Charm CP Violation

Stefan Schacht

Durham University

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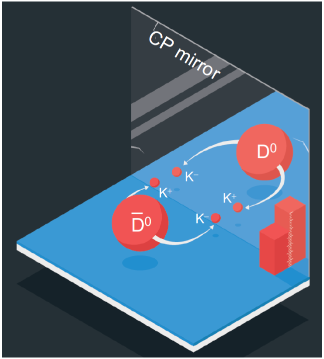
Unique gate to flavor structure of up-type quarks

$$a_{CP}^{\text{dir}}(D^0 \to K^+K^-) - a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)$$
$$= (-0.159 \pm 0.029)\% \,.$$

[LHCb 1903.08726, HFLAV 2411.18639]

The problem: Is it SM?



[CERN]

Direct CP Violation is an Interference Effect

$$a_{CP}^{\text{dir}}(f) \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2} \approx 2 r_{\text{CKM}} r_{\text{QCD}} \sin \varphi_{\text{CKM}} \sin \delta_{\text{QCD}}$$

f = CP-eigenstate.

The decay amplitude:

$$\mathcal{A} = 1 + r_{\text{CKM}}\, r_{\text{QCD}}\, e^{i(\varphi_{\text{CKM}} + \delta_{\text{QCD}})}$$

- r_{CKM} : real ratio of CKM matrix elements.
- φ_{CKM} : weak phase.
- r_{QCD} : real ratio of hadronic matrix elements.
- δ_{QCD} : strong phase.

Where does the interference come from?

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^-, \ldots \xrightarrow{\text{QCD}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-, \ldots \xrightarrow{\text{QCD}} K^+K^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^-$$

Prediction from SM CKM

$$\Delta a_{CP}^{dir} \sim 10^{-3} \times r_{\text{QCD}} \,. \qquad \text{U-spin: } r_{\text{QCD}} = \mathcal{A}^{\Delta U=0} / \mathcal{A}^{\Delta U=1} \,.$$

U-spin $\subset$ SU(3): Approximate symmetry for the light quarks u, d, s.

Can we overcome soft QCD in Charm?

Expansion parameters

- In kaon decays we have m/Λ.
- In B decays we have Λ/m.
- In charm. . . ?

Need to revisit toolbox / find new strategies.

Can we tell a loop from a tree?

$$\Delta a_{CP}^{dir} \sim 10^{-3} \times r_{\text{QCD}}\,, \quad r_{\text{QCD}} = \mathcal{A}^{\Delta U=0}/\mathcal{A}^{\Delta U=1}$$

Assuming the SM, the data implies $r_{\text{QCD}}^{\text{EXP}} = \mathcal{O}(1)$.

What is $r_{\text{QCD}}^{\text{SM}} \equiv |P/T|$?

- Light Cone Sum Rules (LCSR): $r_{\text{QCD}}^{\text{SM}} \sim 0.1$.
  [Petrov Khodjamirian 1706.07780, Chala Lenz Rusov Scholtz 1903.10490, Lenz Piscopo Rusov 2312.13245]
- Large non-pert. effects like in charm $\Delta I = 1/2$ rule: $r_{\text{QCD}}^{\text{SM}} = \mathcal{O}(1)$.
  [Grossman Schacht 1903.10952, Brod Kagan Zupan 1111.5000, Schacht Soni 2110.07619]
- Predictions based on $\pi\pi/KK$ rescattering data:
  [Franco Mishima Silvestrini 1203.3131, Bediaga Frederico Magalhaes 2203.04056, Pich Solomonidi Vale Silva 2305.11951]

A caveat for the interpretation of the data

"The data implies $|P/T| = \mathcal{O}(1)$"

This statement actually relies on an underlying, commonly made assumption:

- The relative strong phase between P and T is assumed $\mathcal{O}(1)$ (from rescattering).

Reminder: CP violation is an interference effect.

$$A = \left(-V_{cd}^* V_{ud}\right) \times T - \left(\frac{V_{cb}^* V_{ub}}{2}\right) \times P\,.$$

Direct CP asymmetry:

$$a_{CP}^f \equiv \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2} = \mathrm{CKM} \times \left|\frac{P}{T}\right| \times \sin\left(\arg\left(\frac{P}{T}\right)\right)$$

How to determine the strong phase from the data

- Strong phases can be obtained from measurements of time-dependent CP violation or quantum-correlated decays. [Xing hep-ph/9606422, Gronau Grossman Rosner hep-ph/0103110, Bevan Inguglia Meadows 1106.5075, Bevan Meadows 1310.0050, Grossman Kagan Zupan 1204.3557, Xing 1903.09566, Grossman Schacht 1903.10952, Schacht 2207.08539]

$$A_{CP}(f,t) \approx a_{CP}^{f} + \Delta Y^{f} \frac{t}{\tau_{D^0}}$$

- Analogous strong phase in multi-body decays can be determined from fit to CP violating time-integrated Dalitz plot.

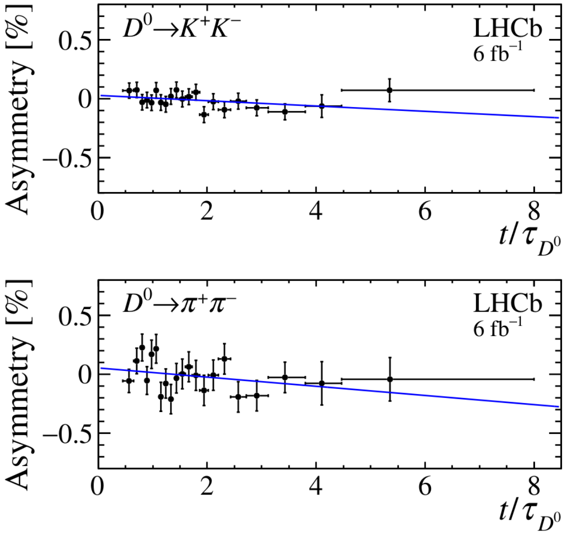
[Dery Grossman Schacht Soffer 2101.02560]

- No measurements of phases yet, despite big experimental advances. ΔY^f have large errors, and sensitivity to phase is subleading.

$$\Delta Y^{K^+K^-} = (-0.3 \pm 1.3 \pm 0.3) \cdot 10^{-4}\,,$$
$$\Delta Y^{\pi^+\pi^-} = (-3.6 \pm 2.4 \pm 0.4) \cdot 10^{-4}\,.$$

[LHCb combination 2105.09889]

$A_{CP}(f,t) \approx a^f_{CP} + \Delta Y^f \times t/\tau_{D^0}$ [LHCb 2105.09889]



Isospin to the rescue: $D \to \pi\pi$

[Gavrilova Grossman Schacht, 2312.10140]

- Assuming SM, isospin allows determination of strong P/T phase from direct CP asymmetries and branching ratios only.
- Also enables extraction of magnitude of P/T without assumptions about phase.
- $D \to \pi\pi$ has same group-theory structure as $B \to \pi\pi$ [Gronau London 1990], however, different approximations are used in the two systems.

Closed-form solution [Gavrilova, Grossman, Schacht 2312.10140]

$$\sin\arg(P/T)^{00} = \frac{-\mathrm{sign}\,(a_{CP}^{00})}{\sqrt{1+\frac{1}{\sin^2\delta_d}\left(\frac{a_{CP}^{+-}}{a_{CP}^{00}}\sqrt{\frac{1}{2}\frac{\mathcal{B}^{+-}}{\mathcal{P}^{+-}}\frac{\mathcal{P}^{00}}{\mathcal{B}^{00}}}+\cos\delta_d\right)^2}}\,,$$

$$\sin\arg(P/T)^{+-} = \frac{-\mathrm{sign}\,(a_{CP}^{+-})}{\sqrt{1+\frac{1}{\sin^2\delta_d}\left(\frac{a_{CP}^{00}}{a_{CP}^{+-}}\sqrt{2\frac{\mathcal{P}^{+-}}{\mathcal{B}^{+-}}\frac{\mathcal{B}^{00}}{\mathcal{P}^{00}}}+\cos\delta_d\right)^2}}\,,$$

$$|P/T|^{00} = \frac{1}{|\mathrm{Im}\,(-\lambda_b/\lambda_d)\,|}\sqrt{(a_{CP}^{00})^2+\frac{(a_{CP}^{+-}\sqrt{\mathcal{B}^{+-}\mathcal{P}^{00}}+a_{CP}^{00}\sqrt{2\mathcal{B}^{00}\mathcal{P}^{+-}}\cos\delta_d)^2}{2\mathcal{B}^{00}\mathcal{P}^{+-}\sin^2\delta_d}}\,,$$

$$|P/T|^{+-} = \frac{1}{|\mathrm{Im}\,(-\lambda_d/\lambda_d)|}\sqrt{\left(a_{CP}^{+-}\right)^2+\frac{\left(a_{CP}^{00}\sqrt{2\mathcal{B}^{00}\mathcal{P}^{+-}}+a_{CP}^{+-}\sqrt{\mathcal{B}^{+-}\mathcal{P}^{00}}\cos\delta_d\right)^2}{\mathcal{B}^{+-}\mathcal{P}^{00}\sin^2\delta_d}}\,.$$

Knowledge of $D \to \pi^+\pi^-$ translates into $D \to \pi^0\pi^0$

[Gavrilova, Grossman, Schacht 2312.10140]

$$\frac{\sin\delta^{+-}}{\sin\delta^{00}} = \frac{a_{CP}^{+-}}{a_{CP}^{00}} \sqrt{\frac{1}{2}\frac{\mathcal{B}^{+-}}{\mathcal{P}^{+-}}\frac{\mathcal{P}^{00}}{\mathcal{B}^{00}}},$$

$$\frac{|P/T|^{00}}{|P/T|^{+-}} = \sqrt{\frac{1}{2}\frac{\mathcal{B}^{+-}}{\mathcal{P}^{+-}}\frac{\mathcal{P}^{00}}{\mathcal{B}^{00}}}.$$

Results

$$|P/T|^{+-} = 5.5^{+14.2}_{-2.7}$$
$$|P/T|^{00} = 5.2^{+13.3}_{-2.4}$$

- Although we have essentially no information about $\sin\delta^{00}$ we can obtain non-trivial information about r^{00}, due to the correlation to r^{+-} from isospin.
- Overall additional relative systematic uncertainty of $\mathcal{O}(10\%)$.
- $|P/T|$ is large. Future data will significantly reduce errors.

Extraction of Penguin over tree in three-body decays

[Dery Grossman Schacht Soffer 2101.02560]

$$\mathcal{A}(D^0 \to \pi^+\rho^-) = -\lambda\, T^{P_1V_2} - V_{cb}^* V_{ub}\, R^{P_1V_2}$$
$$\mathcal{A}(D^0 \to \pi^-\rho^+) = -\lambda\, T^{P_2V_1} - V_{cb}^* V_{ub}\, R^{P_2V_1}$$

- Time-integrated CP asym. of 2-body decays give only combinations

$$|\widetilde{R}^{P_1V_2}|\sin(\delta_{P_1V_2}) \qquad \text{and} \qquad |\widetilde{R}^{P_2V_1}|\sin(\delta_{P_2V_1})\,,$$

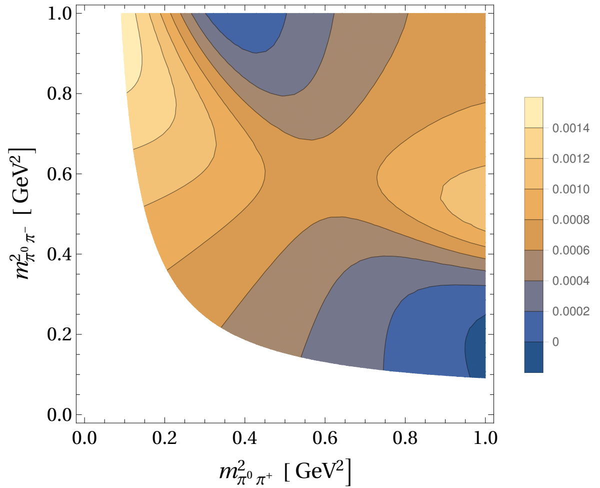
  but **not** magnitudes and phases separately.

- Three body decay changes 2 things:
  - We have additional kinematic dependences.
  - Only in a three-body decay we have interference between $D^0 \to \pi^+(\rho^- \to \pi^-\pi^0)$ and $D^0 \to \pi^-(\rho^+ \to \pi^+\pi^0)$.

↳ Extraction of all parameters from time-integrated CP meas.

Local $a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-\pi^0)$ in overlap region of $\rho^\pm$

[Dery Grossman Schacht Soffer 2101.02560]



Numerical example: $\widetilde{R}^{P_1V_2} = \exp(i\pi/2), \quad \widetilde{R}^{P_2V_1} = \frac{1}{4}\exp(i\pi/3)$

Beyond ΔA_{CP}: A U-spin anomaly?

- Separate measurement of both CP asymmetries allows for first time test of the U-spin expansion in CKM-suppressed amplitudes.

U-spin limit sum rule: Broken at 2.7σ [LHCb, 2209.03179]

$$\Sigma a_{CP}^{dir} \equiv a_{CP}^{dir}(D^0 \to K^+K^-) + a_{CP}^{dir}(D^0 \to \pi^+\pi^-) \overset{\text{U-spin}}{=} 0$$

$$a_{CP}^{\text{dir}}(D^0 \to K^+K^-) = (7.7 \pm 5.7) \cdot 10^{-4}$$

$$a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-) = (23.2 \pm 6.1) \cdot 10^{-4}$$

- U-spin breaking is expected: Only approximate symmetry.
- Amount goes beyond generic expectations of $\sim 30\%$.

Model-Independent Predictions

- Large U-spin breaking indicates large $\Delta U = 1$ operator(s).
- It follows $\mathcal{O}(1)$ breaking of U-spin limit sum rule:

$$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} = -\frac{a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)}{a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-)} \quad \text{broken at } \mathcal{O}(1)\,,$$

- Connected to wider class of decays via SU(3)-flavor symmetry.

$$\text{Expect} \quad \frac{\Gamma(D^+ \to K_S K^+)}{\Gamma(D_s^+ \to K_S \pi^+)} = -\frac{a_{CP}^{\mathrm{dir}}(D_s^+ \to K_S \pi^+)}{a_{CP}^{\mathrm{dir}}(D^+ \to K_S K^+)} \text{ also broken at } \mathcal{O}(1).$$

- Improved versions of these sum rules: [Müller Nierste Schacht 1506.04121]

$$a_{CP}^{dir}(D^0 \to K^+K^-)\,, \quad a_{CP}^{dir}(D^0 \to \pi^+\pi^-)\,, \quad a_{CP}^{dir}(D^0 \to \pi^0\pi^0)\,, \quad \text{and}$$
$$a_{CP}^{dir}(D^+ \to K_S K^+)\,, \quad a_{CP}^{dir}(D_s^+ \to K_S \pi^+)\,, a_{CP}^{dir}(D_s^+ \to K^+\pi^0)\,.$$

These should also be broken at $\mathcal{O}(1)$.

But is U-spin actually a good symmetry?

Spectroscopy: Eightfold way. [Gell-Mann, Ne'eman 1961]

- $SU(3)_F$ limit agrees with baryon octet mass splitting to $\sim 10\%$

[Greiner Müller 1989]

Does it work for rates, too?

- Estimate for breaking on amplitude level: $f_K/f_\pi - 1 \sim 0.2$.
- Two often-cited examples of seemingly $\mathcal{O}(1)$ U-spin breaking:

$$\left.\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)}\right|_{\text{exp}} \sim 3\,, \qquad \left.\frac{\mathcal{B}(D^0 \to K_S K_S)}{\mathcal{B}(D^0 \to K^+K^-)}\right|_{\text{exp}} \sim 0.03\,.$$

- Strict $SU(3)_F$ limit (including phase space):

$$\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)} = 1\,, \qquad \frac{\mathcal{B}(D^0 \to K_S K_S)}{\mathcal{B}(D^0 \to K^+K^-)} = 0\,,$$

Yes. (But we keep testing it at every opportunity.)

[detailed review in Schacht 2207.08539]

A closer look

- Amplitude-level $SU(3)_F$ breaking of $\varepsilon \sim 30\%$ suffices in order to explain the data. [Savage 1991]

$$\frac{(1+\varepsilon)^2}{(1-\varepsilon)^2} \sim 3\,.$$

- Amplitude-level $SU(3)_F$ -breaking in $D^0 \to K_S K_S$:

$$\varepsilon' \sim \sqrt{\frac{\mathcal{B}(D^0 \to K^0 \overline{K}^0)}{\mathcal{B}(D^0 \to K^+ K^-)}} = \sqrt{\frac{2\mathcal{B}(D^0 \to K_S K_S)}{\mathcal{B}(D^0 \to K^+ K^-)}} \sim 0.26\,,$$

- Observations agree with global fits.

[Hiller Jung Schacht 1211.3734, Müller Nierste Schacht 1503.06759]

The picture holds at higher order, too.

[Brod Grossman Kagan Zupan 1203.6659]

Ratio of branching ratios:

$$R_{DPP} \equiv \frac{|\mathcal{A}(D^0 \to K^+K^-)/(V_{cs}V_{us})| + |\mathcal{A}(D^0 \to \pi^+\pi^-)/(V_{cd}V_{ud})|}{|\mathcal{A}(D^0 \to K^+\pi^-)/(V_{cd}V_{us})| + |\mathcal{A}(D^0 \to K^-\pi^+)/(V_{cs}V_{ud})|} - 1$$

U-spin prediction

$$R_{DPP}^{\text{th}} = \mathcal{O}(\varepsilon^2)\,.$$

Data

$$R_{DPP}^{\text{exp}} = 0.046 \pm 0.008\,,$$

- If U-spin breaking were $\mathcal{O}(1)$, we would have $R_{DPP}^{\text{exp}} = \mathcal{O}(1)$.
- Instead, perfectly consistent with $\mathcal{O}(\varepsilon^2)$.

More opportunities: Uncharted Territory

CP Asymmetry	HFLAV avg. [https://hflav.web.cern.ch/]	Experiments
$D^0 \to \pi^0 \eta'$	—	—
$D^0 \to \eta \eta'$	—	—
$D^+ \to \pi^+ \eta'$	$(0.40 \pm 0.20)\%$	LHCb'23, Belle'11, CLEO'10
$D_s^+ \to K^+ \eta'$	$(6.0 \pm 18.9)\%$	CLEO'10

- Formalism and branching ratio fit:
  Slight tension in $\mathcal{B}(D_s^+ \to K^+ \eta')$ and $\mathcal{B}(D^+ \to K^+ \eta')$.
  [Bolognani, Nierste, Schacht, Vos, 2410.08138]

- CP asymmetry predictions: Stay tuned.
  [Bolognani, Nierste, Schacht, Vos, in preparation]

Hot off the press: News on Charmed Baryon CP Violation

Belle II Preprint 2025-024
KEK Preprint 2025-26

30 Sep 2025

Search for CP violation in $\Xi_c^+ \to \Sigma^+ h^+ h^-$ and $\Lambda_c^+ \to p h^+ h^-$ at Belle II

M. Abumusabh, I. Adachi, H. Ahmed, Y. Ahn, H. Aihara, N. Akopov, S. Alghamdi, M. Alhakami, N. Althubiti, K. Amos, N. Anh Ky, D. M. Asner, H. Atmacan, R. Ayad, V. Babu, N. K. Baghel, S. Bahinipati, P. Bambade, Sw. Banerjee, M. Bartl, J. Baudot, A. Beaubien, J. Becker, J. V. Bennett, V. Bertacchi, M. Bertemes, E. Bertholet, S. Bettarini, V. Bhardwaj, D. Biswas, A. Bobrov, D. Bodrov, G. Bonvicini, J. Borah, A. Boschetti, M. Bračko, P. Branchini, R. A. Briere, T. E. Browder, A. Budano, S. Bussino, Q. Campagna, M. Campajola, G. Casarosa, C. Cecchi, P. Chang, P. Cheema, L. Chen, B. G. Cheon, C. Cheshta, H. Chetri, K. Chilikin, J. Chin, K. Chirapatpimol, H.-E. Cho, K. Cho, S.-J. Cho, S.-K. Choi, S. Choudhury, S. Chutia, J. A. Colorado-Caicedo, I. Consigny, L. Corona, J. X. Cui, S. Das, S. A. De La Motte, G. De Nardo, G. De Pietro, R. de Sangro, M. Destefanis, A. Di Canto, Z. Doležal, I. Domínguez Jiménez, T. V. Dong, X. Dong, M. Dorigo, G. Dujany, P. Ecker, D. Epifanov, J. Eppelt, R. Farkas, P. Feichtinger, T. Ferber, T. Fillinger, G. Finocchiaro, F. Forti, B. G. Fulsom, A. Gabrielli

(The Belle II Collaboration)

We report decay-rate CP asymmetries of the singly-Cabibbo-suppressed decays $\Xi_c^+ \to \Sigma^+ h^+ h^-$ and $\Lambda_c^+ \to p h^+ h^-$, with $h = K, \pi$, measured using $428\,\mathrm{fb}^{-1}$ of e^+e^- collisions collected by the Belle II experiment at the SuperKEKB collider. The results,

$$\begin{aligned} A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) &= (3.7 \pm 6.6 \pm 0.6)\%, \\ A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) &= (9.5 \pm 6.8 \pm 0.5)\%, \\ A_{CP}(\Lambda_c^+ \to p K^+ K^-) &= (3.9 \pm 1.7 \pm 0.7)\%, \\ A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) &= (0.3 \pm 1.0 \pm 0.2)\%, \end{aligned}$$

where the first uncertainties are statistical and the second systematic, agree with CP symmetry. From these results we derive the sums

$$\begin{aligned} A_{CP}(\Xi_c^+ \to \Sigma^+ \pi^+ \pi^-) + A_{CP}(\Lambda_c^+ \to p K^+ K^-) &= (13.4 \pm 7.0 \pm 0.9)\%, \\ A_{CP}(\Xi_c^+ \to \Sigma^+ K^+ K^-) + A_{CP}(\Lambda_c^+ \to p \pi^+ \pi^-) &= (\ 4.0 \pm 6.6 \pm 0.7)\%, \end{aligned}$$

which are consistent with the U-spin symmetry prediction of zero. These are the first measurements of CP asymmetries for individual hadronic three-body charmed-baryon decays.

-ph] 27 Nov 2018

U-Spin Sum Rules for CP Asymmetries of Three-Body Charmed Baryon Decays

Yuval Grossman* and Stefan Schacht†

Department of Physics, LEPP, Cornell University, Ithaca, NY 14853, USA

Abstract

Triggered by a recent LHCb measurement and prospects for Belle II, we derive U-spin symmetry relations between integrated CP asymmetries of three-body Λ_c^+ and Ξ_c^+ decays. The sum rules read $A_{CP}(\Lambda_c^+ \to pK^-K^+) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0$, $A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) + A_{CP}(\Xi_c^+ \to \Sigma^+K^-K^+) = 0$, and $A_{CP}(\Lambda_c^+ \to \Sigma^+\pi^-K^+) + A_{CP}(\Xi_c^+ \to pK^-\pi^+) = 0$. No such U-spin sum rule exists between $A_{CP}(\Lambda_c^+ \to pK^-K^+)$ and $A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+)$. All of these sum rules are associated with a complete interchange of d and s quarks. Furthermore, there are no U-spin CP asymmetry sum rules which hold to first order U-spin breaking.

[Belle II: 2509.25765, Grossman Schacht: 1811.11188]

Conclusions

- Charm is a unique gate to flavor structure of up-type quarks.
- This is just the beginning of the exploration of charm CPV.
  - Is the sum rule $a_{CP}^{\rm dir}(D_s^+ \to K_S\pi^+) = -a_{CP}^{\rm dir}(D^+ \to K_S K^+)$ broken at $\mathcal{O}(1)$, like the one between $D^0 \to \pi^+\pi^-, K^+K^-$?
  - How large is P/T in $D^0 \to \rho\pi$?
    Many more opportunities in multi-body decays.
  - Basically uncharted territory:

$$A_{CP}(D^0 \to \pi^0\eta')\,, \quad A_{CP}(D^0 \to \eta\eta')\,, \quad A_{CP}(D_s^+ \to K^+\eta')\,.$$

  - Baryon CP violation, and much more!

BACK-UP

The three $\Delta I = 1/2$ rules for $P \to \pi\pi$

- Relevant ratio of strong isospin matrix elements:

$r_{QCD}^{\Delta I=1/2} \equiv A^{\Delta I=1/2}/A^{\Delta I=3/2}$	Kaon	Charm	Beauty
Data	22	2.5	1.5
"No QCD" limit	$\sqrt{2}$	$\sqrt{2}$	$\sqrt{2}$
Enhancement	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$

[*D*: Franco Mishima Silvestrini 1203.3131, *B*: Grinstein Pirtskhalava Stone Uttayarat 1402.1164]

- Rescattering most important in *K* decays, less important but still significant in *D* decays, and small in *B* decays.