

Penguin Pollution in $B^0 \rightarrow J/\psi K_S$ Decay

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1. Introduction

- $B^0 \rightarrow J/\psi K_S$ is the golden mode for extracting $\sin(2\phi_1)$.

$$a_{J/\psi K_S}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S) - \Gamma(B^0(t) \rightarrow J/\psi K_S)}{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S) + \Gamma(B^0(t) \rightarrow J/\psi K_S)}$$

$$\simeq \sin(2\phi_1) \sin(\Delta M t)$$

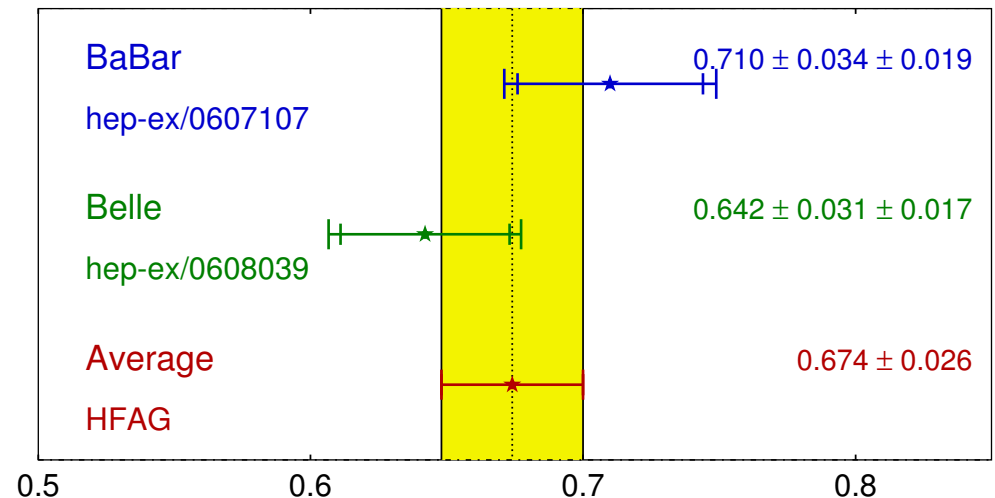
- Penguin pollution is believed to be negligible.

- A complete estimation of its effect is essential for precision measurements.

± 0.019 at Super B ($5ab^{-1}$)

KEK Super B Lol (04)

$\sin(2\beta) \equiv \sin(2\phi_1)$ **HFAG**
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Corrections to Mixing-induced CP Asymmetry

$$a_{J/\psi K_S}(t) = \mathcal{S}_{J/\psi K_S} \sin(\Delta M t) + \mathcal{A}_{J/\psi K_S} \cos(\Delta M t)$$

$$\mathcal{S}_{J/\psi K_S} = \frac{2 \operatorname{Im} \lambda_{J/\psi K_S}}{1 + |\lambda_{J/\psi K_S}|^2}, \quad \mathcal{A}_{J/\psi K_S} = \frac{|\lambda_{J/\psi K_S}|^2 - 1}{1 + |\lambda_{J/\psi K_S}|^2}$$

$$\lambda_{J/\psi K_S} = \frac{q}{p} \frac{A(\bar{B}^0 \rightarrow J/\psi K_S)}{A(B^0 \rightarrow J/\psi K_S)}$$

- Corrections from $B - \bar{B}$ mixing: $\frac{q}{p} \neq e^{-2i\phi_1}$

- Corrections from the decay part:

$$\begin{aligned} A(B^0 \rightarrow J/\psi K_S) &= V_{ub}^* V_{us} A_{J/\psi K_S}^{(u)} + V_{cb}^* V_{cs} A_{J/\psi K_S}^{(c)} + V_{tb}^* V_{ts} A_{J/\psi K_S}^{(t)} \\ &= V_{cb}^* V_{cs} (A_{J/\psi K_S}^{(c)} - A_{J/\psi K_S}^{(t)}) + V_{ub}^* V_{us} (A_{J/\psi K_S}^{(u)} - A_{J/\psi K_S}^{(t)}) \end{aligned}$$

- We do not consider corrections from $K - \bar{K}$ mixing and

$$\Delta\Gamma_B, \lesssim O(10^{-3}). \text{ Grossman, Kagan, Ligeti (02)}$$

Previous Estimations

● Corrections to Mixing and to Decay *Boos, Mannel, Reuter (05)*

● Non-local contributions to Mixing

$$\Delta \mathcal{S}_{J/\psi K_S}^{\text{mix}} = (2.08 \pm 1.23) \times 10^{-4}$$

$$\mathcal{A}_{J/\psi K_S}^{\text{mix}} = (2.59 \pm 1.48) \times 10^{-4}$$

● u -quark loop: $\Delta \mathcal{S}_{J/\psi K_S}^{\text{decay}} \sim O(10^{-4})$

- naïve estimation

- Contributions from penguin operators were overlooked.

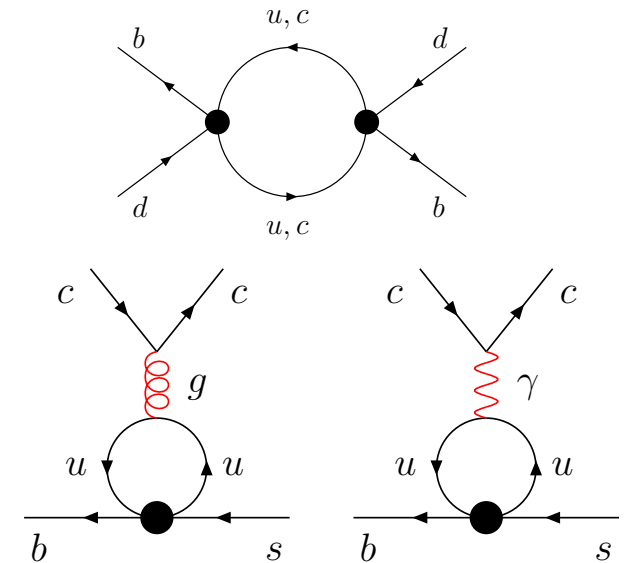
➔ We shall reinvestigate the size of penguin pollution.

● A model-independent analysis using the $B^0 \rightarrow J/\psi \pi^0$ data

Ciuchini, Pierini, Silvestrini (05)

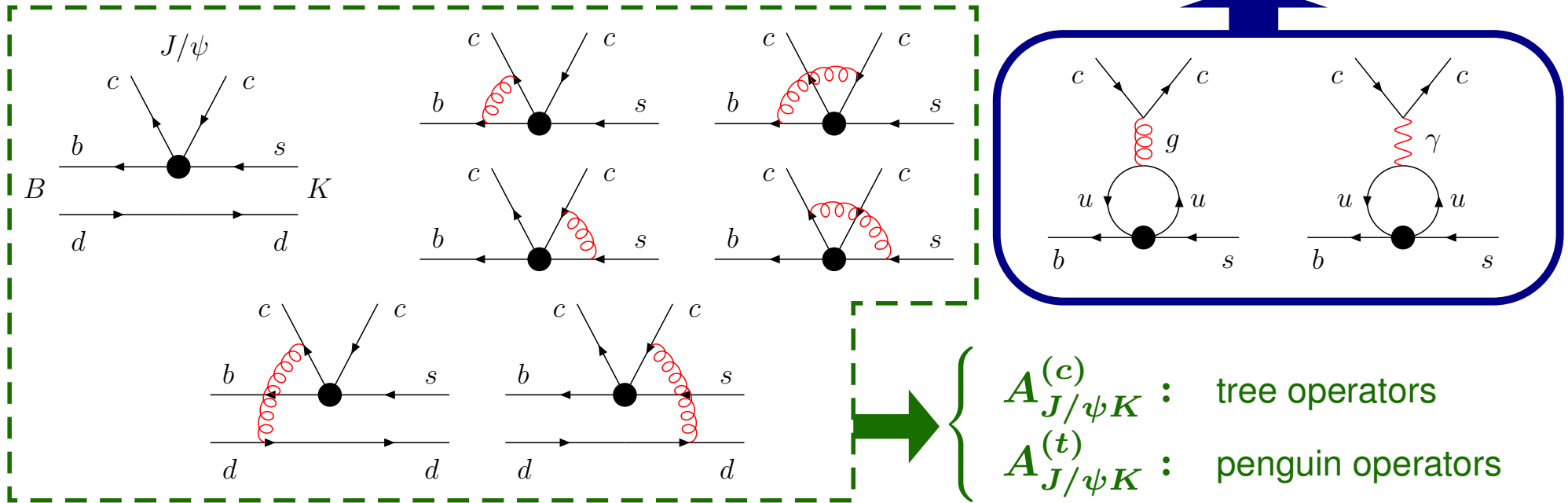
$$\Delta \mathcal{S}_{J/\psi K_S}^{\text{decay}} = 0.000 \pm 0.012$$

● Theoretical uncertainty comes from the exp error.



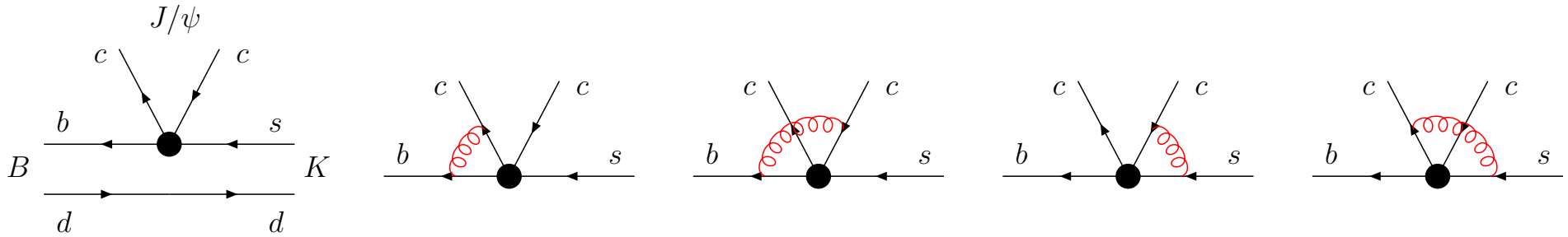
2. Penguin Pollution

$$A(B^0 \rightarrow J/\psi K) = V_{cb}^* V_{cs} (A_{J/\psi K}^{(c)} - A_{J/\psi K}^{(t)}) + V_{ub}^* V_{us} (A_{J/\psi K}^{(u)} - A_{J/\psi K}^{(t)})$$



- We calculate the decay amplitude up to leading power in $1/m_b$ and to NLO in α_s using the framework in Chen, Li (04).
- Nonfactorizable spectator diagrams are essential for $B \rightarrow J/\psi K$ since it is a color-suppressed decay.

Factorizable Contribution



- We adopt QCDF to handle the factorizable amplitudes, since the energy release in $F_+^{BK}(m_{J/\psi}^2)$ is small.

$$\mathcal{A}_{J/\psi K}^{(c)f} = 2\sqrt{2N_c} \int_0^1 dx_c \Psi^L(x_c) a_2(x_c, \mu) F_+^{BK}(m_{J/\psi}^2)$$

$$\mathcal{A}_{J/\psi K}^{(t)f} = 2\sqrt{2N_c} \int_0^1 dx_c \Psi^L(x_c) [a_3(x_c, \mu) + a_5(x_c, \mu)] F_+^{BK}(m_{J/\psi}^2)$$

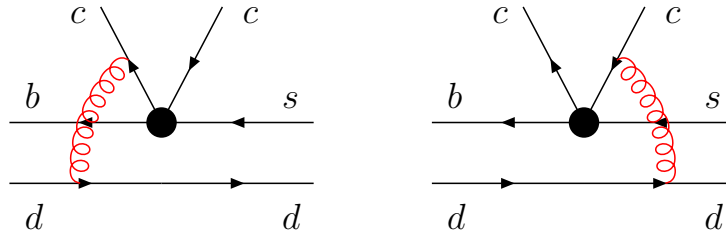
the twist-2 J/ψ meson DA

e.g.

$$a_2(x, \mu) = C_1(\mu) + \frac{C_2(\mu)}{N_c} \left[1 + \frac{\alpha_s(\mu)}{4\pi} C_F \left(-18 + 12 \ln \frac{m_b}{\mu} + f_I(x) \right) \right]$$

a loop function

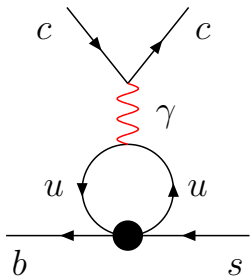
Nonfactorizable Spectator Contribution



- QCDF is not appropriate due to the end-point singularity from vanishing parton momenta.
- We employ PQCD based on k_T factorization theorem, which is free of the end-point singularity.
- The nonfactorizable contribution has a characteristic scale higher than in $F_+^{BK}(m_{J/\psi}^2)$. *Chou,Shih,Lee,Li(02)*
- Nonfactorizable amplitudes are comparable in size to factorizable amplitudes.

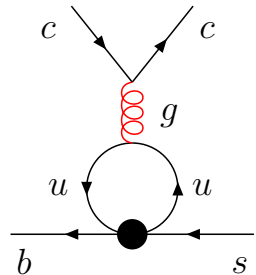
u -loop Contribution

$$\mathcal{H}_{\text{eff}}^{(u)} = -\frac{G_F}{\sqrt{2}} V_{us}^* V_{ub} \left[\frac{\alpha}{3\pi} e_u e_c (N_c C_1 + C_2) (\bar{c}c)_V (\bar{s}b)_{V-A} + \frac{\alpha_s}{3\pi} C_2 (\bar{c}T^a c)_V (\bar{s}T^a b)_{V-A} \right] \left(\frac{2}{3} - \ln \frac{l^2}{\mu^2} + i\pi \right)$$



- The photon emission is less than 5% of $A_{J/\psi K}^{(t)}$ due to α .

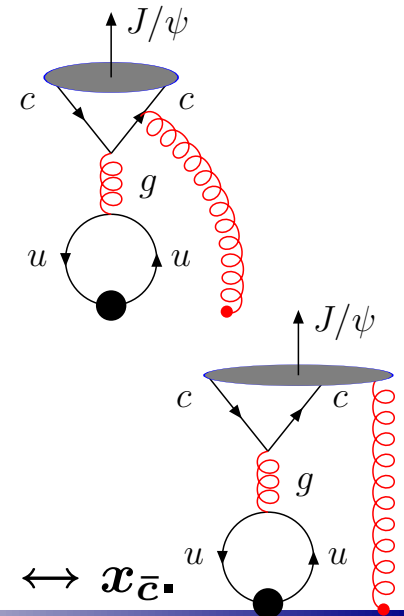
- For the gluon emission, an additional gluon is necessary to form J/ψ .



- hard gluon \rightarrow higher order, $O(\alpha_s^2)$
- soft gluon \rightarrow no contribution

the three-parton DAs are antisymmetric

and the hard kernel is symmetric under $x_c \leftrightarrow x_{\bar{c}}$.



3. Numerical Results

CKM + hadronic uncertainties
 ↓ only hadronic uncertainty

- Our predictions:

$$\text{Br}(B^0 \rightarrow J/\psi K^0) = \left(6.6^{+3.7 (+3.7)}_{-2.3 (-2.3)} \right) \times 10^{-4}$$

$$\Delta \mathcal{S}_{J/\psi K_S}^{\text{decay}} = \left(7.2^{+2.4 (+1.2)}_{-3.4 (-1.1)} \right) \times 10^{-4}$$

$$\mathcal{A}_{J/\psi K_S}^{\text{decay}} = - \left(16.7^{+6.6 (+3.8)}_{-8.7 (-4.1)} \right) \times 10^{-4}$$

- Branching ratio is in agreement with the data,

$$\text{Br}(B^0 \rightarrow J/\psi K^0)|_{\text{Data}} = (8.63 \pm 0.35) \times 10^{-4} \quad \text{HFAG}$$

- Including the correction to $B - \bar{B}$ mixing *Boos, Mannel, Reuter (05)*,

$$\Delta \mathcal{S}_{J/\psi K_S} = \Delta \mathcal{S}_{J/\psi K_S}^{\text{mix}} + \Delta \mathcal{S}_{J/\psi K_S}^{\text{decay}} = \left(9.3^{+3.6}_{-4.6} \right) \times 10^{-4}$$

$$\mathcal{A}_{J/\psi K_S} = \mathcal{A}_{J/\psi K_S}^{\text{mix}} + \mathcal{A}_{J/\psi K_S}^{\text{decay}} = - \left(14.1^{+8.1}_{-10.2} \right) \times 10^{-4}$$

4. Conclusion

- We calculated the penguin pollution in $B^0 \rightarrow J/\psi K_S$ up to leading power in $1/m_b$ and to NLO in α_s .

$$\Delta\mathcal{S}_{J/\psi K_S} = \Delta\mathcal{S}_{J/\psi K_S}^{\text{mix}} + \Delta\mathcal{S}_{J/\psi K_S}^{\text{decay}} = \left(9.3_{-4.6}^{+3.6}\right) \times 10^{-4}$$

$$\mathcal{A}_{J/\psi K_S} = \mathcal{A}_{J/\psi K_S}^{\text{mix}} + \mathcal{A}_{J/\psi K_S}^{\text{decay}} = -\left(14.1_{-10.2}^{+8.1}\right) \times 10^{-4}$$

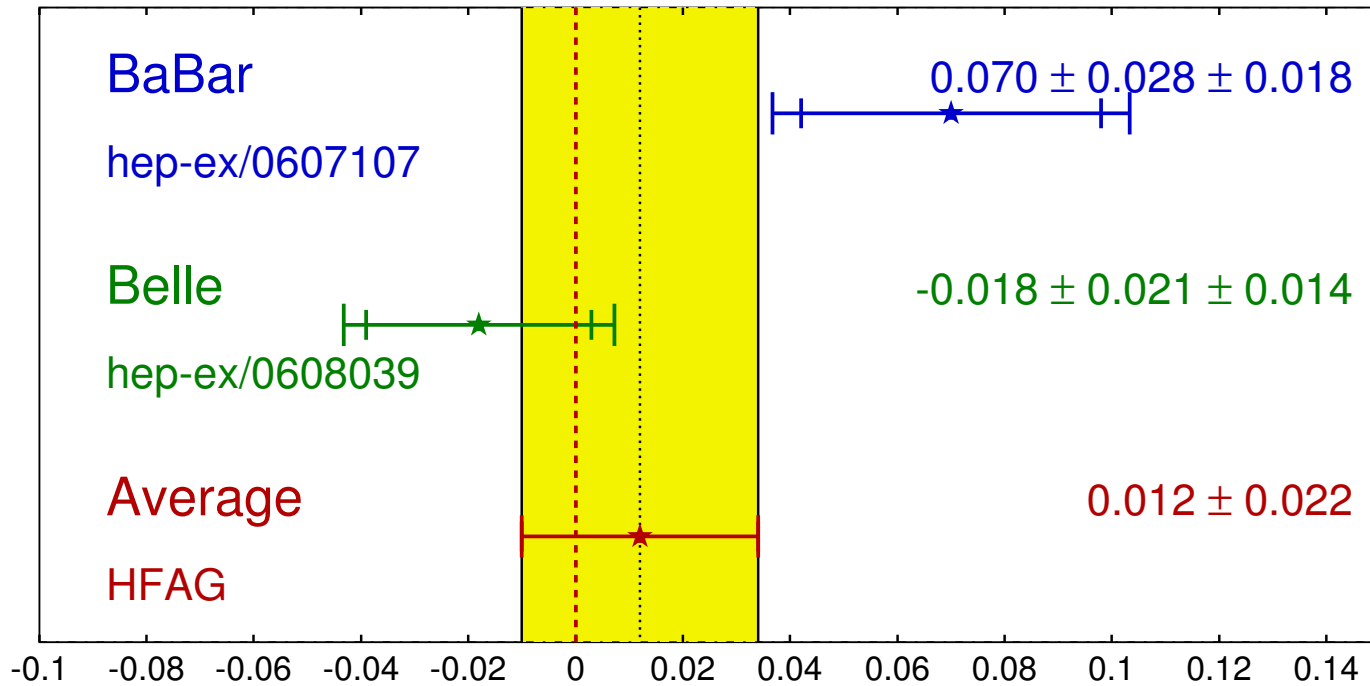
- Including the CP violation from the K - \bar{K} mixing, $\Delta\mathcal{S}_{J/\psi K_S}$ and $\mathcal{A}_{J/\psi K_S}$ remain $O(10^{-3})$.
- Our results provide a SM reference for verifying NP from the $B^0 \rightarrow J/\psi K_S$ data.

Backup

Direct CP Asymmetry

$b \rightarrow ccs$ C_{CP}

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$$\begin{aligned}
 C_{J/\psi K_S} &= -\mathcal{A}_{J/\psi K_S} = -\left(\mathcal{A}_{J/\psi K_S}^{\text{mix}} + \mathcal{A}_{J/\psi K_S}^{\text{decay}} \right) \\
 &= \left(14.1_{-10.2}^{+8.1} \right) \times 10^{-4}
 \end{aligned}$$

Hadronic Parameters

- Distribution amplitudes for the B , J/ψ , K mesons, e.g.,

$$\Psi_{J/\psi}^L(x) = N^L \frac{f_{J/\psi}}{2\sqrt{2N_c}} x(1-x) \left[\frac{x(1-x)}{1-4\alpha x(1-x)} \right]^\alpha$$
$$\Psi_{J/\psi}^t(x) = N^t \frac{f_{J/\psi}^T}{2\sqrt{2N_c}} (1-2x)^2 \left[\frac{x(1-x)}{1-4\alpha x(1-x)} \right]^\alpha$$

where $\alpha = 0.7 \pm 0.1$ and $\int_0^1 dx \Psi_{J/\psi}^{L,t}(x) = \frac{f_{J/\psi}^{(T)}}{2\sqrt{2N_c}}$.

- $B \rightarrow K$ transition form factor, $F_+^{BK}(m_{J/\psi}^2) = 0.62 \pm 0.09$,
quoted from the LCSR calculation.