Precise predictions for penguin contributions to CP asymmetries in B decays

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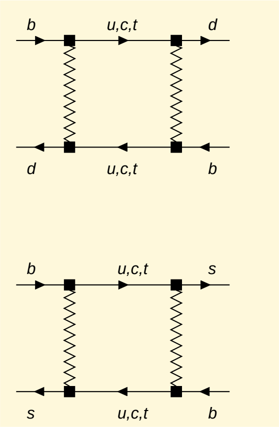
Time-dependent CP asymmetries
(for $q = d$ or s):

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

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



The coefficients S_f, C_f, and $A_{\Delta\Gamma_q}^f$ encode the information on the decay amplitudes $A_f \equiv A(B_q \to f)$ and $\overline{A}_f \equiv A(\overline{B}_q \to \overline{f})$.

Golden mode: B decay into a CP eigenstate $f = f_{\rm CP}$ which only involves a single CKM factor ($\Rightarrow |A_{f_{\rm CP}}| = |\overline{A}_{f_{\rm CP}}|$ and $|\lambda_f| = 1$).

$$CP|f_{\rm CP}\rangle = \eta_{f_{\rm CP}}|f_{\rm CP}\rangle \qquad \text{with } \eta_{f_{\rm CP}} = \pm 1.$$

Time-dependent CP asymmetry:

$$a_{f_{\rm CP}}(t) = -\frac{\mathrm{Im}\,\lambda_f \sin(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) - \mathrm{Re}\,\lambda_f \sinh(\Delta\Gamma_q t/2)},$$

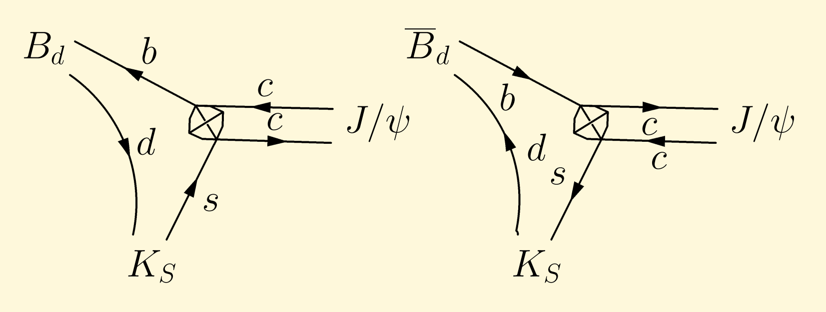
$\mathrm{Im}\,\lambda_f$ quantifies the CP violation in the interference between mixing and decay:

$$\begin{array}{ccc} B & \xrightarrow{q/p} & \overline{B} \\ A_f \searrow & & \swarrow \overline{A}_f \\ & f & \end{array}$$

Recall: $\lambda_f = \dfrac{q}{p}\dfrac{\overline{A}_f}{A_f}$

Example 1:

$B_d \to J/\psi K_S$ $\Rightarrow$ $|\bar{f}\rangle = -|f\rangle$ (CP-odd eigenstate)



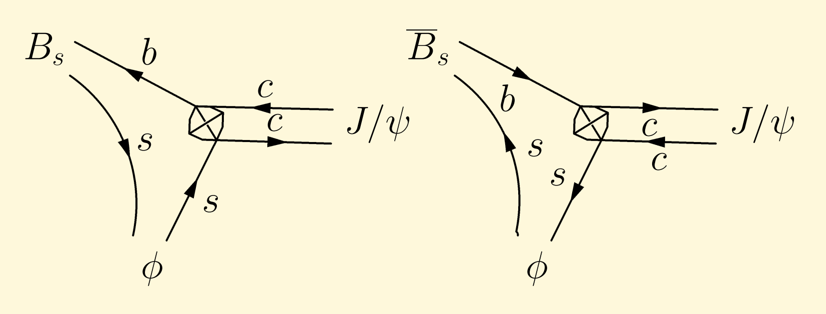
$$a_{J/\psi K_S}(t) \simeq -\sin(2\beta)\sin(\Delta m_d t),$$

where
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

golden mode to measure the angle β of the unitarity triangle

Example 2:

$B_s \to (J/\psi\phi)_{L=0}$ $\Rightarrow$ $|\bar{f}\rangle = |f\rangle$ (CP-even eigenstate)



$$a_{(J/\psi\phi)_{L=0}}(t) = -\frac{\sin(2\beta_s)\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - \cos(2\beta_s)\sinh(\Delta\Gamma_s t/2)},$$

where
$$\beta_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] \simeq \lambda^2\overline{\eta}$$

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

The decay amplitudes $A(B_{d,s} \to J/\psi X)$ are dominated by the CKM structure $V_{cb}V_{cs}^*$, but have a small contribution with $V_{ub}V_{us}^*$, called penguin pollution.

How golden are these modes?

Experimental world average:

$$S_{J/\psi K_S} = 0.665 \pm 0.024$$

Averaging all charmonia and including final states with K_L gives

$$\sin(2\beta) = 0.679 \pm 0.020, \qquad \text{HFAG winter 2015}$$

. . . if the penguin pollution is set to zero.

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, Phys.Rev.Lett. 115 (2015) 061802, 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) flavour
Jung 2012	$\lvert\Delta S\rvert \lesssim 0.01$	$\lvert\Delta\phi_d\rvert \lesssim 0.8^\circ$	SU(3) flavour
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) does not help in $B_s \to J/\psi\phi$, because ϕ is an equal mixture of octet and singlet.

Tree and Penguin

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.

Remark: One can include first-order SU(3) breaking in the extraction of t_f from control channels (Jung 2012).
This is not possible for p_f.

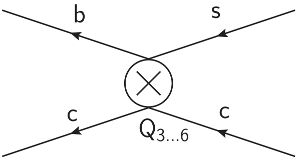
What contributes to the penguin pollution p_f?

Penguin operators:

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

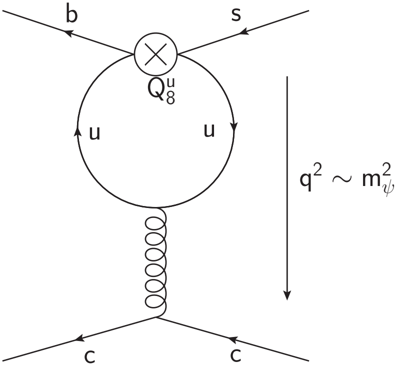
with

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

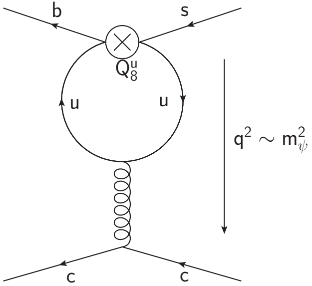


Tree-level operator insertion:

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

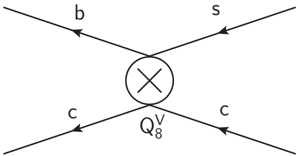


Idea: employ an operator product expansion, to factorise the u-quark loop into a perturbative coefficient and matrix elements of local operators:



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

$\longrightarrow$



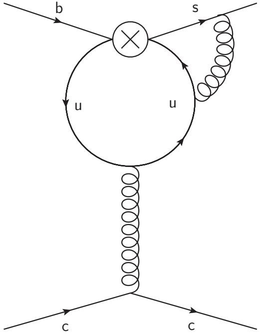
$$Q_{8V} = (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_V$$

Is this Bander Soni Silverman?

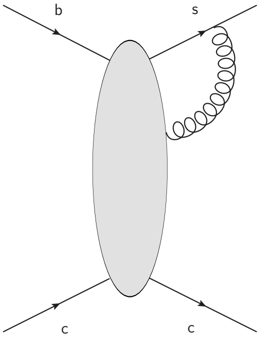
Perturbative approach is due to Bander Soni Silverman (1979) (BSS).
Boos, Mannel and Reuter (2004) applied this method to $B_d \to J/\psi K_S$.
Our study:

- 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

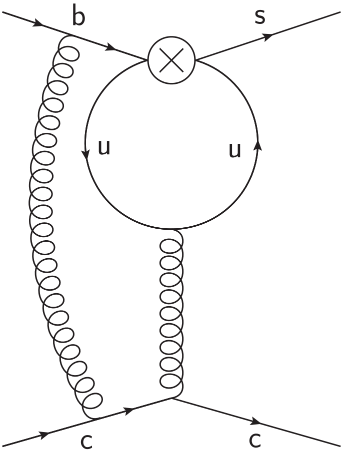


are infrared-safe if summed over

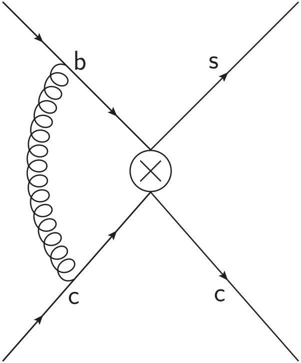


or are individually infrared-safe if considered in a physical gauge.

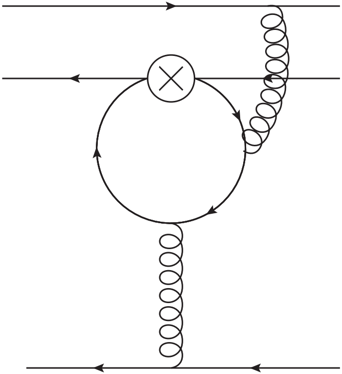
Soft divergent diagrams ... ... factorise.



$\longrightarrow$



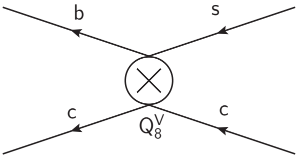
Spectator scattering diagrams. . .



$\longrightarrow$ . . . factorise up to power-suppressed contributions.

- Soft divergences factorise.
- Collinear divergences cancel or factorise.
- Non-factorisable 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?

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

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

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	0.74	0.85	1.13	0.93
$\max(\lvert\Delta S_f\rvert)$ $[10^{-2}]$	0.86	0.94	1.09	1.45	1.19
$\max(\lvert C_f\rvert)$ $[10^{-2}]$	1.33	1.33	1.65	2.19	1.80

…and more.

B_s decays:

Final State	$(J/\psi\phi)^0$	$(J/\psi\phi)^\parallel$	$(J/\psi\phi)^\perp$
$\max(\lvert\Delta\phi_s\rvert)$ [°]	0.97	1.22	0.99
$\max(\lvert\Delta S_f\rvert)$ $[10^{-2}]$	1.70	2.13	1.73
$\max(\lvert C_f\rvert)$ $[10^{-2}]$	1.89	2.35	1.92

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	$J/\psi K_S$
$\max(\lvert\Delta S_f\rvert)$ $[10^{-2}]$	26
$\max(\lvert C_f\rvert)$ $[10^{-2}]$	27

$B_d \to J/\psi\pi^0$: 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:

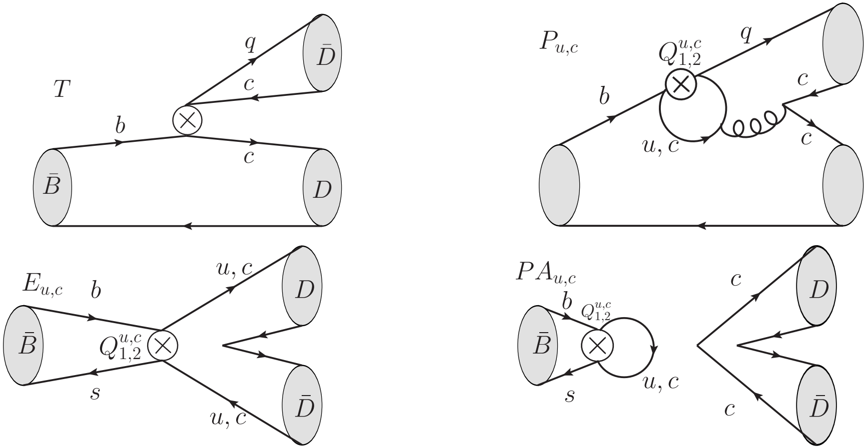
$$-\mathbf{0.86} \le \mathbf{S_{J/\psi\pi^0}} \le -\mathbf{0.50}$$

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

$\to$ Belle favoured

$B \to DD$ decays

Different compared to $B \to \psi X$: (i) more topological amplitudes



New: exchange $E_{u,c}$ and penguin annihilation $PA_{u,c}$.

Different compared to $B \to \psi X$:

(ii) stronger suppression of spectator scattering

Reason: LCDA $\Phi_D(\xi) \sim \begin{cases} m_c/\Lambda_{\rm QCD} & \text{for } \xi \sim \Lambda_{\rm QCD}/m_c, \\ 0 & \text{for } \xi \sim 1. \end{cases}$

(ξ is the fraction of the D meson momentum carried by the spectator quark in the D meson)

(iii) leading term in $1/N_c$ expansion has large Wilson coefficient $C_2 \sim 1$

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The up-penguin annihilation PA_u contribution can be expressed in terms of four-quark operators which also enter E_c, in complete analogy to P_u and T.

Results for decay modes without $PA_{u,c}$ and $E_{u,c}$:

$$
\begin{aligned}
-11.8 \cdot 10^{-2} &\leq C_{B^- \to D^0 D^-} \leq 4.3 \cdot 10^{-2} \\
-0.30 \cdot 10^{-2} &\leq C_{B^- \to D^0 D_s^-} \leq 0.83 \cdot 10^{-2} \\
-0.33 \cdot 10^{-2} &\leq C_{\bar{B}^0 \to D^+ D_s^-} \leq 0.88 \cdot 10^{-2} \\
-13.1 \cdot 10^{-2} &\leq C_{\bar{B}_s \to D_s^+ D^-} \leq 4.9 \cdot 10^{-2}
\end{aligned}
$$

C_f is the coefficient of $\cos(\Delta m_q t)$ in the time-dependent CP asymmetry.

Results for decay modes with contributions from $P_{u,c}$, T, $PA_{u,c}$, and $E_{u,c}$:

$$
\begin{array}{rcccl}
-18.0 \cdot 10^{-2} & \leq & C_{\bar{B}_d \to D^+ D^-} & \leq & 8.4 \cdot 10^{-2} \\
-0.6^\circ & \leq & \Delta\phi_d(\bar{B}_d \to D^+ D^-) & \leq & 11.2^\circ \\
-0.65 \cdot 10^{-2} & \leq & C_{\bar{B}_s \to D_s^+ D_s^-} & \leq & 1.15 \cdot 10^{-2} \\
-0.81^\circ & \leq & \Delta\phi_s(\bar{B}_s \to D_s^+ D_s^-) & \leq & -0.02^\circ
\end{array}
$$

$\Delta\phi_{d,s}$ is the penguin pollution in $\phi_d = 2\beta$ and $\phi_s = -2\beta_s$.

$B_d \to D^+ D^-$: Belle or BaBar?

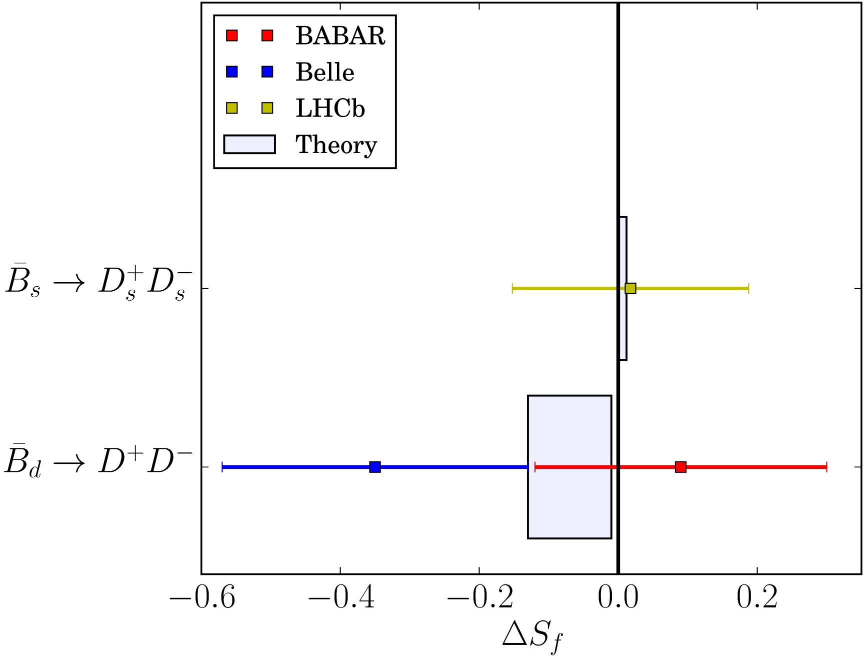
	$S_{D^+D^-}$	$C_{D^+D^-}$
BaBar (Aubert 2008)	-0.62 ± 0.21	0.08 ± 0.17
Belle (Röhrken 2012)	-1.06 ± 0.22	-0.43 ± 0.17

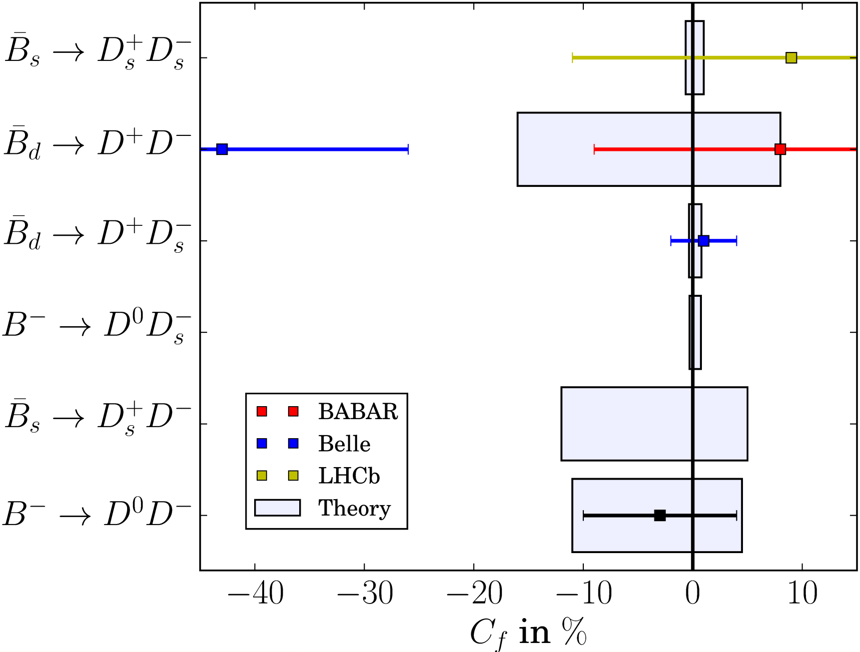
Our results:

$$\mathbf{-0.82 \leq S_{D^+D^-} \leq -0.70}$$

$$\mathbf{-0.18 \leq C_{D^+D^-} \leq 0.08}$$

$\rightarrow$ BaBar favoured


BABAR
Belle
LHCb
Theory
$\bar{B}_s \to D_s^+ D_s^-$
$\bar{B}_d \to D^+ D^-$
-0.6
-0.4
-0.2
0.0
0.2
ΔS_f


$\bar{B}_s \to D_s^+ D_s^-$
$\bar{B}_d \to D^+ D^-$
$\bar{B}_d \to D^+ D_s^-$
$B^- \to D^0 D_s^-$
$\bar{B}_s \to D_s^+ D^-$
$B^- \to D^0 D^-$
BABAR
Belle
LHCb
Theory
−40
−30
−20
−10
0
10
C_f in %

Summary

- OPE works for the penguin pollution in $B_{d,s}$ decays to charmonium, defining the "BSS mechanism" for the up-quark loop.
- No mysterious long-distance enhancement of up-quark penguins.
- Matrix elements are the dominant source of uncertainty. The charm-quark loop is contained in the matrix elements, no justification for the "BSS mechanism" for charm loop.
- Belle measurement of $S_{J/\psi\pi^0}$ is theoretically favoured over BaBar measurement.
- OPE also works for the penguin pollution in $B_{d,s} \to DD$ decays. BaBar measurement of $C_{D^+D^-}$ is theoretically favoured over Belle measurement.

Backup slides

Numerics

Analytic result for the penguin pollution:

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

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

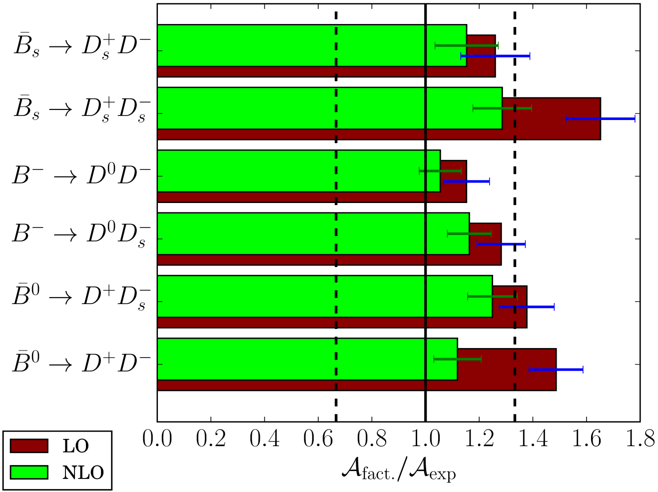
Scan for largest value of $\Delta\phi$ using

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

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

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

$1/N_c$ expansion of branching fractions



Leading (LO) and next-to-leading order (NLO) in $1/N_c$ without charm loop, which is also a $1/N_c$ term.