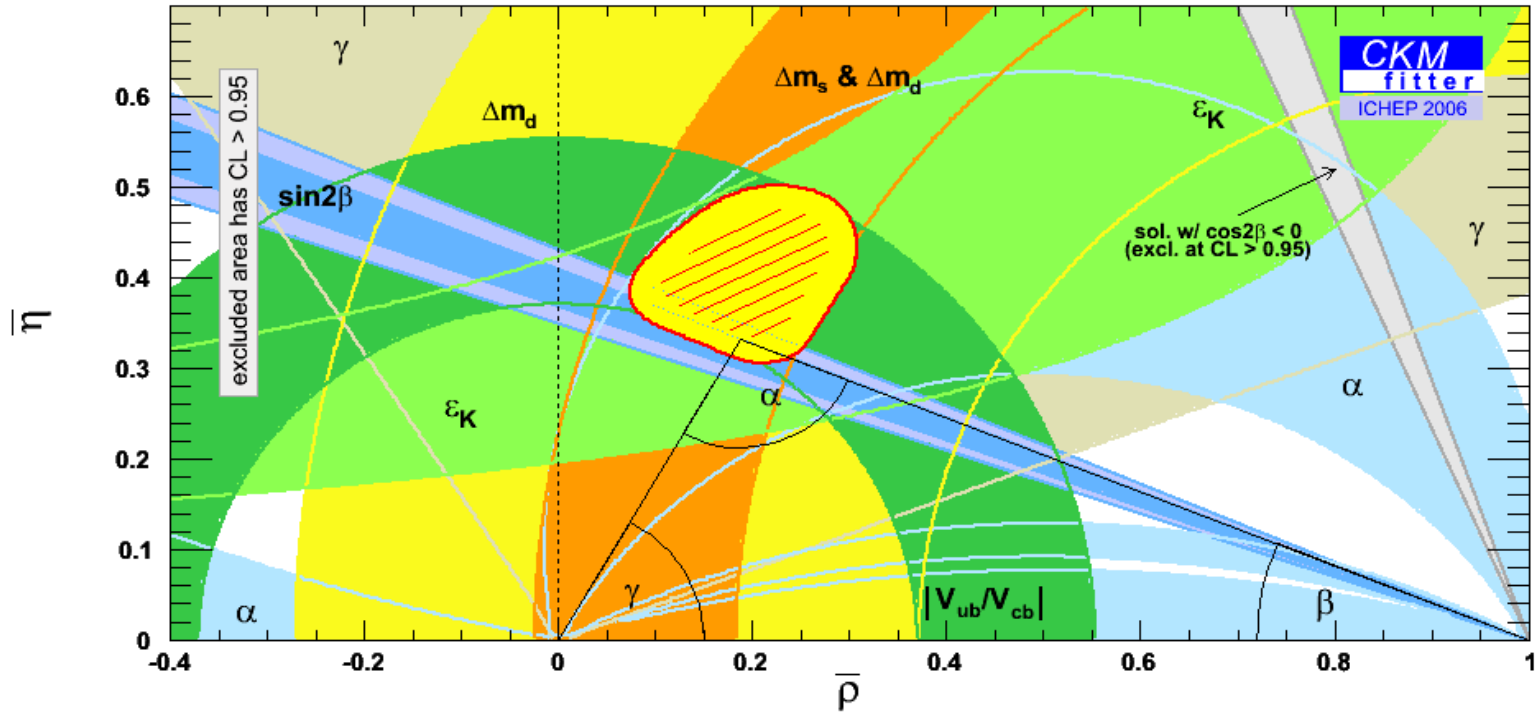
$\sin 2\beta/\phi_1$ via $b \to c\bar{c}s$ decays
&
ambiguity removal
via $\cos 2\beta/\phi_1$

Heiko Lacker, TU Dresden
on behalf of *BABAR* & Belle

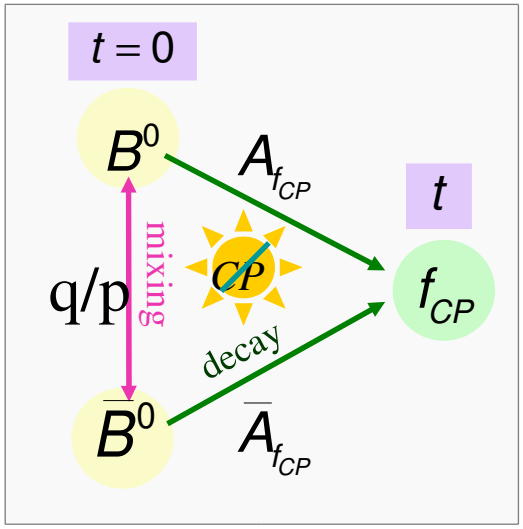
BEAUTY 2006, Oxford
September 25, 2006

Time-dependent CP asymmetry in $b \to c\bar{c}s$ decays

* SM interpretation in terms of sin2β: Theoretically clean (<O(0.01))
* Experimentally "Easy"
* Reference for loop-mediated decays (see talk by Y. Ushiroda)
* Most precise constraint on $\bar{\rho}$–$\bar{\eta}$
* Probe NP phase in B-$\bar{B}$ mixing (Constraint almost tangent to $|V_{ub}|$!)



Time-dependent CP-Asymmetries in B_d system



$$A_{CP}(t)=\frac{\Gamma(\bar{B}^0(t)\to f_{CP})-\Gamma(B^0(t)\to f_{CP})}{\Gamma(\bar{B}^0(t)\to f_{CP})+\Gamma(B^0(t)\to f_{CP})}$$

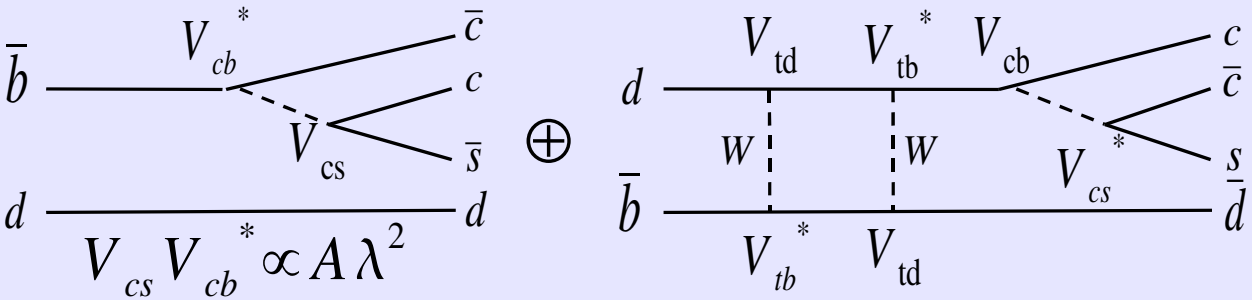
$$\lambda_{f_{CP}}=\eta_{f_{CP}}\frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$=\frac{2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2}\sin(\Delta m_d t)-\frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_d t)$$

$$\| \qquad \| \qquad \|$$

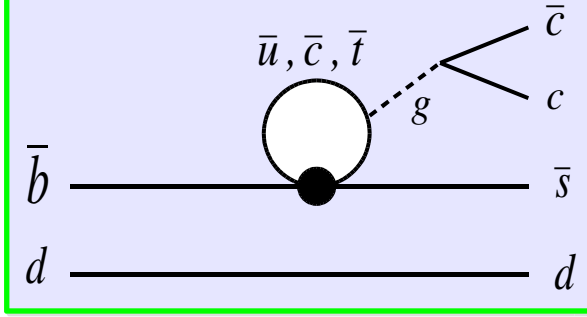
$$S \qquad -A(Belle) \qquad C(BABAR)$$

$$B^0/\bar{B}^0\to(c\bar{c})K^0_{CP}(\text{e.g.}\to\pi^+\pi^-)$$



$$\frac{q}{p}\frac{\bar{A}}{A}\approx e^{-2\cdot i\beta}$$

$$\frac{q}{p}\approx\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}$$



$$V_{cs}V_{cb}^*\propto A\lambda^2$$

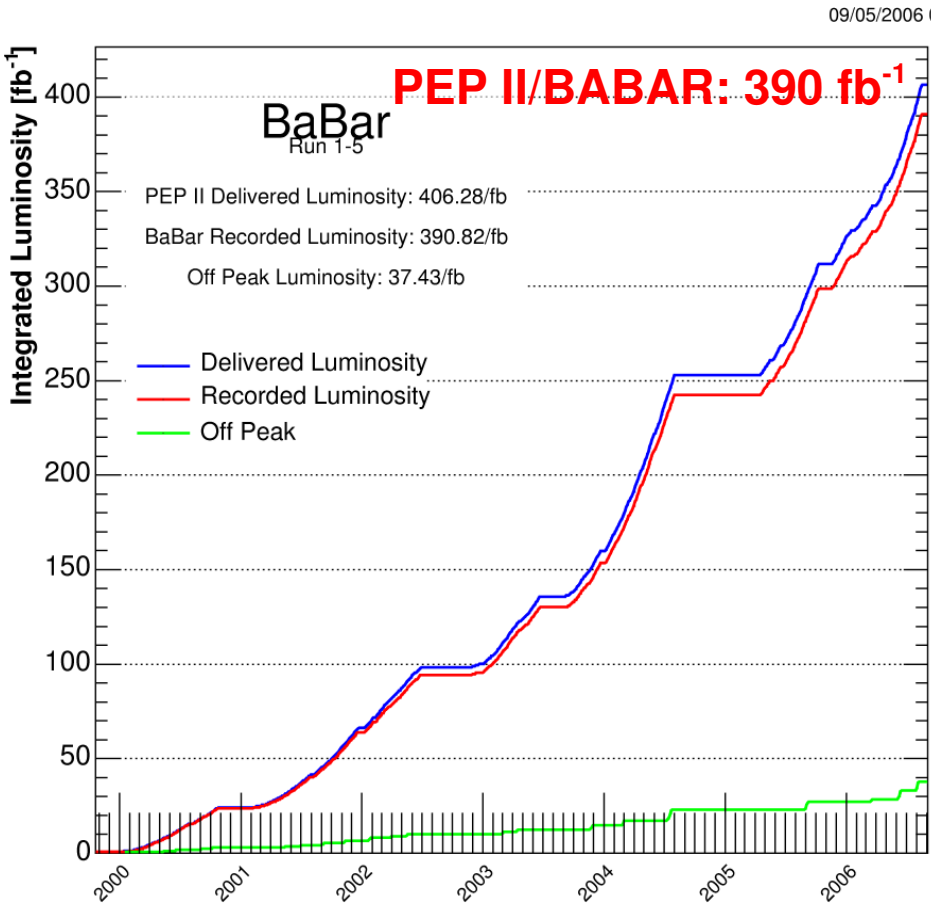
$$V_{ts}V_{tb}^*\propto A\lambda^2$$

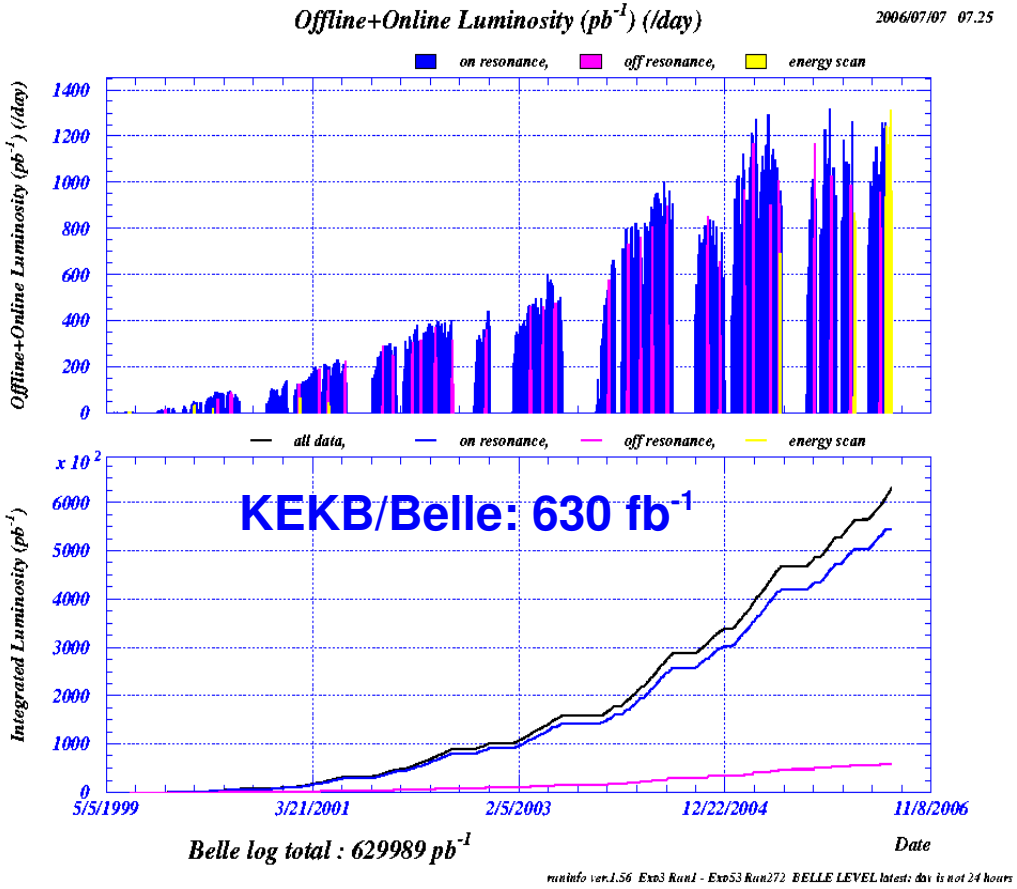
$$V_{us}V_{ub}^*\propto A\lambda^4$$

To a very good approximation:

$$A_{CP}(t)=\sin(2\beta)\cdot\sin(\Delta m_d t)$$

The B-factories have passed 1 ab^{-1}





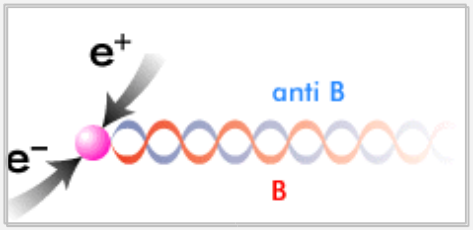
Luminosity Records (10^{34} cm^{-2} s^{-1})

KEKB: 1.6517 (June 29, 2006)

PEP II: 1.207 (August 16, 2006)

Time-dependent CP violation at the Y(4S)

Coherent State



$\Upsilon(4S)$

e^- e^+

9 GeV BABAR/PEPII 3.1 GeV
8 GeV Belle/KEKB 3.5 GeV

$\beta\gamma = 0.56$ (BABAR)
$= 0.425$ (Belle)

$\bar{B}^0_{tag}$ K^- ℓ^-

B^0_{rec} K^0_S π^+ π^- J/ψ μ^- μ^+ Δz

Flavor Tagging
leptons, Kaons,
slow pions from D*

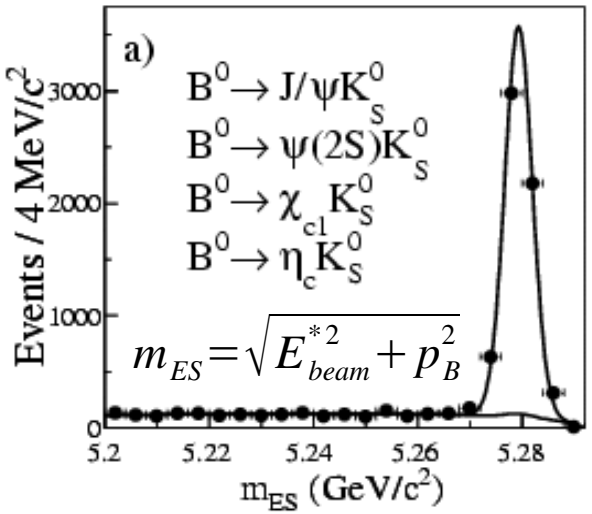
$Q = \Sigma \varepsilon_i (1-2w_i)^2$
$=(30.4\pm0.3)\%$(BABAR)
$=(29 \pm 1)\%$ (Belle)

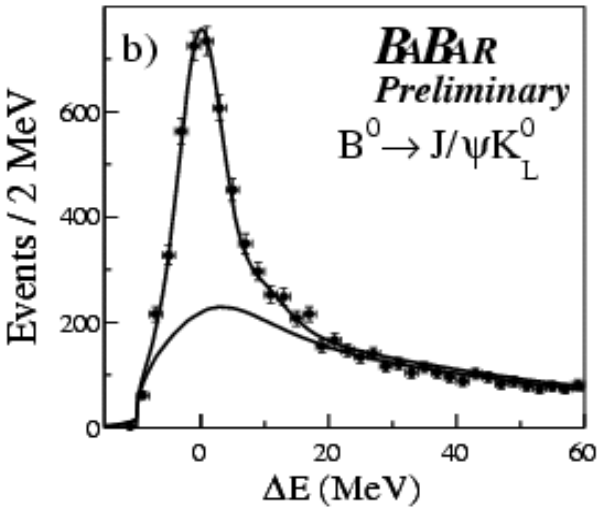
$\Delta t \approx \Delta z \langle \beta\gamma \rangle c$
$\langle \Delta z \rangle \approx 250\mu m$ (BABAR)
$\approx 200\mu m$ (Belle)
$\sigma(\Delta z) \approx 190\ \mu m$

Exclusive *B*-meson reconstruction:

e.g. CP Eigenstate

BABAR (hep-ex/0607107): 348 M $B\bar{B}$





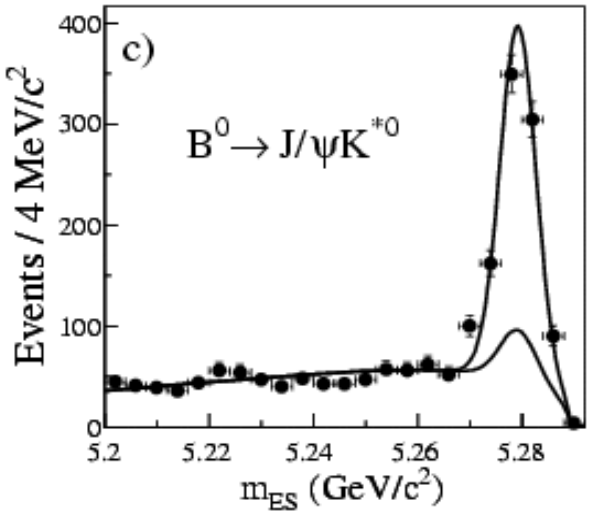
$B \to (c\bar{c}) K^0_S$ **η_{CP} = -1**

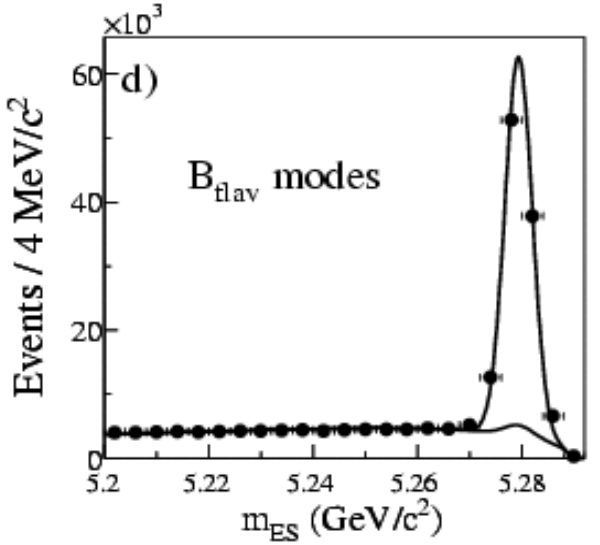
$J/\Psi \to e^+ e^-, \mu^+ \mu^-$

$\Psi(2S) \to e^+ e^-, \mu^+ \mu^-; J/\Psi \pi^+ \pi^-$

$\chi_{c1} \to J/\Psi \gamma$ $\eta_c \to K_S K^+ \pi^-$

$K_S \to \pi^+ \pi^-, (\pi^0 \pi^0)$





$B \to J/\Psi K^{*0}$ $K^{*0} \to K_S \pi^0$

VV-mode => admixture of CP-odd/CP-even final states

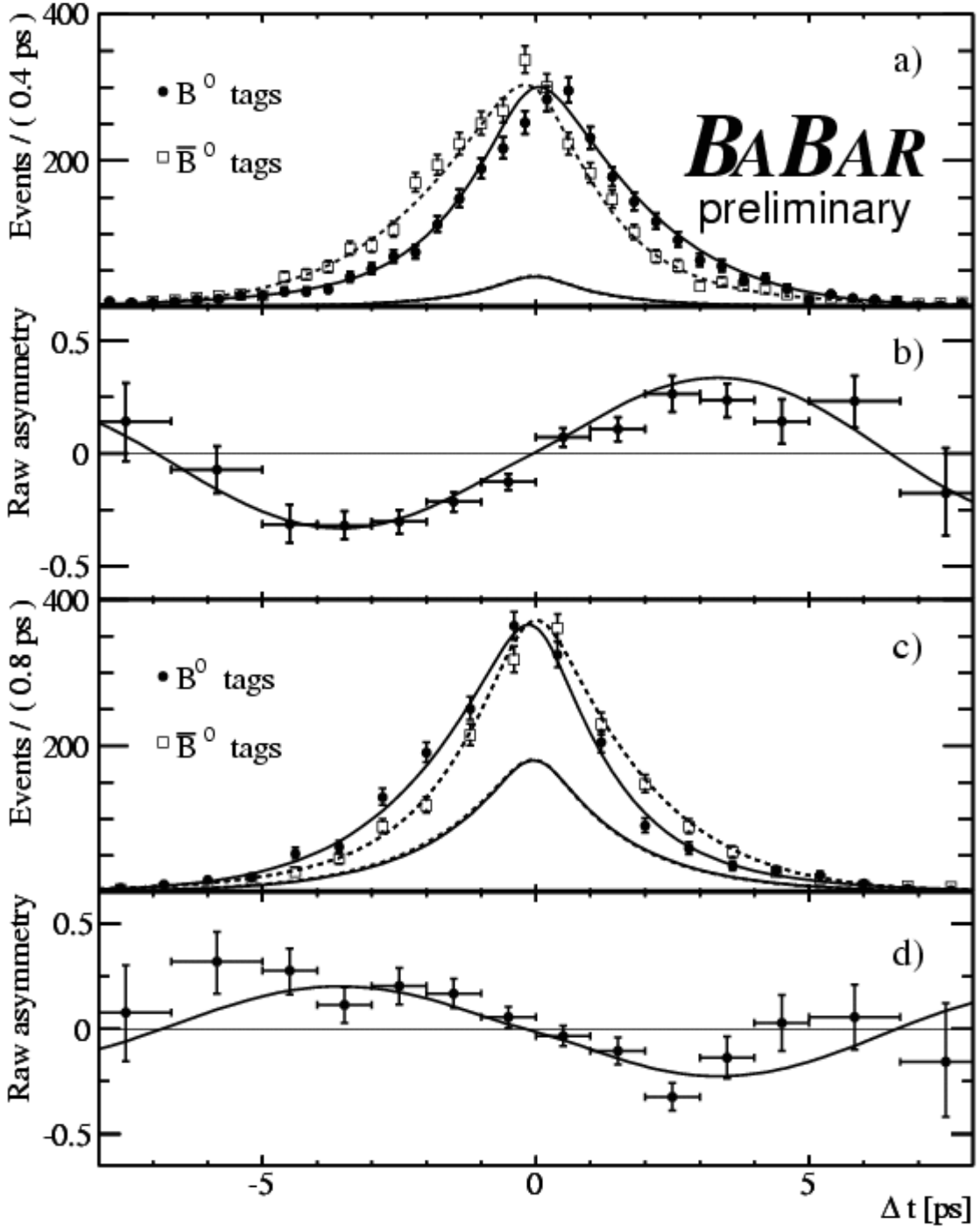
Angular analysis: η_{CP}=0.504 (hep-ex/0607081)

$B \to J/\Psi K^0_L$ **K_L-energy not measured !** **η_{CP} = +1**

Apply kinematic constraint: $M^2_B = (p_{J/\Psi} + p_{K_L})^2$

Remaining degree of freedom: $\Delta E = E^*_{J/\Psi} + E^*_{K_L} - E^*_{beam}$

sin2β: *BABAR* Results



CP odd: $\eta_{CP} = -1$ $\quad B \to (c\bar{c}) K^0_S$

$\sin 2\beta = +0.713 \pm 0.038$

$C = -A = +0.070 \pm 0.028 \pm 0.018$

CP even: $\eta_{CP} = +1$ $\quad B \to J/\Psi\, K^0_L$

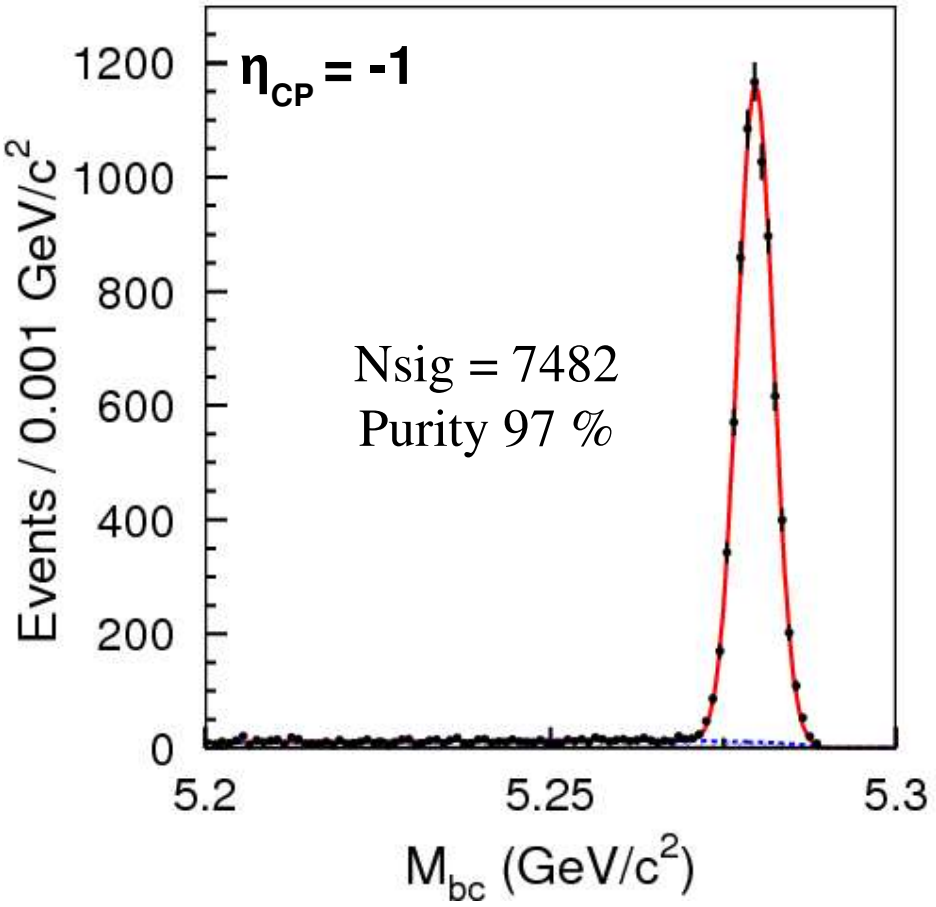
$\sin 2\beta = +0.716 \pm 0.080$

Full CP sample:

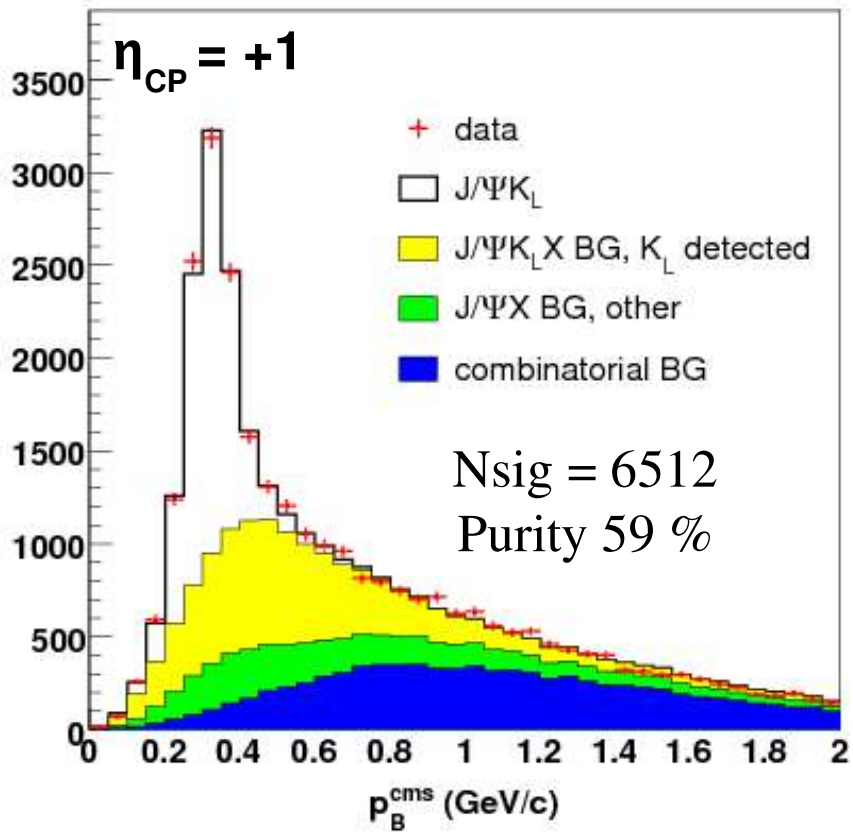
$\sin 2\beta = +0.710 \pm 0.034 \pm 0.019$

Belle (hep-ex/0608039): 532 M $B\bar{B}$

$B \to J/\Psi K_S^0$



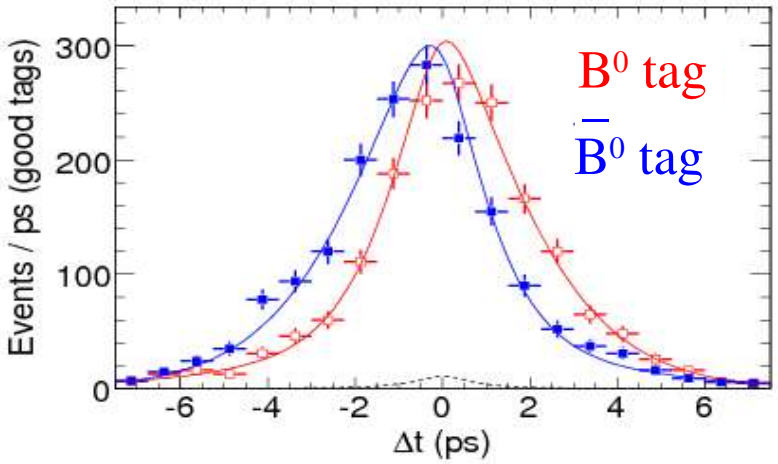
$B \to J/\Psi K_L^0$

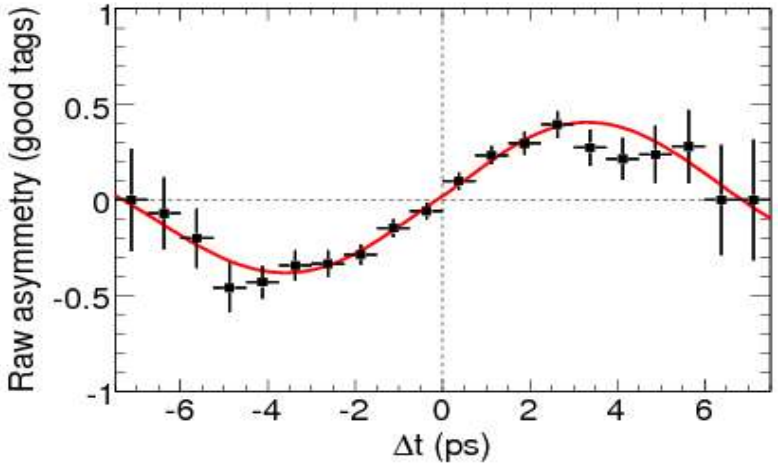


$$M_{bc} = \sqrt{E^{*2}_{beam} - P^{*2}_{J/\psi Ks}}$$

sin2β: Belle Results

CP odd: $\eta_{CP} = -1$ $\quad B \to J/\Psi K^0_S$

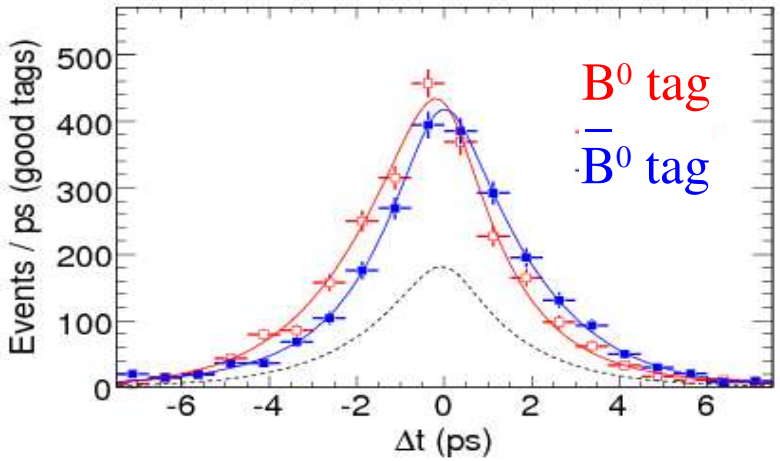


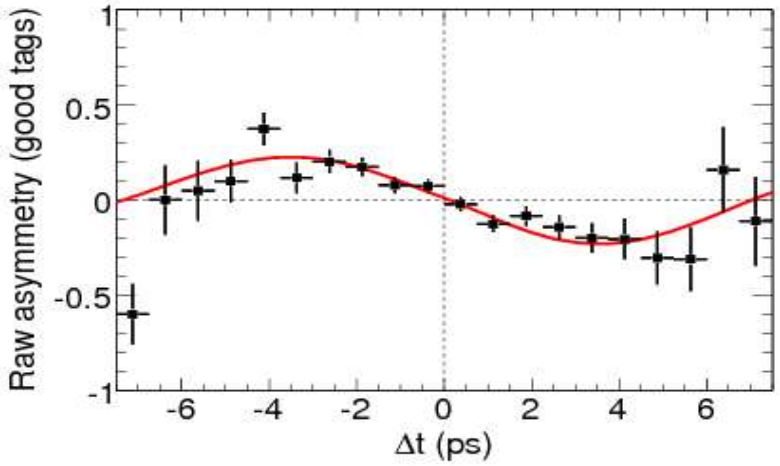


$\sin 2\beta = +0.643 \pm 0.038$

$C = -A = 0.001 \pm 0.028$

CP even: $\eta_{CP} = +1$ $\quad B \to J/\Psi K^0_L$





$\sin 2\beta = +0.641 \pm 0.057$

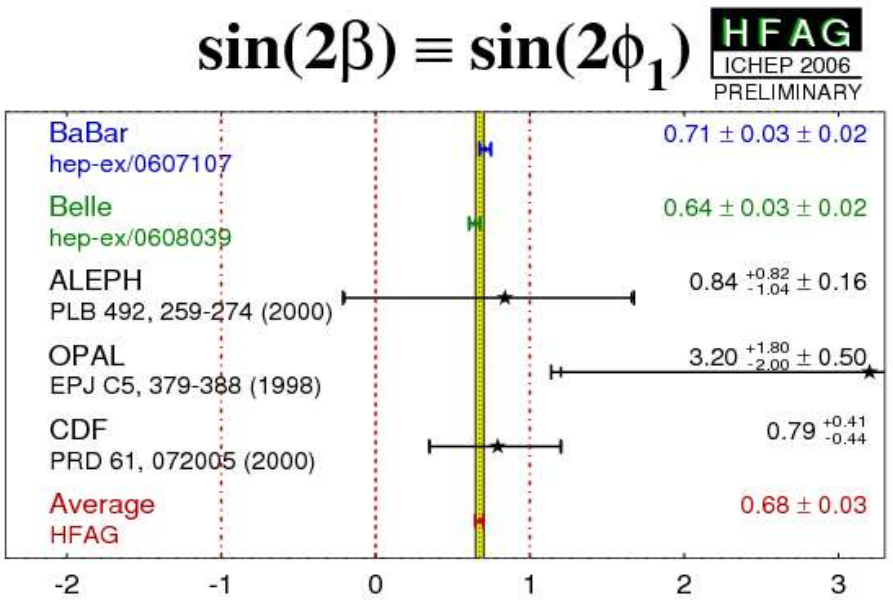
$C = -A = -0.045 \pm 0.033$

Average

$\sin 2\beta = +0.642 \pm 0.031 \pm 0.017$

$C = -A = -0.018 \pm 0.021 \pm 0.014$

sin2β: World Average



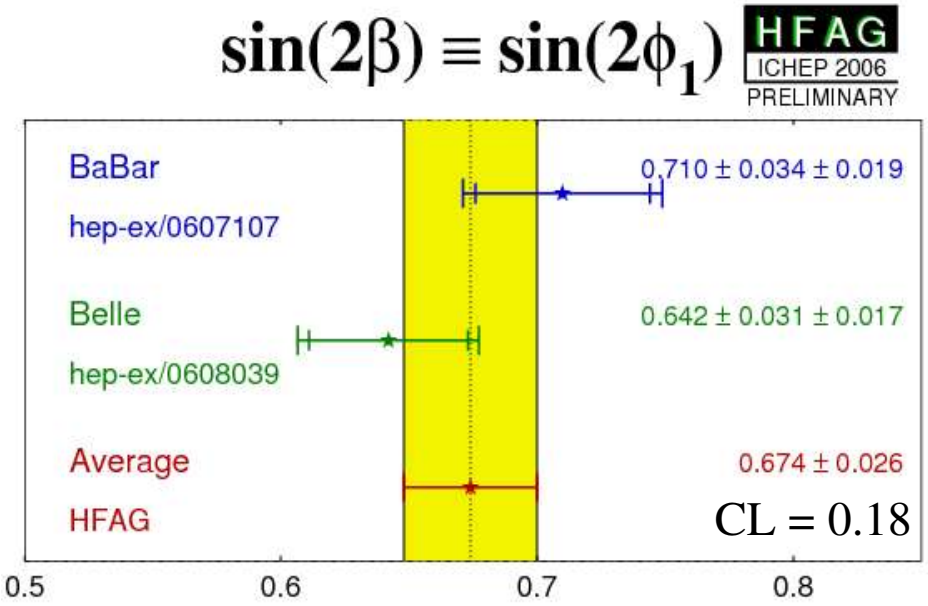
$\sin(2\beta) \equiv \sin(2\phi_1)$ (All charmonium):

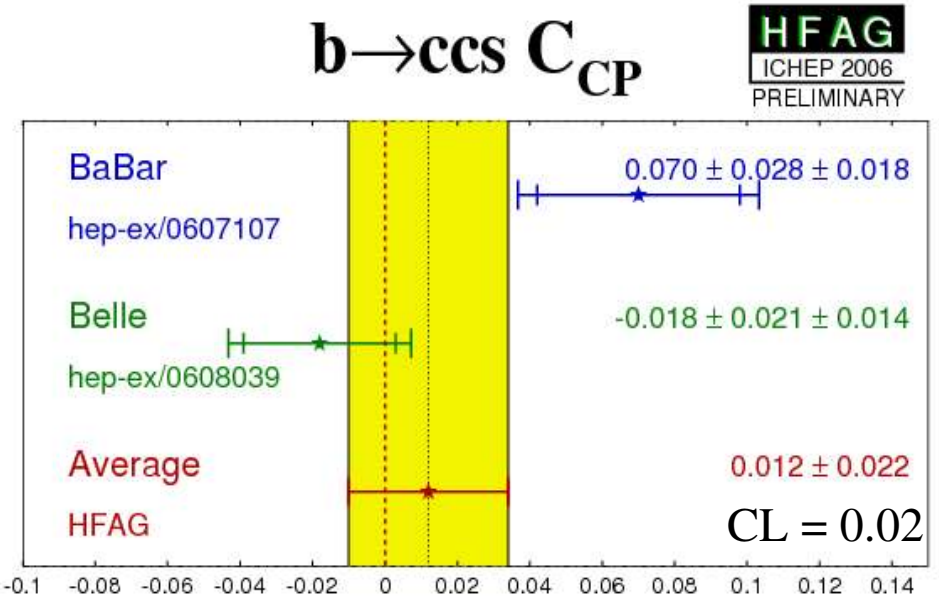
$0.675 \pm 0.023_{stat} \pm 0.012_{sys}$ (CL = 0.36)

Solutions for $\beta \equiv \phi_1$ (in [0, π]) :

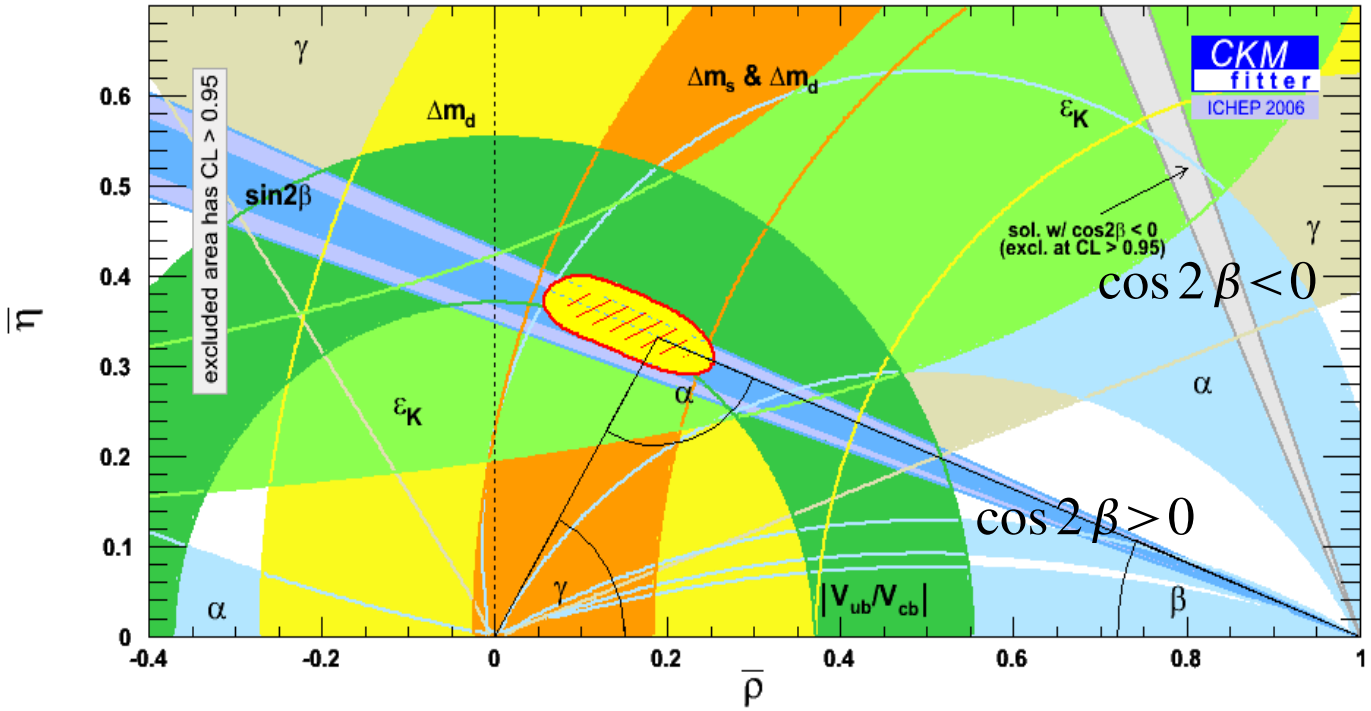
$\beta \equiv \phi_1 = (21.2 \pm 1.0)°$ or $(68.8 \pm 1.0)°$

B-Factories only





sin2β: Interpretation

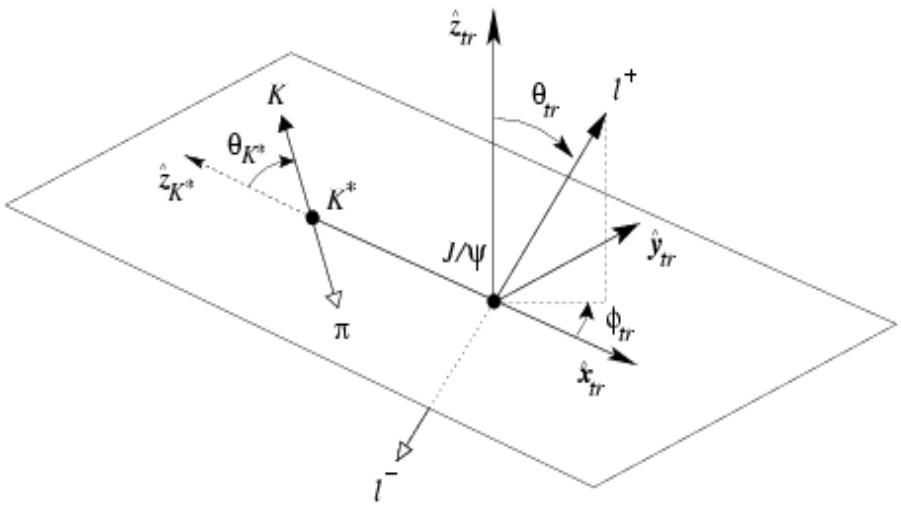


Do we have to care about the cos2β<0 solution?

Yes: In the presence of New Physics in B-mixing we are measuring sin(2β+2Θ$_d$) instead of sin(2β)

Consequence: cos2β<0 solution is not excluded as long as the sign has not been measured

cos2β from B → J/ψ K*



Transversity base to describe differential decay rate:

$$\vec{\omega}=(\theta_{K^*},\theta_{tr},\phi_{tr})$$

$$\vec{A}=(|A_0|e^{i\delta_0},|A_{\|}|e^{i\delta_{\|}},|A_{\perp}|e^{i\delta_{\perp}})$$

Problem: Strong phase ambiguity

$$(\delta_{\|}-\delta_0,\delta_{\perp}-\delta_0,\cos 2\beta)\Leftrightarrow(\delta_0-\delta_{\|},\pi+\delta_0-\delta_{\perp},-\cos 2\beta)$$

BABAR $88\,M\,B\bar{B}$ PRD 71, 032005 (2005)

$\sin 2\beta = 0.10 \pm 0.57 \pm 0.14_{sys}$ $\cos 2\beta = 2.72^{+0.50}_{-0.79} \pm 0.27$ if $\sin 2\beta \equiv 0.731$

$\cos 2\beta = 3.32^{+0.76}_{-0.96} \pm 0.27_{sys}$

$\cos 2\beta > 0$ @ 87% CL **Sign ambiguity resolved using S-P interference in Kπ system**

Belle $275\,M\,B\bar{B}$ PRL 95, 091601 (2005)

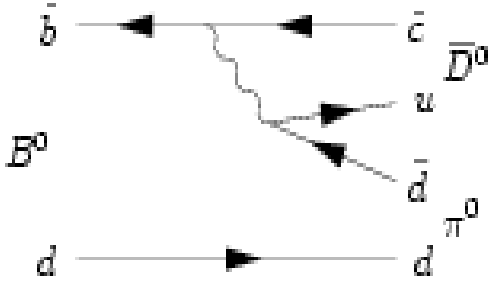
$\sin 2\beta = 0.24 \pm 0.31 \pm 0.05_{sys}$ $\cos 2\beta = 0.87 \pm 0.74 \pm 0.12$ if $\sin 2\beta \equiv 0.726$

$\cos 2\beta = 0.56 \pm 0.79 \pm 0.11_{sys}$

Belle choses solution as expected from s-quark helicity conservation (M. Suzuki, Phys. Rev. D 64, 117503 (2001)) in agreement with the sign found in BABAR's analysis.

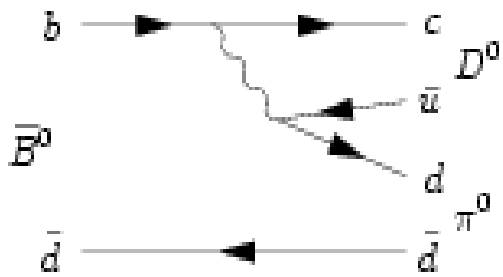
cos2β from B → $D^0/\bar{D}^0$ h^0

A. Bondar, T. Gershon and P. Krokovny, PLB 624, 1 (2005)

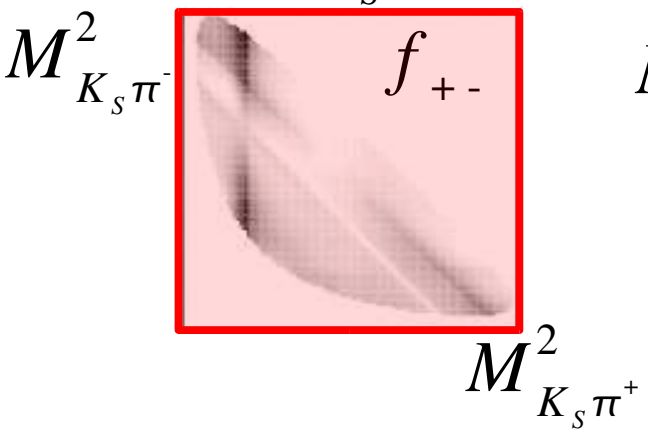


Amplitudes interference like in the Dalitz method to extract γ:

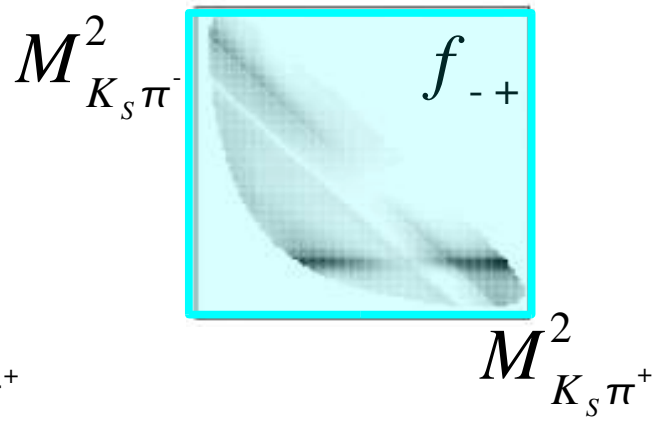
$$D^0/\bar{D}^0 \to K_S\pi^+\pi^-$$



$\bar{D}^0 \to K_S\pi^+\pi^-$



$D^0 \to K_S\pi^+\pi^-$



Amplitudes (no (direct) CP violation in *B* & *D* system):

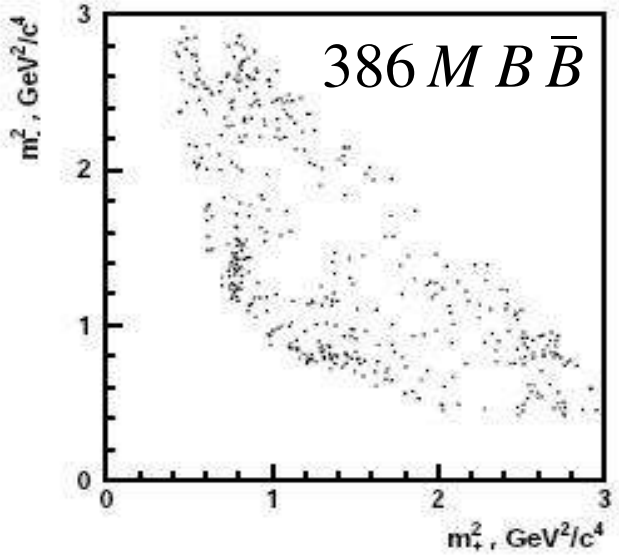
$$M_{\bar{B}^0}(t) = f_{-+}\cos(\Delta m t/2) - i e^{-i2\beta}\eta_{h^0}(-1)^l f_{+-}\sin(\Delta m t/2)$$

$$M_{B^0}(t) = f_{+-}\cos(\Delta m t/2) - i e^{+i2\beta}\eta_{h^0}(-1)^l f_{-+}\sin(\Delta m t/2)$$

η_{h^0} **: CP Eigenvalue,** $l = l(D h^0)$ $\quad f_{+-}, f_{-+}$ known $\Rightarrow \sin 2\beta$ & $\cos 2\beta$

cos2β from $B \to D^0/\bar{D}^0 h^0$

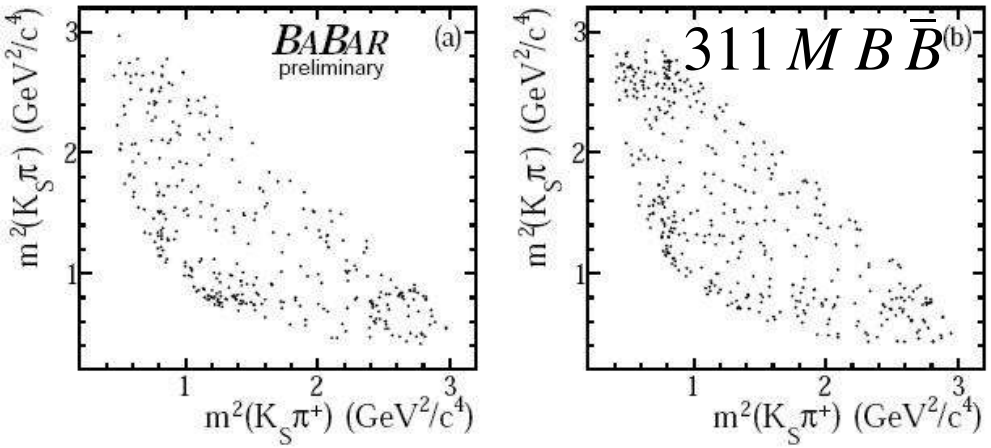
Belle PRL 97, 081801 (2006)



Final state	$\sin 2\phi_1$	$\cos 2\phi_1$
$D\pi^0$, $D\eta[\gamma\gamma]$	$0.80^{+0.54}_{-0.60}$	$2.07^{+0.78}_{-0.91}$
$D\omega$, $D\eta[3\pi]$	0.43 ± 0.90	$1.53^{+0.67}_{-0.93}$
$D^*\pi^0$, $D^*\eta$	1.07 ± 1.14	$3.46^{+1.80}_{-2.01}$
Simultaneous fit	0.78 ± 0.44	$1.87^{+0.40}_{-0.53}$

$$\sin 2\beta = 0.78 \pm 0.44 \pm 0.22_{sys+Dalitz} \qquad \cos 2\beta > 0$$
$$\cos 2\beta = 1.87^{+0.40+0.22}_{-0.53-0.32}(sys+Dalitz) \qquad @\ 98.3\%\ \mathrm{CL}$$

BABAR hep-ex/0607105



Final state	$\cos 2\beta$	$\sin 2\beta$	$\lvert\lambda\rvert$
$D^0\pi^0$	$1.1^{+0.8}_{-0.9}$	1.0 ± 0.5	$1.13^{+0.17}_{-0.14}$
$D^0\eta^{(\prime)}$	0.4 ± 1.1	$-0.1^{+0.9}_{-1.0}$	$0.96^{+0.19}_{-0.16}$
$D^0\omega$	$-0.4^{+1.3}_{-1.4}$	0.7 ± 1.0	$0.61^{+0.17}_{-0.15}$
$D^{*0}\pi^0/\eta$	0.3 ± 1.4	$-0.8^{+1.0}_{-0.9}$	$1.05^{+0.35}_{-0.25}$
All	0.54 ± 0.54	0.45 ± 0.35	0.98 ± 0.09
All	0.55 ± 0.52	0.685 (fixed)	1 (fixed)

$$\sin 2\beta = 0.45 \pm 0.36 \pm 0.05_{sys} \pm 0.07_{Dalitz} \qquad \cos 2\beta > 0$$
$$\cos 2\beta = 0.54 \pm 0.54 \pm 0.08_{sys} \pm 0.18_{Dalitz} \qquad @\ 87\%\ \mathrm{CL}$$

cos2β from $B^0/\bar{B}^0 \to D^{*+} D^{*-} K_s$

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

$$A_{CP}(t;\sin 2\beta,\cos 2\beta) = \eta_y \frac{J_c}{J_0}\cos(\Delta m_d t) - \left(\frac{2J_{s1}}{J_0}\sin 2\beta + \eta_y \frac{2J_{s2}}{J_0}\cos 2\beta\right)\sin(\Delta m_d t)$$

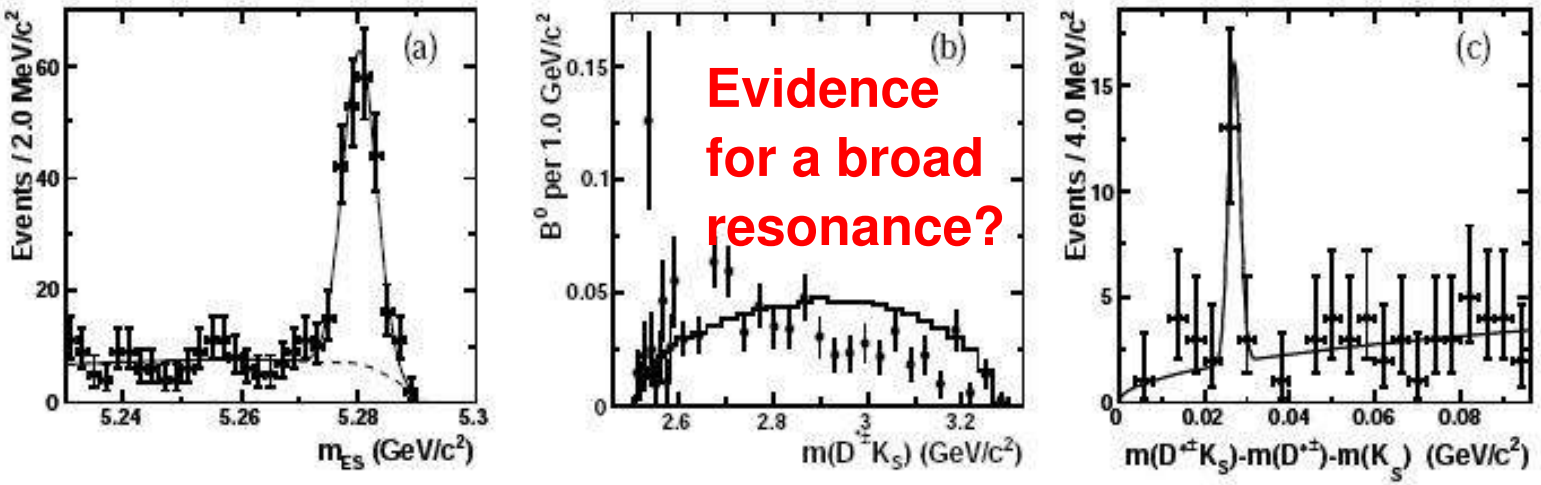
$$\eta_y = -1(+1) \text{ for } s^+ \geq s^- (s^+ \leq s^-) \qquad s^+ = m^2(D^{*+}K_S),\ s^- = m^2(D^{*-}K_S)$$

$$J_0 = \int_{s^+<s^-} (|A|^2 + |\bar{A}|^2)\,ds,\ J_c = \int_{s^+<s^-} (|A|^2 - |\bar{A}|^2)\,ds$$

$$J_{s1} = \int_{s^+<s^-} \Re(\bar{A}A^*)\,ds,\quad J_{s2} = \int_{s^+<s^-} \Im(\bar{A}A^*)\,ds$$

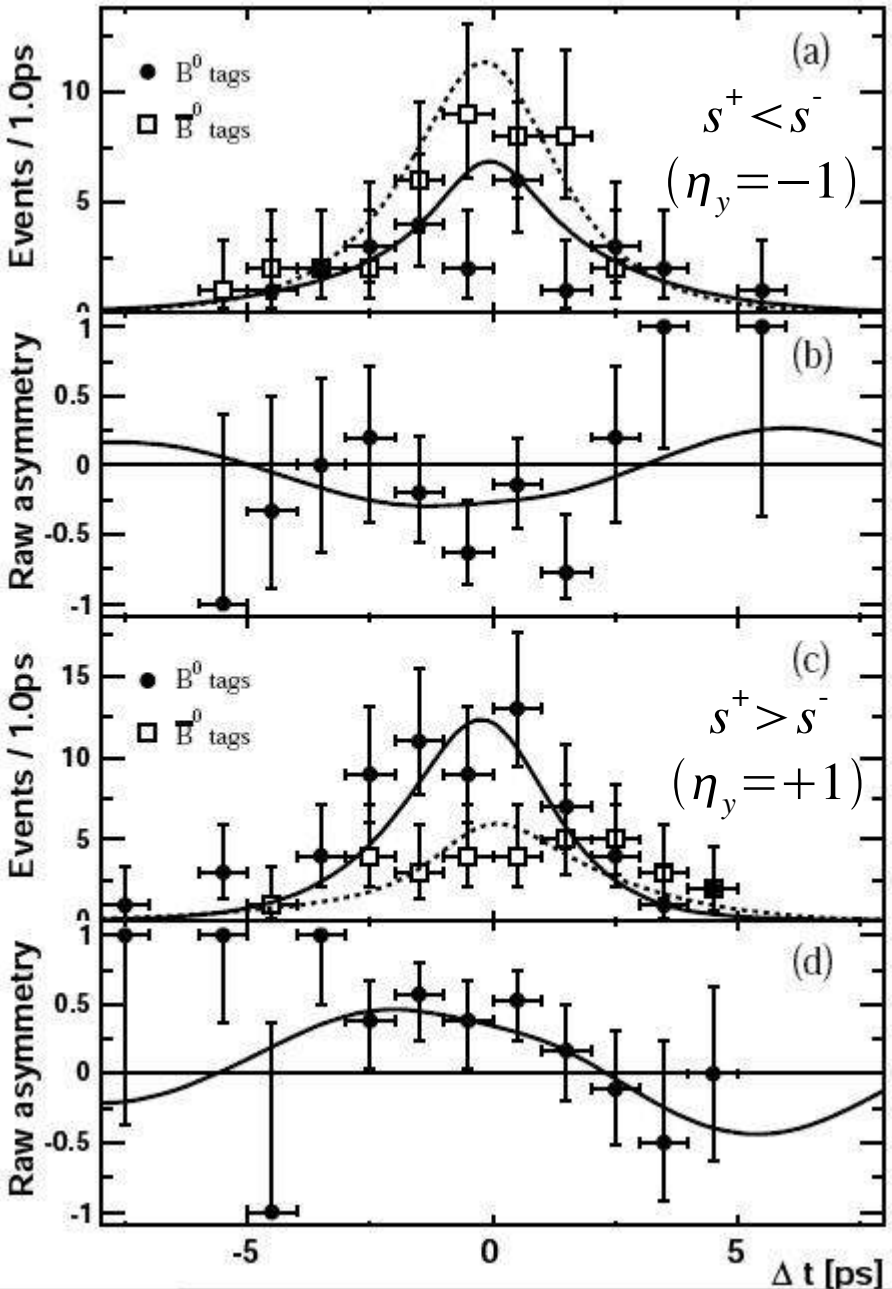
Can be large if a (broad) intermediate resonant state contributes

BABAR hep-ex/0608016 (preliminary) $230\,M\,B\,\bar{B}$



cos2β from $B^0/\bar{B}^0 \rightarrow D^{*+} D^{*-} K_s$

BABAR hep-ex/0608016 (preliminary) $230\, M\, B\, \bar{B}$



Fit results:

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

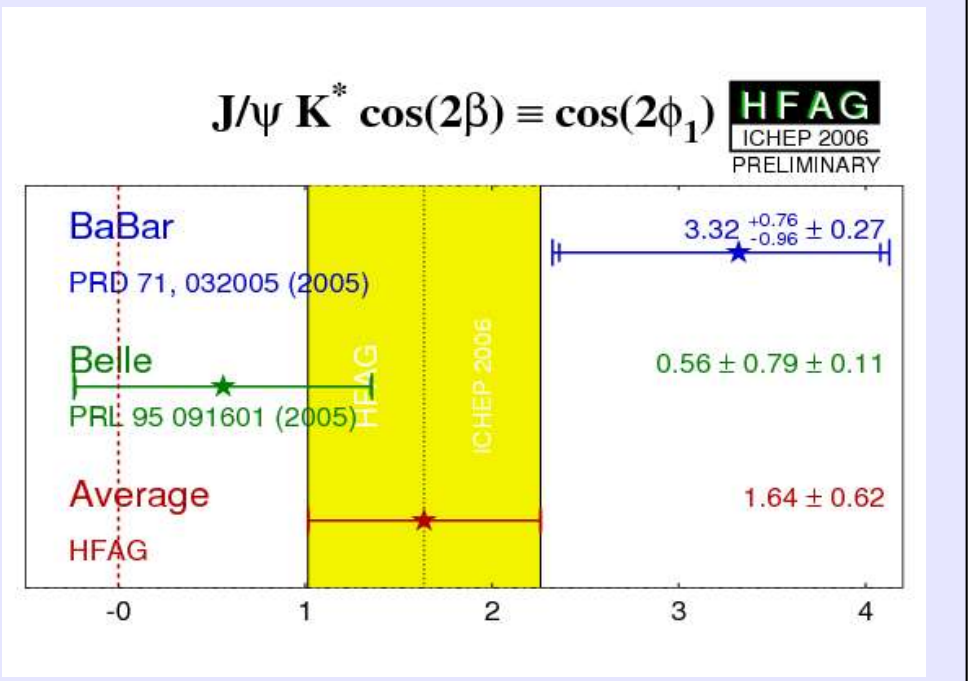
$$\frac{2J_{s1}}{J_0}\sin 2\beta = 0.10 \pm 0.24(\text{stat}) \pm 0.06(\text{syst})$$

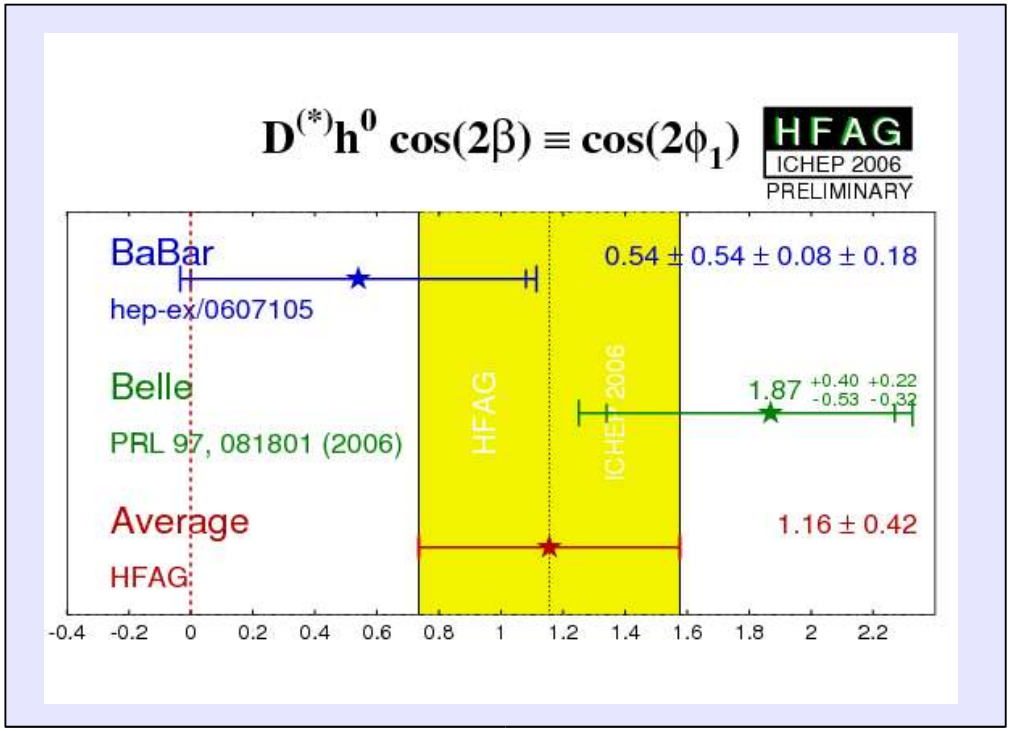
$$\frac{2J_{s2}}{J_0}\cos 2\beta = 0.38 \pm 0.24(\text{stat}) \pm 0.05(\text{syst})$$

$\cos(2\beta)>0$ @ 94% CL assuming $J_{s2}>0$

T.E. Browder, A. Datta, P.J O'Donnell and S. Pakvasa, PRD 61, 054009 (2000) predict $J_{s2}>0$.

cos2β: Summary





B--> D*D*K_s (BABAR): cos(2β)>0 @ 94% CL assuming J_{s2}>0

All results prefer cos2β>0 => SM solution for β

HFAG: PDG recipe to treat asymmetric errors in the average

"Interpretation of the averages have to be done with greatest care!"

Several results have central values outside the physical region!

Conclusions and Outlook

* Time-dependent CP asymmetry in b-->c$\bar{c}$s provides strongest constraint on $\bar{\rho}-\bar{\eta}$: $\sin(2\beta) = +0.675 \pm 0.023_{stat} \pm 0.012_{sys}$

* $C=-A = -0.018 \pm 0.017 \pm 0.014$ (CL=0.02) consistent with zero

* Extrapolated sin2β error (2008): O(0.02) <--> Theory: <O(0.01)

* All cos2β results (BABAR & Belle) consistent with cos2β>0 (SM):

	BABAR	Belle
$B \to J/\psi K^*$	@86% CL	-
$B \to D^0/\bar{D}^0 h^0$	@87% CL	@98.3% CL
$B \to D^* D^* K_S$	@94% CL	

* At present: cos2β average is very difficult to obtain

* Important constraint on NP phase in B_d-$\bar{B}_d$ mixing