Theory of Charm CP Violation

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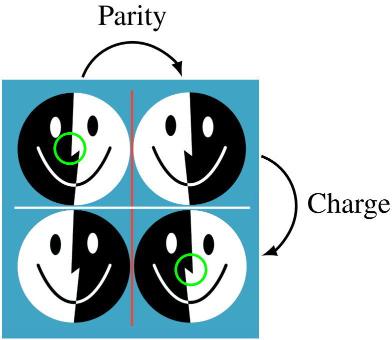
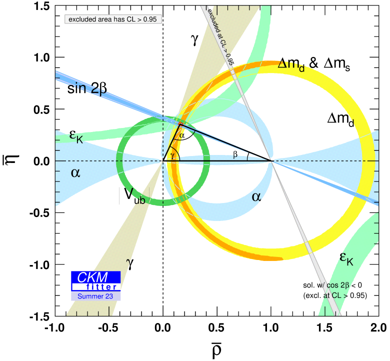
CP Violation in the Standard Model

An artist's view



[www.antimatter-matters.org]

A physicist's view

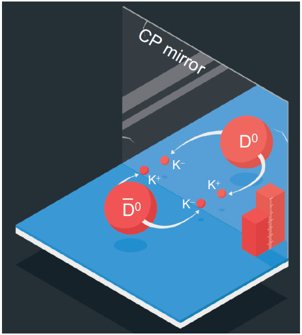


Unique gate to flavor structure of up-type quarks

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

[LHCb 1903.08726, HFLAV 2411.18639]

The problem: Is it SM?



[CERN]

Direct CP Violation is an Interference Effect

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

f = CP-eigenstate.

The decay amplitude:

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

- 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?

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

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

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

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

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.

Weak and strong factors

$$\frac{\mathcal{A}(D \to \pi\pi \to KK)}{\mathcal{A}(D \to KK)} = \left(r_{\mathrm{CKM}} e^{i\varphi_{\mathrm{CKM}}}\right)\left(r_{\mathrm{QCD}} e^{i\delta_{\mathrm{QCD}}}\right)$$

- r_{QCD}: ratio of hadronic amplitudes.
- $\delta_{\mathrm{QCD}} = \mathcal{O}(1)$: strong phase.
- $r_{\mathrm{CKM}} = 1$: ratio of CKM factors, $\left|V_{cd}^* V_{ud}/(V_{cs}^* V_{us})\right|$
- $\varphi_{\mathrm{CKM}} \approx 6 \cdot 10^{-4}$: deviation from 2×2 unitarity.

Prediction

$$\Delta a_{CP}^{dir} \sim 10^{-3} \times r_{\mathrm{QCD}}$$

- U-spin decomposition: $r_{\mathrm{QCD}} = \mathcal{A}^{\Delta U=0}/\mathcal{A}^{\Delta U=1}$.

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.

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 2012, B: Grinstein Pirtskhalava Stone Uttayarat 2014]

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

Can we tell a loop from a tree?

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

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

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

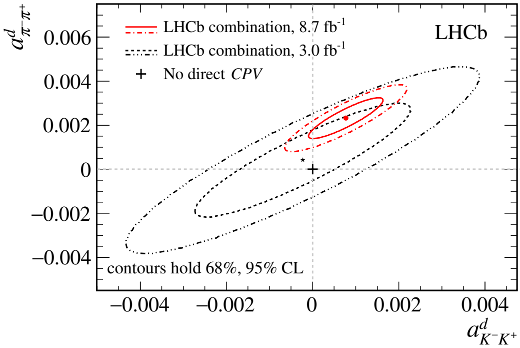
- Light Cone Sum Rules (LCSR): $r_{\mathrm{QCD}}^{\mathrm{SM}} \sim 0.1$.
  [Petrov Khodjamirian 1706.07780, Chala Lenz Rusov Scholtz 1903.10490, Lenz Piscopo Rusov 2312.13245]
- Large non-pert. effects like in charm $\Delta I = 1/2$ rule: $r_{\mathrm{QCD}}^{\mathrm{SM}} = \mathcal{O}(1)$.
  [Grossman 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]

Outline

- Beyond ΔA_{CP} : A U-spin anomaly?
- Flavor Symmetry at any Order
- NLO Rate Sum Rules
- Next Steps@LHCb: A Theorist's View

Beyond ΔA_{CP}: A U-spin anomaly?

Beyond ΔA_{CP}: A U-spin anomaly? [LHCb, 2209.03179]



U-spin limit sum rule: Broken at 2.7σ

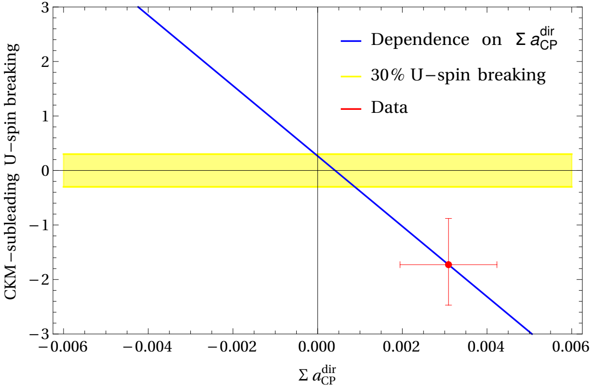
$$\Sigma a_{CP}^{\text{dir}} \equiv a_{CP}^{dir}(D^0 \to K^+K^-) + a_{CP}^{dir}(D^0 \to \pi^+\pi^-) \overset{\text{U-spin}}{=} 0$$

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

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

CKM-subleading U-spin breaking: $\left(173^{+85}_{-74}\right)\%$

[Schacht 2207.08539]



- Separate measurement of CP asymmetries allows for the first time test of U-spin expansion in CKM-suppressed amplitudes.
- Large central value $\sim 2\sigma$ from $\mathcal{O}(30\%)$.

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 PRL 115 (2015) 25, 251802]

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

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

Explanations beyond the SM: "$\Delta U = 1$ models"

- NP models with $\Delta U = 1$ operators can explain breaking of U-spin limit sum rules. [Hiller Jung Schacht 1211.3734]

- Additional operators with flavor content $\bar{s}c\bar{u}s$ and/or $\bar{d}c\bar{u}d$ with non-universal coefficients.

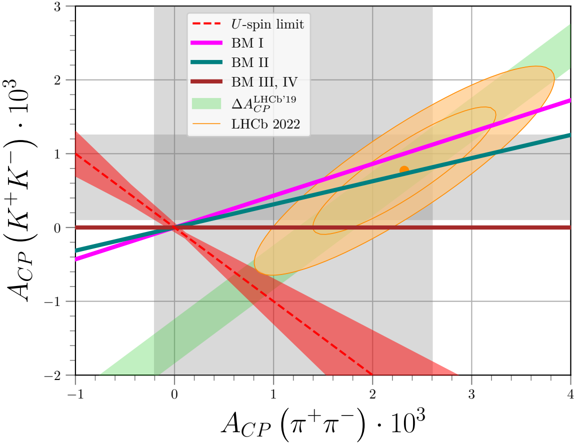
- Example: Z' models where fermion charges depend on generation.

[Bause Gisbert Golz Hiller 2004.01206],
[Bause Gisbert Hiller Höhne Litim Steudtner 2210.16330]

$$\begin{aligned}
\mathcal{L}_{Z'} \supset & \left(g_L^{uc}\bar{u}_L\gamma^\mu c_L Z'_\mu + g_R^{uc}\bar{u}_R\gamma^\mu c_R Z'_\mu + \text{h.c.}\right) \\
& + g_L^d \bar{d}_L\gamma^\mu d_L Z'_\mu + g_R^d \bar{d}_R\gamma^\mu d_R Z'_\mu \\
& + g_L^s \bar{s}_L\gamma^\mu s_L Z'_\mu + g_R^s \bar{s}_R\gamma^\mu s_R Z'_\mu \\
& + g_L^{ll} \bar{l}_L\gamma^\mu l_L Z'_\mu + g_R^{ll} \bar{l}_R\gamma^\mu l_R Z'_\mu
\end{aligned}$$

Z' model predictions

[Bause Gisbert Hiller Höhne Litim Steudtner 2210.16330]



- Viable models with leptophobic Z' below $\mathcal{O}(20\,\mathrm{GeV})$.
- Pattern of CP violation in $D \to \pi\pi$, including $a_{CP}^{dir}(D^+ \to \pi^+\pi^0) \neq 0$.

But is U-spin actually a good symmetry?

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:

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

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

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

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]

Flavor Symmetry at any Order

SU(3)-flavor

- SU(3): Approximate symmetry for the light quarks u, d, s.
- Very useful, but $\mathcal{O}(30\%)$ breaking from corrections.
- Going to higher order: complicated.

$$(\mathbf{15}) \otimes (\mathbf{8}) = (\mathbf{42}) \oplus (\mathbf{24}) \oplus (\mathbf{15_1}) \oplus (\mathbf{15_2}) \oplus (\mathbf{15'}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})$$

$$(\bar{\mathbf{6}}) \otimes (\mathbf{8}) = (\mathbf{24}) \oplus (\mathbf{15}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})$$

Decay d	$B_1^{3_1}$	$B_1^{3_2}$	$B_8^{3_1}$	$B_8^{3_2}$	$B_8^{\bar{6}_1}$	$B_8^{\bar{6}_2}$	$B_8^{15_1}$	$\dots$
$D^0 \to K^+K^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$\frac{1}{10}$	$-\frac{1}{10\sqrt{2}}$	$-\frac{7}{10\sqrt{122}}$	$\dots$
$D^0 \to \pi^+\pi^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$-\frac{1}{10}$	$\frac{1}{10\sqrt{2}}$	$-\frac{11}{10\sqrt{122}}$	$\dots$
$D^0 \to \bar{K}^0K^0$	$-\frac{1}{4\sqrt{10}}$	$-\frac{1}{8}$	$\frac{1}{5\sqrt{2}}$	$\frac{1}{2\sqrt{5}}$	0	0	$-\frac{9}{5\sqrt{122}}$	$\dots$
$D^0 \to \pi^0\pi^0$	$-\frac{1}{8\sqrt{5}}$	$-\frac{1}{8\sqrt{2}}$	$-\frac{1}{20}$	$-\frac{1}{4\sqrt{10}}$	$\frac{1}{10\sqrt{2}}$	$-\frac{1}{20}$	$\frac{11}{20\sqrt{61}}$	$\dots$
$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$	$\dots$

Solving the Problem of Higher Order U-spin

[Gavrilova Grossman Schacht: 2205.12975, Gavrilova Schacht: 2409.03830]

Theorems enabling calculations to arbitrary order.

- We are able to determine a priori up to which order sum rules exist.
- We do not need explicit Clebsches. Big complexity reduction.
- Hope: Opens the door for precision in hadronic decays.
- Close a gap between theory and experiment, especially regarding multi-body decays.

Take advantage of precision data on nonleptonic decays.

Systematics of U-spin breaking

- U-spin breaking from mass difference of strange and down quarks:

$$\varepsilon = \frac{m_s - m_d}{\Lambda_{\text{QCD}}} \sim 0.3\,.$$

- Parametrized by triplet-operator H_ε:

$$\mathcal{H}_{\text{eff}} = \sum_{m,b} f_{u,m}\left(H^u_m \otimes H_\varepsilon^{\otimes b}\right), \qquad H_\varepsilon^{\otimes b} \equiv \underbrace{H_\varepsilon \otimes \cdots \otimes H_\varepsilon}_{b}\,.$$

- Any system can be constructed from tensor products of doublets.
- Moving irreps ("crossing sym.") does not affect structure of sum rules.
- Without loss of generality, consider doublet-only system with

$$0 \to \left(\frac{1}{2}\right)^{\otimes n} \quad \text{and singlet Hamiltonian.}$$

Properties of U-spin pairs

[Gavrilova Grossman Schacht, 2205.12975]

- Amplitude:

$$A_j = \underbrace{(-,-,+,-,+,\dots,+)}_{n} = \sum_\alpha C_{j\alpha} X_\alpha\,.$$

- U-spin conjugated amplitude (complete interchange $s \leftrightarrow d$):

$$\overline{A}_j = \underbrace{(+,+,-,+,-,\dots,-)}_{n} = (-1)^p \sum_\alpha (-1)^b C_{j\alpha} X_\alpha\,.$$

- Notation: Abbreviate m-quantum number: $\pm 1/2 \mapsto \pm$.
  X_α: Reduced matrix element. $C_{j\alpha}$: Clebsches.
- Define (anti-)symmetric combinations of U-spin pairs:

$$a_j \equiv \underbrace{A_j - (-1)^p \overline{A}_j}_{\text{odd in } b}\,, \qquad s_j \equiv \underbrace{A_j + (-1)^p \overline{A}_j}_{\text{even in } b}\,.$$

Results: Sum Rules at any order of U-spin breaking

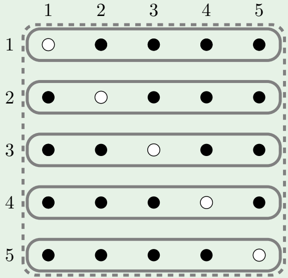
[Gavrilova Grossman Schacht, 2205.12975]

All sum rules at any order b can be written as:

$$\Sigma_j a_j = 0\,, \qquad \Sigma_j s_j = 0\,.$$

Example: $n = 6$ doublets. Lattice dimension $d = n/2 - 1 = 2$.

- Each node $\Leftrightarrow$ U-spin pair.
- Each node (points):
  a-type sum rule valid to $b = 0$.
- Sums of nodes in lines:
  s-type sum rules valid to $b = 1$.
- Sum of all nodes in plane:
  a-type sum rule valid up to $b = 2$.



What next? Generalization to $SU(3)_F$, implications for observables.

NLO Rate Sum Rules

One Sum To Rule Them All

[Gavrilova, Grossman, Papiri, Schacht: 2602.soon]

Any system of weak charm decays related by U-spin satisfies:

$$\frac{\text{(sum of CF and DCS CKM-free rates)}}{\text{(sum of SCS CKM-free rates)}} = 1 + \mathcal{O}(\varepsilon^2)\,.$$

Definition CKM-free rate

$$\hat{\Gamma}(i \to f) \equiv \frac{\Gamma(i \to f)}{f_{\text{CKM}}}\,.$$

Classification of charm decays:

$$f_{\text{CKM}} = \begin{cases} f_{\text{CF}} = |V_{cs}V_{ud}|^2 \simeq 1\,, \\ f_{\text{SCS}} = |V_{cs}V_{us}|^2 \simeq |V_{cd}V_{ud}|^2 \simeq \lambda^2\,, \\ f_{\text{DCS}} = |V_{cd}V_{us}|^2 \simeq \lambda^4\,. \end{cases}$$

Example: $D \to PP$ preliminary

[Grossman, Robinson: 1211.3361, Gavrilova, Grossman, Papiri, Schacht: 2602.soon]

LO Sum Rules

$$\frac{\hat{\Gamma}(D^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to \pi^+\pi^-)} = 2.81 \pm 0.06\,, \qquad \frac{\hat{\Gamma}(D^0 \to \pi^-K^+)}{\hat{\Gamma}(D^0 \to K^-\pi^+)} = 1.21 \pm 0.02\,.$$

NLO Sum Rule

$$\frac{\hat{\Gamma}(D^0 \to \pi^-K^+) + \hat{\Gamma}(D^0 \to K^-\pi^+)}{\hat{\Gamma}(D^0 \to K^-K^+) + \hat{\Gamma}(D^0 \to \pi^-\pi^+)} = 0.84 \pm 0.01\,.$$

- Second-order rate sum rule is satisfied more accurately than the two symmetry-limit relations.

Example: $D \to PV$ preliminary

[Gavrilova, Grossman, Papiri, Schacht: 2602.soon]

LO Sum Rules

$$\frac{\hat{\Gamma}(D^0 \to \pi^- K^{*+})}{\hat{\Gamma}(D^0 \to K^- \rho^+)} = 1.21 \pm 0.45\,, \qquad \frac{\hat{\Gamma}(D^0 \to K^- K^{*+})}{\hat{\Gamma}(D^0 \to \pi^- \rho^+)} = 0.46 \pm 0.03\,.$$

NLO Sum Rule

$$\frac{\hat{\Gamma}(D^0 \to K^- \rho^+) + \hat{\Gamma}(D^0 \to \pi^- K^{*+})}{\hat{\Gamma}(D^0 \to K^- K^{*+}) + \hat{\Gamma}(D^0 \to \pi^- \rho^+)} = 0.89 \pm 0.18\,.$$

Example: $D \to PPP$ preliminary

[Gavrilova, Grossman, Papiri, Schacht: 2602.soon]

LO Sum Rules

$$\frac{\hat{\Gamma}(D^- \to \pi^+ K^- \pi^-)}{\hat{\Gamma}(D_s^- \to K^+ K^- \pi^-)} = 1.537(36) \quad \frac{\hat{\Gamma}(D^- \to K^+ K^- K^-)}{\hat{\Gamma}(D_s^- \to \pi^+ \pi^- \pi^-)} = 0.961(21) \quad \frac{\hat{\Gamma}(D^- \to K^+ \pi^- \pi^-)}{\hat{\Gamma}(D_s^- \to \pi^+ K^- K^-)} = 1.001(27)$$

$$\frac{\hat{\Gamma}(D^- \to K^+ K^- \pi^-)}{\hat{\Gamma}(D_s^- \to \pi^+ \pi^- K^-)} = 0.754(19) \quad \frac{\hat{\Gamma}(D_s^- \to K^+ K^- K^-)}{\hat{\Gamma}(D^- \to \pi^+ \pi^- \pi^-)} = 0.137(13)\,.$$

NLO Sum Rule

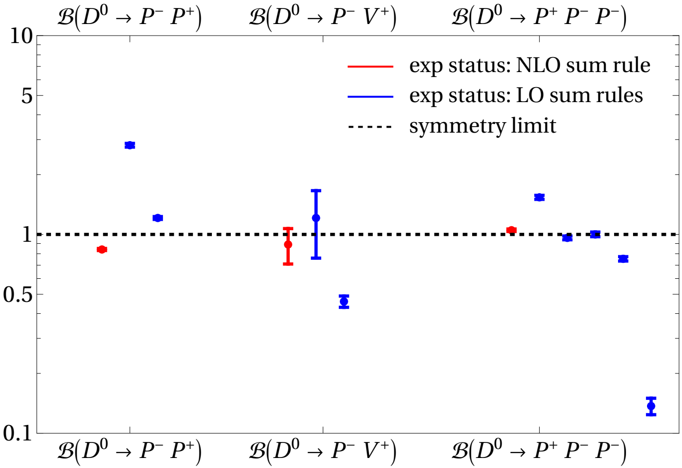
$$\sum\nolimits_{\text{CF, DCS}} \hat{\Gamma} = \hat{\Gamma}(D_s^- \to \pi^+ \pi^- \pi^-) + \hat{\Gamma}(D^- \to K^+ K^- K^-) + \hat{\Gamma}(D_s^- \to \pi^+ K^- K^-) + \hat{\Gamma}(D^- \to K^+ \pi^- \pi^-) + \hat{\Gamma}(D_s^- \to K^+ \pi^- K^-) + \hat{\Gamma}(D^- \to \pi^+ K^- \pi^-)\,,$$

$$\sum\nolimits_{\text{SCS}} \hat{\Gamma} = \hat{\Gamma}(D_s^- \to \pi^+ \pi^- K^-) + \hat{\Gamma}(D^- \to K^+ K^- \pi^-) + \hat{\Gamma}(D_s^- \to K^+ K^- K^-) + \hat{\Gamma}(D^- \to \pi^+ \pi^- \pi^-)\,.$$

$$\frac{\sum_{\text{CF, DCS}} \hat{\Gamma}}{\sum_{\text{SCS}} \hat{\Gamma}} = 1.050 \pm 0.015\,.$$

Overview: Status of NLO Sum Rules preliminary

[Gavrilova, Grossman, Papiri, Schacht: 2602.soon]



NLO Predictions: Unmeasured Rates preliminary

[Gavrilova, Grossman, Papiri, Schacht: 2602.soon]

- Measurements allow to test more NLO sum rules in order to obtain a better understanding of U-spin breaking in charm.

$$\mathcal{B}(D^0 \to \rho^- K^+) = (2.08 \pm 0.19) \cdot 10^{-4}$$

$$\mathcal{B}(\Xi_c^+ \to p\pi^-\pi^+) + \mathcal{B}(\Xi_c^+ \to pK^-K^+) + \mathcal{B}(\Xi_c^+ \to \Sigma^+\pi^-K^+) = (1.19 \pm 0.48) \cdot 10^{-3}$$

$$\frac{\mathcal{B}(\Xi_c^0 \to \Sigma^-\pi^+)}{f_{SCS}} - \frac{\mathcal{B}(\Xi_c^0 \to \Sigma^-K^+)}{f_{DCS}} = (7.75 \pm 3.77) \cdot 10^{-3}$$

$$\frac{\mathcal{B}\left(\Xi_c^0 \to pK^-\right)}{f_{CF}} + \frac{\mathcal{B}\left(\Xi_c^0 \to \Sigma^+\pi^-\right)}{f_{DCS}} - \frac{\mathcal{B}\left(\Xi_c^0 \to p\pi^-\right)}{f_{SCS}} = (3.74 \pm 0.83) \cdot 10^{-2}$$

Next Steps@LHCb: A Theorist's View

Your next grant, WP1: U-spin breaking in charged D decays

1. Increase precision of $a_{CP}^{\rm dir}(D_s^+ \to K_S\pi^+)$ and $a_{CP}^{\rm dir}(D^+ \to K_S K^+)$.
2. Probe U-spin sum rule

$$a_{CP}^{\rm dir}(D_s^+ \to K_S\pi^+) + a_{CP}^{\rm dir}(D^+ \to K_S K^+) = 0\,.$$

3. Measure also $a_{CP}^{\rm dir}(D_s^+ \to K^+\pi^0)$ to probe improved sum rule.

[Müller Nierste Schacht PRL 115 (2015) 25, 251802]

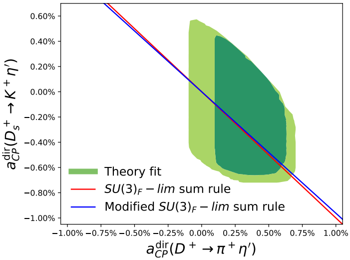
CP Asymmetry	HFLAV avg. $/10^{-4}$ [https://hflav.web.cern.ch/]
$a_{CP}^{dir}(D_s^+ \to K_S\pi^+)$	16 ± 18
$a_{CP}^{dir}(D^+ \to K_S K^+)$	-1 ± 7
$a_{CP}^{dir}(D_s^+ \to K^+\pi^0)$	200 ± 300

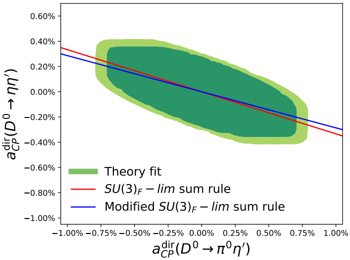
- Sum rule broken like $a_{CP}^{dir}(D^0 \to \pi^+\pi^-) + a_{CP}^{dir}(D^0 \to K^+K^-) = 0$?
- Is $a_{CP}^{\rm dir}(D_s^+ \to K_S\pi^+)$ enhanced, like $D^0 \to \pi^+\pi^-$?
- Is $a_{CP}^{\rm dir}(D^+ \to K_S K^+)$ suppressed, like $D^0 \to K^+K^-$?

Your next grant, WP2: P/T from $D \to P\eta'$

[Bolognani Nierste Schacht Vos 2410.08138 and 2511.20585]

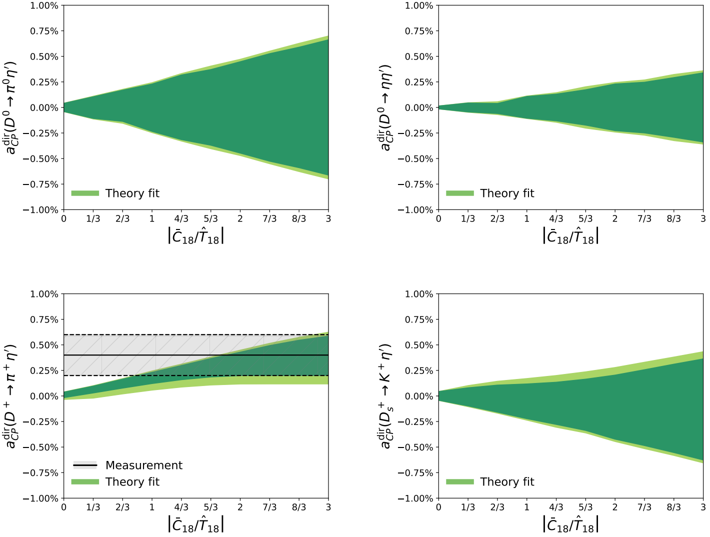
CP Asymmetry	HFLAV avg. [https://hflav.web.cern.ch/]	Experiments
$D^0 \to \pi^0\eta'$	—	—
$D^0 \to \eta\eta'$	—	—
$D^+ \to \pi^+\eta'$	$(0.40 \pm 0.20)\%$	LHCb'23, Belle'11, CLEO'10
$D_s^+ \to K^+\eta'$	$(6.0 \pm 18.9)\%$	CLEO'10





Measure CP asymmetry and read P/T from plot

[Bolognani Nierste Schacht Vos 2410.08138 and 2511.20585]



Your next grant, WP3: P/T in multi-body D decays

[Dery Grossman Schacht Soffer 2101.02560]

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

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

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

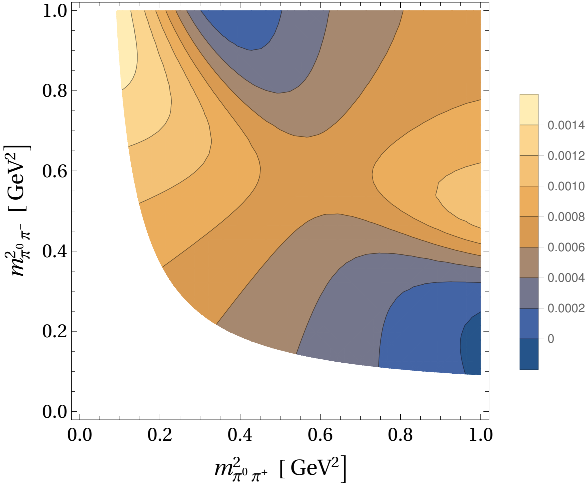
  but **not** magnitudes and phases separately.

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

Conclusions

This is just the beginning of the exploration of charm CP violation.
Will a consistent picture emerge?

- Is the sum rule

$$a_{CP}^{\mathrm{dir}}(D_s^+ \to K_S\pi^+) + a_{CP}^{\mathrm{dir}}(D^+ \to K_S K^+) = 0$$

  broken at $\mathcal{O}(1)$, like $a_{CP}^{dir}(D^0 \to \pi^+\pi^-) + a_{CP}^{dir}(D^0 \to K^+K^-) = 0$?
- Basically uncharted territory:

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

- Probe P/T in multi-body decays, e.g. $D^0 \to \pi^+\pi^-\pi^0$ at $\rho^\pm$.
- Probe anatomy of U-spin breaking with NLO sum rules.
- And much more!