SU(3)$_F$ in nonleptonic Charm Decays

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Can we distinguish new physics in D decays from the Standard Model?

Large direct CP violation in Charm Decays (?!)

Post Moriond 2013: [HFAG 2013, LHCb 2013, Belle 2012, CDF 2012, BaBar 2008]

$$\Delta a_{\mathrm{CP}}^{\mathrm{dir}} = a_{\mathrm{CP}}^{\mathrm{dir}}(D^0 \to K^+K^-) - a_{\mathrm{CP}}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = -0.00329 \pm 0.00121 \quad (2.7\sigma)$$

SM contribution is suppressed. Naive expectation: $\Delta a_{\mathrm{CP}}^{\mathrm{dir}} \lesssim \mathcal{O}(0.001)$

- CKM and QCD factor: $\Delta a_{\mathrm{CP}}^{\mathrm{dir}} \simeq \lambda^4 \cdot P/T \sim 10^{-3} \cdot 0.1$ (?)
- Problem: $\alpha_s(m_c)$ large and expansion in $\Lambda_{\mathrm{QCD}}/m_c$ doubtful.

Data for $D \to PP$

from LHCb, CDF, Belle, BABAR, CLEO and FOCUS

Red: Post Moriond 2013 Update

Observable	Measurement
SCS CP asymmetries	
$\Delta a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-)$	-0.00329 ± 0.00121
$\Sigma a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-)$	$+0.0014 \pm 0.0039$
$A_{CP}(D^0 \to K_S K_S)$	-0.23 ± 0.19
$A_{CP}(D^0 \to \pi^0\pi^0)$	$+0.001 \pm 0.048$
$A_{CP}(D^+ \to \pi^0\pi^+)$	$+0.029 \pm 0.029$
$A_{CP}(D^+ \to K_S K^+)$	-0.0011 ± 0.0025
$A_{CP}(D_s \to K_S\pi^+)$	$+0.012 \pm 0.007$
$A_{CP}(D_s \to K^+\pi^0)$	$+0.266 \pm 0.228$
Indirect CP violation	
a_{CP}^{ind}	$(-0.010 \pm 0.162) \cdot 10^{-2}$
$\delta_L \equiv 2\text{Re}(\varepsilon)/(1 + \lvert\varepsilon\rvert^2)$	$(3.32 \pm 0.06) \cdot 10^{-3}$
$K^+\pi^-$ strong phase difference	
$\delta_{K\pi}$	$18.25^\circ \pm 9.85^\circ$

Observable	Measurement
SCS branching ratios	
$\mathcal{B}(D^0 \to K^+K^-)$	$(3.96 \pm 0.08) \cdot 10^{-3}$
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	$(1.401 \pm 0.027) \cdot 10^{-3}$
$\mathcal{B}(D^0 \to K_S K_S)$	$(0.17 \pm 0.04) \cdot 10^{-3}$
$\mathcal{B}(D^0 \to \pi^0\pi^0)$	$(0.80 \pm 0.05) \cdot 10^{-3}$
$\mathcal{B}(D^+ \to \pi^0\pi^+)$	$(1.19 \pm 0.06) \cdot 10^{-3}$
$\mathcal{B}(D^+ \to K_S K^+)$	$(2.83 \pm 0.16) \cdot 10^{-3}$
$\mathcal{B}(D_s \to K_S\pi^+)$	$(1.21 \pm 0.08) \cdot 10^{-3}$
$\mathcal{B}(D_s \to K^+\pi^0)$	$(0.62 \pm 0.21) \cdot 10^{-3}$
CF branching ratios	
$\mathcal{B}(D^0 \to K^-\pi^+)$	$(3.88 \pm 0.05) \cdot 10^{-2}$
$\mathcal{B}(D^0 \to K_S\pi^0)$	$(1.19 \pm 0.04) \cdot 10^{-2}$
$\mathcal{B}(D^0 \to K_L\pi^0)$	$(1.00 \pm 0.07) \cdot 10^{-2}$
$\mathcal{B}(D^+ \to K_S\pi^+)$	$(1.47 \pm 0.07) \cdot 10^{-2}$
$\mathcal{B}(D^+ \to K_L\pi^+)$	$(1.46 \pm 0.05) \cdot 10^{-2}$
$\mathcal{B}(D_s \to K_S K^+)$	$(1.45 \pm 0.05) \cdot 10^{-2}$
DCS branching ratios	
$\mathcal{B}(D^0 \to K^+\pi^-)$	$(1.47 \pm 0.07) \cdot 10^{-4}$
$\mathcal{B}(D^+ \to K^+\pi^0)$	$(1.83 \pm 0.26) \cdot 10^{-4}$

$\Rightarrow 8 \times a_{CP}^{\text{dir}}$, $16 \times \mathcal{B}$, $1\times$ strong phase = **25 observables**

Symmetry Emergency Kit

We do not know **how to reliably calculate**
the **hadronic matrix elements** $\langle f | O_j | i \rangle$ for charm.

↳What is the best we can do instead?

1. $SU(3)_F$ ⇒ Relate several decay amplitudes of $D \to PP$.
2. **Comprehensive** Fit of $D \to P_8 P_8$ data: 25 observables.

Approximate SU(3)$_F$ Symmetry of QCD

States and operators = representations of SU(3)$_F$

States

- $\left(D^0 = -|c\bar{u}\rangle\,, \quad D^+ = \left|c\bar{d}\right\rangle, \quad D_s = |c\bar{s}\rangle\right) = \bar{\mathbf{3}}$
- Pions and Kaons: $[(\mathbf{8}) \otimes (\mathbf{8})]_S = (\mathbf{1}) \oplus (\mathbf{8}) \oplus (\mathbf{27})$

Operators

$$\mathcal{H}_{\text{eff}} \sim \underbrace{V_{ud}V_{cs}^*\,(\bar{u}d)\,(\bar{s}c)}_{\text{CA}} + \underbrace{V_{us}V_{cs}^*\,(\bar{u}s)\,(\bar{s}c) + V_{ud}V_{cd}^*\,(\bar{u}d)\left(\bar{d}c\right)}_{\text{SCS}} + \underbrace{V_{us}V_{cd}^*\,(\bar{u}s)\left(\bar{d}c\right)}_{\text{DCS}}$$

$$\mathcal{H}_{\text{eff}}^{\text{SCS}} \sim \underbrace{V_{us}V_{cs}^*\left(\mathbf{15} + \bar{\mathbf{6}}\right)}_{\text{CKM leading}} + \underbrace{V_{ub}V_{cb}^*\,(\mathbf{15} + \mathbf{3})}_{\text{CKM suppressed, CPV}}$$

Perturbation from $\mathcal{H}_{\text{break}} \sim m_s\, \bar{s}\, s \propto \mathbf{1} \oplus \mathbf{8}$

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

Decay d	$B_1^{3_1}$	$B_1^{3_2}$	$B_8^{3_1}$	$B_8^{3_2}$	$B_8^{\bar{6}_1}$	$B_8^{\bar{6}_2}$	$B_8^{15_1}$	$B_8^{15_2}$	$B_8^{15_3}$	$B_{27}^{15_1}$	$B_{27}^{15_2}$	$B_{27}^{15_3}$	$B_{27}^{24_1}$	$B_{27}^{24_2}$	B_{27}^{42}
SCS															
$D^0 \to K^+K^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$\frac{1}{10}$	$-\frac{1}{10\sqrt{2}}$	$-\frac{7}{10\sqrt{122}}$	$\frac{\sqrt{\frac{3}{122}}}{5}$	$-\frac{1}{20}$	$-\frac{31}{20\sqrt{122}}$	$-\frac{17}{20\sqrt{366}}$	$\frac{7}{40}$	$-\frac{1}{10\sqrt{6}}$	$\frac{1}{10\sqrt{2}}$	$-\frac{13}{20\sqrt{42}}$
$D^0 \to \pi^+\pi^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$-\frac{1}{10}$	$\frac{1}{10\sqrt{2}}$	$-\frac{11}{10\sqrt{122}}$	$-\frac{2\sqrt{\frac{2}{183}}}{5}$	$\frac{3}{20}$	$-\frac{23}{20\sqrt{122}}$	$\frac{11}{20\sqrt{366}}$	$-\frac{1}{40}$	$\frac{1}{10\sqrt{6}}$	$-\frac{1}{10\sqrt{2}}$	$\frac{\sqrt{\frac{7}{6}}}{20}$
$D^0 \to \bar{K}^0K^0$	$-\frac{1}{4\sqrt{10}}$	$-\frac{1}{8}$	$\frac{1}{5\sqrt{2}}$	$\frac{1}{2\sqrt{5}}$	0	0	$-\frac{9}{5\sqrt{122}}$	$-\frac{1}{5\sqrt{366}}$	$\frac{1}{10}$	$-\frac{9}{20\sqrt{122}}$	$-\frac{1}{20\sqrt{366}}$	$\frac{1}{40}$	$-\frac{1}{2\sqrt{6}}$	$-\frac{1}{2\sqrt{2}}$	$\frac{19}{20\sqrt{42}}$
$D^0 \to \pi^0\pi^0$	$-\frac{1}{8\sqrt{5}}$	$-\frac{1}{8\sqrt{2}}$	$-\frac{1}{20}$	$-\frac{1}{4\sqrt{10}}$	$\frac{1}{10\sqrt{2}}$	$-\frac{1}{20}$	$\frac{11}{20\sqrt{61}}$	$\frac{2}{5\sqrt{183}}$	$-\frac{3}{20\sqrt{2}}$	$-\frac{57}{40\sqrt{61}}$	$\frac{7}{20\sqrt{183}}$	$\frac{1}{40\sqrt{2}}$	$\frac{1}{5\sqrt{3}}$	$\frac{1}{20}$	$-\frac{1}{20\sqrt{21}}$
$D^+ \to \pi^0\pi^+$	0	0	0	0	0	0	0	0	0	$-\frac{2(1-\bar{\Delta})}{\sqrt{61}}$	$\frac{5(1-\bar{\Delta})}{8\sqrt{183}}$	0	$\frac{1-\bar{\Delta}}{4\sqrt{3}}$	0	$\frac{1-\bar{\Delta}}{8\sqrt{21}}$
$D^+ \to \bar{K}^0K^+$	0	0	$\frac{3}{10\sqrt{2}}$	$\frac{3}{4\sqrt{5}}$	$\frac{1}{10}$	$-\frac{1}{10\sqrt{2}}$	$\frac{7}{10\sqrt{122}}$	$-\frac{\sqrt{\frac{3}{122}}}{5}$	$\frac{1}{20}$	$-\frac{3\sqrt{\frac{2}{61}}}{5}$	$-\frac{23}{20\sqrt{366}}$	$\frac{1}{5}$	$-\frac{1}{10\sqrt{6}}$	$-\frac{\sqrt{2}}{5}$	$-\frac{19}{20\sqrt{42}}$
$D_s \to K^0\pi^+$	0	0	$\frac{3}{10\sqrt{2}}$	$\frac{3}{4\sqrt{5}}$	$-\frac{1}{10}$	$\frac{1}{10\sqrt{2}}$	$\frac{11}{10\sqrt{122}}$	$\frac{2\sqrt{\frac{2}{183}}}{5}$	$-\frac{3}{20}$	$-\frac{3}{5\sqrt{122}}$	$\frac{19}{20\sqrt{366}}$	$-\frac{1}{10}$	$-\frac{\sqrt{\frac{2}{3}}}{5}$	$-\frac{1}{10\sqrt{2}}$	$-\frac{19}{20\sqrt{42}}$
$D_s \to K^+\pi^0$	0	0	$-\frac{3}{20}$	$-\frac{3}{4\sqrt{10}}$	$\frac{1}{10\sqrt{2}}$	$-\frac{1}{20}$	$-\frac{11}{20\sqrt{61}}$	$-\frac{2}{5\sqrt{183}}$	$\frac{3}{20\sqrt{2}}$	$-\frac{17}{10\sqrt{61}}$	$\frac{\sqrt{\frac{3}{61}}}{20}$	$\frac{1}{10\sqrt{2}}$	$-\frac{\sqrt{3}}{10}$	$\frac{1}{20}$	$-\frac{\sqrt{\frac{3}{7}}}{20}$
CF															
$D^0 \to K^-\pi^+$	0	0	0	0	$\frac{1}{5}$	$\frac{1}{5\sqrt{2}}$	$-\frac{\sqrt{\frac{2}{61}}}{5}$	$-\frac{7}{5\sqrt{366}}$	$-\frac{1}{5}$	$\frac{\sqrt{\frac{2}{61}}}{5}$	$\frac{7}{5\sqrt{366}}$	$\frac{1}{5}$	$\frac{1}{20\sqrt{6}}$	$\frac{1}{20\sqrt{2}}$	$-\frac{1}{2\sqrt{42}}$
$D^0 \to \bar{K}^0\pi^0$	0	0	0	0	$-\frac{1}{5\sqrt{2}}$	$-\frac{1}{10}$	$\frac{1}{5\sqrt{61}}$	$\frac{7}{10\sqrt{183}}$	$\frac{1}{5\sqrt{2}}$	$\frac{3}{10\sqrt{61}}$	$\frac{7\sqrt{\frac{3}{61}}}{20}$	$\frac{3}{10\sqrt{2}}$	$-\frac{\sqrt{3}}{20}$	$-\frac{3}{20}$	0
$D^+ \to \bar{K}^0\pi^+$	0	0	0	0	0	0	0	0	0	$\frac{1}{\sqrt{122}}$	$\frac{7}{2\sqrt{366}}$	$\frac{1}{2}$	$-\frac{1}{4\sqrt{6}}$	$-\frac{1}{4\sqrt{2}}$	$-\frac{1}{2\sqrt{42}}$
$D_s \to \bar{K}^0K^+$	0	0	0	0	$-\frac{1}{5}$	$-\frac{1}{5\sqrt{2}}$	$-\frac{\sqrt{\frac{2}{61}}}{5}$	$-\frac{7}{5\sqrt{366}}$	$-\frac{1}{5}$	$\frac{\sqrt{\frac{2}{61}}}{5}$	$\frac{7}{5\sqrt{366}}$	$\frac{1}{5}$	$\frac{1}{5\sqrt{6}}$	$\frac{1}{5\sqrt{2}}$	$\frac{1}{\sqrt{42}}$
DCS															
$D^0 \to K^+\pi^-$	0	0	0	0	0	$-\frac{\sqrt{2}}{5}$	$\frac{2\sqrt{\frac{2}{61}}}{5}$	$\frac{7\sqrt{\frac{2}{183}}}{5}$	0	$-\frac{2\sqrt{\frac{2}{61}}}{5}$	$-\frac{7\sqrt{\frac{2}{183}}}{5}$	0	$-\frac{1}{4\sqrt{6}}$	$\frac{3}{20\sqrt{2}}$	$-\frac{1}{2\sqrt{42}}$
$D^0 \to K^0\pi^0$	0	0	0	0	0	$\frac{1}{5}$	$-\frac{2}{5\sqrt{61}}$	$-\frac{7}{5\sqrt{183}}$	0	$-\frac{3}{5\sqrt{61}}$	$-\frac{7\sqrt{\frac{3}{61}}}{10}$	0	$-\frac{\sqrt{3}}{8}$	$-\frac{3}{40}$	0
$D^+ \to K^0\pi^+$	0	0	0	0	0	$\frac{\sqrt{2}}{5}$	$\frac{2\sqrt{\frac{2}{61}}}{5}$	$\frac{7\sqrt{\frac{2}{183}}}{5}$	0	$-\frac{2\sqrt{\frac{2}{61}}}{5}$	$-\frac{7\sqrt{\frac{2}{183}}}{5}$	0	$-\frac{1}{4\sqrt{6}}$	$-\frac{3}{20\sqrt{2}}$	$-\frac{1}{2\sqrt{42}}$
$D^+ \to K^+\pi^0$	0	0	0	0	0	$-\frac{1}{5}$	$-\frac{2}{5\sqrt{61}}$	$-\frac{7}{5\sqrt{183}}$	0	$-\frac{3}{5\sqrt{61}}$	$-\frac{7\sqrt{\frac{3}{61}}}{10}$	0	$-\frac{\sqrt{3}}{8}$	$\frac{3}{40}$	0
$D_s \to K^0K^+$	0	0	0	0	0	0	0	0	0	$-\sqrt{\frac{2}{61}}$	$-\frac{7}{\sqrt{366}}$	0	$\frac{1}{2\sqrt{6}}$	0	$\frac{1}{\sqrt{42}}$

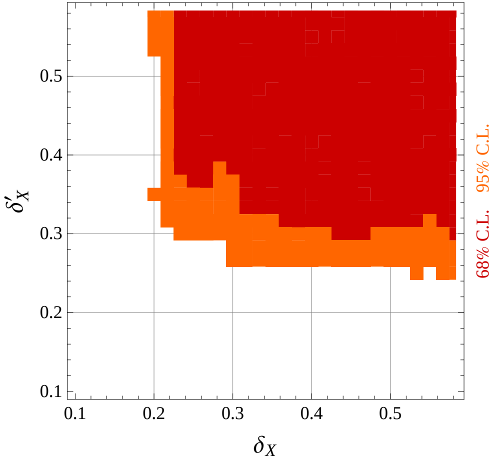
[Table: Hiller Jung StS 2012] [Previous works: Kingsley Treiman Wilczek Zee 1975, Einhorn Quigg 1975, Altarelli Cabibbo Maiani 1975, Voloshin Zakharov Okun 1975, Quigg 1980, Savage 1991, Chau Cheng 1992, Pirtskhalava Uttayarat 2011, Feldmann Nandi Soni 2012, Brod Grossman Kagan Zupan 2012, Bhattacharya Gronau Rosner 2012, Franco Mishima Silvestrini 2012, . . .]

25 observables, 13 matrix elements ⇒ **Fit**

How Large is the Breaking in $D \to PP$?

$$\delta_X \equiv \frac{\max_{ij}|B_i^j|}{\max(|A_{27}^{15}|, |A_8^{\bar{6}}|, |A_8^{15}|)}$$

$$\delta'_X \equiv \max_d \left| \frac{\mathcal{A}_X(d)}{\mathcal{A}(d)} \right|$$

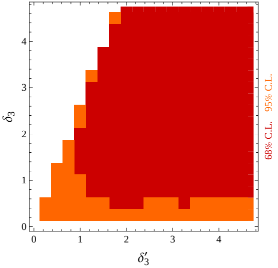


- δ_X ignores suppression by Clebsch-Gordan-coefficients.
- δ'_X ignores possible large cancellations.

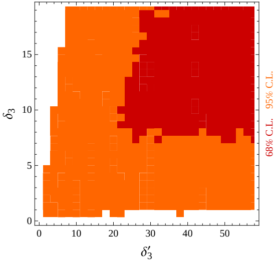
↳ Data can be described by SU(3)-expansion with $\delta_X^{(\prime)} \lesssim 30\%$. ✓

How Large are the Penguins/Triplets?

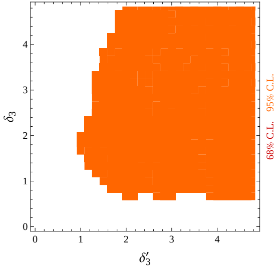
All plots: post Moriond 2013 $\Delta a_{\rm CP}^{\rm dir} \simeq \lambda^4 \cdot P/T$



without large A_{CP}



all data



all data, zoom

δ_3: max(ratios matrix elements)

δ_3': max(ratios amplitudes)

Left: Without $A_{CP}(D^0 \to K_S K_S) = -0.23 \pm 0.19$

$A_{CP}(D_s \to K_S \pi^+) = 0.012 \pm 0.007$

$A_{CP}(D_s \to K^+ \pi^0) = 0.266 \pm 0.228$

$P/T = \delta_3^{(\prime)}$

SU(3)$_F$ Analysis of Models of New Physics

SM: $\mathcal{H}_{\rm SM} \sim V_{us}V_{cs}^* \left(\mathbf{15} + \bar{\mathbf{6}}\right) + V_{ub}V_{cb}^* \left(\mathbf{15} + \mathbf{3}\right)$

Model	Operator	$\mathcal{H}_{\rm CPV}$
Triplet	$(\bar{u}c)\sum \bar{q}q,\ \bar{u}\sigma_{\mu\nu}G^{\mu\nu}c$	$\sim \mathbf{3}^{\rm NP}$
HN [Hochberg Nir 2012]	$(\bar{u}_R c_L)(\bar{u}_L u_R)$	$\sim \mathbf{15}^{\rm NP} + \mathbf{3}^{\rm NP}$
$\Delta U = 1$	$(\bar{s}_R c_L)(\bar{u}_R s_L)$	$\sim \mathbf{15}^{\rm NP} + \bar{\mathbf{6}}^{\rm NP} + \mathbf{3}^{\rm NP}$

SU(3)$_F$ prediction: $A_{CP}(D^0 \to K_S K_S)/A_{CP}(D^0 \to K^+K^-) \sim 1/\delta_X$.

Models have specific signatures.

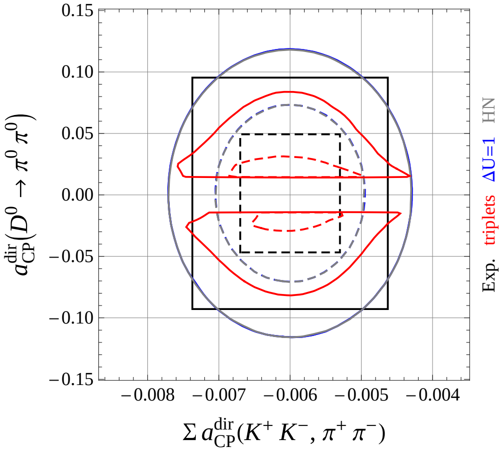
- $(\bar{s}c)(\bar{u}s)$ breaks U spin limit sum rules beyond SU(3)$_F$-X. [Hiller Jung StS 2012]

$$a_{CP}^{\rm dir}(D^0 \to K^+K^-) + a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-) \neq 0$$
$$a_{CP}^{\rm dir}(D^+ \to \bar{K}^0K^+) + a_{CP}^{\rm dir}(D_s \to K^0\pi^+) \neq 0$$

- $a_{CP}(D^+ \to \pi^+\pi^0) \neq 0 \Rightarrow \Delta I = 3/2$-NP, HN. [Grossman Kagan Zupan 2012]
- Present data: NP and SM not distinguishable.

Proof of Principle: NP Models with *Gedanken* Data

- Future scenario with significant hypothetical data.
- Prediction of sizable CPV in $D^0 \to \pi^0\pi^0$ in triplet model (including SM).
- Measurement $a_{CP}^{dir}(D^0 \to \pi^0\pi^0) = \Sigma a_{CP}^{dir}(K^+K^-, \pi^+\pi^-) = 0$ $\Rightarrow$ SM excluded.



Summary

- First comprehensive SU(3)$_F$ analysis of $D \to PP$ decay data without bias.
- Charm Physics remains suspense-packed after Moriond 2013 (!).
- Future data could differentiate new physics from the SM.
- **Key observables:**
  $A_{CP}(D^0 \to K_S K_S)$, $A_{CP}(D_s \to K^+ \pi^0)$, $A_{CP}(D^+ \to \pi^+ \pi^0)$,
  all SCS CP asymmetries.
- Exciting time for searching for New Physics !

BACK-UP

Measurements of ΔA_{CP}

2008	BaBar	$A_{CP}^{K^+K^-} = (0.00 \pm 0.34 \pm 0.13)\%$ $A_{CP}^{\pi^+\pi^-} = (0.24 \pm 0.52 \pm 0.22)\%$
2011	old LHCb result, D^*	$(-0.82 \pm 0.21 \pm 0.11)\%$
2012	Belle	$(-0.87 \pm 0.41 \pm 0.06)\%$
2012	CDF	$(-0.62 \pm 0.21 \pm 0.10)\%$
2013	LHCb, D^*	$(-0.34 \pm 0.15 \pm 0.10)\%$
2013	LHCb, $B \to D^0 \mu X$	$(0.49 \pm 0.30 \pm 0.14)\%$

Average post Moriond March 2013: [HFAG 2013]

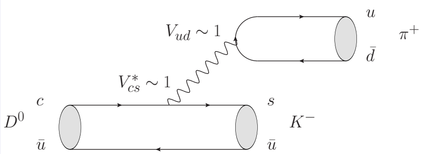
$$\Delta a_{\rm CP}^{\rm dir} = -0.00329 \pm 0.00121 \quad (2.7\sigma)$$

Average pre Moriond March 2013: [HFAG 2012]

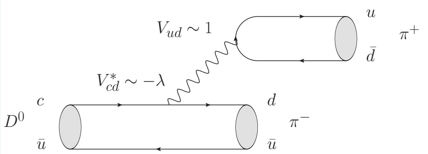
$$\Delta a_{\rm CP}^{\rm dir} = -0.00678 \pm 0.00147 \quad (4.6\sigma)$$

Classification by Cabibbo Suppression

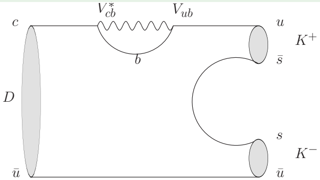
Cabibbo favored: $c \to s\bar{d}u$



Singly-Cabibbo suppressed: $c \to s\bar{s}u$ und $c \to d\bar{d}u$

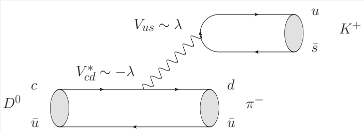


CPV $\propto V_{cb}^* V_{ub}$



+ Penguin contractions of Tree operators (!)

Doubly-Cabibbo suppressed: $c \to d\bar{s}u$



Observables vs. Degrees of Freedom

- 17 amplitudes of $\{D^0, D^+, D_s\}$ to Pions/Kaons.
  ➥ 26 observables: 17 $\mathcal{B}$, 8 SCS A_{CP}, 1 relative strong phase.
  25 measured observables ($\mathcal{B}(D_s \to K_L K^+)$ not measured)
- 3 $SU(3)$ limit MEs coming with Σ, 2 coming with Δ.
  Only relative phases $\Rightarrow$ 9 $SU(3)$ limit params. $\in \mathbb{R}$.
- Linear $SU(3)$ breaking: 15 additional MEs.
- 17×20 matrix of Clebsch-Gordan coefficients: Not full rank.
- Consider terms coming only with Δ separately for calculating the rank.
- Only 13 matrix element combinations have physical meaning.
- Redefine MEs to reduce # MEs from 20 to 13.
  Example: $B^{3_1}_{1,8} \mapsto \sqrt{\frac{7}{2}} B^{3_1}_{1,8} - \sqrt{\frac{5}{2}} B^{3_2}_{1,8}$.
- Further similar replacements found by Gaussian elimination:
  Remove $B^{\bar{6}_2}_{8}$, $B^{15_3}_{8}$, $B^{15_3}_{27}$, $B^{24_2}_{27}$ and B^{42}_{27}.

Direct and Indirect CP Violation

- CP asymmetries with final state K_S or initial state D^0 have contributions from indirect CPV.

- Get pure direct CPV by removing the mixing contributions
  - Kaon mixing: $\propto \delta_L = 2\,\mathrm{Re}\,\varepsilon / \left(1 + |\varepsilon|^2\right) = (3.32 \pm 0.06) \cdot 10^{-3}$. [PDG 2012]
  - D^0 mixing: $a_{CP}^{\mathrm{ind}} = (-0.010 \pm 0.162) \cdot 10^{-2}$. [HFAG 2013]

- Sign depends on appearing K^0 or $\bar{K}^0$ in tree level Feynman diagram.

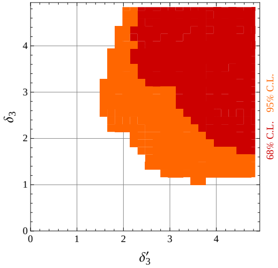
$$A_{CP}^{dir}(D^+ \to K_S K^+) = A_{CP}(D^+ \to K_S K^+) + \delta_L \qquad \text{(with } \bar{K}^0\text{)}$$

$$A_{CP}^{dir}(D_s \to K_S \pi^+) = A_{CP}(D_s \to K_S \pi^+) - \delta_L \qquad \text{(with } K^0\text{)}$$

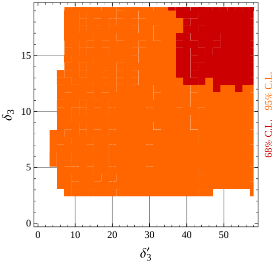
- Neglect K and D mixing in $A_{CP}(D^0 \to K_S K_S) = -0.23 \pm 0.19$.

How Large are the Penguins/Triplets?

Pre Moriond 2013



without large A_{CP}



all data

δ_3: max(ratios matrix elements)

δ'_3: max(ratios amplitudes)

Left: **Without** $A_{CP}(D^0 \to K_S K_S) = -0.23 \pm 0.19$ $\quad A_{CP}(D_s \to K_S \pi^+) = 0.031 \pm 0.015$ $\quad A_{CP}(D_s \to K^+ \pi^0) = 0.266 \pm 0.228$

$P/T = \delta_3^{(\prime)}$

Future Data

Observable	Future data
SCS CP asymmetries	
$\Delta a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-)$	-0.007 ± 0.0005
$\Sigma a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-)$	-0.006 ± 0.0007
$a_{CP}^{\text{dir}}(D^+ \to K_S K^+)$	-0.003 ± 0.0005
$a_{CP}^{\text{dir}}(D_s \to K_S \pi^+)$	0.0 ± 0.0005
$a_{CP}^{\text{dir}}(D_s \to K^+ \pi^0)$	0.05 ± 0.0005
$K^+\pi^-$ strong phase difference	
$\delta_{K\pi}$	$21.4° \pm 3.8°$

SU(3)$_F$-X Clebsch-Gordan Coefficients after Reparametrizations

Decay d	B_1^3	B_8^3	$B_8^{\bar{6}_1}$	$B_8^{15_1}$	$B_8^{15_2}$	$B_{27}^{15_1}$	$B_{27}^{15_2}$	$B_{27}^{24_1}$
SCS								
$D^0 \to K^+K^-$	$\frac{\sqrt{\frac{421}{35}}}{16}$	$\frac{\sqrt{\frac{3937}{7}}}{160}$	$\frac{\sqrt{\frac{2869}{7}}}{80}$	$-\frac{\sqrt{9316783}}{29280}$	$\frac{\sqrt{\frac{2613}{2}}}{610}$	$-\frac{31\sqrt{\frac{5281}{7}}}{4880}$	$-\frac{17\sqrt{\frac{151}{21}}}{610}$	$-\frac{1}{5\sqrt{21}}$
$D^0 \to \pi^+\pi^-$	$\frac{\sqrt{\frac{421}{35}}}{16}$	$\frac{\sqrt{\frac{3937}{7}}}{160}$	$-\frac{\sqrt{\frac{2869}{7}}}{80}$	$-\frac{11\sqrt{\frac{1330969}{7}}}{29280}$	$-\frac{\sqrt{\frac{1742}{3}}}{305}$	$-\frac{23\sqrt{\frac{5281}{7}}}{4880}$	$\frac{11\sqrt{\frac{151}{21}}}{610}$	$\frac{1}{5\sqrt{21}}$
$D^0 \to \bar{K}^0K^0$	$-\frac{\sqrt{\frac{421}{35}}}{16}$	$\frac{\sqrt{\frac{3937}{7}}}{80}$	0	$-\frac{3\sqrt{\frac{1330969}{7}}}{4880}$	$-\frac{\sqrt{\frac{871}{6}}}{610}$	$-\frac{9\sqrt{\frac{5281}{7}}}{4880}$	$-\frac{\sqrt{\frac{151}{21}}}{610}$	$-\frac{1}{\sqrt{21}}$
$D^0 \to \pi^0\pi^0$	$-\frac{\sqrt{\frac{421}{70}}}{16}$	$-\frac{\sqrt{\frac{3937}{14}}}{160}$	$\frac{\sqrt{\frac{2869}{14}}}{80}$	$\frac{11\sqrt{\frac{1330969}{14}}}{29280}$	$\frac{\sqrt{\frac{871}{3}}}{305}$	$-\frac{57\sqrt{\frac{5281}{14}}}{4880}$	$\frac{\sqrt{\frac{1057}{6}}}{305}$	$\frac{2\sqrt{\frac{2}{21}}}{5}$
$D^+ \to \pi^0\pi^+$	0	0	0	0	0	$-\frac{\sqrt{\frac{5281}{14}}(1-\tilde{\Delta})}{61}$	$\frac{5\sqrt{\frac{151}{42}}(1-\tilde{\Delta})}{122}$	$\frac{1-\tilde{\Delta}}{\sqrt{42}}$
$D^+ \to \bar{K}^0K^+$	0	$\frac{3\sqrt{\frac{3937}{7}}}{160}$	$\frac{\sqrt{\frac{2869}{7}}}{80}$	$\frac{\sqrt{9316783}}{29280}$	$-\frac{\sqrt{\frac{2613}{2}}}{610}$	$-\frac{3\sqrt{\frac{5281}{7}}}{610}$	$-\frac{23\sqrt{\frac{151}{21}}}{610}$	$-\frac{1}{5\sqrt{21}}$
$D_s \to K^0\pi^+$	0	$\frac{3\sqrt{\frac{3937}{7}}}{160}$	$-\frac{\sqrt{\frac{2869}{7}}}{80}$	$\frac{11\sqrt{\frac{1330969}{7}}}{29280}$	$\frac{\sqrt{\frac{1742}{3}}}{305}$	$-\frac{3\sqrt{\frac{5281}{7}}}{1220}$	$\frac{19\sqrt{\frac{151}{21}}}{610}$	$-\frac{4}{5\sqrt{21}}$
$D_s \to K^+\pi^0$	0	$-\frac{3\sqrt{\frac{3937}{14}}}{160}$	$\frac{\sqrt{\frac{2869}{14}}}{80}$	$-\frac{11\sqrt{\frac{1330969}{14}}}{29280}$	$-\frac{\sqrt{\frac{871}{3}}}{305}$	$-\frac{17\sqrt{\frac{5281}{14}}}{1220}$	$\frac{\sqrt{\frac{453}{14}}}{305}$	$-\frac{\sqrt{\frac{6}{7}}}{5}$
CF								
$D^0 \to K^-\pi^+$	0	0	$\frac{\sqrt{\frac{2869}{7}}}{40}$	$-\frac{\sqrt{\frac{1330969}{7}}}{7320}$	$-\frac{7\sqrt{\frac{871}{6}}}{610}$	$\frac{\sqrt{\frac{5281}{7}}}{610}$	$\frac{2\sqrt{\frac{1057}{3}}}{305}$	$\frac{1}{10\sqrt{21}}$
$D^0 \to \bar{K}^0\pi^0$	0	0	$-\frac{\sqrt{\frac{2869}{14}}}{40}$	$\frac{\sqrt{\frac{1330969}{14}}}{7320}$	$\frac{7\sqrt{\frac{871}{3}}}{1220}$	$\frac{3\sqrt{\frac{5281}{14}}}{1220}$	$\frac{\sqrt{\frac{3171}{2}}}{305}$	$-\frac{\sqrt{\frac{3}{14}}}{5}$
$D^+ \to \bar{K}^0\pi^+$	0	0	0	0	0	$\frac{\sqrt{\frac{5281}{7}}}{244}$	$\frac{\sqrt{\frac{1057}{3}}}{61}$	$-\frac{1}{2\sqrt{21}}$
$D_s \to \bar{K}^0K^+$	0	0	$-\frac{\sqrt{\frac{2869}{7}}}{40}$	$-\frac{\sqrt{\frac{1330969}{7}}}{7320}$	$-\frac{7\sqrt{\frac{871}{6}}}{610}$	$\frac{\sqrt{\frac{5281}{7}}}{610}$	$\frac{2\sqrt{\frac{1057}{3}}}{305}$	$\frac{2}{5\sqrt{21}}$
DCS								
$D^0 \to K^+\pi^-$	0	0	0	$\frac{\sqrt{\frac{1330969}{7}}}{3660}$	$\frac{7\sqrt{\frac{871}{6}}}{305}$	$-\frac{\sqrt{\frac{5281}{7}}}{305}$	$-\frac{4\sqrt{\frac{1057}{3}}}{305}$	$-\frac{1}{2\sqrt{21}}$
$D^0 \to K^0\pi^0$	0	0	0	$-\frac{\sqrt{\frac{1330969}{14}}}{3660}$	$-\frac{7\sqrt{\frac{871}{3}}}{610}$	$-\frac{3\sqrt{\frac{5281}{14}}}{610}$	$-\frac{\sqrt{6342}}{305}$	$-\frac{\sqrt{\frac{3}{14}}}{2}$
$D^+ \to K^0\pi^+$	0	0	0	$\frac{\sqrt{\frac{1330969}{7}}}{3660}$	$\frac{7\sqrt{\frac{871}{6}}}{305}$	$-\frac{\sqrt{\frac{5281}{7}}}{305}$	$-\frac{4\sqrt{\frac{1057}{3}}}{305}$	$-\frac{1}{2\sqrt{21}}$
$D^+ \to K^+\pi^0$	0	0	0	$-\frac{\sqrt{\frac{1330969}{14}}}{3660}$	$-\frac{7\sqrt{\frac{871}{3}}}{610}$	$-\frac{3\sqrt{\frac{5281}{14}}}{610}$	$-\frac{\sqrt{6342}}{305}$	$-\frac{\sqrt{\frac{3}{14}}}{2}$
$D_s \to K^0K^+$	0	0	0	0	0	$-\frac{\sqrt{\frac{5281}{7}}}{122}$	$-\frac{2\sqrt{\frac{1057}{3}}}{61}$	$\frac{1}{\sqrt{21}}$

Quantum Numbers and Hamiltonian

Initial states: Antitriplet of D Mesons

Notation: $|\mu\rangle_{I, I_3, Y}$

$\left|D^0\right\rangle = |c\bar{u}\rangle = \bar{\mathbf{3}}_{\frac{1}{2},-\frac{1}{2},-\frac{1}{3}}$, $\left|D^+\right\rangle = \left|c\bar{d}\right\rangle = \bar{\mathbf{3}}_{\frac{1}{2},\frac{1}{2},-\frac{1}{3}}$, $\left|D_s^+\right\rangle = |c\bar{s}\rangle = \bar{\mathbf{3}}_{0,0,\frac{2}{3}}$

Final states from Octet of pseudoscalars: Pions and Kaons

- $\left|\pi^+\right\rangle = |\mathbf{8}\rangle_{1,1,0}$, $\left|\pi^0\right\rangle = |\mathbf{8}\rangle_{1,0,0}$, $\left|\pi^-\right\rangle = |\mathbf{8}\rangle_{1,-1,0}$
- $\left|K^+\right\rangle = |\mathbf{8}\rangle_{\frac{1}{2},\frac{1}{2},1}$, $\left|K^-\right\rangle = |\mathbf{8}\rangle_{\frac{1}{2},-\frac{1}{2},-1}$, $\left|K^0\right\rangle = |\mathbf{8}\rangle_{\frac{1}{2},-\frac{1}{2},1}$, $\left|\bar{K}^0\right\rangle = |\mathbf{8}\rangle_{\frac{1}{2},\frac{1}{2},-1}$

Operators: Flavor Structure of Hamiltonian

$$\mathcal{H}_{\text{eff}} \sim \underbrace{V_{ud}V_{cs}^*\,(\bar{u}d)\,(\bar{s}c)}_{\text{CA}} + \underbrace{V_{us}V_{cs}^*\,(\bar{u}s)\,(\bar{s}c) + V_{ud}V_{cd}^*\,(\bar{u}d)\left(\bar{d}c\right)}_{\text{SCS}} + \underbrace{V_{us}V_{cd}^*\,(\bar{u}s)\left(\bar{d}c\right)}_{\text{DCS}}$$