Measurement of sin2β with the BaBar Detector

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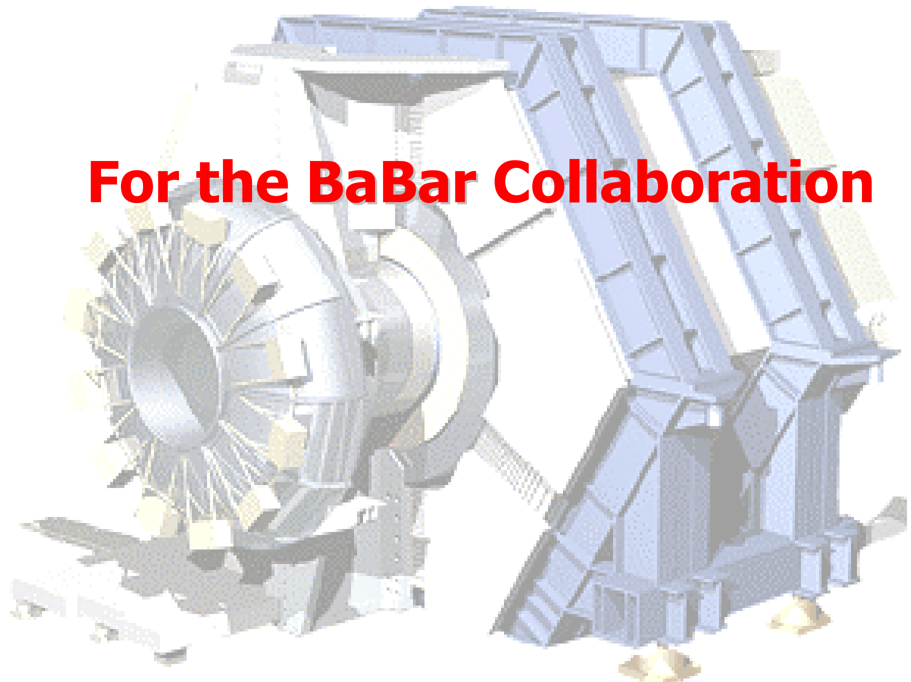
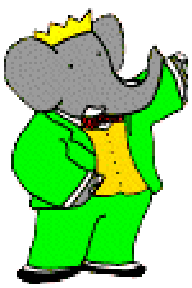


For the BaBar Collaboration



Flavor Physics and CP Violation Conference

Philadelphia, 16 May 2002

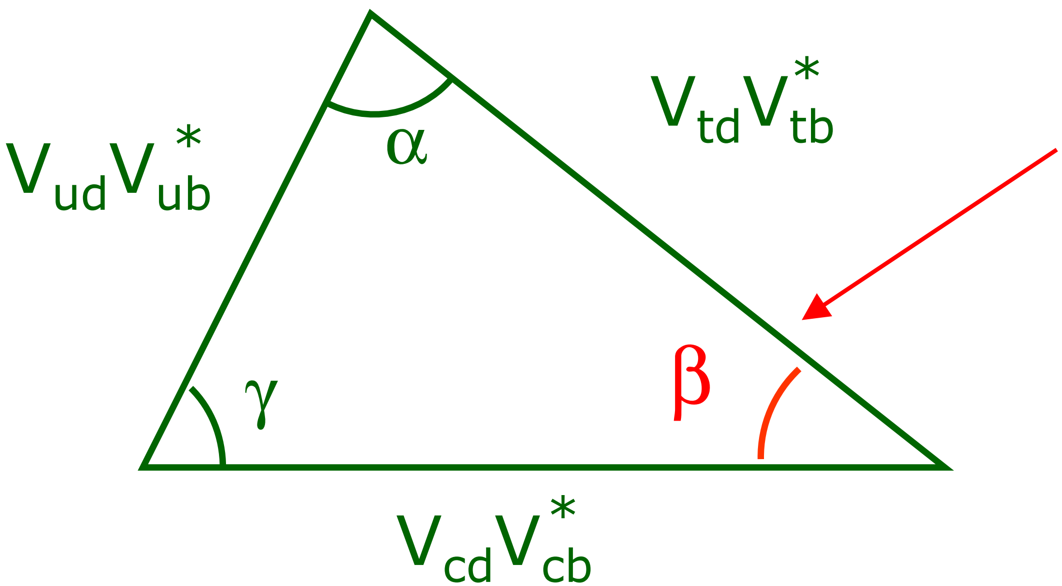
CP Violation in Standard Model

Standard Model with 3 generations accommodates CP violation through a phase in CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Unitarity of the CKM Matrix

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



Measure sin2β in

$B^0 \rightarrow J/\psi\ K_{S,L}, K^{*0}$

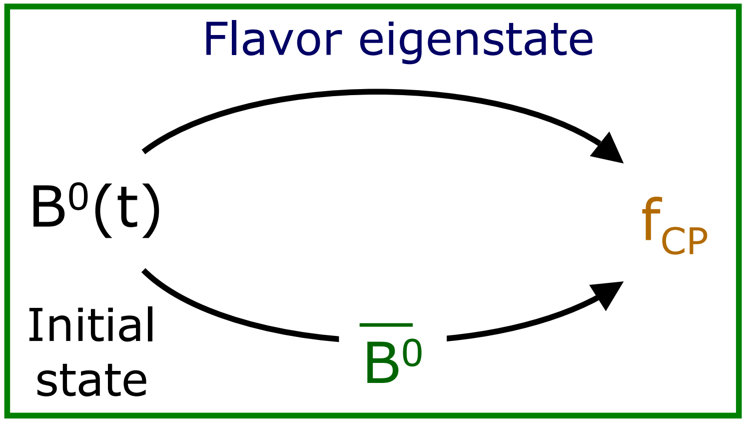
$B^0 \rightarrow \chi_c\ K_S$

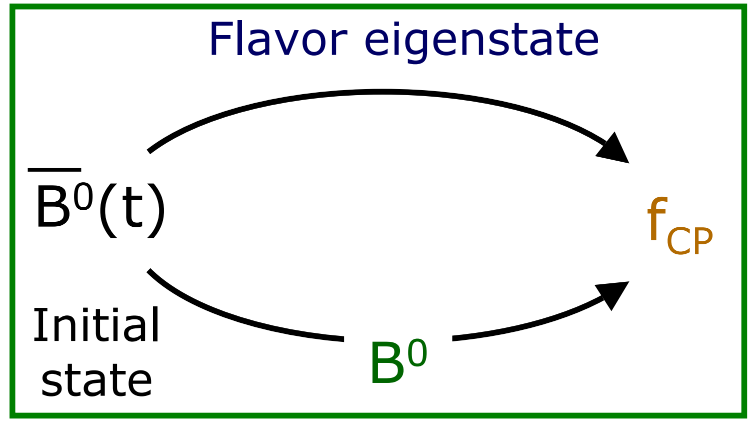
$B^0 \rightarrow \eta_c\ K_S$

$B^0 \rightarrow D^*D^{(*)}$

$B^0 \rightarrow \Phi\ K_s$

CP Violation due to Mixing and Decay





$$f(B^0_{phys} \to f_{CP}, t) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\,[1 + C_f \cos(\Delta m_d t) - S_f \sin(\Delta m_d t)]$$

$$f(\overline{B}^0_{phys} \to f_{CP}, t) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|}\,[1 - C_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t)]$$

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

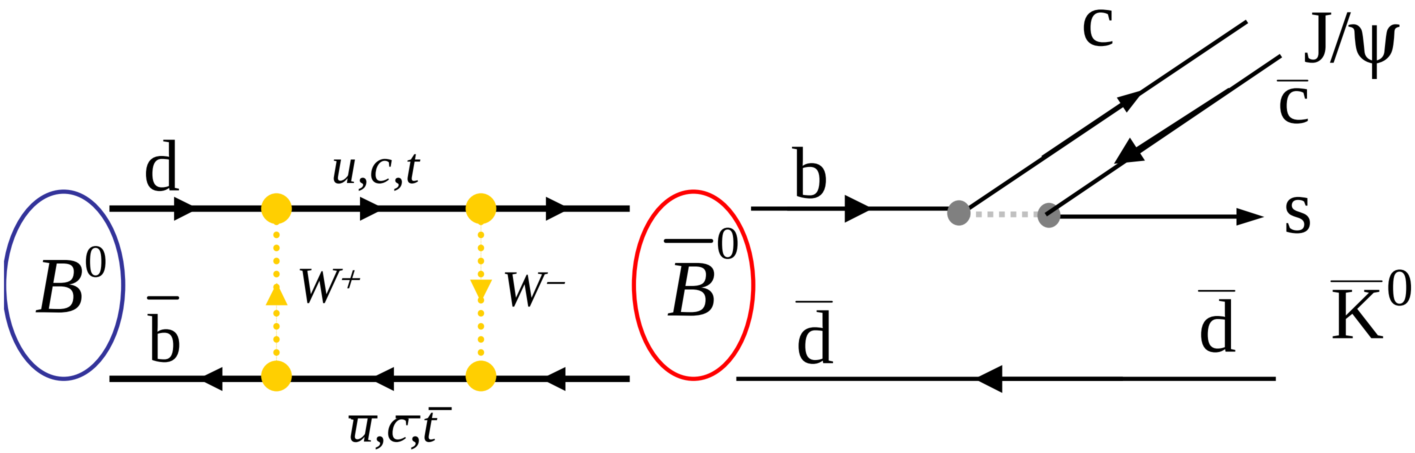
$$C_f = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

Probe of direct CP violation: $\left|\lambda_{f_{CP}}\right| \neq 1$

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

Sensitive to phase of λ even without direct CP Violation

Golden Decay Mode: $B^0 \rightarrow J/\psi\, K^0_S$



K⁰ mixing

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

$$\lambda_{J/\psi\ K^0_{L,S}} = \eta_{CP}\, e^{-i2\beta}$$

- Theoretically clean way to measure the phase of λ ($\sin 2\beta$)
- Clean experimental signature
- Large branching fraction compared to other CP eigenstates

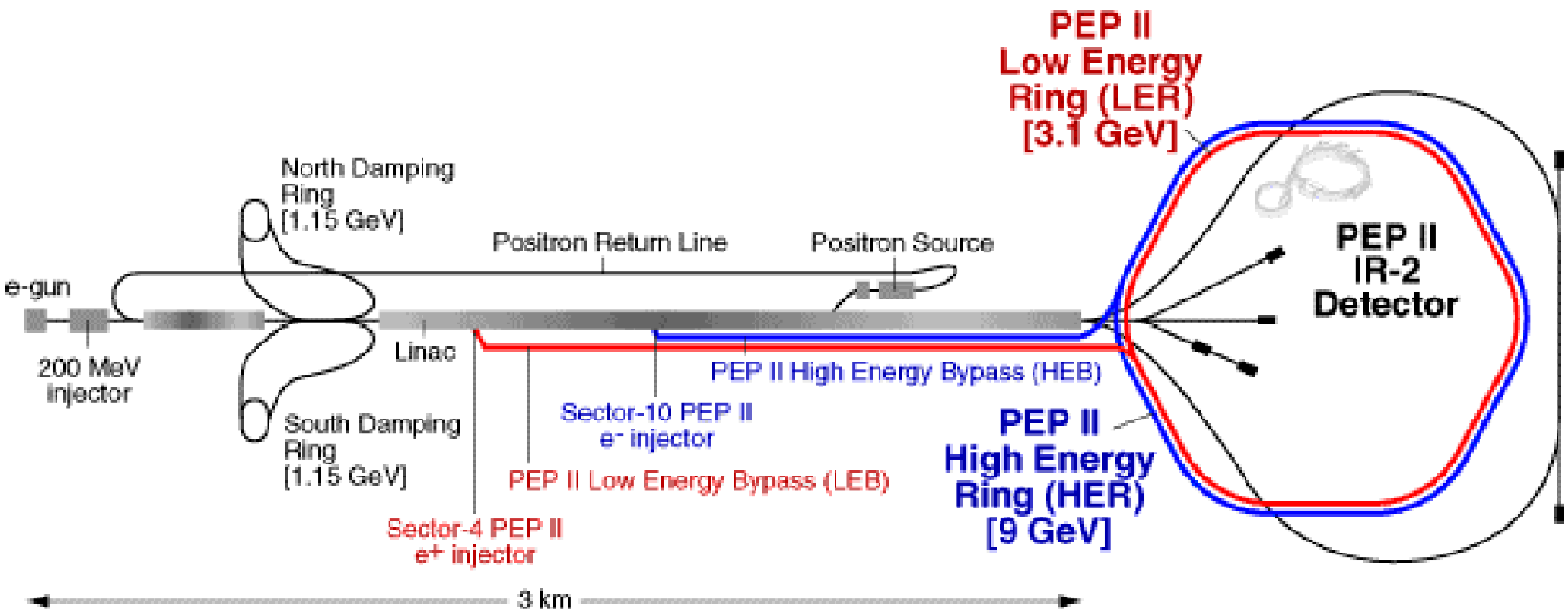
Time-dependent CP asymmetry

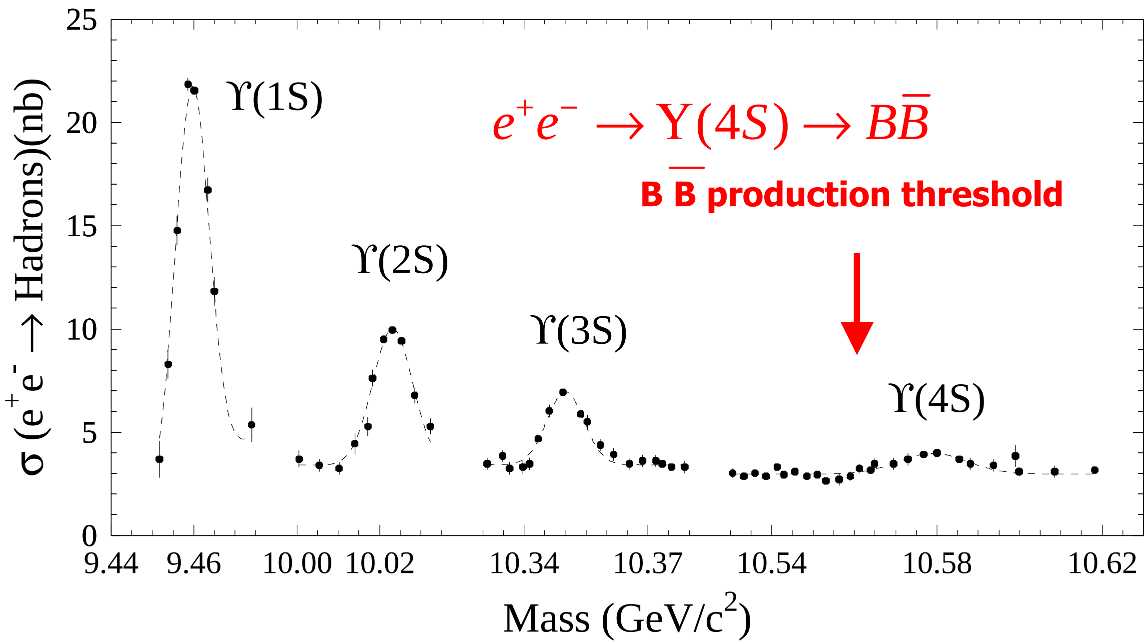
$$A_{CP}(t) = -\eta_{CP} \sin 2\beta\ \sin(\Delta m\ t)$$

"Golden Modes"

- $\eta_{CP} = -1$
  - ✓ $B^0 \rightarrow J/\psi, \psi(2s), \chi_{c1}\ K^0_S$
- $\eta_{CP} = +1$
  - ✓ $B^0 \rightarrow J/\psi\ K^0_L$

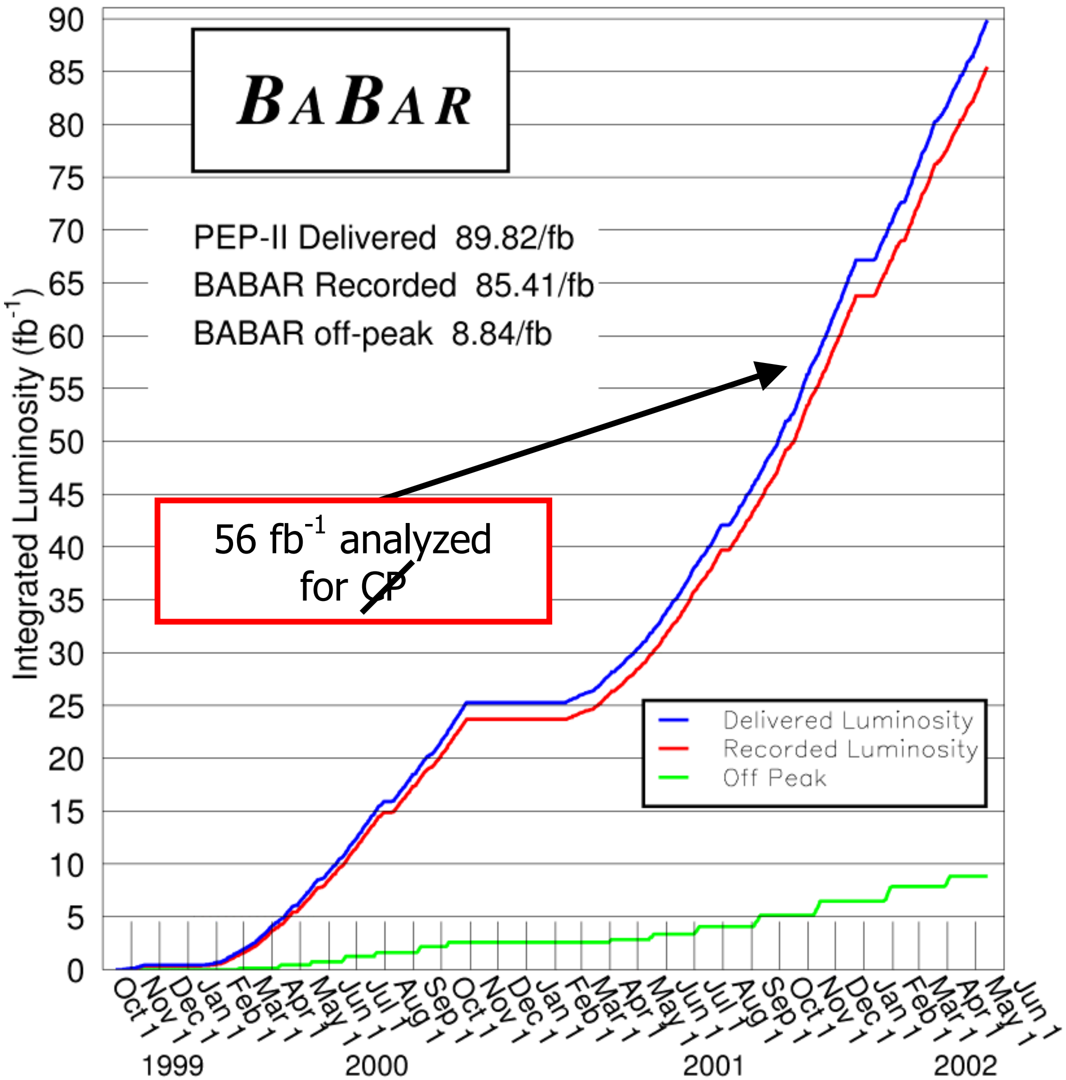
PEP-II Asymmetric B-Factory at SLAC





- 9 GeV e^- on 3.1 GeV e^+
- $\Upsilon(4S)$ boost in lab frame
  - $\beta\gamma = 0.55$

B-Factory Performance



PEP-II top luminosity:
$4.60 \times 10^{33} cm^{-2}s^{-1}$
(design 3.0×10^{33})

Top recorded Lumi/week: $1.8\ fb^{-1}$

Top recorded Lumi/24h: $303\ pb^{-1}$

Top recorded Lumi/8h: $105\ pb^{-1}$

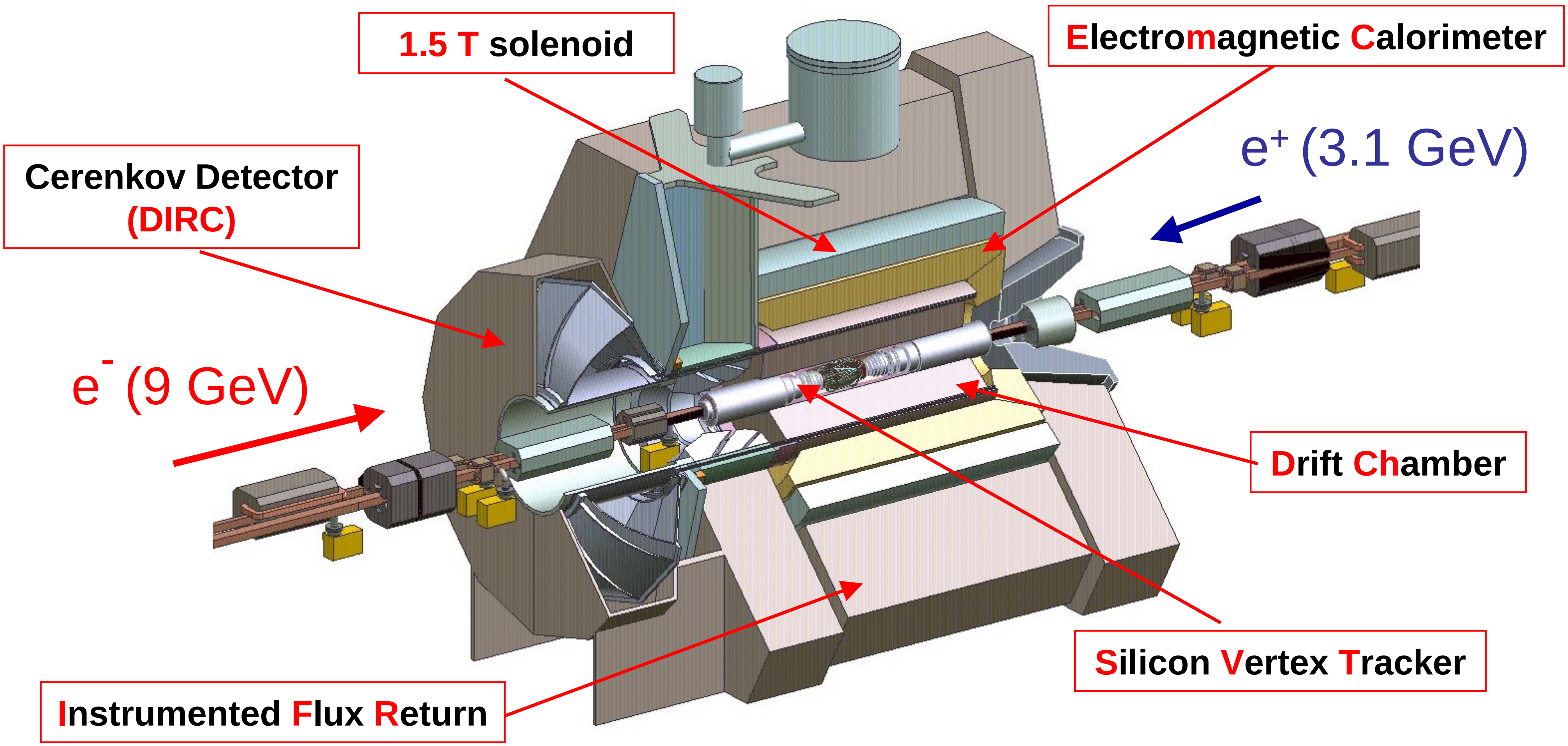
BABAR logging efficiency: > 96%

PEP-II delivered: $89.8\ fb^{-1}$

BABAR recorded: $85.4\ fb^{-1}$ (includes $8.8\ fb^{-1}$ off peak)

161 million B's available !!

The BaBar Detector



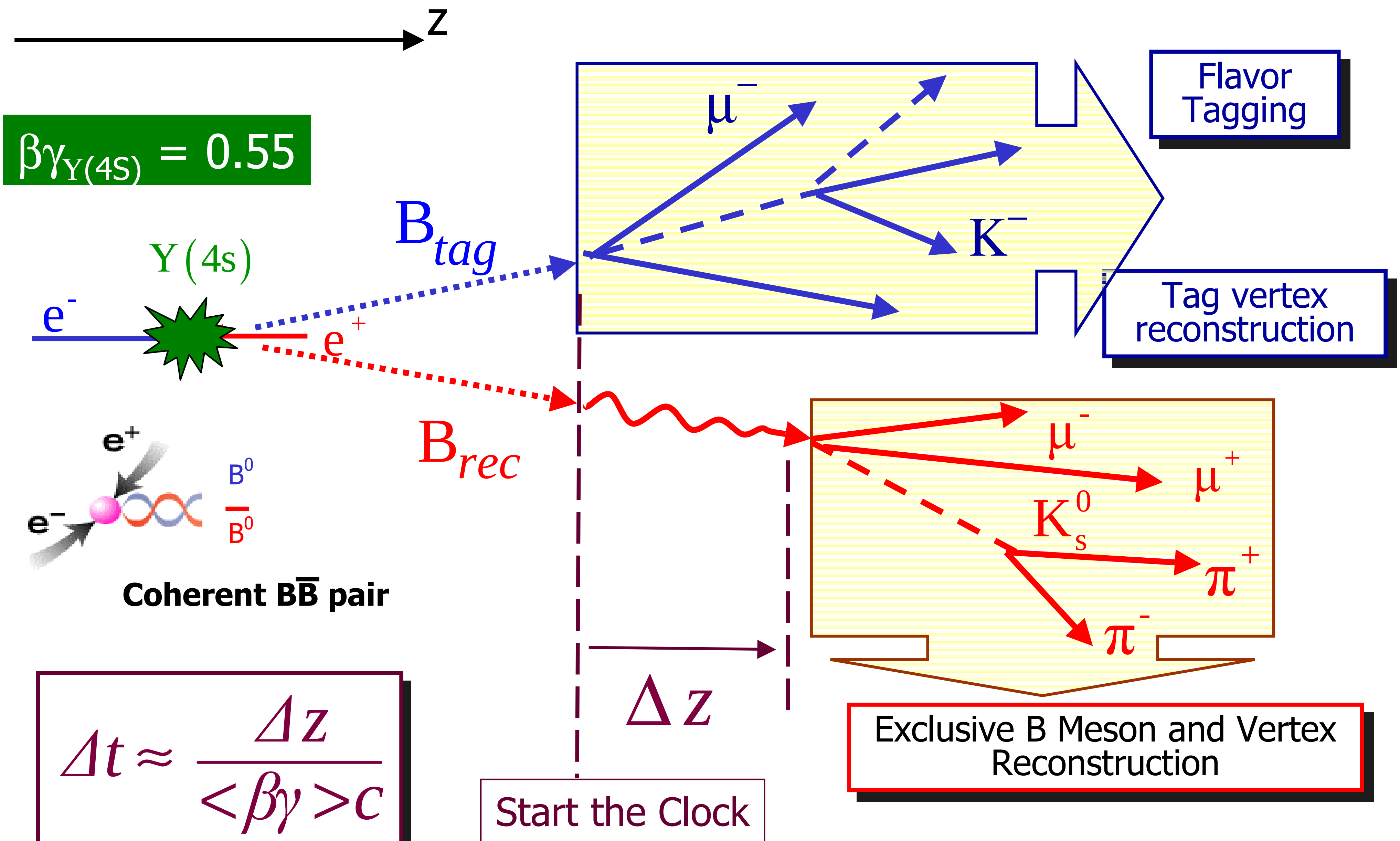
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

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

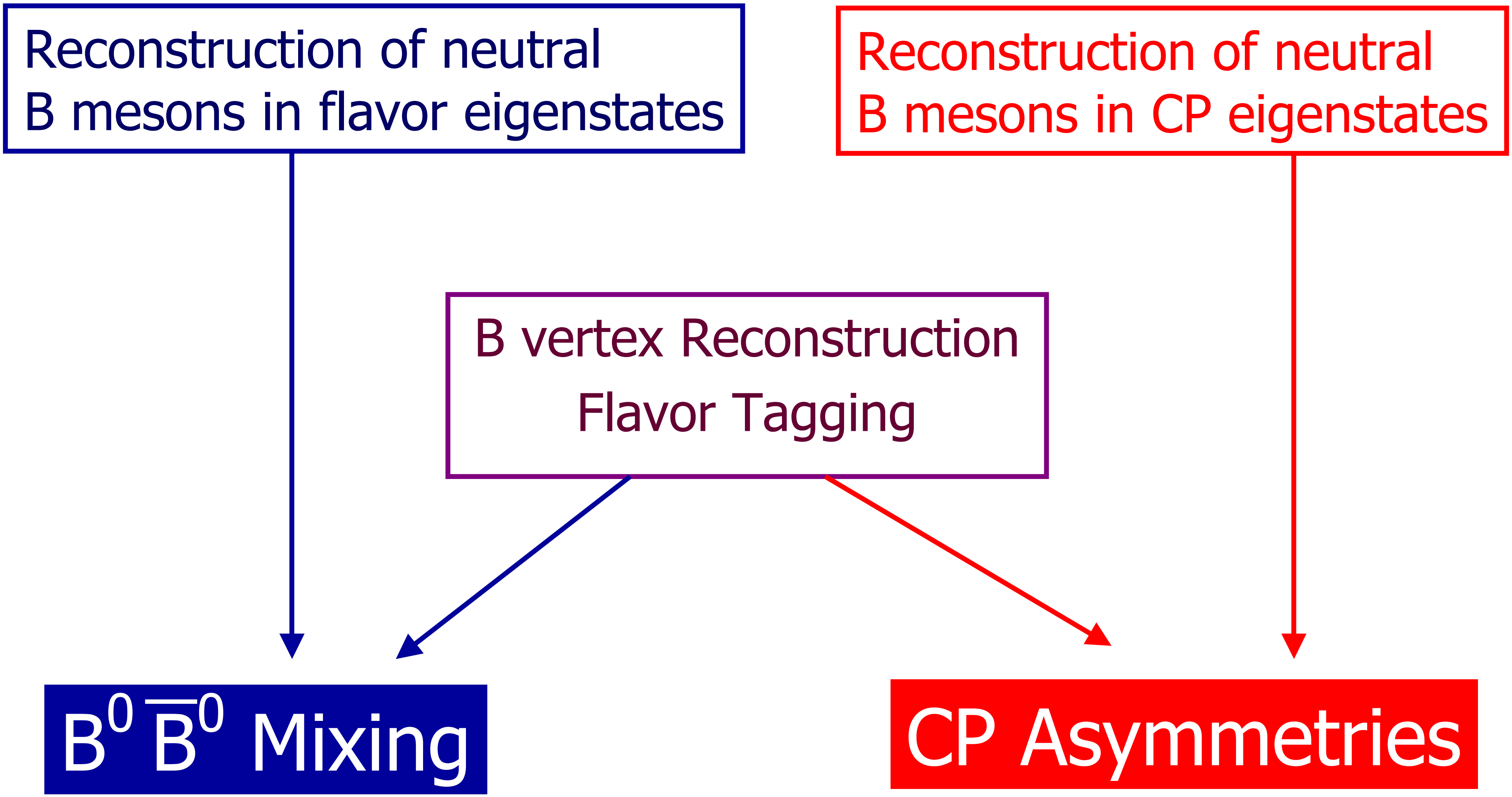
EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

Event Topology



$$\Delta t \approx \frac{\Delta z}{<\beta\gamma>c}$$

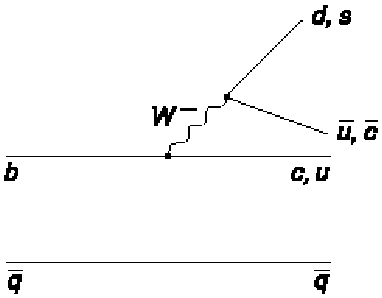
Ingredients for Time-Dependent sin2β Analysis



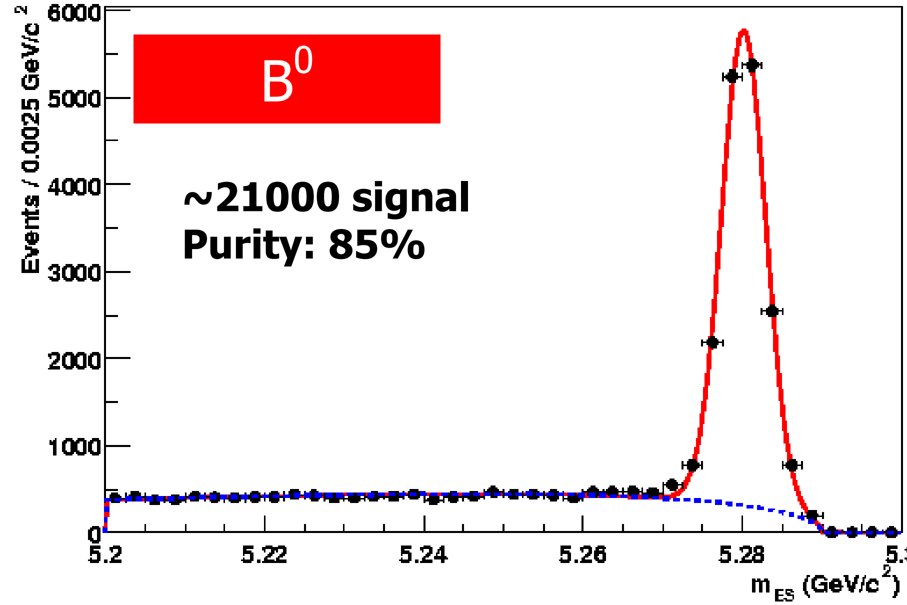
Fully Reconstructed B sample

Cabibbo-favored hadronic decays

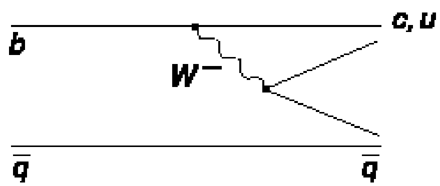
$b \to c \bar{u} d$ "Open Charm" decays



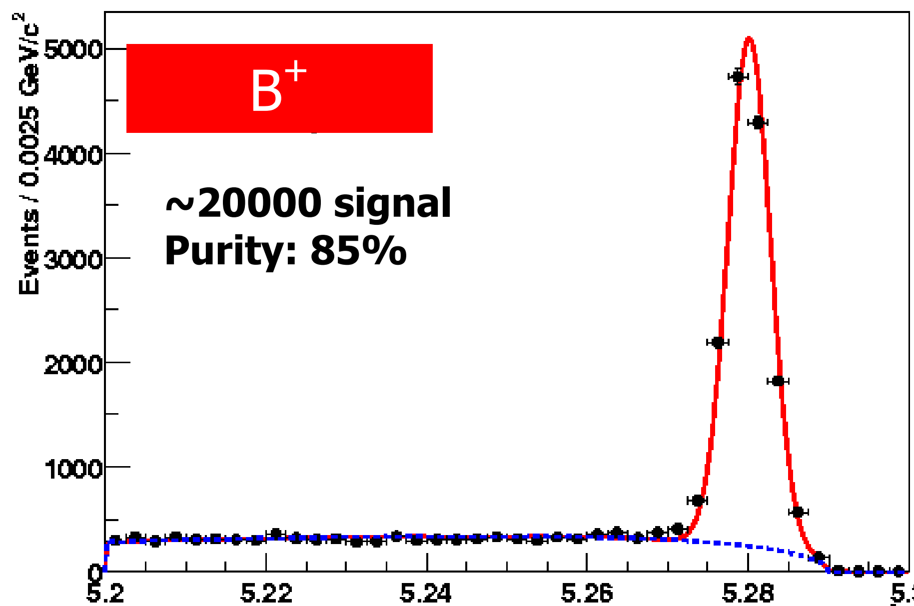
$$B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$$
$$B^- \to D^{(*)0}\pi^-$$



Hadronic decays into final states with Charmonium $b \to (c\ \bar{c})\ s$



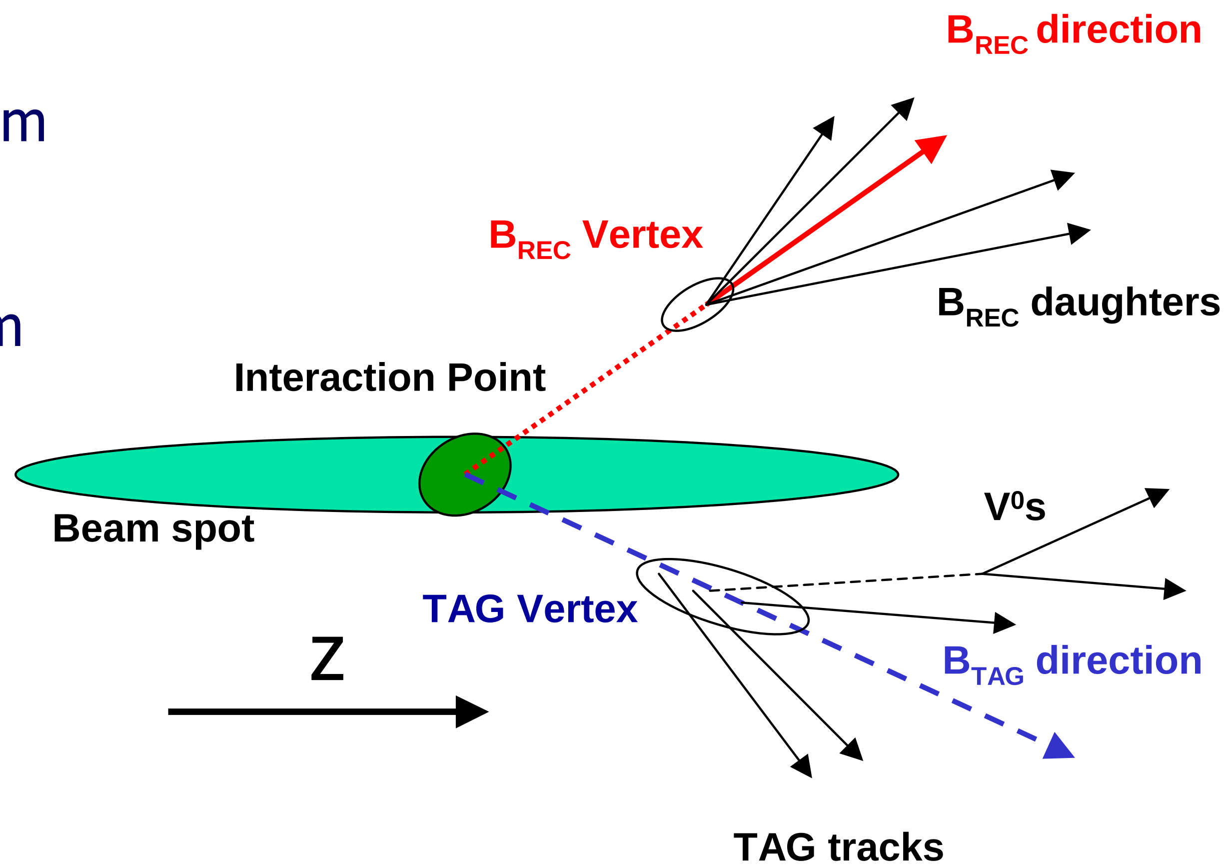
$$B^0 \to J/\psi K^{*0}(K^+\pi^-)$$
$$B^+ \to J/\psi K^+,\ \psi(2S)K^+$$



$$m_{ES} = \sqrt{(E_{beam}^{cm})^2 - (p_B^{cm})^2} \quad [GeV]$$

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

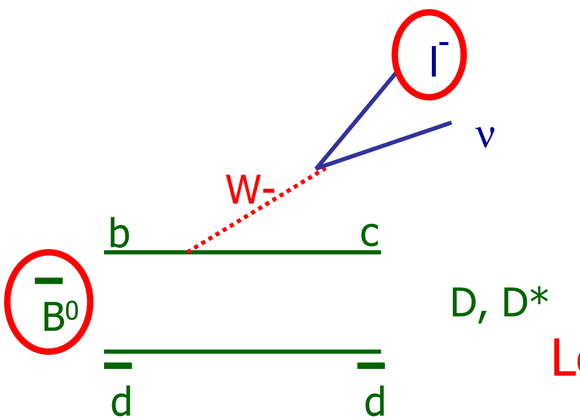


- High efficiency: 97%
- Average Δz resolution is 180 μm ($<|\Delta z|> \sim \beta\gamma c\tau = 260\ \mu$m)
- Δt resolution function measured from data

B Flavor Tagging Methods

Hierarchical Tagging Categories

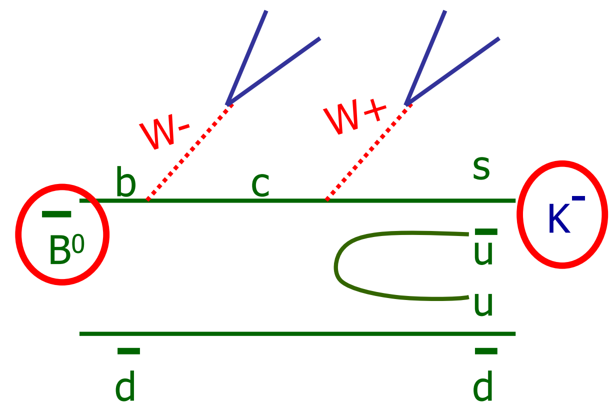
For electrons, muons and Kaons use the charge correlation



$l^- \rightarrow \bar{B}^0$

$l^+ \rightarrow B^0$

Lepton Tag



$\sum_{kaons} Q < 0 \Rightarrow \bar{B}^0$

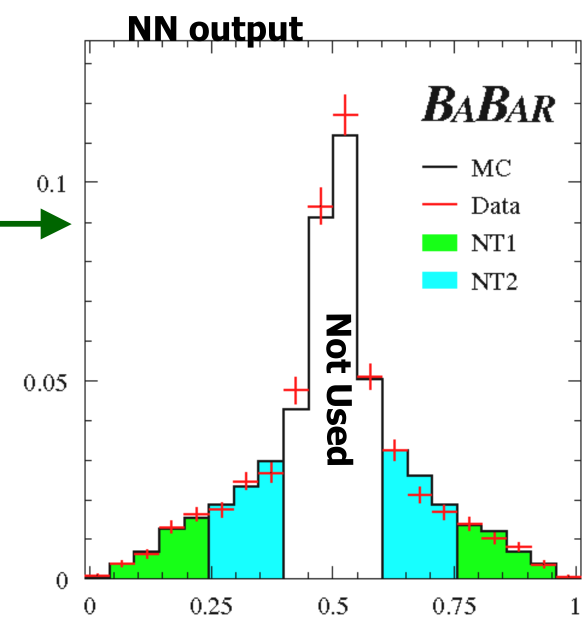
$\sum_{kaons} Q > 0 \Rightarrow B^0$

Kaon Tag

Multivariate analysis exploiting the other kinematic information of the event, e.g.,

- Momentum spectrum of the charged particles
- Information from non-identified leptons and kaons
- Soft π from D* decay

Neural Network



Each category is characterized by the probability of giving the wrong answer (mistag fraction *w*)

Mixing Likelihood Fit

Unbinned maximum likelihood fit to flavor-tagged B^0 sample

All Δt parameters extracted from data

$$f_{\substack{\text{Unmix}\\ \text{Mix}}}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{4\tau_{B_d}} \times \left(1 \pm (1-2w)\ \cos(\Delta m_d \Delta t) \right) \right\} \otimes R$$

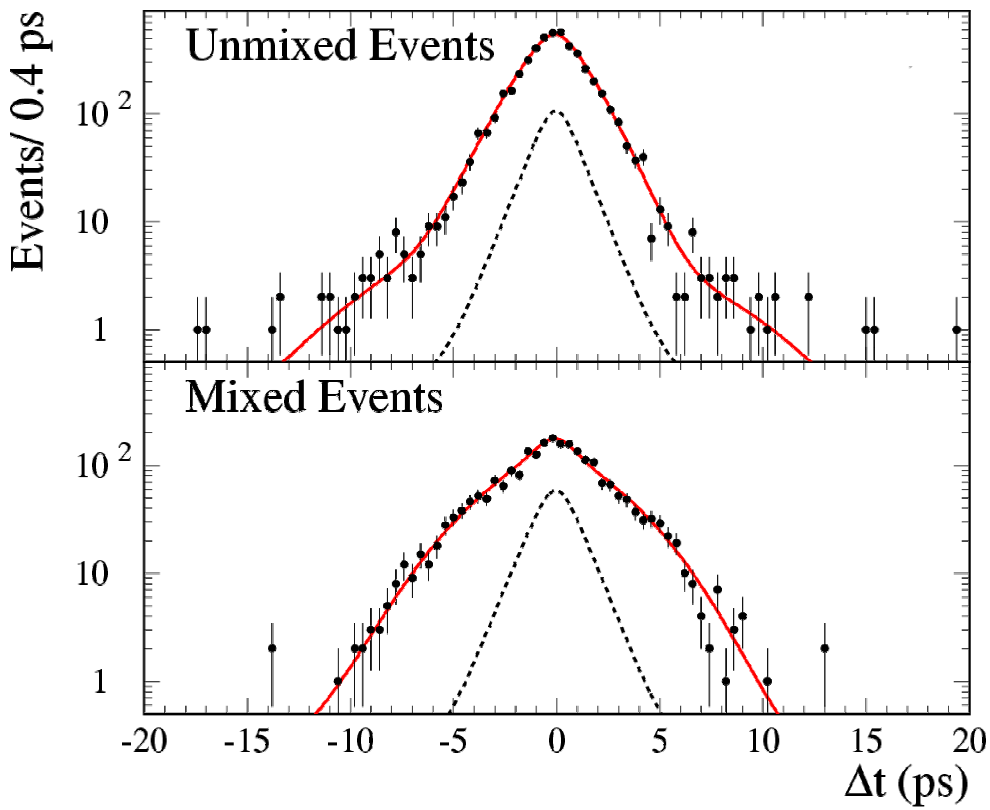
Fit Parameters

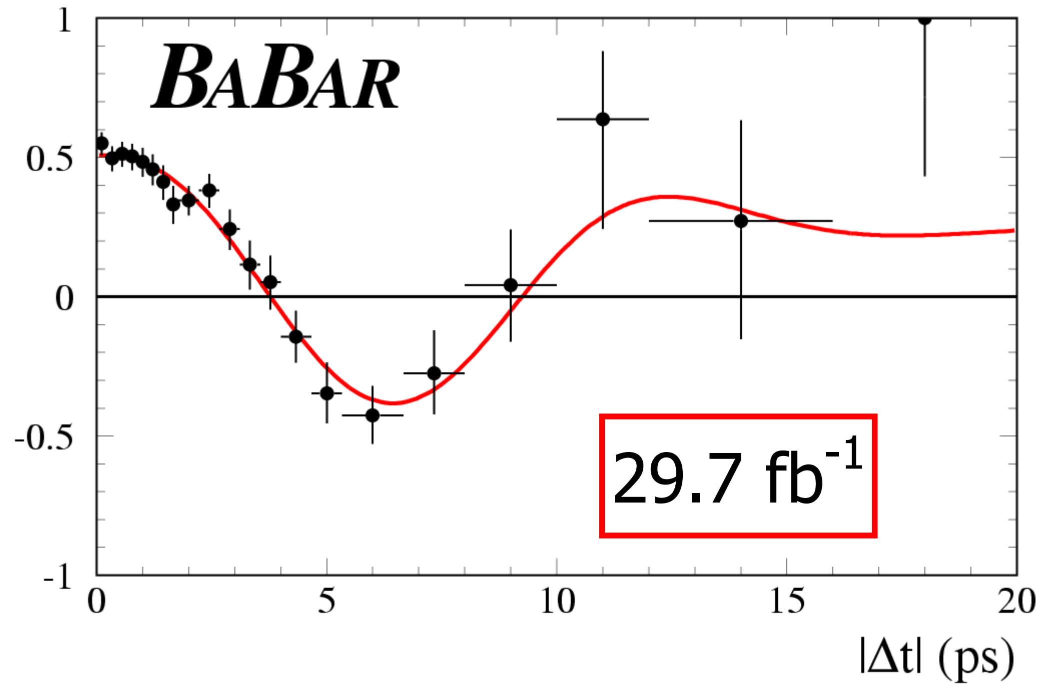
Δm_d	1
Mistag fractions for B^0 and $\overline{B^0}$ tags	8
Signal resolution function	2 x 8
Empirical description of background Δt	16+3
B lifetime fixed (PDG 2000)	τ_B = 1.548 ps

44 total free parameters

$B^0\overline{B}^0$ Mixing Fit Result

$$\text{Asymmetry}(\Delta t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \approx \left(1 - 2\langle w \rangle\right) \times \cos(\Delta m_d \Delta t)$$





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

hep-ex/0112044
Accepted by PRL

World Average: $0.496 \pm 0.007\ ps^{-1}$

Yields for modes with Ks

1999-2001 data

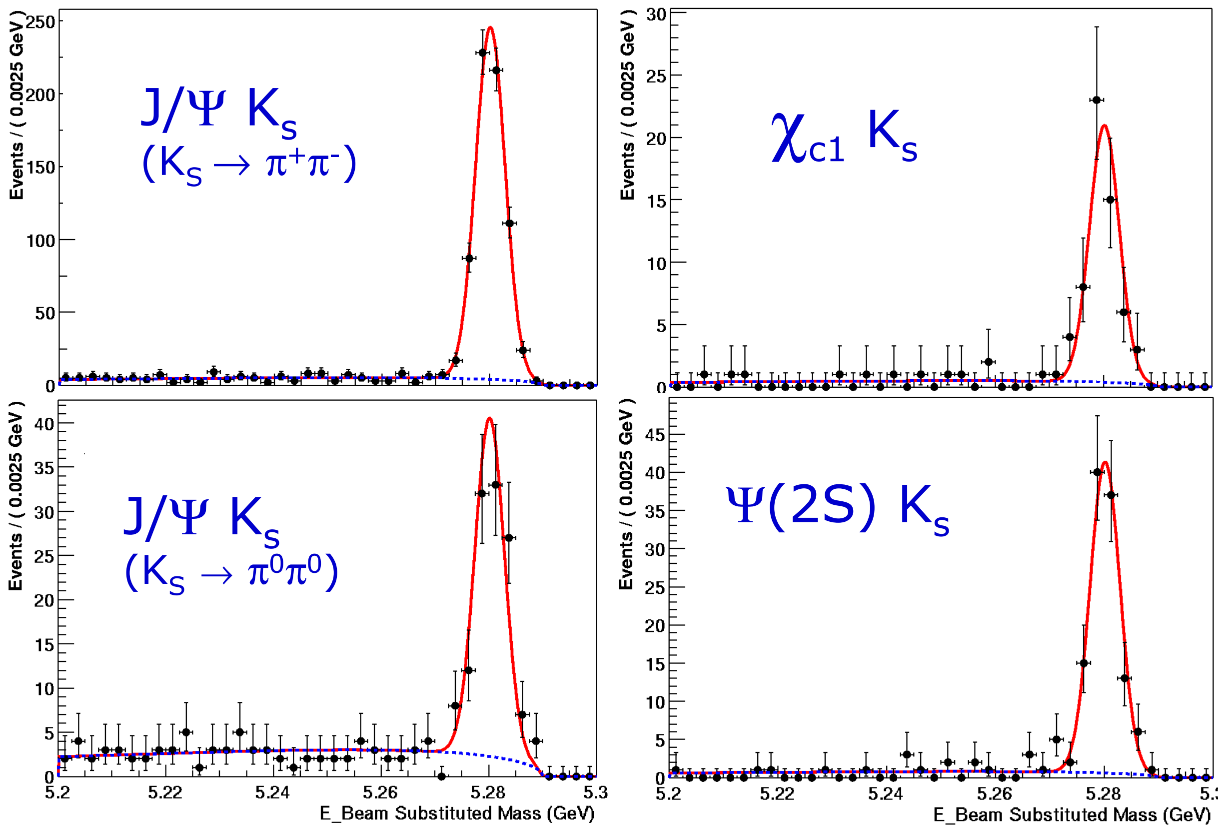
62 x 10^6 $B\bar{B}$ pairs

56.4 fb^{-1} on peak

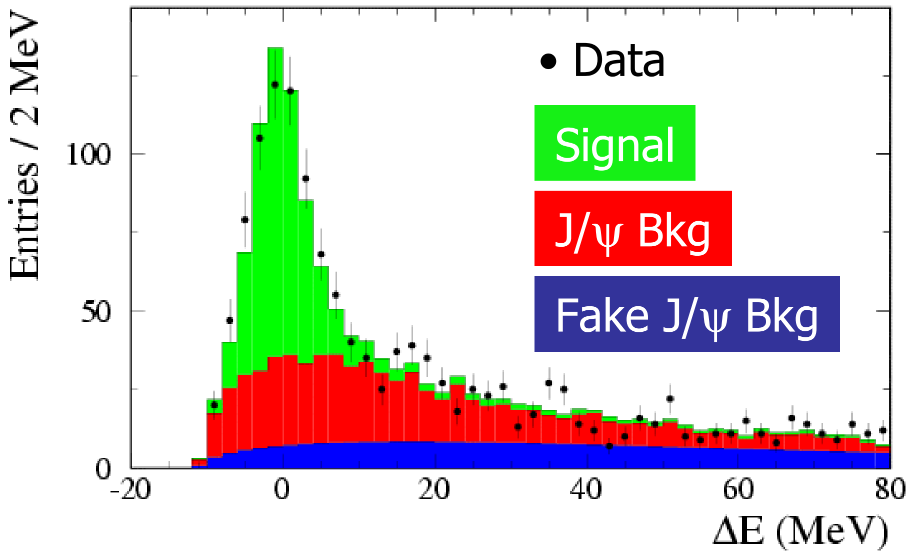
Energy-substituted mass

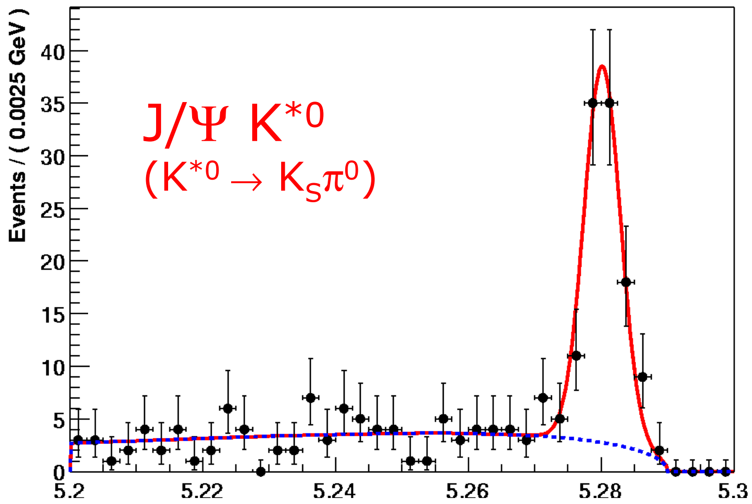
$$m_{ES} = \sqrt{(E_{beam}^{cm})^2 - (p_B^{cm})^2}$$

Sample	N_{tagged}	Purity
$J/\Psi\ K_s(\pi^+\pi^-)$	693	96%
$J/\Psi\ K_s(\pi^0\pi^0)$	123	89%
$\Psi(2S)\ K_s$	119	89%
$\chi_{c1}\ K_s$	60	94%
Total	995	94%



$J/\Psi\ K_L$ and $J/\Psi\ K^{*0}$ Yields





J/ψ background composition and CP content from inclusive J/ψ Monte Carlo

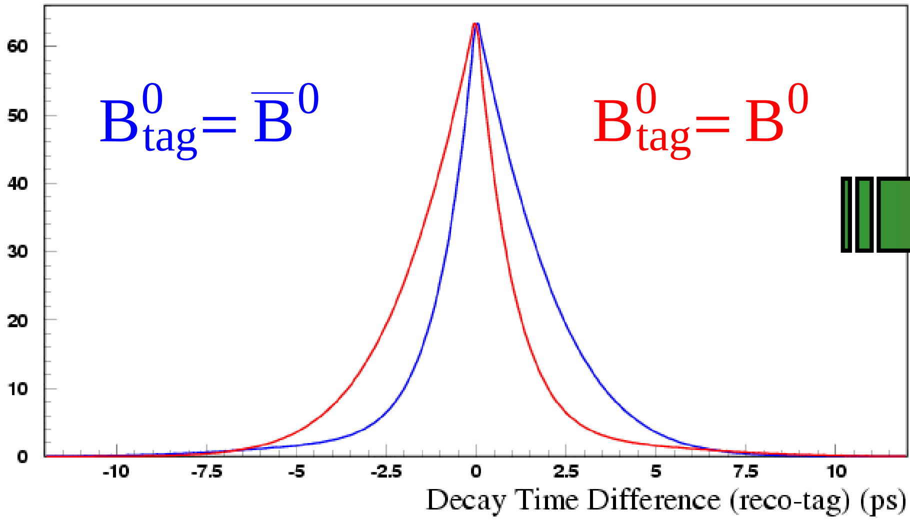
Fake J/ψ background from data sidebands

Full angular analysis

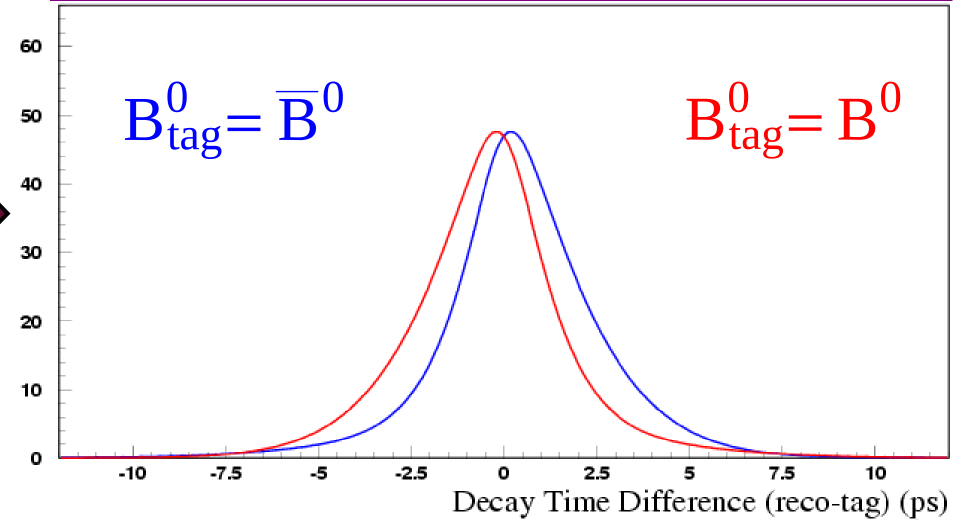
Mode	N_{tagged}	Purity
$(c\bar{c})K_S$	995	94%
$J/\Psi\ K_L$	742	57%
$J/\Psi\ K^{*0}$	113	83%
All CP	1850	79%

Δt Spectrum of CP Events

perfect
flavor tagging & time resolution



realistic
mis-tagging & finite time resolution



Mistag fractions w
And
resolution function R

determined by
flavor sample

CP PDF

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

Mixing PDF

$$f_{mixing,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{4\,\tau_{B_d}} \times \left(1 \pm (1-2w) \cos(\Delta m_d \Delta t) \right) \right\} \otimes R$$

sin2β Likelihood Fit

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

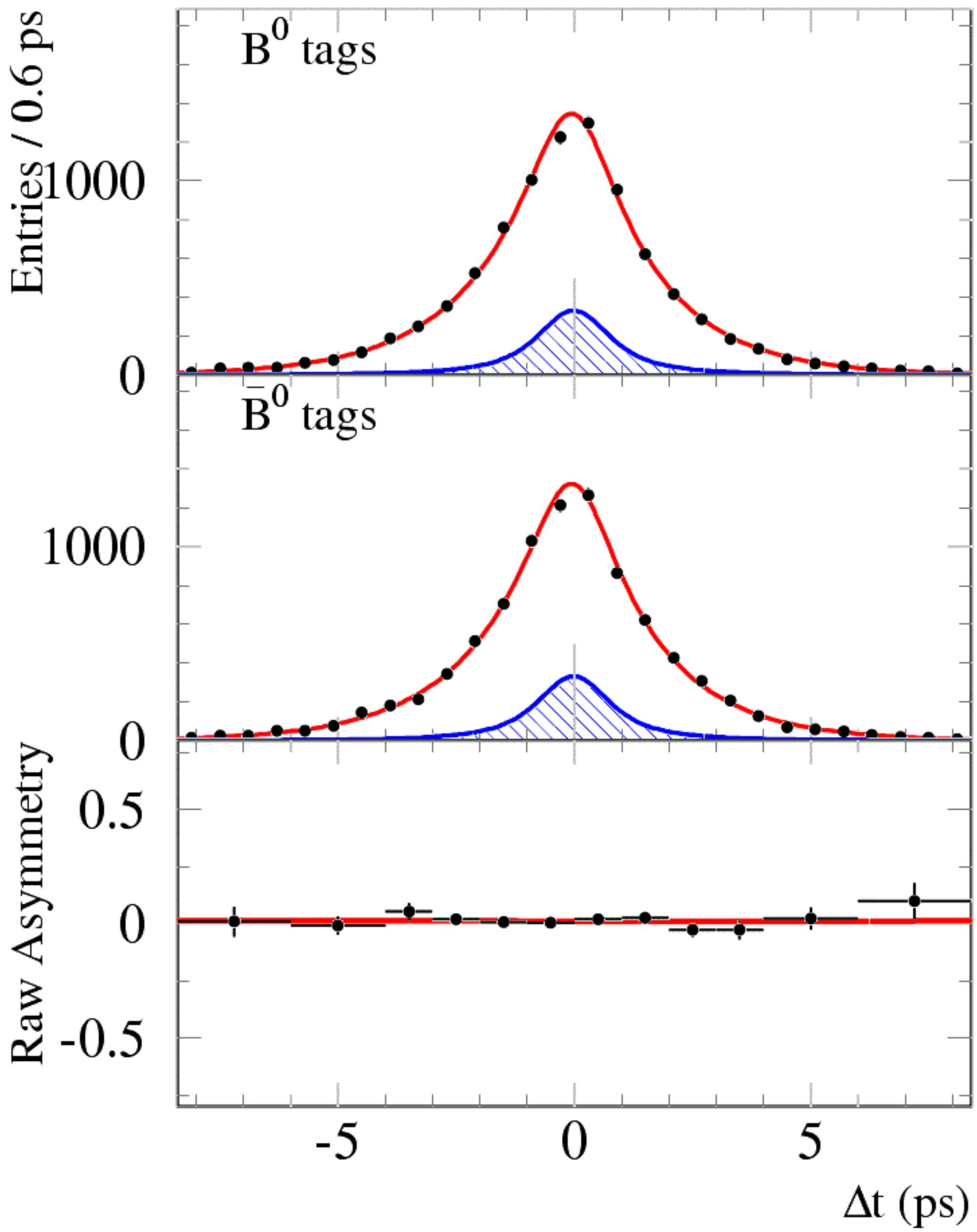
- ✓ All Δt parameters extracted from data
- ✓ Correct estimate of the error and correlations

Fit Parameters

sin2β	1	tagged CP samples
cos2β	1	From $J/\psi\ K^{*0}$ sample
Mistag fractions for B^0 and $\overline{B}^0$ tags	8	tagged flavor sample
Signal resolution function	8	tagged flavor sample
Empirical description of background Δt	17	tagged flavor sample
B lifetime fixed (PDG 2000)	τ_B = 1.548 ps	
Mixing Frequency fixed (PDG 2000)	Δm_d = 0.472 ps^{-1}	

35 total free parameters

Null Test in B Flavor Sample



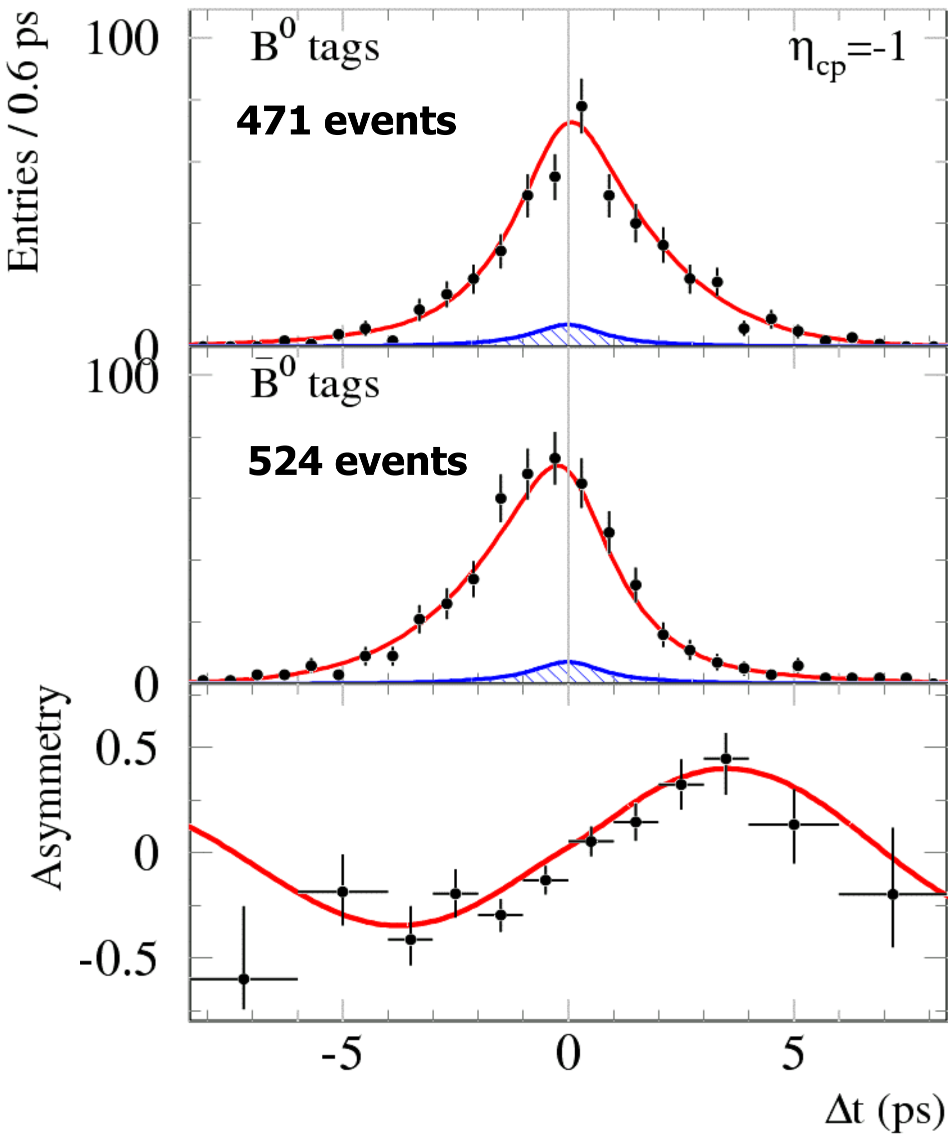
B flavor sample as control sample for CP analysis

Sample	"sin2β"
$B^0 \rightarrow D^{(*)-}\ \pi^+, \rho^+, a_1^+$	-0.01 ± 0.03
$B^0 \rightarrow J/\Psi\ K^{*0}(K^+\pi^-)$	0.00 ± 0.09
$B^- \rightarrow D^{(*)0}\ \pi^-$	-0.01 ± 0.03
$B^- \rightarrow J/\psi, \chi_c\ K^-$	-0.05 ± 0.08

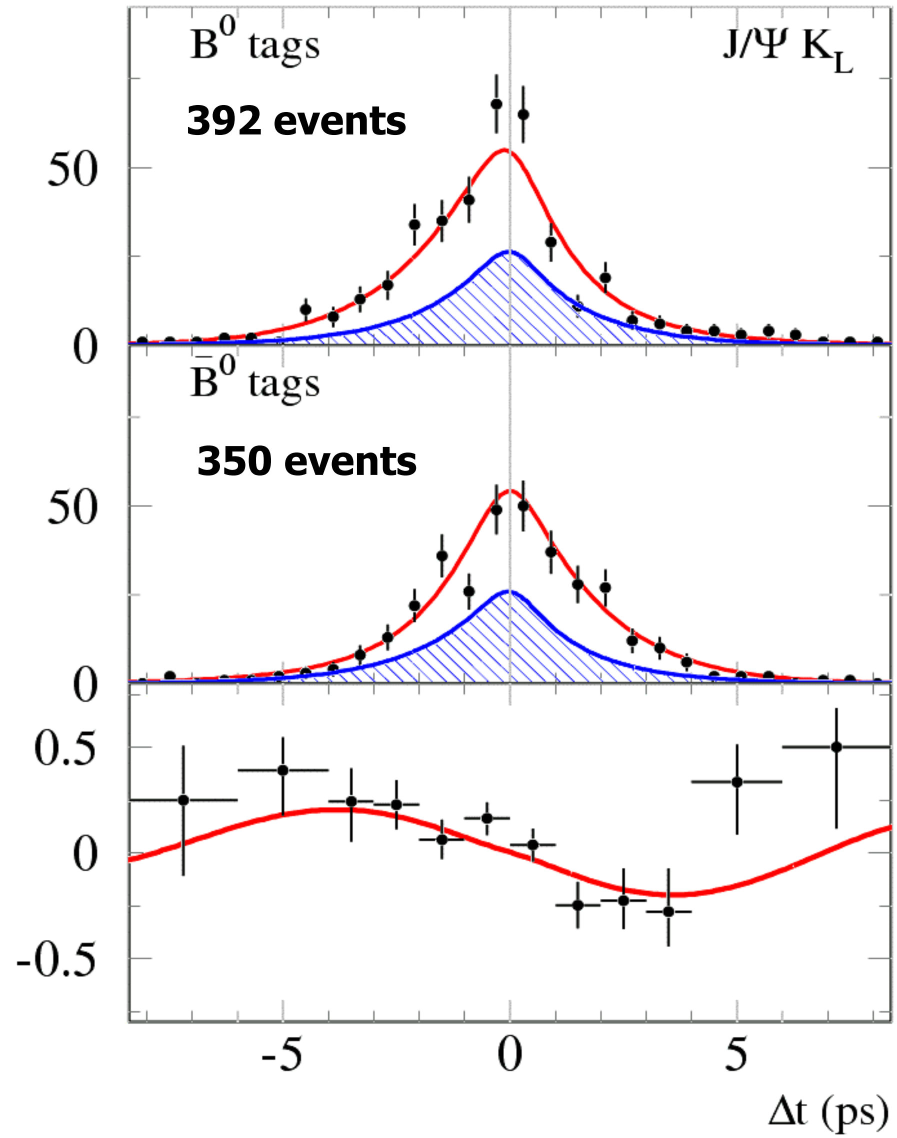
No asymmetry where none is expected!

CP Asymmetry in η_{CP}=-1 and η_{CP}=+1 Samples

sin2β = 0.76 ± 0.10



sin2β = 0.73 ± 0.19



$\sin 2\beta$ Results

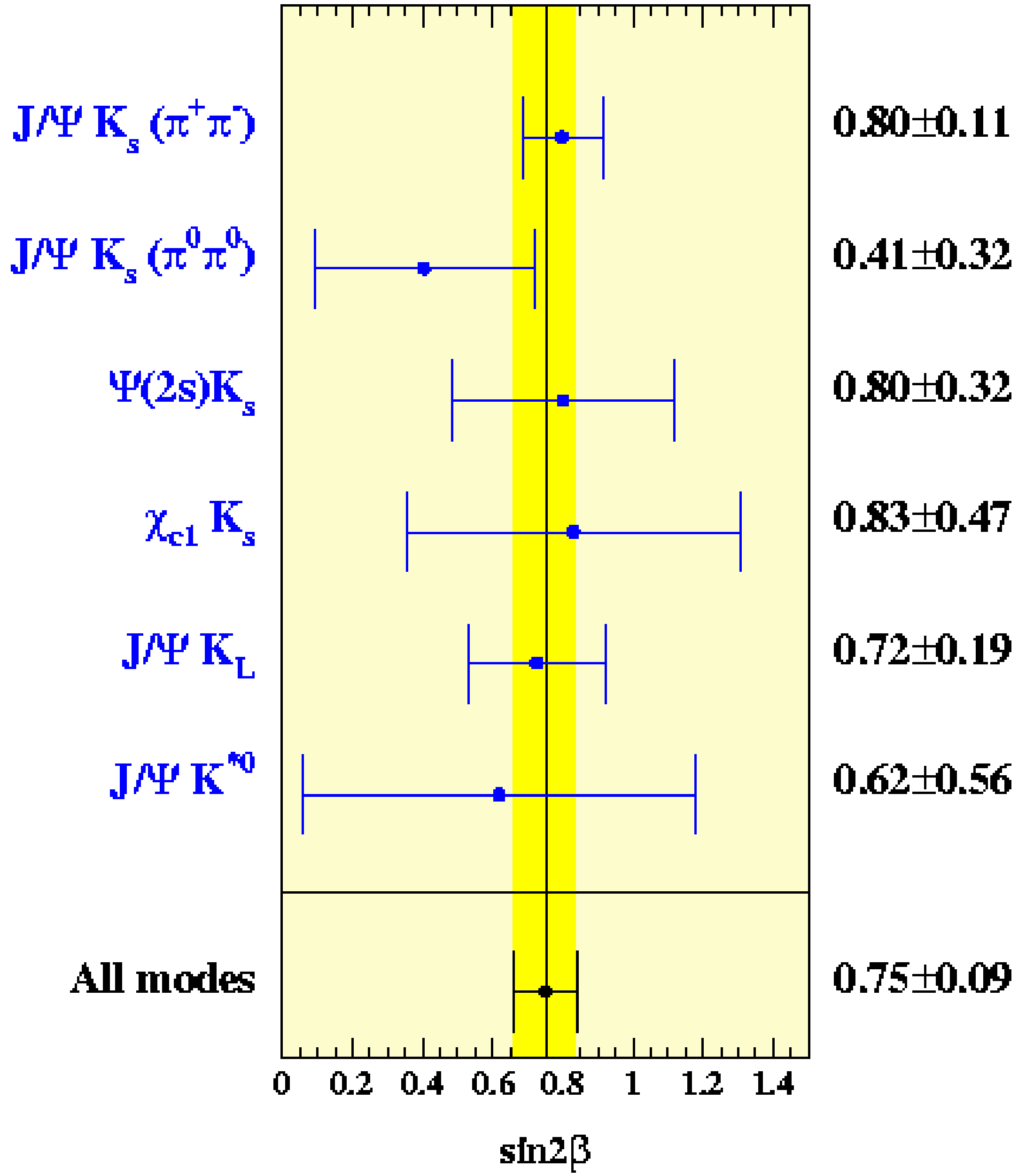
$$\sin 2\beta = 0.75 \pm 0.09$$

Consistency of CP channels
$P(\chi^2) = 70\%$

Goodness of fit(CP Sample):
$P(L_{max} > L_{obs}) > \sim 50\%$

$$\cos 2\beta = +3.3^{+0.6}_{-1.0}{}^{+0.6}_{-0.7}$$

- Using theoretically preferred choice of strong phases
- Need more statistics!



Sources of Systematic Error

- Description of background events — 0.019
  - CP content of background components
  - Event-by-event signal probability
- Δt resolution and detector effects — 0.015
  - Silicon detector misalignment
  - Δt resolution model
- Fixed lifetime and oscillation frequency — 0.014
- Monte Carlo statistics — 0.014
- Composition and content of $J/\psi\, K_L$ background — 0.013

Total systematic error: 0.04

Search for Direct CP in Golden Modes

- In the Standard Model $|\lambda| = 1$

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

Amplitude ratio ($\bar{A}_{f_{CP}}/A_{f_{CP}}$)

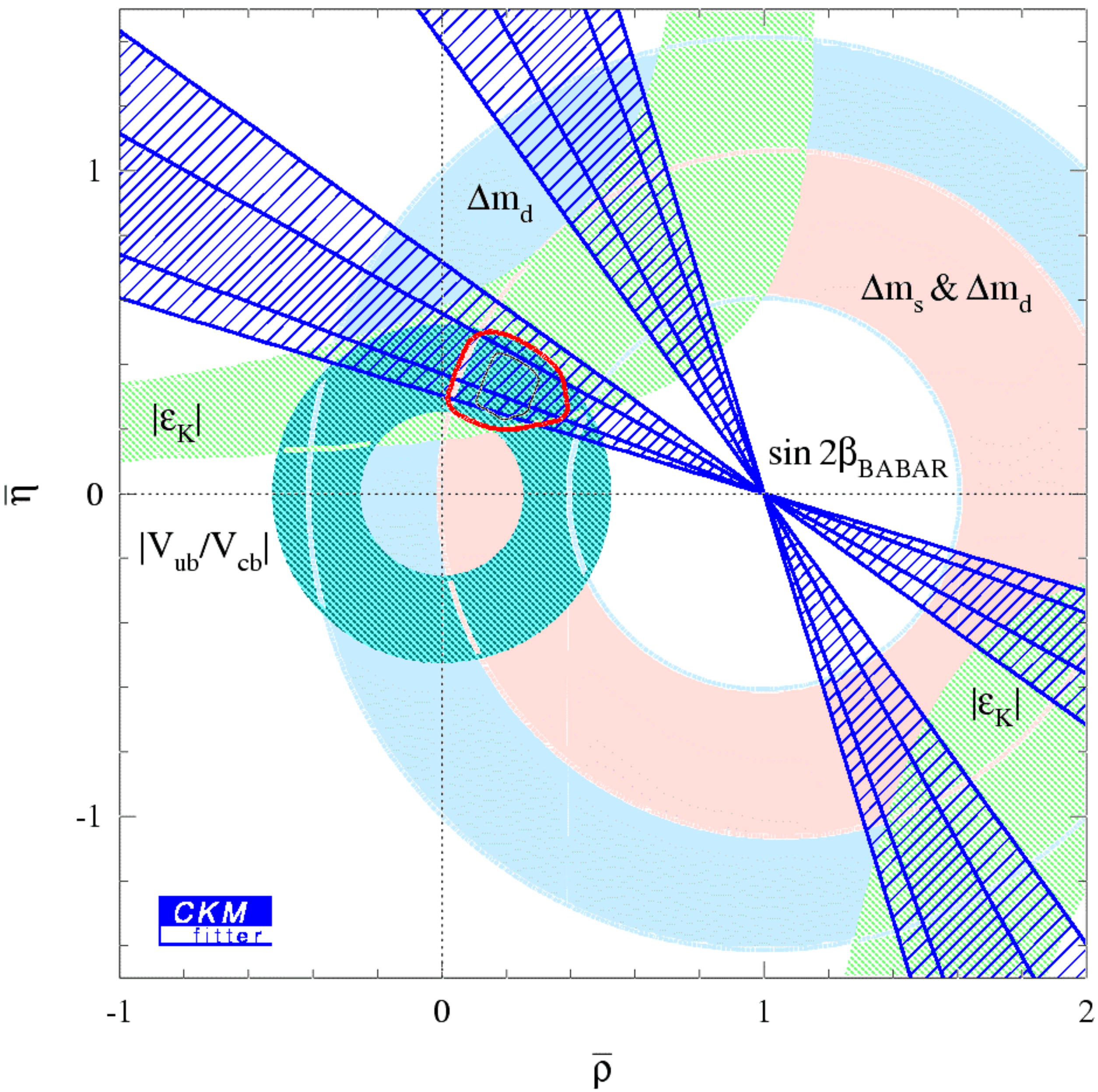
Weak Phase (q/p)

- Probe New Physics beyond the Standard Model
  - No constraint on $|\lambda|$

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

$$S_{f_{CP}} = \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} = 0.76 \pm 0.10 \qquad |\lambda_{f_{CP}}| = 0.93 \pm 0.06 \pm 0.03$$

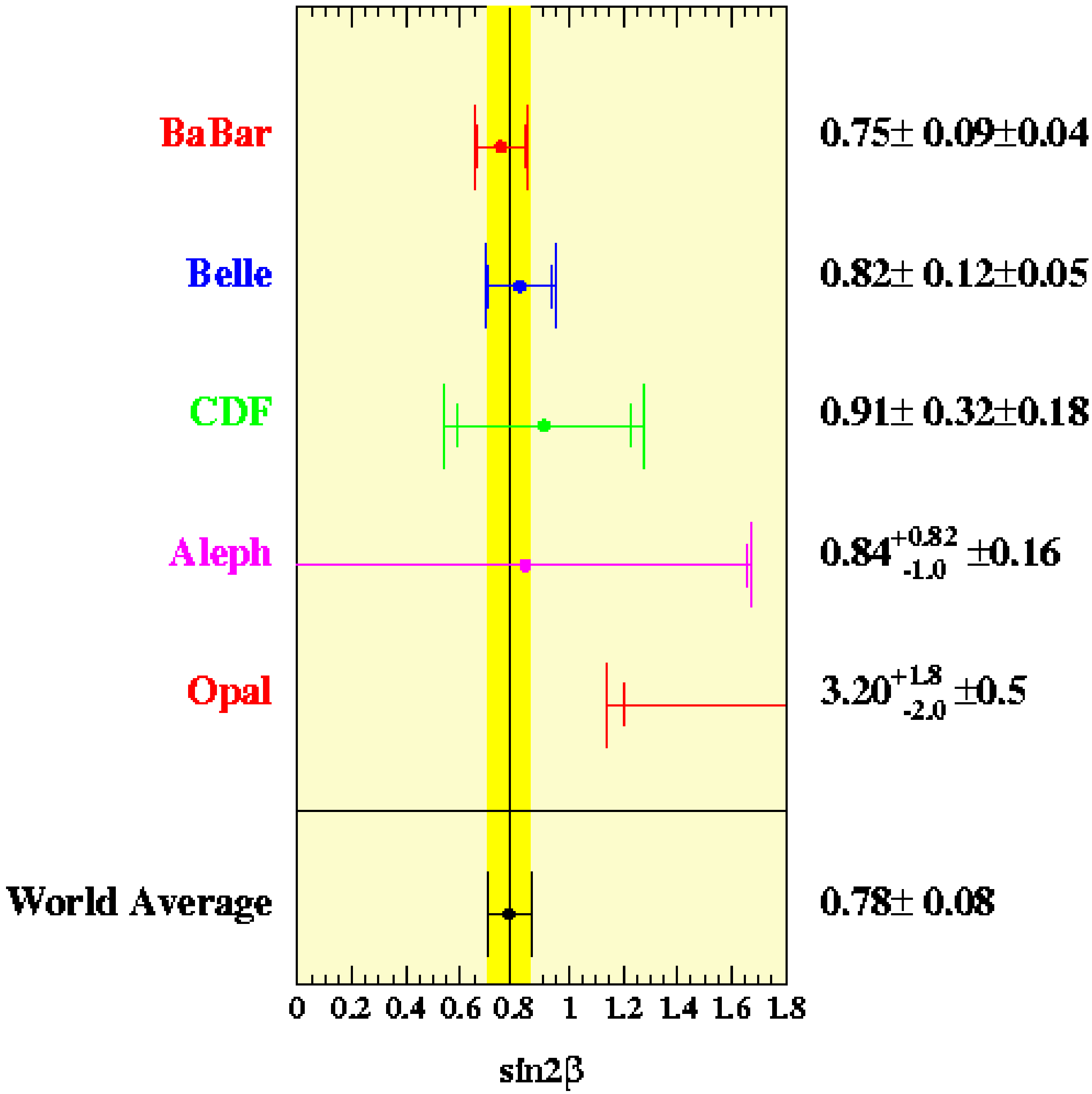
The Unitarity Triangle



One solution for β is consistent with measurements of sides of Unitarity Triangle

Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001 (also other recent global CKM matrix analyses)

New sin2β World Average



New Modes to Measure sin2β

- Enlarge $b \to c\bar{c}s$ sample
  - $B^0 \to \eta_c K_s$
  - Hadronic decays of J/ψ

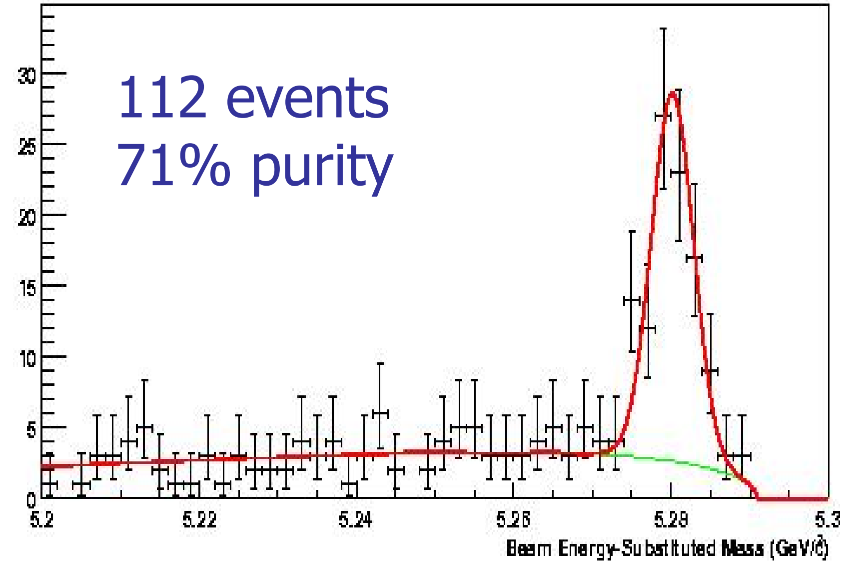
- New tests of the Standard Model
  - Cabibbo suppressed modes in $b \to c\bar{c}d$: $B \to D^* D^{(*)}$
    - Same weak phase but unknown contribution from penguins
    - Not pure CP eigenstate
  - Pure penguin $b \to s\bar{s}s$ modes: $B^0 \to \phi K_s$
    - Experimentally clean
    - Small branching fraction: $O(10^{-5})$
  - Cabibbo suppressed mode: $B^0 \to J/\psi \pi^0$
    - Experimentally more challenging
    - Provides valuable information on penguin contribution

New Charmonium mode

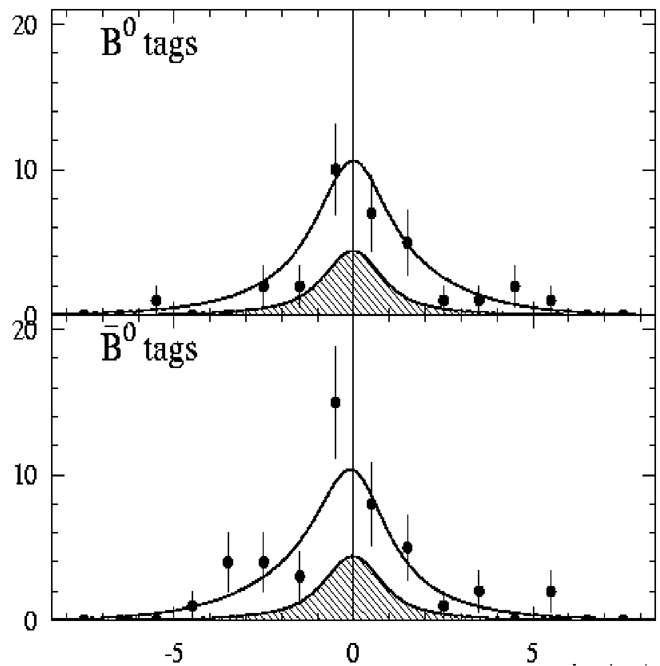
$B^0 \rightarrow \eta_c K_s$

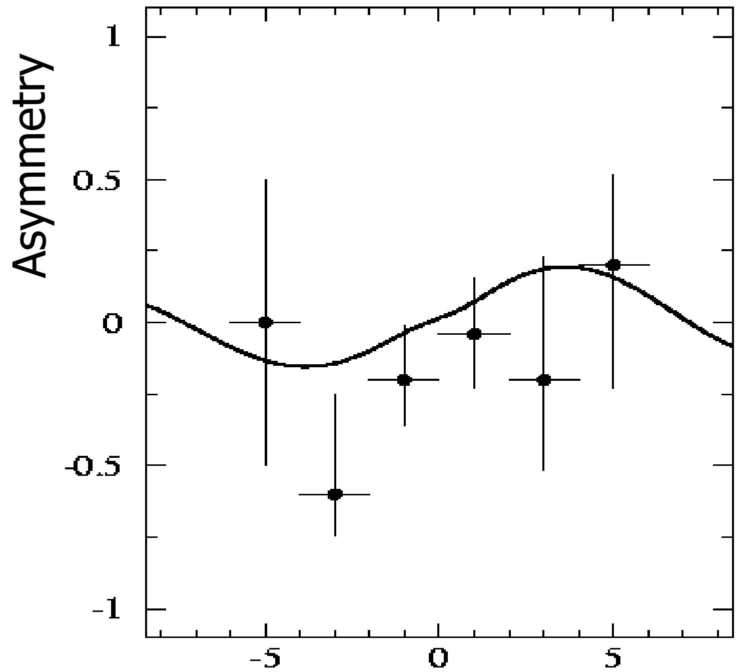
$\eta_c \rightarrow K_s K^{\pm}\pi^{+}, K^{+}K^{-}\pi^{0}$

Higher multiplicity in the final state

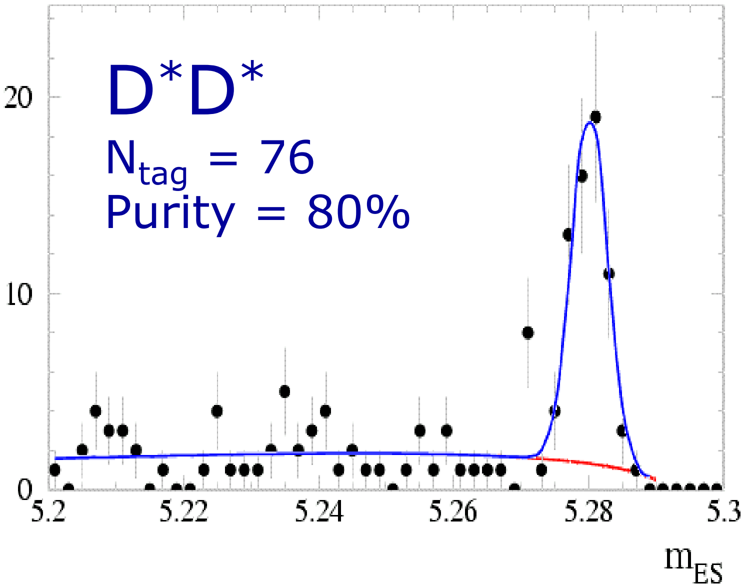


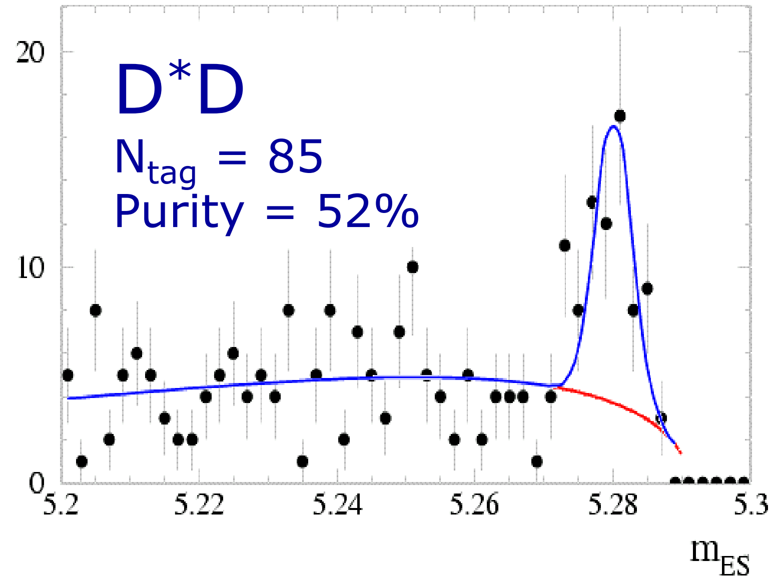
$\sin 2\beta = 0.43 \pm 0.46 \pm 0.08$





CP Asymmetry in D*D* and D*D





- Vector-Vector final state
  - Mixture of CP-odd and CP-even final states
- Fit only for coefficients

$$A_{CP}(\Delta t) = S_{D^*D^*} \sin(\Delta m \Delta t) + C_{D^*D^*} \cos(\Delta m \Delta t)$$

$$S_{D^*D^*} = -0.05 \pm 0.45 \pm 0.07$$

$$C_{D^*D^*} = 0.12 \pm 0.30 \pm 0.03$$

- Different time distribution for $D^{*+}D^{-}$ and $D^{*-}D^{+}$

$$S_{D^{*+}D^{-}} = -0.43 \pm 1.41 \pm 0.20$$

$$C_{D^{*+}D^{-}} = 0.53 \pm 0.74 \pm 0.13$$

$$S_{D^{*-}D^{+}} = 0.38 \pm 0.88 \pm 0.05$$

$$C_{D^{*-}D^{+}} = 0.30 \pm 0.50 \pm 0.08$$

See Yury Kolomensky's talk on Saturday for more details

Conclusions and Prospects

- Updated measurement of $\sin 2\beta$ with BaBar

$$\sin 2\beta = 0.75 \pm 0.09\ (\text{stat}) \pm 0.04\ (\text{syst})$$

hep-ex/0203007

Preliminary

- Going towards a precision measurement with 500 fb^{-1}
  - Systematic error to shrink with enlarged data sample
  - Comparable statistical and systematic error of ≤ 0.03