CP Violation in the *B* Meson System and Outlook

Weak Interactions and Neutrinos 2002
Christchurch, NZ
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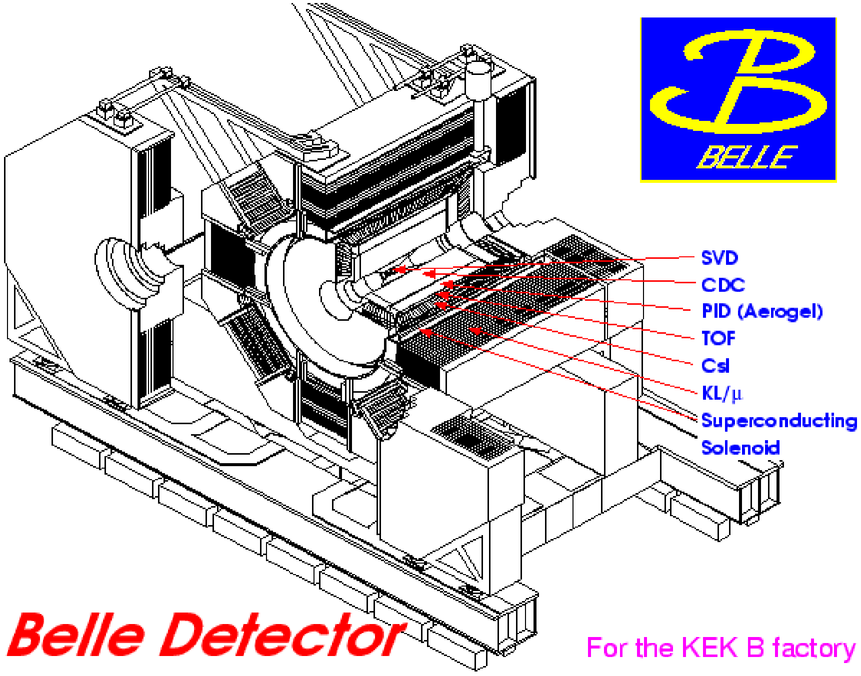
New B Factory Experiments

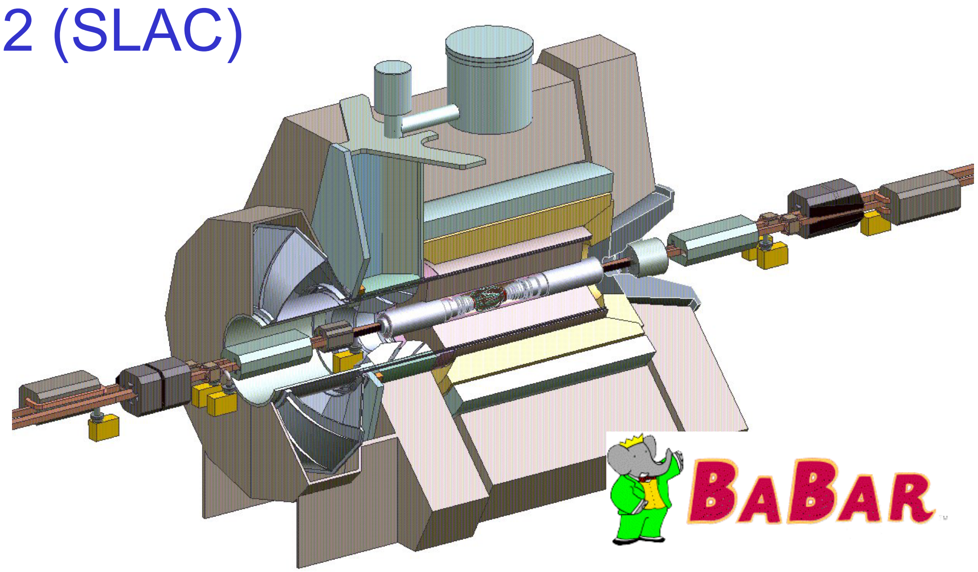
BABAR at PEP-2 (SLAC)

BELLE at KEK-B (KEK)



Belle Detector

For the KEK B factory



and also:

CLEO-3 at CESR (Cornell)

Started taking data in summer 1999

Luminosities at the Υ(4S)

CESR / CLEO

$$\text{peak} = 1.25 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$$
$$\text{day} = 73\ \text{pb}^{-1}$$
$$\text{Int. Lumi} = 16.0\ \text{fb}^{-1}\ (6.7\ \text{off})$$

PEP-2 / BABAR

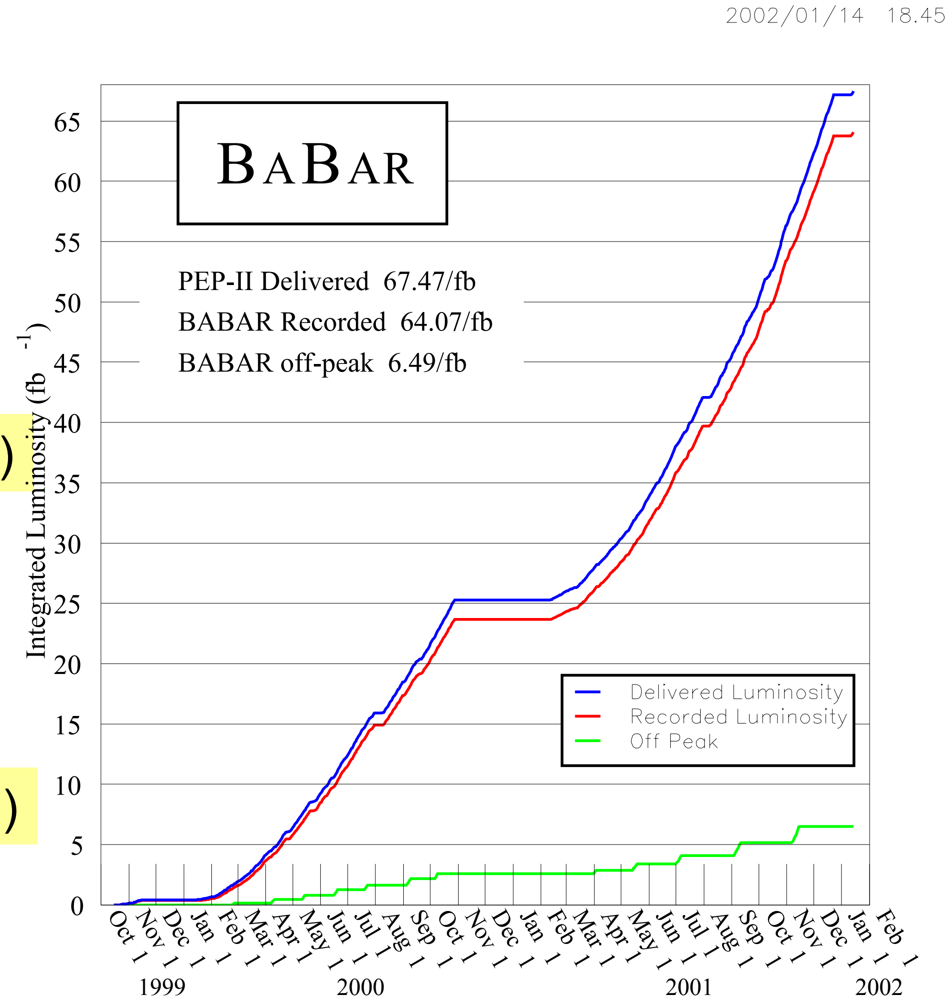
(as of Jan 17, 2002)

$$\text{peak} = 4.51 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$$
$$\text{day} = 303.4\ \text{pb}^{-1}$$
$$\text{Int. Lumi} = 64.7\ \text{fb}^{-1}\ (6.5\ \text{off})$$

KEK-B / BELLE

(as of Jan 17, 2002)

$$\text{peak} = 5.50 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$$
$$\text{day} = 311.5\ \text{pb}^{-1}$$
$$\text{Int. Lumi} = 47.2\ \text{fb}^{-1}\ (4.2\ \text{off})$$



Luminosity at PEP-II and KEK-B the key factor in new results

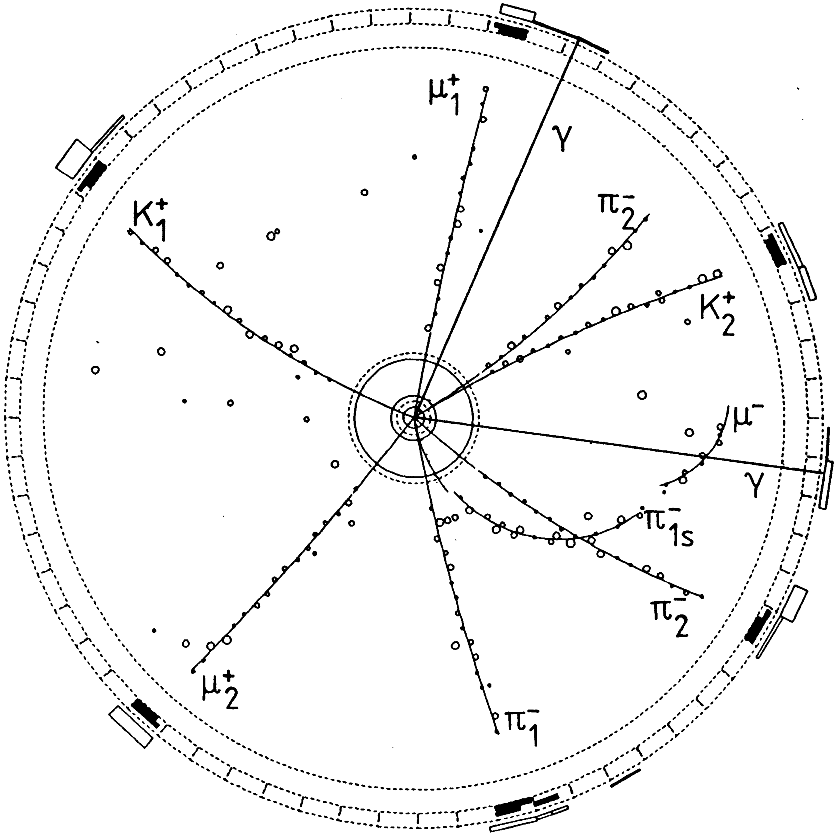
ARGUS, 1987

- Mixed full event and dilepton studies demonstrate mixing

$$B_1^0 \to D_1^{*-}\mu_1^+\nu_1, D_1^{*-} \to \overline{D}^0\pi_1^-$$

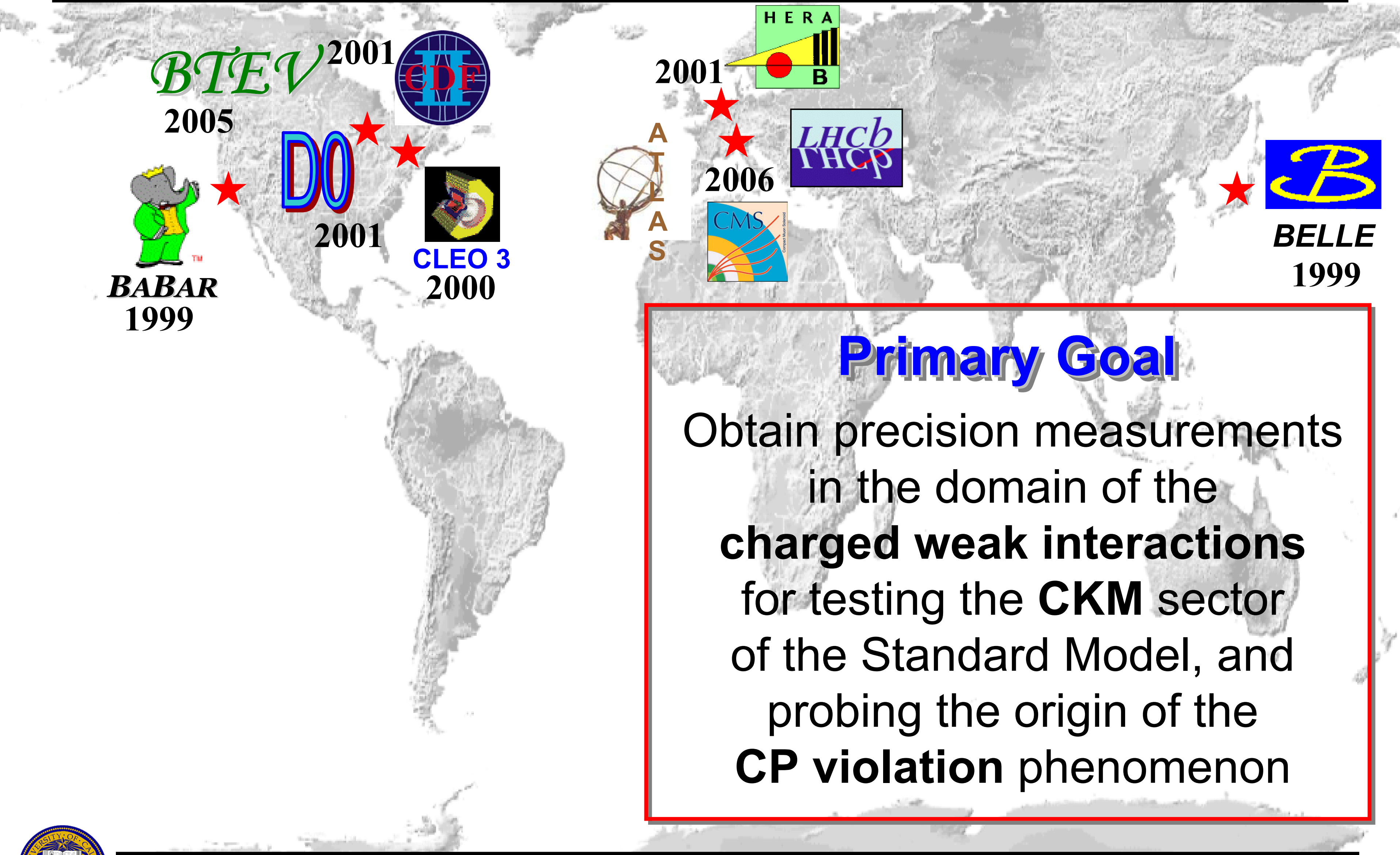
$$B_2^0 \to D_2^{*-}\mu_2^+\nu_2, D_1^{*-} \to D^-\pi^0$$

- Integrated luminosity 1983-87:
  - 103 pb^{-1}



Seeds sown at Snowmass 1988 for asymmetric-energy B Factories

Part of Worldwide Effort



Primary Goal

Obtain precision measurements in the domain of the **charged weak interactions** for testing the **CKM** sector of the Standard Model, and probing the origin of the **CP violation** phenomenon

Four Main Themes in B Physics

- ***CP Violation in neutral B decays***
  - Due to decay amplitude interference or in mixing
  - Due to interference of mixing and decay amplitudes
- ***Studies and searches for rare decays***
  - Sensitive to physics beyond the Standard Model either in rate or direct *CP* violation
- ***Precision determination of CKM matrix elements***
  - Need to significantly improve in order to determine whether observed *CP* violation is consistent with SM predictions
- ***Improving our understanding of B decays***
  - Feeds back into precision SM tests and measurements

Roughly 100 journal and conference papers have been produced by CLEO, BABAR, and BELLE in the last year: This talk will concentrate on CP violation and prospects!

CP Violation in the Standard Model

Mass Eigenstates ≠ Weak Eigenstates ⇒ Quark Mixing

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

CKM Matrix

Complex matrix described by
4 independent real parameters

Wolfenstein parameterization:

phase

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP Violation:

$$J = \text{Im}\left(V_{ik} V_{jk}^{*} V_{j\ell} V_{i\ell}^{*}\right) \neq 0$$

$$J \approx A^2\lambda^6\eta$$

$\eta = 0 \Rightarrow$ no CPV from SM

Unitarity Triangle

Choice of parameters:

$$\boxed{\lambda,\ A,\ \bar{\rho}\ \text{and}\ \bar{\eta}}$$

$$\bar{\rho} = \left(1 - \lambda^2/2\right)\rho$$
$$\bar{\eta} = \left(1 - \lambda^2/2\right)\eta$$

At the 1% level: $|V_{us}|$

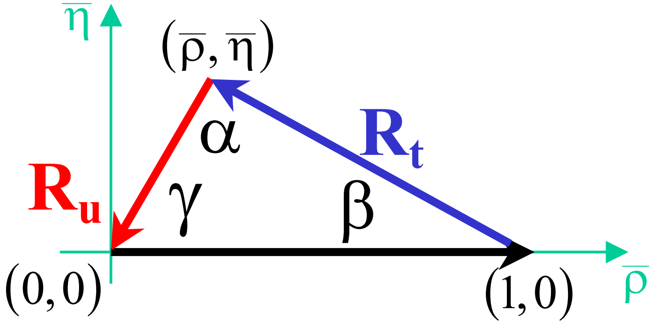
$$\lambda = |V_{us}| = \sin\theta_c$$
$$\lambda = 0.2205 \pm 0.0018$$

At the 5% level: $|V_{cb}|$

$$A = |V_{cb}|/\lambda^2$$
$$A = 0.83 \pm 0.06$$

$|V_{ub}|$ and $|V_{td}|$
$\rightarrow \bar{\rho}$ - $\bar{\eta}$ plane

Unitarity: $1 + R_t + R_u = 0$



$$R_u = \frac{V_{ud}\,V_{ub}^*}{V_{cd}\,V_{cb}^*} \approx -\sqrt{\bar{\rho}^2 + \bar{\eta}^2}\ e^{i\gamma}$$

$$R_t = \frac{V_{td}\,V_{tb}^*}{V_{cd}\,V_{cb}^*} \approx -\sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}\ e^{-i\beta}$$

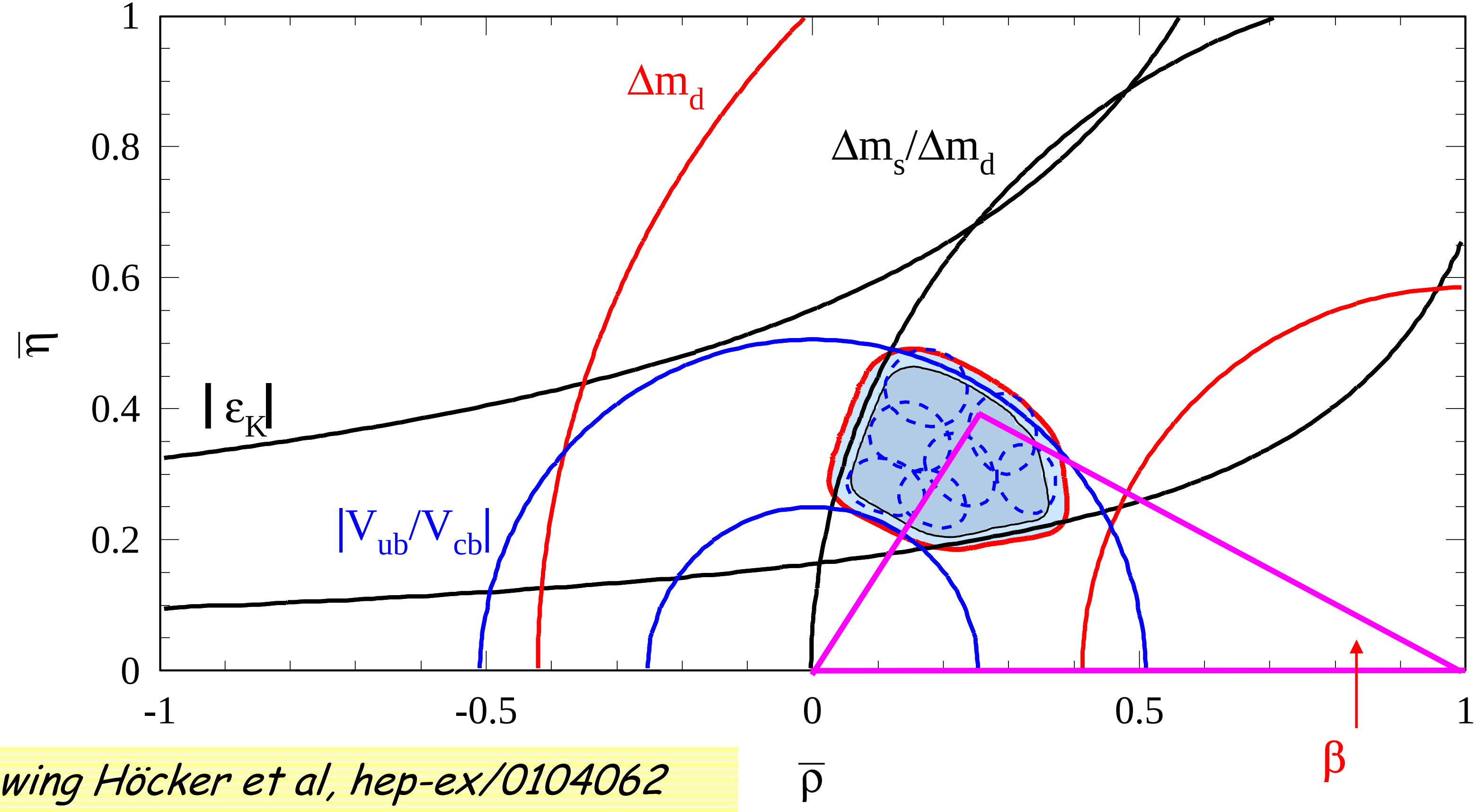
$$\gamma = \arg V_{ub}^*\,,\quad \alpha = \pi - \gamma - \beta$$

Indirect Constraints on Unitarity Triangle

Present experimental knowledge:

(with a range of theor. inputs)

B_d mixing $\Rightarrow \Delta m_d$
$b \rightarrow ul\nu \Rightarrow V_{ub}$, $D^*l\ \nu \Rightarrow V_{cb}$
B_s mixing $\Rightarrow \Delta m_s / \Delta m_d$
Kaon decays $\Rightarrow |\varepsilon_K|$



Following Höcker et al, hep-ex/0104062

CP Violation in the B System

- *CP* Violation in Decay
- *CP* Violation in Mixing
- *CP* Violation in Interference Mixing & Decay

CP Violation in Decay

Interference of Decay Amplitudes

CP violation in decay (direct CPV) results from interference between various terms in the decay amplitude:

$$\left|\bar{A}_{\bar{f}} / A_f\right| \neq 1 \quad \Rightarrow \quad \mathrm{Prob}(\bar{B} \rightarrow \bar{f}) \neq \mathrm{Prob}(B \rightarrow f)$$

CP violation in decay amplitude

Time-independent *CP* observable:

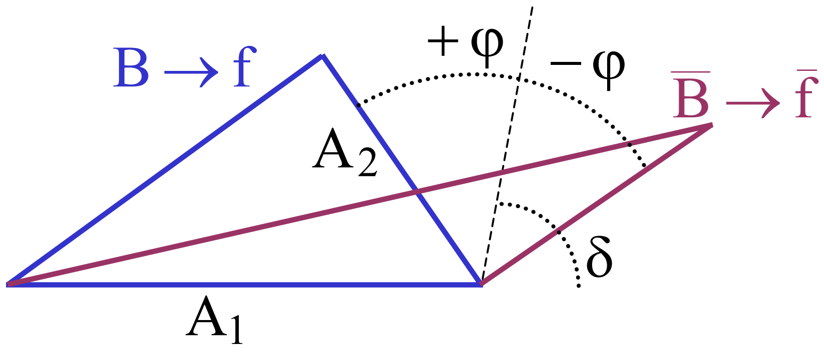
Partial decay rate asymmetry

$$A_{CP} = \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow \bar{f})} \propto 2|A_1||A_2| \sin\delta \sin\varphi$$

2 amplitudes A_1 and A_2

Strong phase difference

Weak phase difference



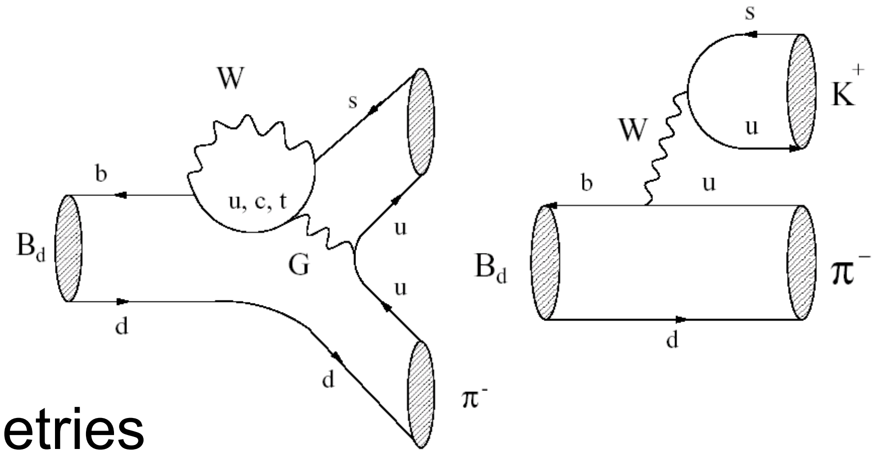
$\delta = 0$ or $\varphi = 0 \Rightarrow$ no CPV

For neutral modes, direct *CP* violation competes with other types of *CP* violation

$B \to K\pi$ and determination of γ

Expect significant interference of tree and penguin amplitudes

$$A_{K\pi} \sim \lambda^2 e^{i\gamma} T + P$$



➡ potentially large *CP* asymmetries

CP-averaged BF measurements can lead to non-trivial constraints (bounds) on *CP* angle γ

General analysis:

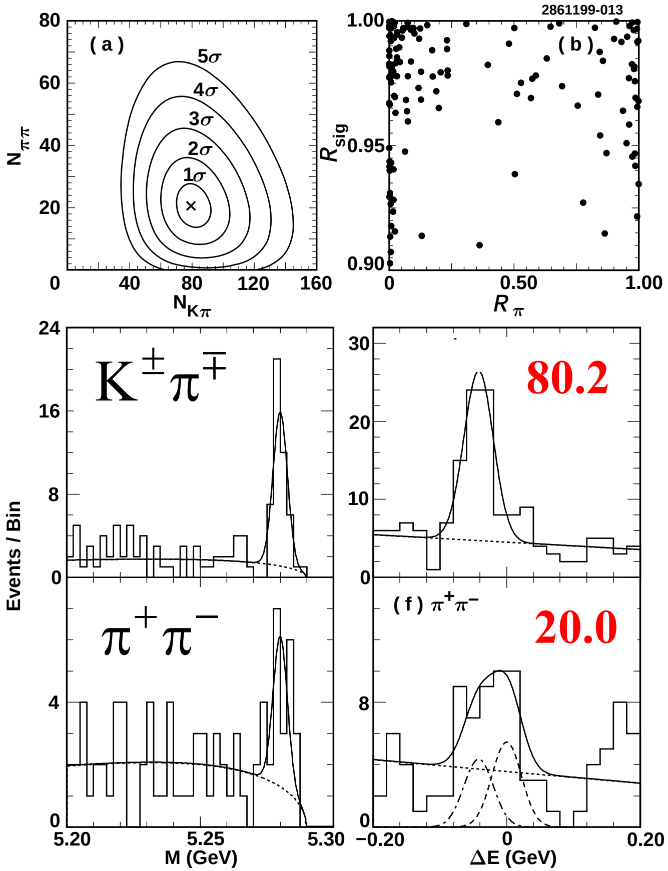
- EW penguins
- SU(3) breaking
- Rescattering (FSI)

Fleischer & Mannel (98)
Gronau, Rosner, London (94, 98)
Neubert & Rosner (98)
Buras & Fleischer (98)
etc.

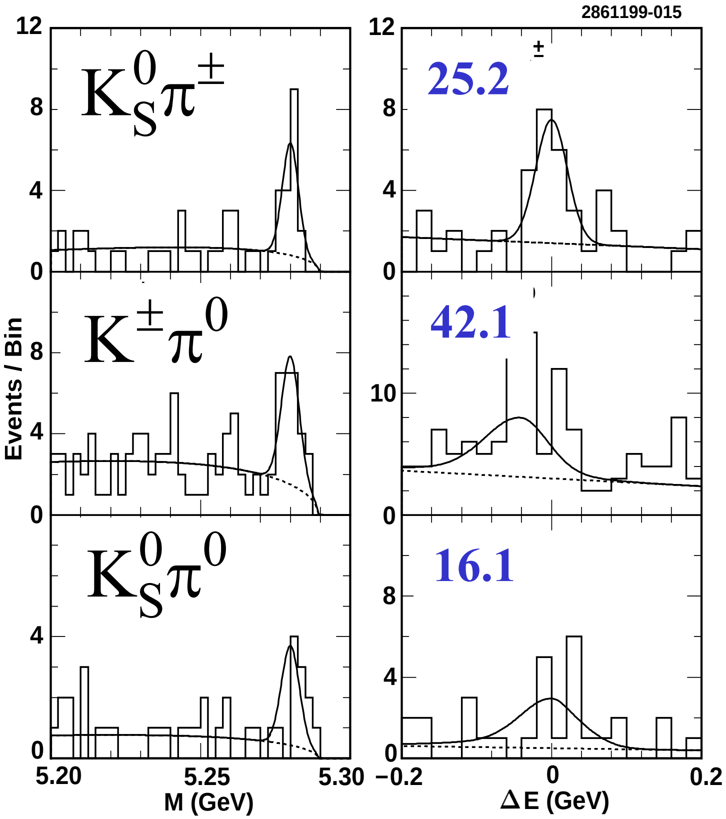
Experimental test:

- Direct *CP* violation in $B \to K\pi$ modes

B→ $K\pi$, $\pi\pi$ at CLEO



CLEO PRL **85** (2000) 515



CLEO
9.1 fb^{-1}

$B \to \pi\pi/K\pi$ BF Summary

BF ($\times 10^6$)	**CLEO** **9.1 fb^{-1}**	***BABAR*** **20.7 fb^{-1}**	**BELLE** **10.5 fb^{-1}**	**World Average**
$B^0 \to \pi^+\pi^-$	$4.3^{+1.6}_{-1.4} \pm 0.5$	$4.1 \pm 1.0 \pm 0.7$	$5.6^{+2.3}_{-2.0} \pm 0.4$	$4.44^{+0.89}_{-0.86}$
$B^0 \to K^+\pi^-$	$17.2^{+2.5}_{-1.4} \pm 1.2$	$16.7 \pm 1.6 \pm 1.3$	$19.3^{+3.4}_{-3.2}{}^{+1.5}_{-0.6}$	$17.37^{+1.47}_{-1.30}$
$B^0 \to K^+K^-$	< 1.9 (90%)	< 2.5 (90%)	< 2.7 (90%)	
$B^+ \to \pi^+\pi^0$	< 12.7 (90%)	$5.7^{+2.0}_{-1.8} \pm 0.8$	< 13.4 (90%)	
$B^+ \to K^+\pi^0$	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$	$10.8^{+2.1}_{-1.9} \pm 1.0$	$16.3^{+3.5}_{-3.3}\ {}^{1.6}_{1.8}$	$12.13^{+1.70}_{-1.67}$
$B^+ \to K^0\pi^+$	$18.2^{+4.6}_{-4.0} \pm 1.6$	$18.2^{+3.3}_{-3.0} \pm 2.0$	$13.7^{+5.7}_{-4.8}\ {}^{1.9}_{1.8}$	$17.41^{+2.60}_{-2.51}$
$B^0 \to K^0\pi^0$	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	$8.2^{+3.1}_{-2.7} \pm 1.2$	$16.0^{+7.2}_{-5.9}{}^{+2.5}_{-2.7}$	$10.73^{+2.66}_{-2.66}$

PRL **85** (2000) 515

PRL **87**, 15802 (2001)

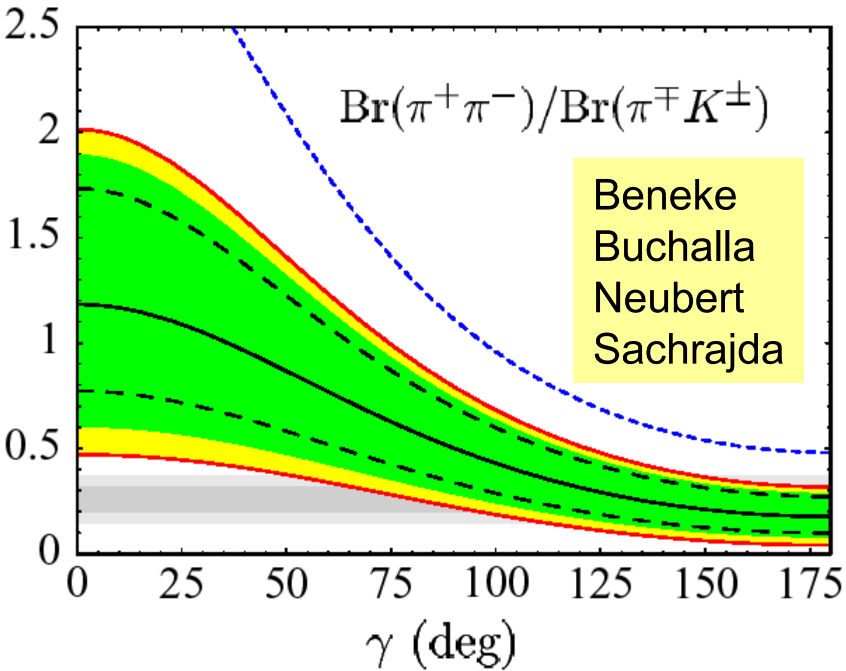
PRL **87**, 101801 (2001)

$K\pi \gg \pi\pi$ suggests $K\pi$ mostly penguin
and $\pi\pi$ may have significant contamination

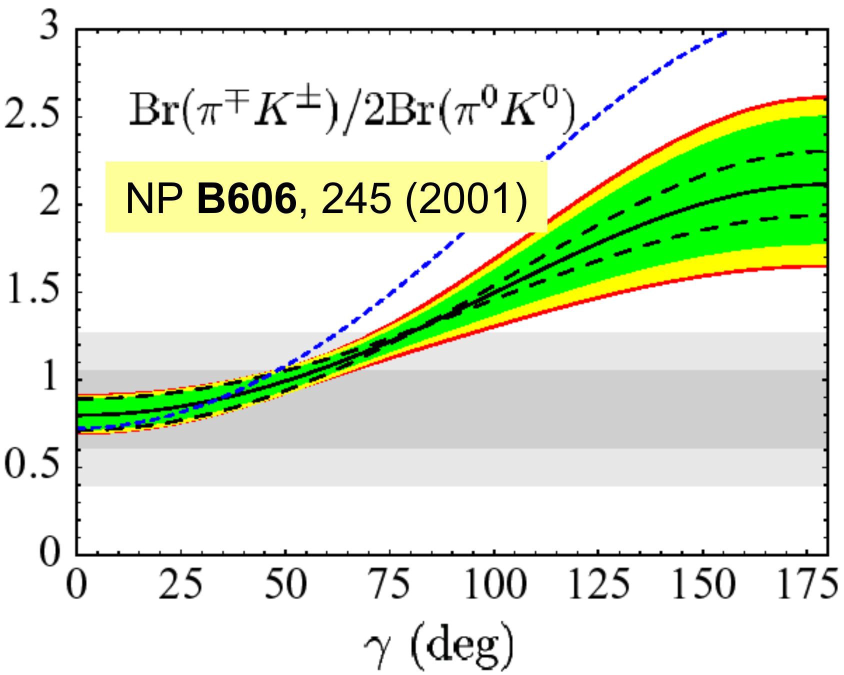
Ratios of Branching Fractions

$$\frac{BF(B\to\pi^+\pi^-)}{BF(B\to K^\pm\pi^\mp)}=0.256\,^{+0.056}_{-0.052} \qquad 2\times\frac{BF(B^\pm\to K^\pm\pi^0)}{BF(B\to K^\pm\pi^\mp)}=1.40\,^{+0.23}_{-0.22}$$

$$\frac{BF(B\to K^\pm\pi^\mp)}{BF(B^\pm\to K\pi^\pm)}=1.00\,^{+0.19}_{-0.15} \qquad \frac{1}{2}\times\frac{BF(B\to K^\pm\pi^\mp)}{BF(B\to K\pi^0)}=0.81\,^{+0.28}_{-0.17}$$

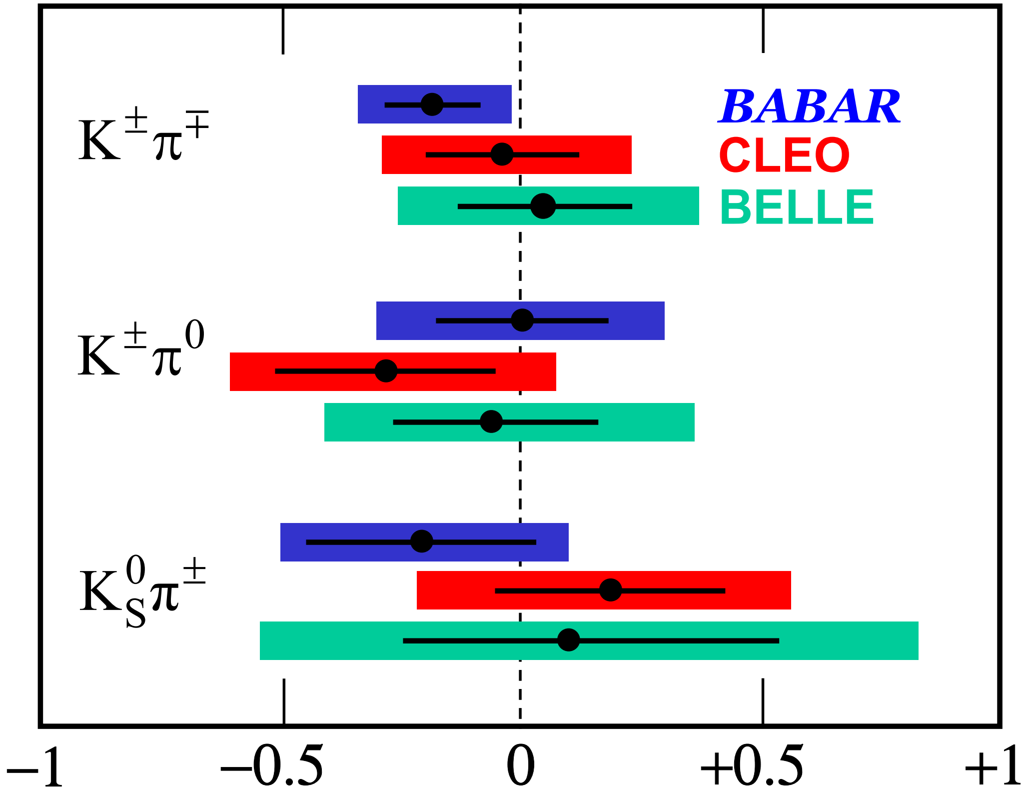


Beneke
Buchalla
Neubert
Sachrajda



NP **B606**, 245 (2001)

CP Charge Asymmetries in $K\pi$ modes



BABAR PRL **87**, 15802 (2001)

$$A_{CP}(K^{\pm}\pi^{\mp}) = -0.19 \pm 0.10$$

$$A_{CP}(K^{\pm}\pi^{0}) = +0.00 \pm 0.18$$

$$A_{CP}(K^0_S\pi^{\pm}) = -0.21 \pm 0.18$$

CLEO PRL **85**, 525 (2000)

$$A_{CP}(K^{\pm}\pi^{\mp}) = -0.04 \pm 0.16$$

$$A_{CP}(K^{\pm}\pi^{0}) = -0.29 \pm 0.23$$

$$A_{CP}(K^0_S\pi^{\pm}) = +0.18 \pm 0.24$$

BELLE PR **D64**, 071101 (2001)

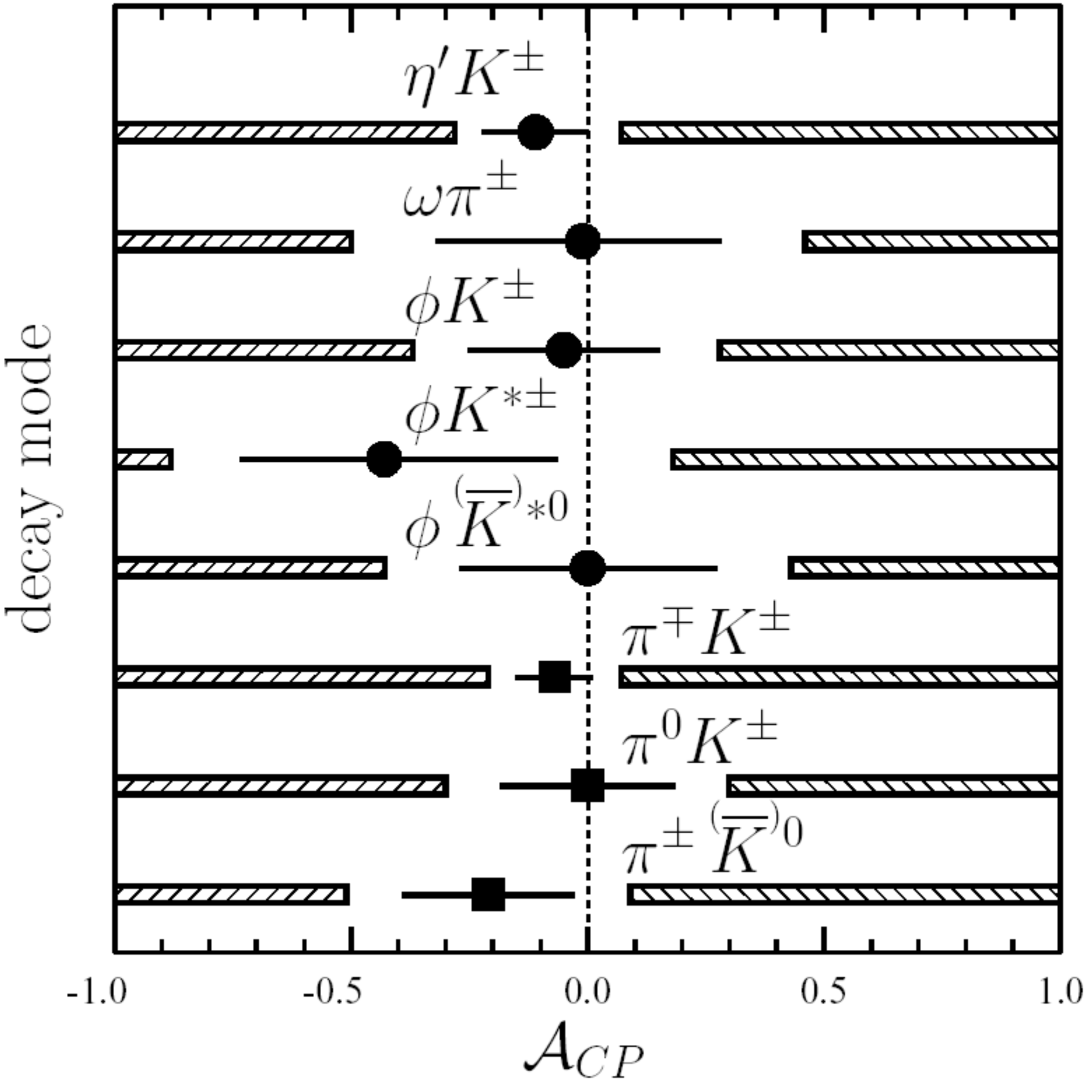
$$A_{CP}(K^{\pm}\pi^{\mp}) = +0.04\,^{+0.19}_{-0.17}$$

$$A_{CP}(K^{\pm}\pi^{0}) = -0.06\,^{+0.22}_{-0.20}$$

$$A_{CP}(K^0_S\pi^{\pm}) = +0.10\,^{+0.43}_{-0.34}$$

Model dependent predictions exist;
possible constraints on *CP* angle γ

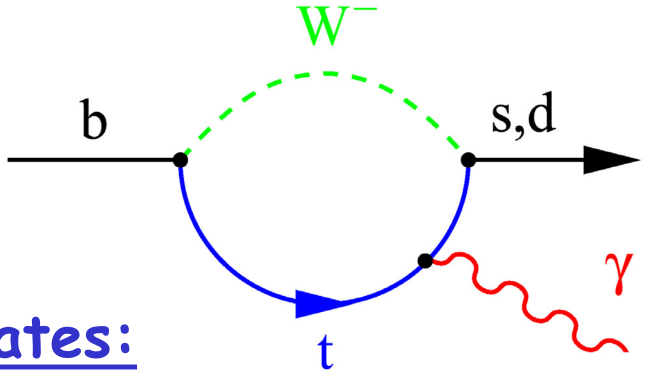
Asymmetries in Other Charmless Modes



BABAR hep-ex/0111087

Penguin b → sg or
CKM suppressed tree

Inclusive $b \to s\gamma$ Decays



- Probes top quark couplings V_{ts}
- SM rate predictions:
  $(3.28 \pm 0.33) \times 10^{-4}$

Chetyrkin et al.
PL **B400**, 206 (1997)

- SM predicts small *CP* asymmetry $(<1\%)$

Rates:

$$BF(b \to s\gamma) \times 10^4 = 3.11 \pm 0.80_{(stat)} \pm 0.72_{(syst)}$$

ALEPH PL **B429**, 169 (1999)

$$BF(b \to s\gamma) \times 10^4 = 3.21 \pm 0.43_{(stat)} \pm 0.27_{(syst)}{}^{+0.18}_{-0.10}{}_{(th)}$$

CLEO PRL **87**, 251807 (2001)

$$BF(b \to s\gamma) \times 10^4 = 3.36 \pm 0.53_{(stat)} \pm 0.42_{(syst)}{}^{+0.50}_{-0.54}{}_{(th)}$$

BELLE PR **B511**, 151 (2001)

CP Asymmetries:

- Non-SM physics may contribute to larger asymmetries

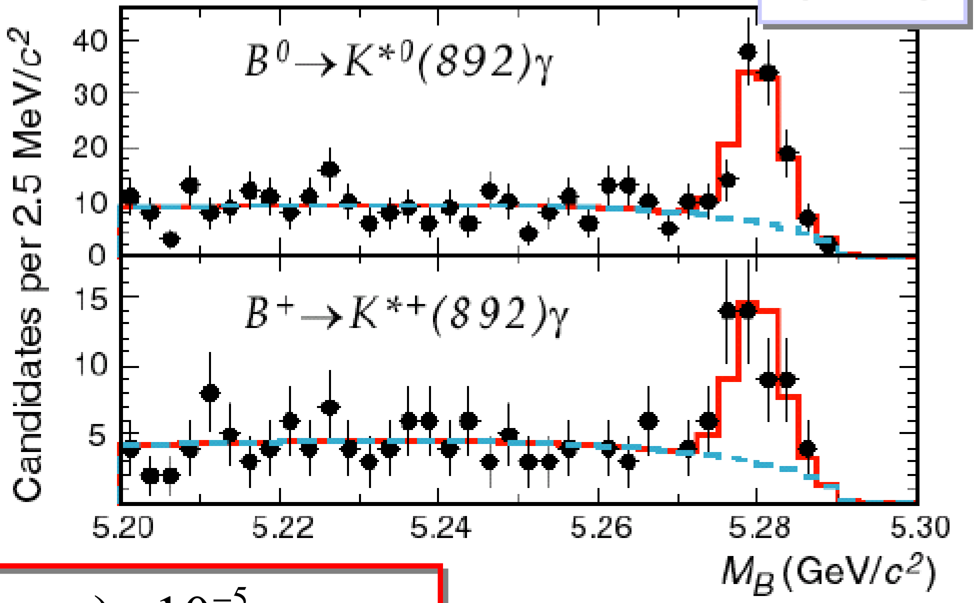
$$\begin{aligned} A_{CP} &= (-0.079 \pm 0.108_{(stat)} \pm 0.022_{(add\ syst)}) \times (1.0 \pm 0.03_{(mult\ syst)}) \\ &= 0.965 \cdot A_{CP}(b \to s\gamma) + 0.02 \cdot A_{CP}(b \to d\gamma) \\ &-0.27 < A_{CP} < +0.10 \quad (90\%CL) \end{aligned}$$

CLEO PRL **86**, 5661 (2001)

Exclusive Radiative Decays

CLEO

- Very little *CP*-violation expected in the K*γ mode (window on **New Physics**)
- Up to ~15% *CP*-Violation effect in the suppressed ργ mode (*not observed*)



$$\mathrm{BF}(B^0 \to K^{*0}\gamma) = (4.55^{+0.72}_{-0.68}{}_{(stat)} \pm 0.34_{(syst)}) \times 10^{-5}$$
$$\mathrm{BF}(B^+ \to K^{*+}\gamma) = (3.76^{+0.89}_{-0.83}{}_{(stat)} \pm 0.28_{(syst)}) \times 10^{-5}$$
$$A_{CP} = +0.08 \pm 0.13_{(stat)} \pm 0.03_{(syst)}$$

CLEO PRL **84**, 5283 (2000)

$$\mathrm{BF}(B^0 \to K^{*0}\gamma) = (4.23 \pm 0.40_{(stat)} \pm 0.22_{(syst)}) \times 10^{-5}$$
$$\mathrm{BF}(B^+ \to K^{*+}\gamma) = (3.83 \pm 0.62_{(stat)} \pm 0.22_{(syst)}) \times 10^{-5}$$
$$A_{CP} = -0.044 \pm 0.076_{(stat)} \pm 0.012_{(syst)}$$

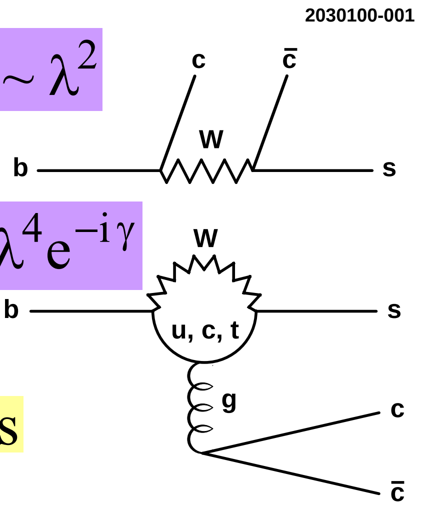
BABAR hep-ex/0110065

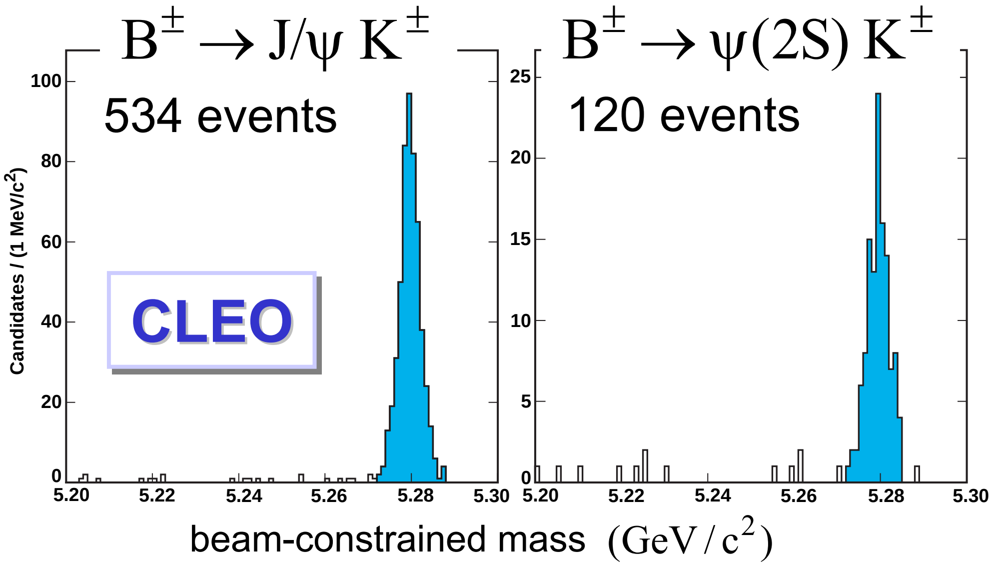
CP Asymmetries in Charmonium B Decays

$V_{cb}V_{cs}^* \sim \lambda^2$

$V_{td}V_{ts}^* \sim \lambda^2, \lambda^4 e^{-i\gamma}$

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





No *CP* asymmetry expected in SM is these channels

$$A_{CP}(J/\psi K^\pm) = (+1.8 \pm 4.3_{(stat)} \pm 0.4_{(syst)})\%$$
$$A_{CP}(\psi(2S)K^\pm) = (+2.0 \pm 9.1_{(stat)} \pm 1.0_{(syst)})\%$$

CLEO PRL **84** (2000) 5940

$$A_{CP}(J/\psi K^+) = (+0.4 \pm 2.9_{(stat)} \pm 0.4_{(syst)})\%$$

BABAR preliminary
(EPS2001)

CP Violation in Decay: Summary

- *Many searches for CP violation in B meson decays*
  - So far, no experimental evidence for direct *CP* violation
- *"Copious" modes (e.g. charmonium)*
  - In general, expect small asymmetries
  - Asymmetry measurements at the few percent level
- *"Rare" modes (charmless, radiative penguin decays)*
  - Potentially large *CP* asymmetries
    - test the validity of theoretical models
  - Best asymmetry measurements at the 10% level
  - Much more statistics is needed!

Nota Bene: Direct *CP* violation is now firmly established in the kaon system

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (17.2 \pm 1.8_{(\mathrm{stat+syst})}) \times 10^{-4}$$

E731, NA31, KTeV, NA48

CP Violation in Mixing

Formalism for CP Violation in Mixing

CP (or T) violation in the $B^0\overline{B}^0$ mixing matrix results from:

Mass Eigenstates $|B_{L,H}\rangle \neq$ *CP* Eigenstates $|B_{\pm}\rangle$

$$|B_{L,H}\rangle = p\,|B^0\rangle \pm q\,|\overline{B}^0\rangle = \frac{1}{\sqrt{1+|\varepsilon_{B_d}|^2}}\left(|B_{\pm}\rangle + \varepsilon_{B_d}\,|B_{\mp}\rangle\right)$$

$$\boxed{\left|\frac{q}{p}\right| = \left|\frac{1-\varepsilon_{B_d}}{1+\varepsilon_{B_d}}\right| \neq 1 \quad \Rightarrow \quad \mathrm{Prob}(B^0 \to \overline{B}^0) \neq \mathrm{Prob}(\overline{B}^0 \to B^0)}$$

Time-dependent *CP* observable:

$$A_T(t) = \frac{\Gamma(\overline{B}^0_{phys}(t) \to \ell^+ \nu X) - \Gamma(B^0_{phys}(t) \to \ell^- \overline{\nu} X)}{\Gamma(\overline{B}^0_{phys}(t) \to \ell^+ \nu X) + \Gamma(B^0_{phys}(t) \to \ell^- \overline{\nu} X)} \approx \frac{4\,\mathrm{Re}(\varepsilon_{B_d})}{1+|\varepsilon_{B_d}|^2}$$

constant with time

In the *B* System, $\Delta m_{B_d} = m_{B_H} - m_{B_L} \gg \Delta\Gamma_{B_d} \Rightarrow \varepsilon_{B_d} \sim$ pure imaginary

SM: $A_T \leq 2.10^{-3}$ $A_T \approx 10^{-2} \Rightarrow$ New Physics

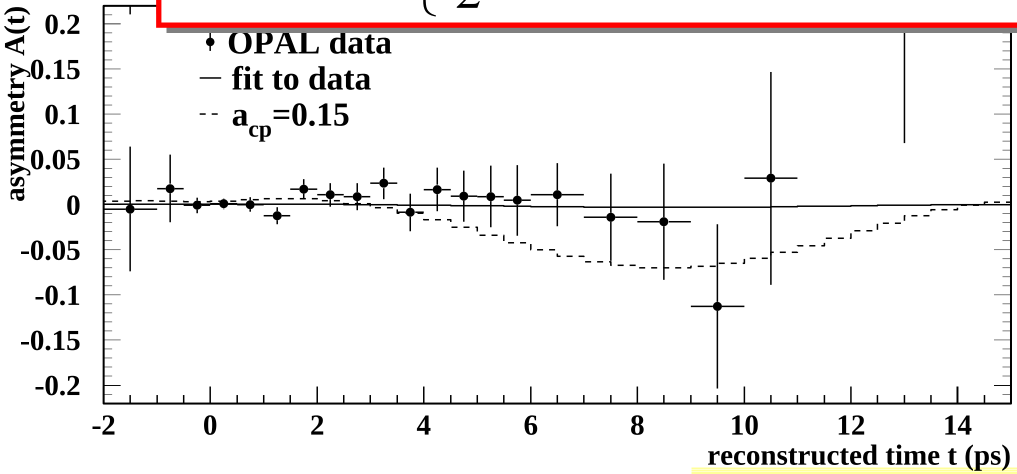
See for instance Bañuls & Bernabéu hep-ph/0005323

Results from LEP

$$A(t) = a_T \cdot \left\{ \frac{1}{2} \Delta m_{B_d} \tau_{B_d} \sin(\Delta m_{B_d} t) - \sin^2(\Delta m_{B_d} t/2) \right\}$$

OPAL

inclusive analysis



Beneke
Buchalla
Dunietz

OPAL Semileptonic sample, 3M had. Z^0

OPAL ZP **C**76 (1997) 401

$$\mathrm{Re}(\varepsilon_{B_d})/(1+|\varepsilon_{B_d}|^2) = \quad 0.002 \pm 0.007_{\,(\mathrm{stat})} \pm 0.003_{\,(\mathrm{syst})}$$

Fully inclusive analysis

OPAL EPJ **C**12 (2000) 609

$$\mathrm{Re}(\varepsilon_{B_d})/(1+|\varepsilon_{B_d}|^2) = \quad 0.001 \pm 0.014\,(\mathrm{stat}) \pm 0.003\,(\mathrm{syst})$$

ALEPH Combined semileptonic and fully inclusive analyses, 4.1M had. Z^0

ALEPH CERN-EP/2000-105 (sub. to EPJ)

$$\mathrm{Re}(\varepsilon_{B_d})/(1+|\varepsilon_{B_d}|^2) = \quad -0.003 \pm 0.007\,(\mathrm{stat}+\mathrm{syst})$$

Results from B Factories

CLEO like-sign dilepton sample,
9.1 fb^{-1} on the $\Upsilon(4S)$, 4.4 fb^{-1} off-peak

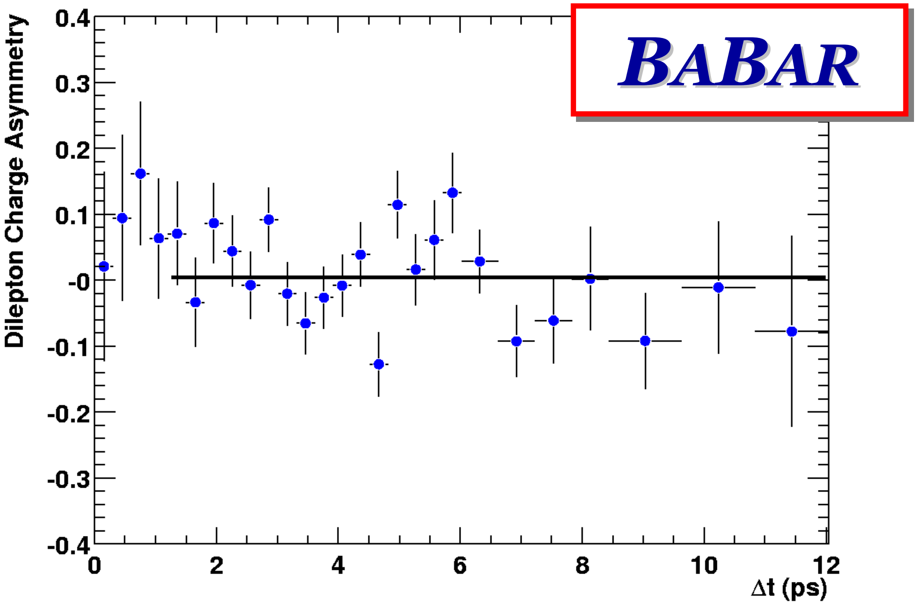
CLEO PRL 86 (2001) 5000

$$\mathrm{Re}(\varepsilon_{B_d})/(1+|\varepsilon_{B_d}|^2) = +0.0035 \pm 0.0103_{(stat)} \pm 0.0015_{(syst)}$$

BABAR like-sign dilepton sample,
20.7 fb^{-1} on the $\Upsilon(4S)$, 2.3 fb^{-1} off-peak

BABAR hep-ex/0107059

$$\mathrm{Re}(\varepsilon_{B_d})/(1+|\varepsilon_{B_d}|^2) = +0.0012 \pm 0.0029_{(stat)} \pm 0.0036_{(syst)}$$



CP Violation in Mixing: Summary

So far, no experimental evidence of large *CP* violation in B^0 mixing

To a good approximation: $|q/p| = 1$

$$q/p = e^{-2i\varphi_M} = -|M_{12}|/M_{12}$$

← dispersive part of the $B^0 \to \overline{B}^0$ amplitude

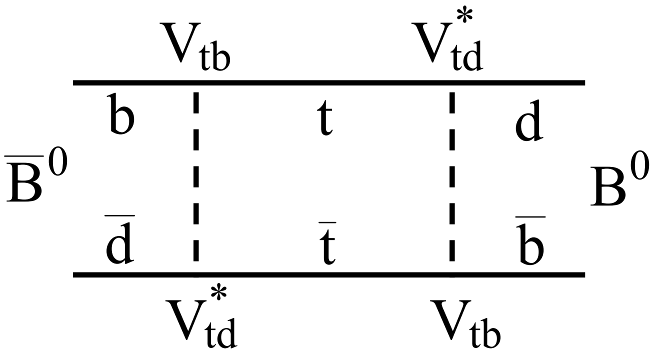
Time evolution of a state produced as a pure B^0 :

$$|B^0_{phys}(t)\rangle \propto \cos(\Delta m_{B_d} t/2)|B^0\rangle + i\,e^{-2i\varphi_M}\sin(\Delta m_{B_d} t/2)|\overline{B}^0\rangle$$

In the SM: $\varphi_M = \arg(V_{td}V_{tb}^*) = \beta$

New physics can change the mixing parameter:

$$M_{12} = M_{12}^{SM} + M_{12}^{NP} \qquad \varphi_M \to \beta + \varphi_{NP}$$



CP Violation in Interference

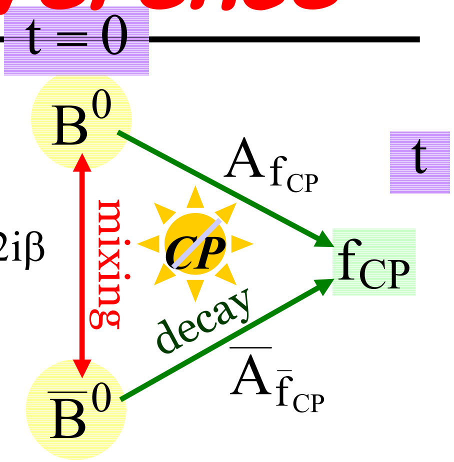
Mixing

Decay

BELLE (10.5 fb^{-1}) PRL **86**, 2509 (2001)
BABAR (20.7 fb^{-1}) PRL **86**, 2515 (2001)
BABAR (29.7 fb^{-1}) PRL **87**, 091801 (2001)
BELLE (29.1 fb^{-1}) PRL **87**, 091802 (2001)
BABAR (29.7 fb^{-1}) hep-ex/0201020

Formalism for *CP* from Interference

CP violation results from interference between decays with and without mixing



$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \cdot \frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

CP eigenvalue

Amplitude ratio

$\approx e^{-2i\beta}$

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

Time-dependent *CP* Observable:

$$A_{f_{CP}}(t) = \frac{\Gamma(\overline{B}^0_{\mathrm{phys}}(t) \to f_{CP}) - \Gamma(B^0_{\mathrm{phys}}(t) \to f_{CP})}{\Gamma(\overline{B}^0_{\mathrm{phys}}(t) \to f_{CP}) + \Gamma(B^0_{\mathrm{phys}}(t) \to f_{CP})}$$

$$= C_{f_{CP}} \cdot \cos(\Delta m_{B_d} t) + S_{f_{CP}} \cdot \sin(\Delta m_{B_d} t)$$

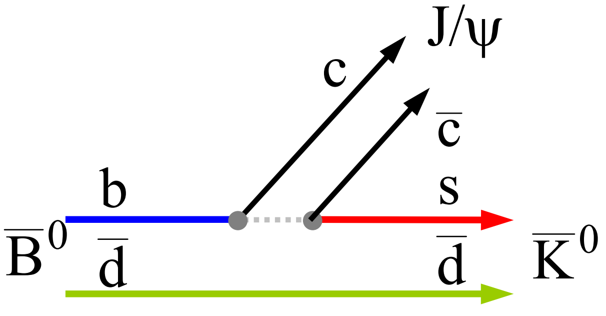
cosine term

sine term

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

Golden Channel: $B^0 \to J/\psi K^0_{S,L}$

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



K^0 mixing is required

$\bar{B}^0 \to J/\psi\, \bar{K}^0$
$B^0 \to J/\psi\, K^0$

$\Rightarrow$

$B^0_{CP=-1} \to J/\psi\, K^0_S$
$B^0_{CP=+1} \to J/\psi\, K^0_L$

Single weak phase → no direct CPV $|\lambda_{J/\psi\, K^0_{S,L}}| = 1$

$$\boxed{A_{J/\psi\, K^0_{S,L}}(t) = -\eta_{J/\psi\, K^0_{S,L}} \cdot \sin 2\beta \cdot \sin(\Delta m_{B_d} t)}$$

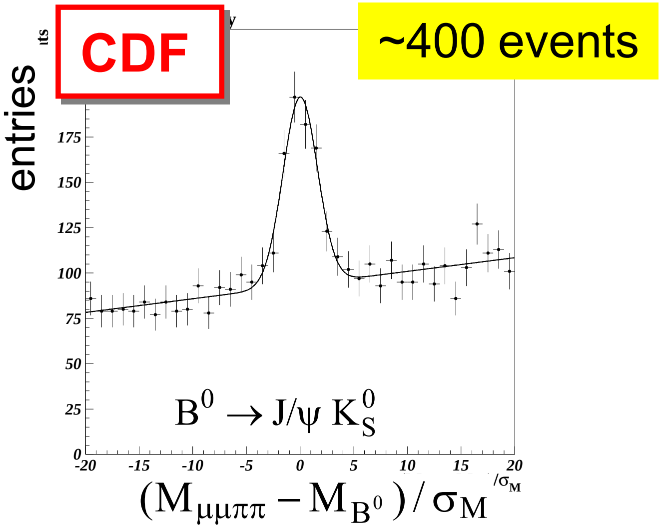
- Theoretically clean way to measure sin2β
- Clear experimental signatures
- Relatively large branching fractions

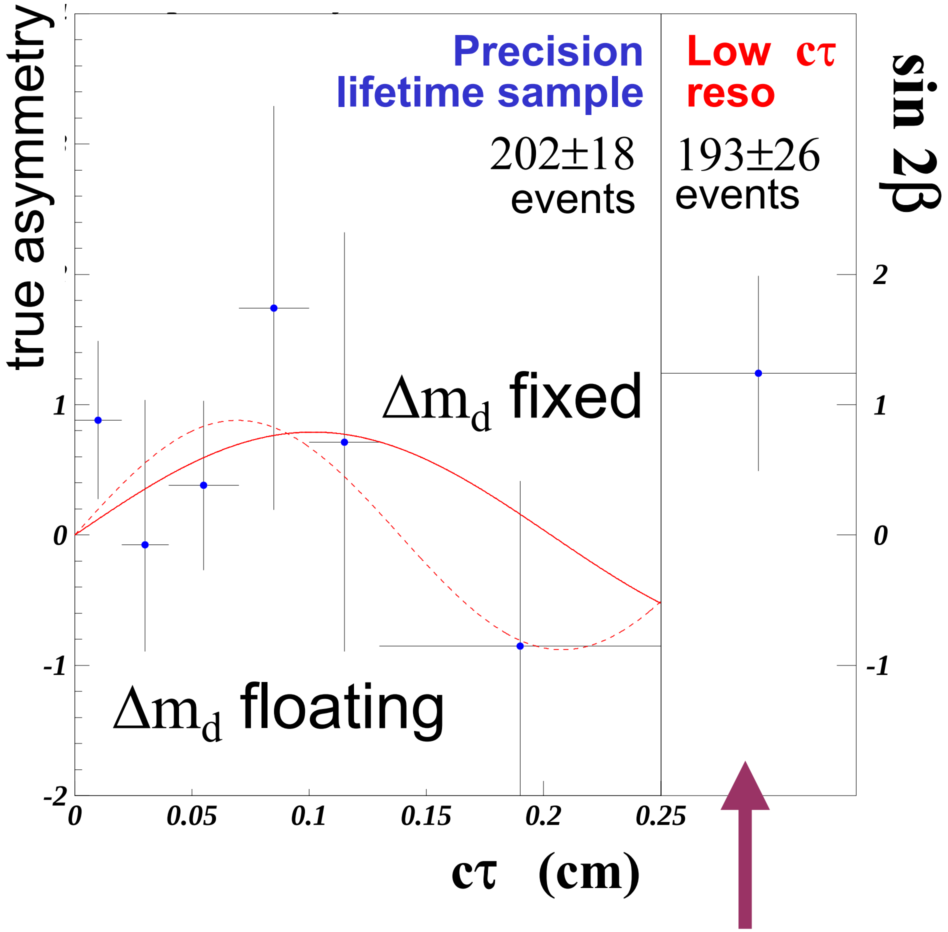
Results from CDF at the Tevatron

CDF Run 1 $(110\ \mathrm{pb}^{-1})$

$$\boxed{\sin 2\beta = 0.79 \pm 0.39 \pm 0.16}$$

CDF PR **D61** (2000)

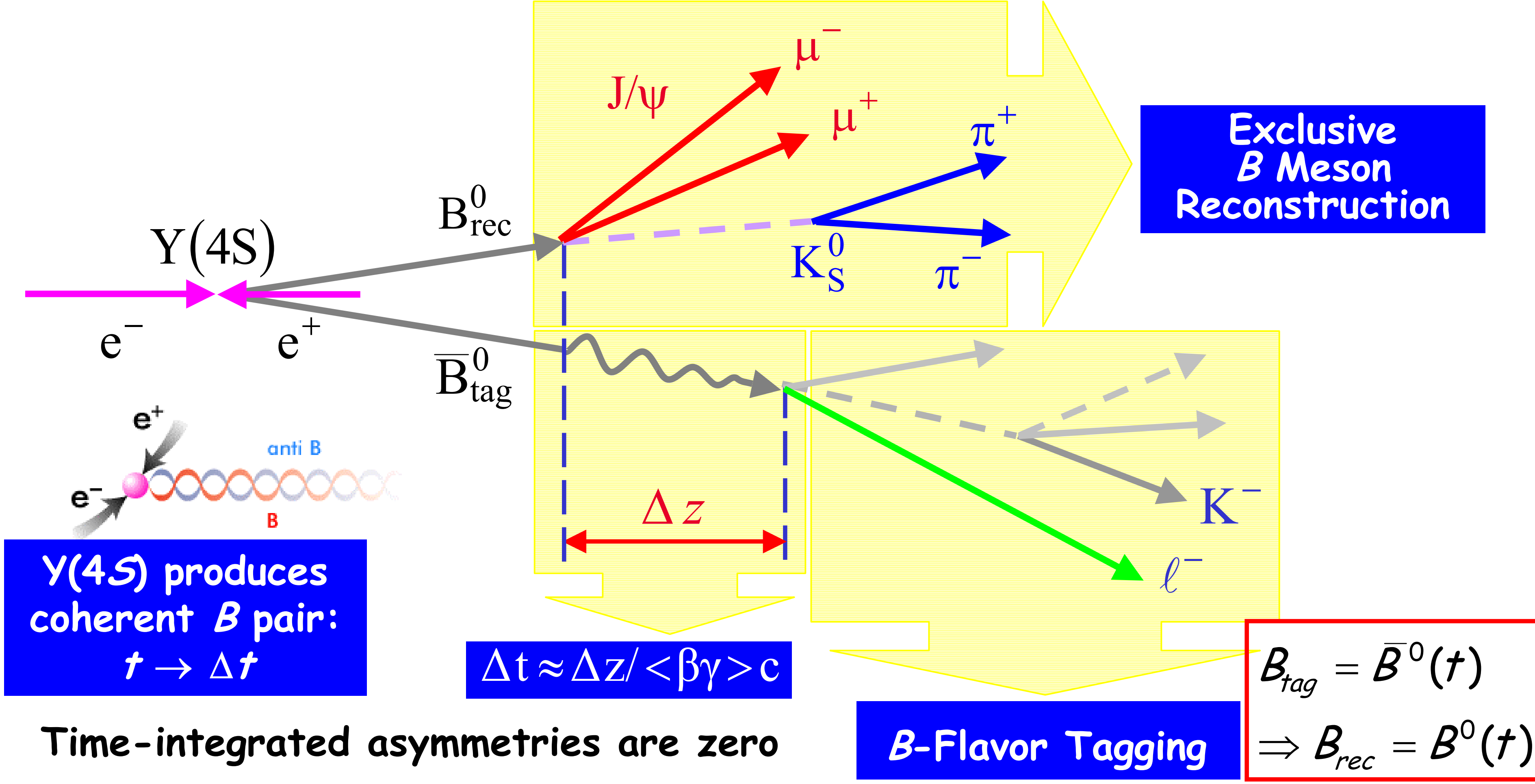




Time-dependent <u>and</u> time-integrated meas.

$$A^{\mathrm{int}}_{J/\psi K^0_S} = \eta_{J/\psi K^0_S} \frac{x_d}{1+x_d} \sin 2\beta \approx 0.47\,\eta_{J/\psi K^0_S} \sin 2\beta$$

Experimental Technique for B Factories



Exclusive *B* Meson Reconstruction

Y(4*S*) produces coherent *B* pair: $t \rightarrow \Delta t$

$\Delta t \approx \Delta z / <\beta\gamma> c$

***B*-Flavor Tagging**

$B_{tag} = \overline{B}^0(t)$

$\Rightarrow B_{rec} = B^0(t)$

Time-integrated asymmetries are zero

$B^0_{rec} = B^0_{flav}$ (flavor eigenstates) ➡ lifetime, mixing analyses

$B^0_{rec} = B^0_{CP}$ (*CP* eigenstates) ➡ *CP* analysis

Shared Analysis Strategies

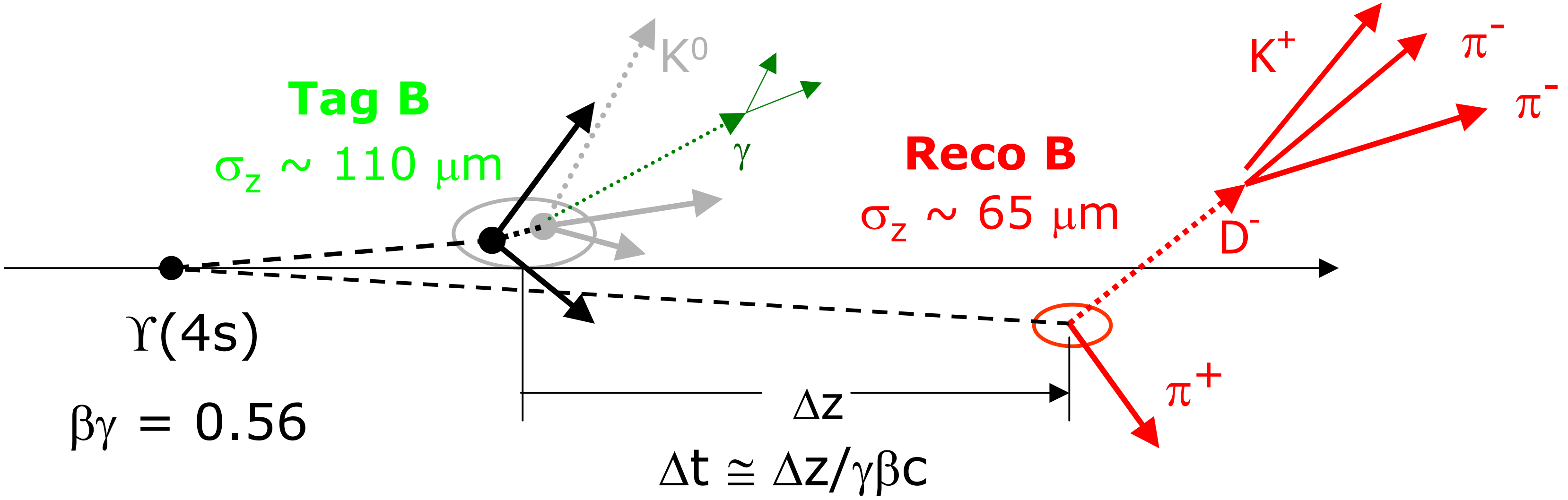
Factorize the analysis into building blocks

Higher precision

Increasing complexity

Measurements	Analysis Ingredient
B^+ / B^0 Lifetimes	a) Reconstruction of *B* mesons in flavor eigenstates *b) B* vertex reconstruction
$B^0\overline{B}^0$ Mixing	c) Flavor Tagging + a + b
CP Asymmetries	d) Reconstruction of neutral *B* mesons in *CP* eigenstates + a + b + c

Measurement of B^0 and B^+ Lifetime



3. Reconstruct Inclusively the vertex of the "other" B meson (B_{TAG})

1. Fully reconstruct one B meson in flavor eigenstate (B_{REC})
2. Reconstruct the decay vertex

4. compute the proper time difference Δt
5. Fit the Δt spectra

Samples of Fully-Reconstructed B Decays

Flavor eigenstates for mixing and lifetime measurements

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

Cabibbo-favored hadronic decays to "open charm" modes

$\bar{B}^0 \to D^{(*)+}\pi^-/\rho^-/a_1^-$

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

Charmonium modes

$B^+ \to J/\psi\ K^+$

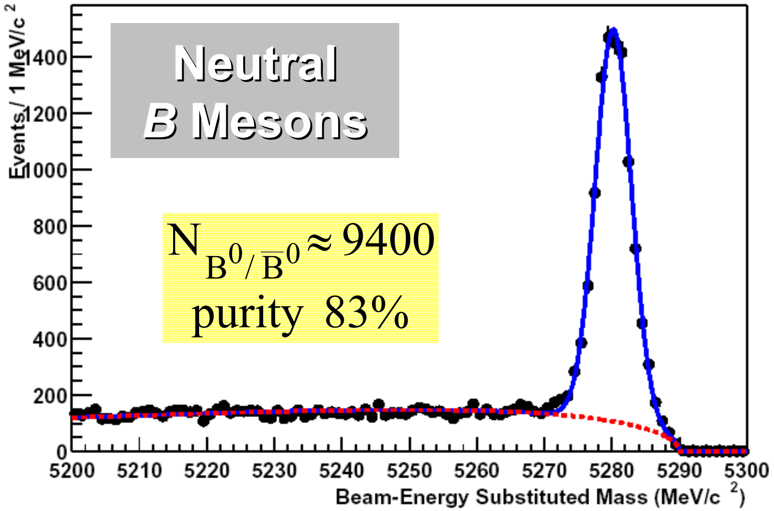
$b \to c(\ell^-\bar{\nu})$

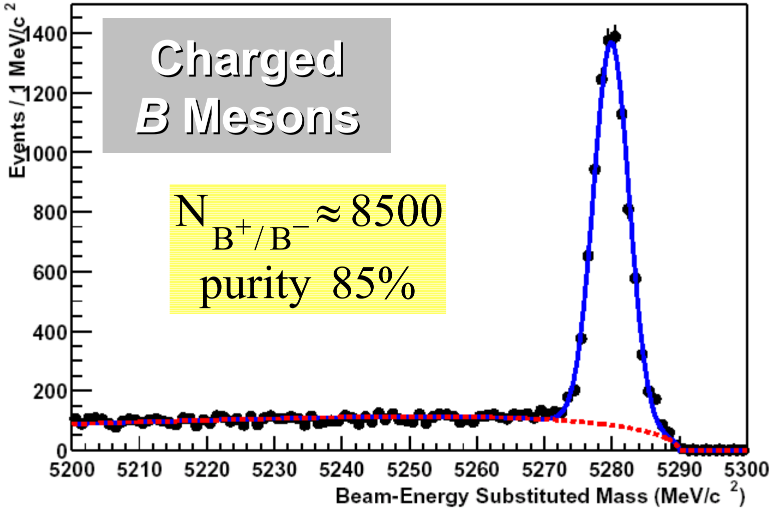
Semileptonic modes

$\bar{B}^0 \to D^{*+}\ \ell^-\ \bar{\nu}$

BABAR

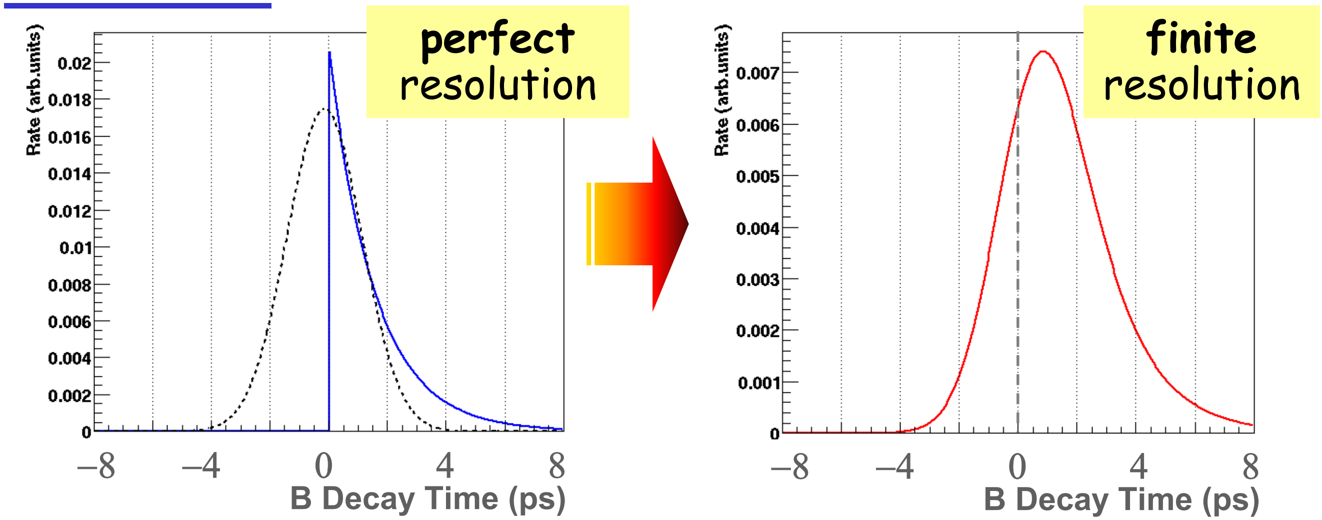
$29.7\ \mathrm{fb}^{-1}$





B-Lifetimes: Time Distributions

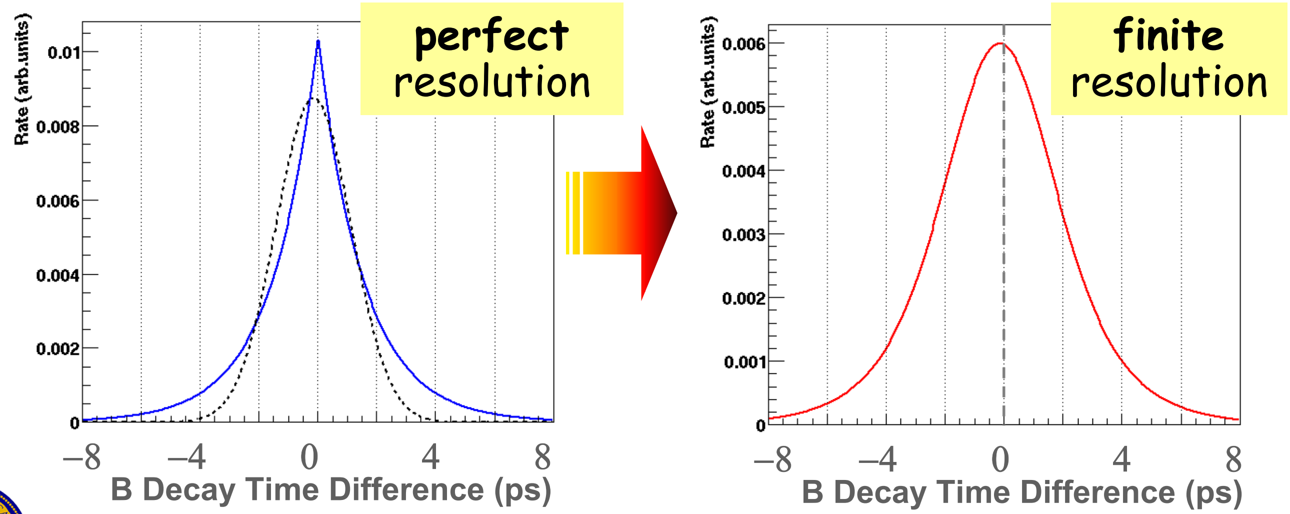
LEP/CDF



Production point of *B* meson is known with good accuracy

Control of the resolution function at negative times

B Factories



Proper time difference obtained from distance Δz between the two *B* vertices

Fit the parameters of the resolution function together with the lifetime

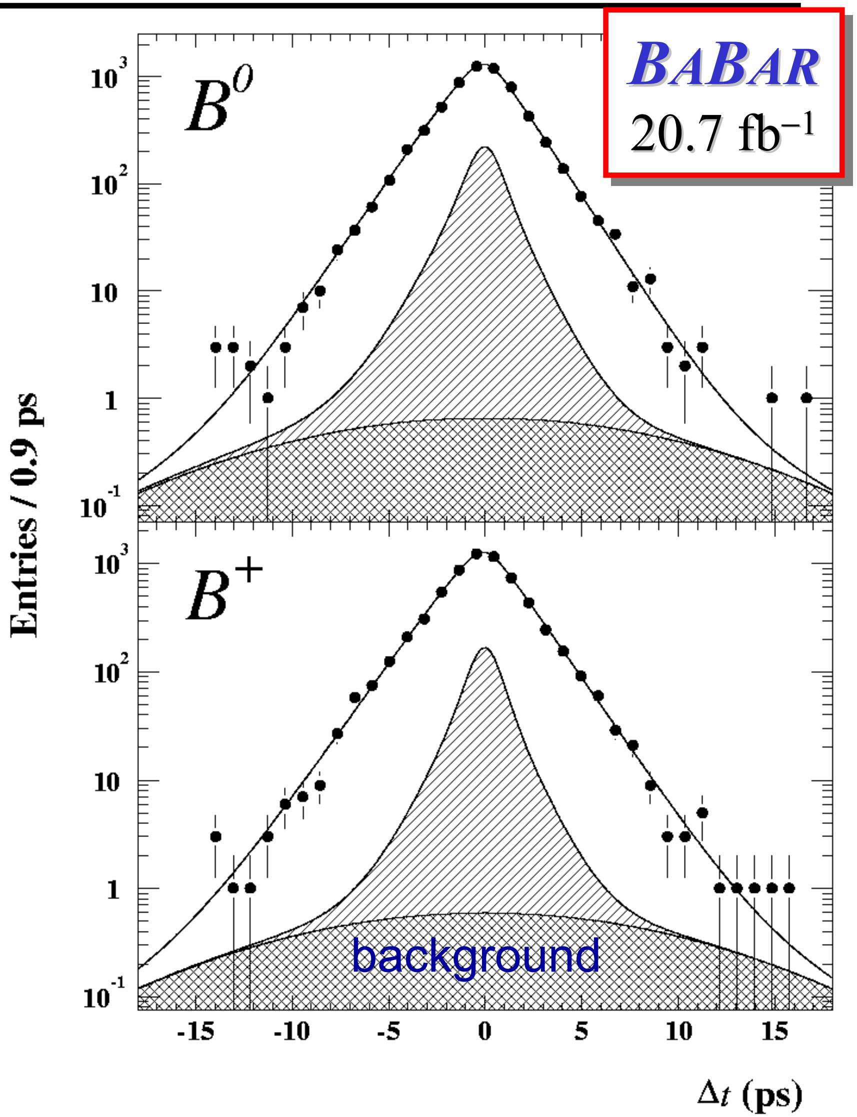
B-Lifetime Measurements

$$
\begin{aligned}
\tau_{B^0} &= 1.546 \pm 0.032 \pm 0.022 \;\; \text{ps} \\
\tau_{B^+} &= 1.673 \pm 0.032 \pm 0.023 \;\; \text{ps} \\
\tau_{B^+} / \tau_{B^0} &= 1.082 \pm 0.026 \pm 0.012
\end{aligned}
$$

BABAR PRL **87**, 201803 (2001)

(error PDG2000 ~ 0.03 ps, stat+syst)

- *Good agreement with previous lifetime measurements*
- *Excellent control of the time resolution function (parameterization, tails)*



Proof of principle for time-dependent analysis at *B* Factories

B-Lifetime Measurements

29.1 fb^{-1}

$$\tau_{B^0} = 1.553 \pm 0.030 \pm 0.013 \text{ ps}$$
$$\tau_{B^+} = 1.681 \pm 0.026 \pm 0.012 \text{ ps}$$
$$\tau_{B^+} / \tau_{B^0} = 1.082 \pm 0.023 \pm 0.011$$

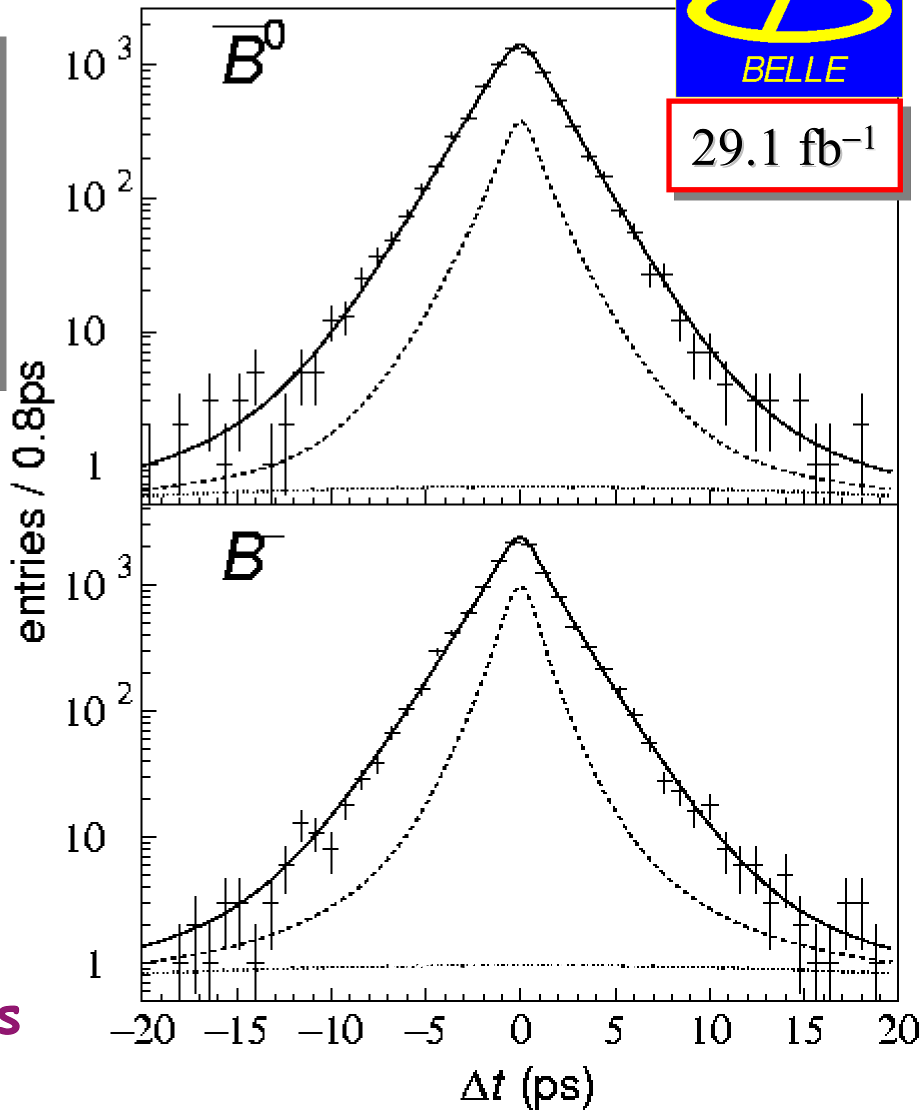
Preliminary **BELLE** KEK5 Workshop

(error PDG2000 ~ 0.03 ps, stat+syst)

From D*lnu sample used for mistag determination:

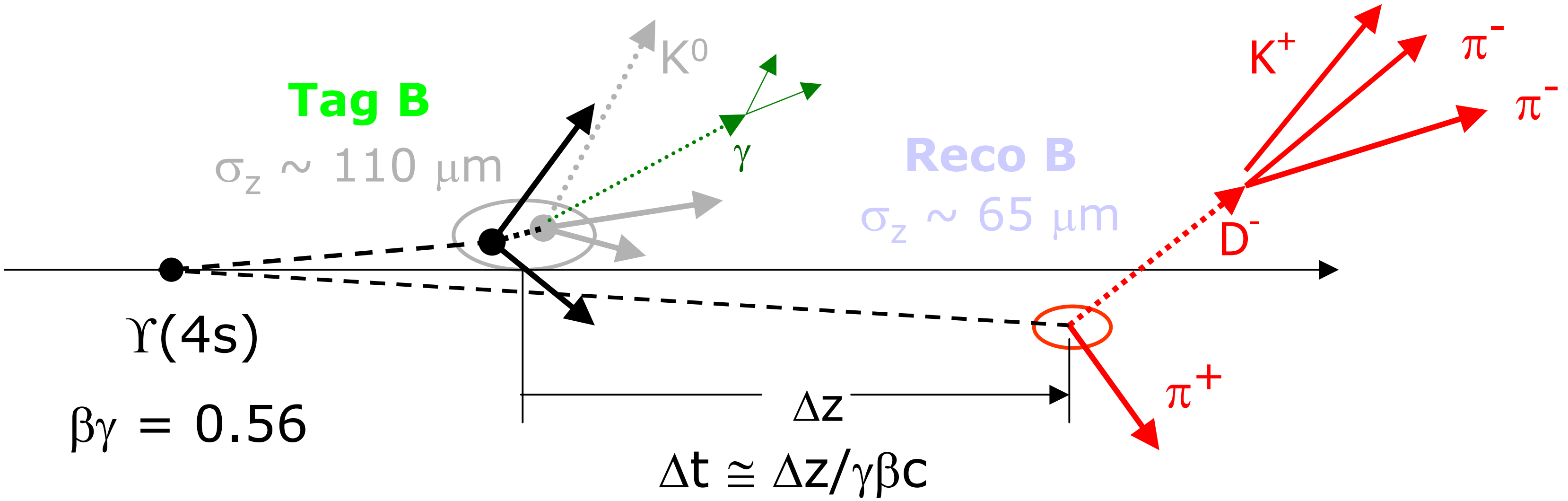
$$\tau_{B^0} = 1.55 \pm 0.02 \text{ ps}$$
$$\tau_{B^+} = 1.64 \pm 0.03 \text{ ps}$$

Proof of principle for time-dependent analysis at *B* Factories



D.MacFarlane at WIN02

Measurement of $B^0\bar{B}^0$ Mixing



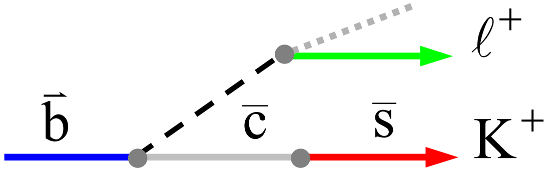
3. Reconstruct Inclusively the vertex of the "other" B meson (B_{TAG}) ✓
4. Determine the flavor of B_{TAG} to separate Mixed and Unmixed events

1. Fully reconstruct one B meson in flavor eigenstate (B_{REC}) ✓
2. Reconstruct the decay vertex ✓

5. compute the proper time difference Δt ✓
6. Fit the Δt spectra of mixed and unmixed events

B Flavor Tagging

- *Use charge of decay products*
  - Lepton $B^0 \to D^{*-} \ell^+ \nu$
  - Kaon $B^0 \to \overline{D} X, \overline{D} \to K^+ X$
  - Soft pion $B^0 \to D^{*-} X^+, D^{*-} \to \overline{D}^0 \pi_s^-$



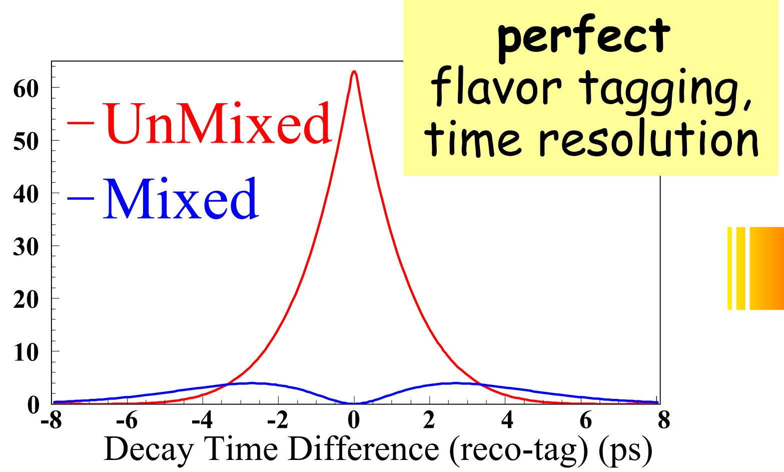
- *Use topological variables*
  - e.g., to distinguish between primary and cascade lepton
- *Different approaches to combining information*
  - *BABAR* – Hierarchical tagging based on physics content
    - Four tagging categories: Lepton, Kaon, NT1, NT2 – ε ~ 70%
  - *BELLE* – Multidimensional Likelihood Method
    - Use all the events – ε ~ 99%
    - Define 6 tagging categories based on tagging performance
- *Similar effective performance*
  - Effective Tagging Efficiency

$$Q = \sum_i \varepsilon_i \times (1 - 2\omega_i)^2$$

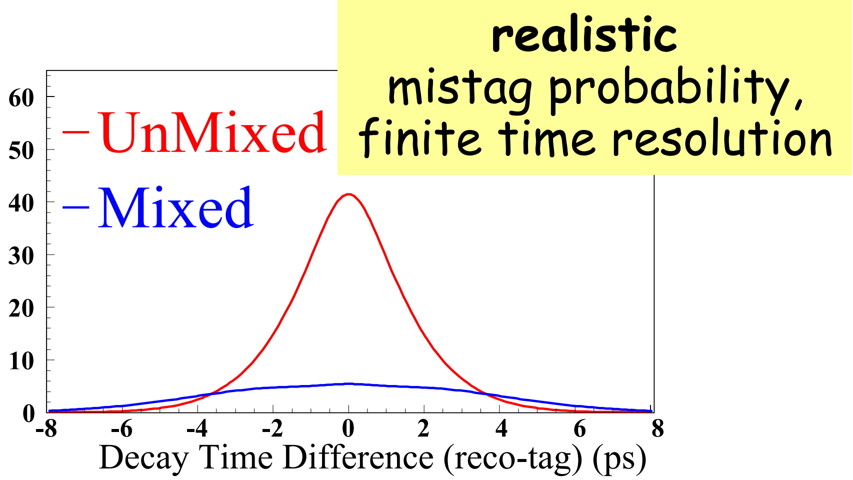
BABAR $Q = 26.1 \pm 1.2\%$

BELLE $Q = 27.0 \pm 2.2\%$

B-Mixing Analysis: Time Distributions



perfect flavor tagging, time resolution



realistic mistag probability, finite time resolution

$$f_{\text{mixing},\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{2\tau_{B_d}} \times \left(1 \pm (1-2\omega).\cos(\Delta m_{B_d} \Delta t) \right) \right\} \otimes R$$

"$f_{\text{mixing},+}$" ⇔ unmixed $(B^0_{\text{flav}} \overline{B}^0_{\text{tag}}$ or $\overline{B}^0_{\text{flav}} B^0_{\text{tag}})$

"$f_{\text{mixing},-}$" ⇔ mixed $(B^0_{\text{flav}} B^0_{\text{tag}}$ or $\overline{B}^0_{\text{flav}} \overline{B}^0_{\text{tag}})$

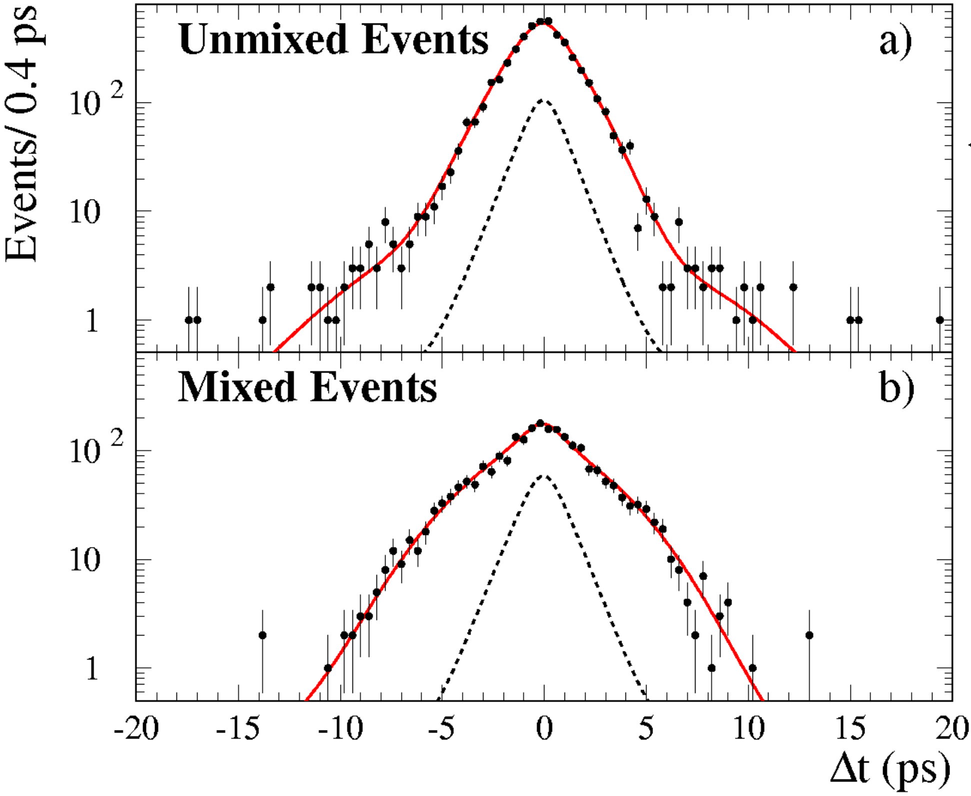
ω is the flavor mis-tag probability

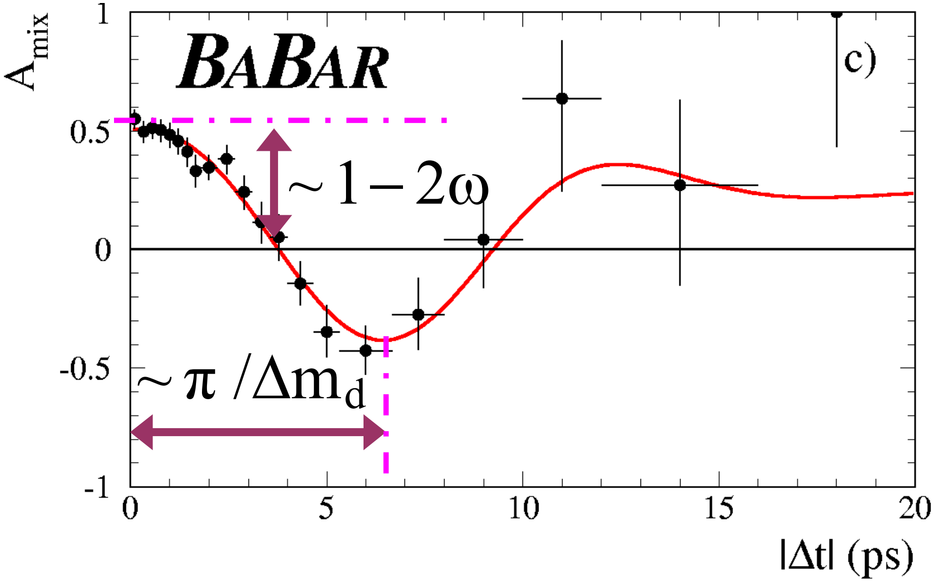
$R(\Delta t)$ is the time resolution function

Mixing with Hadronic Sample

$$A_{\text{mixing}}(\Delta t) \approx (1-2\omega).\cos \Delta m_{B_d} \Delta t$$

BABAR
29.7 fb^{-1}



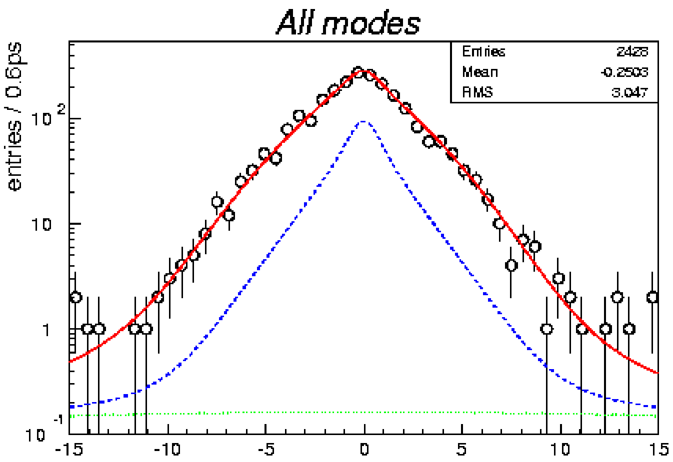


Precision measurement consistent with world average

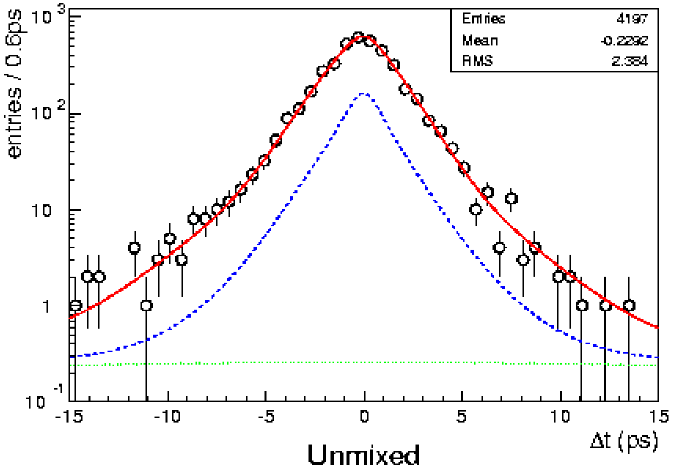
$$\Delta m_{B_d} = (0.516 \pm 0.016_{(stat)} \pm 0.010_{(syst)})\ \text{ps}^{-1}$$

BABAR hep-ex/0112044

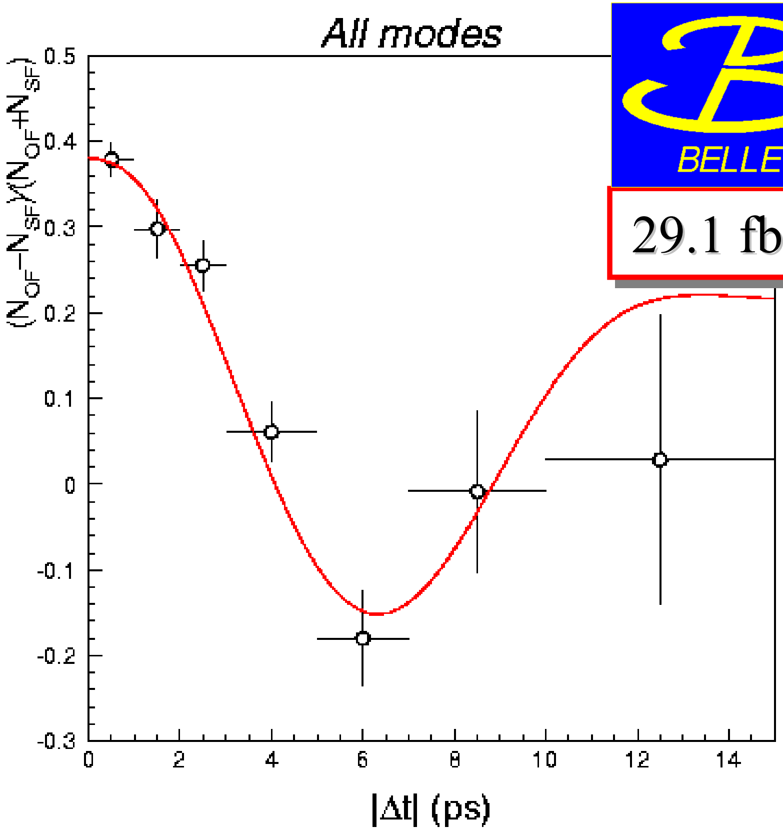
Mixing with Hadronic Sample



Mixed



Unmixed



BELLE

$29.1\ \mathrm{fb}^{-1}$

Precision measurement consistent with world average

$$\Delta m_{B_d} = (0.521 \pm 0.017_{(stat)}{}^{+0.11}_{-0.14(syst)})\ \ \mathrm{ps}^{-1}$$

BELLE KEK TC5

Preliminary

D.MacFarlane at WIN02

Time-Dependent CP Asymmetries

Time-dependence of
$B^0 - \overline{B}^0$ mixing

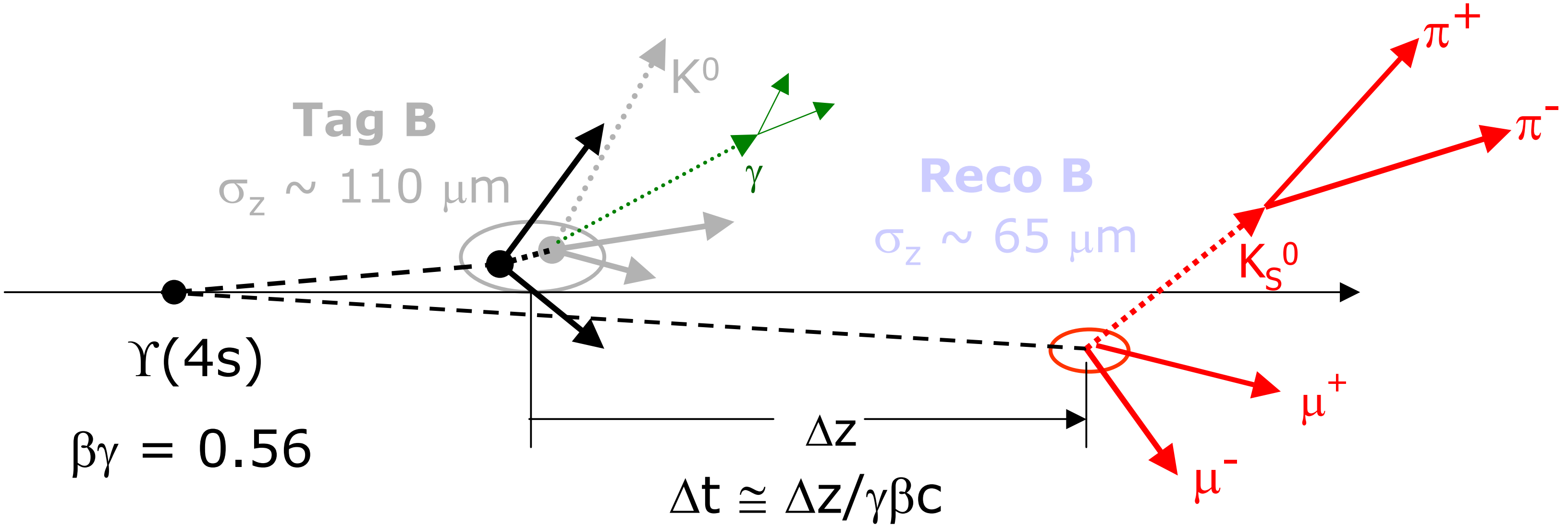
$$A_{\mathrm{mixing}}(\Delta t) = \frac{N(\mathrm{unmixed}) - N(\mathrm{mixed})}{N(\mathrm{unmixed}) + N(\mathrm{mixed})} \approx (1-2\omega).\cos(\Delta m_{B_d} \Delta t)$$

Time-dependence of
CP-violating asymmetry in
$B^0_{CP} \to J/\psi\, K^0_S$

$$A_{CP}(\Delta t) = \frac{N(B_{tag} = B^0) - N(B_{tag} = \overline{B}^0)}{N(B_{tag} = B^0) + N(B_{tag} = \overline{B}^0)} \approx (1-2\omega).\sin 2\beta.\sin(\Delta m_{B_d} \Delta t)$$

Use the large statistics B_{flav} data sample to determine the **mistag probabilities** and the parameters of the **time-resolution function**

Measurement of sin2β



1. Fully reconstruct one B meson in CP eigenstate (B_{REC})
2. Reconstruct the decay vertex ✓

3. Reconstruct Inclusively the vertex of the "other" B meson (B_{TAG}) ✓
4. Determine the flavor of B_{TAG} to separate B^0 and $\overline{B}^0$ ✓

5. compute the proper time difference Δt ✓
6. Fit the Δt spectra of B^0 and $\overline{B}^0$ tagged events

CP Sample for BABAR

29.7 fb-1 or 32 million BB pairs

$\eta_f = -1$ modes

$B^0_{CP} \rightarrow J/\psi K^0_S\{\rightarrow \pi^+\pi^-\}$

$B^0_{CP} \rightarrow J/\psi K^0_S\{\rightarrow \pi^0\pi^0\}$

$B^0_{CP} \rightarrow \psi(2S)\{\rightarrow \ell^+\ell^-$ or $J/\psi\pi^+\pi^-\}K^0_S$

$B^0_{CP} \rightarrow \chi_{c1}\{\rightarrow J/\psi\gamma\}K^0_S$

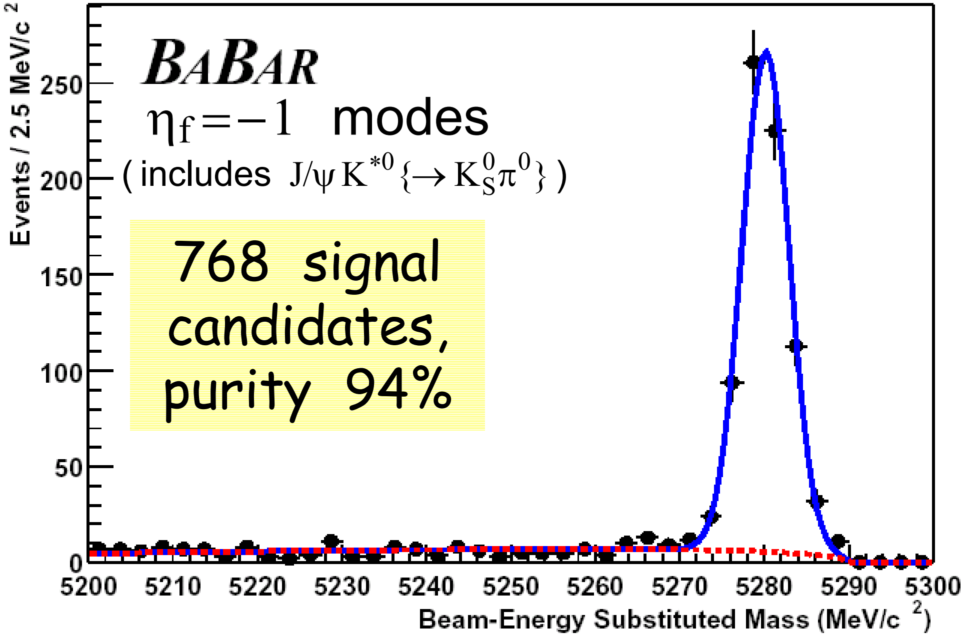
η_f mixed mode

$B^0_{CP} \rightarrow J/\psi K^{*0}\left\{\rightarrow K^0_S\pi^0\right\}$

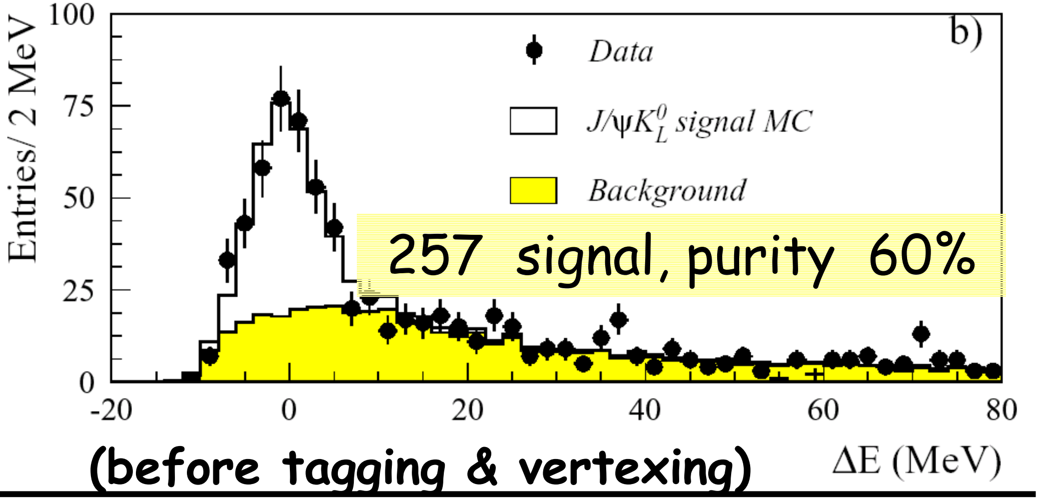
$\eta_f = +1$ mode

$B^0_{CP} \rightarrow J/\psi K^0_L$

Total: 1025 signal candidates (83% purity)



768 signal candidates, purity 94%

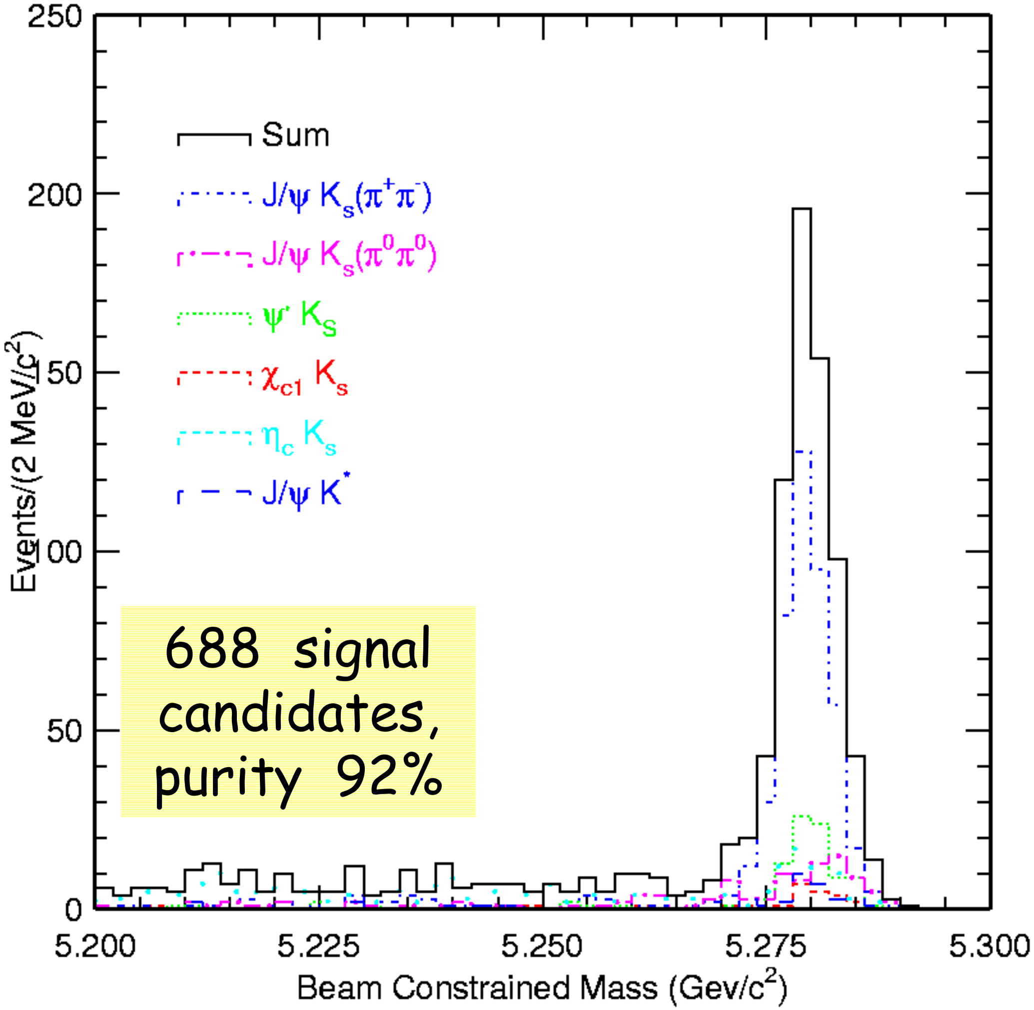


257 signal, purity 60%

(before tagging & vertexing)

CP Sample for BELLE

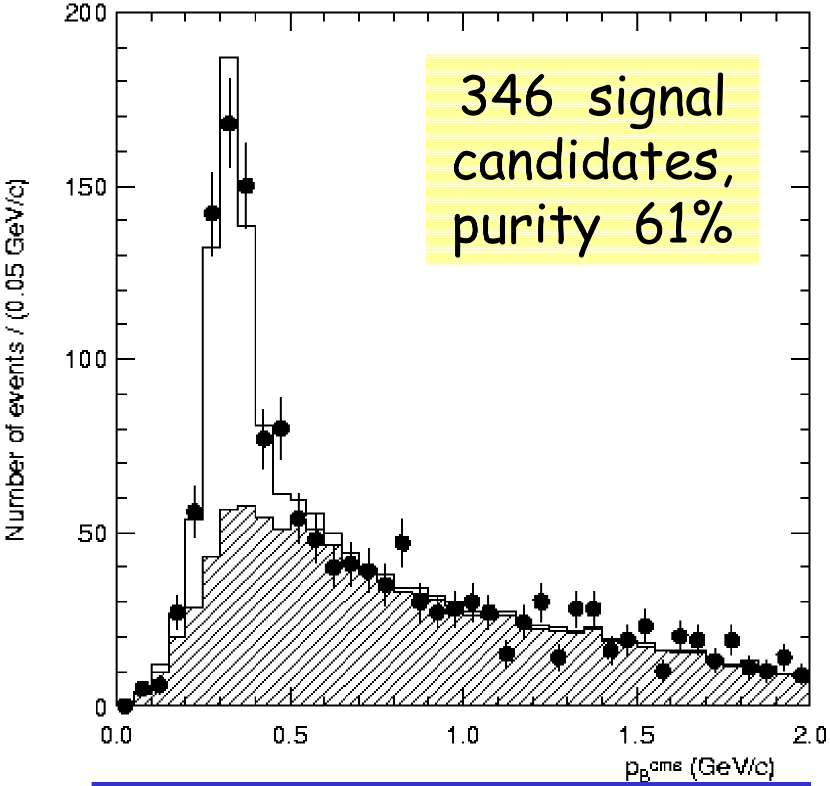
29.1 fb-1 or 31 million BB pairs



688 signal candidates, purity 92%

Additional $\eta_f = -1$ mode

$B^0_{CP} \rightarrow \eta_C K^0_S$



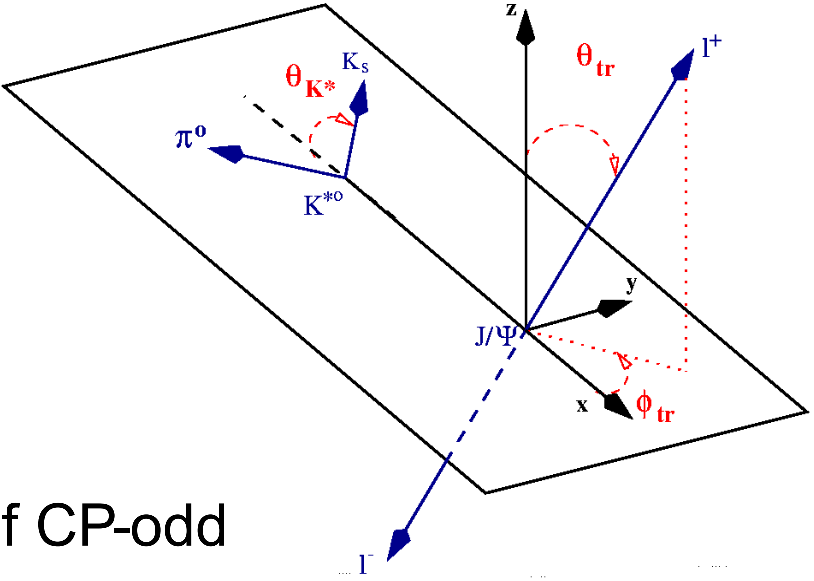
346 signal candidates, purity 61%

Total: 1034 signal candidates (79% purity)

D.MacFarlane at WIN02

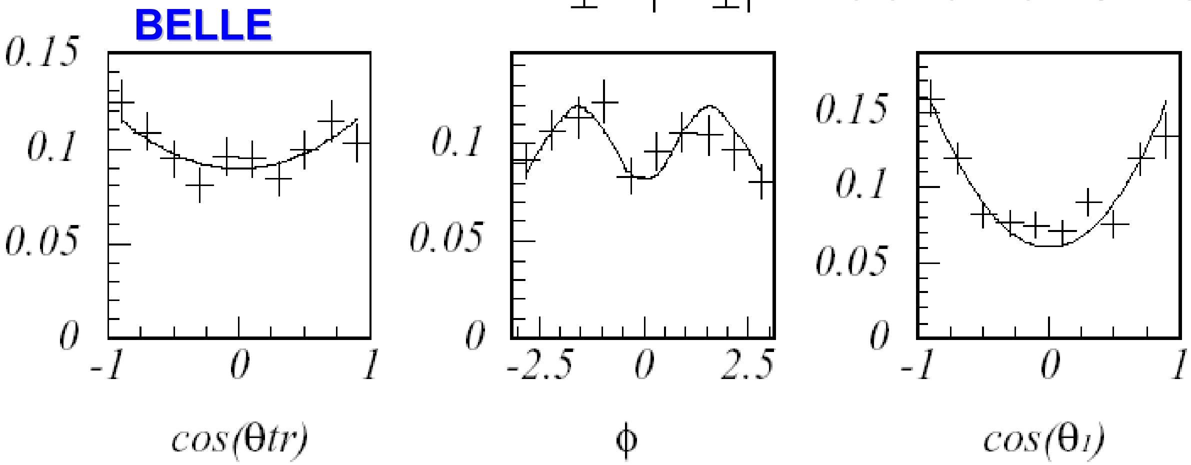
Angular Analysis

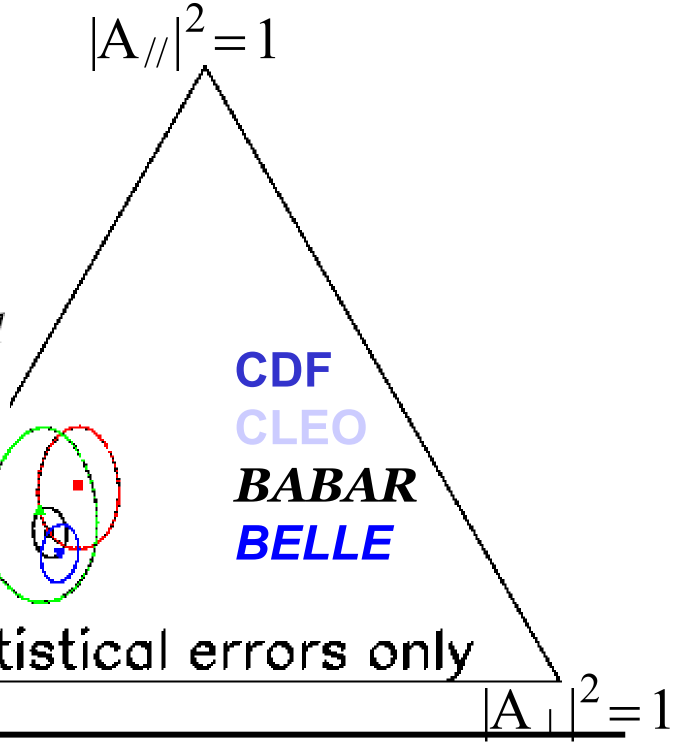
$$B^0 \rightarrow J/\psi\, K^{*0}(\rightarrow K^0_S \pi^0)$$



- ☐ Potentially measures sin2β
- ☐ VV mode → angular analysis
- ☐ *CP*-Dilution: $D_\perp = 1 - 2 \cdot R_\perp,$

$R_\perp \equiv |A_\perp|^2$ fraction of CP-odd





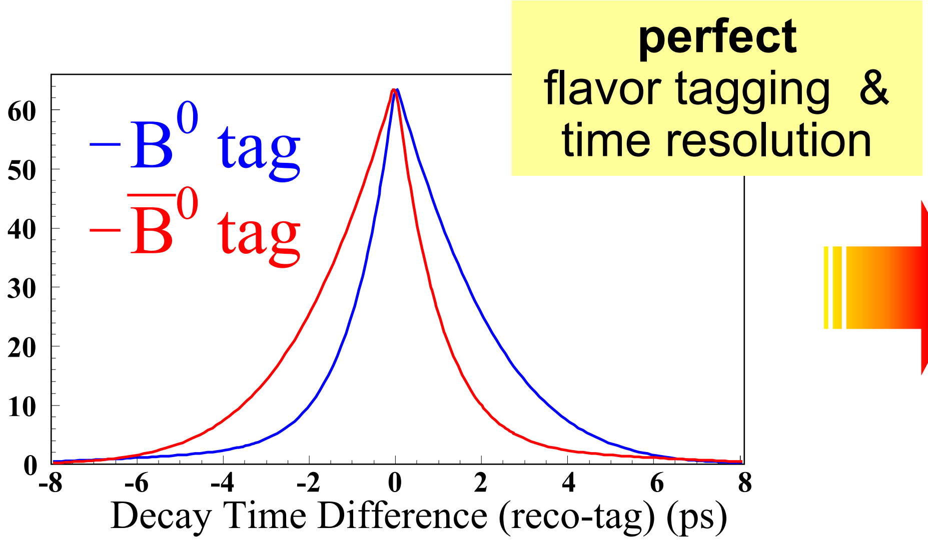
BABAR PRL **87**, 241801 (2001)

$$R_\perp = (16.0 \pm 3.2_{(stat)} \pm 1.4_{(syst)})\%$$

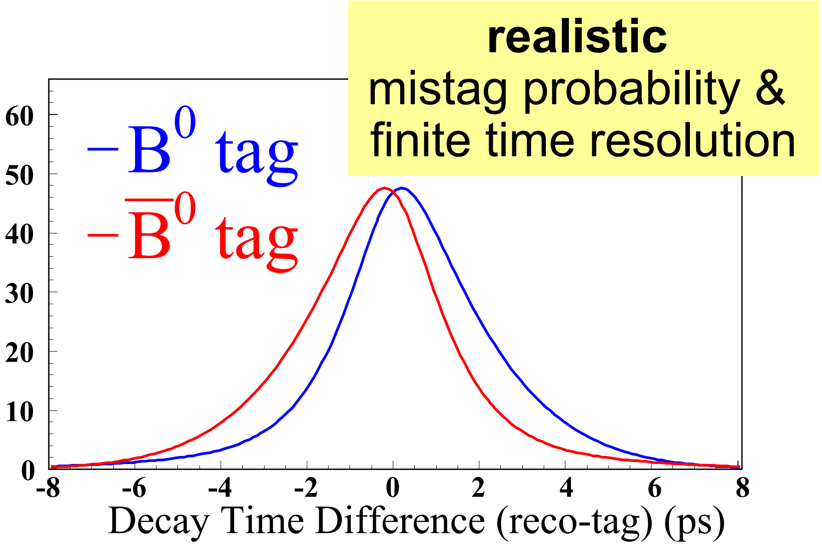
BELLE CONF-0105

$$R_\perp = (19 \pm 4_{(stat)} \pm 4_{(syst)})\%$$

CP Analysis: Time Distributions



perfect
flavor tagging & time resolution



realistic
mistag probability & finite time resolution

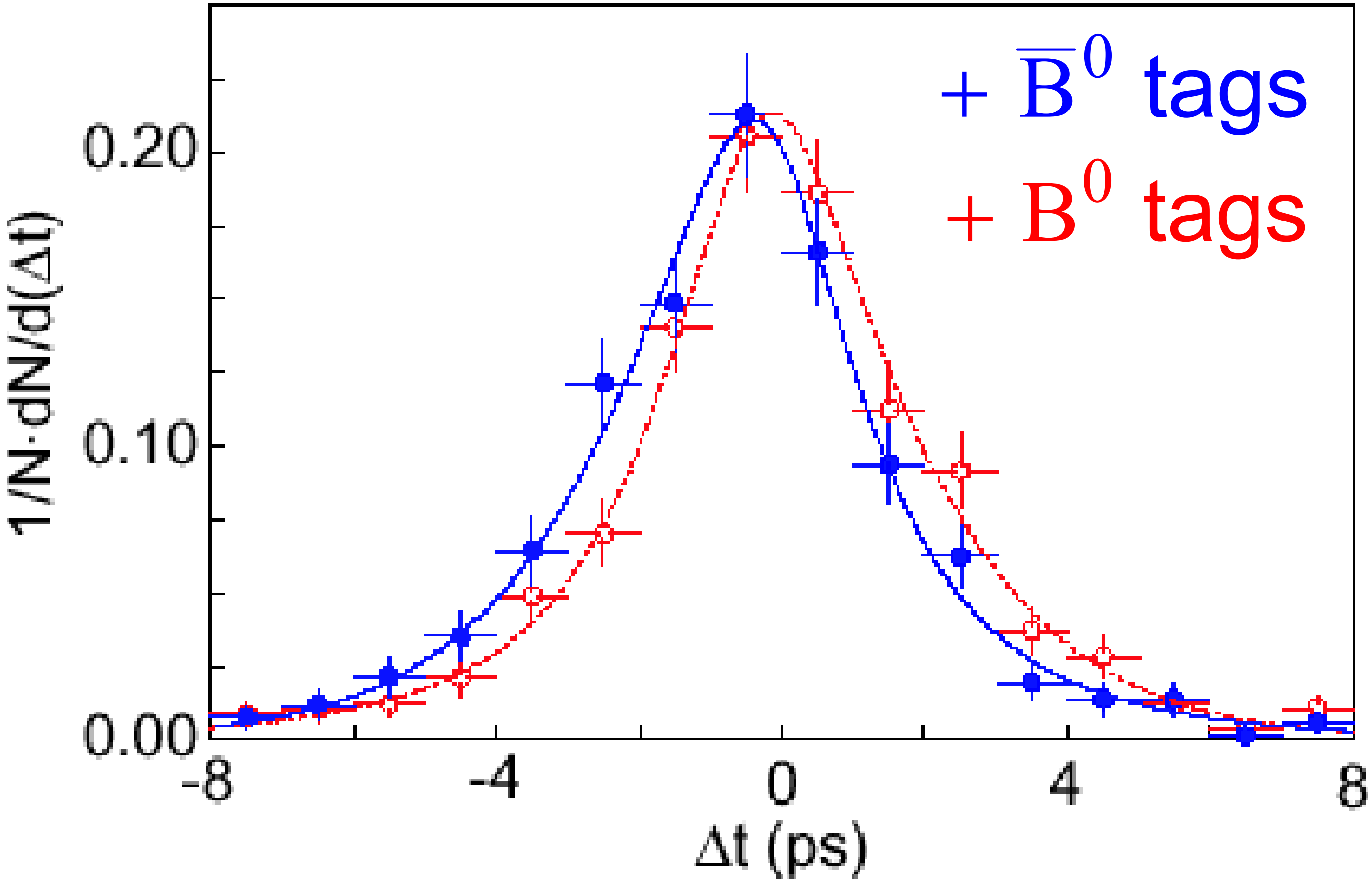
$$f_{CP,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{2\tau_{B_d}} \times \left(1 \mp \eta_f.(1-2\omega).\sin 2\beta.\sin(\Delta m_{B_d} \Delta t) \right) \right\} \otimes R$$

$$"f_{CP,+}" \Leftrightarrow B^0_{tag} = B^0$$

$$"f_{CP,-}" \Leftrightarrow B^0_{tag} = \overline{B}^0$$

same mistag probability ω
and time-resolution function $R(\Delta t)$

Raw Time Distributions



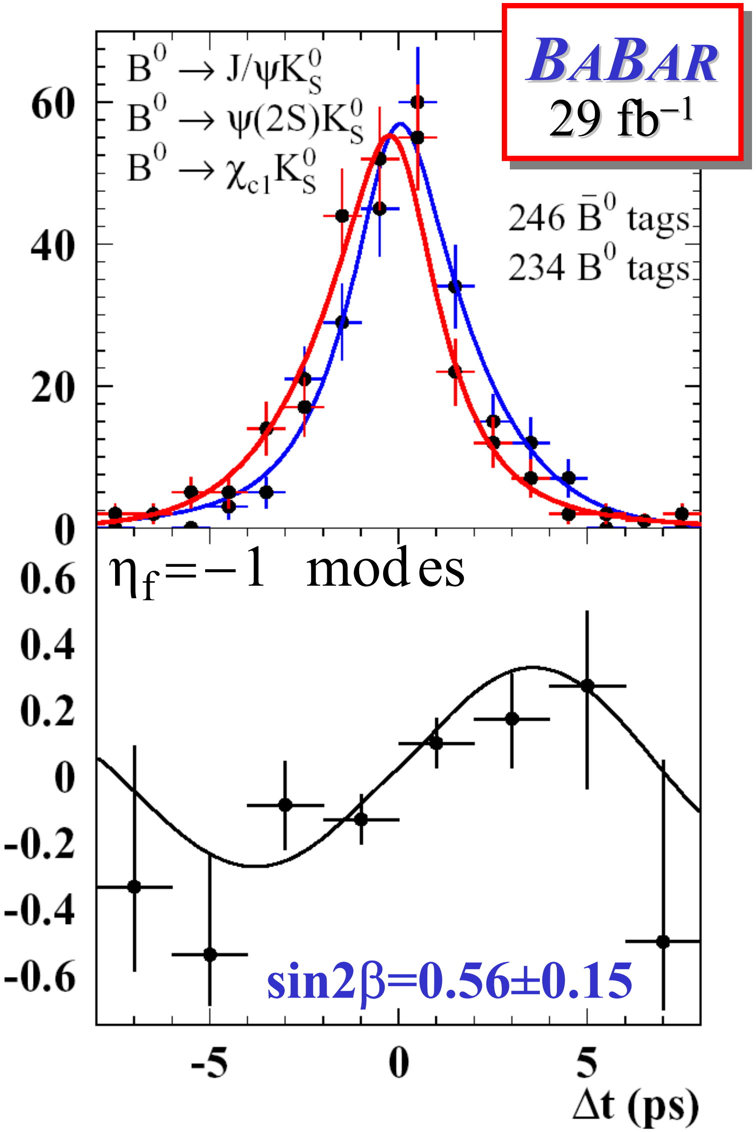
BELLE

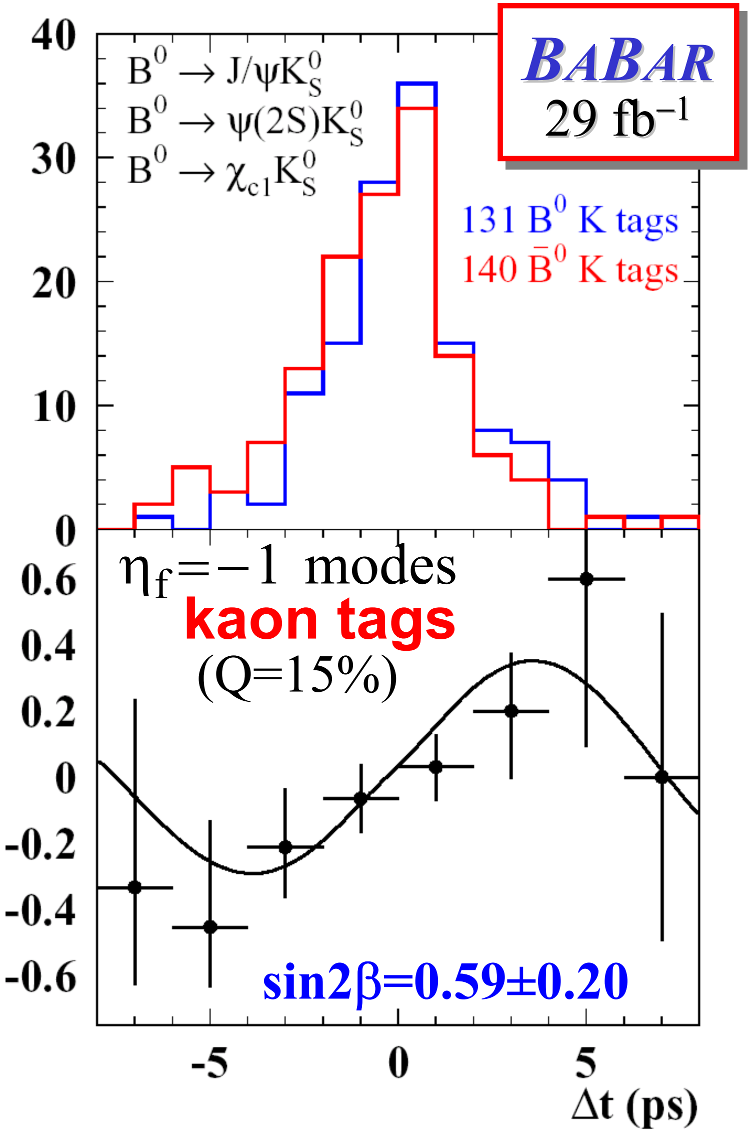
29.1 fb^{-1}

$$\sin 2\beta = 0.99 \pm 0.14_{(stat)} \pm 0.06_{(syst)}$$

Raw Asymmetries

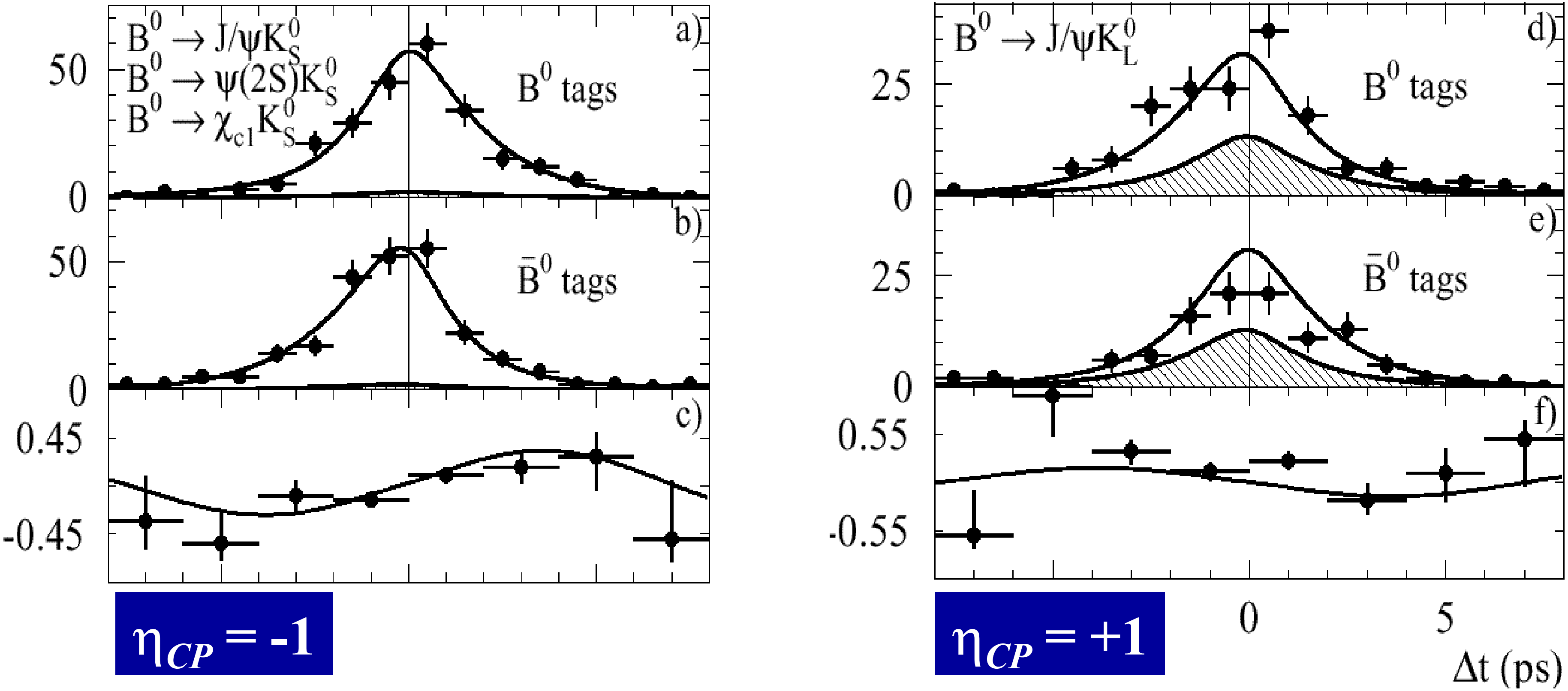
$$A_{CP}(\Delta t) \approx (1-2\omega).\sin 2\beta.\sin(\Delta m_{B_d}\Delta t)$$





BABAR Result for sin2β

$$A_{CP}(\Delta t) \approx (1-2\omega).\sin 2\beta.\sin(\Delta m_{B_d}\Delta t)$$

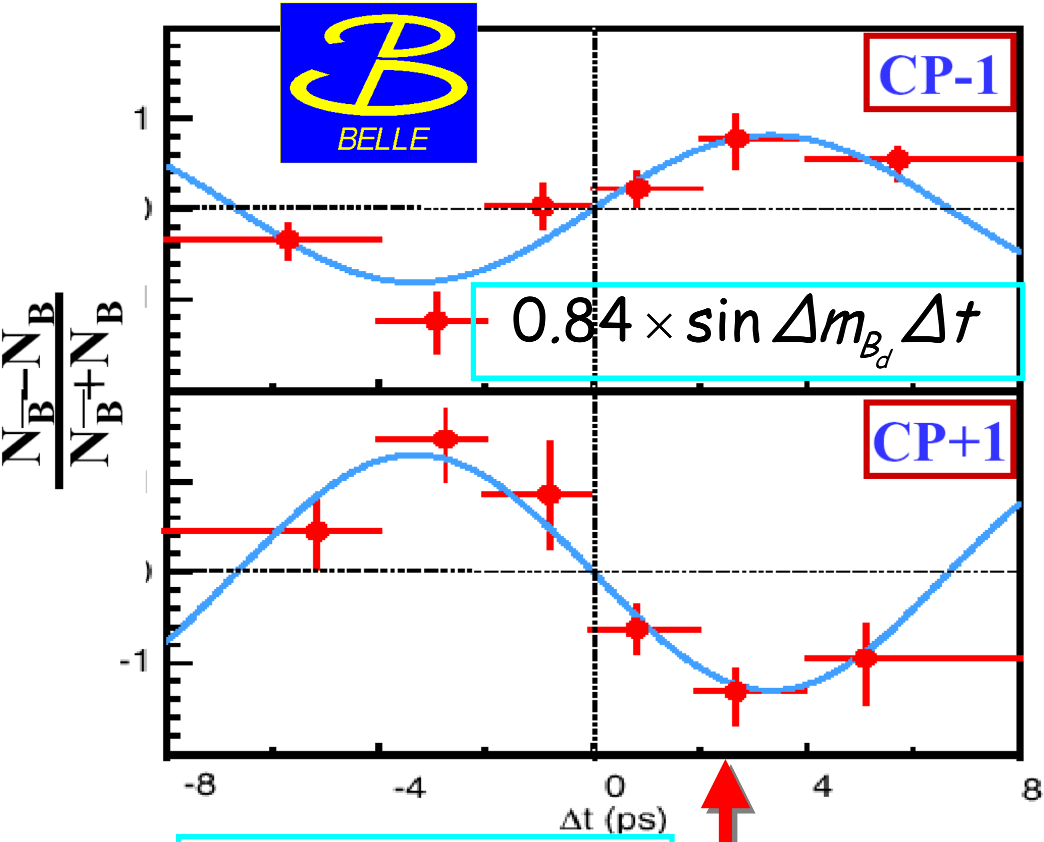


$\eta_{CP} = -1$

$\eta_{CP} = +1$

$$\sin 2\beta = 0.59 \pm 0.14_{(stat)} \pm 0.05_{(syst)}$$

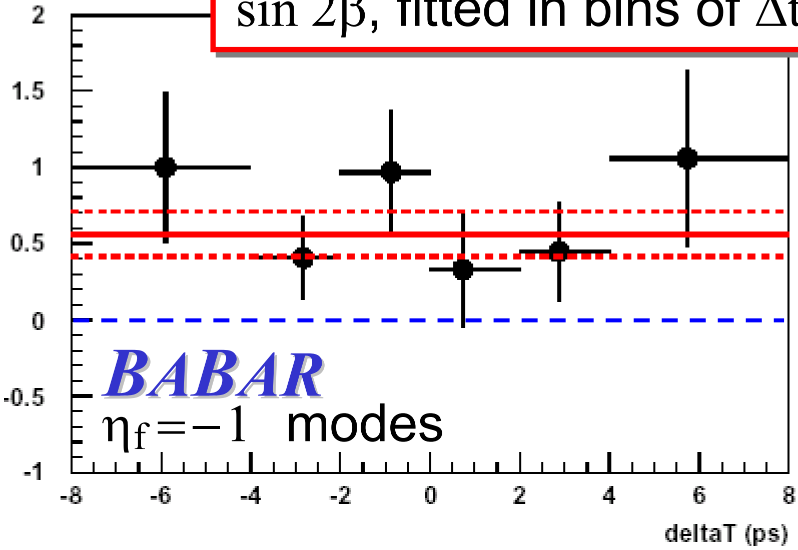
"Corrected" Asymmetries



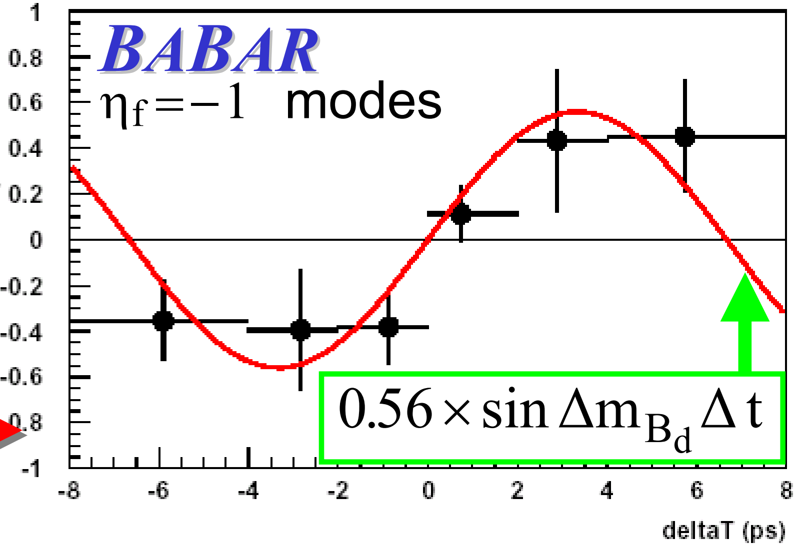
$0.84 \times \sin \Delta m_{B_d} \Delta t$

$1.31 \times \sin \Delta m_{B_d} \Delta t$

sin 2β, fitted in bins of Δt
and multiplied by sin(Δm_{Bd}Δt)



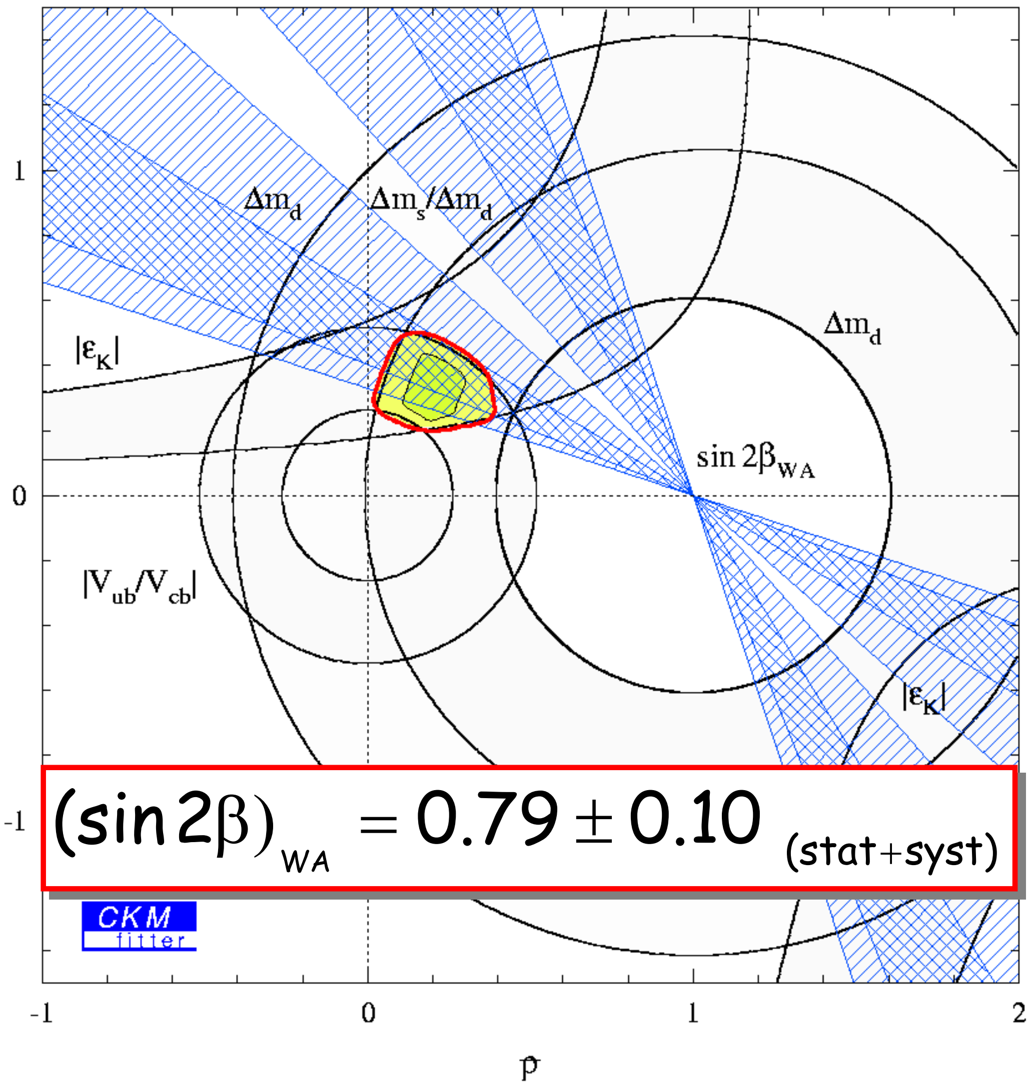
sin 2β, fitted in bins of Δt



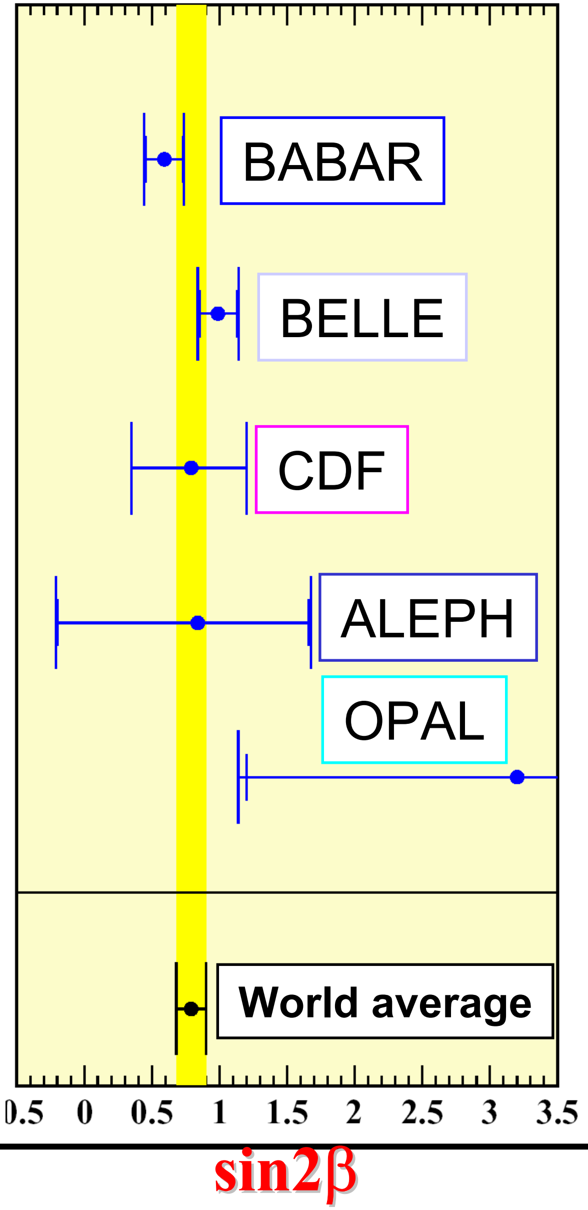
$0.56 \times \sin \Delta m_{B_d} \Delta t$

D.MacFarlane at WIN02

World Average



$$(\sin 2\beta)_{WA} = 0.79 \pm 0.10 \ (\text{stat+syst})$$



Search for Direct CP

$$\boxed{A_{CP} = C_{f_{CP}} \cos \Delta m_d \Delta t + S_{f_{CP}} \sin \Delta m_d \Delta t}$$

(assuming $\Delta\Gamma = 0$)

If more than one amplitude matters
$|\lambda|$ might be different from 1

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

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

Probing new physics: only use $\eta_{CP}=-1$ sample
(contains no mixing background)

BABAR: $|\lambda| = 0.93 \pm 0.09$ (stat.) ± 0.03 (sys.)
BELLE: $|\lambda| = 1.09 \pm 0.14$ (stat.)

No evidence of direct CP violation due to decay amplitude interference; none expected

Coefficient of the "sine" term unchanged

Future sin2β measurements

- *Increase statistics in current modes*

$$\boxed{\sigma_{\sin 2\beta} \sim 0.08 \text{ for } 100 \text{ fb}^{-1} \rightarrow 0.03 \text{ for } 500 \text{ fb}^{-1}}$$

BELLE and BABAR

Summer 2002 **Around 2006**

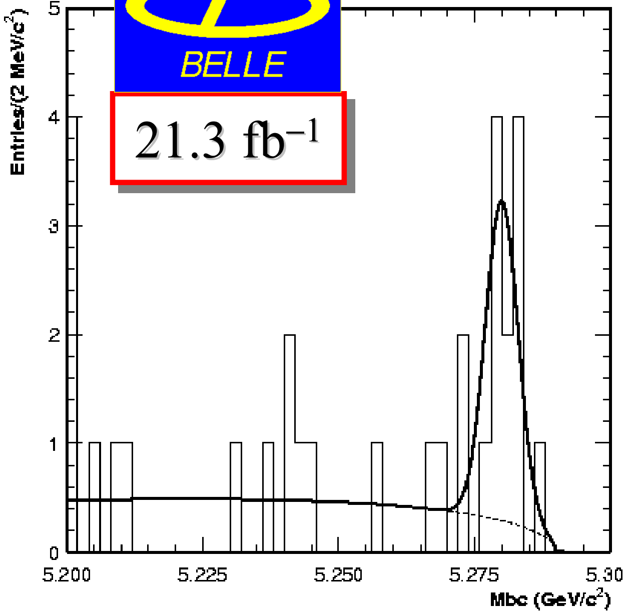
- *Systematic error projections: 0.05 → 0.016*
  - Δt resolution 0.03 → 0.01: better alignment, vertex understanding
  - Tagging 0.03 → 0.01: use flavor samples similar to *CP* events
  - Background CP 0.03 → 0.01: Measure *CP* content
- *Many other CP modes can potentially provide independent measurement of sin2β*
  - Different quark processes
  - Various penguin contributions
  - Angular analysis in VV modes

More CP channels: $B \to D^{(*)}D^{(*)}$

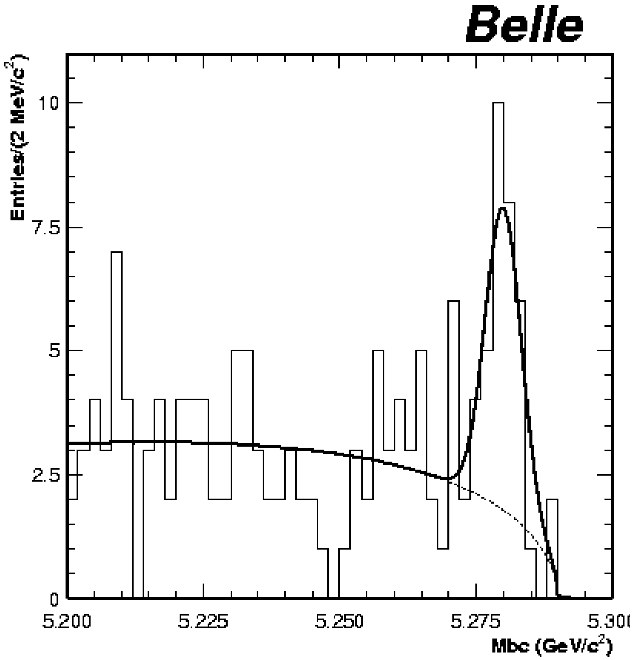
$b \to c\bar{c}d$

21.3 fb^{-1}

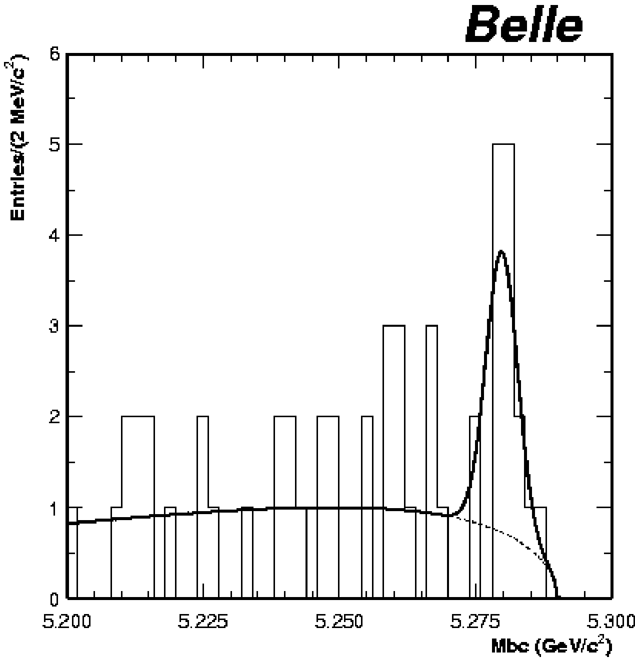
Preliminary, Belle-CONF-0104



$B^0 \to D^{*+}D^{*-}$



$B^0 \to D^{*+}D^{-}$



$B^0 \to D^0 D^{*-} K^+$

Signal events: 11.0 ± 3.7

25.2 ± 6.5

11.2 ± 4.0

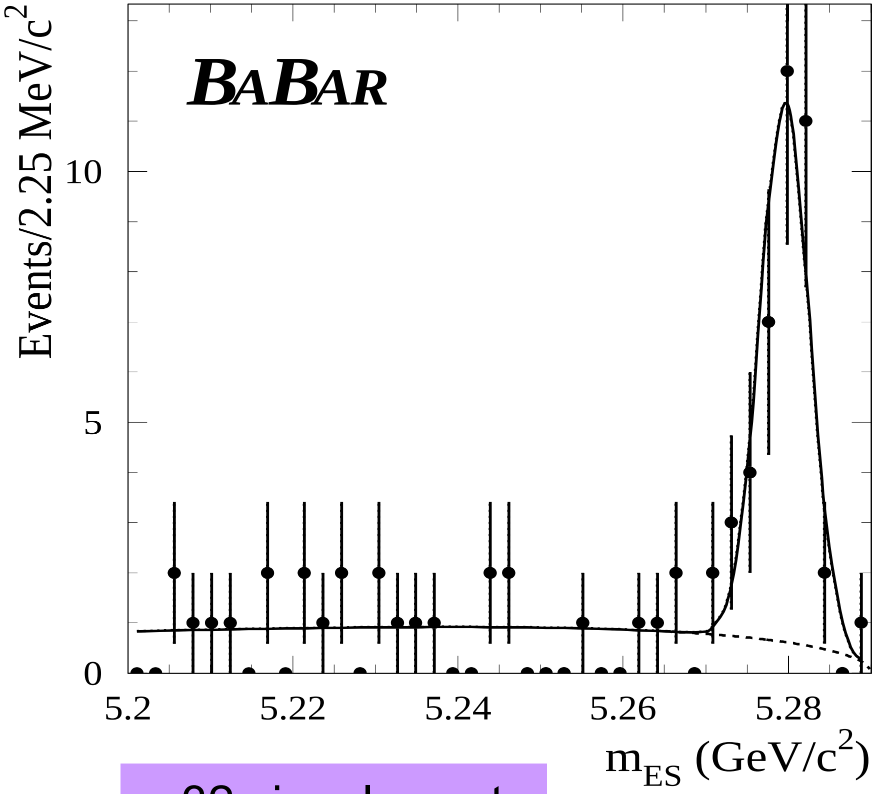
$\text{Im}\,\lambda \sim \sin 2\beta$

$\text{Im}\,\lambda \sim r \sin(2\beta + \phi_{strong})$

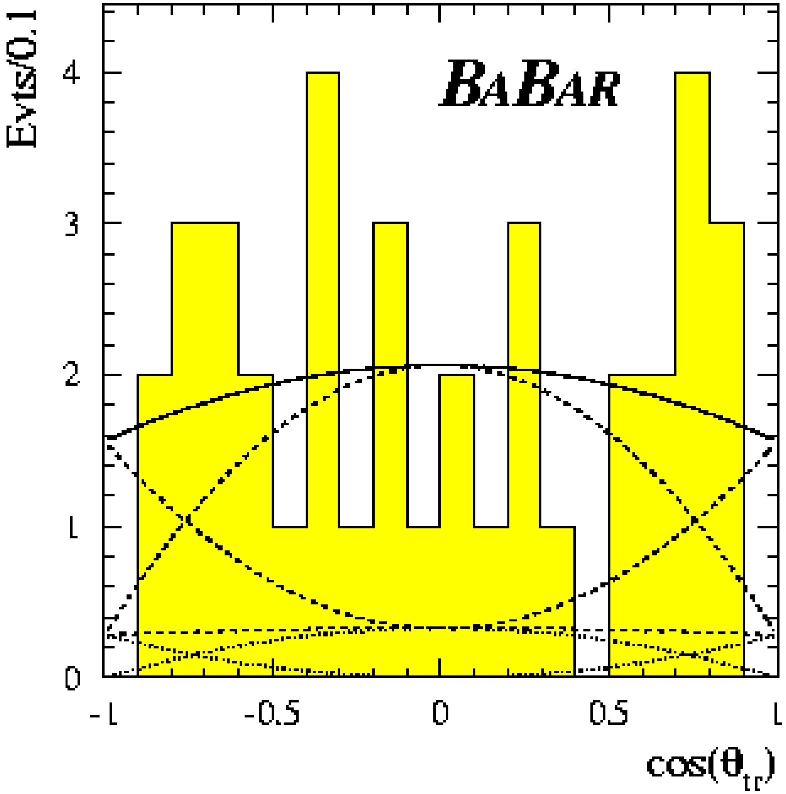
$r = A(\bar{B}^0 \to f) / A(B^0 \to f)$

Measurement of Transversity

$B^0 \to D^{*+} D^{*-}$ $b \to c\bar{c}d$



~ 32 signal events

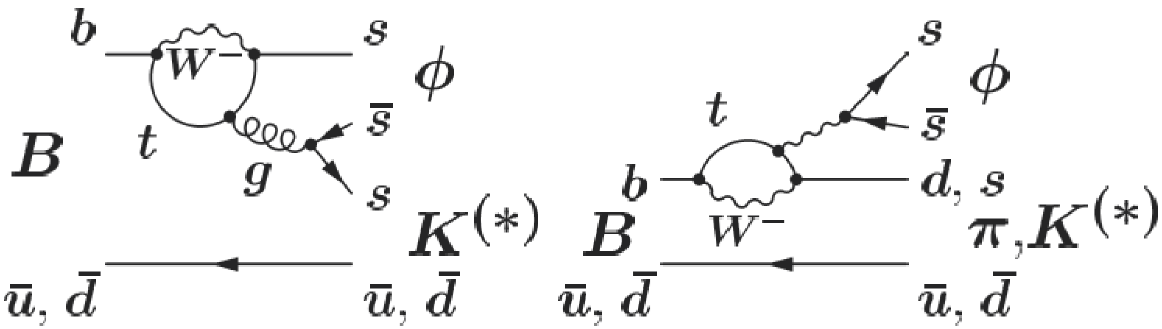


$$R_\perp = 0.22 \pm 0.18_{(stat)} \pm 0.03_{(syst)}$$

Preliminary **BABAR** hep-ex/0109009

More CP channels: B $\rightarrow \phi K^{(*)}$

- *Pure b $\rightarrow$ s penguin process*
- *Provide an independent measurement of CP violation*
  - ϕK^0_S is *CP* = -1 with Im$\lambda \sim \sin 2\beta$
  - *Sensitive to new physics in b $\rightarrow$ s loop diagram*



CLEO PRL **86**, 3718 (2001)

BABAR PRL **87**, 151801 (2001)

Other Modes for sin2β

BABAR

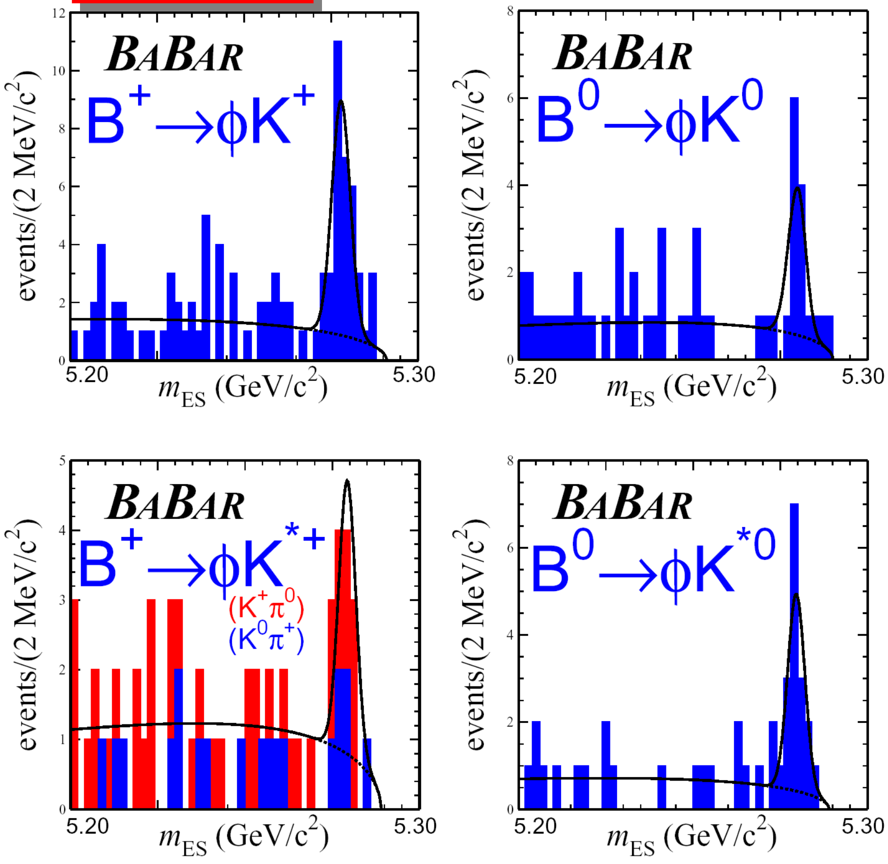
20.7 fb^{-1}

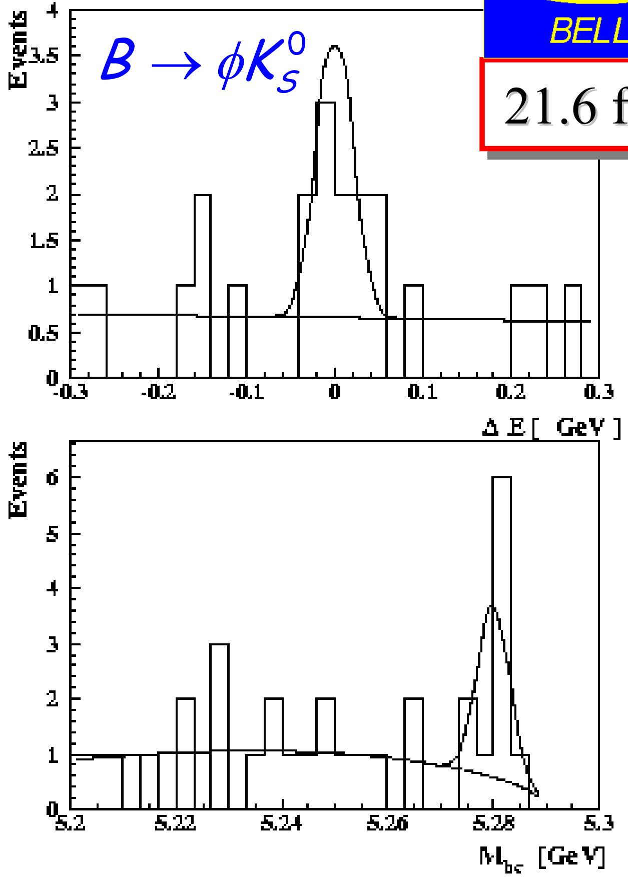
~ 11 events

~ 8 events

BELLE

21.6 fb^{-1}





BABAR PRL **87**, 15801 (2001)

Preliminary, Belle-CONF-0113

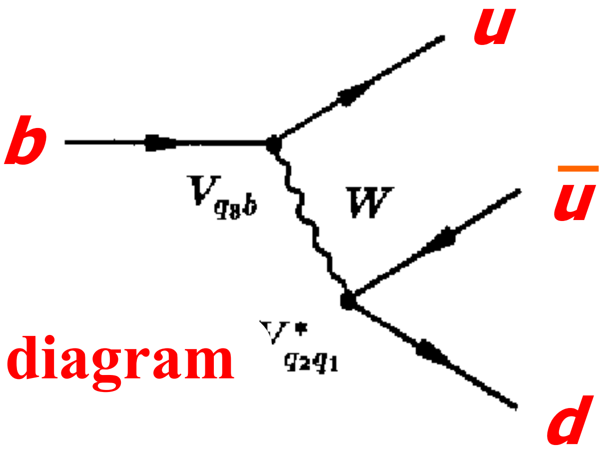
CP Violation in $B^0 \rightarrow \pi^+\pi^-$ Decays

Decay distributions $f_+(f_-)$ when tag = $B^0(\bar{B}^0)$

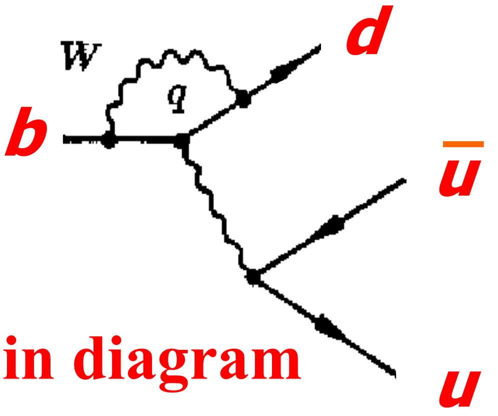
$$f_\pm(\Delta t) = \frac{e^{(-\Delta t/\tau)}}{4\tau}[1 \pm S_f \sin(\Delta m_d \Delta t) \mp C_f \cos(\Delta m_d \Delta t)]$$

$$S_f = \frac{2\,\mathrm{Im}(\lambda)}{1+|\lambda|^2}$$

$$C_f = \frac{1-|\lambda|^2}{1+|\lambda|^2}$$



tree diagram



penguin diagram

For single weak phase

$$\lambda \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f} = \eta_f e^{-2i(\beta+\gamma)} = \eta_f e^{2i\alpha}$$

$$\boxed{C_{\pi\pi} = 0,\ S_{\pi\pi} = \sin 2\alpha}$$

For additional weak phase

$|\lambda| \neq 1 \Rightarrow$ must fit for direct *CP*

Im $(\lambda) \neq \sin 2\alpha \Rightarrow$ need to relate asymmetry to α

$$\boxed{C_{\pi\pi} \neq 0,\ S_{\pi\pi} = \sin 2\alpha_{\mathrm{eff}}}$$

Extraction of sin2α

Without penguins: $C_{\pi\pi} = 0,\ S_{\pi\pi} = -\sin 2\alpha$

Penguins are expected to be sizable: $|P/T| \sim 0.3$

$$C_{\pi\pi} \neq 0,\ S_{\pi\pi} = -\sin\alpha_{eff} = -\sin 2\alpha \times [1 + O(P/T)]$$

$$\boxed{\text{Expect } \delta \sin 2\alpha_{eff} \sim 0.3 - 0.4 \text{ for } 100\ \text{fb}^{-1}}$$

Strategies to extract α from the asymmetry measurement

- Isospin analysis (Gronau/London)
  - Clean theoretically, but challenging experimentally
  - Need $B^0 \to \pi^0\pi^0$ and $\bar{B}^0 \to \pi^0\pi^0$
- Grossman/Quinn Bound

$$\sin^2 \Delta < \frac{BF(B \to \pi^0\pi^0)}{BF(B^\pm \to \pi^\pm\pi^0)} \quad \text{with} \quad \Delta = a_{eff} - a$$

- Theoretical constraints on Penguin pollution

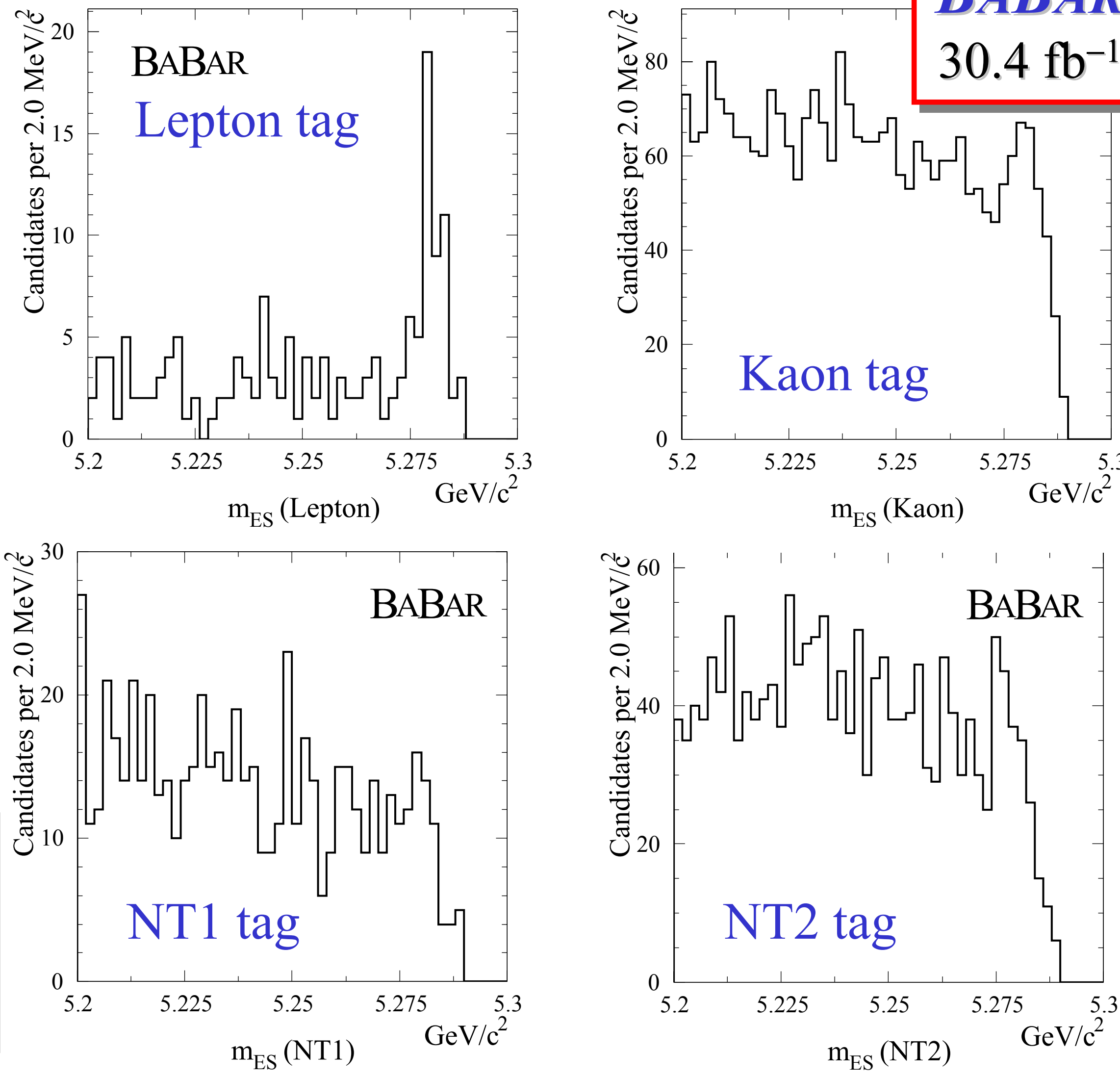
Two-Body Data Sample

BABAR
30.4 fb^{-1}

9741 two-prong candidates in 30.4 fb^{-1} (97% background, almost entirely from continuum)

Sum of $\pi^+\pi^-/\mathbf{K}^+\pi^-$:
No particle ID used
until the fit is performed

m_{ES} distributions for the different tagging categories



Projections of Data Sample

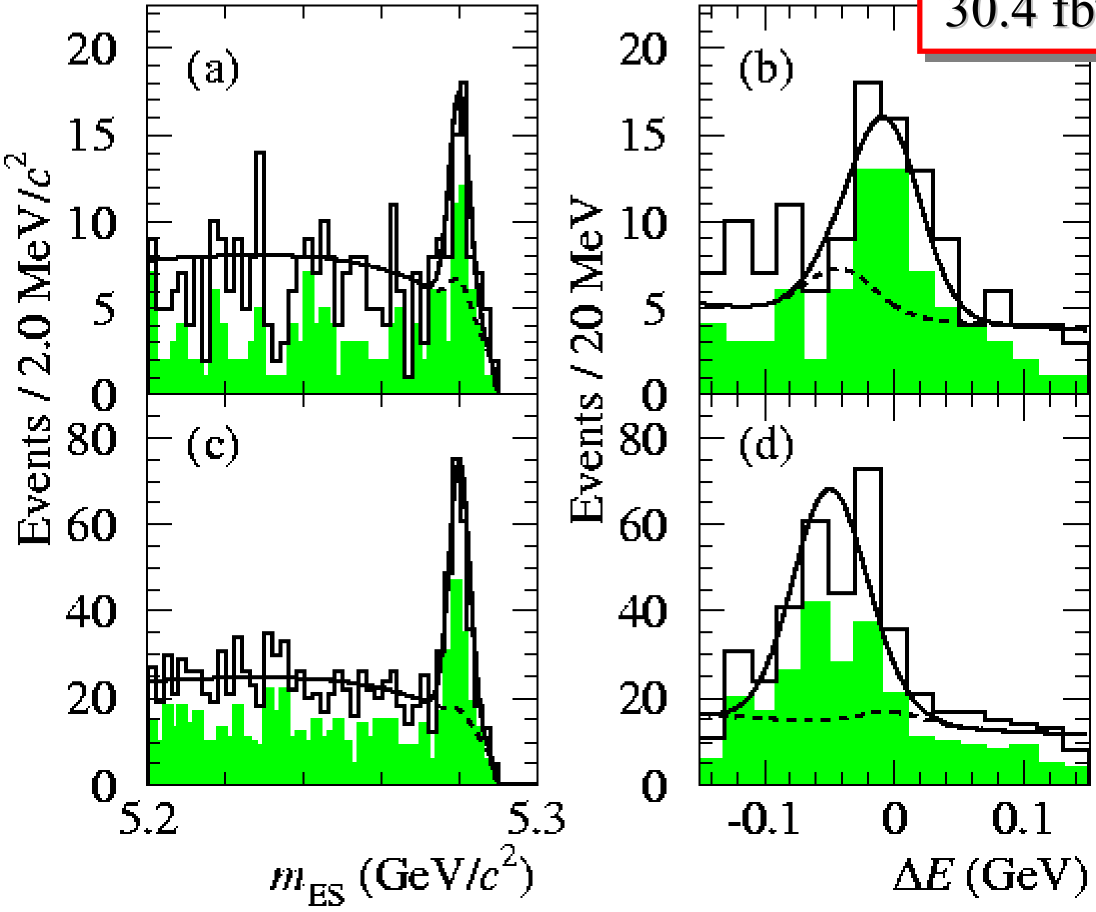
Events after cuts on likelihood ratios for subsample enrichment

(tagged)

ππ projection: 55% efficiency

BABAR

30.4 fb^{-1}



Kπ projection: 85% efficiency

Total Fitted Yields:

$\pi^+\pi^-$	65^{+12}_{-11}
$K^+\pi^-$	217 ± 18
K^+K^-	$4.3^{+6.3}_{-4.3}$

Time distributions and asymmetries

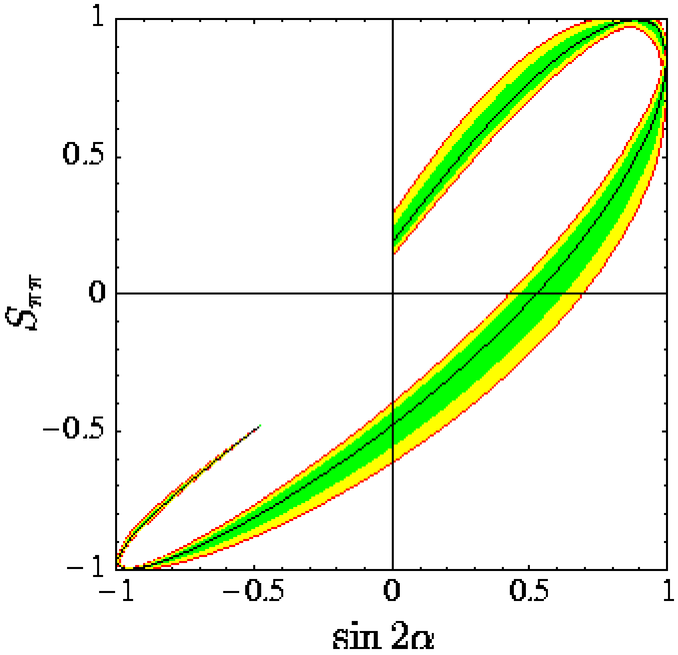
$$S(\pi^+\pi^-) = 0.03^{+0.53}_{-0.56}(\text{stat}) \pm 0.11(\text{syst})$$

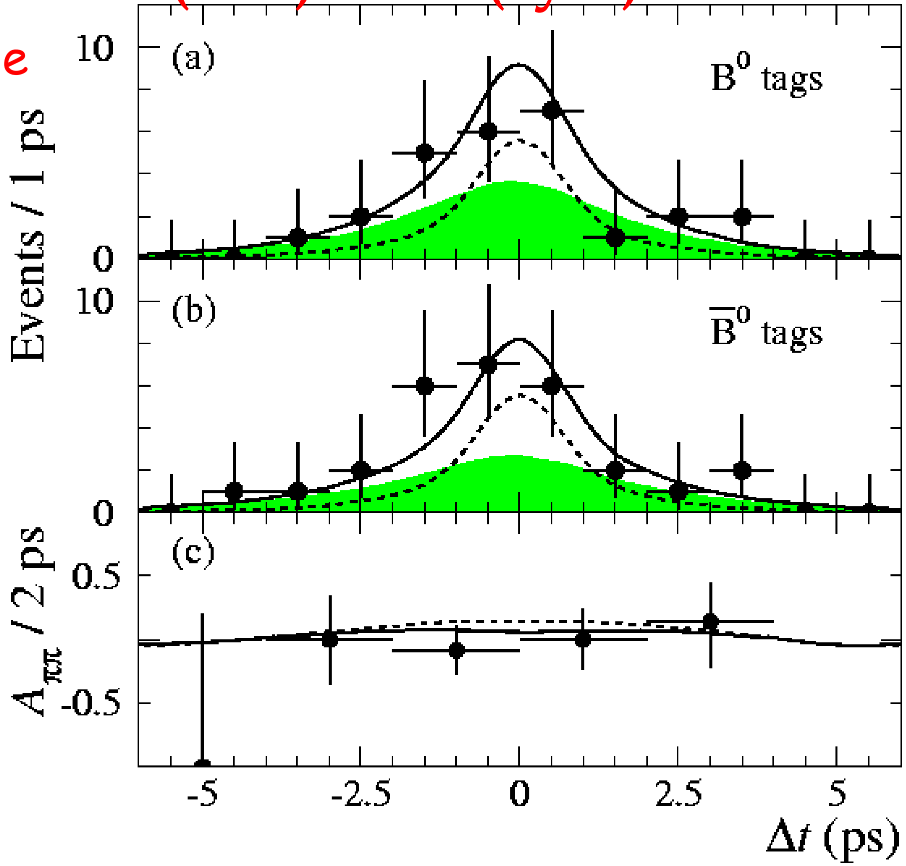
$$C(\pi^+\pi^-) = -0.25^{+0.45}_{-0.47}(\text{stat}) \pm 0.14(\text{syst})$$

$$A_{CP}(K^\pm\pi^\mp) = -0.07 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})$$

(signal)

ππ enhanced subsample

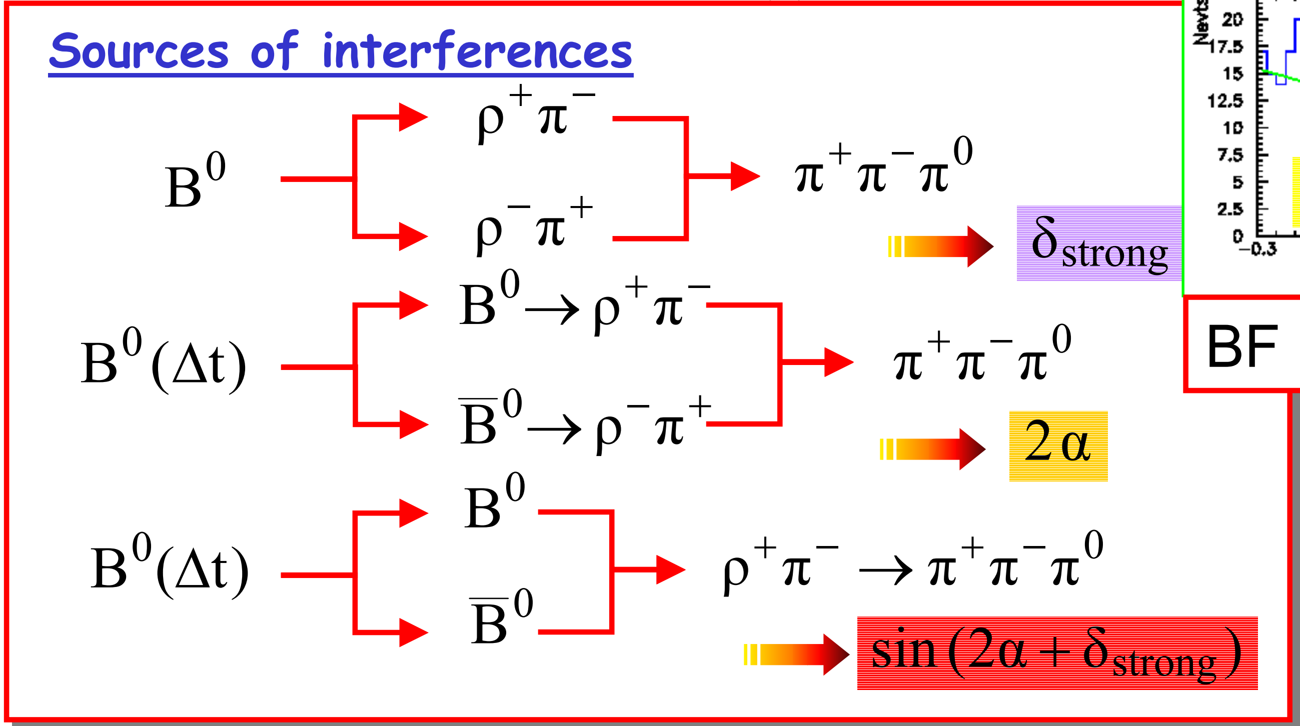




Beneke et al., NP **B606**, 245 (2001)

Measurement of sin2α with $B^0 \to \pi^+\pi^-\pi^0$

- Exploit interferences in the 3π final state
  - Fit to the time-dependent Dalitz plot
  - In principle, extract α without ambiguity
- Need at least 1,500 events with B/S<2
  - $\rho^0\pi^0$ needed, but color-suppressed

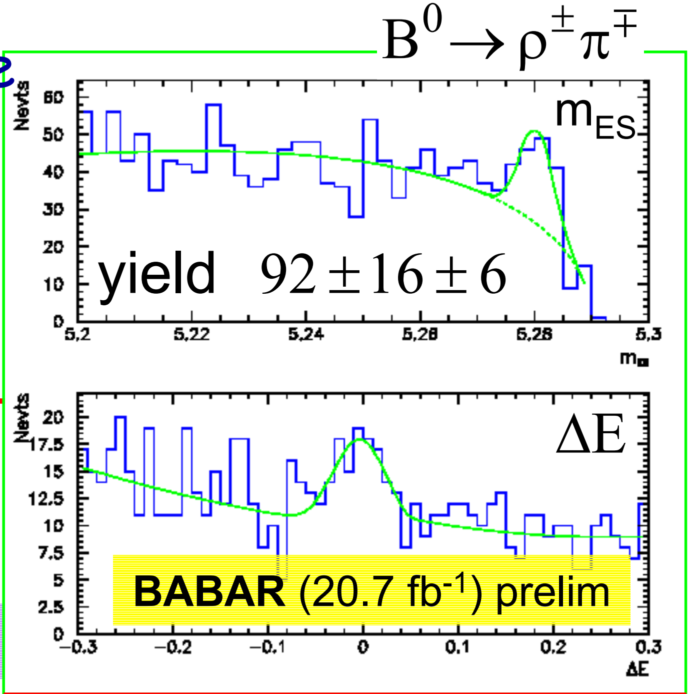


Sources of interferences

$B^0 \to \rho^+\pi^-,\ \rho^-\pi^+ \to \pi^+\pi^-\pi^0$ → δ_{strong}

$B^0(\Delta t) \to B^0\to\rho^+\pi^-,\ \overline{B}^0\to\rho^-\pi^+ \to \pi^+\pi^-\pi^0$ → 2α

$B^0(\Delta t) \to B^0,\ \overline{B}^0 \to \rho^+\pi^- \to \pi^+\pi^-\pi^0$ → $\sin(2\alpha+\delta_{strong})$



$B^0 \to \rho^\pm\pi^\mp$

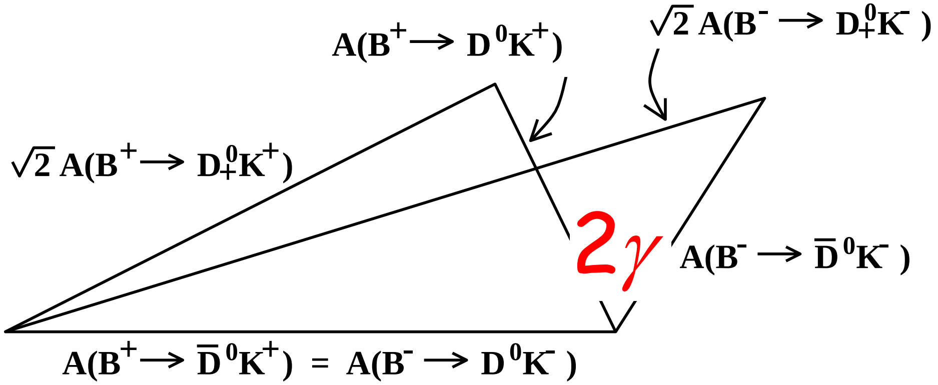
BF $(3.1 \pm 0.5 \pm 0.3) \times 10^{-5}$

Higher πππ resonances, *with different strong phases*, might spoil the measurement

Prospects for Measuring γ

- $D^*\pi$ *decays to extract* $\sin(2\beta + \gamma)$
  - CPV in mixing/decay $B^0 \rightarrow D^{*-}\pi^+ \leftrightarrow \bar{B}^0 \rightarrow D^{*-}\pi^+$ (DCS)
  - clean theoretically,
    - pure tree amplitudes – no penguin pollution
  - …but time-dependent *CP* asymmetries at the few % level
- D^0K^+ where $D^0, \bar{D}^0 \rightarrow f_{CP}$ *decays to extract* γ
  - interference $B^+ \rightarrow \bar{D}^0K^+ \leftrightarrow B^+ \rightarrow D^0K^+$

Original construction by **Gronau & Wiler**:



First Look at BELLE

$CP+ = K^+K^-, \pi^+\pi^-$

$CP- = K_S^0\pi^0, K_S^0\omega, K_S^0\eta, K_S^0\eta'$

BELLE

$29.1\ \text{fb}^{-1}$

Preliminary

	$CP+$	$CP-$
A_{CP}	$A_1 = 0.29^{+0.29}_{-0.24} \pm 0.05$ $-0.14 < A_1 < 0.79$	$A_2 = -0.22^{+0.26}_{-0.22} \pm 0.04$ $-0.60 < A_2 < 0.21$
R_{CP}	$R_1 = 1.38 \pm 0.38 \pm 0.15$	$R_2 = 1.37 \pm 0.36 \pm 0.12$

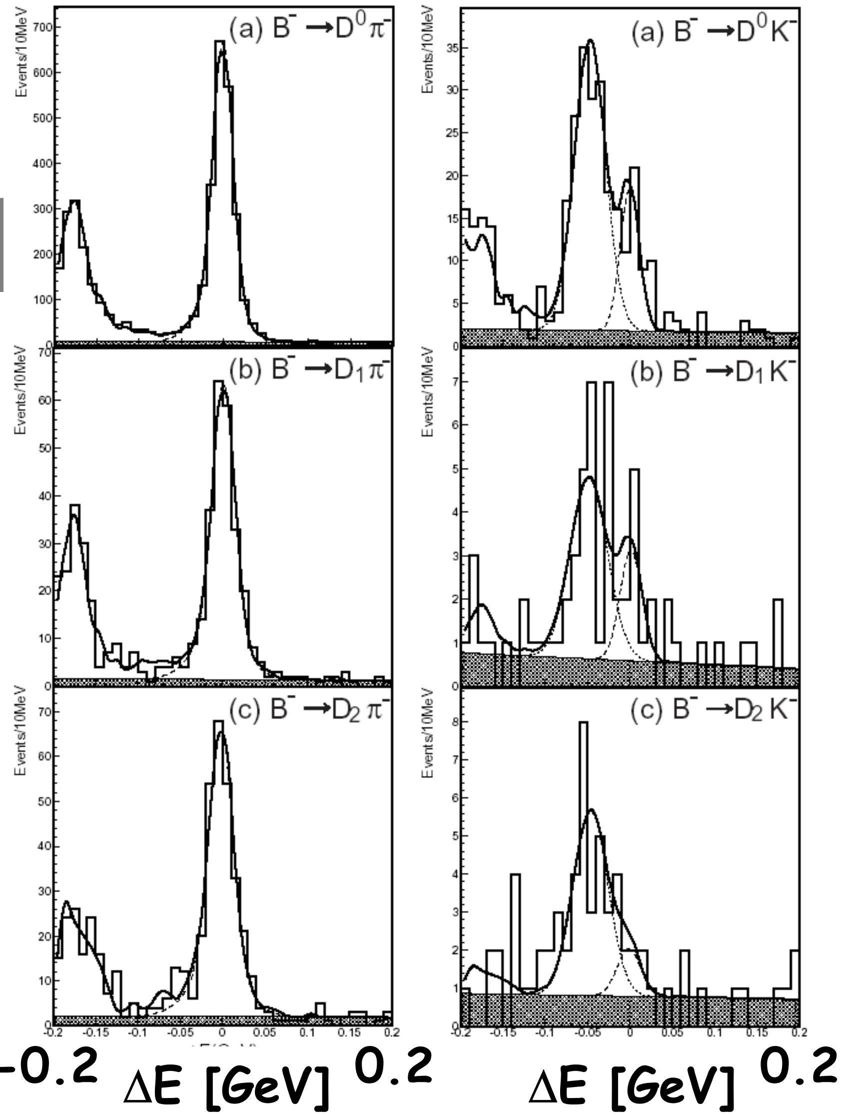
$$R_i \equiv \frac{Br(B^\pm \to D_i K^\pm)/Br(B^\pm \to D_i \pi^\pm)}{Br(B^\pm \to D^0 K^\pm)/Br(B^\pm \to D^0 \pi^\pm)}$$

(Cabibbo suppression factor ratio, D_{CP} vs D^0)

Preliminary

BELLE KEK TC5

Extremely challenging experimentally!



Testing the Standard Model

- ***Assumes |Vcb| ~ 3% and |Vub| ~ 10%***
  - Much experimental and theoretical work underway to achieve this
    - New results on inclusive/exclusive semileptonic decays
    - Will be entering an era of very large tagged samples
- ***Assumes Δm_s known to 0.2% from Tevatron***

ca. 2007:
$\sigma(\sin 2\beta)$ ~ 1%
α ~ 5^o, γ ~ 10^o

CKM fitter

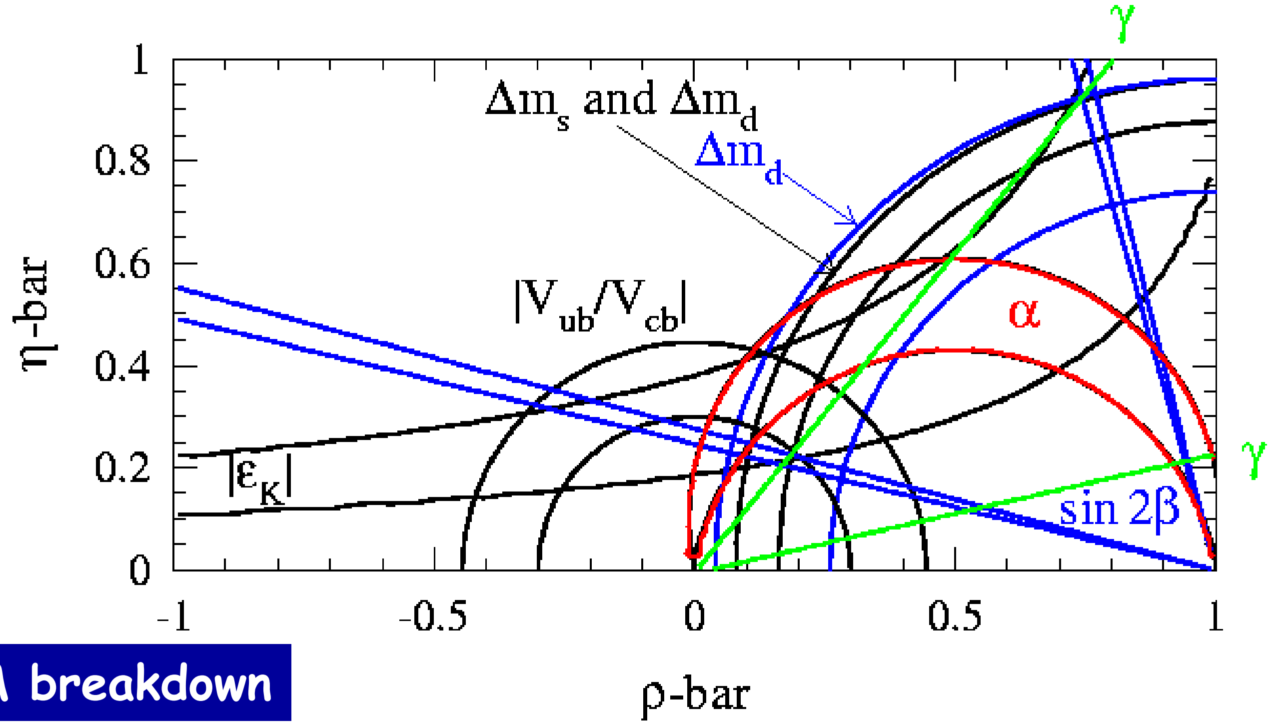


Illustration of SM breakdown

The TEVATRON

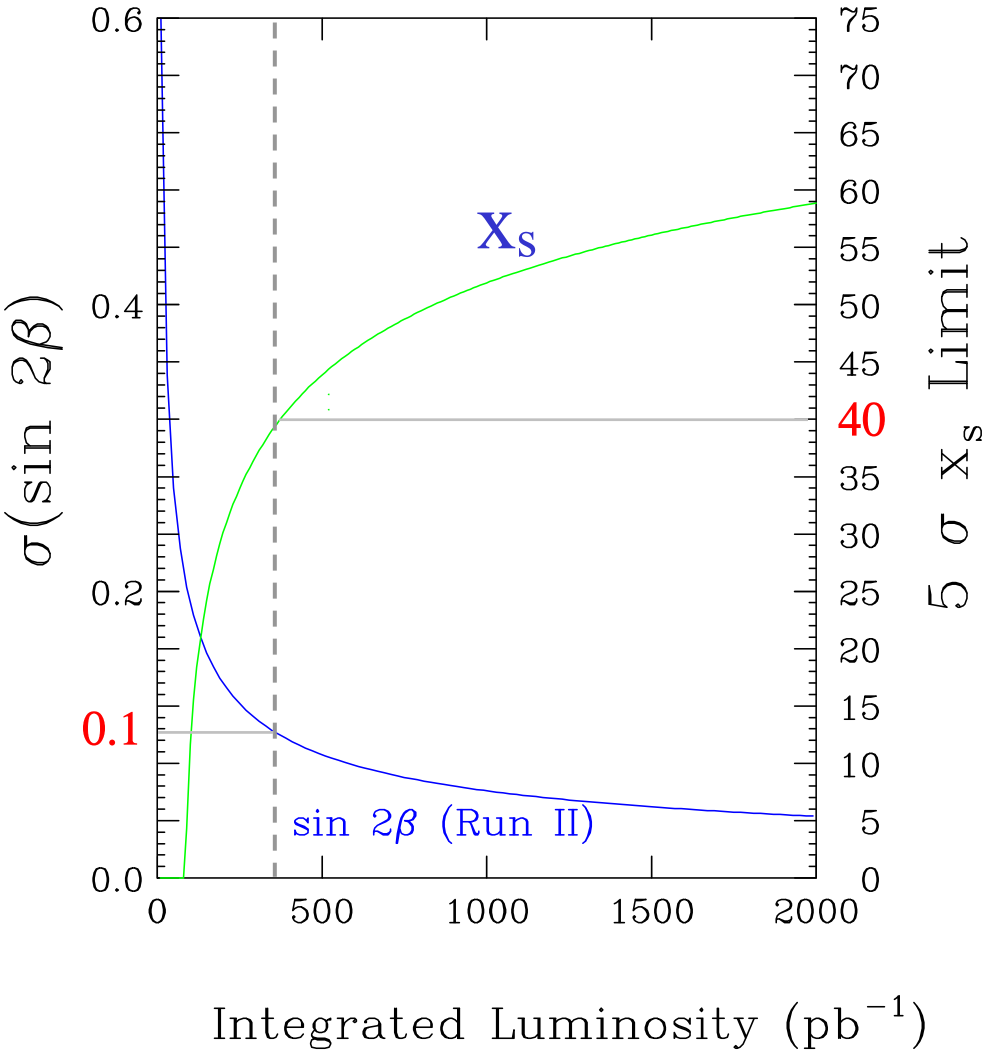
- **Run 2 started**
  - Improved CDF and Dzero detectors
  - Expect 300 pb-1 by end of 2002 and 15 fb-1 by 2007
- **Examples of specific physics strengths**

B_s mixing

$B_s \rightarrow K\pi, KK$

$B_s \rightarrow D_s K$

$B_s \rightarrow J/\psi\phi$



Summary

- *Have entered era of B Factories, with a renaissance of experimental and theoretical activity on B physics*
- *Motivation for these and upcoming facilities is a definitive test of CP violation in the Standard Model*
- *July 2001 saw the beginnings of this program*

Unambiguous observation of CP violation in the B system

$$\boxed{\sin 2\beta = 0.79 \pm 0.10}$$

World average dominated by BELLE and BABAR

- *But…still working towards a definitive consistency test of Standard Model expectations and constraints*

Complementary approaches of the different *B* factories will be needed to tackle this challenge

Backup Slides

Current Experimental Constraints

Based on Höcker *et al.*, Eur.Phys.J. **C21**, 225 (2001)
(many other recent global CKM matrix analyses)

Constraints from $b \to u$ & $b \to c$

- $|V_{cb}|$ (excl.)
  - $B \to D^{(*)} \ell \nu \qquad |V_{cb}| \cdot F_{D^*}(\omega = 1)$
  - $F_{D^*}(1) \sim 1 +$ HQET corrections

CLEO hep-ex/0007052

LEP hep-ex/0009052

- $|V_{cb}|$ (incl.)
  - $B \to X_c \, \ell \nu \qquad |V_{cb}|$ from HQE
  - Assumes Quark/Hadron duality

CLEO PRL**76** (1996) 1570

LEP hep-ex/0009052

$$\boxed{|V_{cb}| = (40.76 \pm 0.50_{(stat+syst)} \pm 2.0_{(theo)}) \times 10^{-3}}$$

- $|V_{ub}|$ (excl.)
  - $B \to \pi(\rho, \omega) \, \ell \nu$
  - Model dependence

CLEO PR **D61** (2000) 052001

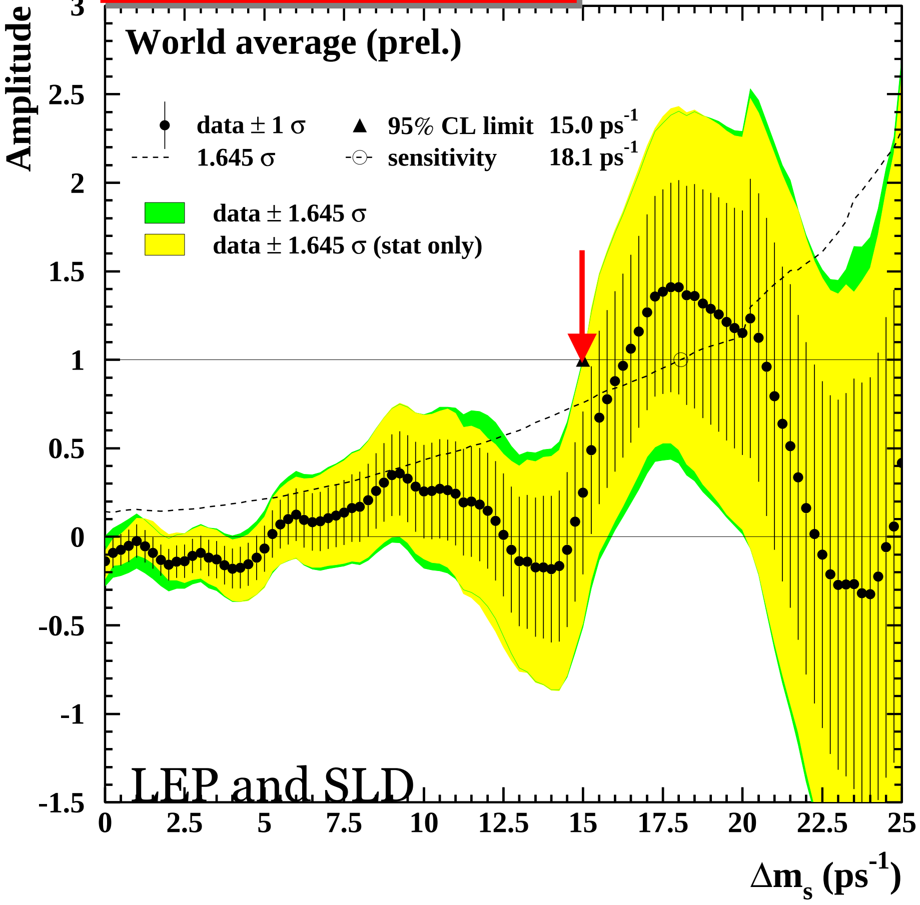
- $|V_{ub}|$ (incl.)
  - $B \to X_u \, \ell \nu \qquad |V_{ub}|$ from HQE
  - Assumes Quark/Hadron duality

LEP hep-ex/0009052

$$\boxed{|V_{ub}| = (3.49 \pm 0.24_{(stat+syst)} \pm 0.55_{(theo)}) \times 10^{-3}}$$

Constraints from Mixing

LEP Working Group
Winter 2001



- $|V_{td}|$ from Δm_{B_d} ($B^0\overline{B}^0$ mixing)
  - Limited by uncertainty on $f_{B_d}\sqrt{\hat{B}_{B_d}}$

$$\Delta m_{B_d} = (0.487 \pm 0.014_{(stat+syst)})\ \text{ps}^{-1}$$

- $|V_{ts}|/|V_{td}|$ from Δm_{B_d} and limit on Δm_{B_s} ($B_s\overline{B}_s$ mixing)
  - limited by uncertainty on $\xi = f_{B_s}\sqrt{\hat{B}_{B_s}} \,/\, f_{B_d}\sqrt{\hat{B}_{B_d}}$ (computed at the 5% level from the lattice)

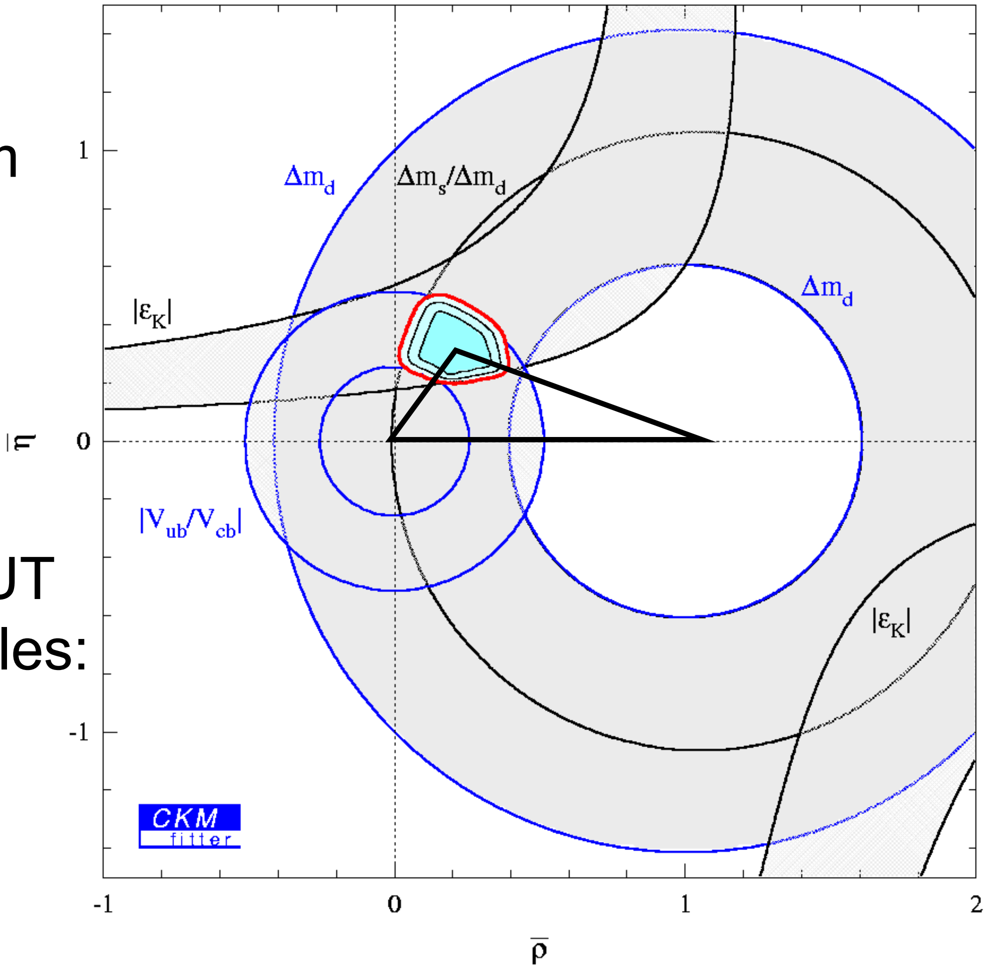
$$\Delta m_{B_s} > 15\,\text{ps}^{-1}\ @\ 95\%\ \text{CL}$$

Indirect Constraints on Unitarity Triangle

- *CP*-averaged measurements:

  $J > 0$ at $\sim 1.7\,\sigma$

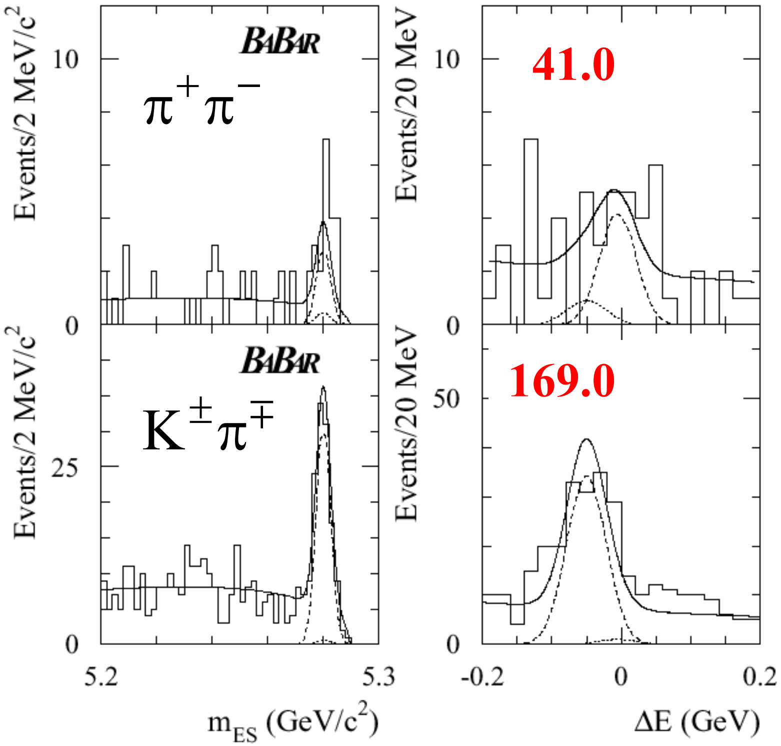
- *Evidence* for *CP* violation from *CP*-averaged observations **consistent** with *CP* violation in kaon system (given by $|\varepsilon_K|$)

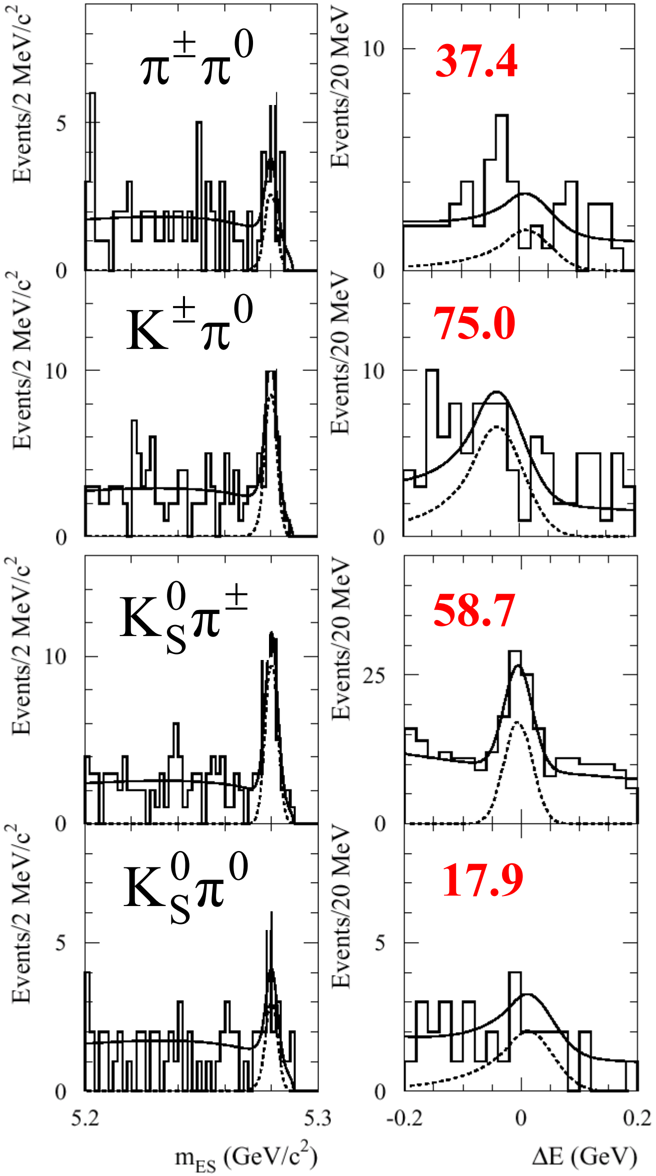


Constraints on apex of UT and *CP*-violating observables:

$$\begin{aligned} \sin 2\beta &\in [0.47 \leftrightarrow 0.89] \\ \sin 2\alpha &\in [-1 \leftrightarrow 0.5] \\ \gamma &\in [34^\circ \leftrightarrow 82^\circ] \end{aligned}$$

B→ Kπ, ππ at BABAR

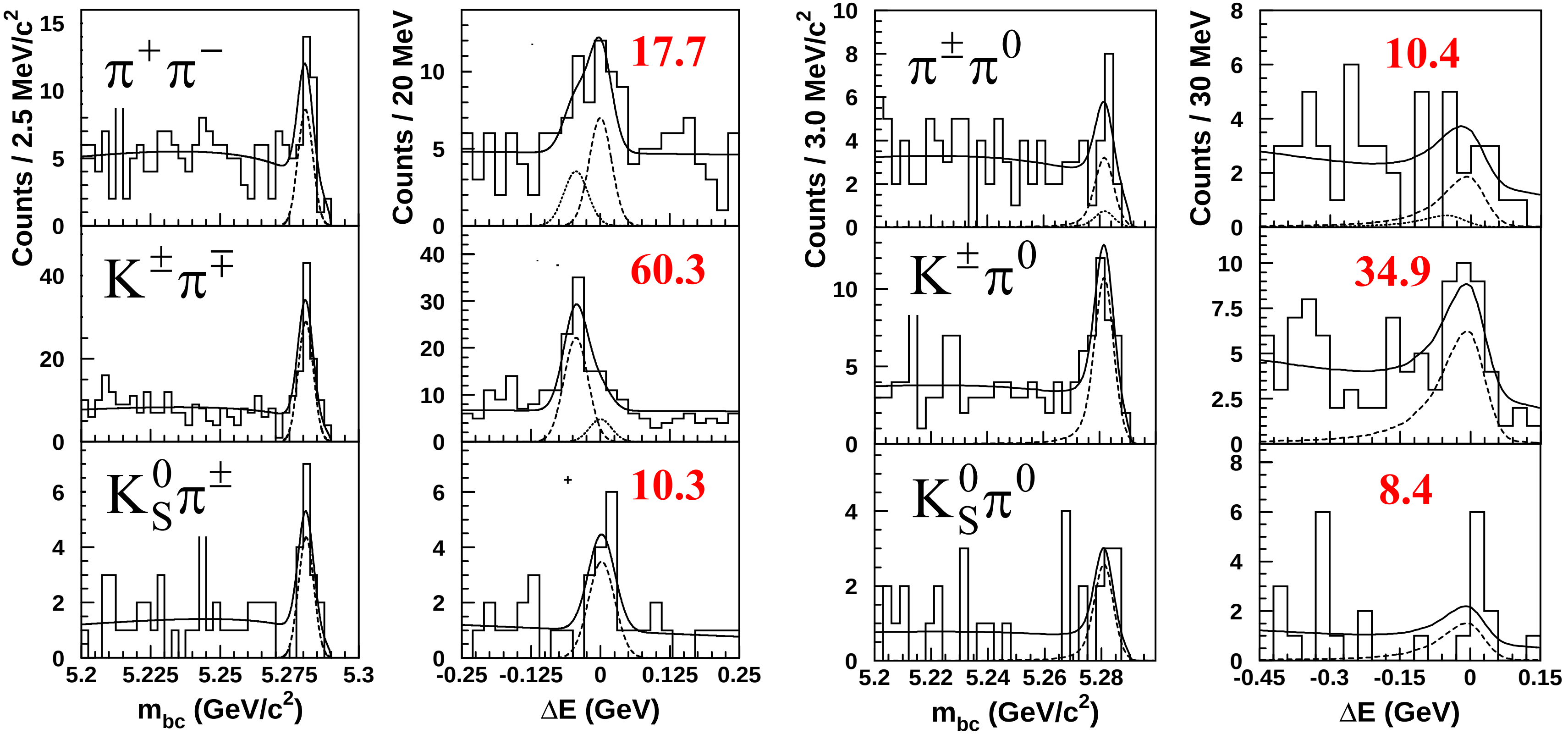




BABAR
20.7 fb^{-1}

BABAR PRL **87**, 15802 (2001)

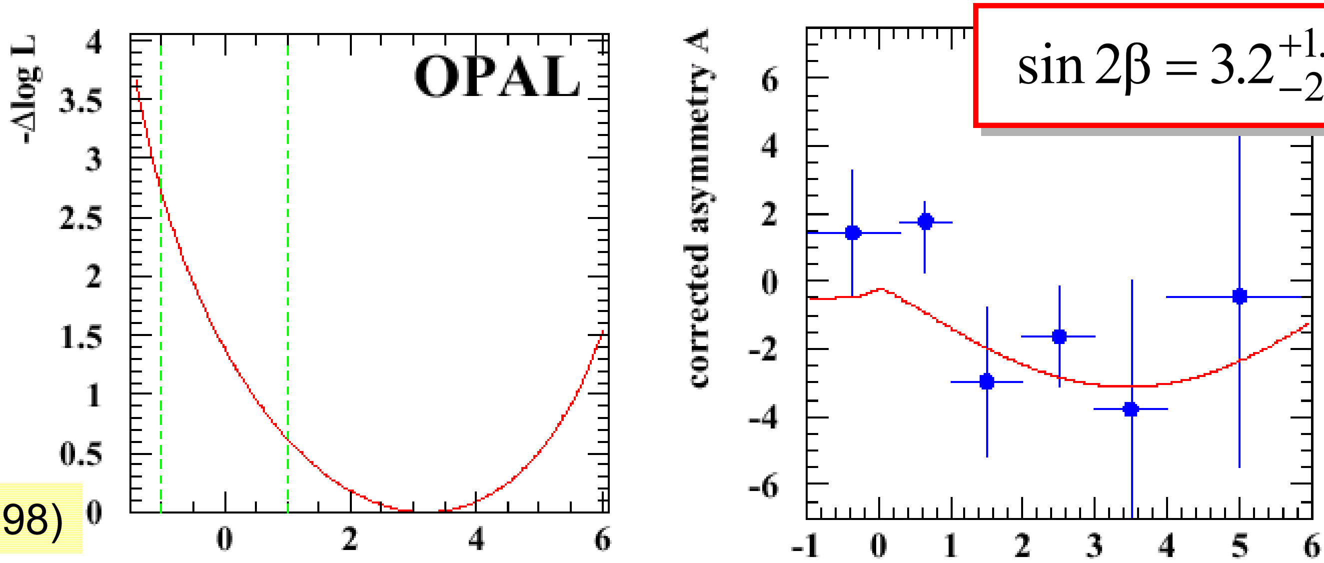
$B \rightarrow K\pi$, $\pi\pi$ at BELLE



BELLE
10.5 fb^{-1}

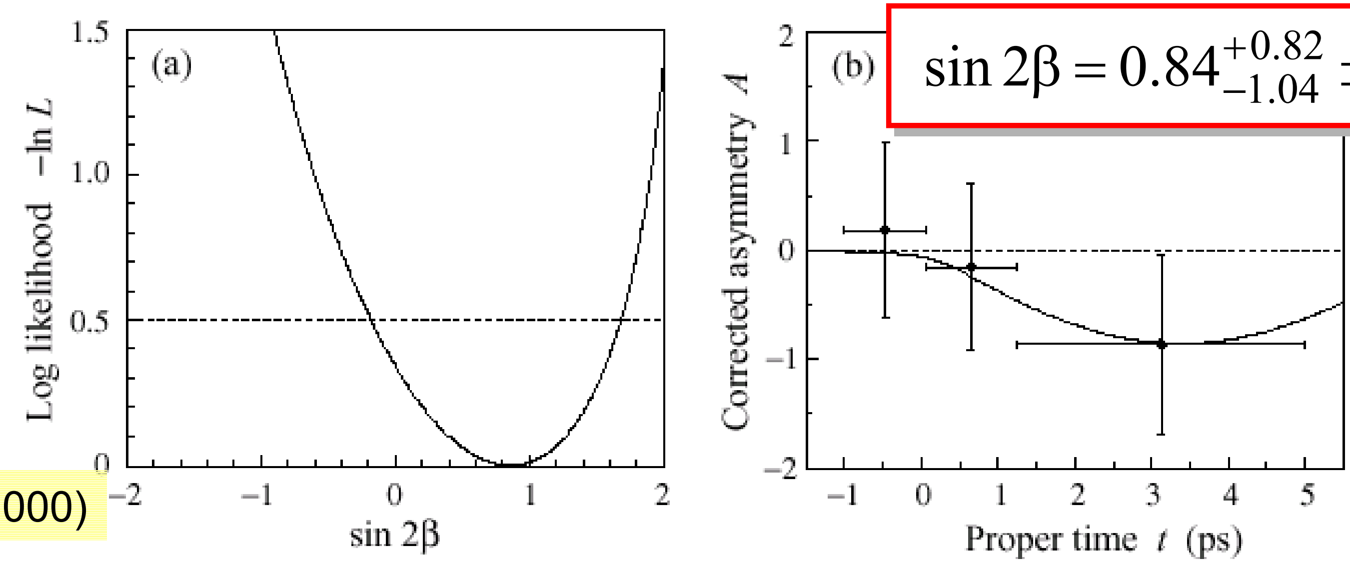
BELLE PRL **87**, 101801 (2001)

Early LEP Results



$$\sin 2\beta = 3.2^{+1.8}_{-2.0} \pm 0.5$$

OPAL EPJ **C**5 (1998)

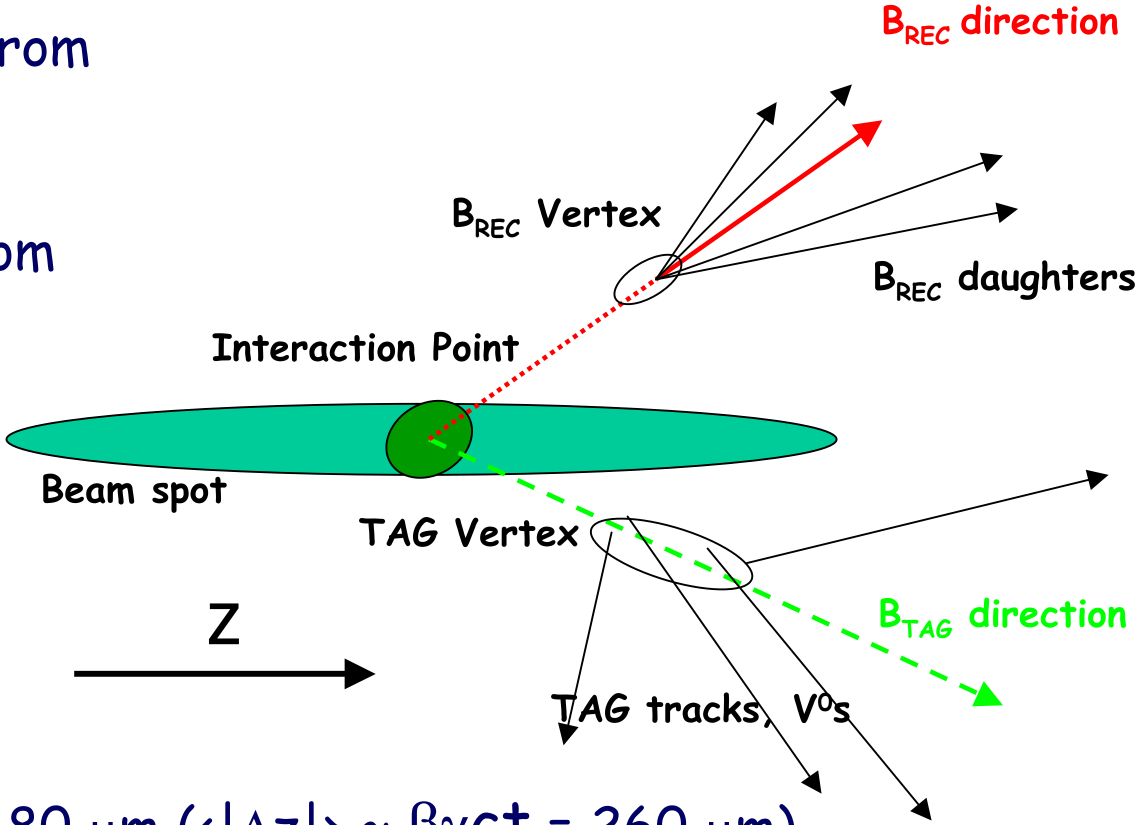


$$\sin 2\beta = 0.84^{+0.82}_{-1.04} \pm 0.16$$

ALEPH PL 492 (2000)

Vertex and Δt Reconstruction

- Reconstruct B_{rec} vertex from
  - charged B_{rec} daughters
- Determine B_{Tag} vertex from
  - charged tracks not belonging to B_{rec}
  - B_{rec} vertex and momentum
  - beam spot and $\Upsilon(4S)$ momentum



- High efficiency (97%)
- Average Δz resolution is 180 μm ($<|\Delta z|> \sim \beta\gamma c t$ = 260 μm)
- Conversion of Δz to Δt takes into account the (small) B momentum in $\Upsilon(4S)$ frame

$$\boxed{\Delta z = \beta\gamma\gamma^*_{rec} c\Delta t + \gamma\beta^*_{rec}\gamma^*_{rec}\cos\theta^*_{rec}\, c(\tau_{B^0} + |\Delta t|)}$$

- Δt resolution function measured directly from data

Flavour Tagging Performance

The large sample of fully reconstructed events provides the precise determination of the tagging parameters required in the CP fit

Tagging category	Fraction of tagged events ε (%)	Wrong tag fraction w (%)	$Q = \varepsilon(1-2w)^2$ (%)
Lepton	10.9 ±0.3	8.9 ± 1.3	7.4 ± 0.5
Kaon	35.8 ±0.5	17.6 ± 1.0	15.0 ± 0.9
NT1	7.8 ±0.3	22.0 ± 2.1	2.5 ± 0.4
NT2	13.8 ±0.3	35.1 ± 1.9	1.2 ± 0.3
ALL	68.4 ±0.7		26.1 ± 1.2

Highest “efficiency”

The error on sin2β and Δm depend on “the quality factor” Q:

$$\sigma(\sin 2\beta) \propto \frac{1}{\sqrt{Q}}$$

Smallest mistag fraction

sin2β likelihood fit

Combined unbinned maximum likelihood fit to Δt spectra of flavor and CP sample

Fit Parameters

		Driven by
sin2β	1	tagged CP samples
Mistag fractions for B^0 and $\bar{B}^0$ tags	8	tagged flavor sample
Signal resolution function	16	
Empirical description of background Δt	20	
B lifetime fixed to the PDG value	$\tau_B = 1.548$ ps	
Mixing Frequency fixed to the PDG value	$\Delta m_d = 0.472\ \mathrm{ps}^{-1}$	

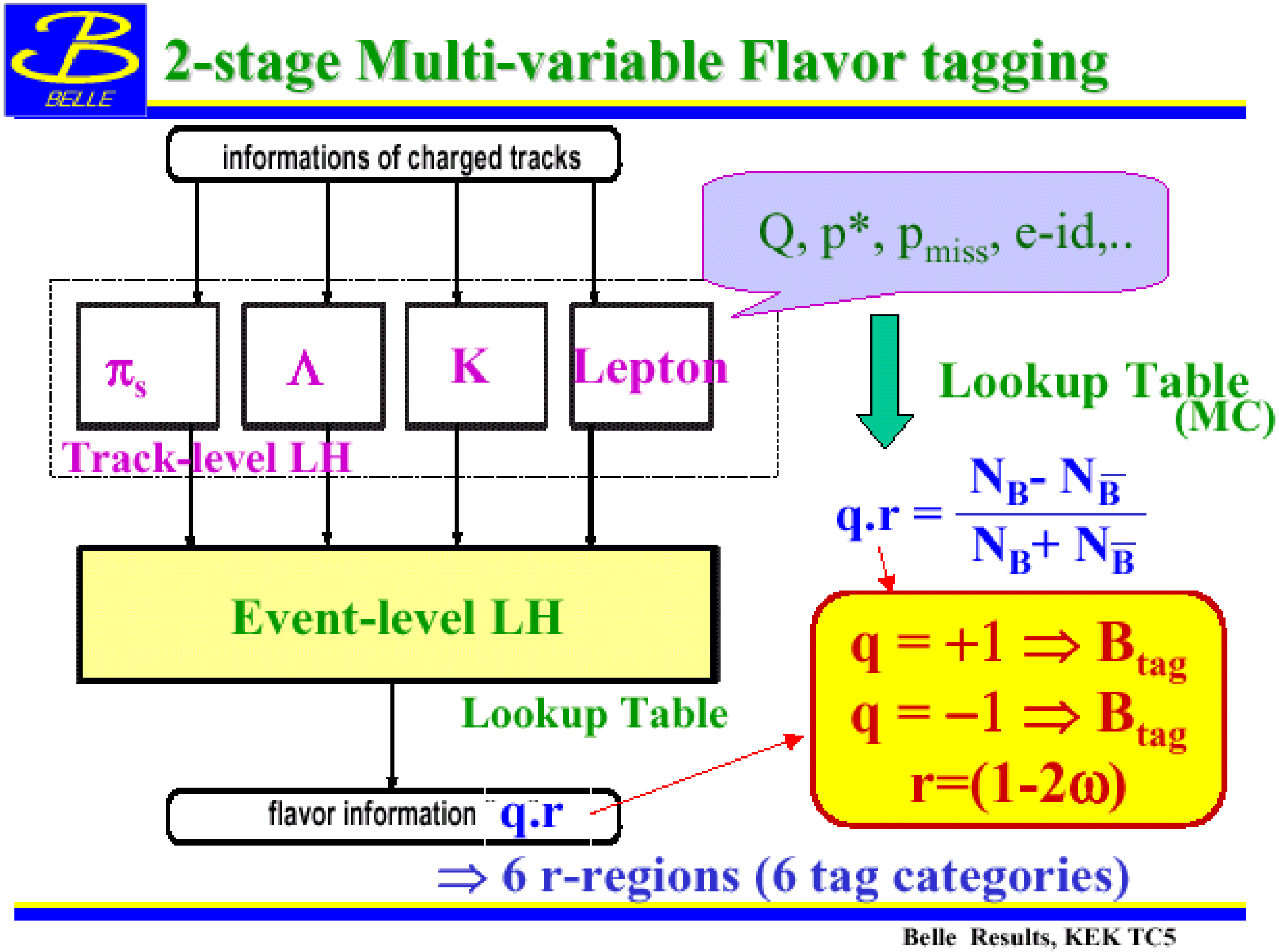
Global correlation coefficient for sin2b: 13%

Different Δt resolution function parameters for Run1 and Run2

45 total free parameters

- ✓ All Δt parameters extracted from data
- ✓ Correct estimate of the error and correlations

Belle Flavour Tagging



2-stage Multi-variable Flavor tagging

informations of charged tracks

Q, p*, p_{miss}, e-id,..

π_s

Λ

K

Lepton

Track-level LH

Lookup Table (MC)

$$q.r = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}$$

Event-level LH

Lookup Table

flavor information q.r

$q = +1 \Rightarrow B_{tag}$

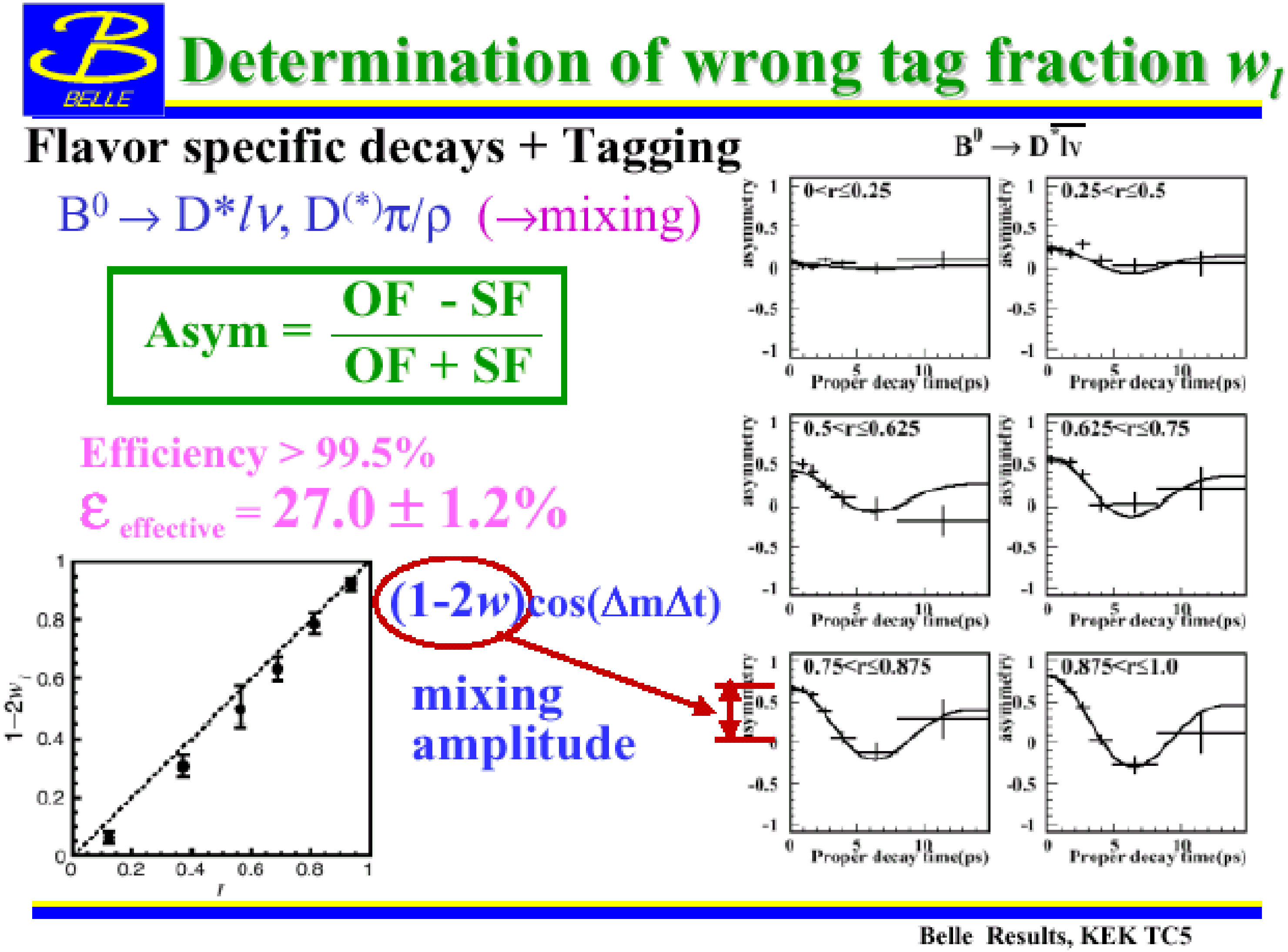
$q = -1 \Rightarrow B_{tag}$

$r = (1-2\omega)$

⇒ 6 r-regions (6 tag categories)

Belle Results, KEK TC5

Belle Flavour Tagging



Determination of wrong tag fraction w_l

Flavor specific decays + Tagging

$B^0 \to D^* l\nu, D^{(*)}\pi/\rho$ (→mixing)

$$\text{Asym} = \frac{\text{OF} - \text{SF}}{\text{OF} + \text{SF}}$$

Efficiency > 99.5%

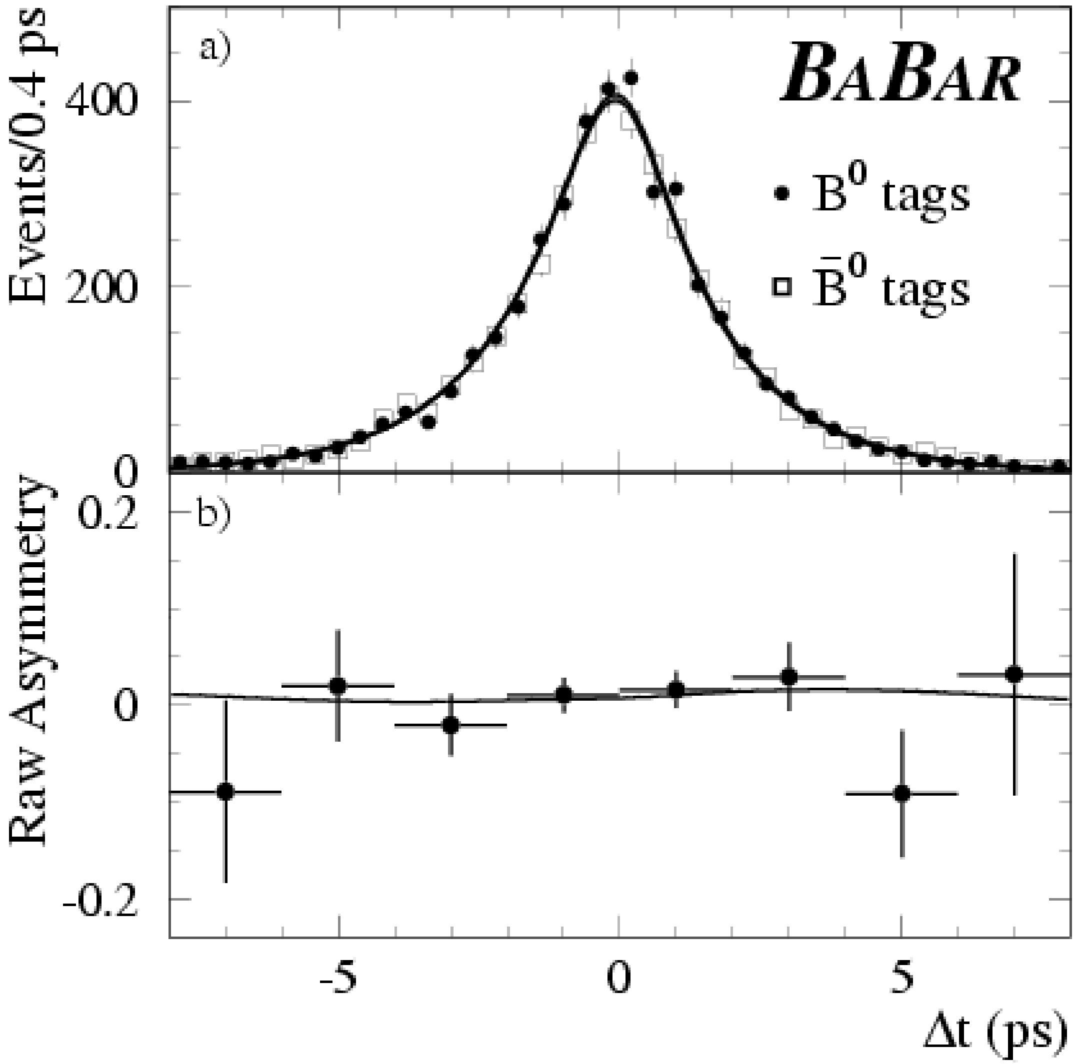
$\varepsilon_{\text{effective}} = 27.0 \pm 1.2\%$

$(1-2w)\cos(\Delta m \Delta t)$

mixing amplitude

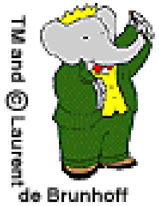
Belle Results, KEK TC5

Check "null" control sample



Input B_{flav} sample to *CP* fit

Systematic Errors on sin2β



BABAR

- ***Signal resolution and vertexing = 0.03***
  - Resolution model, outliers, SVT residual misalignment
- ***Tagging = 0.03***
  - Studies of possible differences between B_{CP} and B_{flavor} samples
- ***Backgrounds = 0.02 (overall)***
  - Signal probability, peaking background, *CP* content of background
  - Total 0.093 for J/Ψ K_L channel; 0.11 for J/Ψ K^{*0}
- ***Total = 0.05 for full sample***

	K_S	K_L	K^{*0}	*Full*
Total Sys	*0.049*	*0.104*	*0.162*	*0.049*
Total Stat	*0.151*	*0.340*	*1.01*	*0.137*

Systematic Errors on sin2β

BELLE

Vertex algorithm	±0.04
Flavor tagging	±0.03
Resolution function	±0.02
K_L background fraction	±0.02
Background shapes	±0.01
Δm_d and τ_{B0} errors	±0.01
Total	±0.06

Fit Results

- ***Extended ML fit to the BFs and CP done simultaneously:***
  - 5 tagging categories (leptons, K, NT1, NT2, untagged)
  - 8 event species (Sig and Bkg: $\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, K^+K^-)
  - Discriminating variables (m_{ES}, ΔE , F, θ_{c1} , θ_{c2} , Δt)
  - Dilutions, $R(\Delta t)$ for the signal taken from sin2β analysis
  - Δm_d, B^0 lifetime fixed as in sin2β analysis
  - $R(\Delta t)$ for the background taken from sidebands in m_{ES} distribution

$$\mathbf{S(\pi^+\pi^-) = 0.03^{+0.53}_{-0.56}(stat) \pm 0.11(syst)}$$

$$\mathbf{C(\pi^+\pi^-) = -0.25^{+0.45}_{-0.47}(stat) \pm 0.14(syst)}$$

$$\mathbf{A_{CP}(K^\pm\pi^\mp) = -0.07 \pm 0.08(stat) \pm 0.02(syst)}$$

BABAR hep-ex/0110062