Measurement of sin2β at BABAR

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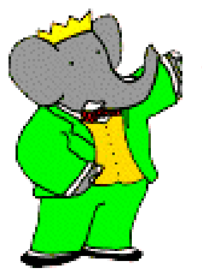
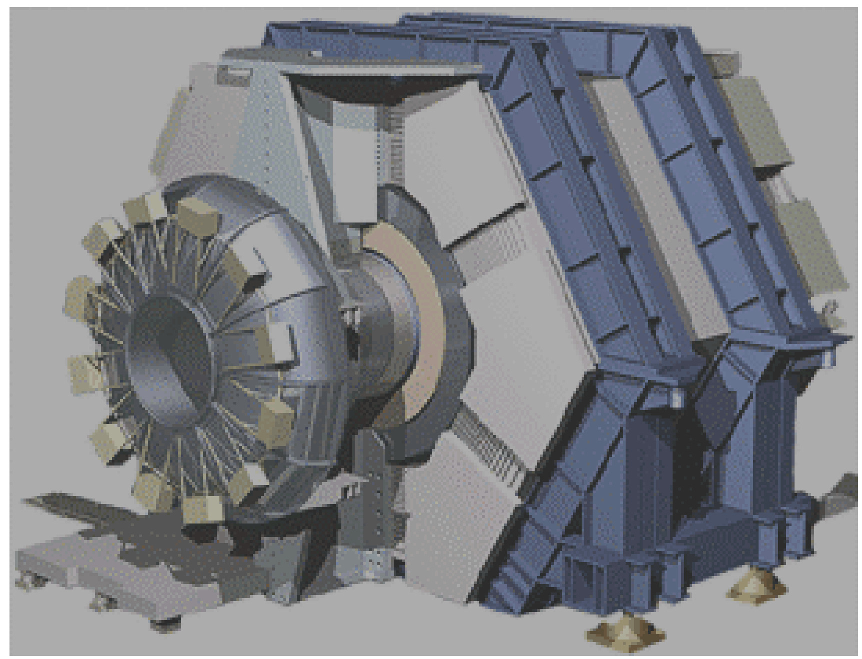
For the BABAR Collaboration

Update $B^0 \rightarrow (c\bar{c}) K^0$
Update $B^0 \rightarrow D^{*+} D^{*-}$
New $B^0 \rightarrow \phi K^0_S$
New $B^0 \rightarrow J/\psi \pi^0$





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Weak interaction of quarks in the Standard Model

CKM Matrix

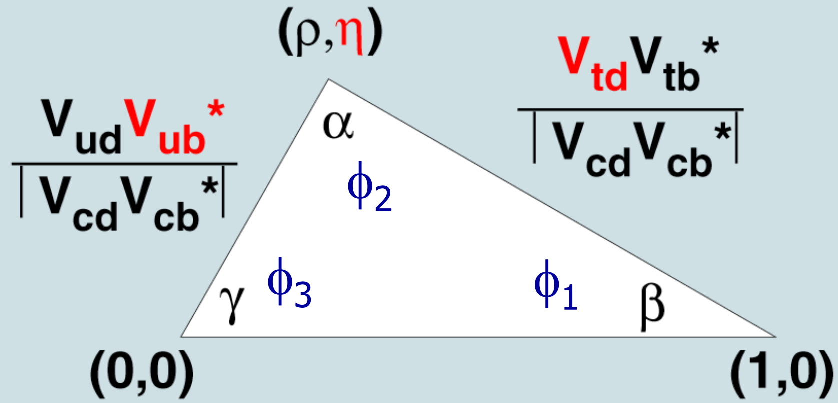
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

$V^\dagger V = I$, and quark phases
$\Rightarrow$ 4 parameters

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

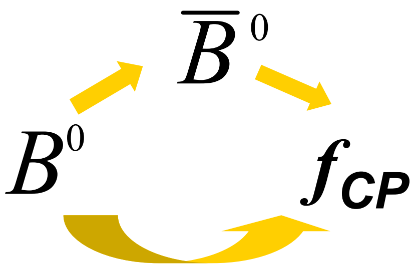
Unitarity Triangle

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



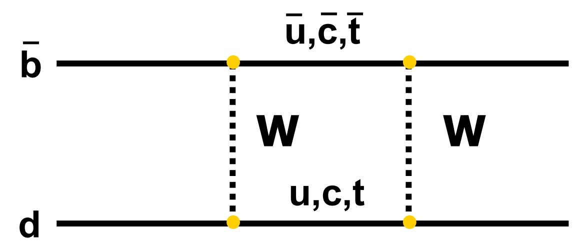
CP violation will arise from complex component of V_{ub}, V_{td}

B^0-$\bar{B}^0$ mixing introduces time-dependant CP violation



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$$

$$\Delta m_d = m_H - m_L$$



top quark box introduces: V_{tb} V_{td}^*

$$f_- = \Gamma(B^0 \to f_{CP})$$
$$f_+ = \Gamma(\bar{B}^0 \to f_{CP})$$

$$\lambda_f = \frac{q}{p}\frac{A(\bar{B}^0 \to f_{CP})}{A(B^0 \to f_{CP})}$$

$$\frac{q}{p} \sim \frac{V_{td}}{V_{td}^*}$$

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

$$S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}$$

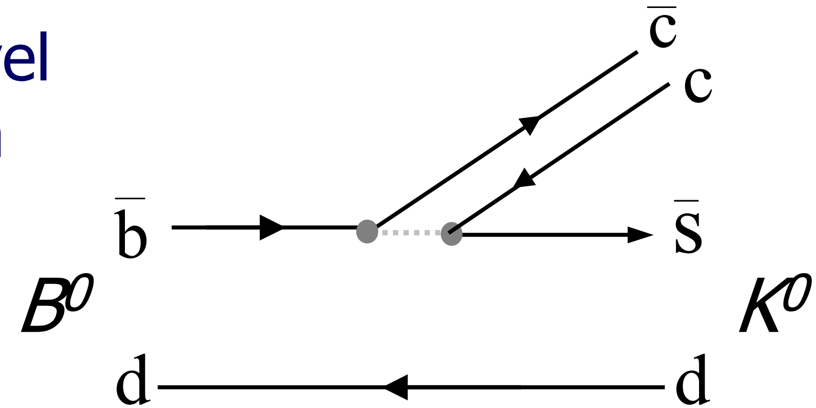
Sensitive to overall phase of λ_f even if no Direct CP Violation

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

Direct CP violation if multiple amplitudes with different phases

CP asymmetry in $B^0 \rightarrow (c\bar{c})K^0$

- Theoretically clean: Tree level dominates and CP only from B^0-$\bar{B}^0$ mixing
- Relatively large branching fractions
- Clear experimental signatures



$$\lambda_f = \frac{q}{p}\frac{A(\bar{B}^0 \rightarrow f_{CP})}{A(B^0 \rightarrow f_{CP})}$$

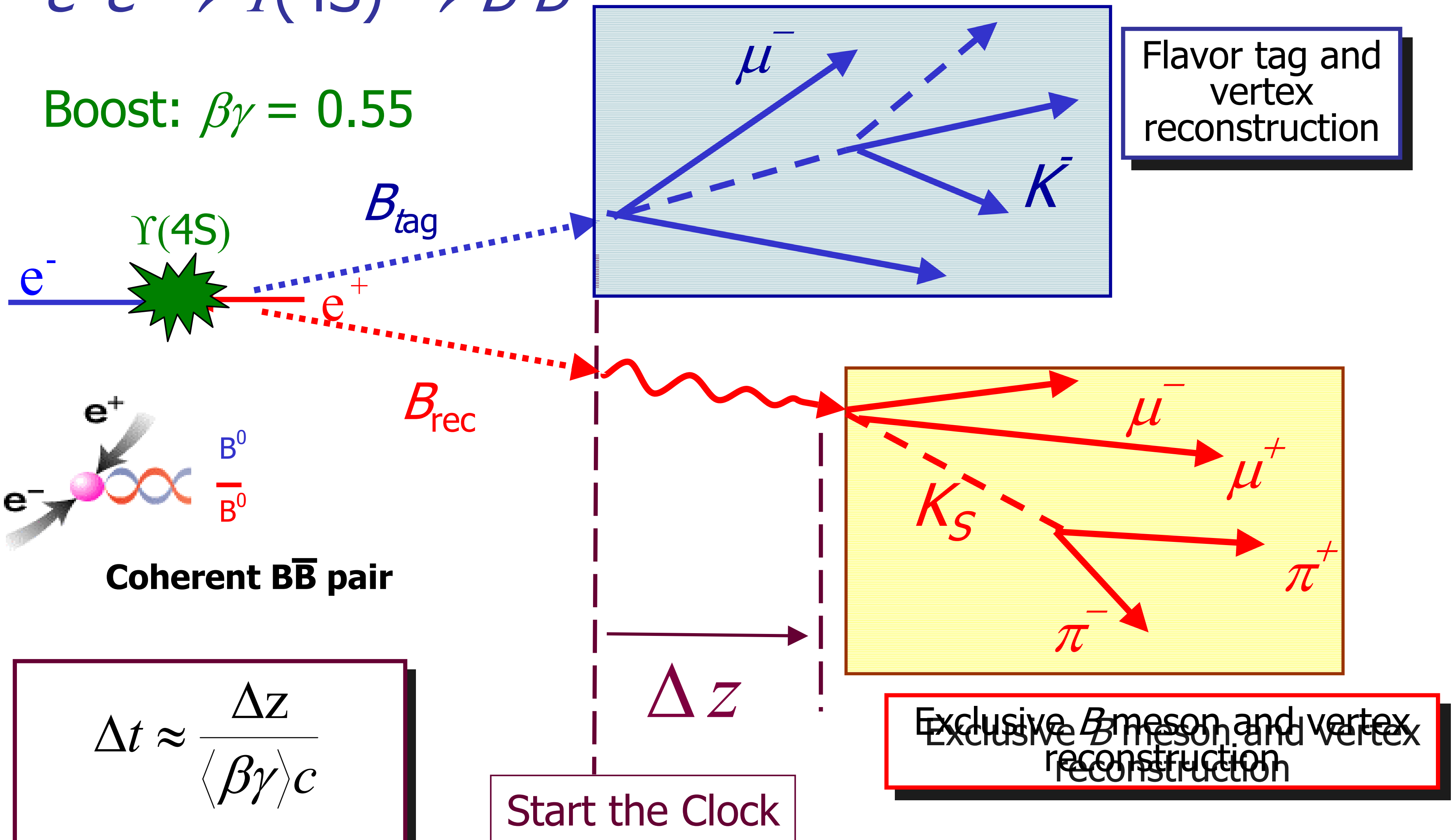
$$\Rightarrow \quad \lambda_f = \eta_f e^{-i2\beta}, \quad \eta_f = \pm 1$$

$$A_{CP}(t) = \frac{f_+ - f_-}{f_+ + f_-} = -\eta_f \sin 2\beta \sin(\Delta m_d t)$$

Experimental technique at the $\Upsilon(4S)$ resonance

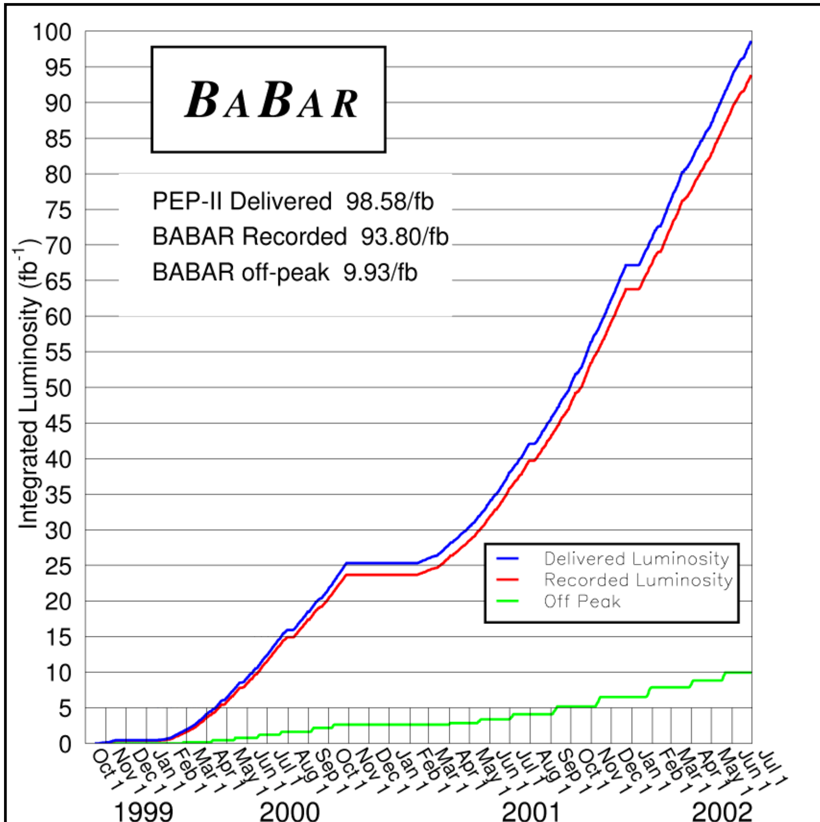
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\,\bar{B}$$

Boost: $\beta\gamma = 0.55$



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

SLAC B Factory performance

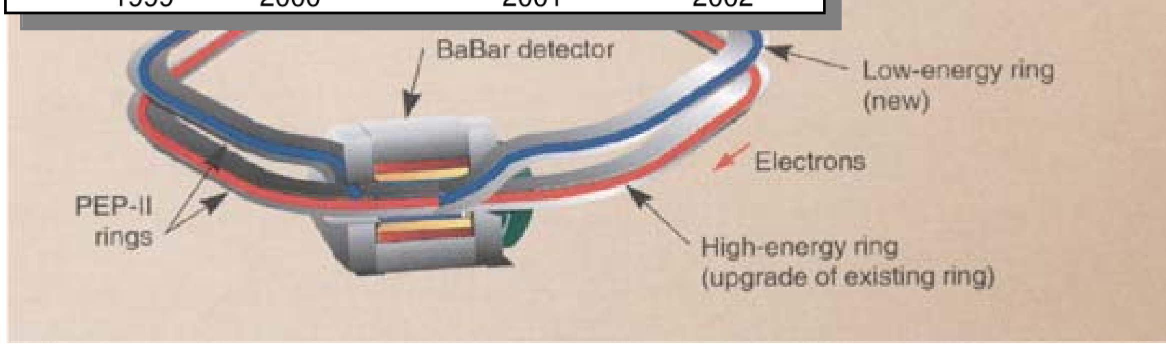


PEP-II top luminosity:
4.60 x 10^{33}cm^{-2}s^{-1}
(exceeded design goal 3.0 x 10^{33})

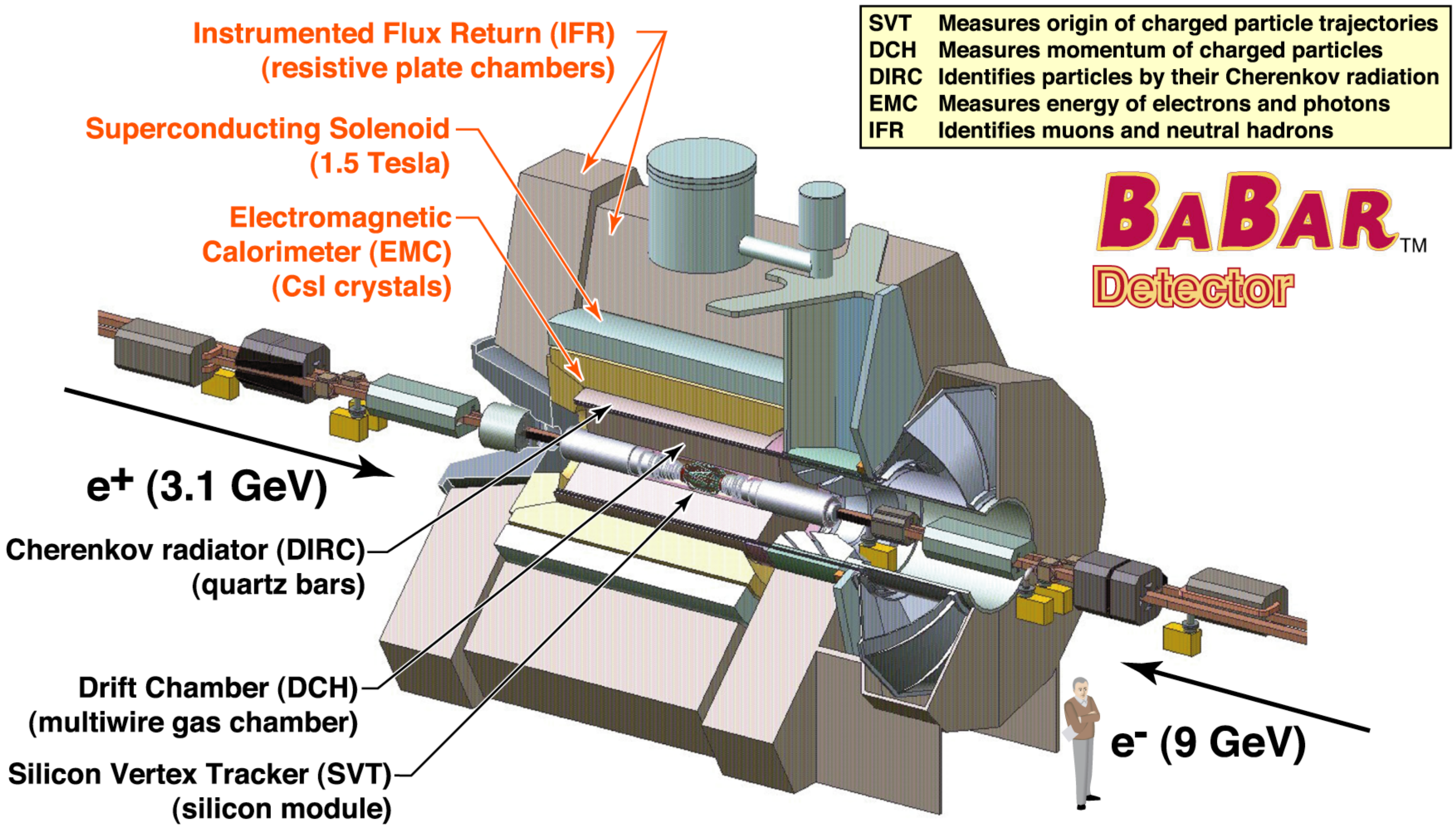
PEP-II delivered	**99 fb^{-1}**
BaBar recorded	**94 fb^{-1}**

In this analysis

On peak	**81 fb^{-1}**
	88M $B\bar{B}$ pairs
Off peak	**10 fb^{-1}**



BABAR Detector



SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

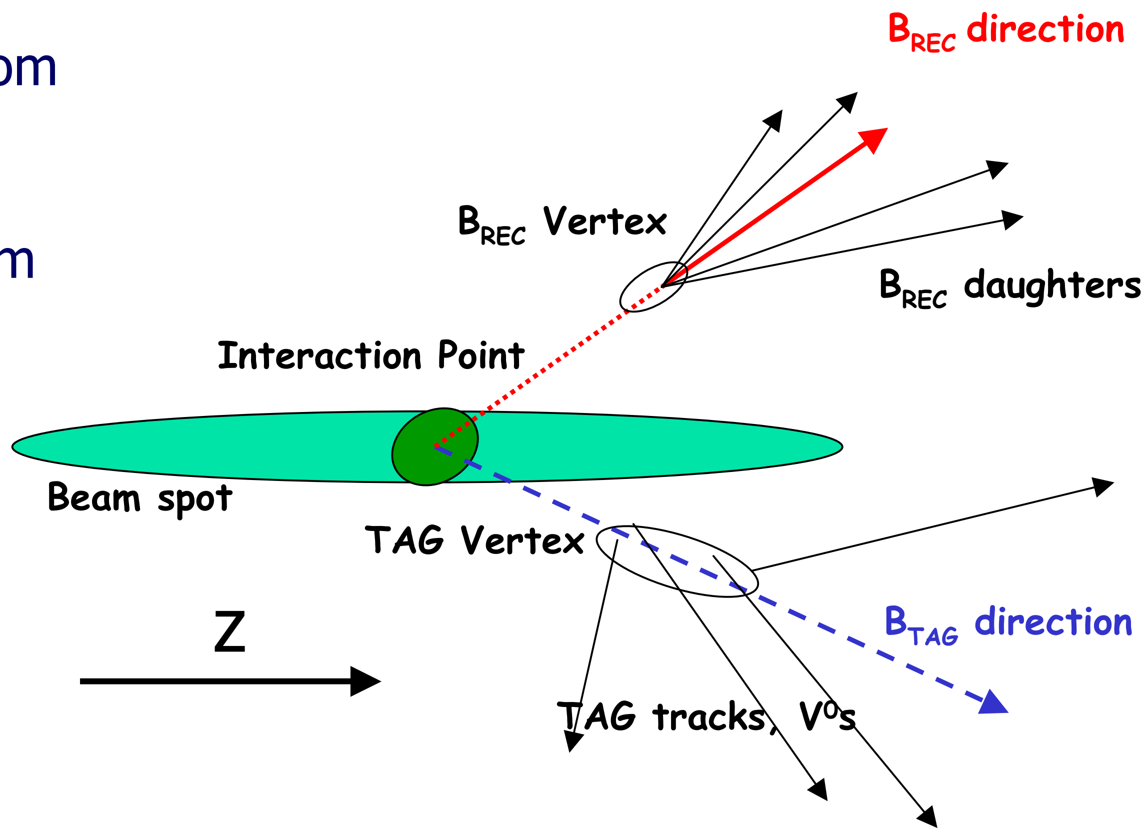
SVT+DCH: $\sigma(p_T)/p_T = 0.13\ \% \times p_T + 0.45\ \%$

DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

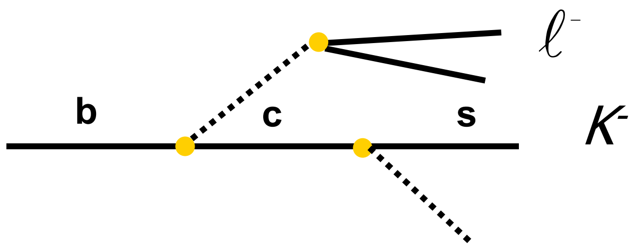
Vertex and Δt Reconstruction

- Reconstruct B_{rec} vertex from charged B_{rec} daughters
- Determine B_{Tag} vertex from
  - All charged tracks not in B_{rec}
  - Constrain with B_{rec} vertex, beam spot, and $\Upsilon(4S)$ momentum
  - Remove high χ^2 tracks (to reject charm decays)



- High efficiency: 95%
- Average Δz resolution ~ 180 μm (dominated by B_{Tag}) ($<|\Delta z|>$ ~ 260 μm)
- Δt resolution function measured from data

B Flavor tagging method



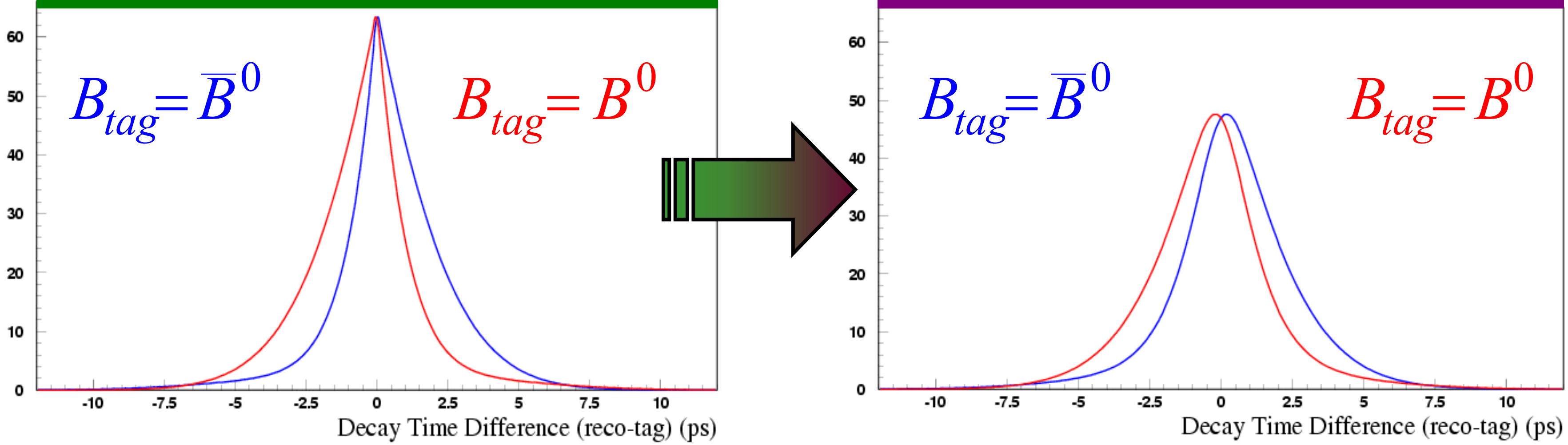
Using tracks with or without particle identification, and kinematic variables, a multilevel neural network assigns each event to one of five mutually-exclusive categories:

- Lepton tag: primary leptons from semileptonic decay
- Kaon1 tag: high quality kaons, correlated K^- *and* π^+_s (from D^*)
- Kaon2 tag: lower quality kaons, π_s from D^*
- Inclusive tag: unidentified leptons, low quality K, π, leptons
- No tag: event is not used for CP analysis

New and improved tagging method

Tagging errors and finite Δt resolution dilute the CP asymmetry

perfect tagging & time resolution → **typical** mistagging & finite time resolution

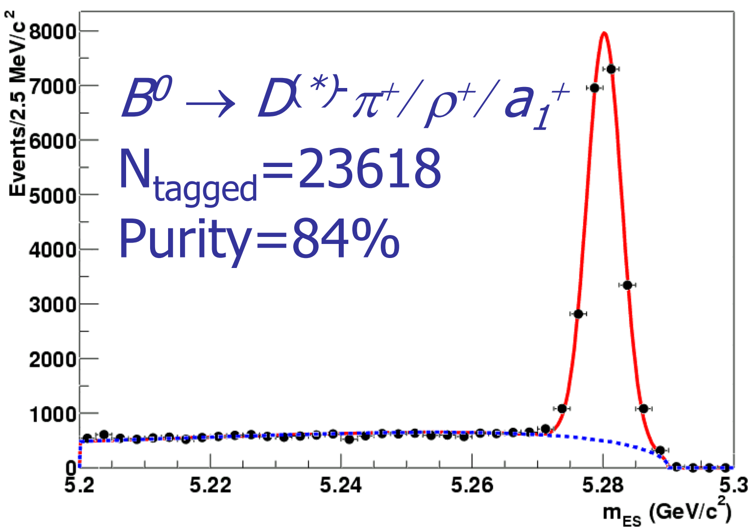


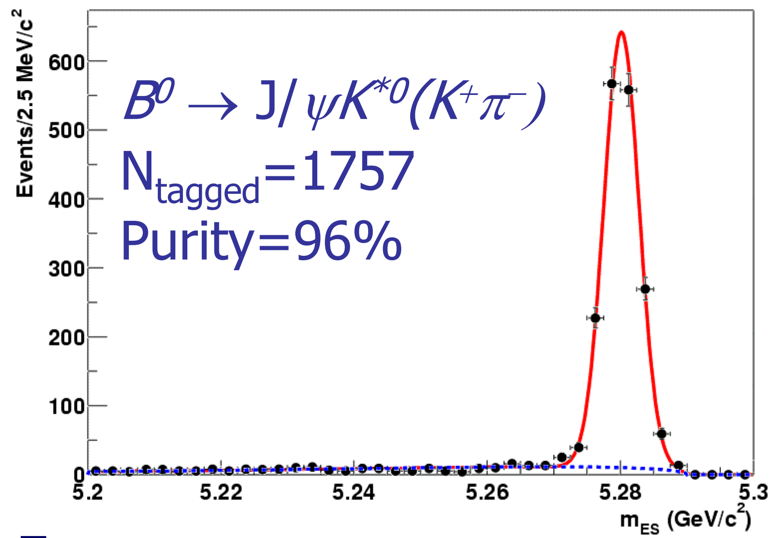
$$f(\Delta t)=\left\{\frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1\mp\eta_f\sin 2\beta(1-2w)\sin(\Delta m_d\Delta t)\right]\right\}\otimes R$$

- Need to know mistag fraction w and Δt resolution function R in order to measure CP asymmetry.
- Can extract these from data with B^0-$\overline{B}^0$ mixing events.

Use self-tagged B_{flav} sample to measure w and R

- Fully reconstruct self-tagged modes:





- Apply B_{tag} to other side, fit for B^0-$\bar{B}^0$ mixing

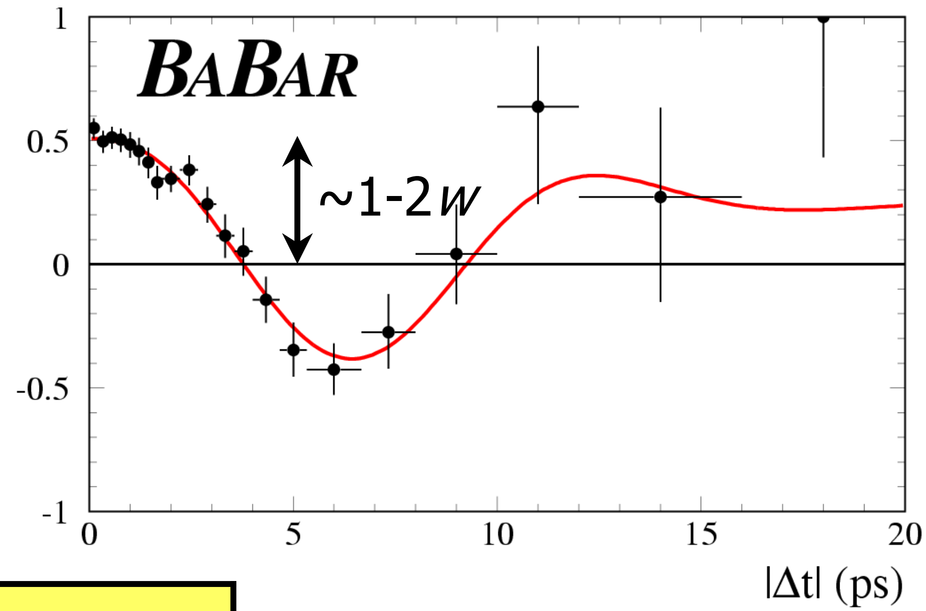
$$f_{\substack{\text{Unmixed}\\\text{Mixed}}}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left[1 \pm (1-2w)\cos(\Delta m_d \Delta t)\right] \right\} \otimes R$$

B_{flav} sample is x10 size of CP sample

Tagging performance from B_{flav} sample

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

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

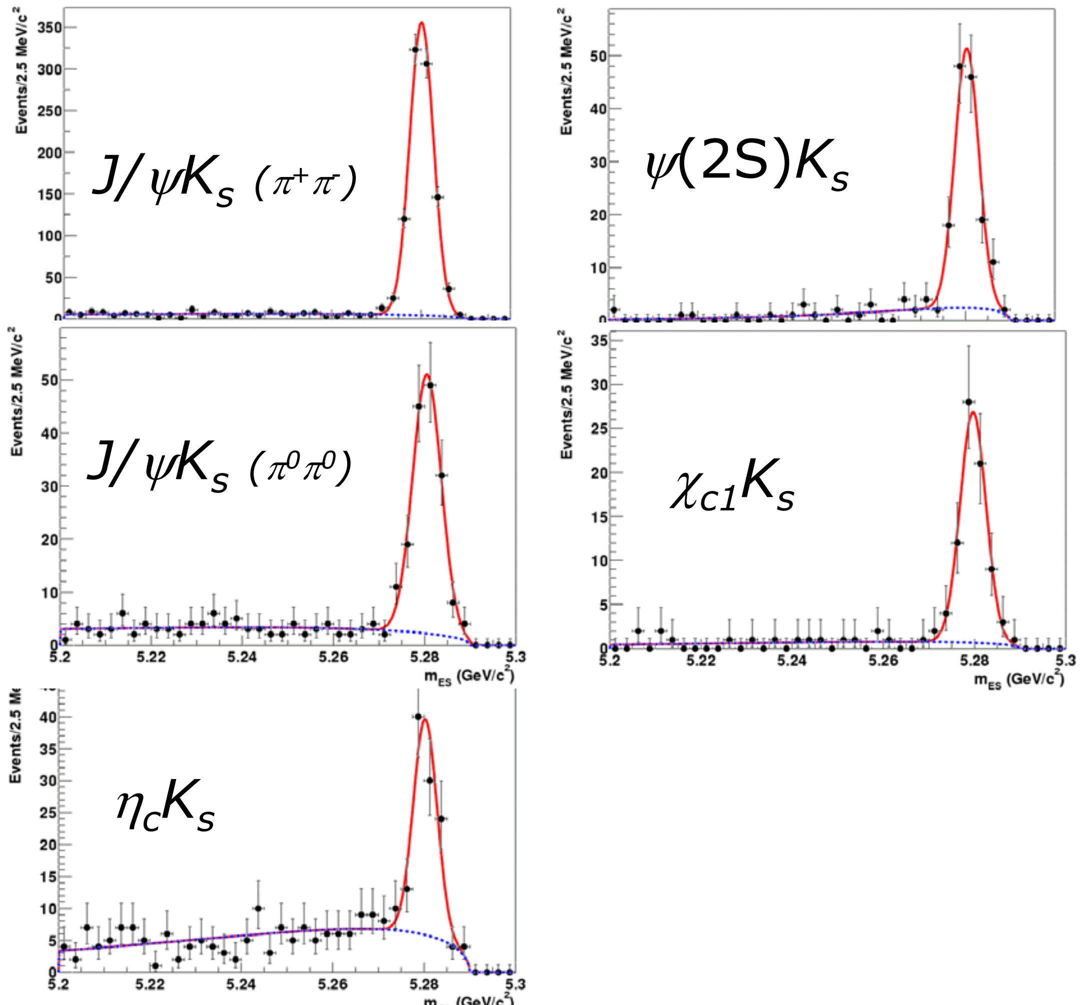


Category	Efficiency (ε)	Mistag Fr. (w)	Q=ε(1-2w)²
Lepton	9.1 ± 0.2	3.3 ± 0.6	7.9 ± 0.3
Kaon1	16.7 ± 0.2	9.9 ± 0.7	10.7 ± 0.4
Kaon2	19.8 ± 0.3	20.9 ± 0.8	6.7 ± 0.4
Inclusive	20.0 ± 0.3	31.6 ± 0.9	2.7 ± 0.3
Total	**65.6 ± 0.5**		**28.1 ± 0.7**

This new tagging method increases Q by 7% compared to the method used in our previous result: PRL87 (Aug 01).

$\sin 2\beta$ golden sample: $(c\bar{c})K_S$ ($\eta_f = -1$)

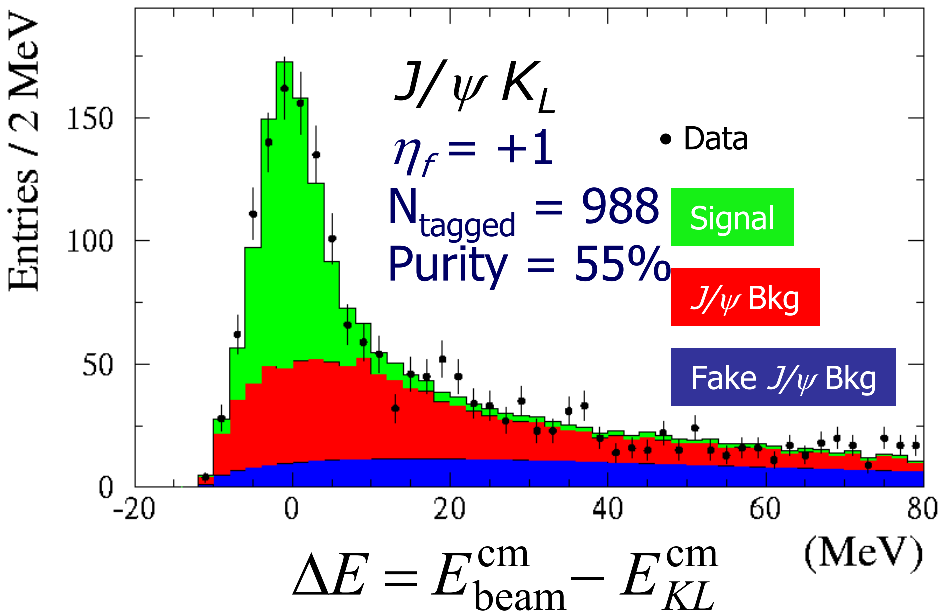
Sample	N_{tagged}	Purity
$J/\psi\ K_S(\pi^+\pi^-)$	974	97%
$J/\psi\ K_S(\pi^0\pi^0)$	170	89%
$\psi(2S)\ K_S$	150	97%
$\chi_{c1}\ K_S$	80	95%
$\eta_c\ K_S$	132	73%
Total	**1506**	**92%**

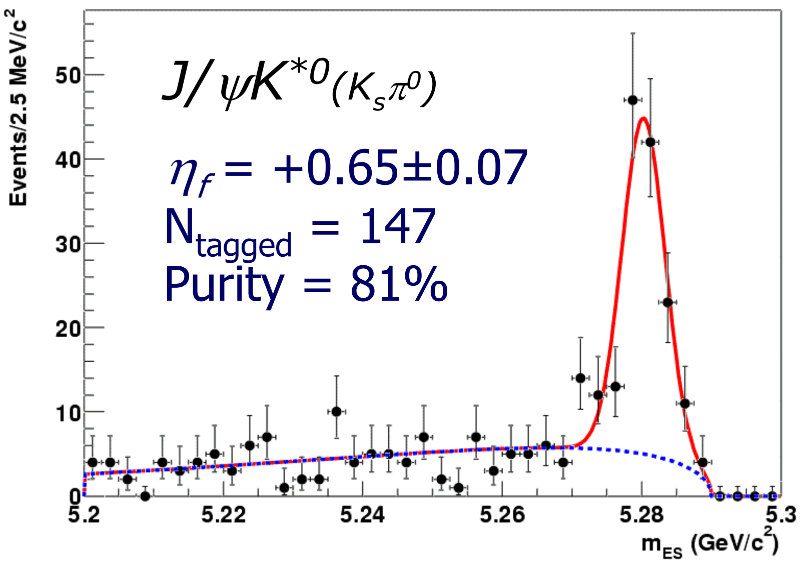


Recent addition:
$B^0 \rightarrow \eta_c K_S$
where $\eta_c \rightarrow K^+K^-\pi^0$ or
$K^+K_S\pi^-$

Energy-substituted mass $m_{ES} = \sqrt{\left(E_{beam}^{cm}\right)^2 + \left(p_B^{cm}\right)^2}$

$\sin 2\beta$ samples: $J/\psi\ K_L$ and $J/\psi\ K^{*0}$





- Use m_B constraint to determine p_{KL}
- J/ψ background shape estimated from Monte Carlo
- Fake J/ψ background shape estimated from data sidebands

- Vector-Vector mode: mixture of CP+ and CP-
- Use angular analysis to determine CP- fraction
- Treat CP- component as dilution $\Rightarrow$ effective η_f

sin2β likelihood fit

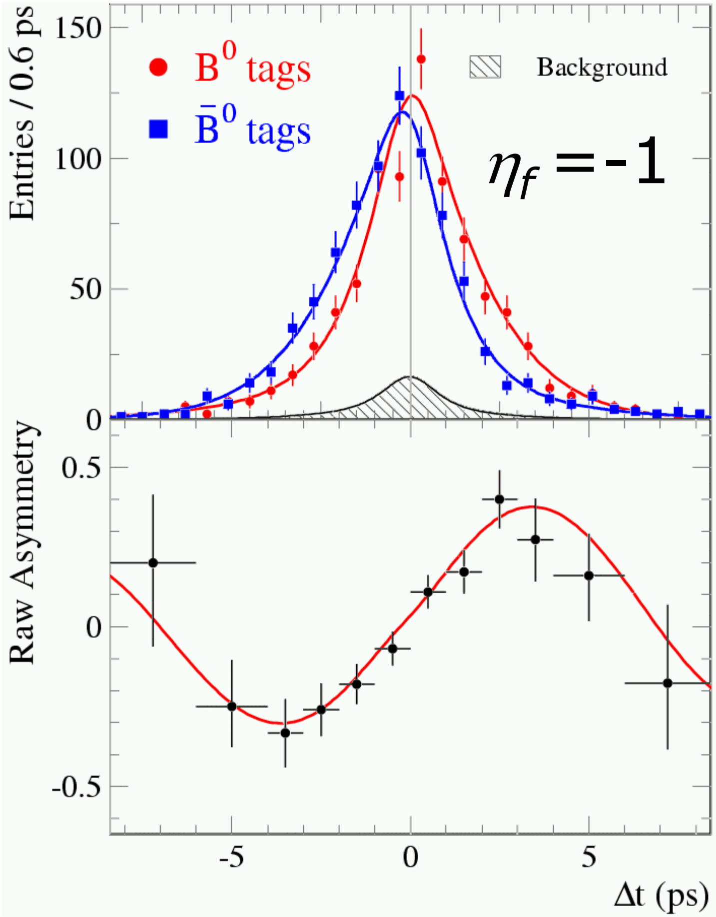
- Simultaneous unbinned maximum likelihood fit of CP and mixing samples

Fit Parameters	34 total	
sin2β	1	B_{CP}
Mistag fractions w for B^0 and B^0 tags	8	B_{flav}
Signal Δt resolution function R	8	B_{flav}
Background properties (mostly from m_{ES} sidebands in data)	17	$B_{CP}+B_{flav}$

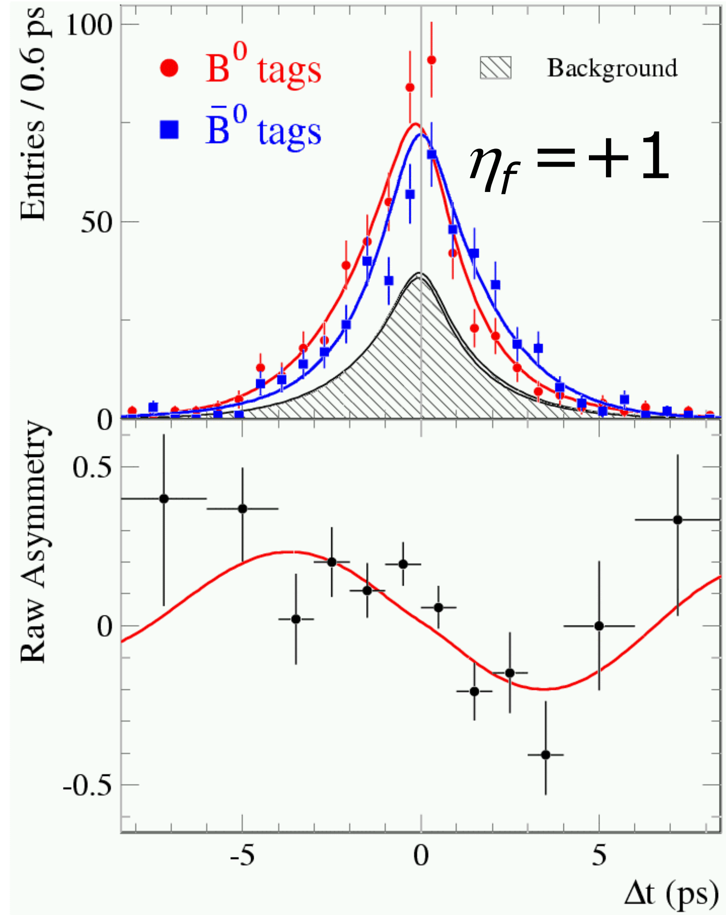
B lifetime fixed (PDG 2002) $\tau_B = 1.542$ ps

Mixing frequency fixed (PDG 2002) $\Delta m_d = 0.489\ ps^{-1}$

Fit results



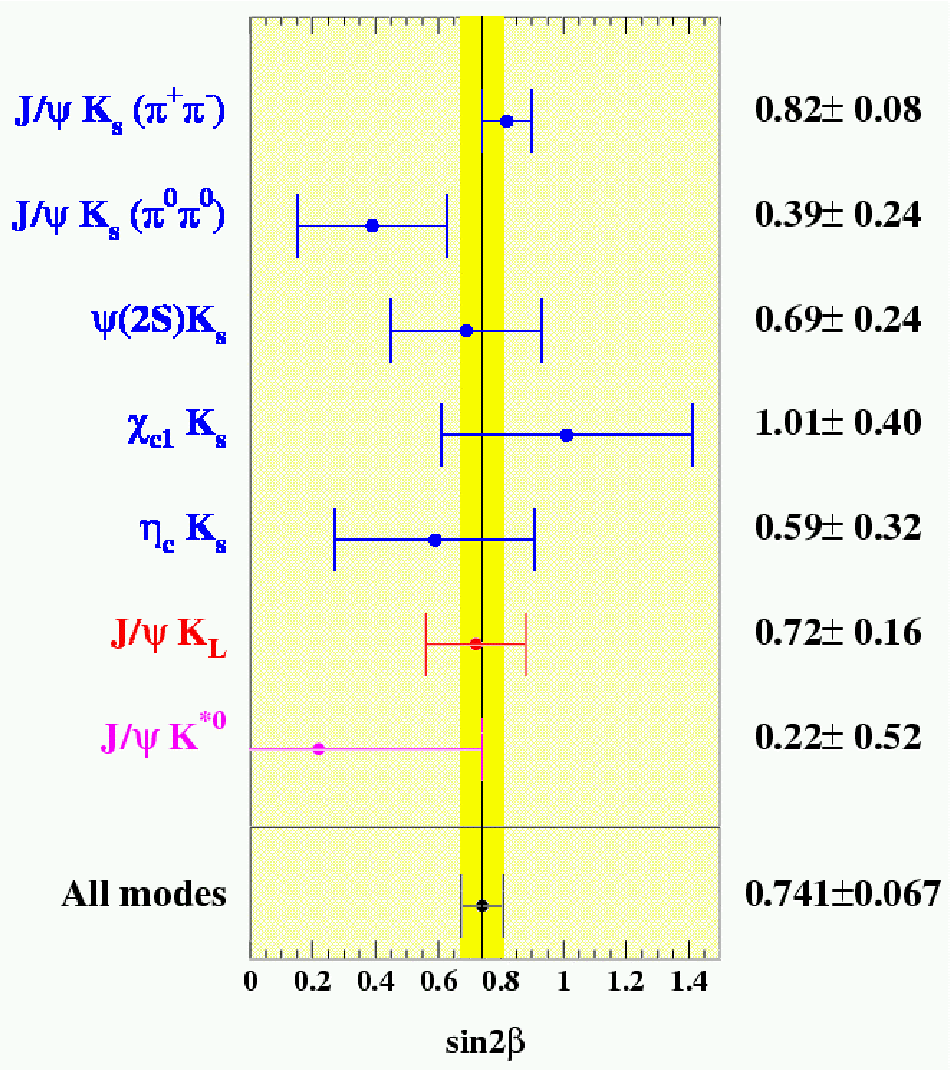
$\sin 2\beta$ = 0.755 ± 0.074



$\sin 2\beta$ = 0.723 ± 0.158

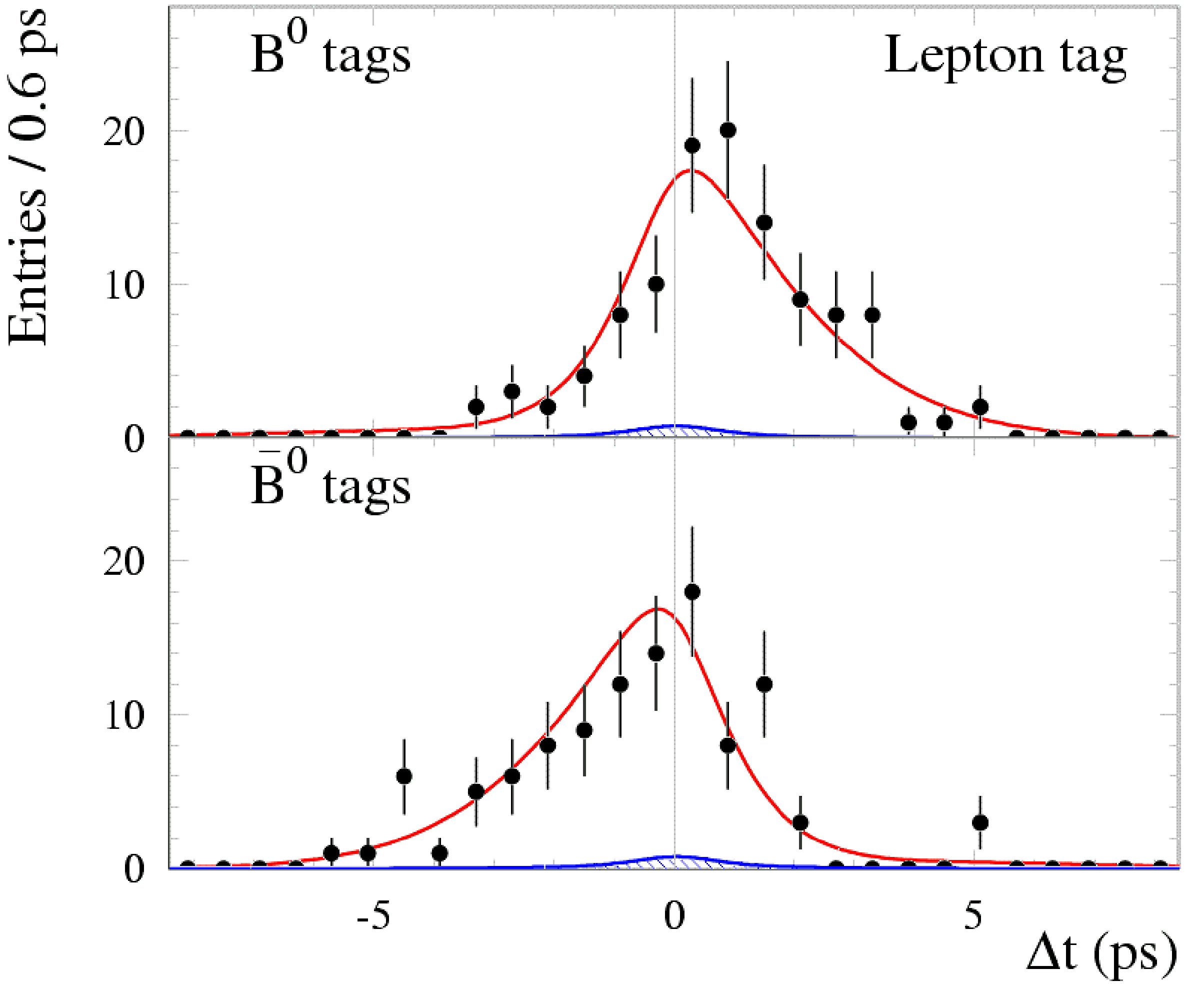
$\sin 2\beta$ = 0.741 ± 0.067 (stat) ± 0.033 (sys)

sin2β fit results by decay mode



Consistency of CP Channels: $P(\chi^2) = 57\%$

Dramatic effect in golden modes with lepton tag



$(c\bar{c})K_S$ with lepton tag

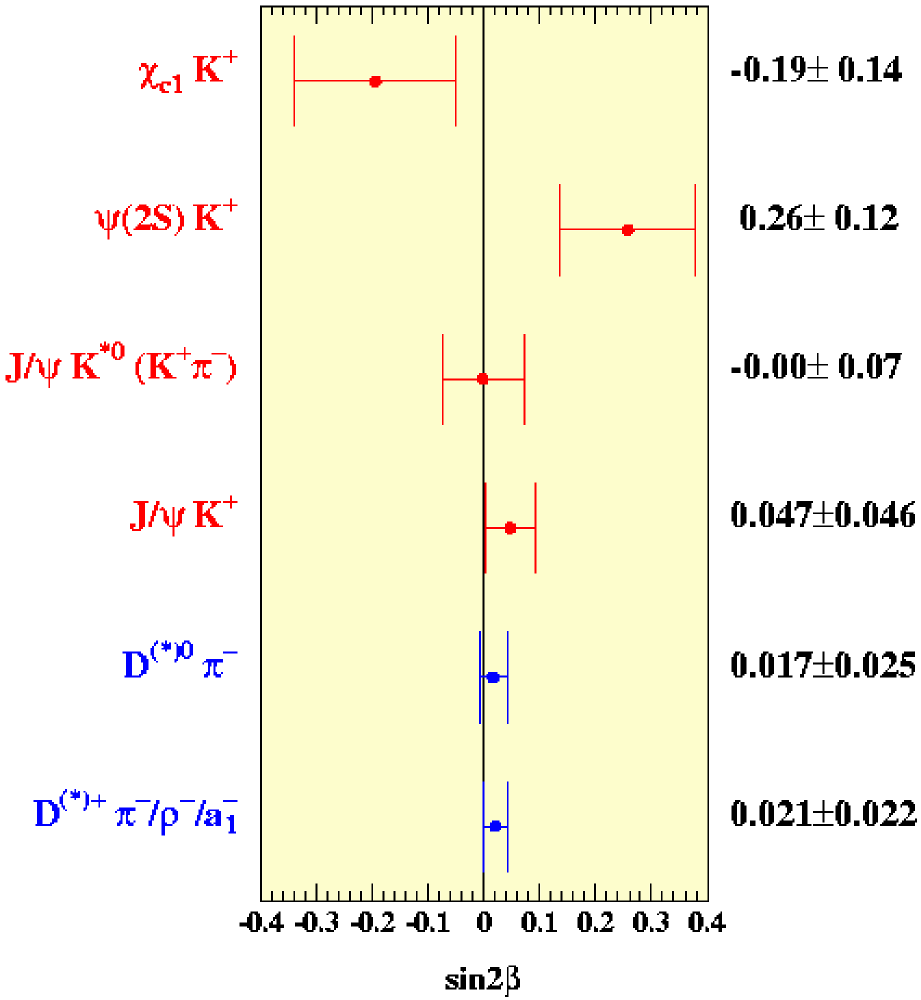
$N_{tagged} = 220$
Purity = 98%

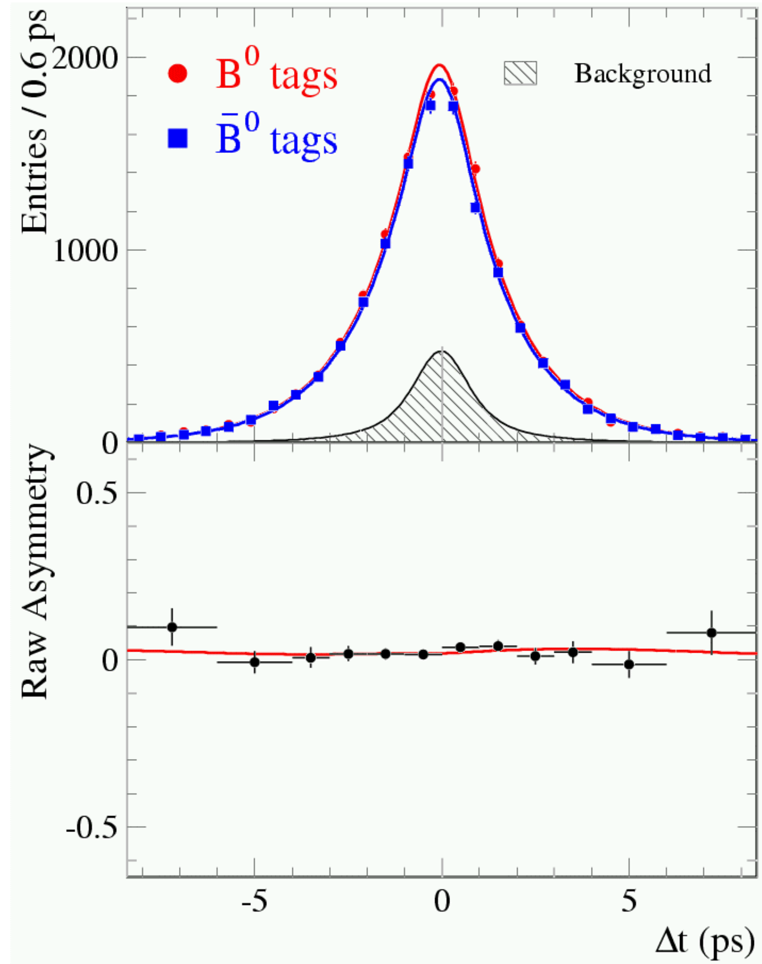
Mistag fraction 3.3%

$\sigma_{\Delta t}$ 20% better than other tag categories

$\sin2\beta = 0.79 \pm 0.11$

Cross-check on data control samples





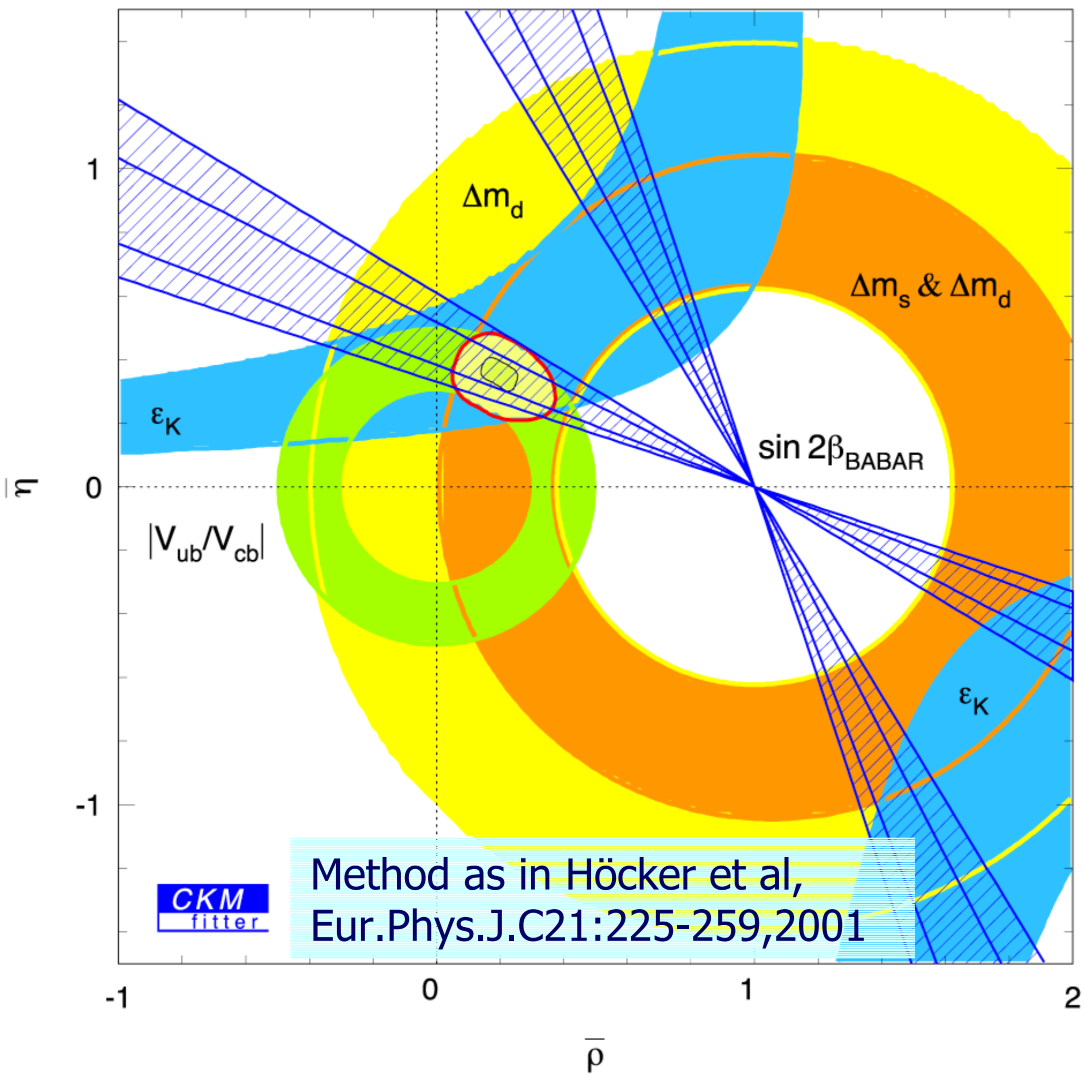
Observed no asymmetry as expected

Sources of Systematic Error

	$\sigma(\sin 2\beta)$
Description of background events	0.017
CP content of background components	
Background shape uncertainties	
Composition and content of $J/\psi\ K_L$ background	0.015
Δt resolution and detector effects	0.017
Silicon detector alignment uncertainty	
Δt resolution model	
Mistag differences between B_{CP} and B_{flav} samples	0.012
Fit bias correction	0.010
Fixed lifetime and oscillation frequency	0.005
TOTAL	0.033

Steadily reducing systematic error: July 2002 = 0.033
July 2001 = 0.05

Standard Model comparison



One solution for β is in excellent agreement with measurements of unitarity triangle apex

$$\rho = \rho\,(1-\lambda^2/2)$$

$$\eta = \eta\,(1-\lambda^2/2)$$

Search for non-Standard Model effects in $(c\bar{c})K_S$

- If another amplitude (new physics) contributes a different phase, then

$$A_{CP}(\Delta t) = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

$$S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

- In the Standard Model $|\lambda_f| = 1$ (which we assume in the nominal $\sin 2\beta$ fit)

$$S_f \to -\eta_f \sin 2\beta \qquad C_f \to 0$$

- Fit $|\lambda_f|$ and S_f using the clean $(c\bar{c})K_s$ modes
  ($\eta_f = -1$, $N_{tagged} = 1506$, Purity = 92%):

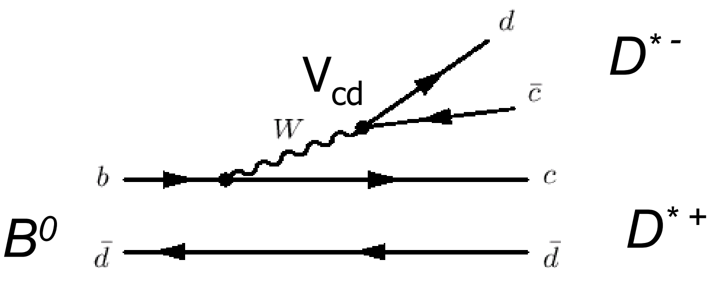
$$|\lambda_f| = 0.948 \pm 0.051\,(\mathrm{stat}) \pm 0.017\,(\mathrm{syst})$$

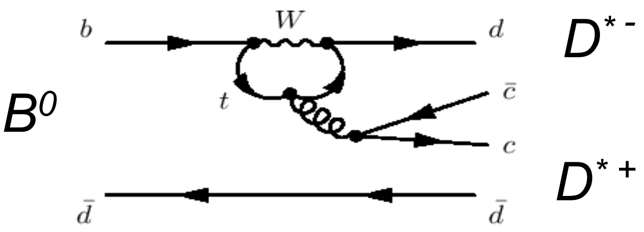
$$S_f = 0.759 \pm 0.074\,(\mathrm{stat}) \pm 0.032\,(\mathrm{syst})$$

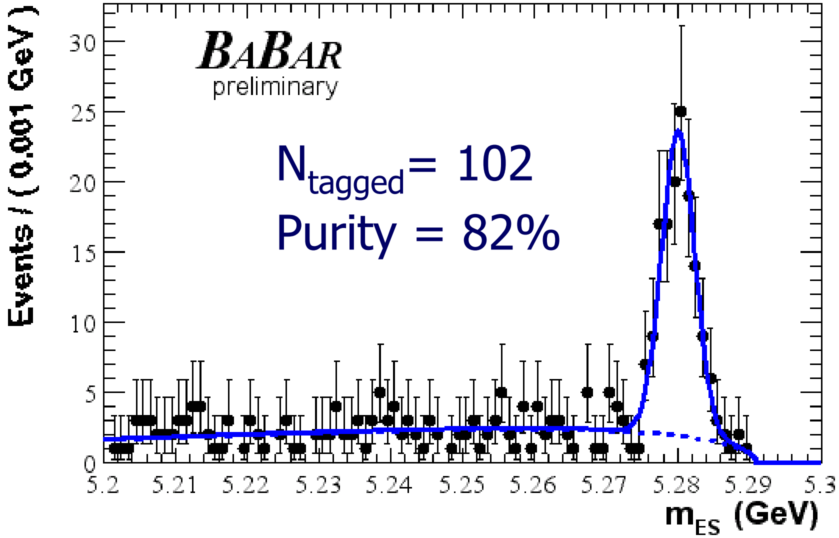
Consistent with the Standard Model expectation of $|\lambda_f|=1$ and nominal fit $\sin 2\beta = 0.755 \pm 0.074$ for $(c\bar{c})K_s$ modes alone.

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

- Cabbibo-suppressed mode with tree level weak phase same as b → c$\bar{c}$s
- Penguin contribution uncertain, expected to be small < 0.1 Tree
- Not a CP eigenstate, mixture of CP even (L=0,2) and CP odd (L=1)
  - Resolve using angular analysis (in transversity basis)





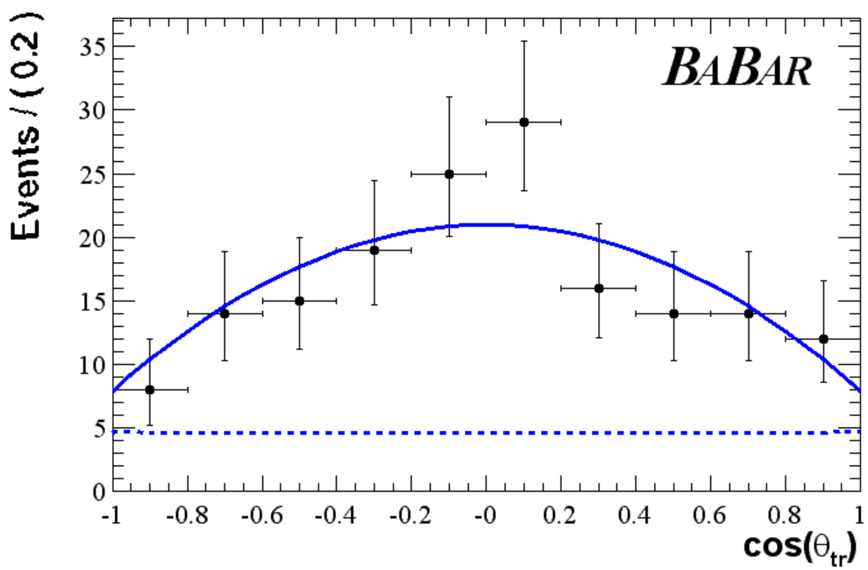


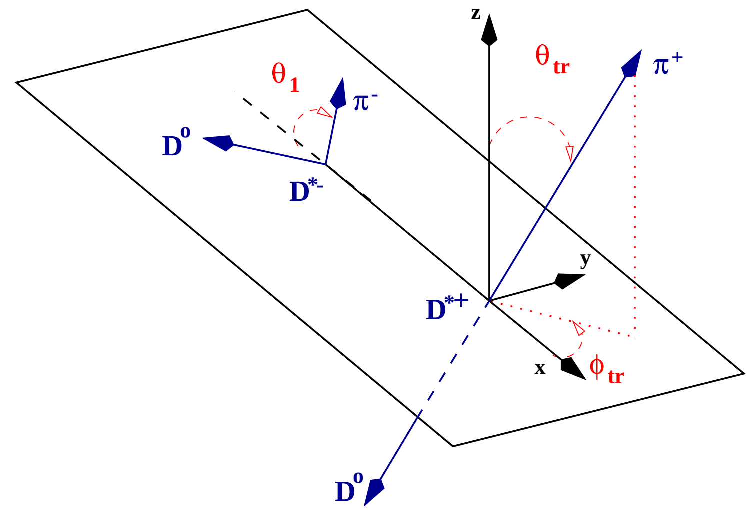
Reconstruct $D^{*+} \to D^0\pi^+$ or $D^+\pi^0$, but not both to π^0 mode

CP composition of $B^0 \rightarrow D^{*+} D^{*-}$

- We measure CP odd fraction (corrected for acceptance) to be small:

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





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

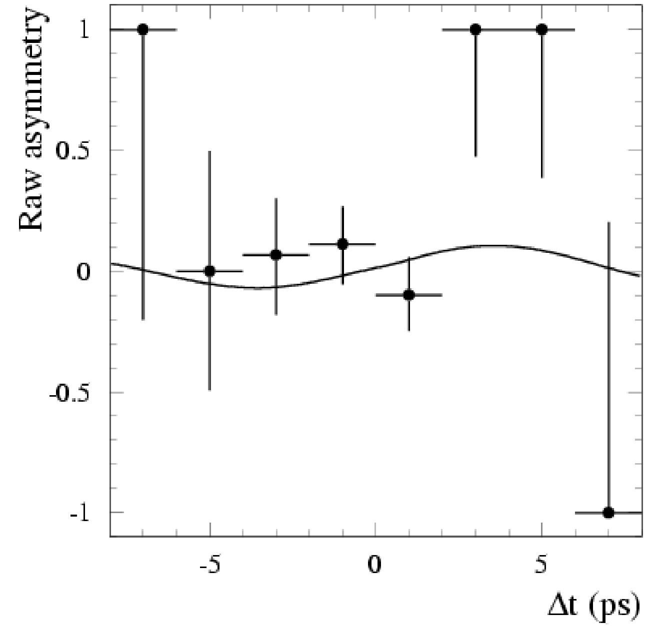
CP asymmetry fit $B^0 \rightarrow D^{*+} D^{*-}$

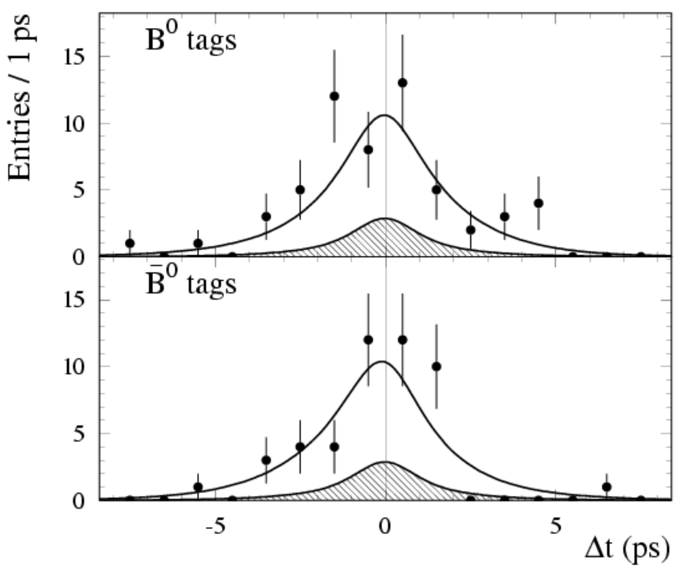
- Improved fitting strategy since winter conferences:
  - Parameterize in terms of CP even (λ_+) and odd ($\lambda_\perp$) components, include angular information from partial-wave analysis
  - Fix CP odd component to
    $\lambda_\perp=1$, $\text{Im}(\lambda_\perp) = -0.741$

$$|\lambda_+| = 0.98 \pm 0.25 \text{ (stat)} \pm 0.09 \text{ (syst)}$$
$$\text{Im}(\lambda_+) = 0.31 \pm 0.43 \text{ (stat)} \pm 0.10 \text{ (syst)}$$

If penguins are negligible, then

$$\text{Im}(\lambda_+) = -\sin 2\beta$$

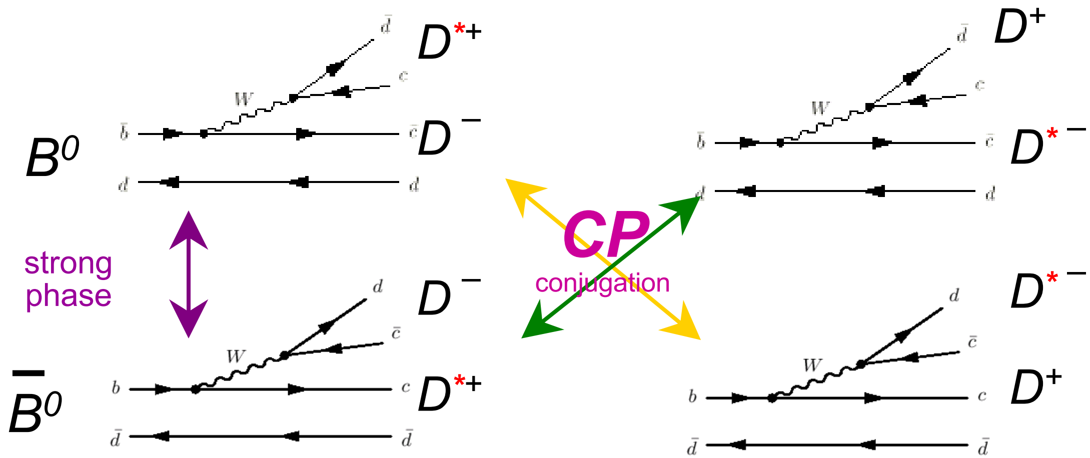




$\text{Im}(\lambda_+)$ measurement ~2.7σ from BaBar $\sin 2\beta$ in charmonium, assuming no penguins.

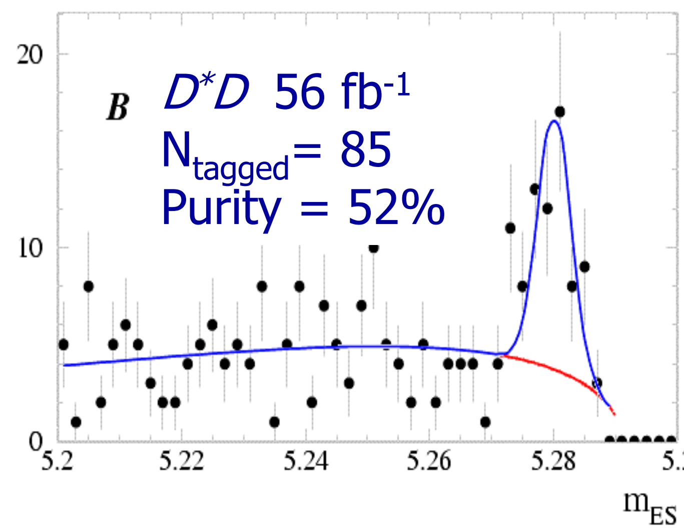
($b \to c\bar{c}d$) mode $B^0 \to D^{*+}D^-$

- D^*D not CP eigenstate
- Possible strong phase contribution (and still have penguins)
- Different (but related) decay time distributions for
  - $B^0 \to D^{*+}D^-$
  - $B^0 \to D^{*-}D^+$



S_{+-} = - 0.43 ± 1.41 ± 0.20
C_{+-} = 0.53 ± 0.74 ± 0.13

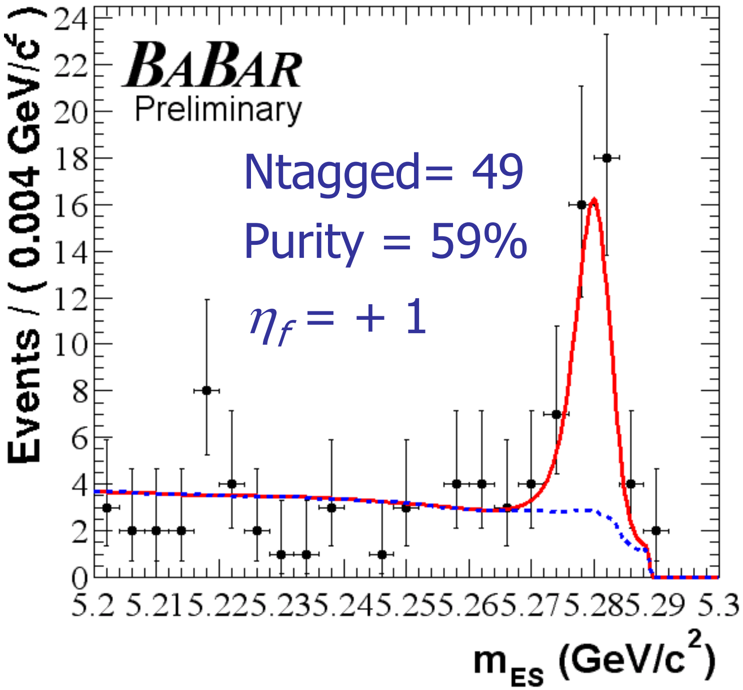
S_{-+} = 0.38 ± 0.88 ± 0.05
C_{-+} = 0.30 ± 0.50 ± 0.08

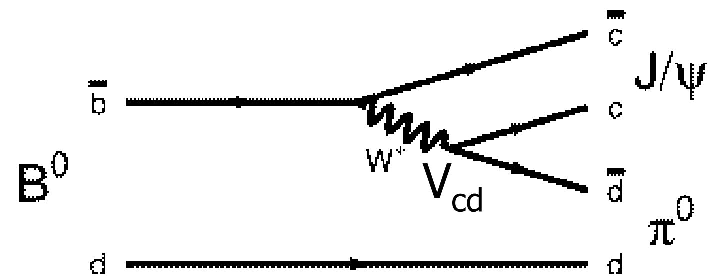


Update to full data set in progress

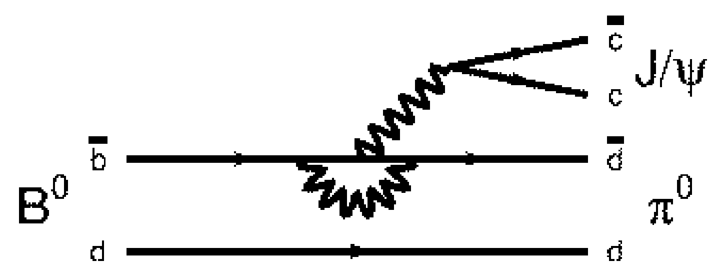
($b \to c\bar{c}d$) mode $B^0 \to J/\psi\, \pi^0$

- Cabibbo and color-suppressed mode with comparable tree and penguin contributions



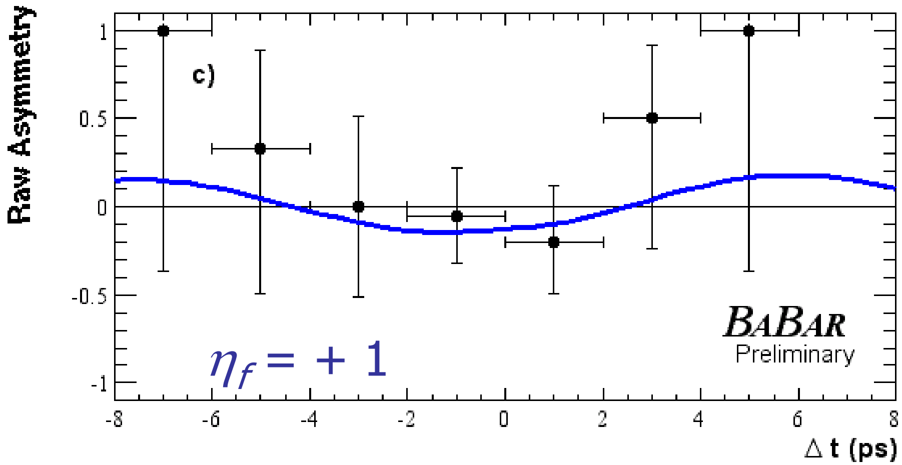


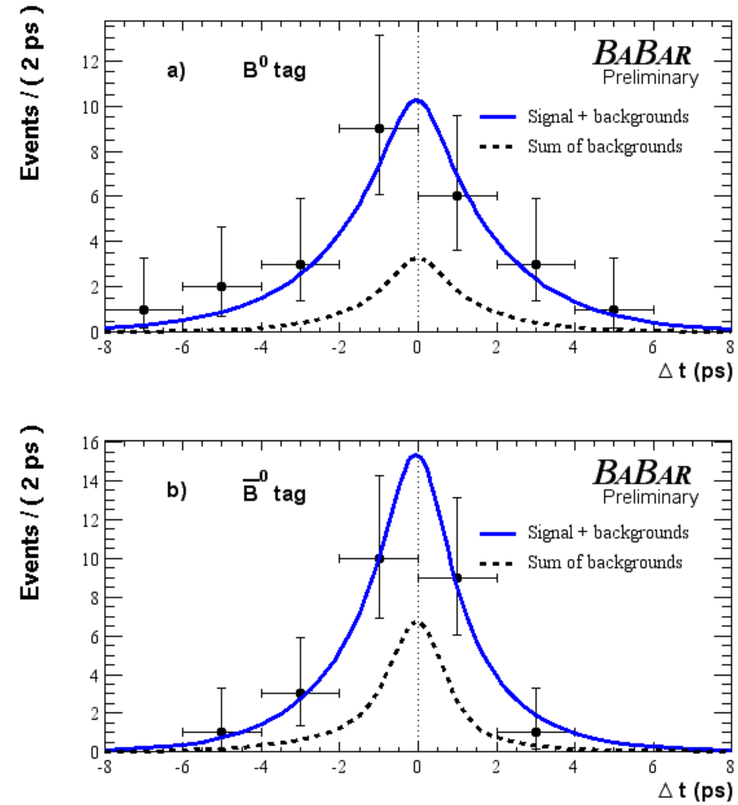
Tree: $\sim V_{cb}V_{cd}^* \sim O(\lambda^3)$
same weak phase as $b \to c\bar{c}s$



Penguin: $\sim V_{cb}V_{cd}^* + V_{ub}V_{ud}^* \sim O(\lambda^3)$
adds additional weak phase

CP asymmetry fit for $B^0 \to J/\psi\ \pi^0$





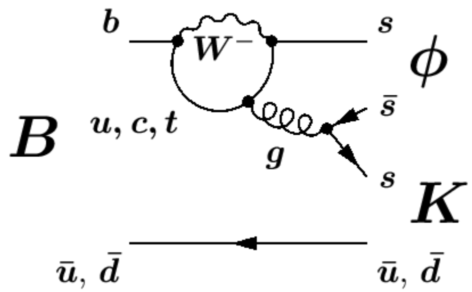
$C_{J/\psi\ \pi^0} = 0.38 \pm 0.41\ (\text{stat}) \pm 0.09\ (\text{syst})$

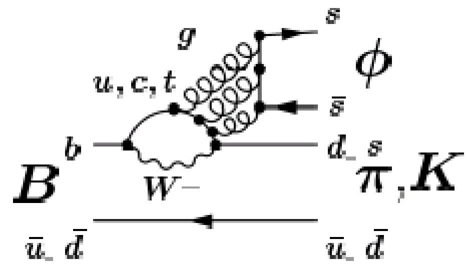
$S_{J/\psi\ \pi^0} = 0.05 \pm 0.49\ (\text{stat}) \pm 0.16\ (\text{syst})$

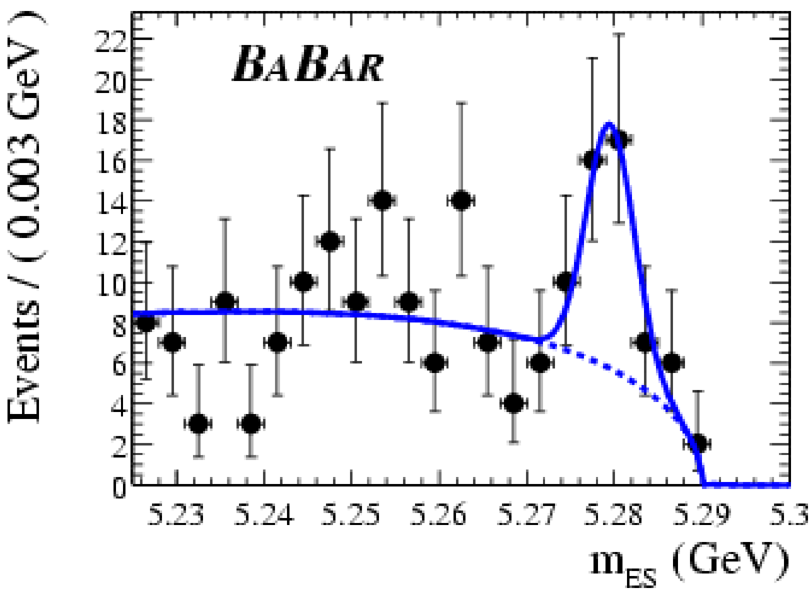
In absence of penguins $C_{\psi\pi}=0$, $S_{\psi\pi} = -\sin 2\beta$

sin2β from penguin mode $B^0 \to \phi K_S$

- Charmless decay dominated by ($b \to s\bar{s}s$) gluonic penguins
  - Weak phase same as $b \to c\bar{c}s$, but sensitive to new physics in loops





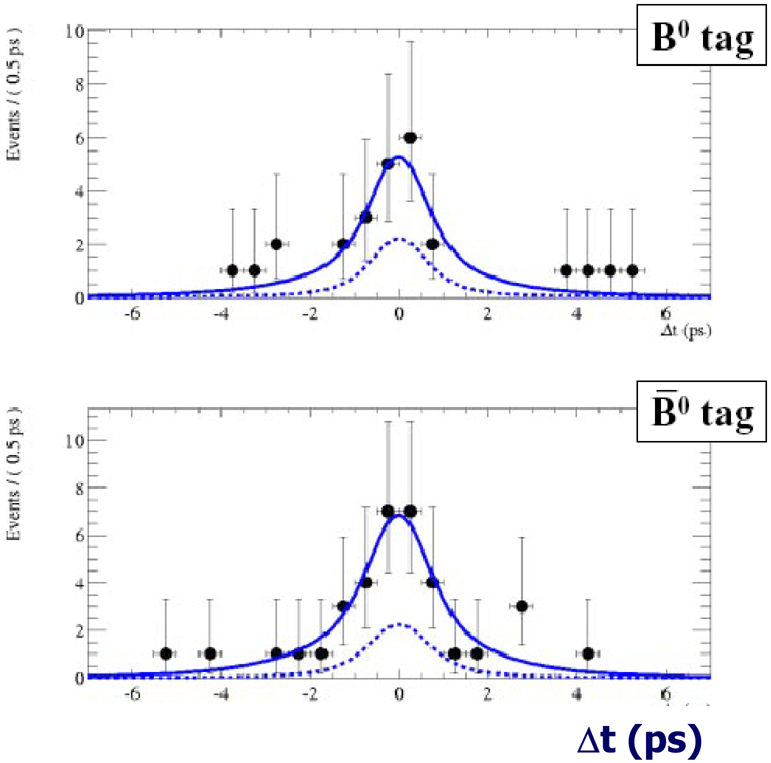


- Small branching fraction O(10^{-5})
- Significant background from $q\bar{q}$ continuum
- Using only $\phi \to K^+K^-$

N_{tagged} = 66
Purity = 50%
η_f = - 1

CP asymmetry fit for $B^0 \to \phi K_S$

- Fix $|\lambda_{\phi K}| = 1$, fit: $S_{\phi K} = -0.19 \,^{+0.52}_{-0.50}$ (stat) $\pm$ 0.09 (syst)



- Cross check on $B^+ \to \phi K^+$
  $S_{\phi K} = 0.26 \pm 0.27$

- Analysis of $B^0 \to \eta' K_S$ in progress

If no new physics, $S_{\phi K} = \sin 2\beta$

Conclusion

- New measurement of $\sin 2\beta$ from charmonium modes (88 x10^6 $B\bar{B}$)

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

Submitted to PRL July 17, 2002
(hep-ex/0207042)

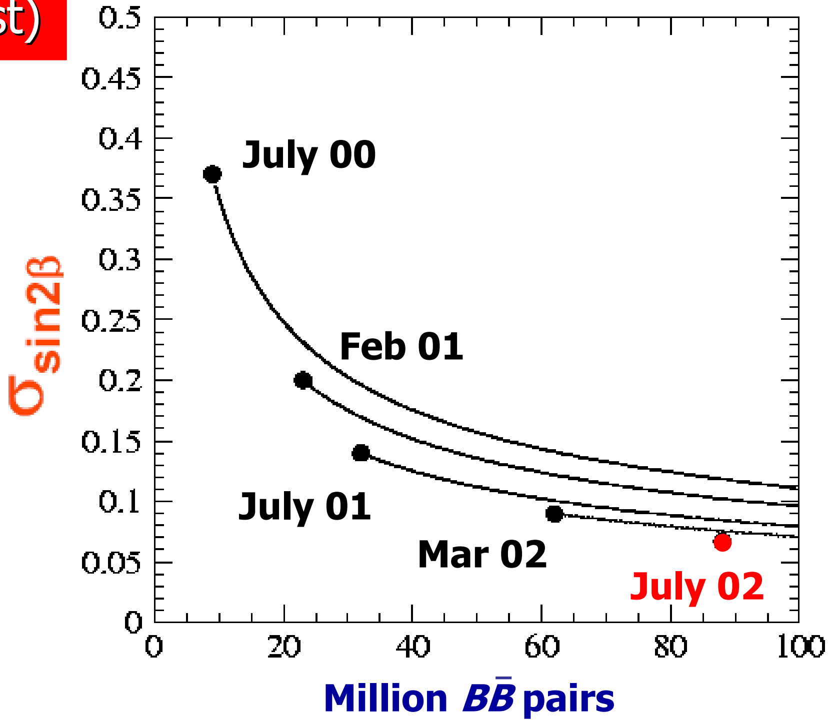
- Begun to probe the same CP-violating phase and possibly new physics via penguin modes:

  $B^0 \to \phi K^0_S$
  $B^0 \to J/\psi\, \pi^0$
  (First BaBar results)

  and open charm modes:

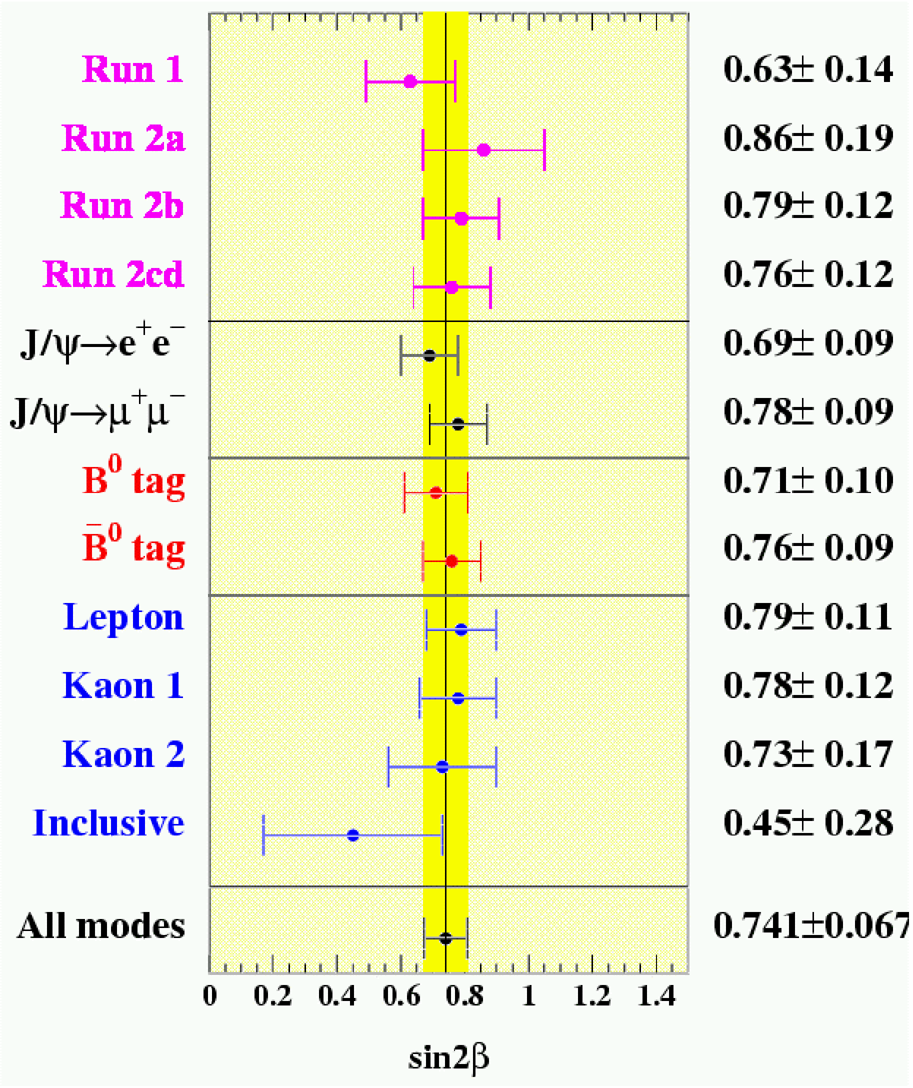
  $B^0 \to D^{*+} D^{*-}$
  $B^0 \to D^{*+} D^-$

Results have been improving by more than just luminosity gain



The Standard Model remains unscathed, but the high statistics future of BaBar will provide further opportunities to challenge the theory.

sin2β in subsamples



Tagging performance

Category	Efficiency (ε)	Mistag Fr. (ω)	δ Mistag	$Q=\varepsilon(1-2\omega)^2$
Lepton	**9.1 $\pm$ 0.2**	**3.3 $\pm$ 0.6**	**-1.4 $\pm$ 1.1**	**7.9 $\pm$ 0.3**
KPiorK	**16.7 $\pm$ 0.2**	**9.9 $\pm$ 0.7**	**-1.1 $\pm$ 1.1**	**10.7 $\pm$ 0.4**
KorPi	**19.8 $\pm$ 0.3**	**20.9 $\pm$ 0.8**	**-4.2 $\pm$ 1.1**	**6.7 $\pm$ 0.4**
Inclusive	**20.0 $\pm$ 0.3**	**31.6 $\pm$ 0.9**	**-2.0 $\pm$ 1.2**	**2.7 $\pm$ 0.3**
Total	**65.6 $\pm$ 0.5**			**28.1 $\pm$ 0.7**

Monte Carlo correction

We evaluated the size of any potential bias on sin2β by fitting the full MC in two ways:

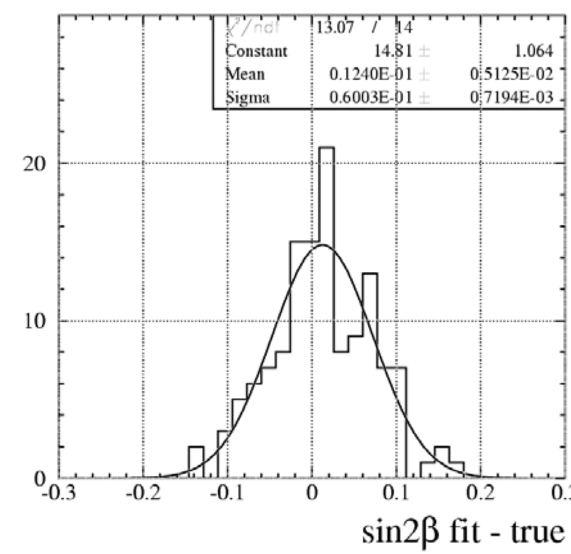
- Fitting data-sized signal MC samples with mistag fractions and Δt resolution fixed to the MC truth values (see plot).

  Average bias = $+0.012 \pm 0.005$.
- Same as above except mistag fractions and Δt resolution from Breco MC.

  Average bias = $+0.014 \pm 0.005$.

One possible source of bias comes from neglecting the known correlation between the mistag fractions (or dilutions) and sigma Δt.

- Estimates from toy and full MC inticate 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.