below current experimental sensitivity, thus making CP asymmetry measurements in D meson decays sensitive to new physics effects. The progress of a CP asymmetry measurement in the singly-Cabibbo-suppressed channel $D^0 \to \pi^+\pi^-\pi^0$ is presented here. Thanks to a different yield-extraction strategy, this measurement is expected to improve on the precision of previous measurements despite similar sample size. Furthermore, preliminary studies on the subdivision of the Dalitz plot to measure the phase-space dependency of the asymmetry are shown.

1. – Introduction

The D^0-$\overline{D}^0$ mixing system is the only mixing system where flavor oscillations involve up-type quarks, making it a unique probe for new physics models where the up sector plays a special role. Additionally, the Standard Model (SM) predicts very small CP asymmetries in D meson decays, typically below current experimental sensitivity, leaving room to interpret any CP violation finding in terms of possible new physics contributions.

Among hadronic D decays, singly-Cabibbo-suppressed decays are unique in their sensitivity to CP violation in the $c \to uq\bar{q}$ transitions, which are accessible neither to Cabibbo-favored decays, nor to doubly-Cabibbo-suppressed decays. Thanks to the larger branching fractions compared to doubly-Cabibbo-suppressed decays, and the larger expected CP asymmetry compared to Cabibbo-favored decays, singly-Cabibbo-suppressed decays are ideal to search for CP violation in the charm sector [1].

$D^0 \to \pi^+\pi^-\pi^0$ is a singly-Cabibbo-suppressed decay. For this channel, the SM predicts a CP asymmetry just below current experimental sensitivity: the $\mathcal{A}_{CP}$ observable,

(*) E-mail: `ludovico.massaccesi@pi.infn.it`

which is defined in eq. 1, is expected to be $\mathcal{O}(0.1\%)$.

$$\mathcal{A}_{CP} = \frac{\Gamma(D^0 \to \pi^+\pi^-\pi^0) - \Gamma(\overline{D}^0 \to \pi^-\pi^+\pi^0)}{\Gamma(D^0 \to \pi^+\pi^-\pi^0) + \Gamma(\overline{D}^0 \to \pi^-\pi^+\pi^0)} \quad (1)$$

Previous *CP* asymmetry measurements in this channel found no evidence of *CP* violation. The most precise $\mathcal{A}_{CP}$ measurement to date was performed by BaBar with $385\,\mathrm{fb}^{-1}$ of data, corresponding to approximately 82×10^3 candidates. The result, which can be found in ref. [2], was $\mathcal{A}_{CP} = (0.31 \pm 0.41 \pm 0.17)\%$, where the first uncertainty is statistical and second is systematic. $\mathcal{A}_{CP}$ was also measured by Belle [3] with $532\,\mathrm{fb}^{-1}$ of data. LHCb also searched for *CP* violation in this channel in *pp* collisions [4] with $6\,\mathrm{fb}^{-1}$ of data.

The Belle II experiment [5] at the SuperKEKB collider [6] has $424\,\mathrm{fb}^{-1}$ of e^+e^- collision data available from its Run 1 (up to June 2022), corresponding to approximately 550×10^6 $e^+e^- \to c\bar{c}$ events. This proceeding reports on the progress of an analysis that aims to use this data to perform a competitive measurement of $\mathcal{A}_{CP}$ in $D^0 \to \pi^+\pi^-\pi^0$ exploiting the improvement in the detector and reconstruction process compared to first-generation *B*-factory experiments, as well as a different analysis strategy that will be explained in sect. **2**. Also, sect. **3** reports on a preliminary study of the possibility to exploit the knowledge of the Dalitz plot distribution of the $D^0 \to \pi^+\pi^-\pi^0$ decay to study the phase-space dependence of $\mathcal{A}_{CP}$.

2. – Analysis strategy

2˙1. *Data and simulated samples.* – The analysis will use all $424\,\mathrm{fb}^{-1}$ of Run 1 data, which includes $364\,\mathrm{fb}^{-1}$ of "on-resonance" runs with collision energy $\sqrt{s} = 10.58\,\mathrm{GeV}$ (the mass of the $\Upsilon(4S)$ resonance), $42\,\mathrm{fb}^{-1}$ of "off-resonance" runs with $\sqrt{s}$ below the $B\overline{B}$ pair production threshold, and $19\,\mathrm{fb}^{-1}$ "5S-scan" runs with $\sqrt{s}$ between 10.65 GeV and 10.81 GeV (around the mass of the $\Upsilon(5S)$ resonance). Also, $1696\,\mathrm{fb}^{-1}$ of Monte Carlo (MC) simulation is used. The simulation is run-dependent, *i.e.* it attempts to reproduce the real data-taking conditions of each run as closely as possible to maximize data-MC agreement.

2˙2. *Candidate reconstruction and selection.* – Neutral pions are reconstructed in the $\pi^0 \to \gamma\gamma$ channel. Photons are required not to be matched to tracks to reject clusters from charged particles; additionally, selections on cluster shape variables are used to reject clusters from other neutral particles, and selections on cluster time are used to reject photons from beam-induced backgrounds.

D^0 candidates are reconstructed from one π^0 candidate and two tracks with opposite charge, assuming the charged pion mass for the tracks. The tracks are required to originate close to the interaction point (IP) of the beams to reject particles from beam-induced backgrounds; additionally, particle identification (PID) variables are used to reject kaons, especially from the Cabibbo-favored $D^0 \to K\pi\pi^0$ channel.

Since $D^0 \to \pi^+\pi^-\pi^0$ and $\overline{D}^0 \to \pi^-\pi^+\pi^0$ decays are experimentally indistinguishable, additional information is required to reconstruct the flavor of the D^0 candidate. This is accomplished with D^* tagging, *i.e.* by reconstructing a charged D^* in the $D^* \to D^0\pi$ strong decay. Since only positive mesons can decay $D^{*+} \to D^0\pi^+$, and only negative mesons can decay $D^{*-} \to \overline{D}^0\pi^-$, the D^0 flavor can be inferred using the charge of the "tag" pion.

To reject D^* mesons produced in B meson decays, the D^* momentum in the collision center-of-mass (CM) frame is required to be larger than its kinematic limit in B meson decays. This avoids biases due to *CP* asymmetries in B physics, and also rejects a substantial fraction of the background.

Finally, a simultaneous vertex fit of the whole decay chain is performed, constraining the D^* vertex at the IP. This improves the resolution of Dalitz plot variables and reduces the smearing of its kinematic boundaries. The probability of the fit is also used for further background rejection by means of a simple cut, and by selecting only the best candidate (*i.e.* the one with the highest probability) in each event.

These selections have a signal efficiency of $(11.80 \pm 0.01)\%$ on MC. The total number of signal candidates expected at $424\,\mathrm{fb}^{-1}$ is 232×10^3, almost three times more than BaBar had in ref. [2] despite similar integrated luminosity. The statistical uncertainty on $\mathcal{A}_{CP}$ would then be about 0.2%, two times better than BaBar. However, this increase in effective sample size, which is mainly due to looser selection criteria, comes at the expense of purity.

Further discrimination between signal and background is provided by the D^0 invariant mass and by ΔM, *i.e.* the invariant mass difference between the D^* and the D^0. The distribution of these variables after applying all selections is shown in fig. 1.

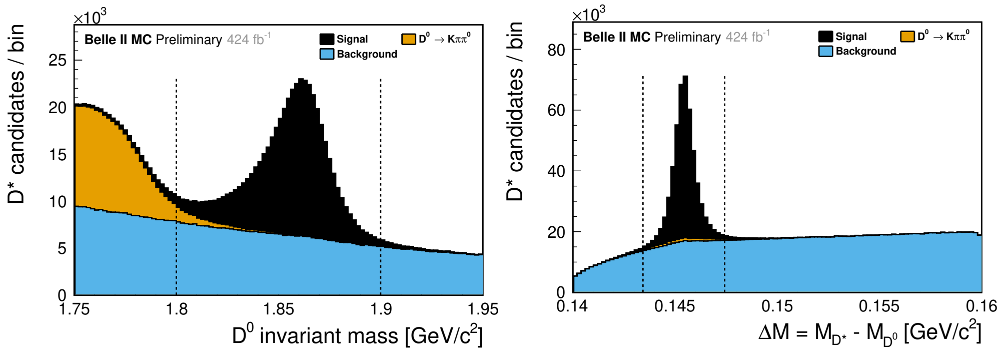

Fig. 1. – Signal-enhanced distributions of the D^0 invariant mass (left) and of ΔM (right). Signal-enhancement is performed by applying the cuts shown by the vertical dotted lines in one figure to produce the other.

2·3. *Yields and asymmetry extraction.* – To handle the lower-purity sample, a change of strategy with respect to previous works is required. Belle and BaBar analyses used tight selections to obtain a very pure sample, and subtracted background estimated from sidebands. This analysis will use a fit to the ΔM variable with a signal-plus-background model to extract the signal yields.

A preliminary model for the signal component uses the sum of a Gaussian distribution function, and a Johnson distribution function with the same mode as the Gaussian. A fit to the signal candidates in the MC sample is shown in fig. 2.

For the asymmetry extraction, the sample will be split by D^0 flavor; the total $(D^0 + \overline{D}^0)$ yield and the raw asymmetry will be used as fit variables to simplify the computation of the asymmetry and its statistical uncertainty. Furthermore, the sample will be split in several bins of θ_{cm} (the D^* momentum polar angle in the collision CM frame), and the asymmetry will be extracted per-bin: this allows to cancel the forward-backward

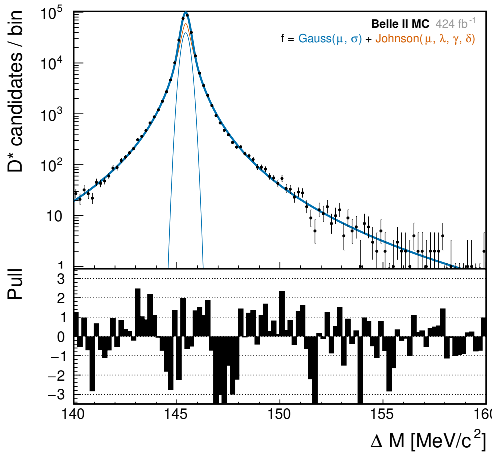

Fig. 2. – Top: ΔM distribution of the signal component from MC (points), best-fit probability density function (thick blue line) with its components (thin lines, Gaussian in blue and Johnson in orange). Bottom: pulls.

production asymmetry (which is due to the physics of $e^+e^- \to c\bar{c}$ events, and is odd in $\cos\theta_{\rm cm}$) by taking the average asymmetry in opposite $\cos\theta_{\rm cm}$ bins. The physical $\mathcal{A}_{CP}$ of the D^0 decay will not be cancelled in the average, as it does not depend on $\theta_{\rm cm}$.

Finally, the tag pion detection asymmetry, which is due to a difference in tracking efficiency for positive and negative tracks with low momentum, must be accounted for. The asymmetry will be estimated on data, using the $D^0 \to K\pi$ control sample, as a function of the polar angle θ and transverse momentum $p_{\rm T}$ of the track in the laboratory frame. This estimate will then be used to correct the detection asymmetry by reweighting the candidates before they are used in the fit.

3. – Dalitz-plot-dependent *CP* asymmetry

Several resonances are involved in the three-body decay $D^0 \to \pi^+\pi^-\pi^0$. The total decay amplitudes, in the simplified case of two resonances, can be written as

$$A(D^0 \to \pi^+\pi^-\pi^0) = A_1 \exp(i(\delta_1 + \phi_1)) + A_2 \exp(i(\delta_2 + \phi_2)) \quad (2a)$$

$$A(\overline{D}^0 \to \pi^-\pi^+\pi^0) = A_1 \exp(i(\delta_1 - \phi_1)) + A_2 \exp(i(\delta_2 - \phi_2)) \quad (2b)$$

where the magnitudes A_i, the *CP*-even or "strong" phases δ_i, and the *CP*-odd or "weak" phases ϕ_i are real functions of the Dalitz variables.

A phase-space dependent *CP* violation can arise if a relative *CP*-odd phase $\Delta\phi = \phi_2 - \phi_1$ exists between the amplitudes. Indeed, the *CP* asymmetry can be written as

$$\mathcal{A}_{CP} \propto |A(D^0)|^2 - |A(\overline{D}^0)|^2 \propto \sin\Delta\delta \sin\Delta\phi \quad (3)$$

where it can be noted that a non-zero $\mathcal{A}_{CP}$ can only arise if a relative *CP*-even phase $\Delta\delta = \delta_2 - \delta_1$ is also present. To maximize sensitivity to this kind of *CP* violation, one could use the knowledge of the *CP*-even phases of the resonances to decide an optimal binning of the Dalitz plot. It should be possible to use the strategy presented in sect. **2**

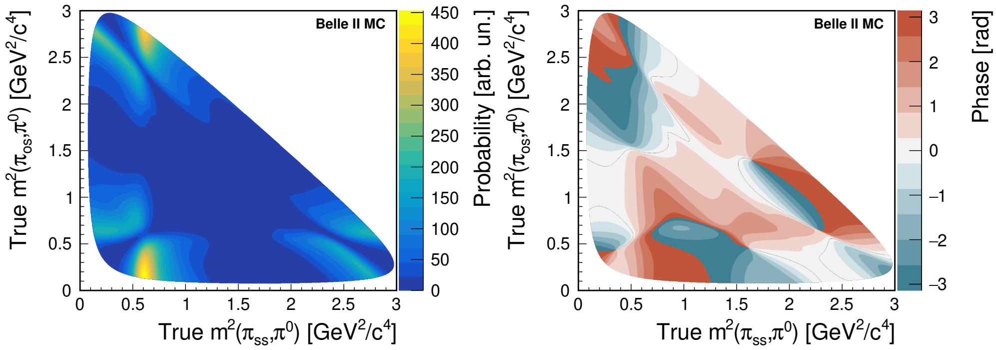

Fig. 3. – The decay probability (squared modulo of the total amplitude, left) and phase of the total amplitude (right) for $D^0 \to \pi^+\pi^-\pi^0$, as a function of the Dalitz plot variables, computed from the fit results in ref. [7]. The Dalitz plot variables are the squared invariant masses of the same-sign pion (π^+ for the D^0, π^- for the $\overline{D}^0$) and the π^0 on the x axis, and the opposite-sign pion (π^- for the D^0, π^+ for the $\overline{D}^0$) and the π^0 on the y axis.

also to measure $\mathcal{A}_{CP}$ separately in each Dalitz plot bin, as long as each bin is sufficiently populated.

An amplitude fit of the $D^0 \to \pi^+\pi^-\pi^0$ decay was performed by *BaBar* in ref. [7]. The results of this fit, which are used in the EvtGen-based [8] Belle II MC simulation, can also be used to compute the strong phases, as shown in fig. 3.

4. – Conclusion

The strategy and progress of a measurement of $\mathcal{A}_{CP}$ in $D^0 \to \pi^+\pi^-\pi^0$ with Belle II Run 1 data has been presented. The analysis will use a fit to the ΔM variable with a signal-plus-background model to extract the asymmetry: this strategy is able to accomodate a less pure sample, allowing to relax selections. Relaxed selection, together with the improved detector and reconstruction performance compared to *BaBar* and Belle, allows to increase the signal efficiency by almost a factor three, significantly improving the statistical uncertainty compared to previous results, despite similar integrated luminosity.

A preliminary study for a Dalitz-plot-dependent $\mathcal{A}_{CP}$ measurement has also been shown. This would be performed by dividing the Dalitz plot into a number of bins and measuring $\mathcal{A}_{CP}$ in each bin separately. The knowledge of resonant contributions to the decay amplitude would be used to decide the binning.

REFERENCES

[1] Grossman, Y. *et al.*, *Phys. Rev. D*, **75** (2007) 036008
[2] Aubert, B. *et al.*, *Phys. Rev. D*, **78** (2008) 051102
[3] Arinstein, K. *et al.*, *Phys. Lett. B*, **662** (2008) 102
[4] Aaij, R. *et al.*, *J. High Energ. Phys.*, **2023** (2023) 129
[5] Abe, T. *et al.*, *Belle II Technical Design Report*, arXiv:1011.0352
[6] Akai, K. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **907** (2018) 188
[7] Aubert, B. *et al.*, *Phys. Rev. Lett.*, **99** (2007) 251801
[8] David J. Lange, *Nucl. Instrum. Methods Phys. Res. A*, **462** (2001) 152