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

Philipp Frings

in collaboration with Ulrich Nierste and Martin Wiebusch

Karlsruhe Institute of Technology

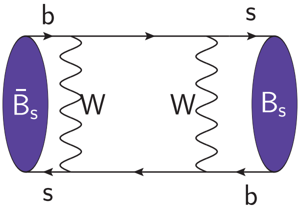
Institute for Theoretical Particle Physics

GK Workshop 2014 Bad Liebenzell

Indirect Search

Indirect Search for New Physics

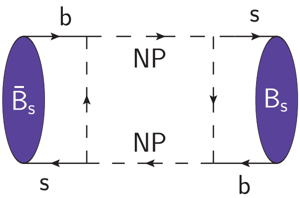
Standard Model



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

$$\phi_s = -2\beta_s$$

New Physics



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

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

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

(approximately)

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

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)

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

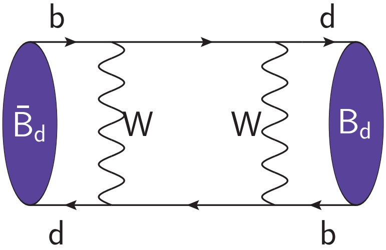
Include $\mathcal{O}(\epsilon)$ and possible NP

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

$\Rightarrow$ 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

$$\phi_d = 2\beta$$

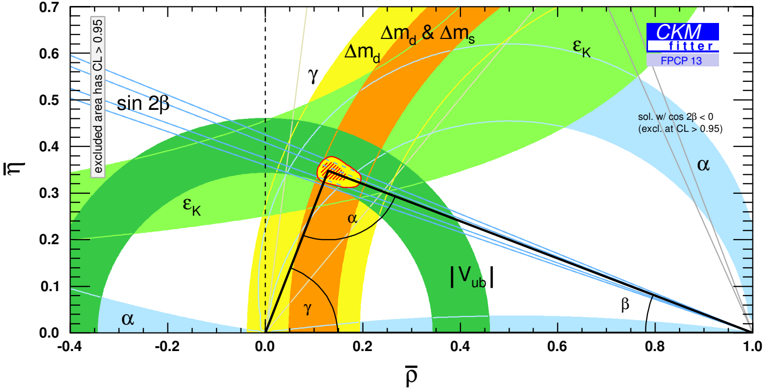
Include $\mathcal{O}(\epsilon)$ and/or NP

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

Unitary CKM matrix:

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

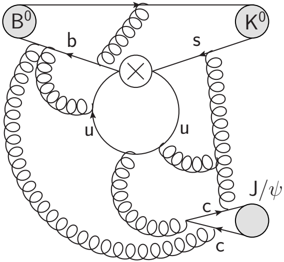
Leads to Unitarity triangle



Penguin Pollution under Debate

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

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



- 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

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	$\|\Delta S\| \lesssim 0.01$	$\|\Delta\phi_d\| \lesssim 0.8^\circ$	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?

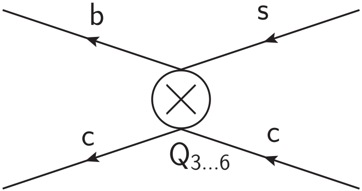
Penguin operators

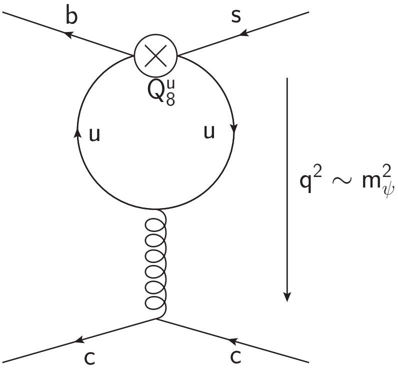
$$\langle f | \sum_{i=3}^{6} C_i Q_i | B \rangle \approx C_8^t \langle f | Q_{8V} | B \rangle$$

Tree-level operator insertion

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

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

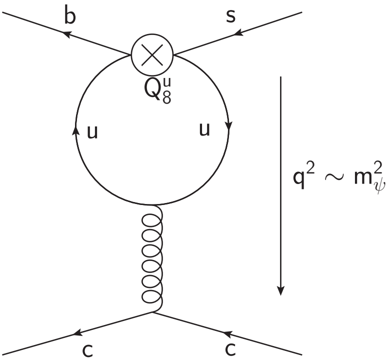




Penguin Pollution by Tree-level Operator Insertion

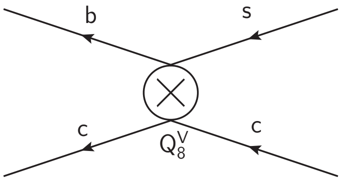
If we can describe the up quark penguin by an effective theory…

…the description of the process simplifies.



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

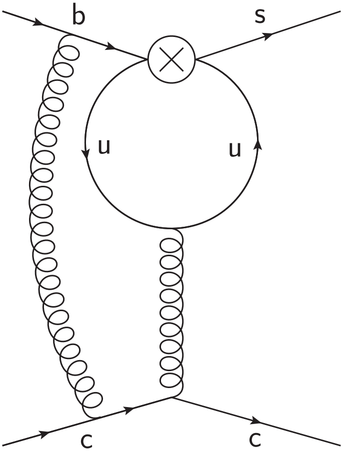
$\longrightarrow$



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

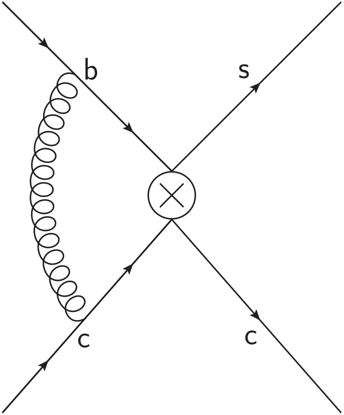
Investigate the Infrared Structure - Soft Divergences

Infrared-soft divergent diagrams ...



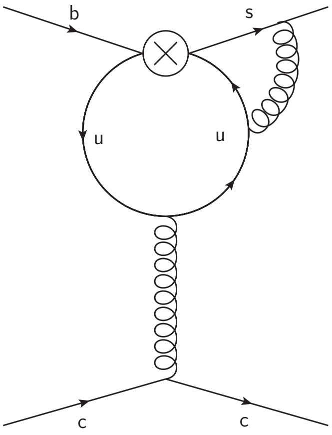
$\longrightarrow$

... factorize.

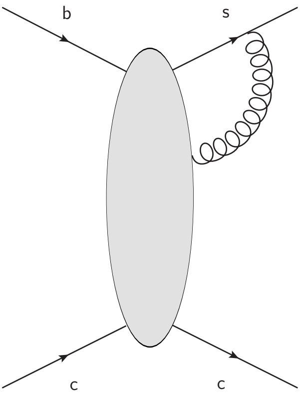


Infrared Structure - Collinear Divergences

Collinear divergent diagrams



are infrared-safe if summed over,



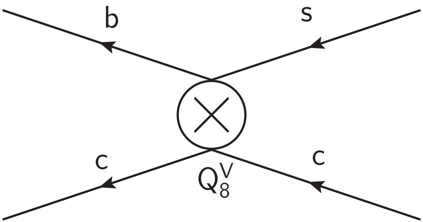
or are infrared-safe if considered in a physical gauge.

Effective Description is Possible

Conclusion

- Soft divergences factorize
- Collinear divergences cancel or factorize

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



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

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

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:

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

Uncertainties from

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

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

Our preliminary conservative results:

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

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:

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

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

$\to$ **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

$$\begin{aligned} C_0 \equiv &\quad C_1 + \frac{1}{N_c} C_2 &= 0.13 \\ C_8 \equiv &\quad 2C_2 &= 2.2 \end{aligned}$$

Important operators:

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

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?

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