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

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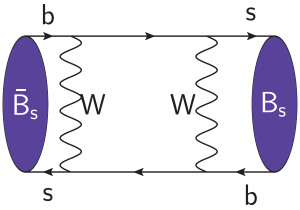
Flavorful Ways to New Physics

28th-31st October 2014, Freudenstadt

Indirect Search

Indirect Search for New Physics

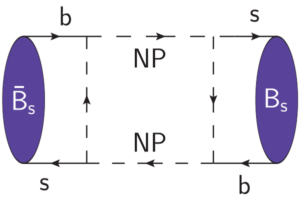
Standard Model



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

$$\phi_s = -2\beta_s$$

New Physics



$$\phi_s = -2\beta_s + \phi_s^{\mathrm{NP}}$$

What is Penguin Pollution?

In the SM

$$
\begin{aligned}
A_{CP}(B_s \to J/\psi\phi)(t) &= \frac{\Gamma(\bar{B}_s \to J/\psi\phi) - \Gamma(B_s \to J/\psi\phi)}{\Gamma(\bar{B}_s \to J/\psi\phi) + \Gamma(B_s \to J/\psi\phi)} \\
&= \sin(\phi_s)\sin(\Delta m_s t)
\end{aligned}
$$

(approximately)

What is Penguin Pollution?

In the SM

$$\begin{aligned} A_{CP}(B_s \to J/\psi\phi)(t) &= \frac{\Gamma(\bar{B}_s \to J/\psi\phi) - \Gamma(B_s \to J/\psi\phi)}{\Gamma(\bar{B}_s \to J/\psi\phi) + \Gamma(B_s \to J/\psi\phi)} \\ &= \sin(\phi_s)\sin(\Delta m_s t) \end{aligned}$$

(approximately)

$$A(B_s \to J/\psi\phi) \propto t_f + \epsilon p_f \qquad \epsilon = 0.02$$

What is Penguin Pollution?

In the SM

$$A_{CP}(B_s \to J/\psi\phi)(t) = \frac{\Gamma(\bar{B}_s \to J/\psi\phi) - \Gamma(B_s \to J/\psi\phi)}{\Gamma(\bar{B}_s \to J/\psi\phi) + \Gamma(B_s \to J/\psi\phi)} = \sin(\phi_s)\sin(\Delta m_s t)$$

(approximately)

$$A(B_s \to J/\psi\phi) \propto t_f + \epsilon p_f \qquad \epsilon = 0.02$$

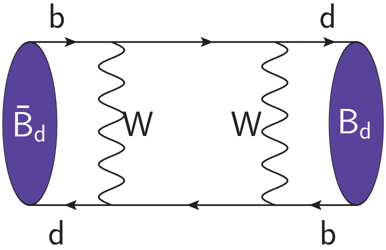
Include $\mathcal{O}(\epsilon)$ and possible NP

$$A_{CP}(B_s \to J/\psi\phi)(t) = \sin(\Delta m_s t)\sin(\phi_s + \Delta\phi_s + \phi_s^{\mathrm{NP}})$$

$\Rightarrow$ Disentangle hadronic phase shift $\Delta\phi_s$ and NP contributions ϕ_s^{NP}

Penguin Pollution in the $B_d - \bar{B}_d$ Mixing Phase

Standard Model



$B_d - \bar{B}_d$ mixing phase

$$\phi_d = 2\beta$$

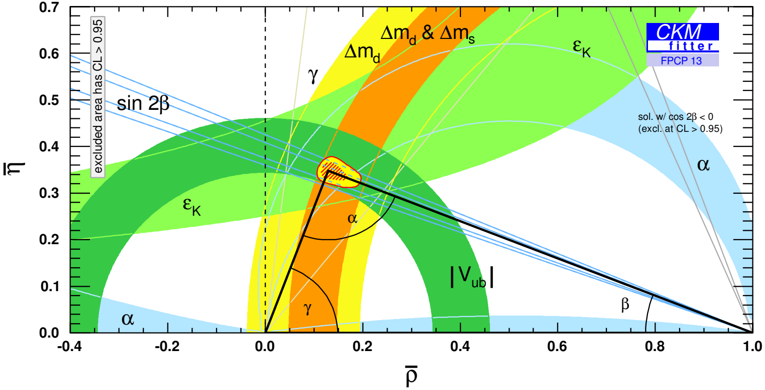
Include $\mathcal{O}(\epsilon)$ and/or NP

$$A_{CP}(B_d \to J/\psi K^0)(t) = \sin(\Delta m_d t)\sin(\phi_d + \Delta\phi_d + \phi_d^{\mathrm{NP}})$$

Unitary CKM matrix:

$$V_{CKM} V_{CKM}^{\dagger} = \mathbf{1}$$

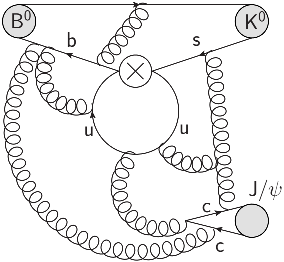
Leads to Unitarity triangle



Penguin Pollution under Debate

$$A_{CP}(t) = \sin(\phi + \Delta\phi)\sin(\Delta m t)$$

	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 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

Flavor Symmetries

Previous works use flavor symmetries:

- Most renown: Isospin $d \leftrightarrow u$
- U-spin $d \leftrightarrow s$
- SU(3) flavor symmetry $u \leftrightarrow d \leftrightarrow s$

Control penguin in

$$B_d \to J/\psi K^0 \quad \text{by} \quad B_d \to J/\psi \pi^0.$$

Overview: Experimental and Theoretical Precision

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

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
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 corrections

$$\Delta\phi_s \quad ?$$

Our Strategy

Our Strategy

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
- $1/N_c$ expansion

Hamiltonian

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

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

Color octet and singlet operators

$$Q_0^q \equiv (\bar{s}b)_{V-A}(\bar{q}q)_{V-A} \qquad Q_8^q \equiv (\bar{s}T^a b)_{V-A}(\bar{q}T^a q)_{V-A}$$

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.

What Contributes to the Penguin Pollution p_f?

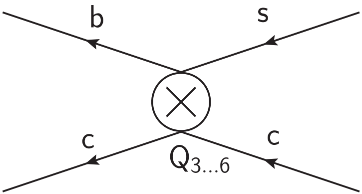
Penguin operators

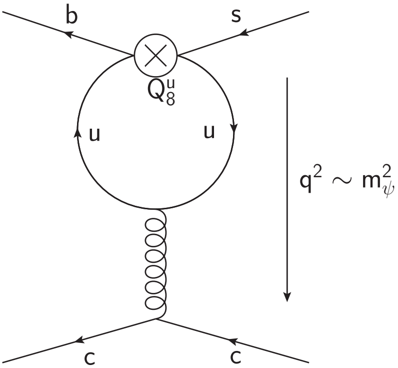
$$\langle f|\sum_{i=3}^{6} C_i Q_i |B\rangle \approx C_8^t \langle f| Q_{8V} |B\rangle$$

Tree-level operator insertion

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

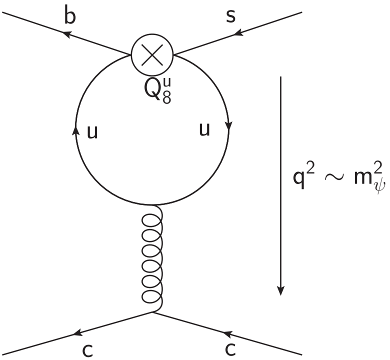
$$Q_{8V} \equiv (\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_V$$





Penguin Pollution by Tree-level Operator Insertion

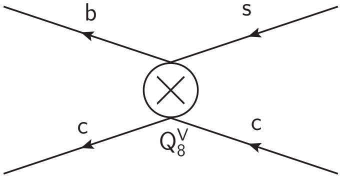
If we can describe the up quark penguin by an effective theory…



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

$\longrightarrow$

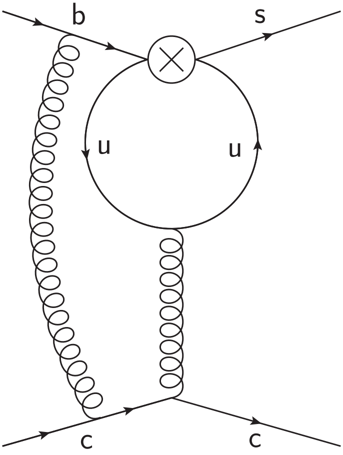
…the description of the process simplifies.



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

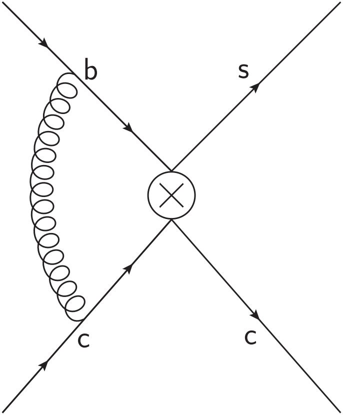
Investigate the Infrared Structure - Soft Divergences

Infrared-soft divergent diagrams ...



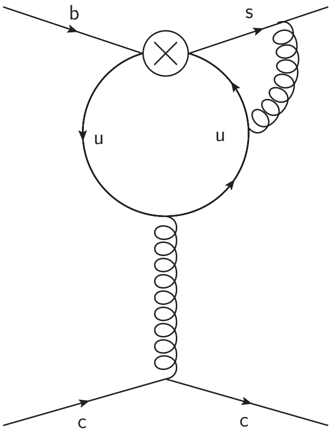
$\longrightarrow$

... factorize.

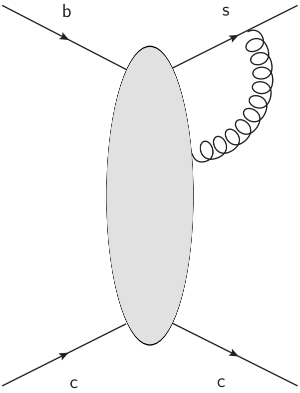


Infrared Structure - Collinear Divergences

Collinear divergent diagrams



are infrared-safe if summed over,



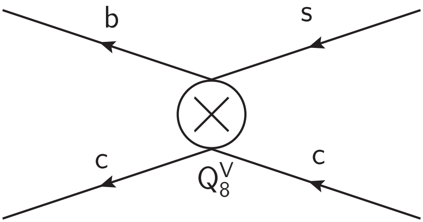
or are infrared-safe if considered in a physical gauge.

Effective Description is Possible

Conclusion

- Soft divergences factorize
- Collinear divergences cancel or factorize

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



$C_8^u Q_{8V}$

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

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

Relevant Matrix Elements

Decay amplitude

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

Three relevant matrix elements only:

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

$1/N_c$ Expansion

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

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

$1/N_c$ expansion

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

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

Numerics

Parametrization of the hadronic phase shift

$$\tan(\Delta\phi) \propto \mathrm{Re}\left(\frac{p_f}{t_f}\right) = \mathrm{Re}\left(\frac{(C_8^u + C_8^t)V_8}{C_0 V_0 + C_8(V_8 - A_8)}\right)$$

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

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

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

Results

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

Our preliminary results:

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

Uncertainties from

- Experimental input ($Br(B \to f)$, CKM) are small for $\Delta\phi$
- 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.

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

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

Experimental results:

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

Our preliminary results:

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

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

$\rightarrow$ **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

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 *et al.* (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
…	…	…	…

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

Appendix

Our preliminary conservative results:

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

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

Appendix

$$C_0 \equiv C_1 + \frac{1}{N_c} C_2 = 0.13$$
$$C_8 \equiv 2C_2 = 2.2$$

Important operators:

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

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

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

Does the $1/N_c$ expansion work?

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