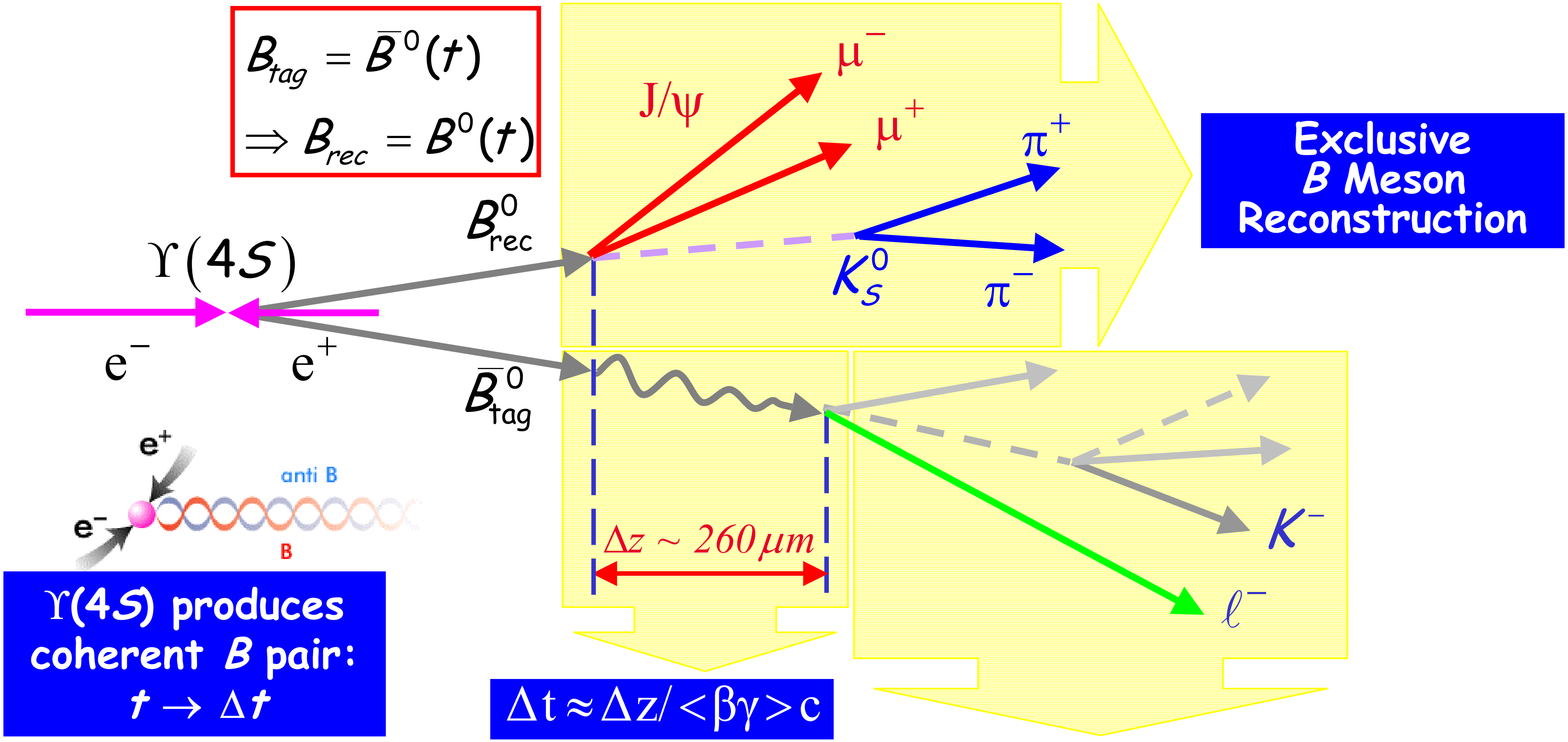
Lecture 3: Time-Dependent Asymmetries as a Test of the Standard Model

- *CP asymmetries in CP eigenstates involving $b \to c\bar{c}s$ transitions*
- *Measuring sin2β in other channels*
- *Asymmetries in 2-body neutral B decays*
- *Brief word on future prospects and plans*

Experimental Technique for B Factories

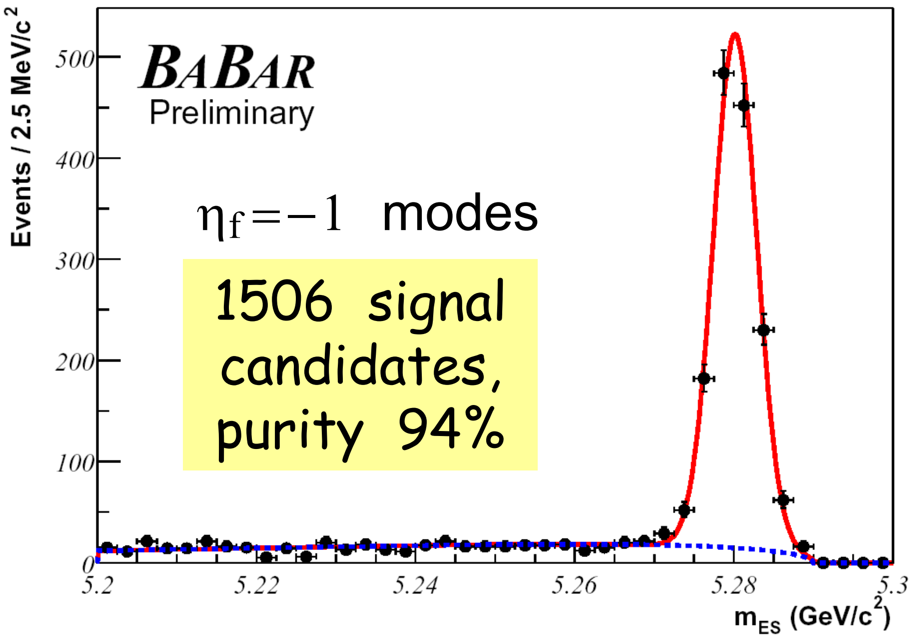


Time-integrated asymmetries are zero

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

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

CP Sample for BABAR

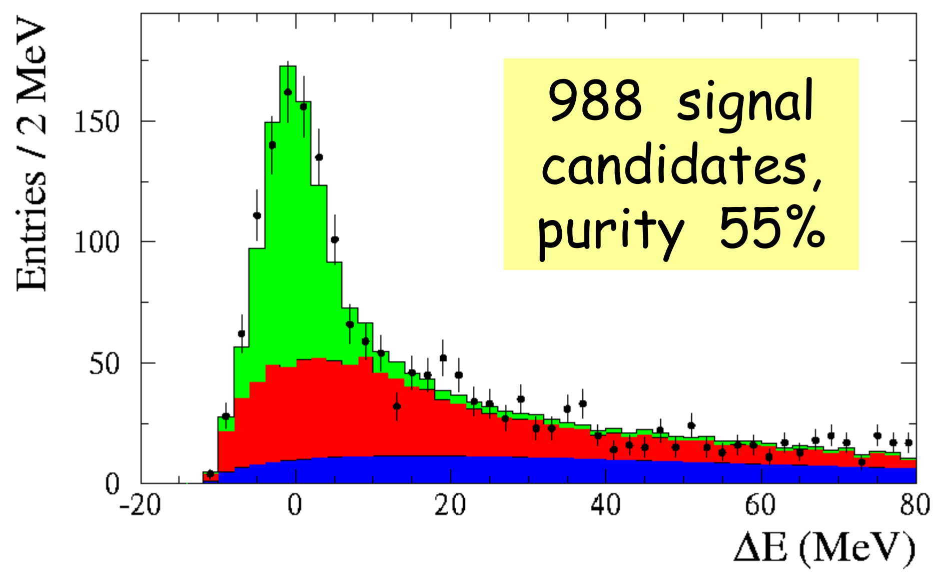


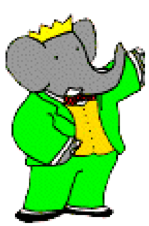
$\eta_f = -1$ modes

$B^0_{CP} \rightarrow J/\psi K^0_S\{\rightarrow \pi^+\pi^-\}$
$B^0_{CP} \rightarrow J/\psi K^0_S\{\rightarrow \pi^0\pi^0\}$
$B^0_{CP} \rightarrow \psi(2S)\{\rightarrow \ell^+\ell^-$ or $J/\psi\pi^+\pi^-\}K^0_S$
$B^0_{CP} \rightarrow \chi_{c1}\{\rightarrow J/\psi\gamma\}K^0_S$
$B^0_{CP} \rightarrow \eta_c\{\rightarrow KK\pi\}K^0_S$

$\eta_f = +1$ mode

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



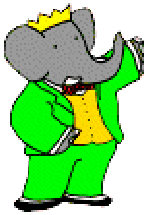


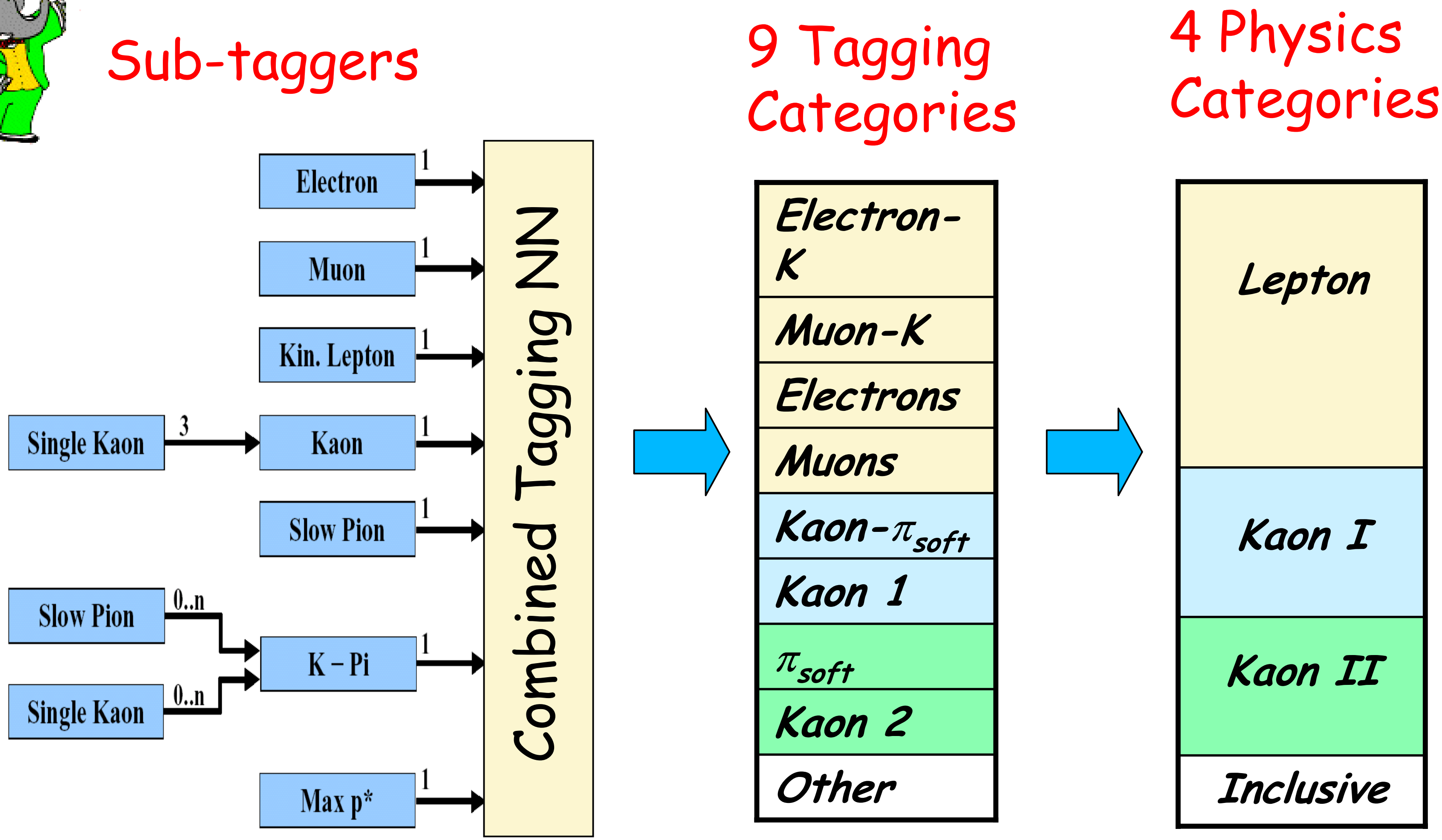
BABAR

81.3 fb^{-1}

(after tagging & vertexing)

Improved Tagging at BABAR





7% improvement in $Q = \varepsilon D^2$ (ΔQ = 1.9%)

Flavor Tagging Performance in Data

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

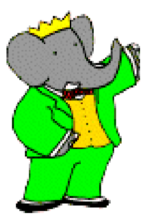
Tagging category	Fraction of tagged events ε (%)	Wrong tag fraction w (%)	Mistag fraction difference Δw (%)	$Q = \varepsilon(1-2w)^2$ (%)
Lepton	9.1 ± 0.2	3.3 ± 0.6	-0.9 ± 0.5	7.9 ± 0.3
Kaon I	16.7 ± 0.2	9.9 ± 0.7	-0.2 ± 0.5	10.7 ± 0.4
Kaon II	19.8 ± 0.3	20.9 ± 0.8	-2.7 ± 0.6	6.7 ± 0.4
Inclusive	20.0 ± 0.3	31.6 ± 0.9	-3.2 ± 0.6	0.9 ± 0.2
ALL	65.6 ± 0.5			28.1 ± 0.7

Highest "efficiency"

Error on sin2β and Δm_d depend on the "quality factor" Q approx. as:

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

Smallest mistag fraction



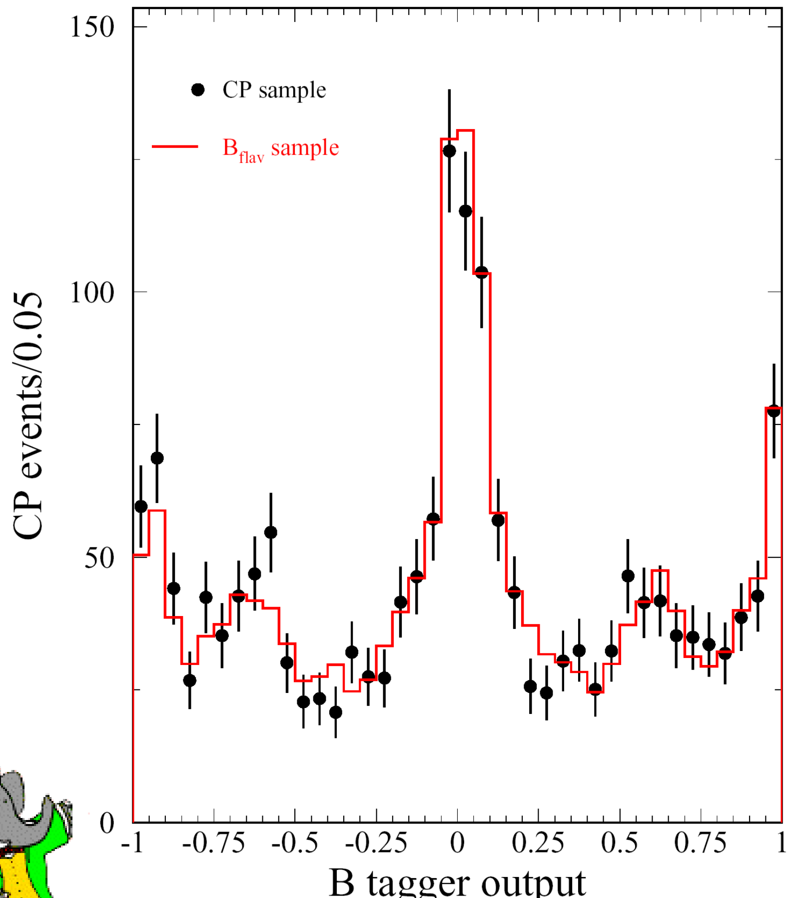
BABAR

$81.3\ \mathrm{fb}^{-1}$

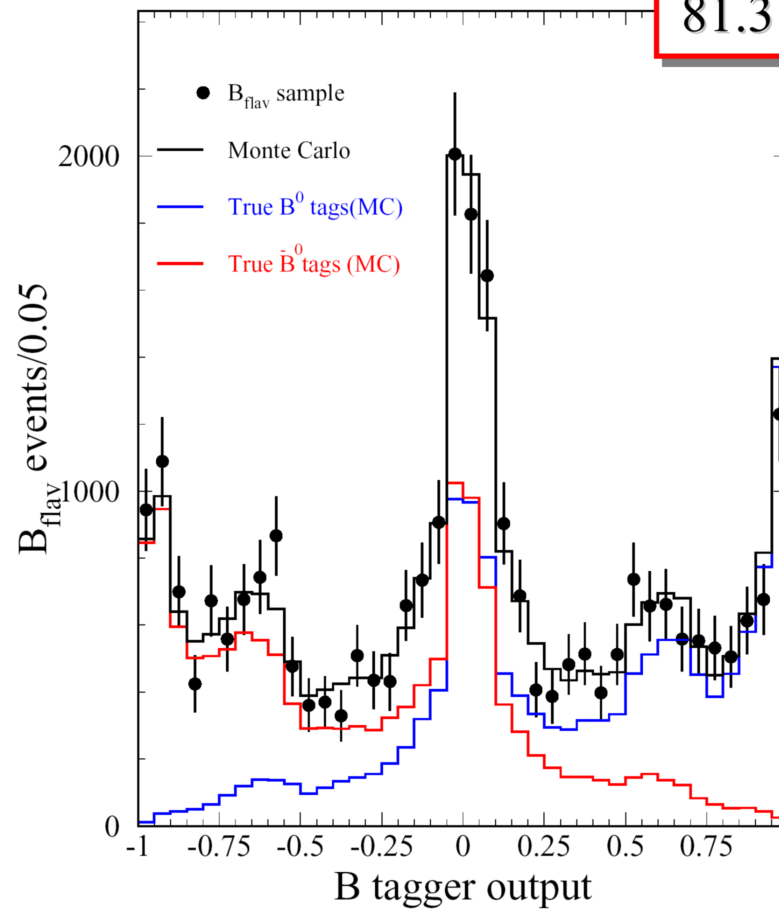
Comparison Tests with New Tagger

Test of crucial underlying assumption:
tagging the same for *CP* & B_{flav} samples

BABAR
81.3 fb^{-1}



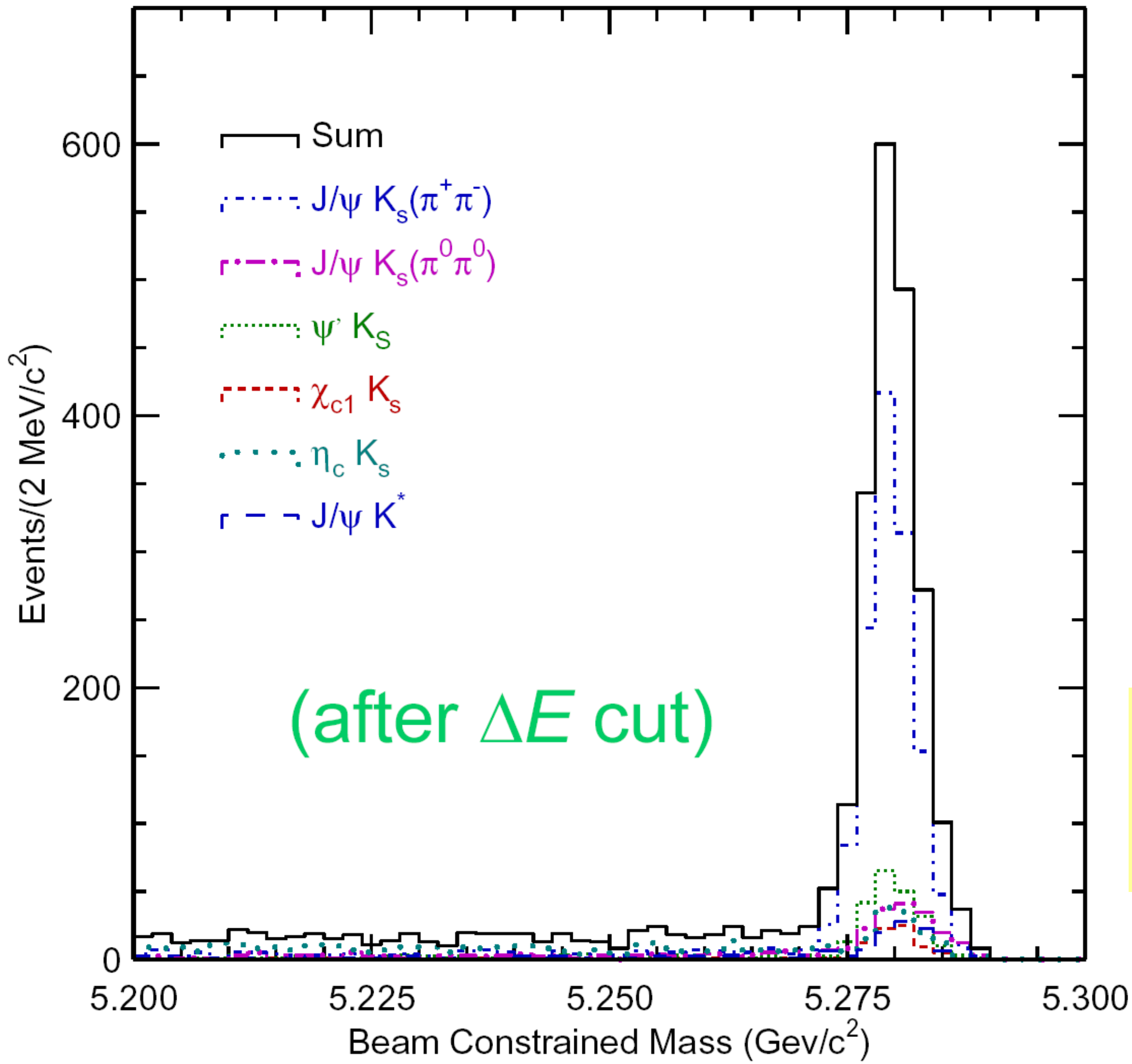
CP vs B_{flav} sample



B_{flav} sample vs MC

Golden Sample: (cc)K_S CP Eigenstates

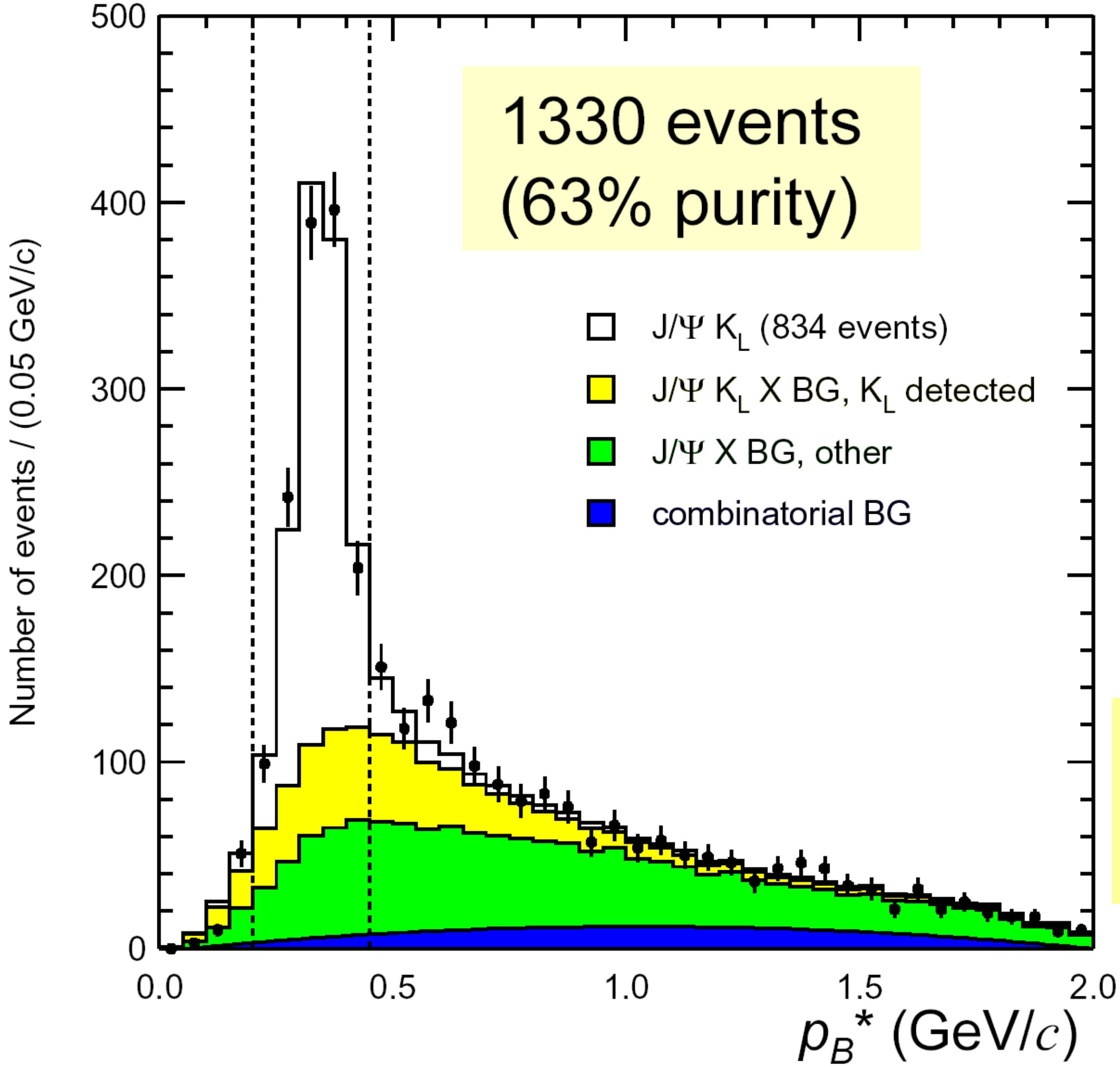
BELLE
78 fb^{-1}



1996 signal candidates, purity 94%

CP Eigenstate Sample: $J/\psi K_L$

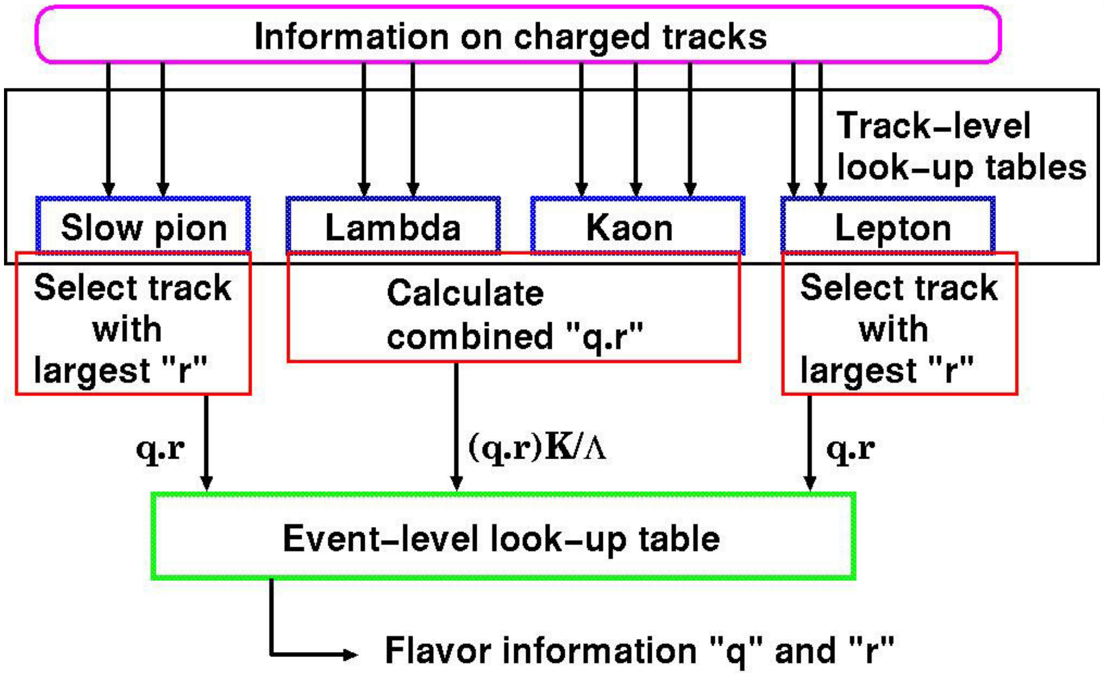
BELLE
78 fb^{-1}



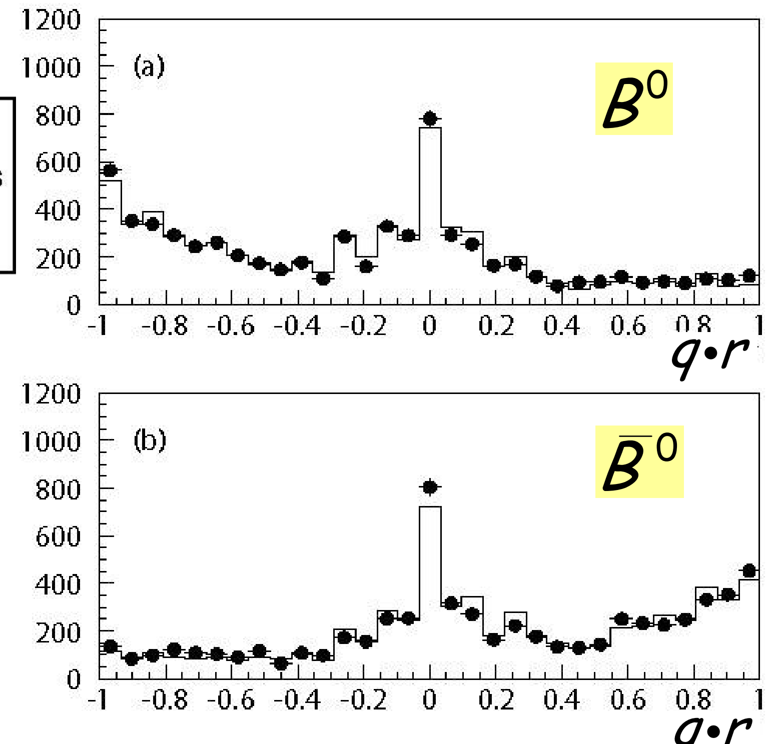
1330 signal candidates, purity 63%

Tagging at Belle

Track level and event level look-up tables



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



$q = +1 : B^0$-like

$q = -1 : \bar{B}^0$-like

Quality factor r varies from
0 = low likelihood
1 = high likelihood

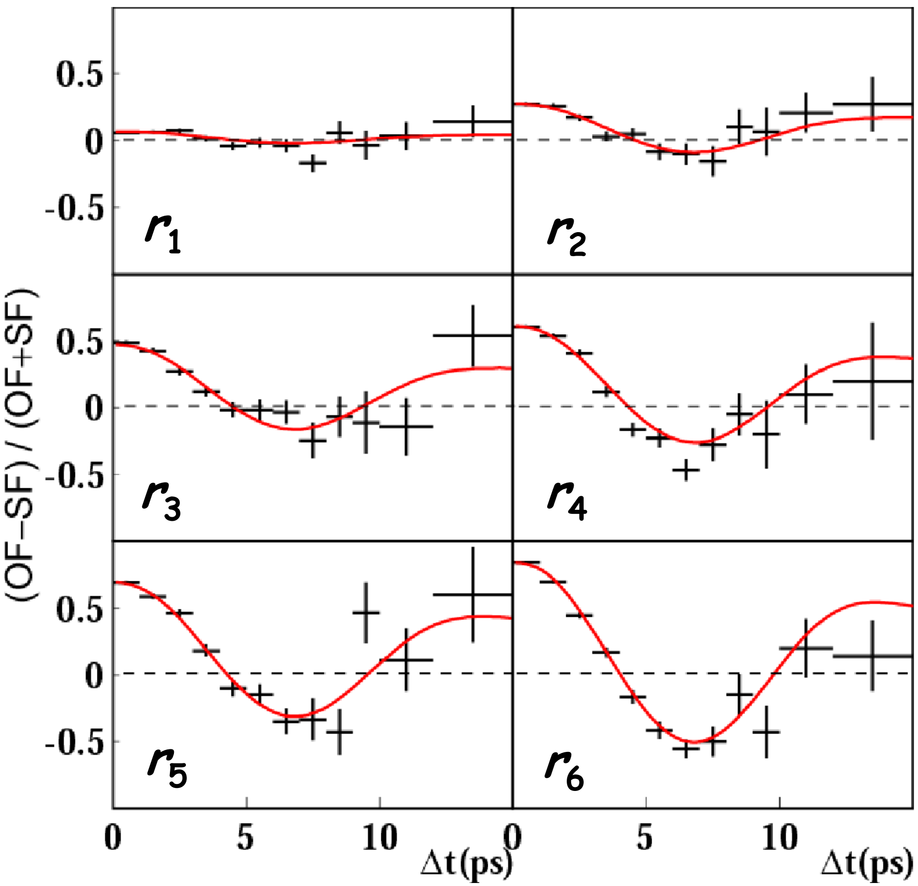
Data vs MC comparison

BELLE
41.8 fb^{-1}

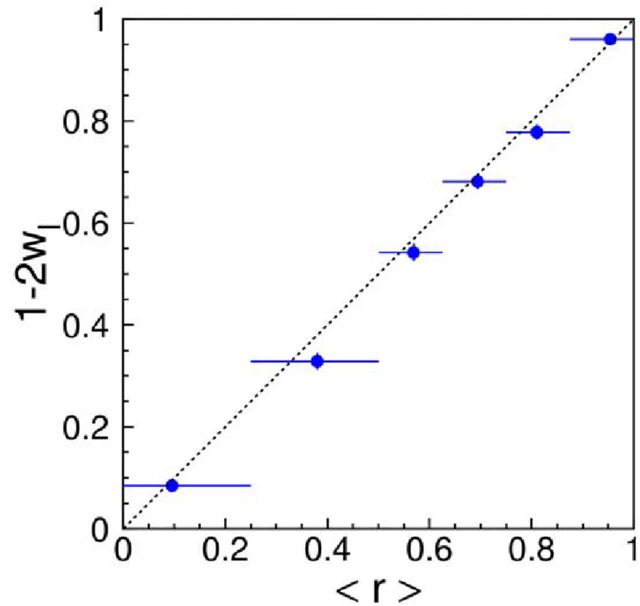
Measuring Mistag Rate

Mistag rate extracted in six bins in r from mixing fit

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



Comparison between measured (1-2w) and quality factor r obtained in 6 bins in r



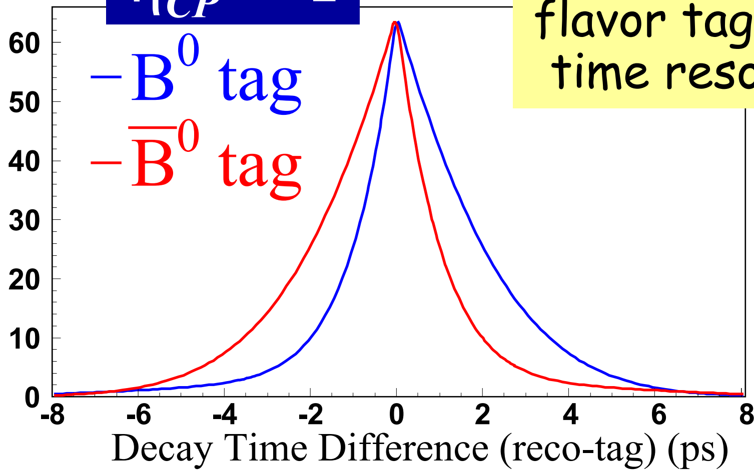
$\varepsilon > 99.5\%, Q = 28.8 \pm 0.5\%$

BELLE 78 fb^{-1}

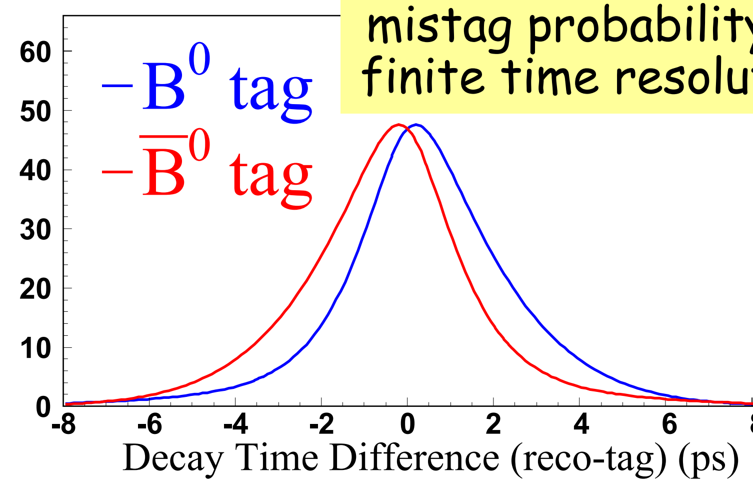
CP Analysis: Time Distributions

$\eta_{CP} = -1$

perfect
flavor tagging & time resolution



realistic
mistag probability & finite time resolution



$$f_{CP,\pm}(\Delta t) \propto \left\{ \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left(1 \mp \eta_f \, (1-2w) \sin 2\beta \sin \Delta m_d \Delta t \right) \right\} \otimes R(\Delta t)$$

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

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

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

Time-Dependent CP Asymmetries

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

$$A_{mixing}(\Delta t) = \frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)} \approx (1-2w)\cos \Delta m_d \Delta t$$

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

(Assuming no confusion of B_{rec} state)

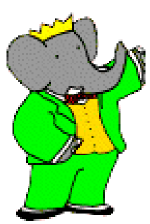
$$A_{CP}(\Delta t) = \frac{N(B_{tag} = B^0) - N(B_{tag} = \bar{B}^0)}{N(B_{tag} = B^0) + N(B_{tag} = \bar{B}^0)} \approx (1-2w)\sin 2\beta \sin \Delta m_d \Delta t$$

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

sin2β Likelihood Fit

Combined unbinned maximum likelihood fit to Δt spectra of B_{flav} and CP samples

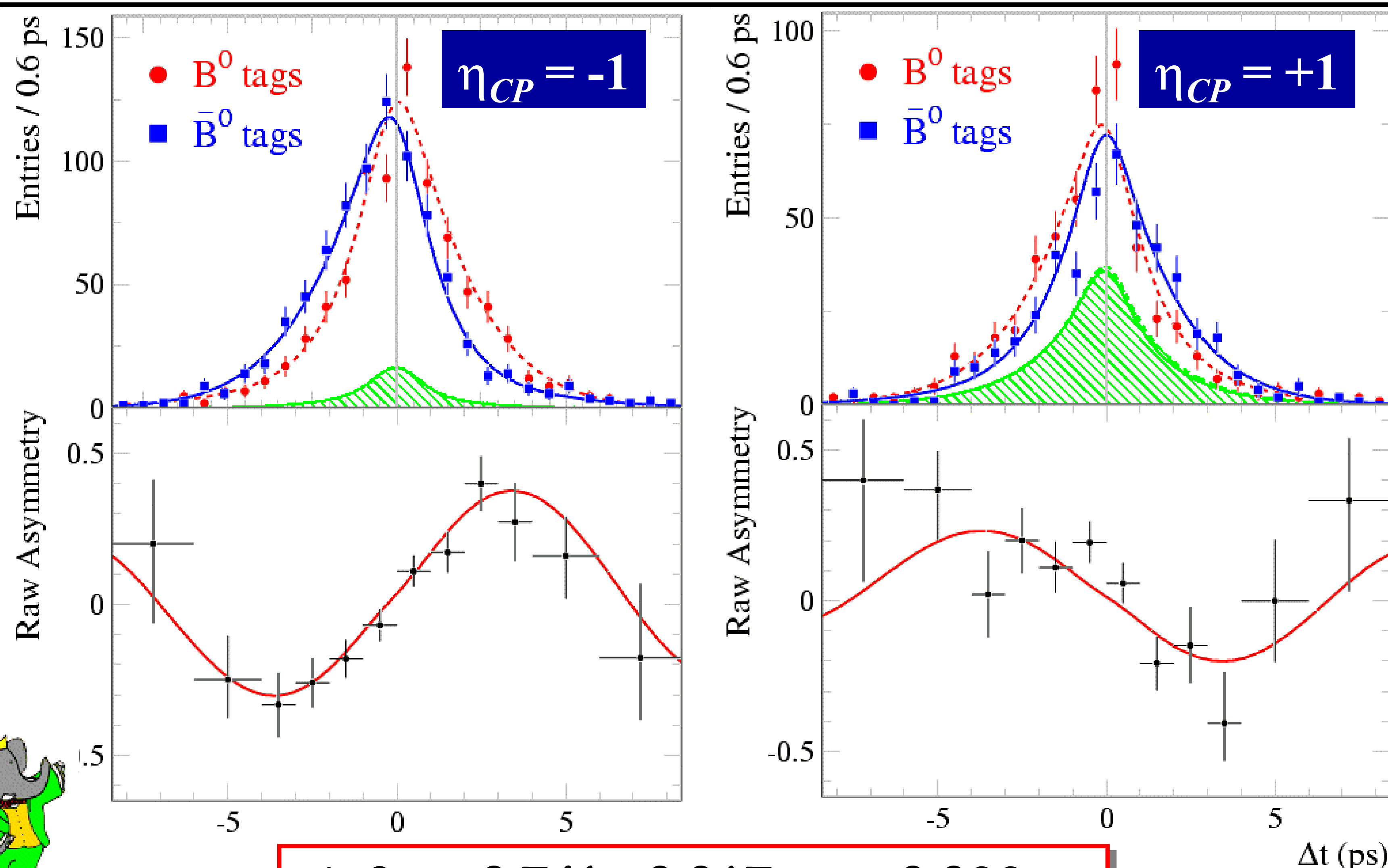
Fit Parameters	*#*	*Main Sample*
Sin2β	*1*	*Tagged CP sample*
Mistag fractions for B^0 and $\bar{B}^0$ tags	*8*	*Tagged flavor sample*
Signal resolution function	*8*	*Tagged flavor sample*
Empirical description of background Δt	*17*	*Sidebands*
B lifetime from PDG 2002	*0*	τ_B = 1.542 ps
Mixing frequency from PDG 2002	*0*	Δm_d = 0.489 ps^{-1}
Total parameters	*34*	

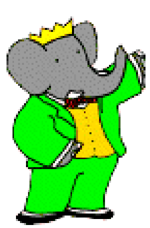


Global correlation coefficient for sin2β: 13%

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

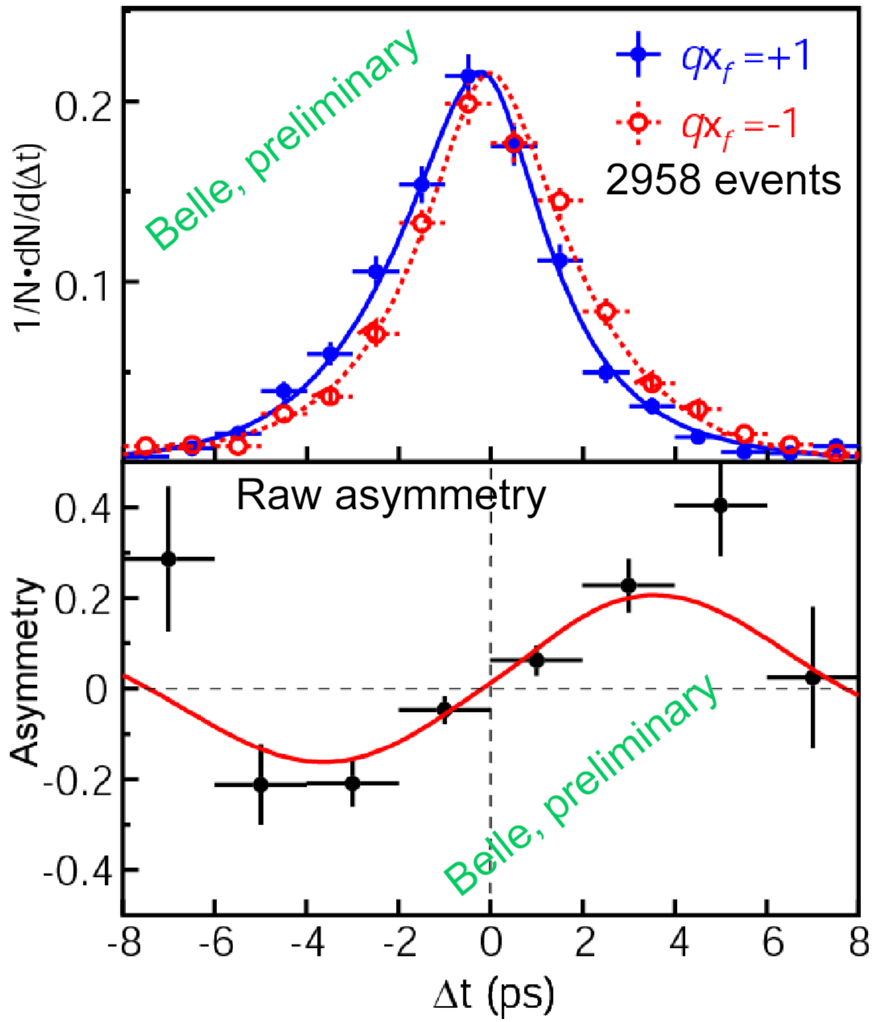
BABAR Result for sin2β





$$\sin 2\beta = 0.741 \pm 0.067_{(stat)} \pm 0.033_{(syst)}$$

Belle Result for sin2β



BELLE

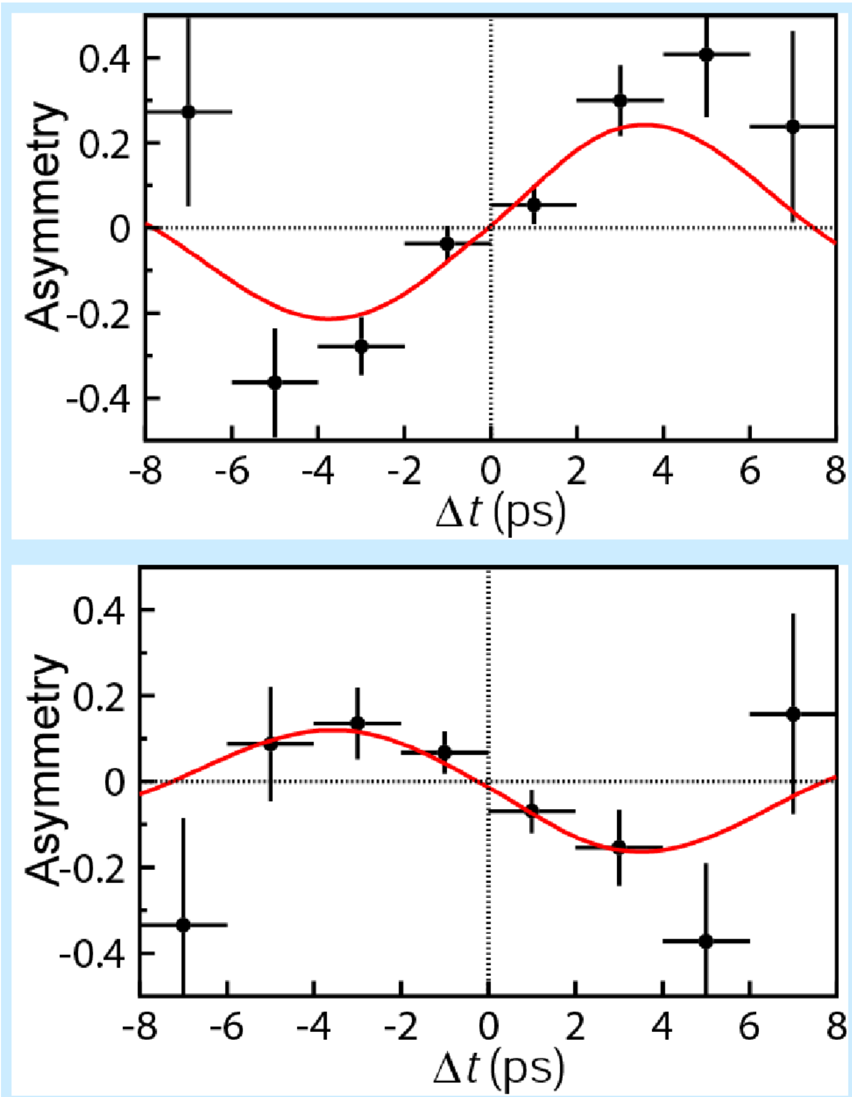
78 fb^{-1}

Checks with control samples where no asymmetry expected

Sample	*"sin2β"*
$B^0 \to D^{*+}\pi^-$	*0.035±0.032*
$B^0 \to J/\psi K^*$	*-0.021±0.093*
$B^0 \to D^* l \nu$	*0.004±0.017*

$$\sin 2\beta = 0.719 \pm 0.074_{(stat)} \pm 0.035_{(syst)}$$

Belle Result for sin2β



$\eta_{CP} = -1$

$\sin 2\beta = 0.716 \pm 0.083_{(stat)}$

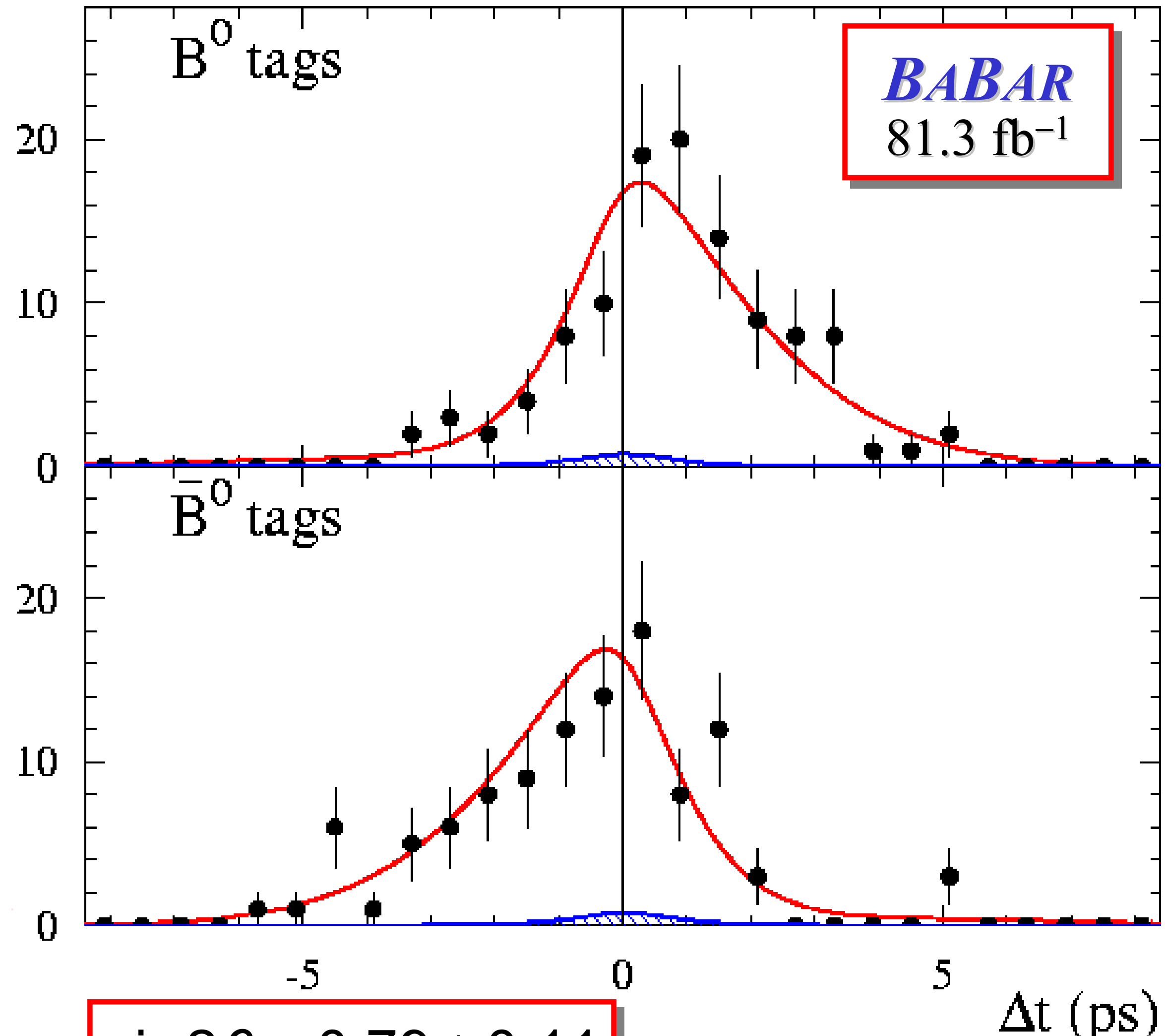
$\eta_{CP} = +1$

$\sin 2\beta = 0.78 \pm 0.17_{(stat)}$

BELLE

78 fb^{-1}

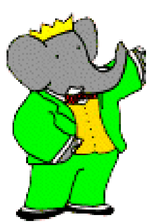
Pure Gold: Lepton Tags Alone



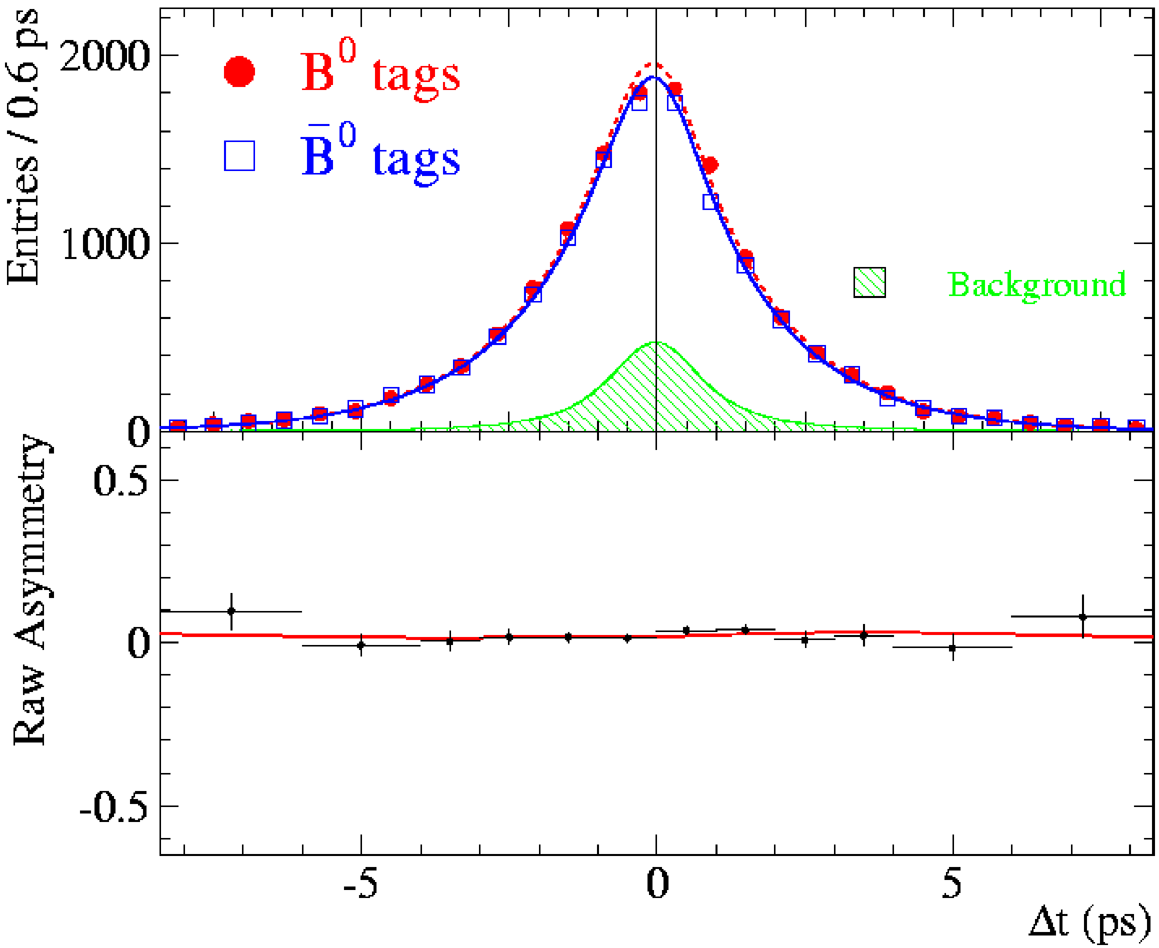
$\sin 2\beta = 0.79 \pm 0.11$

220 lepton-tagged η_f = -1 events

98% purity
3.3% mistag rate
20% better Δt resolution



Check "null" Control Sample at BABAR



Input B_{flav} sample to *CP* fit

No asymmetry expected

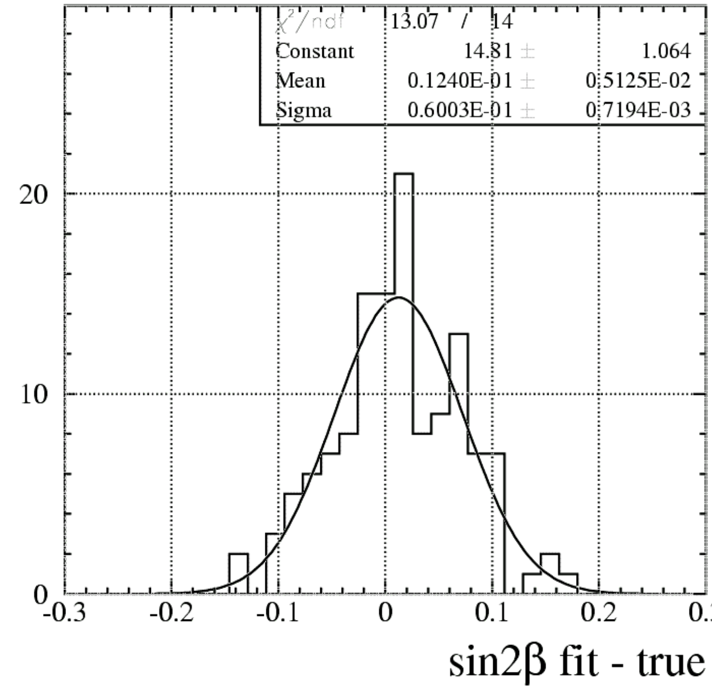
Sample	*"sin2β"*
B_{flav}	*0.021±0.022*
B^+	*0.017±0.025*

Systematic Errors on sin2β from BABAR

	$\sigma[\sin 2\beta]$
Description of background events	**0.017**
CP content of background components	
Background shape uncertainties, peaking component	
Composition and CP content of $J/\psi K_L$ background	**0.015**
Δt resolution and detector effects	**0.017**
Silicon detector residual misalignment	
Δt resolution model (Gexp vs 3G, B_{flav} vs B_{CP})	
Mistag differences between B_{CP} and B_{flav} samples (MC)	**0.012**
Fit bias correction and MC statistics	**0.010**
Fixed lifetime and oscillation frequency	**0.005**
Total	**0.033**

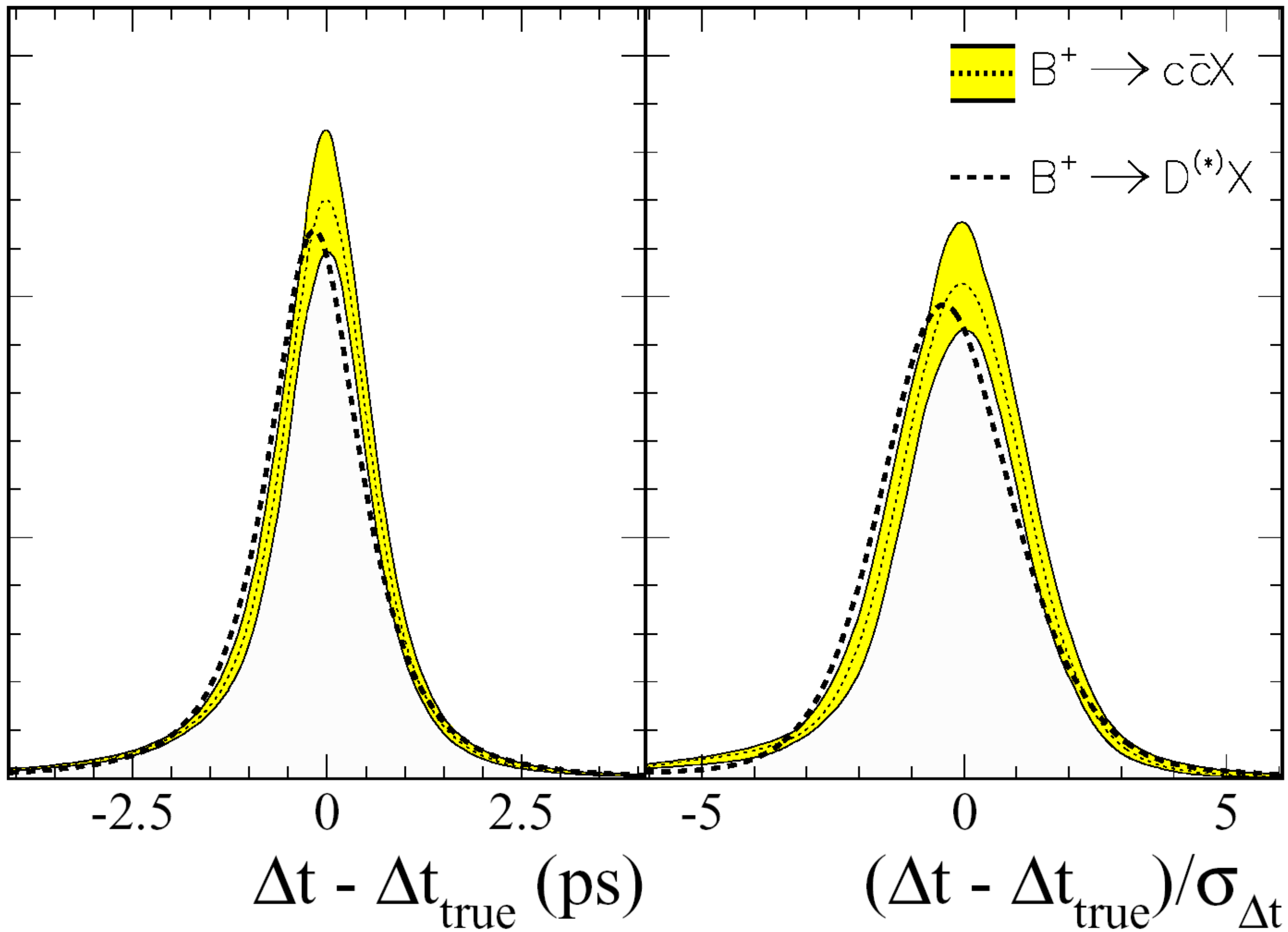
Monte Carlo Correction

- ***Potential bias on sin2β evaluated by fitting full MC in 2 ways:***
  - Fitting data-sized signal MC samples with mistag fractions and Δt resolution fixed to the MC truth values (see plot)
    - Average bias = +0.012 $\pm$ 0.005
  - Same as above except mistag fractions and Δt resolution from B_{reco} MC
    - Average bias = +0.014 $\pm$ 0.005

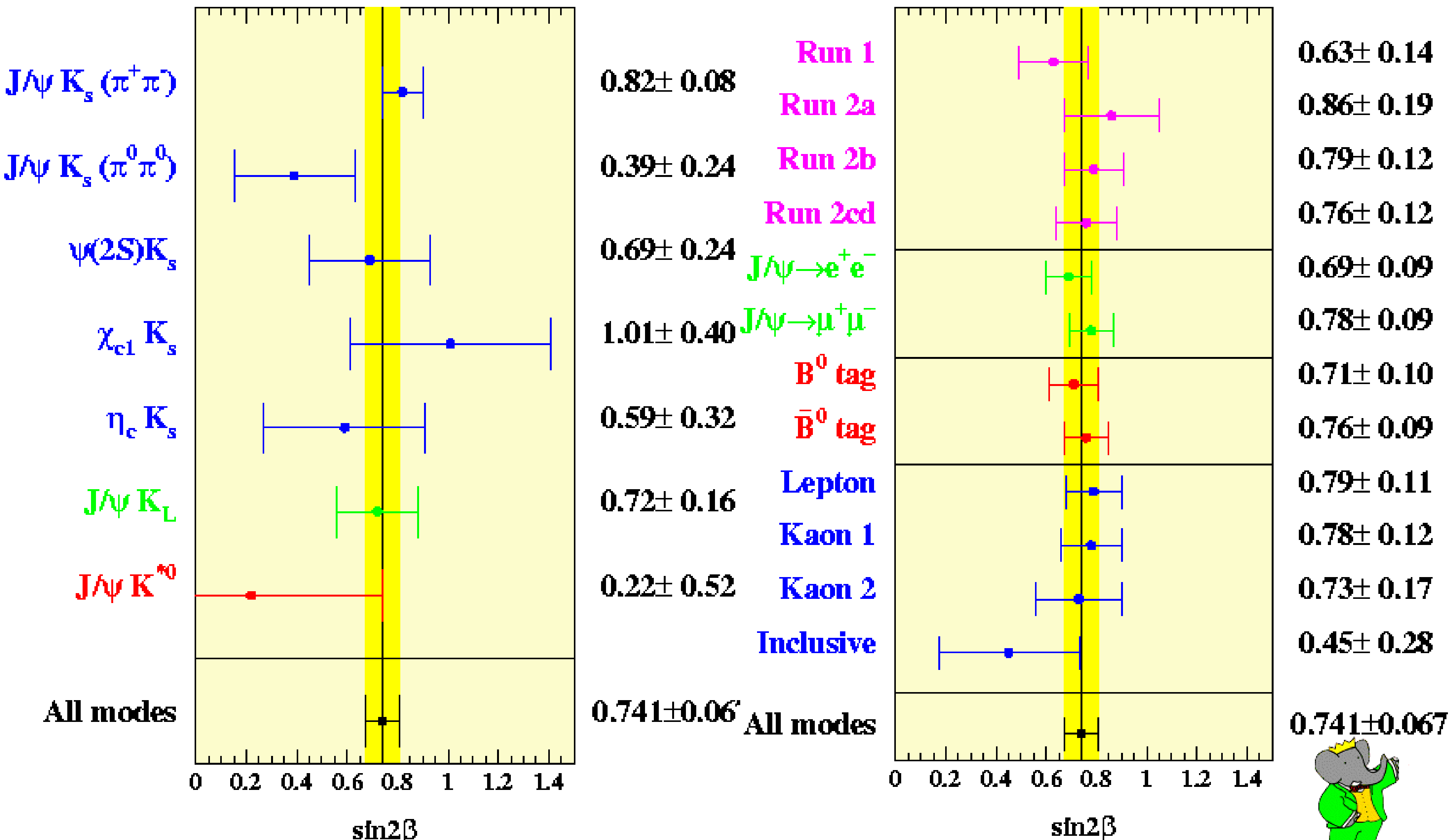


- ***One possible source of bias comes from neglecting the known correlation between the mistag fractions and $\sigma(\Delta t)$***
  - Estimates from toy and full MC indicate a bias at the level of +0.004
- ***We correct the fitted sin2β by subtracting 0.014 and assign a systematic error of 0.010 to this correction***

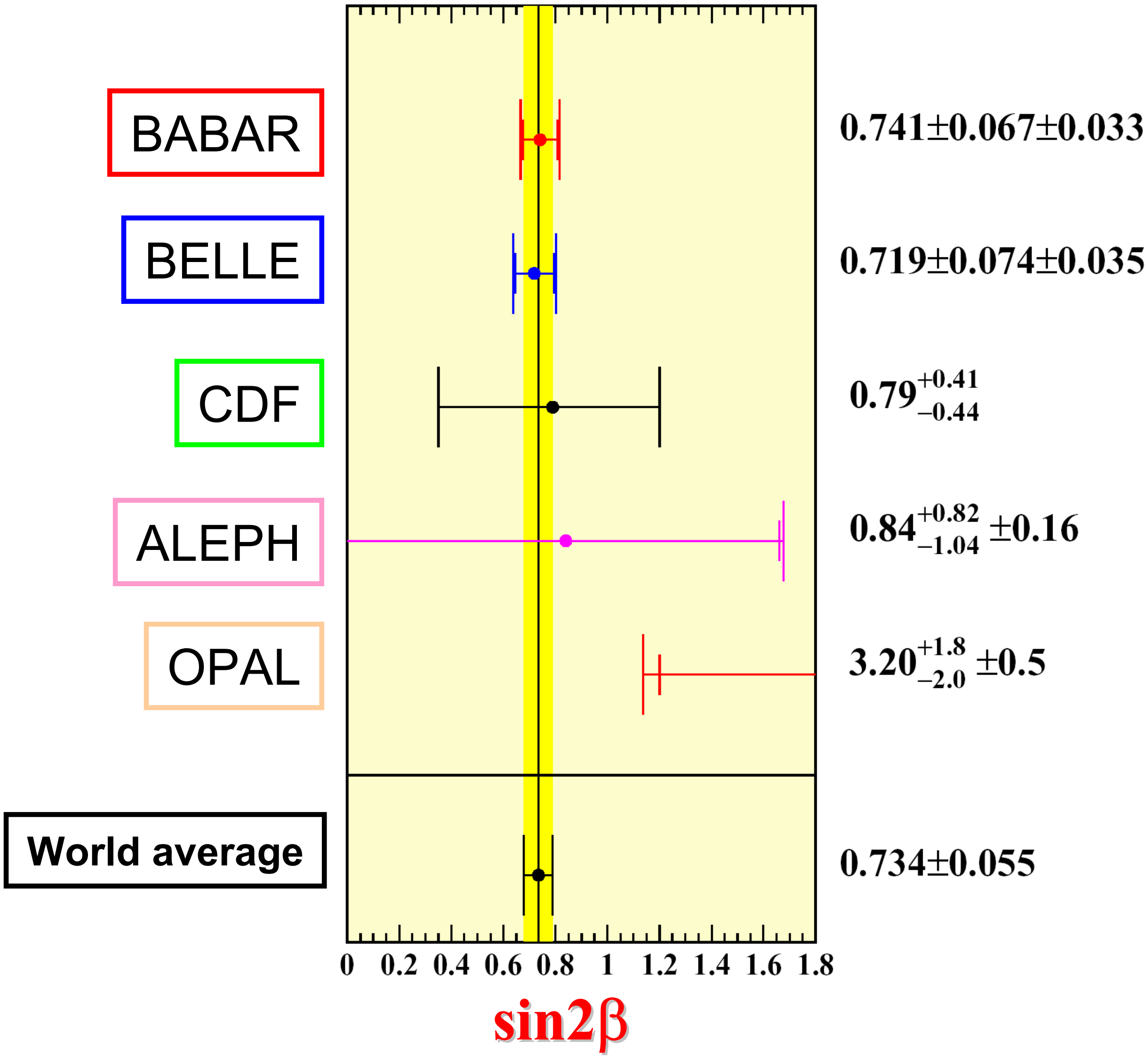
Comparison of Resolution Functions



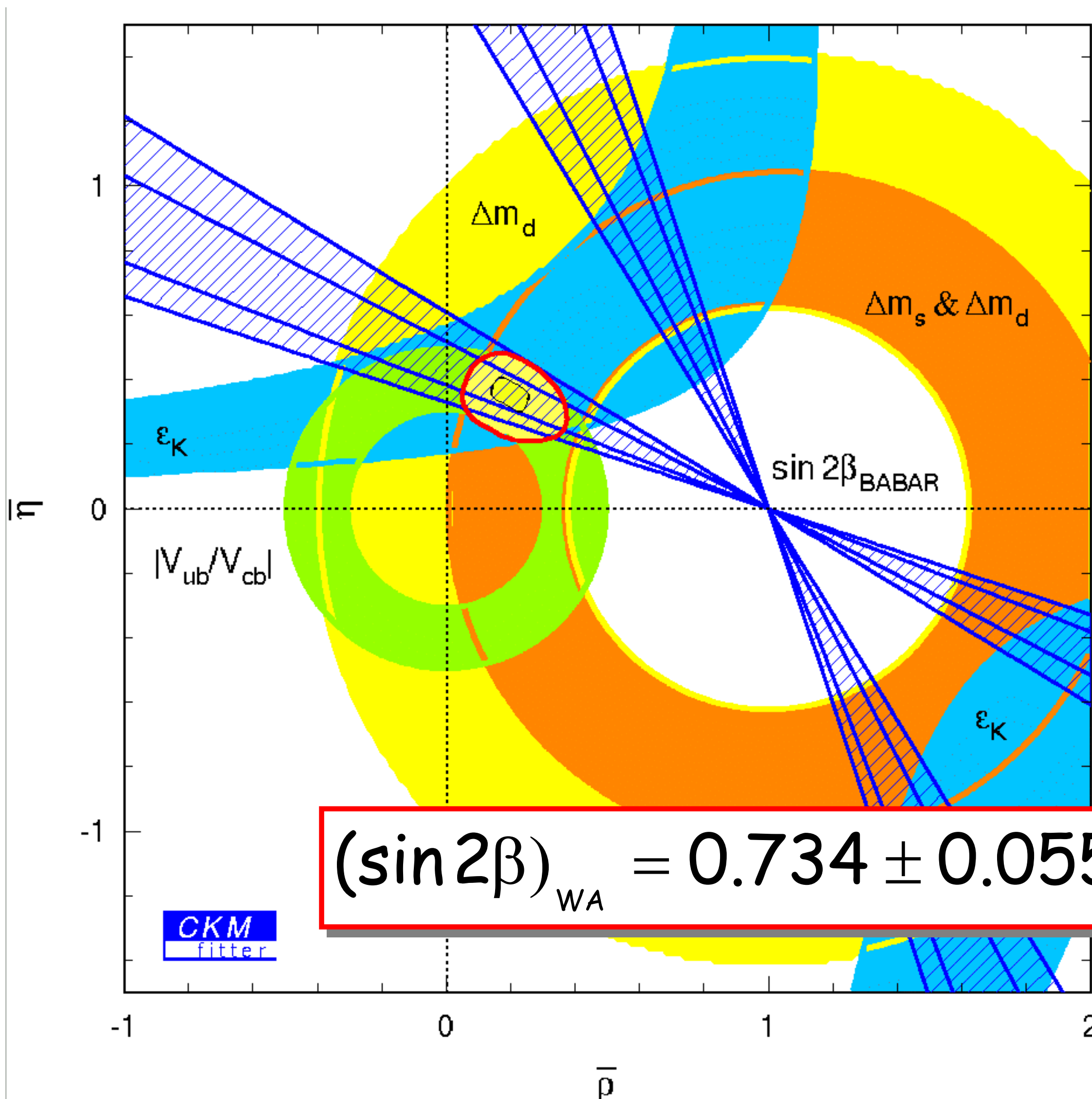
Subsample Checks



World Average



Standard Model Constraints



$$(\sin 2\beta)_{WA} = 0.734 \pm 0.055 \ \text{(stat+syst)}$$

Summary of sin2β from $c\bar{c}s$ modes

- *Precision measurements of sin2β from charmonium modes now available*

sin2β = 0.741 ± 0.067 (stat) ± 0.033 (syst)

BABAR-PUB-02/008, hep-ex/0207042, submitted to PRL

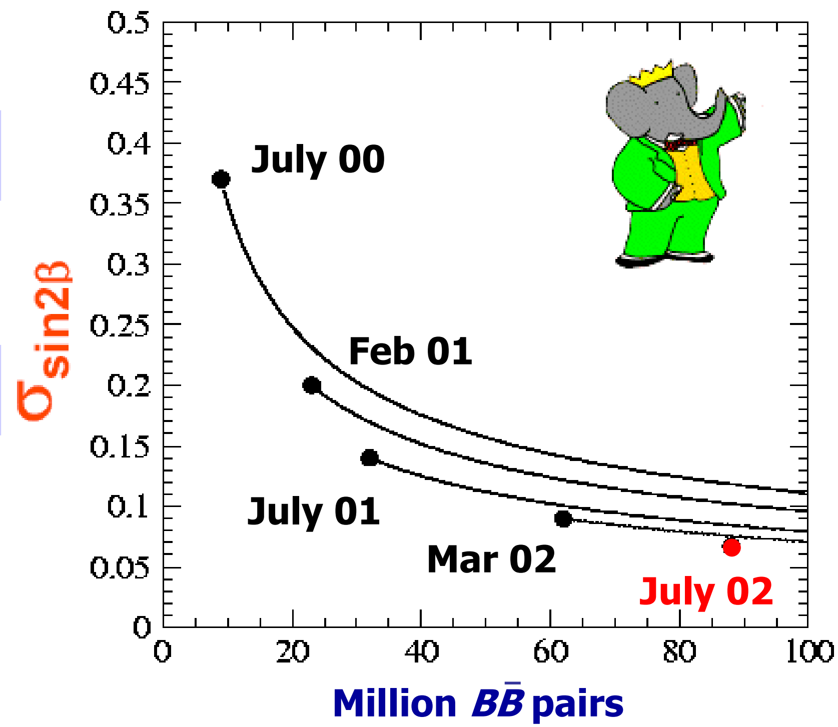
sin2β = 0.719 ± 0.074 (stat) ± 0.035 (syst)

BELLE-CONF-0201, hep-ex/0207098, submitted to ICHEP2002

- *World average*

sin2β = 0.734 ± 0.055 (stat+sys)

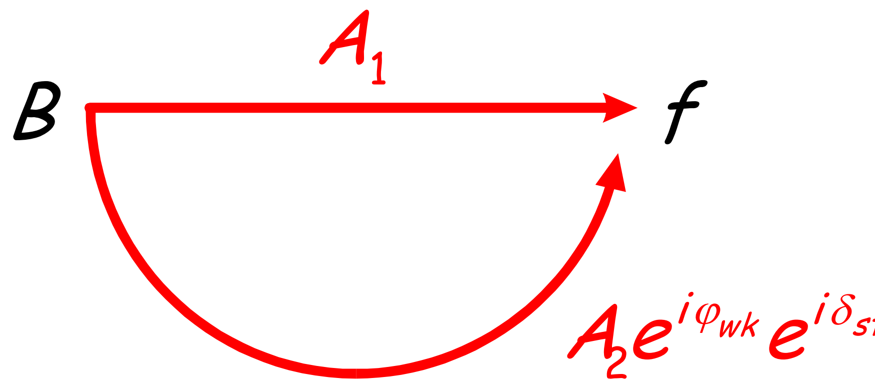
Results have been improving by more than just luminosity gain

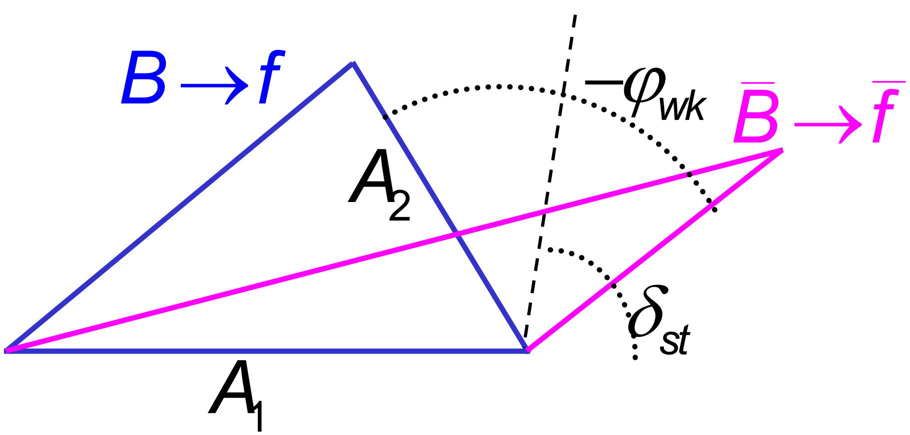


The Standard Model remains unscathed, but the high statistics future of *B* Factories will provide further opportunities to challenge the theory

CP Violation in the B System

> ➢ **CPV through interference of decay amplitudes**





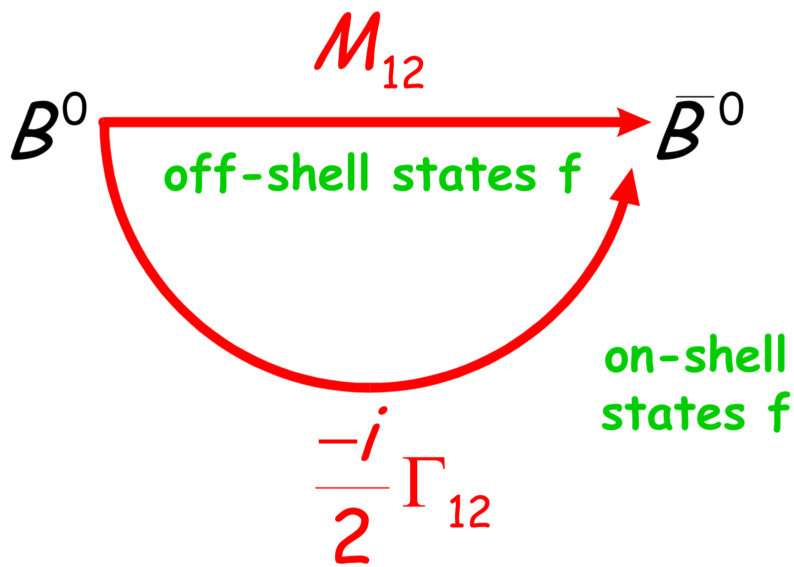
$$\Gamma(B \rightarrow f) = \left| A_1 + A_2 e^{i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

$$\Gamma(\bar{B} \rightarrow \bar{f}) = \left| A_1 + A_2 e^{-i\varphi_{wk}} e^{i\delta_{st}} \right|^2$$

$\Gamma(B \rightarrow f) \neq \Gamma(\bar{B} \rightarrow \bar{f})$
for $\varphi_{wk} \neq 0$ and $\delta_{st} \neq 0$

CP Violation in the B System

- CPV through interference of decay amplitudes
- CPV through interference of mixing diagram



Expected to be very small

Formalism for CP Violation in Mixing

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

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

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

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

Time-dependent CP Asymmetry:

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

constant with time

In the B System, $\Delta m_d = m_{B_H} - m_{B_L} \gg \Delta\Gamma_d \Rightarrow \varepsilon_d \sim$ purely imaginary

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

See for instance Bañuls & Bernabéu hep-ph/0005323

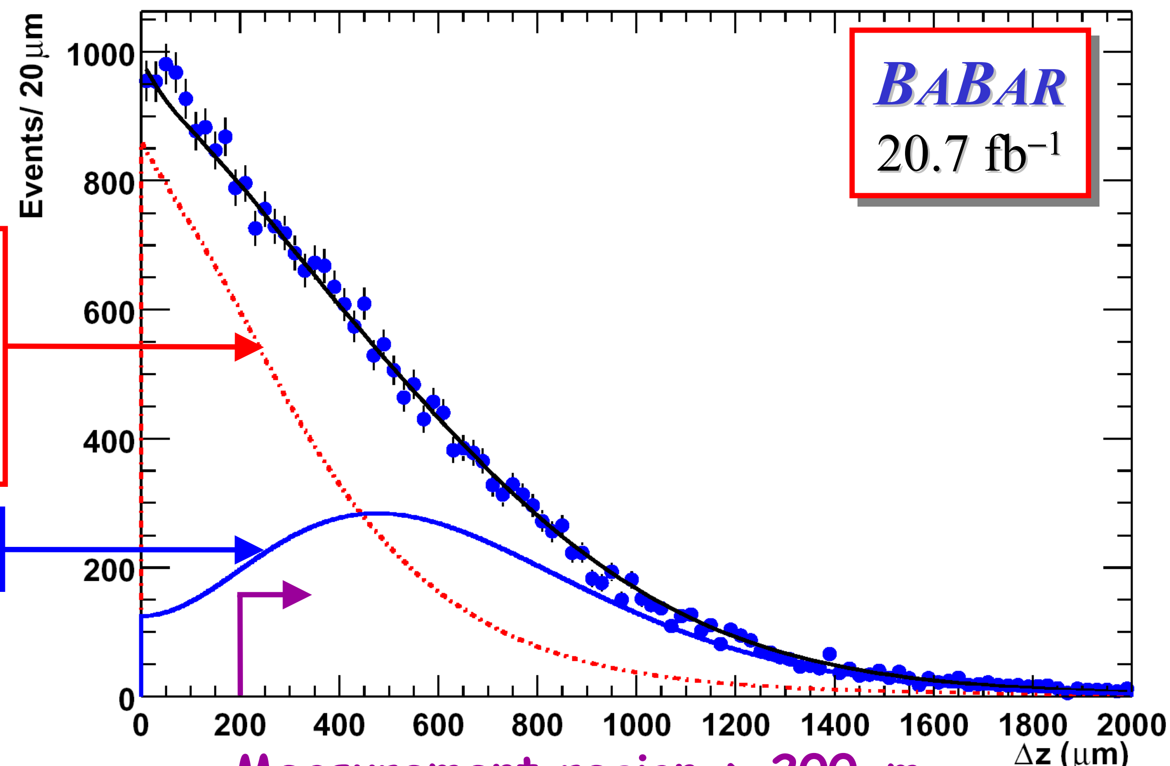
Characterizing the Dilepton Sample

Search for asymmetry in same-sign dilepton sample containing 20381 events

$$A_T^{obs}(\Delta t) = \frac{N(\ell^+\ell^+,\Delta t) - N(\ell^-\ell^-,\Delta t)}{N(\ell^+\ell^+,\Delta t) + N(\ell^-\ell^-,\Delta t)} = A_T \times \frac{S(\Delta t)}{S(\Delta t) + B(\Delta t)}$$

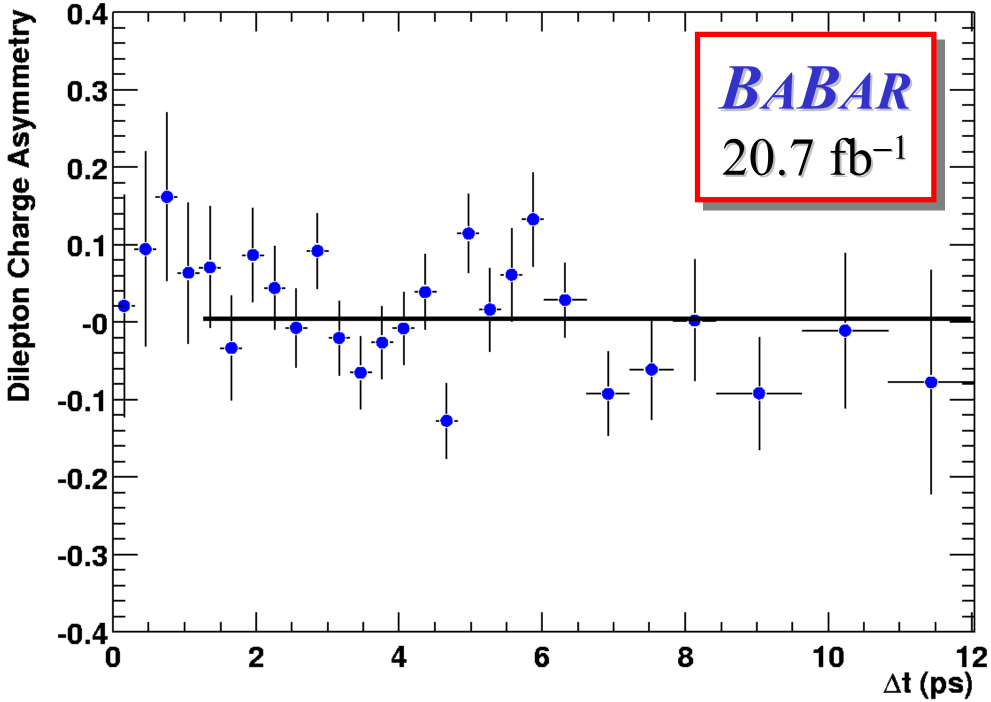
Sample backgrounds $B(\Delta t)$:
4.3% continuum
24% direct+cascade
12% direct+fake

$B^0B^0, \bar{B}^0\bar{B}^0$ signal $S(\Delta t)$



Measurement region > 200µm

Determination of A_T



Find: $+0.005 \pm 0.012_{(stat)} \pm 0.014_{(syst)}$

Conclude: $\mathrm{Re}(\varepsilon_{B_d})/(1+|\varepsilon_{B_d}|^2) =$

$+0.0012 \pm 0.0029_{(stat)} \pm 0.0036_{(syst)}$

$|q/p| = 0.998 \pm 0.006_{(stat)} \pm 0.007_{(syst)}$

BABAR PRL **88**, 231801 (2002)

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

To a good approximation:

$$|q/p| = 1 \text{ and } q/p = e^{-2i\varphi_M} = -|M_{12}|/M_{12}$$

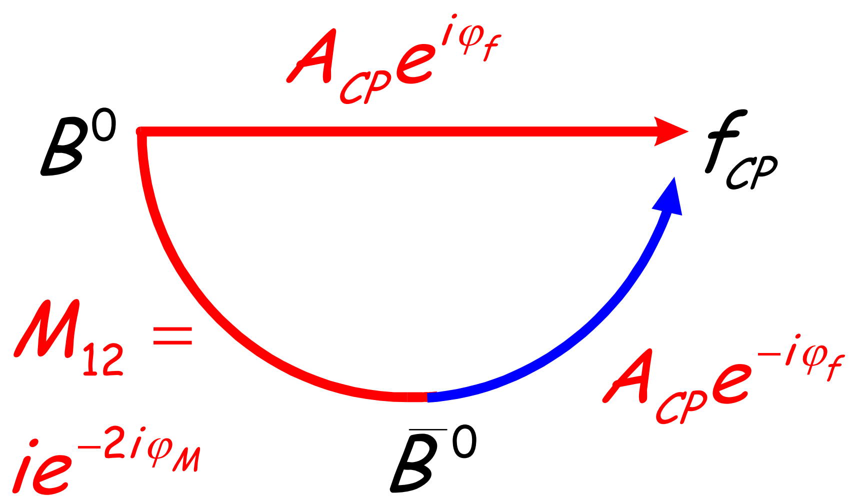
Systematic Errors

Source	$\sigma(A_T)$ [%]	Sample
Detection asymmetry for electrons	0.5	Direct electrons in semileptonic B decays
Detection asymmetry for electrons	0.6	Direct muons in semileptonic B decays
Non-$B\overline{B}$ background asymmetry	0.7	Off-resonance data
$B\overline{B}$ background asymmetry	0.9	* On-resonance data with $\Delta z < 100\mu m$
Total	1.4	
Statistical Error	1.2	

*Would be zero if one assumed *CP* invariance in cascade decays

CP Violation in the B System

- CPV through interference of decay amplitudes
- CPV through interference of mixing diagram
- CPV through interference between mixing and decay amplitudes



Directly related to CKM angles for single decay amplitude

CP Formalism Revisited

For B^0 decays, allowing for more than one amplitude contributing to the decay to f_{CP}

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

Amplitude ratio

CP eigenvalue

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

Full time-dependent distributions and *CP* asymmetry:

$$f_{CP,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left(1 \pm S_{f_{CP}} \sin \Delta m_d \Delta t \mp C_{f_{CP}} \cos \Delta m_d \Delta t \right) \right\}$$

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

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

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

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

Search for Direct CP in Golden Sample

Redo fits tagged time distributions of *CP* sample with sine and cosine terms (assuming $\Delta\Gamma = 0$)

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

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

$$BABAR: \quad |\lambda_{c\bar{c}s}| = 0.948 \pm 0.051_{(stat)} \pm 0.017_{(syst)}$$

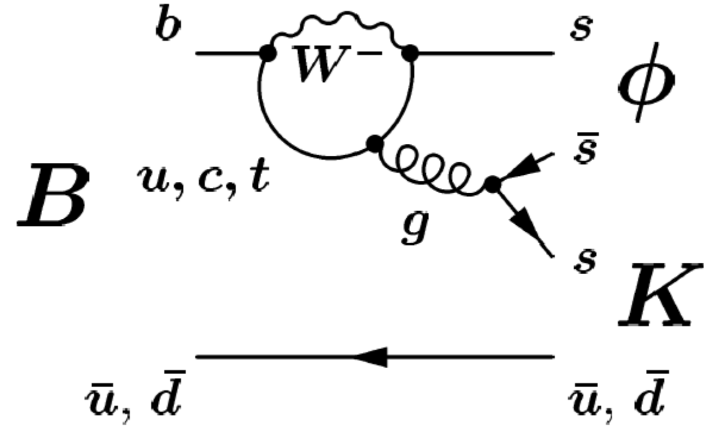
$$Belle: \quad |\lambda_{c\bar{c}s}| = 0.950 \pm 0.049_{(stat)} \pm 0.026_{(syst)}$$

No evidence of direct CP violation due to decay amplitude interference

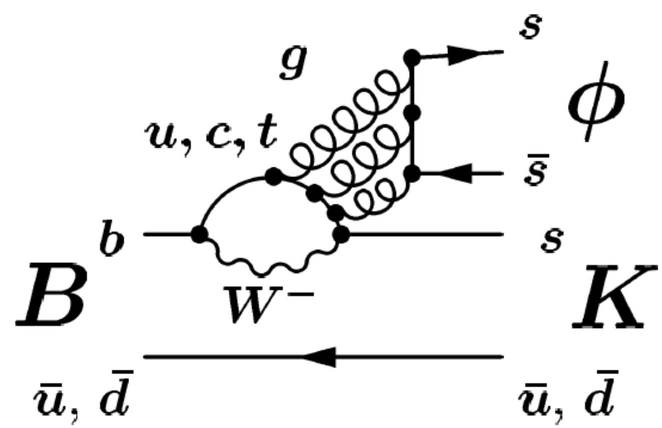
Coefficient of the "sine" term unchanged

Other Modes for sin2β

- **Provide an independent measurement of CP violation**
- **Some possible $b \to s\bar{s}s$ modes**
  - ϕK_S is $CP = -1$ with $\mathrm{Im}\lambda = -\sin 2\beta$
    - *Sensitive to new physics in $b \to s$ loop diagram*
    - Pure $b \to s$ penguin process?
  - *Other examples*
    - *$\eta' K_S$ is $CP=+1$*
    - *$K^+K^-K_S$ appears to be mostly $CP=+1$ according to Belle*
- **Possible double-charm modes**
  - $B \to D^{*+}D^{*-}$ or $B \to D^* D$ channels
    - No K_S mixing, but penguins?
- **Other charmonium modes**



(a)

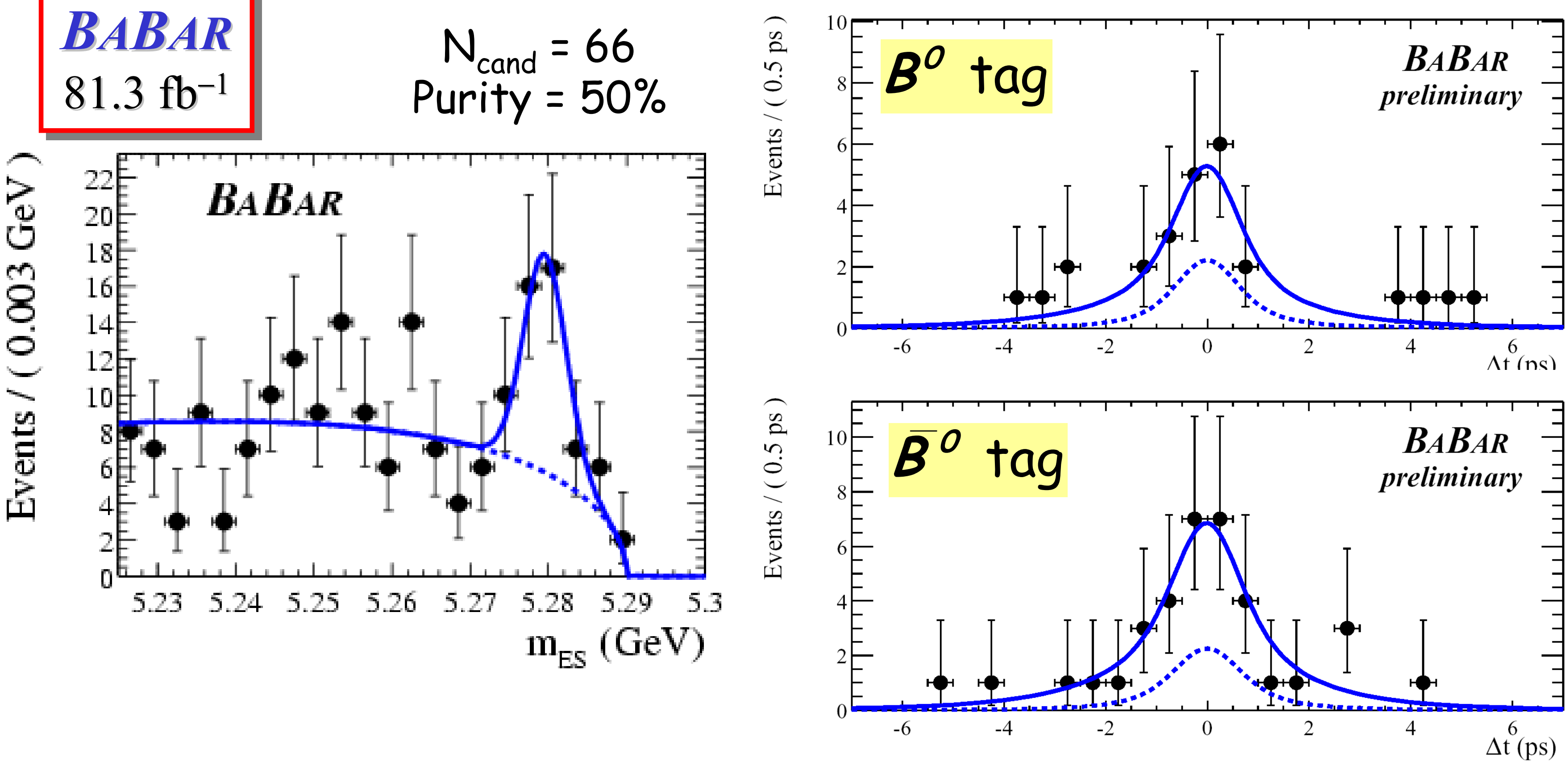


(b)

BABAR Results for ϕK_s

BABAR
81.3 fb^{-1}

$N_{cand} = 66$
Purity = 50%



If pure penguin: $S_{\phi K_s} = \sin 2\beta$

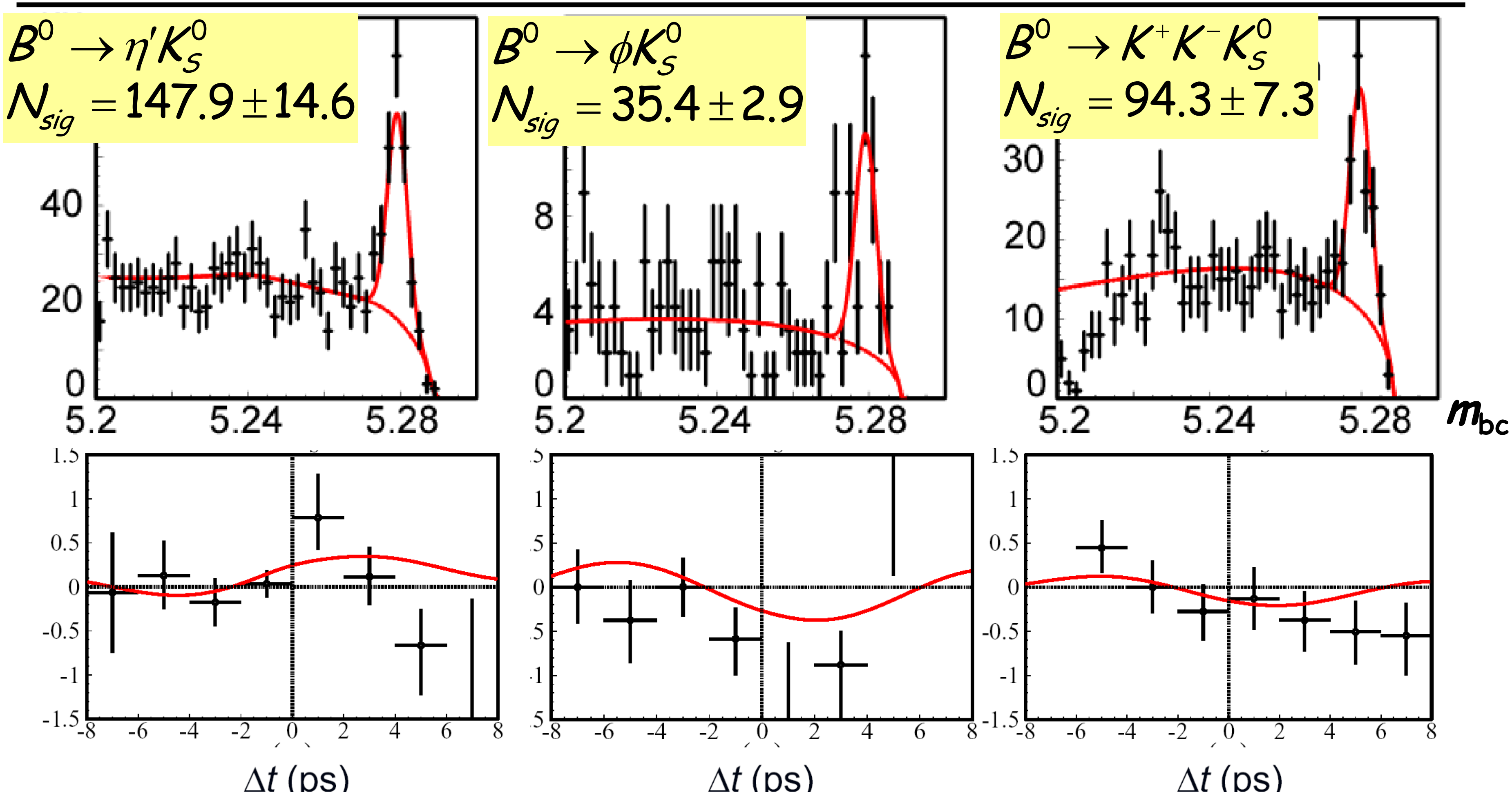
BABAR-CONF-02/016, hep-ex/0207070

Fix $|\lambda_{\phi K_s}| = 1$

$S_{\phi K_s} = -0.19^{+0.52}_{-0.50}\,(stat) \pm 0.09\,(syst)$

Belle Results for $b \to sss$

BELLE-CONF-0225

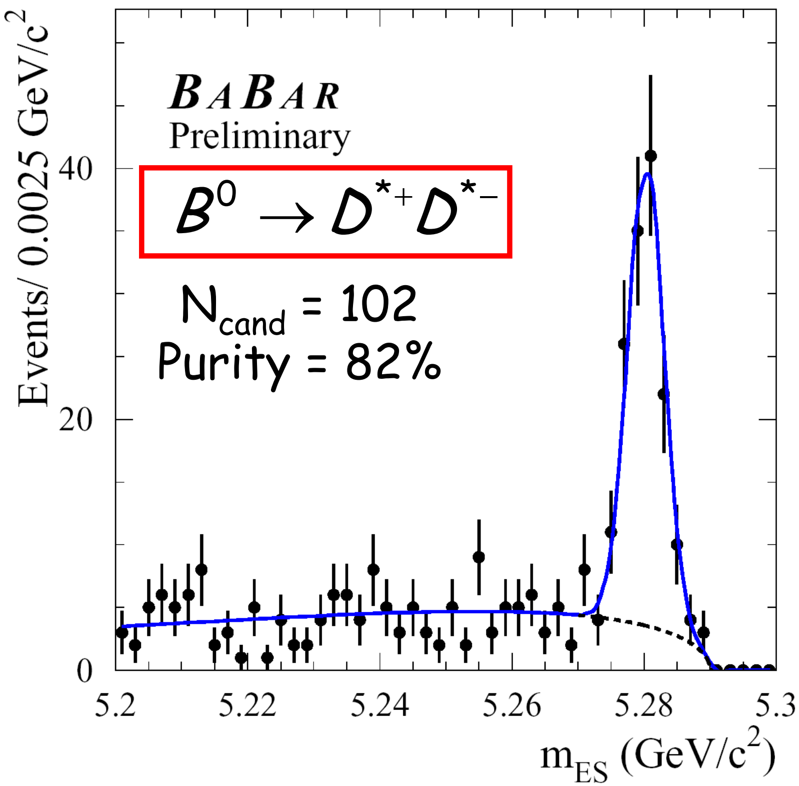


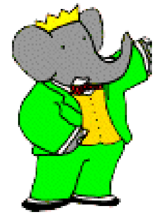
$-S_{\eta' K} = +0.76 \pm 0.36^{+0.05}_{-0.06}$ $S_{\phi K_S} = -0.73 \pm 0.64 \pm 0.18$ $-S_{\eta' K} = +0.52 \pm 0.46 \pm 0.11^{+0.27}_{-0.03}$

$C_{\eta' K} = -0.26 \pm 0.22 \pm 0.03$ $C_{\phi K_S} = +0.56 \pm 0.41 \pm 0.12$ $C_{\eta' K} = +0.42 \pm 0.36 \pm 0.09^{+0.03}_{-0.22}$

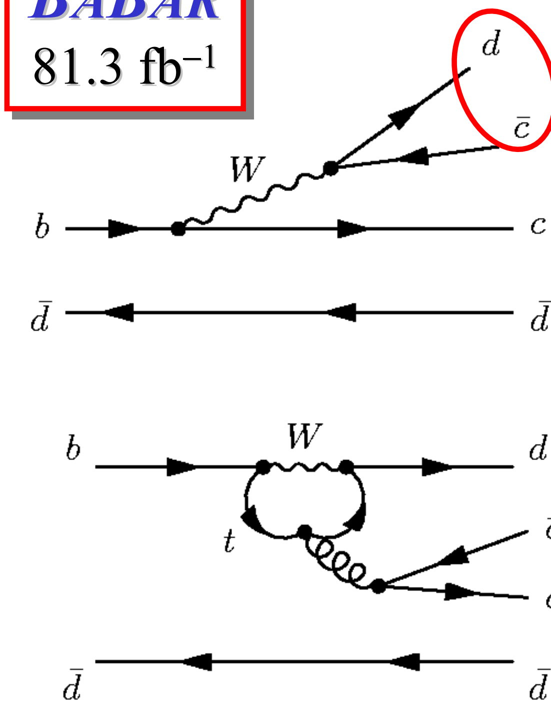
More CP channels: $B \to D^{*+}D^{*-}$

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





BABAR
81.3 fb^{-1}



Cabibbo suppressed

Tree

Penguin

$\mathrm{Im}\,\lambda_{c\bar{c}d} \sim \sin 2\beta$

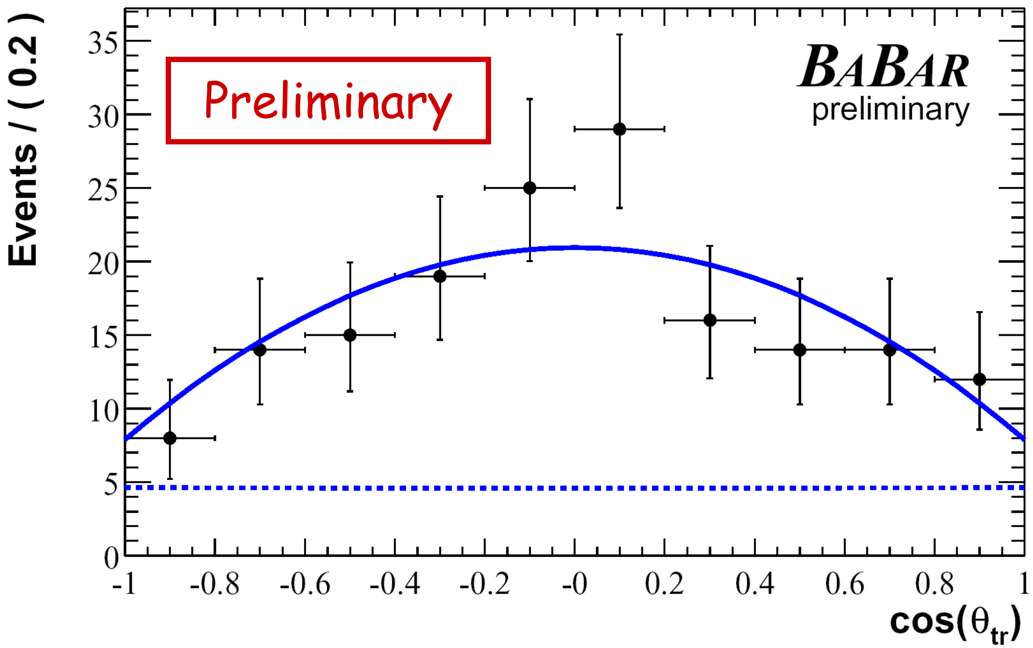
BABAR-CONF-02/014, hep-ex/0207072

- No K_S mixing contribution
- Potential for significant Penguin contamination

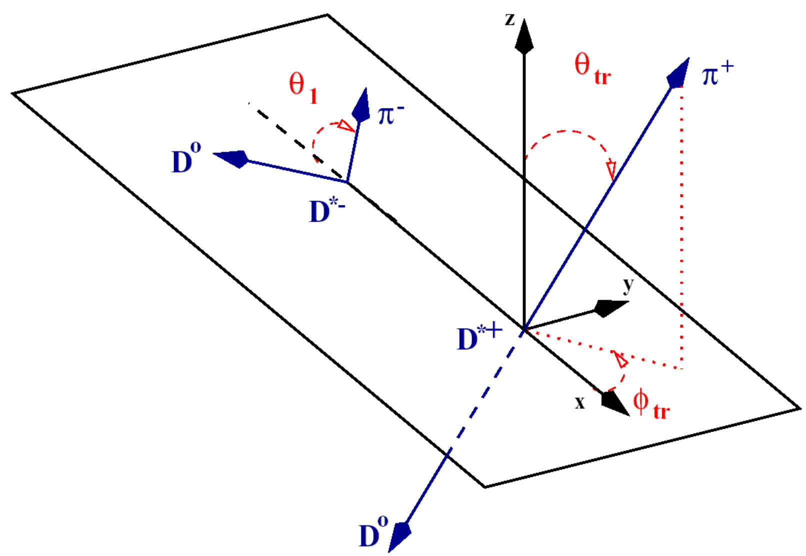
CP Composition of $B^0 \to D^{*+}D^{*-}$

- *Measure small CP odd fraction (corrected for acceptance):*

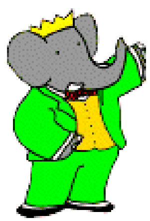
$$R_\perp = 0.07 \pm 0.06\ (\text{stat}) \pm 0.03\ (\text{syst})$$



$P \to VV$: mixture of *CP* states



$$\frac{d\Gamma}{\Gamma d\cos\vartheta_{tr}} = \frac{3}{4}(1-R_\perp)\sin^2\vartheta_{tr} + \frac{3}{2}R_\perp\cos^2\vartheta_{tr}$$



BABAR
$81.3\ fb^{-1}$

The PDF

- *The decay rate $f_+(f_-)$ for a B tagged as a $\overline{B^0}$ (B^0)*

$$f_\pm(\Delta t) = \frac{\Gamma}{2} e^{-\Gamma|\Delta t|}\left\{O \mp \left[S \sin \Delta m_d \Delta t + C \cos \Delta m_d \Delta t\right]\right\}$$

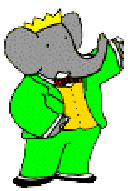
$$O = \frac{3}{4}(1+K)\sin^2\theta_{tr} + \frac{3}{2}(1-K)\cos^2\theta_{tr}$$

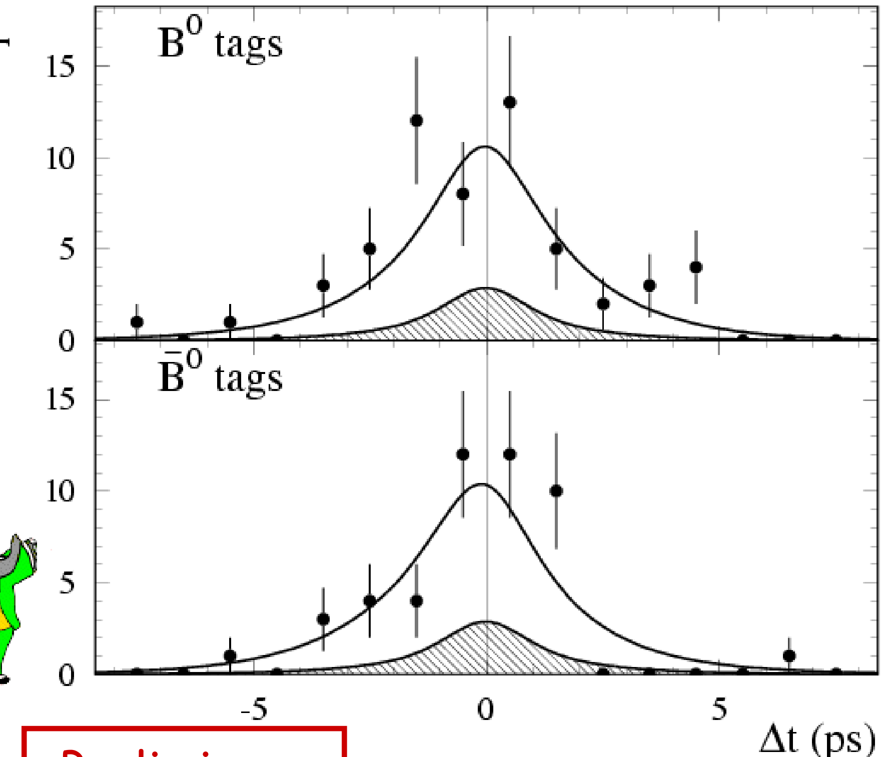
$$C = \frac{3}{4}(1+K)\sin^2\theta_{tr}\frac{1-|\lambda_+|^2}{1+|\lambda_+|^2} + \frac{3}{2}(1-K)\cos^2\theta_{tr}\frac{1-|\lambda_\perp|^2}{1+|\lambda_\perp|^2}$$

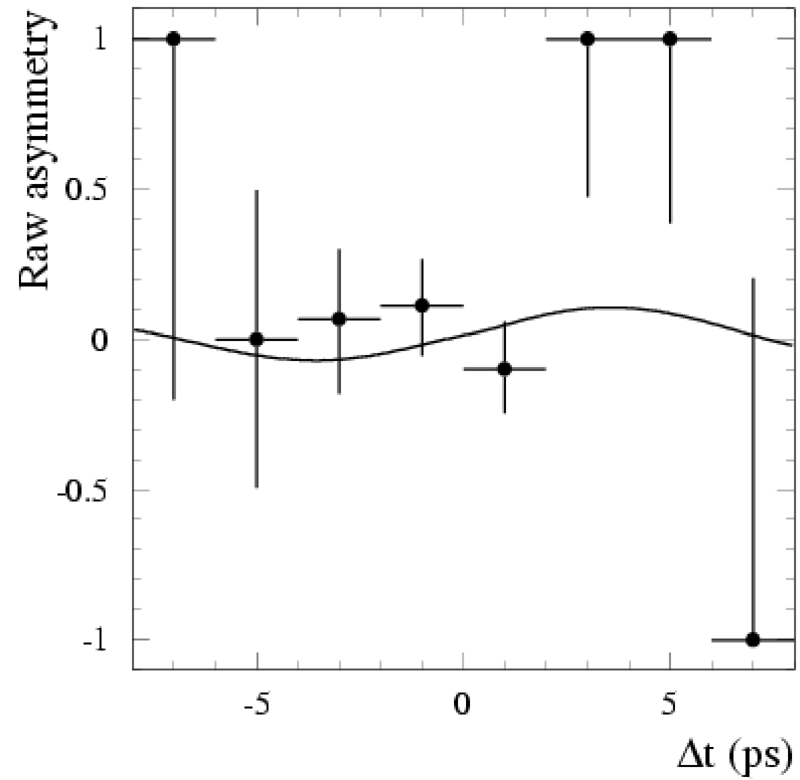
$$S = -\left[\frac{3}{4}(1+K)\sin^2\theta_{tr}\frac{2\,\mathrm{Im}(\lambda_+)}{1+|\lambda_+|^2} - \frac{3}{2}(1-K)\cos^2\theta_{tr}\frac{2\,\mathrm{Im}(\lambda_\perp)}{1+|\lambda_\perp|^2}\right]$$

3 parameters: $|\lambda_+|, \mathrm{Im}\,\lambda_+, |\lambda_\perp| = 1, \mathrm{Im}\,\lambda_\perp = -0.741, K$
since *CP*-odd component small

CP Asymmetry Fit Results







Preliminary

$$|\lambda_+| = 0.98 \pm 0.25_{(stat)} \pm 0.09_{(syst)}$$

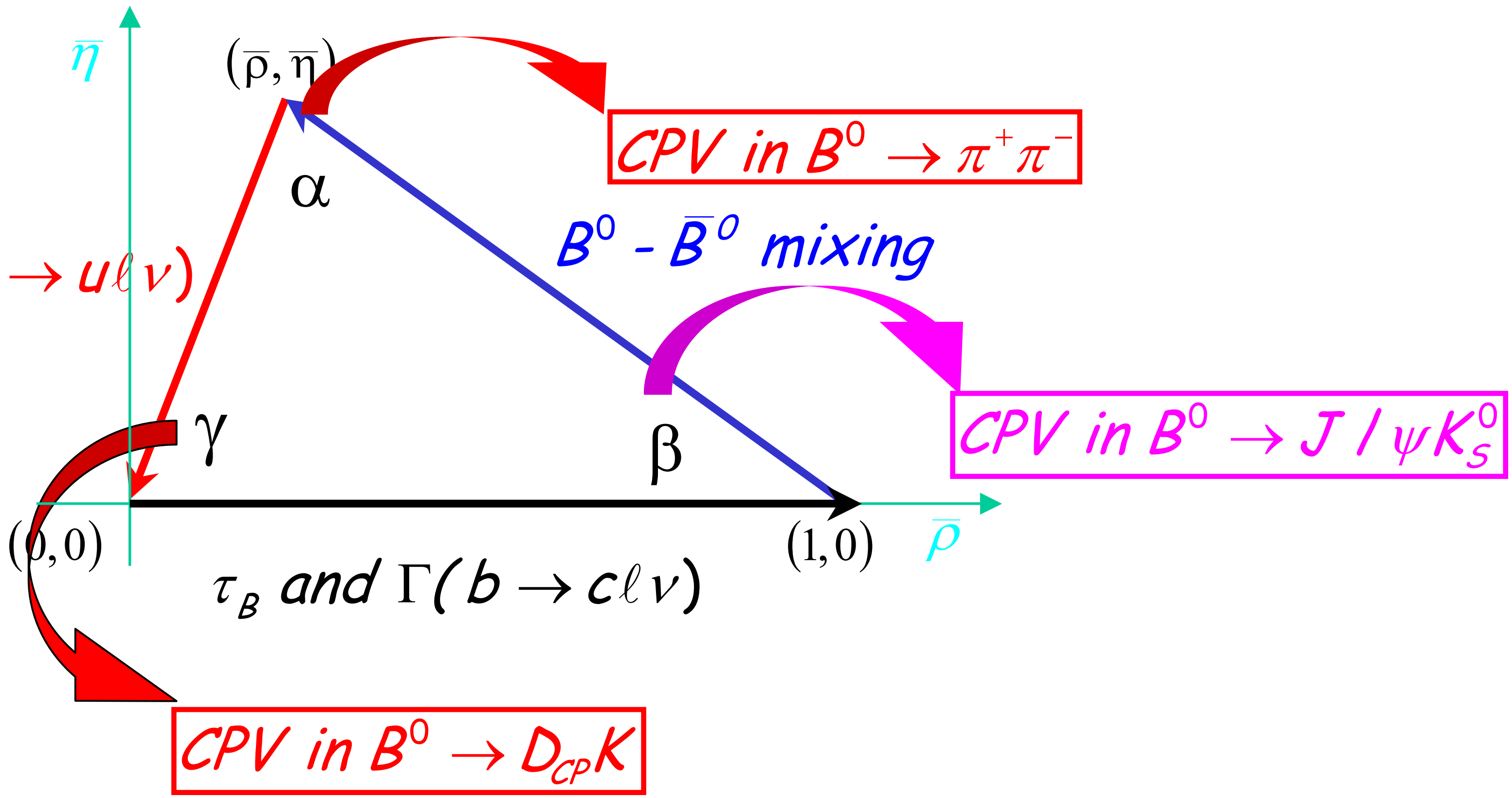
$$\mathrm{Im}\,\lambda_+ = 0.31 \pm 0.43_{(stat)} \pm 0.10_{(syst)}$$

If Penguins are negligible

$|\lambda_+| = 1$ and $\mathrm{Im}\,\lambda_+ = -\sin 2\beta$

i.e., about 2.7σ difference

Testing the Origins of CPV



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

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

$$f_\pm(\Delta t) = \frac{\Gamma}{4} e^{-\Gamma \Delta t}[1 \pm S_{f_{CP}} \sin \Delta m_d \Delta t \mp C_{f_{CP}} \cos \Delta m_d \Delta t]$$

For single weak phase from tree diagram

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

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

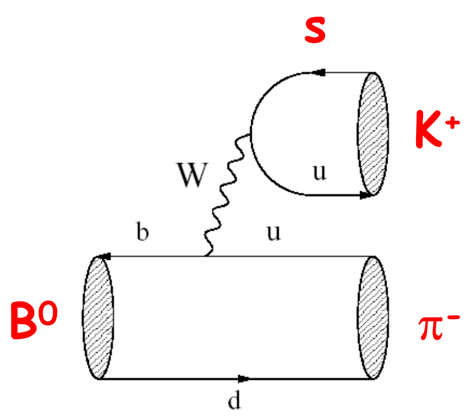
With additional weak phase from penguin diagram

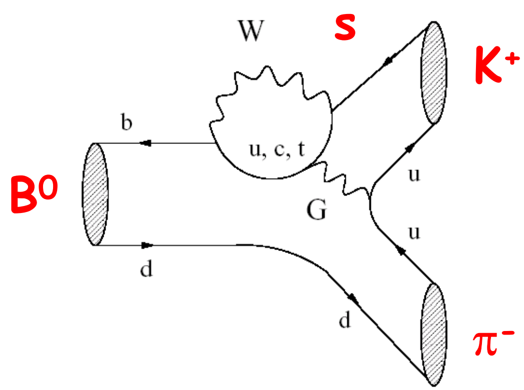
$|\lambda| \neq 1 \Rightarrow$ must fit for direct *CP*
Im $(\lambda) \neq \sin 2\alpha \Rightarrow$ need to relate asymmetry to α

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

Competing Amplitudes for $B \rightarrow h^+h^-$

Tree diagrams | Penguin diagrams



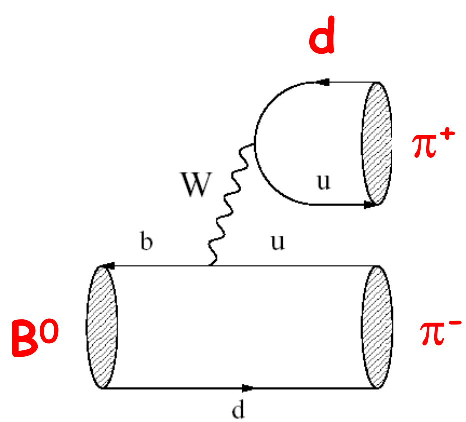


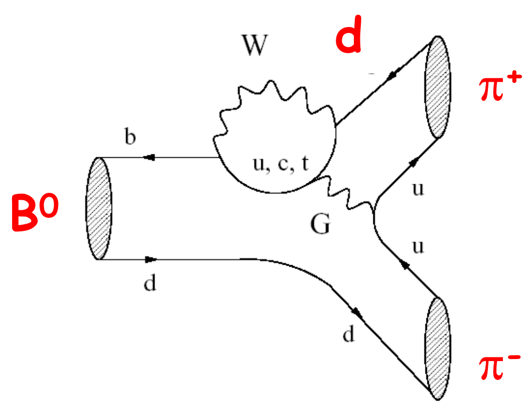
$$BF(B^0 \rightarrow K^+\pi^-) = (17.8 \pm 1.1 \pm 0.8) \times 10^{-6}$$

Penguin dominated:

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

Potential direct *CPV* and constraints on γ





$$BF(B^0 \rightarrow \pi^+\pi^-) = (5.4 \pm 0.7 \pm 0.4) \times 10^{-6}$$

|Penguin| ~ 0.3|Tree|

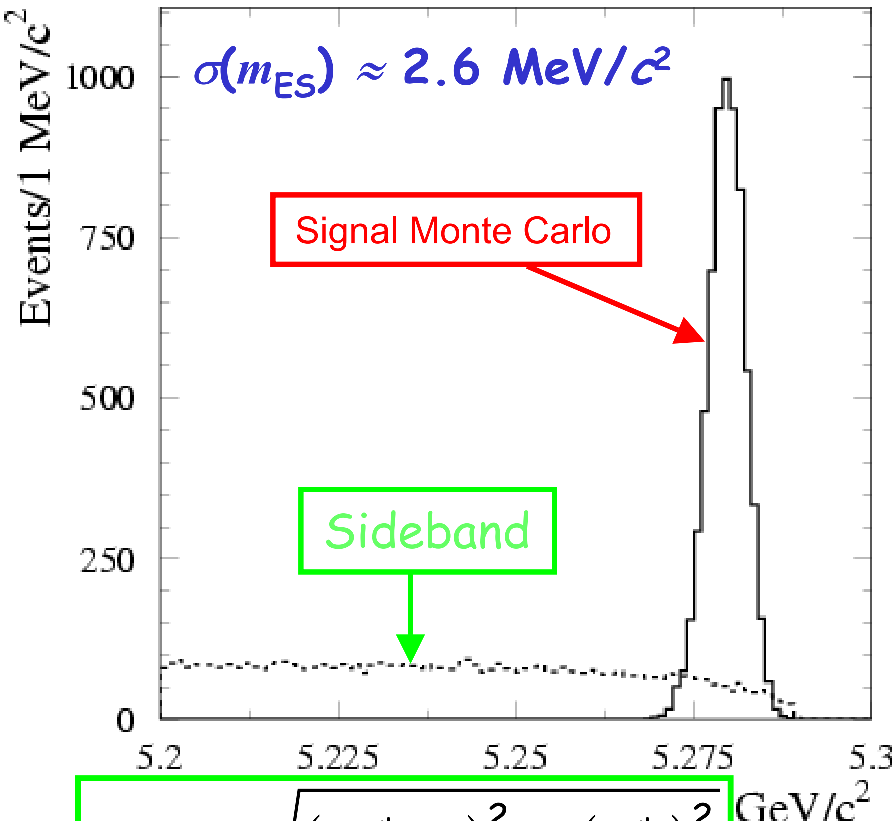
Complicates extraction of α from mixing induced *CPV*

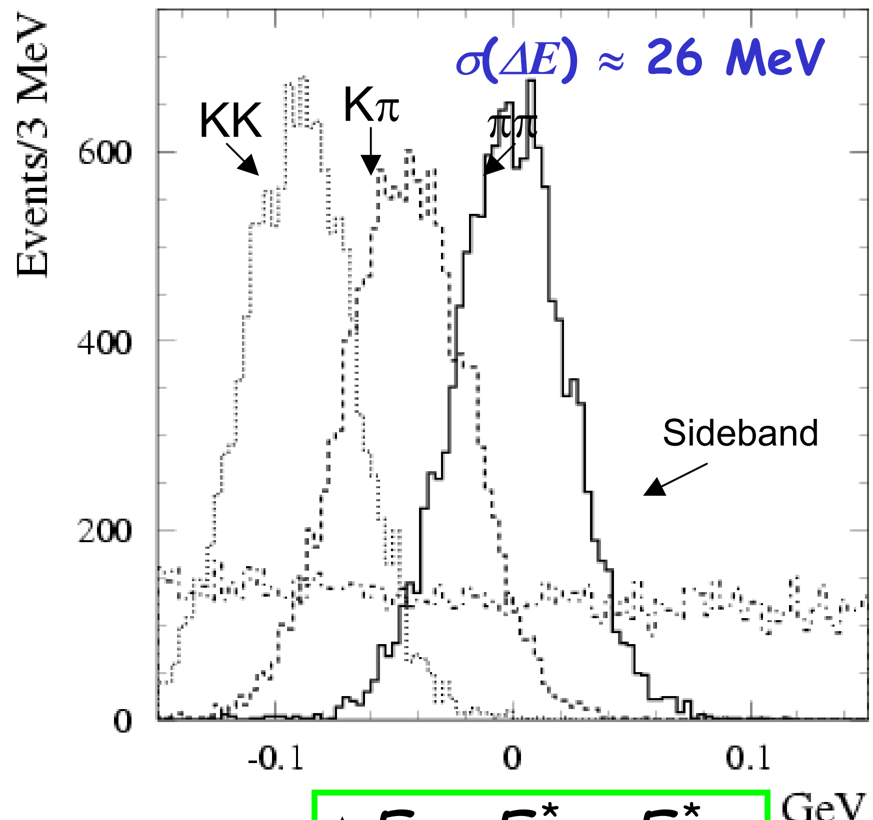
Analysis Overview

- ***Analysis issues: charmless two-body B decays***
  - Rare decays! BR ~ 10^{-5}-10^{-6} → need lots of data (*B* Factories)
  - Large background from $e^+e^- \to q\bar{q}$ → need background suppression
  - Ambiguity between π and *K* → need excellent PID (DIRC or ACC)
- ***CP analysis issues:***
  - Need to determine vertex position of both *B* mesons → standard vertex separation algorithms
  - Need to know the flavor of "other" *B* → standard tagging algorithms
- ***Analysis proceeds at BABAR in two steps:***
  - Use kinematic, topological, and PID information in a global ML fit to extract yields for $\pi\pi$, $K\pi$, and *KK* decays, as well as the asymmetry $A_{K\pi}$
    - Exclude vertexing & tagging information to avoid systematic error
  - Add vertexing and tagging information to extract $S_{\pi\pi}$ and $C_{\pi\pi}$
    - Yields and $A_{K\pi}$ fixed to result of the first fit

Kinematics

Pion mass assumed for all tracks, so shift in ΔE for $K\pi$ and KK decays



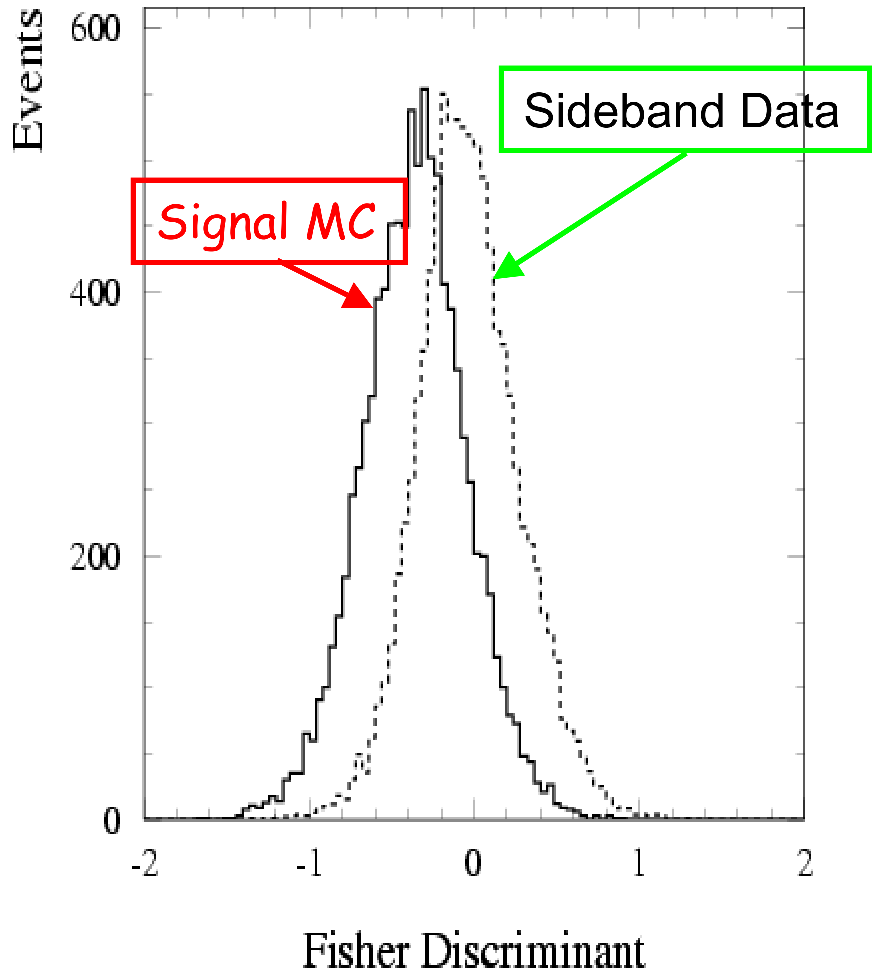


$$m_{ES} = \sqrt{\left(E^*_{beam}\right)^2 - \left(\mathbf{p}^*_B\right)^2}$$

$$\Delta E = E^*_B - E^*_{beam}$$

Background Suppression

- *Background is due to light-quark production $e^+e^- \to q\bar{q}$ (q=u,d,s,c)*
  - Jetty topology, distinct from spherical B decays
- *Cut on angle θ_S between sphericity axes of B candidate and the remaining particles in the event:*
  - $|\cos(\theta_S)| < 0.8$, removes 83% bkg, 20% signal
- *Define Fisher discriminant F derived from momentum flow in the event*
  - Used directly in the ML fit

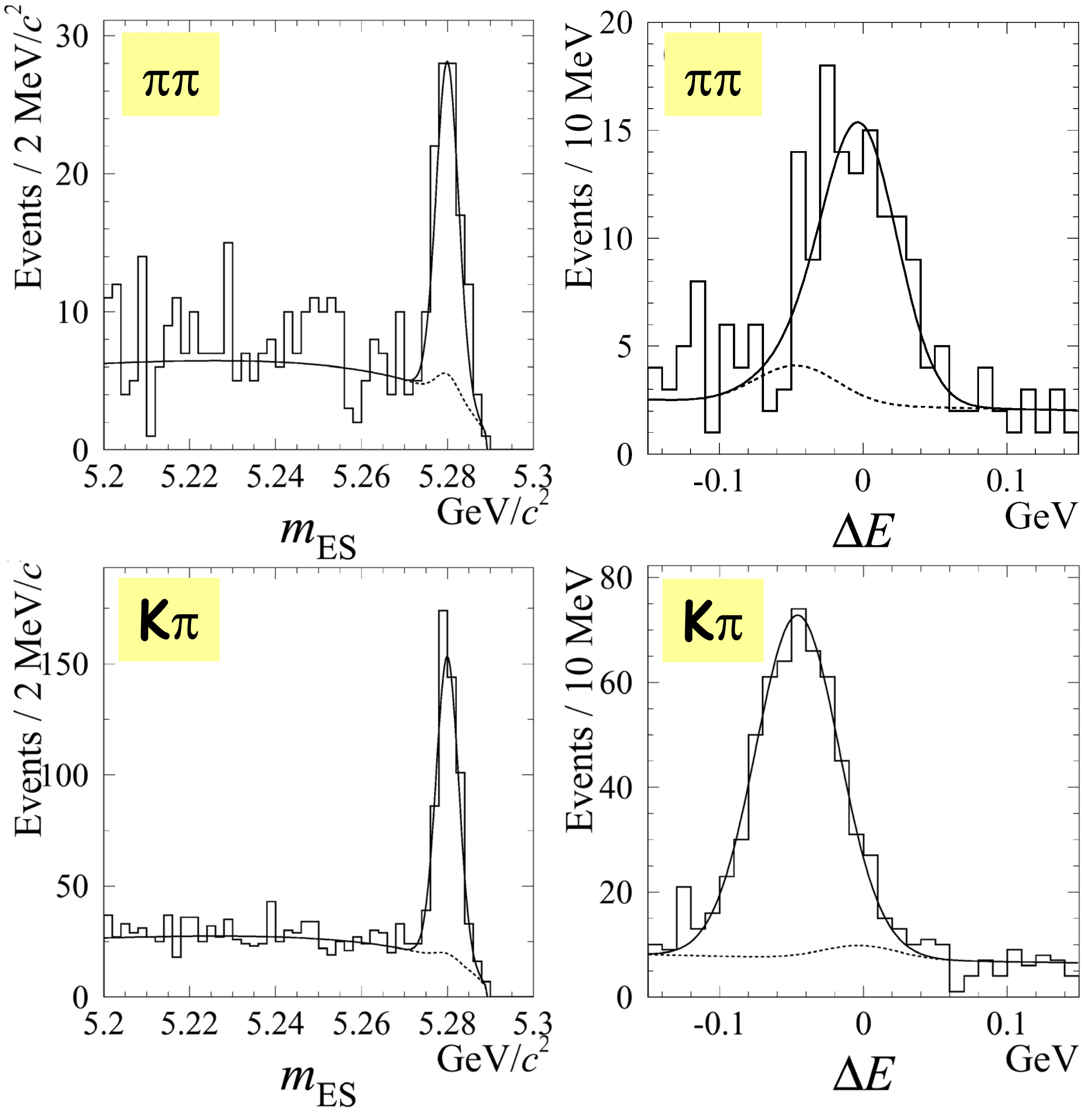


Branching Fraction Fits

Projections in m_{ES} and ΔE

26070 two-prong candidates (97% background, mostly continuum)

BF Likelihood includes PDFs for: m_{ES}, ΔE, Fisher, θ_c for + & - tracks



Proj eff: 52%

Proj eff: 79%

BABAR 81.3 fb^{-1}

Branching Fraction Results

Preliminary

Mode	Yield	BR [10^{-6}]	$A_{CP}(K\pi)$
$B^0 \rightarrow \pi^+\pi^-$	157±19	4.7±0.6±0.2	
$B^0 \rightarrow K^+\pi^-$	589±30	17.9±0.9±0.7	-0.102±0.050±0.016
$B^0 \rightarrow K^+K^-$	1±8	<0.6 [90%CL]	

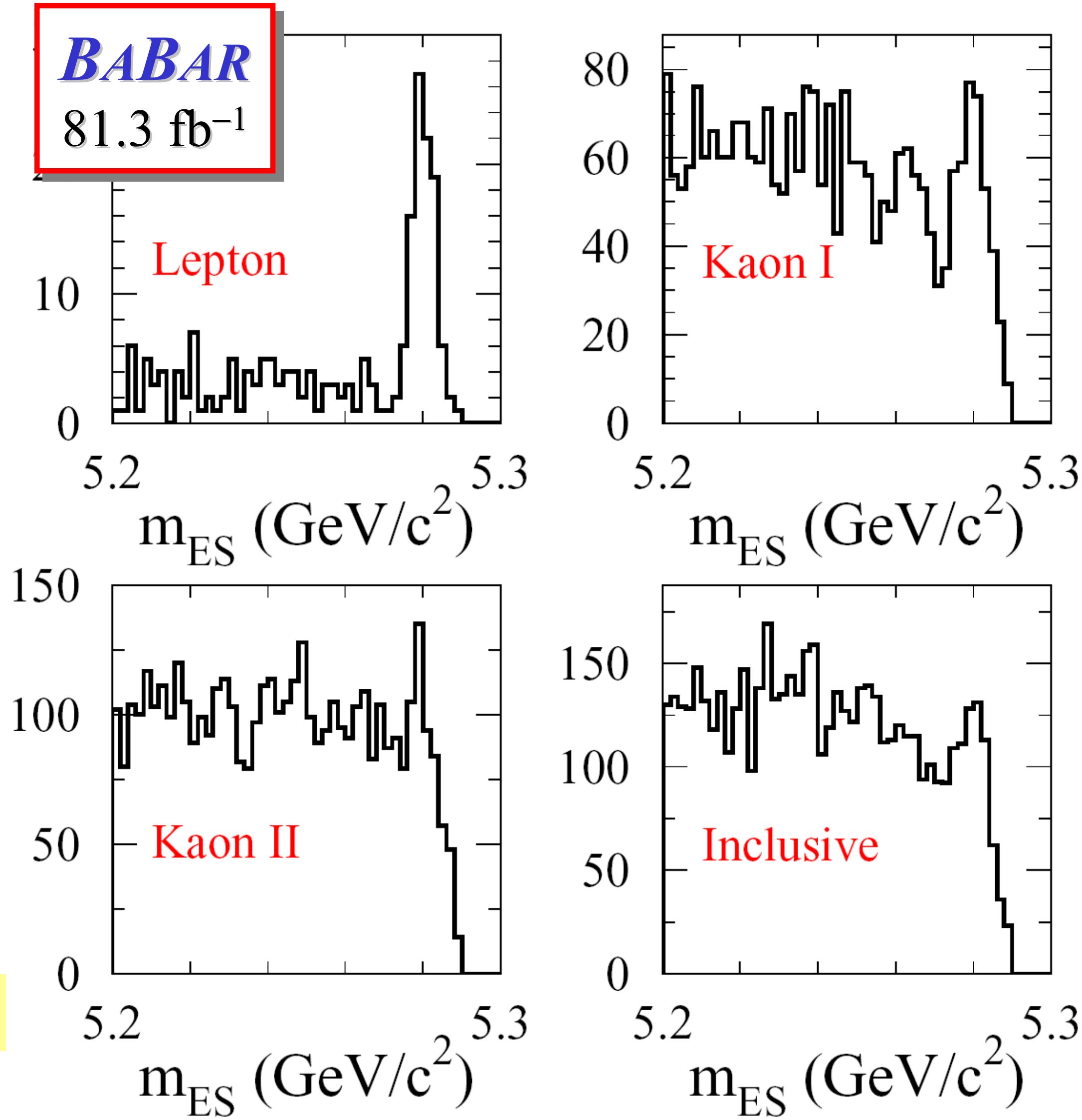
$$A_{K\pi} \equiv \frac{\Gamma(\bar{B}^0 \rightarrow K^-\pi^+) - \Gamma(B^0 \rightarrow K^+\pi^-)}{\Gamma(\bar{B}^0 \rightarrow K^-\pi^+) + \Gamma(B^0 \rightarrow K^+\pi^-)} \sim \left|\frac{P}{T}\right| \sin\gamma \sin\delta$$

BABAR
$81.3\ \mathrm{fb}^{-1}$

BABAR-PUB-02/009, hep-ex/0207055

Two-Body Tagged Sample

- Tagging efficiency is very different for signal and bkg
  - Strong bkg suppression in lowest mistag categories (Lepton/Kaon)
  - Different bkg tagging efficiencies for $\pi\pi$, $K\pi$, KK
- Sum of $\pi^+\pi^-/K^+\pi^-$: No particle ID used until the fit is performed



Untagged category also used

CP Asymmetry Results from BABAR

Fit projection in sample of $\pi\pi$-selected events

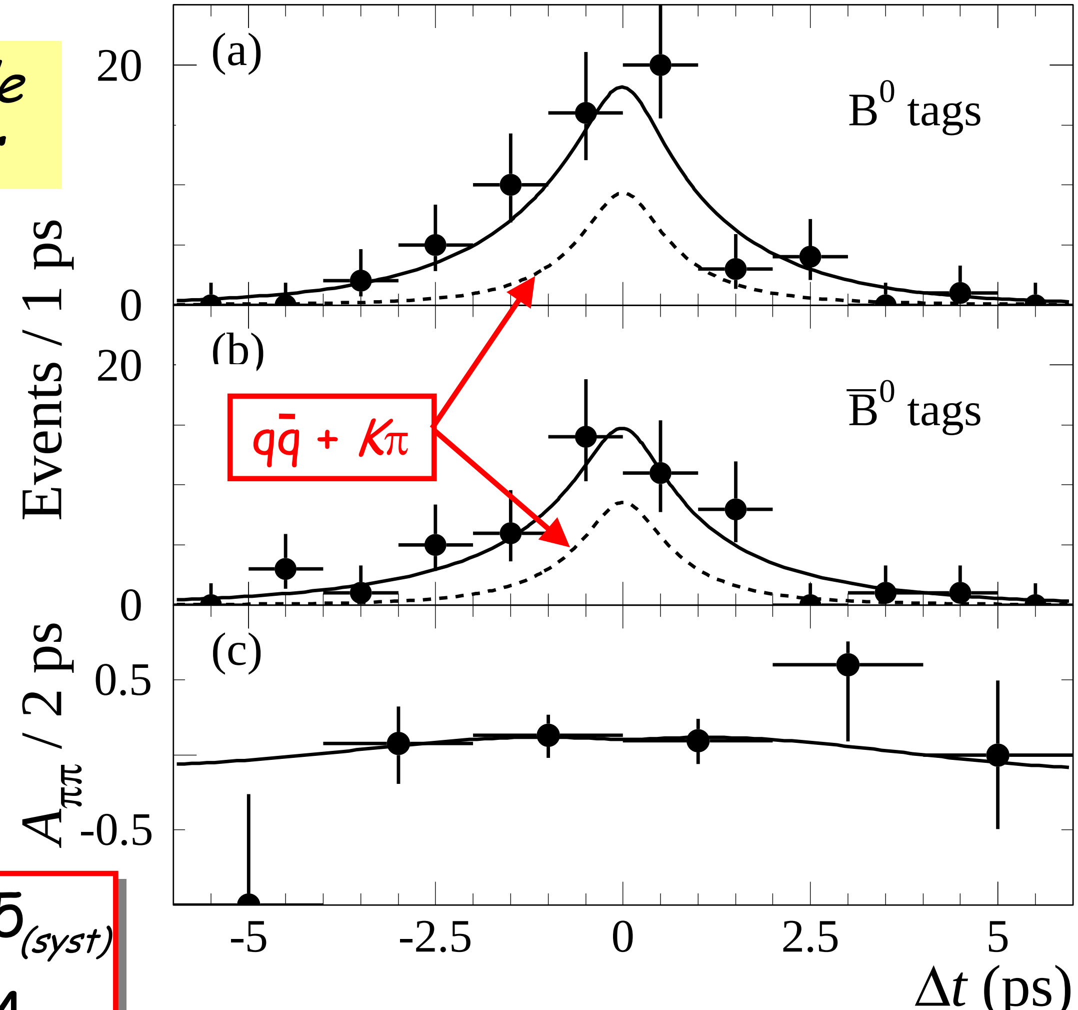
For *CP* asymmetry add tagging and Δt measurement to likelihood but fix yields and $A_{K\pi}$

Preliminary

BABAR
81.3 fb^{-1}

$$S_{\pi\pi} = +0.02 \pm 0.34_{(stat)} \pm 0.05_{(syst)}$$

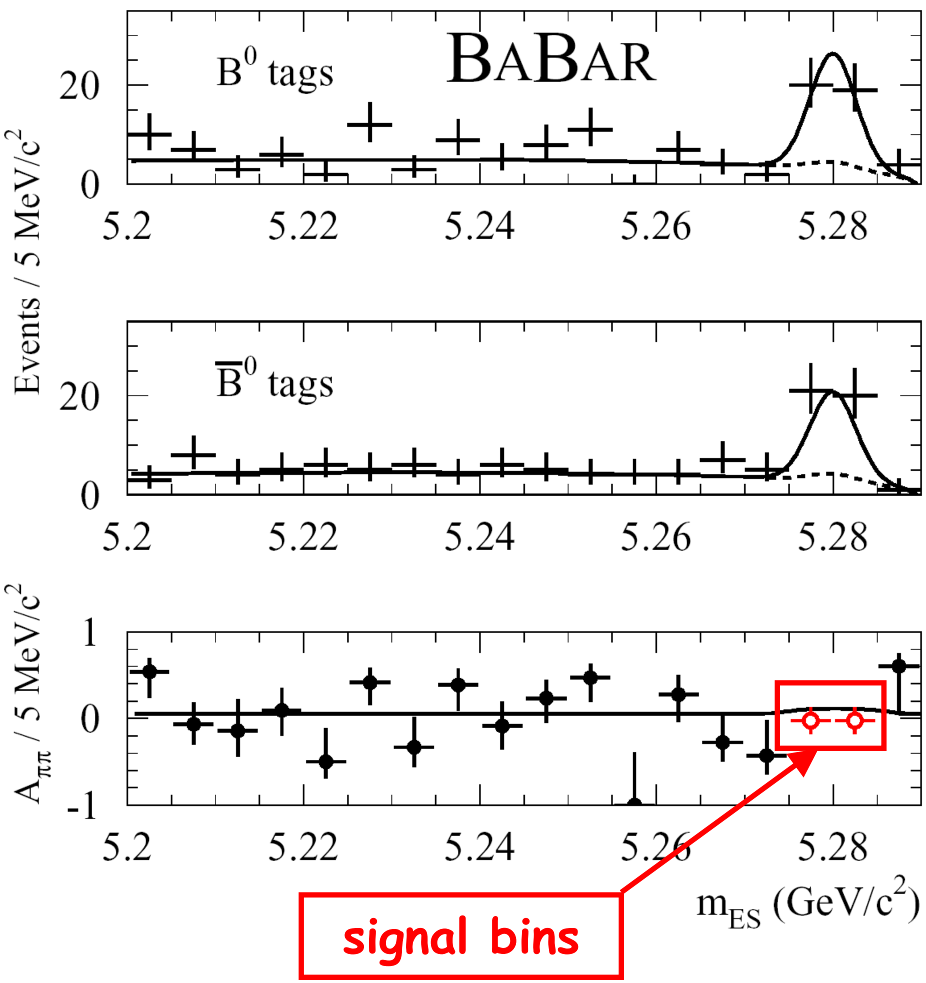
$$C_{\pi\pi} = -0.30 \pm 0.25_{(stat)} \pm 0.04_{(syst)}$$

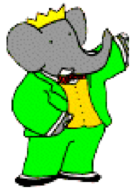


Crosschecks

- ***Inspect $\pi\pi$-selected sample***
  - 2-param fit consistent with full fit
  - Asymmetry vs. m_{ES}
    - Yields consistent with measured value of $C_{\pi\pi}$, which do not suggest large direct *CP* violation
  - Toy MC generated over all allowed values of $S_{\pi\pi}$ and $C_{\pi\pi}$
    - Expected errors consistent with data
    - No significant bias observed
- ***Validated in large samples of signal and background MC events***
- ***Systematic errors dominated by uncertainty in PDF shapes***

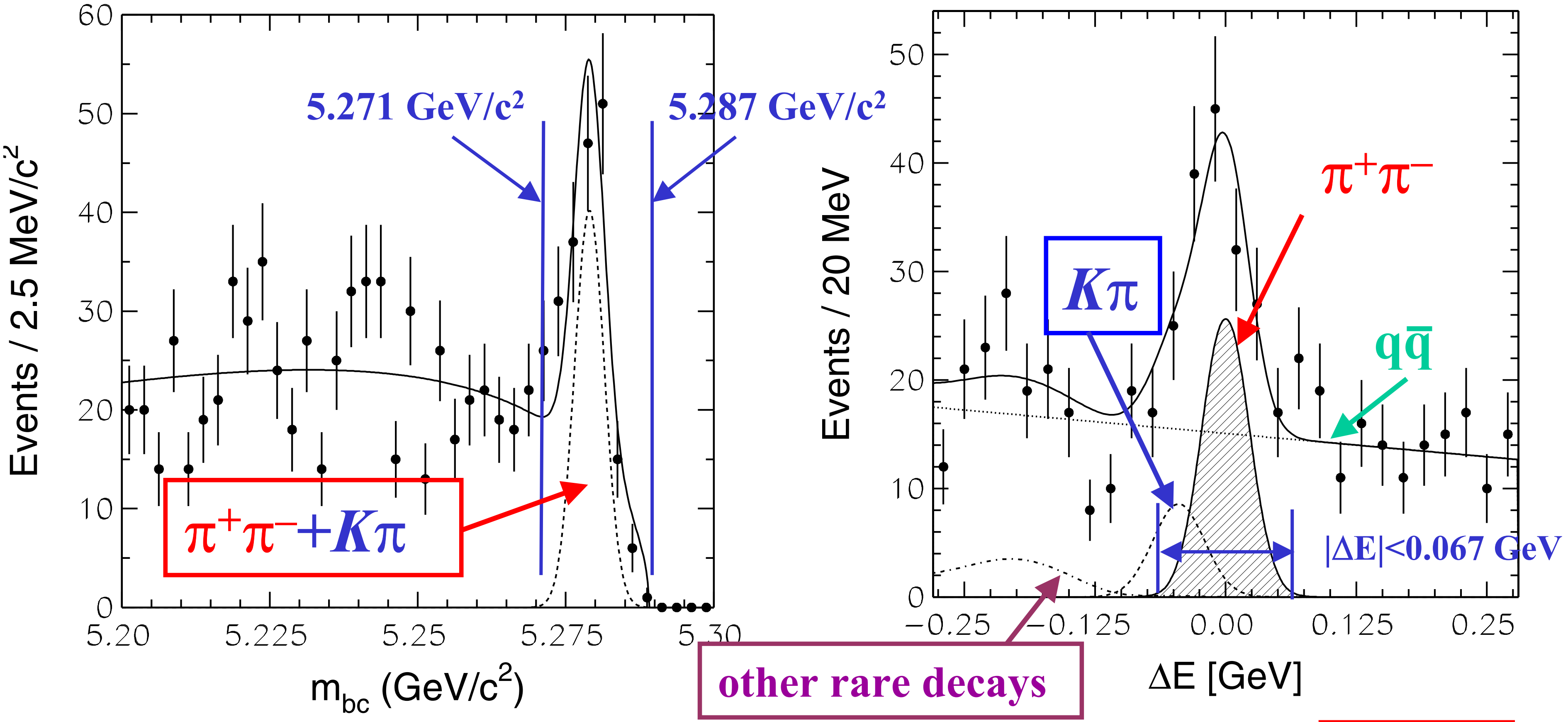
$A_{\pi\pi}$ vs. m_{ES} in sample of $\pi\pi$-selected events





Belle Signal for $B \to \pi^+\pi^-$

Reject most of $K\pi$ feedthrough with PID systems



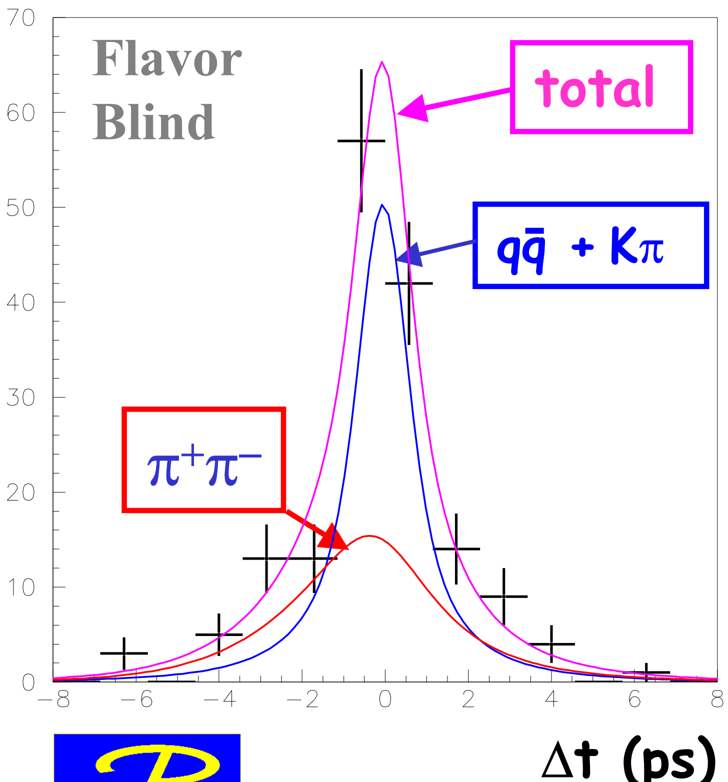
BELLE, hep-ex/0204002

$$N(\pi\pi) = 73.5 \pm 13.8$$
$$N(K\pi) = 28.4 \pm 12.5$$

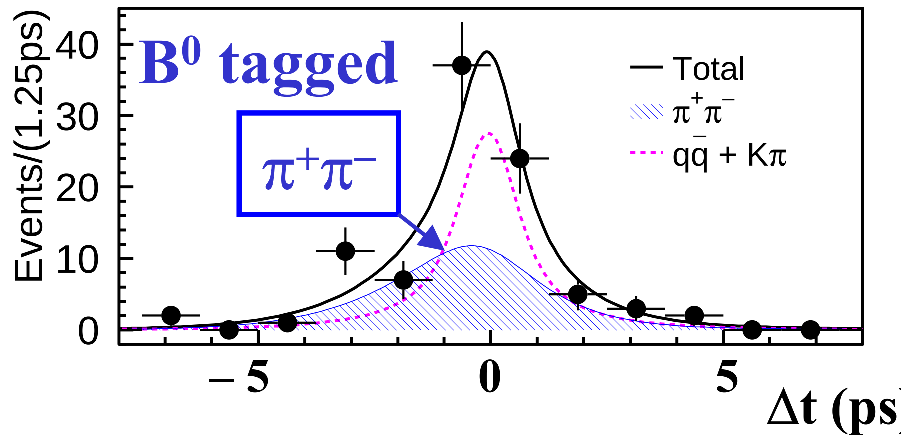
BELLE 41.8 fb^{-1}

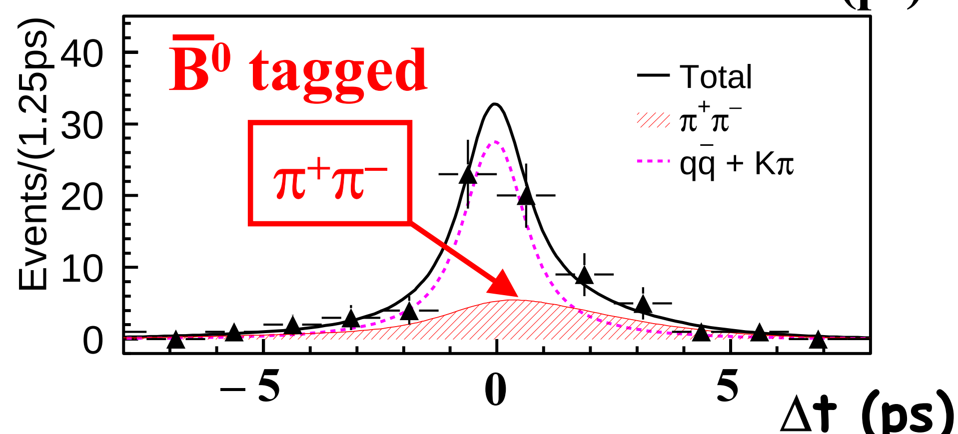
$B \to \pi^+\pi^-$ Time Distributions

162 events after vertexing and flavor tagging
$|\Delta E| < 0.067$ GeV



92 B^0 events
39.9 $B^0 \to \pi^+\pi^-$ events





70 $\bar{B}^0$ events
23.4 $\bar{B}^0 \to \pi^+\pi^-$ events

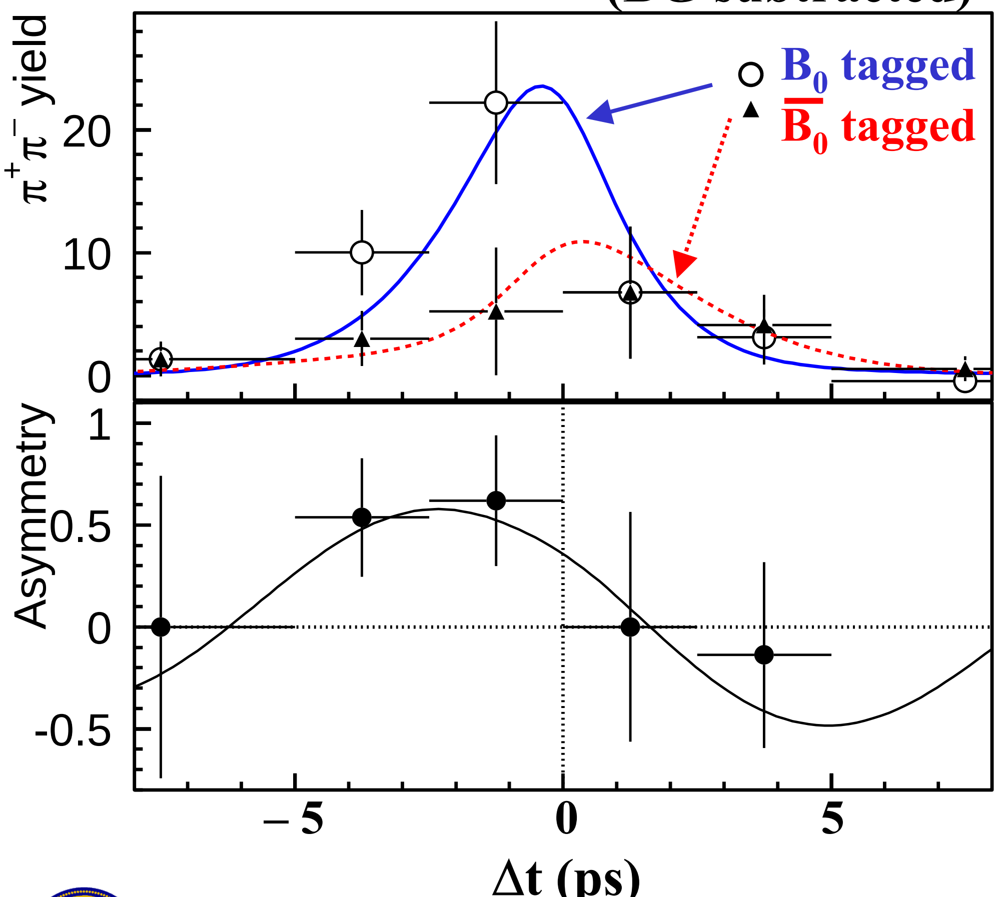
$B \rightarrow \pi^+\pi^-$ Fit Result

BELLE
41.8 fb^{-1}

BELLE

$\pi^+\pi^-$ sample

(BG subtracted)

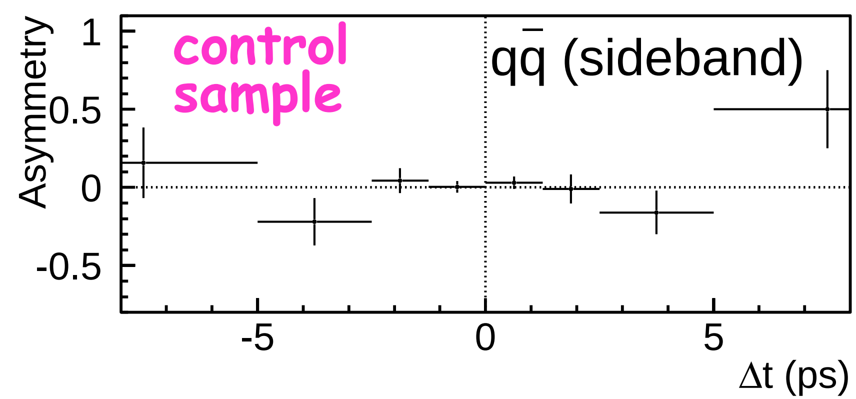


$A_{\pi\pi} = -C_{\pi\pi}$

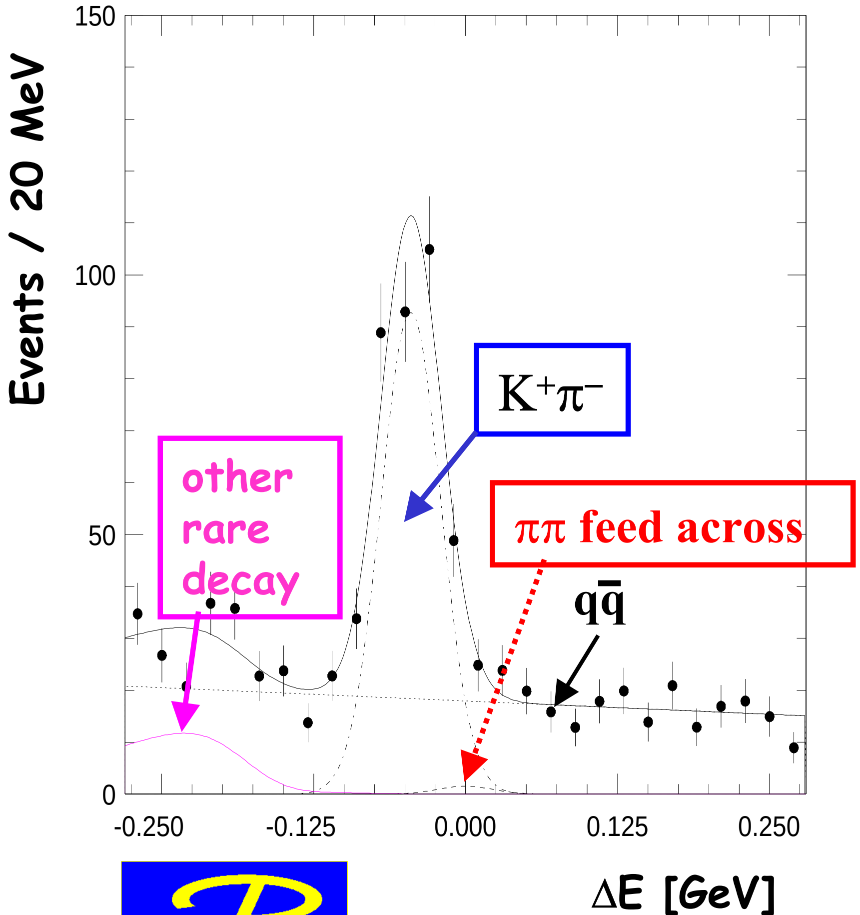
$$A_{\pi\pi} = +0.94^{+0.25}_{-0.31}\,(stat) \pm 0.09_{(syst)}$$

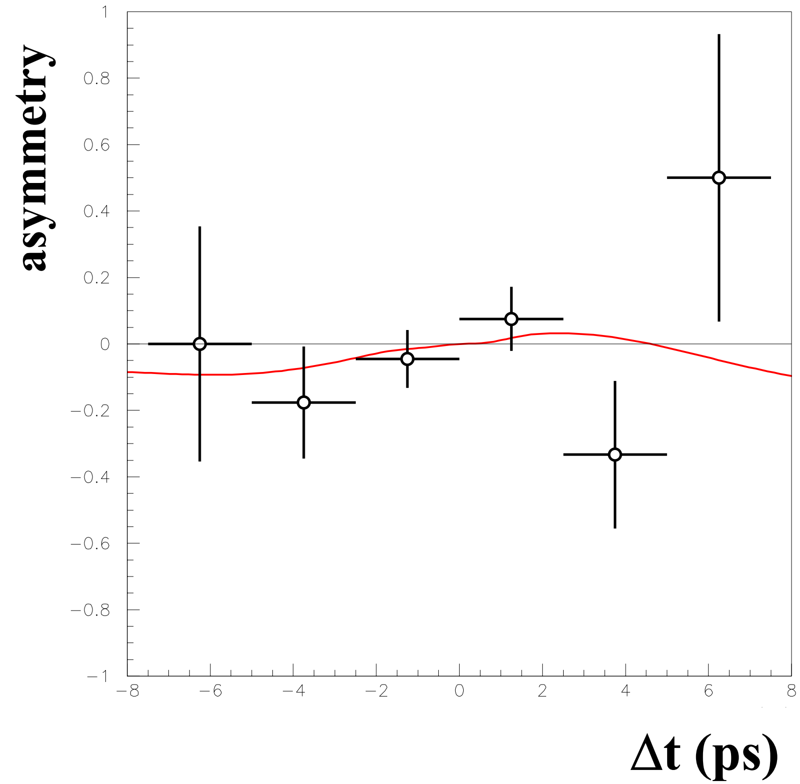
$$S_{\pi\pi} = -1.21^{+0.38}_{-0.17}\,(stat)^{+0.16}_{-0.13}(syst)$$

BELLE, hep-ex/0204002



Crosscheck with $B \to K^+\pi^-$ Sample





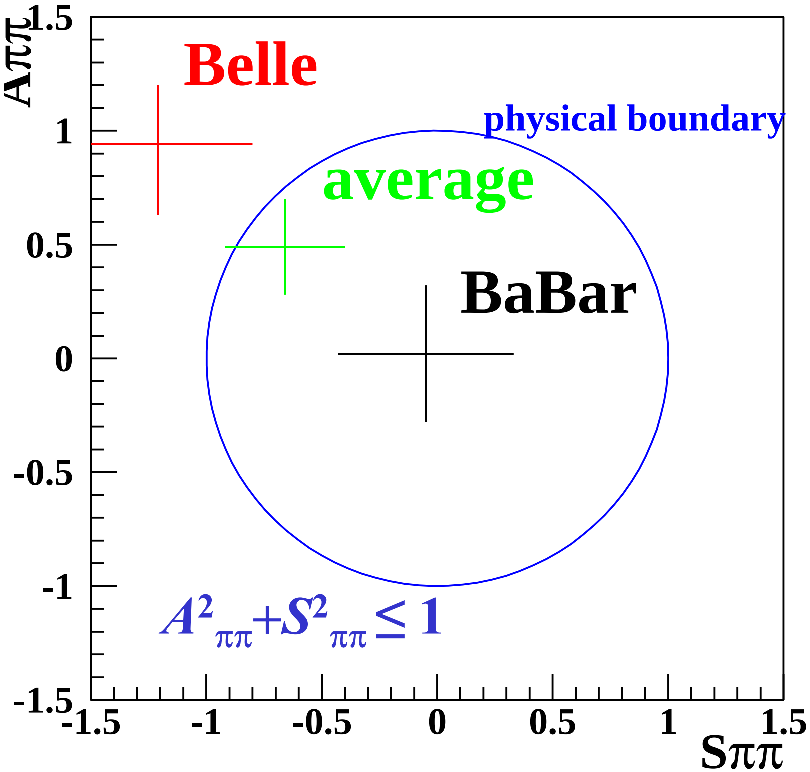
Null Asymmetry

$$A_{K\pi} = 0.07 \pm 0.17$$
$$C_{\pi\pi} = 0.15 \pm 0.24$$

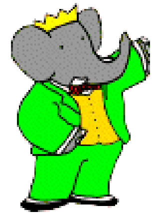
Comparison of Results

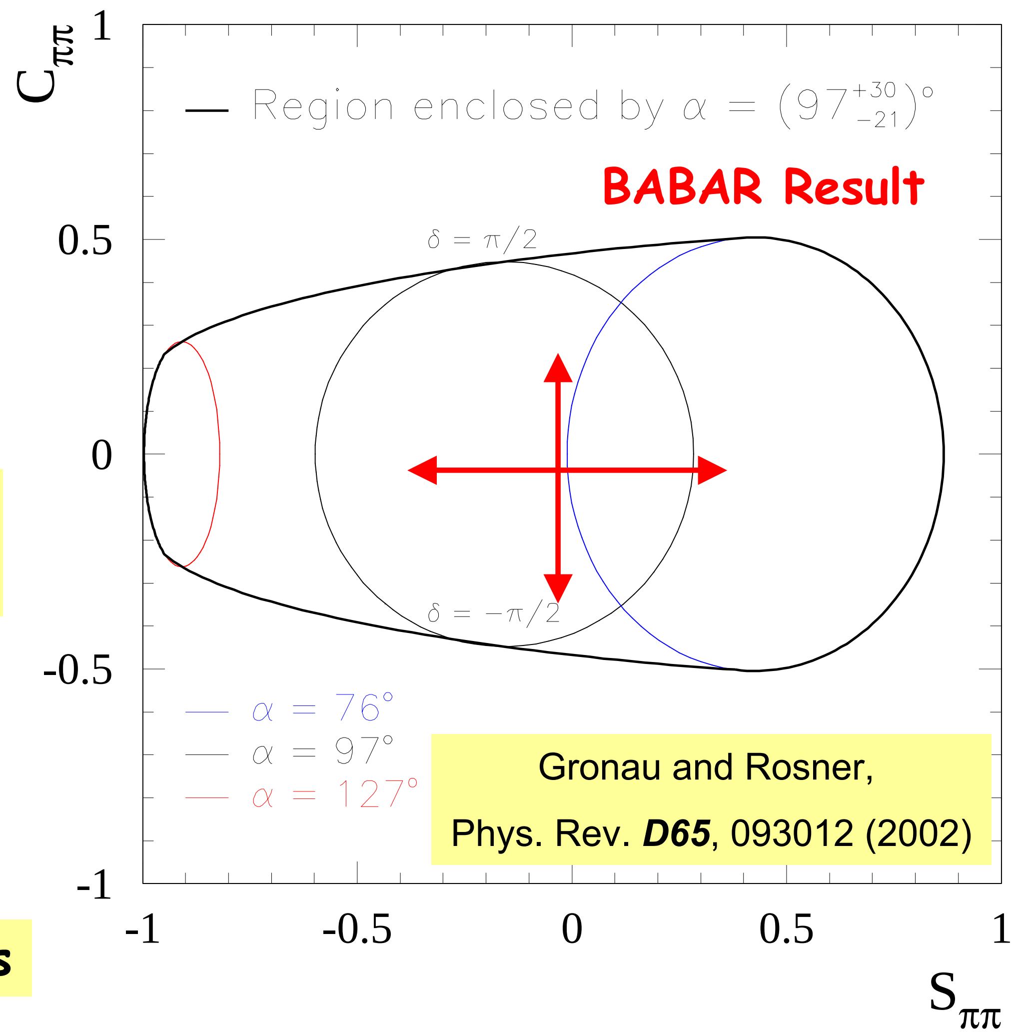
$A_{\pi\pi} = -C_{\pi\pi}$

	BABAR	Belle
$A_{\pi\pi}$	$+0.30 \pm 0.25 \pm 0.04$	$+0.94^{+0.25}_{-0.31} \pm 0.09$
$S_{\pi\pi}$	$+0.02 \pm 0.34 \pm 0.05$	$-1.21^{+0.38}_{-0.17} \pm^{+0.16}_{-0.13}$



Interpretation?





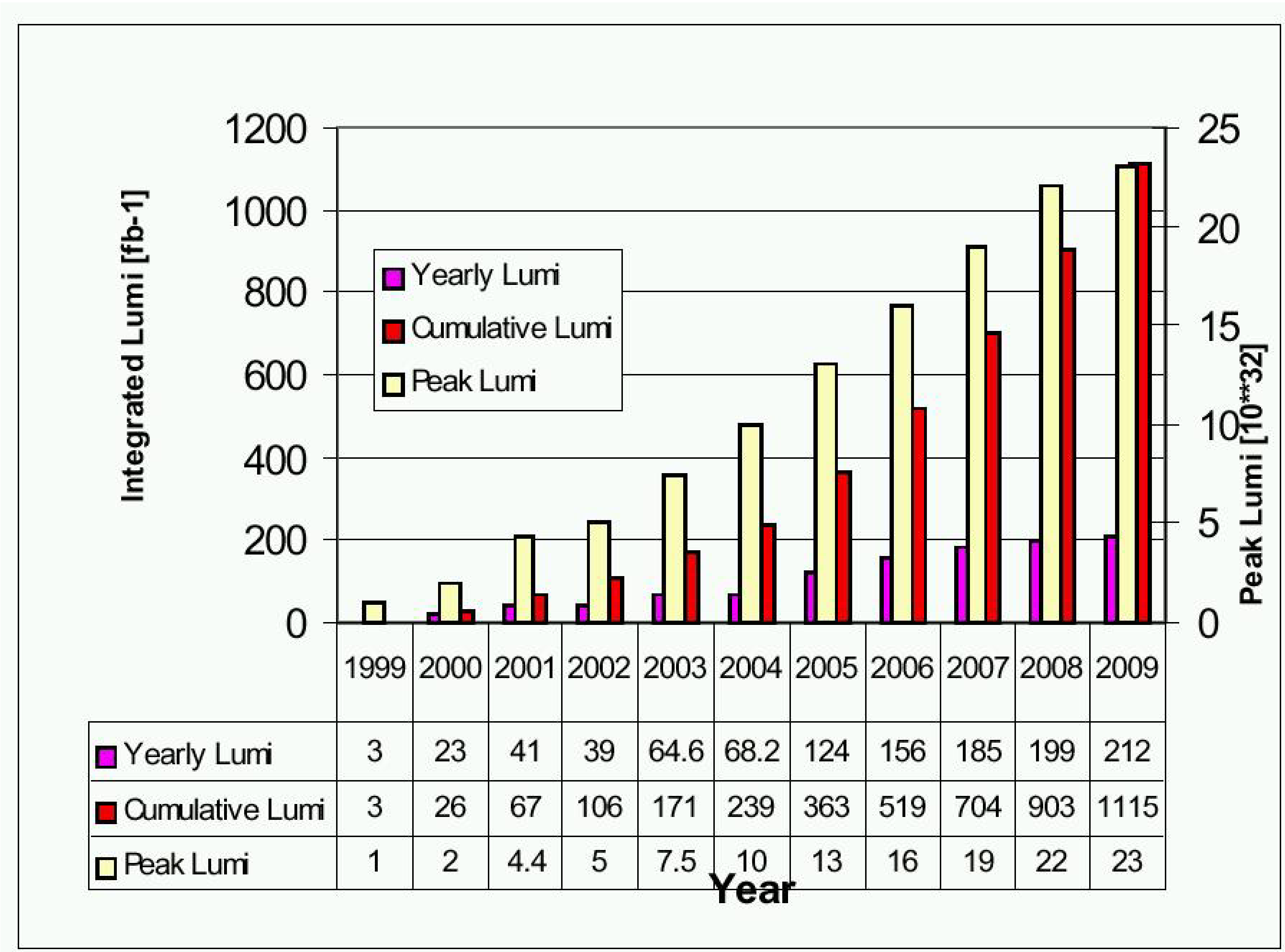
$S_{\pi\pi}$ and $C_{\pi\pi}$ are determined by α, β, $|P/T|$, and δ.

e.g. $\alpha = (97^{+30}_{-21})^\circ, \beta = 26^\circ,$

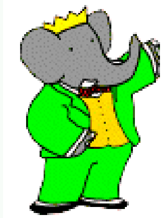
$$|P/T| = -.28, -\frac{\pi}{2} < \delta < +\frac{\pi}{2}$$

Consistent with SM expectations

PEP-II Luminosity Projections

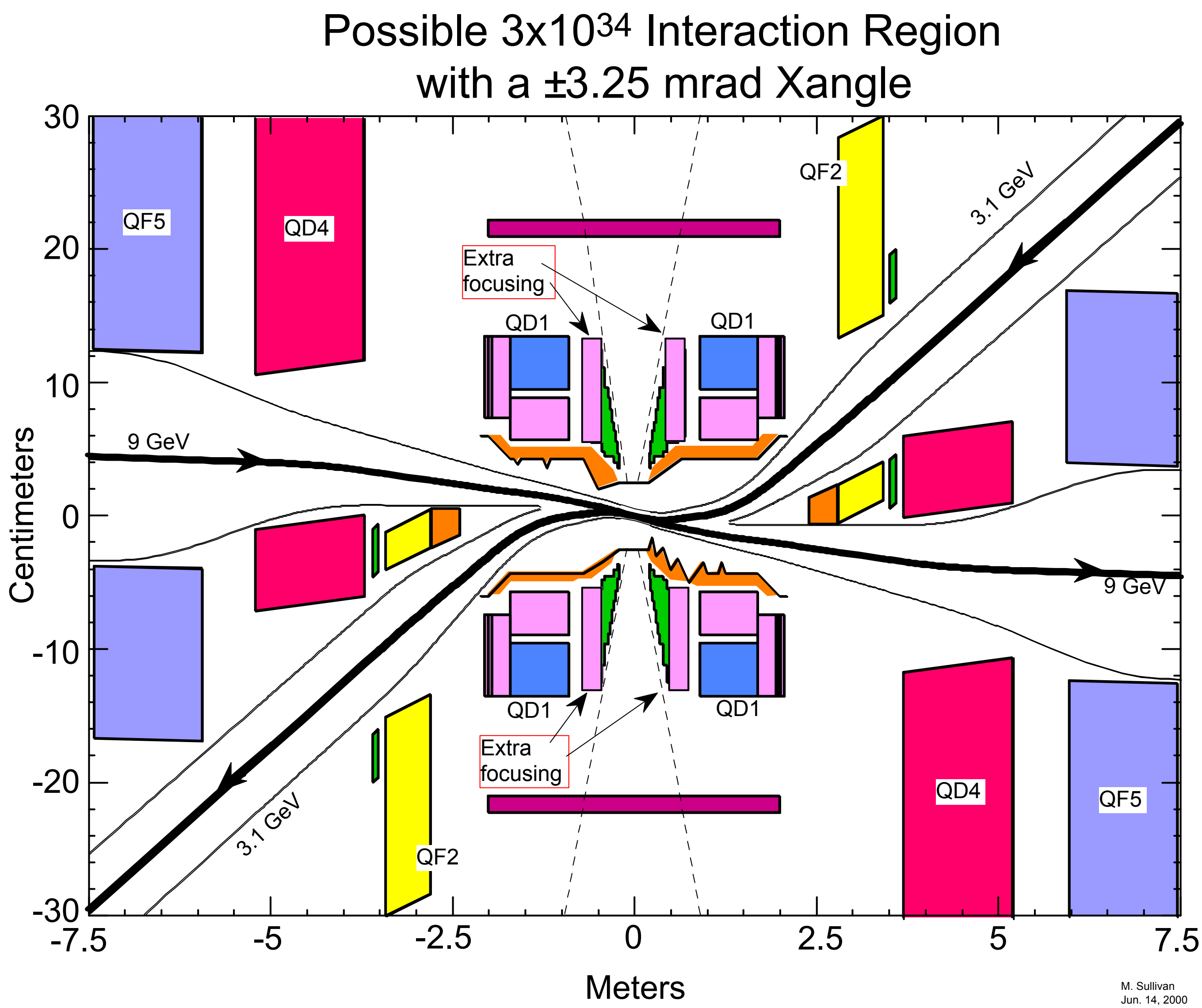


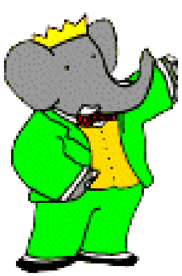
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Yearly Lumi	3	23	41	39	64.6	68.2	124	156	185	199	212
Cumulative Lumi	3	26	67	106	171	239	363	519	704	903	1115
Peak Lumi	1	2	4.4	5	7.5	10	13	16	19	22	23



Equivalent expectation for Belle

Possible PEP-II upgrade





Projections for CP Asymmetry Measurements

Some rough estimates

Param.	Channel	σ(stat)/σ(syst) $56\ fb^{-1}$	σ(stat)/σ(syst) $0.5\ ab^{-1}$	σ(stat)/σ(syst) $2.0\ ab^{-1}$	σ(stat)/σ(syst) $10\ ab^{-1}$
$\sin 2\beta$	$J/\psi K_S$	0.11 / 0.04	0.037 / 0.015	0.018 / 0.015	0.009 / 0.015
	Golden	0.09 / 0.04	0.030 / 0.015	0.015 / 0.015	0.007 / 0.015
	D*D*	0.45 / 0.06	0.15 / ?	0.08 / ?	0.034 / ?
$\sin 2\alpha_{eff}$	$\pi^+\pi^-$	0.37 / 0.07	0.12 / 0.03	0.06 / ?	0.03 / ?
$C_{\pi\pi}$		0.29 / 0.07	0.10 / 0.03	0.05 / ?	0.02 / ?

- Expression of Interest at KEK for 10^{35} machine in spring 2002
- Ongoing workshops to examine this or higher luminosity options
- Snowmass 2001 study of 10^{36} concept and physics capability
  - Aim to be competitive and complementary to LHCb, BTeV on time scale of end of the decade
  - Physics case still being explored; still very early days in the exploration of these possibilities
  - Requires completely new vacuum and rf system, mostly new detector (current technologies cannot handle backgrounds)

Future Tests of 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 <1% from Tevatron in 2004?***

ca. 2007:
$\sigma(\sin 2\beta) \sim 1\%$
$\alpha \sim 5^o$, $\gamma \sim 10^o$

CKM fitter

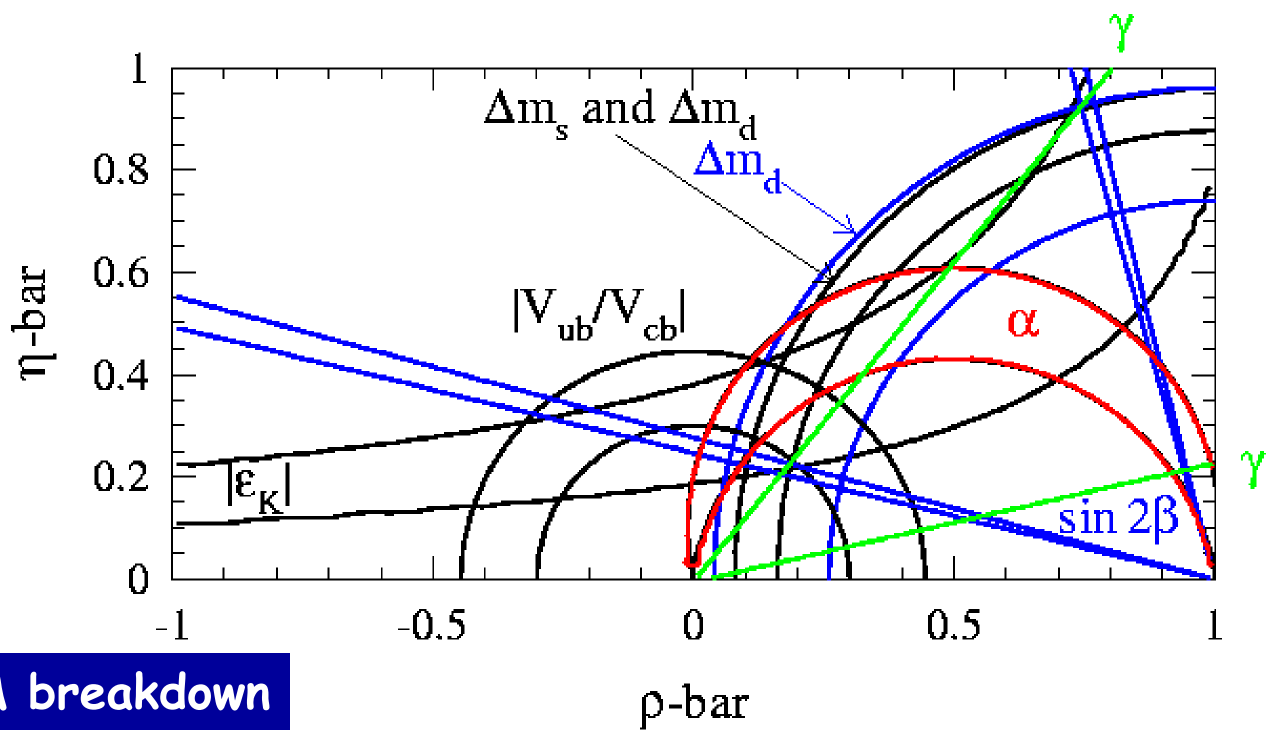


Illustration of SM breakdown

Summary

- *Now in the era of B Factories, with a renaissance of experimental and theoretical activity in B physics*
  - Data samples are 5 times larger than CLEO; will be 10 times larger within a few years

Motivation for these and upcoming facilities is to provide 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

$$\sin 2\beta = 0.734 \pm 0.055$$

July 2002: Textbook plots!

World average dominated by BELLE and BABAR

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

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