Measurement of sin(2β) in Charmonium

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Representing the BaBar Collaboration

CKM08, Rome

September 121th, 2008

Outline

- Introduction
  - CP violation (CPV) in the Standard Model and the angle β
- Experimental Technique
  - Time-dependent analysis method @ Υ(4S)
- Sin(2β) in B → Charmonium Decays
  - $b \longrightarrow c\bar{c}s$
    - $B^0 \to J/\psi K^0$ ($K^0 \to K_S$ or K_L)
    - $B^0 \to \psi(2S)K_S$, $\eta_c K_S$, $\chi_{c1} K_S$
    - $B^0 \to J/\psi K^{*0}$($K^{*0} \to K_S \pi^0$)
  - $b \longrightarrow c\bar{c}d$
    - $B^0 \to J/\psi \pi^0$
- Conclusion

CP Violation in the Standard Model

- SM : single complex phase in Cabibbo-Kobayashi-Maskawa matrix ⇒ CP Violation

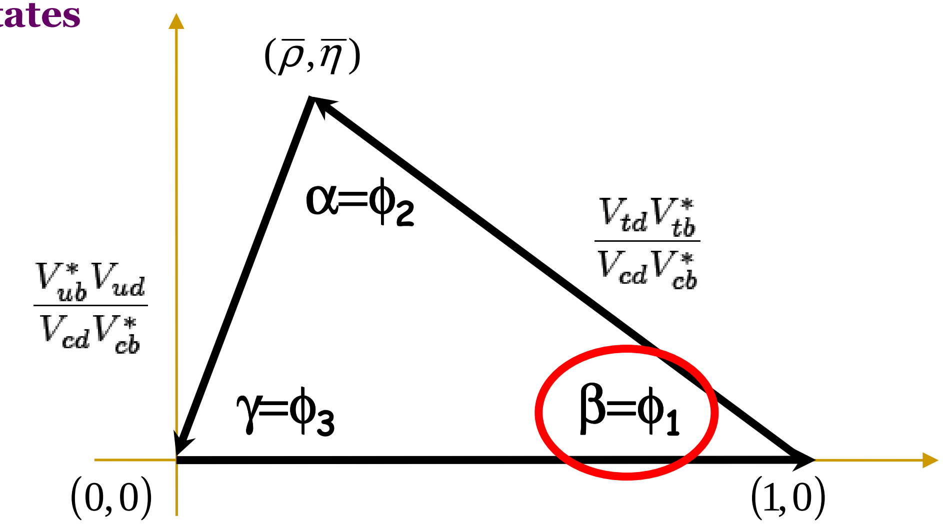
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak interaction eigenstates

Mass eigenstates

Unitarity condition on CKM matrix

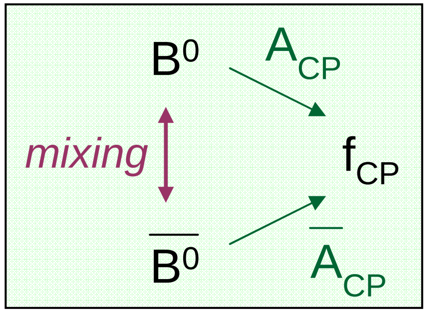
⇒ UNITARITY TRIANGLE
in the complex plane



CPV in the B system

- CPV through interference between mixing and decay amplitudes :

$$\Gamma(B^0(\Delta t) \to f_{CP}) \neq \Gamma(\overline{B}^0(\Delta t) \to f_{CP})$$



- Time-dependent CP observable

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} = S_f \sin(\Delta m \Delta t) - C_f \cos(\Delta m \Delta t)$$

where $S_f = \frac{-2\,\mathrm{Im}(\lambda)}{1+|\lambda|^2}$ $C_f = \frac{1-|\lambda|^2}{1+|\lambda|^2}$ $\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$

CPV in mixing ($\frac{q}{p}$) *CPV in decay* ($\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$)

$A = -C$

- To a good approximation

$$C_f = 0 \Rightarrow A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m \Delta t)$$

η_f *= final state CP value*
-1 for $J/\psi K_S$
+1 for $J/\psi K_L$

- Theoretical expectation : sin2β = 0.65 ± 0.12

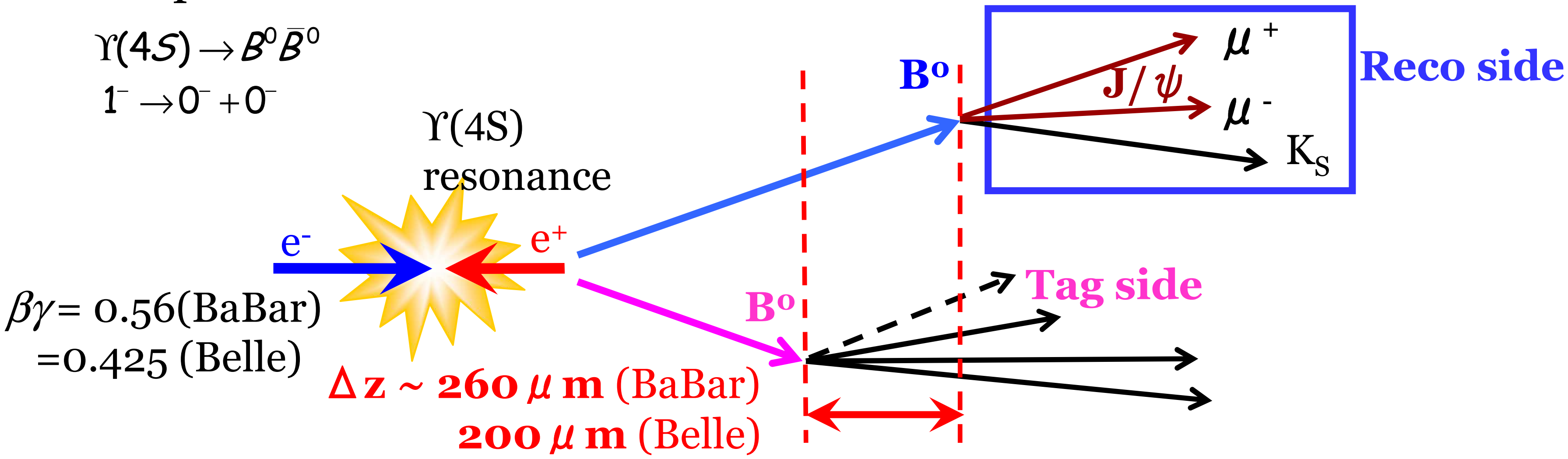
Experimental Technique

CPV studies @ Υ(4S): Time-dependent Analysis method

B's are produced in a boosted frame

$\Upsilon(4S) \rightarrow B^0 \bar{B}^0$

$1^- \rightarrow 0^- + 0^-$

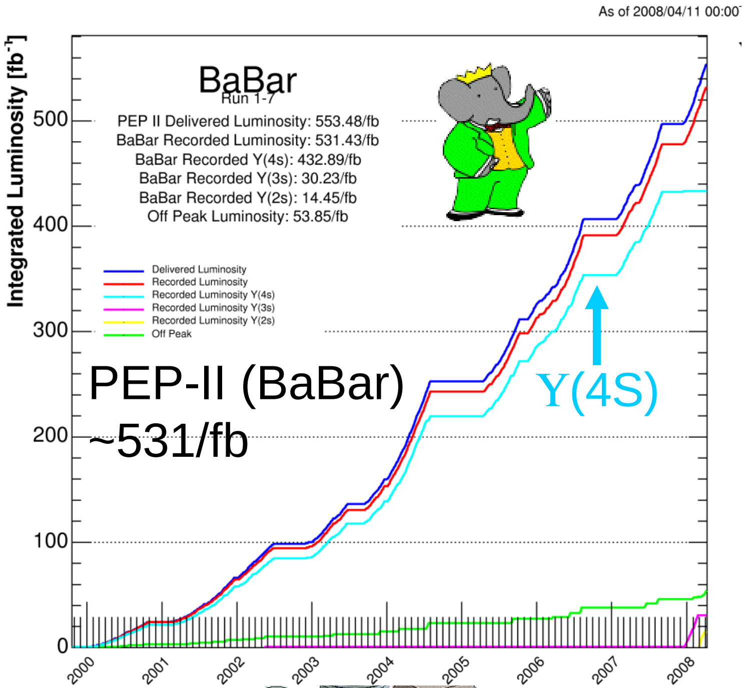


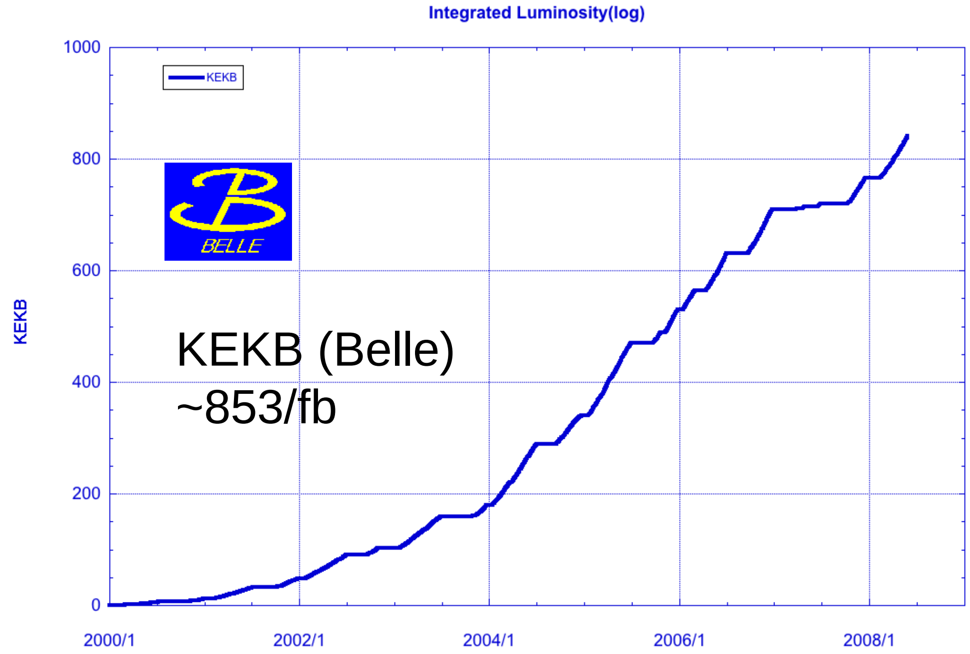
The proper time difference, Δt, is measured from the vertex separation, Δz.

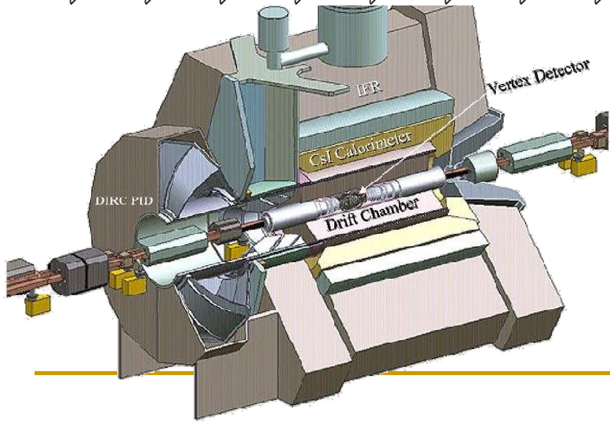
theoretical Δt distribution

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left(1 \pm S_f \sin(\Delta m \Delta t) \mp C_f \cos(\Delta m \Delta t)\right)$$

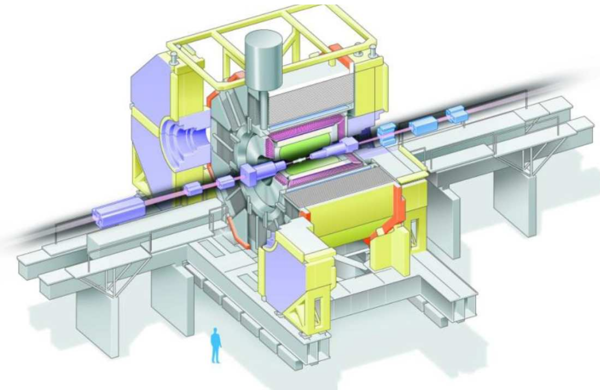
Integrated Luminosity from B Factories







TOTAL
> 1380/fb
~1170/fb at Υ(4S)



Sin2β in Charmonium: $b \to c\bar{c}s$ transition: the golden modes

$b \to c\bar{c}s$

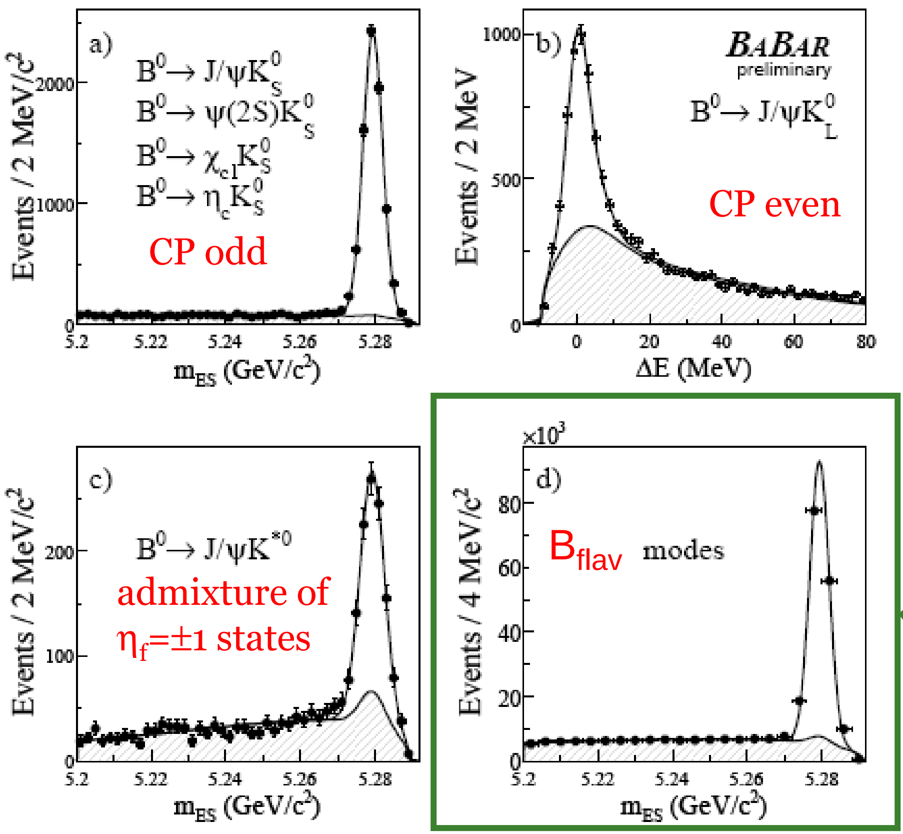
BaBar Charmonium Sample

arXiv:0808.1903v1 [hep-ex]

- N_{tag} = Number of events in the signal region satisfying tagging and vertexing requirements. P(%) = purity.

$(465 \pm 5) \times 10^6 \ B\overline{B}$

Sample	N_{tag}	$P(\%)$
Full CP sample	15481	76
$J/\psi K^0_S(\pi^+\pi^-)$	5426	96
$J/\psi K^0_S(\pi^0\pi^0)$	1324	87
$\psi(2S)K^0_S$	861	87
$\chi_{c1}K^0_S$	385	88
$\eta_c K^0_S$	381	79
$J/\psi K^0_L$	5813	56
$J/\psi K^{*0}$	1291	67
$J/\psi K^0$	12563	77
$J/\psi K^0_S$	6750	95
$\eta_f = -1$	8377	93



"Bflav" = Flavor eigenstate sample used to determine tagging and vertexing performance in CP sample.

$D^{(*)}h^+$ ($h^+ = \pi^+, \rho^+, a_1^+$).

$J/\psi K^{*0}$($K^{*0} \to K^+\pi^-$).

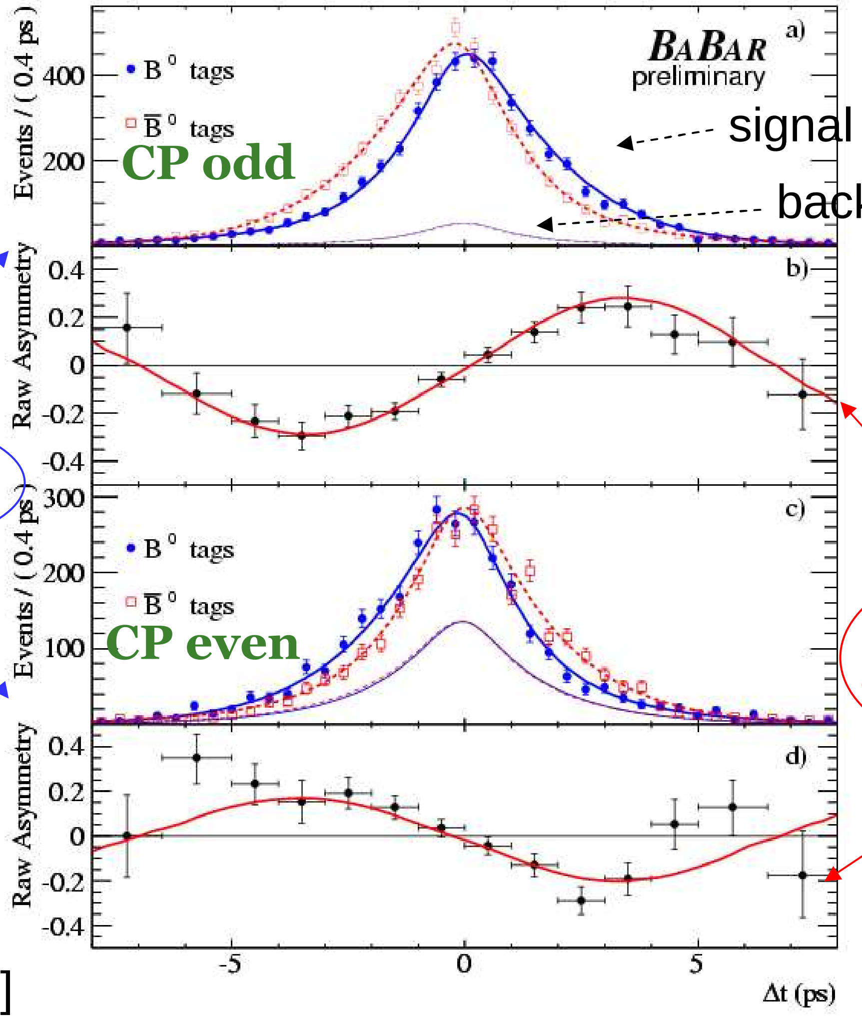
$b \to c\bar{c}s$

BaBar Results

$B^0 \to J/\psi K_S$
$B^0 \to \psi(2S) K_S$
$B^0 \to \eta_c K_S$
$B^0 \to \chi_{c1} K_S$

Δt distributions

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



signal

background

Raw asymmetries

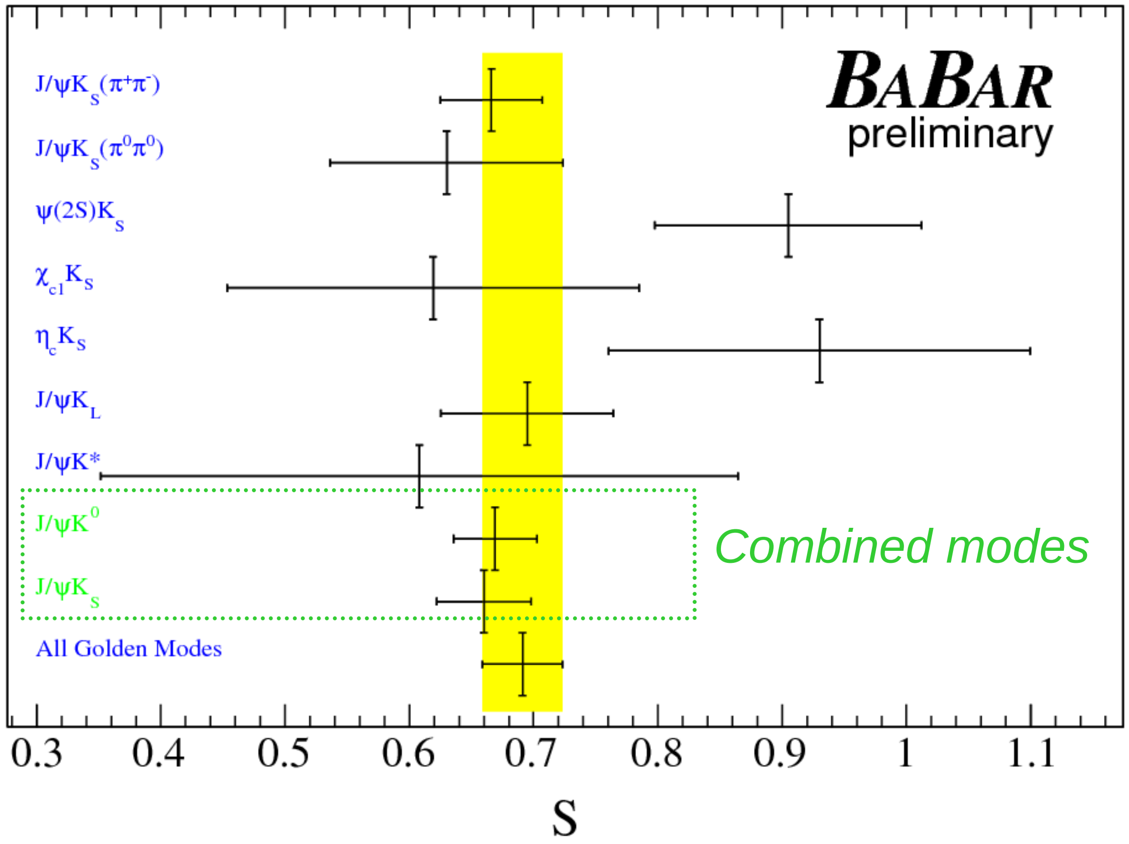
arXiv:0808.1903v1 [hep-ex]

Final Results : S

$b \longrightarrow c\bar{c}s$

$(465 \pm 5) \times 10^6 \; B\overline{B}$

- Summary of results for S
  - Errors are the quadratic sums of statistical
    and systematical errors



- All “golden modes” together configuration:

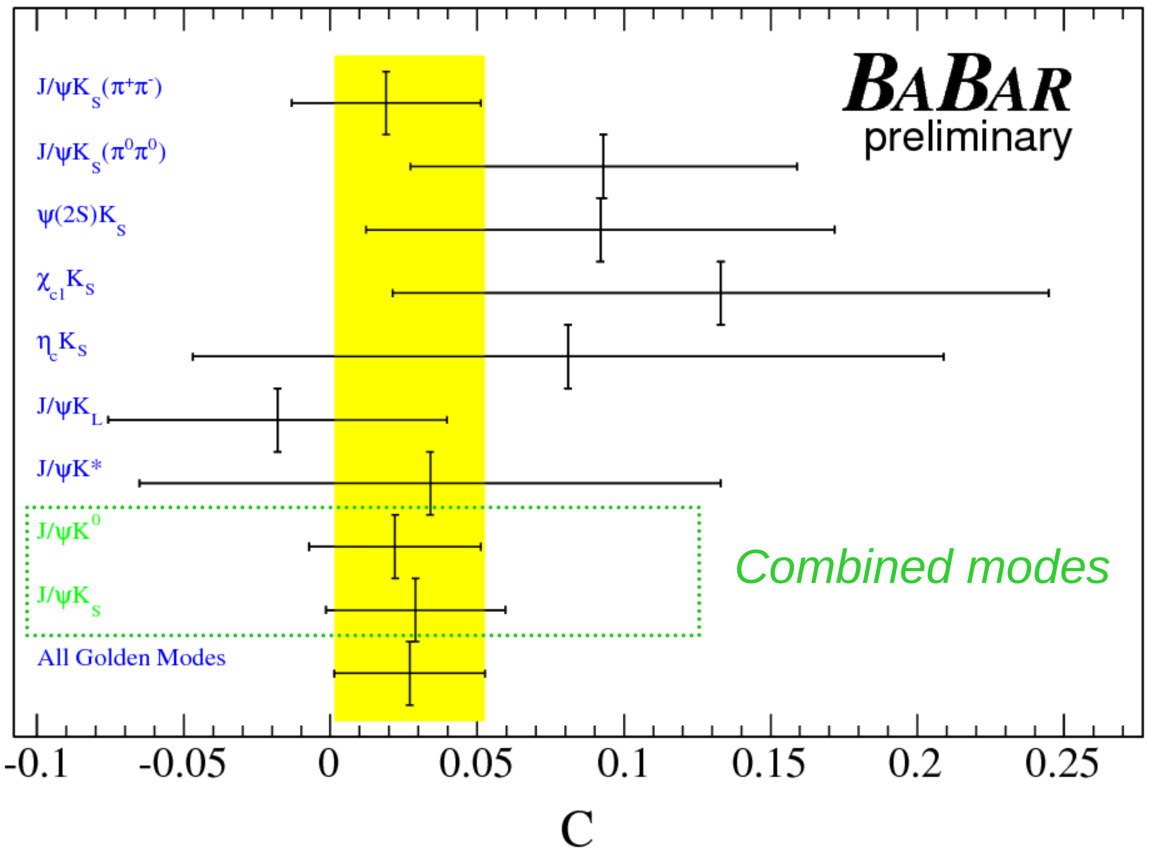
$S = 0.691 \pm 0.029\ (\text{stat}) \pm 0.014\ (\text{syst})$

Final Results : C

$b \to c\bar{c}s$

$(465 \pm 5) \times 10^6\ B\overline{B}$

- Summary of results for C
  - Errors are the quadratic sums of statistical and systematical errors



- All "golden modes" together configuration:

C = 0.026 ± 0.020 (stat) ± 0.016 (syst)

$b \to c\bar{c}s$

Belle Results

$B^0 \to J/\psi K_S, J/\psi K_L$

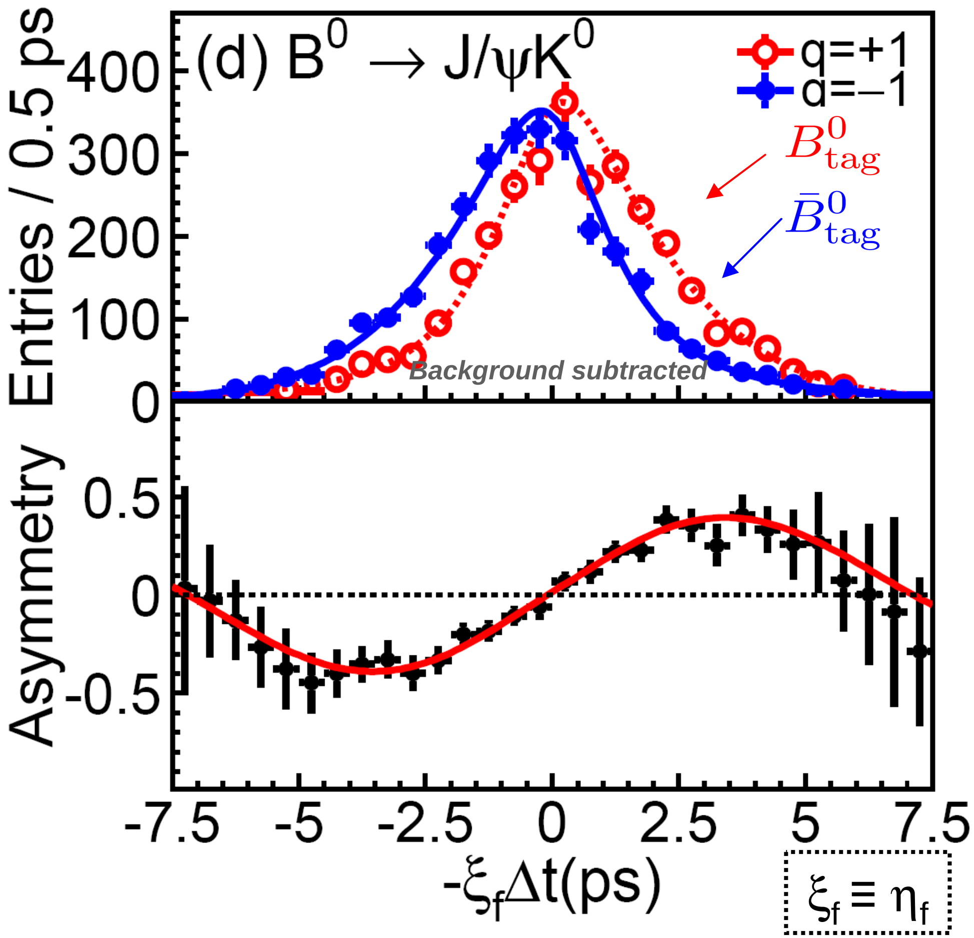
$535 \times 10^6 B\bar{B}$

Signal events:

7484 $J/\psi K_S^0$

6512 $J/\psi K_L^0$

Phys. Rev. Lett. **98**, 031802 (2007)



$$\begin{aligned} \sin 2\phi_1 &= +0.642 \pm 0.031(\text{stat}) \pm 0.017(\text{syst}) \\ A &= 0.018 \pm 0.021(\text{stat}) \pm 0.014(\text{syst}) \end{aligned}$$

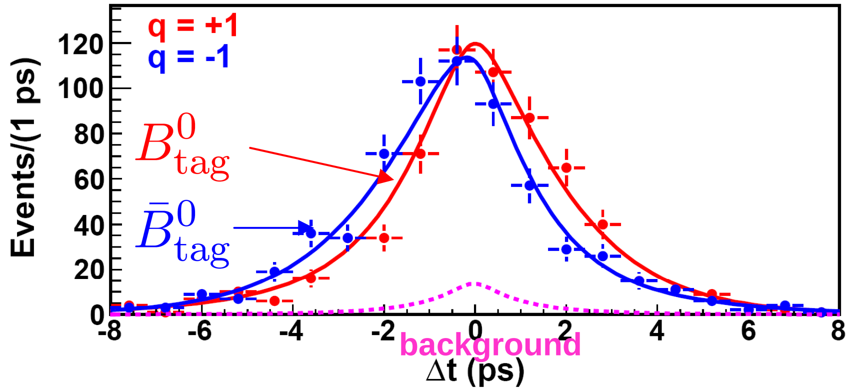
Belle Results

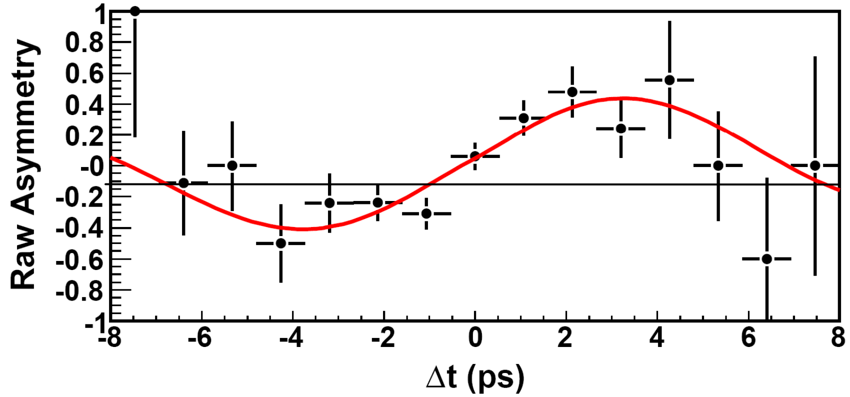
$B^0 \to \psi(2S) K_S$

$657 \times 10^6 B\bar{B}$

Signal events:

1384 $\psi(2S)K_S^0$



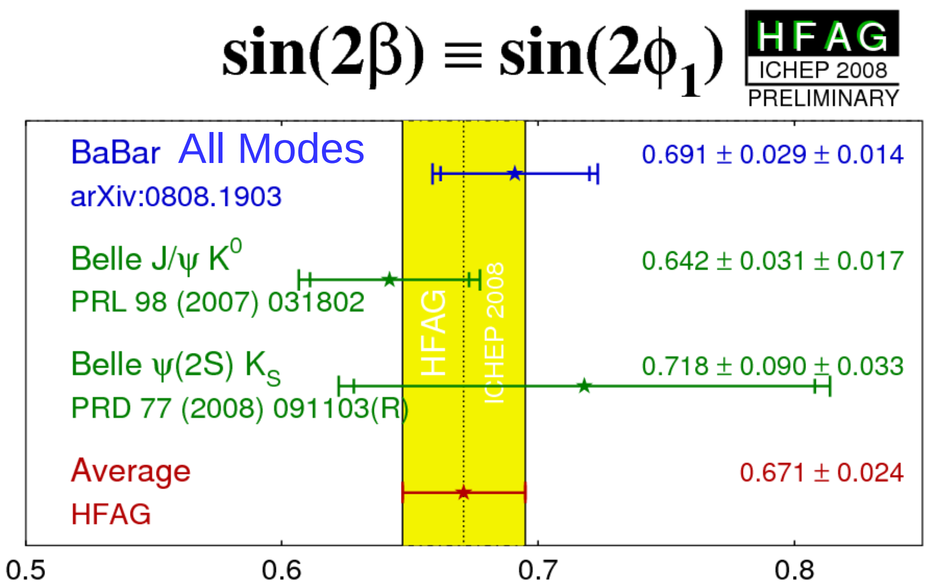


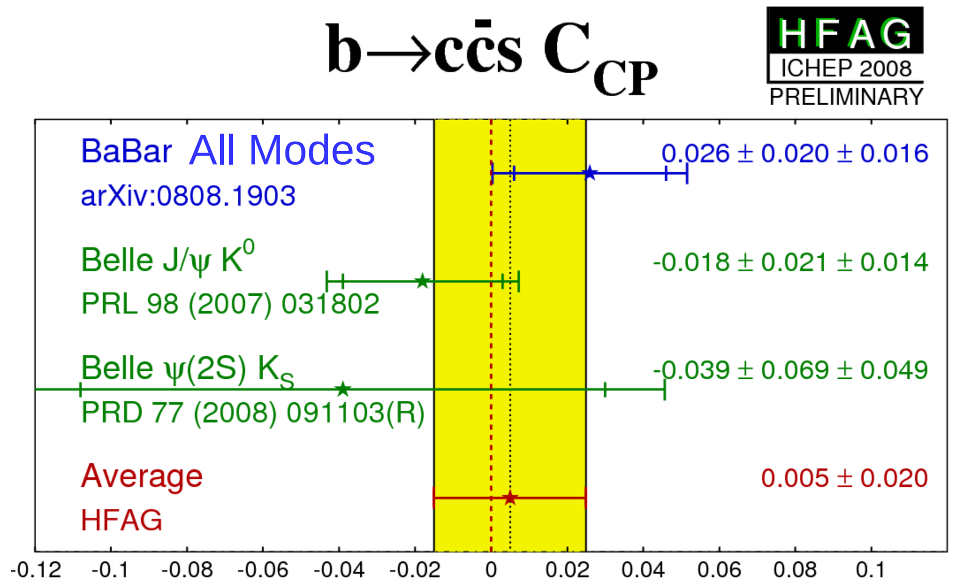
PRD 77, 091103 (R) (2008)

$$\mathcal{S}_{\psi(2S)K_S^0} = +0.72 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$$
$$\mathcal{A}_{\psi(2S)K_S^0} = +0.04 \pm 0.07(\text{stat}) \pm 0.05(\text{syst})$$

$b \to c\bar{c}s$

Results Summary : BaBar/Belle





[SM expectation: C=0, S=sin2β]

Sin2β in Charmonium: $b \to c\bar{c}d$ transition

BaBar Result

$b \to c\bar{c}d$

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

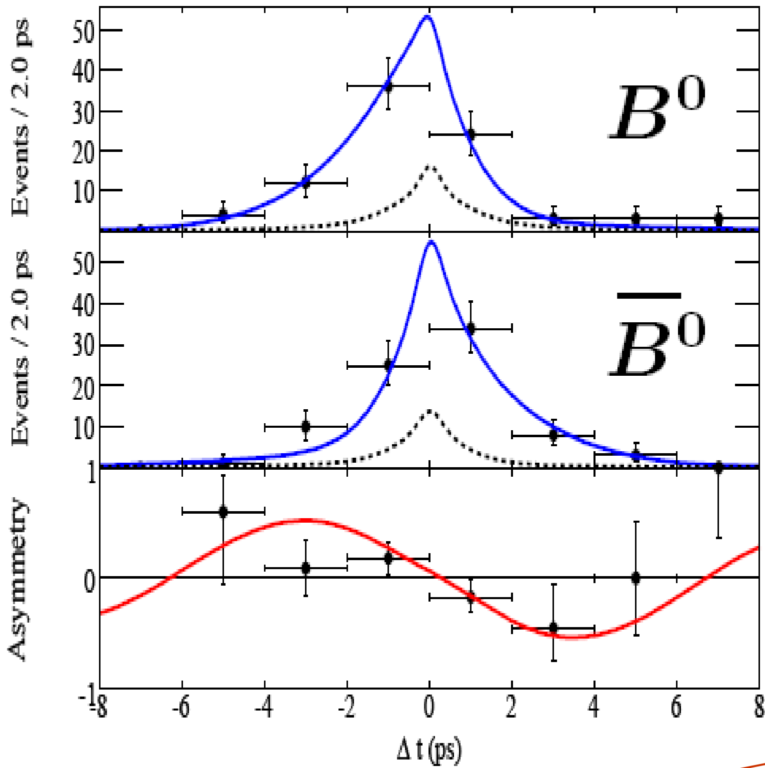
$466 \times 10^6 B\bar{B}$

$\eta_f = +1$

Expectation in absence of penguin pollution

S = - sin2β
C = 0

PRL 101, 021801 (2008)



$$S = -1.23 \pm 0.21(\text{stat}) \pm 0.04(\text{syst})$$
$$C = -0.20 \pm 0.19(\text{stat}) \pm 0.03(\text{syst})$$

4σ from S=C=0
Evidence for CPV

Belle Result

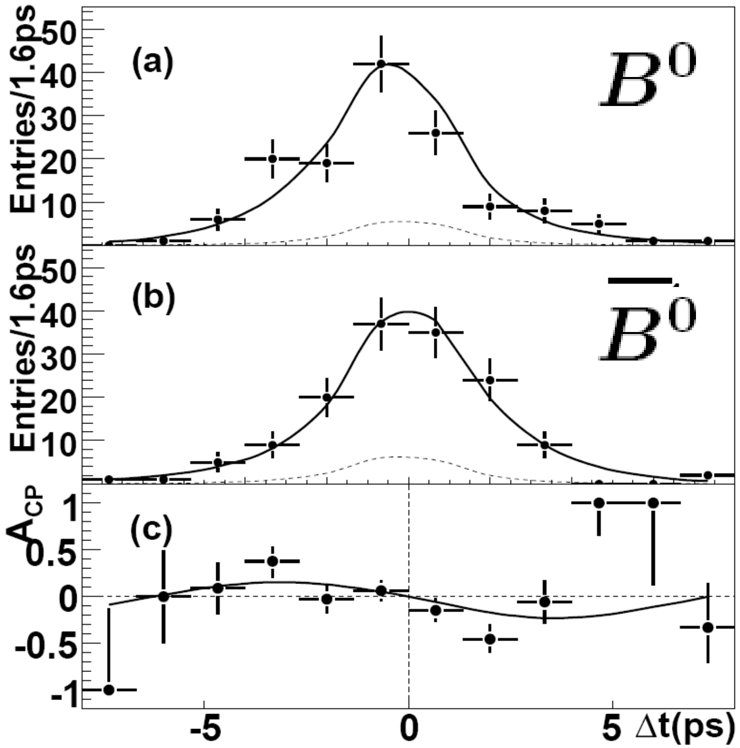
$$B^0 \to J/\psi\pi^0$$

$535 \times 10^6 B\bar{B}$

$\eta_f = +1$

Expectation in absence of penguin pollution

S = - sin2β
C = 0

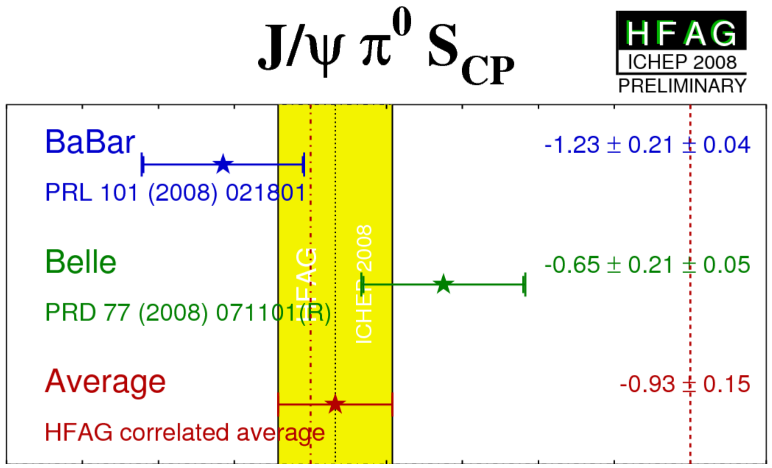


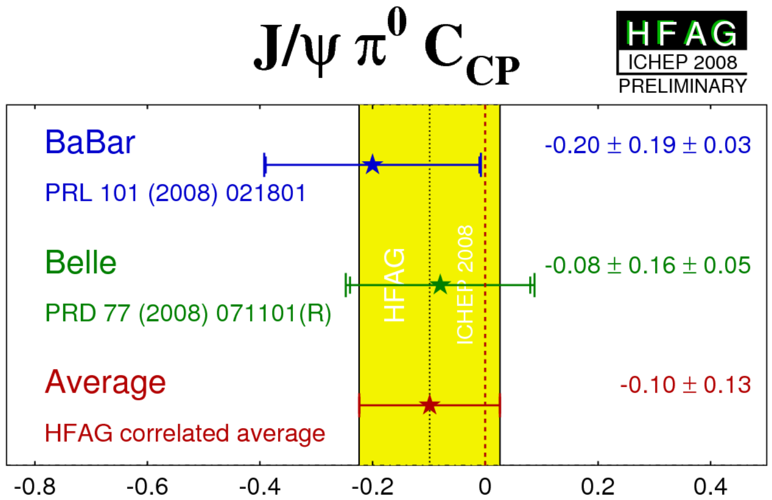
Phys. Rev. D **77**, 071101 (2008)

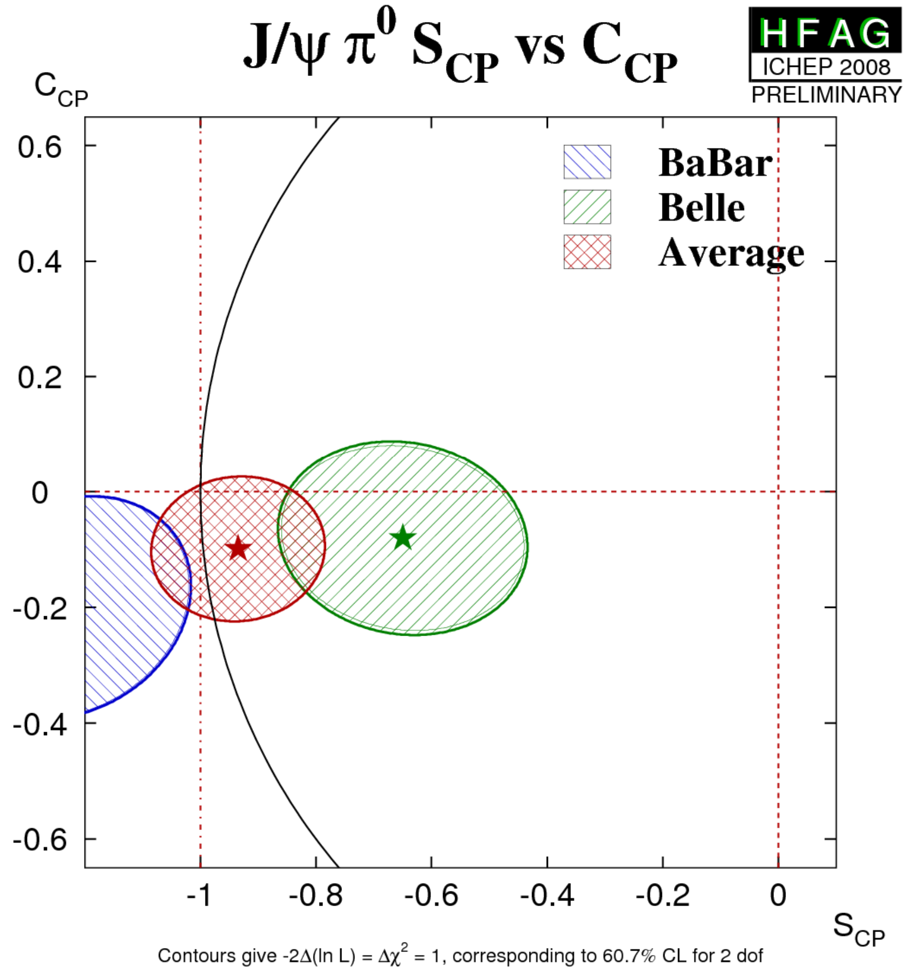
$$\mathcal{S}_{J/\psi\,\pi^0} = -0.65 \pm 0.21(\text{stat}) \pm 0.05(\text{syst})$$
$$\mathcal{A}_{J/\psi\,\pi^0} = +0.08 \pm 0.16(\text{stat}) \pm 0.05(\text{syst})$$

$b \to c\bar{c}d$

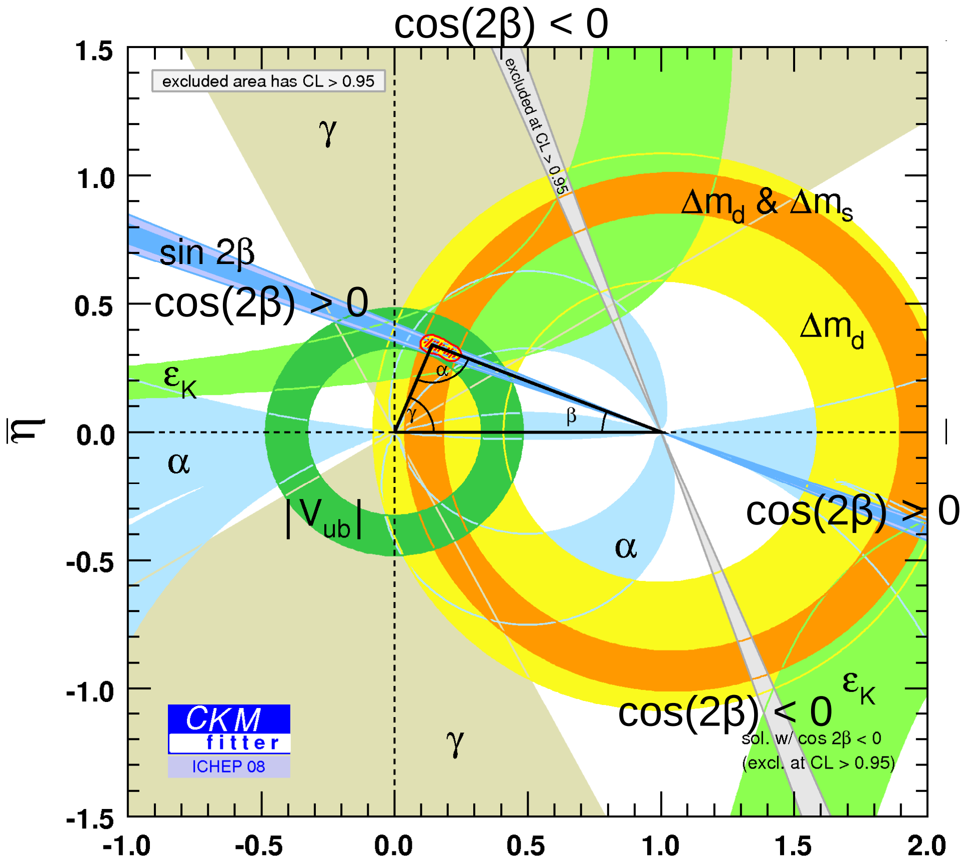
Results Summary : BaBar/Belle





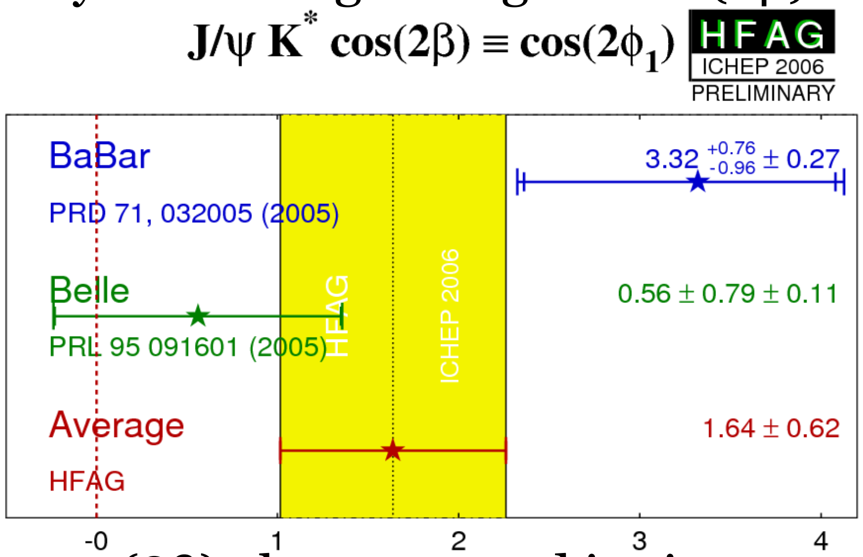


Global CKM view



Negative solutions of cos(2β) excluded at CL > 0.95

- sin(2β) measurement has a four-fold ambiguity in the determination of the angle β.
- Reduce this to a two-fold ambiguity by measuring the sign of cos(2β):

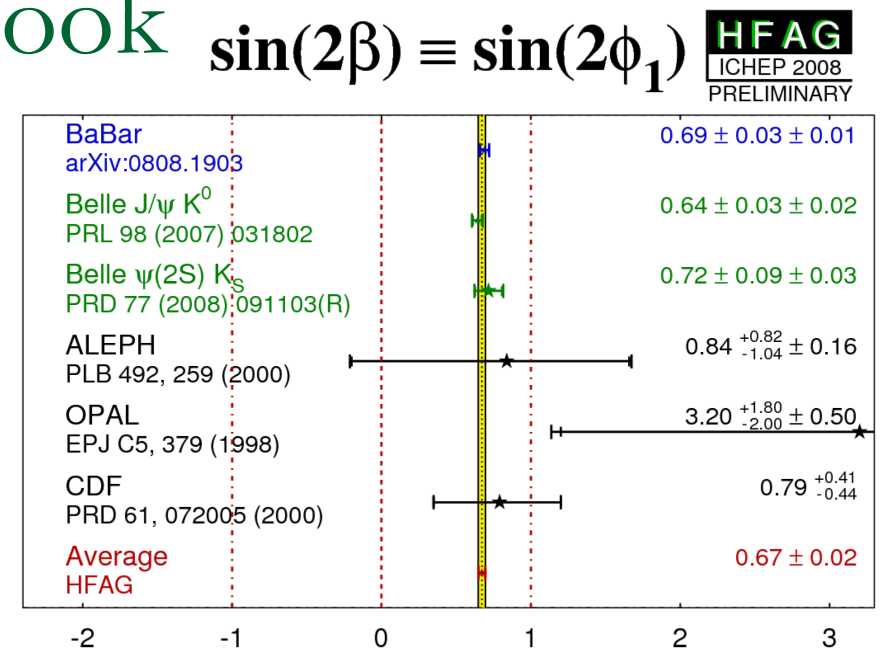


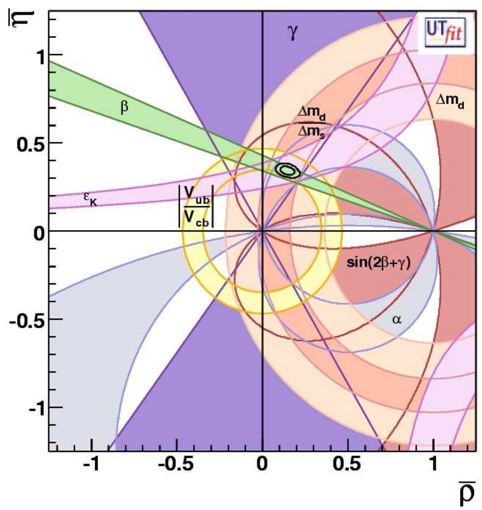
- cos(2β) also measured in time-dependent Dalitz plot analyses of $B^0 \rightarrow D^{*0}h^0$ and $B^0 \rightarrow D^{*+}D^{*-}K^0_S$
- See also J. Dalseno's talk in WGVI ($B^0 \rightarrow K^0_S K^+K^-$, $B^0 \rightarrow K^0_S \pi^+\pi^-$)

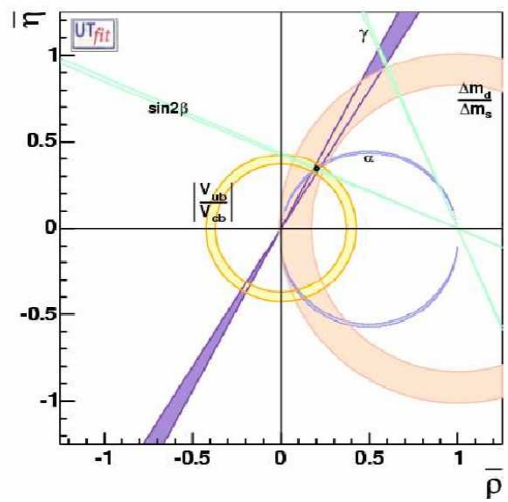
Excellent agreement with Standard Model!

Conclusion and Outlook

- $\sin(2\beta) \equiv \sin(2\Phi_1)$ has been measured in B → Charmonium decays with great accuracy.
  - *Excellent agreement with Standard Model.*
- Looking forward to high precision measurements from at LHCb, SuperB and KEKb upgrade!



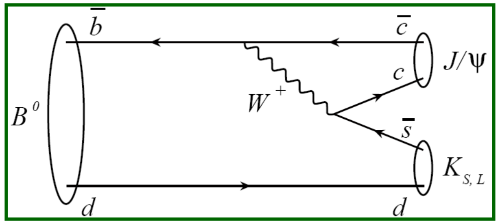


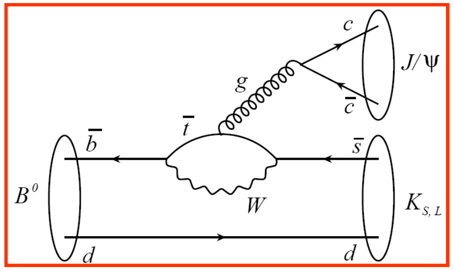


Back up

Theoretical background

- $b \to c\bar{c}s$ transition:





$BR(B^0 \to (c\bar{c})K^{(*)0})$
$\sim O(10^{-3}) \div O(10^{-4})$

colour suppressed tree diagram   gluonic penguin (same weak phase wrt the tree)

- Standard Model predictions: penguin amplitude « tree amplitude

$\Rightarrow S_{golden} = \eta_{golden} \sin 2\beta, \quad C_{golden} = 0 \qquad (\eta_f = \text{CP eigenvalue})$

- Theoretical uncertainties:
  - model independent data-driven calculation:

[M. Ciuchini, M. Pierini, L. Silvestrini, Phys.Rev. Lett. 95,221804 (2005)]

assuming SU(3) invariance, use $B^0 \to J/\psi\pi^0$ data to constrain penguin pollution in $J/\psi K^0 \Rightarrow \Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta = 0.000 \pm 0.012$

Result shown at CKM06

  - theoretical estimates
    - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-3})$
    - $\Delta S_{J/\psi K^0} = S_{J/\psi K^0} - \sin 2\beta \sim O(10^{-4})$

[H. Li, S. Mishima hep-ph/0610120]
[Boos et al. Phys. Rev. D 70 0360006 (2006)]

Fit configuration

- RooFit-based fitter – almost unchanged since previous analysis
- Fit CP and BFlav sample simultaneously to measure C and S
  - previous fit sin2β and λ
- *Signal*
  - triple gaussian resolution function
  - mistag parameters and tag efficiency split by tagging categories
  - reconstruction efficiency difference between B0 and B0 fitted
- *Background sources*
  - continuum events : prompt time dependent component
  - B^+B^- and B^0B^0 : combinatorial bgd with "effective" lifetime B^+B^- and B^0B^0 and **mixing frequency**
    - bg effective mixing frequency was fixed to Δmd - now a free parameter in the fit
    - Vary between 0 and Δmd to evaluate sys error
  - peaking background
- *Fit input*
  - Δm_d, t_{B0}, t_{B+} from PDG 2006
  - effective CP eigenvalue for $B^0 \rightarrow J/\psi K^{*0}(K_s \pi^0)$ from Run1-4 Angular analysis
  - peaking background fraction computed on inclusive J/ψ and generic MC
  - $J/\psi K_L$ background parameters from J/ψ sidebands and inclusive J/ψ MC

Systematic Errors

- The table shows a summary of the systematic error for the configuration where all the modes are fitted together.
- Each systematic error is also calculated for each fit configuration and modes.

Source/sample		Full
Beamspot	S_f	0.0013
	C_f	0.0006
Mistag differences	S_f	0.0077
	C_f	0.0047
Δt resolution	S_f	0.0067
	C_f	0.0027
$J/\psi K^0_L$ background	S_f	0.0057
	C_f	0.0007
Background fraction	S_f	0.0046
and CP content	C_f	0.0029
m_{ES} parameterization	S_f	0.0022
	C_f	0.0004
$\Delta m_d, \tau_B, \Delta\Gamma_d/\Gamma_d$	S_f	0.0030
	C_f	0.0013
Tag-side interference	S_f	0.0014
	C_f	0.0143
Fit bias	S_f	0.0023
(MC statistics)	C_f	0.0026
Total	S_f	0.0135
	C_f	0.0164

Systematic Errors by mode (1/2)

Source/sample		Full	$J/\psi K^0$	$J/\psi K^0_S$	$J/\psi K^0_L$
Beamspot	S_f	0.0013	0.0021	0.0027	0.0000
	C_f	0.0006	0.0010	0.0021	0.0001
Mistag differences	S_f	0.0077	0.0057	0.0059	0.0083
	C_f	0.0047	0.0069	0.0053	0.0052
Δt resolution	S_f	0.0067	0.0068	0.0069	0.0071
	C_f	0.0027	0.0029	0.0034	0.0070
$J/\psi K^0_L$ background	S_f	0.0057	0.0063	0.0000	0.0271
	C_f	0.0007	0.0008	0.0000	0.0036
Background fraction	S_f	0.0046	0.0034	0.0036	0.0044
and CP content	C_f	0.0029	0.0021	0.0009	0.0107
m_{ES} parameterization	S_f	0.0022	0.0020	0.0026	0.0006
	C_f	0.0004	0.0005	0.0008	0.0002
$\Delta m_d, \tau_B, \Delta\Gamma_d/\Gamma_d$	S_f	0.0030	0.0033	0.0036	0.0040
	C_f	0.0013	0.0012	0.0011	0.0013
Tag-side interference	S_f	0.0014	0.0014	0.0014	0.0014
	C_f	0.0143	0.0143	0.0143	0.0143
Fit bias	S_f	0.0023	0.0044	0.0041	0.0063
(MC statistics)	C_f	0.0026	0.0044	0.0041	0.0060
Total	S_f	0.0135	0.0131	0.0119	0.0311
	C_f	0.0164	0.0187	0.0167	0.0270

Systematic Errors by mode (2/2)

Source/sample		$J/\psi K_S^0(\pi^+\pi^-)$	$J/\psi K_S^0(\pi^0\pi^0)$	$\psi(2S)K_S^0$	$\chi_{c1}K_S^0$	$\eta_c K_S^0$	$J/\psi K^{*0}$
Beamspot	S_f	0.0027	0.0020	0.0078	0.0284	0.0010	0.0058
	C_f	0.0017	0.0032	0.0084	0.0115	0.0001	0.0001
Mistag differences	S_f	0.0075	0.0074	0.0089	0.0065	0.0064	0.0117
	C_f	0.0039	0.0046	0.0052	0.0067	0.0047	0.0019
Δt resolution	S_f	0.0072	0.0074	0.0072	0.0099	0.0163	0.0259
	C_f	0.0030	0.0043	0.0070	0.0039	0.0036	0.0062
$J/\psi K_L^0$ background	S_f	0.0001	0.0000	0.0001	0.0000	0.0001	0.0001
	C_f	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Background fraction	S_f	0.0032	0.0073	0.0156	0.0174	0.0506	0.0564
and CP content	C_f	0.0012	0.0034	0.0056	0.0098	0.0187	0.0256
m_{ES}	S_f	0.0021	0.0089	0.0238	0.0061	0.0023	0.0372
parameterization	C_f	0.0007	0.0063	0.0008	0.0017	0.0005	0.0080
$\Delta m_d, \tau_B, \Delta\Gamma_d/\Gamma_d$	S_f	0.0031	0.0073	0.0157	0.0025	0.0158	0.0140
	C_f	0.0014	0.0013	0.0010	0.0009	0.0020	0.0013
Tag-side interference	S_f	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
	C_f	0.0143	0.0143	0.0143	0.0143	0.0143	0.0143
Fit bias	S_f	0.0048	0.0040	0.0079	0.0072	0.0073	0.0271
(MC statistics)	C_f	0.0042	0.0030	0.0019	0.0042	0.0070	0.0389
Total	S_f	0.0129	0.0179	0.0365	0.0398	0.0566	0.0876
	C_f	0.0160	0.0187	0.0209	0.0257	0.0271	0.0540