Flavor symmetry in charm decays

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based on works with G. Hiller, M. Jung, S. Müller, U. Nierste

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

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

Red: Update in 2014

Observable	Measurement
SCS CP asymmetries	
$\Delta a_{CP}^{\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$	-0.00253 ± 0.00104
$\Sigma a_{CP}^{\mathrm{dir}}(K^+K^-, \pi^+\pi^-)$	-0.0011 ± 0.0026
$a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)$	-0.23 ± 0.19
$a_{CP}^{\mathrm{dir}}(D^0 \to \pi^0\pi^0)$	-0.0004 ± 0.0064
$a_{CP}^{\mathrm{dir}}(D^+ \to \pi^0\pi^+)$	$+0.029 \pm 0.029$
$a_{CP}^{\mathrm{dir}}(D^+ \to K_S K^+)$	$+0.0011 \pm 0.0017$
$a_{CP}^{\mathrm{dir}}(D_s \to K_S\pi^+)$	$+0.006 \pm 0.005$
$a_{CP}^{\mathrm{dir}}(D_s \to K^+\pi^0)$	$+0.266 \pm 0.228$
Indirect CP violation	
a_{CP}^{ind}	0.00013 ± 0.00052
$\delta_L \equiv 2\mathrm{Re}(\varepsilon)/(1+\lvert\varepsilon\rvert^2)$	$(3.32 \pm 0.06)\cdot 10^{-3}$
$K^+\pi^-$ strong phase difference	
$\delta_{K\pi}$	$(11.7 \pm 10.2)^\circ$

Observable	Measurement
SCS branching ratios	
$\mathcal{B}(D^0 \to K^+K^-)$	$(3.96 \pm 0.08)\cdot 10^{-3}$
$\mathcal{B}(D^0 \to \pi^+\pi^-)$	$(1.402 \pm 0.026)\cdot 10^{-3}$
$\mathcal{B}(D^0 \to K_S K_S)$	$(0.17 \pm 0.04)\cdot 10^{-3}$
$\mathcal{B}(D^0 \to \pi^0\pi^0)$	$(0.820 \pm 0.035)\cdot 10^{-3}$
$\mathcal{B}(D^+ \to \pi^0\pi^+)$	$(1.19 \pm 0.06)\cdot 10^{-3}$
$\mathcal{B}(D^+ \to K_S K^+)$	$(2.83 \pm 0.16)\cdot 10^{-3}$
$\mathcal{B}(D_s \to K_S\pi^+)$	$(1.22 \pm 0.06)\cdot 10^{-3}$
$\mathcal{B}(D_s \to K^+\pi^0)$	$(0.63 \pm 0.21)\cdot 10^{-3}$
CF branching ratios	
$\mathcal{B}(D^0 \to K^-\pi^+)$	$(3.88 \pm 0.05)\cdot 10^{-2}$
$\mathcal{B}(D^0 \to K_S\pi^0)$	$(1.19 \pm 0.04)\cdot 10^{-2}$
$\mathcal{B}(D^0 \to K_L\pi^0)$	$(1.00 \pm 0.07)\cdot 10^{-2}$
$\mathcal{B}(D^+ \to K_S\pi^+)$	$(1.47 \pm 0.07)\cdot 10^{-2}$
$\mathcal{B}(D^+ \to K_L\pi^+)$	$(1.46 \pm 0.05)\cdot 10^{-2}$
DCS branching ratios	
$\mathcal{B}(D^0 \to K^+\pi^-)$	$(1.35 \pm 0.02)\cdot 10^{-4}$
$\mathcal{B}(D^+ \to K^+\pi^0)$	$(1.83 \pm 0.26)\cdot 10^{-4}$

Symmetry emergency kit: SU(3)$_F$

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

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

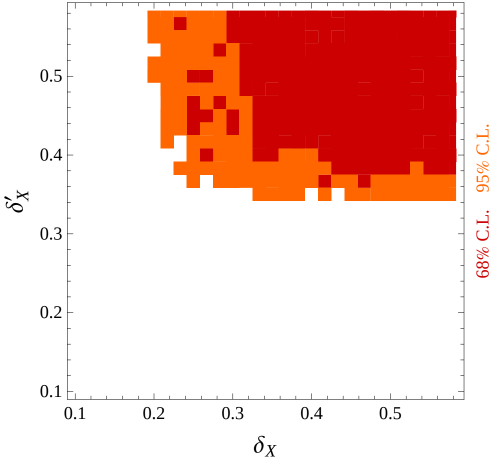
$$\mathcal{H}_{\mathrm{eff}}^{\mathrm{SCS}} \sim \underbrace{V_{us}V_{cs}^*\left(\mathbf{15}+\bar{\mathbf{6}}\right)}_{\text{CKM leading}} + \underbrace{V_{ub}V_{cb}^*\,(\mathbf{15}+\mathbf{3})}_{\text{CKM suppressed, CPV}}$$

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

[Hiller Jung StS 2014] [preliminary result]

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

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

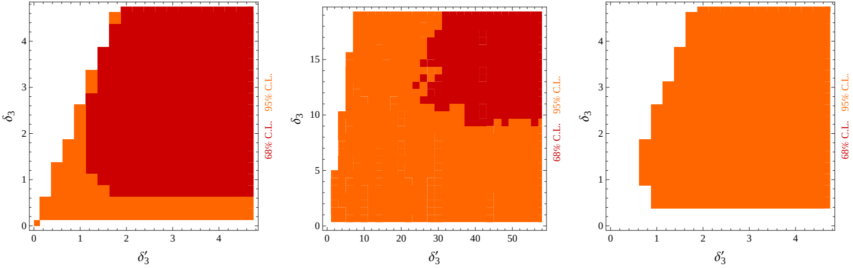


- δ_X ignores suppression by Clebsch-Gordan-coefficients.
- δ'_X ignores possible large cancellations.

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

How Large are the Penguins/Triplets?

All plots: June 2014, no confirmation of enhancement (yet?) $\Delta a_{\mathrm{CP}}^{\mathrm{dir}} \simeq \lambda^4 \cdot P/T$



wo. large insignificant A_{CP} | all data | all data, zoom

δ_3: max(ratios matrix elements) δ_3': max(ratios amplitudes)

Left: Without $A_{CP}(D^0 \to K_S K_S) = -0.23 \pm 0.19$ $A_{CP}(D_s \to K^+ \pi^0) = 0.266 \pm 0.228$ [preliminary results]

[Hiller Jung StS 2014]

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

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: $A_{CP}(D^0\rightarrow K_SK_S)/A_{CP}(D^0\rightarrow K^+K^-)\sim 1/\delta_X$.

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]

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

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

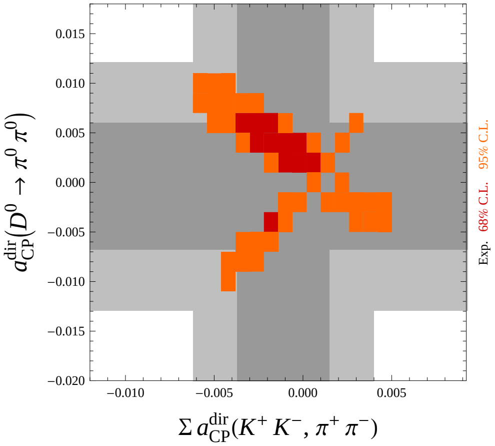
- $a_{CP}(D^+\rightarrow \pi^+\pi^0)\neq 0 \Rightarrow \Delta I = 3/2$-NP, HN. [Grossman Kagan Zupan 2012]
- Present data: NP and SM not distinguishable.

Correlation of Iso- and U-spin related Decays in $SU(3)_F$

[Hiller Jung StS 2014]

[preliminary result]

- All data, June 2014.
- Plain $SU(3)_F$.
- $SU(3)_F$ breaking $\leq 50\%$.
- Measurement $a_{CP}^{\text{dir}}(D^0 \to \pi^0\pi^0) = 0$ and $|\Sigma a_{CP}^{\text{dir}}(K^+K^-, \pi^+\pi^-)| \neq 0$ sizeable
  $\Rightarrow$ SM excluded.



Let's be prepared for future data: Strategies for insights into strong dynamics

1. Structural form of $\Lambda_{\mathrm{QCD}}/m_c$-expansion. [Hiller Jung StS 2014]
   Do not aim for quantitative description by QCDF.
2. $1/N_c$ + topologic $\mathrm{SU}(3)_F$ breaking. [Müller Nierste StS 2014]

➥Get to grips with $\mathrm{SU}(3)_F$ breaking.

➥Finally improve predictions for CP asymmetries.

Taming SU(3)$_F$ breaking

1

Structural form of Λ_{QCD}/m_c-expansion

[Beneke Buchalla Neubert Sachrajda 2001]

$$\langle P_1 P_2 | H_{\text{eff}} | D \rangle = \langle P_1 P_2 | \mathcal{T}_A + \mathcal{T}_B | D \rangle$$

- $\mathcal{T}_A$
  I : Leading contribution + vertex corrections.
  II: Hard spectator corrections.
  Parameterized by $a_i = a_{i,I} + a_{i,II}$
- $\mathcal{T}_B$: Annihilation contributions
  Parameterized by b_i

Example:

$$\mathcal{A}^{\text{factor}}(D^0 \to \pi^+\pi^-) = -\Sigma \left(a_1 f_\pi (m_D^2 - m_\pi^2) F_0^{D\pi}(m_\pi^2) + f_D f_\pi^2 \, b_1^{\pi\pi} \right)$$

$$\mathcal{A}^{\text{factor}}(D^0 \to \pi^0\pi^0) = -\frac{\Sigma}{\sqrt{2}} \left(a_2^{D\pi\pi} f_\pi (m_D^2 - m_\pi^2) F_0^{D\pi}(m_\pi^2) - f_D f_\pi^2 \, b_1^{\pi\pi} \right)$$

Illustration only: How bad is $m_c \to \infty$?

- Zero annihilation: $b_i \to 0$.
- $a_{1,I}^{P_1P_2} = C_1 + \frac{C_2}{N_c}\left(1 + \frac{C_F\alpha_s}{4\pi}V_{P_2}\right)$ $\qquad$ $a_{2,I}^{P_1P_2} = C_2 + \frac{C_1}{N_c}\left(1 + \frac{C_F\alpha_s}{4\pi}V_{P_1}\right)$
- $a_{2,II}^{D_{(s)}P_1P_2}\Big|_{\text{finite}} = \frac{C_1 C_F \pi\alpha_s}{N_c^2}\frac{f_{D_{(s)}}f_{P_1}}{m_{D_{(s)}}\lambda_{D_{(s)}}F_0^{D_{(s)}P_1}(m_{P_2}^2)}\beta^{P_1P_2}$ [Beneke Buchalla Neubert Sachrajda 2001]
- $\beta^{P_1P_2}$: Dependence on Gegenbauer moments.
- $\lambda_{D_{(s)}}$: Parametrization of ignorance of $D_{(s)}$ distribution amplitude.

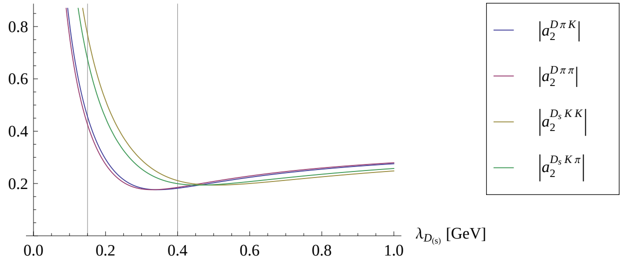
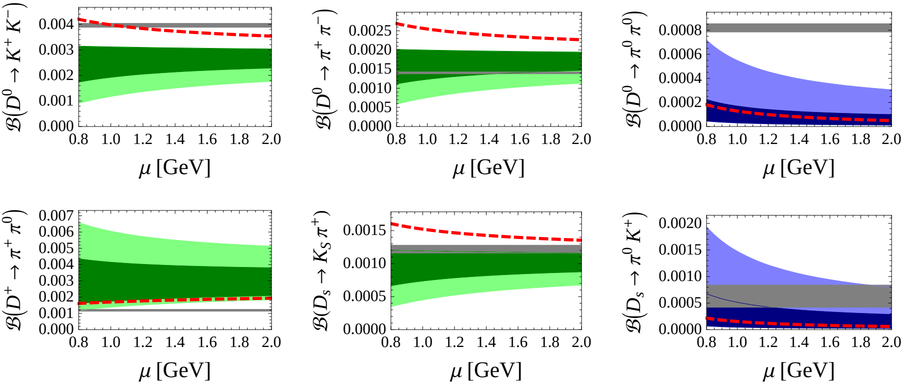


Illustration only, cont'd: $m_c \to \infty$ not so bad, actually

Dark: $\lambda_{D_{(s)}} \in [150, 400]$ MeV.
Light: $\lambda_{D_{(s)}} \in [100, 400]$ MeV.
Red : $\lambda_{D_{(s)}} \to \infty$.

Green: T-dominated.
Blue: C-dominated.



➥Annihilation is important. Especially for C-dominated decays.

Illustration over. Do not calculate a_i, b_i.

- No quantitative input of QCDF.
- Use parametric dependence of amplitudes on a_i, b_i.
- Elimination of a_i, $b_i \Rightarrow$ New heavy quark sum rules in addition to SU(3)$_F$ sum rules.
- Match QCDF-expressions on SU(3)$_F$ expansion of amplitudes.
- Use a consistent power counting for this, *e.g.*

$$f_K = f_P(1+\delta(f_P)) \qquad f_\pi = f_P(1-\delta(f_P))$$
$$f_{D_s} = f_d(1+\delta(f_d)) \qquad f_D = f_d(1-\delta(f_d)).$$

- Check of expansion: 6 SU(3)$_F$-breaking sum rules respected. ✓

[Grossman Robinson 2012]

How many additional heavy quark sum rules are there?

- a_1 dominated by leading flavor-universal term.
  ➥a_1 approx. universal.
  10 unknowns for 17 decays:

$$a_1, a_2^{D_sKK}, a_2^{D\pi\pi}, a_2^{D_sK\pi}, b_1^{K\pi}, b_1^{KK}, b_1^{\pi\pi}, b_{1s}^{KK}, b_2^{K\pi}, b_{2s}^{KK}.$$

  ➥7 sum rules ⇒ 1 heavy quark sum rule.
- Additionaly, in QCDF b_1 and b_2 involve same convolution of LCDAs.
  ➥$r \equiv b_2/b_1 = C_2/C_1$.
  8 unknowns for 17 decays:

$$a_1, a_2^{D_sKK}, a_2^{D\pi\pi}, a_2^{D_sK\pi}, b_1^{K\pi}, b_1^{KK}, b_1^{\pi\pi}, b_{1s}^{KK}.$$

  ➥9 sum rules ⇒ 3 heavy quark sum rules.

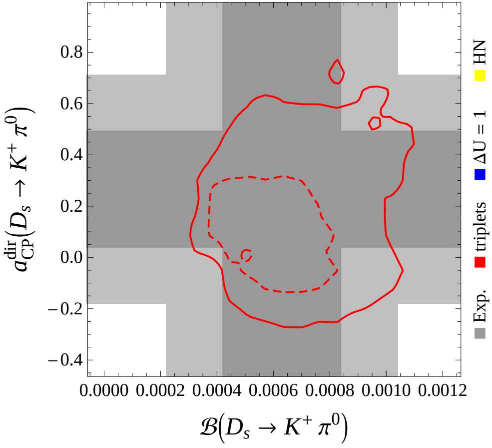
Use heavy quark sum rules to eliminate $SU(3)_F$-breaking matrix elements.
Do not touch $SU(3)_F$ limit matrix elements.

Correlation for $D_s \to K^+\pi^0$ including three Heavy Quark Sum Rules

[Hiller Jung StS 2014]

[preliminary result]

- All data, June 2014.
- $SU(3)_F$ breaking $\leq 50\%$.
- Plain $SU(3)_F$: Circle.
- $\mathcal{B}$'s are important.



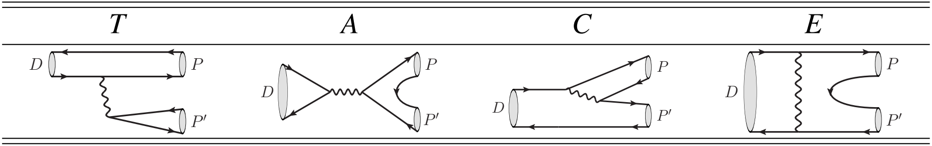
Taming SU(3)$_F$ breaking

2

Topologic approach: Flavor-flow diagrams

[Zeppenfeld 1981, Chau 1983, Gronau Hernandez London Rosner 1995, Buras Silvestrini 1998, Bhattacharya Gronau Rosner 2012, ...]

- The language of $SU(3)_F$-breaking matrix elements does not allow for a physical interpretation.
- Solution: Equivalent topologic parameterization.
- Important: Include $SU(3)_F$-breaking in a meaningful way.



Topologic SU(3)$_F$ breaking

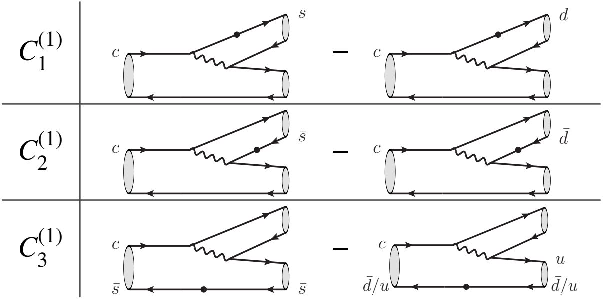
- Mass insertion formalism for difference of s and d quark mass.

  [Gronau Hernandez London Rosner 1995]

- 3 diagrams for each T, C, E, A; SU(3)$_F$-breaking penguin $P_d - P_s$.

  [Brod Grossman Kagan Zupan 2012]

- Up to now: ⇔ SU(3)$_F$: Same rank. Same 6 sum rules.
- Dynamical input:
  Chance to constrain SU(3)$_F$ breaking in each topology (!)



Equivalence to $SU(3)_F$

- Explicit Matching on $SU(3)_F$ (excerpt).

$SU(3)_F$ ME	...	E	$E_1^{(1)}$	$E_2^{(1)}$	$E_3^{(1)}$	P^{break}
A_{27}^{15}	...	0	0	0	0	0
A_{8}^{15}	...	$-\frac{5}{2\sqrt{2}}$	0	$-\frac{5}{3\sqrt{2}}$	$-\frac{5}{6\sqrt{2}}$	0
$A_{8}^{\bar{6}}$	...	$\frac{\sqrt{5}}{2}$	0	0	$\frac{\sqrt{5}}{2}$	0
B_{1}^{3}	...	0	$-\frac{16\sqrt{\frac{35}{421}}}{3}$	$\frac{32\sqrt{\frac{35}{421}}}{3}$	$\frac{32\sqrt{\frac{35}{421}}}{3}$	$-\frac{32\sqrt{\frac{35}{421}}}{3}$
B_{8}^{3}	...	0	$\frac{40\sqrt{\frac{7}{3937}}}{3}$	$-\frac{20\sqrt{\frac{7}{3937}}}{3}$	$-\frac{20\sqrt{\frac{7}{3937}}}{3}$	$-\frac{160\sqrt{\frac{7}{3937}}}{3}$
$B_{8}^{\bar{6}_1}$	...	0	0	$20\sqrt{\frac{7}{2869}}$	$-20\sqrt{\frac{7}{2869}}$	0
$B_{8}^{15_1}$	...	0	$-840\sqrt{\frac{7}{1330969}}$	$460\sqrt{\frac{7}{1330969}}$	$20\sqrt{\frac{133}{70051}}$	0
$B_{8}^{15_2}$	...	0	$10\sqrt{\frac{6}{871}}$	$-20\sqrt{\frac{6}{871}}$	$10\sqrt{\frac{6}{871}}$	0
$B_{27}^{15_1}$	...	0	0	0	0	0
$B_{27}^{15_2}$	...	0	0	0	0	0
$B_{27}^{24_1}$	...	0	0	0	0	0

Theoretical Input in the Language of Topologies

- Corrections to T and A diagrams $1/N_C^2$ suppressed.
  $\Rightarrow$ Factorization good approximation.
- Topologic measures of SU(3)$_F$ breaking:
  1. $\delta_X^{\prime,\mathcal{T}} \equiv \max_d \left|\mathcal{A}_X^{\mathcal{T}}(d)/\mathcal{A}(d)\right|$
     $\mathcal{T} = C, E, P_{\text{break}}$ and $\mathcal{A}_X^{\mathcal{T}}(d)$ part of amplitude of decay d stemming from corresponding SU(3)$_F$-breaking parameter(s) only.
  2. $\delta_X^{\prime,\text{topo}} \equiv \max_d \left|\sum_{\mathcal{T}} A_X^{\mathcal{T}}(d)/\mathcal{A}(d)\right|$
     overall amount of SU(3)$_F$ breaking introduced by all linear corrections to the topologies C, E and P_{break}.
  3. $\delta_X^{C_i/C} \equiv |C_i/C|$
  4. $\delta_X^{E_i/E} \equiv |E_i/E|$

Fit: all measures $\leq 50\%$ for reasonable SU(3)$_F$ expansion.
Perfect fit of approach to branching ratios: $\chi^2 \sim 0$.

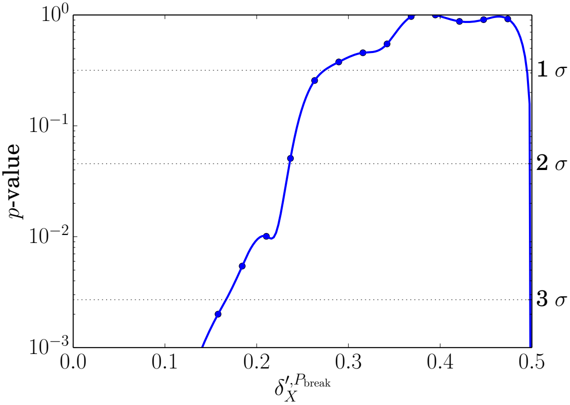
Interpret $SU(3)_F$ breaking in the topologic approach

How large is the $SU(3)_F$-X penguin compared to the full amplitude?

[Müller Nierste StS 2014]

[preliminary result]

- Fit to branching ratios only.
- All $SU(3)_F$-breaking measures $\leq 50\%$.
- $T_{i\to f}$ and $A_{i\to f}$ calculated in factorization.



➥Implications for CP asymmetries ⇒ Stay tuned.

Conclusion

- Charm physics remains suspense-packed.
- Correlations can already be obtained in plain SU(3)$_F$.
- Only little theoretical input on SU(3)$_F$ breaking helps to disentangle NP/SM with future data.
  - $1/N_c$ and/or $1/m_c$ counting.
  - Heavy quark sum rules.
  - Topologic SU(3)$_F$ breaking.
- Future key observables:
  $A_{CP}(D^0 \to K_S K_S)$, $A_{CP}(D_s \to K^+ \pi^0)$, $A_{CP}(D^+ \to \pi^+ \pi^0)$.