Theoretical status of two-body charm decays

Stefan Schacht
Università di Torino & INFN Sezione di Torino

Towards the Ultimate Precision in Flavour Physics

Warwick, UK, 16-18 April 2018

based on:

Phys. Rev. Lett. **119**, no. 25, 251801 (2017) [arXiv:1708.03572],
Phys. Rev. Lett. **115**, no. 25, 251802 (2015) [arXiv:1506.04121],
Phys. Rev. D **92**, no. 5, 054036 (2015) [arXiv:1508.00074],
Phys. Rev. D **92**, no. 1, 014004 (2015) [arXiv:1503.06759],
Phys. Rev. D **87**, no. 1, 014024 (2013) [arXiv:1211.3734]

Recent experimental achievements

Status of ΔA_{CP}: Waiting for run 2 update

$$\Delta a_{CP}^{\text{dir}} \equiv a_{CP}^{\text{dir}}(D^0 \to K^+K^-) - a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)$$
$$= -0.00134 \pm 0.00070\,,$$ [HFLAV av. 08/17]

including the two 3fb^{-1} LHCb measurements with different techniques:

$$\Delta A_{CP} = +0.0014 \pm 0.0016 \pm 0.0008\,,$$ [$B \to D^0 \mu X$, LHCb 1405.2797]

$$\Delta A_{CP} = -0.0010 \pm 0.0008 \pm 0.0003\,.$$ [prompt D^*, LHCb 1602.03160]

Recent improvements in New Physics and Observation Channels

$$a_{CP}^{\text{dir}}(D^+ \to \pi^+\pi^0) = +0.0231 \pm 0.0124 \pm 0.0023$$ [Belle 1712.00619]

$$A_{CP}(D^0 \to K_S K_S) = -0.029 \pm 0.052 \pm 0.022$$ [LHCb 3fb^{-1} 1508.06087]

$$A_{CP}(D^0 \to K_S K_S) = -0.0002 \pm 0.0153 \pm 0.0002 \pm 0.0017$$ [Belle 1705.05966]

Please improve $A_{CP}(D_s^+ \to K^+\pi^0) = -0.266 \pm 0.238 \pm 0.009\,.$ [CLEO 0906.3198]

Problems for Theory

Disentangle QCD-Effects from New Physics

Bound state effects of the strong interaction (old physics) or new physics beyond the Standard Model?

$$B^0 = \bar{b}d \qquad\qquad D^0 = c\bar{u}$$

Reduced theory toolbox for charm decays

- Charm is not really heavy compared to Λ_{QCD}.
- Perturbative expansion in $\Lambda_{\mathrm{QCD}}/m_c$ will not work.
- We cannot calculate so many things.

CKM structure of SCS D decays

For SCS decays:

$$\mathcal{A} = \lambda_{sd}\mathcal{A}_{sd} - \frac{\lambda_b}{2}\mathcal{A}_b$$

Direct CP asymmetry:

$$a_{CP}^{\rm dir} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} = \mathrm{Im}\frac{\lambda_b}{\lambda_{sd}}\mathrm{Im}\frac{\mathcal{A}_b}{\mathcal{A}_{sd}}$$

- $\lambda_q \equiv V_{cq}^* V_{uq}\,, \quad q = d, s, b\,, \quad \lambda_{sd} \equiv (\lambda_s - \lambda_d)/2\,, \quad \lambda_d + \lambda_s + \lambda_b = 0.$
- $|\mathcal{A}_{sd}|$ fixed from measured branching ratios.
- Need $|\mathcal{A}_b|$ and phase $\arg\left(\frac{\mathcal{A}_b}{\mathcal{A}_{sd}}\right)$ to predict $a_{CP}^{\rm dir}$.

$SU(3)_F$ symmetry

Approximate $SU(3)_F$ symmetry of QCD:
Because of $m_{u,d,s} \ll \Lambda_{\mathrm{QCD}}$ the hadronic amplitudes are approximately invariant under unitary rotations of

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix} .$$

➥Correlations between various $D \to K\pi$ decays.

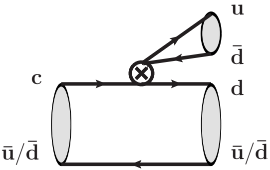
Example: In the limit of exact $SU(3)_F$ symmetry :

$$\mathcal{A}_{sd}(D^0 \to \pi^+\pi^-) = -\mathcal{A}_{sd}(D^0 \to K^+K^-) .$$

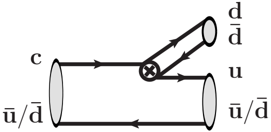
Topological Amplitudes

[Chau 1980,1982; Zeppenfeld 1981, Buras Silvestrini 1998]

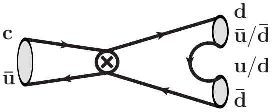
SU(3)$_F$ limit amplitudes contributing to A_{sd} :



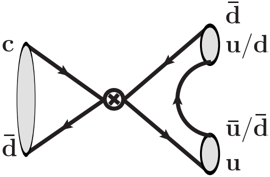
tree (T)



color-suppressed tree (C)



exchange (E)

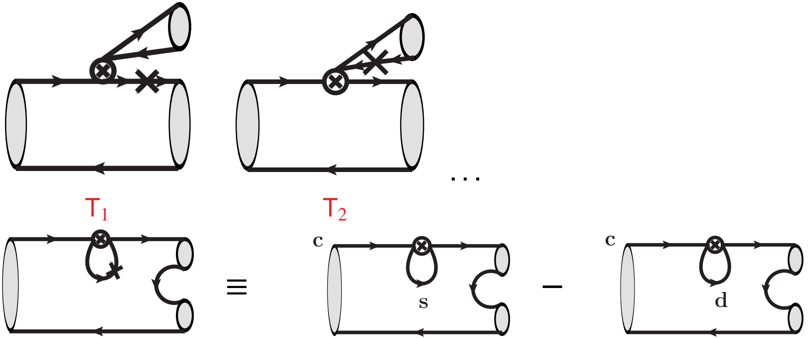


annihilation (A)

Diagrammatic SU(3)$_F$ breaking

- Feynman rule from $H_{\cancel{SU(3)}_F} = (m_s - m_d)\bar{s}s$: dot on s-quark line. [Gronau 1995]
- Find 14 new topological amplitudes:
  3 diagrams for each T, C, E, A; $P_{\text{break}} \equiv P_d - P_s$; $PA_{\text{break}} \equiv PA_d - PA_s$.

[Brod Grossman Kagan Zupan 2012]



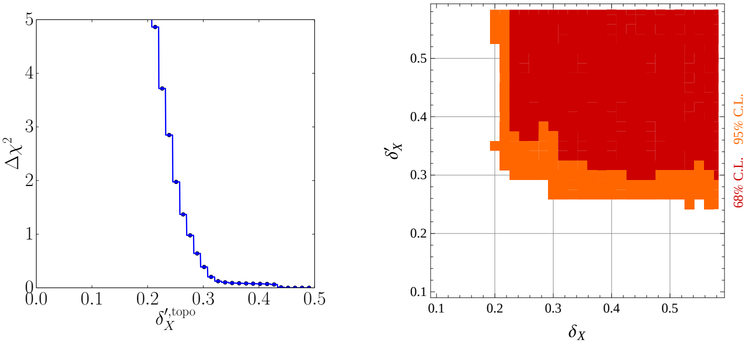
penguin (P_{break})

Most general 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													
$D^0 \to K^+K^-$	1	1	1	0	0	0	0	0	0	0	0	0	...
$D^0 \to \pi^+\pi^-$	-1	0	0	0	0	0	0	0	0	0	0	0	...
$D^0 \to \bar{K}^0K^0$	0	0	0	0	0	0	0	0	0	0	0	0	...
$D^0 \to \pi^0\pi^0$	0	0	0	0	0	0	0	0	$-\frac{1}{\sqrt{2}}$	0	0	0	...
$D^+ \to \pi^0\pi^+$	$-\frac{1}{\sqrt{2}}$	0	0	0	0	0	0	0	$-\frac{1}{\sqrt{2}}$	0	0	0	...
$D^+ \to \bar{K}^0K^+$	1	1	1	0	-1	0	0	-1	0	0	0	0	...
$D_s \to K^0\pi^+$	-1	0	0	-1	1	1	1	0	0	0	0	0	...
$D_s \to K^+\pi^0$	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													
$D^0 \to K^-\pi^+$	1	1	0	0	0	0	0	0	0	0	0	0	...
$D^0 \to \bar{K}^0\pi^0$	0	0	0	0	0	0	0	0	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	0	0	...
$D^+ \to \bar{K}^0\pi^+$	1	1	0	0	0	0	0	0	1	1	0	0	...
$D_s \to \bar{K}^0K^+$	0	0	0	0	1	1	0	1	1	1	0	1	...
DCS													
$D^0 \to K^+\pi^-$	1	0	1	0	0	0	0	0	0	0	0	0	...
$D^0 \to K^0\pi^0$	0	0	0	0	0	0	0	0	$\frac{1}{\sqrt{2}}$	0	$\frac{1}{\sqrt{2}}$	0	...
$D^+ \to K^0\pi^+$	0	0	0	0	1	0	1	0	1	0	1	0	...
$D^+ \to K^+\pi^0$	$\frac{1}{\sqrt{2}}$	0	$\frac{1}{\sqrt{2}}$	0	$-\frac{1}{\sqrt{2}}$	0	$-\frac{1}{\sqrt{2}}$	0	0	0	0	0	...
$D_s \to K^0K^+$	1	0	1	1	0	0	0	0	1	0	1	1	...

Calculate T and A using $1/N_c$ input. Fit the rest from branching ratio data.

Quantify SU(3)$_F$-breaking

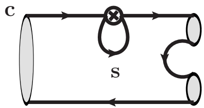


- Data shows at least $\mathcal{O}(30\%)$ SU(3)$_F$ breaking in the decay amplitudes.
- The SU(3)$_F$ limit is ruled out by more than 5σ .
- Not possible to determine upper bound just from a fit to data:
  Fit allows also for larger SU(3)$_F$ breaking.
  (And of course even for an inversion of the meaning of parameters.)

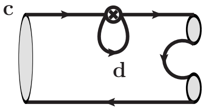
Problem of CP Asymmetry Predictions:

- New hadronic quantities appear which cannot be extracted from $\mathcal{B}$ measurements.

- $\mathcal{B}$'s involve only

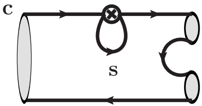


−

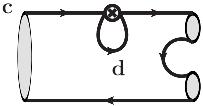


$\Rightarrow$ Difference can be extracted.

- A_{CP}'s involve also



+



The sum is **unknown.**

[Brod, Grossman, Kagan, Zupan 2012]

Solution: CP asymmetry sum rules

Strategy: Sum rules among CP asymmetries.

- Build combinations out of several CP asymmetries...
- ...containing only those topological amplitudes in coefficients which can be extracted from the global fit to the branching ratios.

Extent known SU(3)$_F$ limit sum rules

[see, *e.g.*, Grossman Kagan Nir 2006, Hiller Jung Schacht 2012, Grossman Ligeti Robinson 2014]

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

valid at zeroth order SU(3)$_F$ breaking.

- Include corrections of sum rules due to SU(3)$_F$ breaking in the CKM-leading part of the amplitude...

⇒Sum rules correlating three direct CP asymmetries

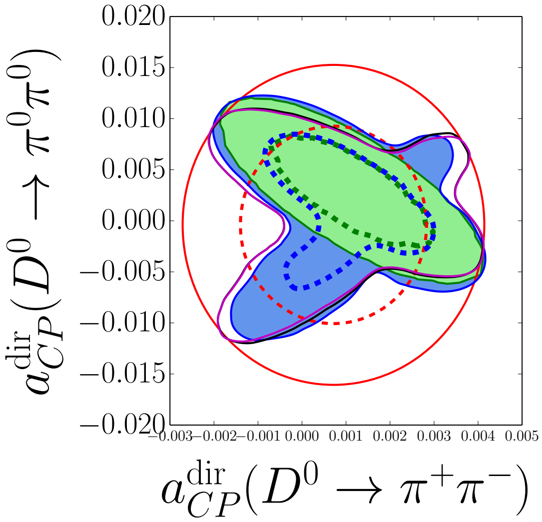
I $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to \pi^0\pi^0$,
and
II $D^+ \to \overline{K}^0K^+$, $D_s^+ \to K^0\pi^+$, and $D_s^+ \to K^+\pi^0$.

- Note: Still works to zeroth order in SU(3)$_F$ breaking only, as SU(3)$_F$ breaking in CKM-subleading part of amplitudes is not taken into account, e.g. SU(3)$_F$ breaking of $P_s + P_d$.
- Still: theoretical accuracy of new-physics tests only limited by the assumed size of SU(3)$_F$ breaking, i.e. generically $\mathcal{O}(30\%)$.
- Great progress compared to spread of past predictions.

Shopping list for NP tests

- Please test sum rules with improved measurements of A_{CP} **and** $\mathcal{B}$'s.
- Sum rule II only useful with improved measurement of $A_{CP}(D_s^+ \to K^+\pi^0) = -0.266 \pm 0.238 \pm 0.009$ [CLEO 0906.3198] **and** $\mathcal{B}$'s.

Sum rules induce nontrivial correlations



Red solid:
95% CL measurement

Red dashed:
68% CL measurement

Present data:

Light blue:
95% CL from global fit

Dark blue dashed:
68% CL from global fit

Future scenario:
assume $\sqrt{50}$ better branching ratios, but $a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-)$ as today.

Light green:
95% CL from global fit

Dark green dashed:
68% CL from global fit

Two different scientific goals

Data does not show order-of-magnitude enhancement over SM estimate

$$a_{CP}^{\mathrm{dir}} = \mathrm{Im}\frac{\lambda_b}{\lambda_{sd}}\mathrm{Im}\frac{A_b}{A_{sd}} = -6\cdot 10^{-4}\cdot \mathrm{Im}\frac{A_b}{A_{sd}}\,.$$

1) Discover charm CP violation.

➥Need decay mode with large SM prediction for a_{CP}^{dir}.

2) Falsify the SM.

➥Need decay mode with clean SM predictions for a_{CP}^{dir}, or sum rules.

Charm CPV Discovery Modes I: $D^0 \to K_S K_S$

$$\mathcal{A}(D^0 \to K_S K_S) = \lambda_{sd}\mathcal{A}_{sd} - \frac{\lambda_b}{2}\mathcal{A}_b \qquad |a_{CP}^{\text{dir}}| \leq 1.1\% \quad \text{@95\% CL}$$

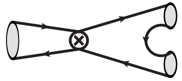
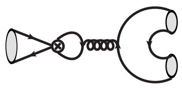
including $1/N_c$ color counting hierarchies: $|a_{CP}^{\text{dir}}| \leq 0.6\%$.

Special Feature 1

- In the SU(3)$_F$ limit $\mathcal{A}_{sd} = 0$ while $\mathcal{A}_b \neq 0$.

➥ Suppressed $\mathcal{B}(D^0 \to K_S K_S)$, enhanced $a_{CP}^{\text{dir}} \propto \text{Im}(A_b/A_{sd})$.

Special Feature 2

- a_{CP}^{dir} from sizable tree level exchange diagrams. 
- Even if penguin topology vanishes! 

Advantage compared to $a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)$ and $a_{CP}^{\text{dir}}(D^0 \to K^+K^-)$, i.e., ΔA_{CP}.

Charm CPV Discovery Modes II: $D^0 \to K_S K^{0*}$

Additional features compared to $D^0 \to K_S K_S$ [first steps: LHCb 1509.06628]

Probably best charm CP discovery channel.

Special Feature 3

- Prompt decay $K^{0*} \to K^+\pi^-$ with charged tracks helps in the experiment, since K_S lives too long.

Special Feature 4

- In Dalitz plot analysis one can explore the region of $K^+\pi^-$ invariant mass a bit away from the K^{*0} resonance to hunt for favorable strong phases which maximise a_{CP}^{dir}.

Special Feature 5

- No flavor tagging needed, essentially undiluted untagged CP asym.:

$$a_{CP}^{\mathrm{dir}}(\overset{(-)}{D} \to K_S K^{*0}) \approx a_{CP}^{\mathrm{dir}}(D^0 \to K_S K^{0*}) \leq 0.3\% \,.$$

Interesting new routes to a better understanding of QCD relevant for Charm

- First conceptual steps on the lattice: [Hansen Sharpe 1204.0826]
  Generalization of Lellouch-Lüscher formula.
  Possible application to charm: long-term endeavor.

- Applying QCD light-cone sum rules + quark-hadron duality.
  $\Rightarrow$ Prediction: $|\Delta a_{\mathrm{CP}}^{\mathrm{dir}}| < 0.00020 \pm 0.00003$ [Khodjamirian Petrov 1706.07780]

Conclusion: Goals of the Charm CP Physics Program

1) Discover charm CP violation.

➥Need decay mode with large SM prediction for a_{CP}^{dir}.

Discovery modes: $D^0 \to K_S K_S$ and $D^0 \to K_S K^{0*}$.

$$a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S) \leq 1.1\% \qquad a_{CP}^{\mathrm{dir}}(\overset{(-)}{D} \to K_S K^{*0}) \leq 0.3\%$$

- $a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)$ dominated by tree level exchange diagrams: No penguins needed $\Rightarrow$ No loop suppression.
- No flavor tagging required for $D^0 \to K_S K^{0*}$.

2) Falsify the SM.

➥Need decay mode with clean SM predictions for a_{CP}^{dir}, or sum rules.

"null test" mode $A_{CP}(D^+ \to \pi^+\pi^0)$,

1) Sum rule $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$,

2) Sum rule $D^+ \to \overline{K}^0 K^+$, $D_s^+ \to K^0\pi^+$, $D_s^+ \to K^+\pi^0$.

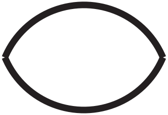
BACK-UP

't Hooft 1974: Study $SU(3)_C \Rightarrow SU(N_c)_C$

N_c = number of colors.

- Asymptotic freedom ⇒ Expansion in $\alpha_s(\mu)$ works for high energies.
- Breaks down for low energy QCD ⇒ Nonperturbative regime.
- Consider $N_c \to \infty$ and expand in $1/N_c$.
- $g = g_0/\sqrt{N_c}$, $g^2 \sim 1/N_c$.

gluon vertex:  $\mathcal{O}(1/\sqrt{\mathbf{N_c}})$

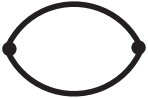
closed loop:  $\mathcal{O}(\mathbf{N_c})$

meson vertex:  $\mathcal{O}(1/\sqrt{\mathbf{N_c}})$

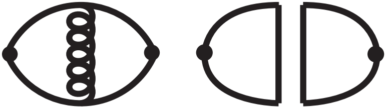
['t Hooft 1974, Buras Gerard Rückl 1986]

$1/N_c$ power counting for charm

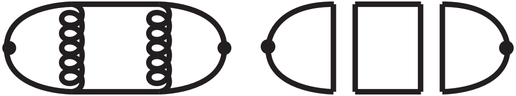
Corrections of the same order: ['t Hooft 1974, Buras Gerard Rückl 1986]



$\mathcal{O}(\mathbf{N_c})$

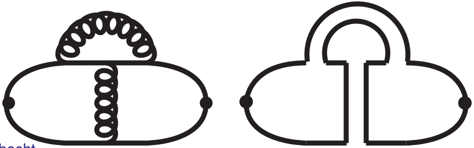


$\mathcal{O}(\mathbf{N_c})$



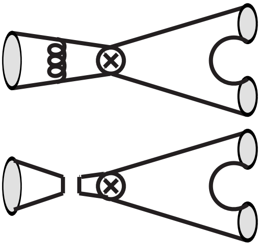
$\mathcal{O}(\mathbf{N_c})$

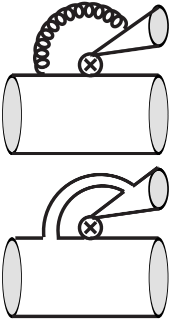
Suppressed corrections:



$\mathcal{O}(\mathbf{1/N_c})$

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





same order in $1/N_c$

$\Rightarrow$ fit E.

$1/N_c^2$-suppressed.

$\Rightarrow$ fit $\delta_T \leq 15\%$ in $T = T^{\text{fac}}(1+\delta_T)$,

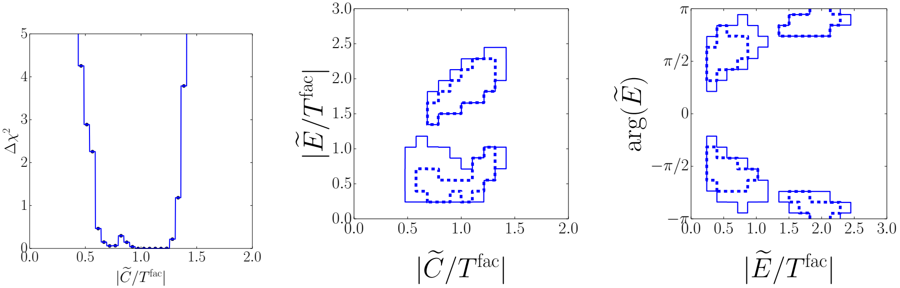
analogous: $\Rightarrow$ fit $\delta_A \leq 15\%$ in $A = A^{\text{fac}}(1+\delta_A)$

for example:

$$T(D^0 \to K^+K^-) = \frac{G_F}{\sqrt{2}} a_1 f_K (m_D^2 - m_K^2) F^{DK}(m_K^2) \left(1 + \mathcal{O}(1/N_c^2)\right)$$

$$A(D_s^+ \to K^0\pi^+) = \frac{G_F}{\sqrt{2}} a_1 f_{D_s} (m_K^2 - m_\pi^2) F^{K\pi}(m_{D_s}^2) \left(1 + \mathcal{O}(1/N_c^2)\right)$$

Extract parameters from branching ratio data



- Perfect fit to branching ratios: $\chi^2 \sim 0$: under-determined problem.
- But: Nontrivial result due to many parameter constraints:
  Permit only up to 50% SU(3)$_F$-breaking.
- Broad and Multiple Fit Solutions

Relative Importance of Diagrams: Likelihood Ratio Tests

Hypothesis	Significance of rejection
$P_{\text{break}} = 0$	0.7σ
$P_{\text{break}} = E_i^{(1)} = C_i^{(1)} = 0 \, \forall \, i$	$> 5\sigma$
$E_i^{(1)} = 0 \, \forall \, i$	3.0σ
$E = E_i^{(1)} = 0 \, \forall \, i$	$> 5\sigma$
$C_i^{(1)} = 0 \, \forall \, i$	4.3σ
$C = C_i^{(1)} = 0 \, \forall \, i$	$> 5\sigma$

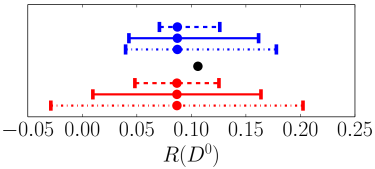
- Clear need for SU(3)$_F$ breaking.
- P_{break} allowed to be zero at 0.7σ.

Probe of DCS amplitudes

Asymmetry $D^0 \to K_{S,L}\pi^0$

$$R(D^0) \equiv \frac{\mathcal{B}(D^0 \to K_S\pi^0) - \mathcal{B}(D^0 \to K_L\pi^0)}{\mathcal{B}(D^0 \to K_S\pi^0) + \mathcal{B}(D^0 \to K_L\pi^0)}$$

Blue: $1, 2, 3\sigma$. Black: SU(3)$_F$-limit. [Bigi Yamamoto 1994, Rosner 2006, Gao 2006]



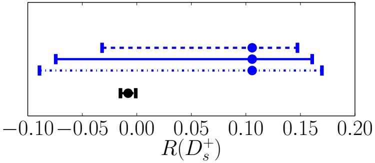
$\mathcal{B}(D_s^+ \to K_L K^+)$ not measured yet.

Prediction:

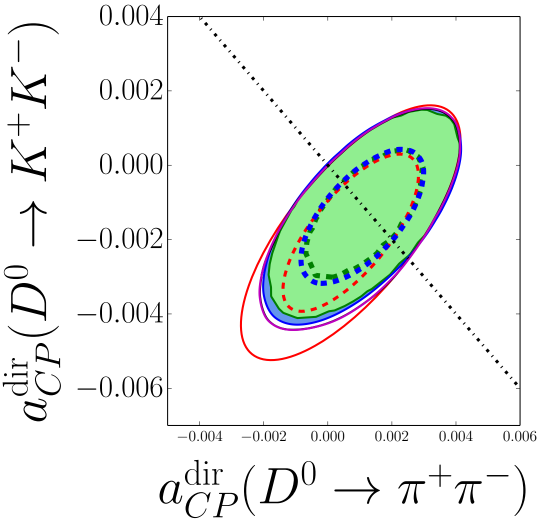
$\mathcal{B}(D_s^+ \to K_L K^+) = 0.012^{+0.007}_{-0.002}$ at 3σ

$$R(D_s^+) \equiv \frac{\mathcal{B}(D_s^+ \to K_S K^+) - \mathcal{B}(D_s^+ \to K_L K^+)}{\mathcal{B}(D_s^+ \to K_S K^+) + \mathcal{B}(D_s^+ \to K_L K^+)}$$

Black: QCDF@1σ [Gao 2014]



Implications of sum rule I



Black dashed: SU(3)$_F$ limit

Red solid:
95% CL measurement

Red dashed:
68% CL measurement

Present data:

Light blue:
95% CL from global fit

Dark blue dashed:
68% CL from global fit

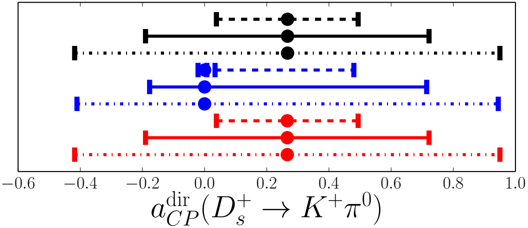
Future scenario:
assume $\sqrt{50}$ better branching ratios, but $a_{CP}^{\rm dir}(D^0 \to K^+K^-)$ as today.

Light green:
95% CL from global fit

Dark green dashed:
68% CL from global fit

Implications of sum rule II

Use measured values of $D^+ \to \overline{K}^0 K^+$ and $D_s^+ \to K^0\pi^+$ to predict $a_{CP}^{\rm dir}(D_s^+ \to K^+\pi^0)$:



Blue: prediction from $a_{CP}^{\rm dir}(D^+ \to \overline{K}^0 K^+)$, $a_{CP}^{\rm dir}(D_s^+ \to K^0\pi^+)$, and global fit to branching ratios.

Black: same as blue, but without $1/N_c$ constraints.

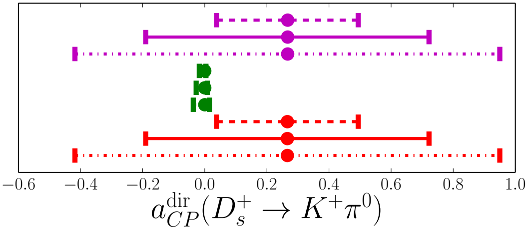
Red: measurement. Dashed: 1σ, solid: 2σ, dot-dashed: 3σ.

Not shown: error from $\text{SU}(3)_F$ breaking in $P_s + P_d$.

$\Rightarrow$ yet another successful postdiction.

Implications of sum rule II, future scenario

But: Assuming better measurements of the branching ratios by a factor of $\sqrt{50}$ changes the picture:



Green: prediction from $a_{CP}^{\text{dir}}(D^+ \to \overline{K}^0 K^+)$, $a_{CP}^{\text{dir}}(D_s^+ \to K^0\pi^+)$, and global fit to branching ratios.

Magenta: same as blue, but without $1/N_c$ constraints.

Red: measurement. Dotted: 1σ, solid: 2σ, dot-dashed: 3σ.

Not shown: error from $SU(3)_F$ breaking in $P_s + P_d$.