Charm CP Violation

Stefan Schacht

University of Manchester

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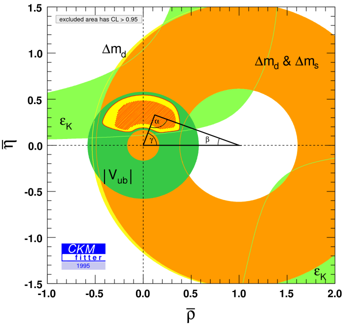
This is where we are in Quark-Flavor.

[CKMfitter, http://ckmfitter.in2p3.fr]



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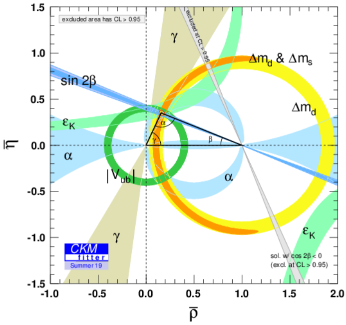


EPS-HEP 2019

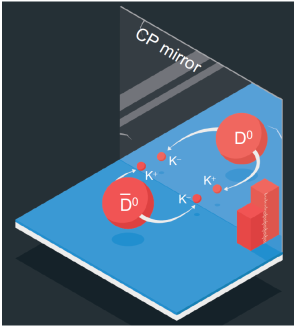
- Community effort due to both theoretical and experimental progress.

Direct Charm CP Violation

2019: Discovery of Charm CP Violation
New unique gate to flavor structure of up-type quarks.

$$\Delta A_{CP} \approx a_{CP}^{\rm dir}(D^0 \to K^+K^-) - a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-) = (-0.164 \pm 0.028)\%$$

[LHCb 1903.08726, HFLAV 1909.12524]



Expected to be unobservably tiny. But it is not.

Direct CP Violation is an Interference Effect

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

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?

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

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

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

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

$KK \leftrightarrow \pi\pi$ rescattering into same final state.

Weak and strong factors

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

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

Prediction

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

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

"$\Delta U = 0$ rule": $r_{\text{QCD}} \sim 1$ [Grossman StS 1903.10952]

- We claim $\Delta U = 0$ follows similar pattern as generalized $\Delta I = 1/2$ rule.
- Both due to low energy QCD, rescattering.

"$\Delta I = 1/2$ rules" for isospin in $P^+ \to \pi^+\pi^0$, $P^0 \to \pi^+\pi^-$, $P^0 \to \pi^0\pi^0$

- 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.

Comparison of approaches: What is r_{QCD}?

Data

Assuming the SM, and $\delta_{\text{QCD}} = \mathcal{O}(1)$, the data implies $r_{\text{QCD}}^{\Delta U=0} \sim 1$.

Ref.	**Theory Method/Assumptions**	$r_{QCD}^{\Delta U=0}$	SM/NP
[Grossman StS 1903.10952]	Analogy to $\Delta I = 1/2$ rules Low energy QCD, rescattering is $\mathcal{O}(1)$	$\mathcal{O}(1)$	SM
[Brod Kagan Zupan 1111.5000]	Phenomenological analysis	$\mathcal{O}(1)$	SM
[Soni 1905.00907, StS Soni 2110.07619]	Resonance model	$\mathcal{O}(1)$	SM
[Petrov Khodjamirian 1706.07780] [Chala Lenz Rusov Scholtz 1903.10490]	Light Cone Sum Rules Resonances in principle incorporable.	$\mathcal{O}(\alpha_s/\pi)$	NP

What next? Apply methods to $\Delta I = 1/2$ rule in charm!

Reproduction of $\Delta I = 1/2$ crucial for NP case in $\Delta U = 0$.

The jury is still out: Is it SM or not?

- No matter what it is, we learn sth new.
- We have a good argument why it is QCD.
- Assumption of large rescattering at low energy agrees with the data.

$$\text{Loop/Tree} = \mathcal{O}(1)$$

Key insight: Charm is not heavy.

A_{CP} Sum Rules: Overconstrain the SM

Challenge for predicting CP asymmetries

- New hadronic quantities appear.
- These cannot be extracted from $\mathcal{B}$ measurements.

Solution

Make up SU(3)$_F$ sum rules in which these cancel.

SU(3)$_F$ limit sum rules

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

What next? Key Measurements at Belle II

Observable	Current HFLAV Avg.	Impact
$A_{CP}(D^0 \to \pi^0\pi^0)$	-0.0003 ± 0.0064	SM sum rule 1/isospin analysis
$A_{CP}(D_s^+ \to K^+\pi^0)$	$+0.020 \pm 0.030$	SM sum rule 2
$A_{CP}(D^+ \to \pi^+\pi^0)$	$+0.004 \pm 0.008$	$= 0$. Higher orders<sensitivity.
$A_{CP}(D^0 \to K_S K_S)$	-0.019 ± 0.010	$\lesssim 1\%$ in SM.

A_{CP} sum rules including breaking effects [Müller Nierste StS 1506.04121]

- SM sum rule 1: $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$.
- SM sum rule 2: $D^+ \to K_S K^+$, $D_s^+ \to K_S\pi^+$, $D_s^+ \to K^+\pi^0$.

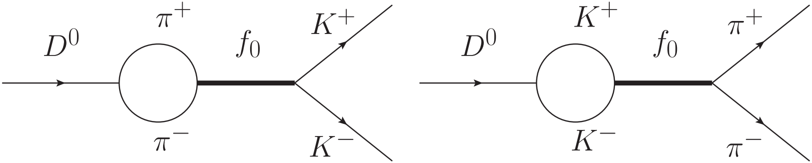
Isospin Analysis [Grossman Kagan Zupan 1204.3557]

- $D^0 \to \pi^+\pi^-$, $D^+ \to \pi^+\pi^0$, $D^0 \to \pi^0\pi^0$ give $\Delta I = 1/2$ and $\Delta I = 3/2$ MEs.

What next? Check dynamical mechanism from data.

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

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



Assumptions

[StS and A. Soni, 2110.07619]

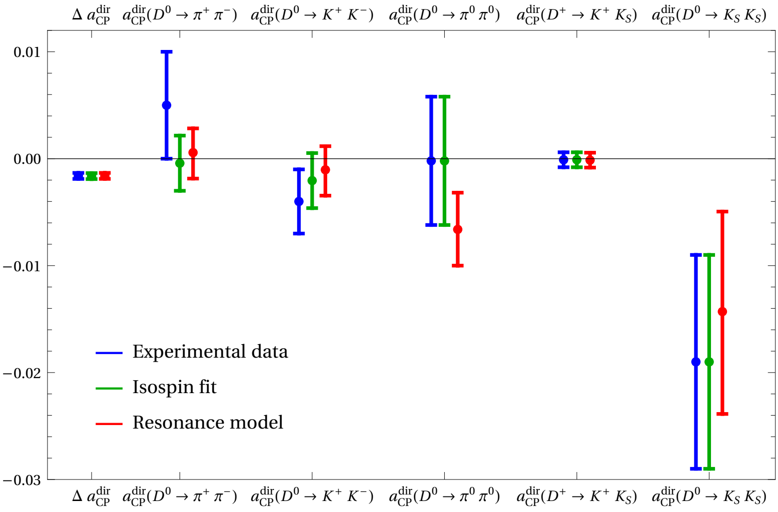
- Amplitudes to $I = 0$ states dominated by f_0 close to D^0 mass.
- Amplitudes into $I = 1$ states relatively suppressed.

Resonance structure can also be incorporated in future LCSR calculations.

[Khodjamirian Petrov 1706.07780]

Predictions in Scalar Resonance Model

[StS and A. Soni, 2110.07619]



What next? Study of $\Delta U = 0$ in three-body decays

[Dery Grossman StS 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

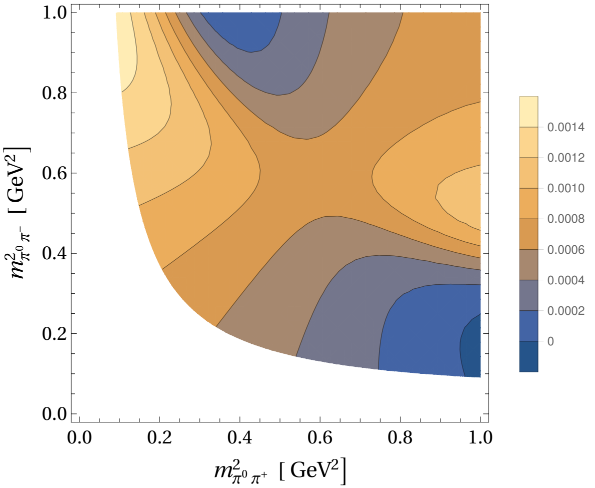
$$|\widetilde{R}^{P_1V_2}|\sin(\delta_{P_1V_2}) \qquad \text{and} \qquad |\widetilde{R}^{P_2V_1}|\sin(\delta_{P_2V_1})\,,$$

  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 StS Soffer 2101.02560]



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

What next? Higher-Order SU(3)-flavor

[Gavrilova Grossman StS, 21xx.soon]

- 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.

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

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

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

[Table: Hiller Jung StS 1211.3734]

Solving the Problem of Higher Order SU(3)

[Gavrilova Grossman StS, 21xx.soon]

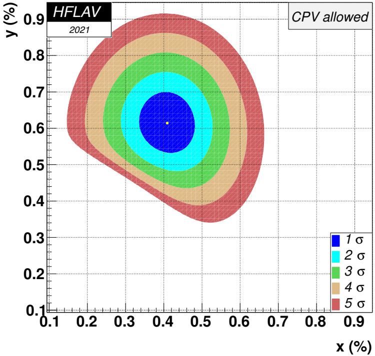
We proved several theorems enabling calculations to arbitrary order.

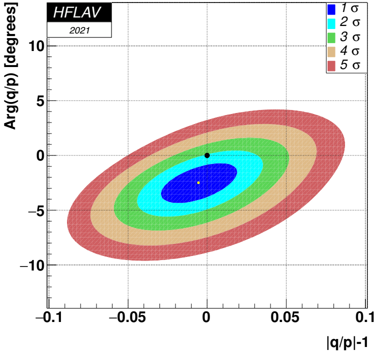
- We are able to determine a priori up to which order sum rules exist.
- We do not need explicit Clebsches. Big complexity reduction.
- Hope: Opens the door for precision in hadronic decays.
- Close a gap between theory and experiment.

Take advantage of precision data on nonleptonic decays.

Charm Mixing and Indirect CP Violation

Status





- Mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$.
- 2021: First observation of $x \neq 0$ with $> 7\sigma$. [LHCb 2106.03744].
- Uncertainty of y reduced by a factor two in [LHCb 2110.02350].
- $|q/p| \neq 1$ would indicate CPV in mixing.
- $\mathrm{Arg}(q/p) \neq 0$ would indicate CPV from interference mixing/decay.
- SM: hard to calculate. Qualitative agreement with SM.

Exclusive Approach: Hadron-Level

$$\Gamma_{12}^{D} = \sum_{n} \rho_n \left\langle \overline{D^0} \right| \mathcal{H}_{eff}^{\Delta C=1} |n\rangle \langle n| \mathcal{H}_{eff}^{\Delta C=1} \left| D^0 \right\rangle ,$$

$$M_{12}^{D} = \sum_{n} \left\langle \overline{D^0} \right| \mathcal{H}_{eff}^{\Delta C=2} \left| D^0 \right\rangle + \mathcal{P} \sum_{n} \frac{\left\langle \overline{D^0} \right| \mathcal{H}_{eff}^{\Delta C=1} |n\rangle \langle n| \mathcal{H}_{eff}^{\Delta C=1} \left| D^0 \right\rangle}{m_D^2 - E_n^2}$$

- n: all possible hadronic states. ρ_n: density of state. $\mathcal{P}$: principal value.
- Result: $y \sim 1\%$, agreeing with measurements.

What next?

- More experimental input needed (BRs and phases).
- Theory: Need to take into account more $\mathrm{SU}(3)_F$ breaking effects.
- Long-term: Lattice predictions?

Inclusive Approach: Quark-Level

- Heavy-Quark Expansion (HQE), motivated by $\tau(D^+)/\tau(D^0)$.
- Needed non-perturbative matrix elements from sum rules or Lattice
- Severe GIM-cancellations may take place.

Recent Developments

[Lenz Piscopo Vlahos 2007.03022]

- GIM depends on scales entering different box contributions. These contain different amounts of strangeness.
- No need that these scales are the same ⇒ GIM cancellation broken.
- HQE uncertainty gets larger, including y^{exp}.

What next?

- Higher orders in HQE expansion.
- After Γ_{12} also M_{12}, e.g. with dispersion relations.

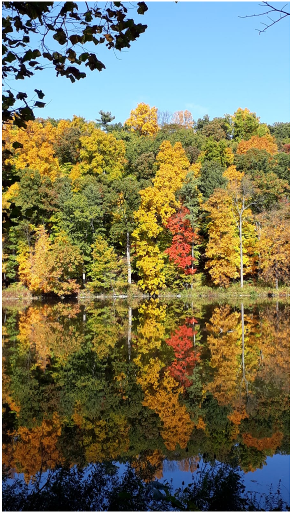
What will charm reveal next?

- Will the global charm fit give a consistent picture?
- Sum rules for baryon decays, including fully general $SU(3)_F$ breaking.
- How to define ΔA_{CP} for 4-body decays in an advantageous way?
- Optimal observable for detecting CPV in multibody decays? Smart binning?
- How to describe $SU(3)_F$-breaking effects from Dalitz phase space?
- How good is charm described by Light-Cone Sum Rules (LCSR) ?
- How good is charm described by QCD factorization (BBNS)?
- What can we learn about η–η'-mixing from charm decays?
- Isospin-breaking and electroweak corrections to nulltest isospin relations like $A_{CP}(D^+ \to \pi^0\pi^+) = 0$.
- What more can correlated D^0–$\overline{D}^0$ states tell us, e.g. at a future τ-charm factory?

Conclusions

- So much more data and theory ideas: New era in flavor physics.
- We need to keep:

  Theory error $<$ Experimental error .
- No matter what, we will learn sth new: QCD or New Physics.



[Discrete symmetries at Beebe lake, Cornell]