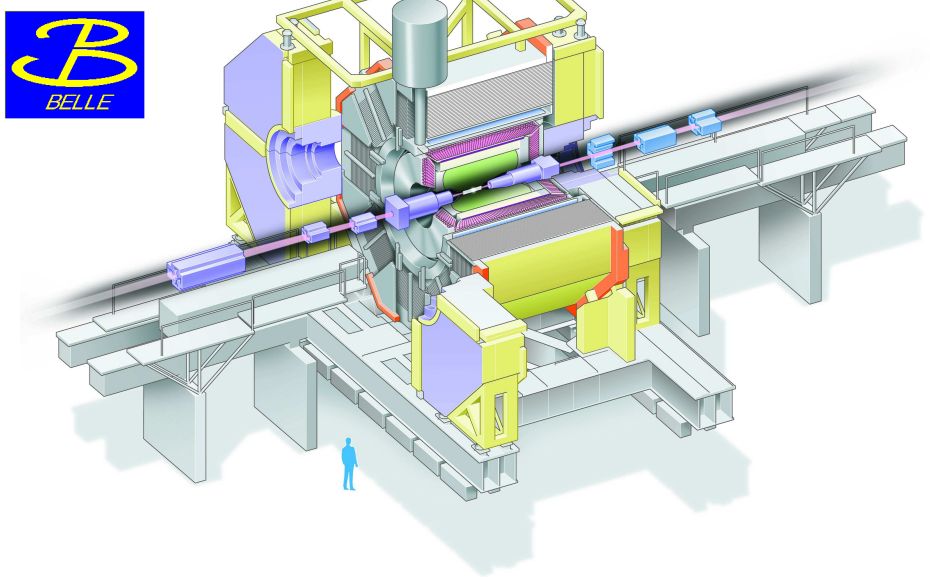
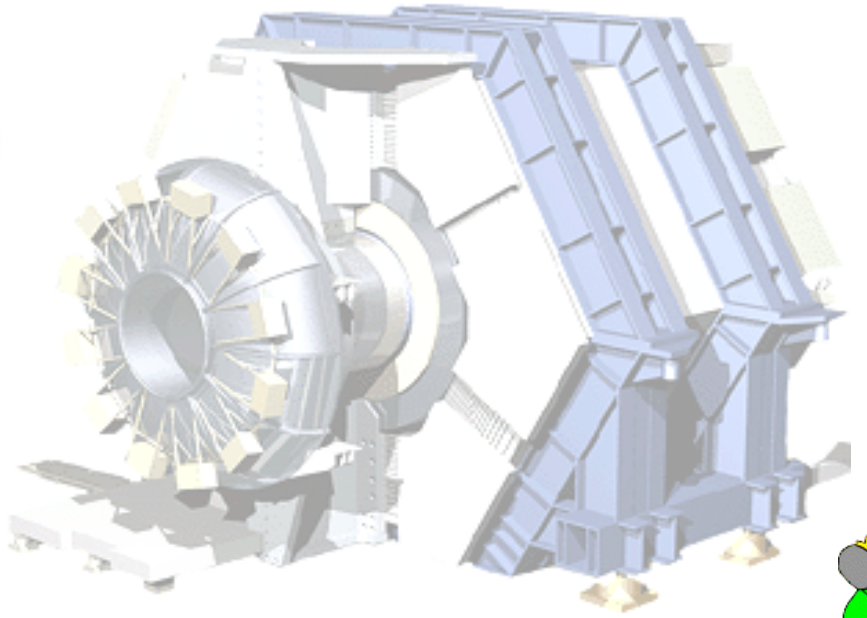
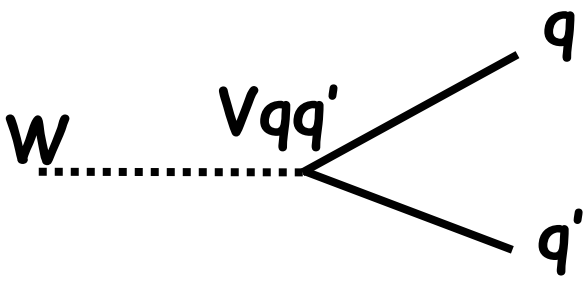
The Measurement of β: New results from Belle and BABAR





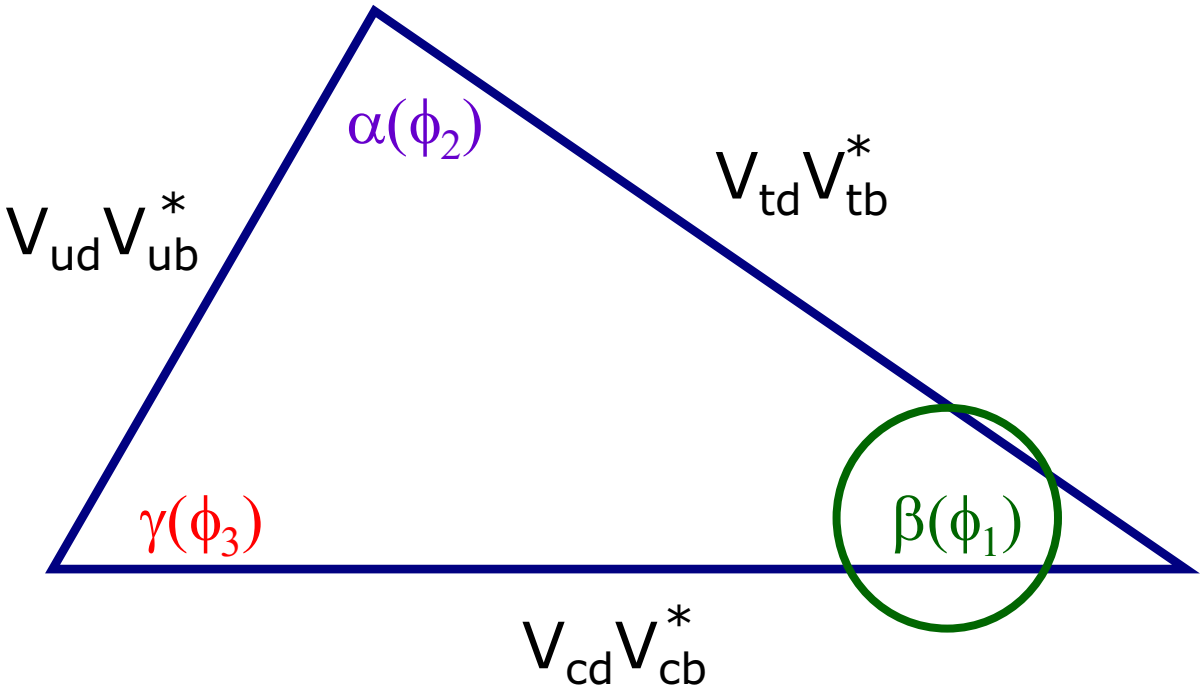
David J Lange
Lawrence Livermore National Laboratory
March 12, 2007

B Factory mission: Measure (and overconstrain) angles and sides of Unitarity Triangle



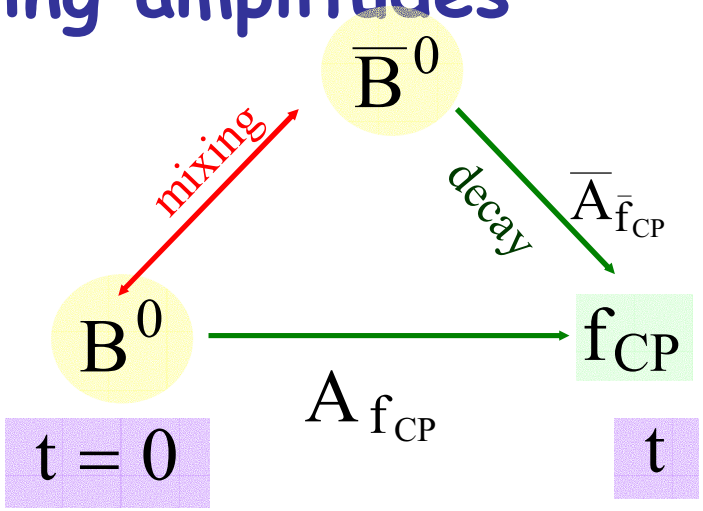
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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



Measure sin2β in time-dependent analysis: Interference of decay and mixing amplitudes

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



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

(ΔΓ=0)

$$A_{f_{CP}}(t) = \frac{\Gamma(\overline{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\overline{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})} = -C_{f_{CP}} \cdot \cos(\Delta m_{B_d} t) + S_{f_{CP}} \cdot \sin(\Delta m_{B_d} t)$$

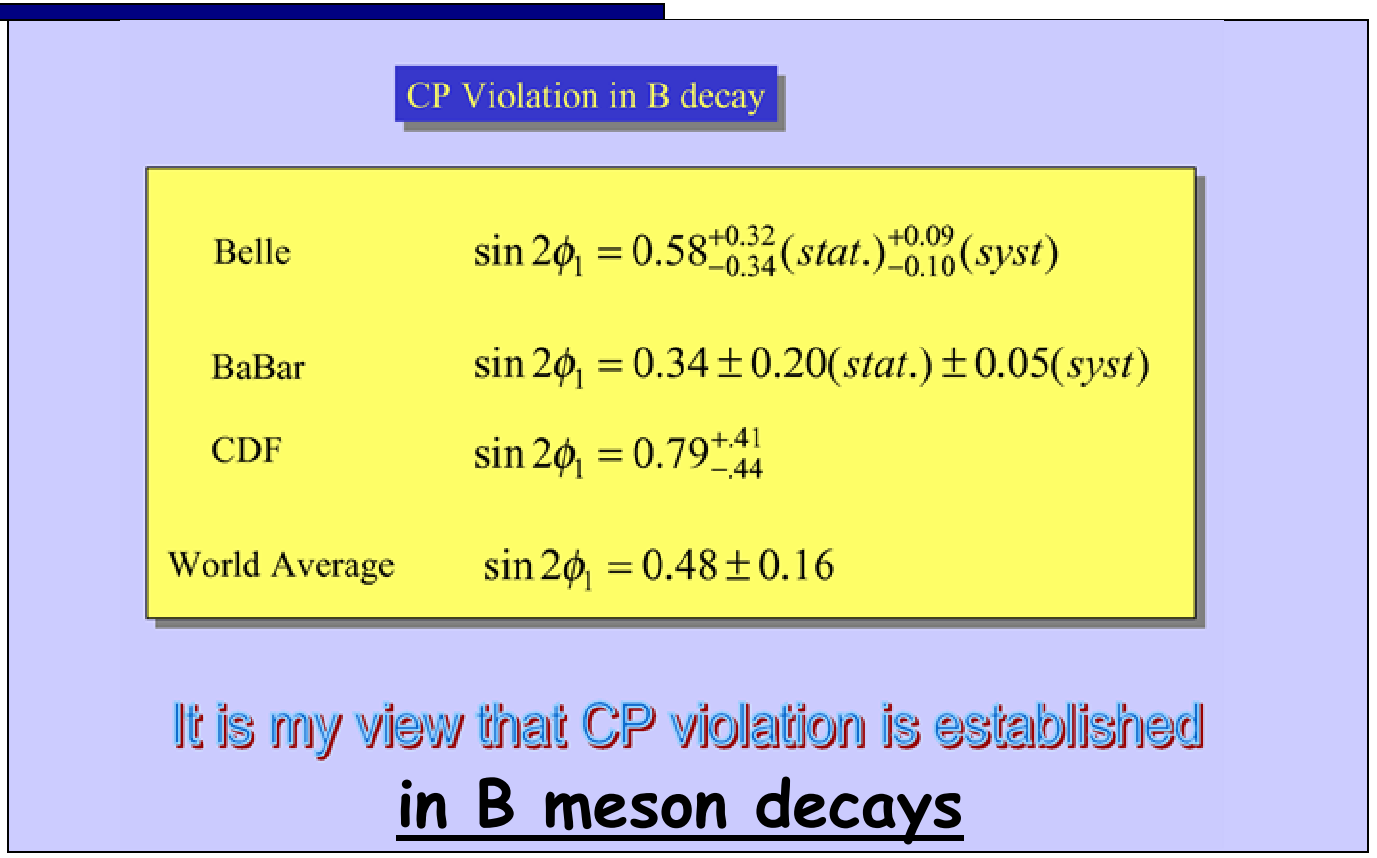
$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$S_{f_{CP}} - \frac{-2\,\mathrm{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

For modes in this talk: SM expectation is C=0, S=±sin2β

Rencontres de Moriond 2001:

A. I. Sanda



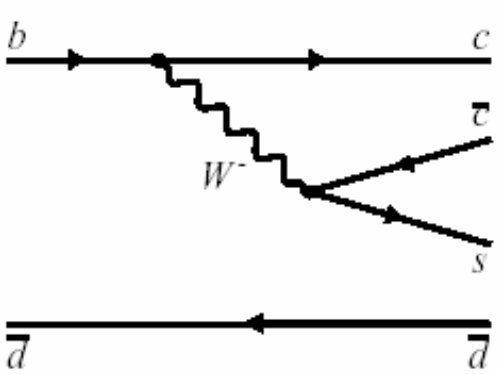
2001-2007:
1. Precision analysis of sin2β in golden modes
2. sin2β in tree vs penguin modes
3. Sign of cos2β

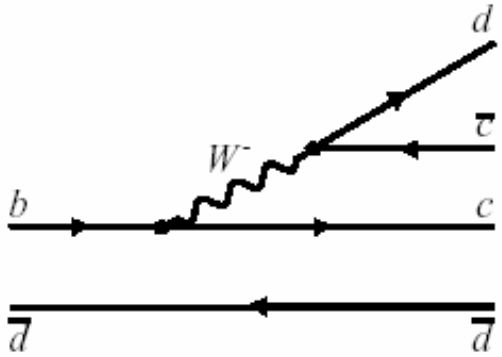
Several ways to measure sin2β

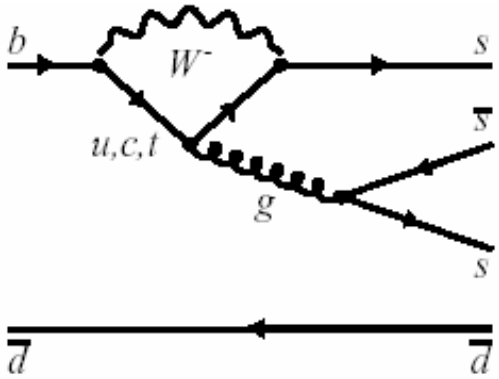
a) $b \to c\bar{c}s$ (charmonium)

b) $b \to c\bar{c}d$ charm (and charmonium)

c) Penguin-dominated $b \to d\bar{d}s, b \to s\bar{s}s$







$J/\psi K^0_S, \psi(2S)K^0_S, \chi_{c1}K^0_S,$ $\eta_c K^0_S, J/\psi K^0_L,$ $J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K^0_S,$ $K^0_S K^0_S K^0_S, \eta' K^0, K^0_S\pi^0,$ $\omega K^0_S, f_0(980)K^0_S$

Increasing tree diagram amplitude

Increasing sensitivity to new physics in CP measurements

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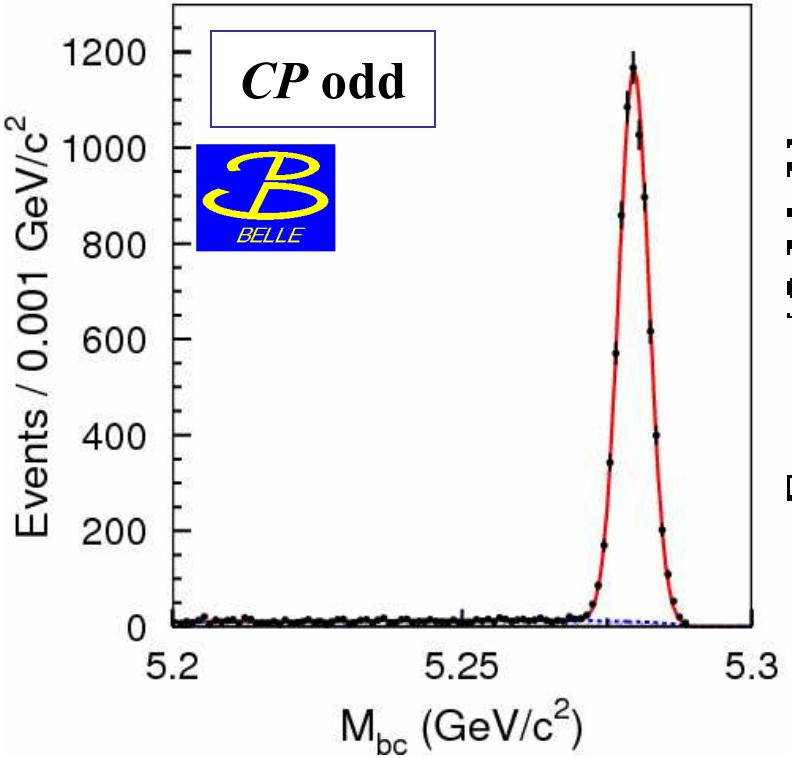
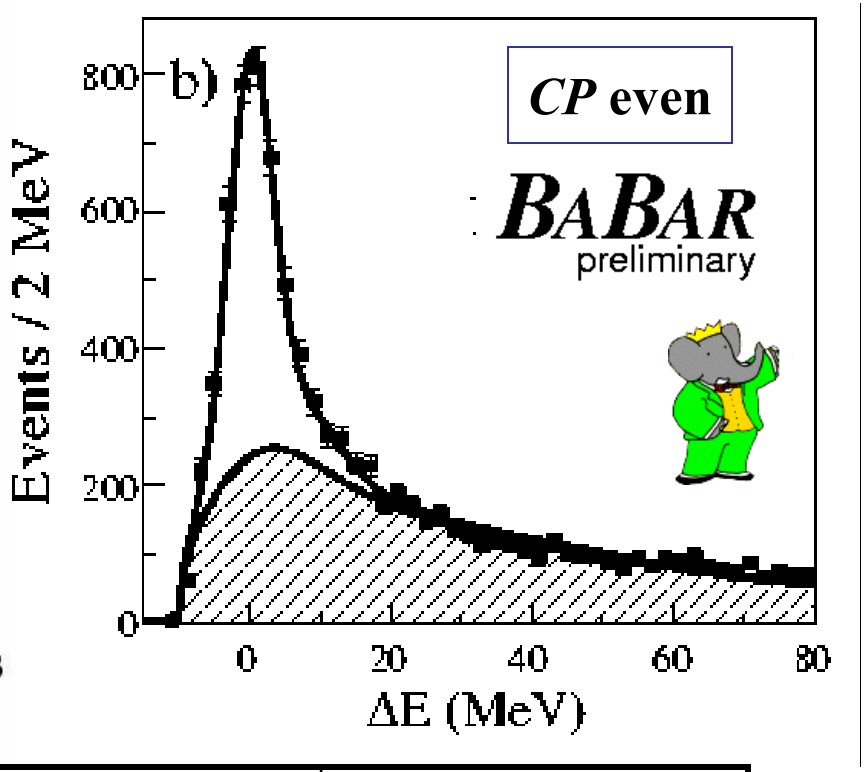
384 10^6 $B\bar{B}$

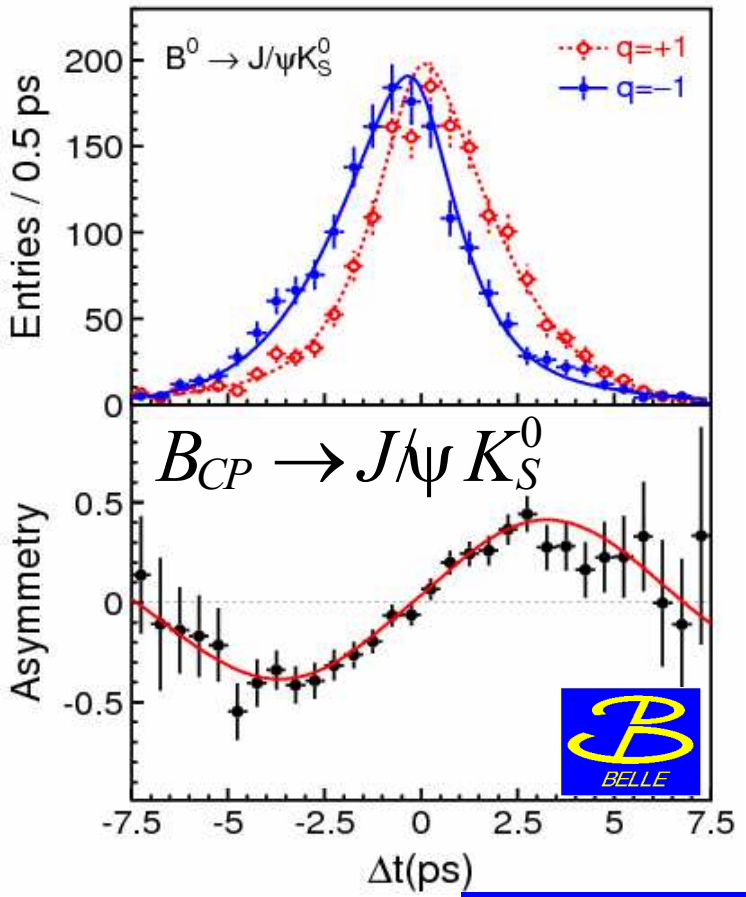
sin2β in B→(cc̄)K: "Golden" modes

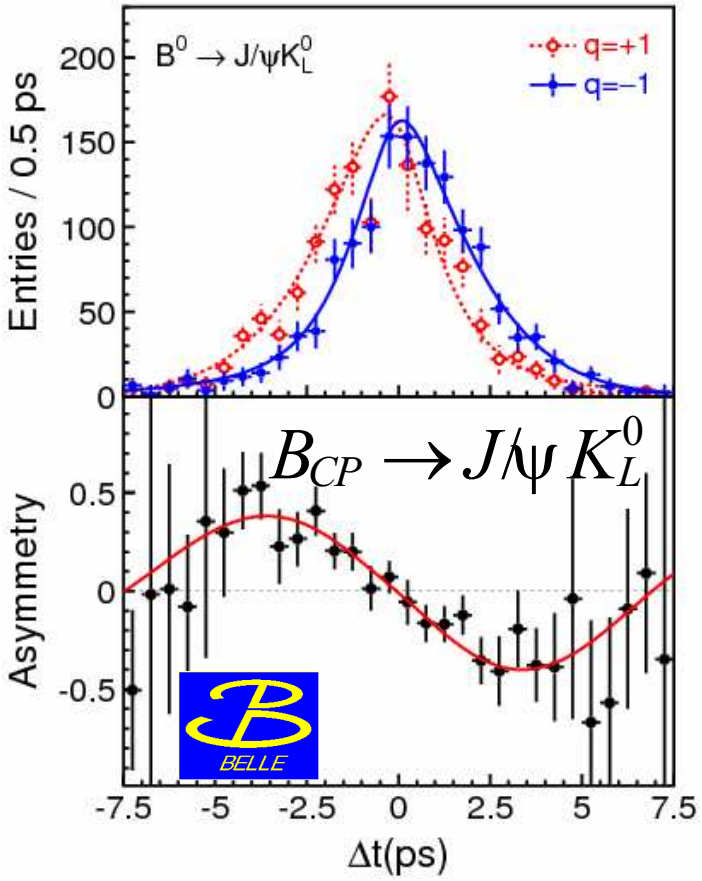




Nsig (Purity)	CP Odd	CP Even
BABAR	6900 (92%)	3700 (55%)
Belle	7482 (97%)	6512 (59%)

Belle results for $B \to J/\psi K_S$ and $B \to J/\psi K_L$

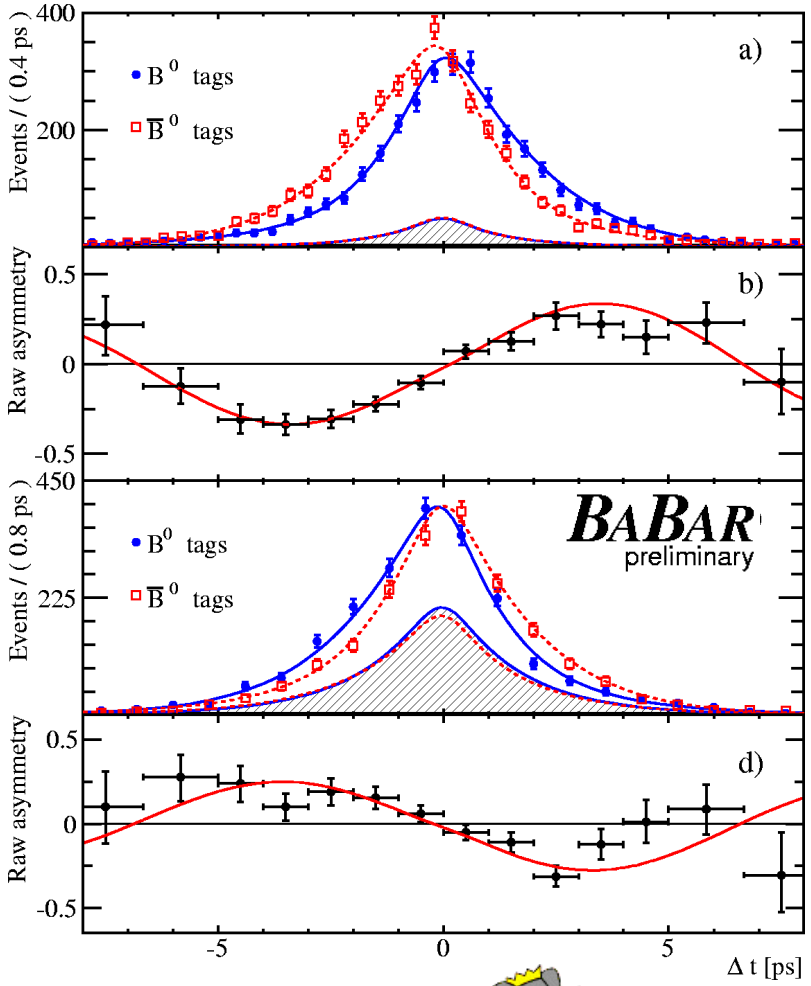




PRL 98, 031802 (2007)

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

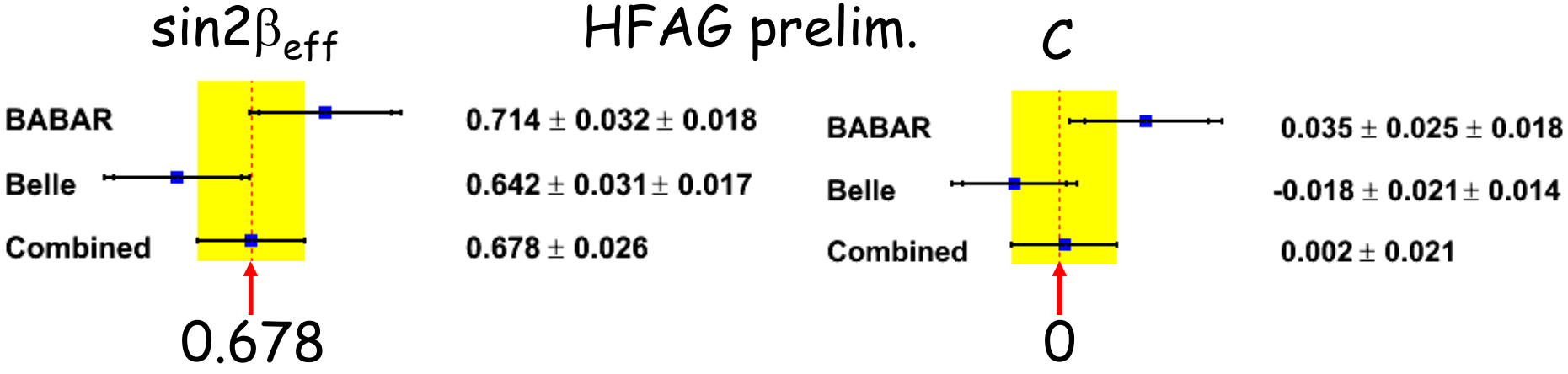
New BABAR results: sin2β measured including systematic errors for each decay channel



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

Submitted to PRL

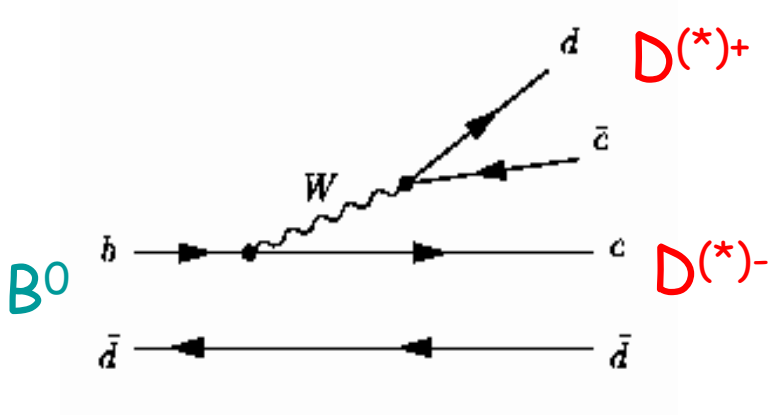
Summary of measurements of sin2β from B→(cc̄)K

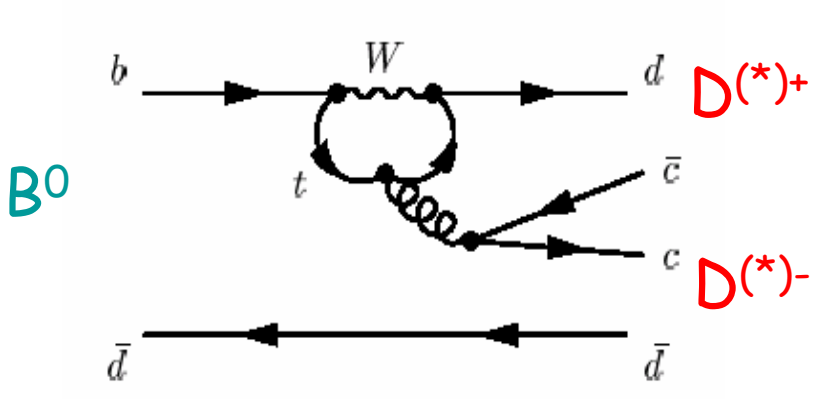


The measured sin2β$_{eff}$ equals sin2β to a very good precision

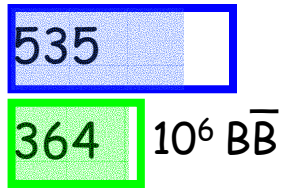
Ciuchini etal, PRL 95 221804 (2005)	0 ± 0.012
Boos etal, PRD 70 036006 (2004)	-(2.2 ± 2.2)x10-4
Li, Mishima, ph/0610120	$(9.3 \pm^{4}_{5})$x10-4

CP Violation in b→cc̄d decays: B→D(*)D(*)

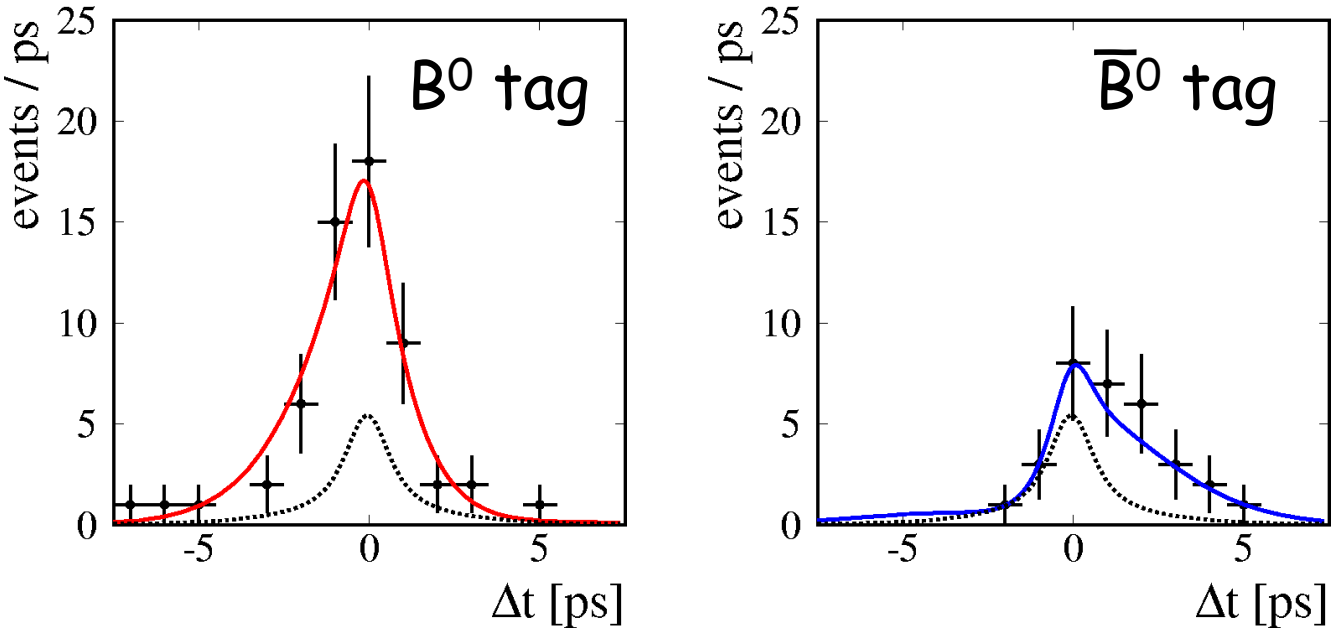




- TD asymmetry ~sin2β: B→D⁺D⁻: C=0, S=-sin2β
- Penguin contribution expected to be minimal
  - 2-10% [Phys.Rev.D61:014010,2000]
- Sensitive to new physics in loops



Belle: Evidence for large CPV in $B \to D^+D^-$



~150 signal events

$$\sin 2\beta_{eff} = +1.13 \pm 0.37 \pm 0.09$$
$$C = -0.91 \pm 0.23 \pm 0.06$$

- $(\sin 2\beta, C) = (0,0)$ point excluded at 4.1σ confidence

hep-ex/0702031, Submitted to PRL

BABAR does not confirm the large CP violation observed by Belle

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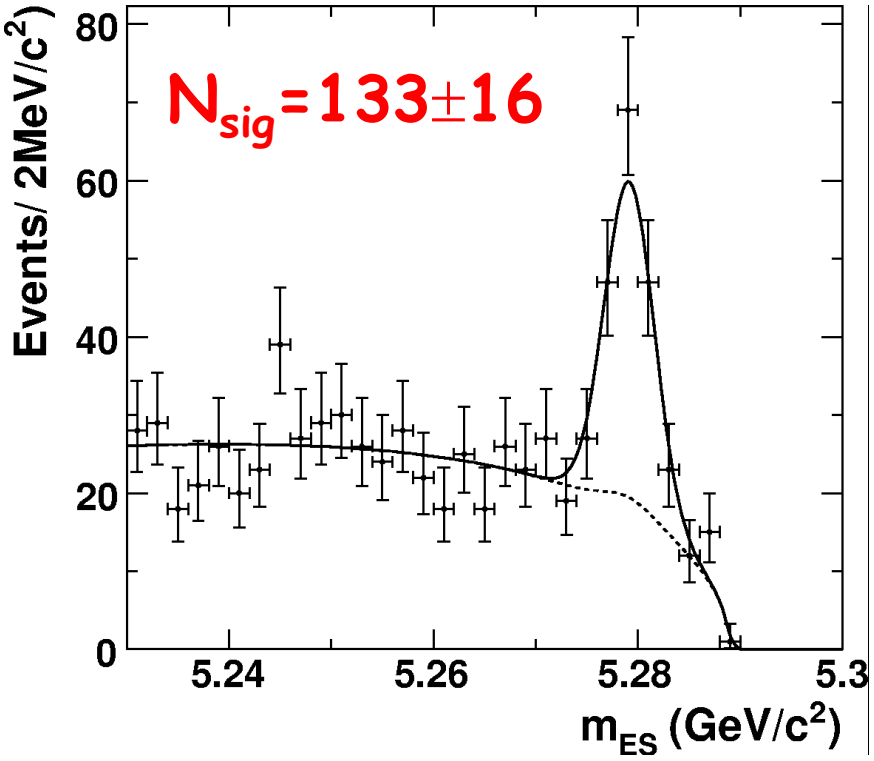
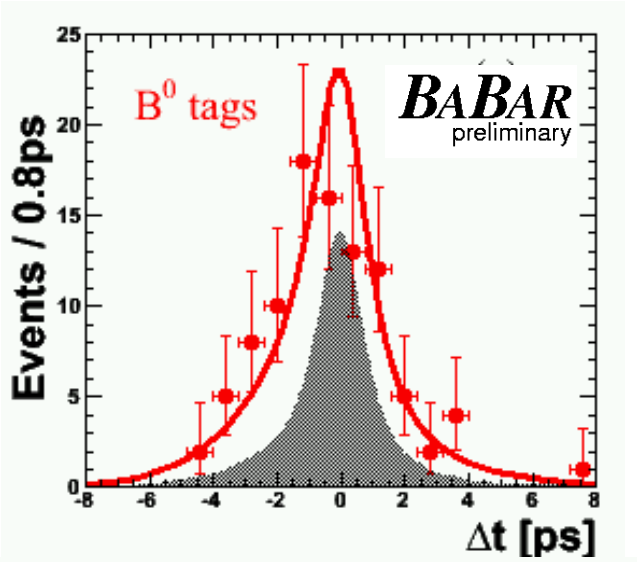
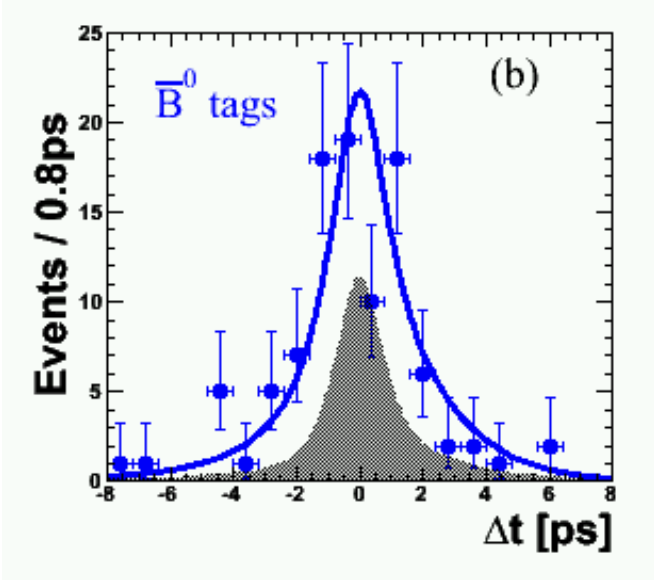
364 10^6 $B\bar{B}$

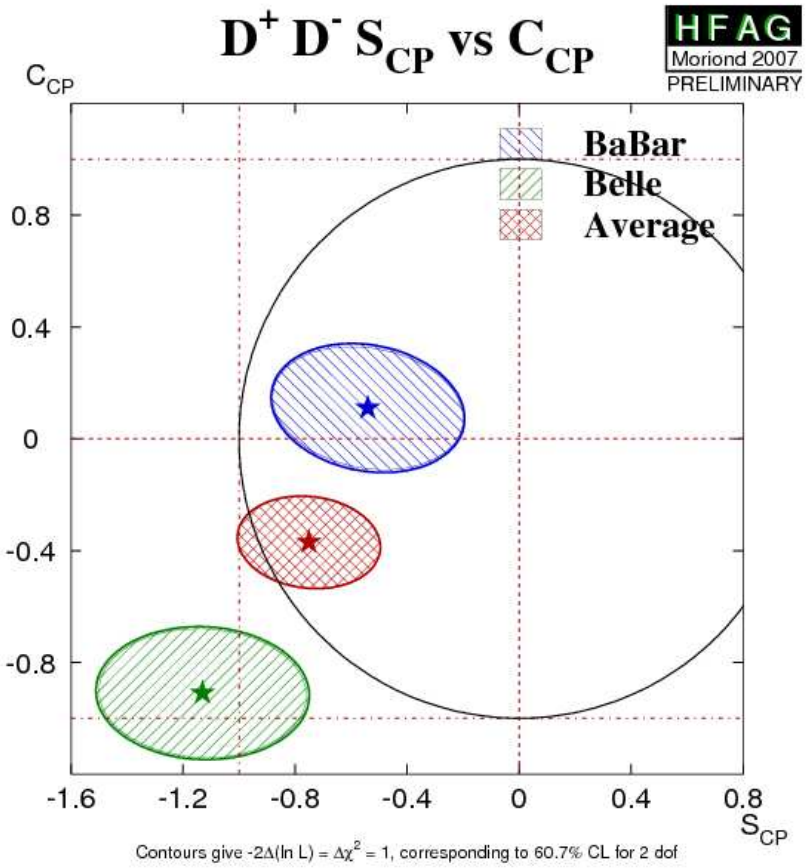


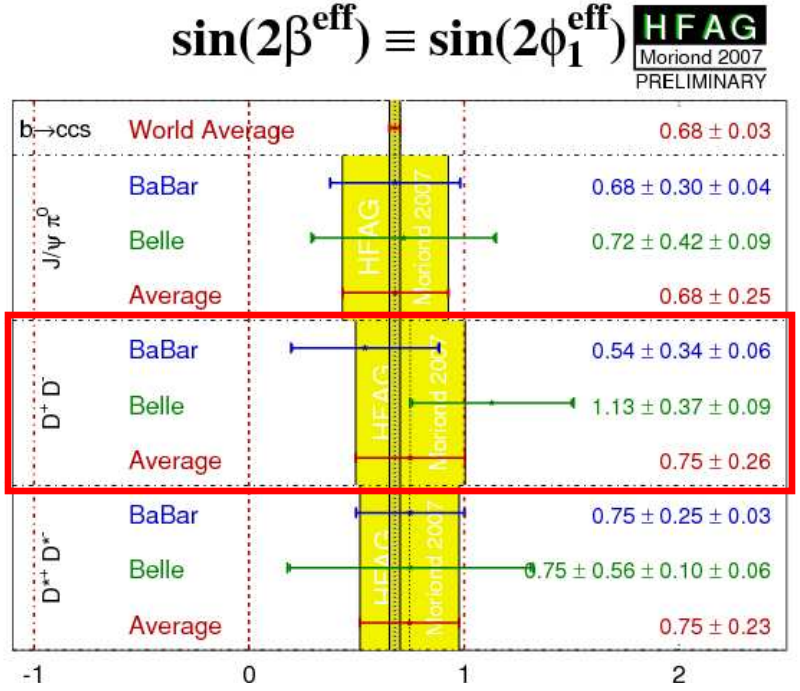


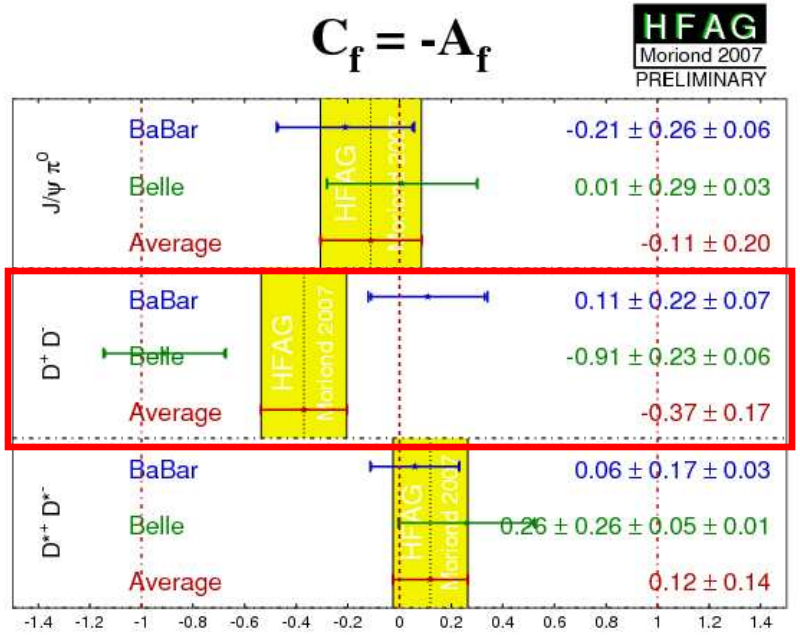


$$\sin\beta_{eff} = +0.54 \pm 0.34 \pm 0.06$$
$$C = 0.11 \pm 0.22 \pm 0.07$$

B→D⁺D⁻ Comparison ~3σ difference in (S,C)







- Handle B→D⁺D⁻ average with care given nonphysical result

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364 10^6 $B\bar{B}$

$B\to D^{*+}D^-$ and $B\to D^{*-}D^+$

- Not a CP eigenstate, analyze $B\to D^{*+}D^-$ and $B\to D^{*-}D^+$ separately

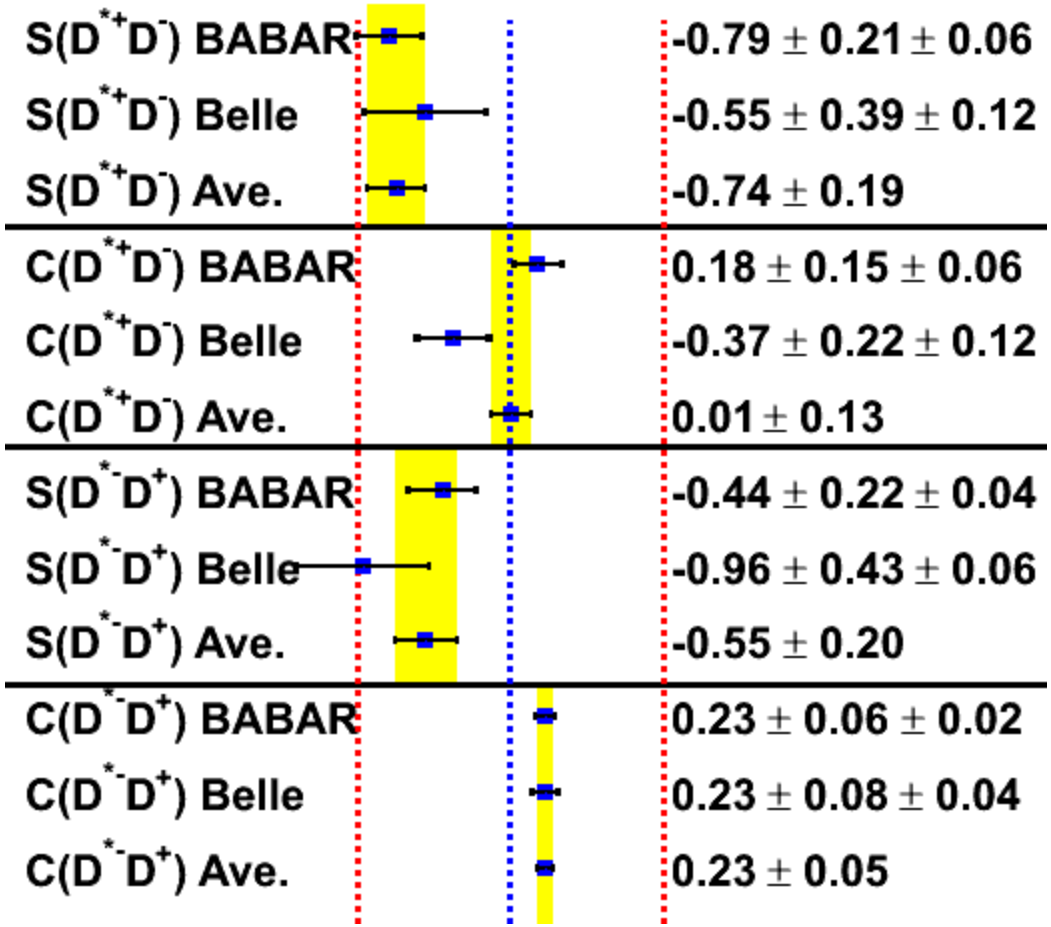
$$\frac{A(D^{*+}D^-)}{A(D^{*-}D^+)}=Re^{i\delta}$$

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

If no CPV:

$C_+ = -C_-$ and $S_+=-S_-$

(neglecting penguins)

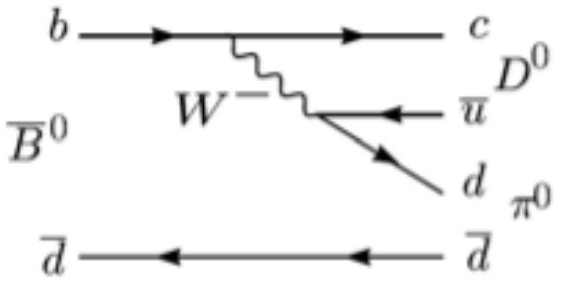


Signs for CPV: $S_+\neq S_-$ ~4σ

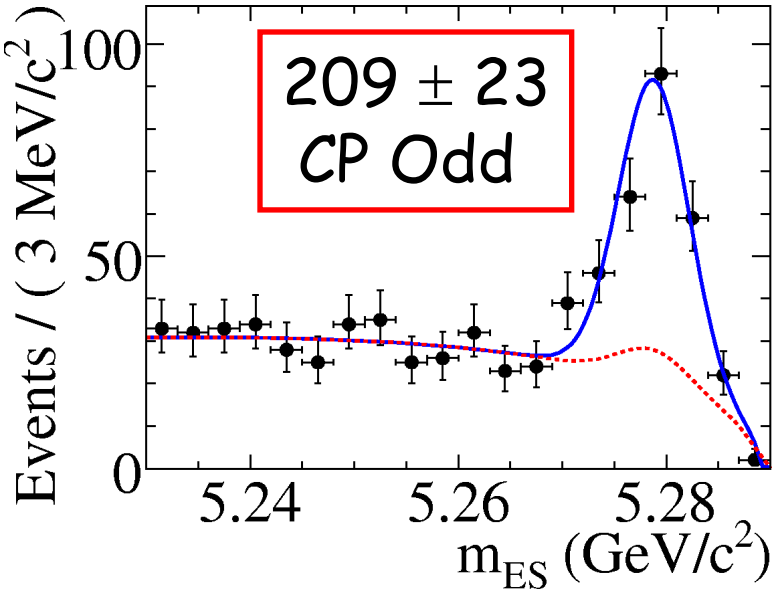
Updated results

New BABAR results: sin2β in $B \to D h^0$ using $D^0 \to K^+K^-$, $D^0 \to K_S\omega$, and $D^0 \to K_S\pi^0$

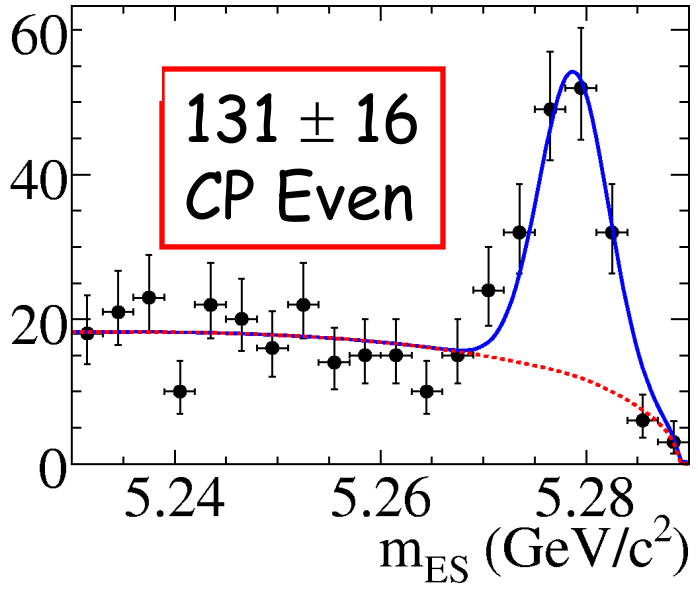
384 10^6 $B\bar{B}$



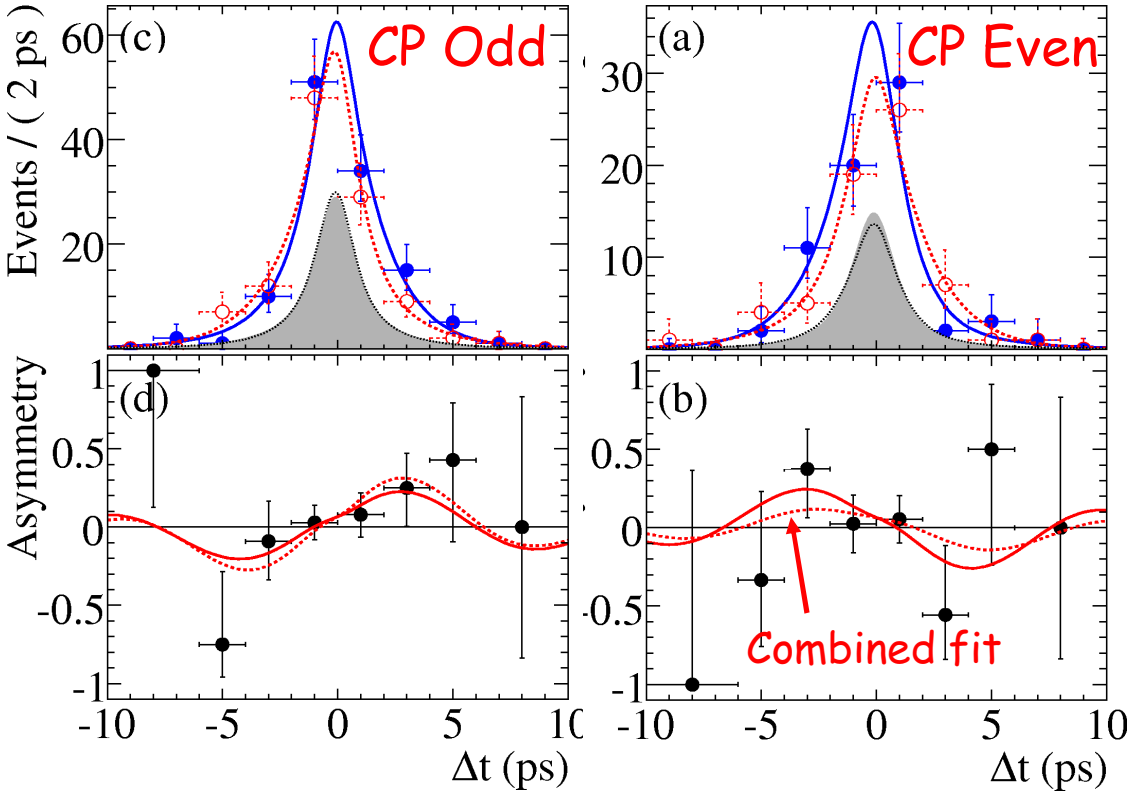
- No penguin diagrams
- DSCD contribution has small impact on measured CP ($\Delta\sin2\beta<0.05$)
- $D \to K_S\pi^+\pi^-$ previously used to measure cos2β

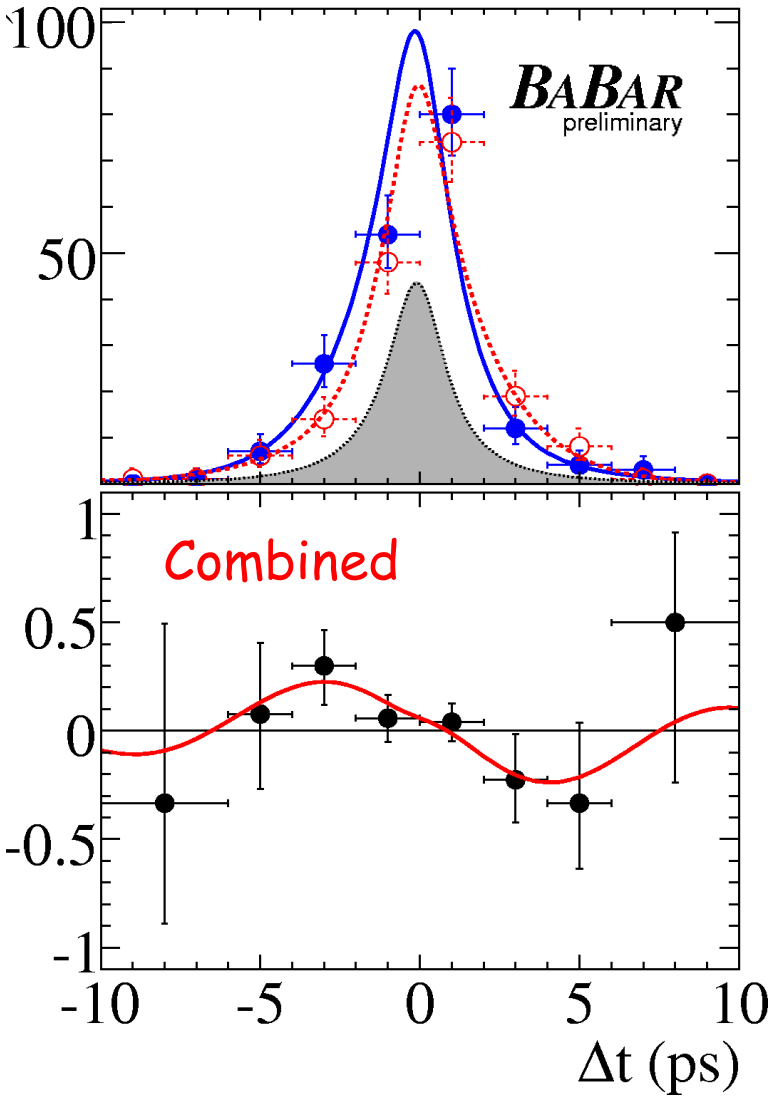


BABAR preliminary



CPV results: sin2β in B→Dh^0



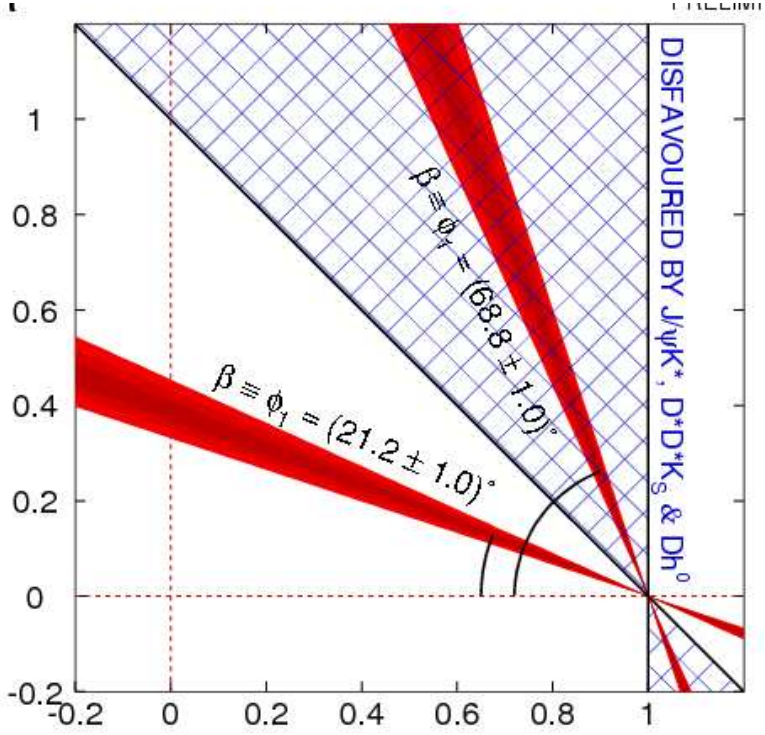


$$\sin 2\beta_{eff} = +0.56 \pm 0.23 \pm 0.05$$
$$C = -0.23 \pm 0.16 \pm 0.04$$

Measurements of the sign of cos2β: cos2β>0 from B→Dh, B→J/ψKπ, B→D*D*K$_S$

Different approaches determine that cos2β>0:

- $B^0 \to D^{(*)}h^0$ time-dependent Dalitz analysis.
  - Belle: 98.3% CL PRL 97, 081801 (2006)
  - BABAR: 87% CL hep-ex/0607105
- $B^0 \to D^{*+}D^{*-}K_S$ time-dependent Dalitz analysis.
  - BABAR: 94% CL hep-ex/0608016



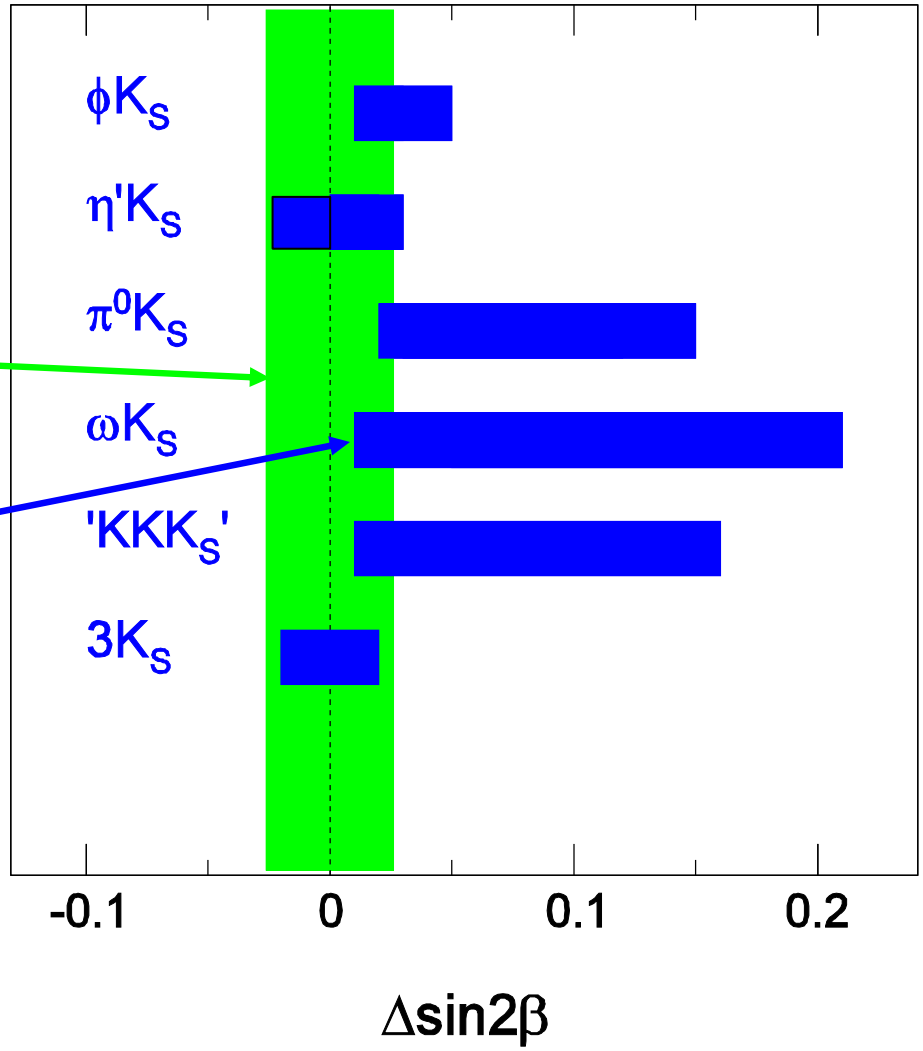
Resolve strong phase ambiguity to distinguish interference effects of cos2β>0 vs. cos2β<0

sin2β from charmless B decays

Compare sin2β measured in penguin modes to sin2β from $(c\bar{c})K$

sin2β experimental uncertainty from $(c\bar{c})K$

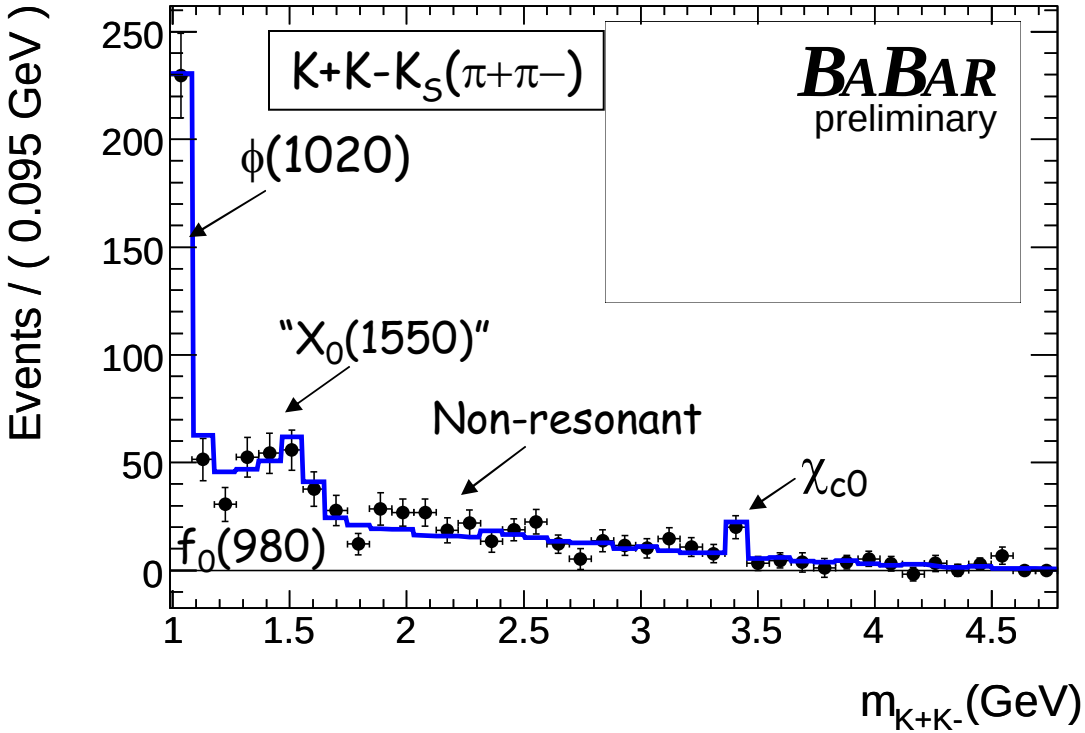
b→s penguin theory uncertainty



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

$B \to K^+K^-K^0$ ($B \to \phi K^0$ and friends)

$B \to K^+K^-K^0$ final state has mixed CP



- Differing approaches to CP analysis:
  - Belle: Resonant $B \to \phi K$ and nonresonant $K^+K^-K_S$ analyses
  - BABAR: β from time-dependant Dalitz analysis

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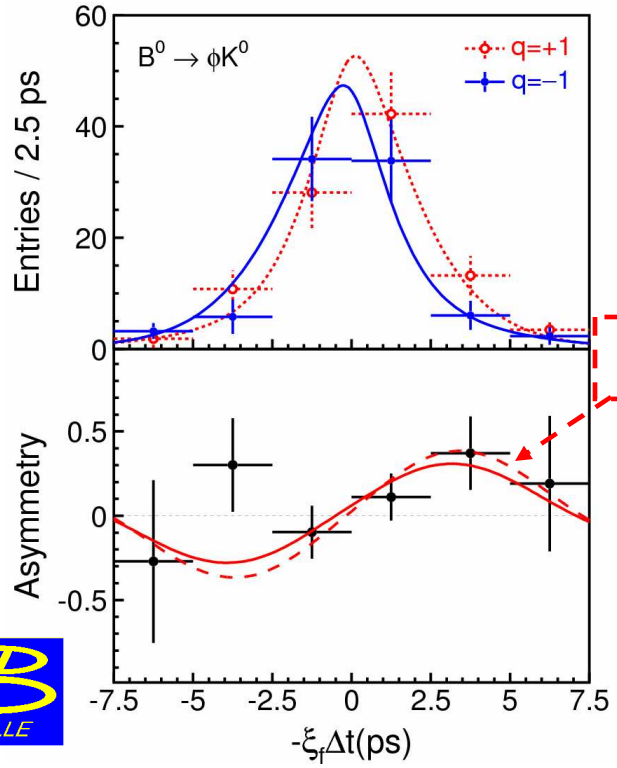
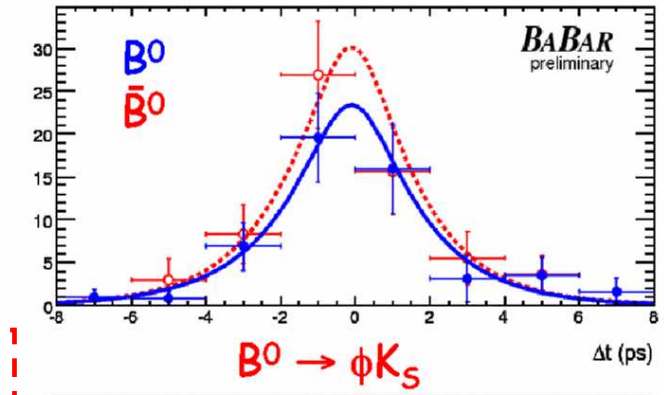
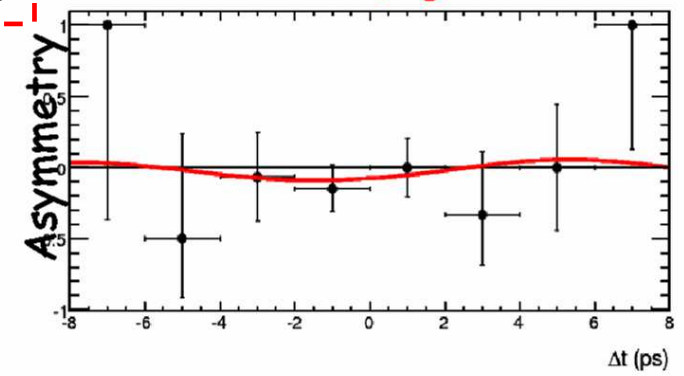
384 10^6 $B\bar{B}$

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



S=0.642, C=0





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

PRL 98, 031802 (2007)

$\beta_{eff} = +0.06 \pm 0.16 \pm 0.05$
$C = -0.18 \pm 0.20 \pm 0.10$

hep-ex/0607112

$B \to K_S K_S K_S$ is a pure CP eigenstate- No Dalitz analysis required

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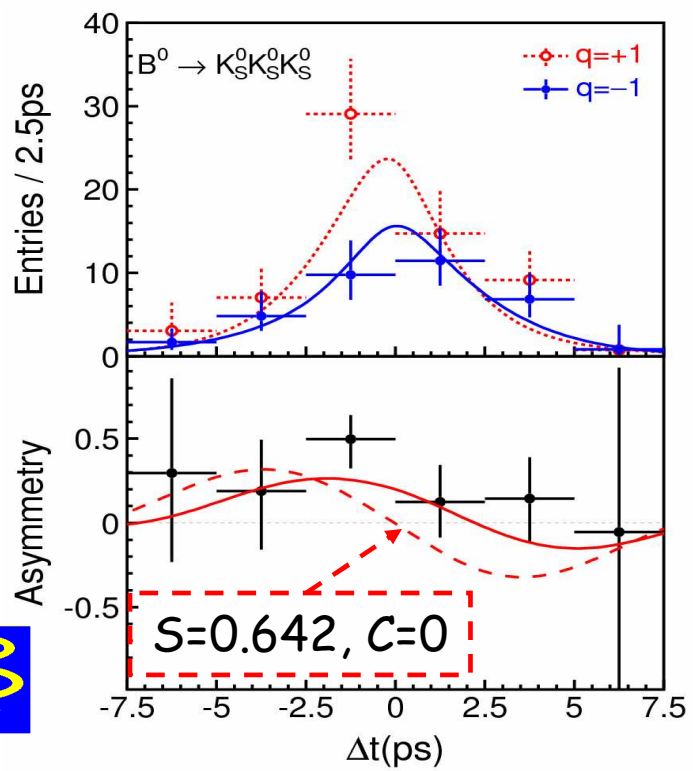
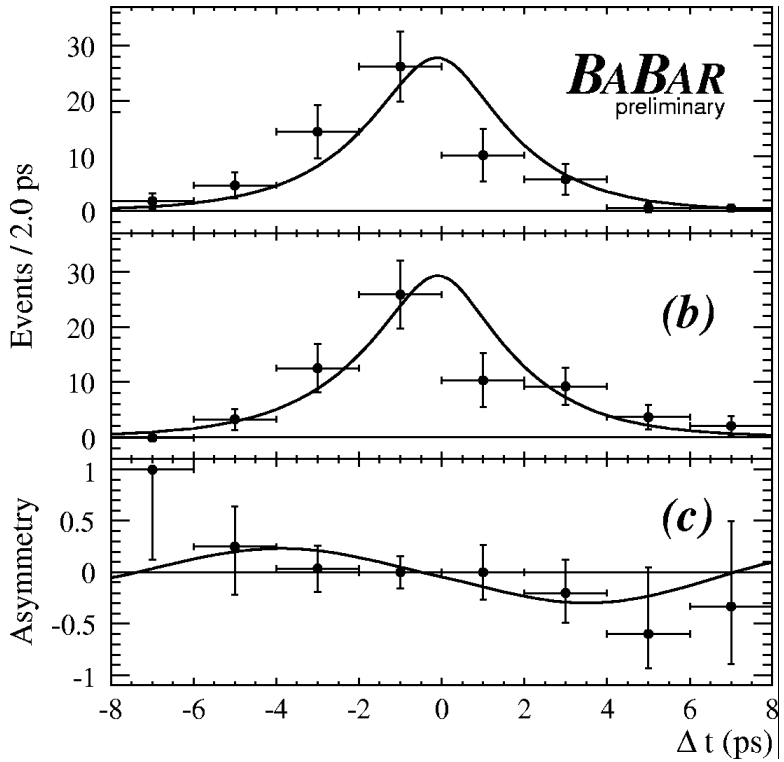
384 10^6 $B\bar{B}$





$\sin 2\beta_{eff} = +0.30 \pm 0.32 \pm 0.08$

$C = +0.31 \pm 0.20 \pm 0.07$

PRL 98, 031802 (2007)

$\sin 2\beta_{eff} = +0.71 \pm 0.24 \pm 0.04$

$C = +0.02 \pm 0.21 \pm 0.05$

hep-ex/0702046 (submitted to PRL)

$\eta' K_S$ and $\eta' K_L$ event samples: >3000 $\eta' K$ events for CP analysis

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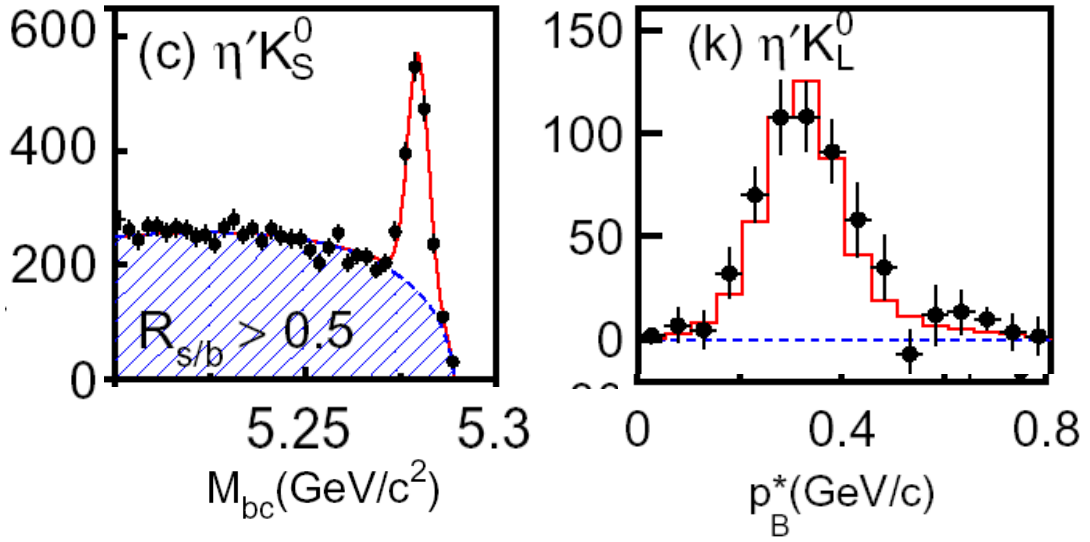
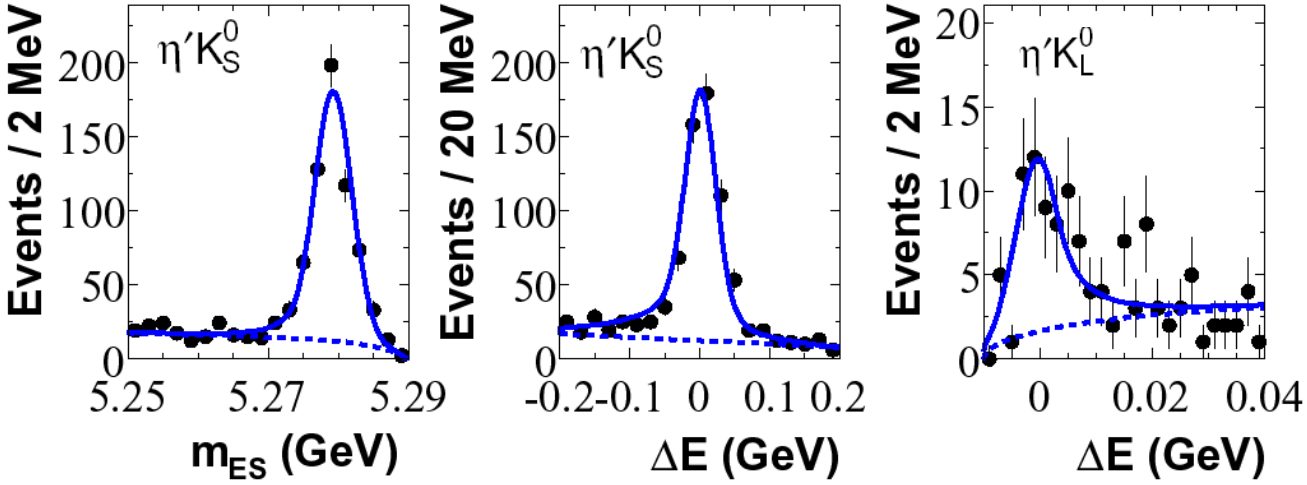
384 10^6 $B\bar{B}$

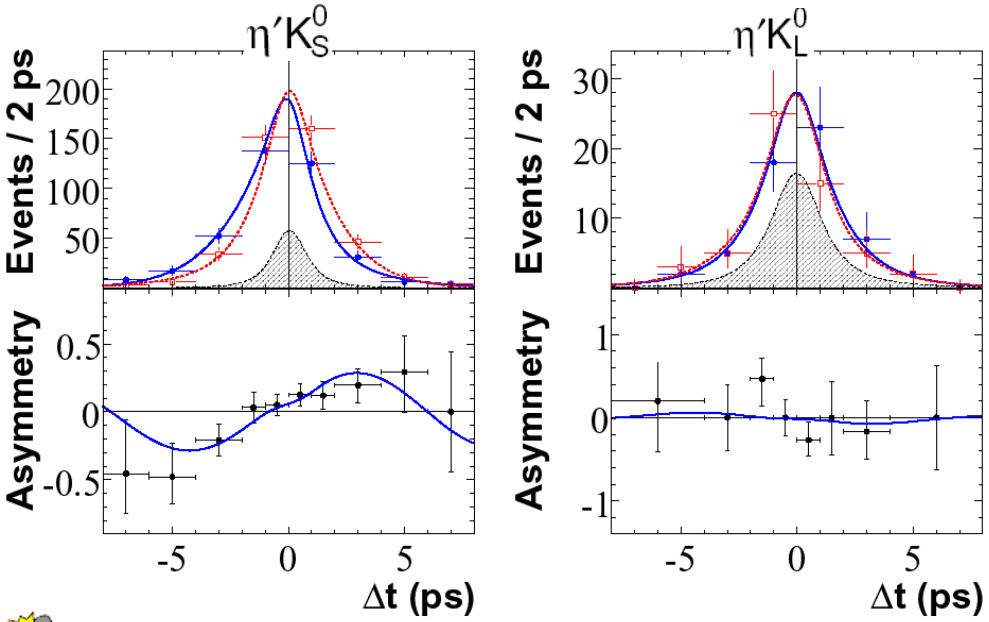
~1900 signal events



~1250 signal events

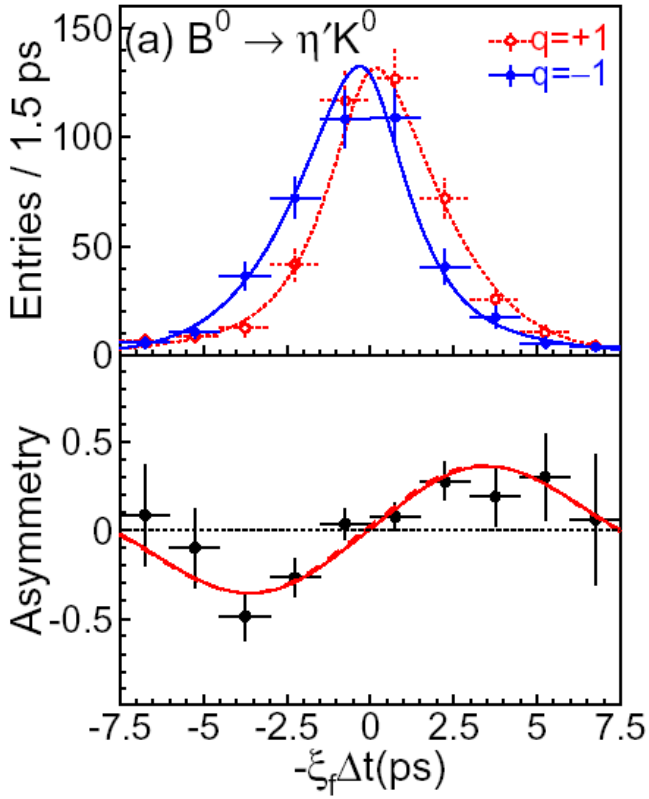


B→η'K Results: CP Violation established in charmless B decays



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

PRL 98, 031801 (2007)

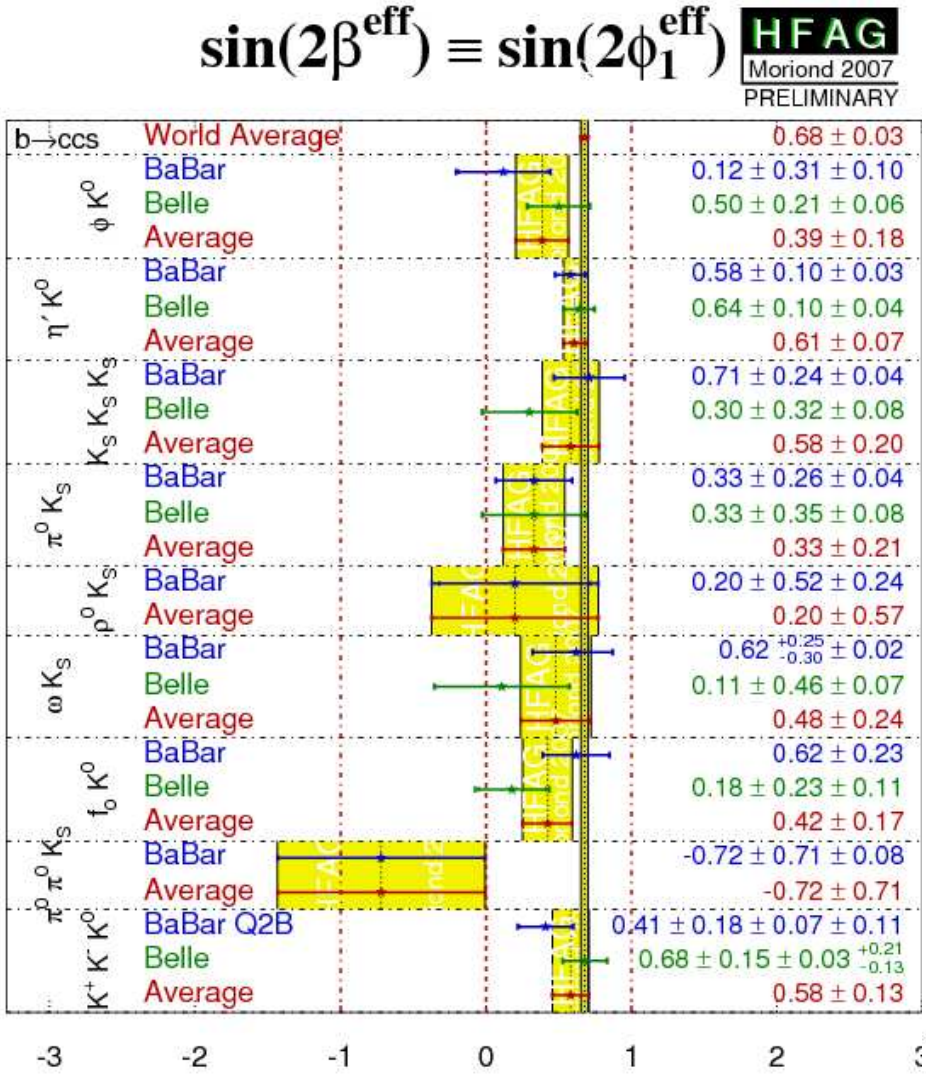


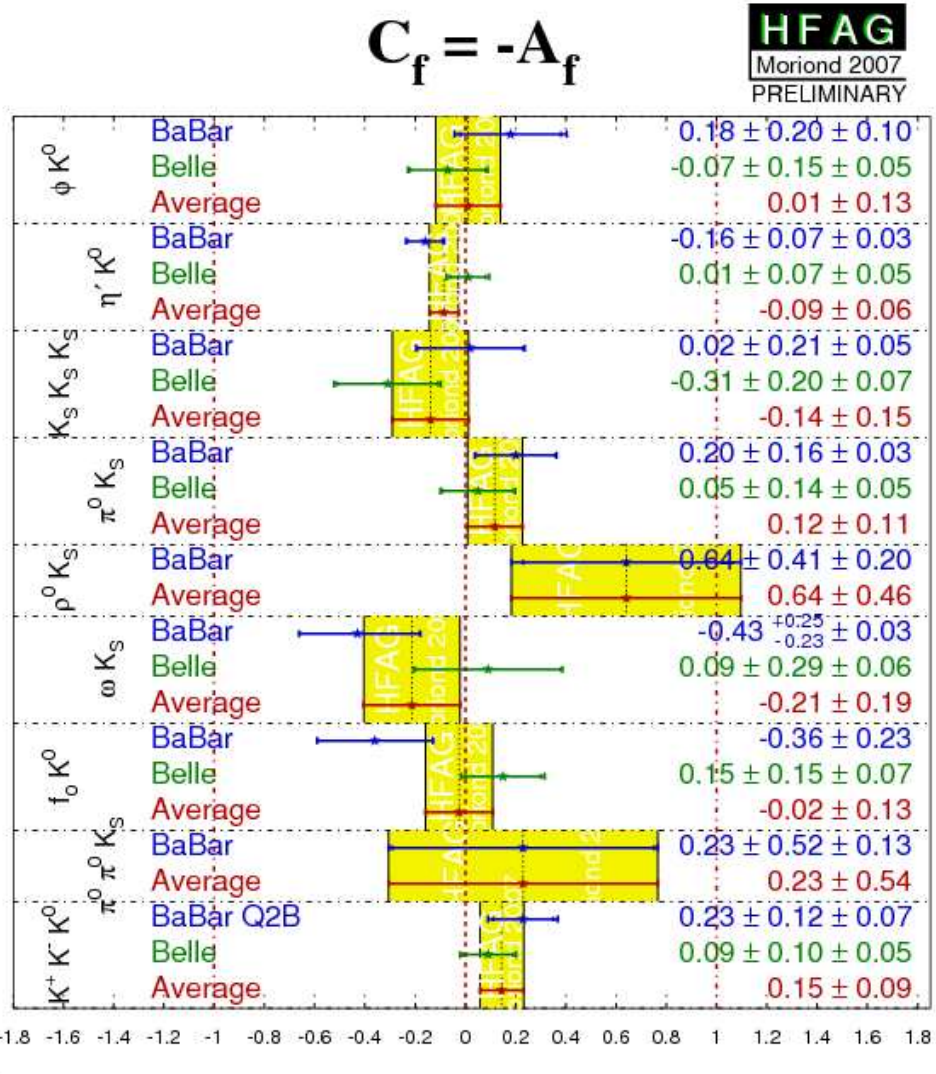
$\sin 2\beta_{eff} = +0.64 \pm 0.10 \pm 0.04$
$C = +0.01 \pm 0.07 \pm 0.05$

PRL 98, 031802 (2007)

Both experiments measure $\sin 2\beta_{eff}$ with >5σ significance

CPV in charmless B decays: Hints that "sin2β" < sin2β(B→(cc̄)K) persist





Conclusion: sin2β measurements are precise tests of CKM picture of CP Violation

- Updated results on sin2β in $B \to (c\bar{c})K$ and $B \to D^{(*+)}D^{-}$ from BABAR.
  - Uncertainly on combined Belle+BABAR sin2β from $B \to (c\bar{c})K$ now 4% (>900M BB total)
- $B \to D^{+}D^{-}$ puzzle. Evidence for CPV in $B \to D^{*}D$

- Ambiguity broken: cos2β>0

$$\beta = (21.3 \pm 1.0)^{\circ}$$

- Hints of difference between sin2β in trees and penguins persists:

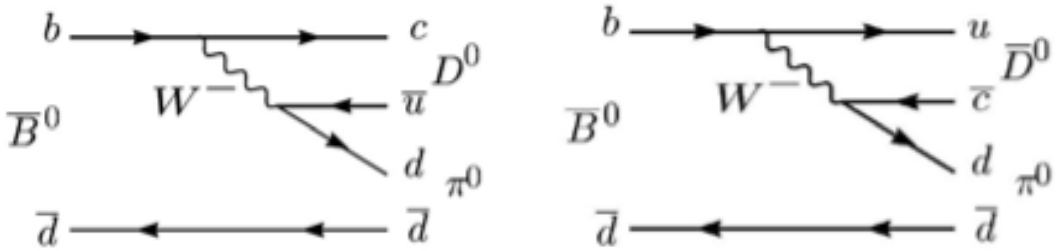
$$\Delta S = 0.15 \pm 0.05$$ [very naïve average]

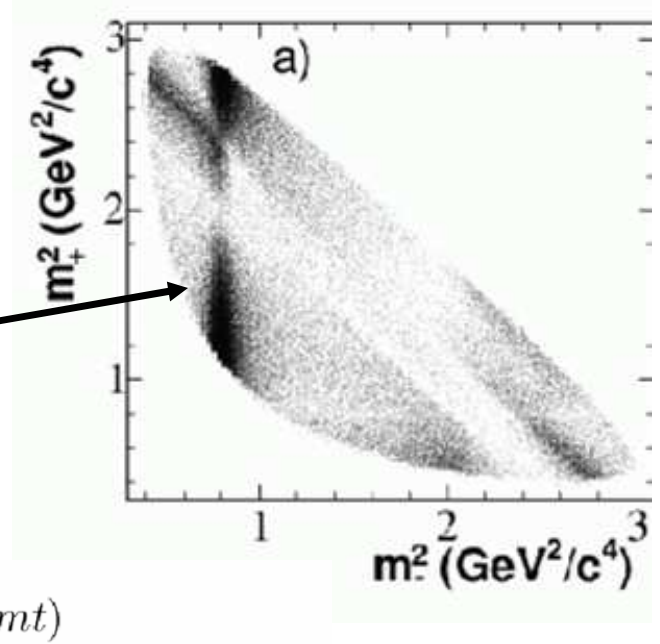
Backup slides

B→Dh⁰ (h⁰=π⁰,η,η',ω) decays provide more stringent constraint on cos2β

386

311





- Common final state: $D \to K_S\pi^+\pi^-$
- Resolve strong phase, distinguish cos2β>0 vs cos2β<0

$$\mathcal{P}_\pm = \frac{1}{2}e^{-\Gamma t}|A|^2 \cdot \Big[(|A_{\bar{D}}|^2 + |A_D|^2) \mp (|A_{\bar{D}}|^2 - |A_D|^2)\cos(\Delta m t) \pm 2\eta_{h^0}(-1)^L \mathrm{Im}\left(e^{-2i\beta} A_D A^*_{\bar{D}}\right)\sin(\Delta m t)\Big]$$

	N(sig)	sin2β	cos2β	CL cos2b>0
Belle	325±31	0.78 ± 0.44 ± 0.22	1.87 $\pm^{0.40}_{0.53}\pm^{0.22}_{0.32}$	98.3%
BABAR	384±28	0.45 ± 0.35 ± 0.05 ± 0.07	+0.54 ± 0.54 ± 0.08 ± 0.18	87%

CPV in charmless B decays: Hints that "sin2β" < sin2β(B→(cc̄)K) persist