CP violation revealed in B decays in the angle β/ϕ_1: precision measurements, rare decays, and the search for new physics

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(*BaBar* collaboration)

Outline

Covering both *BaBar* and Belle results...

- – Apologies to those results not covered for lack of time...
  will include them in the proceedings paper

- Introduction
  - – Weak interactions & the CKM matrix
  - – *CP* violation in the *B* system
  - – The angle β: $\overline{B} \to charmonium$ decays and others
- Measurement technique
- sin2β – and β – in $b \to ccs$ (tree) decays
- "sin2β" in $b \to s$ penguin decays
- Conclusions

Many thanks to BaBar and Belle collaborators for inputs
and especially to D. MacFarlane

A good year to celebrate

- 25 years since I.I. Bigi & A.I. Sanda
  "Notes on the observability of *CP* violations in *B* decays"

- 20 years in January since P. Oddone's suggestion of measurements at the Y(4S) in an asymmetric collider

- Result: 8 years of data from two *B*-factories, ~1ab^{-1} of luminosity, and ~one billion *BB* pairs observed

  ➢ A remarkable variety of physics results already achieved, with many more ahead

Weak Interaction in Standard Model

CKM mixing matrix & quark masses are fundamental constants associated with EW symmetry breaking

SM: single complex phase in 3x3 matrix
$\Rightarrow$ **CP violation**

$$\begin{array}{ccc} d & s & b \end{array}$$

$$\begin{matrix} u \\ c \\ t \end{matrix}$$

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

$\bar{\eta}$

Apex at $(\bar{\rho},\ \bar{\eta})$

Radiative penguin decays

$\alpha = \phi_2$

$\Gamma(b \to u\ell\nu)$

$B^0 - \bar{B}^0$ mixing

CP violation

$\gamma = \phi_3$

$\beta = \phi_1$

$(0,0)$

$(1,0)$

τ_B and $\Gamma(b \to c\ell\nu)$

**Unitarity Triangle as a summary of Standard Model *b* physics**
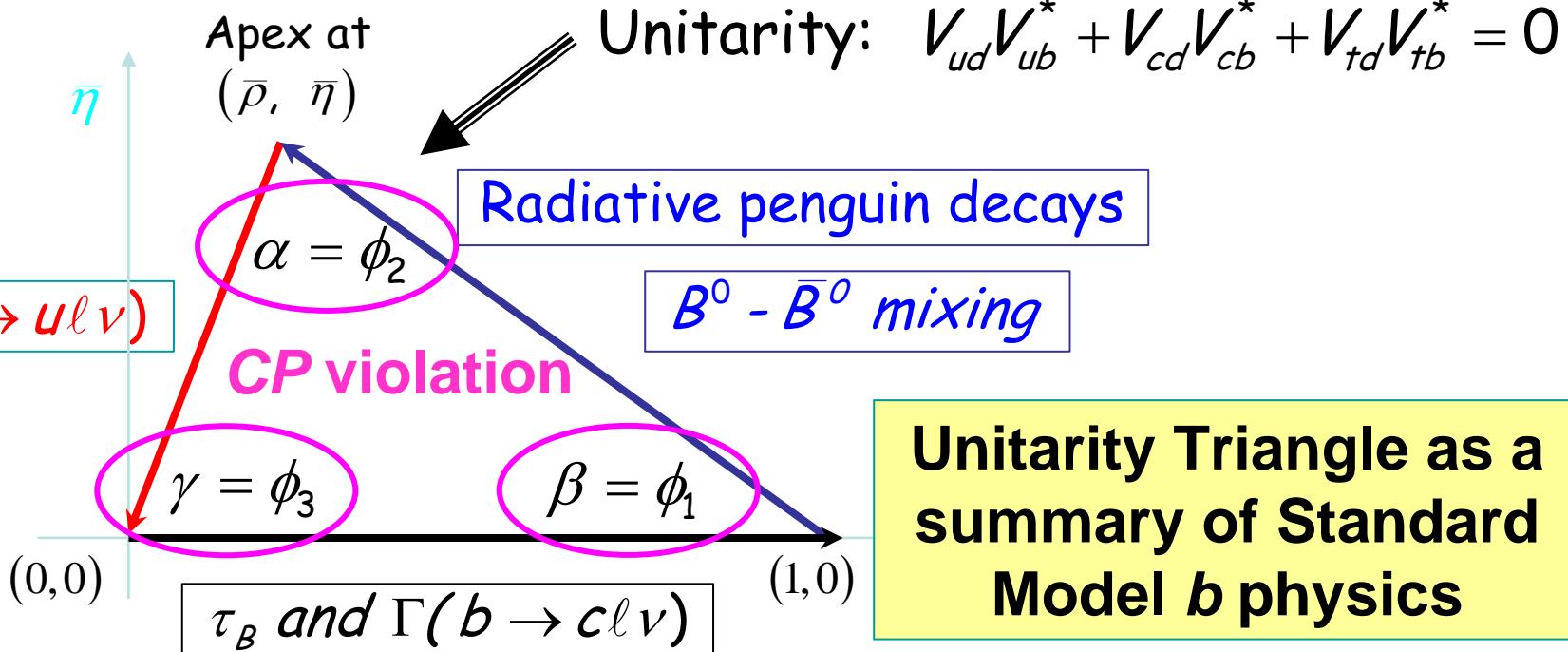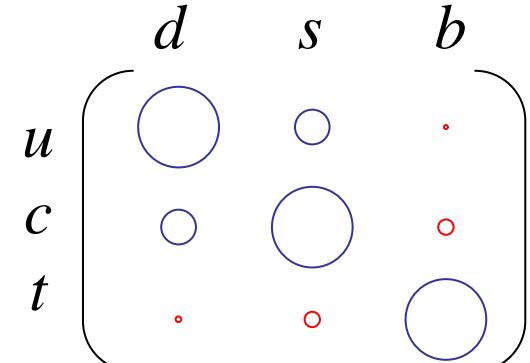
CP Violation in the B System

> **CPV through interference between mixing and decay amplitudes**

Directly related to CKM angles for single decay amplitude

$$A_{CP}e^{i\varphi_f}$$

$$B^0 \longrightarrow f_{CP}$$

$$\frac{q}{p} = e^{-2i\beta}$$

$$\bar{B}^0$$

$$A_{CP}e^{-i\varphi_f}$$

Asymmetry
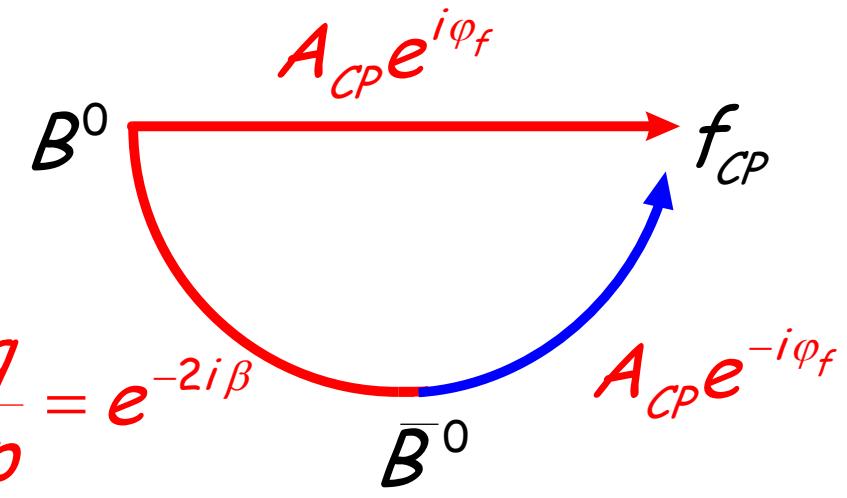
$$A_{f_{CP}}(\Delta t) = \frac{f_+ - f_-}{f_+ + f_-} = S_{f_{CP}} \sin \Delta m_d \Delta t - C_{f_{CP}} \cos \Delta m_d \Delta t$$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} = 0 \qquad S_{f_{CP}} = \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} = \mathrm{Im}\,\lambda_{f_{CP}} \qquad \lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

For single amplitude

CPV in charmonium modes

$\bar{\eta}$

$(\bar{\rho}, \bar{\eta})$

$\alpha = \phi_2$

$B^0 - \bar{B}^0$ mixing

$\Gamma(b \rightarrow u\ell\nu)$

$\gamma = \phi_3$

$\beta = \phi_1$

CPV in $B^0 \rightarrow J/\psi K_s^0$

$(0,0)$

$(1,0)$ $\bar{\rho}$

τ_B and $\Gamma(b \rightarrow c\ell\nu)$
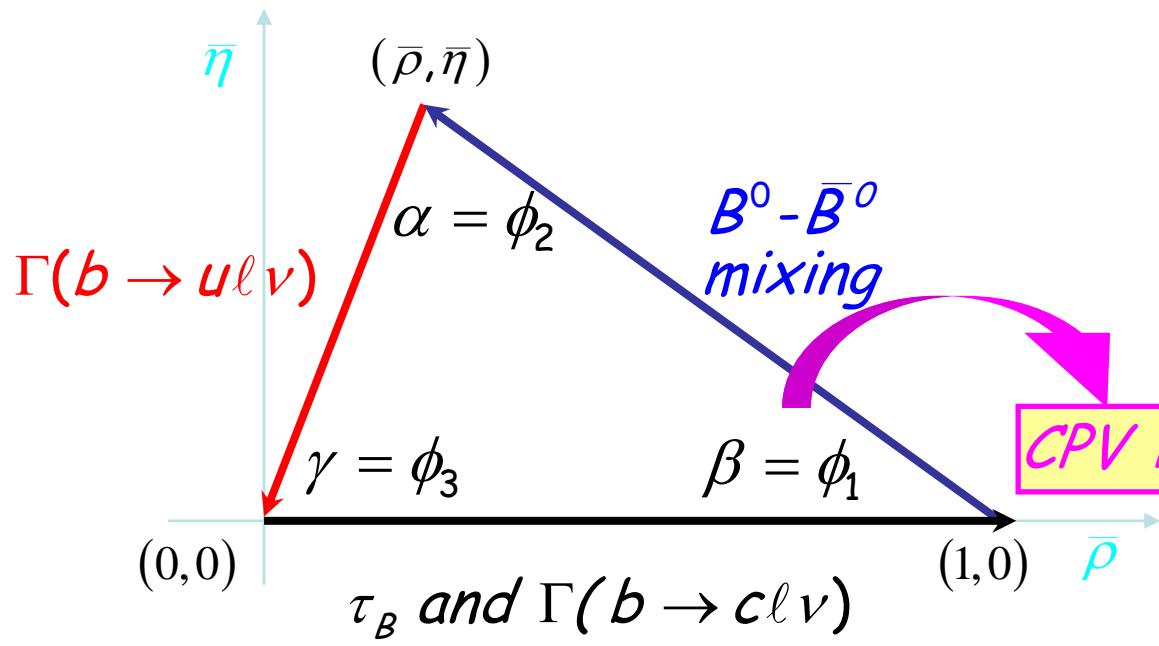
Interference of $b \rightarrow c$ tree decay with mixing

b c J/ψ
$\bar{c}$
$\bar{B}^0$ W^-
s $\bar{K}^0$
$\bar{d}$ $\bar{d}$

b d
$\bar{B}^0$ W t W B^0
$\bar{d}$ $\bar{t}$ $\bar{b}$
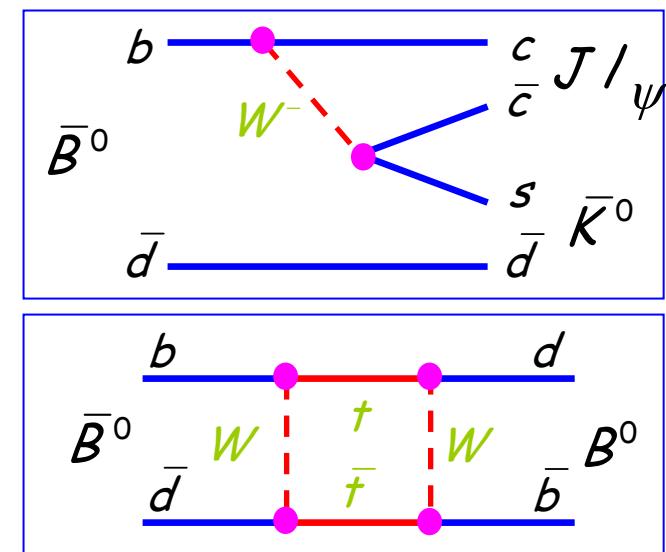
The many ways to measure sin2β

Can use 3 different categories of B^0 decays to measure β:

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

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

c) Penguin-dominated $b \to d\bar{d}s$, $b \to s\bar{s}s$
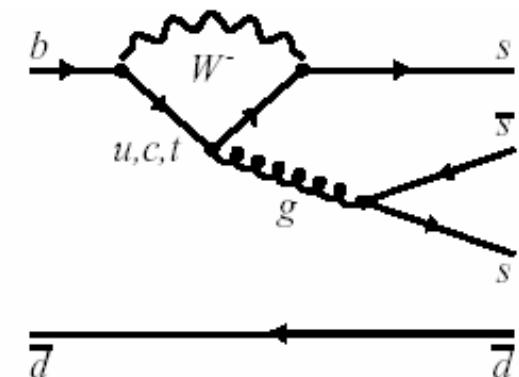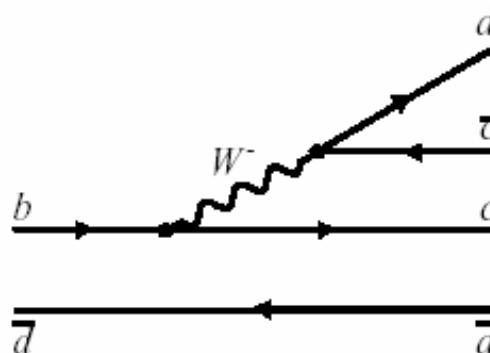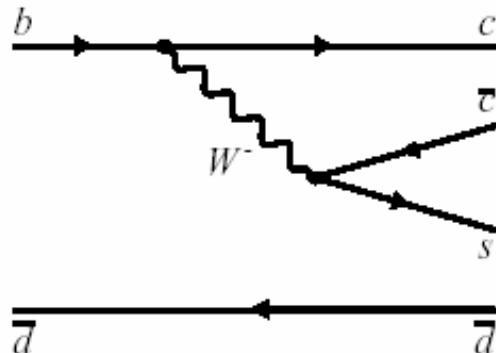
$J/\psi K_S^0$ **golden mode**

$\psi(2S)K_S^0, \chi_{c1}K_S^0, \eta_c K_S^0$

$J/\psi K_L^0$

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

$D^{*+}D^-, D^+D^-$

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

$\phi K^0, K^+K^-K_S^0,$

$K_S^0 K_S^0 K_S^0, \eta' K^0, K_S^0 \pi^0,$

$\omega K_S^0, f_0(980)K_S^0$

Measuring CP violation

$$\beta\gamma_{\Upsilon(4S)} = 0.56$$

$\bar{B}_{rec}$

e^-

$\Upsilon(4S)$

e^+

B_{tag}

J/ψ

μ^-

μ^+

π^+

K_S^0

π^-

z

$\Delta z \sim 260\,\mu m$

Δz

K^-

ℓ^-

Exclusive B Meson & vertex reconstruction

B-flavor tag & tag vertex reconstruction

$$\Delta t \approx \frac{\Delta z}{\langle\beta\gamma\rangle}\frac{1}{c}$$

Δt measurement

Δt is a signed quantity

$\sigma_{\Delta t} \sim 1\ \text{ps} \Leftrightarrow 170\ \mu m$

$\tau_B \sim 1.6\ \text{ps} \Leftrightarrow 250\ \mu m$

Start the clock

Tagging performance: Q = 30.5%
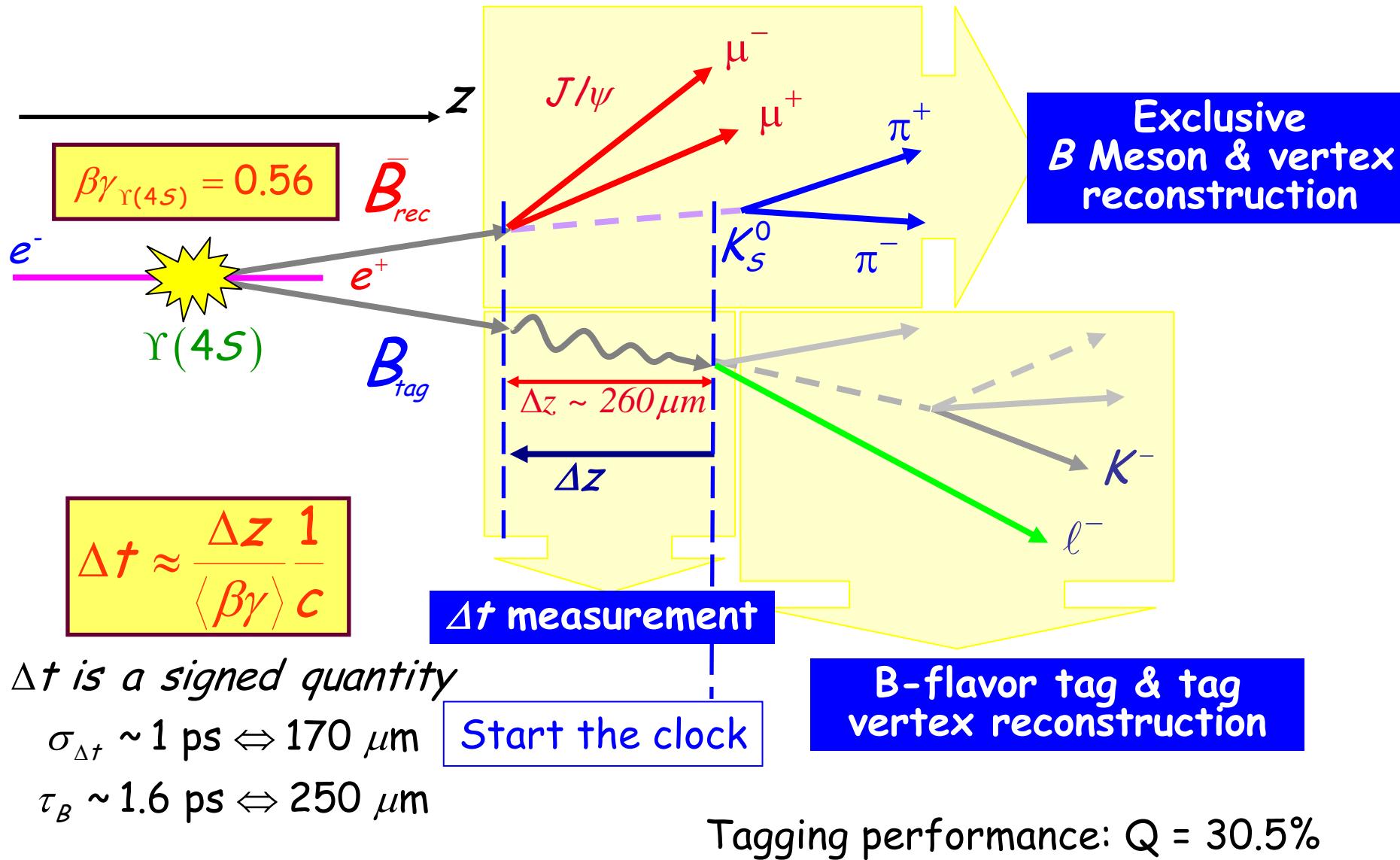
Brief history of sin2β from B⁰→charmonium K⁰
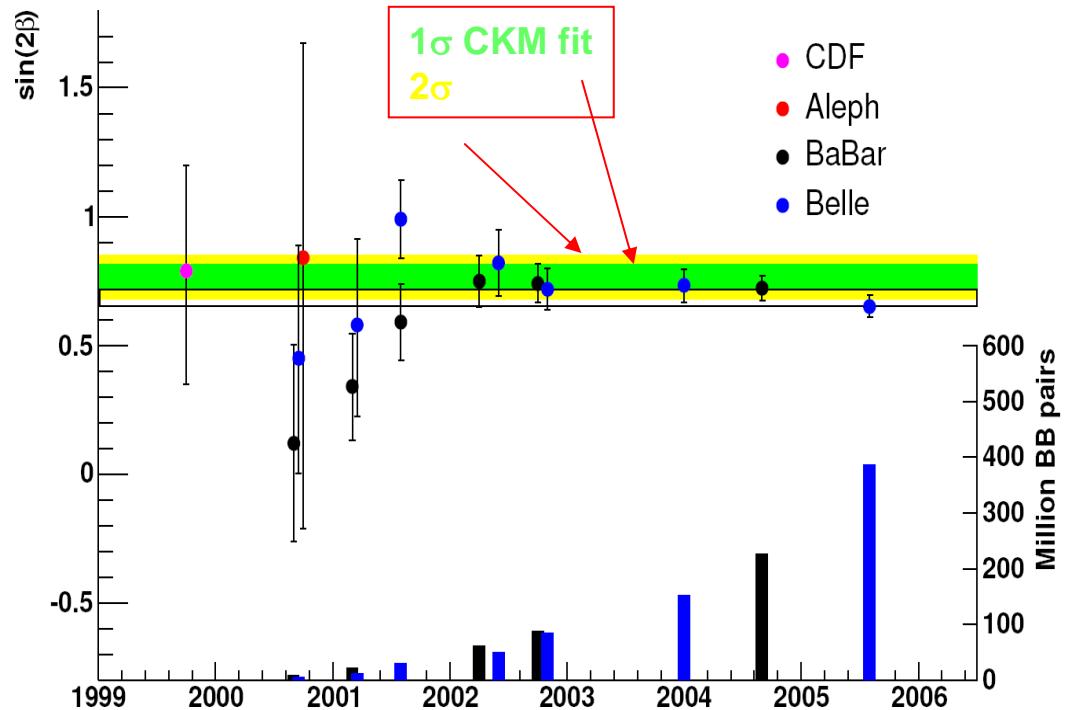
World Average

$\sin 2\beta_{[WA]} = 0.687 \pm 0.032$

From external constraints

$\sin 2\beta_{UTFit} = 0.793 \pm 0.033$ (sides)
$\sin 2\beta_{UTFit} = 0.734 \pm 0.024$ (all)

Great success for Standard Model
Great success for all of us

theorists, experimentalists, accelerator physicists

# BABAR charmonium sample

$N_{sig} = 6028$
$P = 92\%$

$N_{sig} = 4323$
$P = 55\%$

$N_{sig} = 965$
$P = 68\%$

$N_{sig} = 112878$
$P = 83\%$

In panel a):

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

In panel b):

BABAR Preliminary
$B^0 \rightarrow J/\psi K_L^0$

In panel c):

$B^0 \rightarrow J/\psi K^{*0}$

In panel d):

B_{flav} modes
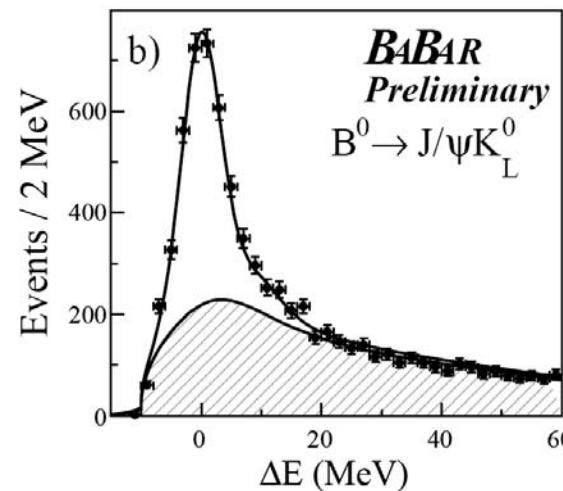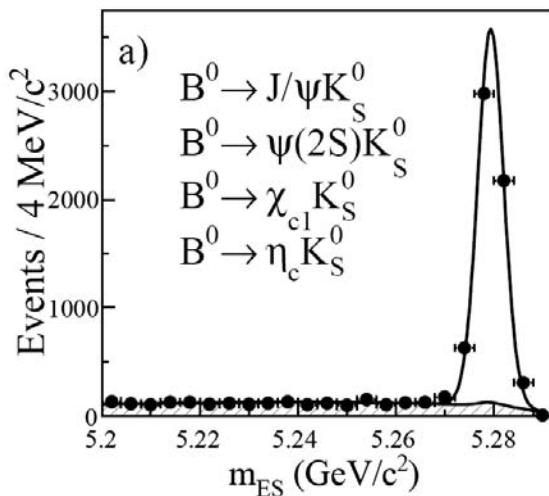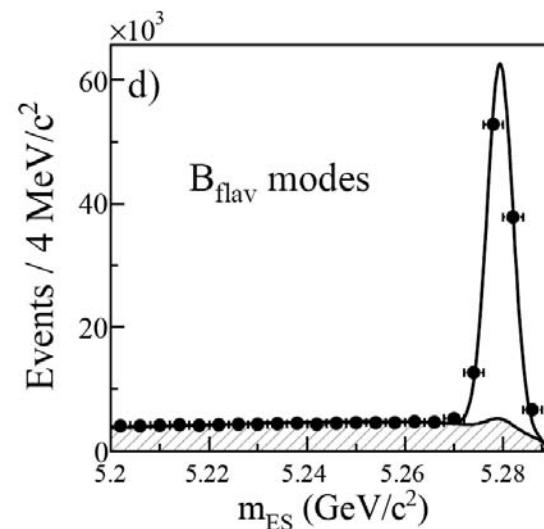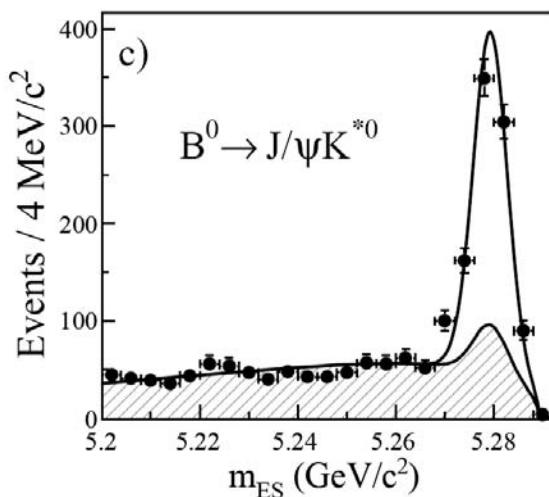
Latest BABAR results for sin2β

$(c\bar{c})K_S^0$ (CP odd) modes

$(c\bar{c})K_L^0$ (CP even) modes
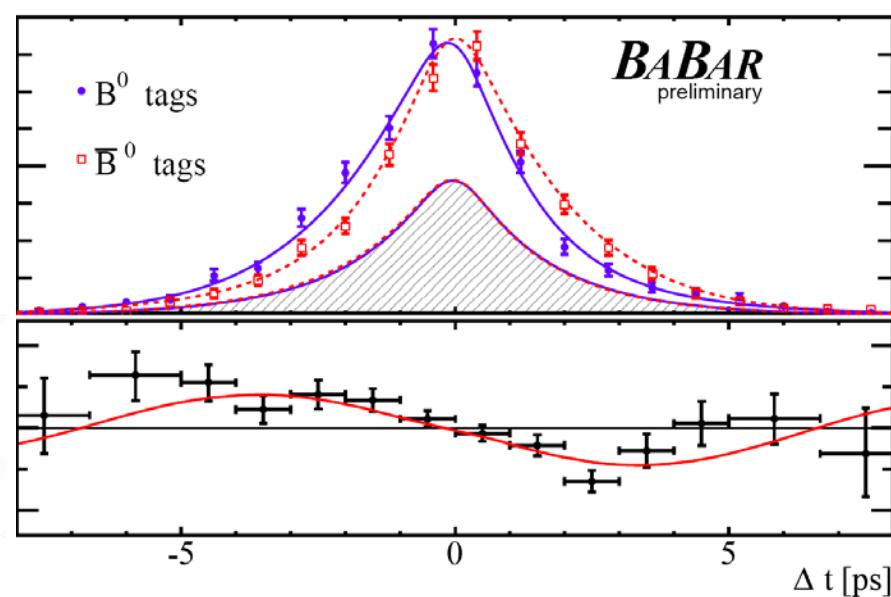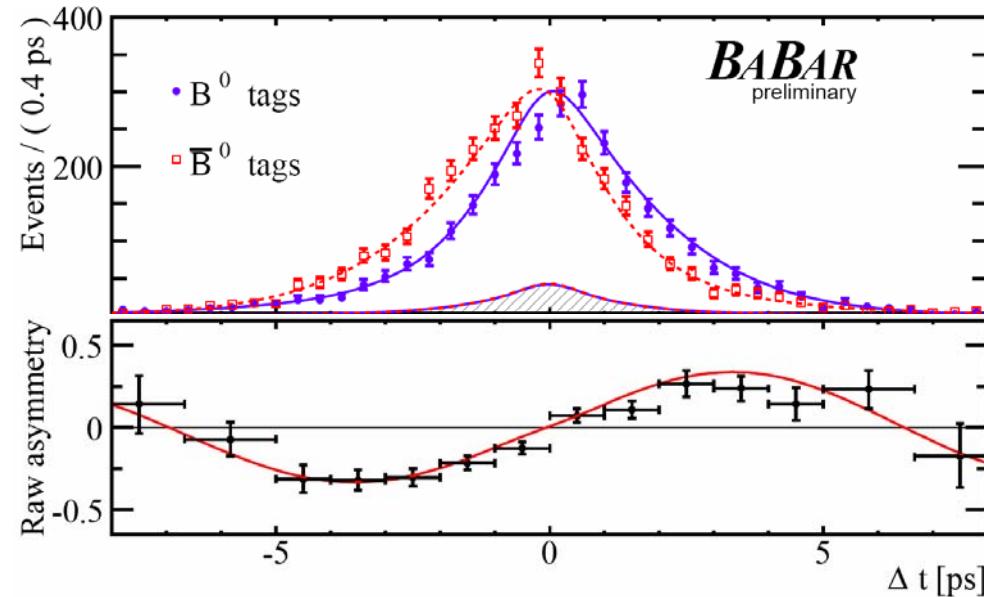
$$\sin 2\beta = 0.710 \pm 0.034 \pm 0.019$$
$$C = -A = 0.070 \pm 0.028 \pm 0.018$$

$J/\psi K_S^0$ +
*$J/\psi K_L^0$*

BABAR CONF-06/036

$316 fb^{-1}$ on peak or $532 M$ $B\bar{B}$ pairs
11496 CP events (tagged signal)

Latest Belle results for sin2β

$J/\psi K_S^0$ (CP odd) mode

$J/\psi K_L^0$ (CP even) mode
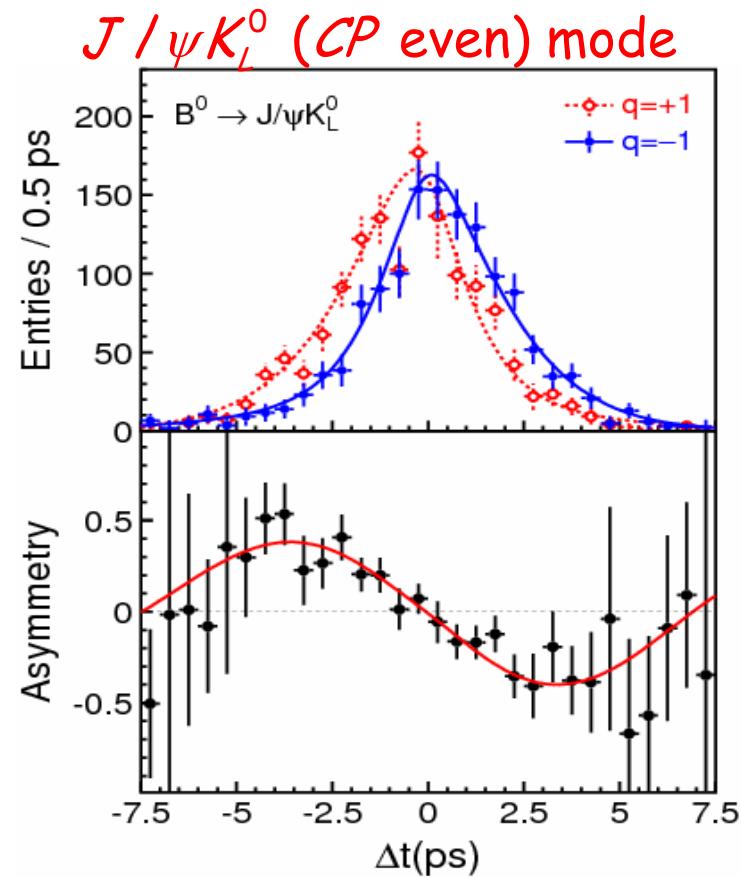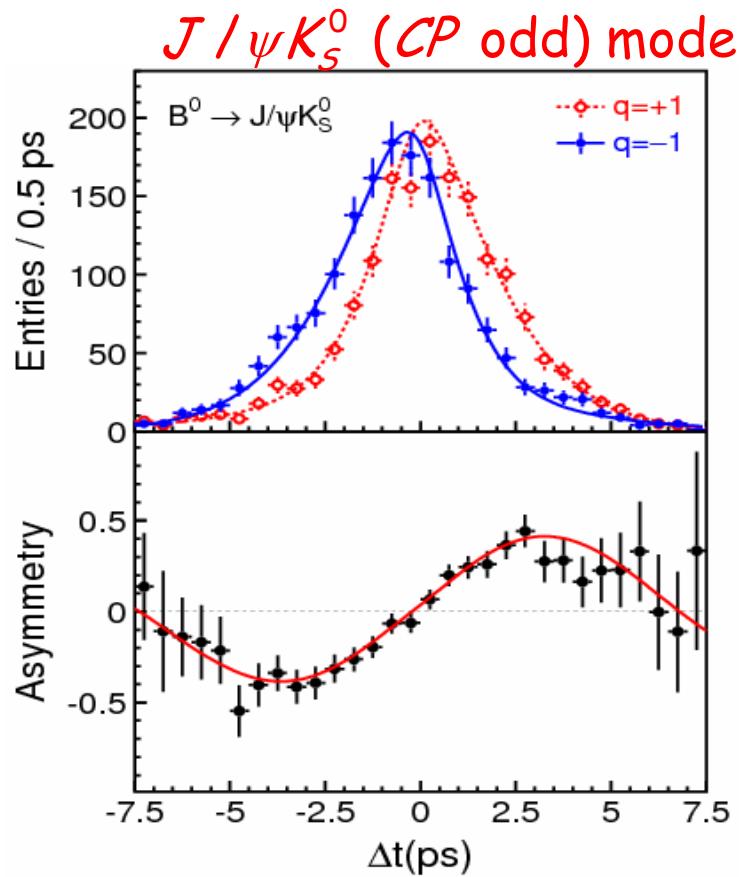
BELLE-CONF-0647

$$\sin 2\beta = 0.642 \pm 0.031 \pm 0.017$$
$$C = -A = -0.018 \pm 0.021 \pm 0.014$$

$(c\bar{c})K_S^0 +$
$(c\bar{c})K_L^0$

$492 fb^{-1}$ on peak or $532M$ $B\bar{B}$ pairs
13994 CP events (tagged signal)

Removing 4-fold ambiguity for β

Preliminary

$\beta \equiv \phi_1$

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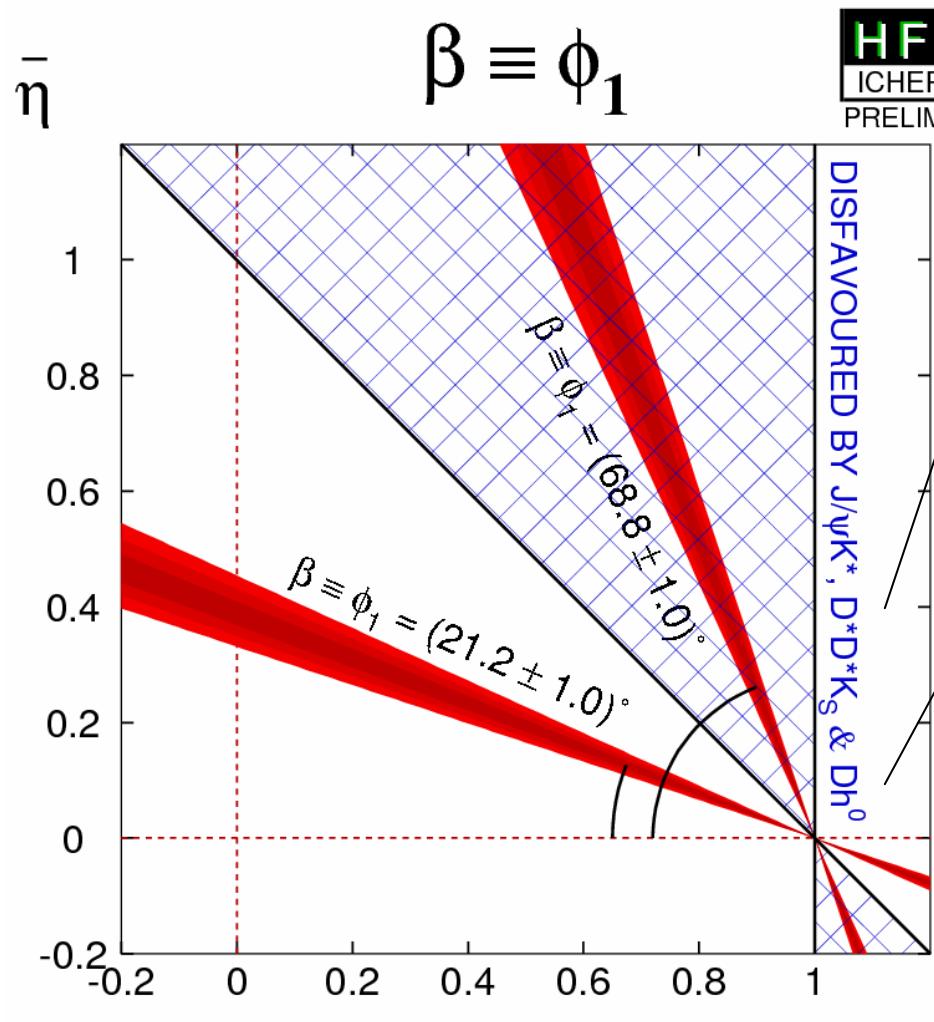
$B^0 \rightarrow D^{*+}D^{*-}K_S$
Time-dependent Dalitz analysis
(T. Browder, A. Datta et al. 2000)
→ $\cos 2\beta > 0$
(94%CL, model-dependent)

$B^0 \rightarrow Dh^0$ ($h^0 = \pi^0$ etc.)
Time-dependent Dalitz analysis
→ $\cos 2\beta > 0$
Belle: 98.3%CL
(hep-ex/0605023, to appear in PRL)
BaBar 87% CL
(BABAR-CONF-06/017)

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

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

DISFAVOURED BY J/ψK*, D*D*K$_S$ & Dh^0

$\bar{\eta}$

$\bar{\rho}$

CPV in Penguin Modes

$\bar{\eta}$

$(\bar{\rho}, \bar{\eta})$

$\Gamma(b \to u\ell\nu)$

$\alpha = \phi_2$

$B^0 - \bar{B}^0$ mixing

$\gamma = \phi_3$

$\beta = \phi_1$

$(0,0)$

$(1,$

τ_B and $\Gamma(b \to c\ell\nu)$

CPV in $B^0 \to \phi K_S^0, \eta' K_S^0, \ldots$

Interference of suppressed $b \to s$ Penguin decay with mixing

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

W^+

$\bar{u}, \bar{c}, \bar{t}$

$\bar{b}$ g $\bar{s}$ ϕ s

d $\bar{s}$ K_S^0 d
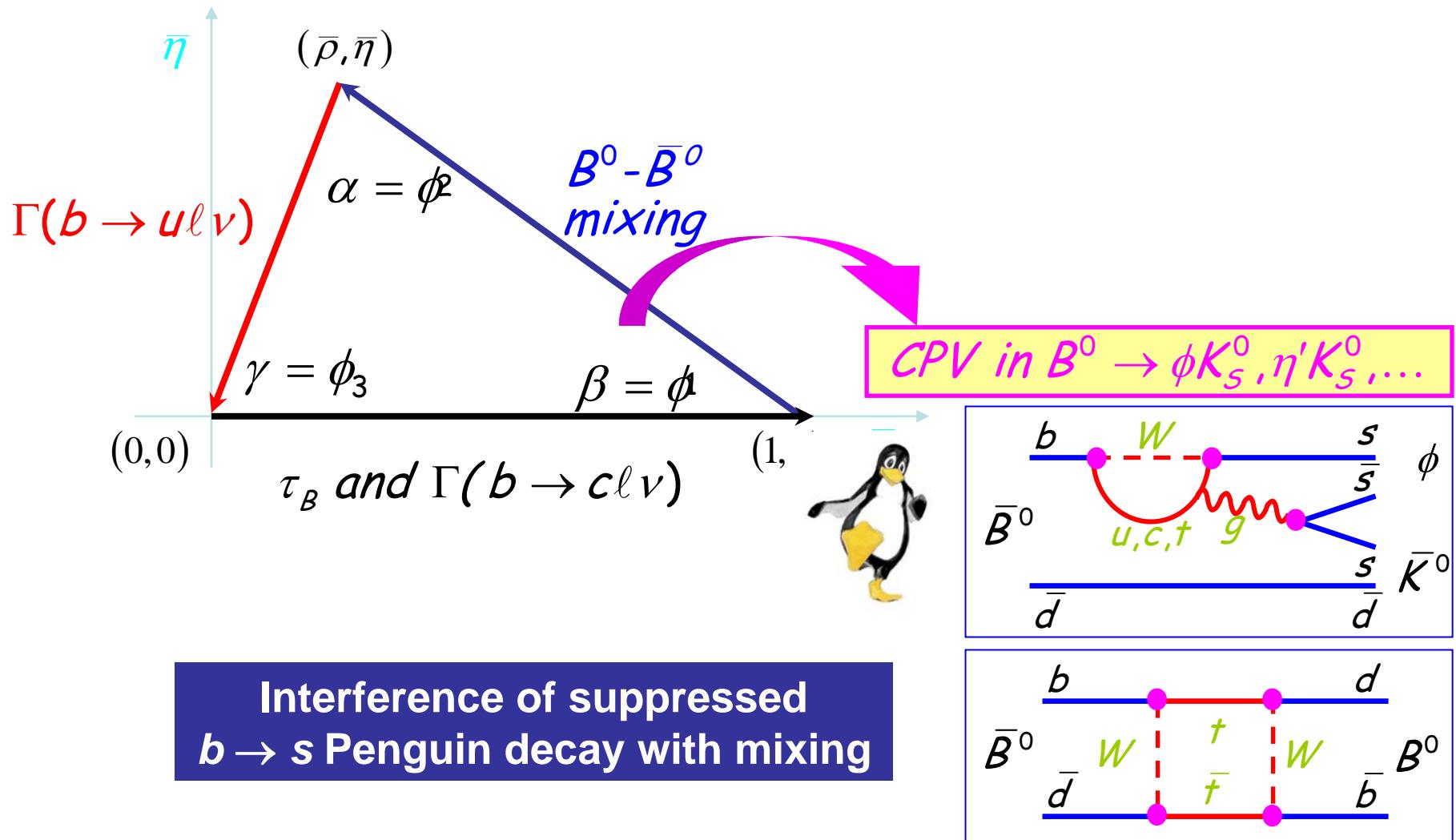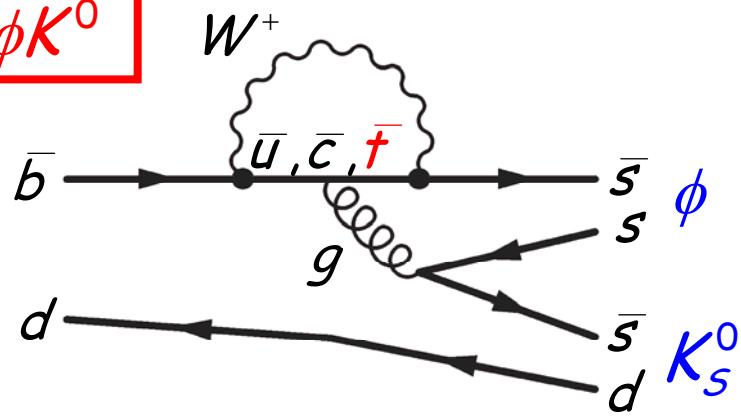
"Internal Penguin"

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

W^+

$\bar{b}$ $\bar{s}$ η' s

B^0 $\bar{t}$ g $\bar{s}$

d K_S^0 d

New physics in loops?

$\tilde{g}$

$\bar{b}$ $\bar{s}$ ϕ

$\tilde{b}_R$ $(\delta_{RR}^d)_{23}$ s

B^0 $\tilde{s}_R$ g $\bar{s}$

d d K_S^0
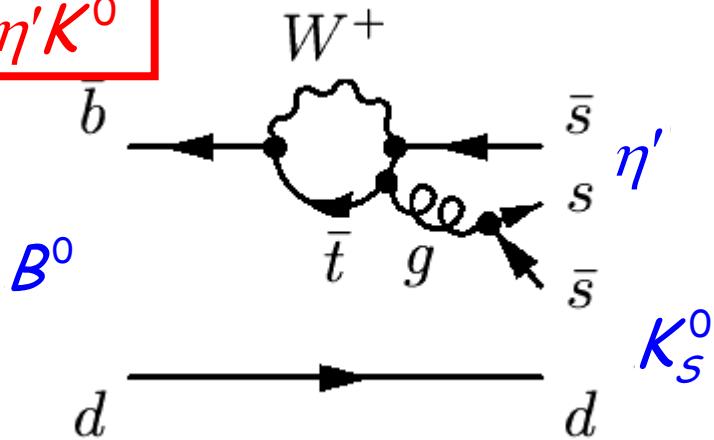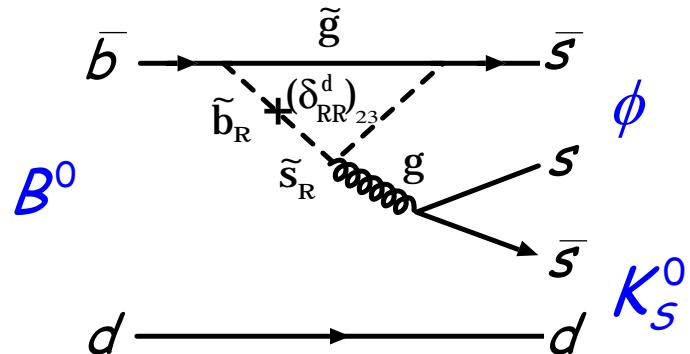
SUSY contribution with new phases

$\tilde{g}$

$\bar{b}$ $\bar{s}$ η'

$\tilde{b}_R$ $(\delta_{RR}^d)_{23}$ s

B^0 $\tilde{s}_R$ g $\bar{s}$

d d K_S^0
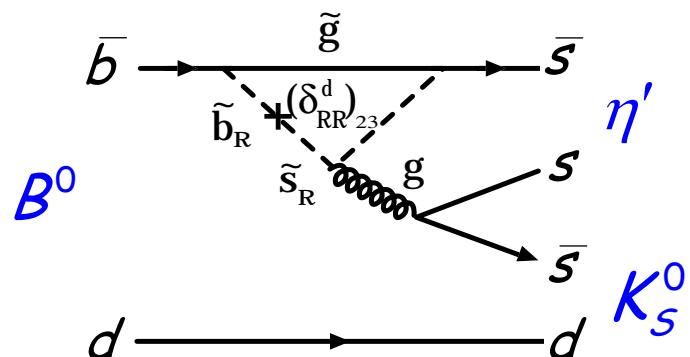
Δt distribution and asymmetry
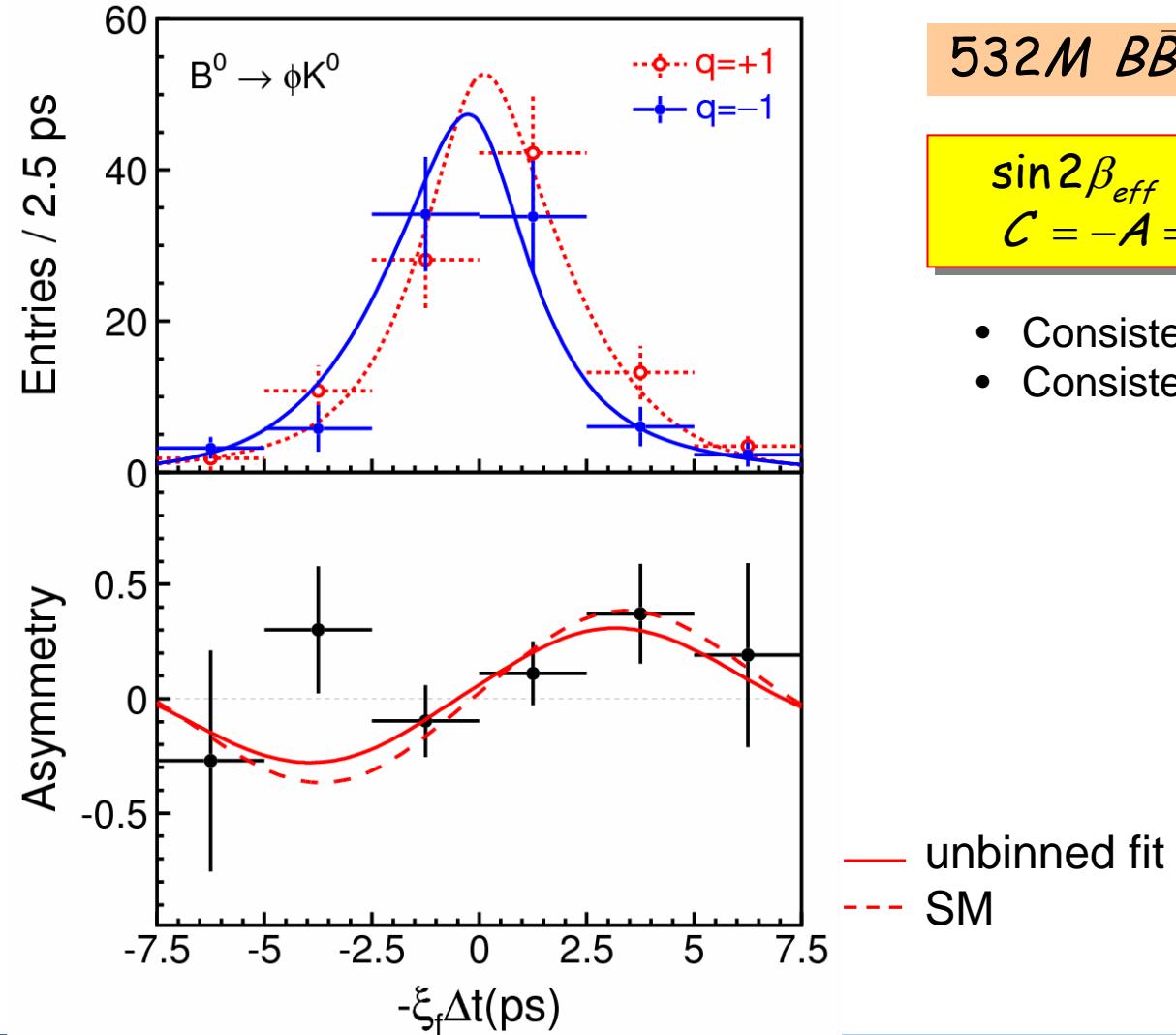
Preliminary

$532M\ B\bar{B}$ pairs

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

- Consistent with SM (~1σ lower)
- Consistent with Belle 2005

BELLE-CONF-0647

BABAR 2006: tCPV in $B^0 \rightarrow K^+K^-K^0$

Obtain CP parameters for 2-body and 3-body modes simultaneously by time-dependent Dalitz fit:

Isobar model includes $\phi(1020)K^0, f_0(980)K^0,$
$X_0(1550)K^0$, non-resonant $K^+K^-K^0, D^+K^-, D_s^+K^-$

Channels included

$K^+K^-K_S^0(\rightarrow \pi^+\pi^-)$
$K^+K^-K_S^0(\rightarrow \pi^0\pi^0)$
$K^+K^-K_L^0$

$N_{sig} = 1516 \pm 65$

$K+K-K_S(\pi+\pi-)$

$\phi(1020)$
879 ± 36

"$X_0(1550)$"

Non-resonant

χ_{c0}

$f_0(980)$

Events / (0.095 GeV)

m_{K+K-}(GeV)

BABAR preliminary

Events / (0.0028 GeV)

m_{K+K-}(GeV)
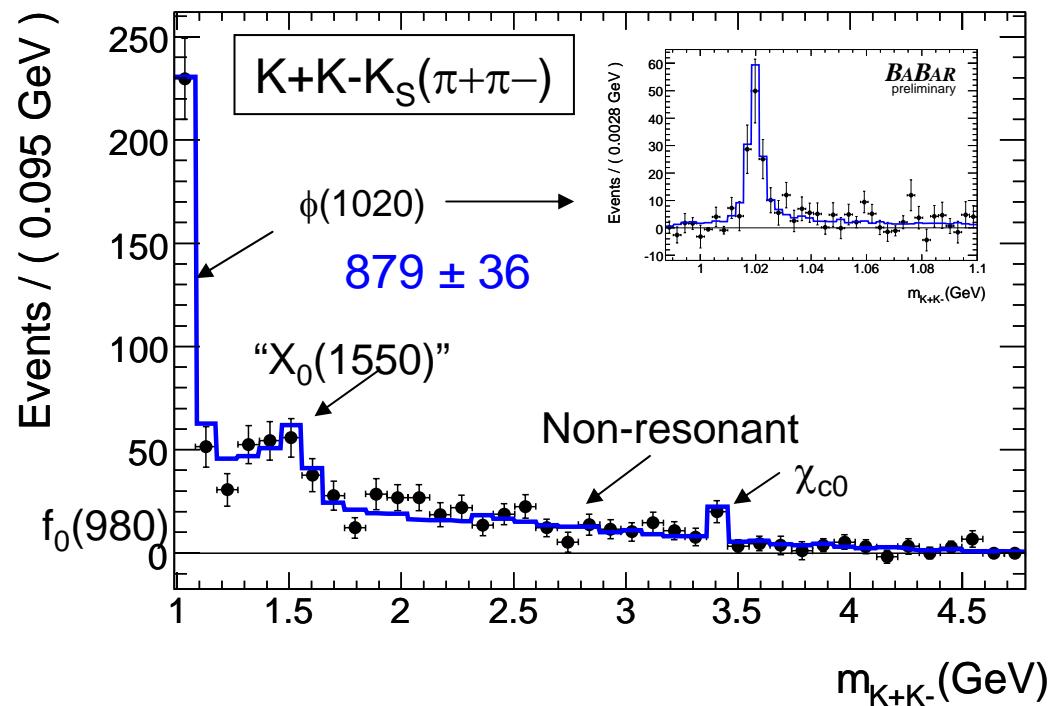
BABAR CONF-06/040

β measurement (not sin2β)

$$A_{CP} = -0.034 \pm 0.079 \pm 0.025$$
$$\beta_{eff} = +0.361 \pm 0.079 \pm 0.037$$

SM:
$A_{CP}=0$
$\beta=0.370$

Rejected
(within SM)
4.6σ
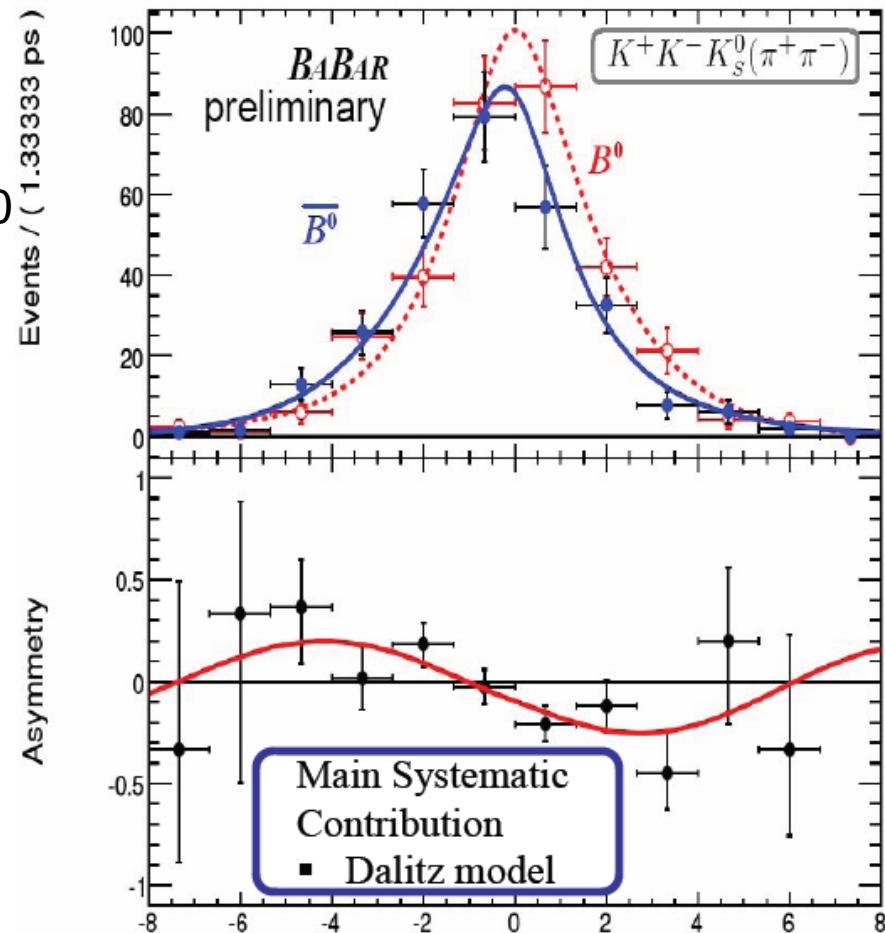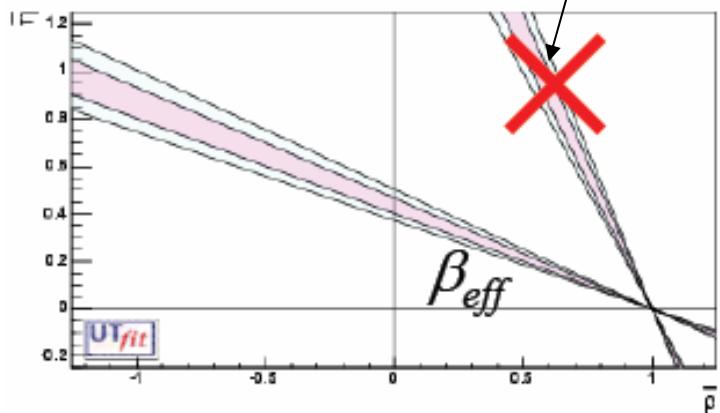
BABAR 2006: CPV in low K+K- mass

asymmetry plot ±15MeV under φ


Events / (2 ps)

Asymmetry

Δt (ps)

BABAR preliminary
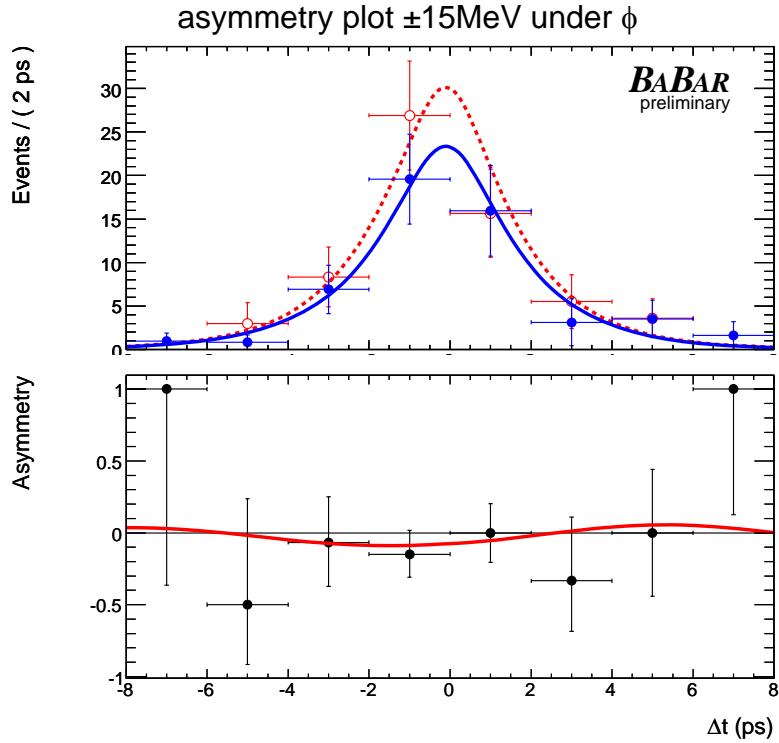
Resonant fractions for m(K⁺K⁻) < 1.1GeV

$\phi(1020)K^0$	57%
$f_0(980)K^0$	34%
Non-res	13%

ϕK_S

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

SM:
$A_{CP}=0$
$\beta=0.370$

$f_0 K_S$

$$A_{CP} = +0.45 \pm 0.28 \pm 0.10$$
$$\beta_{eff} = +0.18 \pm 0.19 \pm 0.04$$

- Cross-check with Q2B analysis
- Syst. errors dominated by Dalitz plot model
- Consistent with SM, Belle

- CPV measurements in f_0Ks and φKs correlated (one background for the other)

$\eta'K_S^0$ (CP odd) mode

$\eta'K_L^0$ (CP even) mode
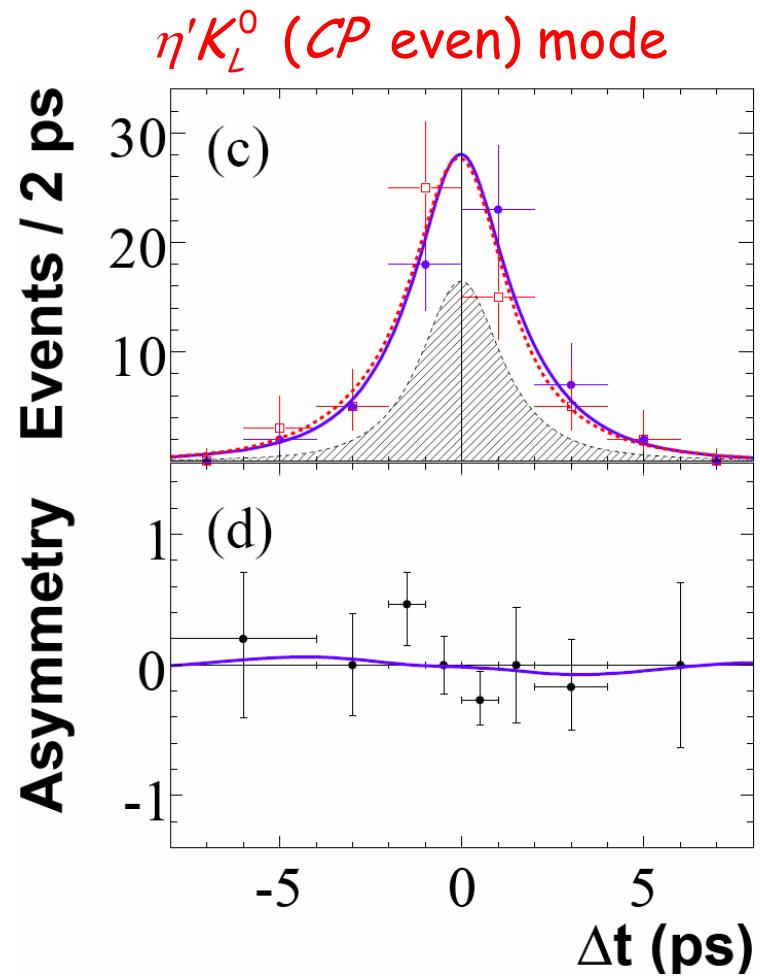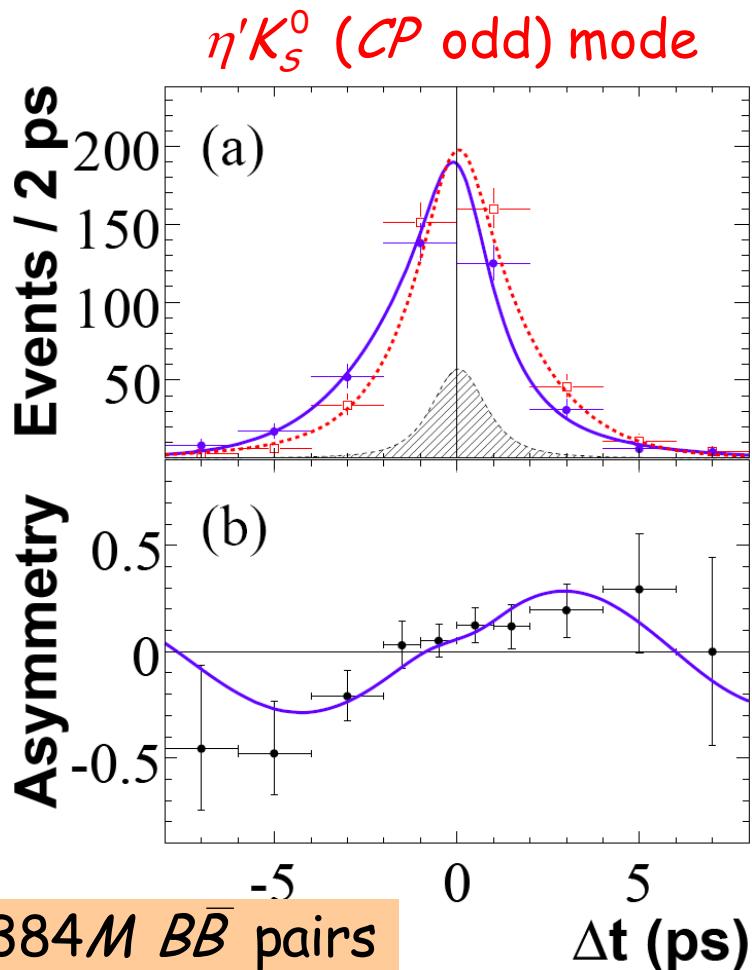
384M $B\bar{B}$ pairs

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

~5.6σ observation of CPV in a $b \rightarrow s$ mode

BABAR hep-ex/0609052, submitted to PRL

Belle 2006: tCPV in $B^0 \to \eta' K^0$

Δt distribution and asymmetry
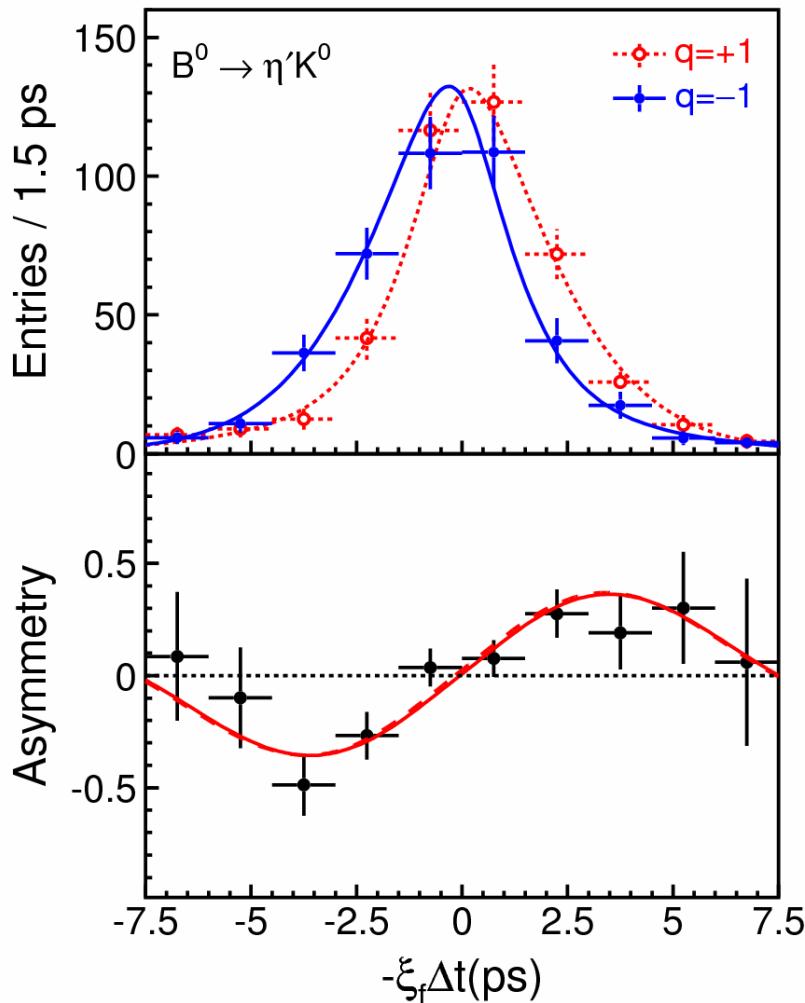
Preliminary

$532M \; B\bar{B}$ pairs

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

- Also ~5.6σ observation of CPV in a $b \to s$ mode
- Consistent with SM
- Consistent with Belle 2005

*BELLE-CONF-0647*

Summary of sin2β in b→s penguin modes

$$\sin(2\beta^{\mathrm{eff}}) \equiv \sin(2\phi_1^{\mathrm{eff}})$$

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b→ccs		sin(2β^eff)
	World Average	0.68 ± 0.03
φ K⁰	BaBar	$0.12 \pm 0.31 \pm 0.10$
	Belle	$0.50 \pm 0.21 \pm 0.06$
	Average	0.39 ± 0.18
η' K⁰	BaBar	$0.55 \pm 0.11 \pm 0.02$
	Belle	$0.64 \pm 0.10 \pm 0.04$
	Average	0.59 ± 0.08
K_S K_S K_S	BaBar	$0.66 \pm 0.26 \pm 0.08$
	Belle	$0.30 \pm 0.32 \pm 0.08$
	Average	0.51 ± 0.21
π⁰ K_S	BaBar	$0.33 \pm 0.26 \pm 0.04$
	Belle	$0.33 \pm 0.35 \pm 0.08$
	Average	0.33 ± 0.21
ρ⁰ K_S	BaBar	$0.17 \pm 0.52 \pm 0.26$
	Average	0.17 ± 0.58
ω K_S	BaBar	$0.62 ^{+0.25}_{-0.30} \pm 0.02$
	Belle	$0.11 \pm 0.46 \pm 0.07$
	Average	0.48 ± 0.24
f_0 K⁰	BaBar	0.62 ± 0.23
	Belle	$0.18 \pm 0.23 \pm 0.11$
	Average	0.42 ± 0.17
π⁰ π⁰ K_S	BaBar	$-0.84 \pm 0.71 \pm 0.08$
	Average	-0.84 ± 0.71
K⁺ K⁻ K⁰	BaBar Q2B	$0.41 \pm 0.18 \pm 0.07 \pm 0.11$
	Belle	$0.68 \pm 0.15 \pm 0.03 ^{+0.21}_{-0.13}$
	Average	$0.58 \pm 0.13 ^{+0.12}_{-0.09}$

-2   -1   0   1   2

Naïve[2] Average: 0.52 ± 0.05 (2.6σ)

Representative theory estimates

φK_S
η'K_S
π⁰K_S
ωK_S
KKK_S
3K_S

Δsin2β

-0.1   0   0.1   0.2
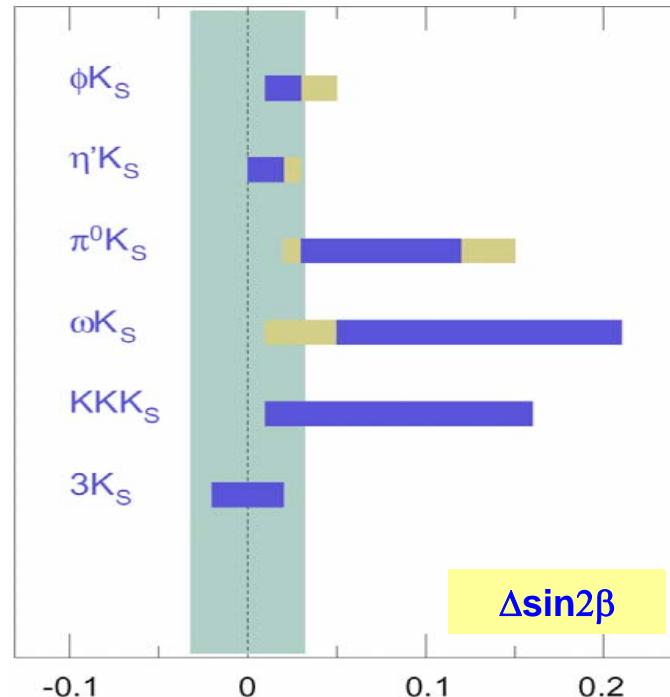
Example from recent calculations (QCD factorization)
2-body: [Beneke; PL B620, 143 (2005)]
3-body: [Cheng,Chua,Soni; PRD72, 094003 (2005)]
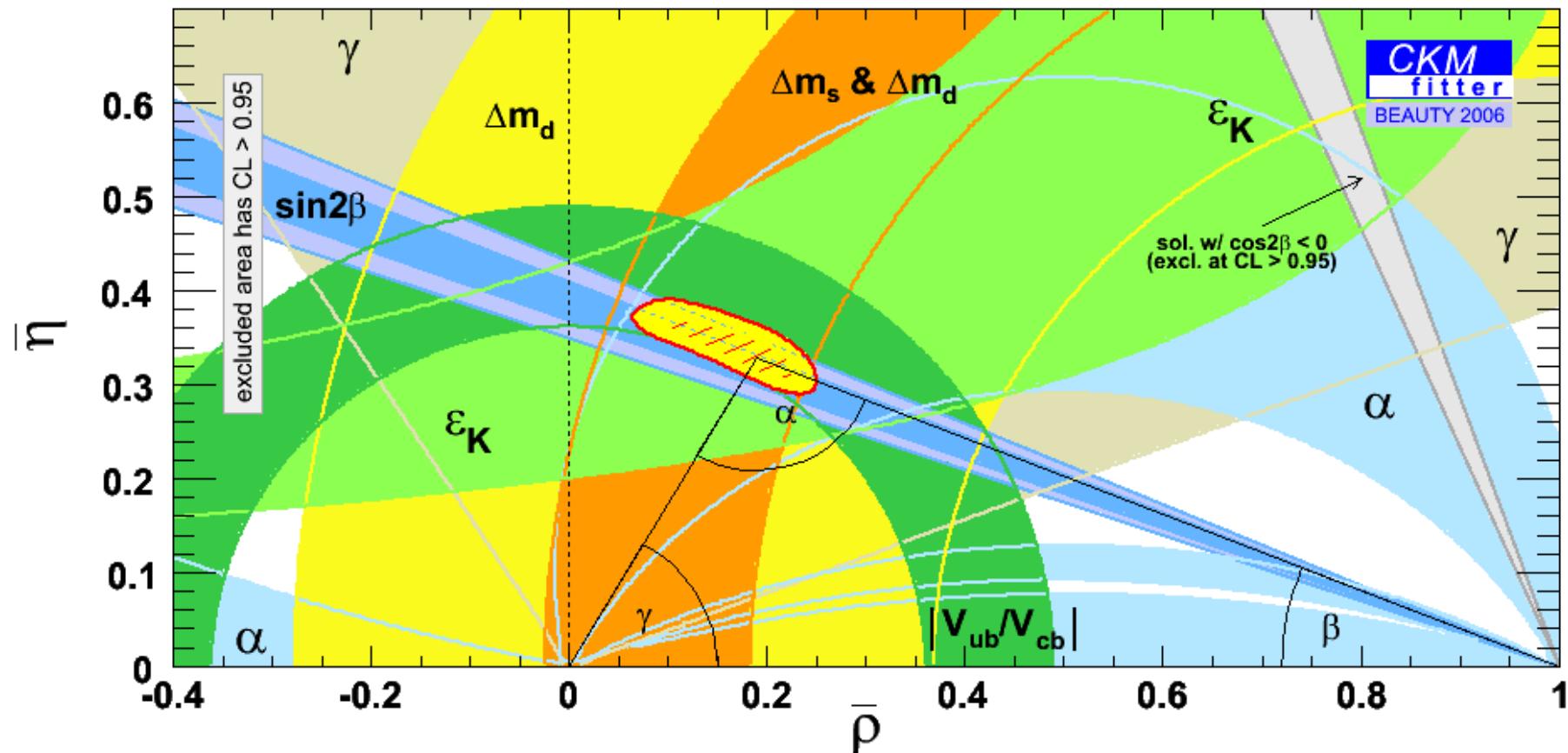
Conclusions

- "Golden mode" measurement precision now better than 4%

- Penguin mode measurements improving
  – Still tantalizing hints, no confirmation, of unexpected outcomes

- Integration of all *B* physics results (including B_s mixing) is allowing the program originally envisioned for the *B*-factory era to be carried out beyond expectations
  – See α and γ, UT side measurements at this conference
  – Picture still looks generally consistent - constraints on new physics are becoming interesting

- Still have a further more-than-doubling of the global *B*-factory data sample ahead...
  – Very rewarding time to be working in this area!