CP Violation in Charm Decays

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based on Grossman Schacht 1903.10952, 1811.11188

The Discovery of Direct Charm CP Violation

[LHCb, 1903.08726]

First Observation of CP Violation in Charmed Hadrons by LHCb

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

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

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

HFLAV Update Moriond 2019

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

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

- The external quarks involve only first two generations.
  Jarlskog: 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 $\Lambda_{\rm QCD}$: 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.

CKM Anatomy of Singly-Cabibbo Suppressed Decays

- Hamiltonian of SCS decays:

$$\mathcal{H}_{\text{eff}} \sim \frac{V_{cs}^* V_{us} - V_{cd}^* V_{ud}}{2} Q^{\Delta U=1} + \frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{2} Q^{\Delta U=0} ,$$

$$V_{cs}^* V_{us} \approx -V_{cd}^* V_{ud} \approx \lambda ,$$

$$\frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{2} = -\frac{V_{cb}^* V_{ub}}{2} \sim \lambda^5 .$$

- $\Rightarrow$ Amplitudes have CKM-leading and CKM-suppressed part:

$$\mathcal{A} = \lambda A_{sd} - \frac{\lambda_b}{2} A_b , \qquad |\lambda| \gg |\lambda_b| .$$

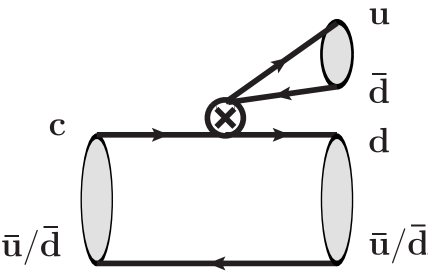
- A_b: "Rescattering", "penguin contraction of tree operator".
- Misalignment between $V_{cs}^* V_{us}$ and $V_{cd}^* V_{ud}$.
- 3rd generation enters via non-unitarity of the 2x2 submatrix of CKM

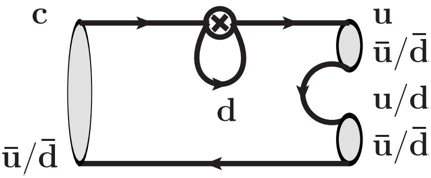
$$\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} .$$

- b penguin less important.

Topological Diagrams

[Chau 1980,1982; Zeppenfeld 1981, Gronau 1995, Buras Silvestrini 1998]





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:

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

- 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]

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

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

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

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

- 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 of four categories.

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)

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

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

(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

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

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

Numerical Results

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

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 $\tilde{p}_1$.

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.
- Setting $C = 0$ (i.e. no LD contribution to $\tilde{p}_0$) corresponds to only $Q^{\bar{s}s}$ can produce K^+K^- and only $Q^{d\bar{d}}$ 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 in this limit $B = 1$ since

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

$\delta = \mathcal{O}(1)$ 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 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 $\Delta a_{CP}^{\text{dir}} = 1 \times 10^{-4}$,assuming $O(1)$ strong phase, corresponds to $C \sim 0.04$.
- **If** there is a strong argument for C must be of category (1) $\Rightarrow \Delta a_{CP}^{\text{dir}}$ 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 $B \to \pi\pi$

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

- 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.

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

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

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

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

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

Emerging picture

- $\Delta I = 1/2$ rule in B decays compatible or close to the "no QCD" limit.
- $\Delta I = 1/2$ rule in kaon physics clearly belongs to category (3): $C \gg \mathcal{O}(1)$: Large non-perturbative effects with significant magnitude changes and strong phases from rescattering.
- $\Delta I = 1/2$ rule in charm decays is intermediate and shows an $\mathcal{O}(1)$ enhancement, similar to the $\Delta U = 0$ rule.
- Understand differences from different mass scales that govern K, D and B decays.
- Rescattering effects most important in K decays, less important but still significant in D decays, and small in B decays.

Conclusions

- From the recent determination of $\Delta a_{CP}^{\text{dir}}$ we derive the ratio of $\Delta U = 0$ over $\Delta U = 1$ amplitudes as

$$|\tilde{p}_0| \sin(\delta_{\text{strong}}) = 0.65 \pm 0.11\,.$$

- Hard to be convinced that BSM physics is required.
- Interpretation in SM: Moderate non-perturbative effect and nominal $SU(3)_F$ breaking. Two qualitative predictions:

$$\delta_{\text{strong}} \sim \mathcal{O}(1), \qquad a_{CP}^{\text{dir}}(D^0 \to K^+K^-) \approx -a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)\,.$$

- Verifying predictions will make SM interpretation of data more solid.
- We need $\Sigma a_{CP}^{\text{dir}}$ and time-dependent measurements.

BACK-UP

$\Delta I = 1/2$ 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?

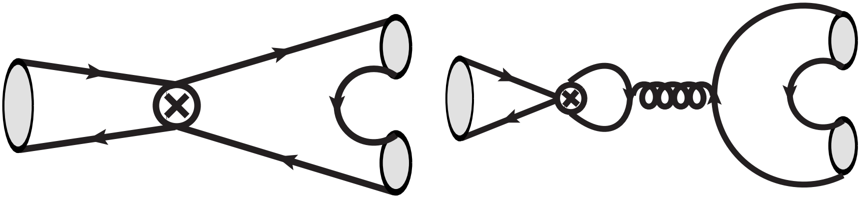
- Need decay mode with large SM prediction for a_{CP}^{dir}.
- Such a mode is $D^0 \to K_S K_S$.

[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)]

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

[first exp. results: LHCb 1509.06628]

Three-body Baryon Decays:

U-spin sum rules for CP asymmetries

[Grossman Schacht 1811.11188]

Recent LHCb Measurement

[LHCb, 1712.07051]

Difference of CP asymmetries of three-body SCS Λ_c^+ decays

$$A_{CP}(\Lambda_c \to pK^+K^-) - A_{CP}(\Lambda_c \to p\pi^+\pi^-) = (0.30 \pm 0.91 \pm 0.61)\%$$

- a_{CP} : CP asymmetry at a certain point in the Dalitz plot.
- A_{CP} : CP asymmetry of rates integrated over whole phase space.

$$a_{CP} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2}$$

$$A_{CP} \equiv \frac{\int |\mathcal{A}|^2 dp - \int |\overline{\mathcal{A}}|^2 dp}{\int |\mathcal{A}|^2 dp + \int |\overline{\mathcal{A}}|^2 dp}$$

$\int dp$ = integration over all phase space variables.

Which CP asymmetries should we compare?

(from a theory perspective)

For mesons:
U-spin limit sum rules for direct CP asymmetries

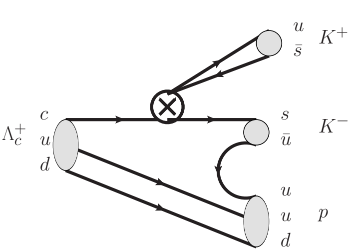
$$a_{CP}^{\text{dir}}(D^0 \to K^+K^-) + a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-) = 0$$
$$a_{CP}^{\text{dir}}(D^+ \to K_S K^+) + a_{CP}^{\text{dir}}(D_s^+ \to K_S\pi^+) = 0$$

Generalization including SU(3)$_F$ breaking is also available.

[Grossman Robinson 2012, Grossman Ligeti Robinson 2013, Müller Nierste Schacht 2015]

Are there also sum rules for Λ_c^+ decays?

Diagrammatical Decomposition: $\Lambda_c^+ \to pK^-K^+$



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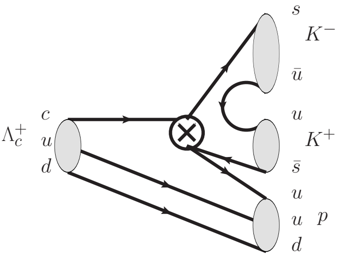
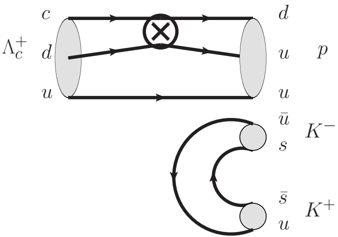
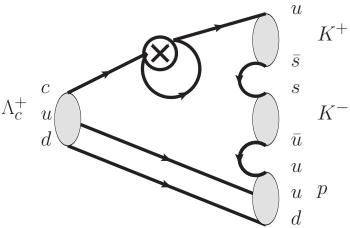


C_1

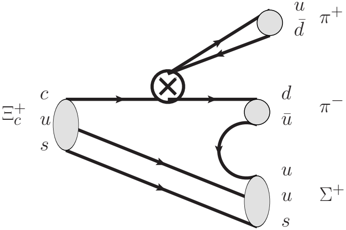


E_2



P_1

Exchange all $d \leftrightarrow s$ quarks: $\Xi_c^+ \to \Sigma^+ \pi^- \pi^+$



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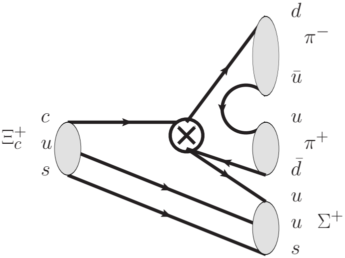
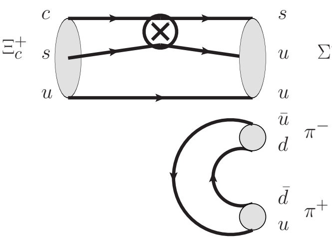
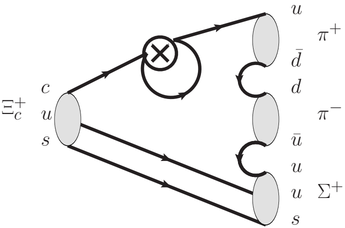


C_1

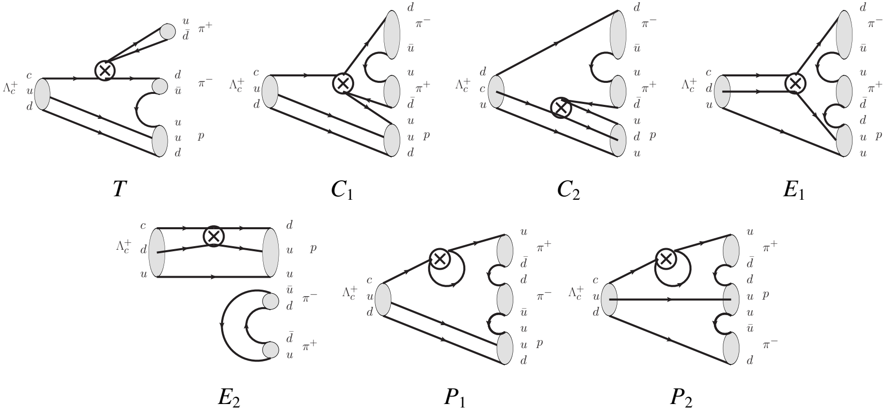


E_2



P_1

$\Lambda_c^+ \to p\pi^-\pi^+$ has more diagrams than $\Lambda_c^+ \to pK^-K^+$



- Presence of the spectator quark has nontrivial implications.
- Three-body decay allows more combinatorial possibilities.
- d spectator can end in proton or pion, but not in $K^\pm$.

Pointwise CP asymmetry sum rules

[Grossman Schacht 1811.11188]

Insert amplitude sum rules into $a_{CP} = \mathrm{Im}\left(\frac{-2\Delta}{\Sigma}\right)\mathrm{Im}\left(\frac{A_\Delta}{A_\Sigma}\right)$

$$a_{CP}(\Lambda_c^+ \to pK^-K^+) + a_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0$$

$$a_{CP}(\Lambda_c^+ \to \Sigma^+\pi^-K^+) + a_{CP}(\Xi_c^+ \to pK^-\pi^+) = 0$$

$$a_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) + a_{CP}(\Xi_c^+ \to \Sigma^+K^-K^+) = 0$$

- Correlation of Λ_c^+ and Ξ_c^+ decays.
- Only trivial sum rules stemming from interchanging all d and s quarks.

[Fleischer 1999, Gronau Rosner 2000, Gronau 2000]

Phase space integrated CP asymmetry

[Grossman Schacht 1811.11188]

U-spin limit + linear order in Δ/Σ

$$A_{CP} \equiv \frac{\int |\mathcal{A}|^2 dp - \int |\overline{\mathcal{A}}|^2 dp}{\int |\mathcal{A}|^2 dp + \int |\overline{\mathcal{A}}|^2 dp} = \mathrm{Im}\left(\frac{-2\Delta}{\Sigma}\right) I_p\,, \quad I_p = \frac{\int \mathrm{Im}\left(A_\Sigma^* A_\Delta\right) dp}{\int |A_\Sigma|^2 dp}\,.$$

Promoting pointwise to integrated sum rules

- When can we promote a sum rule for
  - pointwise CP asymmetries a_{CP}
  - to a sum rule between CP asymmetries of integrated rates A_{CP}?
- It is necessary that $|I_p|$ agrees for the involved CP asymmetries.
- Check: For two-body meson decays trivially $A_{CP} = a_{CP}$, as it must be.
- No complication from indirect CP violation for baryon decay.

Integrated CP asymmetry sum rules

[Grossman Schacht 1811.11188]

- Clearly, criterion fulfilled by all three pairs of pointwise sum rules.

All of the pointwise sum rules can be promoted to integrated ones

$$A_{CP}(\Lambda_c^+ \to pK^-K^+) + A_{CP}(\Xi_c^+ \to \Sigma^+\pi^-\pi^+) = 0$$

$$A_{CP}(\Lambda_c^+ \to \Sigma^+\pi^-K^+) + A_{CP}(\Xi_c^+ \to pK^-\pi^+) = 0$$

$$A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+) + A_{CP}(\Xi_c^+ \to \Sigma^+K^-K^+) = 0$$

- No U-spin sum rule for $A_{CP}(\Lambda_c^+ \to pK^-K^+)$ and $A_{CP}(\Lambda_c^+ \to p\pi^-\pi^+)$ whose difference recently has been measured by LHCb.

Corrections from U-spin breaking

- $m_d \neq m_s \Rightarrow$ triplet spurion operator.
- Perturbation theory: tensor product with unperturbed Hamiltonian

$$(1,0) \otimes (1,0) = \sqrt{\frac{2}{3}}(2,0) - \sqrt{\frac{1}{3}}(0,0)\,.$$

- Implications for meson decays *e.g.* [Brod Grossman Kagan Zupan 2012, Feldmann Nandi Soni 2012, Jung Mannel 2009, Fleischer Jaarsma Vos 2016]

- No U-spin amplitude sum rules valid at this order. [Grossman Schacht 1811.11188]
- Not even pointwise CP asymmetry sum rules, not to mention integrated ones.

➥ All the sum rules are expected to get corrections of $\mathcal{O}(30\%)$

[Brod Grossman Kagan Zupan 2012, Hiller Jung Schacht 2012, Müller Nierste Schacht 2015]