Breaking SU(3)-Flavor in nonleptonic Charm Decays without Prejudice

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Recent Spectacular Results: Large Direct CP Violation in Charm Decays

The Data

[Gersabeck 2012, Belle 2012, LHCb 2012, CDF 2012, BaBar 2008]

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

SM contribution is suppressed

- Effectively 2-generational system, 3rd gen. and CPV entering in loops
- CKM factor $\propto 2\,\mathrm{Im}\left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) \approx 1.2 \cdot 10^{-3}$
- Loop factor $\mathcal{O}\left(\frac{\alpha_s(m_c)}{\pi}\right) \sim 0.1$ (?)

↳Naive expectation: $\Delta a_{\rm CP}^{\rm dir} \lesssim \mathcal{O}(0.001)$

- Drawback: Position in spectrum, relative to QCD:

  $m_c \ggg \Lambda_{\rm QCD}$ but also $m_c \nsim \Lambda_{\rm QCD}$

Charming Physics

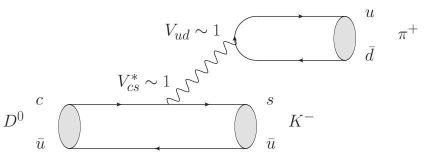
Probing the up sector for New Physics (NP)

- Complementarity to B and K physics
- Only up quark with mesons that oscillate
- Large amounts of D mesons produced at colliders
- Direct CP Violation is measured.

Observable	Measurement	Experiment
	SCS CP asymmetries	
$\Delta a_{CP}^{\mathrm{dir}}(K^+K^-,\pi^+\pi^-)$	-0.00678 ± 0.00147	LHCb, CDF, Belle, BABAR
$\Sigma a_{CP}^{\mathrm{dir}}(K^+K^-,\pi^+\pi^-)$	$+0.0014 \pm 0.0039$	LHCb, CDF, Belle, BABAR
$A_{CP}(D^0 \to K_S K_S)$	-0.23 ± 0.19	CLEO
$A_{CP}(D^0 \to \pi^0\pi^0)$	$+0.001 \pm 0.048$	CLEO
$A_{CP}(D^+ \to \pi^0\pi^+)$	$+0.029 \pm 0.029$	CLEO
$A_{CP}(D^+ \to K_S K^+)$	-0.0011 ± 0.0025	CLEO, BABAR, FOCUS, Belle
$A_{CP}(D_s \to K_S\pi^+)$	$+0.031 \pm 0.015$	CLEO, BABAR, Belle
$A_{CP}(D_s \to K^+\pi^0)$	$+0.266 \pm 0.228$	CLEO

Cabibbo-favored (CF):

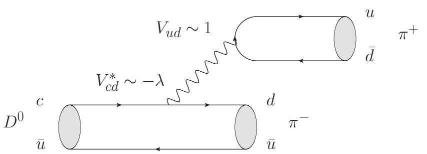
$c \to s\bar{d}u \propto V^*_{cs}V_{ud} \approx 1$



Singly-Cabibbo suppressed (SCS):

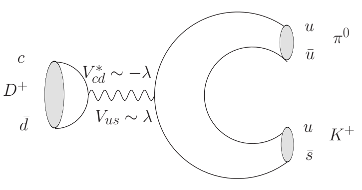
$c \to s\bar{s}u$ or $c \to d\bar{d}u$

$\propto V^*_{cs}V_{us} \approx -V^*_{cd}V_{ud} \approx \lambda$

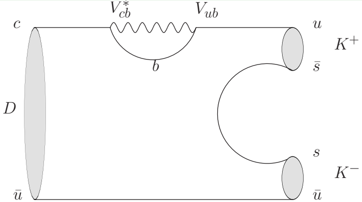


Doubly-Cabibbo suppressed (DCS):

$c \to d\bar{s}u \propto V^*_{cd}V_{us} \approx -\lambda^2$



CPV in SCS decays $\propto V^*_{cb}V_{ub}$



Low Energy Effective Field Theory

$\Delta C = 1$-Hamiltonian: $\mathcal{H}_{\text{eff}}^{\Delta C=-1} = \mathcal{H}_{CA} + \mathcal{H}_{SCS} + \mathcal{H}_{DCS}$

$$\mathcal{H}_{\text{SCS}} = \frac{4G_F}{\sqrt{2}}\left[\sum_{i=1,2}\sum_{D=d,s} V_{cD}^* V_{uD} C_i \mathcal{O}_{i,D}^{\text{SCS}} - V_{cb}^* V_{ub} \sum_{i=3,\ldots,6} C_i \mathcal{O}_i\right]$$

$\mathcal{O}^X$: Tree operators, $C_i \sim 1$

$\mathcal{O}_{3,\ldots,6}$: Penguin operators, $C_i \sim \alpha_s$

- Hierarchy could be destroyed by hadronic matrix elements.

We do not know **how to reliably calculate** the **hadronic matrix elements** $\langle f|\, \mathcal{O}_j\, |i\rangle$ for charm.

➥What is the best we can do instead?
Take them from data using a symmetry!

There is indeed lots of data for $D \to PP$

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

Observable	Measurement
SCS CP asymmetries	
$\Delta a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-)$	-0.00678 ± 0.00147
$\Sigma a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-)$	$+0.0014 \pm 0.0039$
$A_{CP}(D^0 \to K_S K_S)$	-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
$A_{CP}(D_s \to K_S\pi^+)$	$+0.031 \pm 0.015$
$A_{CP}(D_s \to K^+\pi^0)$	$+0.266 \pm 0.228$
Indirect CP Violation	
a_{CP}^{ind}	$(-0.027 \pm 0.163) \cdot 10^{-2}$
$\delta_L \equiv 2\text{Re}(\varepsilon)/(1+\lvert\varepsilon\rvert^2)$	$(3.32 \pm 0.06) \cdot 10^{-3}$
$K^+\pi^-$ strong phase difference	
$\delta_{K\pi}$	$21.4^\circ \pm 10.4^\circ$

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

Emergency Toolkit for Uncalculable Matrix Elements

1. Use flavor symmetry to relate several decay amplitudes of $D \to PP$.
2. Fit them from data.
   Take **all** data.
3. Make predictions from symmetry correlations in different (NP) models.

↳ Can we distinguish models?

Approximate SU(3)$_F$ Symmetry of QCD for $D \to P_8 P_8$

[Gell-Mann, Ne'eman 1961]

- Approximation: $m_u \sim m_d \sim m_s \ll \Lambda_{\text{QCD}}$
  ↳ u,d,s form $SU(3)$ triplet
- SU(3) symmetry broken by mass terms $\sum_q m_q \bar{q}q$ $\quad m_s \neq m_{u,d}$

Initial states: Antitriplet of D Mesons

$$\bar{\mathbf{3}} = \left(D^0 = |c\bar{u}\rangle\,, \quad D^+ = \left|c\bar{d}\right\rangle, \quad D_s = |c\bar{s}\rangle\right)$$

Final states: Pions and Kaons belonging to Octet of pseudoscalars

Identical bosons ⇒ Symmetrized product final states

↳ $[(\mathbf{8}) \otimes (\mathbf{8})]_S = (\mathbf{1}) \oplus (\mathbf{8}) \oplus (\mathbf{27})$

Reduce Parameters

Operators: Flavor Structure of Hamiltonian

- Operator tensor product of $(\bar{u}s)(\bar{s}c)$, $(\bar{u}d)(\bar{d}c)$, ...

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

$$\Rightarrow \mathcal{H}_{\text{eff}}^{\text{SCS}} \sim \underbrace{\lambda\left(\mathbf{15} + \bar{\mathbf{6}}\right)}_{\text{CKM leading}} + \underbrace{\lambda^5 (i\bar{\eta} - \bar{\rho})(\mathbf{15} + \mathbf{3})}_{\text{CKM suppressed, CPV}}$$

- $\mathbf{15}$ and $\mathbf{6}$ fixed already by $\mathcal{B}$. Explain large CPV by $\mathbf{3}$ (penguins)

Reduce Parameters: Wigner-Eckart Theorem

- The matrix elements only depend on the representation.
- Not on other quantum numbers ⇒ Clebsch-Gordan coefficients

⇒ Express amplitudes by reduced matrix elements.

SU(3) decomposition in the limit $m_s = m_d = m_u$

[Quigg 1980]

$$\mathcal{A}_0(d) = \text{CKM} \times \sum_{i,j} c_{d;ij} A_i^j$$

How to read this table

- $\mathcal{A}_0(D^0 \to K^-\pi^+) = V_{cs}^* V_{ud} \left(\frac{\sqrt{2}}{5} A_{27}^{15} - \frac{\sqrt{2}}{5} A_8^{15} + \frac{1}{\sqrt{5}} A_8^{\bar{6}} \right)$

Does SU(3) limit work?

- SCS: $\frac{\mathcal{B}(D^0 \to K^+K^-)}{\mathcal{B}(D^0 \to \pi^+\pi^-)} \sim 2.8 \neq 1$
- CA/DCS: $\frac{\mathcal{B}(D^0 \to K^+\pi^-)}{\lambda^4 \mathcal{B}(D^0 \to K^-\pi^+)} \sim 1.5 \neq 1$
- Complete fit: $\chi^2/\text{dof} \sim$ **100**
- Only $\mathcal{B}(\text{CA}, \text{DCS})$: $\chi^2/\text{dof} \sim$ **9**

No! Not even for the $\mathcal{B}$!

Decay d	A_{27}^{15}	A_8^{15}	$A_8^{\bar{6}}$	A_1^3	A_8^3
SCS					
$D^0 \to K^+K^-$	$\frac{3\tilde{\Delta}+4}{10\sqrt{2}}$	$\frac{\tilde{\Delta}-2}{5\sqrt{2}}$	$\frac{1}{\sqrt{5}}$	$\frac{\tilde{\Delta}}{2\sqrt{2}}$	$\frac{\tilde{\Delta}}{\sqrt{10}}$
$D^0 \to \pi^+\pi^-$	$\frac{3\tilde{\Delta}-4}{10\sqrt{2}}$	$\frac{\tilde{\Delta}+2}{5\sqrt{2}}$	$-\frac{1}{\sqrt{5}}$	$\frac{\tilde{\Delta}}{2\sqrt{2}}$	$\frac{\tilde{\Delta}}{\sqrt{10}}$
$D^0 \to \bar{K}^0K^0$	$\frac{\tilde{\Delta}}{10\sqrt{2}}$	$\frac{\sqrt{2}\tilde{\Delta}}{5}$	0	$-\frac{\tilde{\Delta}}{2\sqrt{2}}$	$\sqrt{\frac{2}{5}}\tilde{\Delta}$
$D^0 \to \pi^0\pi^0$	$\frac{7\tilde{\Delta}-6}{20}$	$-\frac{\tilde{\Delta}+2}{10}$	$\frac{1}{\sqrt{10}}$	$-\frac{\tilde{\Delta}}{4}$	$-\frac{\tilde{\Delta}}{2\sqrt{5}}$
$D^+ \to \pi^0\pi^+$	$\frac{\tilde{\Delta}-1}{2}$	0	0	0	0
$D^+ \to \bar{K}^0K^+$	$\frac{\tilde{\Delta}+3}{5\sqrt{2}}$	$-\frac{\tilde{\Delta}-2}{5\sqrt{2}}$	$\frac{1}{\sqrt{5}}$	0	$\frac{3\tilde{\Delta}}{\sqrt{10}}$
$D_s \to K^0\pi^+$	$\frac{\tilde{\Delta}-3}{5\sqrt{2}}$	$-\frac{\tilde{\Delta}+2}{5\sqrt{2}}$	$-\frac{1}{\sqrt{5}}$	0	$\frac{3\tilde{\Delta}}{\sqrt{10}}$
$D_s \to K^+\pi^0$	$\frac{2\tilde{\Delta}-1}{5}$	$\frac{\tilde{\Delta}+2}{10}$	$\frac{1}{\sqrt{10}}$	0	$-\frac{3\tilde{\Delta}}{2\sqrt{5}}$
CF					
$D^0 \to K^-\pi^+$	$\frac{\sqrt{2}}{5}$	$-\frac{\sqrt{2}}{5}$	$\frac{1}{\sqrt{5}}$	0	0
$D^0 \to \bar{K}^0\pi^0$	$\frac{3}{10}$	$\frac{1}{5}$	$-\frac{1}{\sqrt{10}}$	0	0
$D^+ \to \bar{K}^0\pi^+$	$\frac{1}{\sqrt{2}}$	0	0	0	0
$D_s \to \bar{K}^0K^+$	$\frac{\sqrt{2}}{5}$	$-\frac{\sqrt{2}}{5}$	$-\frac{1}{\sqrt{5}}$	0	0
DCS					
$D^0 \to K^+\pi^-$	$\frac{\sqrt{2}}{5}$	$-\frac{\sqrt{2}}{5}$	$\frac{1}{\sqrt{5}}$	0	0
$D^0 \to K^0\pi^0$	$\frac{3}{10}$	$\frac{1}{5}$	$-\frac{1}{\sqrt{10}}$	0	0
$D^+ \to K^0\pi^+$	$\frac{\sqrt{2}}{5}$	$-\frac{\sqrt{2}}{5}$	$-\frac{1}{\sqrt{5}}$	0	0
$D^+ \to K^+\pi^0$	$\frac{3}{10}$	$\frac{1}{5}$	$\frac{1}{\sqrt{10}}$	0	0
$D_s \to K^0K^+$	$\frac{1}{\sqrt{2}}$	0	0	0	0

SU(3)-Flavor is broken: $m_s \neq m_{u,d}$

Now it becomes complicated...

Include SU(3) breaking $\mathcal{A}(d) = \mathcal{A}_0(d) + \mathcal{A}_X(d)$

- Symmetry breaking term: $\mathcal{H} \sim m_s\, \bar{s}\, s$
- $\mathcal{A}_X(d) = \mathrm{CKM} \times \sum_{i,k} c_{d;ij}\, B_i^j$
- Expansion in $\varepsilon \equiv m_s/\Lambda_{QCD} \sim 30\%$

$$
\begin{aligned}
(\mathbf{15}) \otimes (\mathbf{8}) &= (\mathbf{42}) \oplus (\mathbf{24}) \oplus (\mathbf{15_1}) \oplus (\mathbf{15_2}) \oplus (\mathbf{15'}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})\,, \\
(\bar{\mathbf{6}}) \otimes (\mathbf{8}) &= (\mathbf{24}) \oplus (\mathbf{15}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})\,, \\
(\mathbf{3}) \otimes (\mathbf{8}) &= (\mathbf{15}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})\,.
\end{aligned}
$$

[Savage 1991, Hinchliffe Kaeding 1995, program by Kaeding Williams 1996, Grinstein Lebed 1996, Pirtskhalava Uttayarat 2011]

Clebsch-Gordan Coefficients of SU(3) Breaking

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	$-\frac{2(1-\Delta/\Sigma)}{\sqrt{61}}$	$\frac{5(1-\Delta/\Sigma)}{8\sqrt{183}}$	0	$\frac{1-\Delta/\Sigma}{4\sqrt{3}}$	0	$\frac{1-\Delta/\Sigma}{8\sqrt{21}}$
$D^+ \to \bar{K}^0K^+$	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	$\frac{1}{\sqrt{42}}$

Full and correct table NEW!

Hiller Jung S.S., arXiv:1211.3734

How to abolish Prejudices about Charm

- Use only the symmetry.
- Do not assume a further dynamical understanding of QCD.
- Do not assume that certain matrix elements are more important than others.
- Every matrix element has in general a complex phase.

Questions

Status:

25 observables, 13 complex matrix elements $\Rightarrow$ Fit

- Is SU(3) a reasonable expansion for charm decays?
- How large is the penguin $(\mathbf{3})$ enhancement?
- Are there patterns of NP that are distinguishable from Standard Model / Minimal Flavor Violation?

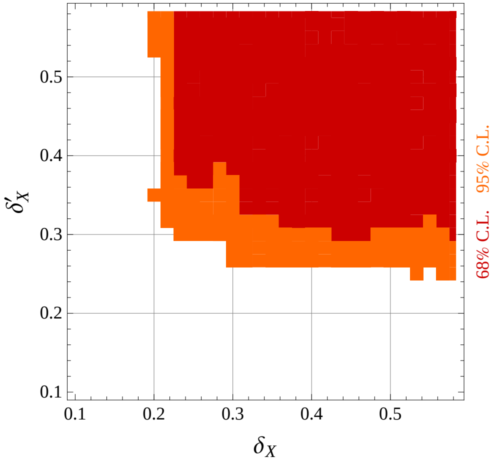
How Large is the Breaking in $D \to PP$? NEW!

Evaluation of Convergence of SU(3)-expansion using complementary measures

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

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

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



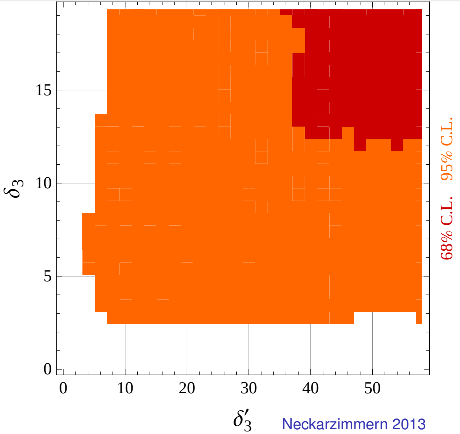
➥ Data can be described by SU(3)-expansion with $\delta_X^{(\prime)} \lesssim 30\%$ ✓

How Large Are the Penguins?

Naive expectation: $\delta_3^{(\prime)} \ll 1$

$$\delta_3 = \frac{\max(|A_1^3|, |A_8^3|)}{\max(|A_{27}^{15}|, |A_8^{\bar{6}}|, |A_8^{15}|)} \qquad \delta_3' \sim \frac{1}{\lambda^4} \max_d \left| \frac{\text{total amplitude by } A_1^3, A_8^3}{\text{total amplitude by } A_{27}^{15}, A_8^{\bar{6}}, A_8^{15}} \right|$$

- Enhanced triplets $\delta_3 \sim 2$, $\delta_3' \sim 7$ required at 95% C.L. 68% C.L. region far away
- Extremely unexpected!
- Regions of cancellations of large triplet matrix elements



What drives the Penguins?

Large CP asymmetries

- **Not only** $\Delta a_{CP,\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$
- Further CP asymmetries with largish measured central values

$$A_{CP}(D^0 \to K_S K_S) = -0.23 \pm 0.19$$

[CLEO 2001]

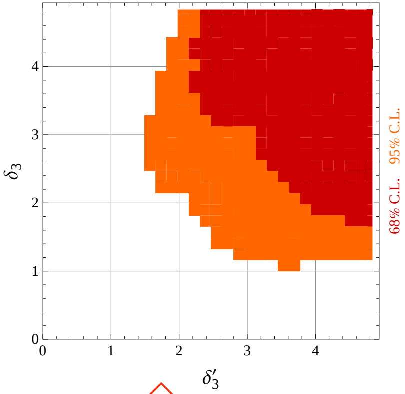
$$A_{CP}(D_s \to K_S \pi^+) = 0.031 \pm 0.015$$

[BarBar 2012, CLEO 2010, Belle 2010]

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

[CLEO 2010]

- Plot: **Without** these A_{CP}'s: $\delta_3^{(\prime)} \sim 3$ allowed at 68% C.L.



- In agreement with previous U spin analyses

[Feldmann Nandi Soni, 2012, Brod Grossman Kagan Zupan, 2012]

What have we learned?

- The SU(3) expansion does work.
- The triplet (penguin) matrix elements are enhanced.

$$\text{SM:} \quad \delta_3^{(\prime)\,\text{naive}} \sim 0.1$$

$$\delta_3^{(\prime)} \sim 1 \qquad \text{enhanced}$$

$$\delta_3^{(\prime)} \sim ? \qquad \text{unlikely ?}$$

...we cannot tell for sure...

SU(3)-Flavor Analysis of New Physics Models

- There are many possible new physics models.
- Match them on our ansatz:
  Analyze their SU(3)-flavor structure
- Characteristic SU(3)-flavor structure
  $\Rightarrow$ Correlations and patterns?

Assume SU(3)-X of reasonable size: $\delta_X^{(\prime)} \leq 50\%$

Characteristic SU(3)-Flavor Structures

MFV/SM: $\mathcal{H}_{\mathrm{SM}} \sim \lambda\left(\mathbf{15} + \bar{\mathbf{6}}\right) + \underbrace{V_{cb}^* V_{ub}\,(\mathbf{15} + \mathbf{3})}_{\mathcal{H}_{\mathrm{CPV}}}$

Replace $\mathcal{H}_{\mathrm{CPV}}$ by CKM × (NP operator)

- **Triplet model:** $(\bar{u}c)\sum \bar{q}q,\ \bar{u}\sigma_{\mu\nu}G^{\mu\nu}c \sim \mathbf{3}^{\mathrm{NP}}$
- **Hochberg/Nir (HN) model:** $(\bar{u}c)(\bar{u}u) \sim \mathbf{15}^{\mathrm{NP}} + \mathbf{3}^{\mathrm{NP}}$

  [Hochberg Nir 2012]
- **$\Delta \mathrm{U} = 1$ model:** $(\bar{s}c)(\bar{u}s) \sim \mathbf{15}^{\mathrm{NP}} + \bar{\mathbf{6}}^{\mathrm{NP}} + \mathbf{3}^{\mathrm{NP}}$

Phenomenology

General

- Not able to distinguish SM and triplet model in nonleptonic decays.
- CKM-leading part of $D^0 \to K^0 \bar{K}^0$ only from SU(3)-X
  ➥general prediction $a_{CP}^{\text{dir}}(D^0 \to K^0 \bar{K}^0) \sim \mathcal{O}(\text{CKM}/\delta_X^{(\prime)}) \sim 1\%$.

$\Delta U = 1$ model

- $(\bar{s}c)(\bar{u}s)$ operator breaks discrete U-spin symmetry of Hamiltonian
- Breaking of SU(3) limit relations

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

at $\mathcal{O}(1)$ in addition to SU(3)-X.

HN model: $(\bar{u}c)(\bar{u}u) \sim \mathbf{15}^{\mathrm{NP}} + \mathbf{3}^{\mathrm{NP}}$

Smoking gun: $a_{CP}(D^+ \to \pi^+\pi^0) \neq 0$ [Grossman Kagan Zupan 2012]

MFV/SM	A_{27}^{15}	A_8^{15}	$A_8^{\bar{6}}$	A_1^3	A_8^3
$D^+ \to \pi^0\pi^+$	$\frac{\tilde{\Delta}-1}{2}$	0	0	0	0

Strong **and** weak phase difference needed for direct CPV.

Besides Smoking Guns: Quantitative Study

- With present data no clear separation of different NP models possible.

Two Ways to make progress

1. Insights in the strong dynamics, especially in SU(3) breaking.
2. Significantly improved 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	
$\delta_{K\pi}$	$21.4^\circ \pm 3.8^\circ$

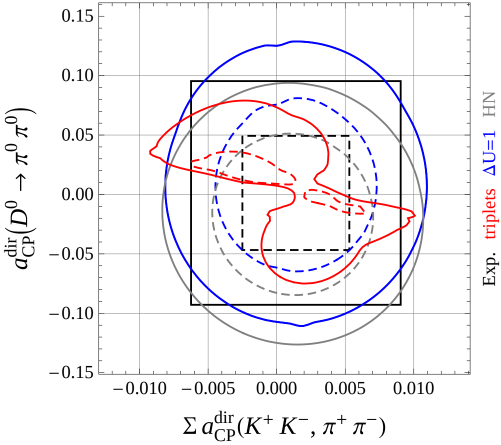
Proof of Principle: NP Models in Future Scenarios I

NEW!

- Current data, future improved knowledge on SU(3) breaking

- Only 3 breaking matrix elements.

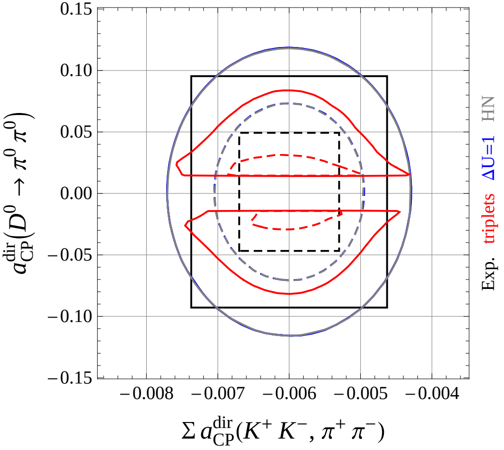
- Correlation of $a_{CP}^{\mathrm{dir}}(D^0 \to \pi^0\pi^0)$ and $\Sigma a_{CP}^{\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$ in triplet model



Proof of Principle: NP Models in Future Scenarios II

NEW!

- Future data, all breaking matrix elements.
- Prediction of sizable CPV in $D^0 \to \pi^0\pi^0$ in triplet model.
- $a_{CP}^{\text{dir}}(D^0 \to \pi^0\pi^0) = \Sigma a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-) = 0$ disfavored by triplet model.



Summary

- First unbiased comprehensive SU(3) analysis of $D \to PP$ decays.
- Current data can be described with reasonable $SU(3)$ breaking.
- Higher representations are important in the $SU(3)$ breaking.
- CP Violation indicates strongly enhanced penguins or New Physics beyond MFV.
- More precise measurements of all A_{CP} desperately needed.
  Especially: $A_{CP}(D^0 \to K_S K_S)$, $A_{CP}(D_s \to K_S \pi^+)$, $A_{CP}(D_s \to K^+ \pi^0)$.
- Current data allows to exclude various scenarios of SU(3) breaking.
- Future data or theoretical insights in SU(3) breaking could differentiate the triplet model from other models.

BACK-UP

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: $B_{1,8}^{3_1} \mapsto \sqrt{\frac{7}{2}} B_{1,8}^{3_1} - \sqrt{\frac{5}{2}} B_{1,8}^{3_2}$
- Further similar replacements found by Gaussian elimination:
  Remove $B_8^{\bar{6}_2}$, $B_8^{15_3}$, $B_{27}^{15_3}$, $B_{27}^{24_2}$ and B_{27}^{42}.

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: $a_{CP,\mathrm{ind}} = (-0.027 \pm 0.163) \cdot 10^{-2}$ [Gersabeck 2012]
- 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 $A_{CP}(D^0 \to K_S K_S) = -0.23 \pm 0.19$.

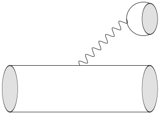
SU(3)-X Clebsch-Gordan Coefficients after Reparametrizations

Decay d	B_1^3	B_8^3	$B_8^{6_1}$	$B_8^{15_1}$	$B_8^{15_2}$	$B_{27}^{15_1}$	$B_{27}^{15_2}$	$B_{27}^{24_1}$
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	$-\frac{\sqrt{\frac{5281}{14}}(1-\Delta/\Sigma)}{61}$	$\frac{5\sqrt{\frac{151}{42}}(1-\Delta/\Sigma)}{122}$	$\frac{1-\Delta/\Sigma}{\sqrt{42}}$
$D^+ \to \bar{K}^0K^+$	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	$-\frac{\sqrt{\frac{5281}{7}}}{122}$	$-\frac{2\sqrt{\frac{1057}{3}}}{61}$	$\frac{1}{\sqrt{21}}$

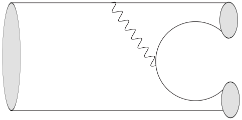
Classification of Decay Topologies I: Tree and Weak Annihilation

[Chau 1980, 1983, Chau Cheng 1986, 1989, Gronau Hernandez London Rosner 1994, 1995]

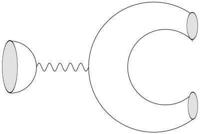
- *Color-favored tree*
 = *external W emission* = T



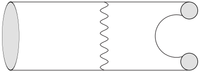
- *Color-suppressed tree*
 = *internal W emission* = C



- *W-annihilation* = A



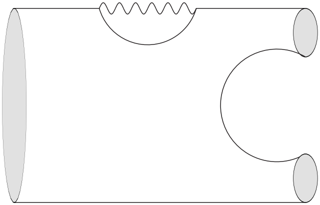
- *W-exchange* = E



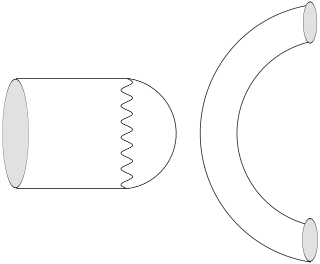
- Simplification of QCD with exact flavor flow.

Classification of Decay Topologies II: Penguin and Penguin Annihilation

- *Penguin* = P



- *Penguin annihilation* = PA



Quantum Numbers and Hamiltonian

Initial states: Antitriplet of D Mesons   Notation: $|\mu\rangle_{I,I_3,Y}$

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

Final states from Octet of pseudoscalars: Pions and Kaons

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

Operators: Flavor Structure of Hamiltonian

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

Many solutions in different configurations of SU(3)-X

- For reasonable fit: At least two SU(3) breaking MEs must be present

- Only B_1^3, B_8^3 $\Rightarrow$ Bad fit again with $\chi^2/\mathrm{dof} = 8.6$
  No contrubution to SU(3)-X in CF/DCS decays
  ↳Need for higher representations in breaking

- Good fit with B_1^3, $B_{27}^{15_2}$: $\chi^2/\mathrm{dof} = 1.3$