Charm and Charmonium ϕ_1 Measurements@Belle

Measurements of ϕ_1 in B Decays to Charm and Charmonium at Belle

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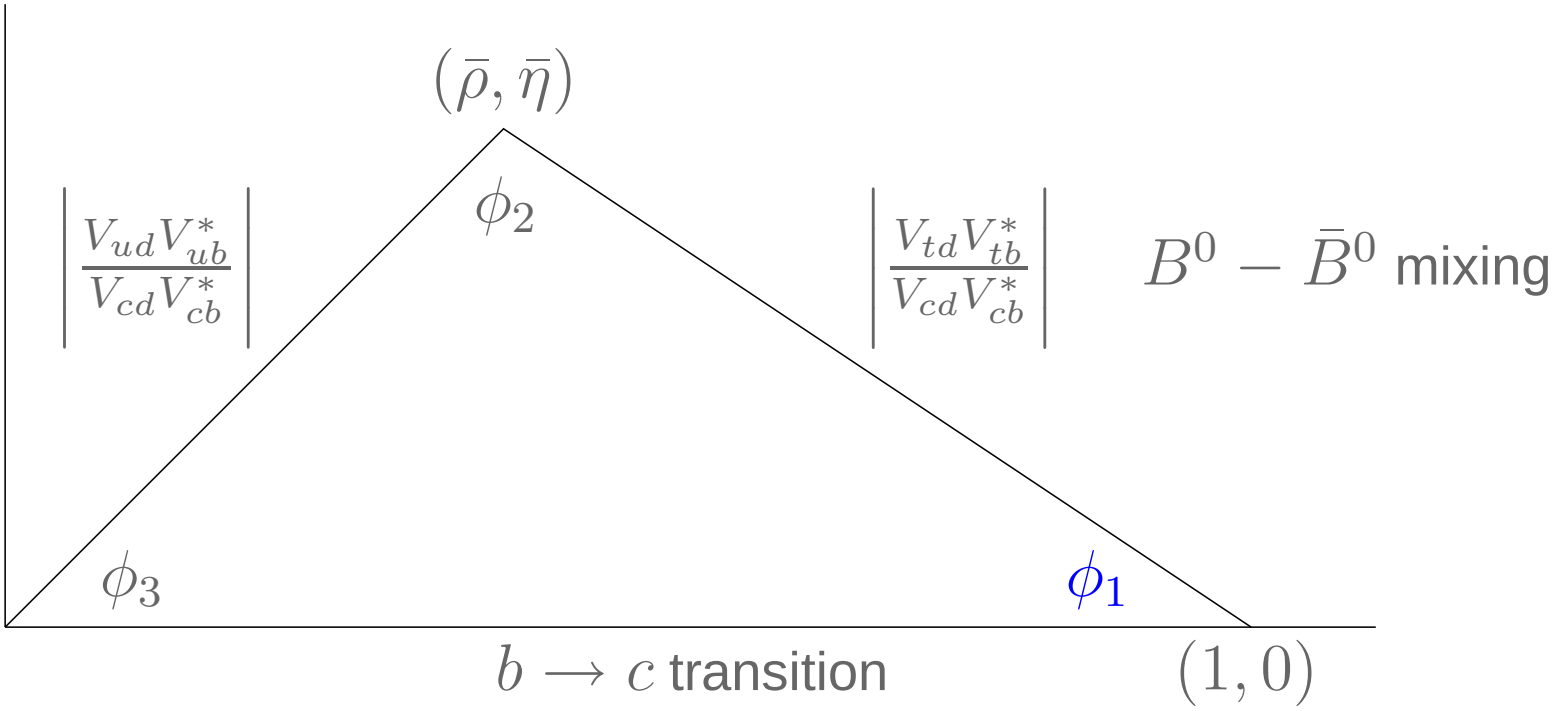
Preamble

From unitarity of CKM matrix,

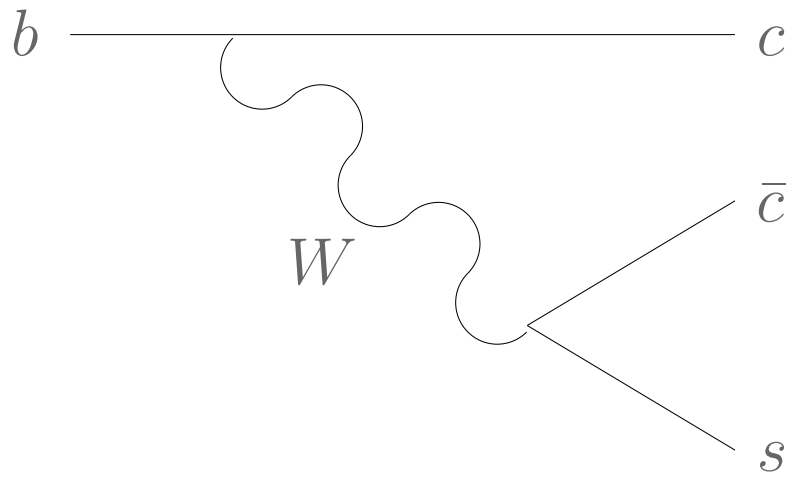
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



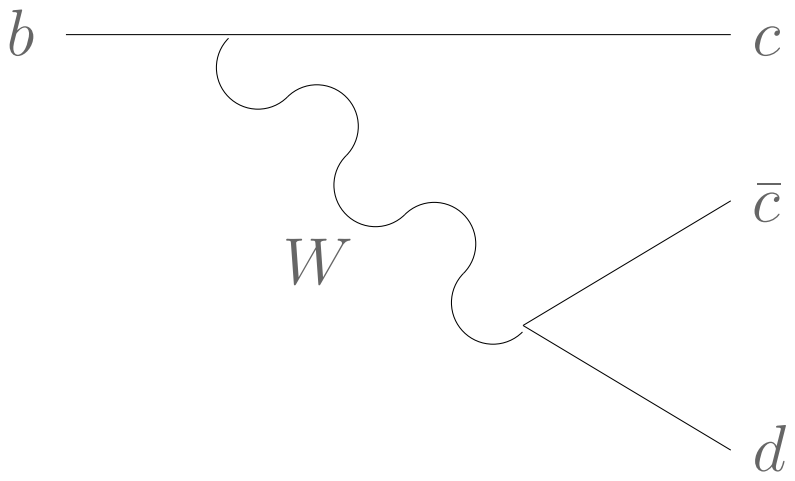
Interference between $b \to c$ decay and $B^0 - \bar{B}^0$ mixing $\rightsquigarrow$ Measure ϕ_1

Outline

Two quark level transitions in this category



I. $B^0 \to D^{*+}\, D^{*-}\, K^0_S$



II. $B^0 \to J/\psi\, \pi^0$

Both new results from Belle!

Charm and Charmonium ϕ_1 Measurements@Belle

I. $B^0 \to D^{*+} D^{*-} K^0_S$

$B^0 \to D^{*+}\ D^{*-}\ K^0_S$ Motivation

T. E. Browder, A. Datta, P. J. O'Donnell and S. Pakvasa, Phys. Rev. D **61**, 054009 (2000)

Extract CP parameters from time-dependent decay rate asymmetry,

$$\frac{\bar{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\bar{\Gamma}(\Delta t) + \Gamma(\Delta t)} = \mathcal{A}_{D^{*+}\ D^{*-}\ K^0_S} \cos \Delta m_{\mathrm{d}} \Delta t + \mathcal{S}_{D^{*+}\ D^{*-}\ K^0_S} \sin \Delta m_{\mathrm{d}} \Delta t$$

If penguin contribution negligible,

$$\mathcal{A}_{D^{*+}\ D^{*-}\ K^0_S} = 0, \mathcal{S}_{D^{*+}\ D^{*-}\ K^0_S} = D \sin 2\phi_1$$

D - dilution factor

Contributing partial waves have different $CP \rightsquigarrow$ Final state CP admixture

$D^{*+}\ K^0_{\mathrm{S}}$ resonant structure contaminates CP eigenstate $\rightsquigarrow$ No indirect CP

$B^0 \to D^{*+}\, D^{*-}\, K^0_S$ Motivation

Assuming no direct CP violation,

Time-dependent decay rate asymmetry in the half-Dalitz space,

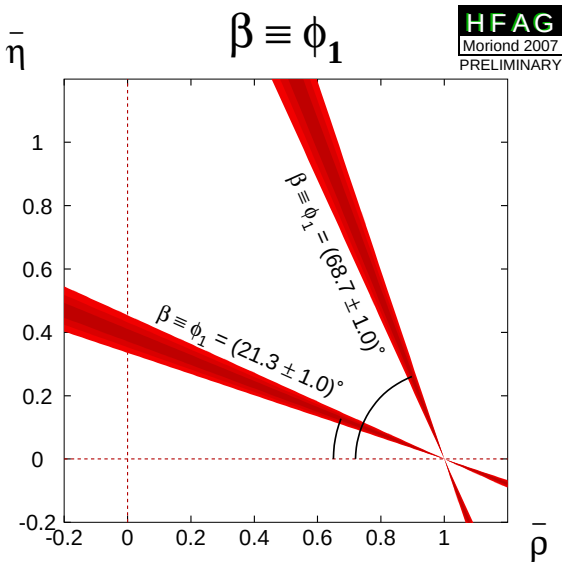
$$\frac{\bar{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\bar{\Gamma}(\Delta t) + \Gamma(\Delta t)} = \eta_y \frac{J_c}{J_0} \cos \Delta m_d \Delta t - \left(\frac{2J_{s1}}{J_0} \sin 2\phi_1 + \eta_y \frac{2J_{s2}}{J_0} \cos 2\phi_1 \right) \sin \Delta m_d \Delta t$$

3-parameter fit: J_c/J_0, $2J_{s1}/J_0 \sin 2\phi_1$, $2J_{s2}/J_0 \cos 2\phi_1$

Possibility to extract $\cos 2\phi_1$

Great precision on $\sin 2\phi_1$ from $B^0 \to J/\psi\, K^0_S$

Resolve $\sin 2\phi_1$ two-fold ambiguity



$B^0 \to D^{*+} D^{*-} K^0_S$ Motivation

$$\frac{\bar{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\bar{\Gamma}(\Delta t) + \Gamma(\Delta t)} = \eta_y \frac{J_c}{J_0} \cos \Delta m_d \Delta t - \left(\frac{2J_{s1}}{J_0} \sin 2\phi_1 + \eta_y \frac{2J_{s2}}{J_0} \cos 2\phi_1 \right) \sin \Delta m_d \Delta t$$

J_c, J_0, J_{s1}, J_{s2} are decay amplitude integrals over the half-Dalitz space

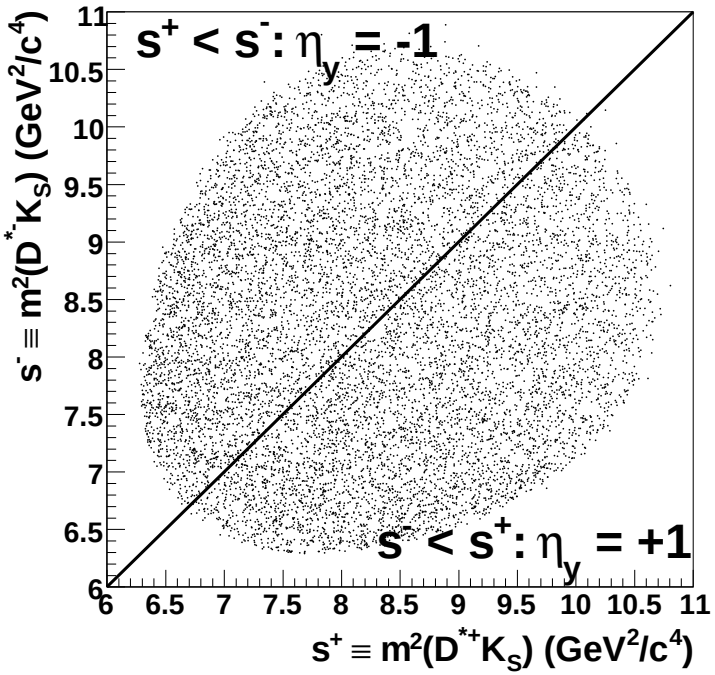
If $B^0 \to D^{*+} D^{*-} K^0_S$ is pure 3-body,

- J_c/J_0 expected to be very small $\sim \mathcal{O}(1\%)$
- $J_{s2} = 0$, ~~$\cos 2\phi_1$~~

If quasi-2-body decay contributes,

- J_c can be large
- Narrow resonance $\rightsquigarrow$ Small J_{s2}
- Wide resonance $\rightsquigarrow$ Large J_{s2}

Dalitz plot from signal MC



Event Reconstruction

Analysis based on 449×10^6 $B\bar{B}$ pairs

Reconstruct,

$B^0 \to D^{*+}\ D^{*-}\ K^0_S$

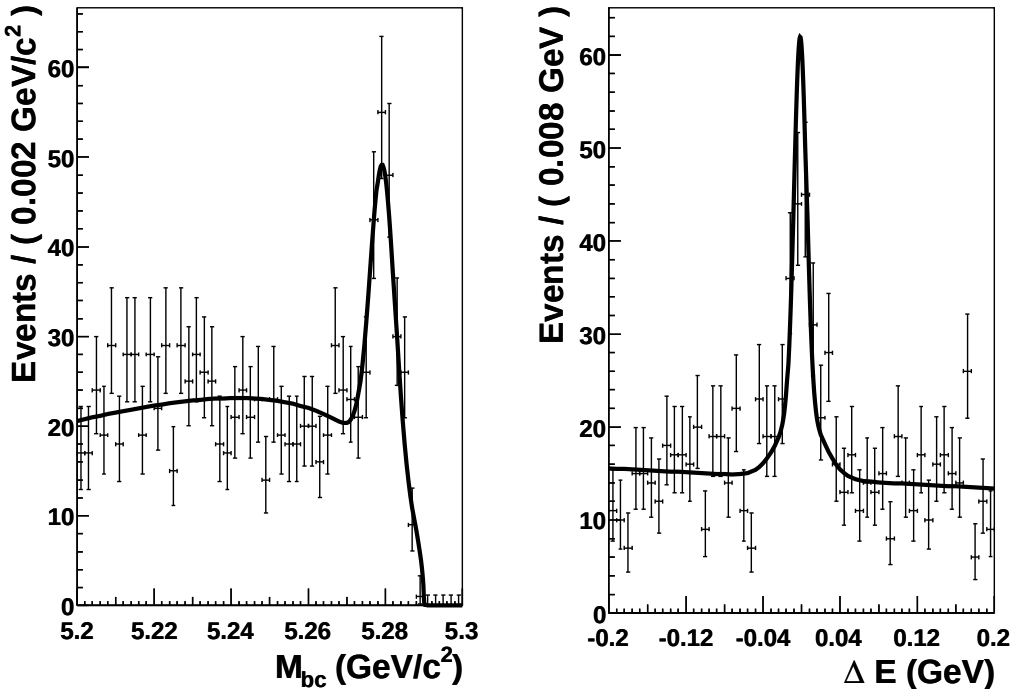
$D^{*+} \to D^0\ \pi^+$
$\quad\to D^+\ \pi^0$

$D^0 \to K^-\ \pi^+$
$\quad\to K^0_S\ \pi^+\ \pi^-$
$\quad\to K^-\ \pi^+\ \pi^0$
$\quad\to K^-\ \pi^+\ \pi^+\ \pi^-$
$\quad\to K^-\ K^+$

$D^+ \to K^-\ \pi^+\ \pi^+$
$\quad\to K^-\ K^+\ \pi^+$

$B^0 \to D^{*+}\, D^{*-}\, K^0_S$ Yield

$$M_{\rm bc} \equiv \sqrt{(E^{CMS}_{\rm beam})^2 - (p^{CMS}_B)^2}, \quad \Delta E \equiv E^{CMS}_B - E^{CMS}_{\rm beam}$$



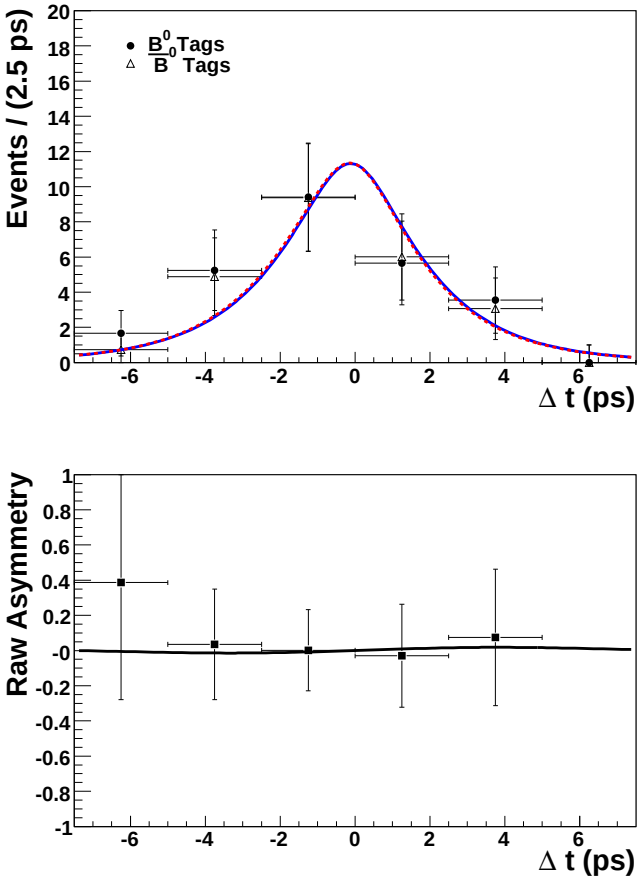
Purity $\sim 47\%$

$$\Upsilon(B^0 \to D^{*+}\, D^{*-}\, K^0_S) = 131.2^{+14.8}_{-14.1}\ (\text{stat})\ \text{events}$$

Background mostly $B\bar{B}$ events

2-parameter TCPV Fit

$$\frac{\bar{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\bar{\Gamma}(\Delta t) + \Gamma(\Delta t)} = \mathcal{A}_{D^{*+}\ D^{*-}\ K^0_S} \cos \Delta m_{\rm d} \Delta t + D \sin 2\phi_1 \sin \Delta m_{\rm d} \Delta t$$



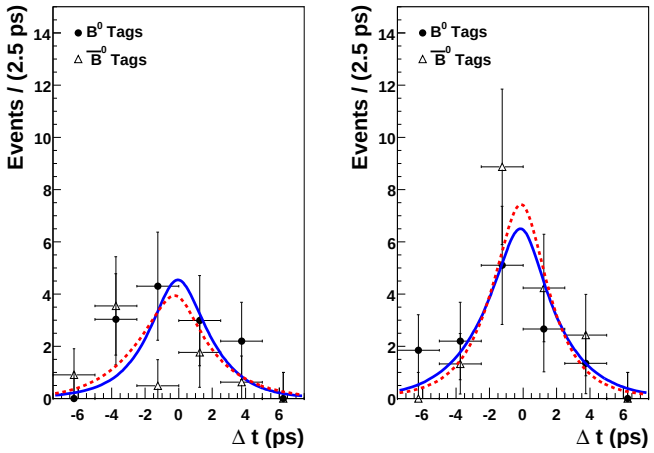
Blue curve - B^0 tags, Red curve - $\bar{B}^0$tags

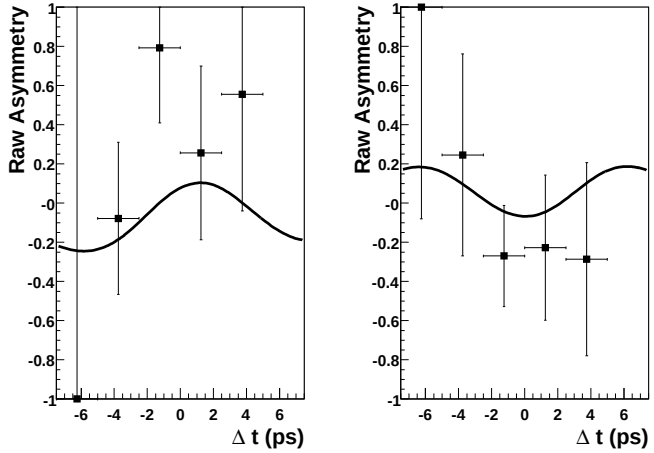
$$\mathcal{A}_{D^{*+}\ D^{*-}\ K^0_S} = -0.012^{+0.284}_{-0.282}\ (\text{stat}) \pm 0.090\ (\text{syst})$$
$$D \sin 2\phi_1 = 0.061^{+0.448}_{-0.436}\ (\text{stat}) \pm 0.058\ (\text{syst})$$

No evidence for direct or mixing-induced CP violation

3-parameter TCPV Fit

$$\frac{\bar{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\bar{\Gamma}(\Delta t) + \Gamma(\Delta t)} = \eta_y \frac{J_c}{J_0} \cos \Delta m_d \Delta t - \left(\frac{2J_{s1}}{J_0} \sin 2\phi_1 + \eta_y \frac{2J_{s2}}{J_0} \cos 2\phi_1 \right) \sin \Delta m_d \Delta t$$





Blue curve - B^0 tags, Red curve - $\bar{B}^0$tags,

Left - $s^- < s^+$, Right - $s^- > s^+$

$$J_c/J_0 = 0.60^{+0.25}_{-0.28}\ (\text{stat}) \pm 0.08\ (\text{syst})$$

$$2J_{s1}/J_0 \sin 2\phi_1 = -0.17^{+0.42}_{-0.42}(\text{stat}) \pm 0.09\ (\text{syst})$$

$$2J_{s2}/J_0 \cos 2\phi_1 = -0.23^{+0.43}_{-0.41}(\text{stat}) \pm 0.13\ (\text{syst})$$

Large J_c/J_0 could indicate broad unknown D_s^{**+} state

Large dilution of $\sin 2\phi_1$ from partial wave contributions and resonant structure

J_{s2}/J_0 predicted to be positive assuming D_s^{**+} exists

No model-dependent sign of $\cos 2\phi_1$ with current statistics

Charm and Charmonium ϕ_1 Measurements@Belle

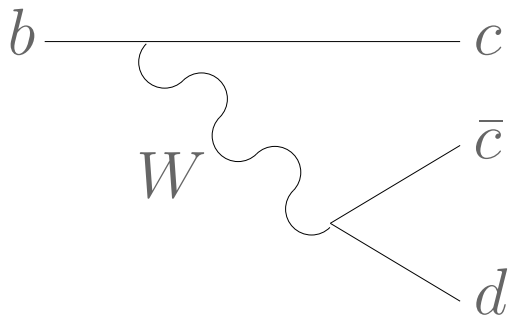
II. $B^0 \to J/\psi\ \pi^0$

$B^0 \to J/\psi\ \pi^0$ Motivation

Extract CP parameters from time-dependent decay rate asymmetry,

$$\frac{\bar{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\bar{\Gamma}(\Delta t) + \Gamma(\Delta t)} = \mathcal{A}_{J/\psi\ \pi^0} \cos \Delta m_{\rm d} \Delta t + \mathcal{S}_{J/\psi\ \pi^0} \sin \Delta m_{\rm d} \Delta t$$

Same weak phase as $b \to c\bar{c}s$ transitions



If penguin contribution negligible,

$$\mathcal{A}_{J/\psi\ \pi^0} = 0, \mathcal{S}_{J/\psi\ \pi^0} = -\sin 2\phi_1$$

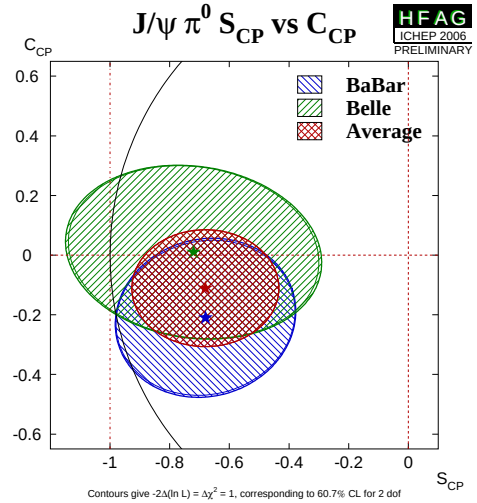
M. Ciuchini, M. Pierini and L. Silvestrini, Phys. Rev. Lett **95**, 221804 (2005)

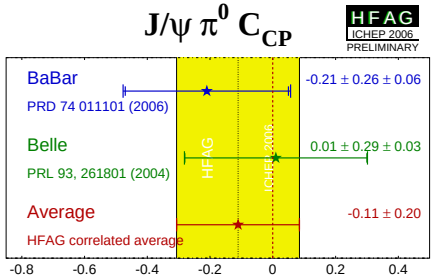
$B^0 \to J/\psi\ \pi^0$ result $\rightsquigarrow$ Estimate penguin pollution in $B^0 \to J/\psi\ K^0_S$

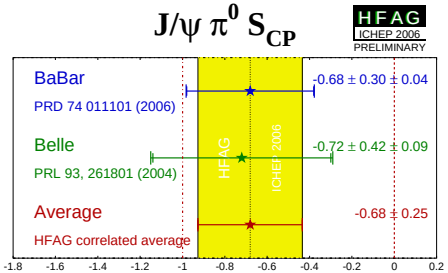
$\Rightarrow$ Precise determination of $\sin 2\phi_1$

But this is statistically limited by $B^0 \to J/\psi\ \pi^0$ precision

Previous Measurements







Previous Belle measurement based on $152 \times 10^6\ B\bar{B}$ pairs

S. U. Kataoka *et al.* (Belle Collaboration),

Phys. Rev. Lett. **93**, 261801 (2004)

$$\mathcal{A}_{J/\psi\,\pi^0} = -0.01 \pm 0.29\ (\text{stat}) \pm 0.03\ (\text{syst})$$
$$\mathcal{S}_{J/\psi\,\pi^0} = -0.72 \pm 0.42\ (\text{stat}) \pm 0.09\ (\text{syst})$$

Measurement at BaBar based on $232 \times 10^6\ B\bar{B}$ pairs

B. Aubert *et al.* (BaBar Collaboration),

Phys. Rev. D **74**, 011101(R) (2006)

$$\mathcal{A}_{J/\psi\,\pi^0} = 0.21 \pm 0.26\ (\text{stat}) \pm 0.06\ (\text{syst})$$
$$\mathcal{S}_{J/\psi\,\pi^0} = -0.68 \pm 0.30\ (\text{stat}) \pm 0.04\ (\text{syst})$$

$B^0 \to J/\psi\ \pi^0$ Yield Extraction

New measurement based on 535×10^6 $B\bar{B}$ pairs

Reconstruct,

$B^0 \to J/\psi\ \pi^0$

$J/\psi \to \mu^+\ \mu^-$ $\qquad$ $\pi^0 \to \gamma\gamma$

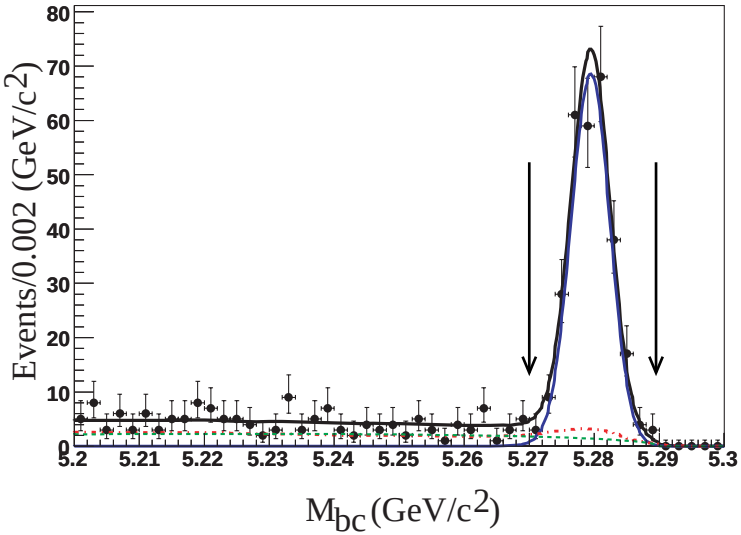
$\to e^+\ e^-$

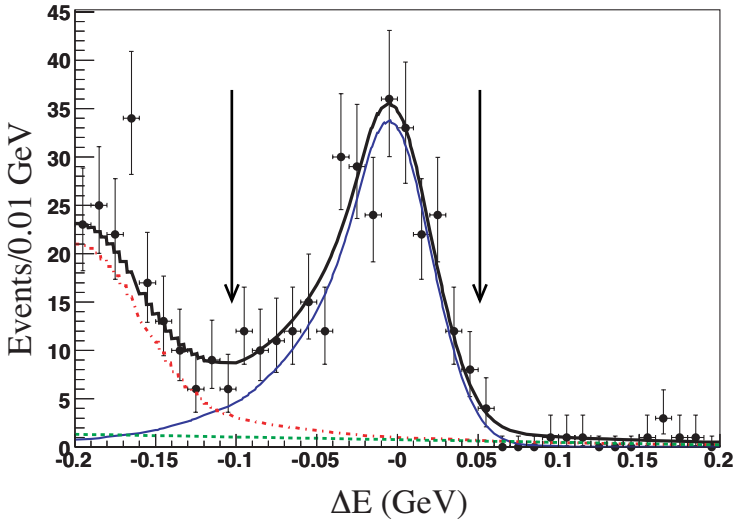
Blue curve - Signal

Green curve - Combinatorial background

Red curve - $J/\psi\ X$ background

$290\ J/\psi\ \pi^0$ candidates, Purity $= 88 \pm 7\%$





TCPV Extraction

$$P_{\rm Sig}(\Delta t, q) = \left\{ \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 - q\Delta w + q(1-2w)\left(\mathcal{A}_{J/\psi\ \pi^0} \cos\Delta m_{\rm d}\Delta t + \mathcal{S}_{J/\psi\ \pi^0} \sin\Delta m_{\rm d}\Delta t \right) \right] \right\} \otimes R_{\rm Sig}$$

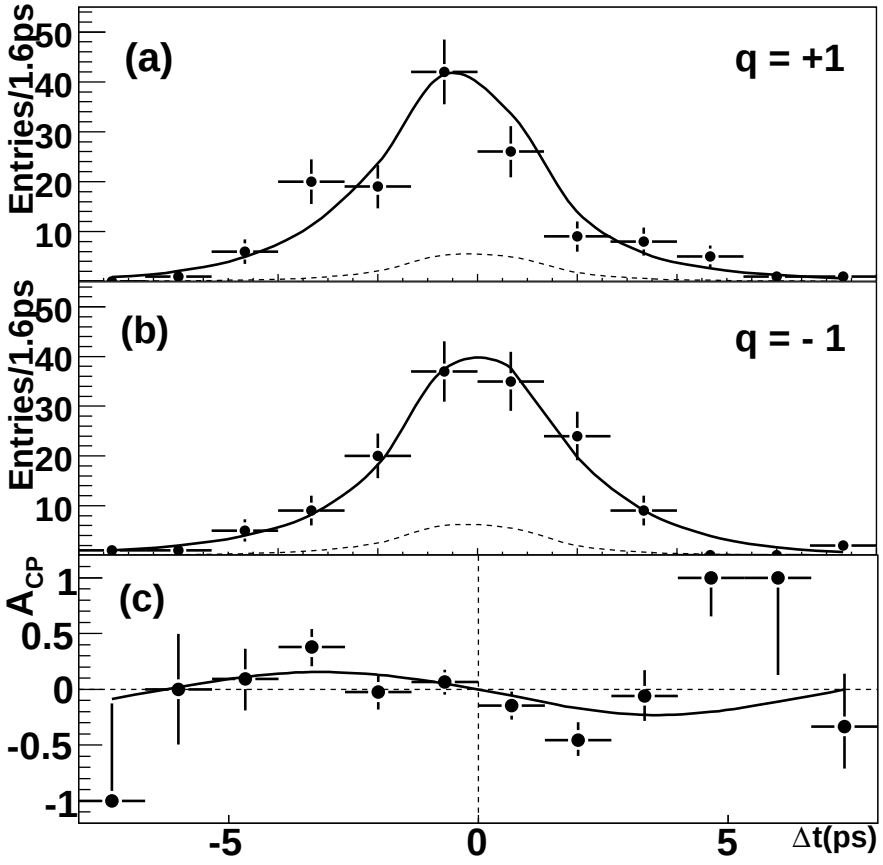
Account for background with CP asymmetry, $B^0 \to J/\psi\ K^0$

Fix $\mathcal{A}_{J/\psi K^0}$ and $\mathcal{S}_{J/\psi K^0}$ to current world average

$$P(\Delta t, q) = f_{\rm Sig} P_{\rm Sig}(\Delta t, q) + f_{J/\psi K^0} P_{J/\psi K^0}(\Delta t, q) + \frac{1}{2} f_{\rm Bkg} P_{\rm Bkg}(\Delta t)$$

$$\mathcal{A}_{J/\psi\ \pi^0} = 0.08 \pm 0.16\ (\text{stat}) \pm 0.05\ (\text{syst})$$
$$\mathcal{S}_{J/\psi\ \pi^0} = -0.65 \pm 0.21\ (\text{stat}) \pm 0.05\ (\text{syst})$$

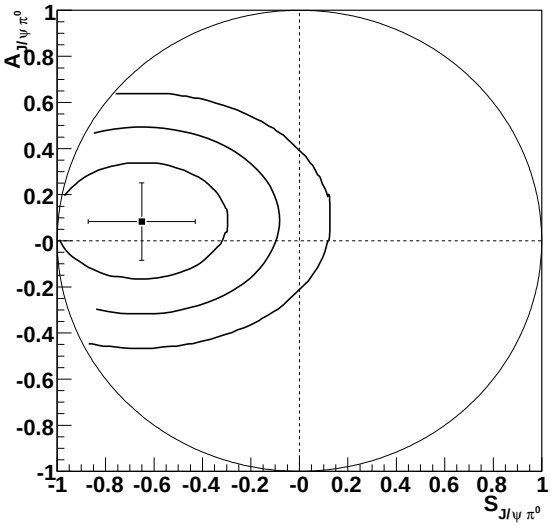
$B^0 \to J/\psi\, \pi^0$ Conclusion



Dashed curve -

Background contribution

Feldman-Cousins approach



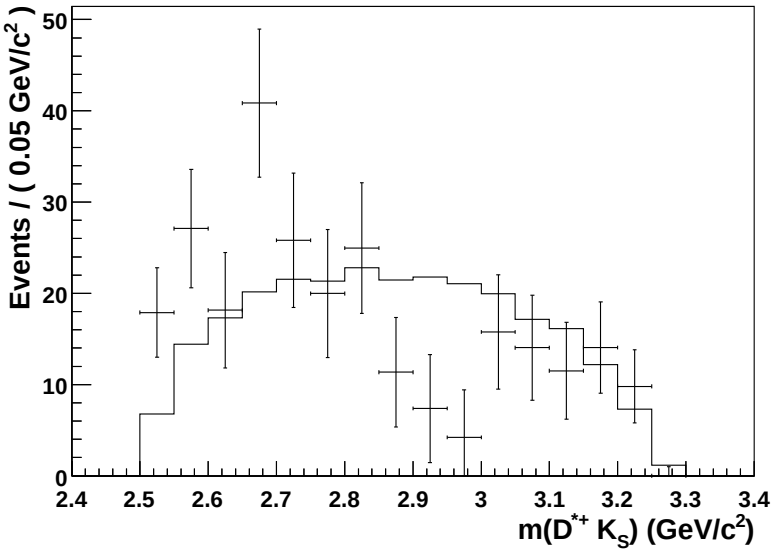
Mixing induced CP violation significance - 2.4σ

No evidence for direct CP violation

Conclusion

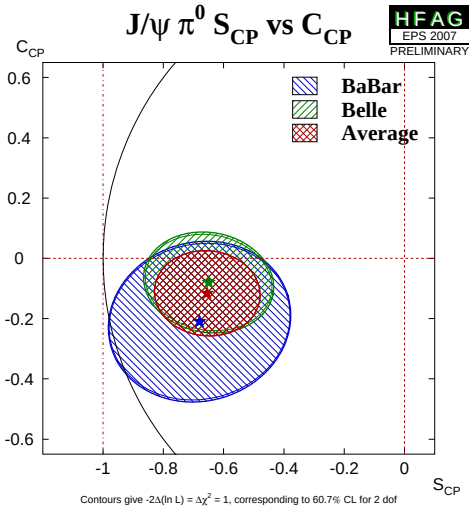
$B^0 \to D^{*+}\, D^{*-}\, K^0_S$

- Hint of broad unknown D^{**+}_s state?
- Cannot infer sign of $\cos 2\phi_1$ with current statistics
- No evidence for direct CP violation
- For more details $\rightsquigarrow$ arXiv:0706.2045



$B^0 \to J/\psi\, \pi^0$

- Measured mixing induced CP violation with 2.4σ significance
- Consistent with other $B^0 \to c\bar{c}\, K^0$ decays
- No evidence for direct CP violation



$B^0 \to D^{*+} D^{*-} K^0_S$ Backup

Measurement at BaBar based on 232×10^6 $B\bar{B}$ pairs

$$J_c/J_0 = 0.76 \pm 0.18\ (\text{stat}) \ \pm 0.07\ (\text{syst})$$

$$2J_{s1}/J_0 \sin 2\phi_1 = 0.10 \pm 0.24\ (\text{stat}) \ \pm 0.06\ (\text{syst})$$

$$2J_{s2}/J_0 \cos 2\phi_1 = 0.38 \pm 0.24\ (\text{stat}) \ \pm 0.05\ (\text{syst})$$