CP asymmetries in bottom and charm decays

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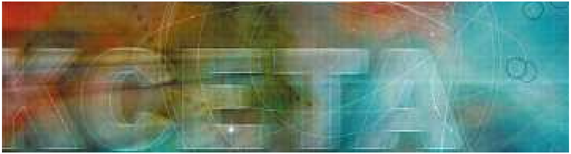


Particle Phenomenology from the
Early Universe to High-energy Colliders
Portorož, 7-10 April 2015

Contents

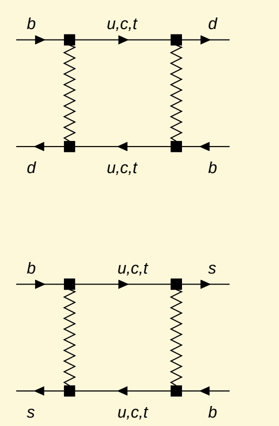
$\mathrm{B}-\overline{\mathrm{B}}$ mixing

$\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing probe new physics from scales beyond 100 TeV.

Mixing-induced CP asymmetries
(for $q = d$ or s):

$$A_{\mathrm{CP}}^{B_q \to f}(t) = \frac{S_f \sin(\Delta m_q t) - C_f \cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + A_{\Delta\Gamma_q} \sinh(\Delta\Gamma_q t/2)}$$

Δm_q: mass difference
$\Delta\Gamma_q$: width difference



Penguin pollution in $b \to c\bar{c}s$ decays

$$S(B_q \to f) = \sin(\phi_q + \Delta\phi_q)$$

If one neglects $\lambda_u = V_{ub}V_{us}^*$ in the decay amplitude, $S(B_q \to f)$ measures ϕ_q with

$$\begin{array}{ll} B_d \to J/\psi K^0: & \phi_d = \ \ 2\beta \\ B_s \to J/\psi \phi: & \phi_s = -2\beta_s \end{array}$$

The penguin pollution $\Delta\phi_q$ is parametrically suppressed by $\epsilon \equiv \left| \frac{V_{us}V_{ub}}{V_{cs}V_{cb}} \right| = 0.02$.

New method to constrain $\Delta\phi_q$:

Ph. Frings, UN, M. Wiebusch, arXiv:1503.00859

$$\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin\phi_d \qquad S_{J/\psi K^0} = \sin(\phi_d + \Delta\phi_d)$$

HFAG 2014:

$$\sigma_{S_{J/\psi K^0}} = 0.02 \qquad \sigma_{\phi_d} = 1.5^\circ$$

Author	$\Delta S_{J/\psi K^0}$	$\Delta\phi_d$	Method
De Bruyn, Fleischer 2014	-0.01 ± 0.01	$-\left(1.1^\circ{}^{+0.70}_{-0.85}\right)^\circ$	SU(3) flavor
Jung 2012	$\|\Delta S\| \lesssim 0.01$	$\|\Delta\phi_d\| \lesssim 0.8^\circ$	SU(3) flavor
Ciuchini *et al.* 2011	0.00 ± 0.02	$0.0^\circ \pm 1.6^\circ$	U-spin
Faller *et al.* 2009	$[-0.05, -0.01]$	$[-3.9, -0.8]^\circ$	U-spin
Boos *et al.* 2004	$-(2 \pm 2) \cdot 10^{-4}$	$0.0^\circ \pm 0.0^\circ$	perturbative calculation

SU(3)

Extract penguin contribution from $b \to c\bar{c}d$ control channels such as $B_d \to J/\psi\pi^0$ or $B_s \to J/\psi K_S$, in which the penguin contribution is Cabibbo-unsuppressed.

Drawbacks:

- statistics in control channels smaller by factor of 20
- size of $SU(3)$ breaking in penguin contributions to $B_{d,s} \to J/\psi X$ decays unclear

$SU(3)$ breaking can be large, e.g. a b quark fragments into a B_d four times more often than into a B_s.

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$SU(3)$ breaking can be large, e.g. a b quark fragments into a B_d four times more often than into a B_s.

- SU(3) does not help in $B_s \to J/\psi\phi$, because ϕ is an equal mixture of octet and singlet.

Define $\lambda_q = V_{qb} V_{qs}^*$ and use $\lambda_t = -\lambda_u - \lambda_c$.

Generic B decay amplitude:

$$A(B \to f) = \lambda_c t_f + \lambda_u p_f$$

Terms $\propto \lambda_u = V_{ub} V_{us}^*$ lead to the penguin pollution.
Useful: color singlet and color octet operators

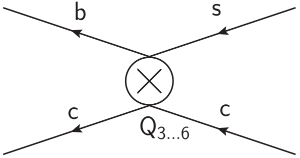
$$\begin{aligned} Q_0^c &\equiv (\bar{s}b)_{V-A}(\bar{c}c)_{V-A} & \qquad C_0 &\equiv C_1 + \frac{1}{N_c} C_2 &= 0.13 \\ Q_8^c &\equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_{V-A} & \qquad C_8 &\equiv 2C_2 &= 2.2 \end{aligned}$$

Penguin operators:

$$\langle f | \sum_{i=3}^{6} C_i Q_i | B \rangle \approx C_8^t \langle f | Q_{8V} | B \rangle$$

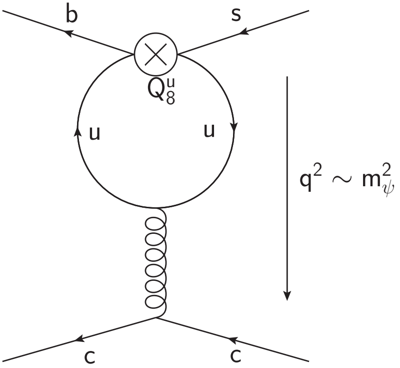
with

$$C_8^t \equiv 2(C_4 + C_6)$$
$$Q_{8V} \equiv (\bar{s} T^a b)_{V-A} (\bar{c} T^a c)_V$$



Tree-level operator insertion:

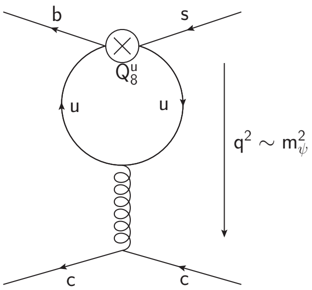
$$\langle f | C_0 Q_0^u + C_8 Q_8^u | B \rangle$$



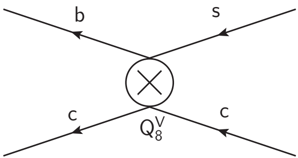
Feared and respected: the up-quark loop

Idea: employ an operator product expansion,

to factorise the *u*-quark loop into a perturbative coefficient and matrix elements of local operators:



$$q^2 \gg \Lambda^2_{QCD}$$
$$\longrightarrow$$



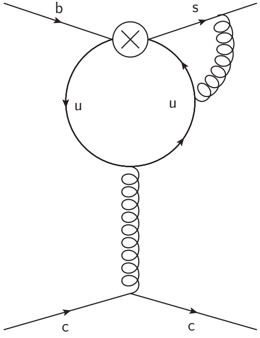
$$Q_{8V} = (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_V$$

Is this Bander Soni Silverman?

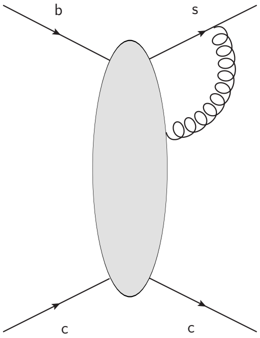
Perturbative approach is due to Bander Soni Silverman (1979) (BSS).
Boos, Mannel and Reuter (2004) applied this method to $B_d \to J/\psi K_S$.
Our study:

- Investigate soft and collinear infrared divergences to prove factorization.
- Analyse spectator scattering.
- Organise matrix elements by $1/N_c$ counting, no further assumptions on magnitudes and strong phases.

Collinear divergent diagrams



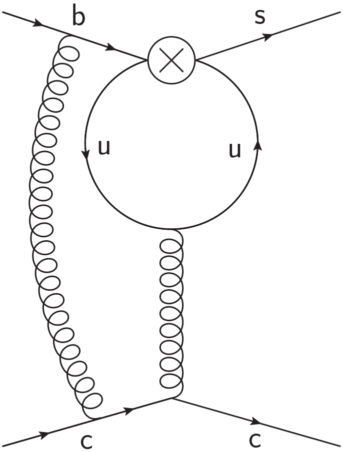
are infrared-safe if summed over



or are individually infrared-safe if considered in a physical gauge.

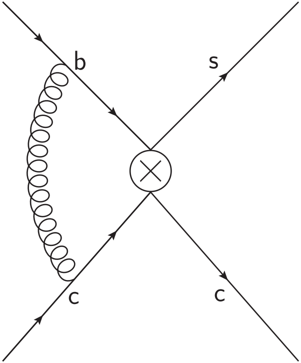
Infrared Structure - Soft Divergences

Soft divergent diagrams ...

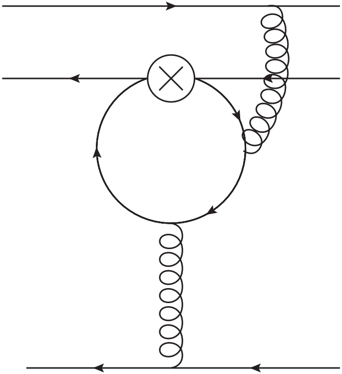


$\longrightarrow$

... factorise.



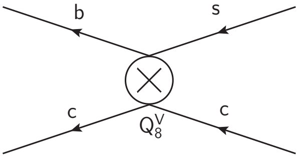
Spectator scattering diagrams...



$\longrightarrow$ ...are power-suppressed.

- Soft divergences factorise.
- Collinear divergences cancel or factorise.
- Spectator scattering is power-suppressed.

$\Rightarrow$ Up-quark penguin can be absorbed into a Wilson coefficient C_8^u!



$C_8^u Q_{8V}$

Local operators:

$$Q_{0V} \equiv (\bar{s}b)_{V-A}(\bar{c}c)_V \qquad Q_{0A} \equiv (\bar{s}b)_{V-A}(\bar{c}c)_A$$
$$Q_{8V} \equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_V \qquad Q_{8A} \equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_A$$

$1/N_c$ counting

For example: $B_d \to J/\psi K^0$

$$V_0 = \langle J/\psi K^0 | Q_{0V} | B_d \rangle = 2 f_\psi m_B p_{cm} F_1^{BK} \left[1 + \mathcal{O}\left(\frac{1}{N_c^2} \right) \right]$$

$1/N_c$ counting for $V_8, A_8 \equiv \langle J/\psi K^0 | Q_{8V,8A} | B_d \rangle$:

- Octet matrix elements are suppressed by $1/N_c$ w.r.t. singlet V_0
- Motivated by $1/N_c$ counting set the limits: $|V_8|, |A_8| \leq V_0/3$

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Does the $1/N_c$ expansion work?

$$\frac{BR(B_d \to J/\psi K^0)\big|_{\text{th}}}{BR(B_d \to J/\psi K^0)\big|_{\text{exp}}} = 1 \quad \Rightarrow \quad 0.06|V_0| \leq |V_8 - A_8| \leq 0.19|V_0|$$

Numerics

Analytic result for the penguin pollution:

$$\frac{p_f}{t_f} = \frac{(C_8^u + C_8^t)V_8}{C_0 V_0 + C_8(V_8 - A_8)}$$

$$\tan(\Delta\phi) \approx 2\epsilon \sin(\gamma) \text{Re}\left(\frac{p_f}{t_f}\right) \qquad \epsilon \equiv \left|\frac{V_{us}V_{ub}}{V_{cs}V_{cb}}\right|$$

Scan for largest value of $\Delta\phi$ using

$$V_0 = 2 f_\psi m_B p_{cm} F_1^{BK}$$

$$\begin{array}{rcl} 0 \leq & |V_8| & \leq V_0/3 \\ 0 \leq & \arg(V_8) & < 2\pi \\ 0 \leq & |A_8| & \leq V_0/3 \\ 0 \leq & \arg(A_8) & < 2\pi \end{array}$$

and varying all input quantities within their experimental and theoretical uncertainties.

Results

$$A_{\rm CP}^{B_q\to f}(t) = \frac{S_f \sin(\Delta m_q t) - C_f \cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + A_{\Delta\Gamma_q}\sinh(\Delta\Gamma_q t/2)}$$

B_d decays:

Final State:	$J/\psi K_S$	$\psi(2S)K_S$	$(J/\psi K^*)^0$	$(J/\psi K^*)^\parallel$	$(J/\psi K^*)^\perp$
$\max(\lvert\Delta\phi_d\rvert)$ [°]	0.68	0.75	0.85	1.13	0.93
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	0.86	0.96	1.09	1.45	1.19
$\max(\lvert C_f\rvert)$ [10^{-2}]	1.33	1.35	1.65	2.19	1.80

…and more.

B_s decays:

Final State	$(J/\psi\phi)^0$	$(J/\psi\phi)^\parallel$	$(J/\psi\phi)^\perp$
$\max(\lvert\Delta\phi_s\rvert)$ [°]	1.09	1.18	1.03
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	1.91	2.06	1.80
$\max(\lvert C_f\rvert)$ [10^{-2}]	2.12	2.27	2.00

Cabibbo-unsuppressed p_f/t_f

We can also constrain p_f/t_f in $b \to c\bar{c}d$ decays:

B_d decays:

Final State	$J/\psi\pi^0$	$(J/\psi\rho)^0$	$(J/\psi\rho)^{\parallel}$	$(J/\psi\rho)^{\perp}$
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	18	22	27	22
$\max(\lvert C_f\rvert)$ [10^{-2}]	29	35	41	36

B_s decays:

Final State	$J/\psi K_S$
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	25
$\max(\lvert C_f\rvert)$ [10^{-2}]	26

$B_d \to J/\psi\pi^0$: Belle or BaBar?

	$S_{J/\psi\pi^0}$	$C_{J/\psi\pi^0}$
BaBar (Aubert 2008)	-1.23 ± 0.21	-0.20 ± 0.19
Belle (Lee 2007)	-0.65 ± 0.22	-0.08 ± 0.17

Our results:

$$-\mathbf{0.86} \le \mathbf{S_{J/\psi\pi^0}} \le -\mathbf{0.50}$$

$$-\mathbf{0.29} \le \mathbf{C_{J/\psi\pi^0}} \le \mathbf{0.29}$$

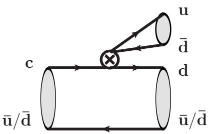
$\to$ Belle favoured

Goal: Get the most out of the measurements of the branching fractions of $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^0 \to K_S K_S$, $D^0 \to \pi^0\pi^0$, $D^+ \to \pi^0\pi^+$, $D^+ \to K_S K^+$, $D_s^+ \to K_S\pi^+$, $D_s^+ \to K^+\pi^0$, $D^0 \to K^-\pi^+$, $D^0 \to K_S\pi^0$, $D^0 \to K_L\pi^0$, $D^+ \to K_S\pi^+$, $D^+ \to K_L\pi^+$, $D_s^+ \to K_S K^+$, $D^0 \to K^+\pi^-$, $D^+ \to K^+\pi^0$,
and the $K^+\pi^-$ strong phase difference $\delta_{K\pi} = 6.45^\circ \pm 10.65^\circ$ to predict CP asymmetries in these decays.

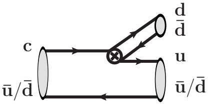
S. Müller, UN, St. Schacht, arXiv:1503.06759:

Combine topological amplitudes (Chau 1980,1982; Zeppenfeld 1981) with linear $SU(3)_F$ breaking (Gronau 1995).

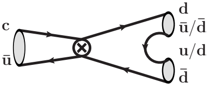
$SU(3)_F$ limit:



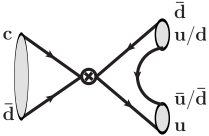
tree (T)



color-suppressed tree (C)



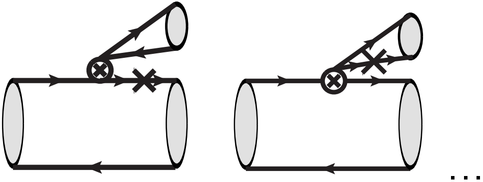
exchange (E)



annihilation (A)

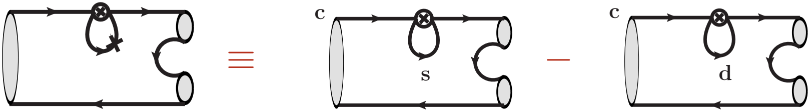
SU(3)$_F$ beaking

Feynman rule from $H_{\cancel{\mathrm{SU(3)}}_F} = (m_s - m_d)\bar{s}s$: dot on s-quark line.
Find 14 new topological amplitudes such as



T$_1$ T$_2$

Important:



penguin (P_{break})

Steps:

i) Invoke colour counting to justify factorisation of tree and annihilation amplitudes à la

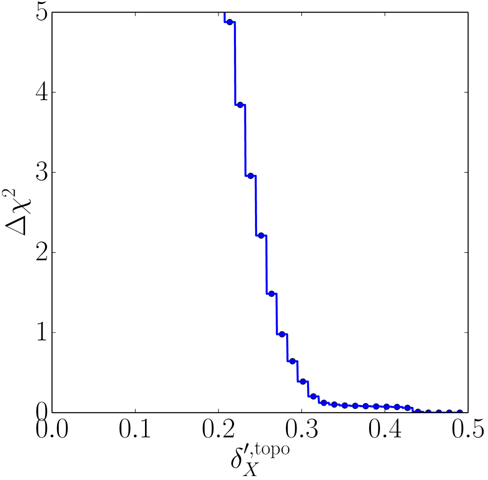
$$T = T^{\rm fac}\left[1+\mathcal{O}\left(\frac{1}{N_c^2}\right)\right]$$

with $T^{\rm fac}$ expressed in terms of decay constants and form factors.

ii) Null hypothesis of a Frequentist analysis: Global fit to data permitting up to 50% SU(3)$_F$-breaking and $\frac{1}{N_c^2}$-corrections of up to 15%. $\rightarrow$ find multi-dimensional valley with perfect $\chi^2 = 0$.

iii) Perform likelihood tests for various hypothesis. Race horse: *my*Fitter, M. Wiebusch 2012

$\Delta\chi^2$ profile of the parameter $\delta_X^{\prime,\mathrm{topo}}$ which quantifies the overall size of $SU(3)_F$-breaking:



Results:

i) The $SU(3)_F$ limit $\delta_X^{\prime,\mathrm{topo}} = 0$ is ruled out by more than 5σ.

ii) At 68% CL there is at least 28% of $SU(3)_F$ breaking.

The theory community has delivered a perfect service to the experimental colleagues:

Predict CP asymmetries in D decays

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Every measurement hinting at some non-zero CP asymmetry was successfully postdicted offering interpretations both

Predict CP asymmetries in *D* decays

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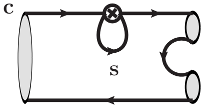
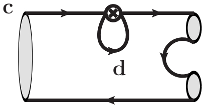
- within the Standard Model
  and
- as evidence for new physics!

Generic problem: CP asymmetries involve new hadronic quantities which are not constrained by branching fractions. E.g. new SU(3) representations or, in our analysis, new topological-amplitudes.

Prominent example:



and



Penguins P_s and P_d

appear in other combinations than $P_{\text{break}} = P_s - P_d$. Therefore we also need $P_s + P_d$.

Correlate CP asymmetries

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

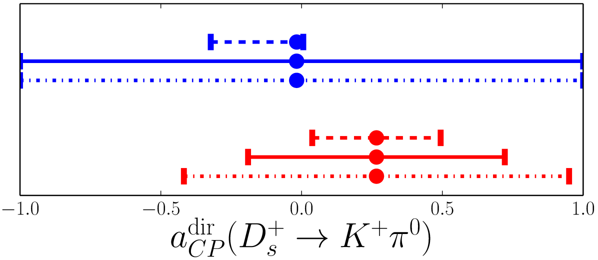
$\rightarrow$ sum rules among CP asymmetries.

Our finding: Two sum rules each correlating three direct CP asymmetries in

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

Unfortunately: only works to zeroth order in $SU(3)_F$ breaking. Still: theoretical accuracy of new-physics tests only limited by the assumed size of $SU(3)_F$ breaking; great progress compared to the $\mathcal{O}(1000\%)$ spread of past predictions.

Use the 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.

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

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

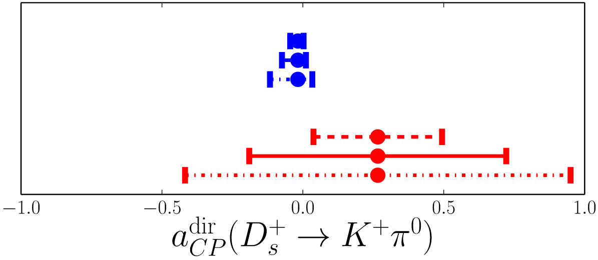
$\Rightarrow$ yet another successful postdiction.

For an $SU(3)_F$ analysis with new physics see:

G. Hiller, M. Jung, St. Schacht, PRD87 (2013) 014024.

Future scenario

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



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

Summary

- OPE works for the penguin pollution in $B_{d,s}$ decays to charmonium
- no mysterious long-distance enhancement of up-quark penguins
- matrix elements are the dominant source of uncertainty
- Belle measurement of $S_{J/\psi\pi^0}$ is theoretically favoured

HFAG 2014 $\qquad \sigma_{S_{J/\psi K^0}} = 0.02 \qquad \sigma_{\phi_d} = 1.5^\circ$

Analysis	$\Delta S_{J/\psi K^0}$	$\Delta\phi_d$	Method
Our study	$\lvert\Delta S\rvert < 0.01$	$\lvert\Delta\phi_d\rvert < 0.68^\circ$	OPE
De Bruyn, Fleischer 2014	-0.01 ± 0.01	$-\left(1.1^\circ{}^{+0.70}_{-0.85}\right)^\circ$	$SU(3)_F$
Jung 2012	$\lvert\Delta S\rvert \lesssim 0.01$	$\lvert\Delta\phi_d\rvert \lesssim 0.8^\circ$	$SU(3)_F$
…	…	…	…

Our study: $\quad \lvert\Delta S^{\parallel}_{J/\psi\phi}\rvert \leq 0.02, \qquad \lvert\Delta\phi^{\parallel}_s\rvert \leq 1.3^\circ$

Summary

- Global fit of $D \to PP'$ branching ratios to topological amplitudes including linear $\mathrm{SU}(3)_F$ breaking gives multiply degenerate best-fit solutions.
  The method permits likelihood ratio test to quantify e.g. the size of $\mathrm{SU}(3)_F$ breaking.
- CP asymmetries involve topological amplitudes not constrained by the fit. These can be eliminated by forming judicious combinations of several CP asymmetries $\to$ sum rules .
- The sum rules test the quality of $\mathrm{SU}(3)_F$ in penguin amplitudes and/or new physics.