$SU(3)_F$ methods and CPV in D 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	
$\Delta a_{CP}^{dir}(K^+K^-,\pi^+\pi^-)$	-0.00253 ± 0.00104
$\Sigma a_{CP}^{dir}(K^+K^-,\pi^+\pi^-)$	-0.0011 ± 0.0026
$a_{CP}^{dir}(D^0 \to K_S K_S)$	-0.23 ± 0.19
$a_{CP}^{dir}(D^0 \to \pi^0\pi^0)$	-0.0004 ± 0.0064
$a_{CP}^{dir}(D^+ \to \pi^0\pi^+)$	$+0.029 \pm 0.029$
$a_{CP}^{dir}(D^+ \to K_S K^+)$	$+0.0011 \pm 0.0017$
$a_{CP}^{dir}(D_s \to K_S\pi^+)$	$+0.006 \pm 0.005$
$a_{CP}^{dir}(D_s \to K^+\pi^0)$	$+0.266 \pm 0.228$
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

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

Operators

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

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

Data can be described by SU(3)-expansion with SU(3)-Xing $\lesssim 30\%$. ✓

2014: no confirmation of penguin enhancement (yet?)
Let's be prepared for future data

Strategies for insights into strong dynamics

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

➥Get to grips with $\text{SU}(3)_F$ breaking.
➥Finally improve predictions for CP asymmetries.

Taming SU(3)$_F$ breaking

1

Structural form of $\Lambda_{\mathrm{QCD}}/m_c$-expansion

[Beneke Buchalla Neubert Sachrajda 2001]

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

- $\mathcal{T}_A$
  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:

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

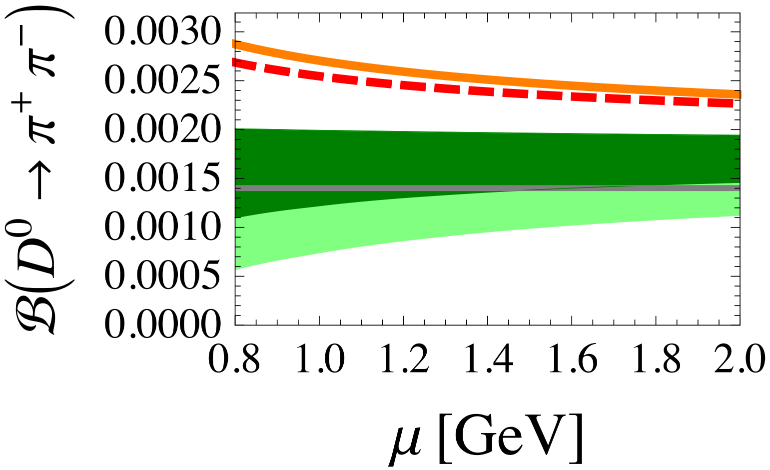
$$\mathcal{A}^{\mathrm{factor}}(D^0 \to \pi^0\pi^0) = -\frac{\Sigma}{\sqrt{2}}\left(a_2^{D\pi\pi} f_\pi (m_D^2 - m_\pi^2) F_0^{D\pi}(m_\pi^2) - f_D f_\pi^2\, b_1^{\pi\pi}\right)$$

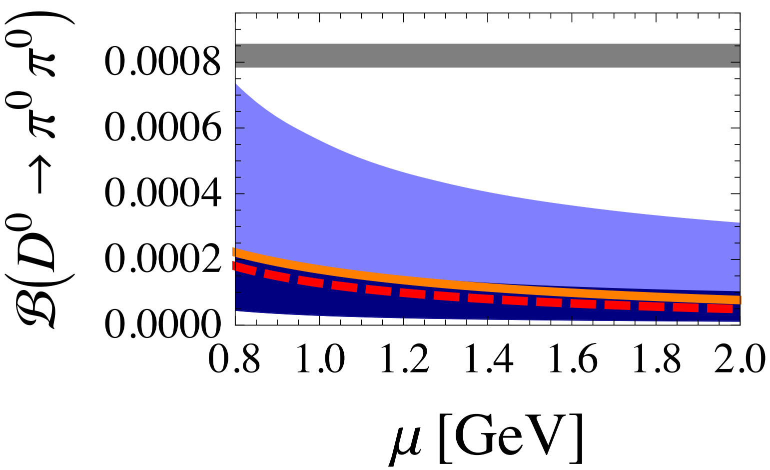
- Assume no enhancement of $SU(3)_F$-breaking penguin here.

Illustration only: $m_c \to \infty$ is not so bad, actually

Zero annihilation: $b_i \to 0$.

$\lambda_{D_{(s)}}$: Parametrization of ignorance of $D_{(s)}$ distribution amplitude.





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.
Orange: N_C-leading contribution only.

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

Heavy Quark Sum Rule

Illustration over.

- Do not calculate a_i, b_i.
- Use parametric dependence of amplitudes on a_i, b_i.
  ↳Eliminate them by linear combinations of amplitudes.

a_1 dominated by leading flavor-universal term.

- $\Rightarrow a_1$ 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 $\Rightarrow$ 1 heavy quark sum rule.

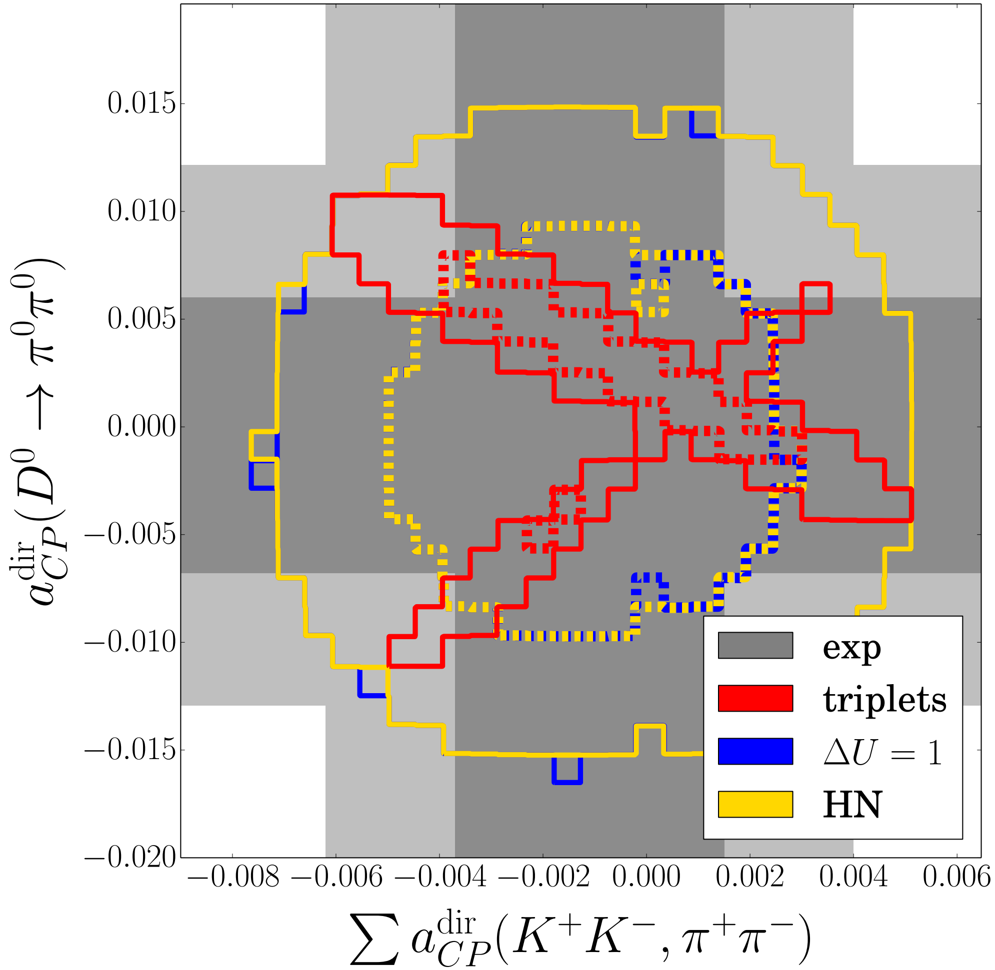
- Eliminate one SU(3)$_F$-breaking matrix element from the fit.
- Do not touch SU(3)$_F$-limit matrix elements.

A_{CP}-Correlations in Plain $SU(3)_F$

[Hiller Jung StS 2014]

[preliminary result]

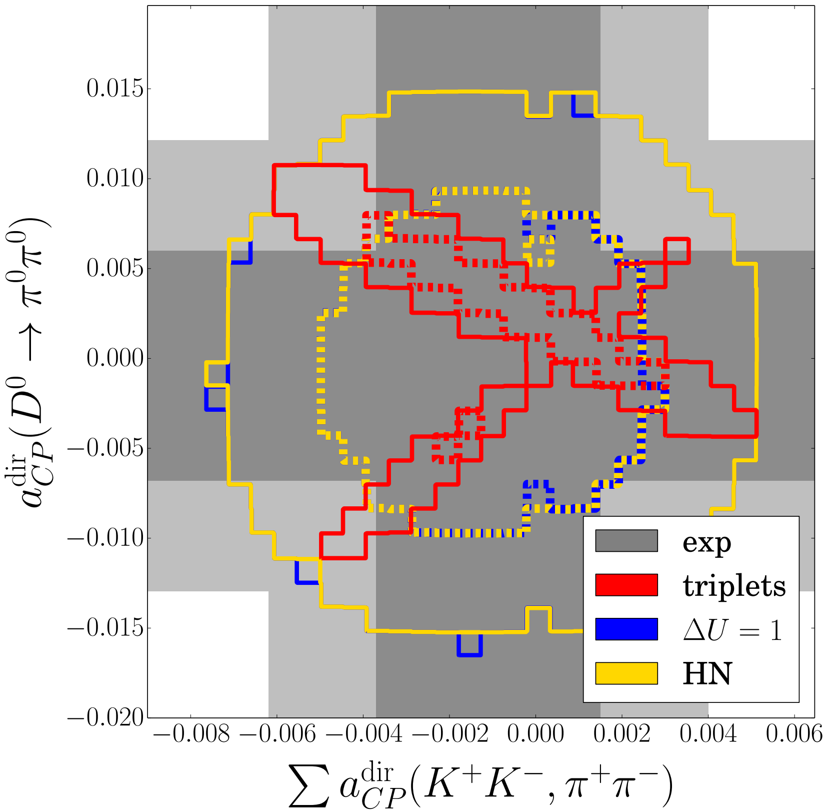
- All data 2014.
- $SU(3)_F$ breaking $\leq 50\%$.
- Red: SM/Triplet model.
  $\mathcal{H}_{\text{SM}} \sim$
  $V_{us}V_{cs}^* \left(\mathbf{15} + \bar{\mathbf{6}}\right) + V_{ub}V_{cb}^* \left(\mathbf{3}\right)$
- Blue/Yellow: NP models.

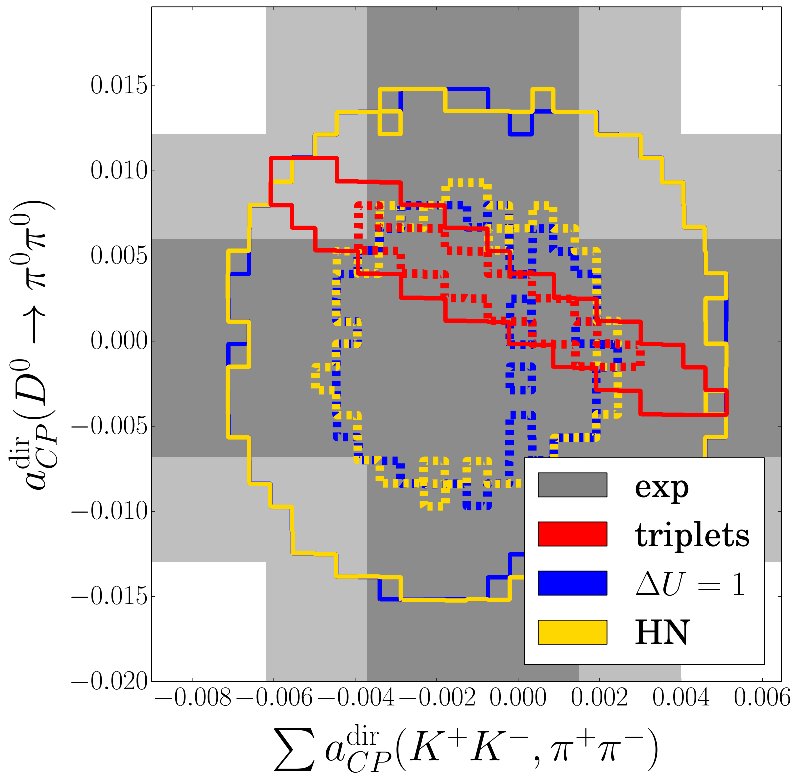


Dynamical Input: One Heavy Quark Sum Rule

[Hiller Jung StS 2014]

[preliminary result]





Plain SU(3)$_F$ (≡ last slide).

Including sum rule from universal a_1.

➥ Remove one solution.

Taming SU(3)_F breaking

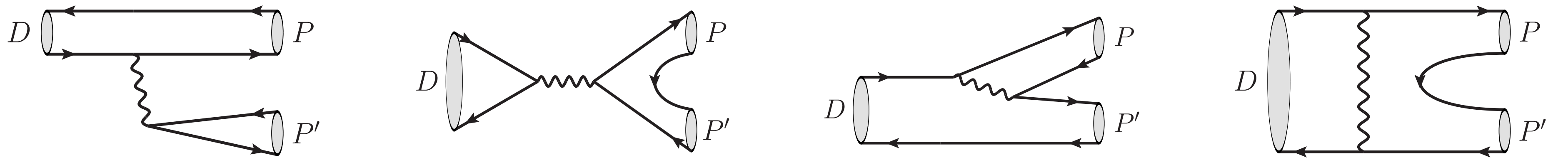
2

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.

T	A	C	E



Topologic SU(3)$_F$ breaking

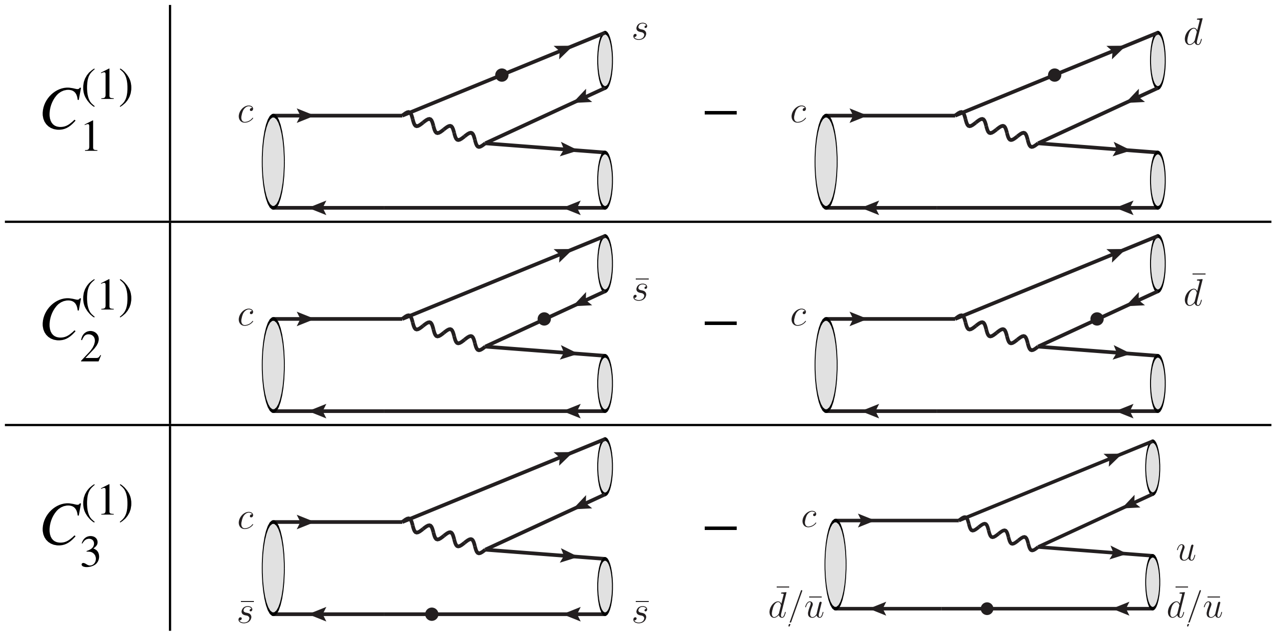
- Mass insertion formalism for difference of s and d quark mass.

[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 $\mathrm{SU}(3)_F$

- Explicit Matching on $\mathrm{SU}(3)_F$ (excerpt).

$\mathrm{SU}(3)_F$ ME	...	E	$E_1^{(1)}$	$E_2^{(1)}$	$E_3^{(1)}$	P^{break}
A_{27}^{15}		0	0	0	0	0
A_8^{15}		$-\frac{5}{2\sqrt{2}}$	$-\frac{5}{3\sqrt{2}}$	$-\frac{5}{6\sqrt{2}}$	0	0
$A_8^{\bar{6}}$		$\frac{\sqrt{5}}{2}$	0	$\frac{\sqrt{5}}{2}$	0	0
B_1^3		0	$\frac{32\sqrt{\frac{35}{421}}}{3}$	$\frac{32\sqrt{\frac{35}{421}}}{3}$	$-\frac{16\sqrt{\frac{35}{421}}}{3}$	$\frac{32\sqrt{\frac{35}{421}}}{3}$
B_8^3		0	$-\frac{20\sqrt{\frac{7}{3937}}}{3}$	$-\frac{20\sqrt{\frac{7}{3937}}}{3}$	$\frac{40\sqrt{\frac{7}{3937}}}{3}$	$\frac{160\sqrt{\frac{7}{3937}}}{3}$
$B_8^{\bar{6}_1}$		0	$20\sqrt{\frac{7}{2869}}$	$-20\sqrt{\frac{7}{2869}}$	0	0
$B_8^{15_1}$		0	$460\sqrt{\frac{7}{1330969}}$	$20\sqrt{\frac{133}{70051}}$	$-840\sqrt{\frac{7}{1330969}}$	0
$B_8^{15_2}$		0	$-20\sqrt{\frac{6}{871}}$	$10\sqrt{\frac{6}{871}}$	$10\sqrt{\frac{6}{871}}$	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. $\delta_X^{\prime,\mathcal{T}} \equiv \max_d \left|\mathcal{A}_X^{\mathcal{T}}(d)/\mathcal{A}(d)\right|$

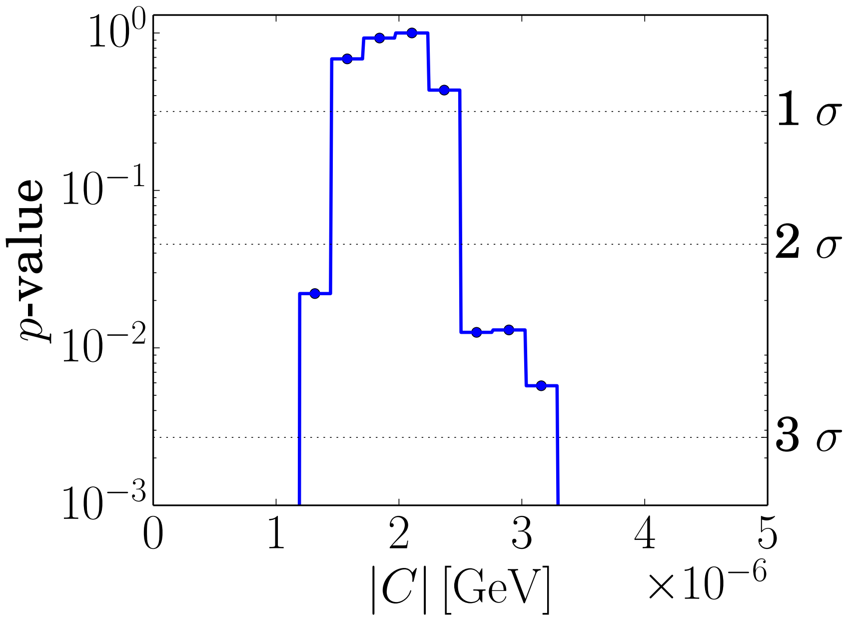
     $\mathcal{T} = C, E, P_{\text{break}}$ and $\mathcal{A}_X^{\mathcal{T}}(d)$ part of amplitude of decay d stemming from corresponding SU(3)$_F$-breaking parameter(s) only.
  2. $\delta_X^{\prime,\text{topo}} \equiv \max_d \left|\sum_{\mathcal{T}} A_X^{\mathcal{T}}(d)/\mathcal{A}(d)\right|$

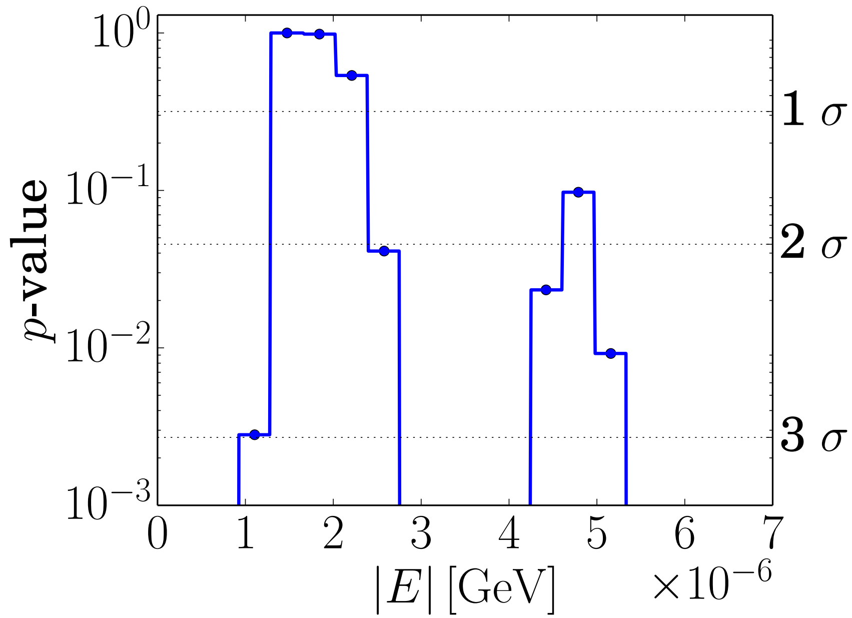
     overall amount of SU(3)$_F$ breaking introduced by all linear corrections to the topologies C, E and P_{break}.
  3. $\delta_X^{C_i/C} \equiv |C_i/C|$
  4. $\delta_X^{E_i/E} \equiv |E_i/E|$

Fit the Topologies

[Müller Nierste StS 2014]

[preliminary results]





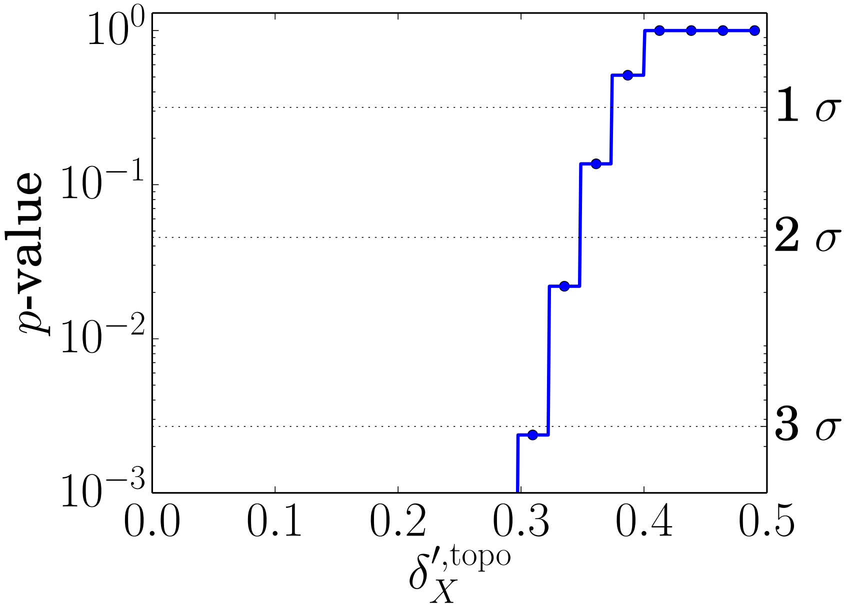
- SU(3)$_F$-breaking measures $\leq 50\%$ $\Rightarrow$ reasonable SU(3)$_F$ expansion.
- $T_{i\to f}$ and $A_{i\to f}$ calculated in factorization.
- Perfect fit to branching ratios: $\chi^2 \sim 0$.

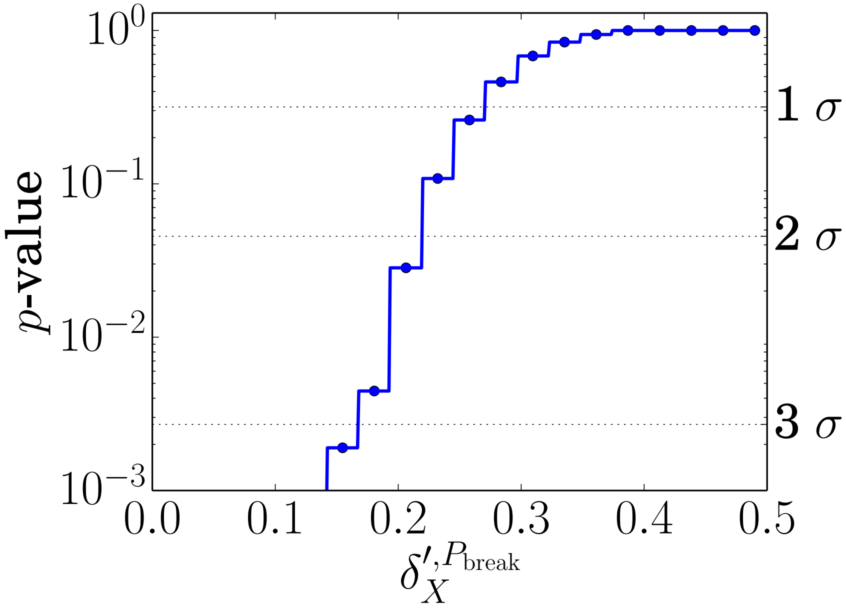
Interpret SU(3)$_F$ breaking in the topologic approach

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

[Müller Nierste StS 2014]

[preliminary result]





➥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:

$$A_{CP}(D^0 \to K_S K_S), \quad A_{CP}(D_s \to K^+ \pi^0), \quad A_{CP}(D^+ \to \pi^+ \pi^0)$$
$$A_{CP}(D^0 \to \pi^0 \pi^0), \quad A_{CP}(D^0 \to K^+ K^-), \quad A_{CP}(D^0 \to \pi^+ \pi^-).$$