Direct CP-violation in charmed meson decays

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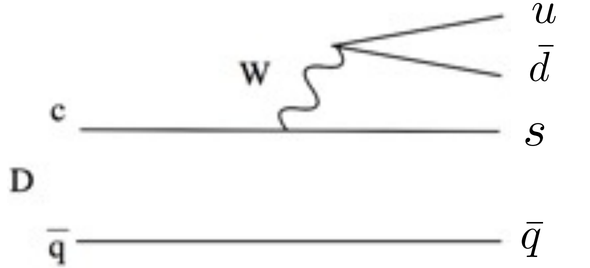
Nonleptonic charm quark decay

★ Can be classified by SM CKM suppression

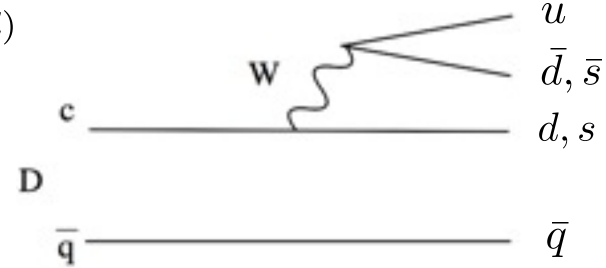
$V_{cs}V_{ud}^*$



★ Cabibbo-favored (CF) decay

- originates from $c \to s u\bar{d}$
- examples: $D^0 \to K^-\pi^+$

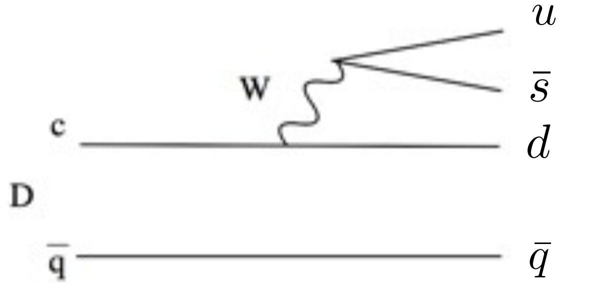
$V_{cs(d)}V_{us(d)}^*$



★ Singly Cabibbo-suppressed (SCS) decay

- originates from $c \to q u\bar{q}$
- examples: $D^0 \to \pi\pi$ and $D^0 \to KK$

$V_{cd}V_{us}^*$



★ Doubly Cabibbo-suppressed (DCS) decay

- originates from $c \to d u\bar{s}$
- examples: $D^0 \to K^+\pi^-$

Direct CP-violation (charged D's)

★ At least two components of the transition amplitude are required

Look at charged D's (SCS): $A\left(D^{+} \rightarrow f\right) \equiv A_{f} = \left|A_{1}\right| e^{i\delta_{1}} e^{i\phi_{1}} + \left|A_{2}\right| e^{i\delta_{2}} e^{i\phi_{2}}$

Then, a charge asymmetry will provide a CP-violating observable

$$a_{f} = \frac{\Gamma\left(D^{+} \rightarrow f\right) - \Gamma\left(D^{-} \rightarrow \overline{f}\right)}{\Gamma\left(D^{+} \rightarrow f\right) + \Gamma\left(D^{-} \rightarrow \overline{f}\right)} = \frac{2\,\mathrm{Im}\, A_{1}A_{2}^{*} \sin\left(\delta_{1} - \delta_{2}\right)}{\left|A_{1}\right|^{2} + \left|A_{2}\right|^{2} + 2\,\mathrm{Re}\, A_{1}A_{2}^{*} \cos\left(\delta_{1} - \delta_{2}\right)}$$

...or, introducing $r_f = |A_2/A_1|$: $a_{f} = 2 r_{f} \sin\phi \sin\delta$

Prediction sensitive to details of hadronic model ($\delta = \delta_1 - \delta_2$)

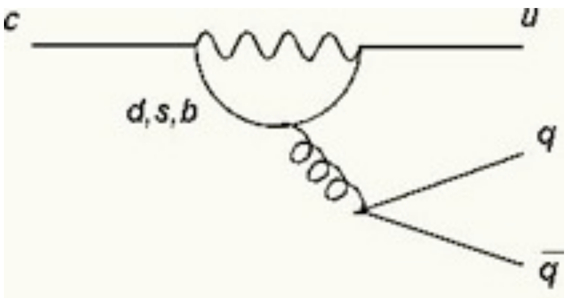
★ Same formalism applies if one of the amplitudes is generated by New Physics

- need $r_f \sim 1$ % for O(1%) charge asymmetry assuming that sin δ~1
- need to efficiently detect neutrals (not good for LHCb)

A comment

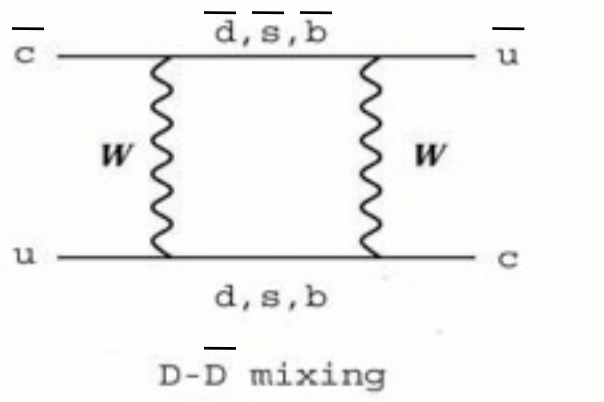
★ Generic expectation is that CP-violating observables in the SM are small

$\Delta c = 1$ amplitudes



Penguin amplitude

$\Delta c = 2$ amplitudes



★ The Unitarity Triangle for charm:

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim \lambda \qquad \sim \lambda \qquad \sim \lambda^5$$

With b-quark contribution neglected: only **2** generations contribute
$\Rightarrow$ **real 2x2 Cabibbo matrix**

Any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$

Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

Direct CP-violation (neutral D's)

★ Consider partial decay rate asymmetries for neutral decays

$$a_f = \frac{\Gamma(D\to f) - \Gamma(\overline{D}\to \overline{f})}{\Gamma(D\to f) + \Gamma(\overline{D}\to \overline{f})} \quad \text{and} \quad a_{\overline{f}} = \frac{\Gamma(D\to \overline{f}) - \Gamma(\overline{D}\to f)}{\Gamma(D\to \overline{f}) + \Gamma(\overline{D}\to f)}$$

★ Each of those asymmetries can be expanded as

$$a_f = a_f^d + a_f^m + a_f^i$$

direct mixing interference

$$a_f^d = 2 r_f \sin\phi_f \sin\delta_f$$

$$a_f^m = -R_f \frac{y'_f}{2}\left(R_m - R_m^{-1}\right)\cos\phi$$

$$a_f^i = R_f \frac{x'_f}{2}\left(R_m + R_m^{-1}\right)\sin\phi$$

Y. Grossman, A. Kagan, Y. Nir, Phys Rev D 75, 036008, 2007

1. similar formulas available for $\overline{f}$
2. for CP-eigenstates: $f=\overline{f}$, $R_f \to \eta_{CP}$, and $y_f' \to y$

Those observables are of the <u>first</u> order in CPV parameters

→ - need to separate a_{cp} in mixing from direct a_{cp}

LHCb/CDF analyses: idea

★ IDEA: consider the DIFFERENCE of decay rate asymmetries: $D \to \pi\pi$ vs $D \to KK$

D^0: no neutrals in the final state!

$$a_f = a_f^d + a_f^m + a_f^i$$

direct mixing interference

★ A reason: $a^m_{KK}=a^m_{\pi\pi}$ and $a^i_{KK}=a^i_{\pi\pi}$, so, ideally, mixing asymmetries cancel...

$$a_f^d = 2r_f \sin\phi_f \sin\delta_f$$

★ ... and the resulting DCPV asymmetry is $\Delta a_{CP} = a^d_{KK} - a^d_{\pi\pi} \approx 2a^d_{KK}$

$$A_{KK} = \frac{G_F}{\sqrt{2}}\lambda\left[(T+E+P_{sd}) + a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

$$A_{\pi\pi} = \frac{G_F}{\sqrt{2}}\lambda\left[(-(T+E)+P_{sd}) + a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

★ ... so it is doubled in the limit of $SU(3)_F$ symmetry

SU(3) is badly broken in D-decays

LHCb/CDF analyses: theory

★ Since we are comparing D^0 and anti-D^0: need to tag the flavor at production

$$D^{*+} \to D^0 \pi_s^+$$

"D*-trick" -- tag the charge of the slow pion

★ The difference Δa_{CP} is also preferable experimentally, as

$$a_f^{\rm raw} = a_f^{CP} + a_f^{\rm detect,\ D} + a_D^{\rm detect,\ \pi_s} + a_{D*}^{\rm prod}$$

- a_f^{CP}: physics
- $a_f^{\rm detect,\ D}$: detection asymmetry of D^0
- $a_D^{\rm detect,\ \pi_s}$: detection asymmetry of soft pion
- $a_{D*}^{\rm prod}$: production asymmetry of D^{*+}

★ D* production asymmetry and soft pion asymmetries are the same for KK and ππ final states-- they cancel in Δa_{CP}!

★ Also: no D^0 detection asymmetry for KK and ππ final states

``Theoretically," the difference is robust against systematic errors

LHCb needs to check that!
CDF did a careful analysis?

LHCb/CDF analyses: experiment

★ Let's expand time-dependent decay rates in (x, y) and form CP-asymmetry

$$a_{CP}(f;t) \approx a_f^d + \frac{t}{\tau} a_f^{ind}$$

where

$$a_f^d = a_{CP}(f; t=0) = \frac{\Gamma(D^0 \to f^+ f^-) - \Gamma(\bar{D}^0 \to f^+ f^-)}{\Gamma(D^0 \to f^+ f^-) + \Gamma(\bar{D}^0 \to f^+ f^-)}$$

$$a_f^{ind} = \frac{1}{2}\left[y \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right| \right) \cos\phi - x \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right| \right) \sin\phi \right]$$

★ Now, if we integrate over time,

$$a_{CP,\ f} = \int_0^\infty a_{CP}(f;t) D(t) dt = a_f^d + \frac{\langle t \rangle}{\tau} a_f^{ind}$$

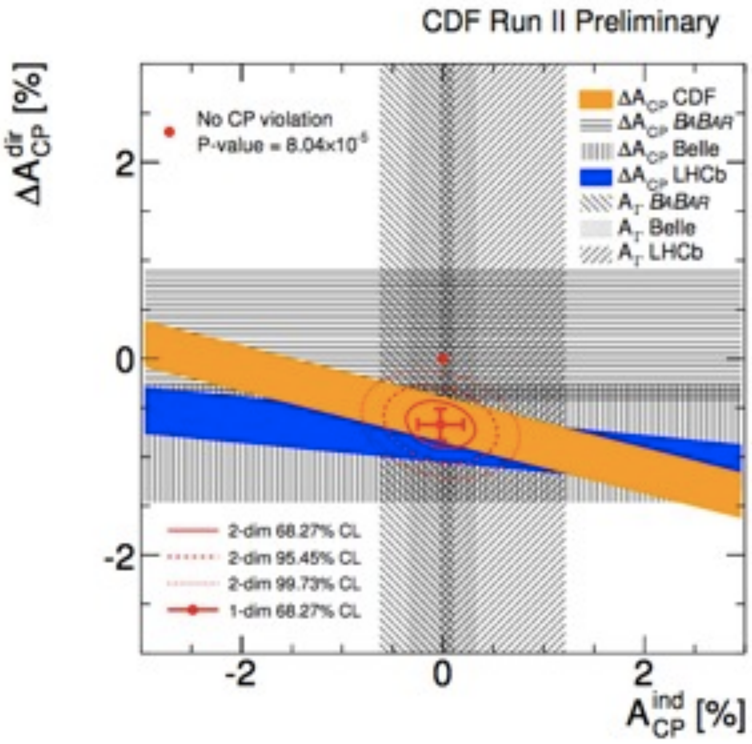
distribution of proper decay time

Not quite "clean" direct CP-violating asymmetry, but close

LHCb/CDF analyses: experiment

★ Now form the difference of CP-asymmetries: $\Delta a_{CP} = a_{CP,KK} - a_{CP,\pi\pi}$

★ ...estimate the indirect CPV contribution... $\frac{\Delta \langle t \rangle}{\tau} = \frac{\langle t_{KK} \rangle}{\tau} - \frac{\langle t_{\pi\pi} \rangle}{\tau} = (9.8 \pm 0.9)\%$



★ ... and report the results:

LHCb: $\Delta a_{CP} = (-0.82 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (sys)})\%$

CDF : $\Delta a_{CP} = (-0.46 \pm 0.31 \text{ (stat)} \pm 0.12 \text{ (sys)})\%$

Belle: $\Delta a_{CP} = (-0.86 \pm 0.62 \text{ (comb; mine)})\%$

★ along with a "new" result:

2.7 sigma away from No CP!

$$\Delta A_{CP} = (-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{sys}))\%$$

CDF Public Note 10784

It looks like CP is broken in charm transitions! Now what?

Is it Standard Model or New Physics??

★ Honestly, we don't yet know...

★ one can fit the data (no prediction) to get constraints on P...

Bhattacharya, Gronau, Rosner; Isidori, Kamenik, Ligeti, Perez; Brod, Kagan, Zupan ...

★ ...or one can attempt a combined approach: QCD factorization plus global fit

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★ Let's consider CF, SCS and DCS amplitudes together

$$\mathcal{H}_{CF} = \frac{G_F}{\sqrt{2}} V_{ud} V_{cs}^* \left[C_1(\mu)\mathcal{O}_1 + C_2(\mu)\mathcal{O}_2\right] + \text{h.c},$$

$$\mathcal{O}_1 = (\bar{s}_i \Gamma_\mu c_i)(\bar{u}_k \Gamma^\mu d_k), \qquad \widetilde{\mathcal{O}}_1 = (\bar{s}\Gamma_\mu \frac{\lambda^a}{2} c)(\bar{u}\Gamma^\mu \frac{\lambda^a}{2} d),$$

$$\mathcal{O}_2 = (\bar{s}_i \Gamma_\mu c_k)(\bar{u}_k \Gamma^\mu d_i), \qquad \widetilde{\mathcal{O}}_2 = (\bar{s}\Gamma_\mu \frac{\lambda^a}{2} d)(\bar{u}\Gamma^\mu \frac{\lambda^a}{2} c).$$

$$\mathcal{H}_{CS} = \frac{G_F}{\sqrt{2}} \sum_{q=s,d} V_{uq} V_{cq}^* \left[C_1(\mu)\mathcal{O}_1^q + C_2(\mu)\mathcal{O}_2^q\right]$$

$$- \frac{G_F}{\sqrt{2}} V_{ub} V_{cb}^* \sum_{n=3}^{6} C_n(\mu)\mathcal{O} + \text{h.c},$$

$$\mathcal{O}_1 = (\bar{q}_i \Gamma_\mu c_i)(\bar{u}_k \Gamma^\mu q_k),$$

$$\mathcal{O}_2 = (\bar{q}_i \Gamma_\mu c_k)(\bar{u}_k \Gamma^\mu q_i),$$

Theoretical framework

★ Factorizing decay amplitudes, e.g.

$$\langle P_1, P_2 | H_w | D \rangle = \left(C_1 + \frac{C_2}{3}\right) \langle P_1 | \bar{q}_1 \Gamma_\mu q_2 | 0 \rangle \langle P_2 | \bar{q}_3 \Gamma^\mu c | D \rangle + 2C_2 \langle P_1, P_2 | \bar{q}_1 \Gamma_\mu \frac{\lambda^a}{2} q_2 \bar{q}_3 \Gamma^\mu \frac{\lambda^a}{2} c | D \rangle$$

★ If you are lucky: B-physics (QCD factorization)

$$\langle \pi(p')\pi(q) | Q_i | \bar{B}(p) \rangle = f^{B\to\pi}(q^2) \int_0^1 dx\, T_i^I(x) \Phi_\pi(x) + \int_0^1 d\xi dx dy\, T_i^{II}(\xi, x, y) \Phi_B(\xi) \Phi_\pi(x) \Phi_\pi(y),$$

← **perturbative!**

★ Gluon exchanges with spectators are not perturbative in D-decays

- calculate tree/color suppressed factorizable amplitudes
- treat remaining non-factorizable amplitudes as parameters and fit

$$r e^{i\delta_r} = \frac{\langle P_1 P_2 | \widetilde{O}_{1,2} | D \rangle}{\langle P_1 P_2 | O_{1,2} | D \rangle}$$

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Combined fit: CF/DCS amplitudes

★ CF amplitudes:

$$A(D^+ \to \bar{K}^0 \pi^+) = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^* \left[t_{\pi K}^{\rm fact} \left(a_1 + 2C_2 \ r e^{i\delta_r} \right) + t_{K\pi}^{\rm fact} \left(a_2 + 2C_1 \ r e^{i\delta_r} \right) \right]$$

$$A(D^0 \to K^- \pi^+) = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^* \left[t_{\pi K}^{\rm fact} \left(a_1 + 2C_2 \ r e^{i\delta_r} \right) + 2C_1 E e^{i\delta_E} \right]$$

$$A(D_s \to \bar{K}^0 K^+) = \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^* \left[t_{KK}^{\rm fact} \left(a_2 + 2C_1 \ r e^{i\delta_r} \right) + 2C_2 E e^{i\delta_E} \right]$$

★ DCS amplitudes:

$$A(D^0 \to \pi^- K^+) = \frac{G_F}{\sqrt{2}} V_{cd} V_{us}^* \left[t_{K\pi}^{\rm fact} \left(a_1 + 2C_2 \ r e^{i\delta_r} \right) + 2C_1 E e^{i\delta_E} \right]$$

$$A(D^+ \to \pi^0 K^+) = \frac{G_F}{2} V_{cd} V_{us}^* \left[t_{K\pi}^{\rm fact} \left(a_1 + 2C_2 \ r e^{i\delta_r} \right) - 2C_2 E e^{i\delta_E} \right]$$

★ Only four parameters to fit ($a_1=c_1+C_2/3$, $a_2=c_2+C_1/3$)

- calculate tree/color suppressed amplitudes
- assume SU(3) flavor symmetry for E and δ_E
- assume SU(3) flavor symmetry for r and δ_r

$$r e^{i\delta_r} = \frac{\langle P_1 P_2 | \widetilde{O}_{1,2} | D \rangle}{\langle P_1 P_2 | O_{1,2} | D \rangle}$$

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Combined fit: SCS amplitudes

★ Analysis of SCS amplitudes is considerably more complicated

- calculate tree/color suppressed amplitudes
- utilize r and δ_r from CF/DCS analysis...
- ... but not E and δ_E (as it is topologically equivalent to "penguin annihilation")
- can drop SM "penguin operator" contribution (small Wilson coefficient)...
- ... but contributions from penguin-like contractions with s and d-quarks are big!

★ Use the fit from CF/DCS decays

- r = 0.25, δ_r = 1.78, E = -0.02 GeV, and δ_E =-0.17
- ... for r and δ_r
- refit for other amplitudes, e.g.,

$$A_{KK} = \frac{G_F}{\sqrt{2}}\lambda\left[(T+\overline{E}+P_{sd})+a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

$$A_{\pi\pi} = \frac{G_F}{\sqrt{2}}\lambda\left[(-(T+\overline{E})+P_{sd})+a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

$P_{ss}-P_{dd}$ $\quad$ $P_{bb}-P_{dd}$

★ Work in progress to fit all amplitudes and predict other CPVAs

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Conclusions

- Charm provides great opportunities for New Physics studies
  - unique access to up-type quark sector
- Observation of CP-violation in the current round of experiments provides further handle for studies of New Physics
  - Different observables should be used to disentangle CP-violating contributions to $\Delta c=1$ and $\Delta c=2$ amplitudes
  - Conservatively, current results can be ascribed to SM...
  - ... but global fit differs significantly from B-decays
  - The smoke from the smoking gun is quickly dissipating...

Additional slides

CP-violation in charmed baryons

- Other observables can be constructed for baryons, e.g.

$$A(\Lambda_c \to N\pi) = \bar{u}_N(p,s)\left[A_S + A_P\gamma_5\right]u_{\Lambda_c}(p_\Lambda, s_\Lambda)$$

These amplitudes can be related to "asymmetry parameter" $\alpha_{\Lambda_c} = \dfrac{2\,\mathrm{Re}\left(A_S^* A_P\right)}{\left|A_S\right|^2 + \left|A_P\right|^2}$

… which can be extracted from $\dfrac{dW}{d\cos\vartheta} = \dfrac{1}{2}\left(1 + P\alpha_{\Lambda_c}\cos\vartheta\right)$

Same is true for $\overline{\Lambda}_c$-decay

If CP is conserved $\alpha_{\Lambda_c} \overset{CP}{\Rightarrow} -\bar{\alpha}_{\Lambda_c}$, thus CP-violating observable is

$$A_f = \frac{\alpha_{\Lambda_c} + \overline{\alpha}_{\Lambda_c}}{\alpha_{\Lambda_c} - \overline{\alpha}_{\Lambda_c}}$$

FOCUS[2006]: $A_{\Lambda\pi}$=-0.07±0.19±0.24