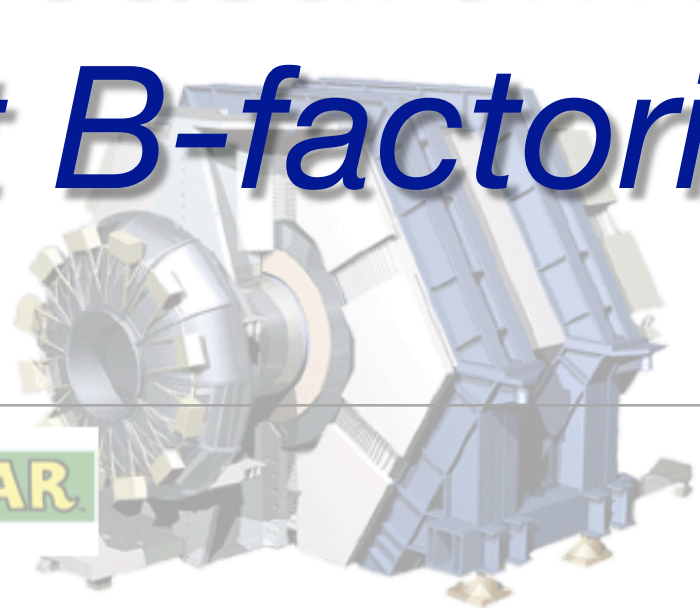
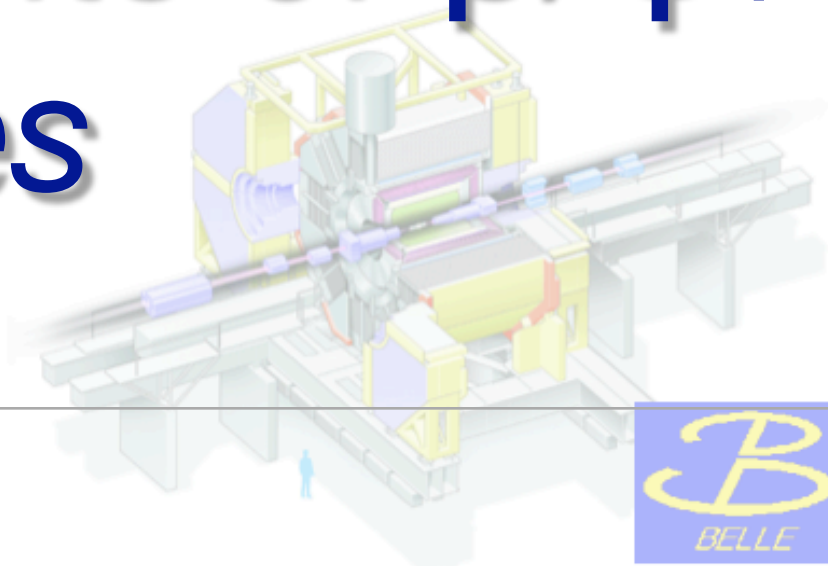
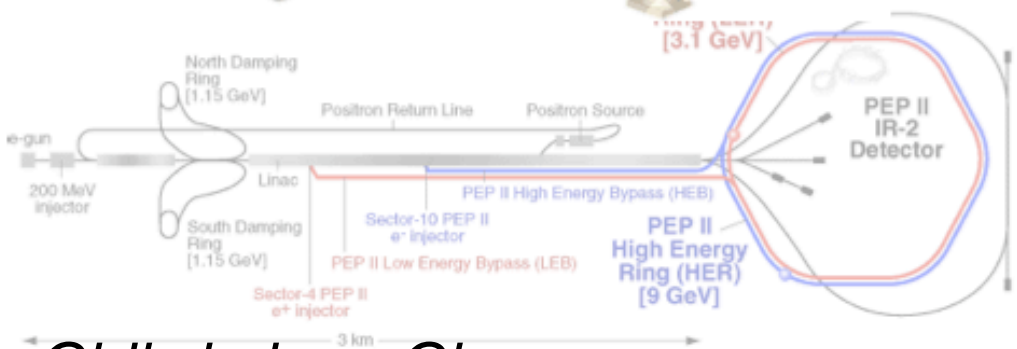
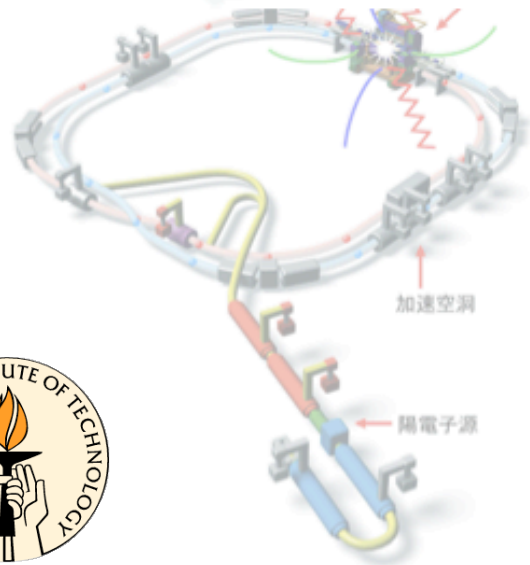
Measurements of β/ϕ_1 at B-factories





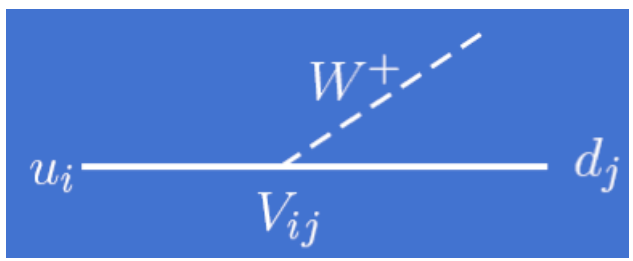




Chih-hsiang Cheng
California Institute of Technology
May 13, FPCP 2007, Bled, Slovenia

Main mission of B-factories: measure and over-constrain the CKM unitarity triangle

- Weak charged current and the CKM matrix.

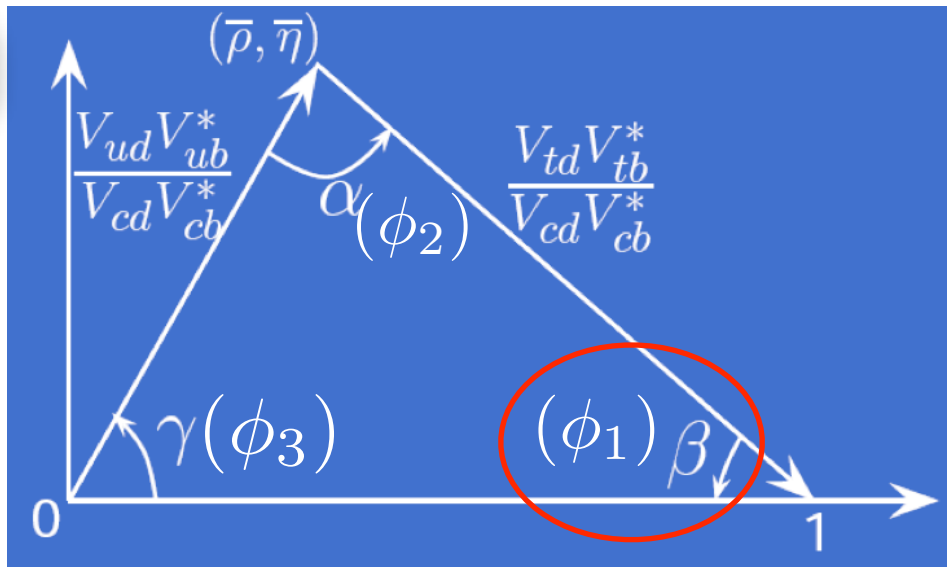


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Unitarity:

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

- Measure sides and angles in multiple ways to constrain the CKM matrix and search for possible inconsistency, which might indicate new physics.



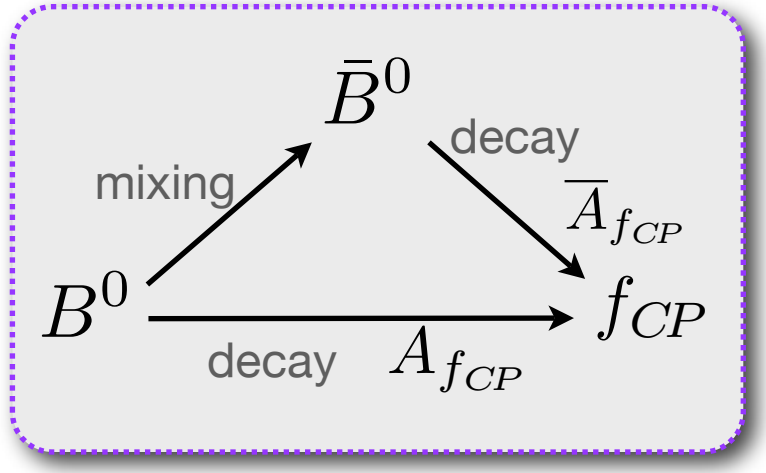
Sin2β (Sin2φ$_1$) in time-dependent CP asymmetry

- A B^0 meson can mix with its antiparticle before decay.
- Interference is parameterized by

$$\lambda = \frac{q}{p} \cdot \frac{\overline{A}}{A}$$

phase factor due to mixing

decay amplitude ratio



$$\lambda_{f_{CP}} \neq \pm 1 \quad \Rightarrow \mathrm{Prob}(\overline{B}^0_{\mathrm{phys}}(t) \to f_{CP}) \neq \mathrm{Prob}(B^0_{\mathrm{phys}}(t) \to f_{CP})$$

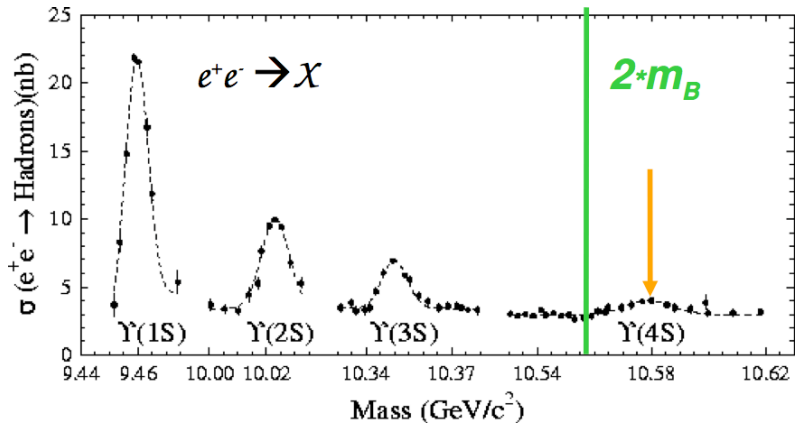
$$A_{CP} = \frac{\Gamma(\overline{B}^0_{\mathrm{phys}}(t) \to f_{CP}) - \Gamma(B^0_{\mathrm{phys}}(t) \to f_{CP})}{\Gamma(\overline{B}^0_{\mathrm{phys}}(t) \to f_{CP}) + \Gamma(B^0_{\mathrm{phys}}(t) \to f_{CP})} = S \cdot \sin(\Delta m_d t) - C \cdot \cos(\Delta m_d t)$$

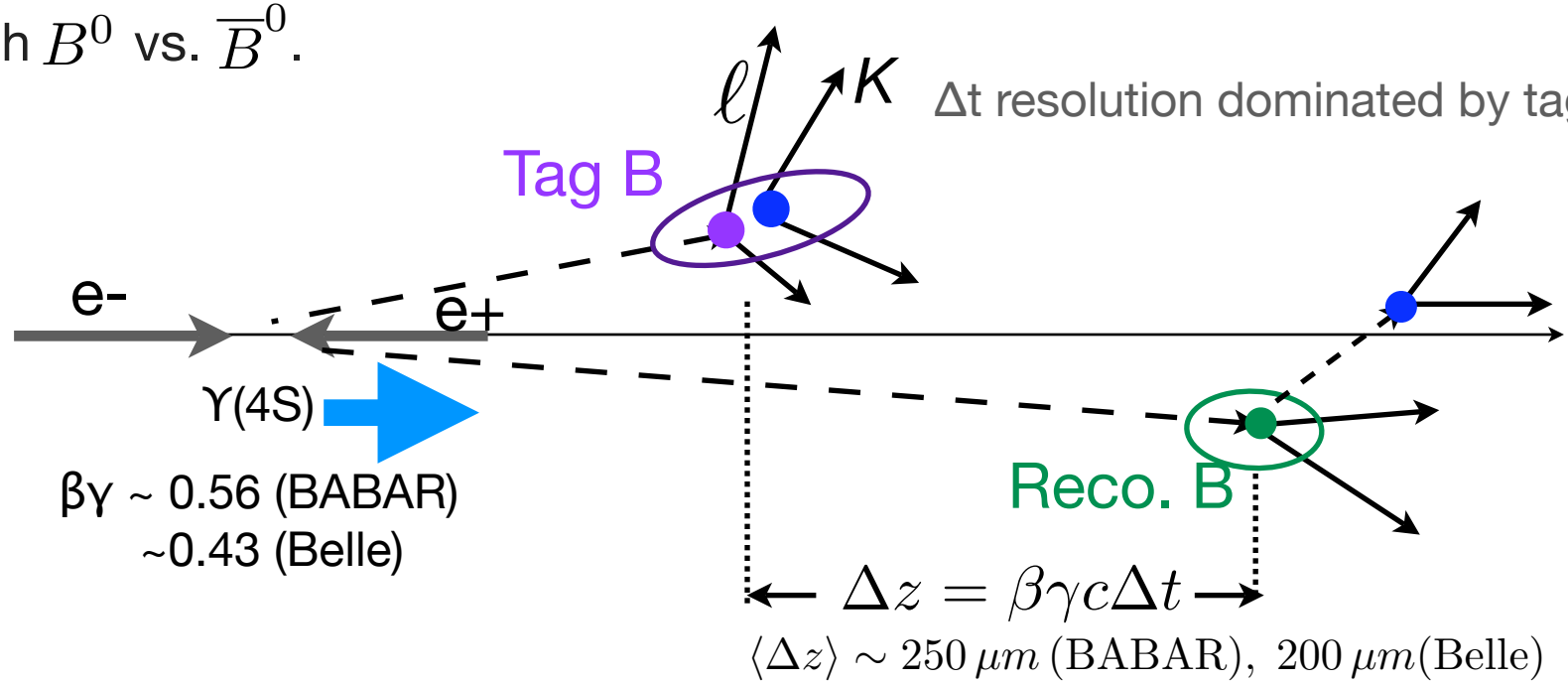
$$S = \frac{2\,\mathrm{Im}\,\lambda}{1+|\lambda|^2} \quad C = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

- For modes in this talk, Standard Mode expects S= ±sin2β (sin2φ$_1$), C=0.

Measure time-dependent $\not{CP}$ at B-factories

- $\Upsilon(4S)$ resonance is just over $B\overline{B}$ threshold and decays to $B\overline{B}$ coherently.
- Center-of-mass is boosted to separate the two B decay vertices.
- One B, decaying to f_{CP}, is fully reconstructed.
- Decay products of the other B allow us to distinguish B^0 vs. $\overline{B}^0$.

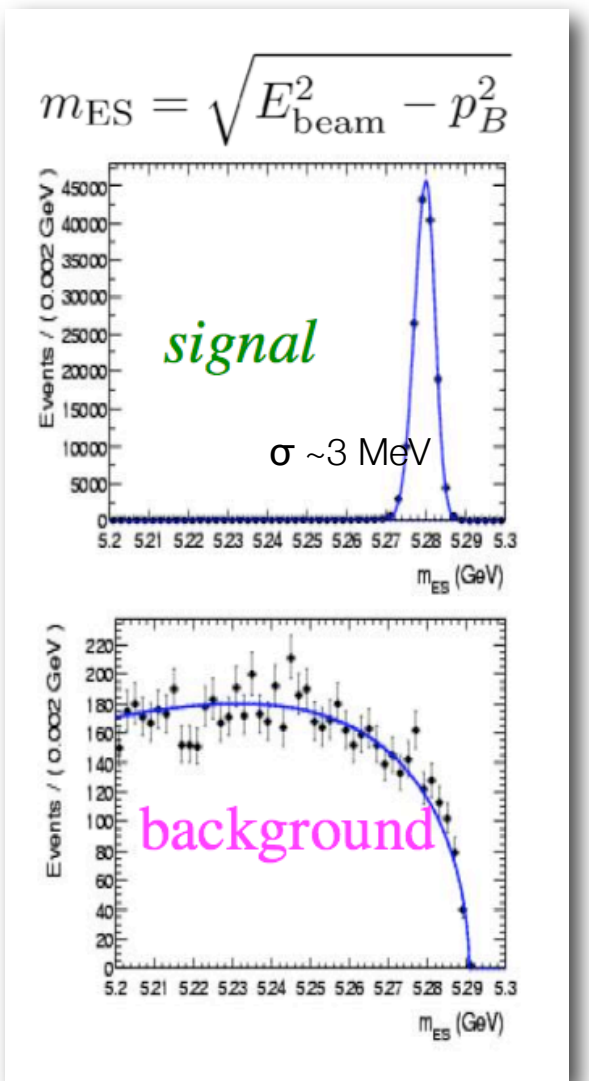


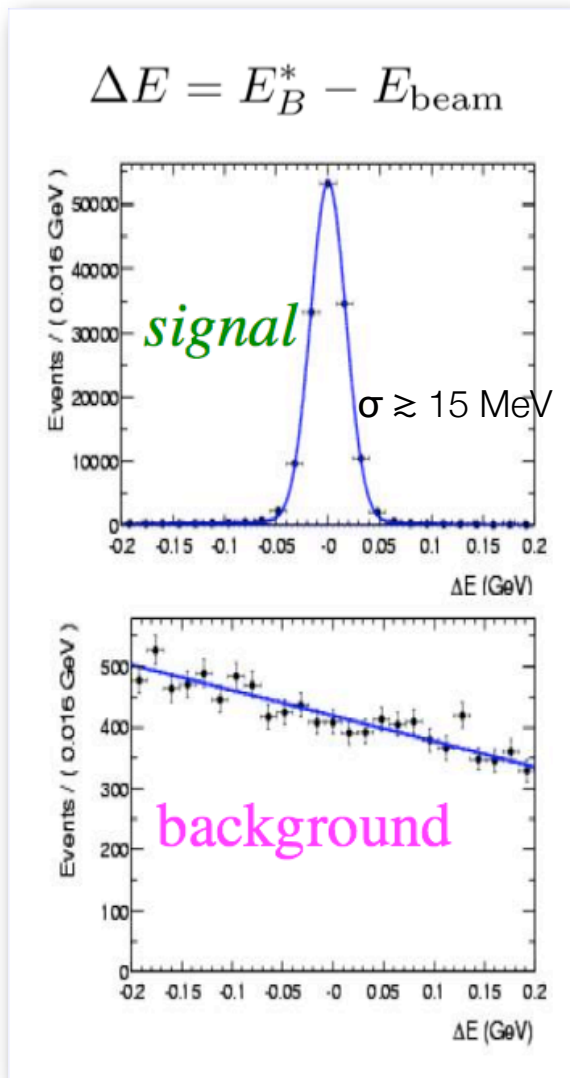


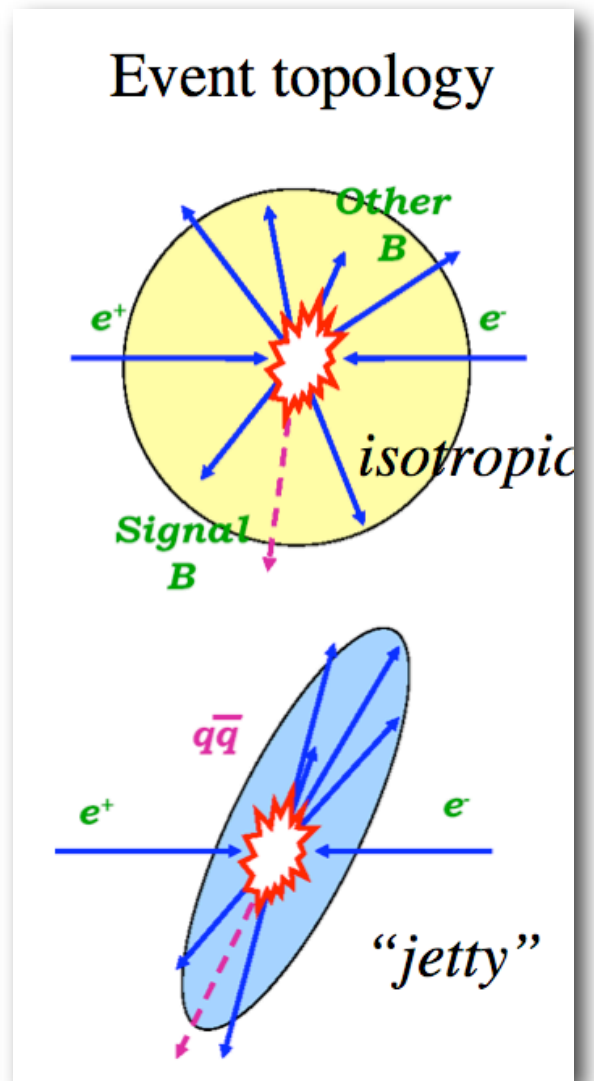
Δt resolution dominated by tag B

How to find a B meson

- Typical variables used to isolate $\Upsilon(4S) \rightarrow B\overline{B}$ events:

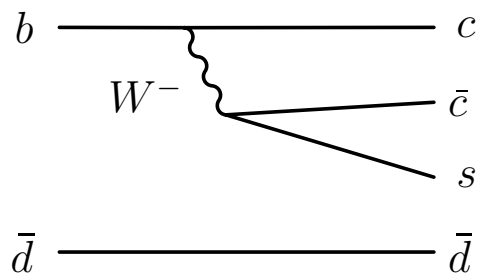


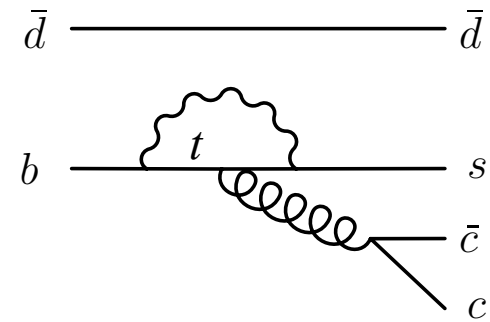




Golden modes: $B^0 \to (c\bar{c})K_S$

- Tree diagram dominates. Dominant penguin diagram has the same weak phase.





- Small SM theoretical correction/uncertainty on sin2β_{eff}:

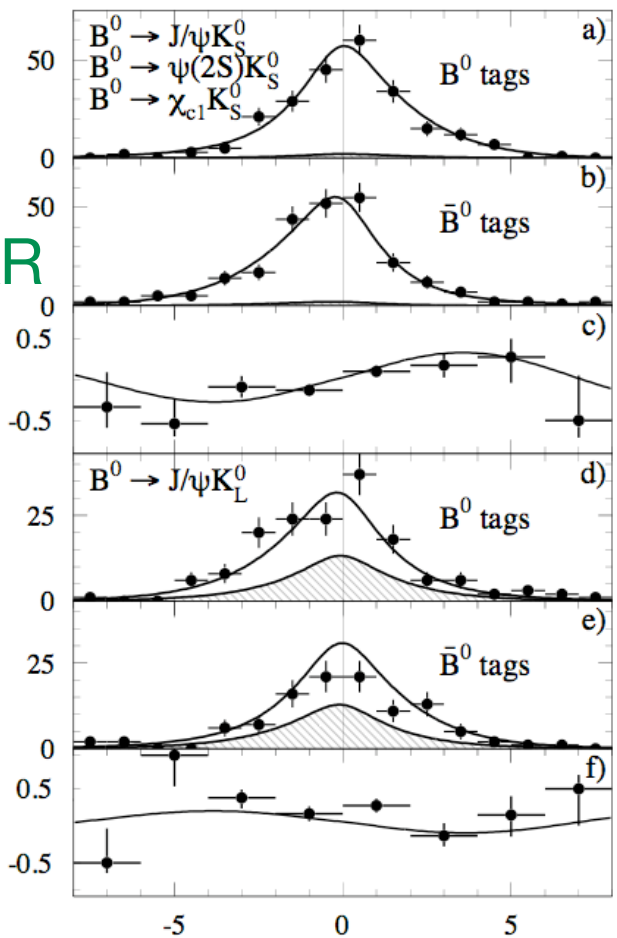
Boos etal, PRD 70, 036006 (2004)	$-(2.2 \pm 2.2) \times 10^{-4}$
Li, Mishima, hep-ph/0610120	$(9.3^{+4}_{-5}) \times 10^{-4}$
Ciuchini etal, PRL 95, 221804 (2005)	0 ± 0.012

- Relatively large branching fraction, ~ O(10e-4).
- Clean final states, e.g., $B^0 \to J/\psi\, K_S,\ J/\psi \to \ell^+\ell^-,\ K_S \to \pi^+\pi^-$

$\not{CP}$ in B established at each B factory in 2001 using golden modes

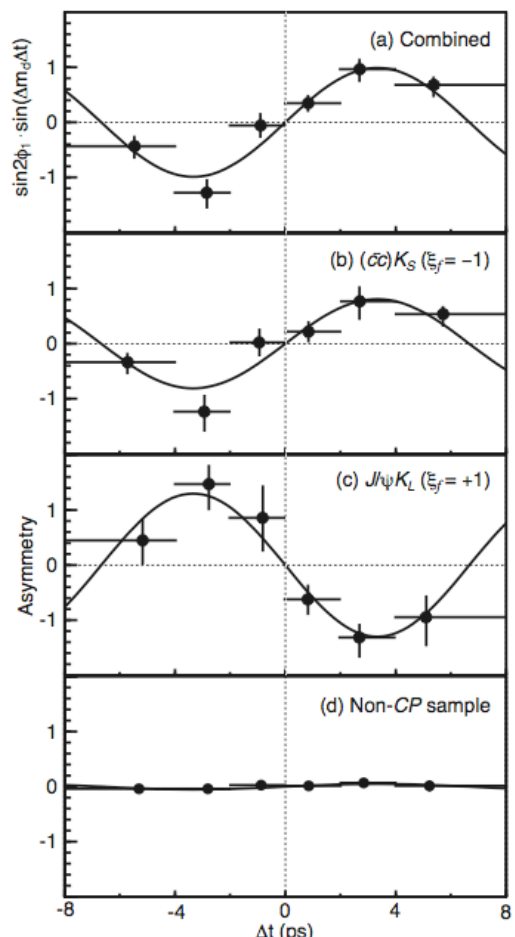
- Each experiment used ~32 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays, obtaining ~1000 signal events, and established time-dependent CP violation in neutral B meson decays.

BABAR



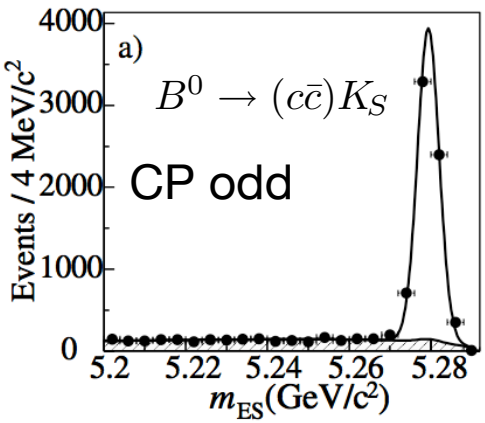
Phys.Rev.Lett.87:091801

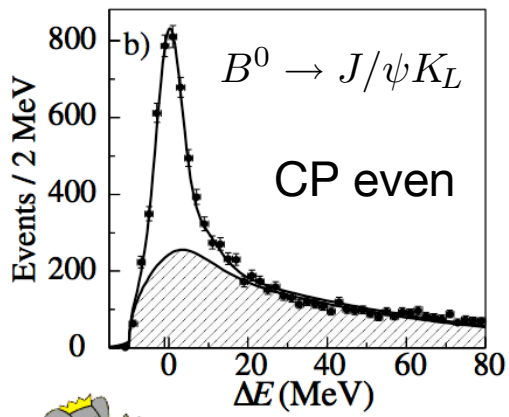
Belle



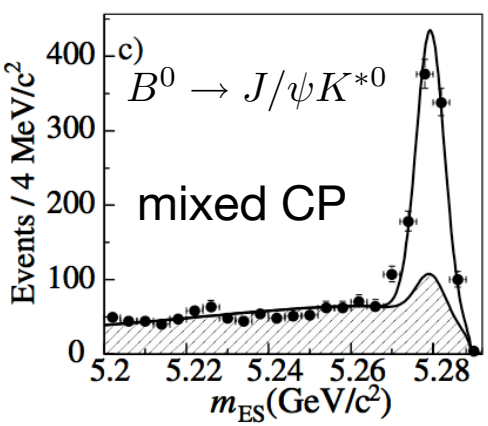
Phys.Rev.Lett.87:091802

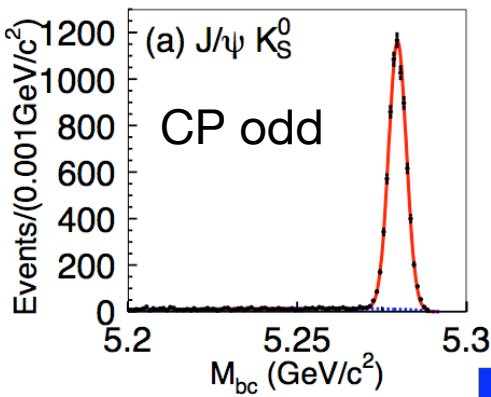
Today, more than 10 times more data later

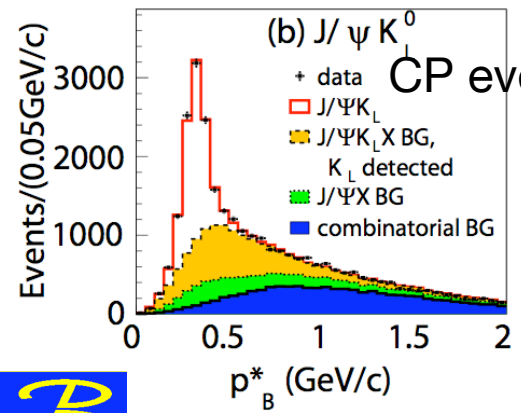




$383 \times 10^6 B\overline{B}$





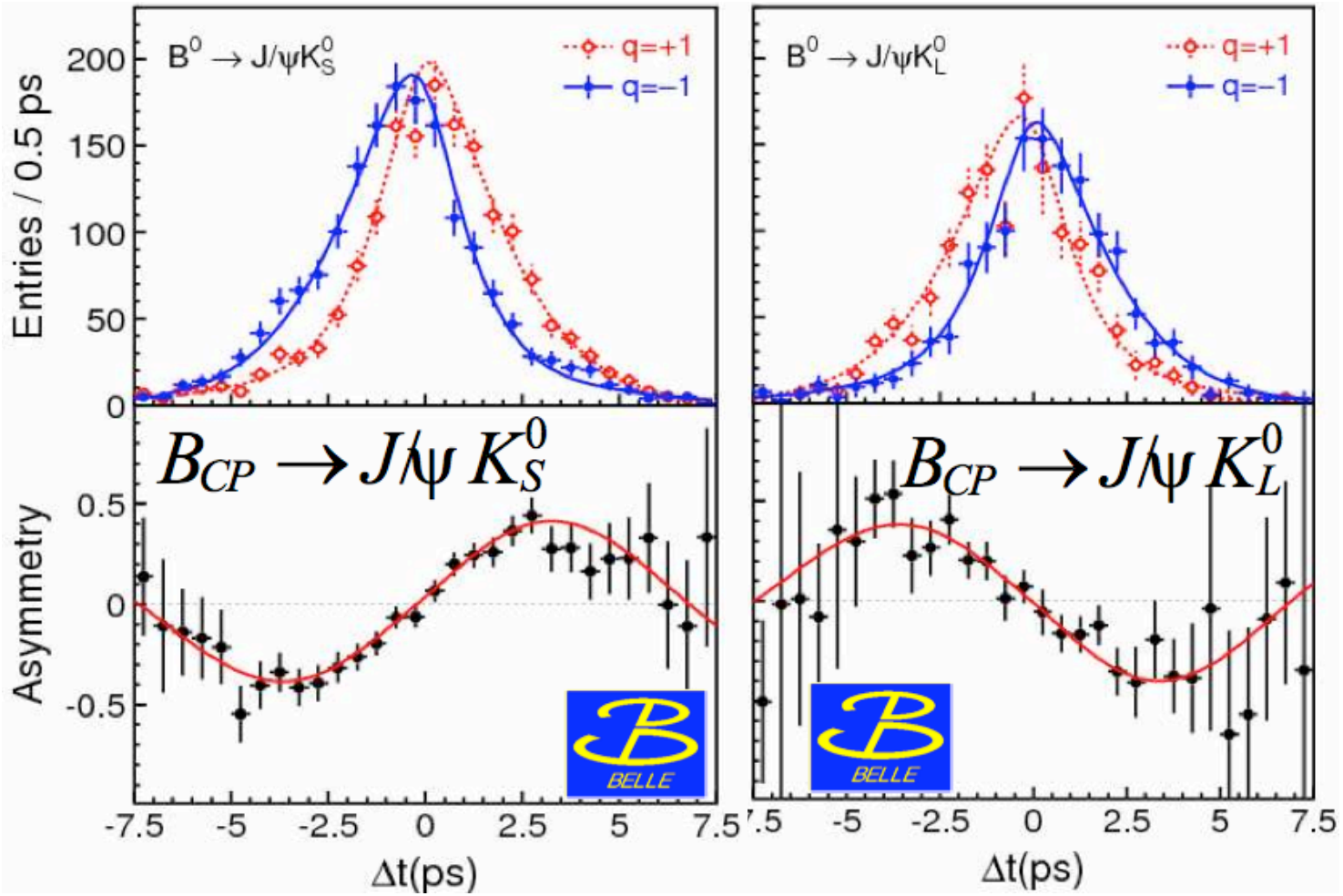


$535 \times 10^6 B\overline{B}$

N signal (purity)	CP Odd	CP even
BABAR	6900 (92%)	3700 (55%)
Belle	7482 (97%)	6512 (59%)

Belle results for J/ψ Ks and J/ψ KL

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

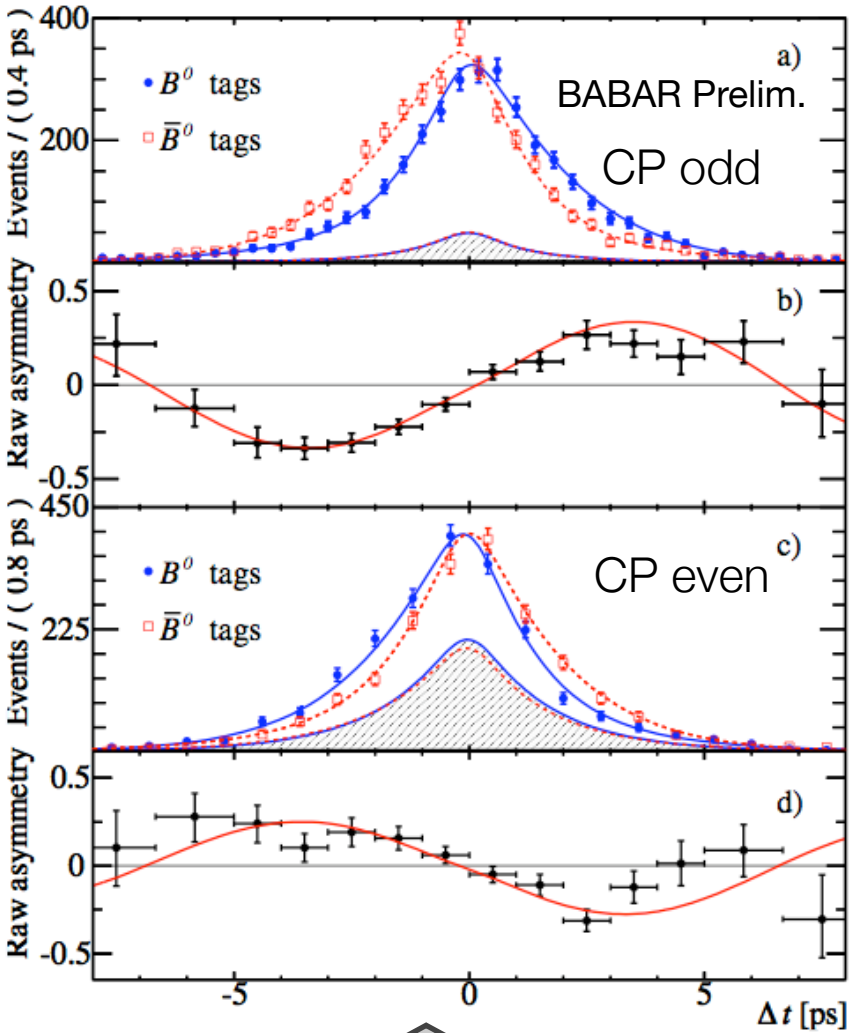


- PRL 98, 031802 (2007)

$$\sin 2\beta_{\rm eff} = +0.642 \pm 0.031 \pm 0.017$$
$$C = -0.018 \pm 0.021 \pm 0.014$$

BABAR results: sin2β for individual decay modes

$383 \times 10^6 B\overline{B}$



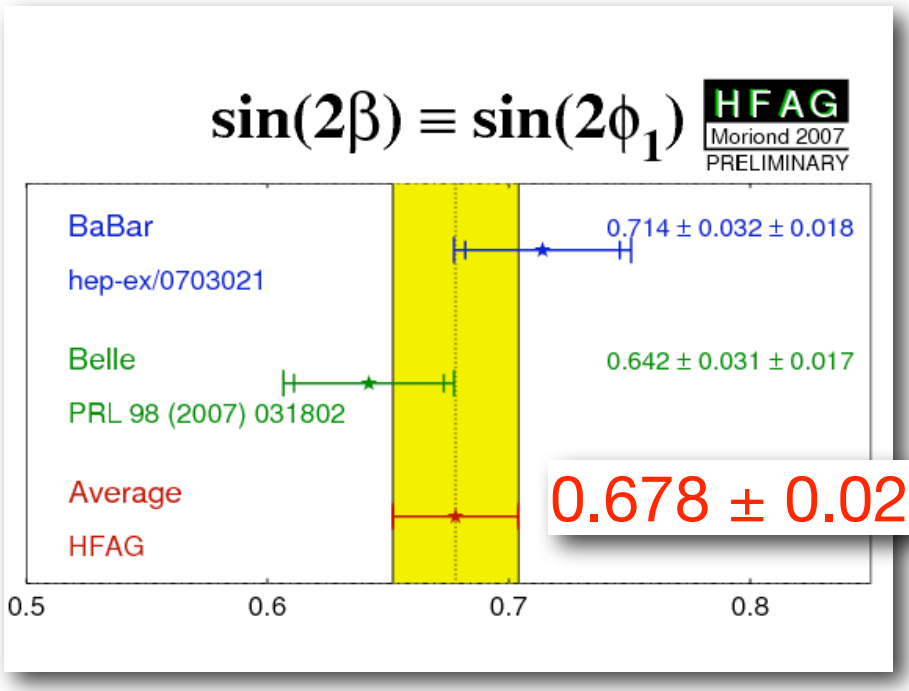
All modes combined

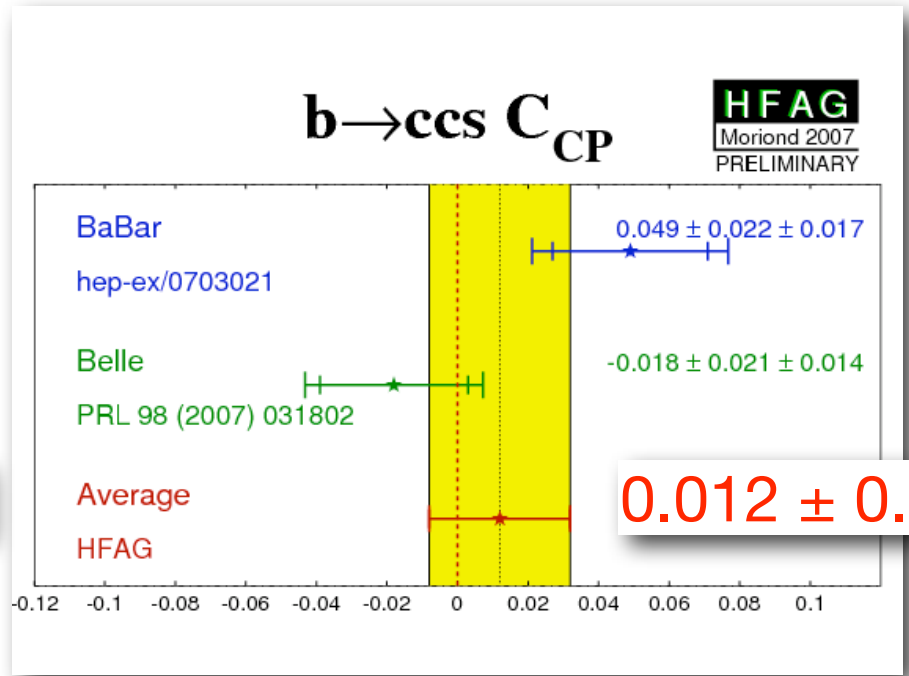
$J/\psi K_S$ ($\pi^+\pi^-$)	$0.702 \pm 0.042 \pm 0.020$
$J/\psi K_S$ ($\pi^0\pi^0$)	$0.617 \pm 0.103 \pm 0.036$
$\psi(2S)K_S$	$0.947 \pm 0.112 \pm 0.062$
$\chi_{c1}K_S$	$0.759 \pm 0.170 \pm 0.037$
$\eta_c K_S$	$0.778 \pm 0.195 \pm 0.093$
$J/\psi K^*$	$0.477 \pm 0.271 \pm 0.155$
$J/\psi K_S$	$0.686 \pm 0.039 \pm 0.015$
$J/\psi K_L$	$0.735 \pm 0.074 \pm 0.067$
$J/\psi K^0$	$0.697 \pm 0.035 \pm 0.016$
All	$0.714 \pm 0.032 \pm 0.018$

systematic

- hep-ex/0703021, submitted to PRL

Summary of sin2β measurements from $(c\bar{c})K^0$

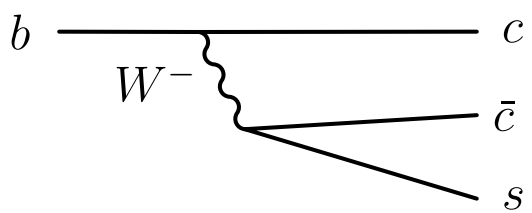




- Two experiments agree very well.
- Experimental uncertainty on sin2β ~ 4%.
- Small theoretical uncertainty in the Standard Model.

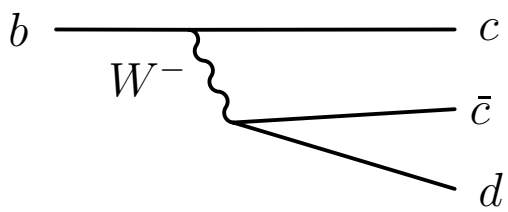
Many ways to measure sin2β

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



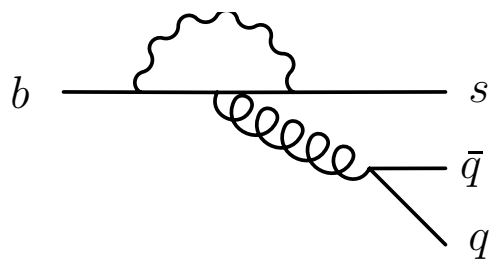
$J/\psi K_S, \psi(2S)K_S, \chi_{c1}K_S$
$\eta_c K_S, J/\psi K_L$
$J/\psi K^{*0}(K_S\pi^0)$

- $b \to c\bar{c}d$
  charm or
  charmonium



$D^{(*)+}D^{(*)-},\ J/\psi\pi^0$

- $b \to ss\bar{s},\ sd\bar{d}$
  penguin-dominated

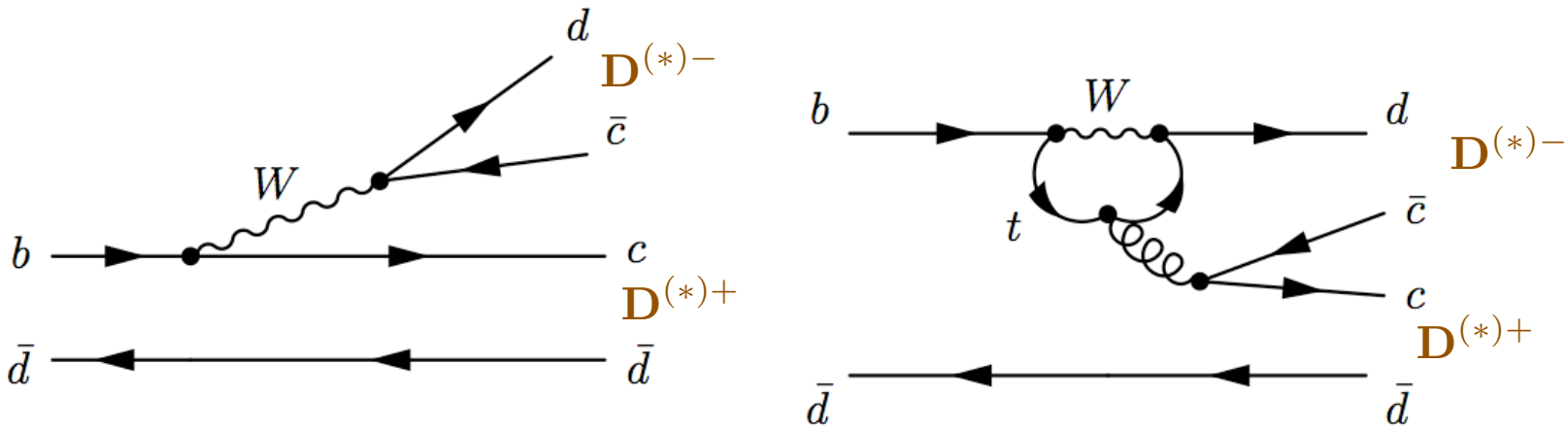


$\phi K_S, K^+K^-K^0,$
$K_SK_SK_S, \eta' K_S, K_S\pi^0,$
$\omega K_S, f_0 K_S$

Increase tree diagram contribution

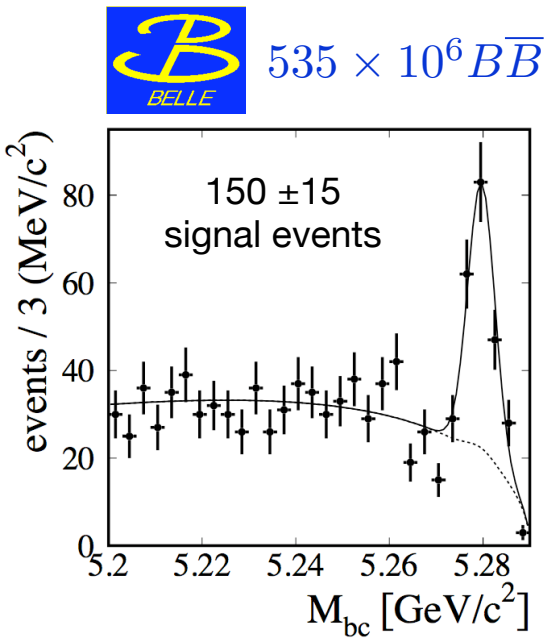
Increase sensitivity to new physics

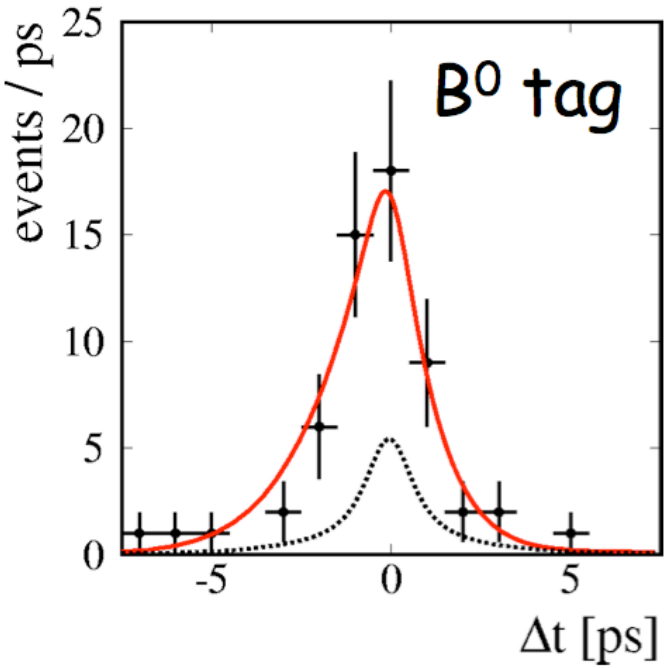
CP in $b \to c\bar{c}d$ decays: $B^0 \to D^{(*)} D^{(*)}$

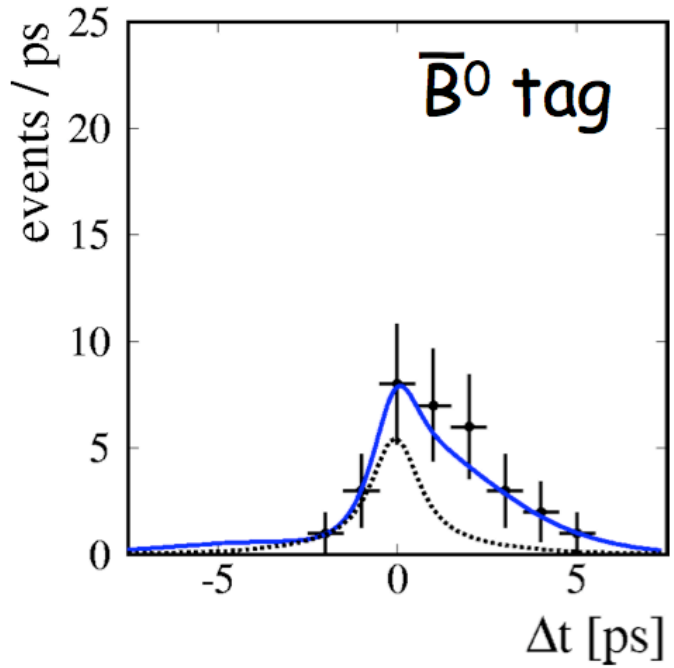


- D^+D^- is a CP eigenstate. $D^{*+}D^{*-}$ is a mixture of CP even and odd state (angular analysis is needed). $D^{*\pm}D^{\mp}$ are not CP eigenstates. But the S's are closely related to sin2β.
- C=0, S≃ –sin2β in the Standard Model.
- Penguin contribution is expected to be small
  - 2--10% correction [Xing PRD 61, 014010 (2000)]
- Sensitive to new physics in the loop.

Belle's evidence of large direct $\not{CP}$ in $B^0 \to D^+ D^-$







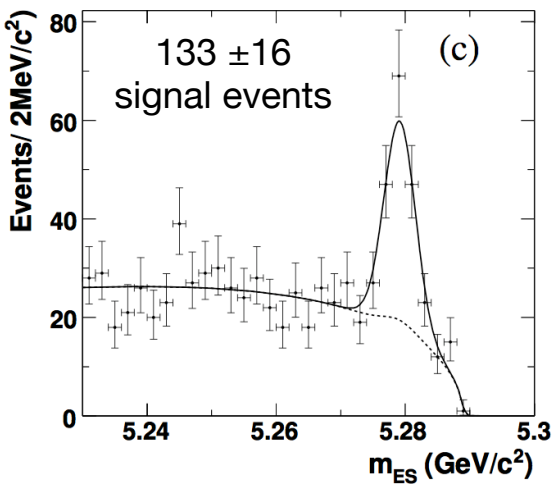
$$\mathcal{S} = -1.13 \pm 0.37 \pm 0.09$$

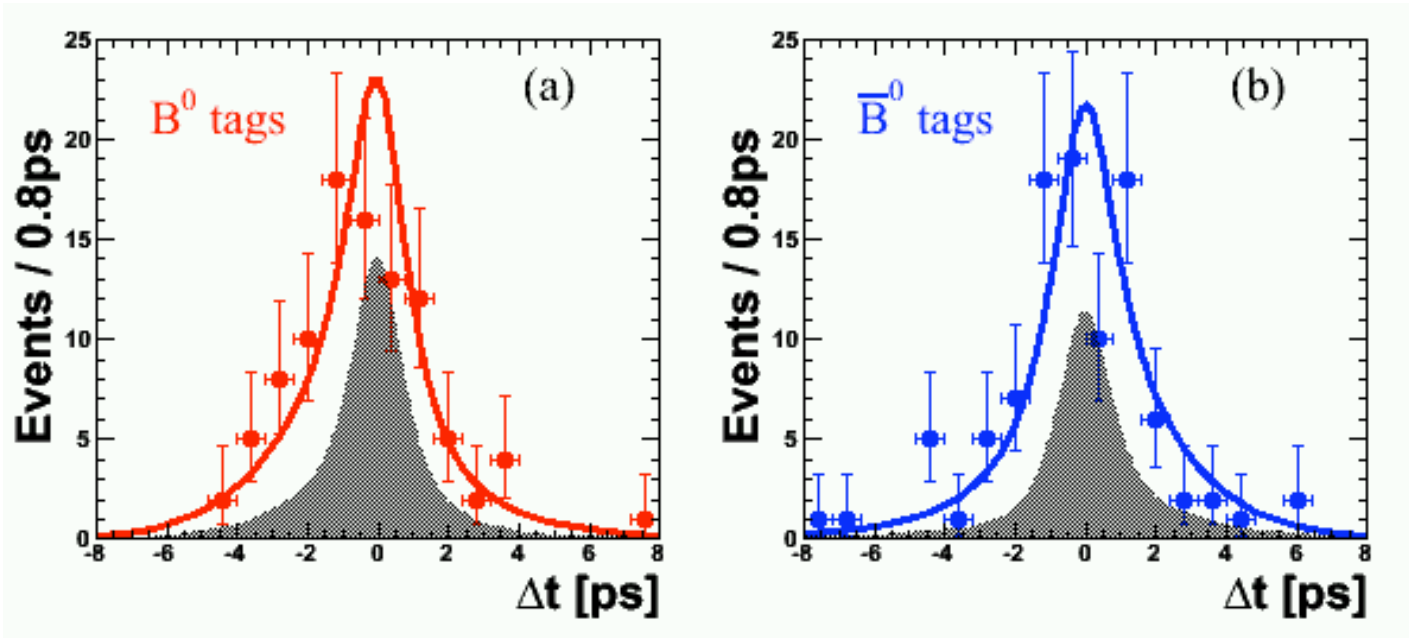
$$\mathcal{A} = +0.91 \pm 0.23 \pm 0.06 \quad (= -\mathbf{C})$$

- S = A = 0 is excluded at 4.1σ level. [hep-ex/0702031, submitted to PRL]
- Direct CPV at 3.2σ level.

BABAR does *not* confirm the large ~~CP~~ observed by Belle in $B^0 \to D^+ D^-$

$383 \times 10^6 B\overline{B}$



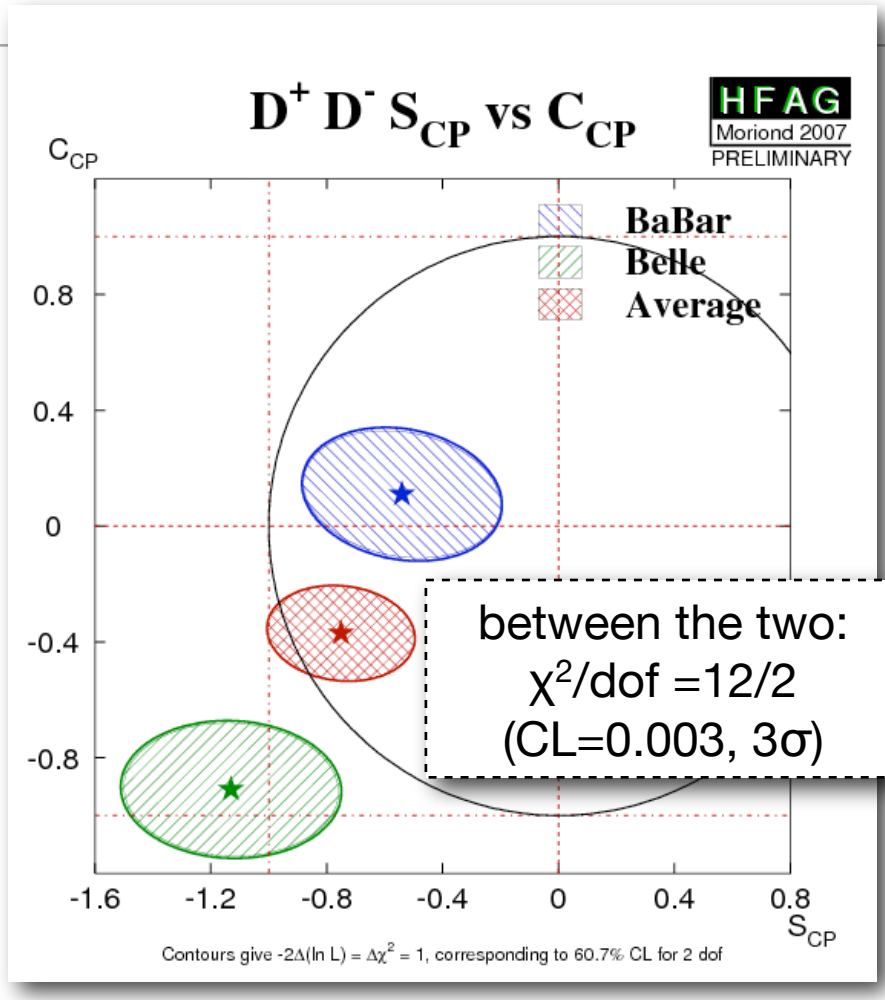


$$S = -0.54 \pm 0.34 \pm 0.06$$
$$C = +0.11 \pm 0.22 \pm 0.07$$

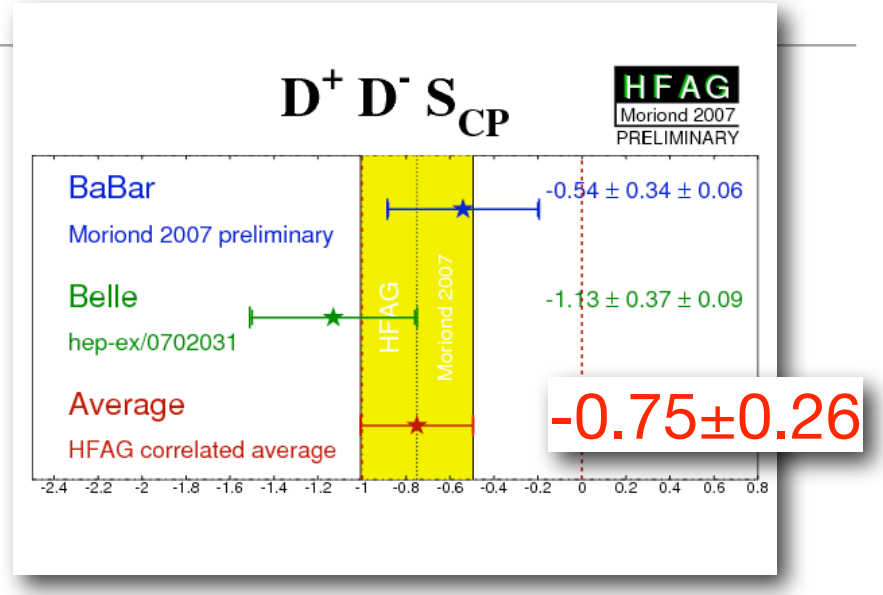
- Consistent with the SM expectation.

[arXiv:0705.1190v1 [hep-ex] submitted to PRL]

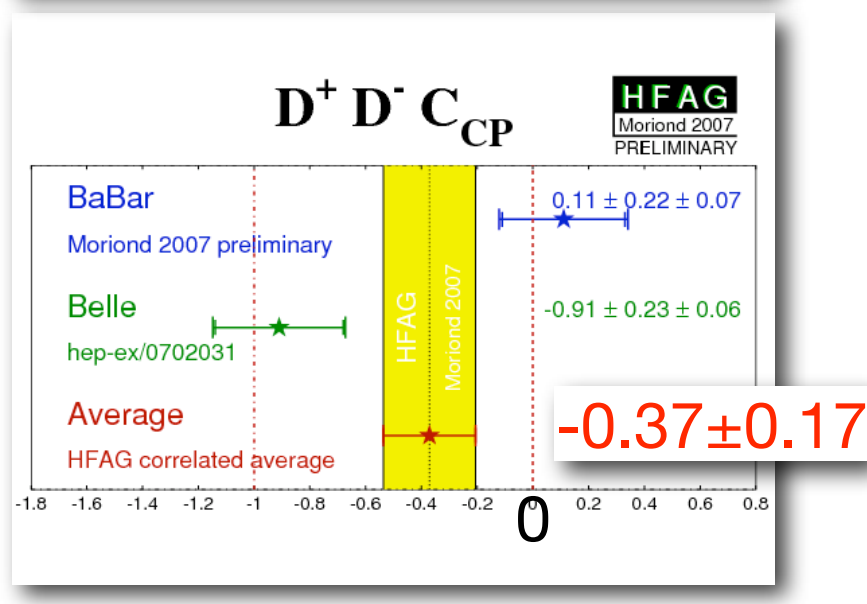
Comparison between *BABAR* and Belle's $B^0 \to D^+ D^-$ result



between the two:
χ^2/dof =12/2
(CL=0.003, 3σ)



-0.75±0.26



-0.37±0.17

- Handle average with care due to possible non-gaussian tails.

Evidence of CPV in $B^0 \to D^{*\pm} D^{\mp}$

$152 \times 10^6 B\overline{B}$ [PRL 93, 201802 (2004)]

$383 \times 10^6 B\overline{B}$ [hep-ex/0705xxx]

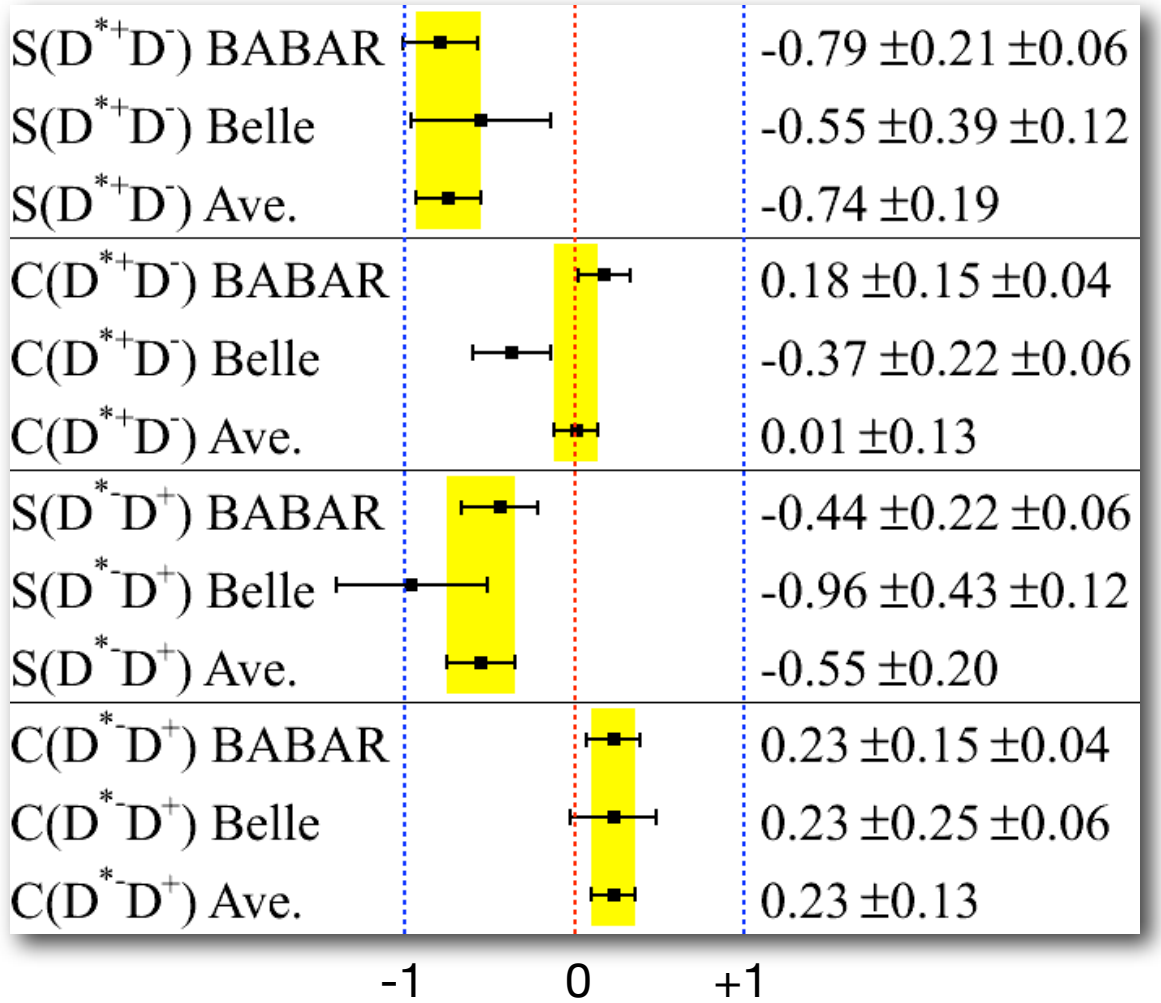
- $D^{*\pm}D^{\mp}$ is not a CP eigenstate.
- Analyze D*+D- and D*-D+ modes separately.

$$\frac{A(D^{*+}D^{-})}{A(D^{*-}D^{+})} = Re^{i\delta}$$

$$S_{\pm} = \frac{2R\sin(2\beta \pm \delta)}{1+R^2}$$

$$(S_+ + S_-)/2 = \frac{2R}{1+R^2}\cos\delta\sin 2\beta$$

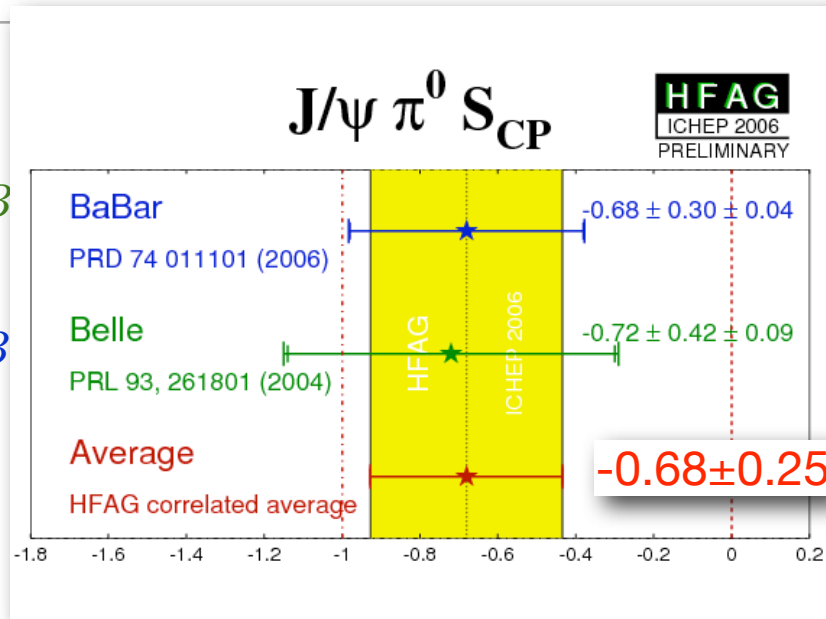
- If no CPV (and no penguin), $S_+ = -S_-$, $C_+ = -C_-$.
- $\cos\delta\sin 2\beta \neq 0$ at ~4σ level.

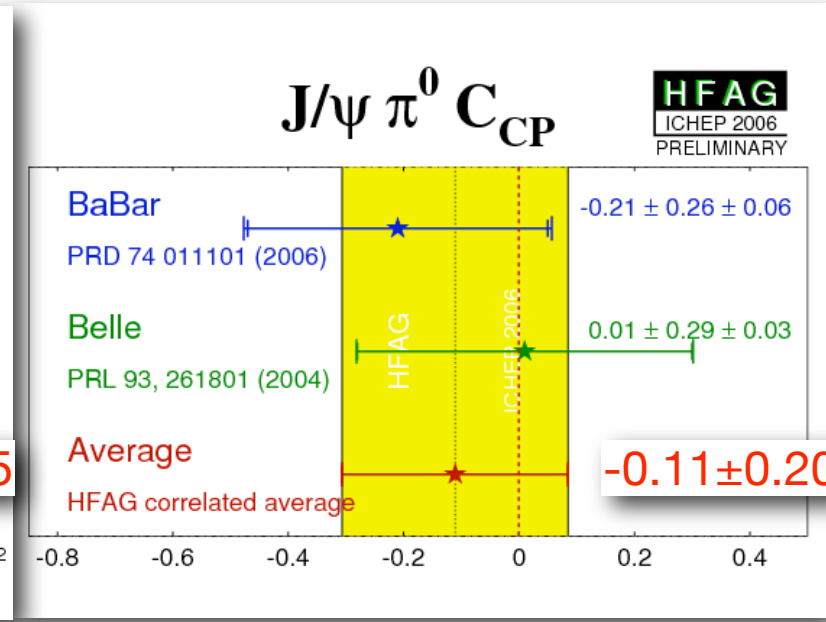


CP in $b \to c\bar{c}d$ decay: $B^0 \to J/\psi\ \pi^0$

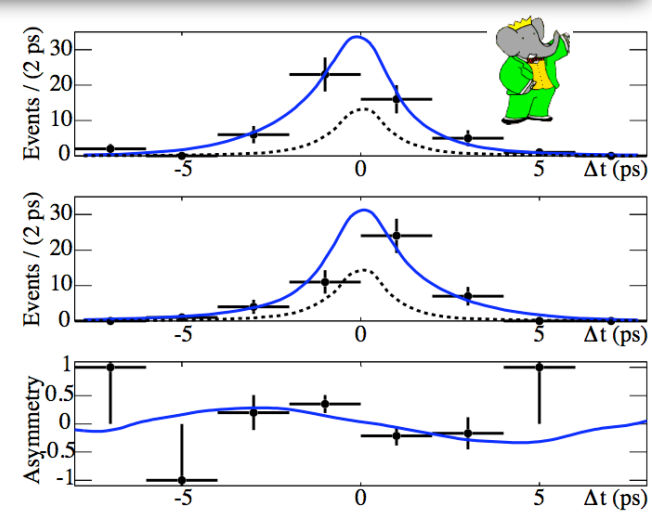
$232 \times 10^6 B$

$152 \times 10^6 B$





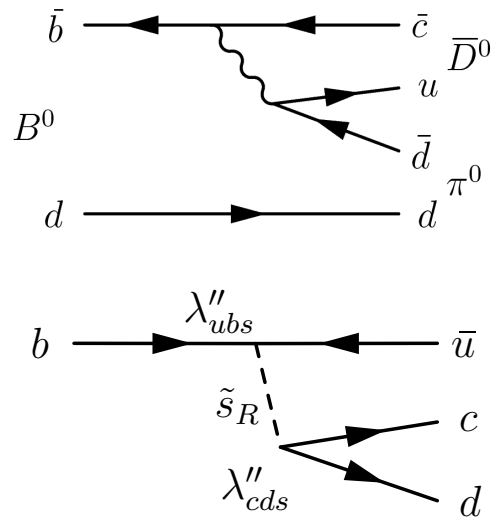
- Same tree and penguin diagrams as golden modes except the s quark is replaced by d. But the penguin with a different weak phase can have a more significant contribution than in golden modes.
- Can be used to constrain the penguin pollution in the golden mode in a model-independent way. [Ciuchini et al., PRL 95, 221804 (2005)]

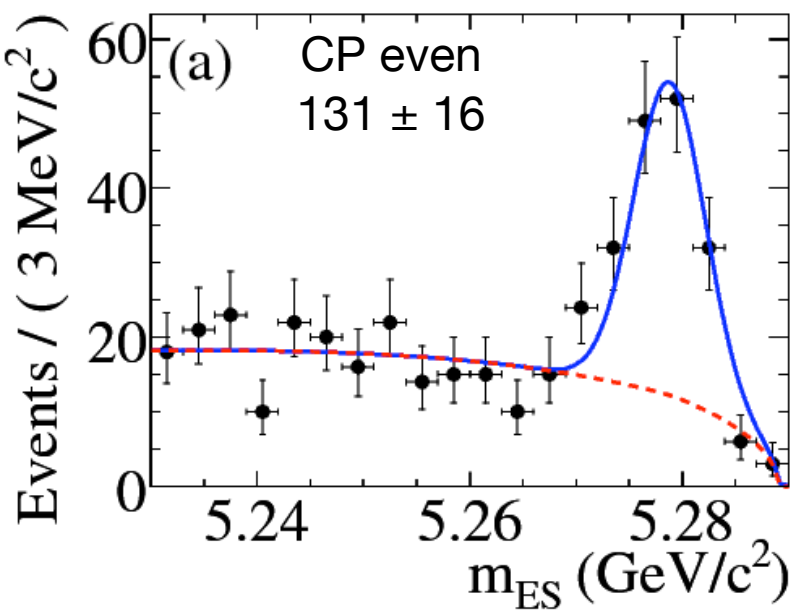


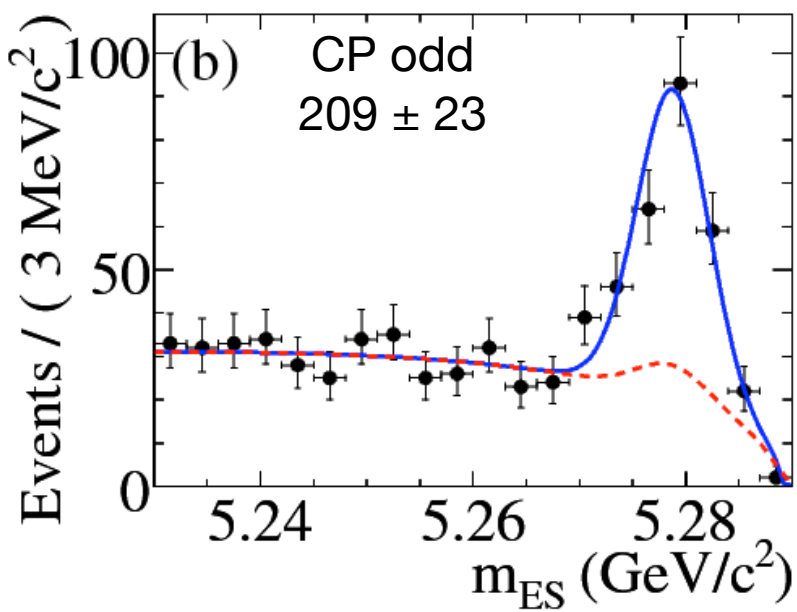
New *BABAR* result: $B^0 \to D^{(*)0} h^0$ using $D^0 \to K^+K^-,\ K_S\,\omega,\ K_S\,\pi^0$

$383 \times 10^6 B\overline{B}$

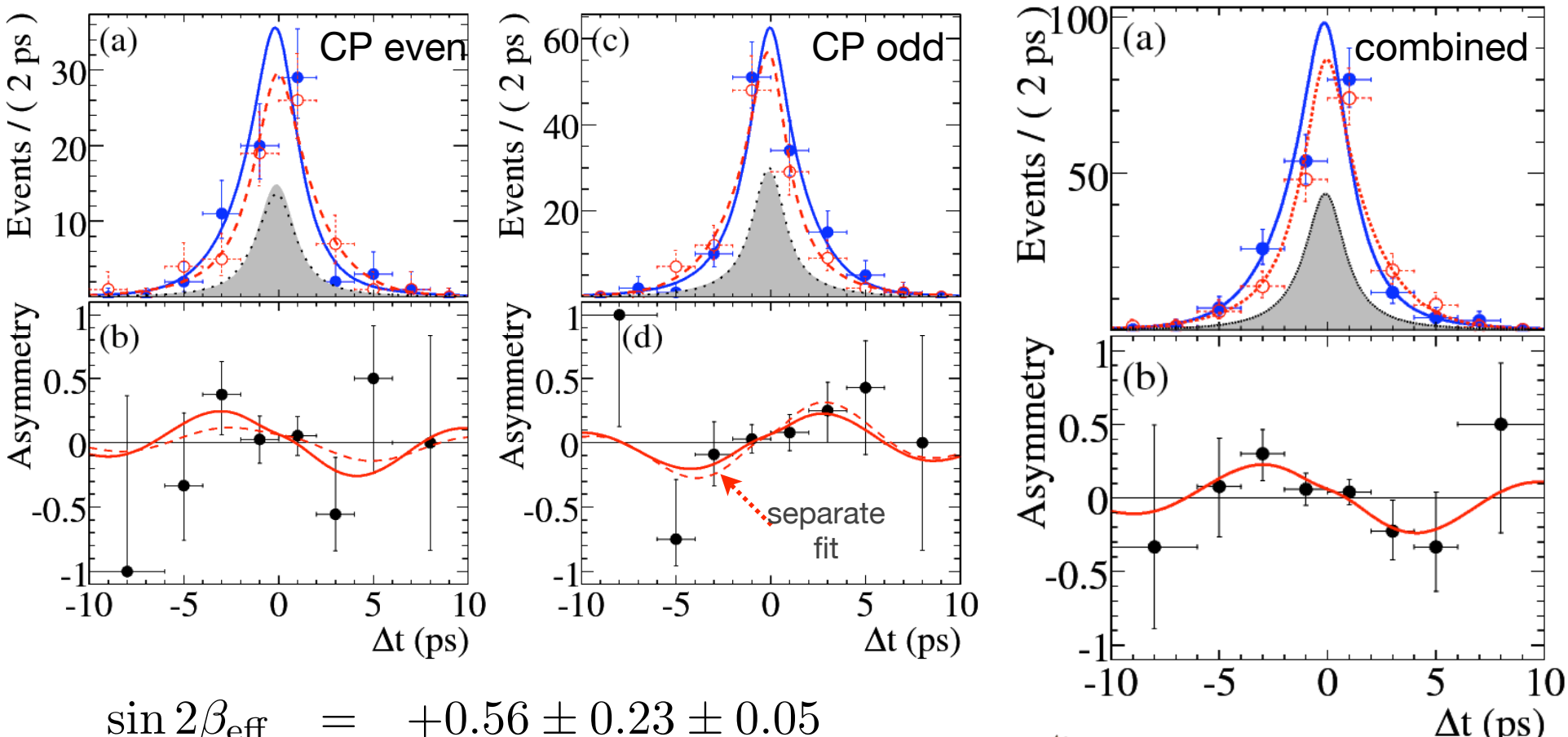
- Color-suppressed tree diagram.
- Doubly-Cabbibo suppressed (tree) amplitude has small effect: $\Delta S \lesssim 0.05$.
- No penguin diagrams ⇒ sensitive to different kind of new physics.







sin2β in $B^0 \to D^{(*)0} h^0$



$$\sin 2\beta_{\rm eff} = +0.56 \pm 0.23 \pm 0.05$$

$$C = -0.23 \pm 0.16 \pm 0.04$$

[hep-ex/0703019, submitted to PRL]

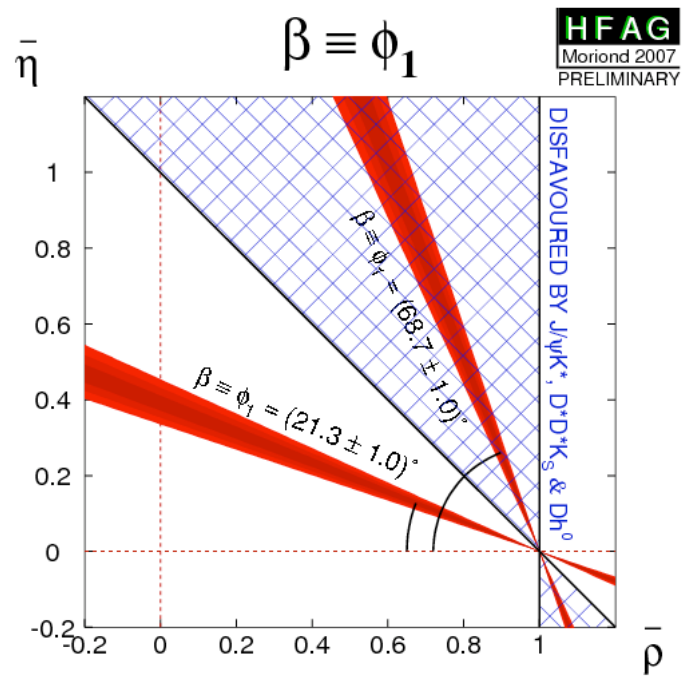
- 2.3σ from CP conservation.

Compared with S=C=0: $\sqrt{2\Delta \ln \mathcal{L}} = 2.80$, => p=0.0198 for dof=2.
equivalent to 2.3σ for dof=1.

Resolve ambiguity in β

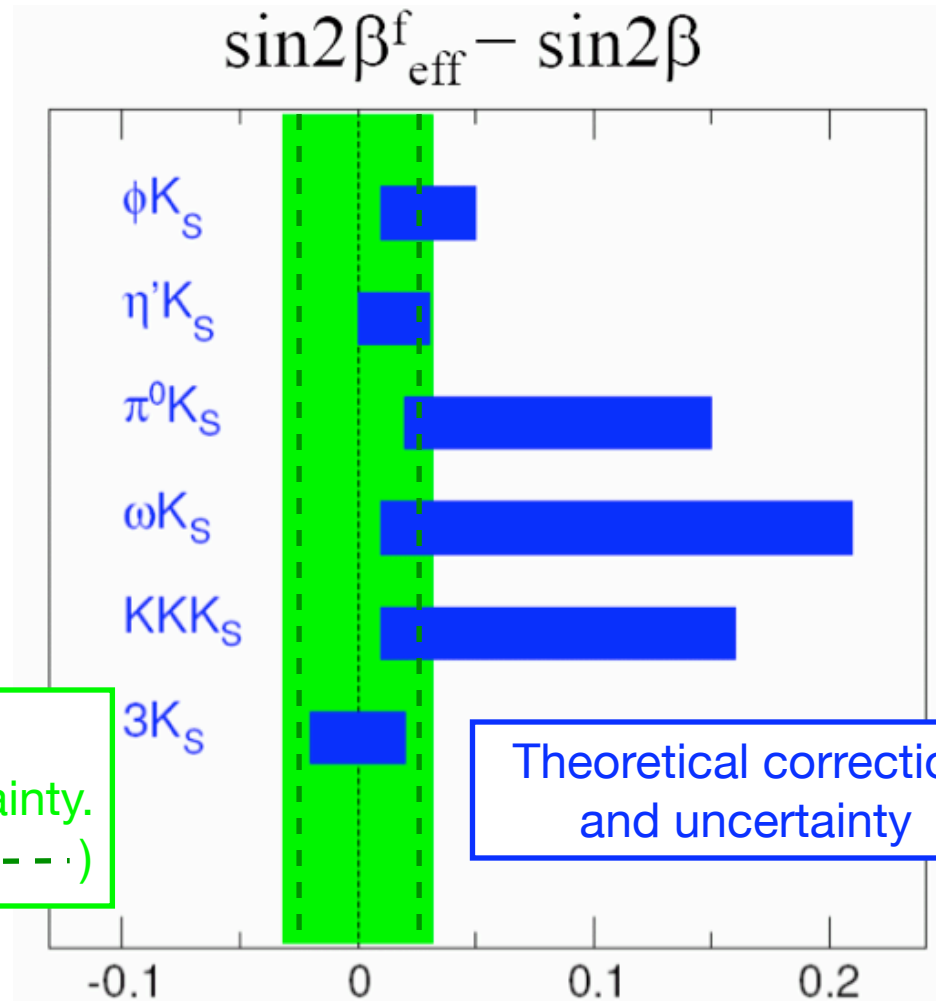
- Measuring sin2β resulting in 4-fold ambiguity in β.
- Can be reduced to 2-fold by measuring (the sign of) cos2β. Negative cos2β is ruled out by:
  - $B^0 \to J/\psi\, K\pi$: Interference between CP even and odd; resolve strong phase using Kπ S- and P-wave.
    - BABAR [PRD 71, 032005 (2005)]
    - Belle [PRL 95, 091601 (2005)]
  - $B^0 \to D^0[K_S\pi^+\pi^-]\, h^0$: Time-dependent Dalitz analysis
    - Belle [PRL 97, 081801 (2006)] 98.3% CL
    - BABAR [hep-ex/0607105] 87% CL.
  - $B^0 \to D^{*}D^{*}K_S$: Time-dependent Dalitz analysis
    - BABAR [PRD 74, 091101] 94% CL.
  - $B^0 \to K^+K^-K^0$: Time-dependent Dalitz analysis

    ★21° is favored over 69° at 4.6σ level. (detail later)



sin2β in b→s penguin dominated modes

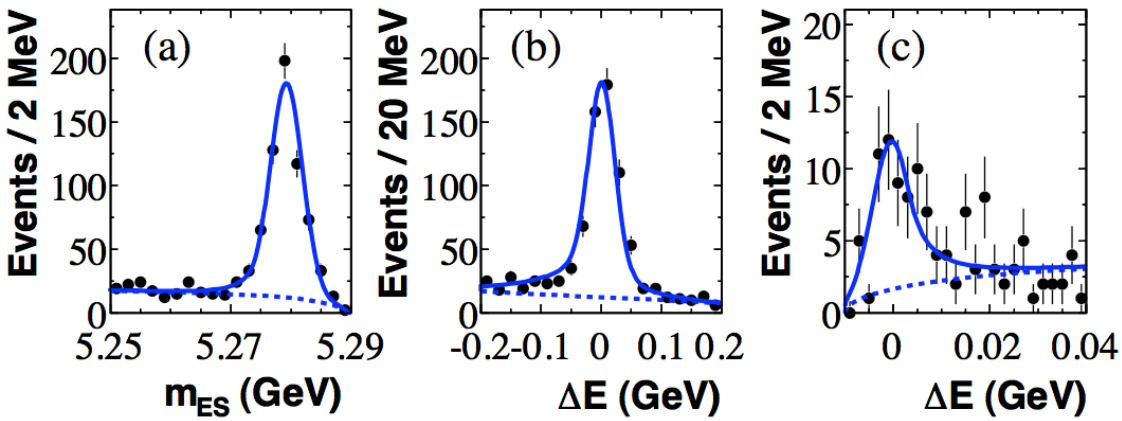
- Different charmless modes have different Standard Model corrections and uncertainties.
  - Considering, e.g., Cabbibo-suppressed trees, final state interaction long distance effect.
- Significant deviation from golden mode sin2β would indicate new physics.



Beneke, PLB 620, 143 (2005)
Mishima, Sanda, PRD 72, 114005 (2005)
Williamson, Zupan, PRD 74, 014003 (2006)
Cheng, Chua, Soni, PRD, 014006 (2005)

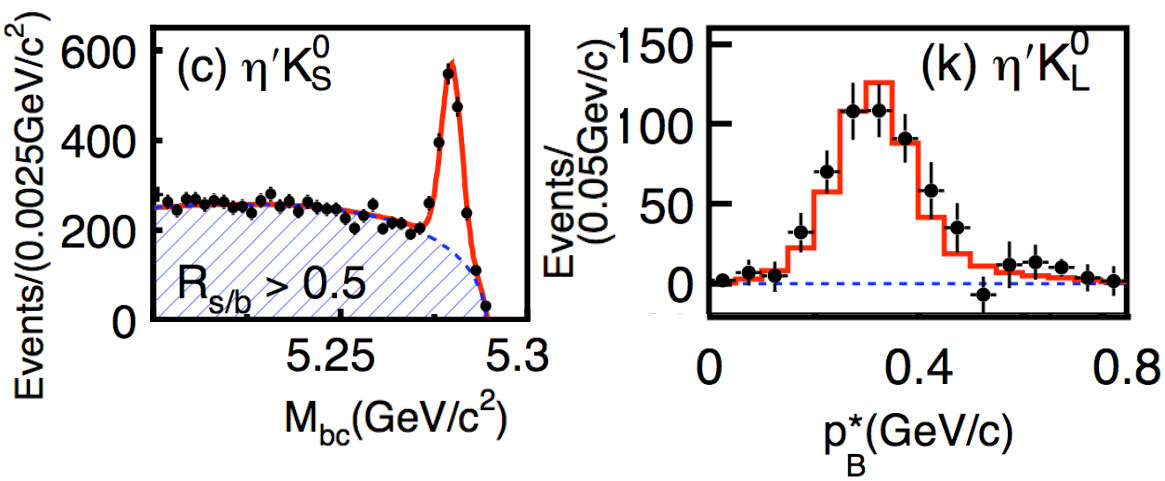
"Golden" charmless mode: $B^0 \to \eta' K^0$

- Small SM uncertainty, relatively large yield.



$383 \times 10^6 B\overline{B}$

~1050 η'K_S events
~250 η'K_L events

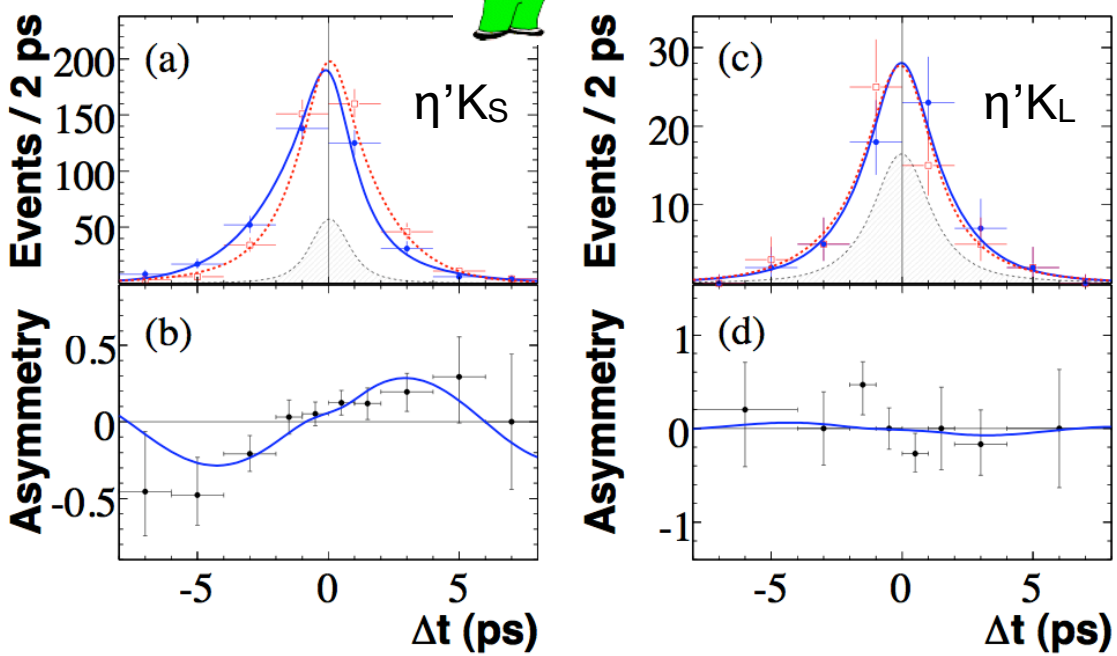


$535 \times 10^6 B\overline{B}$

~1420 η'K_S events
~450 η'K_L events

$\not{CP}$ established in charmless mode

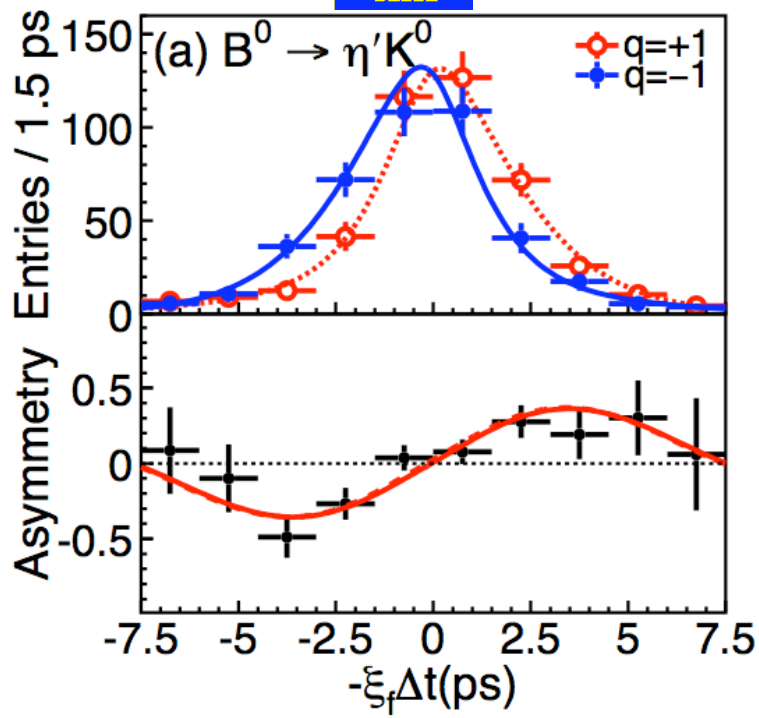
$383 \times 10^6 B\overline{B}$



$$\sin 2\beta_{\rm eff} = +0.58 \pm 0.10 \pm 0.03$$
$$C = -0.16 \pm 0.07 \pm 0.03$$

[PRL98, 031801 (2007)]

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



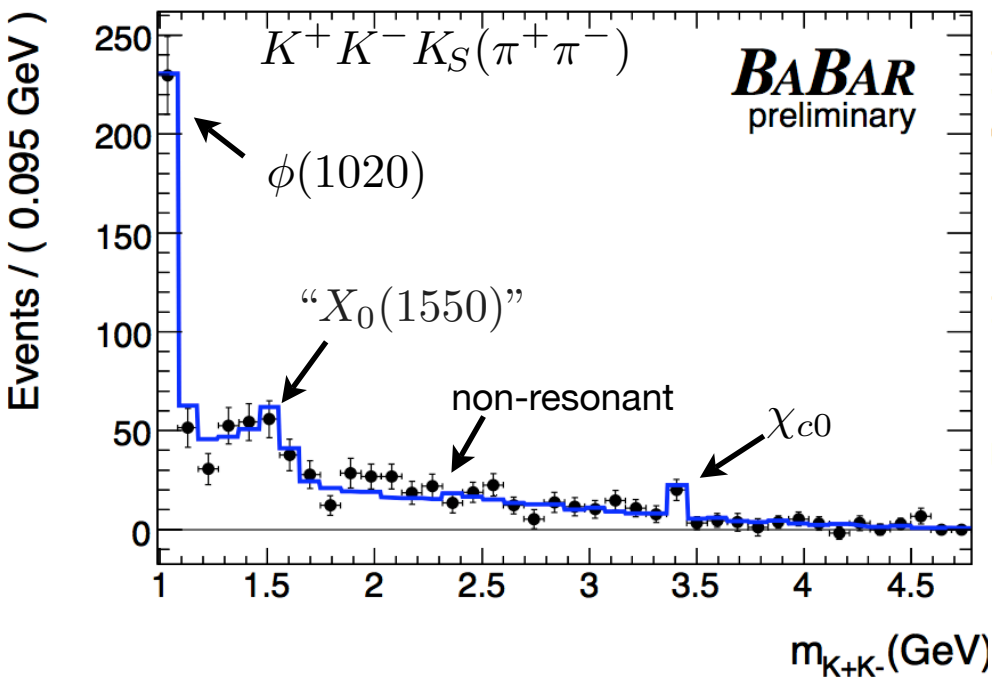
$$\sin 2\beta_{\rm eff} = +0.64 \pm 0.10 \pm 0.04$$
$$C = +0.01 \pm 0.07 \pm 0.05$$

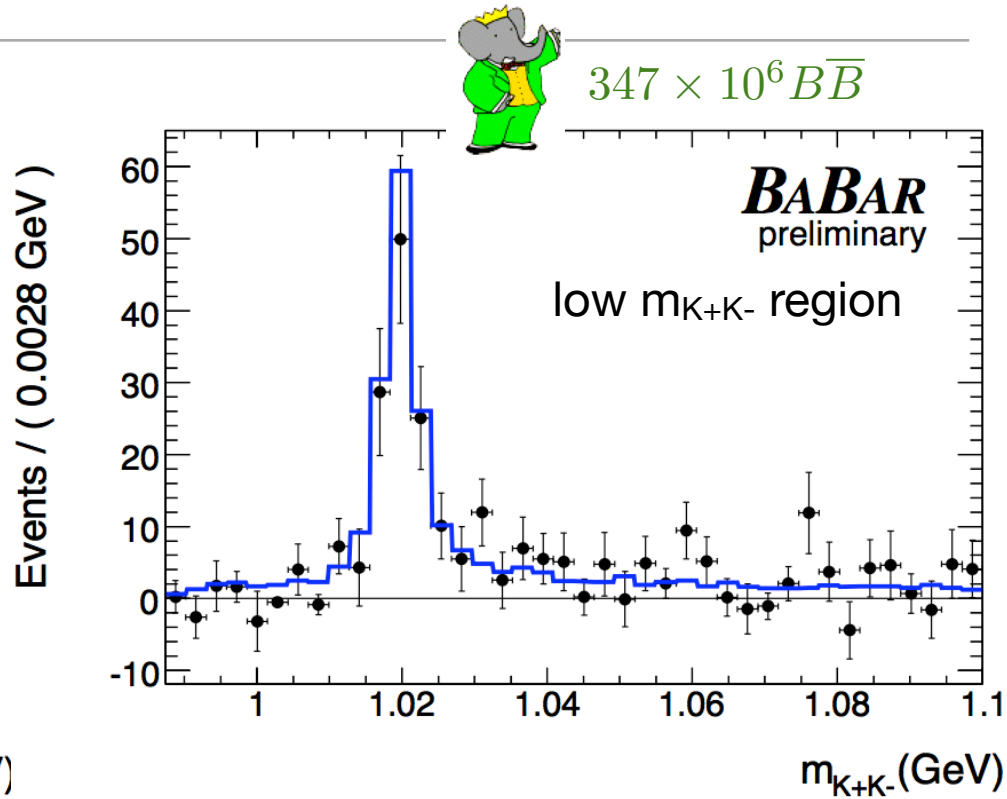
[PRL98, 031802 (2007)]

- Both experiments observe more than 5σ CP violation in charmless mode.

BABAR time-dependent Dalitz analysis

$$B^0 \to K^+K^-K^0$$





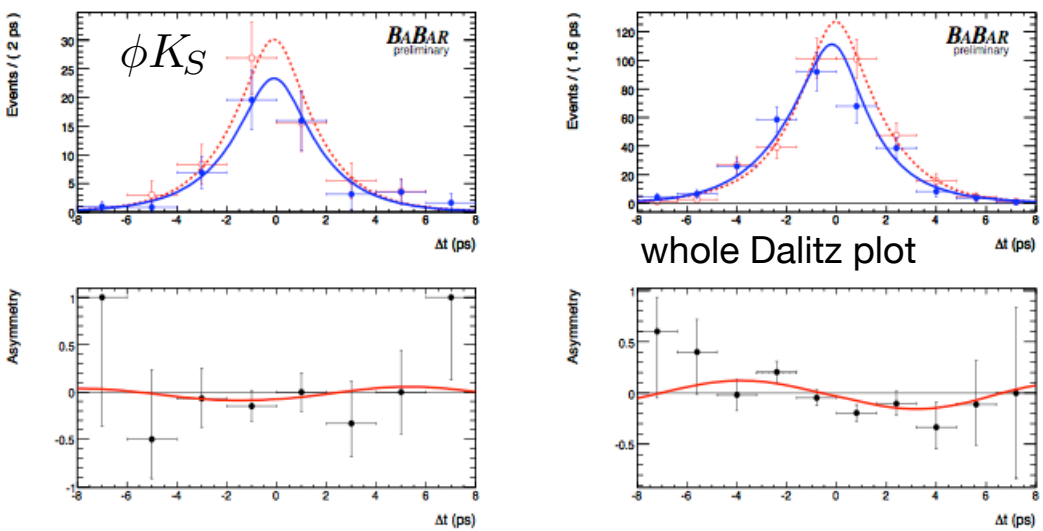
- Final state is a mixture of CP even/odd depending on the resonances.
- Signal events: ~1000 $K^+K^-K_S$, ~500 $K^+K^-K_L$.
- Time-dependent Dalitz analysis to extract Dalitz structures and CP asymmetry.
  - Resonances: $f_0(980)$, $\phi(1020)$, $X_0(1550)$, χ_{c0}, and non-resonant.

Extract β from time-dependent Dalitz analysis of $B^0 \to K^+K^-K^0$

$$\frac{d\Gamma}{d\Delta t} \propto \frac{e^{-|\Delta t|/\tau}}{2\tau} \times \Big[\; |\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2 + q_{\rm tag}\; 2Im\left(\xi \mathcal{A}\mathcal{A}^*\right) \sin \Delta m_d \Delta t - q_{\rm tag} \left(|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2\right) \cos \Delta m_d \Delta t \Big]$$

$$\xi = \eta_{CP} e^{-2i\beta}$$

sensitive to 2β directly if $\bar{A}A^*$ is not real.



- Fit the whole Dalitz plot, and then fit $m_{K^+K^-} < 1.1$ GeV region.

[hep-ex/0607112]

~4.5σ from CP conservation

whole	$\beta_{\rm eff}$	$=$	$0.361 \pm 0.079 \pm 0.037$
ϕK^0	$\beta_{\rm eff}$	$=$	$0.06 \pm 0.16 \pm 0.05$
$f_0 K^0$	$\beta_{\rm eff}$	$=$	$0.18 \pm 0.19 \pm 0.04$

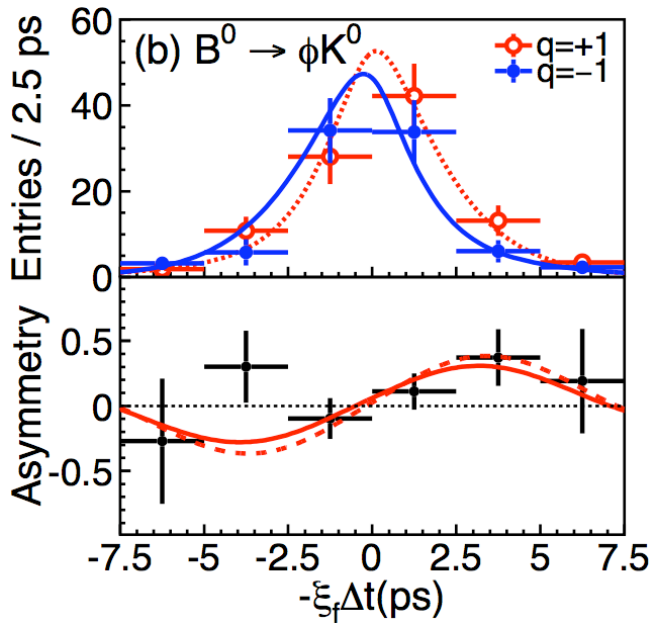
Belle separates ϕK^0 and $K^+K^-K_S$

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

$B^0 \to \phi K^0$

Quasi-2body approach

Nsig ~ 420

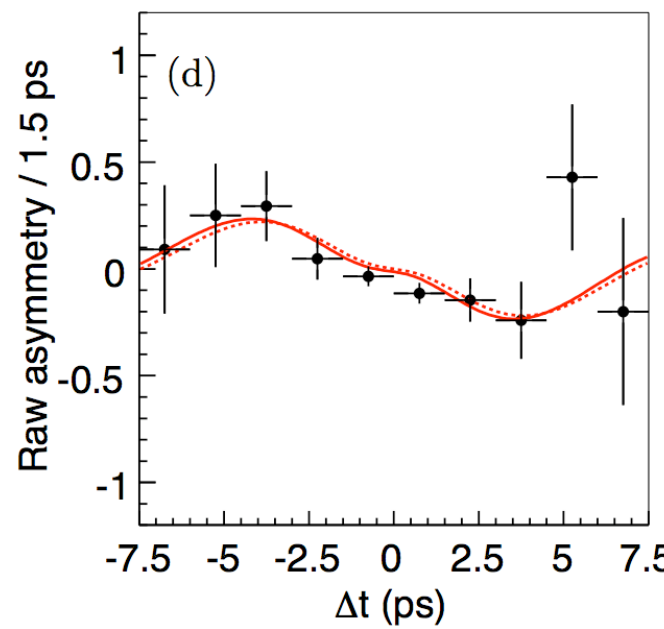


$$\sin 2\beta_{\rm eff} = +0.50 \pm 0.21 \pm 0.06$$
$$C = -0.07 \pm 0.15 \pm 0.05$$

[PRL98, 031802 (2007)]

$B^0 \to K^+K^-K^0$

Average CP content is determined using isospin relations and the BFs of $B^+ \to K^+K_SK_S$ and $B^0 \to K^+K^-K^0$



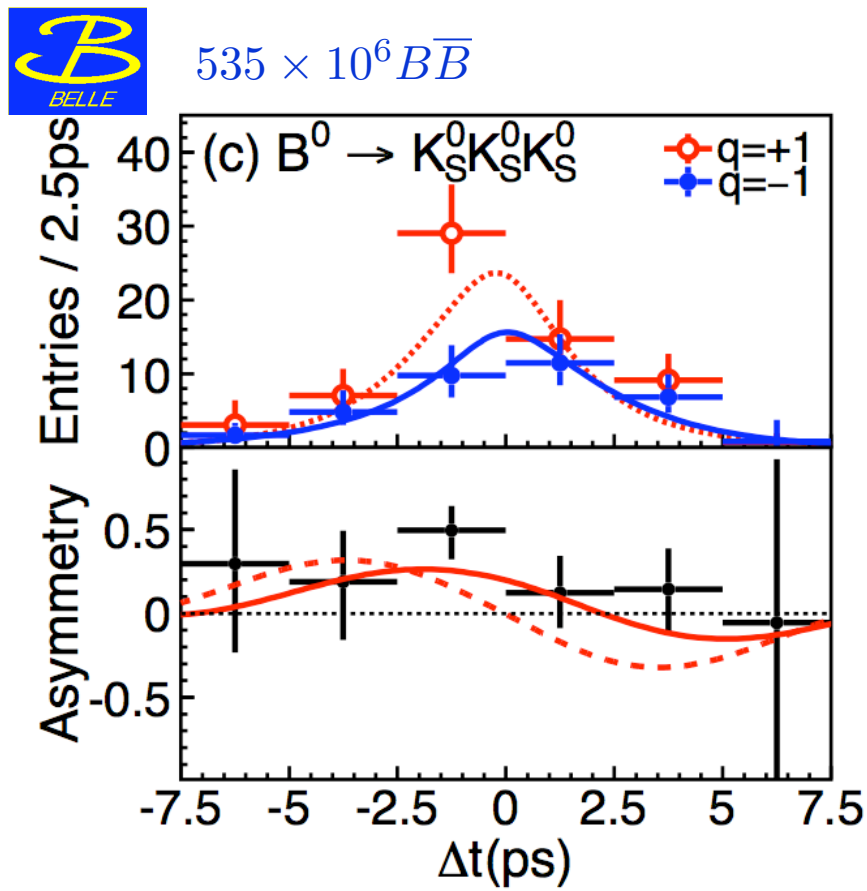
Nsig ~ 840

CP-content uncertainty

$$\sin 2\beta_{\rm eff} = +0.68 \pm 0.15 \pm 0.03 {}^{+0.21}_{-0.13}$$
$$C = +0.09 \pm 0.10 \pm 0.05$$

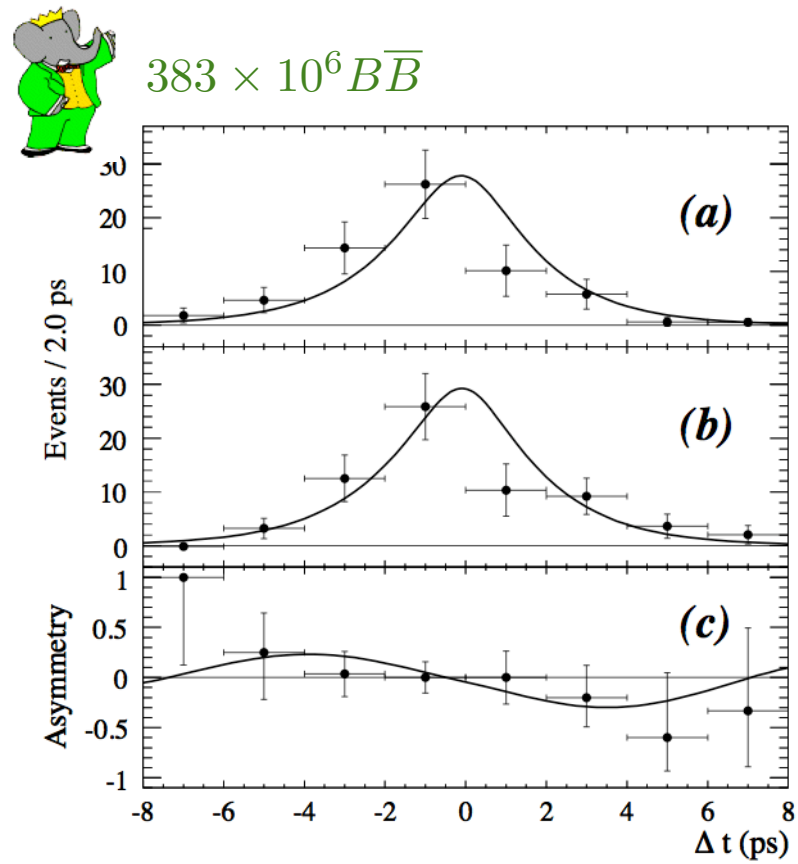
[hep-ex/0609006]

$B^0 \to K_S K_S K_S$ is a CP eigenstate, no Dalitz analysis is necessary



$$\sin 2\beta_{\rm eff} = +0.30 \pm 0.32 \pm 0.08$$
$$C = -0.31 \pm 0.20 \pm 0.07$$

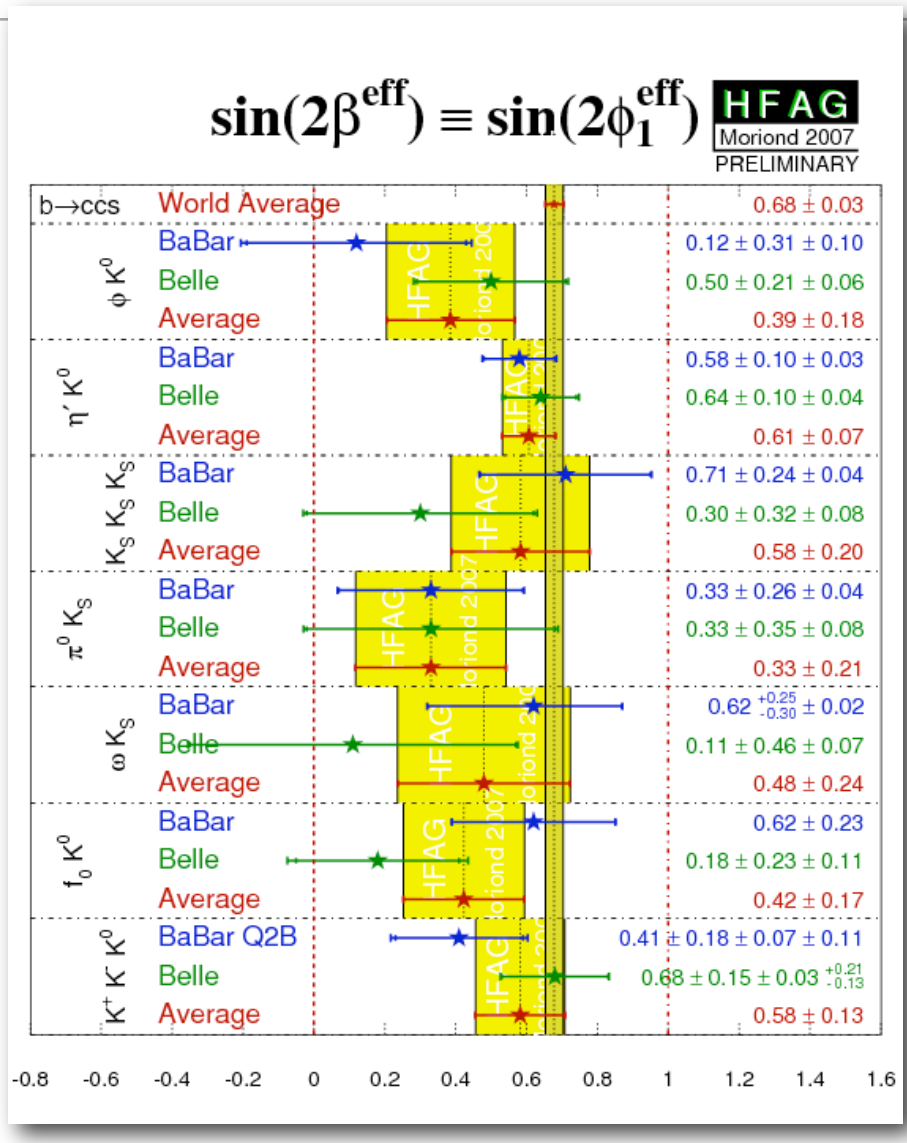
[PRL98, 031802 (2007)]

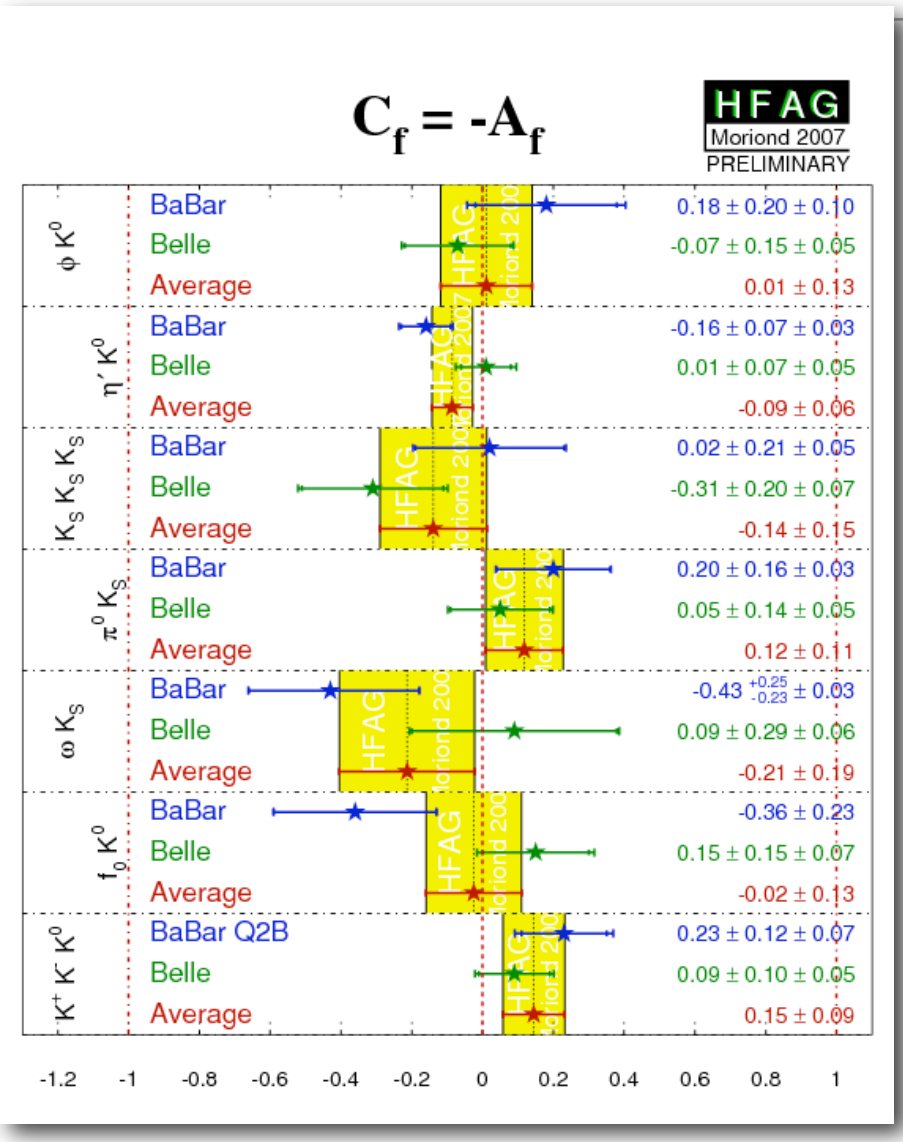


$$\sin 2\beta_{\rm eff} = +0.71 \pm 0.24 \pm 0.04$$
$$C = +0.02 \pm 0.21 \pm 0.05$$

[hep-ex/0702046 submitted to PRL]

Hint of $\sin 2\beta_{eff}$(charmless) < $\sin 2\beta_{eff}$(golden modes)





Conclusion

- Measuring the CKM angle β is a rich program at B-factories.
  - (CPV >5σ) $B^0 \to J/\psi K^0$ $B^0 \to \eta' K^0$
  - (CPV >4σ) $B^0 \to K^+K^-K^0$ $B^0 \to D^+D^-$? $B^0 \to D^{*\pm}D^{\mp}$
- sin2β has been measured to 4% precision. More than 900 million BB pairs analyzed.
- $B^0 \to D^+D^-$ puzzle.
- Ambiguity broken: cos2β>0, β = (21.3 ± 1.0) degrees.
- Hint of inconsistent $\sin 2\beta_{\text{eff}}$ between penguin modes and golden modes persists.