

# SU(3)<sub>F</sub> breaking in Charm Physics

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based on works with S. Müller and 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	
$\Delta a_{CP}^{\text{dir}}(K^+ K^-, \pi^+ \pi^-)$	$-0.00253 \pm 0.00104$
$\Sigma a_{CP}^{\text{dir}}(K^+ K^-, \pi^+ \pi^-)$	$-0.0011 \pm 0.0026$
$a_{CP}^{\text{dir}}(D^0 \rightarrow K_S K_S)$	$-0.23 \pm 0.19$
$a_{CP}^{\text{dir}}(D^0 \rightarrow \pi^0 \pi^0)$	$-0.0004 \pm 0.0064$
$a_{CP}^{\text{dir}}(D^+ \rightarrow \pi^0 \pi^+)$	$+0.029 \pm 0.029$
$a_{CP}^{\text{dir}}(D^+ \rightarrow K_S K^+)$	$+0.0011 \pm 0.0017$
$a_{CP}^{\text{dir}}(D_s \rightarrow K_S \pi^+)$	$+0.006 \pm 0.005$
$a_{CP}^{\text{dir}}(D_s \rightarrow K^+ \pi^0)$	$+0.266 \pm 0.228$
Indirect CP violation	
$a_{CP}^{\text{ind}}$	$0.00013 \pm 0.00052$
$\delta_L \equiv 2\text{Re}(\varepsilon)/(1 +  \varepsilon ^2)$	$(3.32 \pm 0.06) \cdot 10^{-3}$
$K^+ \pi^-$ strong phase difference	
$\delta_{K\pi}$	$(6.45 \pm 10.65)^\circ$

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

# Symmetry emergency kit: $SU(3)_F$



## States

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

## Operators

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

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

2014: no confirmation of penguin enhancement (yet?)

Let's be prepared for future data



## Strategy

[Müller Nierste StS 2015]

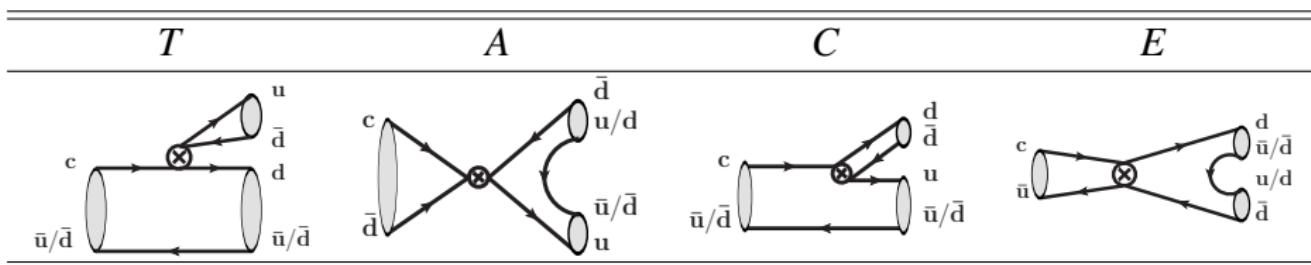
- $1/N_c$  + diagrammatic  $SU(3)_F$  breaking.
- Improve predictions for CP asymmetries without assumptions on penguins.

➡ Obtain future **new physics tests**.

# Diagrammatic approach: Flavor-flow diagrams

[Chau 1980/83, Zeppenfeld 1981, Gronau Hernandez London Rosner 1995, Buras Silvestrini 1998, Bhattacharya Gronau Rosner 2012]

- The language of  $SU(3)_F$  matrix elements does not give insight into dynamics of large  $\cancel{SU(3)_F}$ .
- Solution: **Equivalent** diagrammatic parameterization.
- Important: **Include  $\cancel{SU(3)_F}$**  in a meaningful way.



# Diagrammatic $SU(3)_F$ breaking

- Feynman rule for first order  $\cancel{SU(3)_F}$ .

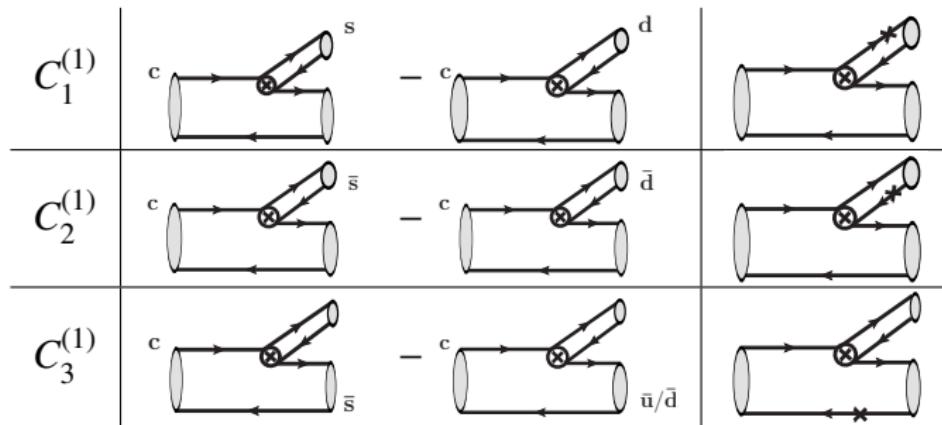
[Gronau Hernandez London Rosner 1995]

- 3 diagrams for each  $T, C, E, A$  +  $\cancel{SU(3)_F}$  penguin  $P_{\text{break}} \equiv P_d - P_s$ .

[Brod Grossman Kagan Zupan 2012]

- Dynamical input:

Chance to constrain  $\cancel{SU(3)_F}$  in each topology (!)



# Diagrammatic Parameterization (excerpt)

Decay $d$	$T$	$T_1^{(1)}$	$T_2^{(1)}$	$T_3^{(1)}$	$A$	$A_1^{(1)}$	$A_2^{(1)}$	$A_3^{(1)}$	$C$	$C_1^{(1)}$	$C_2^{(1)}$	$C_3^{(1)}$	...
SCS													
$D^0 \rightarrow K^+ K^-$	1	1	1	0	0	0	0	0	0	0	0	0	...
$D^0 \rightarrow \pi^+ \pi^-$	-1	0	0	0	0	0	0	0	0	0	0	0	...
$D^0 \rightarrow \bar{K}^0 K^0$	0	0	0	0	0	0	0	0	0	0	0	0	...
$D^0 \rightarrow \pi^0 \pi^0$	0	0	0	0	0	0	0	0	$-\frac{1}{\sqrt{2}}$	0	0	0	...
$D^+ \rightarrow \pi^0 \pi^+$	$-\frac{1}{\sqrt{2}}$	0	0	0	0	0	0	0	$-\frac{1}{\sqrt{2}}$	0	0	0	...
$D^+ \rightarrow \bar{K}^0 K^+$	1	1	1	0	-1	0	0	-1	0	0	0	0	...
$D_s \rightarrow K^0 \pi^+$	-1	0	0	-1	1	1	1	0	0	0	0	0	...
$D_s \rightarrow K^+ \pi^0$	0	0	0	0	$-\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$	$-\frac{1}{\sqrt{2}}$	0	$-\frac{1}{\sqrt{2}}$	0	0	$-\frac{1}{\sqrt{2}}$	...
CF													
$D^0 \rightarrow K^- \pi^+$	1	1	0	0	0	0	0	0	0	0	0	0	...
$D^0 \rightarrow \bar{K}^0 \pi^0$	0	0	0	0	0	0	0	0	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	0	0	...
$D^+ \rightarrow \bar{K}^0 \pi^+$	1	1	0	0	0	0	0	0	1	1	0	0	...
$D_s \rightarrow \bar{K}^0 K^+$	0	0	0	0	1	1	0	1	1	1	0	1	...
DCS													
$D^0 \rightarrow K^+ \pi^-$	1	0	1	0	0	0	0	0	0	0	0	0	...
$D^0 \rightarrow K^0 \pi^0$	0	0	0	0	0	0	0	0	$\frac{1}{\sqrt{2}}$	0	$\frac{1}{\sqrt{2}}$	0	...
$D^+ \rightarrow K^0 \pi^+$	0	0	0	0	1	0	1	0	1	0	1	0	...
$D^+ \rightarrow K^+ \pi^0$	$\frac{1}{\sqrt{2}}$	0	$\frac{1}{\sqrt{2}}$	0	$-\frac{1}{\sqrt{2}}$	0	$-\frac{1}{\sqrt{2}}$	0	0	0	0	0	...
$D_s \rightarrow K^0 K^+$	1	0	1	1	0	0	0	0	1	0	1	1	...

# Equivalence to $SU(3)_F$

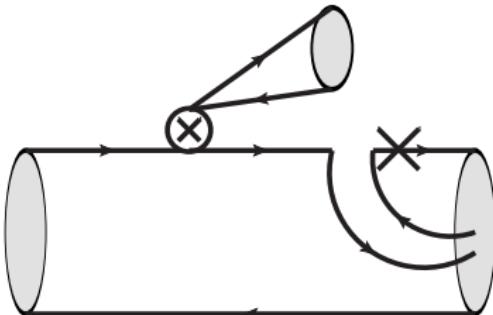
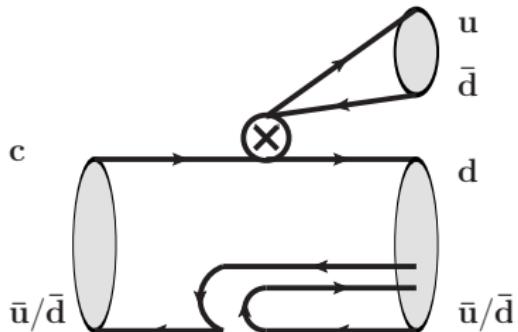
- Diagrammatic parameterization  $\Leftrightarrow$  matrix which expresses decay amplitudes in terms of  $SU(3)_F$  matrix elements.
- Same rank. Same 6 sum rules. Explicit matching (excerpt):

$SU(3)_F$ ME	...	$E$	$E_1^{(1)}$	$E_2^{(1)}$	$E_3^{(1)}$	$P^{\text{break}}$
$A_{27}^{15}$	...	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

# Consequences of Equivalence to $SU(3)_F$

- Contributions from **additional diagrams** cannot be algebraically independent.
- All further diagrammatic contributions can be **absorbed**.
- Example: Contributions from **higher Fock states**:

$$|K^0\rangle = |d\bar{s}\rangle + |d\bar{s}g\rangle + |d\bar{s}u\bar{u}\rangle + \dots$$



# Theoretical Input I

Corrections to  $T$  and  $A$  diagrams  $1/N_c^2$  suppressed.

- Factorization good approximation.
- Fit  $1/N_c$  breaking by nuisance parameter  $(1 + k) \times T$ ,  
 $0 \leq |k| \leq 10\%$ ,  $0 \leq \arg(k) \leq 2\pi$ .

Examples:

$$T_{D^0 \rightarrow K^+ K^-}^{\text{fac}} = (1 + k) \Sigma \frac{iG_F}{\sqrt{2}} a_1 f_K (m_D^2 - m_K^2) F_0^{DK}(m_K^2),$$
$$T_{D^0 \rightarrow \pi^+ \pi^-}^{\text{fac}} = -(1 + k) \Sigma \frac{iG_F}{\sqrt{2}} a_1 f_\pi (m_D^2 - m_\pi^2) F_0^{D\pi}(m_\pi^2).$$

## Theoretical Input II

Diagrammatic measures of  $SU(3)_F$  breaking  $\leq 50\%$

①  $\delta_X'^{\mathcal{T}} \equiv \max_d |\mathcal{A}_X^{\mathcal{T}}(d)/\mathcal{A}(d)|, \quad \mathcal{T} = C, E, P_{\text{break}}$

individual amount of  $\cancel{SU(3)_F}$  by topology  $\mathcal{T}$ .

②  $\delta_X'^{\text{topo}} \equiv \max_d \left| \sum_{\mathcal{T}} A_X^{\mathcal{T}}(d) / \mathcal{A}(d) \right|$

overall amount of  $\cancel{SU(3)_F}$ .

③  $\delta_X^{C_i/C} \equiv |C_i/C| \quad \cancel{SU(3)_F}$  in  $C$ -parameters.

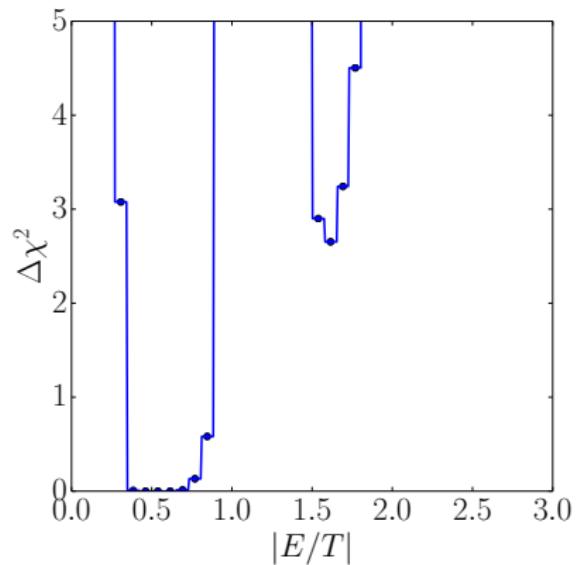
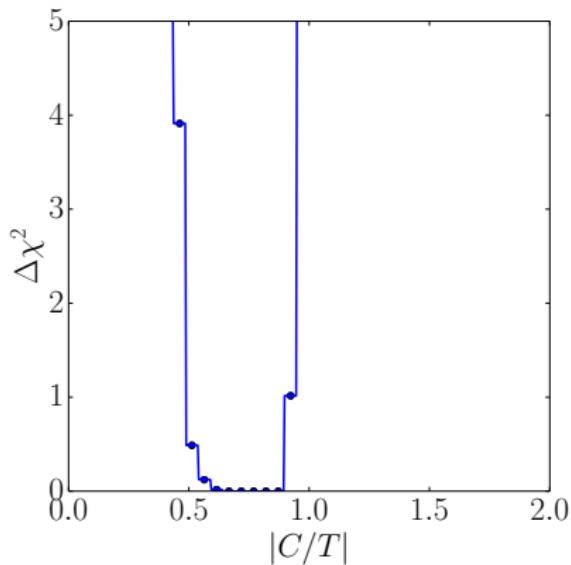
④  $\delta_X^{E_i/E} \equiv |E_i/E| \quad \cancel{SU(3)_F}$  in  $E$ -parameters.

$\mathcal{A}_X^{\mathcal{T}}(\textcolor{red}{d})$ :  $\cancel{SU(3)_F}$  part of the amplitude of decay  $\textcolor{red}{d}$   
stemming from topology  $\mathcal{T}$ .

# Branching Ratio Fit of Diagrammatic Parameterization

[Müller Nierste StS 2015]

[preliminary results]

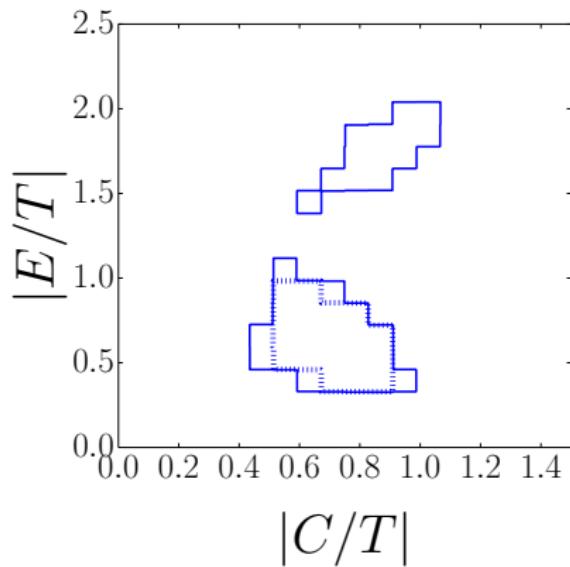
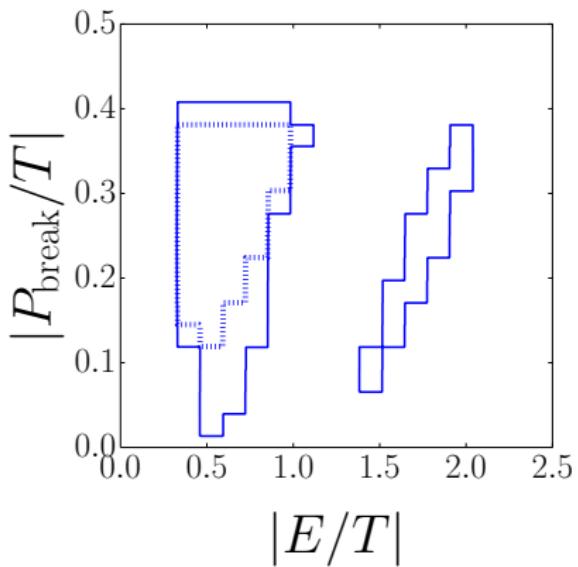


- Perfect fit to branching ratios:  $\chi^2 \sim 0$ , due to under-determined problem.

# Broad and Multiple Fit Solutions

[Müller Nierste StS 2015]

[preliminary results]



# Relative Importance of Diagrams: Likelihood Ratio Tests

[Müller Nierste StS 2015]

[preliminary results]

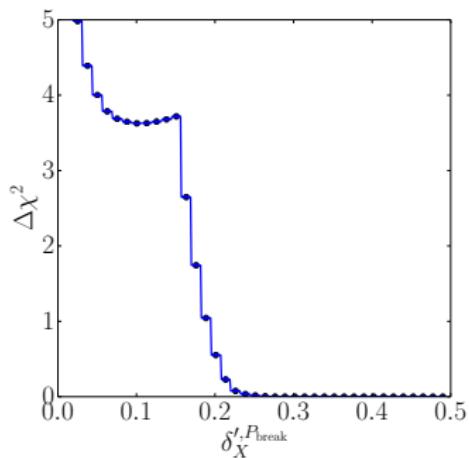
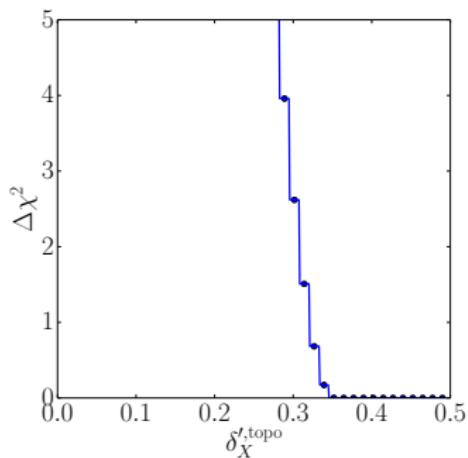
Hypothesis	Significance of rejection	$\chi^2$
$P_{\text{break}} = 0$	$2.1\sigma$	6.8
$P_{\text{break}} = E_i = C_i = 0 \forall i$	$> 5\sigma$	547.4
$E_i = 0 \forall i$	$3.6\sigma$	25.3
$E = E_i = 0 \forall i$	$> 5\sigma$	155.4
$C_i = 0 \forall i$	$5.0\sigma$	39.5
$C = C_i = 0 \forall i$	$> 5\sigma$	376767.4

- Clear need for  $SU(3)_F$  breaking.
- Especially in the color suppressed diagrams.

# Size of $SU(3)_F$ breaking: $\delta_X'^{\text{topo}} \sim 30\%$

[Müller Nierste StS 2015]

[preliminary results]



- $\delta_X'^{\text{topo}}$ : maximal  $SU(3)\cancel{F}$  part of amplitudes.
- Individual  $SU(3)_F$  breaking may be smaller.
- Allowed at  $1\sigma$ :  $|E_3/E| \sim 0\%$ ,  $\delta_X'^C \sim 20\%$  or  $\delta_X'^E \sim 10\%$ , respectively.

# Predict $a_{CP}^{\text{dir}}(D^0 \rightarrow \pi^0\pi^0)$

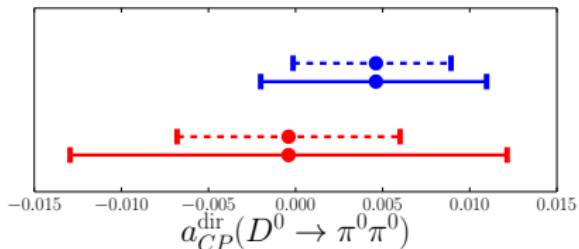
[Müller Nierste StS 2015]

## Input

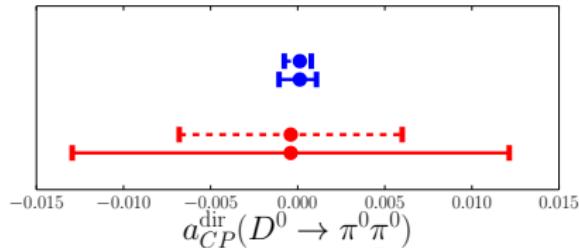
- Branching ratio fit.
- Correlation with measured  $a_{CP}^{\text{dir}}(D^0 \rightarrow K^+K^-)$ ,  $a_{CP}^{\text{dir}}(D^0 \rightarrow \pi^+\pi^-)$ .

↳ Blue: SM prediction. Red: Current measurement. [preliminary results]

Current data



$$a_{CP}^{\text{dir}}(d) = 0, \text{ errors } \times 1/\sqrt{50}$$



# Predict $a_{CP}^{\text{dir}}(D_s \rightarrow K^+ \pi^0)$

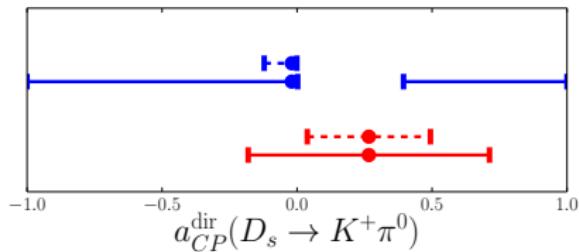
[Müller Nierste StS 2015]

## Input

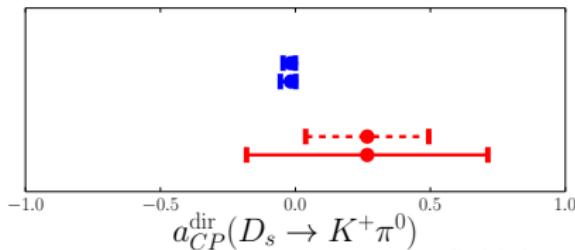
- Branching ratio fit.
- Correlation with measured  $a_{CP}^{\text{dir}}(D^+ \rightarrow K_S K^+)$ ,  $a_{CP}^{\text{dir}}(D_s \rightarrow K_S \pi^+)$ .

↳ Blue: SM prediction. Red: Current measurement. [preliminary results]

Current data



$\mathcal{B}$  errors  $\times 1/\sqrt{50}$



# Conclusion

- Charm physics remains **a fast-moving field**.
- **Symmetry correlations** between different channels.
  - ↳ Possible future **new physics tests**.
- Improved **branching ratio** measurements improve predictions for **CP asymmetries**.
- Further improvement through measurement of **correlated CP asymmetries**.
- Future **key observables**:  
 $A_{CP}(D^0 \rightarrow K_S K_S)$ ,  $A_{CP}(D_s \rightarrow K^+ \pi^0)$ ,  $A_{CP}(D^+ \rightarrow \pi^+ \pi^0)$   
 $A_{CP}(D^0 \rightarrow \pi^0 \pi^0)$ ,  $A_{CP}(D^0 \rightarrow K^+ K^-)$ ,  $A_{CP}(D^0 \rightarrow \pi^+ \pi^-)$ .