[More details in Session IV plenary talks]

Measurements of sin(2β) with charmonium and penguin decays

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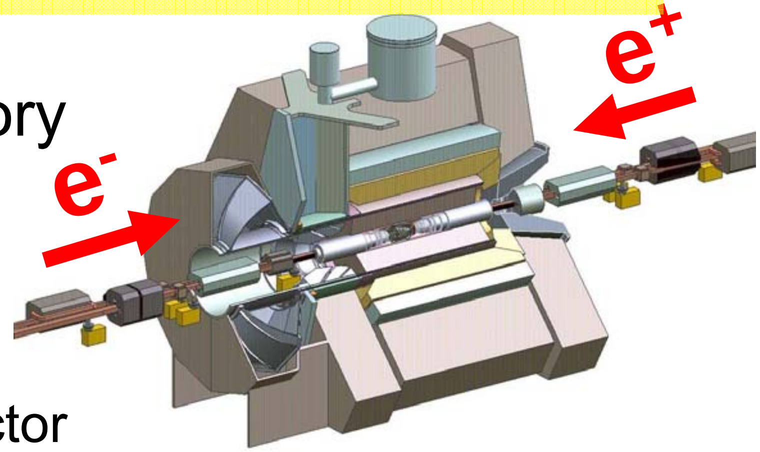
Introduction

- BaBar detector at the SLAC B-factory

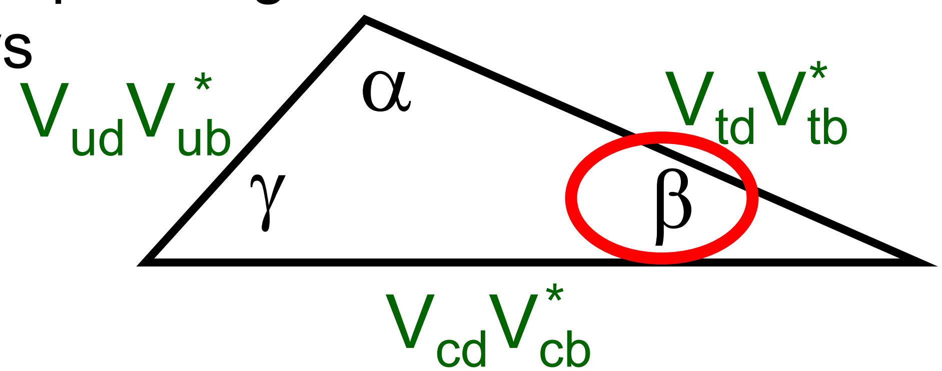
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$



- Physics Goal
  - Study CP-violation in the B-meson sector

- 9.0 GeV e^-, 3.1 GeV e^+
- 311.2 fb^{-1} delivered

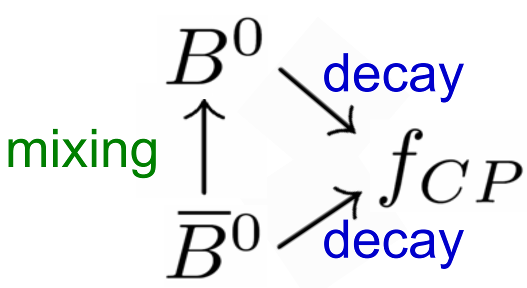
- Key measurement - the angle β through the study of B^0 meson decays
  - Precise test of the SM
  - Searches for New Physics



Experimental Technique

- Study CP violation through measurements of the time-dependent CP asymmetry $A_{CP}(t)$

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



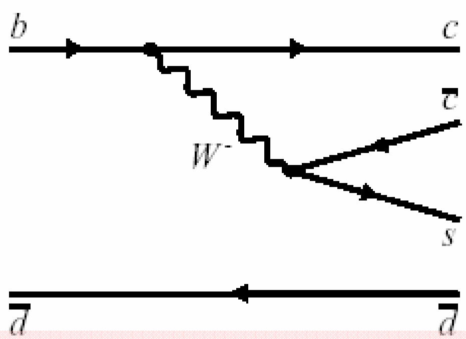
- Decay into CP eigenstate f_{CP} after time t between two B decays
- A_{CP} determined from unbinned maximum likelihood fit to time distributions of B^0 and $\overline{B}^0$ tagged events

- Unless otherwise stated, all measurements presented here are based on a dataset of 232×10^6 $B\overline{B}$ events (~211fb^{-1})

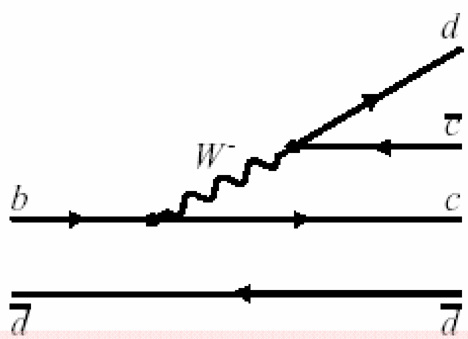
Independent measurements of β

- Can independently measure β using three different categories of B^0 decays

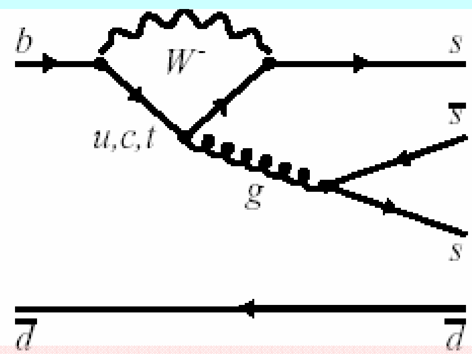
(a) Charmonium
$b \to c\bar{c}s$



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



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



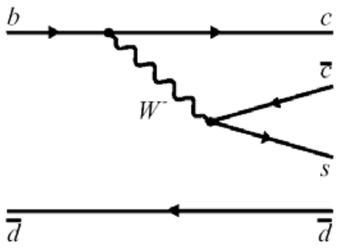
(a) $J/\psi\ K_S$, $\psi(2S)\ K_S$, $\chi_{c1}\ K_S$, $\eta_c\ K_S$, $J/\psi\ K_L$, $J/\psi\ K^{*0}\ (K^{*0} \to K_S\,\pi^0)$

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

(c) $\varphi\ K^0$, $K^+ K^- K_S$, $K_S K_S K_S$, $\eta'\ K^0$, $K_S\,\pi^0$, $\omega\ K_S$, $f_0(980)\ K_S$,

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

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

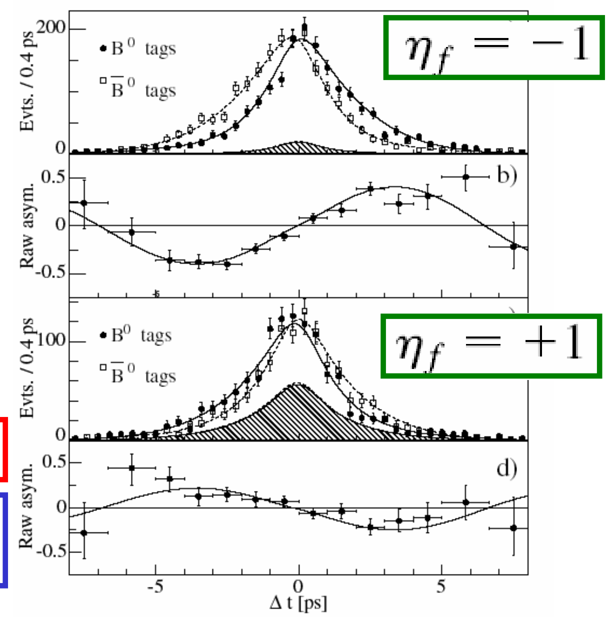


- "Golden modes" dominated by $b \to c\bar{c}s$ tree level diagram with internal W boson emission
- Leading penguin contribution to the final state has the same weak phase as the tree diagram

- To a good approximation: $C_f = 0$

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

 Experimentally clean (J/ψ resonance) with relatively large branching fractions (~10e-4)
- Unbinned maximum likelihood fit to the Δt distribution



PRL **94,** 161803 (2005)

$\sin 2\beta = 0.722 \pm 0.040(\text{stat}) \pm 0.023(\text{syst})$

Measuring the sign of cos(2β)

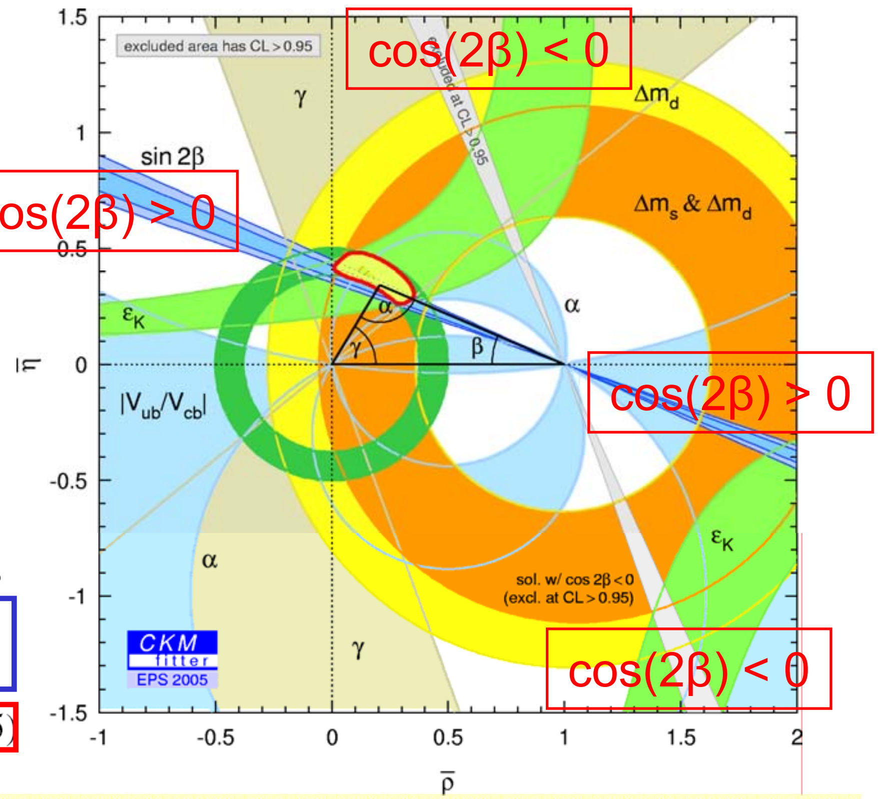
$$B \to J/\psi K^{*0}(K^0_S \pi^0)$$

- Measurement of sin(2β) leads to 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).
- Time-dependent angular analysis using 81.9 fb^{-1} measures

$$cos2\beta = +2.72^{+0.50}_{-0.79} \pm 0.27$$

PHYSICAL REVIEW D **71,** 032005 (2005)

- This excludes negative solutions of cos(2β) at 86% CL.

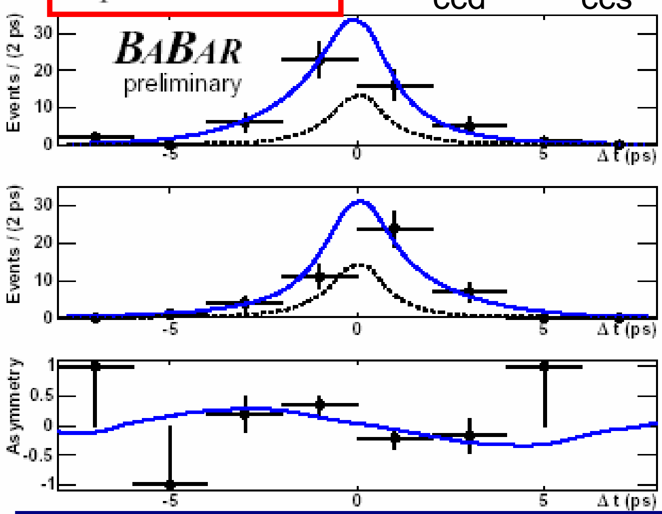


Constraints in the (ρ,η) plane not including the angle measurements in the global fit.

b →c$\bar{c}$d decays
$B^0 \rightarrow D^{*+}D^{*-}$ and $B^0 \rightarrow J/\psi\pi^0$

- b→c$\bar{c}$d tree amplitudes have same weak phase as b→c$\bar{c}$s.
- b→c$\bar{c}$d penguins have different weak phase than the tree amplitude
- If there are significant penguin amplitudes in b→c$\bar{c}$d decays then

hep-ex/0507074 $S_{ccd} \neq S_{ccs}$ and $C_{ccs} \neq 0$ [Grossman, Worah. Phys Lett B 395 241 (1997)]



$$C_{J/\psi\,\pi^0} = -0.21 \pm 0.26(\mathrm{stat}) \pm 0.09(\mathrm{syst}),$$
$$S_{J/\psi\,\pi^0} = -0.68 \pm 0.30(\mathrm{stat}) \pm 0.04(\mathrm{syst}),$$

- $B^0 \rightarrow D^{*+}D^{*-}$: admixture of CP-odd and CP-even components. CP-odd fraction extracted by means of a transversity analysis

$$f_{\mathrm{odd}} = 0.125 \pm 0.044 \pm 0.070$$

PRL **95,** 151804 (2005)

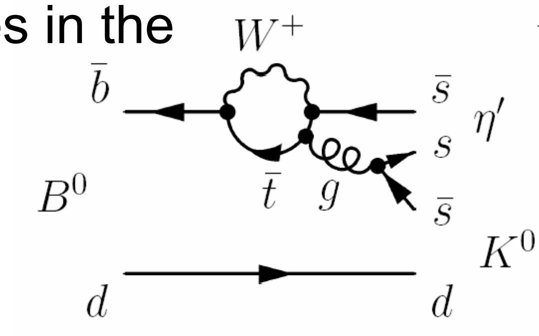
$$C_+ = 0.06 \pm 0.17(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$
$$S_+ = -0.75 \pm 0.25(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$

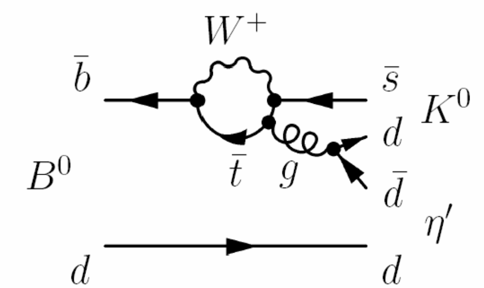
- In agreement with SM expectations

Searches for New Physics in penguin decays

- SM predicts the amplitude of CP violation in $b \to s\bar{q}q\ (q = d, s)$ charmless hadronic final states $\sin 2\beta_{\text{eff}}$ to be approximately $\sin 2\beta$
- $b \to s\bar{q}q$ dominated by one-loop transitions
  - Potentially accommodate large virtual particle masses
  - Contributions from physics beyond the SM could invalidate this ⇒ sensitivity to New Physics
- Modes which are noted as having small theoretical uncertainties in the measurement of β_{eff} are
  - $B^0 \to \phi K^0$
  - $B^0 \to K_S K_S K_S$

Phys. Lett. B **596**, 163 (2004)





$B^0 \to \eta' K^0$ decay via internal gluonic penguin.

Colour-supressed tree diagram not shown

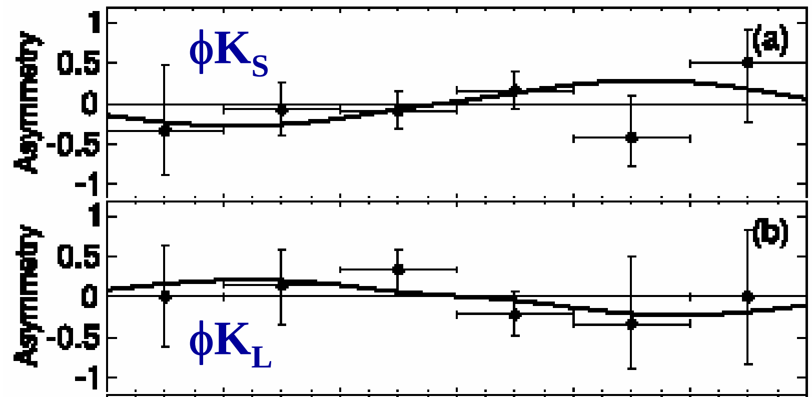
$B^0 \rightarrow \phi K^0$

PHYSICAL REVIEW D **71,** 091102 (2005)

- Almost pure $b \longrightarrow s\bar{s}s$ penguin
- Theoretical prediction:
  - $\beta_{J/\psi Ks}$ - $\beta_{\phi Ks}$ ~ few %

[e.g. Grossman,Ligeti,Nir,Quinn: PRD 68 015004 (2003)]

- Experimentally very clean:
  - narrow ϕ resonance allows powerful background suppression.
- Small BF ($\approx$ 8 x 10^{-6})
- Combined ϕK_S and ϕK_L fit
- Measured sin($2\beta_{eff}$) consistent within 1σ of sin(2β) from $b \longrightarrow c\bar{c}s$



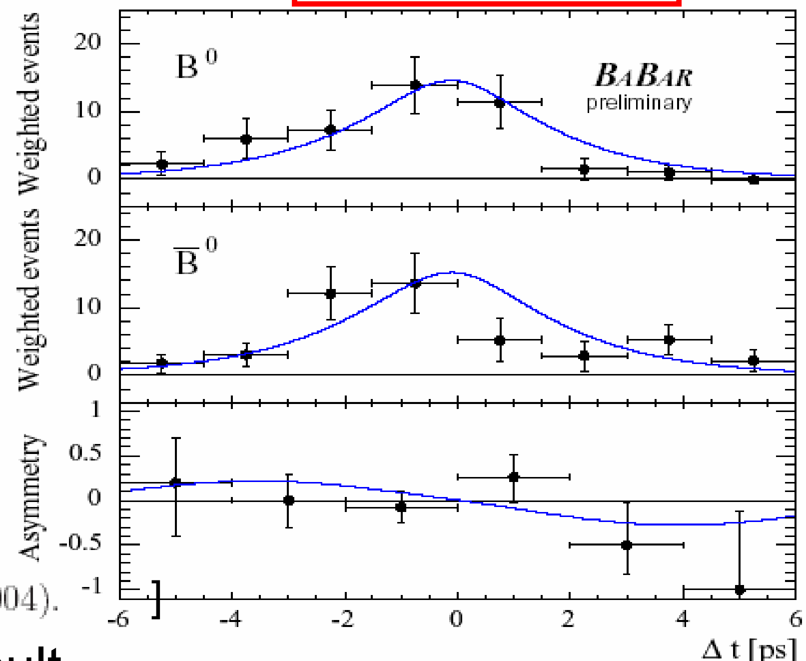
Enhanced by a cut on the likelihood ratio.

	ϕK^0_S	ϕK^0_L
$\sin 2\beta_{\rm eff}$	$+0.50 \pm 0.25^{+0.07}_{-0.04}$	
$f_{\rm even}$	0	1
S	$+0.50 \pm 0.25^{+0.07}_{-0.04}$	
C	$0.00 \pm 0.23 \pm 0.05$	
Yield	114 ± 12	98 ± 18

$B^0 \rightarrow K_S K_S K_S$

hep-ex/0507052

- Reconstruct B^0 with two $K_S \rightarrow \pi^+\pi^-$, one $K_S \rightarrow \pi^0\pi^0$
- Experimentally challenging
  - Absence of charged tracks originating from B^0 decay vertex
  - B^0 decay vertex uses K_S pseudo particles and beam spot constraint
    - Developed for the $B^0 \rightarrow K_S\pi^0$ analysis: Phys. Rev. Lett. **93**, 131805 (2004).
- Combine with previous $K_sK_sK_s$ result ($3\, K_S \rightarrow \pi^+\pi^-$) Phys. Rev. Lett. **95**, 011801 (2005).
- Result agrees with SM expectations



$$S = -0.63^{+0.32}_{-0.28}\,(\text{stat}) \pm 0.04(\text{syst})$$
$$C = -0.10 \pm 0.25\,(\text{stat}) \pm 0.05, (\text{syst})$$

$B^0 \rightarrow \eta' K^0$

- Additional contributions from weak phases are expected to be small
  - Gronau: Phys. Lett. B 596, 107 (2003),
  - Beneke, Neubert: Nucl. Phys. B675. 333 (2003)
- Theoretical predictions for ΔS:
  - SU(3): ΔS < 0.1 [Gronau et al. Phys Lett B 596 107 (2004)]
  - QCD: ΔS~0.01 [Beneke,Neubert. Nucl. Phys. B675. 333 (2003)]
- Combined fit using both $\eta' K_S$ and $\eta' K_L$

Mode	Signal yield	S	C
$\eta'_{\eta\pi\pi} K^0_L$	137 ± 22	0.38 ± 0.44	0.34 ± 0.29
$\eta'_{\rho\gamma} K^0_L$	303 ± 49	0.88 ± 0.43	-0.15 ± 0.29
$\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^+\pi^-}$	188 ± 15	0.01 ± 0.28	-0.18 ± 0.18
$\eta'_{\rho\gamma} K^0_{\pi^+\pi^-}$	430 ± 26	0.44 ± 0.19	-0.30 ± 0.13
$\eta'_{\eta(3\pi)\pi\pi} K^0_{\pi^+\pi^-}$	54 ± 8	0.79 ± 0.47	0.11 ± 0.35
$\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^0\pi^0}$	44 ± 9	-0.04 ± 0.57	-0.65 ± 0.42
$\eta'_{\rho\gamma} K^0_{\pi^0\pi^0}$	89 ± 23	-0.45 ± 0.68	0.41 ± 0.40
Combined fit	1245 ± 67	0.36 ± 0.13	-0.16 ± 0.09

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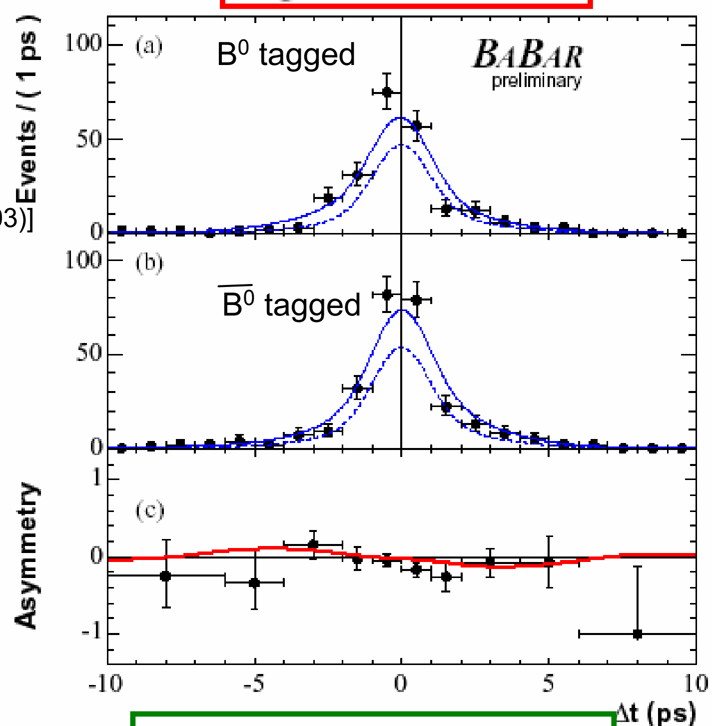


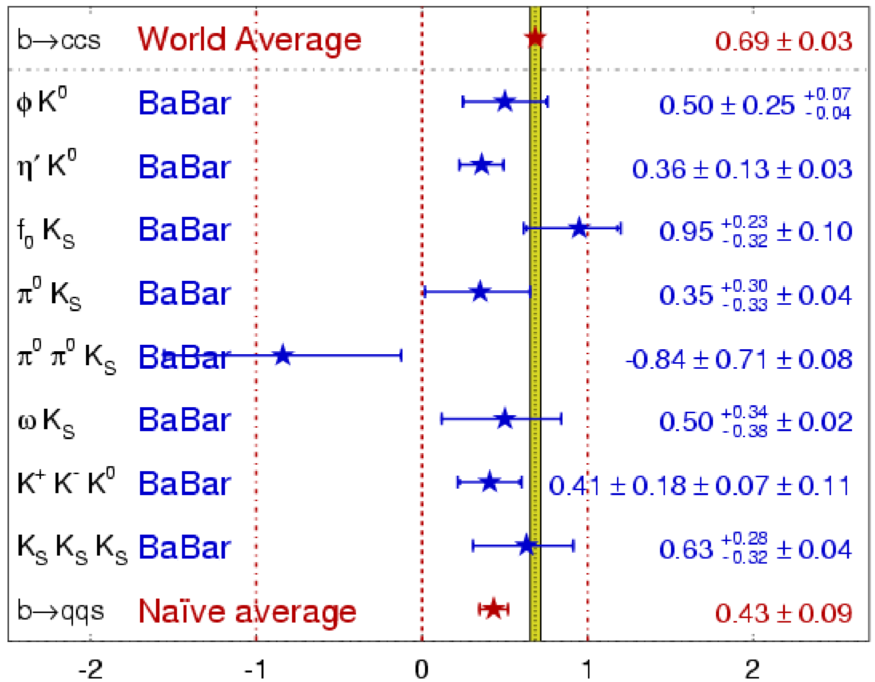
Projections onto Δt for $\eta' K^0_L$

- S differs from that measured in $J/\psi K_S$ by 2.8σ

BABAR measurements of sin(2β_{eff}) in penguin dominated channels

World average (charmonium + K^0)

Average (s-penguin modes)



- s-penguin "average" value of sin(2β_{eff}) differs from J/ψKs sin(2β)
  - Interpret this with CAUTION as each mode
    - is theoretically affected by new physics in a different way
    - has different SM uncertainties

Summary

- $\sin(2\beta)$ from $b \to c\bar{c}s$ ($B^0 \to$ charmonium + K^0) decays have been measured to 5% precision

$$\sin 2\beta = 0.722 \pm 0.040(\mathrm{stat}) \pm 0.023(\mathrm{syst})$$

- Measuring $\sin(2\beta)$ in additional (independent) ways allows us to probe for New Physics
  - $b \to c\bar{c}d$ decays : results are consistent with SM
  - penguin decays : some deviations.
    - First signs of New Physics ? Statistical fluctuation?
- Measurements are heavily dominated by statistical errors.
  - BaBar is aiming to double its dataset by summer 2006 and quadruple it by 2008