Penguin Pollution in $B_d \to J/\psi K_S$

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The Golden Mode $B_d \to J/\psi K_S$

Measure B_d - $\overline{B}_d$ mixing phase

$$\phi_d = 2\beta$$

in

$$A_{CP}(B_d \to J/\psi K_S)(t) = S_{J/\psi K_S} \sin(\Delta m_d t) - C_{J/\psi K_S} \cos(\Delta m_d)$$

with

$$S_{J/\psi K_S} = \sin(2\beta + \Delta\phi_d)$$

$\Delta\phi_d$ due to penguin pollution, which is

- parametrically suppressed by $\epsilon \equiv \left|\frac{V_{us}V_{ub}}{V_{cs}V_{cb}}\right| = 0.02$
- non-perturbative (could still be very large)
- In the past, different estimates for penguin pollution

Overview: Experimental and Theoretical Precision

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

HFAG 2015 $\quad \sigma_{S_{J/\psi K_S}} = 0.02 \quad \sigma_{\phi_d} = 1.5^\circ$

Author	$\Delta S_{J/\psi K_S}$	$\Delta\phi_d$	Method
Fleischer 2015	-0.01 ± 0.01	$-1.1^\circ \pm 0.7^\circ$	SU(3) flavor
Jung 2012	$\lvert\Delta S\rvert \lesssim 0.01$	$\lvert\Delta\phi_d\rvert \lesssim 0.8^\circ$	SU(3) flavor
Boos *et al.* 2004	$-(2 \pm 2) \cdot 10^{-4}$	$0.0^\circ \pm 0.0^\circ$	perturbative

Our Idea

What Contributes to the Penguin Pollution p_f?

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 $\Delta\phi$.

Top Quark Penguins:

$$p_f \supset \langle f | \sum_{i=3}^{6} C_i Q_i | B \rangle$$

Up Quark Penguins

$$p_f \supset \langle f | C_1 Q_1^u + C_2 Q_2^u | B \rangle$$

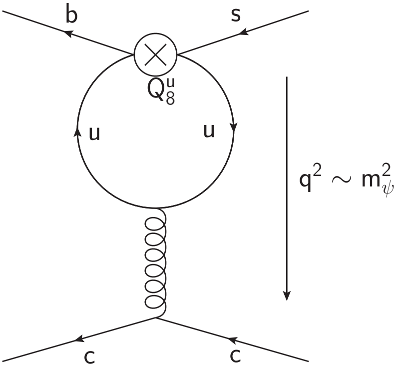
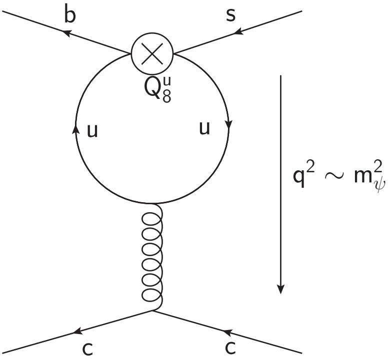


Figure: Up Quark Penguin

Our Idea - Employ OPE to Describe Up Penguin

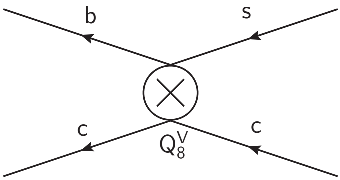
We rely on field-theoretic methods only

- Exploit the heaviness of the J/ψ mass $m_\psi = 3.1$ GeV $\gg \Lambda_{QCD}$
- Factorization of hard and soft scales
- Large N_C counting



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

$\longrightarrow$



$C_8^u Q_{8V}$

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

Is this Bander Soni Silverman?

Comparison to literature

Boos, Mannel and Reuther (2004) computed the up-quark loop motivated by Bander Soni Silverman (1979) (BSS).

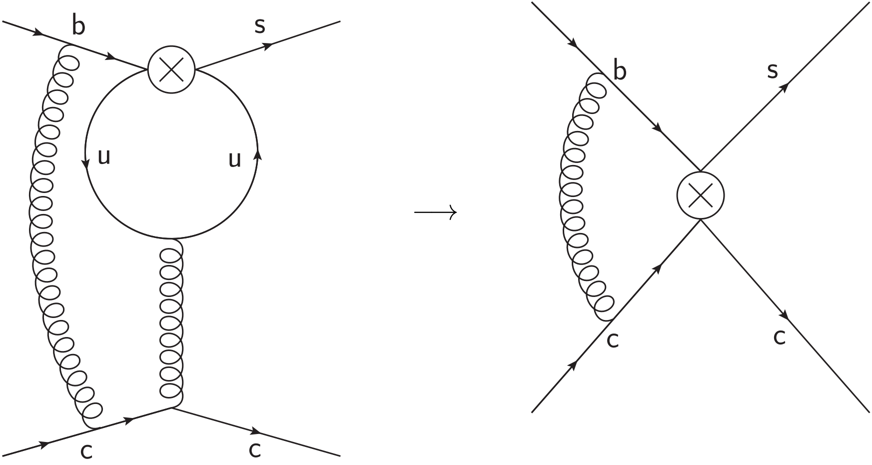
Our calculation is more:

- Without the field-theoretic proof the validity of BSS is not ensured.
- Reliable estimate of the matrix elements via N_C counting.

Elements of the Proof

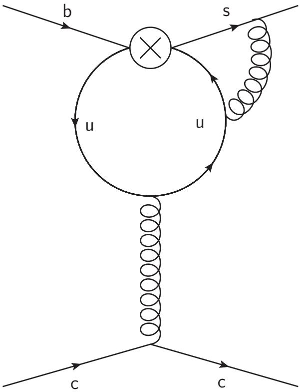
Investigate the Infrared Structure - Soft Divergences

Infrared-soft divergent diagrams ... ... factorize.



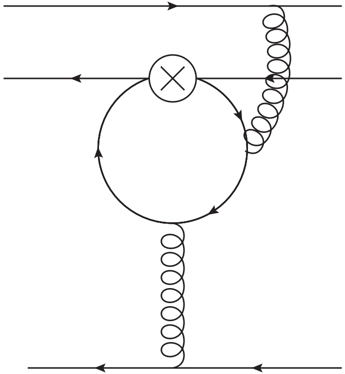
Other Elements

Collinear divergent diagrams



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

Spectator scattering diagrams



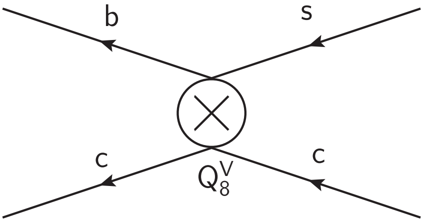
are power suppressed.

Effective Description is Possible

Conclusion of the Proof

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

$\Rightarrow$ Up quark penguin can be described by an effective vertex!



$$C_8^u Q_{8V}$$

Results

Results for B_d Decays

Highlight:

For the decay $B_d \to J/\psi K_S$ we find:

$$|\Delta\phi_d| \leq 0.68^\circ$$

OPE applicable for all $B_q \to$ charmonium $+X$ decays
(X pseudoscalar or vector particle)

Final State f	$J/\psi K_S$	$J/\psi\pi^0$	$(J/\psi\rho)^0$	$(J/\psi\rho)^\parallel$	$(J/\psi\rho)^\perp$
$\max(\vert\Delta S_f\vert)$ $[10^{-2}]$	0.86	18	22	27	22
$\max(\vert C_f\vert)$ $[10^{-2}]$	1.33	29	35	41	36

…and more!

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

Experiment

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

Our results:

$$-\mathbf{0.87} \leq S_{J/\psi\pi^0} \leq -\mathbf{0.51}$$

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

$\to$ **Belle favored**

Results for B_s Decays

$B_s - \bar{B}_s$ mixing phase

Very precisely known in the SM

$$\phi_s = -2\beta_s = (-2.1 \pm 0.1)^\circ$$

Final State f	$J/\psi K_S$	$(J/\psi\phi)^0$	$(J/\psi\phi)^\parallel$	$(J/\psi\phi)^\perp$
$\max(\lvert\Delta\phi_s\rvert)$ [°]	n.a.	0.97	1.22	0.99
$\max(\lvert\Delta S_f\rvert)$ [10^{-2}]	26.	1.70	2.13	1.73
$\max(\lvert C_f\rvert)$ [10^{-2}]	27.	1.89	2.35	1.92

...and more!

Summary

- OPE gives a limit for the size of the penguin pollution.
- No long-distance enhanced up quark penguins
- Belle's measurement of $S_{J/\psi\pi^0}$ is theoretically favored

Author	$\Delta S_{J/\psi K_S}$	$\Delta\phi_d$	Method
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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

Estimates based on Flavor Symmetries

Flavor SU(3)

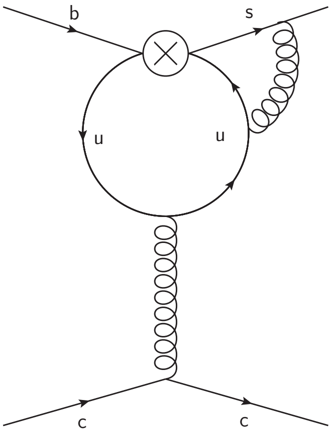
- relates $u \leftrightarrow d \leftrightarrow s$
- measure penguin pollution in $B_d \to J/\psi\pi^0$, use $S_{J/\psi\pi^0}$
- broken by terms $\mathcal{O}\left(m_s/\Lambda_{QCD}\right)$

Drawbacks of flavor symmetries

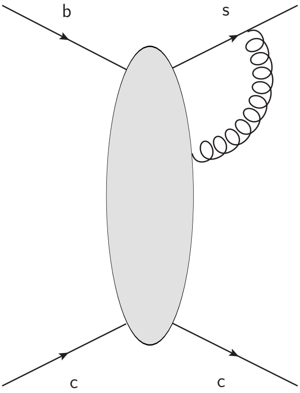
- breaking hard to quantify
- low statistics in Cabibbo suppressed decays such as $B_d \to J/\psi\pi^0$

Infrared Structure - Collinear Divergences

Collinear divergent diagrams



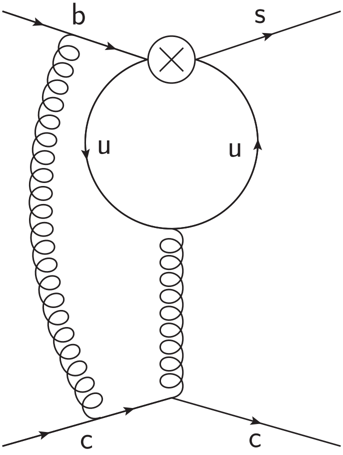
are infrared-safe if summed over,



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

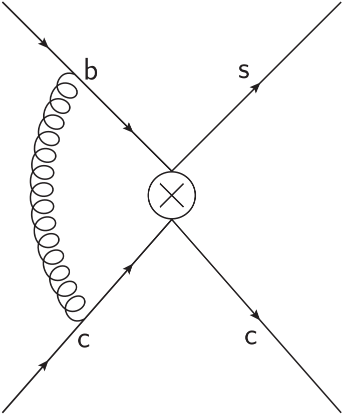
Investigate the Infrared Structure - Soft Divergences

Infrared-soft divergent diagrams ...



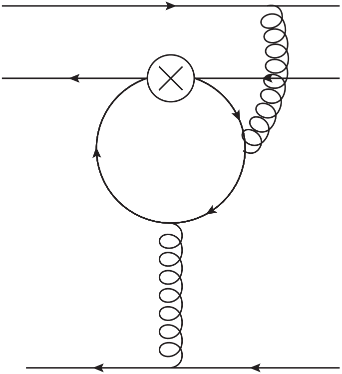
$\longrightarrow$

... factorize.



Spectator Scattering

Spectator scattering



$\longrightarrow$ ... is power suppressed.

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

Only write down operators, that contribute significantly:

$$\mathcal{H}_{eff} = \lambda_c \left(C_0 Q_0 + C_8 (Q_{8V} - Q_{8A}) \right) + \lambda_u (C_8^u + C_8^t) Q_{8V} + \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{q^2} \right)$$

- 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:

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

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: $B_d \to J/\psi K_S$

$$V_0 = \langle J/\psi K_S | \, Q_0 \, | B_d \rangle \quad = 2 f_\psi m_B p_{cm} F_1^{BK} \left(1 + \mathcal{O}\left(\frac{1}{N_C^2}\right)\right) \quad \sim \mathcal{O}\left(N_C^2\right)$$

$$V_8 = \langle J/\psi K_S | \, Q_8 \, | B_d \rangle \qquad \sim \mathcal{O}\left(N_C\right)$$

Does the $1/N_C$ expansion work?

$$\frac{BR(B_d \to J/\psi K_S)|_{\text{fact.}}}{BR(B_d \to J/\psi K_S)|_{\text{exp.}}} = 0.24 \Rightarrow 0.06 |V_0| \leq |V_8 - A_8| \leq 0.19 |V_0|$$

Numerics

Parametrization of the penguin pollution

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

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

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

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

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