Enhanced Charm *CP* Asymmetries from Final State Interactions

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We show that final state interactions (FSI) within a *CPT* invariant two-channel framework can enhance the charge-parity (*CP*) violation difference between $D^0 \rightarrow \pi^- \pi^+$ and $D^0 \rightarrow K^- K^+$ decays up to the current experimental value. This result relies upon (i) the dominant tree level diagram, (ii) the well-known experimental values for the $D^0 \rightarrow \pi^- \pi^+$ and $D^0 \rightarrow K^- K^+$ branching ratios, and (iii) the $\pi\pi \rightarrow \pi\pi$ and $\pi\pi \rightarrow KK$ scattering data to extract the strong phase difference and inelasticity. Based on well-grounded theoretical properties, we find the sign and bulk value of the ΔA_{CP} and $A_{CP}(D^0 \rightarrow \pi^- \pi^+)$ recently observed by the LHCb Collaboration.

Introduction.—Physics beyond the standard model (BSM), in general, predicts new sources of charge-parity violation (*CPV*). Experimentally, the high sensitivity and the clear signatures to observe the *CPV* in heavy meson decays [1–5] led the search for these asymmetries to become an important branch of flavor physics. In particular, *CPV* in charm meson decay, suppressed by the standard model, became a special tool to search for BSM effects, as suggested by Bigi and Sanda years ago, calling it "The dark horse candidate" [5].

Recently the LHCb Collaboration made a significant step ahead in the understanding of *CPV* in charm, with the observation of the difference between the *CP* asymmetries of the singly Cabibbo-suppressed (SCS) $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^-$ decays [6]:

$$\Delta A_{CP}^{\text{LHCb}} = A_{CP}(D^0 \rightarrow K^- K^+) - A_{CP}(D^0 \rightarrow \pi^- \pi^+)$$
$$= -(1.54 \pm 0.29) \times 10^{-3}. \quad (1)$$

This result is dominated by the direct *CP* asymmetry, with a negligible contribution from the $D^0 - \bar{D}^0$ oscillation [7]. The observed value of ΔA_{CP} was understood to be at the

borderline of the standard model and BSM interpretations [3]. The world average is [8]

$$\Delta A_{CP}^{\text{av}} = -(1.61 \pm 0.28) \times 10^{-3}, \quad (2)$$

with the channel asymmetries defined as

$$A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}, \quad (3)$$

where f represents the final state.

There are several theoretical frameworks that address *CPV* in charm within the Standard Model. They can be divided between those using the QCD short-distance approach [9,10] and those considering long-distance effects through FSI [11,12], including the topological approach with SU(3) breaking [13–16]. In the charm sector, QCD has known problems to access the charm penguin contribution and the QCD based approach [9] has predicted ΔA_{CP} one order of magnitude lower than the experimental value. On the other hand, the available long-distance approach tries to explain the *CPV* result in charm by exploring model-dependent fitting to nonperturbative aspects of QCD.

The importance of FSI in charm decays has been known for a long time [17–19] but only recently used to investigate *CPV* effects [11,12]. In this Letter, we go beyond the previous FSI analysis. Within a *CPT* conserving framework, where the total width of the particle and antiparticle should be the same [20], and considering the rescattering process $\pi^+ \pi^- \rightarrow K^+ K^-$, one can produce the interference
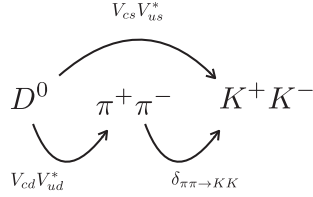
FIG. 1. Illustration of the mechanism for direct CPV in D^0 (and $\overline{D^0}$) decays driven by $\pi^+\pi^- \to K^+K^-$ rescattering.

necessary to magnify the CPV in the $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ amplitude decays. For the meson scattering amplitudes, we use the values observed in the 1980s [21,22]. Such a mechanism is illustrated in Fig. 1 and can explain the sign and bulk values of ΔA_{CP} and the $A_{CP}(D^0 \to \pi^-\pi^+)$ observed recently by LHCb [6,23].

The interference mechanism between $\pi^+\pi^-$ and K^+K^- states due to the strong final state interaction (FSI) in the S wave, was also shown to explain the large amount of CPV observed in some regions of the phase space of charmless three-body B decays [24–26], as reviewed in [2]. In D decays, this idea is also present in Grossman and Schacht [12] within symmetry approach.

Here we only consider contributions from tree level diagrams, as given in Fig. 2, and build the corresponding decay amplitudes with well-grounded properties of the SM: (i) the CPT invariance assumption relating decays with the same quantum numbers; (ii) the Watson theorem relating the strong phase of the rescattering process $\pi^+\pi^- \to K^+K^-$ to the decay amplitudes; and (iii) the unitarity of the strong S matrix.

CPT implications for CPV.—The CPT constraint has been used in charmless B decays with exciting results for experimental analysis [27,28] and phenomenological interpretations [24–26,29]. The large phase space available in B decays allows, in principle, several possible rescattering contributions for each channel, which brings into question the CPT invariance constraint. However, this argument does not hold for charm meson decays with a small and well-explored phase space.

The final states of nonleptonic SCS D^0 decays involves only mesons, with the dominance of pion and kaon (M) channels. In principle, the FSI could mix all these states,
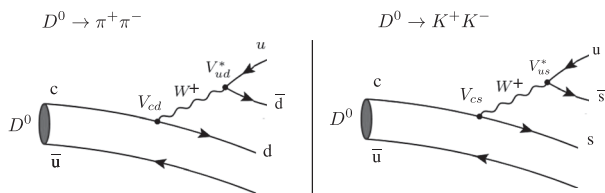

FIG. 2. Quark tree diagrams for the $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays.

through the general strong S matrix, involving any number of mesons, allowed by the phase space:

$$S = \begin{pmatrix} S_{2M,2M} & S_{2M,3M} & S_{2M,4M} & \cdots \\ S_{3M,2M} & S_{3M,3M} & S_{3M,4M} & \cdots \\ S_{4M,2M} & S_{4M,3M} & S_{4M,4M} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix}, \qquad (4)$$

where each element is a matrix representing the strong coupling between the channels with a number of mesons n, labeled by (nM). In particular, considering the final state interactions in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays, we know that two pions cannot branch to three pions due to the G parity. For the purpose of finding the main mechanism that drives CPV, we can ignore four pion coupling to the $2M$ channel, namely, $S_{2M,4M} \approx 0$ and $S_{4M,2M} \approx 0$ (based on $1/N_c$ counting arguments [30,31]), and the coupling to the $\eta\eta$ channel [32], considering that their couplings to the $\pi\pi$ channel are suppressed with respect to the $K\bar{K}$ one.

We remark that although the $D^0 \to 4\pi$ decays have a large branching fraction, there is no clear evidence of strong coupling between the two and four pion channels in the D^0 mass region. The only observable that decays in both channels is the $f_0(1500)$ scalar resonance. For other scalar states such as $f_0(980)$ and $f_0(1710)$, the dominant channels are $K\bar{K}$ and two pions, with no observation of four pions reported.

Consequently, for CPV studies of $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays, it is a good approximation to consider $S_{2M,2M}$ restricted to the $(\pi\pi, KK)$ S-wave channels. The $S_{2M,2M}$ unitarity leads to an important CPT constraint in which the A_{CP}'s must have opposite signs.

FSI and CPT constraint.—If we assume that the single Cabibbo suppressed $D^0 \to \pi^-\pi^+$ and $D^0 \to K^-K^+$ decays proceed via tree level amplitudes, neglecting the suppressed contribution from penguins ($P/T \sim 0.1$ [3]), as depicted in Fig. 2, there is no possibility to generate CP violation other than coupling these two channels, which have different weak phases, via the strong interaction. This is fulfilled by the rescattering mechanism explicitly illustrated in Fig. 1.

The weak phase difference comes from the CKM matrix elements in the tree amplitudes of Fig. 2, with the CP violating phase carried by $V_{cd}V^*_{ud}$. The weak phase in $V_{cs}V^*_{us}$ was neglected, as it is much smaller than the one in $V_{cd}V^*_{ud}$ [33].

The Watson theorem says that the strong phase $\delta_{\pi\pi \to KK}$ is the same, independent of the initial process. Therefore, we can use the parameters obtained in the $\pi\pi$ scattering from the $\pi N \to \pi\pi N$ and $\pi N \to KKN$ reactions [21,22,34]. These experiments observed two important properties in the $\pi^+\pi^-$ S wave: the inelasticity parameter decreases
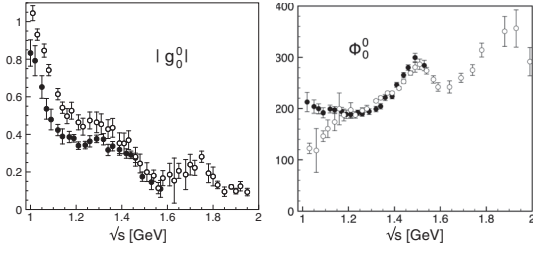
FIG. 3. $\pi\pi \to K\bar{K}$ amplitude $|g_0^0|$ (left) and phase Φ_0^0 in degrees (right), associated with $S_{\pi\pi,KK}$ Eq. (6). Experimental data from Argonne [21] (full) and Brookhaven [22] (empty).

drastically above 1 GeV with the opening of the KK channel [34]; and the KK channel dominates the inelasticity of the $\pi^+\pi^-$ one below 2 GeV, which also supports our previous discussion. To be more concrete, in Fig. 3 we show two experimental results for the $\pi\pi \to K\bar{K}$ scattering amplitude in the scalar-isoscalar state. From this figure, we can extract the transition amplitude needed to compute the rescattering effects in the $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays near the D_0 mass.

For our purpose, it is enough to know the S-wave S matrix for the coupled channels $\pi^-\pi^+$ and K^-K^+:

$$S_{2M,2M} = \begin{pmatrix} S_{\pi\pi,\pi\pi} & S_{\pi\pi,KK} \\ S_{KK,\pi\pi} & S_{KK,KK} \end{pmatrix}, \qquad (5)$$

where $S_{\pi\pi,\pi\pi} = \eta e^{2i\delta_{\pi\pi}}$, $S_{KK,KK} = \eta e^{2i\delta_{KK}}$, and $S_{\pi\pi,KK} = S_{KK,\pi\pi} = \iota\sqrt{1-\eta^2}e^{\iota(\delta_{\pi\pi}+\delta_{KK})}$, with $\delta_{\pi\pi}$ and δ_{KK} the elastic phase shifts, and $0 \le \eta \le 1$ the absorption parameter. To quantify η, we used the parametrization of the off-diagonal S-matrix element from [35,36]:

$$S_{\pi\pi,KK}(s) = i4\sqrt{\frac{q_\pi q_K}{s}}|g_0^0(s)|e^{i\phi_0^0(s)}\Theta(s-4m_K^2), \quad (6)$$

where $\phi_0^0 = \delta_{\pi\pi} + \delta_{KK}$, $q_\pi = \frac{1}{2}\sqrt{s-4m_\pi^2}$ and $q_K = \frac{1}{2}\sqrt{s-4m_K^2}$. From Fig. 3 one finds that, at the D^0 mass $|g_0^0(M_D^2)| = 0.125 \pm 0.025$, which from [35,36] gives $\sqrt{1-\eta^2} = 0.229 \pm 0.046$ and $\eta = 0.973 \pm 0.011$. Also, we have $\phi_0^0(M_D^2) = 343° \pm 8°$.

Summarizing our assumptions up to this point, we (i) ignored the sub-leading diagrams of the amplitude decay; (ii) considered the dominant FSI in $\pi\pi$ to be the KK channel; and (iii) used a data driven approach to extract both $\pi\pi$ and $\pi\pi \to KK$ magnitude and phases at the D_0 mass energy. With these assumptions, the total D^0 decay amplitudes produced by the tree diagrams of Fig. 2 are dressed by the hadronic FSI and receive contribution from both diagonal and off-diagonal S-matrix elements from Eq. (5). The resulting amplitude is denoted by $\mathcal{A}_{D^0 \to f}$, with

f labeling the 0^+ final states restricted to the $f \equiv \pi^+\pi^-$ and K^+K^- channels:

$$\mathcal{A}_{D^0 \to KK} = \eta e^{2i\delta_{KK}}V_{cs}^*V_{us}a_{KK}$$
$$+ i\sqrt{1-\eta^2}e^{i(\delta_{\pi\pi}+\delta_{KK})}V_{cd}^*V_{ud}a_{\pi\pi},$$
$$\mathcal{A}_{D^0 \to \pi\pi} = \eta e^{2i\delta_{\pi\pi}}V_{cd}^*V_{ud}a_{\pi\pi}$$
$$+ i\sqrt{1-\eta^2}e^{i(\delta_{\pi\pi}+\delta_{KK})}V_{cs}^*V_{us}a_{KK}. \qquad (7)$$

For the $\bar{D}^0 \to f$ decay amplitude, $\mathcal{A}_{\bar{D}^0 \to f}$, the CKM matrix elements are their complex conjugates.

The amplitudes a_{KK} and $a_{\pi\pi}$ do not carry any strong or weak phases, due to the tree level nature of the decay process. All of the hadronic FSI comes from S-matrix elements that has been factored out and included in the D^0 and $\bar{D}^0$ decay amplitudes. Equation (7) is equivalent to the leading order amplitudes due to the strong interaction derived in [24] and based on Refs. [5,20].

The CPT constraint restricted to the two-channels corresponds to

$$\sum_{f=(\pi\pi,KK)} (|\mathcal{A}_{D^0 \to f}|^2 - |\mathcal{A}_{\bar{D}^0 \to f}|^2) = 0, \qquad (8)$$

which is fulfilled by the proposed decay amplitudes of Eq. (7) and their charge conjugate ones. It is worth noting that the essential ingredients to derive the result shown in (8) are the unitarity of the S matrix of the two-channel model and the weak phase assigned by the products of the CKM matrix elements. One could write the analogous of Eq. (8) including more strongly coupled channels. However, as we argued before, we want to investigate the main mechanism and so we keep only the dominant $(\pi\pi, KK)$ channels.

The identity expressed by (8) illustrates how the so called "compound" CP asymmetry [37,38], including the effects of the weak and strong phases, has the important property of the two terms canceling one other, when summed over all final states, in order to satisfy the CPT condition.

CP asymmetries in $D^0 \to \pi^-\pi^+$ and $D^0 \to K^+K^-$.—The CPV difference in the partial decay widths of D^0 and $\bar{D}^0$ is defined as $\Delta\Gamma_f = \Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)$. By considering the amplitudes in Eq. (7) and those for the charge conjugate state, we get the following:

$$\Delta\Gamma_{\pi\pi} = -\Delta\Gamma_{KK} = 4\text{Im}[V_{cs}V_{us}^*V_{cd}^*V_{ud}]$$
$$\times a_{\pi\pi}a_{KK}\eta\sqrt{1-\eta^2}\cos\phi, \qquad (9)$$

where $\phi = \delta_{KK} - \delta_{\pi\pi}$, remembering that $a_{\pi\pi}$ and a_{KK} are real and have the same sign. Note that the sign of $\Delta\Gamma_f$ is determined by the elements of the CKM matrix and the elastic S-wave phase-shifts in the two final state channels.

In order to obtain the A_{CP}'s, one has to estimate $a_{\pi\pi}$ and a_{KK}, which can be done using the partial widths of the decays $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$, extracted from the amplitudes given in Eq. (7). Assuming that $\sqrt{1-\eta^2} \ll 1$ at the D^0 mass, we have

$$\Gamma_{\pi\pi} \approx \eta^2 |V_{cd}^* V_{ud}|^2 a_{\pi\pi}^2 \quad \text{and} \quad \Gamma_{KK} \approx \eta^2 |V_{cs}^* V_{us}|^2 a_{KK}^2. \quad (10)$$

If we use the branching fraction information $\mathrm{Br}(D^0 \to \pi\pi)$ and $\mathrm{Br}(D^0 \to KK)$, we can determine $a_{\pi\pi}$ and a_{KK} with Eq. (10). Here, we do not address the values of the branching ratios and assume they are consistent with the standard model. Our data driven approach tackles only the difference between the two decay widths and we use the experimentally measured values of the branching ratios as inputs for the computation of A_{CP}. We observe that the branching ratio values have been the subject of investigation in the literature [16–18].

The CP asymmetries are then, from Eqs. (9) and (3), given by

$$A_{CP}(f) \approx \pm 2 \frac{\mathrm{Im}[V_{cs}V_{us}^* V_{cd}^* V_{ud}]}{|V_{cs}V_{us}^* V_{cd}^* V_{ud}|}$$
$$\times \eta^{-1}\sqrt{1-\eta^2}\cos\phi \left[\frac{\mathrm{Br}(D^0 \to K^+K^-)}{\mathrm{Br}(D^0 \to \pi^+\pi^-)}\right]^{\pm\frac{1}{2}}, \quad (11)$$

where $+$ and $-$ stand for $f = \pi^+\pi^-$ and K^+K^-, respectively, and the CKM factors ratio reads [33]

$$\frac{\mathrm{Im}[V_{cs}V_{us}^* V_{cd}^* V_{ud}]}{|V_{cs}V_{us}^* V_{cd}^* V_{ud}|} = (6.02 \pm 0.32) \times 10^{-4}. \quad (12)$$

Estimation of the CP asymmetries.—Inspecting the CP asymmetry in Eq. (11), the remaining unknown quantity is the difference between the KK and $\pi\pi$ S-wave phase shifts. Ideally, to quantify the contribution from $\cos(\delta_{KK} - \delta_{\pi\pi})$ at the M_D energy, we could directly inspect the phase data at this point. However, differently from $\pi\pi$, there is no $K\bar{K}$ scattering data from meson-nucleon interactions. Without precise knowledge of the $K\bar{K}$ phase, we use $\delta_{KK} - \delta_{\pi\pi} = (\delta_{KK} + \delta_{\pi\pi}) - 2\delta_{\pi\pi} = \phi_0^0 - 2\delta_{\pi\pi}$. From $\pi\pi$ scattering data [34,39] and the $\pi\pi \to KK$ phase, given in Fig. 3, we obtained $\cos(\delta_{KK} - \delta_{\pi\pi}) \lesssim 1$ in the high mass region. This can be verified from 1.58 to 1.78 GeV, the upper limit of the data [34]. The $\cos\phi$'s extracted from the updated CERN-Munich data for $\delta_{\pi\pi}$ [39] and $\phi_0^0 = \delta_{KK} + \delta_{\pi\pi}$ from [35] are very close to 1. At M_{D^0} energy, $\delta_{\pi\pi}$ comes from the extrapolation given in [36] (Solution II, which is consistent with the data [34] and [39]), resulting in $\cos\phi = 0.99 \pm 0.18$. Note that at this energy the parametrization [36] has a large error bar.

Given the branching fraction values [33]:

$$\mathrm{Br}(D^0 \to \pi^+\pi^-) = (1.455 \pm 0.024) \times 10^{-3},$$
$$\mathrm{Br}(D^0 \to K^+K^-) = (4.08 \pm 0.06) \times 10^{-3}. \quad (13)$$

all parameters for calculating the CP asymmetries, of Eq. (11), are well defined, except for η. So we factorize its dependence as

$$A_{CP}(\pi\pi) = (1.99 \pm 0.37) \times 10^{-3}\sqrt{\eta^{-2} - 1},$$
$$A_{CP}(KK) = -(0.71 \pm 0.13) \times 10^{-3}\sqrt{\eta^{-2} - 1}, \quad (14)$$

and from that

$$\Delta A_{CP}^{\mathrm{th}} = -(2.70 \pm 0.50) \times 10^{-3}\sqrt{\eta^{-2} - 1}. \quad (15)$$

As we pointed out earlier in Fig. 3, there is only one datum for $\pi\pi \to KK$ with center mass energy above 1.8 GeV, needed to reach the D^0 mass. The solution gives $\eta \approx 0.973 \pm 0.011$ [35], which implies

$$\Delta A_{CP}^{\mathrm{th}} = -(0.64 \pm 0.18) \times 10^{-3}. \quad (16)$$

The result we found for $\Delta A_{CP}^{\mathrm{th}}$ clearly shows the relevant enhancement of FSI for this quantity, arriving at the sign and bulk value of the LHCb observation. This indeed is the largest theoretical prediction within SM without relying on fitting parameters [3].

Although the systematic uncertainties are absent in $|g_0^0|$ seen in Fig. 3, the experimental study used to extract these values at high energies [22], reported high systematic uncertainties in their estimate of other experimental parameters obtained in that analysis. Therefore the quoted error in η in this case is underestimated, which impacts the error in Eq. (16).

In order to explore other possible values of the inelasticity, if instead of using the $\pi\pi \to KK$ data, one uses $\pi\pi \to \pi\pi$ from Grayer *et al.* [40], one finds $\eta = 0.78 \pm 0.08$. In this case, the approximation $\sqrt{1-\eta^2} \ll 1$ does not hold and we considered the complete solution of Eq. (7). In order to keep $a_{\pi\pi}$ and a_{KK} real, we choose $\delta_{\pi\pi} - \delta_{kk} = 30°$, that is within the quoted error for $\cos\phi$. That gives

$$\Delta A_{CP}^{\mathrm{th}} = (-1.31 \pm 0.20) \times 10^{-3}. \quad (17)$$

This value is compatible with the LHCb experimental results within 1σ, and relies on our assumption that the $K\bar{K}$ channel saturates the inelasticity in $\pi\pi$ scattering at the D^0 mass.

Independently of the value for η, we can make a prediction for future experimental results of the ratio:

$$\frac{A_{CP}(D^0 \to \pi^-\pi^+)}{A_{CP}(D^0 \to K^-K^+)} = -\frac{\mathrm{Br}(D^0 \to K^-K^+)}{\mathrm{Br}(D^0 \to \pi^-\pi^+)} = -2.8 \pm 0.06.$$

In fact, relying only on the *CPT* constraint for two channels, given by Eq. (8), one can easily obtain the *CP* asymmetries as follows:

$$A_{CP}(\pi\pi) = -\frac{\Delta A_{CP}\text{Br}(D^0 \to K^+K^-)}{\text{Br}(D^0 \to K^+K^-) + \text{Br}(D^0 \to \pi^+\pi^-)},$$

$$A_{CP}(KK) = \frac{\Delta A_{CP}\text{Br}(D^0 \to \pi^+\pi^-)}{\text{Br}(D^0 \to K^+K^-) + \text{Br}(D^0 \to \pi^+\pi^-)}, \quad (18)$$

which are also valid for the A_{CP}'s from Eq. (11). Using experimental inputs for ΔA_{CP} and Br's we predict the values for the A_{CP}'s:

$$A_{CP}(\pi\pi) = (1.135 \pm 0.021) \times 10^{-3},$$
$$A_{CP}(KK) = -(0.405 \pm 0.077) \times 10^{-3}. \quad (19)$$

Summary.—We predict an enhancement of the A_{CP}'s and ΔA_{CP} for the SCS decays $D^0(\bar{D}^0) \to \pi^-\pi^+$ and $D^0(\bar{D}^0) \to K^-K^+$, relying solely on SM physics. The enhancement is a consequence of $\pi^+\pi^-$ and K^+K^- coupling via the FSI, whose strong phase contribute to both amplitudes with opposite sign, due to *CPT* invariance. Our approach takes into account the final state interaction in accordance with the Watson theorem, besides the standard CKM matrix elements. If our prediction for the A_{CP}'s ratio is confirmed, the forthcoming data could constrain the *S*-wave phase-shift difference in the $\pi^+\pi^-$ and K^+K^- elastic channels at the D^0 mass, as well as the magnitude of the off-diagonal *S* matrix.

Very recently, during the revision process of this Letter, the LHCb Collaboration presented new results for $D^0(\bar{D}^0) \to \pi^-\pi^+$ and $D^0(\bar{D}^0) \to K^-K^+$ [23] which confirms our prediction that $|A_{CP}(\pi\pi)| > |A_{CP}(KK)|$:

$$A_{CP}^{LHCb}(\pi\pi) = (2.32 \pm 0.61) \times 10^{-3},$$
$$A_{CP}^{LHCb}(KK) = (0.77 \pm 0.57) \times 10^{-3}, \quad (20)$$

with the result for $\pi\pi$ channel being the first evidence of an individual charm decay asymmetry. Note that both LHCb new A_{CP} values are statistically compatible with ours results. From Eqs. (17) and (18), we find the central values $A_{CP}(\pi\pi) = (0.97 \pm 0.05) \times 10^{-3}$ and $A_{CP}(KK) = -(0.34 \pm 0.15) \times 10^{-3}$. These values are compatible with the experimental ones within 2σs and also with the results given by Eq. (19), obtained from ΔA_{CP}^{LHCb} and the experimental branching ratios. If the hint for a positive $A_{CP}(KK)$ is confirmed by a more precise measurement, the scenario presented here would be disfavored as a solution to the ΔA_{CP} puzzle.

The same rescattering mechanism can contribute to *CPV* in three-body SCS *D* decays. In fact, one expects that the *CP* asymmetry must be enhanced in the three-body $D^+ \to \pi^+\pi^-\pi^+$ and $D^+ \to K^+K^-\pi^+$ phase-space distribution

[41], where the $\pi^+\pi^- \to K^+K^-$ rescattering is relevant in a large fraction of the phase space available to K^+K^-, as seen in Fig. 3. This is left for future study.

Furthermore, as pointed out several times [1,4], the SM gives almost no contribution to *CPV* in double Cabibbo suppressed (DCS) decays. If *CPV* is observed in DCS modes, this will point to new physics. Following the present approach, the best channels to observe *CPV* in DCS, are the $D^+ \to K^+\pi^-\pi^+$ and $D^+ \to K^+K^-K^+$, which also has the rescattering $\pi^-\pi^+ \to K^-K^+$ as a mechanism to enhance the observable *CP* violation.

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