B meson mixing within and beyond the SM

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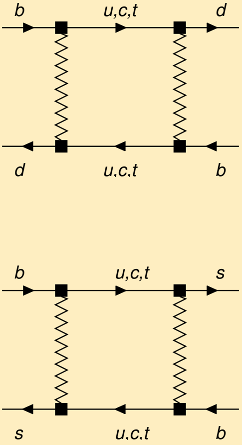
$\mathrm{B}-\overline{\mathrm{B}}$ mixing

$\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ 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



CP phases

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

with
$S_f = S(B_q \to f)$

If one neglects the “penguin pollution” from doubly Cabibbo-suppressed terms,

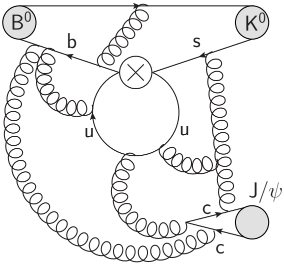
$$S(B_d \to J/\psi K_S) \simeq \sin(2\beta), \qquad S(B_s \to (J/\psi\phi)_{L=0,2}) \simeq \sin(-2\beta_s)$$

determine fundamental CP phases with high sensitivity to new physics modifying the $\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ box diagrams.

Penguin Pollution under Debate

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

	ϕ
$B^0 \to J/\psi K^0$	$\phi_d = \quad 2\beta$
$B_s^0 \to J/\psi \phi$	$\phi_s = \quad -2\beta_s$



- Penguin pollution $\Delta\phi_q$ parametrically suppressed by $\epsilon \equiv \left|\frac{V_{us}V_{ub}}{V_{cs}V_{cb}}\right| = 0.02$
- Hadronic matrix element non-perturbative $\Rightarrow$ penguin pollution not under control?

Overview: Experimental and Theoretical Precision

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

HFAG 2014	$\sigma_{S_{J/\psi K^0}} = 0.02$	$\sigma_{\phi_d} = 1.5^\circ$	
Author	$\Delta S_{J/\psi K^0}$	$\Delta\phi_d$	Method
Fleischer 2014	-0.01 ± 0.01	$-1.0^\circ \pm 0.7^\circ$	SU(3) flavor
Jung 2012	$\lvert\Delta S\rvert \lesssim 0.01$	$\lvert\Delta\phi_d\rvert \lesssim 0.8^\circ$	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

$$\Delta\phi_s \quad ?$$

$SU(3)$

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.
Useful: color singlet and color octet operators

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

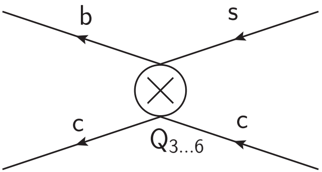
What Contributes to the Penguin Pollution p_f?

Penguin operators

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

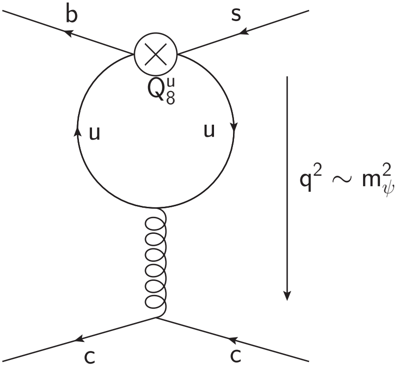
With

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



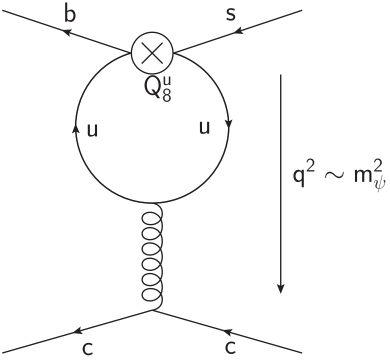
Tree-level operator insertion

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



Feared and Respected: the Up-quark Loop

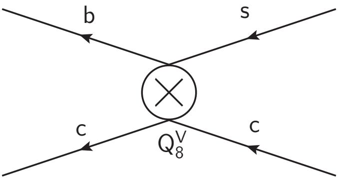
Idea: employ an operator product expansion,



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

$$\longrightarrow$$

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



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

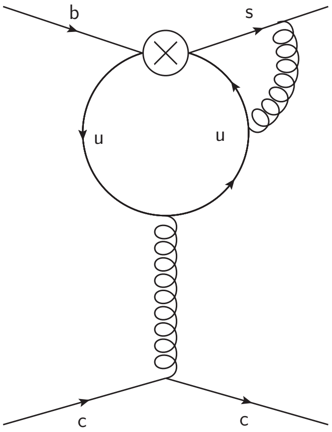
Is this Bander Soni Silverman?

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:

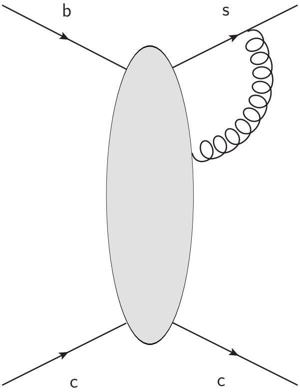
- Investigate soft and collinear infrared divergences to prove factorization.
- Organize matrix elements by $1/N_c$ counting, no further assumptions on magnitudes and strong phases.

Infrared Structure - Collinear Divergences

Collinear divergent diagrams



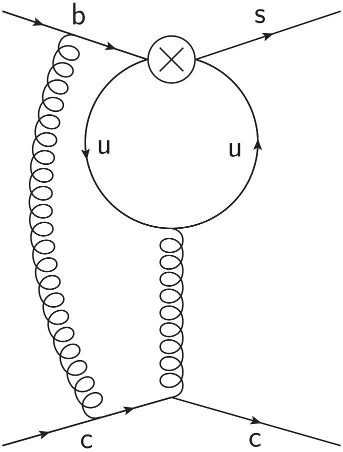
are infrared-safe if summed over



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

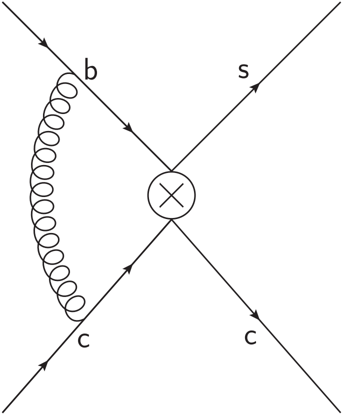
Infrared Structure - Soft Divergences

Infrared-soft divergent diagrams ...



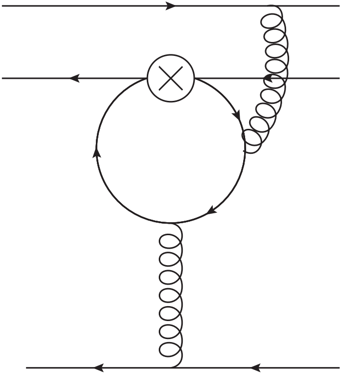
$\longrightarrow$

... factorize.



Infrared Structure - Spectator Scattering

Spectator Scattering diagrams...



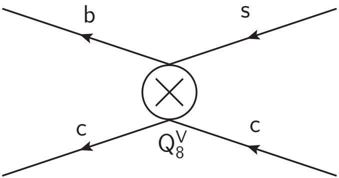
$\longrightarrow$ ... are power-suppressed.

Operator Product Expansion Works!

Conclusion

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

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



$C_8^u Q_{8V}$

$$C_8^u(\mu) = \frac{2}{3}\frac{\alpha_s(\mu)}{4\pi} C_8(\mu) \left[\ln \frac{q^2}{\mu^2} - i\pi - \frac{2}{3} + \mathcal{O}(\alpha_s) \right]$$

Operator Product Expansion in $\frac{1}{q^2}$ is Possible

- Penguin pollution is dominated by $Q_{8V} = (\bar{b}T^a s)_{(V-A)}(\bar{c}T^a c)_V$
- Only few operators contribute

Important operators:

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

Relevant Matrix Elements

Decay amplitude

$$\lambda_c t_f + \lambda_u p_f = \lambda_c \langle f| C_0 Q_0 + C_8(Q_{8V} - Q_{8A}) |B\rangle + \lambda_u \langle f| (C_8^u + C_8^t) Q_{8V} |B\rangle$$

Three relevant matrix elements only:

$$V_0 \equiv \langle f| Q_0 |B\rangle , \qquad V_8 \equiv \langle f| Q_{8V} |B\rangle , \qquad A_8 \equiv \langle f| Q_{8A} |B\rangle .$$

Large N_c Counting

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

$$V_0 = \left\langle J/\psi K^0 \right| Q_0 \left| B^0 \right\rangle = 2 f_\psi m_B p_{cm} F_1^{BK} \left(1 + \mathcal{O}\left(\frac{1}{N_c^2}\right)\right)$$

Large N_c counting

- Octet matrix elements are suppressed by $\mathcal{O}\left(\frac{1}{N_c}\right)$ w.r.t. singlet V_0
- Motivated by N_c counting set the limits:

$$\begin{aligned} |V_8| &\leq V_0/3 \\ |A_8| &\leq V_0/3 \end{aligned}$$

Does the $1/N_c$ expansion work?

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

Numerics

Parametrization of the penguin pollution

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

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

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

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

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

Results for $\Delta\phi_d$ and $\Delta\phi_s$

Our preliminary results:

$$\begin{aligned} |\Delta\phi_d| &\leq 0.56^\circ \pm 0.02^\circ \\ |\Delta\phi_s^{\parallel}| &\leq 0.75^\circ \pm 0.09^\circ \quad \text{for} \quad A_{\parallel} \end{aligned}$$

Uncertainties from

- experimental input ($Br(B \to f)$, CKM) are small ($\Delta\phi_d$) or moderate ($\Delta\phi_s^{\parallel}$).
- operator product expansion (OPE) are small.

Conservative Results for $\Delta\phi_d$ and $\Delta\phi_s$

Our preliminary conservative results:

$$
\begin{aligned}
|\Delta\phi_d| &\leq 0.83^\circ \pm 0.03^\circ \\
|\Delta\phi_s^{\|}| &\leq 1.12^\circ \pm 0.16^\circ
\end{aligned}
$$

Biggest uncertainty due to $1/N_c$ counting because of

$$\Delta\phi \propto \frac{p_f}{t_f} \propto |V_8|.$$

For the conservative value, we set

$$|V_8| \leq V_0/2$$

Can we tackle Cabibbo favored decays as well?

CP Violation Observables in $B^0 \to J/\psi\pi^0$

Experimental results:

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

Our preliminary results:

$$-\mathbf{0.83} \pm 0.02 \leq S_{J/\psi\pi^0} \leq -\mathbf{0.49} \pm 0.03$$

$$-\mathbf{0.23} \pm 0.01 \leq C_{J/\psi\pi^0} \leq \mathbf{0.23} \pm 0.01$$

Our preliminary conservative results:

$$-\mathbf{0.89} \pm 0.01 \leq S_{J/\psi\pi^0} \leq -\mathbf{0.38} \pm 0.03$$

$$-\mathbf{0.34} \pm 0.01 \leq C_{J/\psi\pi^0} \leq \mathbf{0.34} \pm 0.01$$

$\rightarrow$ **Belle favored**

Summary

- OPE works for the penguin pollution
- no mysterious long-distance enhancement of up-quark penguins
- matrix elements are the dominant source of uncertainty
- Belle's measurement of $S_{J/\psi\pi^0}$ is theoretically favored

HFAG 2014	$\sigma_{S_{J/\psi K^0}} = 0.02$	$\sigma_{\phi_d} = 1.5^\circ$	
Analysis	**$\Delta S_{J/\psi K^0}$**	**$\Delta\phi_d$**	**Method**
Our study (prelim.)	$\lvert\Delta S\rvert < 0.02$	$\lvert\Delta\phi_d\rvert < 0.9^\circ$	OPE
Fleischer 2014	-0.01 ± 0.01	$-1.0^\circ \pm 0.7^\circ$	SU(3) flavor
Jung 2012	$\lvert\Delta S\rvert \lesssim 0.01$	$\lvert\Delta\phi_d\rvert \lesssim 0.8^\circ$	SU(3) flavor
...	...	...	...

Our study (prelim.):

$$|\Delta S^{\|}_{J/\psi\phi}| \le 0.02 \qquad |\Delta\phi^{\|}_s| \le 1.2^\circ$$