Charm CP Violation

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based on Grossman Schacht JHEP 1907 (2019) 020 [1903.10952]

The Discovery of Direct Charm CP Violation

[LHCb, 1903.08726]

First Observation of CP Violation in Charmed Hadrons by LHCb

$\Delta A_{CP} = (-0.154 \pm 0.029)\%$, 5.3σ from zero.

$$\Delta a_{CP}^{\text{dir}} \equiv a_{CP}^{\text{dir}}(D^0 \to K^+K^-) - a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)$$
$$= (-0.156 \pm 0.029)\%$$

$$a_{CP}^{\text{dir}}(f) \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2}\,, \qquad (f = \text{CP-eigenstate})$$

HFLAV Update Moriond 2019

$$\Delta a_{CP}^{\text{dir}} = (-0.164 \pm 0.028)\%$$

Why was it so hard to find? Because it is smaller than in B physics!

- The external quarks involve only first two generations.
  Kobayashi Maskawa: Need all three generations for CP violation.
  2x2 Cabibbo matrix is real.
  CP violation in charm basically from small nonunitarity of 2x2 submatrix.

- Hierarchy: $V_{cb}^* V_{ub} \sim \lambda^5 \ll V_{cs}^* V_{us} \sim -V_{cd}^* V_{ud} \sim \lambda$.
  Different from hierarchy in B system $V_{tb}^* V_{td} \sim V_{cb}^* V_{cd} \sim V_{ub}^* V_{ud} \sim \lambda^3$

- $m_b \ll m_W$ in charm decay loop, but $m_t > m_W$ in beauty decay loop.

Why is Charm challenging?

- Physics is about small parameters we expand in.
- In Charm there is none.
- Intermediate mass compared to Λ_{QCD} : Not heavy, not light.
- Do methods like Heavy Quark Expansion and Factorization work?
- Need to find new ways to make predictions
  and play the game of QCD.
- That makes life more interesting.

$SU(3)_F$ symmetry and Flavor Structure of Operators

- Approximate symmetry from $m_{u,d,s} \ll \Lambda_{QCD}$.
- QCD approx. invariant under unitary rotations of (u, d, s).
- Correlations and sum rules between various charm decays.
- Isospin and U-spin: $SU(2) \subset SU(3)_F$ connecting u, d and d, s.

U-spin Flavor Structure of Hamiltonian for SCS Decays

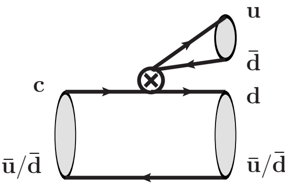
$$Q^{\bar{s}s} = (\bar{s}u)(\bar{c}s) \qquad Q^{\bar{d}d} = (\bar{d}u)(\bar{c}d)$$

$$Q^{\Delta U=1} = \frac{Q^{\bar{s}s} - Q^{\bar{d}d}}{2} \qquad Q^{\Delta U=0} = \frac{Q^{\bar{s}s} + Q^{\bar{d}d}}{2}$$

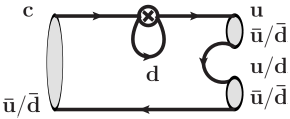
$$\mathcal{H}_{\text{eff}} \sim \underbrace{\frac{V_{cs}^* V_{us} - V_{cd}^* V_{ud}}{2}}_{\approx \lambda} Q^{\Delta U=1} + \underbrace{\frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{2}}_{= -\frac{V_{cb}^* V_{ub}}{2} \approx \lambda^5} Q^{\Delta U=0}$$

CP Violation from nonunitarity of 2x2 submatrix of CKM

Tree diagram



"Rescattering":
Penguin contraction of tree operator



$$\mathcal{A}^{\mathrm{SCS}} = \lambda\, \mathcal{A}_{sd} - \frac{V_{cb}^* V_{ub}}{2} \mathcal{A}_b \,, \qquad |\lambda| \gg |V_{cb}^* V_{ub}|$$

$$a_{CP}^{\mathrm{dir}} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} = \mathrm{Im}\frac{V_{cb}^* V_{ub}}{\lambda} \mathrm{Im}\frac{\mathcal{A}_b}{\mathcal{A}_\Sigma}$$

- Misalignment between $V_{cs}^* V_{us}$ and $V_{cd}^* V_{ud}$. $\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix}$
- 3rd generation enters via non-unitarity of the 2x2 submatrix of CKM
- b penguin less important.

This talk: What do we learn from the new result? Is it physics beyond the SM?

[Grossman Schacht 1903.10952]

Direct CP asymmetries in SCS Charm decays:

$$a_{CP}^{\mathrm{dir}} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} = \underbrace{\mathrm{Im}\frac{V_{cb}^* V_{ub}}{\lambda}}_{-6\cdot 10^{-4}} \mathrm{Im}\frac{A_b}{A_{sd}}\,.$$

- The new measurement allows for the first time to determine the CKM-suppressed amplitude.
- $\Rightarrow$ Im($\Delta U = 0$ over $\Delta U = 1$ matrix elements).

Overview: Implications of $\Delta a_{CP}^{\mathrm{dir}}$

- Completely general U-spin SM parametrization.

- The $\Delta U = 0$ rule.

- Comparison to $\Delta I = 1/2$ rules in K, D and B decays.

Completely general U-spin SM parametrization

U-spin quartet of $D \to P^+P^-$

[Brod Grossman Kagan Zupan 2012]

$$\mathcal{A}(K\pi) = V_{cs}V_{ud}^* \left(t_0 - \frac{1}{2}t_1\right),$$

$$\mathcal{A}(\pi\pi) = -\lambda\left(t_0 + s_1 + \frac{1}{2}t_2\right) - V_{cb}V_{ub}^*\left(p_0 - \frac{1}{2}p_1\right),$$

$$\mathcal{A}(KK) = \lambda\left(t_0 - s_1 + \frac{1}{2}t_2\right) - V_{cb}V_{ub}^*\left(p_0 + \frac{1}{2}p_1\right),$$

$$\mathcal{A}(\pi K) = V_{cd}V_{us}^* \left(t_0 + \frac{1}{2}t_1\right).$$

- Subscript = level of U-spin breaking, if power-counting switched on.
- Parametrization completely general: Independent from U-spin.
- Mainly interested in ratios:

$$\tilde{t}_1 \equiv \frac{t_1}{t_0}, \quad \tilde{t}_2 \equiv \frac{t_2}{t_0} \in \mathbb{R}, \quad \tilde{s}_1 \equiv \frac{s_1}{t_0} \in \mathbb{R}, \quad \tilde{p}_0 \equiv \frac{p_0}{t_0}, \quad \tilde{p}_1 \equiv \frac{p_1}{t_0}.$$

- 8 real parameters and 8 observables: system exactly solvable.

Branching ratio measurements (3 observables)

$$|A_\Sigma(KK)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to K^+K^-))}{|\Sigma|^2 \mathcal{P}(D^0, K^+, K^-)}\,, \qquad |A_\Sigma(\pi\pi)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to \pi^+\pi^-)}{|\Sigma|^2 \mathcal{P}(D^0, \pi^+, \pi^-)}\,,$$

$$|A(K\pi)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to K^+\pi^-)}{|V_{cs}V_{ud}^*|^2 \mathcal{P}(D^0, K^+, \pi^-)}\,, \quad |A(\pi K)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to K^-\pi^+)}{|V_{cd}V_{us}^*|^2 \mathcal{P}(D^0, K^-, \pi^+)}\,.$$

- Neglect the tiny effects of order $|\lambda_b/\Sigma|$.

$$R_{K\pi} \equiv \frac{|\mathcal{A}(K\pi)|^2 - |\mathcal{A}(\pi K)|^2}{|\mathcal{A}(K\pi)|^2 + |\mathcal{A}(\pi K)|^2} = -0.11 \pm 0.01\,,$$

$$R_{KK,\pi\pi} \equiv \frac{|\mathcal{A}(KK)|^2 - |\mathcal{A}(\pi\pi)|^2}{|\mathcal{A}(KK)|^2 + |\mathcal{A}(\pi\pi)|^2} = 0.534 \pm 0.009\,,$$

$$R_{KK,\pi\pi,K\pi} \equiv \frac{|\mathcal{A}(KK)|^2 + |\mathcal{A}(\pi\pi)|^2 - |\mathcal{A}(K\pi)|^2 - |\mathcal{A}(\pi K)|^2}{|\mathcal{A}(KK)|^2 + |\mathcal{A}(\pi\pi)|^2 + |\mathcal{A}(K\pi)|^2 + |\mathcal{A}(\pi K)|^2} = 0.071 \pm 0.009\,.$$

Strong phase which does not require CPV (1 observable)

- Can be obtained from time-dependent measurements.
- Or correlated $D^0\bar{D}^0$ decays at a charm-τ factory.

Both methods: Strong phase between the CF and DCS decay modes.

$$\delta_{K\pi} \equiv \arg\left(\frac{\mathcal{A}(\bar{D}^0 \to K^-\pi^+)}{\mathcal{A}(D^0 \to K^-\pi^+)}\right) = \arg\left(\frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(D^0 \to K^-\pi^+)}\right) = \left(8.6^{+9.1}_{-9.7}\right)^\circ \,.$$

[Grossman Kagan Nir 2006, Browder Pakvasa 1995, Wolfenstein 1995, Falk Nir Petrov 1999, Gronau Rosner 2000, Bergmann Grossman Ligeti Nir Petrov 2000, Falk Grossman Ligeti Petrov 2001, Bigi Sanda 1986, Xing 1996, Gronau Grossman Rosner 2001]

Integrated direct CP asymmetries (2 observables)

$$\Delta a_{CP}^{\mathrm{dir}} \equiv a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) - a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)$$
$$= -0.00164 \pm 0.00028 \qquad \text{(HFLAV)}\,,$$

$$\Sigma a_{CP}^{\mathrm{dir}} \equiv a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) + a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-)$$
$$= 0.002 \pm 0.002\,.$$

(our result from HFLAV av. of $A_{CP}(D^0 \to K^+K^-)$ and $A_{CP}(D^0 \to \pi^+\pi^-)$)

[Einhorn Quigg 1975, Abbott Sikivie Wise 1980, Golden Grinstein 1989, Brod Grossman Kagan Zupan 2012, Franco Mishima Silvestrini 2012, Hiller Jung Schacht 2012, Mller Nierste Schacht 2015, Buccella Lusignoli Miele Pugliese Santorelli 1994, Grossman Kagan Nir 2006, Artuso Meadows Petrov 2008, Khodjamirian Petrov 2017, Cheng Chiang 2012, Feldmann Nandi Soni 2012, Li Lu Yu 2012, Atwood Soni 2012, Grossman Robinson 2012, Buccella Paul Santorelli, 2019, Yu Wang Li, 2017, Brod Kagan Zupan 2011]

Strong phases that require CP violation (2 observables)

[e.g. Gronau Grossman Rosner 2001, Nierste Schacht 2015]

$$\delta_{KK} \equiv \arg\left(\frac{\mathcal{A}(\bar{D}^0 \to K^+K^-)}{\mathcal{A}(D^0 \to K^+K^-)}\right), \qquad \delta_{\pi\pi} \equiv \arg\left(\frac{\mathcal{A}(\bar{D}^0 \to \pi^+\pi^-)}{\mathcal{A}(D^0 \to \pi^+\pi^-)}\right).$$

- Relative phases of the amplitudes of a $\bar{D}^0$ and D^0 going into one of the CP eigenstates.
- Can be obtained from time-dependent measurements or measurements of correlated $D^0\bar{D}^0$ pairs.

The system is exactly solvable.

For application to current data use U-spin power counting

Examples:

$$R_{K\pi} = -\mathrm{Re}(\tilde{t}_1)(1 + \mathcal{O}(\varepsilon^2))\,,$$
$$R_{KK,\pi\pi} = -2\,\tilde{s}_1\,(1 + \mathcal{O}(\varepsilon^2))\,,$$

$$\Delta a_{CP}^{\mathrm{dir}} = \mathrm{Im}\left(\frac{\lambda_b}{\Sigma}\right) \times 4\,\mathrm{Im}\,(\tilde{p}_0)\,(1 + \mathcal{O}(\varepsilon^2))\,,$$

and

$$\Sigma a_{CP}^{\mathrm{dir}} = 2\mathrm{Im}\left(\frac{\lambda_b}{\Sigma}\right) \times \left[2\,\mathrm{Im}(\tilde{p}_0)\tilde{s}_1 + \mathrm{Im}(\tilde{p}_1)\right]\left(1 + \mathcal{O}(\varepsilon^2)\right)\,.$$

- Relations to parameters only get relative correction at order $\mathcal{O}(\varepsilon^2)$.

The $\Delta U = 0$ rule

Parametrize ratio of $\Delta U = 0$ over $\Delta U = 1$ matrix elements

The numerical result

$$\Delta a_{CP}^{\text{dir}} = 4\,\text{Im}\left(\frac{\lambda_b}{\Sigma}\right) |\tilde{p}_0| \sin(\delta_{\text{strong}})\,,$$

$$|\tilde{p}_0| \sin(\delta_{\text{strong}}) = 0.65 \pm 0.12\,.$$

Group theory language of $\tilde{p}_0 = p_0/t_0$

- t_0 : matrix element of $Q^{\Delta U=1} = (Q^{\bar{s}s} - Q^{\bar{d}d})/2$.
- p_0 : matrix element of $Q^{\Delta U=0} = (Q^{\bar{s}s} + Q^{\bar{d}d})/2$.

Decomposition into "no QCD" part, plus corrections

$$\tilde{p}_0 = B + Ce^{i\delta}\,.$$

- B: short-distance. $Ce^{i\delta}$: long distance.
- b quark in the loop perturbative, quarks lighter than the charm are not.

$B = 1$ in $\tilde{p}_0 = B + Ce^{i\delta}$

- Perturbatively, diagrams with intermediate b are negligible.
- The limit $C = 0$ (i.e. no LD contribution to $\tilde{p}_0$) corresponds to only $Q^{\bar{s}s}$ can produce K^+K^- and only $Q^{\bar{d}d}$ can produce $\pi^+\pi^-$:

$$\left\langle K^+K^- \right| Q^{\bar{d}d} \left| D^0 \right\rangle = \left\langle \pi^+\pi^- \right| Q^{\bar{s}s} \left| D^0 \right\rangle = 0\,,$$

  and

$$\left\langle K^+K^- \right| Q^{\bar{s}s} \left| D^0 \right\rangle \neq 0\,, \qquad \left\langle \pi^+\pi^- \right| Q^{\bar{d}d} \left| D^0 \right\rangle \neq 0\,.$$

  We then see that $B = 1$ since

$$\frac{\left\langle K^+K^- \right| Q^{\Delta U=0} \left| D^0 \right\rangle}{\left\langle K^+K^- \right| Q^{\Delta U=1} \left| D^0 \right\rangle} = 1\,.$$

- That means in the no QCD limit $\tilde{p}_0 = 1$.

$\delta = \mathcal{O}(1)$ in $\tilde{p}_0 = B + Ce^{i\delta}$

- Non-perturbative effects involve on-shell particles, giving rise to large strong phases to the LD effects independent of the magnitude of the LD amplitude.
- In other words: Generically, rescattering can always give $\mathcal{O}(1)$ phases.

It follows, with $\sin\delta = \mathcal{O}(1)$:

$$\Delta a_{CP}^{\mathrm{dir}} = 4\,\mathrm{Im}\left(\frac{\lambda_b}{\Sigma}\right) \times C \times \sin\delta$$

Different predictions depending on size of corrections to no QCD limit C in

$$\tilde{p}_0 = 1 + Ce^{i\delta}\,, \qquad \Rightarrow \mathrm{Im}(\tilde{p}_0) = C\sin\delta.$$

What is C ?

1. $C = \mathcal{O}(\alpha_s/\pi)$: Perturbative corrections to $\tilde{p}_0$.
2. $C = \mathcal{O}(1)$: Non-perturbative corrections that produce strong phases from rescattering but do not significantly change the magnitude of $\tilde{p}_0$.
3. $C \gg \mathcal{O}(1)$: Large non-perturbative effects with significant magnitude changes and strong phases from rescattering to $\tilde{p}_0$.

- Note that (2) and (3) are in principle not different: Both include non-perturbative effects, differing only in their size.
- Numerical example: A value $\Delta a_{CP}^{\mathrm{dir}} = 1 \times 10^{-4}$,assuming $O(1)$ strong phase, corresponds to $C \sim 0.04$.
- **If** there is a strong argument for C must be of category (1) $\Rightarrow \Delta a_{CP}^{\mathrm{dir}}$ is a sign of New Physics.

The $\Delta U = 0$ rule

The $\Delta U = 0$ rule in charm

- With current data, C is consistent with category (2).
- SM picture: measurement of $\Delta a_{CP}^{\mathrm{dir}}$ proves the non-perturbative nature of the $\Delta U = 0$ matrix elements with a mild enhancement from $\mathcal{O}(1)$ rescattering effects. This is the $\Delta U = 0$ rule for charm.

What to do next, to learn more about the $\Delta U = 0$ rule in charm?

- Future data on phases δ_{KK} and $\delta_{\pi\pi}$ gives the phase δ in $\tilde{p}_0 = 1 + Ce^{i\delta}$.
- With that it will be possible to completely determine the characteristics of the emerging $\Delta U = 0$ rule.

Comparison to $\Delta I = 1/2$ rules in

K, D and B decays

The $\Delta I = 1/2$ rule in Kaon Physics

Isospin decomposition of $K \to \pi\pi$ decays.

$$\mathcal{A}(K^+ \to \pi^+\pi^0) = \frac{3}{2} A_2^K e^{i\delta_2^K}$$

$$\mathcal{A}(K^0 \to \pi^+\pi^-) = A_0^K e^{i\delta_0^K} + \sqrt{\frac{1}{2}} A_2^K e^{i\delta_2^K}$$

$$\mathcal{A}(K^0 \to \pi^0\pi^0) = A_0^K e^{i\delta_0^K} - \sqrt{2} A_2^K e^{i\delta_2^K}$$

[Gell-Mann Pais 1955, Gell-Mann Rosenfeld 1957, Gaillard Lee 1974, Bardeen Buras Gerard 1987, Buras Gerard Bardeen 2014. Lattice: RBC-UKQCD 2012, Blum Boyle Christ Garron Goode 2011, 2012]

Data: $\Delta I = 1/2$ rule: category (3)

- $A_0^K / A_2^K = 22.35$ $\qquad$ $\delta_0^K - \delta_2^K = (47.5 \pm 0.9)^\circ$
- Non-perturbative rescattering affects not only the phases but also the magnitudes of the corresponding matrix elements.

The $\Delta I = 1/2$ rule in Kaon Physics, Contd.

Characteristics of the Kaon $\Delta I = 1/2$ rule

- $A^K_{0,2}$ have small imaginary part from CKM.
- Very good approximation: real parts stem only from tree operators.

Parametrization as "no QCD" plus corrections for K, D and $B \to \pi\pi$

$$A_0/A_2 = B + Ce^{i\delta}$$

- Limit of "no QCD": Only Q_2 contributes, [Buras 1989]

$$B = \sqrt{2}\,.$$

- Corresponds to $\tilde{p}_0 = 1$ in "no QCD" limit for $\Delta U = 0$ rule.

$$\Rightarrow C \gg \mathcal{O}(1)\,.$$

$\Delta I = 1/2$ rules in D and B decays

$D \to \pi\pi$ [Franco Mishima Silvestrini 2012]

$$\left|\frac{A_0^D}{A_2^D}\right| = 2.47 \pm 0.07\,, \qquad \delta_0^D - \delta_2^D = (\pm 93 \pm 3)^\circ$$

Intermediate $\Delta I = 1/2$ rule: $\mathcal{O}(1)$ enhancement, similar to $\Delta U = 0$ rule.

$B \to \pi\pi$ [Grinstein Pirtskhalava Stone Uttayarat 2014]

$\left|\frac{A_0^B}{A_2^B}\right| \sim \sqrt{2}$ well compatible with data. Best fit point: $\left|\frac{A_0^B}{A_2^B}\right| = 1.5$

$\Delta I = 1/2$ rule compatible or close to the "no QCD" limit.

- Understand differences from mass scales governing K, D, B decays.
- Rescattering effects most important in K decays, less important but still significant in D decays, and small in B decays.

Conclusions

- The recent discovery of CP violation in charm decays opens a whole new field, as we are now ready to explore CP violation in regions we did not have access to before.
- This will teach us more about New Physics and QCD.
- It is yet hard to be convinced that BSM physics is required.
- Assuming it is SM, we learn about QCD:
  Moderate non-perturbative effect, nominal $SU(3)_F$ breaking.
- We need $\Sigma a_{CP}^{\mathrm{dir}}$ and time-dependent measurements.

BACK-UP

Numerical Results

$$\mathrm{Re}(\tilde{t}_1) = 0.109 \pm 0.011\,,$$
$$\mathrm{Im}(\tilde{t}_1) = -0.15^{+0.16}_{-0.17}\,,$$
$$\tilde{s}_1 = -0.2668 \pm 0.0045\,,$$
$$-\frac{1}{4}(\mathrm{Im}\tilde{t}_1)^2 + \mathrm{Re}(\tilde{t}_2) = 0.075 \pm 0.018\,, \quad \mathrm{Im}\,\tilde{p}_0 = -0.65 \pm 0.12\,,$$
$$2\mathrm{Im}(\tilde{p}_0)\tilde{s}_1 + \mathrm{Im}(\tilde{p}_1) = 1.7 \pm 1.6\,.$$

1. $\tilde{p}_1$ is the least constrained parameter: basically no information. Learn more: $\Sigma a_{CP}^{\mathrm{dir}}$, δ_{KK} and $\delta_{\pi\pi}$.
2. The higher order U-spin breaking parameters consistently smaller than the first order ones.
3. Second order ones even smaller: U-spin expansion works.
4. $SU(3)_F$ breaking of tree smaller than broken penguin.
5. Rough estimate: $\mathcal{O}(\varepsilon^2)$ in $\Delta a_{CP}^{\mathrm{dir}}$ is $\sim 10\%$. Need knowledge of $\tilde{p}_1$.

$\Delta I = 1/2$ enhancement much larger than $\Delta U = 0$ one. So why is Kaon direct CPV smaller than Charm direct CPV?

Write amplitudes very generically up to a normalization

$$\mathcal{A} = 1 + r\, a\, e^{(i\phi + \delta)}\,,$$

- r real and depends on CKM matrix elements,
- a real ratio of the respective hadronic matrix elements.
- For kaons a is ratio of matrix elements of $Q^{\Delta I=1/2}$ over $Q^{\Delta I=3/2}$.
- For charm a is ratio of matrix elements of operators $Q^{\Delta U=0}$ over $Q^{\Delta U=1}$.

$\Delta I = 1/2$ rule reduces CPV, $\Delta U = 0$ rule enhances CPV

Limit of two generations

$$\mathcal{A}_{\text{Kaon}} = V_{us}V_{ud}^{*}\left(A_{1/2} + r_{\text{Clebsch}}\,A_{3/2}\right),$$
$$\mathcal{A}_{\text{Charm}} = V_{cs}V_{us}^{*}\,A_{1}.$$

Switch on Third generation

- Nonunitarity of 2×2 CKM induces small correction.
- $|r_{\text{Kaon}} - 1| \ll 1$ and $r_{\text{Charm}} \ll 1$.
- Kaon weak phase from SD penguins with $V_{ts}V_{td}^{*}$
- Both cases: $\delta \sim \mathcal{O}(1)$ from non-perturbative rescattering.

$$A_{CP} = -\frac{2ra\sin(\delta)\sin(\phi)}{1+(ra)^2+2ra\cos(\delta)\cos(\phi)} \approx \begin{cases} 2r\,a\;\sin(\delta)\sin(\phi) & ,\ r\,a \ll 1 \ \text{(charm)}, \\ 2(ra)^{-1}\;\sin(\delta)\sin(\phi) & ,\ r\,a \gg 1 \ \text{(kaons)}. \end{cases}$$

- For $ra \ll 1$ increasing a gives enhancement (charm).
- While for $ra \gg 1$ it is suppressed (kaons).

In which modes will we

observe charm CPV next?

In which modes will we observe charm CPV next?

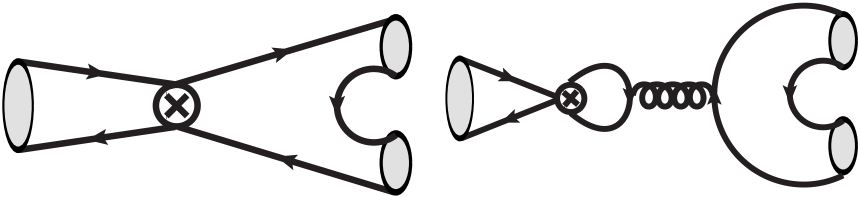
- Need decay mode with large SM prediction for a_{CP}^{dir}.
- Such a mode is $D^0 \to K_S K_S$.

[Brod Kagan Zupan 2011, Hiller Jung Schacht 2012, Atwood Soni 2012, Nierste Schacht 2015]

Special Features

- Suppressed $\mathcal{B}(D^0 \to K_S K_S)$
  $\Rightarrow$ enhanced a_{CP}^{dir} due to normalization.
- a_{CP}^{dir} dominated by tree level exchange diagrams.
  $\Rightarrow$ No penguin needed, no loop suppression.

Diagrams for $D^0 \to K_S K_S$: $SU(3)_F$-breaking Exchange and Penguin Annihilation



- CP violation from interference of exchange diagram with $SU(3)_F$ breaking exchange diagrams.
- No need for a penguin.
- Different than in $a_{CP}(D^0 \to K^+K^-) \sim \mathrm{Im}(P/T)$.

Timeline of $A_{CP}(D^0 \to K_S K_S)$ Measurements

SM prediction [Nierste Schacht 2015]

$|a_{CP}^{\rm dir}(D^0 \to K_S K_S)| \leq 1.1\%$ @95% CL

including $1/N_c$ color counting hierarchies: $|a_{CP}^{\rm dir}| \leq 0.6\%$.

Year	Experiment	$A_{CP}(D^0 \to K_S K_S)$	Ref.
2001	CLEO	$(-23 \pm 19)\%$	PRD63, 071101(R) (2001)
2015	LHCb	$(-2.9 \pm 5.2 \pm 2.2)\%$	JHEP 10 055 (2015)
2017	Belle	$(-0.02 \pm 1.53)\%$	PRL119, 171801 (2017)
2018	LHCb	$(4.3 \pm 3.4 \pm 1.0)\%$	JHEP 1811 (2018) 048
2018	LHCb combin.	$(2.3 \pm 2.8 \pm 0.9)\%$	JHEP 1811 (2018) 048

Close to possible observation of SM CP violation.

A decay mode with even more special features: $D^0 \to K_S K^{0*}$

Special Features on top of $D^0 \to K_S K_S$

- Prompt decay $K^{0*} \to K^+ \pi^-$ with charged tracks.
- Hunt for favorable strong phases in Dalitz plot.
- No flavor tagging needed, essentially undiluted untagged CP asymmetry.

SM prediction

[Nierste Schacht PRL119 251801 (2017)]

$$a_{CP}^{\text{dir}}(\overset{(-)}{D} \to K_S K^{*0}) \approx a_{CP}^{\text{dir}}(D^0 \to K_S K^{0*}) \lesssim 0.3\,\% \,.$$

[first exp. results: LHCb 1509.06628]