

Penguin Pollution in $B^0 \rightarrow J/\psi K^0$ and $B_s^0 \rightarrow J/\psi \phi$ Decays

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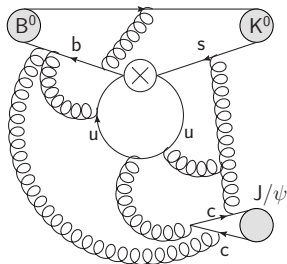
CKM2014 Vienna



Motivation: Penguin Pollution under Debate

$$S(B \rightarrow f) = \sin(\phi + \Delta\phi)$$

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



- Penguin pollution 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 could be very large
- In the past, different estimates for penguin pollution

Overview: Experimental and Theoretical Precision

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

HFAG 2014

$$\sigma_{S_{J/\psi K^0}} = 0.02$$

$$\sigma_{\phi_d} = 0.8^\circ$$

Author

$$\Delta S_{J/\psi K^0}$$

$$\Delta\phi_d$$

Method

Fleischer 2014

$$-0.01 \pm 0.01$$

$$-1.0^\circ \pm 0.7^\circ$$

SU(3) flavor

Jung 2012

$$|\Delta S| \lesssim 0.01$$

$$|\Delta\phi_d| \lesssim 0.8^\circ$$

SU(3) flavor

Ciuchini *et al.* 2011

$$0.00 \pm 0.02$$

$$0.0^\circ \pm 1.6^\circ$$

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
corrections

$$\Delta\phi_s ?$$

We rely on field-theoretic methods only

- Exploit the heaviness of the J/ψ mass $m_{J/\psi} = 3.1 \text{ GeV} \gg \Lambda_{QCD}$
- Factorization of hard and soft scales
- $1/N_c$ expansion

Hamiltonian

Color octet and singlet operators

$$\mathcal{H}^{\Delta B=1} = \sum_{q \in \{u,c\}} \lambda_q \left(C_0 Q_0^q + C_8 Q_8^q + \sum_{i=3}^6 C_i Q_i \right)$$

$$\lambda_q = V_{qb} V_{qs}^*$$

$$Q_0^q \equiv (\bar{s}b)_{V-A} (\bar{q}q)_{V-A}$$

$$C_0 \equiv C_1 + \frac{1}{N_c} C_2 = 0.13$$

$$Q_8^q \equiv (\bar{s}T^a b)_{V-A} (\bar{q}T^a q)_{V-A}$$

$$C_8 \equiv 2C_2 = 2.2$$

Generic B decay amplitude:

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

Terms $\propto \lambda_u = V_{ub} V_{us}^*$ lead to the **penguin pollution**.

What Contributes to the Penguin Pollution p_f ?

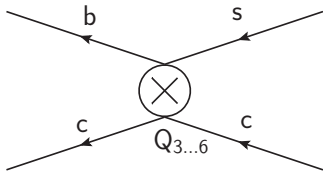
Penguin operators

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

With

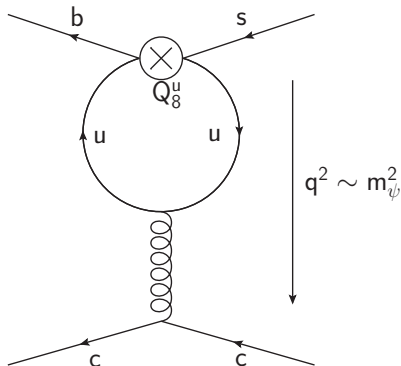
$$C_8^t \equiv 2(C_4 + C_6)$$

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



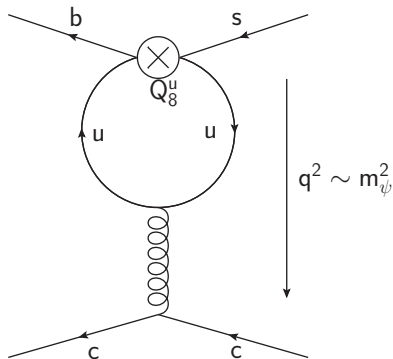
Tree-level operator insertion

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



Penguin Pollution by Tree-level Operator Insertion

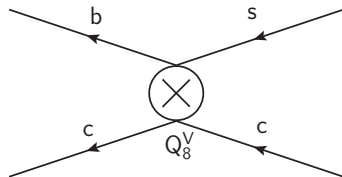
If we can describe the up quark penguin by an effective theory...



$$q^2 \gg \Lambda_{QCD}^2$$



... the description of the process simplifies.



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

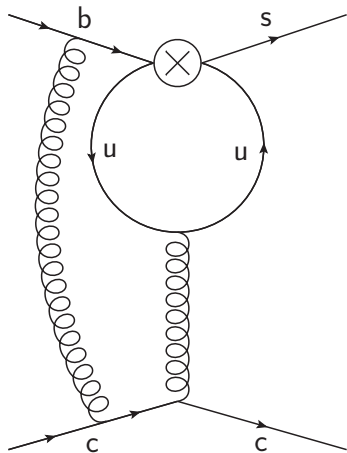
Boos, Mannel and Reuter (2004) computed the up-quark loop motivated by Bander, Soni and Silverman (1979) (BSS).

Our calculation

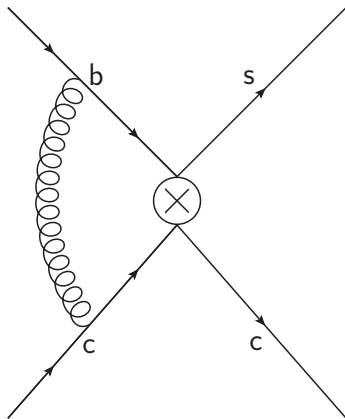
Analysis of the BSS idea in the context of a field-theoretic factorization proof

Investigate the Infrared Structure - Soft Divergences

Infrared-soft divergent diagrams ...

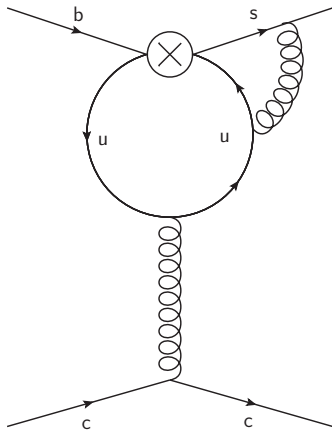


... factorize.

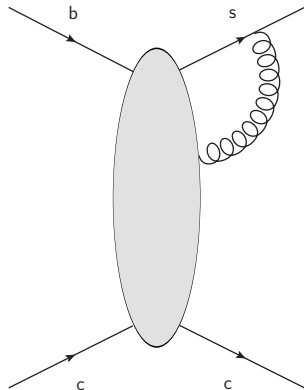


Infrared Structure - Collinear Divergences

Collinear divergent diagrams



are infrared-safe if summed over,



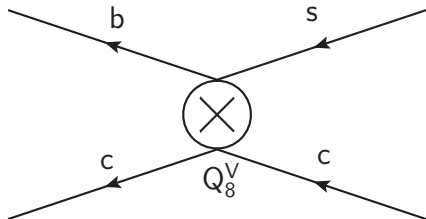
or are infrared-safe if considered in a physical gauge.

Effective Description is Possible

Conclusion

- Soft divergences factorize
- Collinear divergences cancel or factorize

⇒ Up quark penguin can be described by an effective vertex!



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

$$C_8^u(\mu) = \frac{2}{3} \frac{\alpha_s(\mu)}{4\pi} C_8(\mu) \left(\ln(q^2/\mu^2) - i\pi - \frac{2}{3} \right)$$

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

Only write down operators, that contribute significantly:

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

- 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:

$$\begin{aligned} Q_0 &\equiv (\bar{s}b)_{V-A}(\bar{c}c)_{V-A} \\ Q_{8V} &\equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_V \\ Q_{8A} &\equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_A \end{aligned}$$

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:

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

$1/N_c$ Expansion

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

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

$1/N_c$ expansion

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

$$|V_8| \leq V_0/3$$

$$|A_8| \leq V_0/3$$

Does the $1/N_c$ expansion work?

$$\frac{BR(B^0 \rightarrow J/\psi K^0)|_{\text{fact.}}}{BR(B^0 \rightarrow J/\psi K^0)|_{\text{exp.}}} = 0.24 \Rightarrow 0.06|V_0| \leq |V_8 - A_8| \leq 0.19|V_0|$$

Parametrization of the penguin pollution

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

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

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

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

$$0 \leq |V_8| \leq V_0/3$$

$$0 \leq \arg(V_8) < 2\pi$$

$$0 \leq |A_8| \leq V_0/3$$

$$0 \leq \arg(A_8) < 2\pi$$

Our preliminary results:

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

Uncertainties from

- Experimental input ($Br(B \rightarrow f)$, CKM) are small for $\Delta\phi_d$
- Experimental input ($Br(B \rightarrow f)$, CKM) are moderate for $\Delta\phi_s^\parallel$.
- Operator product expansion (OPE) are small.

Our preliminary conservative results:

$$|\Delta\phi_d| \leq 0.83^\circ \pm 0.03^\circ$$

$$|\Delta\phi_s^{\parallel}| \leq 1.12^\circ \pm 0.16^\circ$$

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

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

For the conservative value, we set

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

**Can we tackle other decays
as well?**

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

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:

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

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

→ **Belle favored**

Summary

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

$$\text{HFAG 2014} \quad \sigma_{S_{J/\psi K^0}} = 0.02 \quad \sigma_{\phi_d} = 0.8^\circ$$

Author	$\Delta S_{J/\psi K^0}$	$\Delta\phi_d$	Method
PF <i>et al.</i> (prelim.)	$\Delta S < 0.02$	$\Delta\phi_d < 0.9^\circ$	OPE
Fleischer 2014	-0.01 ± 0.01	$-1.0^\circ \pm 0.7^\circ$	SU(3) flavor
Jung 2012	$ \Delta S \lesssim 0.01$	$ \Delta\phi_d \lesssim 0.8^\circ$	SU(3) flavor
...

$$|\Delta S_{J/\psi\phi}^{\parallel}| \leq 0.02 \quad |\Delta\phi_s^{\parallel}| \leq 1.2^\circ$$