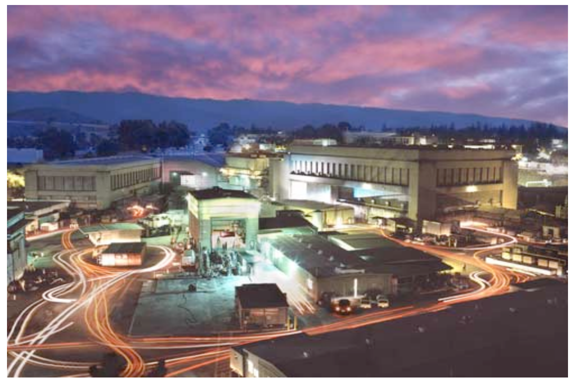
$b \rightarrow c\bar{c}s$ decays at BaBar

Charmonium $\sin 2\beta$ and $\cos 2\beta$ from $D^{*+}D^{*-}K^0_s$ and $J/\psi\ K^{*0}$



(c)Peter Ginter (2002)

Katherine George

(on behalf of the BaBar Collaboration)

Queen Mary, University of London

Overview

Mainly

- $\sin 2\beta$ from $B^0 \to$ charmonium + $K^0_{S,L}$
  - 316 fb^{-1} . hep-ex/0607107. (Preliminary !)
- $\cos 2\beta$ from $B^0 \to D^{*+} D^{*-} K^0_S$
  - 209 fb^{-1}. Phys. Rev. D **74**, 091101(R) (2006)

Overview

Mainly

- $\sin 2\beta$ from $B^0 \rightarrow$ charmonium + $K^0_{S,L}$
  - 316 fb^{-1} . hep-ex/0607107. (Preliminary !)
- $\cos 2\beta$ from $B^0 \rightarrow D^{*+}D^{*-}K^0_S$
  - 209 fb^{-1}. Phys. Rev. D 74, 091101(R) (2006)

Mentioning briefly

- $\cos 2\beta$ from $B^0 \rightarrow J/\psi\ K^{*0}$
  - 82 fb^{-1}. Phys.Rev. D 71 (2005) 032005
- More $\cos 2\beta$ in A. Gaz's talk (WG5-14-PM1)

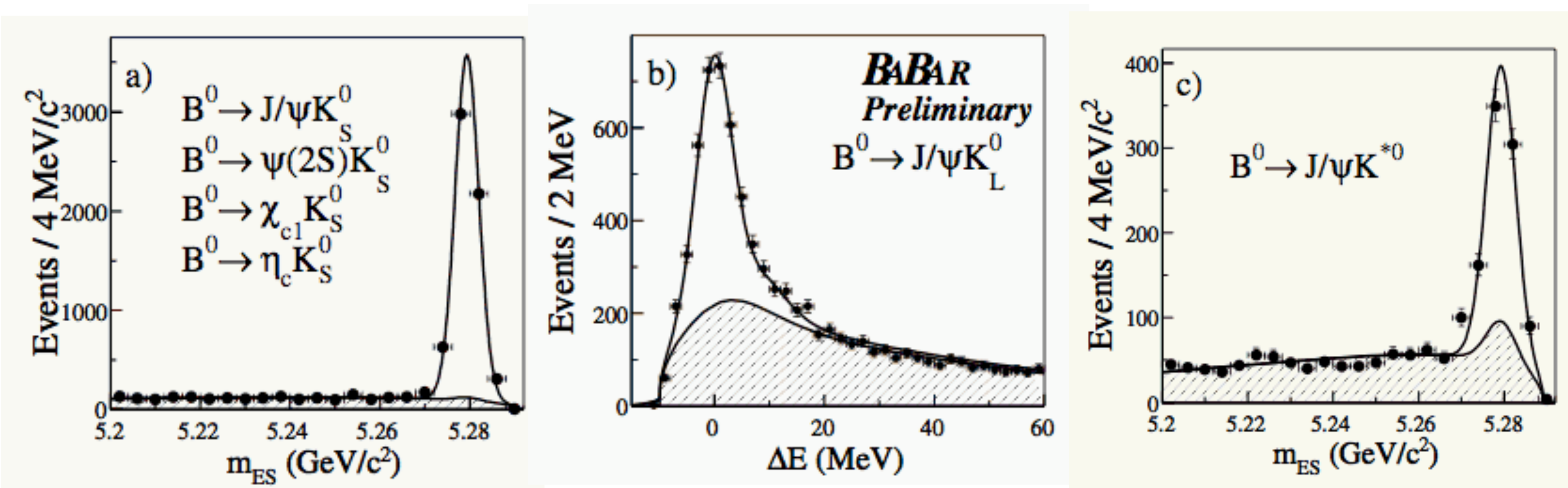
$\sin 2\beta$ from

$B^0 \to \text{charmonium} + K^0_{S,L}$

sin2β from $B^0 \rightarrow$ charmonium + $K^0_{S,L}$

316 fb^{-1}. hep-ex/0607017. (Preliminary)

- Measure sin2β and $|\lambda|$ in 7 different modes.

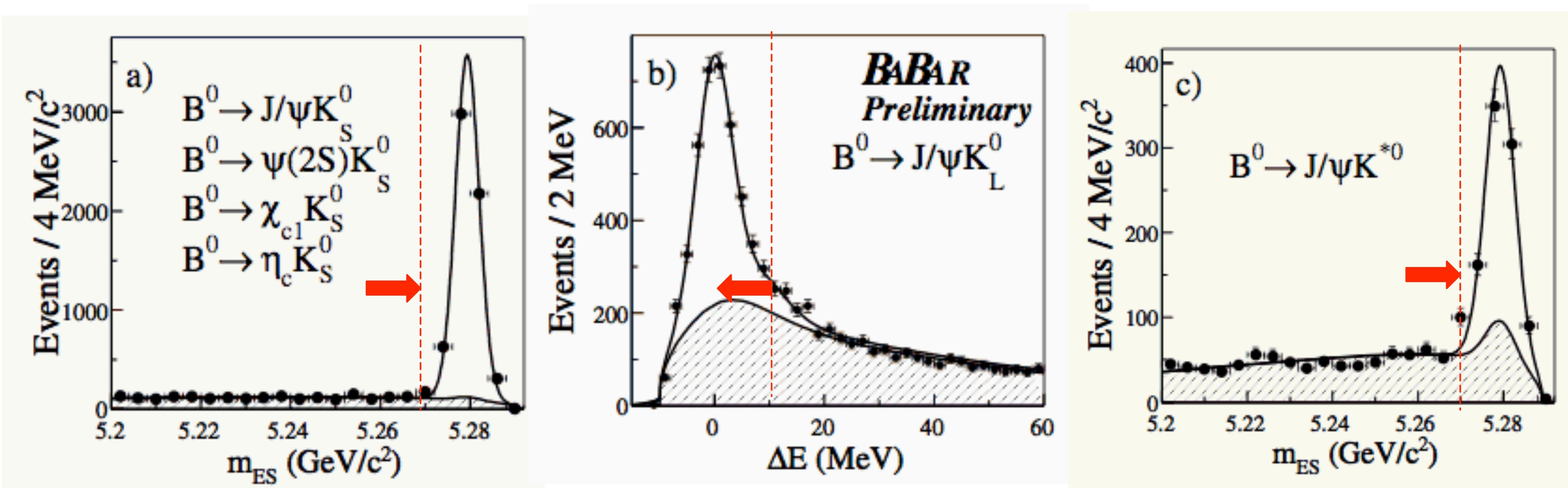


$(c\bar{c})K^0_S$ (CP odd modes) $(c\bar{c})K^0_L$ (CP even mode) CP admixture

sin2β from $B^0 \rightarrow$ charmonium + $K^0_{S,L}$

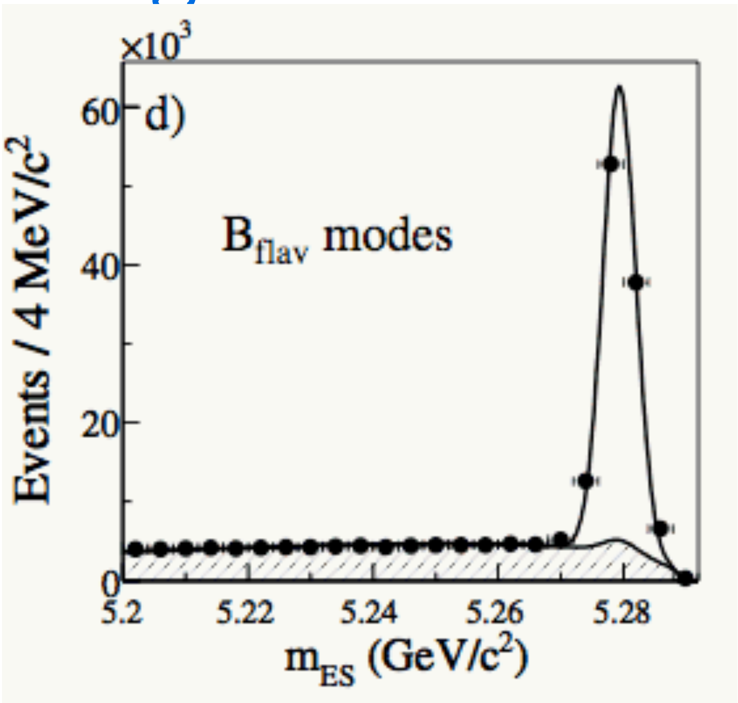
316 fb^{-1}. hep-ex/0607017. (Preliminary)

- Measure sin2β and $|\lambda|$ in 7 different modes.



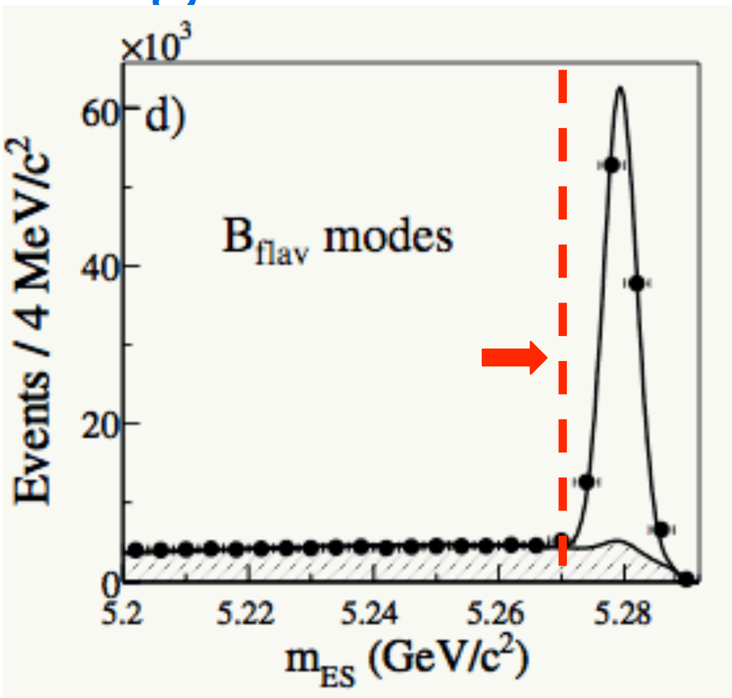
$(c\bar{c}) K^0_S$ (CP odd modes)	$(c\bar{c}) K^0_L$ (CP even mode)	CP admixture
$N_{tag} = 6028$	$N_{tag} = 4323$	$N_{tag} = 965$
P(%) = 92	P(%) = 55	P(%) = 68

Fully reconstructed B flavor eigenstate channels



- Flavor eigenstate sample used to determine tagging and vertexing performance in CP events.
  - $D^{(*)}h^+$ ($h^+ = \pi^+, \rho^+, a_1^+$).
  - $J/\psi K^{*0}$ ($K^{*0} \rightarrow K^+\pi^-$).

Fully reconstructed B flavor eigenstate channels



- Flavor eigenstate sample used to determine tagging and vertexing performance in CP events.
  - $D^{(*)}h^+$ $(h^+ = \pi^+, \rho^+, a_1^+)$.
  - $J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$.

$N_{tag} = 112878$
$P(\%) = 83$

- Simultaneous fit to incorporate statistical uncertainty of tagging and vertexing parameters into the sin2b statistical error.

$$f(\Delta t) \sim \left\{ \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left[1 \pm (1-2\omega)\cos(\Delta m_d \Delta t) \right] \right\} \otimes R$$

$\sin 2\phi_1$ from $B^0 \rightarrow$ charmonium + $K^0_{S,L}$

Tagging algorithm performance

- Use the same flavor tagging algorithm as for the 205 fb^{-1} result. (Phys. Rev. Lett. 94 (2005) 161803.)
- Catagorizes events as:
  - Category 1 'Lepton' : Primary leptons.
  - Caregories 2-6 : Split remaining events based on estimated mistag rate (comes from neural net).

$\sin 2\beta$ from $B^0 \to$ charmonium + $K^0_{S,L}$

Tagging algorithm performance

- Use the same flavor tagging algorithm as for the 205 fb^{-1} result. (Phys. Rev. Lett. 94 (2005) 161803.)
- Catagorizes events as:
  - Category 1 'Lepton' : Primary leptons.
  - Caregories 2-6 : Split remaining events based on estimated mistag rate (comes from neural net).

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	8.67 ± 0.08	3.0 ± 0.3	-0.2 ± 0.6	7.67 ± 0.13
Kaon I	10.96 ± 0.09	5.3 ± 0.4	-0.6 ± 0.7	8.74 ± 0.16
Kaon II	17.21 ± 0.11	15.5 ± 0.4	-0.4 ± 0.7	8.21 ± 0.19
Kaon-Pion	13.77 ± 0.10	23.5 ± 0.5	-2.4 ± 0.8	3.87 ± 0.14
Pion	14.38 ± 0.10	33.0 ± 0.5	5.2 ± 0.8	1.67 ± 0.10
Other	9.61 ± 0.08	41.9 ± 0.6	4.6 ± 0.9	0.25 ± 0.04
All	74.60 ± 0.12			30.4 ± 0.3

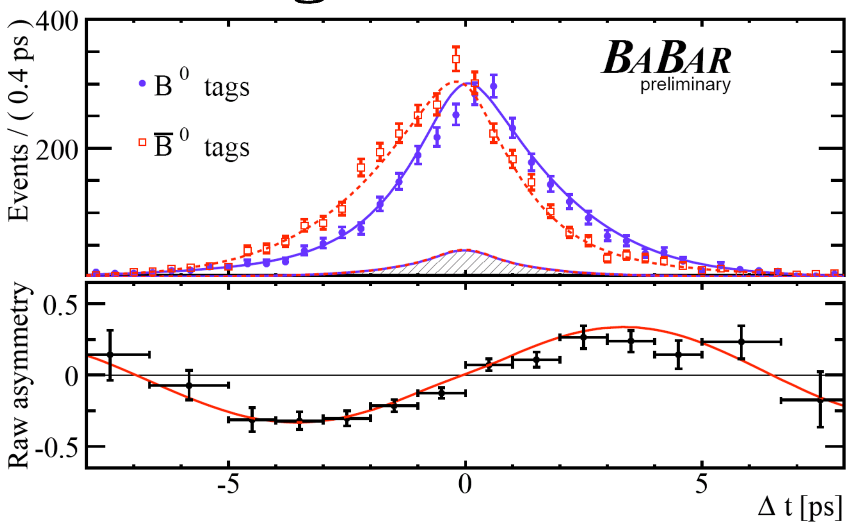
- Efficiency ε.
- Mistag fraction ω, mistag fraction difference $\Delta\omega$.
- Measure of tagging performance $Q = \varepsilon(1-2\omega)^2$.
- ε from m_{ES} fits to 'BFlav' sample. Other parameters from Δt fit to 'BFlav' sample.

Compare with $Q = (30.5 \pm 0.4)\%$ on 205 fb^{-1}

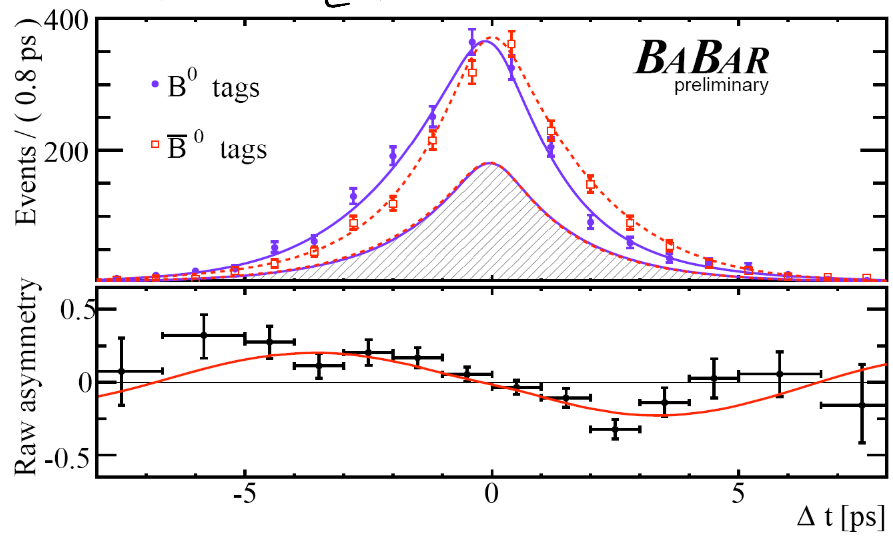
sin2β from $B^0 \rightarrow$ charmonium + $K^0_{S,L}$

316 fb^{-1}. hep-ex/0607017. (Preliminary)

$(c\bar{c})K^0_S$ (CP odd modes)



$(c\bar{c})K^0_L$ (CP even) modes



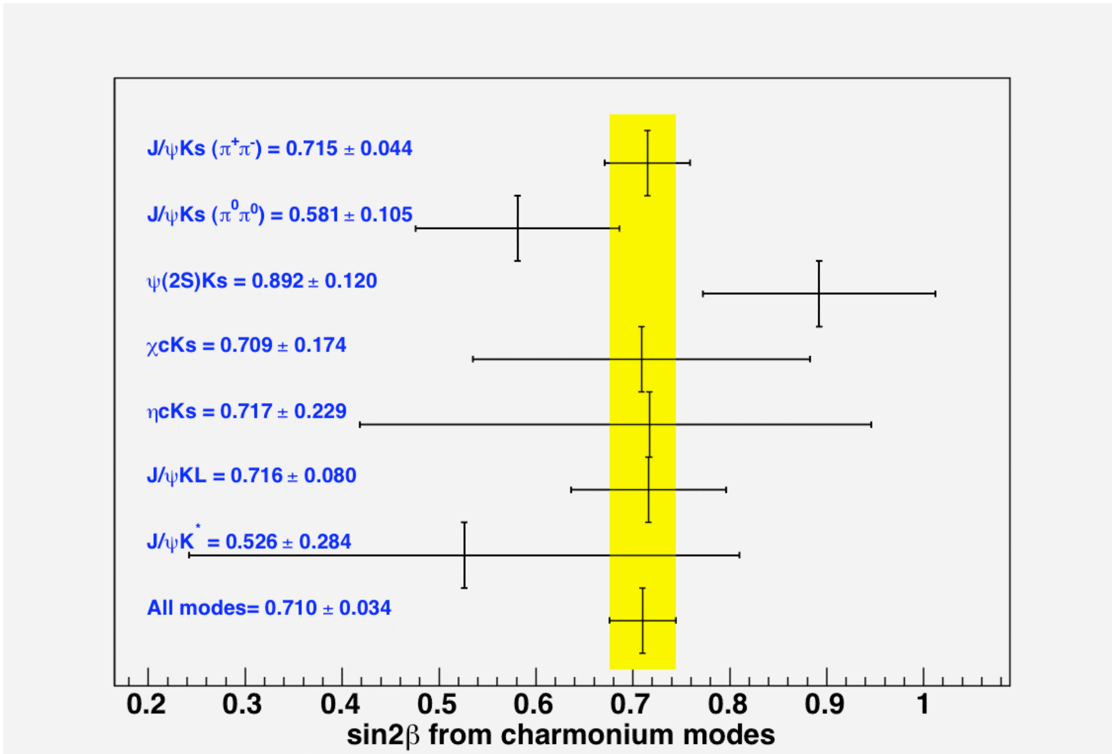
We measure:

- $\sin 2\beta = 0.710 \pm 0.034\ (\text{stat}) \pm 0.019\ (\text{syst})$.
- $|\lambda| = 0.932 \pm 0.026\ (\text{stat}) \pm 0.017\ (\text{syst})$.

Differences between CP submodes

(statistical errors only)

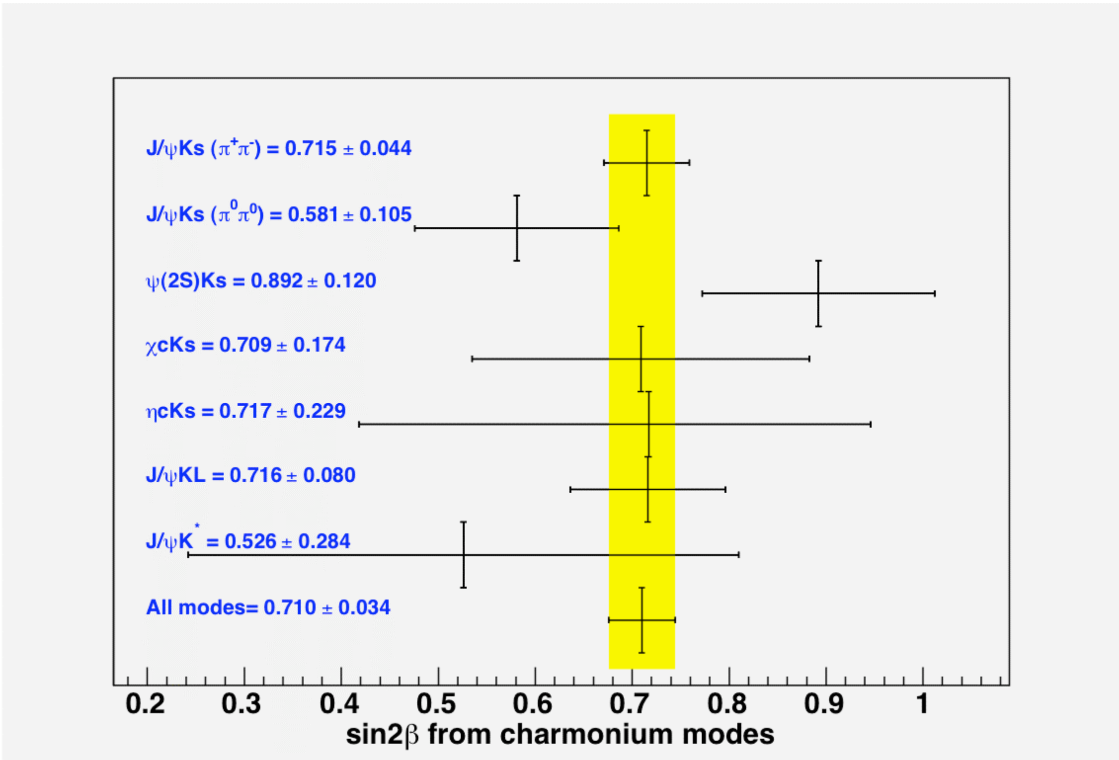
- Some differences between submodes:



Differences between CP submodes

(statistical errors only)

- Some differences between submodes:



- Should work towards determining sin2β for each submode separately.

Contributions to the systematic error on sin2b

(At 316 fb^{-1} : Total systematic error = $\pm$ 0.019, total statistical error = $\pm$ 0.034)

- Description of background events — ± 0.007
  - CP content of peaking background
  - Background shape uncertainties
- Mistag differences between B_{CP} and BFlav samples — ± 0.009
- Composition and content of $J/\psi\ K^0_L$ background — ± 0.007
- Δt resolution and detector effects — ± 0.008
  - Silicon detector and alignment uncertainty
  - Δt resolution model
- Beam spot position — ± 0.008
- Fixed Δm, $\Delta\Gamma/\Gamma$ — ± 0.003
- Tag-side interference/DCSD decays — ± 0.002
- MC statistics/bias — ± 0.003

Contributions to the systematic error on sin2b

(At 316 fb^{-1} : Total systematic error = ± 0.019, total statistical error = ± 0.034)

- Description of background events — ±0.007
  - CP content of peaking background
  - Background shape uncertainties

Improved treatment of what was the largest syst. error in 2004. Now vary backgrounds by their known CP rather than ±1.

- Mistag differences between B_{CP} and BFlav samples — ±0.009
- Composition and content of $J/\psi\ K^0_L$ background — ±0.007
- Δt resolution and detector effects — ±0.008
  - Silicon detector and alignment uncertainty
  - Δt resolution model
- Beam spot position — ±0.008
- Fixed Δm, $\Delta\Gamma/\Gamma$ — ±0.003
- Tag-side interference/DCSD decays — ±0.002
- MC statistics/bias — ±0.003

Contributions to the systematic error on sin2b

(At 316 fb^{-1} : Total systematic error = ± 0.019, total statistical error = ± 0.034)

- Description of background events — ±0.007
  - CP content of peaking background
  - Background shape uncertainties

- Mistag differences between B_{CP} and BFlav samples — ±0.009
- Composition and content of $J/\psi\ K^0_L$ background — ±0.007

- Δt resolution and detector effects — ±0.008
  - Silicon detector and alignment uncertainty
  - Δt resolution model

Does not scale with sqrt(N)

- Beam spot position — ±0.008
- Fixed Δm, $\Delta\Gamma/\Gamma$ — ±0.003
- Tag-side interference/DCSD decays — ±0.002
- MC statistics/bias — ±0.003

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \rightarrow J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \rightarrow J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from sin2β:
    - $\Delta S_{J/\psi\ KS} \equiv S_{J/\psi\ KS} - \sin 2\beta = 0.000 \pm 0.017$

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \rightarrow J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \rightarrow J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from sin2β:
    - $\Delta S_{J/\psi\ KS} \equiv S_{J/\psi\ KS} - \sin 2\beta = 0.000 \pm 0.017$

Comparable to B-factory systematic error!

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \to J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \to J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from sin2β:
    - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta = 0.000 \pm 0.017$

Comparable to B-factory systematic error!

- Theoretical estimates ?
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta \sim O(10^{-3})$. Li and Mishima. hep-ph/0610120
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta \sim O(10^{-4})$. Boos et. al. Phys. Rev. D. 70 036006 (2006)

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \to J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \to J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from sin2β:
    - $\Delta S_{J/\psi\ KS} \equiv S_{J/\psi\ KS} - \sin 2\beta = 0.000 \pm 0.017$

Comparable to B-factory systematic error!

- Theoretical estimates ?
  - $\Delta S_{J/\psi\ KS} \equiv S_{J/\psi\ KS} - \sin 2\beta \sim O(10^{-3})$. Li and Mishima. hep-ph/0610120
  - $\Delta S_{J/\psi\ KS} \equiv S_{J/\psi\ KS} - \sin 2\beta \sim O(10^{-4})$. Boos et. al. Phys. Rev. D. 70 036006 (2006)
    - Away from our current experimental sensitivity at the B-factories.

Corrections to determining $\sin 2\beta$ from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in $\sin 2\beta$ from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \rightarrow J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \rightarrow J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from $\sin 2\beta$:
    - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta = 0.000 \pm 0.017$

- Theoretical estimates ?
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta \sim O(10^{-3})$. Li and Mishima. hep-ph/0610120
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta \sim O(10^{-4})$. Boos et. al. Phys. Rev. D. 70 036006 (2006)
    - Away from our current experimental sensitivity at the B-factories.

- Additional useful measurements ?

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

Improved $B^0 \rightarrow J/\psi\pi^0$

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \rightarrow J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \rightarrow J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from sin2β:
    - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta = 0.000 \pm 0.017$

- Theoretical estimates ?
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta\ \sim O(10^{-3})$. Li and Mishima. hep-ph/0610120
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta\ \sim O(10^{-4})$. Boos et. al. Phys. Rev. D. 70 036006 (2006)
    - Away from our current experimental sensitivity at the B-factories.

- Additional useful measurements ?

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

Improved $B^0 \rightarrow J/\psi\pi^0$

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \rightarrow J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \rightarrow J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from sin2β:
    - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta = 0.000 \pm 0.017$

$A_{CP}(B^+ \rightarrow J/\psi K^+)$ observed at > 1% would indicate new physics.
Hou. et. al. hep-ph/0605090.

- Theoretical estimates ?
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta\ \sim O(10^{-3})$. Li and Mishima. hep-ph/0610120
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta\ \sim O(10^{-4})$. Boos et. al. Phys. Rev. D. 70 036006 (2006)
    - Away from our current experimental sensitivity at the B-factories.

- Additional useful measurements ?

Corrections to determining sin2β from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in sin2β from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

Improved $B^0 \rightarrow J/\psi\pi^0$

- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \rightarrow J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \rightarrow J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from sin2β:
    - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta = 0.000 \pm 0.017$

$A_{CP}(B^+ \rightarrow J/\psi K^+)$ observed at > 1% would indicate new physics.
Hou. et. al. hep-ph/0605090.

- Theoretical estimates ?
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta\ \sim O(10^{-3})$. Li and Mishima. hep-ph/0610120
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta\ \sim O(10^{-4})$. Boos et. al. Phys. Rev. D. 70 036006 (2006)
    - Away from our current experimental sensitivity at the B-factories.

- Additional useful measurements ?

Uncertainties eliminated using $B^0_S \rightarrow J/\psi\ K^0_S$
Fleischer. Eur. Phys. J. C. 10., 299 (1999).

Corrections to determining $\sin 2\beta$ from $J/\psi K^0_S$

caveat : current knowledge of an experimentalist

- Statistical & systematic uncertainty in $\sin 2\beta$ from $J/\psi\ K^0_S$ is at ~few % level
  - And we have much more data to come !

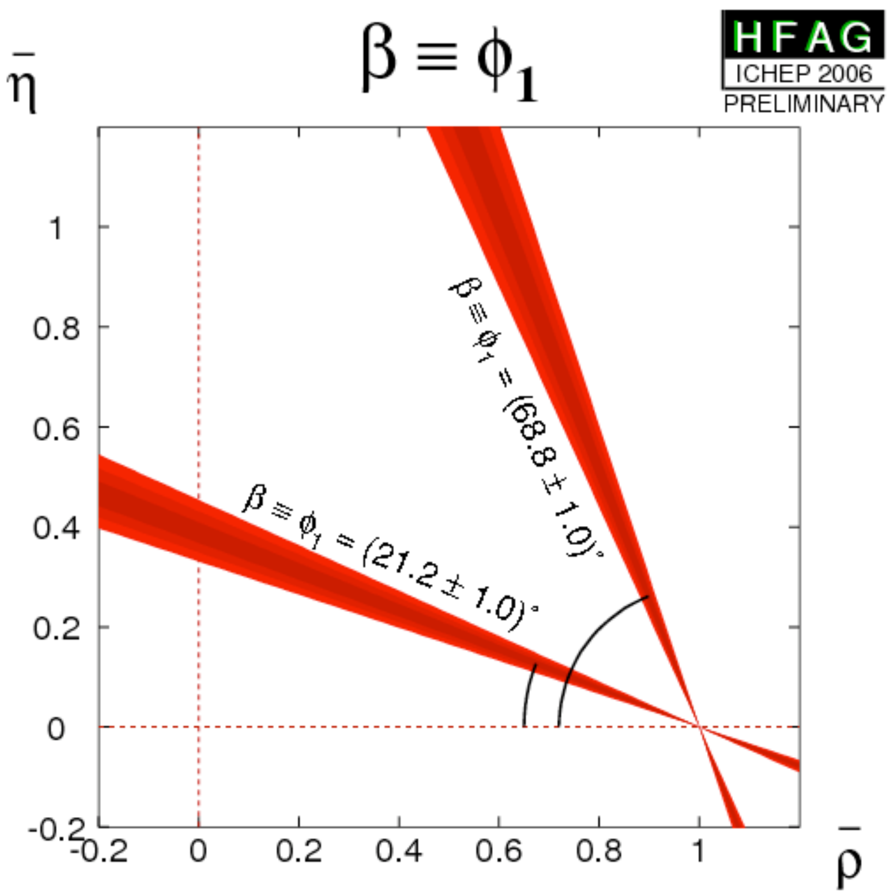
- From fits to experimental data (model independent)
  - Ciuchini et. al. Phys. Rev Lett. 95 221804 (2005)
  - Uses $B^0 \to J/\psi\pi^0$ to quantify long-distance contributions from penguin contractions in $B^0 \to J/\psi K^0_S$.
  - Deviation of measured S_{CP} term from $\sin 2\beta$:
    - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta = 0.000 \pm 0.017$

- Theoretical estimates ?
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta \sim O(10^{-3})$. Li and Mishima. hep-ph/0610120
  - $\Delta S_{J/\psi\ Ks} \equiv S_{J/\psi\ Ks} - \sin 2\beta \sim O(10^{-4})$. Boos et. al. Phys. Rev. D. 70 036006 (2006)
    - Away from our current experimental sensitivity at the B-factories.

- **Will be interesting to hear what the next two speakers have to say !**

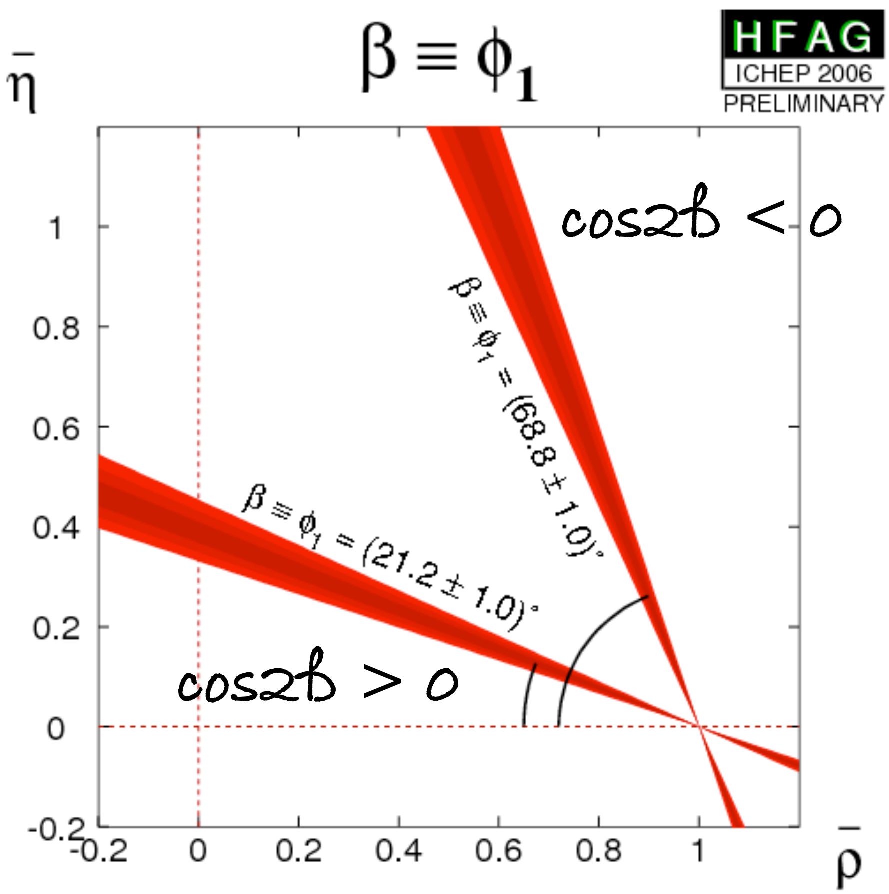
$\cos 2\beta$ from $B^0 \rightarrow D^{*+} D^{*-} K^0{}_S$ and $B^0 \rightarrow J/\psi\ K^{*0}$

Resolving the two-fold ambiguity in the $\bar{\rho}$-$\bar{\eta}$ plane



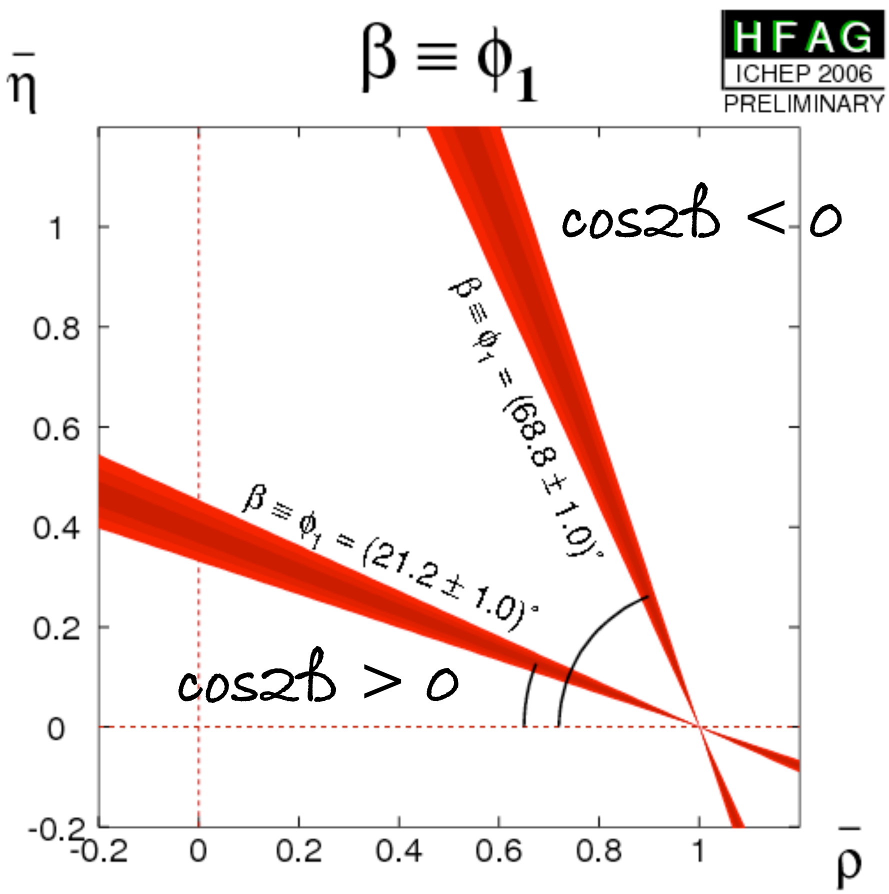
- 4 solutions of β from the $b \to c\bar{c}s$ sin2β measurement
- Resolution of the two-fold ambiguity $\beta \to \pi/2 - \beta$ via the following $b \to c\bar{c}s$ decays:
  - Time-dependent analysis of $B^0 \to D^{*+}D^{*-}K^0_S$
  - Time-dependent angular analysis of $B^0 \to J/\psi\, K^{*0}$

Resolving the two-fold ambiguity in the $\bar{\rho}$-$\bar{\eta}$ plane



- 4 solutions of b from the $b \to c\bar{c}s$ sin2b measurement
- Resolution of the two-fold ambiguity b $\to \pi/2$ -b via the following $b \to c\bar{c}s$ decays:
  - Time-dependent analysis of $B^0 \to D^{*+}D^{*-}K^0_S$
  - Time-dependent angular analysis of $B^0 \to J/\psi\, K^{*0}$
- Extract cos2b if we know the strong phase e.g. Dalitz.

Resolving the two-fold ambiguity in the $\bar{\rho}$-$\bar{\eta}$ plane



- 4 solutions of β from the $b \to c\bar{c}s$ sin2β measurement
- Resolution of the two-fold ambiguity $\beta \to \pi/2 - \beta$ via the following $b \to c\bar{c}s$ decays:
  - Time-dependent analysis of $B^0 \to D^{*+}D^{*-}K^0_S$
  - Time-dependent angular analysis of $B^0 \to J/\psi\, K^{*0}$
- BaBar cos2β measurements from $b \to c\bar{u}d$ to be shown by A. Gaz tomorrow afternoon.
- Extract cos2β if we know the strong phase e.g. Dalitz.

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

209 fb^{-1}. Phys. Rev. D **74**, 091101(R) (2006)

- B^0 ($\bar{B}^0$) $\rightarrow D^{*+}D^{*-}K^0_S$ $\Rightarrow$ CP asymmetry is expected.
- Dominated by a single tree diagram (external W-emission).
- Neglect penguin contributions $\Rightarrow$ no direct CP.

Theoretical overview

- B^0 ($\bar{B}^0$) $\rightarrow D^{*+}D^{*-}K^0_S$ $\Rightarrow$ CP asymmetry is expected.
- Dominated by a single tree diagram (external W-emission).
- Neglect penguin contributions $\Rightarrow$ no direct CP.

In the presence of resonance contributions …

- Divide the decay in 2 half Dalitz planes.

$$\left.\frac{\Gamma_{\overline{B}^0}(t)-\Gamma_{B^0}(t)}{\Gamma_{\overline{B}^0}(t)+\Gamma_{B^0}(t)}\right|_{y>0} = -\frac{J_c}{J_0}\cos(\Delta m_d t) + (-\frac{2J_{s1}}{J_0}\sin 2\beta + \frac{2J_{s2}}{J_0}\cos 2\beta)\sin(\Delta m_d t).$$

$$\left.\frac{\Gamma_{\overline{B}^0}(t)-\Gamma_{B^0}(t)}{\Gamma_{\overline{B}^0}(t)+\Gamma_{B^0}(t)}\right|_{y<0} = +\frac{J_c}{J_0}\cos(\Delta m_d t) + (-\frac{2J_{s1}}{J_0}\sin 2\beta - \frac{2J_{s2}}{J_0}\cos 2\beta)\sin(\Delta m_d t).$$

Theoretical overview

- B^0 ($\bar{B}^0$) $\rightarrow D^{*+}D^{*-}K^0_S$ $\Rightarrow$ CP asymmetry is expected.
- Dominated by a single tree diagram (external W-emission).
- Neglect penguin contributions $\Rightarrow$ no direct CP.

In the presence of resonance contributions …

- Divide the decay in 2 half Dalitz planes.

$$\left.\frac{\Gamma_{\overline{B}^0}(t)-\Gamma_{B^0}(t)}{\Gamma_{\overline{B}^0}(t)+\Gamma_{B^0}(t)}\right|_{y>0} = -\frac{J_c}{J_0}\cos(\Delta m_d t) + \left(-\frac{2J_{s1}}{J_0}\sin 2\beta + \frac{2J_{s2}}{J_0}\cos 2\beta\right)\sin(\Delta m_d t).$$

$$\left.\frac{\Gamma_{\overline{B}^0}(t)-\Gamma_{B^0}(t)}{\Gamma_{\overline{B}^0}(t)+\Gamma_{B^0}(t)}\right|_{y<0} = +\frac{J_c}{J_0}\cos(\Delta m_d t) + \left(-\frac{2J_{s1}}{J_0}\sin 2\beta - \frac{2J_{s2}}{J_0}\cos 2\beta\right)\sin(\Delta m_d t).$$

- J_0 J_c J_{s1} and J_{s2} are integrals over the half Dalitz space in terms of the decay amplitudes a and $\bar{a}$.

$$\boxed{\begin{aligned} a &= A(B^0 \to D^{*+}D^{*-}K^0_S) \\ \bar{a} &= A(\bar{B}^0 \to D^{*+}D^{*-}K^0_S) \end{aligned}}$$

$$\begin{aligned} J_0 &= \int_{s^+<s^-} (|a|^2+|\bar{a}|^2)ds^+ds^- & J_{s1} &= \int_{s^+<s^-} Re(\bar{a}a^*)ds^+ds^- \\ J_c &= \int_{s^+<s^-} (|a|^2-|\bar{a}|^2)ds^+ds^- & J_{s2} &= \int_{s^+<s^-} Im(\bar{a}a^*)ds^+ds^- \end{aligned}$$

Complications from new resonances ...

$$A(t) \equiv \frac{\Gamma_{\overline{B}^0} - \Gamma_{B^0}}{\Gamma_{\overline{B}^0} + \Gamma_{B^0}} = \eta_y \frac{J_c}{J_0} \cos(\Delta m_d t) - \left(\frac{2J_{s1}}{J_0} \sin 2\beta + \eta_y \frac{2J_{s2}}{J_0} \cos 2\beta \right) \sin(\Delta m_d t)$$

If $B^0 \to D^{*+} D^{*-} K^0{}_S$ is 100% non-resonant decay:

- J_c/J_0 is expected to be very small ~ a few % level.
- $2J_{s1}/J_0$ expected to be large but $J_{s2}/J_0 = 0$.

Complications from new resonances …

$$A(t) \equiv \frac{\Gamma_{\overline{B}^0} - \Gamma_{B^0}}{\Gamma_{\overline{B}^0} + \Gamma_{B^0}} = \eta_y \frac{J_c}{J_0} \cos(\Delta m_d t) - \left(\frac{2J_{s1}}{J_0} \sin 2\beta + \eta_y \frac{2J_{s2}}{J_0} \cos 2\beta \right) \sin(\Delta m_d t)$$

If $B^0 \rightarrow D^{*+} D^{*-} K^0{}_S$ is 100% non-resonant decay:

- J_c/J_0 is expected to be very small ~ a few % level.
- $2J_{s1}/J_0$ expected to be large but $J_{s2}/J_0 = 0$.

If there is resonant contribution D_{sJ}:

- Narrow width ⇒ small contribution to J_{s2}
- Large width ⇒ J_{s2} large .
- Two known states above mass threshold:
  - $D_{sJ}(2536)$ and $D_{sJ}(2573)$, which are both narrow.
- Quark Model: expect another P-wave excited D_{s1} with a large width.
  - But if D_{s1} is $D_{sJ}(2317)$ or $D_{sJ}(2460)$, which are lower than mass threshold ⇒ no contribution to J_c and J_{s2}

Complications from new resonances ...

$$A(t) \equiv \frac{\Gamma_{\overline{B}^0} - \Gamma_{B^0}}{\Gamma_{\overline{B}^0} + \Gamma_{B^0}} = \eta_y \frac{J_c}{J_0} \cos(\Delta m_d t) - \left(\frac{2J_{s1}}{J_0} \sin 2\beta + \eta_y \frac{2J_{s2}}{J_0} \cos 2\beta \right) \sin(\Delta m_d t)$$

If $B^0 \to D^{*+} D^{*-} K^0_S$ is 100% non-resonant decay:

- J_c/J_0 is expected to be very small ~ a few % level.
- $2J_{s1}/J_0$ expected to be large but $J_{s2}/J_0 = 0$.

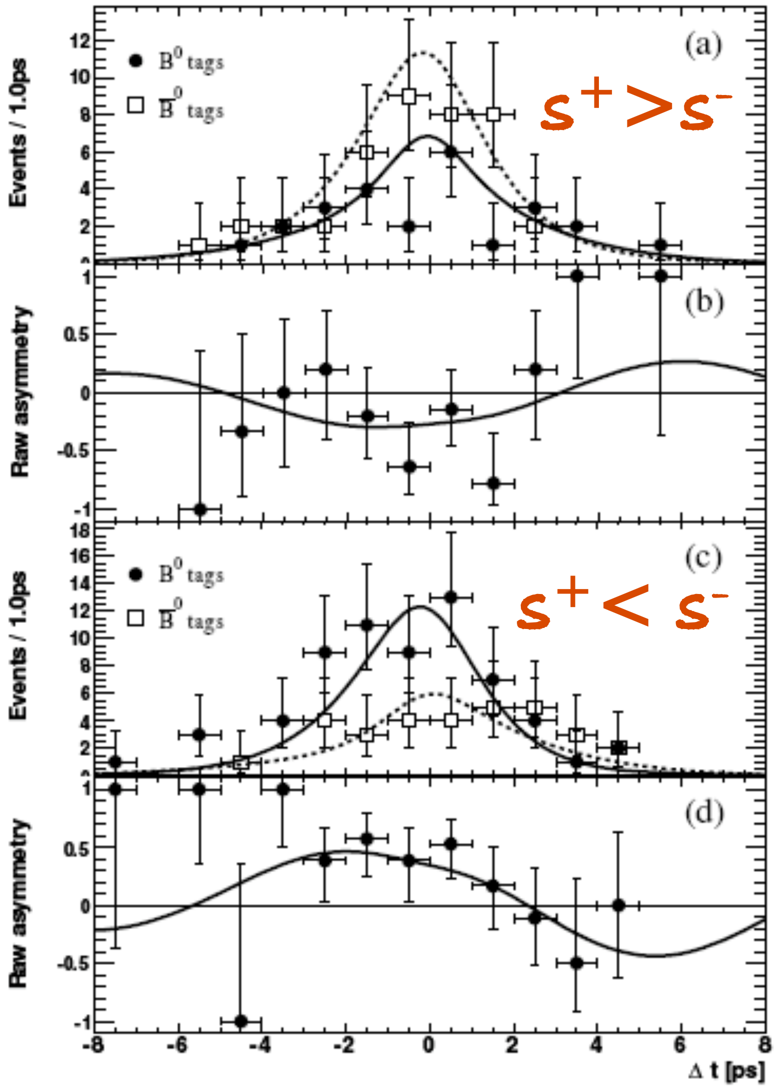
If there is resonant contribution D_{sJ}:

- Narrow width ⇒ small contribution to J_{s2}.
- Large width ⇒ J_{s2} large.
- Two known states above mass threshold:
  - $D_{sJ}(2536)$ and $D_{sJ}(2573)$, which are both narrow.
- Quark Model: expect another P-wave excited D_{s1} with a large width.
  - But if D_{s1} is $D_{sJ}(2317)$ or $D_{sJ}(2460)$, which are lower than mass threshold ⇒ no contribution to J_c and J_{s2}.

Procedure ....

- Measure J_c/J_0, $2J_{s1}/J_0 \sin 2b$ and $2J_{s2}/J_0 \cos 2b$.
- Determine sign of $\cos 2b$ if $J_{s2} \neq 0$. Browder et al. Phys Rev D 61054009 (2000)

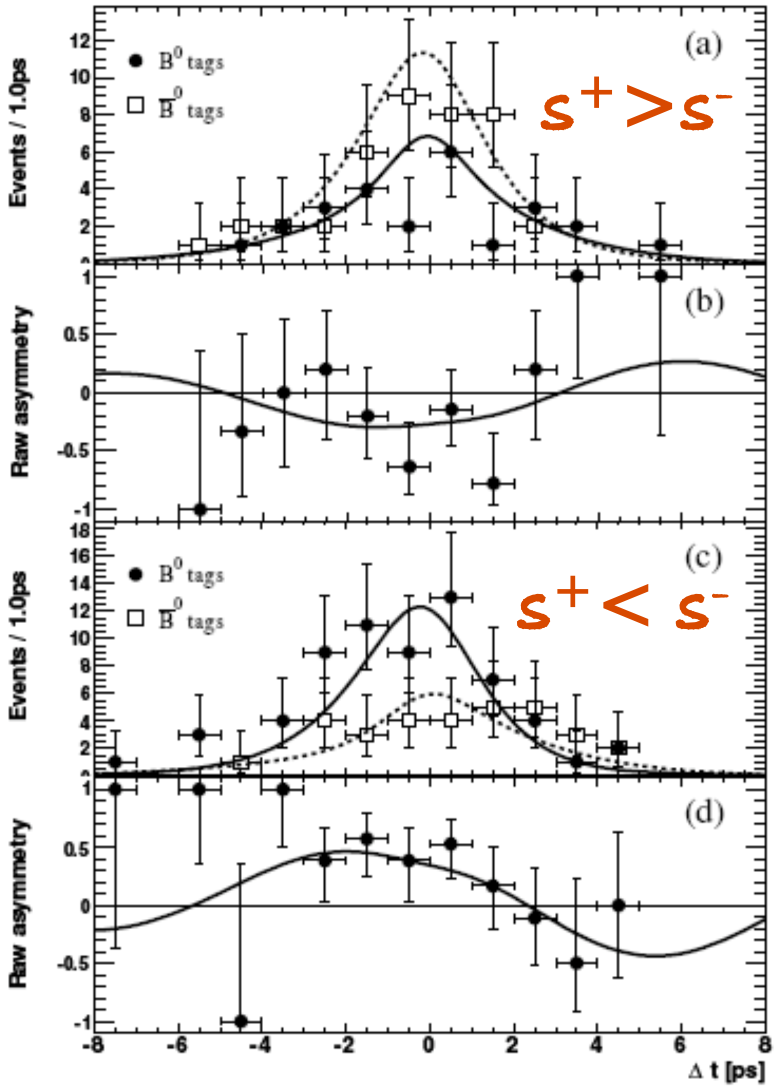
Results



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

- J_c/J_0 significantly deviates from 0.
- Implies that there is a possible large contribution from an unknown broad resonant state D_{S1}.

Results



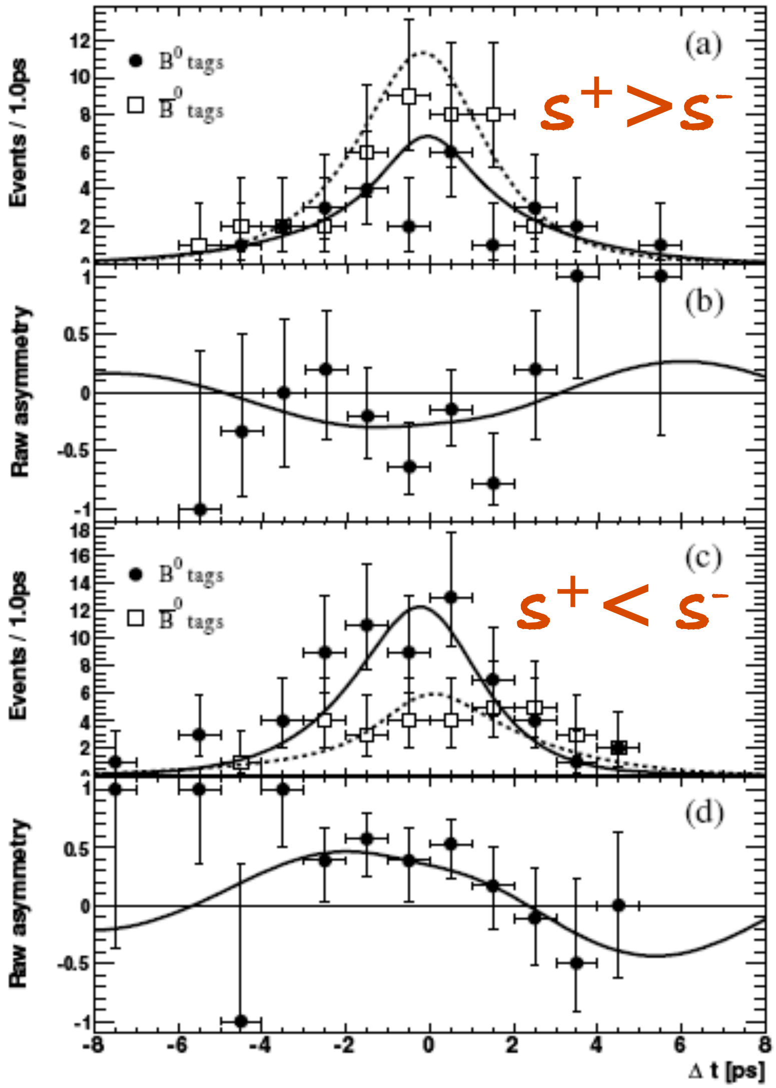
$$\frac{J_c}{J_0} = 0.76 \pm 0.18(\mathrm{stat}) \pm 0.07(\mathrm{syst})$$

- J_c/J_0 significantly deviates from 0.
- Implies that there is a possible large contribution from an unknown broad resonant state D_{S1}.

$$\frac{2J_{s1}}{J_0}\sin 2\beta = 0.10 \pm 0.24(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$
$$\frac{2J_{s2}}{J_0}\cos 2\beta = 0.38 \pm 0.24(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

- $J_{s2}/J_0 > 0$
  - Implies that we can extract cos2b. Browder et al.. Phys. Rev. D 61 054009 (2000

Results



$$\frac{J_c}{J_0} = 0.76 \pm 0.18(\mathrm{stat}) \pm 0.07(\mathrm{syst})$$

- J_c/J_0 significantly deviates from 0.
- Implies that there is a possible large contribution from an unknown broad resonant state D_{S1}.

$$\frac{2J_{s1}}{J_0}\sin 2\beta = 0.10 \pm 0.24(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$
$$\frac{2J_{s2}}{J_0}\cos 2\beta = 0.38 \pm 0.24(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

- $J_{s2}/J_0 > 0$
  - Implies that we can extract cos2b. Browder et al.. Phys. Rev. D 61 054009 (2000
- cos2b preferred >0 at 94% C.L.

$B^0 \to J/\psi\ K^{*0};\ K^* \to K^0_S \pi^0$

82 fb^{-1}. Phys.Rev. D 71 (2005) 032005.

Synopsis ...

- Interference of CP-even ($L = 0,2$) and CP-odd ($L = 1$) states give terms proportional to $\cos 2\beta$ in the decay rate.
- Strong phase differences and transversity amplitudes are measured in a separate time-integrated angular analysis of $B^\pm \to J/\psi K^{*\pm}$ and $B^0 \to J/\psi K^{*0} (K^{*0} \to K^+\pi^-)$.
- Study of $K\pi$ S-P wave relative phase variation with $K\pi$ mass resolves strong phase ambiguity.
  - Experimental review given by M. Verderi at the last CKM workshop http://ckm2005.ucsd.edu/WG/WG5/wed3/Verderi-WG5-S2.pdf

$B^0 \rightarrow J/\psi\ K^{*0};\ K^* \rightarrow K^0{}_S\pi^0$

82 fb^{-1}. Phys.Rev. D 71 (2005) 032005.

Synopsis …

- Interference of CP-even (L = 0,2) and CP-odd (L= 1) states give terms proportional to cos2b in the decay rate.
- Strong phase differences and transversity amplitudes are measured in a separate time-integrated angular analysis of $B^\pm \rightarrow J/\psi K^{*\pm}$ and $B^0 \rightarrow J/\psi K^{*0} (K^{*0} \rightarrow K^+\pi^-)$.
- Study of $K\pi$ S-P wave relative phase variation with $K\pi$ mass resolves strong phase ambiguity.
  - Experimental review given by M. Verderi at the last CKM workshop http://ckm2005.ucsd.edu/WG/WG5/wed3/Verderi-WG5-S2.pdf

Result …

- Use angular and time-dependent asymmetry to measure

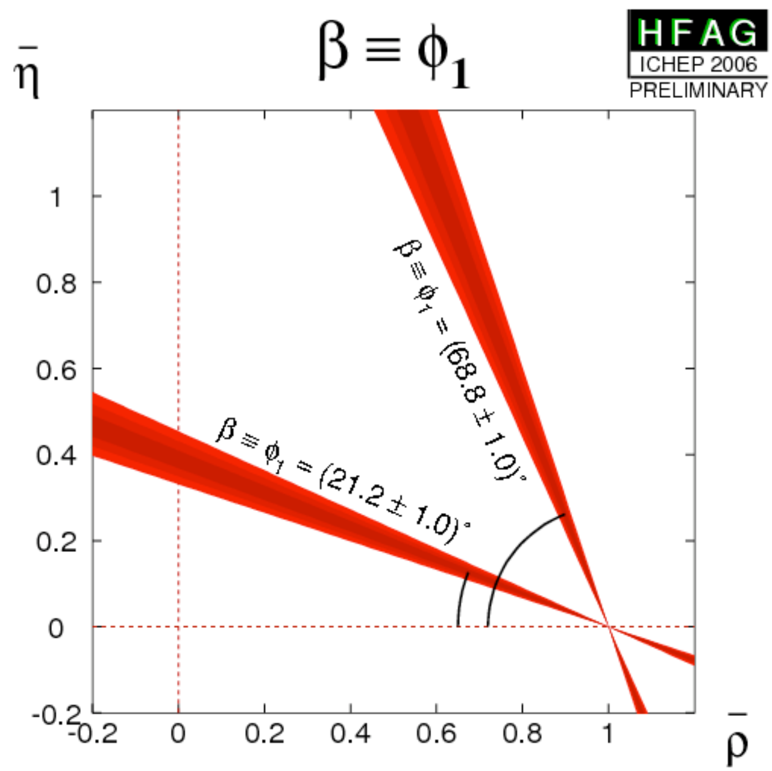
$$\cos 2b = 2.72\ ^{+0.50}_{-0.79}\ (\text{stat}) \pm 0.27\ (\text{syst})$$

and hence determine that cos2b > 0 at 86 % C.L.

Assume that sin2b is fixed to 0.731 (W.A. at that time)

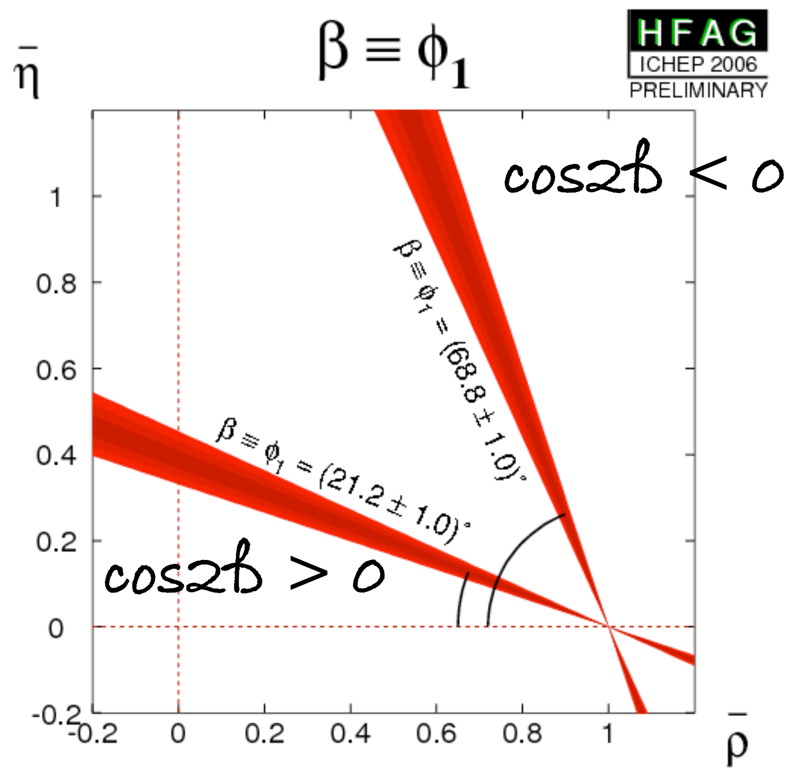
Conclusions

- sin2b from charmonium + K^0
  - 0.710 ± 0.034 (stat) ± 0.019 (syst).
  - Will be statistics limited at $1ab^{-1}$
    - ± 0.034 (stat) $\rightarrow \sim\pm 0.020$ (stat)
  - Shouldn't stop us trying to reduce our systematic errors ...



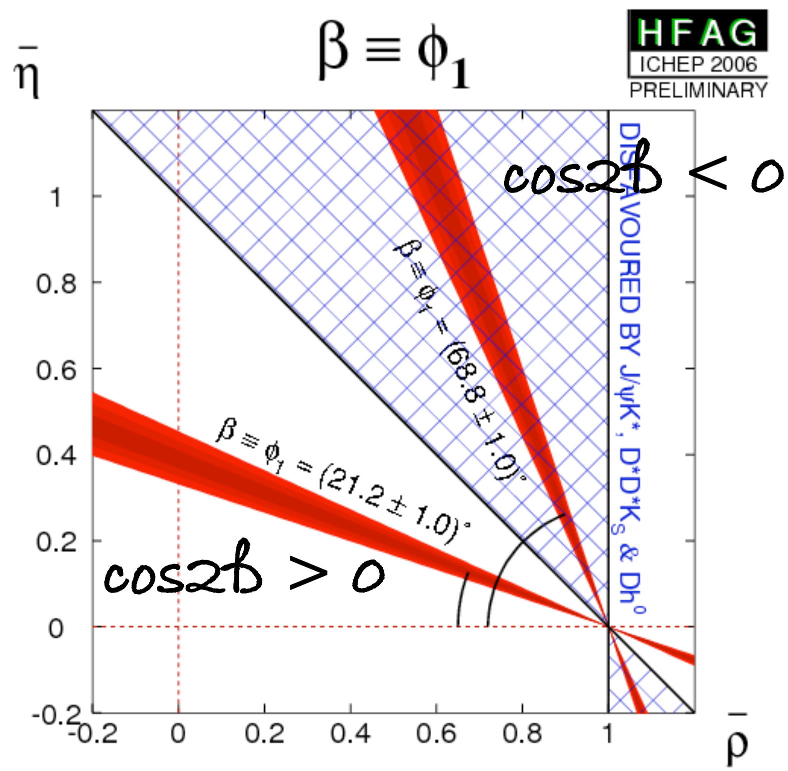
Conclusions

- $\sin 2\beta$ from charmonium + K^0
  - 0.710 ± 0.034 (stat) ± 0.019 (syst).
  - Will be statistics limited at $1ab^{-1}$
    - ± 0.034(stat) $\rightarrow \sim\pm 0.020$(stat)
  - Shouldn't stop us trying to reduce our systematic errors …
- Both of the $b \rightarrow c\bar{c}s$ $\cos 2\beta$ measurements strongly favour positive values of $\cos 2\beta$.
- $\cos 2\beta$ from $D^{*+}D^{*-} K^0_S$
  - $\cos 2\beta > 0$ at 94% C.L.
- $\cos 2\beta$ from $J/\psi K^{*0}$
  - $\cos 2\beta > 0$ at 86% C.L.



Conclusions

- $\sin 2\beta$ from charmonium + K^0
  - 0.710 ± 0.034 (stat) ± 0.019 (syst).
  - Will be statistics limited at $1ab^{-1}$
    - ± 0.034(stat) $\rightarrow \sim\pm 0.020$(stat)
  - Shouldn't stop us trying to reduce our systematic errors …
- Both of the $b \rightarrow c\bar{c}s$ $\cos 2\beta$ measurements strongly favour positive values of $\cos 2\beta$.
- $\cos 2\beta$ from $D^{*+}D^{*-}K^0_S$
  - $\cos 2\beta > 0$ at 94% C.L.
- $\cos 2\beta$ from $J/\psi K^{*0}$
  - $\cos 2\beta > 0$ at 86% C.L.
- Add in $b \rightarrow c\bar{u}d$ to get this !
  - Will also be statistics limited at $1ab^{-1}$



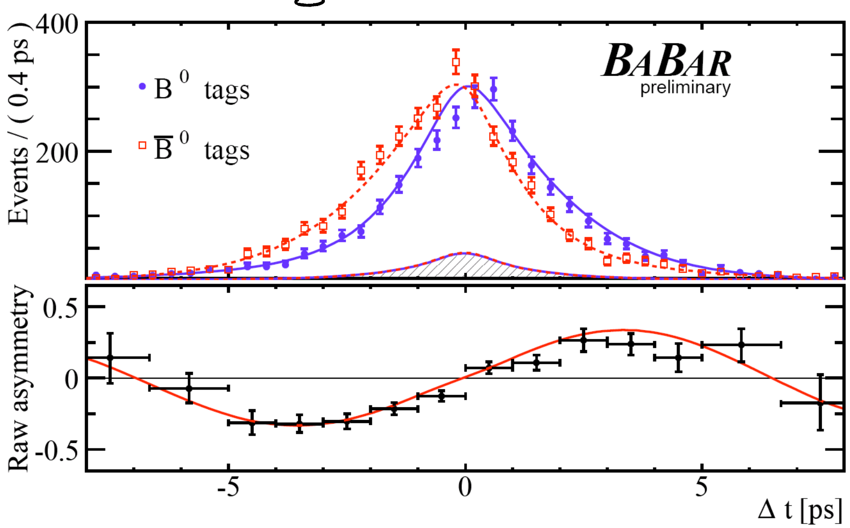
$\Rightarrow \beta = (21.2 \pm 1.0)^\circ$
(Belle + BaBar)


Extra slides

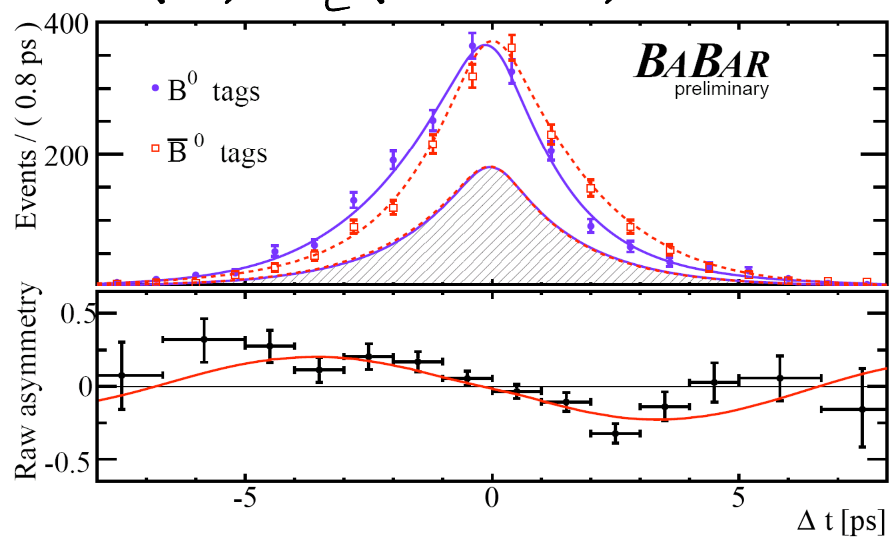
sin2β from $B^0 \to$ charmonium + $K^0_{S,L}$

316 fb^{-1}. hep-ex/0607017. (Preliminary)

(cc) K^0_S (CP odd modes)



(cc) K^0_L (CP even) modes



We measure:

- sin2β = 0.710 ± 0.034 (stat) ± 0.019 (syst).
- $|\lambda|$ = 0.932 ± 0.026 (stat) ± 0.017 (syst).

Previous result:

- sin2β = 0.722 ± 0.040 (stat) ± 0.023 (syst).
- $|\lambda|$ = 0.950 ±0.031 (stat) ± 0.015 (syst).
  - 205 fb^{-1}. Phys. Rev. Lett. 94 (2005) 161803.

$\sin 2\beta$ from $B^0 \to$ charmonium + $K^0_{S,L}$

fits split by Run, year, tag category ...

Sample	N_{tag}	$P(\%)$	$\sin 2\beta$
Full CP sample	11496	76	0.710 ± 0.034
$J/\psi K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$,$\eta_c K^0_S$	6028	92	0.713 ± 0.038
$J/\psi K^0_L$	4323	55	0.716 ± 0.080
$J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$	965	68	0.526 ± 0.284
1999-2002 data	3084	79	0.755 ± 0.067
2003-2004 data	4850	77	0.724 ± 0.052
2005-2006 data	3562	74	0.663 ± 0.062
$J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ only ($\eta_f = -1$)			
$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$)	4076	96	0.715 ± 0.044
$J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$)	988	88	0.581 ± 0.105
$\psi(2S)K^0_S$ ($K^0_S \to \pi^+\pi^-$)	622	83	0.892 ± 0.120
$\chi_{c1}K^0_S$	279	89	0.709 ± 0.174
$\eta_c K^0_S$	243	75	0.717 ± 0.229
Lepton category	703	97	0.754 ± 0.068
Kaon I category	900	93	0.713 ± 0.066
Kaon II category	1437	91	0.711 ± 0.075
Kaon-Pion category	1107	89	0.635 ± 0.117
Pion category	1238	91	0.587 ± 0.175
Other category	823	89	0.454 ± 0.469
B_{flav} sample	112878	83	0.016 ± 0.011
B^+ sample	27775	93	0.008 ± 0.017

sin2β from $B^0 \rightarrow$ charmonium + $K^0_{S,L}$

systematic uncertainties

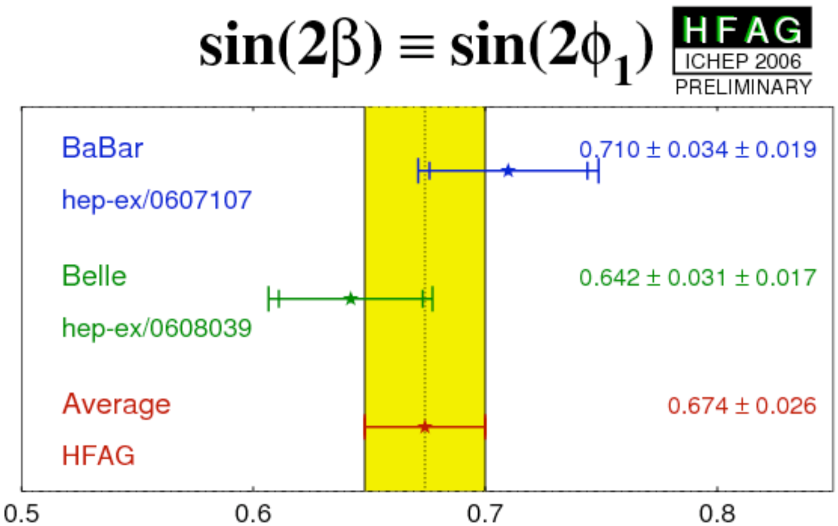
Source	$\sigma(\sin 2\beta)$	$\sigma(\lvert\lambda\rvert)$
CP backgrounds	0.012	0.002
Δt resolution function	0.011	0.003
$J/\psi K^0_L$ backgrounds	0.011	N/A
Mistag fraction differences	0.007	0.001
Beam spot	0.007	0.001
Δm_d, τ_B, $\Delta\Gamma/\Gamma$, $\lvert\lambda\rvert$	0.005	0.001
Tag-side interference	0.001	0.014
MC statistics	0.003	0.003
Total systematic error	0.023	0.015

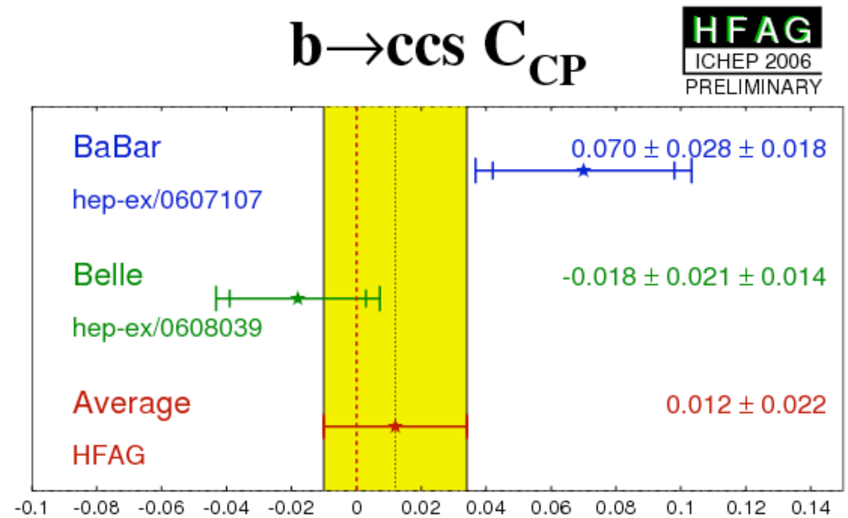
205 fb^{-1}

Source	$\sigma(\sin 2\beta)$	$\sigma(\lvert\lambda\rvert)$
CP backgrounds	0.007	0.002
Δt resolution function	0.008	0.002
$J/\psi K^0_L$ backgrounds	0.007	N/A
Mistag fraction differences	0.009	0.007
Beam spot	0.008	0.004
Δm_d, τ_B, $\Delta\Gamma_d/\Gamma_d$, $\lvert\lambda\rvert$	0.003	0.001
Tag-side interference	0.002	0.014
MC statistics	0.003	0.005
Total systematic error	0.019	0.017

316 fb^{-1}

BaBar and Belle comparison





Some differences ...

- Belle measure the $J/\psi K^0_S$ and $J/\psi K^0_L$ modes.
- BaBar measures $|\lambda|$ (and not C) where $C = \dfrac{1+|\lambda|^2}{1-|\lambda|^2}$

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

Systematic uncertainties

Source	I	II	III
Acceptance	0.060	0.040	0.030
Peaking backgrounds	0.009	0.016	0.002
Δt resolution function	0.015	0.006	0.008
Mistag fraction differences	0.016	0.015	0.015
Detector Alignment	0.005	0.015	0.015
Δm_d, τ_B	0.001	0.001	0.001
MC statistics	0.021	0.032	0.032
Others	0.005	0.004	0.005
Total	0.068	0.058	0.050

TABLE I: Sources of systematic error on J_c/J_0 (Column I), $(2J_{s1}/J_0)\sin2\beta$ (Column II) and $(2J_{s1}/J_0)\cos2\beta$ (Column III).

$$\boxed{J_c = \int_{s^+<s^-} (|a|^2 - |\bar{a}|^2)\, ds^+ ds^-}$$

- Large sys error due to acceptance. Estimate possible deviation using MC
- Total uncertainties dominated by the statistical uncertainties.

$B^0 \rightarrow J/\psi K^*; K^* \rightarrow K^0_S \pi^0$

Systematic uncertainties

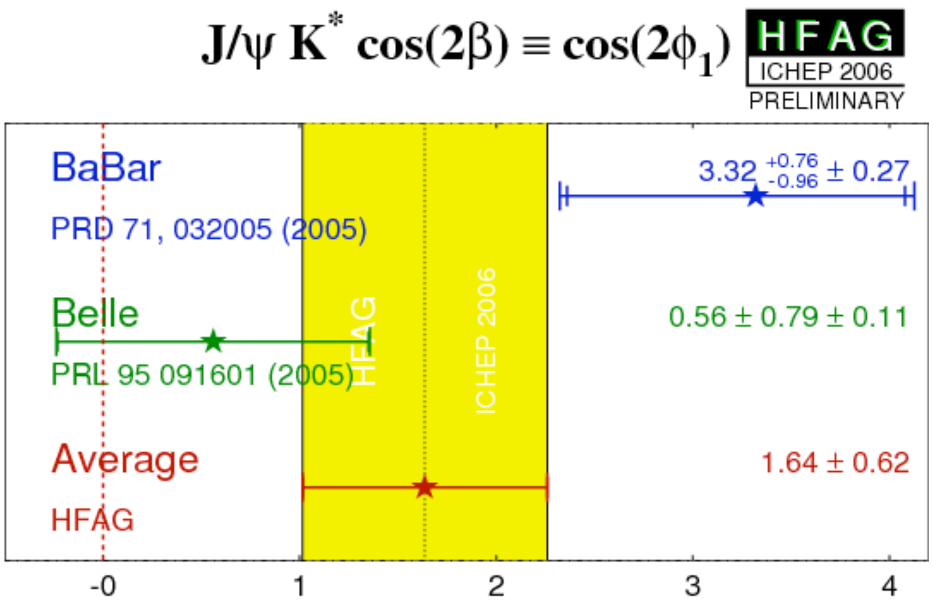
Source	sin 2β	cos 2β
Signal Properties		
(a) Δt-resolution function	± 0.002	± 0.002
(b) signal dilution B_{CP} vs B_{flav}	± 0.012	± 0.013
(c) Gaussian model for *outliers*	± 0.001	± 0.000
(d) f_{tail} parameter	± 0.002	± 0.003
(e) resolution/tagging correlation	± 0.001	± 0.001
(f) SVT alignment	± 0.010	± 0.030
Background properties: B_{flav}		
(g) signal probability	± 0.001	± 0.001
(h) ARGUS m_0 parameter	± 0.002	± 0.010
(i) oscillating contribution	± 0.001	± 0.022
(j) δ_{peak} contribution	± 0.001	± 0.003
J/ψ $(K^0_S \pi^0)$ specific		
(k) background fraction and *CP* parity	± 0.032	± 0.142
(m) background dilutions	± 0.002	± 0.006
(n) amplitude uncertainties	± 0.016	± 0.154
(o) statistics used for moments	± 0.030	± 0.030
(p) angular background distribution	± 0.024	± 0.064
External parameters		
(q) z scale and "*boost*"	± 0.001	± 0.001
(r) beam spot	± 0.010	± 0.040
(s) B^0 lifetime	± 0.014	± 0.040
(t) Δm	± 0.018	± 0.032
Monte Carlo		
(u) Monte Carlo statistics	± 0.130	± 0.140
Total systematic uncertainty	± 0.14	± 0.27
Statistical uncertainty	± 0.57	$^{+0.76}_{-0.96}$

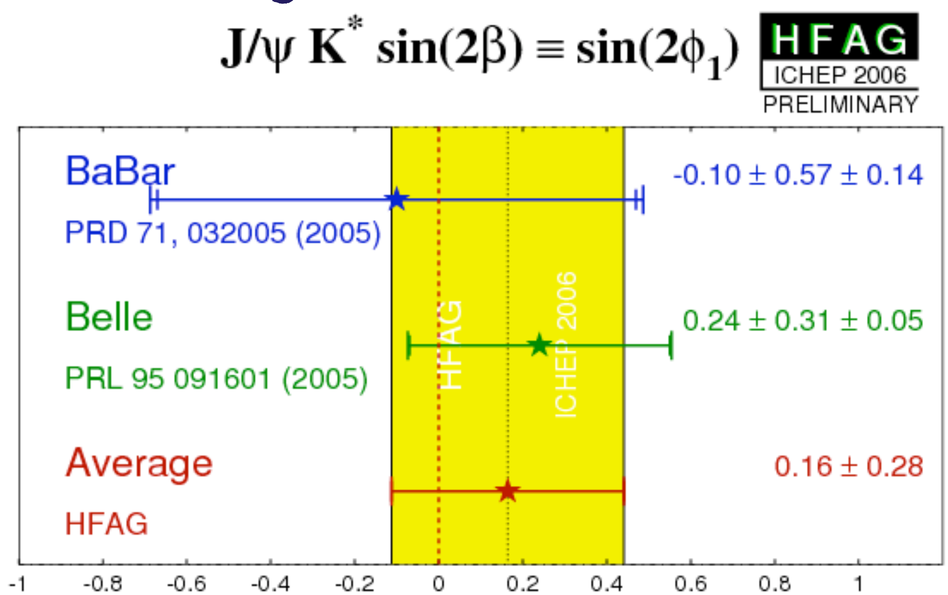
$B^0 \rightarrow J/\psi\, K^{*0};\ K^* \rightarrow K^0{}_S \pi^0$

82 fb^{-1}. Phys.Rev. D 71 (2005) 032005.

Measure

- $\cos 2\beta = +3.32\ ^{+0.76}_{-0.96}$ (stat) $\pm$ 0.27 (syst)
- $\sin 2\beta = -0.10 \pm 0.57$ (stat) $\pm$ 0.14 (syst)





BaBar : 82 fb^{-1}.
Belle: 253 fb^{-1}.

Fixing sin2β to 0.731 (W.A. at that time)

- $\cos 2\beta = 2.72\ ^{+0.50}_{-0.79}$ (stat) $\pm$ 0.27 (syst)