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Charm: Rare, CPV and Mixing

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In this proceeding recent results on charm physics from the LHCb collaboration and from the Belle and Belle II collaboration are presented. In particular, searches for rare decays of charm mesons and baryons, searches for CP violation and measurements of mixing parameter for various charm mesons will be reported. These kind of analyses are powerful probes for new physics and offer unique insights on standard model parameters. These results have world leading precisions thanks to the high-statistics datasets collected by LHCb, Belle and Belle II experiments.

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1. Introduction

Charm physics focuses on the study of particles containing charm quarks. It plays a crucial role in understanding the dynamics of the strong and weak interactions within the standard model (SM) and offers a sensitive probe for potential new physics (NP) beyond it. In particular, flavour changing neutral currents (FCNC) and charge-parity symmetry violation (CP violation) in charm decays, receive small contributions from the SM. Thus, a small deviation from the SM is a powerful probe for NP. The LHCb experiment has been able to perform precise measurements of charm mixing, CP violation, and rare decay processes, resulting in the discovery of CP violation in decays of D^0 mesons in 2019 [1]. Complementing LHCb's searches, the Belle experiment and its successor Belle II operates in the clean environment of electron-positron collisions. In this proceeding recent results on charm physics from LHCb, Belle and Belle II collaborations will be presented.

2. Search for rare decays at LHCb

FCNC processes are suppressed in the SM and forbidden at tree level as a consequence of the Glashow-Ilipoulos-Maiani (GIM) mechanism. However, extensions of the SM could include new diagrams for which these process can happen, providing a probe for NP.

2.1 Search for D^0 meson decays to $\pi^+\pi^-e^+e^-$ and $K^+K^-e^+e^-$ final states

A search for the decay modes $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ has been conducted with data collected from the LHCb experiment during the Run 2 data-taking campaign, with proton-proton collisions at centre of mass of $\sqrt{s} = 13$ TeV with a total integrated luminosity of $\mathcal{L} = 6$ fb^{-1} [2].

In this analysis, the D^0 candidates come from the $D^*(2010)^+ \to D^0\pi^+$ decays, where the $D^*(2010)^+$ meson is produced promptly in the proton-proton collision and will be referred to as D^{*+} throughout. This allows to determine the flavour of the D^0 meson, corresponding to the charge of the pion. The candidates are required to pass a set of online requirements in the LHCb trigger, and then a loose cut-based selection is applied offline. A multivariate algorithm is trained on data and simulation to further reduce combinatorial background. The requirement on its output is optimized simultaneously with the Particle IDentification (PID) variables to reduce mis-identified backgrounds from the $D^0 \to K^+K^-\pi^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays, where the two pions are mis-identified as electrons. This optimization is performed independently for the two different decays modes. To normalize the branching fractions, the $D^0 \to K^-\pi^+e^+e^-$ decay is considered, selected with the selection algorithm of $D^0 \to K^+K^-e^+e^-$ or $D^0 \to \pi^+\pi^-e^+e^-$, depending on the measured branching ratio.

Signal and normalization yield are extracted in bins of $m(e^+e^-)$, according to the presence of resonances, via an unbinned extended likelihood fit to the $m(h^+h^-e^+e^-)$ distribution. The resulting branching fractions obtained for each bin of $m(e^+e^-)$ are reported in Table 1. By integrating over the di-lepton invariant mass spectra above the threshold $m(e^+e^-) > 2m_\mu$, the branching fraction of the observed $D^0 \to \pi^+\pi^-e^+e^-$ decay results to be

$$\mathcal{B}(D^0 \to \pi^+\pi^-[e^+e^-]_{m(e^+e^-)>2m_\mu}) = (13.3 \pm 1.1 \pm 1.7 \pm 1.8) \times 10^{-7}, \quad (1)$$

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$m(e^+e^-)$ region	[MeV/c^2]	$\mathcal{B}[10^{-7}]$
	$D^0 \to \pi^+\pi^-e^+e^-$	
Low mass	$2m_\mu - 525$	< 4.8 (5.4)
η	525 – 565	< 2.3 (2.7)
ρ^0/ω	565 – 950	$4.5 \pm 1.0 \pm 0.7 \pm 0.6$
ϕ	950 – 1100	$3.8 \pm 0.7 \pm 0.4 \pm 0.5$
High Mass	> 1100	< 2.0 (2.2)
	$D^0 \to K^+K^-e^+e^-$	
Low mass	$2m_\mu - 525$	< 1.0 (1.1)
η	525 – 565	< 0.4 (0.5)
ρ^0/ω	> 565	< 2.2 (2.5)

Table 1: Resulting branching fractions for the decay $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ in each di-lepton invariant mass bin. In the bins where the significance is smaller then 3σ, only upper limits are reported at 90%(95%) confidence intervals. For bins in which the decays are observed the measure is reported in which the first uncertainty is statistical, the second one is systematic and the last is due to external input on the branching fraction of $D^0 \to K^-\pi^+e^-e^+$.

where the first uncertainty is statistical, the second one systematic and the third one due to uncertainty on the BR of $D^0 \to K^-\pi^+e^-e^+$. No evidence is found for the $D^0 \to K^+K^-e^+e^-$ decay so only upper limits in each bin have been set. The results are then compared with the results of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays measured at LHCb in a previous analysis [3] and are found to be consistent at the current precision.

2.2 Search for the rare decay of charmed baryon Λ_c^+ into $p\mu^+\mu^-$ final state

A search for the non-resonant $\Lambda_c^+ \to p\mu^+\mu^-$ decay is conducted using the data collected at LHCb during 2016-2018 with proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV with an integrated luminosity of 5.4 fb^{-1} [4]. A similar analysis has already been performed by LHCb with Run 1 data [5].

Candidate decays are selected online via the LHCb trigger, and offline must satisfy a requirement based on the output of a boosted decision tree (BDT). This boosted decision tree is trained using simulated signals and real data background from sideband of the invariant mass distribution. Requirements on the output of the BDT and PID requirements on the proton and muons are optimized simultaneously. The sample is then divided in bins of di-muon invariant mass, $m(\mu^+\mu^-)$, if either there are no expected intermediate resonance contributions (signal-region) or if there are expected resonances (no-signal-region).

In each bin, an unbinned extended maximum likelihood fit to the Λ_c^+ candidates mass distribution is performed where the signal yield and the combinatorial background yield are floating parameters. Additionally, the double mis-identified $\Lambda_c^+ \to p\pi^+\pi^-$ background yield is estimated in the full di-lepton invariant mass while its fractions in each bin are fixed from simulation data. In each region, the branching fraction is computed with $\Lambda_c^+ \to p(\phi \to \mu^+\mu^-)$ decay as normalization channel. The resulting branching fractions are reported in Table 2, where the an upper limit is calculated if the observed sensitivity is below 3σ. Combining the two signal regions, an upper

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$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$	Significance
low-mass	211.32 – 507.86	$< 0.93\ (1.1) \times 10^{-8}$	0.3σ
high-mass	1059.46 – 1348.13	$< 3.0\ (3.3) \times 10^{-8}$	2.8σ
η	507.86 – 587.86	$(1.67 \pm 0.69 \pm 0.23 \pm 0.34) \times 10^{-3}$	3.0σ
ρ	587.86 – 742.65	$(1.52 \pm 0.34 \pm 0.14 \pm 0.24) \times 10^{-3}$	5.6σ
	OR 822.65 – 965.20		
ω	742.65 – 822.65	$(9.82 \pm 1.23 \pm 0.73 \pm 2.79) \times 10^{-4}$	$> 7\sigma$

Table 2: Resulting branching fractions and significances for $\Lambda_c^+ \to p\mu^-\mu^+$ decays in bins of di-lepton invariant mass. In the regions where the significance is smaller then 3σ only upper limits are reported at 90%(95%) confidence. In the bins with a significance larger then 3σ, measurements are reported where the first uncertainty is statistical, the second systematic and the third reflects the uncertainty on the external input.

limit on the branching fraction of the non-resonant contribution of the decay $\Lambda_c^+ \to p\mu^+\mu^-$ in this di-muon mass region is found to be $\mathcal{B} < 2.9\ (3.2) \times 10^{-8}$ at 90% (95%) CL.

3. Charge-parity violation and mixing at LHCb and Belle

The neutral mesons D^0 are produced as eigenstates of the strong interaction with a well defined charm quantum number. However, due to the weak interaction they evolve in time into a mixture of D^0 and $\overline{D}^0$ with a process called mixing. Furthermore, due to the weak interaction, charm mesons decays can also violate the CP symmetry. Three possible CP violation processes can occur: in the decay (direct CP violation), in the mixing (indirect CP violation) or in the interference between the two processes. Direct CP violation is parametrized in terms of the CP asymmetry

$$A_{CP} = \frac{\Gamma(H_c \to f) - \Gamma(\overline{H}_c \to \overline{f})}{\Gamma(H_c \to f) + \Gamma(\overline{H}_c \to \overline{f})}, \tag{2}$$

where H_c is a charm hadron decaying to the final state f. This CP violation process has been observed in D^0 decays at LHCb [1] and is the only possible CP violation that can occur for charged $D^{\pm}_{(s)}$. Mixing has been observed in neutral charm mesons [6] [7] and is governed by the parameters

$$x_{12} \equiv \frac{2\,|M_{12}|}{\Gamma}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}, \tag{3}$$

where M_{12}, Γ_{12} are the off-diagonal elements of the 2×2 effective hamiltonian $\mathbf{H} \equiv \mathbf{M} - \frac{\mathbf{i}}{\mathbf{2}}\mathbf{\Gamma}$, while Γ is the width of the D^0 meson. Indirect CP violation can then be parametrized in terms of absorptive and dispersive phases $\phi_2^M \sim \arg(M_{12})$, $\phi_2^\Gamma \sim \arg(\Gamma_{12})$ [8].

3.1 Measurement of $D^0 - \overline{D}^0$ mixing and search for CP violation with $D^0 \to K^+\pi^-$ decays

The measurement of mixing and CP violating parameters in $D^0 \to K^+\pi^-$ decays is conducted with prompt $D^{*+} \to D^0\pi^+$ decays [9]. The analysis uses a dataset produced in proton-proton collisions recorded at LHCb during Run 2 data-taking campaign, corresponding to an integrated luminosity of 6 fb^{-1} at centre-of-mass energy of $\sqrt{s} = 13$ TeV. This analysis extends a previous

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analysis of Run 1 and 2016 data by including data from 2017 and 2018 and improving the analysis technique [10]. To infer mixing and CP violating parameters, the time dependent ratios $R^{\pm}_{K\pi}(t)$ of double Cabibbo suppressed decays $D^0 \to K^+\pi^-$ (Wrong Sign, WS) and Cabibbo favoured decays $D^0 \to K^-\pi^+$ (Right Sign, RS) are measured. The ratios are defined as

$$R^{+}_{K\pi} \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \text{ and } R^{-}_{K\pi} \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}. \tag{4}$$

These ratios can be expanded in powers of x_{12}, y_{12} and consequentially in t as

$$R^{\pm}_{K\pi} \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})t + (c'_{K\pi} \pm \Delta c'_{K\pi})t^2, \tag{5}$$

where $R_{K\pi}, A_{K\pi}, c_{K\pi}, \Delta c_{K\pi}, c'_{K\pi}, \Delta c'_{K\pi}$ are the parameter of interest defined as

$$R_{K\pi} \equiv \frac{1}{2}\left(\left|\frac{A_{\overline{f}}}{\overline{A}_{\overline{f}}}\right|^2 + \left|\frac{\overline{A}_f}{A_f}\right|^2\right), \quad A_{K\pi} \equiv \frac{\left|A_{\overline{f}}/\overline{A}_{\overline{f}}\right|^2 - \left|\overline{A}_f/A_f\right|^2}{\left|A_{\overline{f}}/\overline{A}_{\overline{f}}\right|^2 + \left|\overline{A}_f/A_f\right|^2} \approx a^d_{DCS} \tag{6}$$

$$c_{K\pi} \approx y_{12}\cos\phi^{\Gamma}_f \cos\Delta_f + x_{12}\cos\phi^{M}_f \sin\Delta_f, \tag{7}$$

$$\Delta c_{K\pi} \approx x_{12}\sin\phi^{\Gamma}_f \cos\Delta_f - y_{12}\sin\phi^{M}_f \sin\Delta_f, \tag{8}$$

$$c'_{K\pi} \approx \frac{1}{4}(x^2_{12} + y^2_{12}), \quad \Delta c'_{K\pi} \approx \frac{1}{2}x_{12}y_{12}\sin(\phi^{M}_f - \phi^{\Gamma}_f). \tag{9}$$

Here A_f ($\overline{A}_f$) is the decay amplitude of $D^0(\overline{D}^0)$ into the final state $f = K^-\pi^+$, $A_{\overline{f}}$ ($\overline{A}_{\overline{f}}$) is the decay amplitude of $D^0(\overline{D}^0)$ in the final state $f = K^+\pi^-$, a^d_{DCS} is the direct CP asymmetry of the doubly Cabibbo suppressed decay, Δ_f is the strong phase and $\phi^M_f, \phi^{\Gamma}_f$ are final state dependent weak phases. The six parameters of interest can be organized in CP-even observables ($R_{K\pi}, c_{K\pi}, c'_{K\pi}$) and CP-odd ($A_{K\pi}, \Delta c_{K\pi}, \Delta c'_{K\pi}$).

Candidates must pass a set of online requirements in the LHCb trigger and further filtered with an offline cut-based approach. The sample is divided in subsamples depending on the year of data-taking and in bins of lifetime of the D^0. In each sub-sample and bin of lifetime, the ratios of WS-to-RS are measured with a simultaneous χ^2 fit to the WS and the RS samples, on the D^* invariant mass. Potential sources of bias that might affect the ratio are accounted for, the ratios are corrected, and fitted via a χ^2 fit to extract the parameters. Two cases are considered: no CP violation allowed and CP violation allowed. The results are then combined with Run 1 results and are reported in Table 3. These results are compatible with the hypothesis of CP conservation.

3.2 Search for charge-parity violation in semileptonically tagged $D^0 \to K^+\pi^-$ decays

The measurement of mixing and CP violation parameters of $D^0 \to K^+\pi^-$ decays is conducted with $\overline{B} \to D^{*+}\mu^- X$ decays where $D^{*+} \to D^0\pi^+$ [11]. The flavour of D^0 mesons is tagged with both the pion and the muon. This analysis has already been performed with Run 1 data [12]. Similarly to the analysis discussed in the previous section, to extract the parameters, a time dependent ratio of WS and RS decays is measured at second order in decay time t. However the ratios are parametrized in a different way as

$$R^{\pm} = R^{\pm}_D + \sqrt{R^{\pm}_D}y'^{\pm}\left(\frac{t}{\tau_{D^0}}\right) + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau_{D^0}}\right)^2, \tag{10}$$

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Parameters		Correlations [%]					
		$R_{K\pi}$	$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(342.7 \pm 1.9) \times 10^{-5}$	100.0	−92.7	80.3	0.9	−0.7	0.2
$c_{K\pi}$	$(52.8 \pm 3.3) \times 10^{-4}$		100.0	−94.2	−1.3	1.2	−0.7
$c'_{K\pi}$	$(12.0 \pm 3.5) \times 10^{-6}$			100.0	0.7	−0.7	0.2
$A_{K\pi}$	$(-6.6 \pm 5.7) \times 10^{-3}$				100.0	−91.9	79.7
$\Delta c_{K\pi}$	$(2.0 \pm 3.4) \times 10^{-4}$					100.0	−94.1
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6) \times 10^{-6}$						100.0

Table 3: Results of the combination of Run 1 and Run 2 χ^2 fits to the ratios dependence on decay time. Correlation and uncertainty includes both statistical and systematic contributions.

with

$$\begin{pmatrix} x'^{\pm} \\ y'^{\pm} \end{pmatrix} = |q/p|^{\pm 1} \begin{pmatrix} \cos(\delta \pm \phi) & \sin(\delta \pm \phi) \\ -\sin(\delta \pm \phi) & \cos(\delta \pm \phi) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}. \tag{11}$$

and $R_D^+ \equiv \left| A_{K^+\pi^-} / \overline{A}_{K^+\pi^-} \right|^2$, $R_D^- \equiv \left| \overline{A}_{K^-\pi^+} / A_{K^-\pi^+} \right|^2$. Here A_f ($\overline{A}_f$) are the amplitudes of $D^0(\overline{D}^0)$ to the final state f, δ, ϕ are the differences of phases between the WS and RS decays respectively of the strong phase and of the weak phase, x, y are defined as $x \equiv \Delta M/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, with ΔM difference between the eigenstate masses and $\Delta\Gamma$ the difference between the eigenstate decay widths. The dataset analysed has been collected from LHCb during Run 2 from 2016 to 2018 with a total integrated luminosity of 5.4 fb^{-1}. Candidates are selected by the trigger of LHCb, with a cut-based approach and a multivariate classifier to enhance purity. They are then divided in bins of lifetime of the D^0 meson. Ratios $R^{\pm}$ are then extracted via an extended maximum likelihood fit to the data, while the parameters of interest are extracted from a χ^2 fit to the ratios dependence on time. This last fit is performed with three different assumptions: no CP violation allowed, no direct CP violation allowed and CP violation allowed. The results with CP violation allowed are then combined with results from Run 1 and are reported in Table 4. They are compatible with the hypothesis of no CP violation. The increase in precision due to this analysis to the mixing parameters is significantly more than expected from the sample size alone, thanks to the low decay-time coverage of this analysis.

Parameters		Correlations [%]					
		R_D^+	y'^+	$(x'^+)^2$	R_D^-	y'^-	$(x'^-)^2$
R_D^+	$(350.0 \pm 6.9 \pm 2.3) \times 10^{-5}$	100.0	−74.9	62.4	−1.3	0.0	0.0
y'^+	$(4.1 \pm 2.0 \pm 0.3) \times 10^{-3}$		100.0	−94.3	0.0	0.0	0.0
$(x'^+)^2$	$(0.8 \pm 1.5 \pm 0.1) \times 10^{-4}$			100.0	0.0	0.0	0.0
R_D^-	$(344.0 \pm 7.0 \pm 2.3) \times 10^{-5}$				100.0	−74.5	62.9
y'^-	$(6.8 \pm 2.1 \pm 0.3) \times 10^{-3}$					100.0	−94.6
$(x'^-)^2$	$(-0.5 \pm 1.7 \pm 0.1) \times 10^{-4}$						100.0

Table 4: Results of the combination of Run 1 and Run 2 χ^2 fit to the ratio dependence on the decay time of the D^0. For the parameters the first uncertainty is statistical and the second is the systematic one. Correlations include both statistical and systematic contributions.

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3.3 Measurement of CP violation observables in $D^+ \to K^-K^+\pi^+$ decays

A model-independent search for CP violation is performed with $D^+ \to K^-K^+\pi^+$ decays [13]. The data analysed corresponds to 5.4 fb^{-1} of integrated luminosity collected by LHCb during 2016-2018. The Dalitz plot is divided in bins with equivalent statistics, except for regions around the ϕ and $\overline{K}^{*0}$ resonances, where they are divided with internal boundaries across the resonance. In each bin i of the Dalitz plot the raw asymmetry is computed as

$$A_{\text{raw}}^{i,X} = \frac{N_+^{i,X} - N_-^{i,X}}{N_+^{i,X} + N_-^{i,X}}, \tag{12}$$

where $X = S, C$ refers to the signal channel or to the control channel $D_s^+ \to K^-K^+\pi^+$, and $N_\pm^{i,X}$ is the number of events extracted from a fit to the data corresponding to the binning. For each bin then the ΔA_{CP}^i observable is defined as $\Delta A_{CP}^i = A_{\text{raw}}^{i,S} - A_{\text{raw}}^{i,C} - \Delta A_{\text{raw}}^{\text{global}}$, where $\Delta A_{\text{raw}}^{\text{global}}$ accounts for possible global differences in the asymmetry over the Dalitz plot and is extracted directly by averaging the raw asymmetries across the Dalitz. The test statistic $\chi^2(\mathcal{S}_{\Delta_{CP}})$ is defined as $\chi^2(\mathcal{S}_{\Delta_{CP}}) = \sum_i^{N_{\text{bins}}} \left(\Delta A_{CP}^i / \sigma_{\Delta A_{CP}^i}\right)$, where $\sigma_{\Delta A_{CP}^i}$ are the statistical uncertainties. The resulting χ^2/n_{dof} is 31.8/22 and a p-value of 8.1% can be extracted, which is compatible with the hypothesis of no localized CP violation in the phase space.

Furthermore, a search for localized CP asymmetries across the region of the Dalitz corresponding to the resonance mediated decays $D^+ \to \phi\pi^+$ and $D^+ \to \overline{K}^{*0}K^+$ is performed. The CP asymmetry is defined as

$$A_{CP|S} = \frac{1}{2}\left[\left(\Delta A_{\text{raw}}^{\text{top-left}} + \Delta A_{\text{raw}}^{\text{bottom-right}}\right) - \left(\Delta A_{\text{raw}}^{\text{top-right}} + \Delta A_{\text{raw}}^{\text{bottom-left}}\right)\right], \tag{13}$$

where the indications of bottom, top, left, right, refer to the bins in the different areas with respect to the position of the resonance. The resulting asymmetries are found to be

$$A_{CP|S}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}, \tag{14}$$

$$A_{CP|S}^{\overline{K}^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}, \tag{15}$$

where the first error is the statistical error and the second is the systematic. Both results are compatible with the hypothesis of CP conservation.

3.4 Search for CP violation in $D_{(s)}^+ \to K_S^0K^-\pi^+\pi^-$

The search of CP violation in four body decays of charmed mesons D^+, D_s^+ is conducted through the asymmetries in triple products of momenta of daughters A_{CP}^{TP} [14]. This asymmetry is proportional to $\cos\delta \sin\phi$ where δ, ϕ are differences, respectively, in strong phase and weak phase between different amplitudes that lead to the same final state. The triple product is defined as $C_{TP} \equiv (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$ where $\vec{p}_{1,2,3}$ are the momenta of, respectively, K_S^0, K^- and π^+ measured in the $D_{(s)}^+$ rest frame. The analysis also includes a search of CP violation in asymmetries in the quadruple product $C_{QP} \equiv (\vec{p}_1 \times \vec{p}_2) \cdot (\vec{p}_3 \times \vec{p}_4)$ and in helicity angles. The observables for which asymmetries are extracted are C_{TP}, C_{QP}, $\cos\theta_{K_S^0} \cdot \cos\theta_{K^-}$, where $\theta_{K_S^0}$ and θ_{K^-} are the helicity

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angles, and the products of these quantities. For each observable X, the two asymmetries $A_X(D^+_{(s)})$ and $A_{\overline{X}}(D^-_{(s)})$ are defined as

$$A_X(D^+_{(s)}) = \frac{N(X>0) - N(X<0)}{N(X>0) + N(X<0)} \text{ and } A_{\overline{X}}(D^-_{(s)}) = \frac{N(\overline{X}>0) - N(\overline{X}<0)}{N(\overline{X}>0) + N(\overline{X}<0)}, \tag{16}$$

where $N(X \lessgtr 0)$ are $D^+_{(s)}$ yields, $N(\overline{X} \lessgtr 0)$ are $D^-_{(s)}$ yields and $\overline{X} = -1 \cdot X$ if X is proportional to C_{TP}. From these two asymmetries, we can quantify the CP violation with the CP asymmetry $A^X_{CP} = (A_X(D^+_{(s)}) - A_{\overline{X}}(D^-_{(s)}))/2$. These asymmetries are measured independently with Belle and Belle II dataset, with an integrated luminosity of 980 fb^{-1} for the former and 428 fb^{-1} for the latter. The data are collected from e^+e^- collisions with a centre-of-mass energy at or near the $\Upsilon(4S)$ resonance. The resulting asymmetries from Belle and Belle II and their combination are reported in Table 5. All the results are compatible with the hypothesis of CP conservation. These measurements are the world most precise measurements to date of asymmetry of triple products in single Cabibbo suppressed D^+ decays while the other observables are measured for the first time in charmed-meson decays.

	X	A^X_{CP} Belle$[10^{-3}]$	A^X_{CP} Belle II$[10^{-3}]$	Combined $A^X_{CP}[10^{-3}]$	Significance
D^+	C_{TP}	$-4.0 \pm 5.9 \pm 3.0$	$-0.2 \pm 7.0 \pm 1.8$	$-2.3 \pm 4.5 \pm 1.5$	0.5σ
	C_{QP}	$-1.0 \pm 5.9 \pm 2.5$	$-0.4 \pm 7.0 \pm 2.4$	$-0.7 \pm 4.5 \pm 1.7$	0.2σ
	$C_{TP}C_{QP}$	$+6.4 \pm 5.9 \pm 2.2$	$+0.6 \pm 7.0 \pm 1.3$	$+3.9 \pm 4.5 \pm 1.1$	0.8σ
	$\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-4.7 \pm 5.9 \pm 2.0$	$-0.6 \pm 6.9 \pm 3.0$	$-2.9 \pm 4.5 \pm 2.1$	0.6σ
	$C_{TP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$+1.9 \pm 5.9 \pm 2.0$	$-0.2 \pm 7.0 \pm 1.9$	$+1.0 \pm 4.5 \pm 1.4$	0.2σ
	$C_{QP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$+14.9 \pm 5.9 \pm 1.4$	$+7.0 \pm 7.0 \pm 1.6$	$+11.6 \pm 4.5 \pm 1.1$	2.5σ
D^+_s	C_{TP}	$-0.3 \pm 3.1 \pm 1.3$	$+1.0 \pm 3.9 \pm 1.1$	$+0.2 \pm 2.4 \pm 0.8$	0.1σ
	C_{QP}	$+0.6 \pm 3.1 \pm 1.2$	$+2.0 \pm 3.9 \pm 1.4$	$+1.1 \pm 2.4 \pm 0.9$	0.4σ
	$C_{TP}C_{QP}$	$+1.5 \pm 3.2 \pm 1.4$	$-2.7 \pm 3.9 \pm 1.7$	$-0.2 \pm 2.5 \pm 1.1$	0.1σ
	$\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-3.7 \pm 3.1 \pm 1.1$	$-6.3 \pm 3.9 \pm 1.2$	$-4.7 \pm 2.4 \pm 0.8$	1.8σ
	$C_{TP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-4.4 \pm 3.2 \pm 1.4$	$+0.8 \pm 3.9 \pm 1.4$	$-2.2 \pm 2.5 \pm 1.0$	0.8σ
	$C_{QP}\cos\theta_{K^0_S}\cos\theta_{K^-}$	$-1.6 \pm 3.1 \pm 1.3$	$-0.0 \pm 3.9 \pm 1.7$	$-1.0 \pm 2.4 \pm 1.0$	0.4σ

Table 5: Results of asymmetries A^X_{CP} for each observable X from both Belle and Belle II samples and their combination. The first uncertainty is statistical while the second one is systematic. Significance is computed against the hypothesis of $A^X_{CP} = 0$.

4. Conclusions

In this contribution recent studies of charmed-hadrons from LHCb, Belle, and Belle II have been presented. The decay $D^0 \to \pi^+\pi^-e^+e^-$ has been observed for the first time by the LHCb collaboration. Upper limits on non-resonant contribution of Λ_c^+ have been measured by the LHCb Collaboration. LHCb has also reported complementary measurements of $D^0 - \overline{D}^0$ mixing and CP violation parameters with both π-tagged and μ-tagged analyses of the decay $D^0 \to K^+\pi^-$, reporting no evidence of CP violation. A search for localized CP violation in the three body decay $D^+ \to K^-K^+\pi^+$ has been performed reporting no evidence of CP violation by the LHCb collaboration. Finally, the Belle and Belle II collaborations have searched for CP violation in four body decays of $D^+_{(s)} \to K^0_S K^-\pi^+\pi^-$ resulting in no observation of CP violation.

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