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

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Outlines

1. Introduction
   - Corrections to $\mathcal{S}_{J/\psi K_S}$
   - Previous Estimations
2. Penguin Pollution
3. Numerical Results
4. Conclusion

1. Introduction

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

Carter,Sanda (81); Bigi,Sanda (81)

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

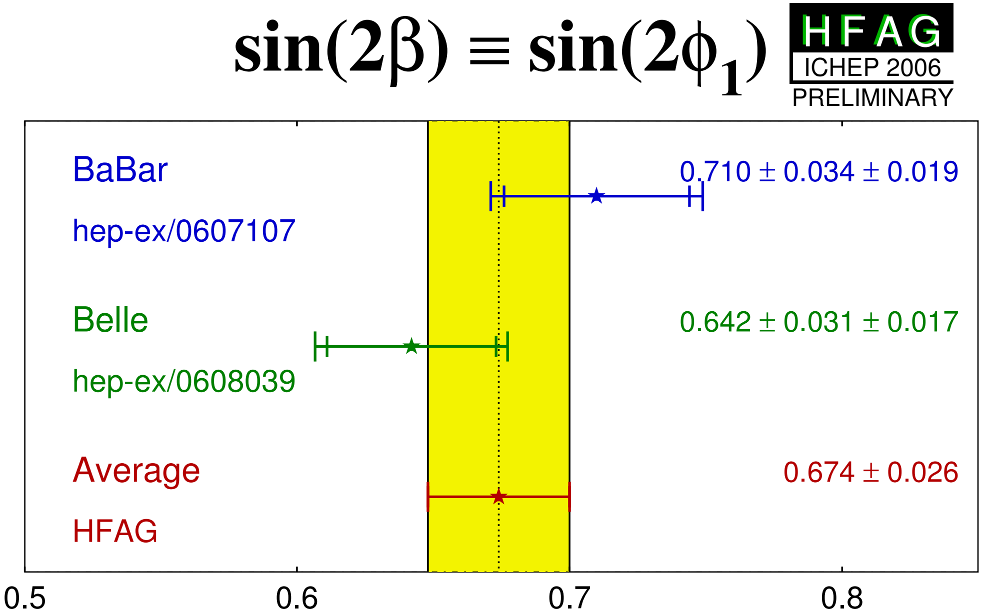
$$\simeq \sin(2\phi_1)\sin(\Delta M t)$$

- **Penguin pollution is believed to be negligible.**

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

± 0.019 **at Super B (5 ab^{-1})**

KEK Super B LoI (04)



Corrections to CP Asymmetries

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

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

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

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

$$A(B^0 \to J/\psi K_S) = V_{ub}^* V_{us}\, A^{(u)}_{J/\psi K_S} + V_{cb}^* V_{cs}\, A^{(c)}_{J/\psi K_S} + V_{tb}^* V_{ts}\, A^{(t)}_{J/\psi K_S}$$
$$= V_{cb}^* V_{cs}\,(A^{(c)}_{J/\psi K_S} - A^{(t)}_{J/\psi K_S}) + V_{ub}^* V_{us}\,(A^{(u)}_{J/\psi K_S} - A^{(t)}_{J/\psi K_S})$$

- **We do not consider corrections from $K - \bar{K}$ mixing and $\Delta\Gamma_B$, $\lesssim O(10^{-3})$.** *Grossman,Kagan,Ligeti (02)*

Previous Estimation — flavor SU(3) *Ciuchini,Pierini,Silvestrini (05)*

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

$$A(B^0 \to J/\psi K^0) = V_{cb}^* V_{cs} (E_2 - P_2) + V_{ub}^* V_{us} (P_2^{\rm GIM} - P_2)$$

$$A(B^0 \to J/\psi \pi^0) = V_{cb}^* V_{cd} (E_2 - P_2) + V_{ub}^* V_{ud} (P_2^{\rm GIM} - P_2 - EA_2)$$

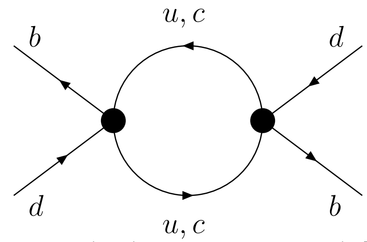
Tree $\quad$ u-quark loop

Assumptions:

1. EA_2 (Emission Annihilation) **is negligible.**
2. **Flavor SU(3) gives reasonable estimates for the range of variation of parameters.**

- **They extracted the range of $|P_2^{\rm GIM} - P_2|$ from the data of Br($J/\psi\pi^0$), $\mathcal{S}_{J/\psi\pi^0}$, $\mathcal{A}_{J/\psi\pi^0}$, and used it to evaluate $\Delta S_{J/\psi K_S}$.**
- $\Delta\mathcal{S}_{J/\psi K_S}^{\rm decay} = 0.000 \pm 0.012$ **from the current data.**
- **Theoretical uncertainty comes from the exp error.**

Previous Estimation — perturbative calc. *Boos,Mannel,Reuter (05)*



- **Non-local contributions to Mixing**
  - **Non-local operators:**

$$T_1 = -\frac{i}{2}\int d^4x\, \mathrm{T}\Big[[(\bar{b}_L\gamma_\mu c_L)(\bar{c}_L\gamma^\mu d_L)](x)[(\bar{b}_L\gamma_\nu c_L)(\bar{c}_L\gamma^\nu d_L)](0)\Big]$$

$$T_2 = -\frac{i}{2}\int d^4x\, \mathrm{T}\Big[[(\bar{b}_L\gamma_\mu c_L)(\bar{u}_L\gamma^\mu d_L)](x)[(\bar{b}_L\gamma_\nu u_L)(\bar{c}_L\gamma^\nu d_L)](0)\Big]$$

$$T_3 = -\frac{i}{2}\int d^4x\, \mathrm{T}\Big[[(\bar{b}_L\gamma_\mu u_L)(\bar{u}_L\gamma^\mu d_L)](x)[(\bar{b}_L\gamma_\nu u_L)(\bar{u}_L\gamma^\nu d_L)](0)\Big]$$

  - **N-l operators mix into $\Delta B = 2$ local operators of dim 8 through renormalization-group effects.**

$$Q_1 = \Box(\bar{b}_L\gamma_\mu d_L)(\bar{b}_L\gamma^\mu d_L), \quad Q_2 = \partial^\mu\partial^\nu(\bar{b}_L\gamma_\mu d_L)(\bar{b}_L\gamma_\nu d_L)$$

$$Q_3 = m_c^2(\bar{b}_L\gamma_\mu d_L)(\bar{b}_L\gamma^\mu d_L)$$

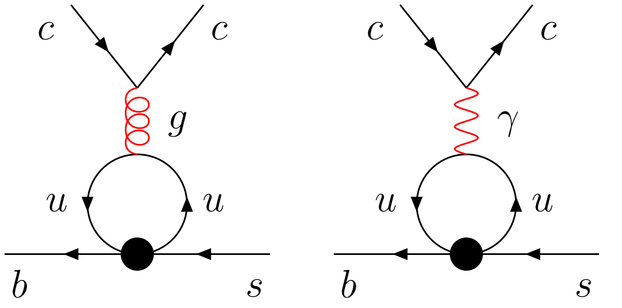
$$\Rightarrow \quad \Delta\mathcal{S}^{\mathrm{mix}}_{J/\psi K_S} = (2.08 \pm 1.23) \times 10^{-4}$$

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

Previous Estimation — perturbative calc. *Boos,Mannel,Reuter (05)*

- **Corrections to Decay**
  - **Naïve estimation of u-quark loop**

$$\Delta\mathcal{S}^{\text{decay}}_{J/\psi K_S} = -(4.24 \pm 1.94) \times 10^{-4}$$



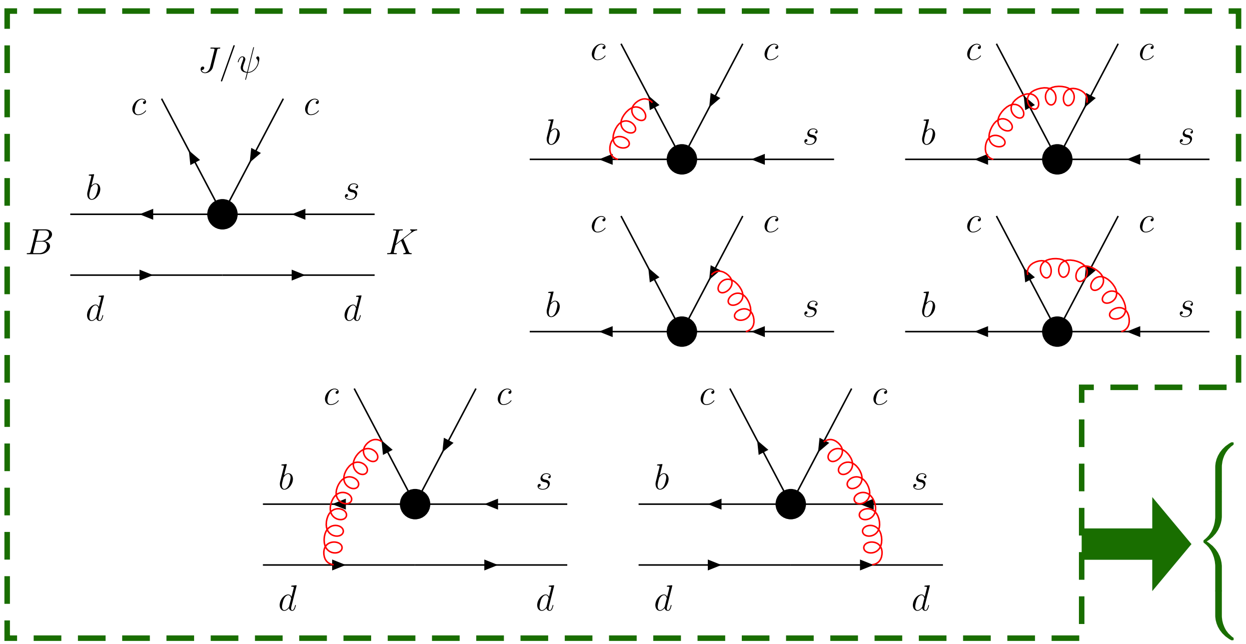
  - **Contributions from penguin operators were overlooked.**

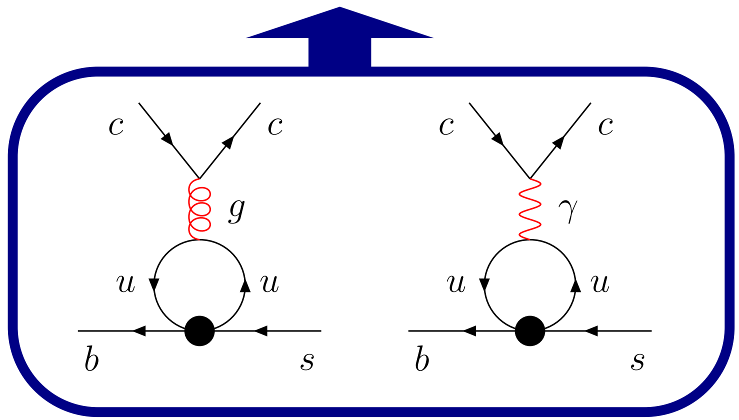
$$A(B^0 \to J/\psi K_S) = V^*_{cb}V_{cs}\,(A^{(c)}_{J/\psi K_S} - A^{(t)}_{J/\psi K_S}) + V^*_{ub}V_{us}\,(A^{(u)}_{J/\psi K_S} - A^{(t)}_{J/\psi K_S})$$

⇒ **We shall reinvestigate the size of penguin pollution.**

2. Penguin Pollution

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

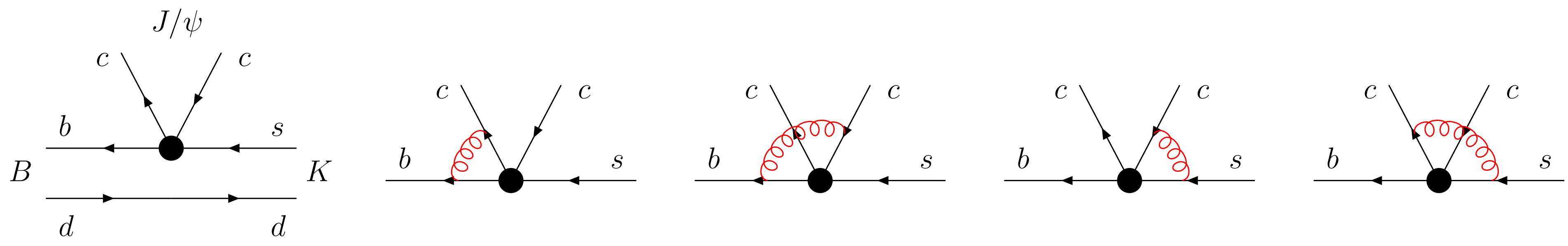




- $A^{(c)}_{J/\psi K}$: tree operators
- $A^{(t)}_{J/\psi K}$: penguin operators

- **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 $B \to J/\psi K$ 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.

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

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

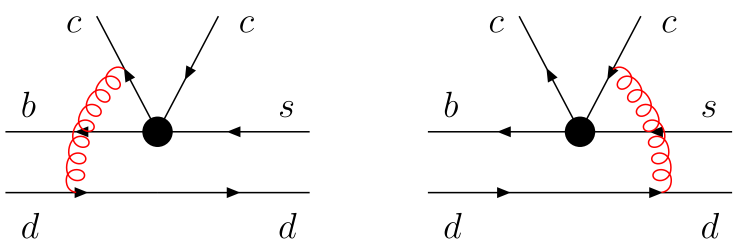
the twist-2 J/ψ meson DA

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

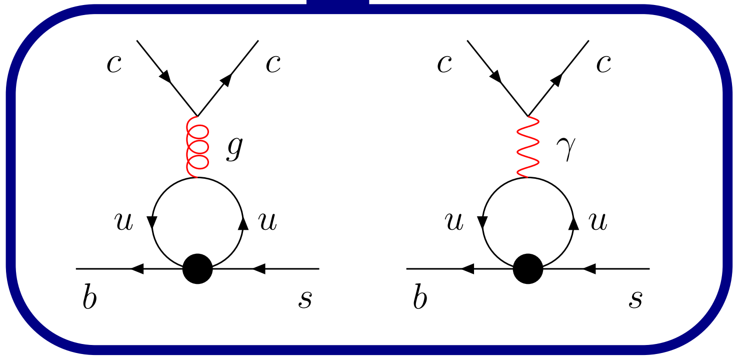
Nonfactorizable Spectator Contribution



- **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-quark Loop Contribution

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



- **Can we calculate u-quark loop diagrams in perturbation theory?**

- **The u- and c-quark loops are well-behaved in perturbation theory without any infrared singularity, which has been known as the BSS mechanism.**

  Bander,Silverman,Soni (79)

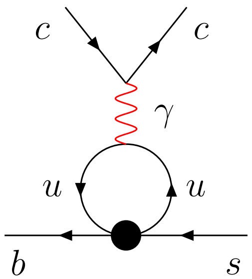
  ➡ **Long-distance contribution is unlikely to be large.**

- **The LCSR analysis has suggested that the u- and c-loops are dominated by short-distance contribution.**

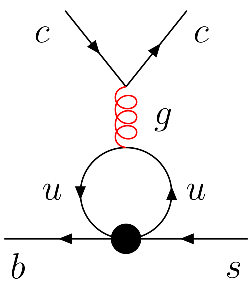
  Khodjamirian,Mannel,Melic (03)

u-quark Loop Contribution

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

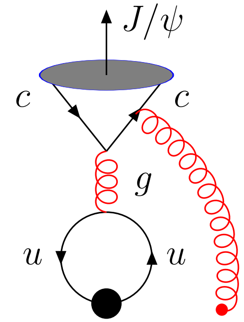


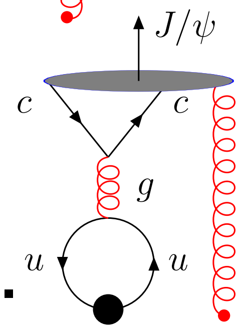
- The photon emission is less than 5% of $A_{J/\psi K}^{(t)}$ due to α.



- For the gluon emission, an additional gluon is necessary to form J/ψ.
  - hard gluon ➡ higher order, $O(\alpha_s^2)$
  - soft gluon ➡ no contribution

    the three-parton DAs are antisymmetric and the hard kernel is symmetric under $x_c \leftrightarrow x_{\bar{c}}$.





Source of Theoretical Uncertainty

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

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

$$\Psi^t_{J/\psi}(x) = N^t \frac{f^T_{J/\psi}}{2\sqrt{2N_c}} (1-2x)^2 \left[\frac{x(1-x)}{1-4\alpha x(1-x)} \right]^\alpha$$

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

- $F^{BK}_+(m^2_{J/\psi}) = 0.62 \pm 0.09$**, quoted from the LCSR calc.**
- **CKM elements:** $|V_{ub}| = (4.31 \pm 0.30) \times 10^{-3}$, $\phi_3 = (70 \pm 30)^\circ$
- **Higher-order in α_s and higher-power in $1/m_B$**

3. Numerical Results

CKM + hadronic uncertainties
only hadronic uncertainty

- **Our predictions:**

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

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

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

- **Branching ratio is in agreement with the data,**

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

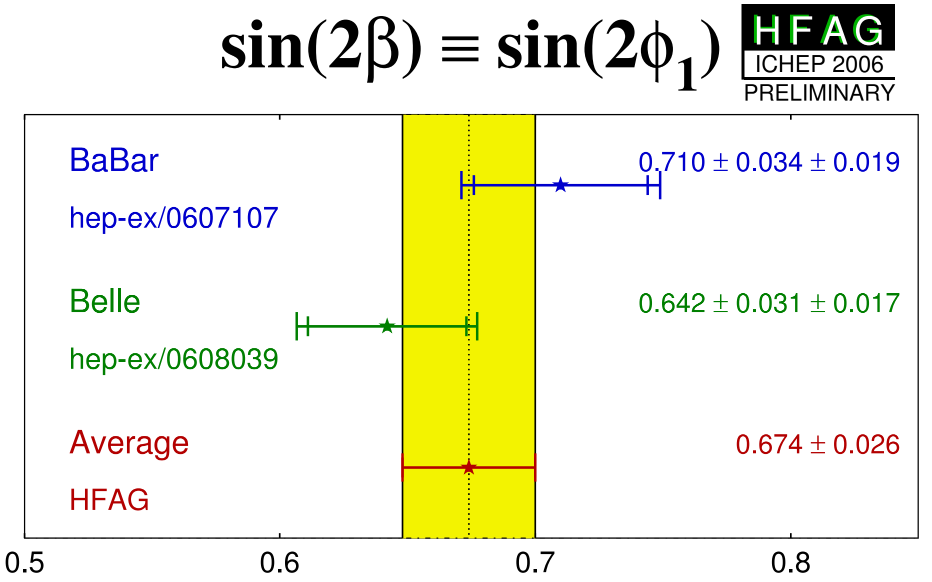
- **Including the correction to $B - \bar{B}$ mixing** *Boos,Mannel,Reuter (05)* **,**

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

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

Mixing-induced CP Asymmetry

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



- **For $L \gtrsim 2$ ab^{-1}, the systematic error will be larger than the statistical one.**

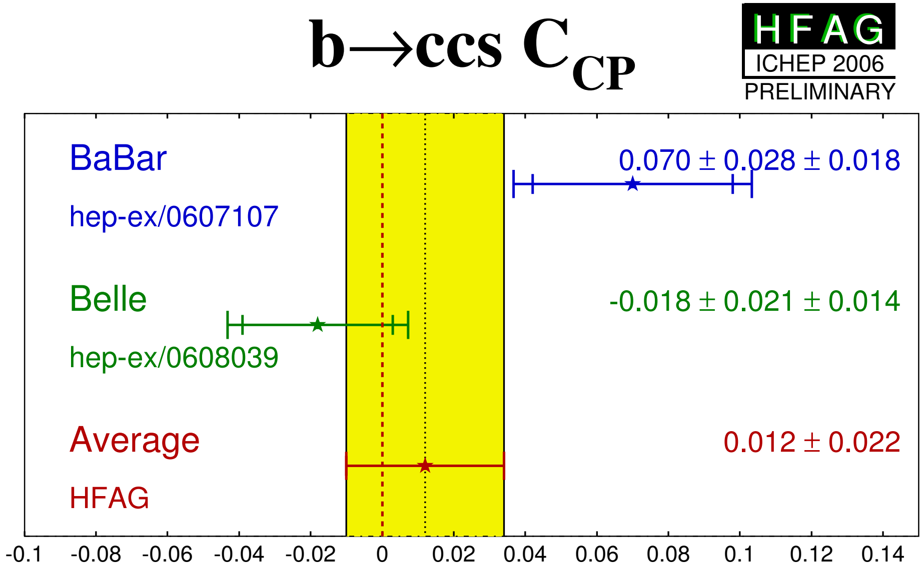
$\pm 0.010(\mathrm{stat}) \pm 0.014(\mathrm{syst})$ at $5\,\mathrm{ab}^{-1}$

$\pm 0.003(\mathrm{stat}) \pm 0.013(\mathrm{syst})$ at $50\,\mathrm{ab}^{-1}$

Nakahama, CKM2006

Direct CP Asymmetry

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



- **Our result supports the claim that $A_{CP}(B \to J/\psi K) \gtrsim 1\,$% would indicate NP.**

Hou,Nagashima,Soddu (06)

4. Conclusion

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

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

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

- **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 $B^0 \to J/\psi K_S$ data.**

- **Our prediction for $\Delta\mathcal{S}_{J/\psi K_S}$ is smaller than the expected systematic error in the future data.**