Recent Results from BABAR

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SLAC

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Outline

- CP Violation, CKM Matrix and the Unitarity Triangle
- CP Violation in due to CP Mixture of mass eigenstates, ε_b
- Observation of CP Violation in the interference of decay and mixing of flavor eigenstates $\Rightarrow$ sin2β
  - The PEP-II B Factory & The BABAR Detector
  - The three linked steps towards the sin2β measurement
    - B Lifetime
    - B Mixing
    - CP Asymmetry
- Test of CP Violation in $B^0 \to \pi^+\pi^-/K^+\pi^-$
- Summary and Outlook

CP Violation

- CP Violation was discovered in 1964 in K_L decay

$$\eta_{+-} = \frac{K_L^0 \to \pi^+\pi^-}{K_L^0 \to all} = 2\times 10^{-3}$$

- Three decades of intense study of this and other manifestations in K mesons have not produced a conclusive understanding of this phenomenon
- In neutral K meson decays there are two problems
  - *Experimental: effects are small*
  - *Theoretical: it is difficult to relate the measurements to quark level processes, where theory has predictive power*
- In neutral B meson decay the situation is different
  - *Experimental: effects are large, but BR small*
  - *Theoretical: measurements are interpretable at quark level*

CP Violation

- *CP Violation one of the necessary ingredients to explain the imbalance of matter and anti-matter in our universe*
- *The Standard Model of Weak Interactions makes definite predictions for the size of CP violating effects, it predicts sizable effect in neutral B meson decay*
- *However, the size of these predicted effects are orders of magnitudes too small to explain the Baryogenesis.*
- *Thus, we need to look beyond the SM to find explanations for the matter dominance – probably not weak interactions!*
- *BABAR is designed to perform a comprehensive study of B decays and in particular measure CP violating effects in neutral B meson decays.*

Tests of CP Violation in B Decays

- Direct *CP* Violation, both in neutral and charged B decays
  - *Total amplitude for a decay mode and its CP conjugate have different magnitudes*
  - *asymmetries expected to be relatively small*
  - *Large hadronic uncertainties - strong phases !*
- *CP* Violation in Mixing, in neutral B decays
  - *charge asymmetry in semi-leptonic decays*
  - *effects expected to be small in Standard Model* ($\Delta\Gamma << \Delta M$)
- *CP* Violation in the interference of mixed and unmixed decays
  - *Study decays to CP eigenstate* (f_{CP})
  - *Large time dependent asymmetries expected in Standard Model*
  - *Asymmetries can be directly related to CKM parameters, in many cases, without hadronic uncertainties*

CP Violation in B Mixing

- Relation between mass eigenstates and CP eigenstates :

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

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

- CP observable :

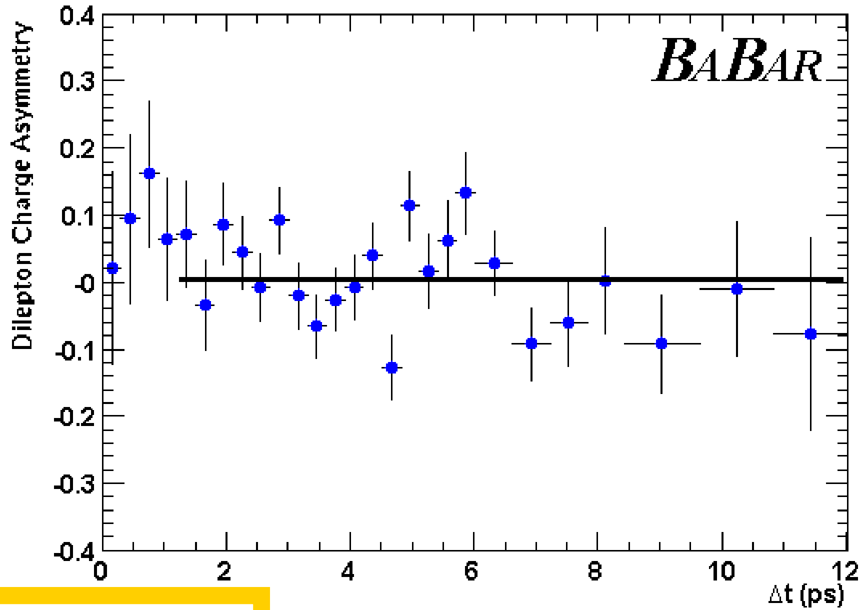
$$A_{CP}(\Delta t) = \frac{N(\ell^+\ell^+)(\Delta t) - N(\ell^-\ell^-)(\Delta t)}{N(\ell^+\ell^+)(\Delta t) + N(\ell^-\ell^-)(\Delta t)} \approx \frac{4\,\text{Re}(\varepsilon_{\text{B}_\text{d}})}{1+|\varepsilon_{\text{B}_\text{d}}|^2}$$

  - Time independent
  - Use dilepton events to measure $A_{CP}(\Delta t)$

CP Violation in B Mixing - Results

$$A_{CP}(\Delta t) = \frac{N(\ell^+\ell^+)(\Delta t) - N(\ell^-\ell^-)(\Delta t)}{N(\ell^+\ell^+)(\Delta t) + N(\ell^-\ell^-)(\Delta t)}$$

- Data sample :
  - 20.7 fb^{-1} on, 2.6 fb^{-1} off-peak
- Systematic corrections
  - Charge asymmetry in lepton detection : $\sigma(A_t) = 0.8\%$
  - Charge asymmetry in non-$B\overline{B}$ background : $\sigma(A_t) = 0.7\%$
  - $B\overline{B}$ background charge asymmetry : $\sigma(A_t) = 0.9\%$
- Preliminary result :



$$\frac{\mathrm{Re}(\varepsilon_{B_d})}{1+|\varepsilon_{B_d}|^2} = (1.2 \pm 2.9_{stat} \pm 3.6_{sys}) \times 10^{-3}$$

Mass Eigenstates $\neq$ Weak Eigenstates $\Rightarrow$ 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 parameters

Wolfenstein parametrization:

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

phase

CP Violation arises from a single phase in the CKM Matrix

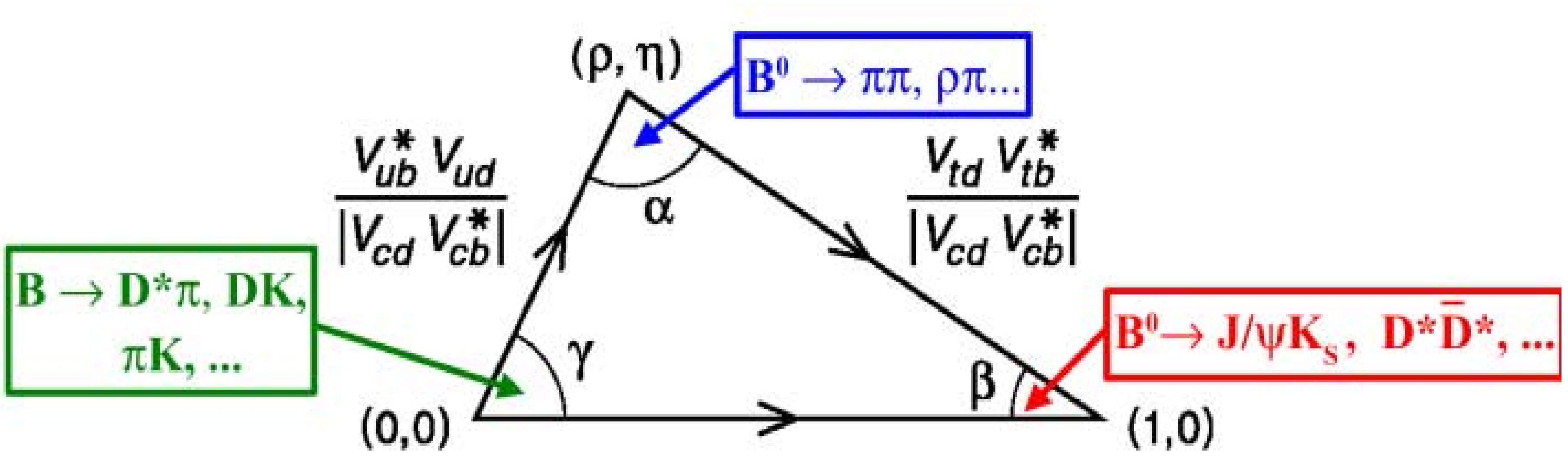
$\eta = 0 \rightarrow$ *NO CP Violation in SM*

CP Violation in the Standard Model

Unitarity of V implies, e.g.

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

Can be represented as 'unitary triangle' in complex plane



CP asymmetries in B^0 decays give information on angles α, β, γ !

Unitarity Triangle

CKM parameters: $\lambda,\ A,\ \bar\rho$ and $\bar\eta$

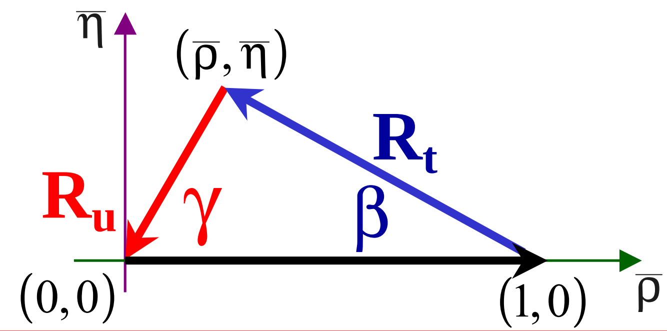
$$\bar\rho = \left(1-\lambda^2/2\right)\rho$$
$$\bar\eta = \left(1-\lambda^2/2\right)\eta$$

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: $1 + R_t + R_u = 0$



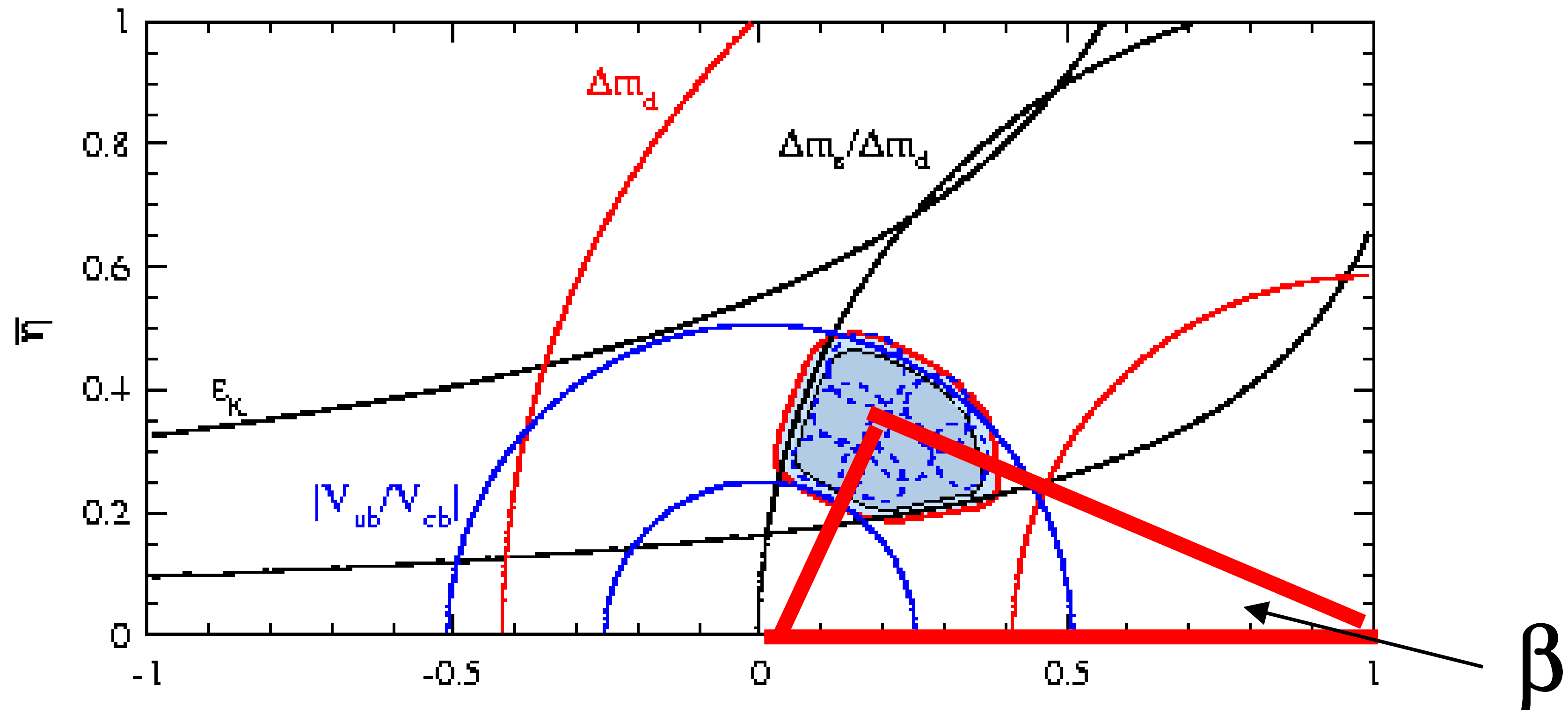
$$R_u = \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \approx -\sqrt{\bar\rho^2+\bar\eta^2}\ e^{i\gamma}$$

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

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

The Unitarity Triangle without CP Violation Measurements

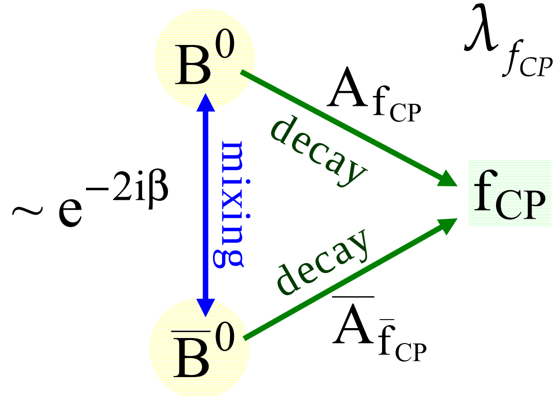
Method described in Höcker et al, hep-ex/0104062



BABAR's Goal:
Test SM by over-constraining Unitarity Triangle with measurements of sides **and** angles

CP Violation in Interference between Mixing and Decay

CP violation results from interference between decays with and without mixing



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

- $\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$: amplitude ratio
- $\frac{q}{p} \approx e^{-2i\beta}$
- $\eta_{f_{CP}}$: CP eigenvalue

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

Define time-dependent CP asymmetry:

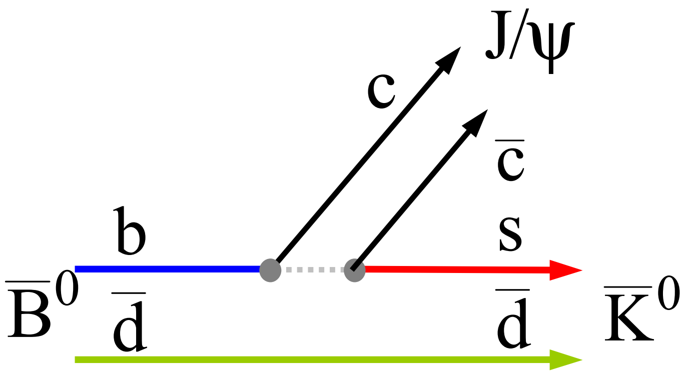
$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})}$$

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

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

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

The "Golden" Decay Mode: $B^0 \to J/\psi\, K^0_S$



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

K^0 mixing

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

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

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

- Theoretically clean mode to measure sin2β
- Clean experimental signature
- "Large" branching fraction compared to other CP eigenstates

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Requirements for CP Measurement

- Since BR ($B \to f_{CP}$) ~ 10^{-4} large # of B Mesons
  - *high luminosity*
  - *excellent reconstruction efficiency*
- Separate B^0 from $\overline{B}^0$ B Flavor Tagging
  - *Particle ID: leptons and kaons*
- Measure a time-dependent asymmetry
  - *B Mesons need to have sufficient momentum*
  - *A high precision tracking system*

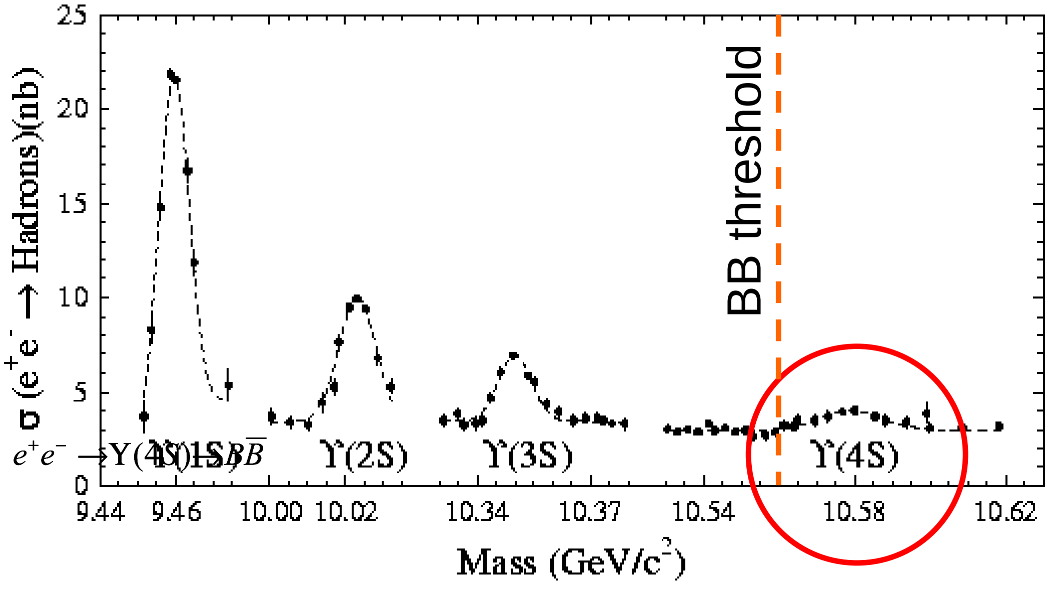
⇒ BABAR Detector @ PEP-II B Factory

The Υ(4S) Resonance

Clean source of B mesons:

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

at √s=10.58 GeV,
About 50% B^0, 50% $B^\pm$



bb signal =1.05 nb,
udsc background =3 nb

The BB system evolves coherently, until one of the B meson decays.

PEP-II - Asymmetric Energy B-Factory at SLAC

Collides 9 GeV e^- on 3.1 GeV e^+

Υ(4S) boost in lab frame : $\beta\gamma = 0.56$

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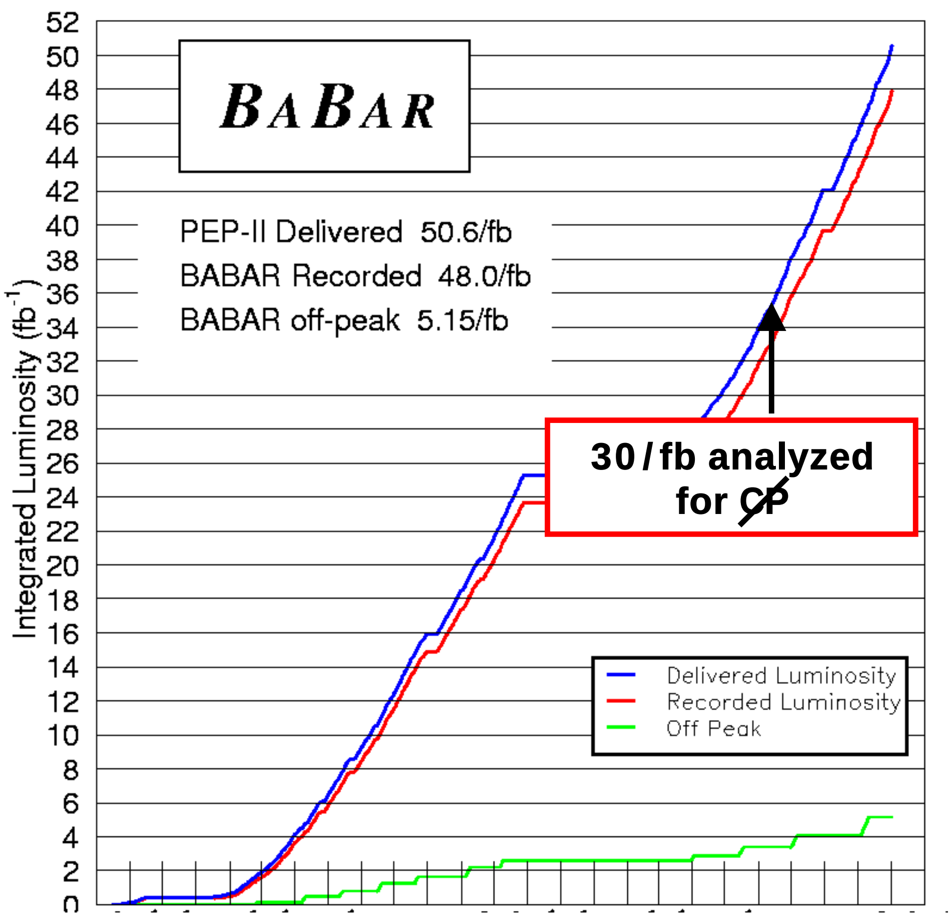
Spectacular Performance of PEP II



October 99 **October 2001**

PEP-II maximum luminosity

$4.21 \times 10^{33} cm^{-2}s^{-1}$

(design: 3.0×10^{33})

Max. recorded L/month: 5 fb^{-1}

Max. recorded L/day 282 pb^{-1}

BABAR logging efficiency: > 96%

PEP-II delivered: 50.6 fb^{-1}

BABAR recorded: 48.0 fb

(includes 5.15 fb^{-1} off peak)

The *BABAR* Collaboration

9 Countries
72 Institutions
554 Physicists

USA [35/276]

California Institute of Technology
UC, Irvine
UC, Los Angeles
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
Florida A&M
U of Iowa
Iowa State U
LBNL
LLNL
U of Louisville
U of Maryland
U of Massachusetts, Amherst
MIT
U of Mississippi
Mount Holyoke College
Northern Kentucky U
U of Notre Dame
ORNL/Y-12
U of Oregon
U of Pennsylvania
Prairie View A&M
Princeton
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Dallas
Vanderbilt
U of Wisconsin
Yale

Canada [4/16]

U of British Columbia
McGill U
U de Montréal
U of Victoria

China [1/6]

Inst. of High Energy Physics, Beijing

France [5/50]

LAPP, Annecy
LAL Orsay
LPNHE des Universités Paris 6/7
Ecole Polytechnique
CEA, DAPNIA, CE-Saclay

Germany [3/21]

U Rostock
Ruhr U Bochum
Technische U Dresden

Italy [12/89]

INFN and U Bari
INFN and U Ferrara
Lab. Nazionali di Frascati dell' INFN
INFN and U Genova
INFN and U Milano
INFN and U Napoli
INFN and U Padova
INFN and U Pavia
INFN, SNS and U Pisa
INFN, Roma and U "La Sapienza"
INFN and U Torino
INFN and U Trieste

Norway [1/3]

U of Bergen

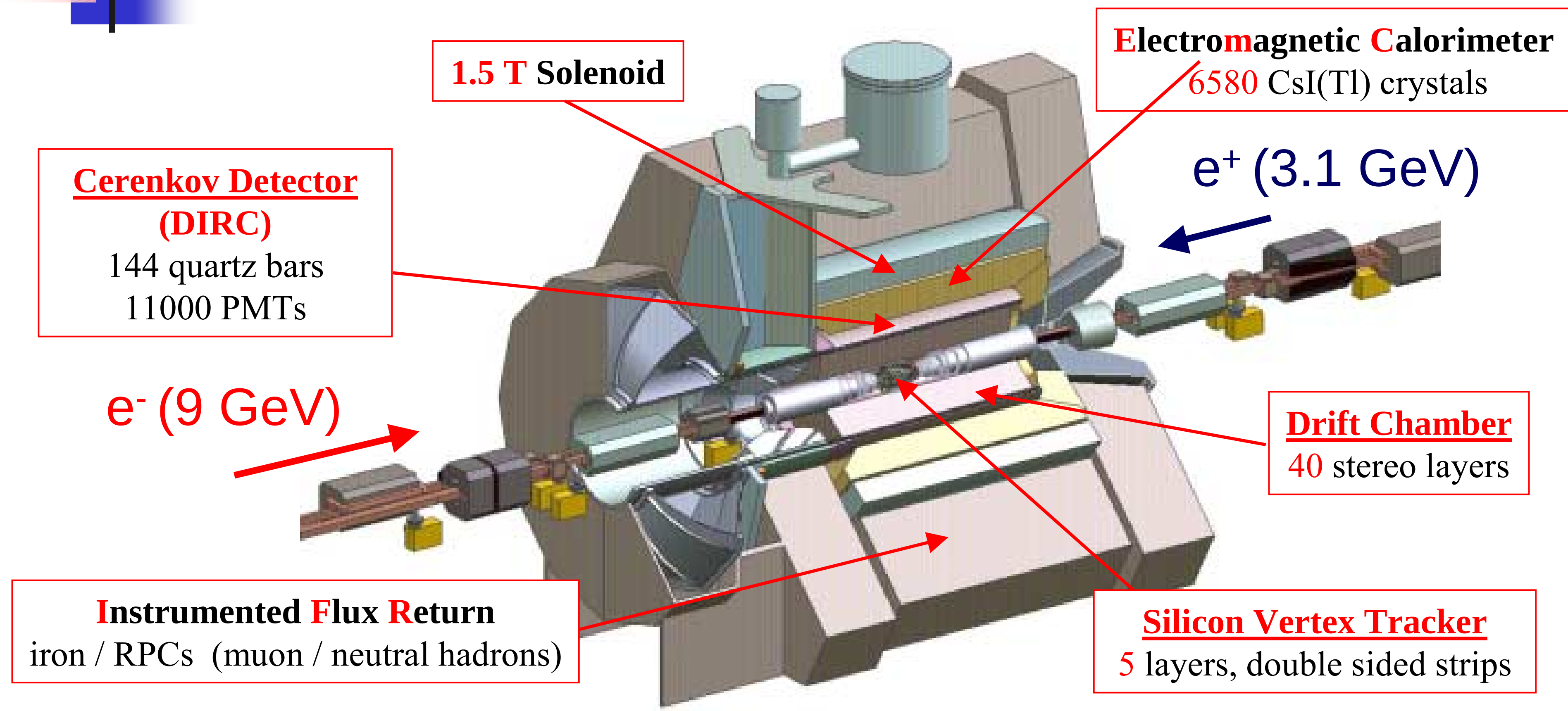
Russia [1/13]

Budker Institute, Novosibirsk

United Kingdom [10/80]

U of Birmingham
U of Bristol
Brunel University
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary & Westfield College
Royal Holloway, University of London
U of Manchester
Rutherford Appleton Laboratory

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

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Particle Identification

Electron
- $E/p \sim 1$
- dE/dx measured in DCH
- EMC shower shape

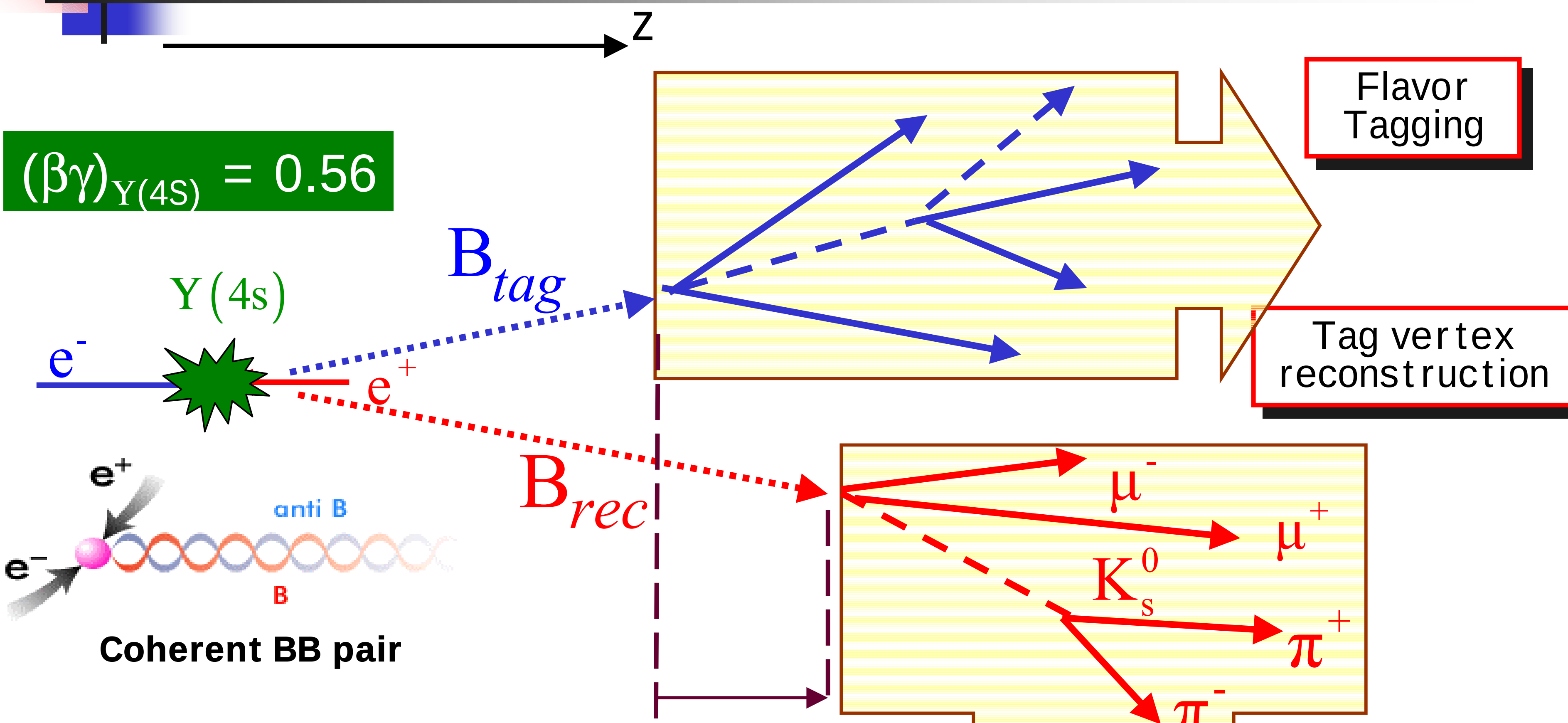
Muon
- interaction length λ traversed
- $\Delta\lambda$ between measured and expected λ for penetrating muon
- number and rms of hits per layer
- *good* χ^2 fit

Photon
- EMC cluster with E> 30 MeV
- no match with charged tracks

$K^{\pm}$
- dE/dx measured in SVT and DCH
- θ_C from Cherenkov rings in DIRC
- likelihood ratio for K/π discrimination

K_L
- reconstructed from "neutral clusters" in EMC or IFR
- π^0 and γ rejection by EMC shower shape
- minimum separation from IFR clusters associated to tracks

Event Topology at the Boosted ϒ(4S)



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

Sin2β Analysis Strategy

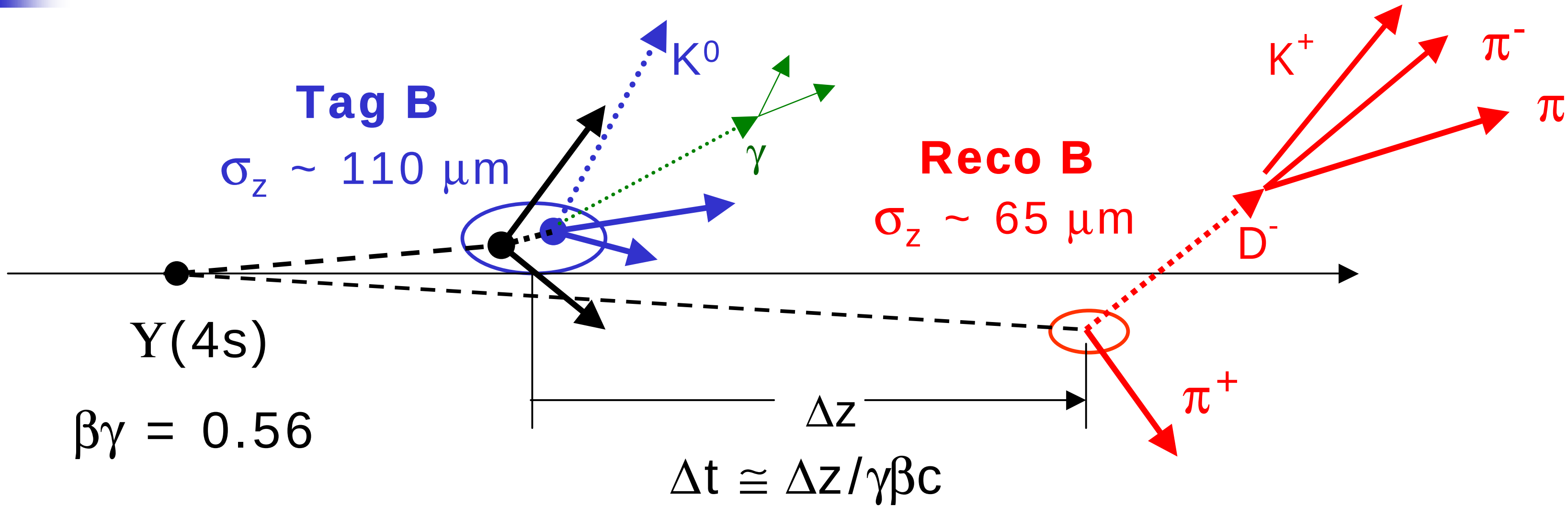
Factorize the time-dependent analysis in 3 building blocks
Obtain All analysis ingredients from DATA (not MC)

Higher precision

Measurements		Analysis Ingredient
$B^{\pm}/B^0$ Lifetimes	→	(a) Reconstruction of B mesons in flavor eigenstates (b) B vertex reconstruction
$B^0\overline{B}^0$-Mixing	→	(c) B Flavor Tagging + a + b
CP-Asymmetry	→	Reconstruction of neutral B mesons in CP eigenstates + a + b + c

Increasing complexity

Measurement of the B^0 and B^+ Lifetime



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

1. **Fully reconstruct one B meson in self tagging (B_{REC})**
2. **Reconstruct the decay vertex**

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

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Fully-Reconstructed Hadronic B Decays

Flavor Eigenstates B_{flav}

for lifetime and mixing measurements

Self-tagging hadronic decays:

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

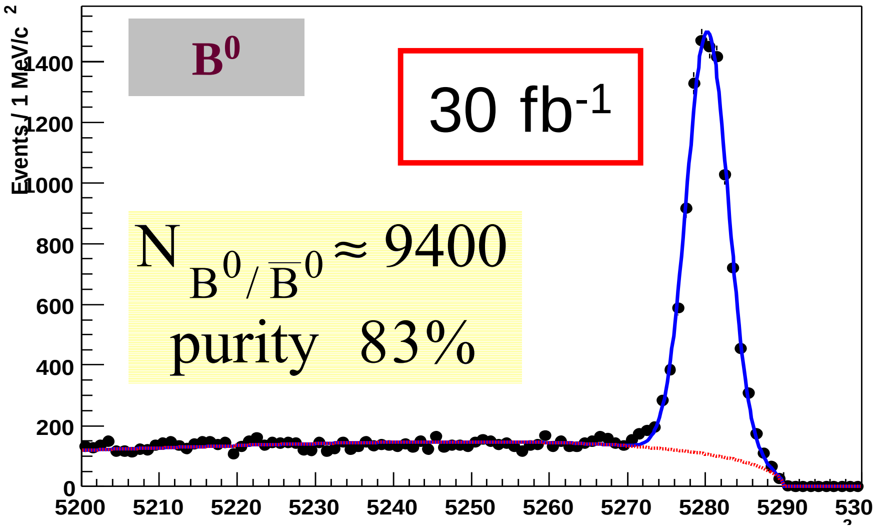
$$B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$$
$$B^- \to D^{(*)0}\pi^-$$

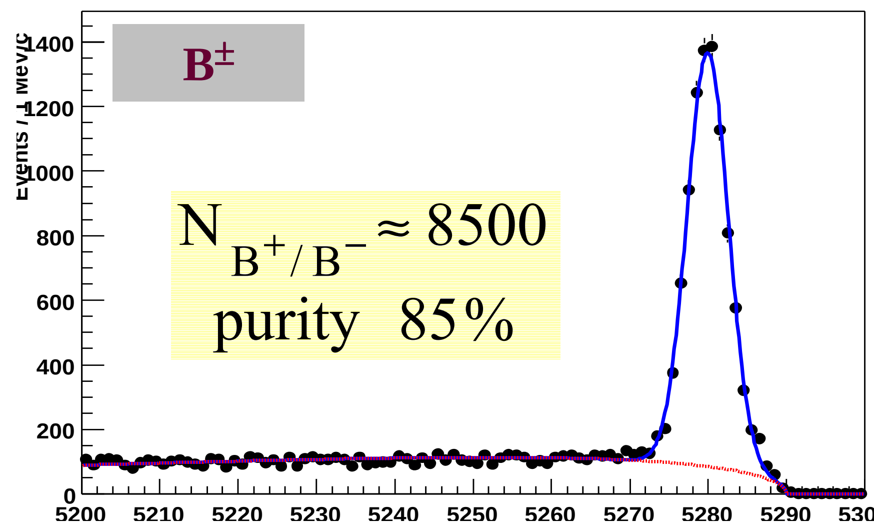
"

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

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

$$B^+ \to J/\psi K^+,\ \psi(2S)K^+$$



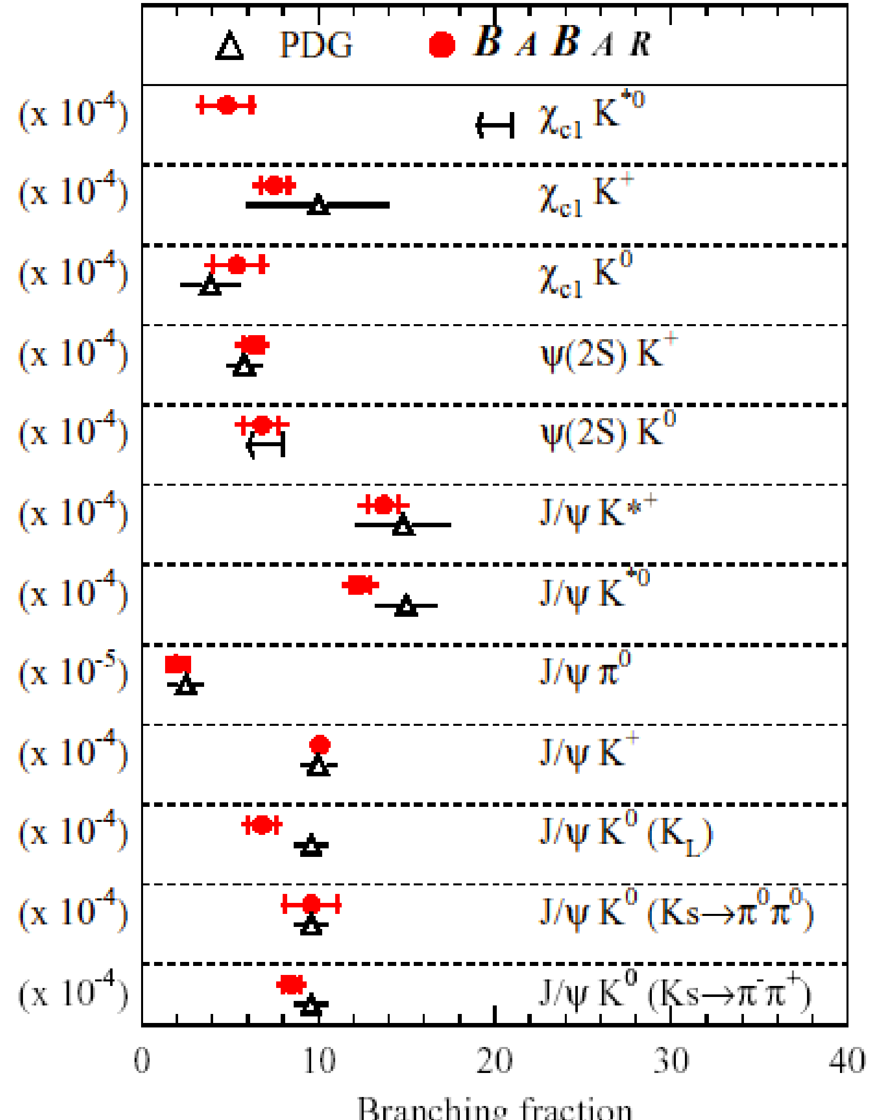


$$m_{ES} = \sqrt{(E_{beam}^{cm})^2 - (p_B^{cm})^2} \quad [\text{GeV}]$$

Exclusive B Decays to Charmonium States

BRANCHING FRACTIONS

Mode	BR ($\times 10^{-4}$)
$B^0 \to J/\psi K^0$	8.5 ± 0.5 ± 0.6
$B^+ \to J/\psi K^+$	10.1 ± 0.3 ± 0.5
$B^0 \to J/\psi K^{*0}$	12.4 ± 0.5 ± 0.9
$B^+ \to J/\psi K^{*+}$	13.7 ± 0.9 ± 1.1
$B^0 \to J/\psi \pi^0$	0.20 ± 0.06 ± 0.02
$B^0 \to J/\psi \pi^+ \pi^-$	0.46 ± 0.11 ± 0.08
$B^0 \to \psi(2S) K^0$	6.8 ± 1.0 ± 1.1
$B^+ \to \psi(2S) K^+$	6.3 ± 0.5 ± 0.8
$B^0 \to \chi_{c1} K^0$	5.4 ± 1.4 ± 1.1
$B^+ \to \chi_{c1} K^+$	7.5 ± 0.8 ± 0.8
$B^0 \to \chi_{c1} K^{*0}$	4.8 ± 1.4 ± 0.9



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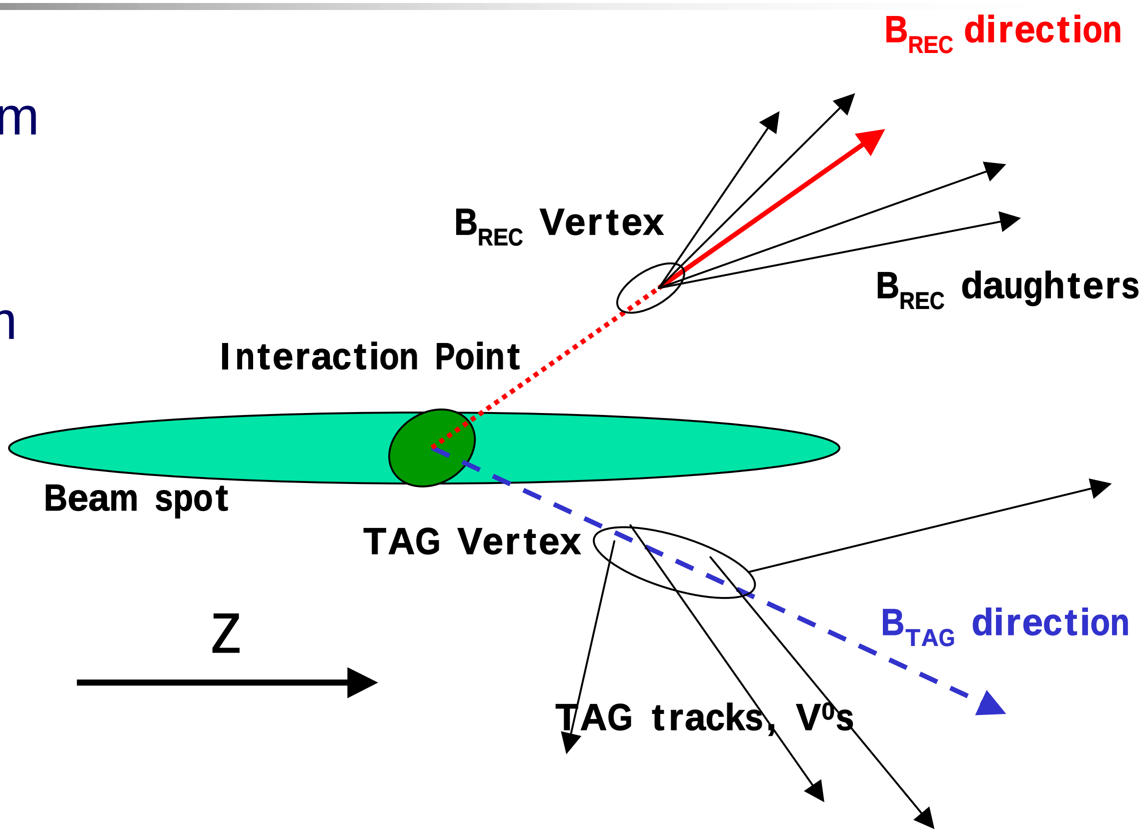
Δz Reconstruction

- Reconstruct B_{rec} vertex from
  - charged B_{rec} secondaries
- 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 μm)
- Δt resolution function measured from data (B_{flav} sample)

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τ_B Measurement at $\Upsilon(4S)$

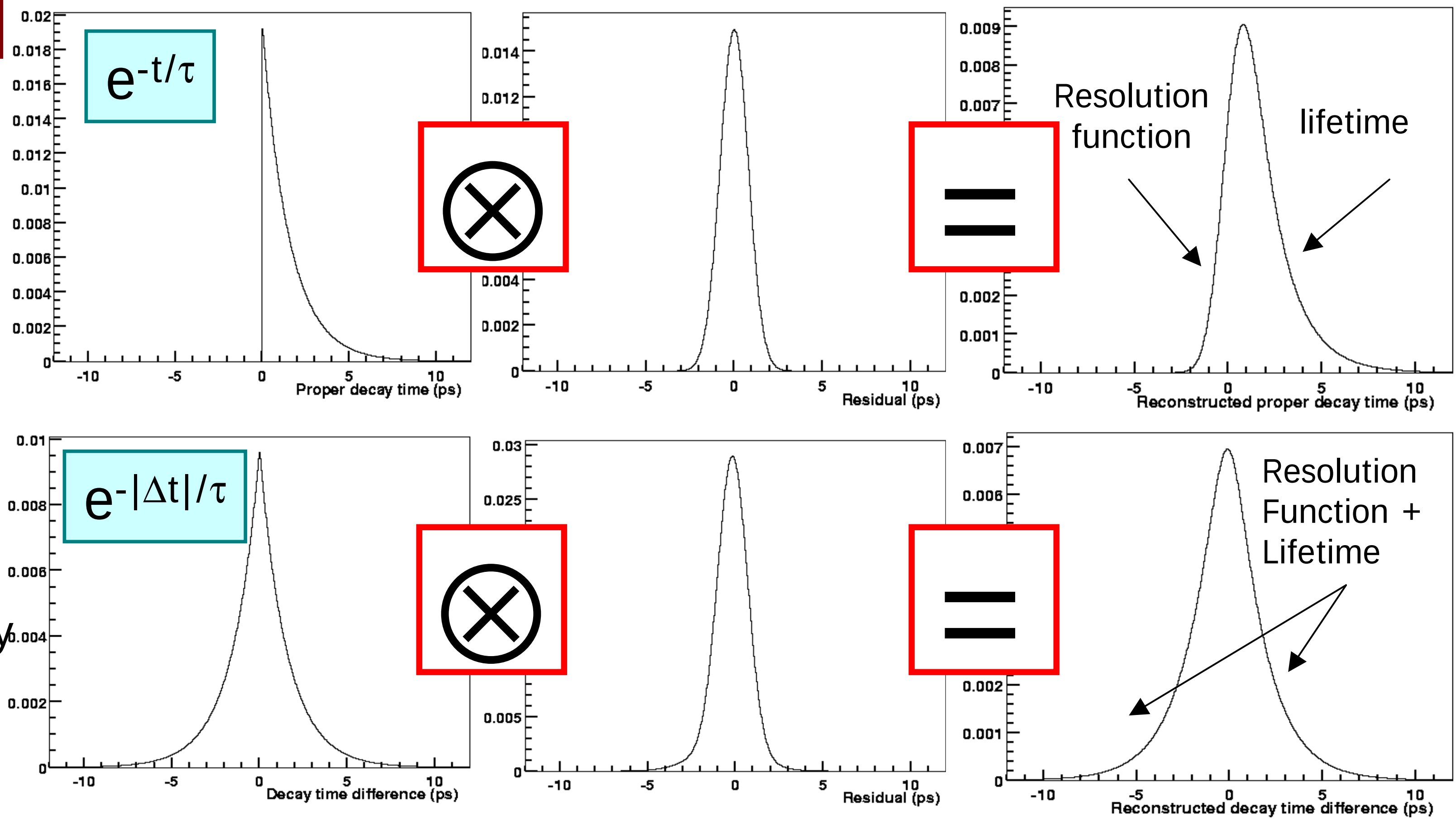
	true Δt	Δt resolution	measured Δt

LEP/CDF

B production point known eg. from beam spot

BABAR

Either B_{rec} or B_{tag} can decay first (this analysis)



Need to disentangle resolution function from physics

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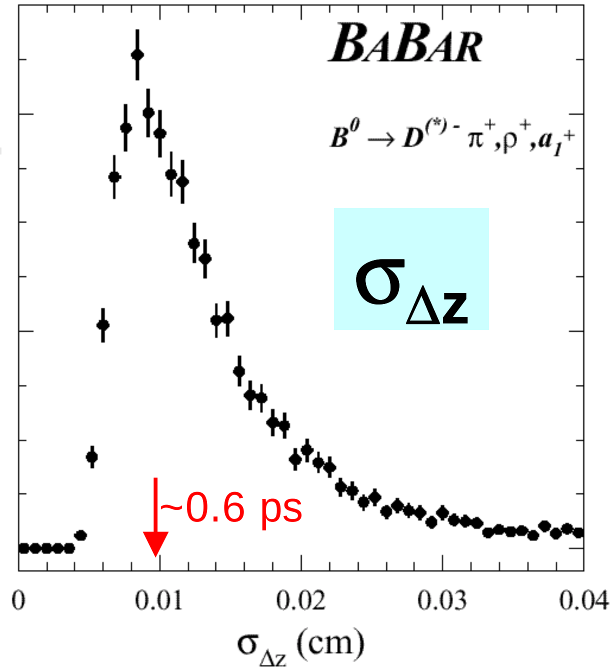
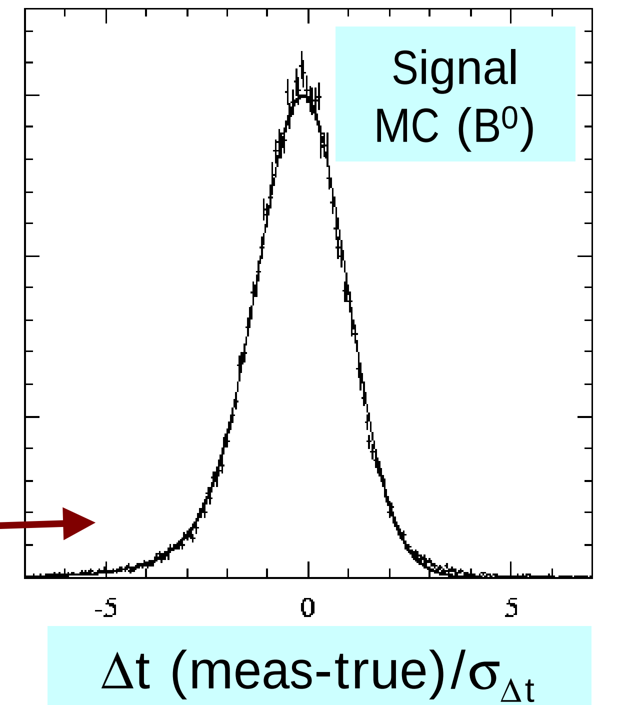
Δt Resolution Function

- event-by-event σ(Δt) from vertex errors, dominated by tag vertex error
- Charm Lifetime induced bias leads to small correlation between the lifetime and the Resolution Function parameters



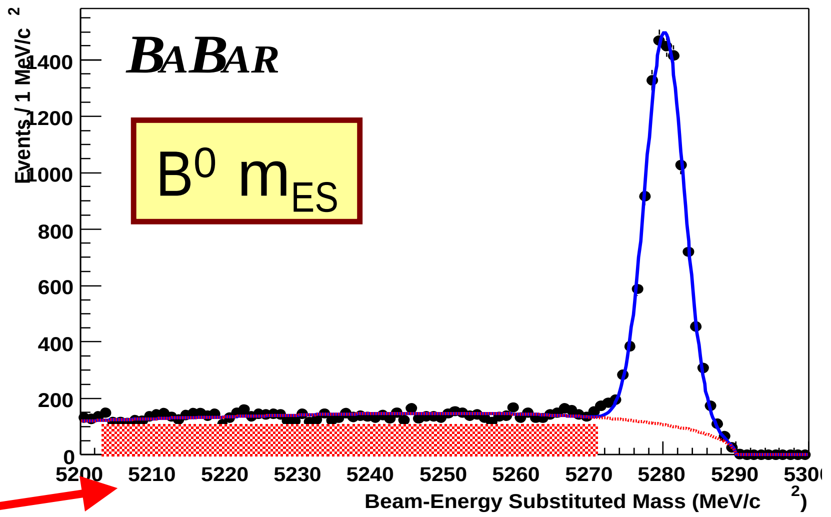
$$R = (1 - f_{tail} - f_{outlier}) G(S\sigma_{\Delta t}, \mu_{core} = 0)$$
$$+ f_{tail} G(S\sigma_{\Delta t}, \mu = 0) \otimes \exp(-\Delta t / \sigma_{\Delta t} \tau_{bias})$$
$$+ f_{outlier} G(\sigma_{outlier}, \mu_{outlier})$$

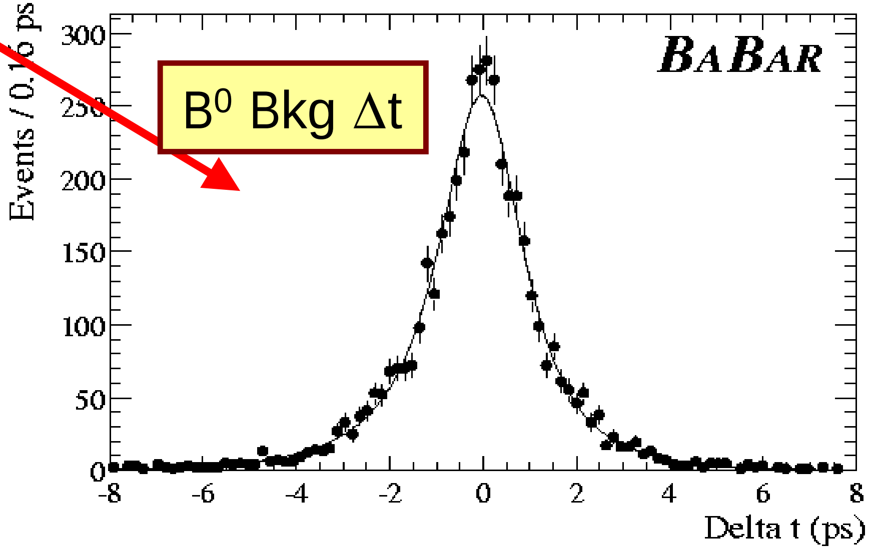
tracks from long-lived D's in tag vertex
asymmetric Resolution Function



B Lifetime Likelihood Fit

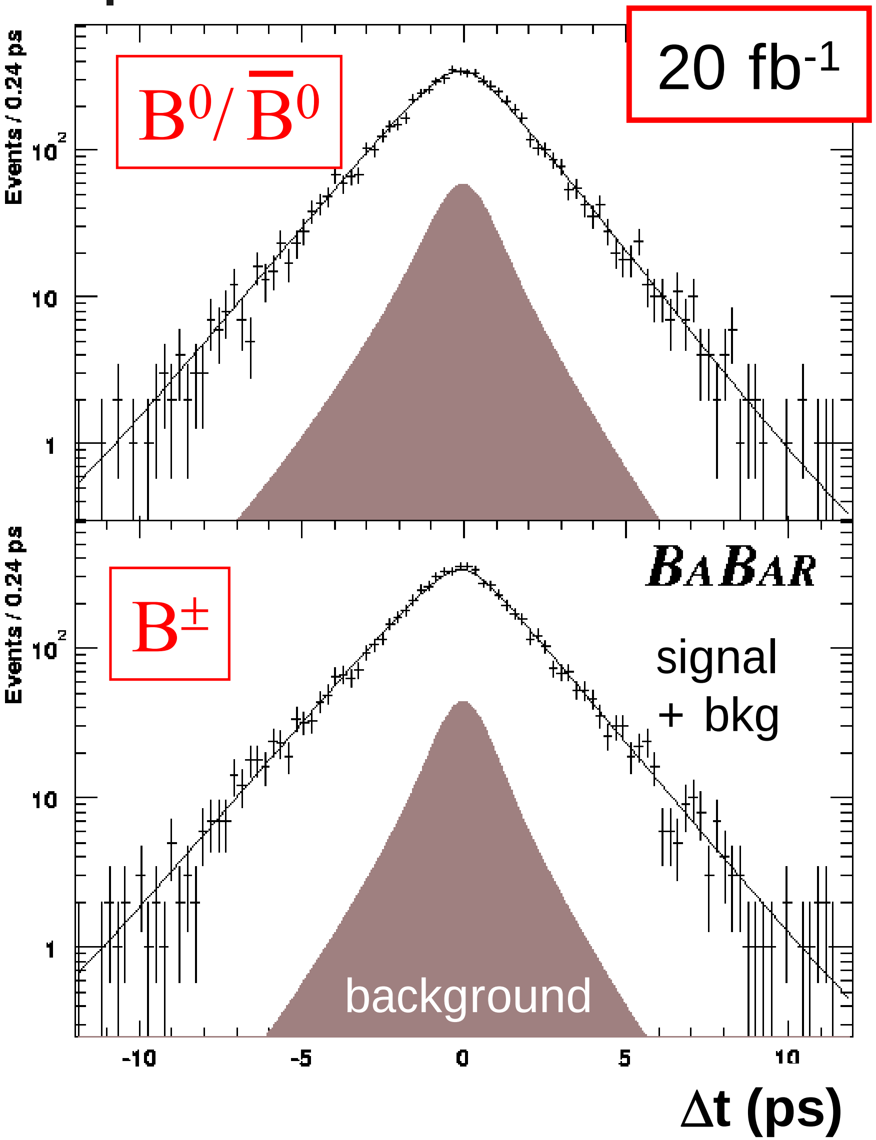
- Simultaneous unbinned maximum likelihood fit to B^0/B^+ samples
- Use data to extract the properties of background events
  - Mass distribution provides the signal probability
  - Use the events in the sideband (m_{ES} < 5.27) to determine the Δt structure of the background events under the signal peak





- 19 free parameters
  - $\tau(B^+)$ and $\tau(B^0)$ 2
  - Δt signal resolution 5
  - empirical background description 12

B Lifetime Results:Calibration of BABAR Clock



τ_0 = 1.546 ± 0.032 ± 0.022 ps

PDG: 1.548 ± 0.032 ps

$\tau_\pm$ = 1.673 ± 0.032 ± 0.022 ps

PDG: 1.653 ± 0.028 ps

$\tau_\pm/\tau_0$ = 1.082 ± 0.026 ± 0.011

PDG: 1.062 ± 0.029

- Precision measurement !
  - 2 % statistical error
  - 1.5% systematic error
- Dominant systematic errors:
  - Parameterization of the Δt resolution function
  - Description of events with large measured Δt (outliers)

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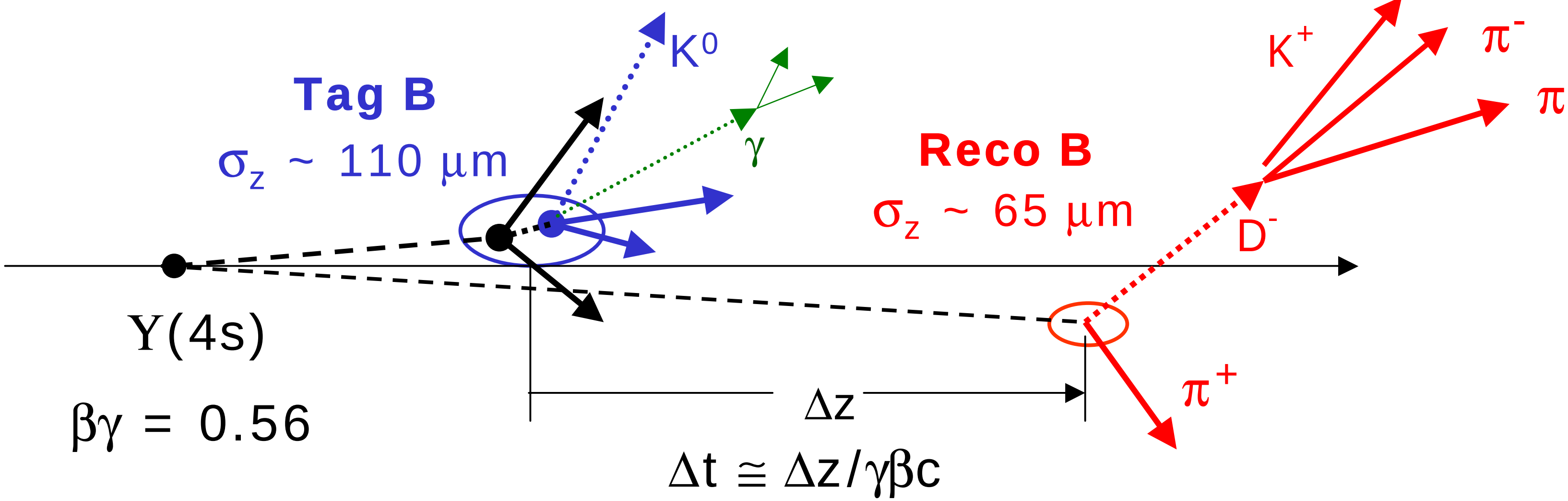
$B^0\overline{B}^0$ Mixing with Fully Reconstructed Decays



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

4. Determine the flavor of B_{TAG}

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

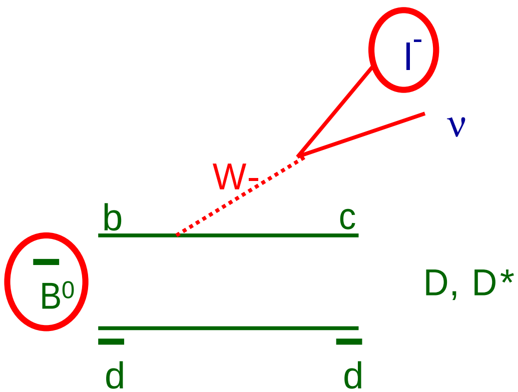
5. compute the proper time difference Δt ✓

6. Fit the Δt spectra of mixed and unmixed events

B Flavor Tagging Methods

Hierarchical Tagging Categories

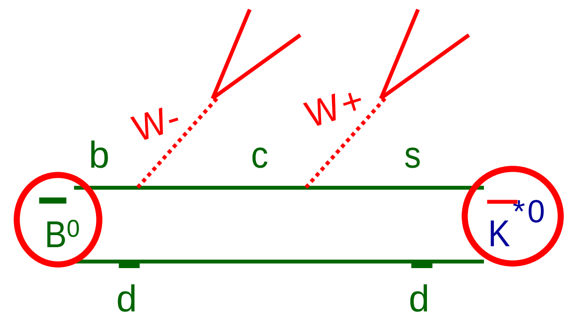
For electrons, muons and Kaons use the charge correlation



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

$l^+ \to B^0$

Lepton Tag



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

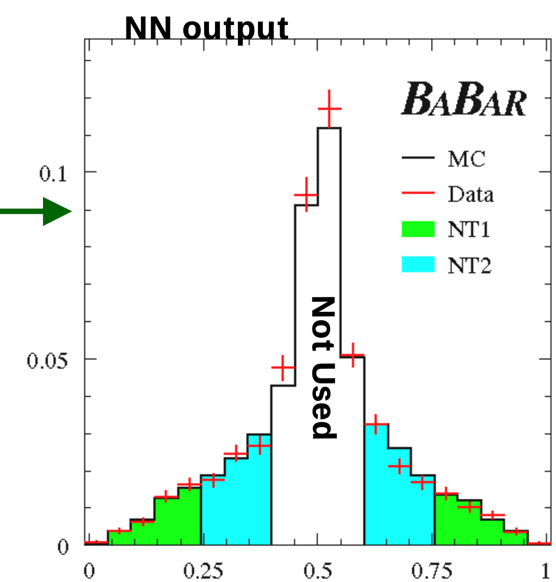
$\sum_{kaons} Q > 0 \Rightarrow B^0$

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*)

V. Lüth

B Flavor Tagging Performance Using B Mixing

The large sample of fully reconstructed hadronic B decays provides the precise determination of the tagging performance

Tagging category	Fraction of tagged events ε (%)	Wrong tag fraction w (%)	Q = ε $(1-2w)^2$ (%)
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"

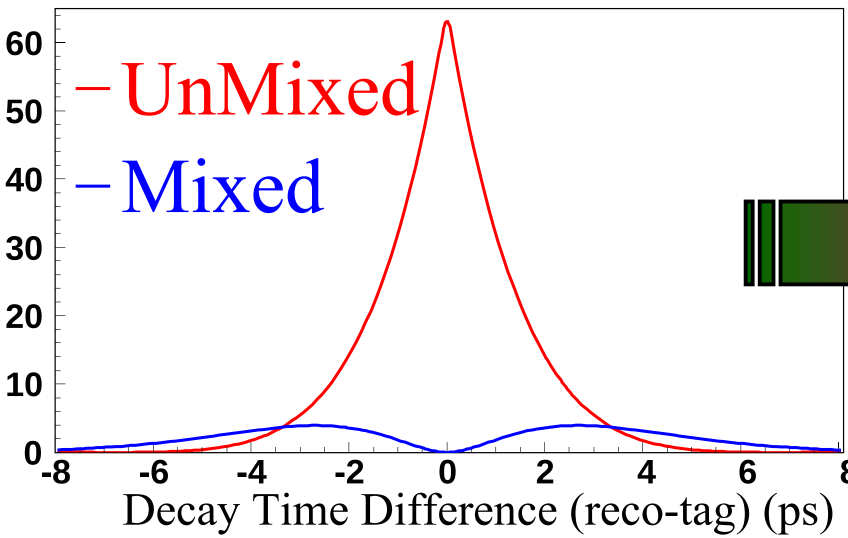
Smallest mistag fraction

The error on sin2β: Quality Factor Q

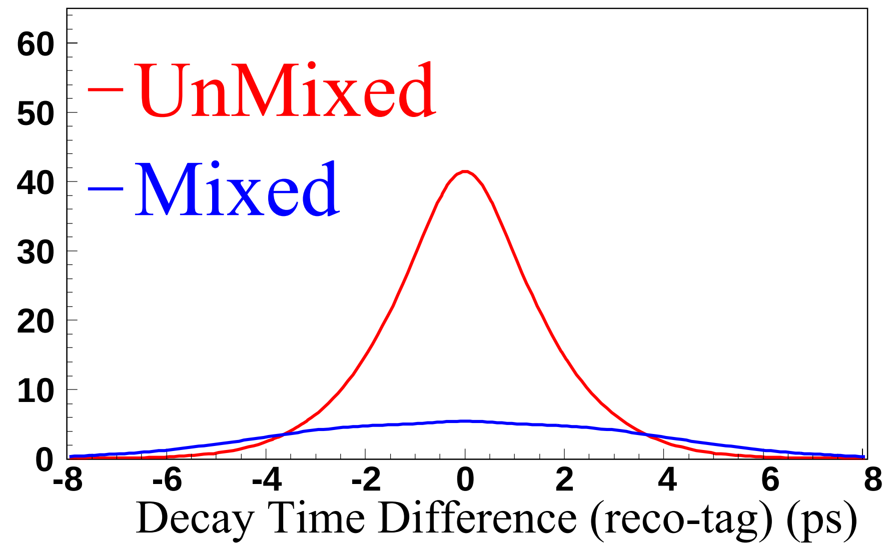
$$\sigma(\sin 2\beta) \propto \frac{1}{\sqrt{Q}}$$

Δt Spectrum of Mixed and Unmixed B Events

perfect
flavor tagging & time resolution



realistic
mis-tagging & finite time resolution



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

w: the fraction of wrongly tagged events

Δm_d: oscillation frequency

Unmixed: $B^0_{flav}\bar{B}^0_{tag}$ or $\bar{B}^0_{flav}B^0_{tag}$

Mixed: $B^0_{flav}B^0_{tag}$ or $\bar{B}^0_{flav}\bar{B}^0_{tag}$

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Δt Resolution Function for Δm and CP Fit

$$R(\delta\Delta t) = (1 - f_{tail} - f_{outl}) \cdot G_{core}(\delta\Delta t, S_{core}, \delta_{core,i})$$
$$+ f_{tail} \cdot G_{tail}(\delta\Delta t, S_{tail}, \delta_{tail})$$
$$+ f_{outl} \cdot G_{outl}(\delta\Delta t, \sigma_{outl} = 8\,ps, \delta_{outl} = 0)$$

Core **0.70**

Tail **0.29**

Outlier **0.01**

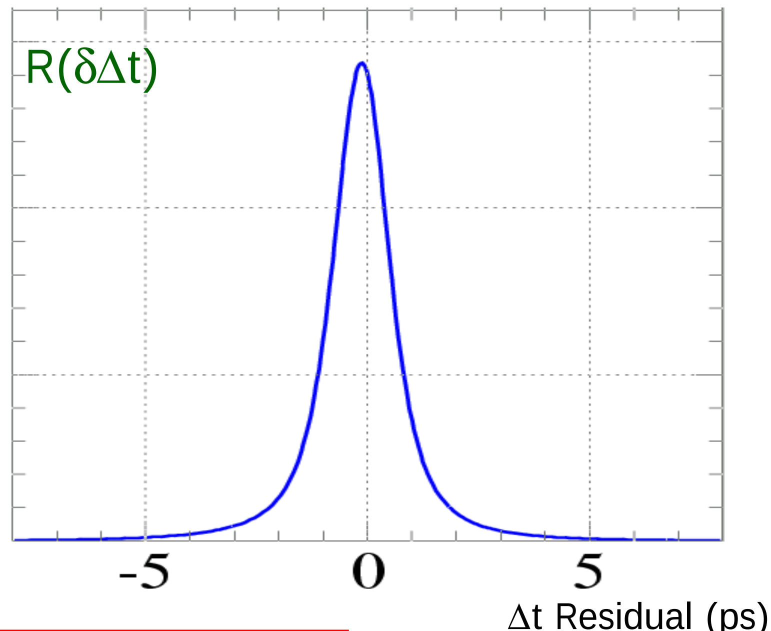
$$\sigma_{core} = S_{core} \cdot \sigma^{evt}_{\Delta t}$$

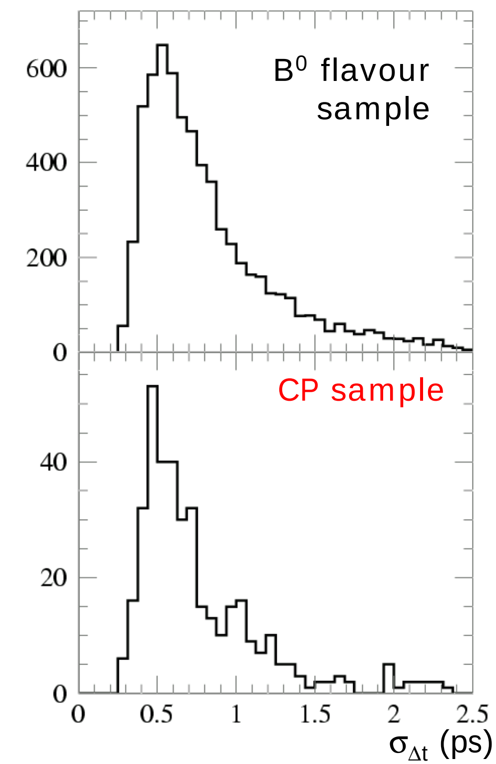
$$\sigma_{tail} = S_{tail} \cdot \sigma^{evt}_{\Delta t}$$

Use the event-by-event uncertainty on Δt

Parameter
S_{Core}
S_{Tail}
f_{Tail} (%)
f_{Outlier} (%)
$\delta_{\mathrm{Core,Lepton}}$ (ps)
$\delta_{\mathrm{Core,Kaon}}$ (ps)
$\delta_{\mathrm{Core,NT1}}$ (ps)
$\delta_{\mathrm{Core,NT2}}$ (ps)
δ_{Tail} (ps)

Different bias For each tagging category





Likelihood Fit for Mixing Samples

Unbinned maximum likelihood fit to flavor-tagged neutral Bs

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

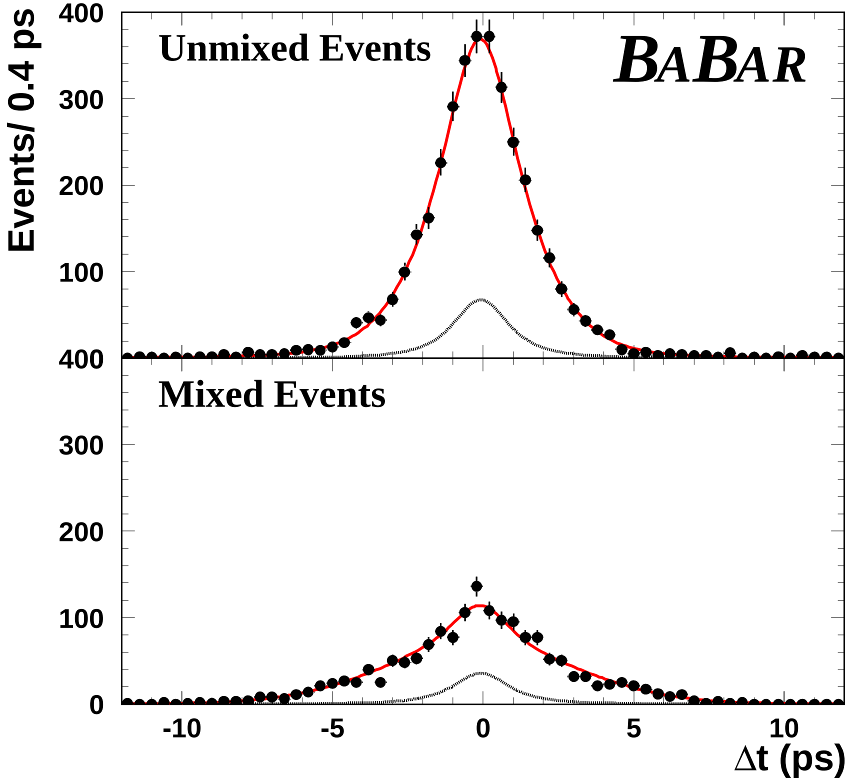
Fit Parameters

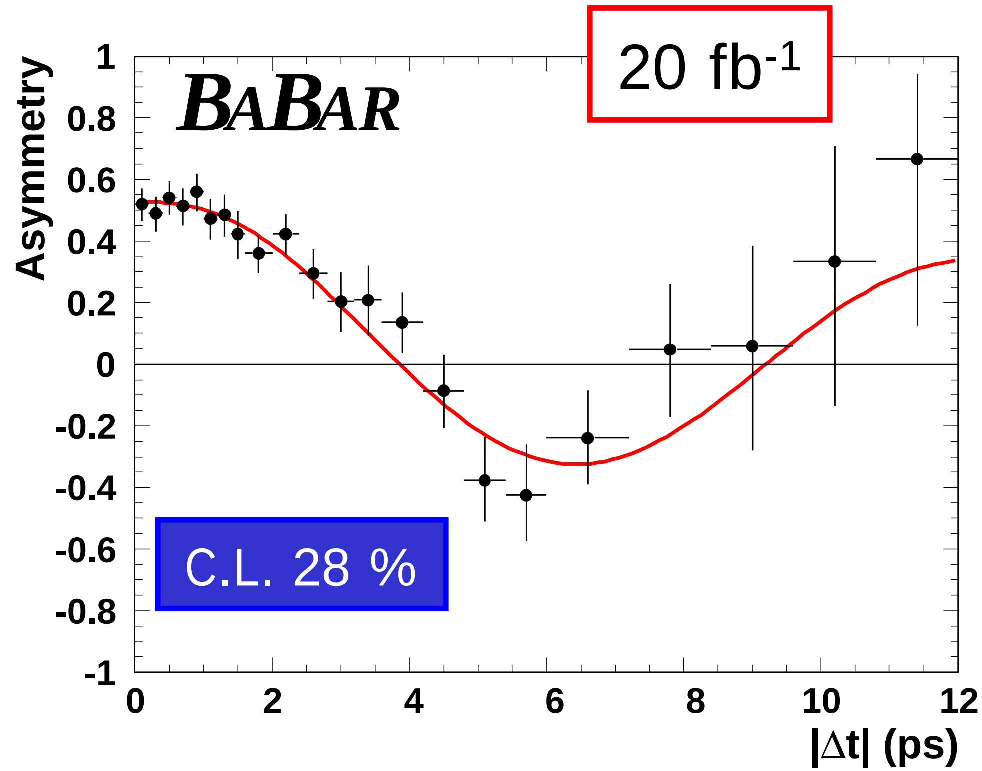
Δm_d	1
Mistag fractions for B^0 and $\overline{B^0}$ tags	8
Signal resolution function(scale factor,bias,fractions)	9
Empirical description of background Δt	16
B lifetime fixed to the PDG value	τ_B = 1.548 ps

34 total free parameters ⇒ All Δt parameters extracted from data

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

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





Δm_d = 0.519 ± 0.020 (stat) ± 0.016 (syst) ħ ps^{-1}

Preliminary

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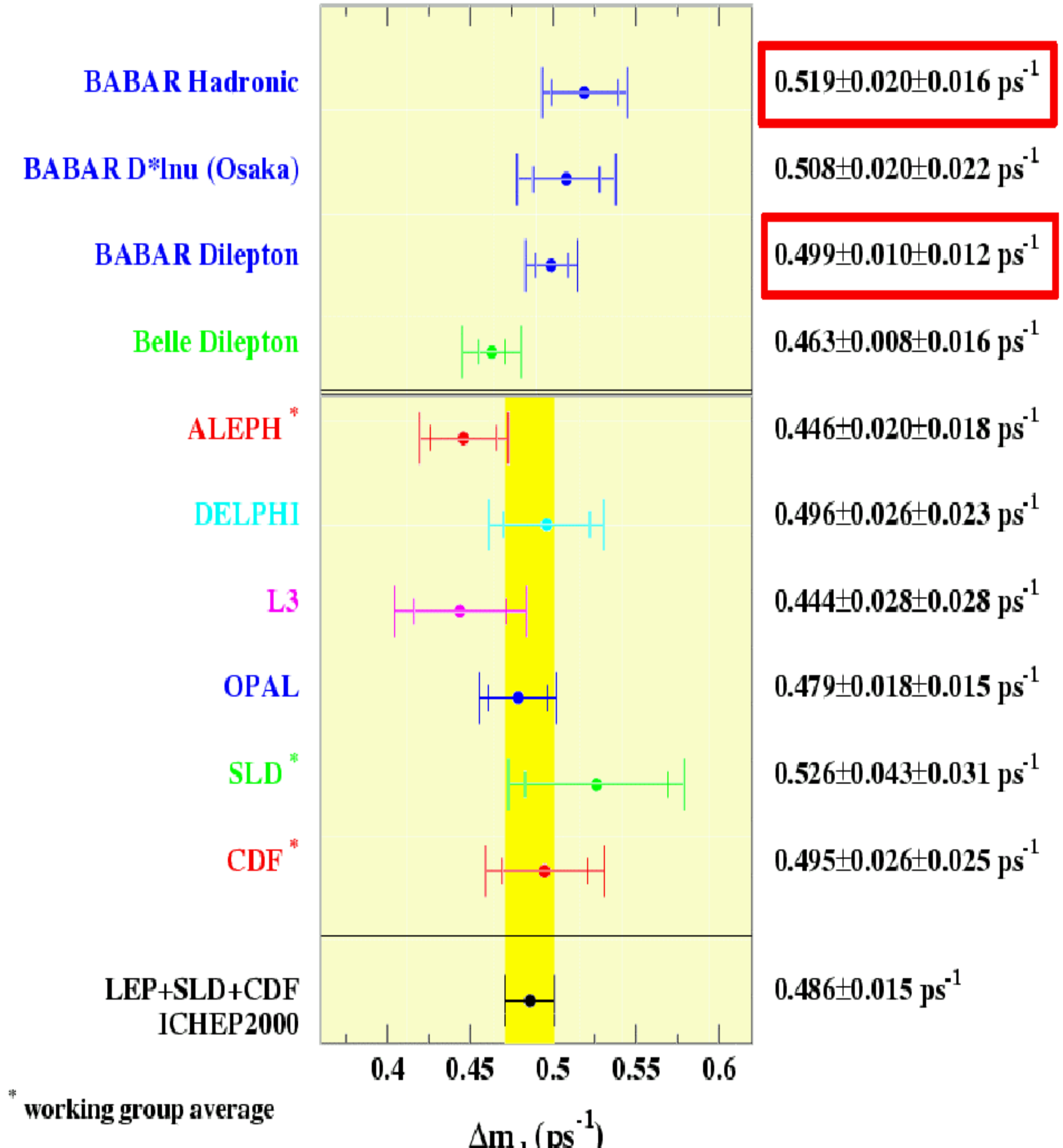
Δm_d Measurement in Comparison

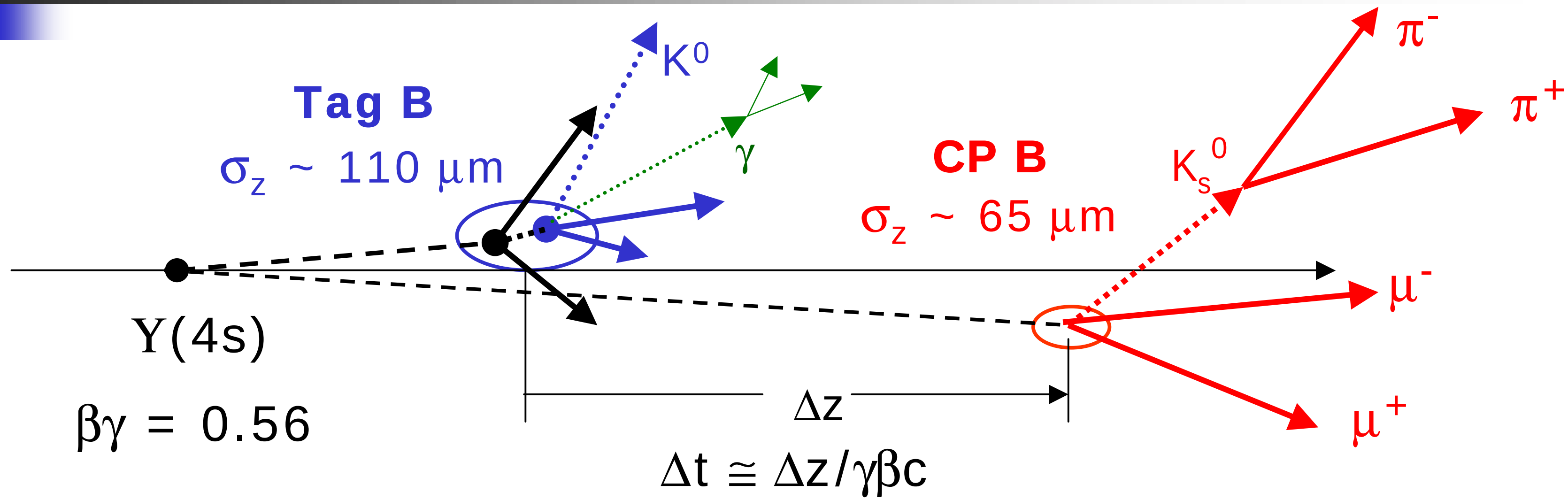


preliminary

Precision Δm_d measurement

- 4% statistical error
- 3% systematic error dominated by MC correction

Measurement of CP Asymmetry : Sin2β



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

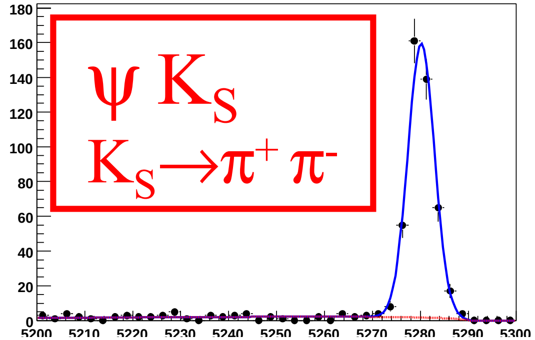
1. Fully reconstruct one B meson in CP eigenstate (B_{CP})

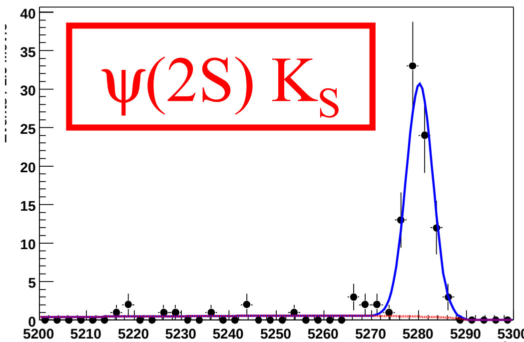
2. Reconstruct the decay vertex ✓

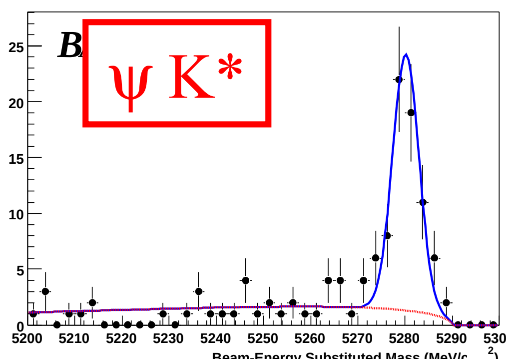
5. compute the proper time difference Δt ✓

6. Fit the Δt spectra of B^0 and $\overline{B^0}$ tagged events

The CP Event Sample







Plots before flavor tagging

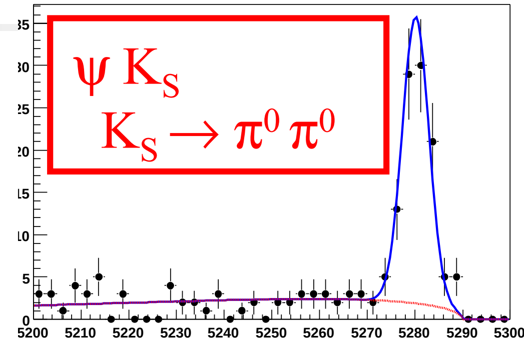
<u>1999-2001 Data</u>

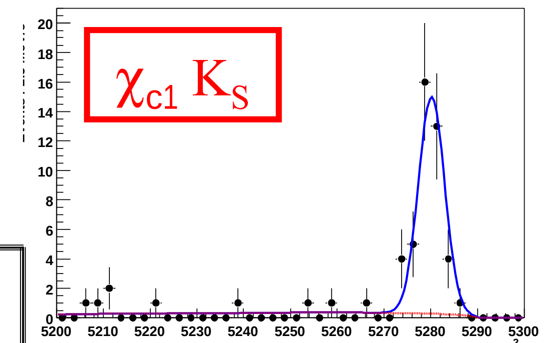
32 x 10^6 $B\bar{B}$ pairs

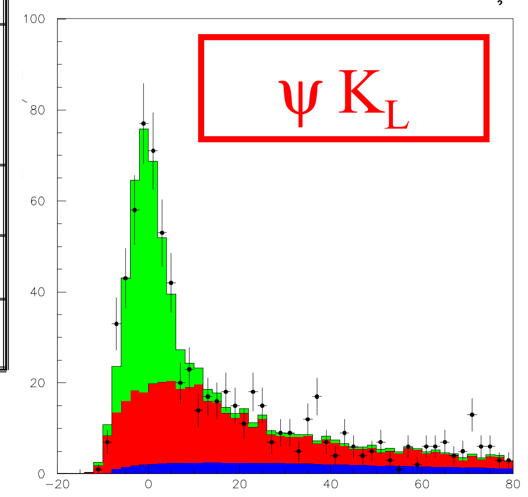
29 fb^{-1} on peak

Sample	tagged events	Purity	*CP*
$[\psi, \psi(2S), \chi_{c1}]$ K_S	480	96%	-1
ψK_L	273	51%	+1
$\psi K^{*0}(K_S\pi^0)$	50	74%	mixed
Full *CP* sample	803	80%	

Results after flavor tagging



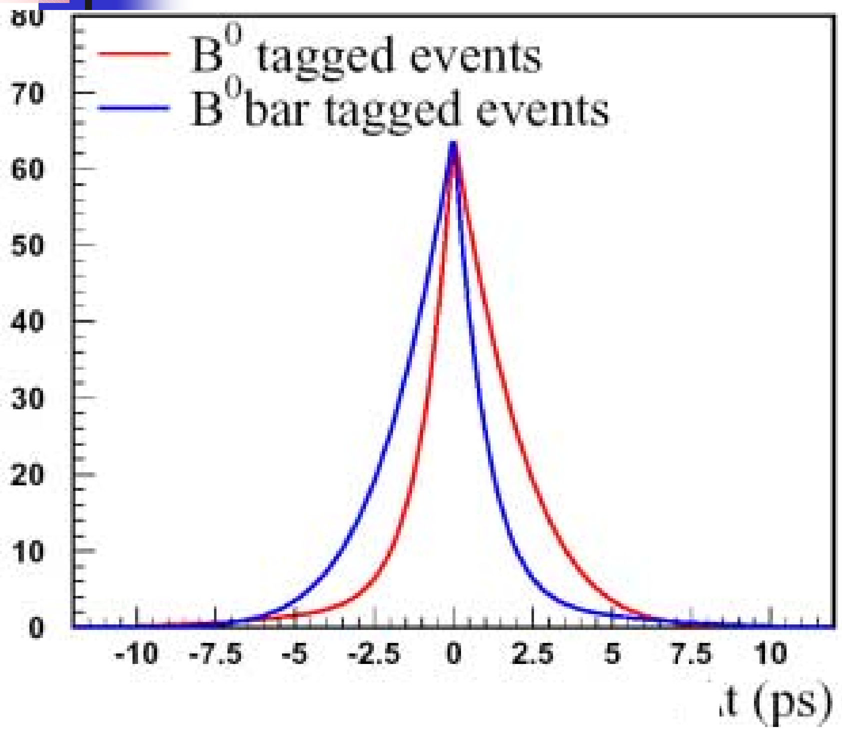




V. Lüth $m_{ES} = \sqrt{(E_{beam}^{cm})^2 - (p_B^{cm})^2}$

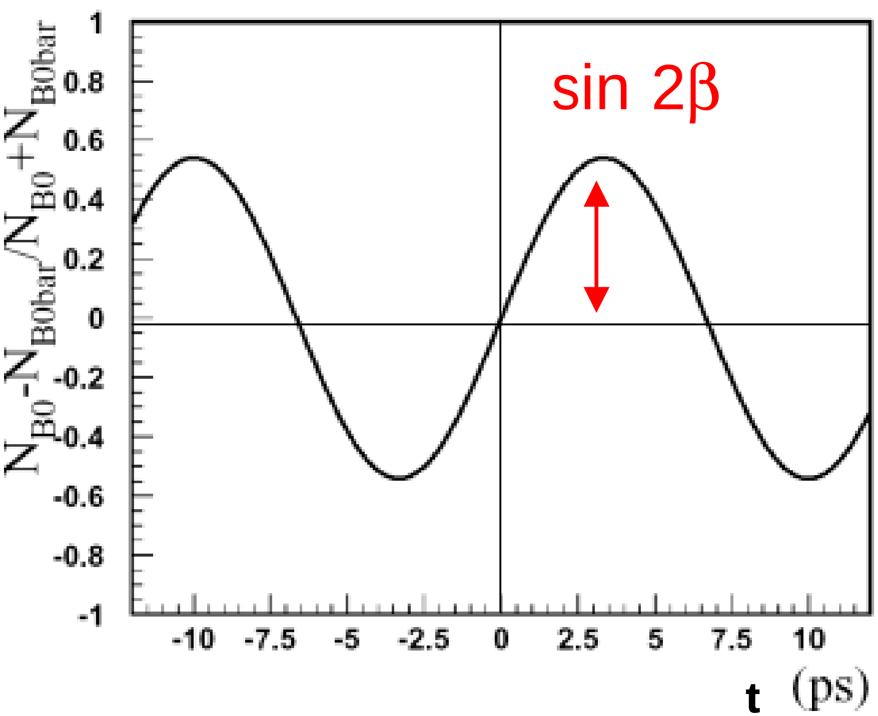
$$\Delta E = E_{J/\psi} + E_{K_L} - E_{beam}^{cm}$$

Decay Time Evolution & A_{CP} for $B^0 \to \psi K^0_S$



- Δt spectrum and the observed asymmetry for a perfect detector (with sin2β = 0.6)
- Visible difference between B^0 and $\overline{B}^0$ decay rates

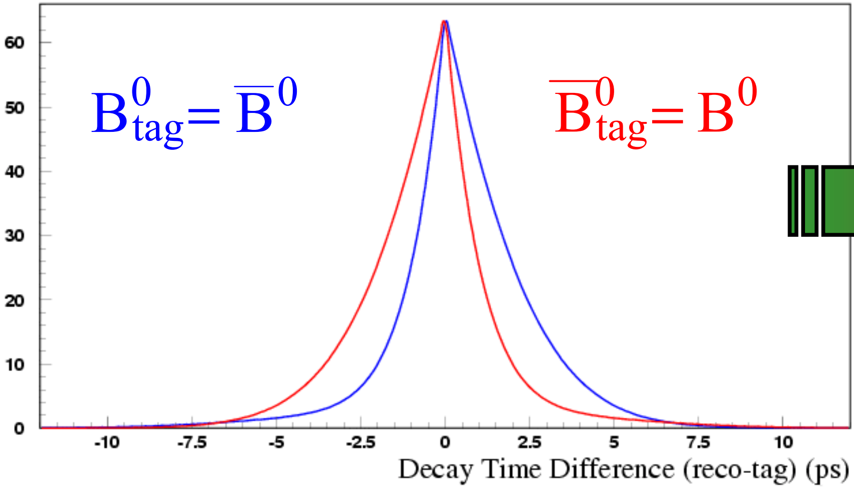
$$A_{CP}(t) = -\eta_f \sin 2\beta \sin(\Delta m_d t)$$



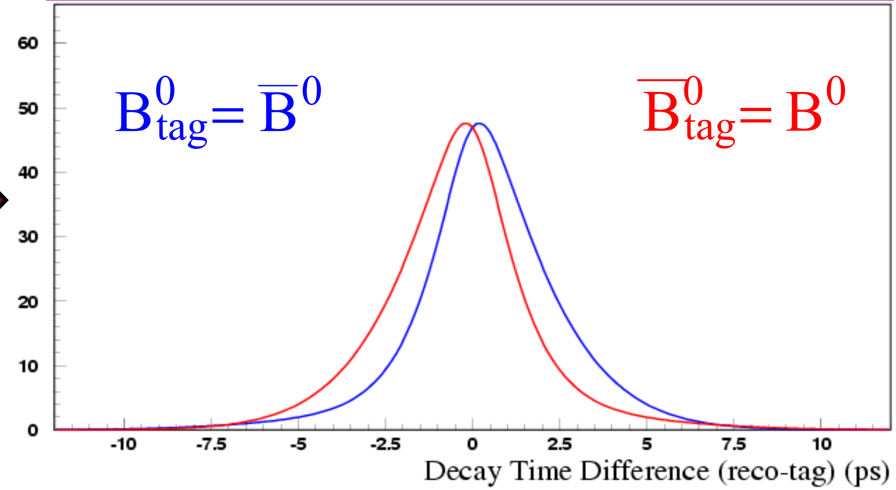
- In this ideal case, the amplitude is the CP Asymmetry
- the time-integrated asymmetry is 0

Δt Spectrum of CP Events

perfect
flavor tagging & time resolution



realistic
mis-tagging & finite time resolution



CP PDF

$$f_{CP,\pm}(\Delta t)=\left\{\frac{e^{-|\Delta t|/\tau_{B_d}}}{4\,\tau_{B_d}}\times\left(1\mp\eta_f\ \sin2\beta(1-2w)\sin(\Delta m_d\Delta t)\right)\right\}\otimes \boldsymbol{R}$$

Mistag fractions w
and
Resolution function R

determined from the flavor sample

Mixing PDF

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

V. Lüth

sin2β Likelihood Fit

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

Fit Parameters

Sin2β	1	tagged CP samples
Mistag fractions for B^0 and $\overline{B^0}$ tags in each Cat.	8	tagged flavor sample
Signal resolution function	16	
Empirical description of background Δt	20	
B lifetime fixed to the PDG value	τ_B = 1.548 ps	
Mixing Frequency fixed to the PDG value	Δm_d = 0.472 ps^{-1}	

Global correlation coefficient for sin2β: 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

Blind Analysis

The sin2β analysis was done blind to eliminate possible experimenters' bias

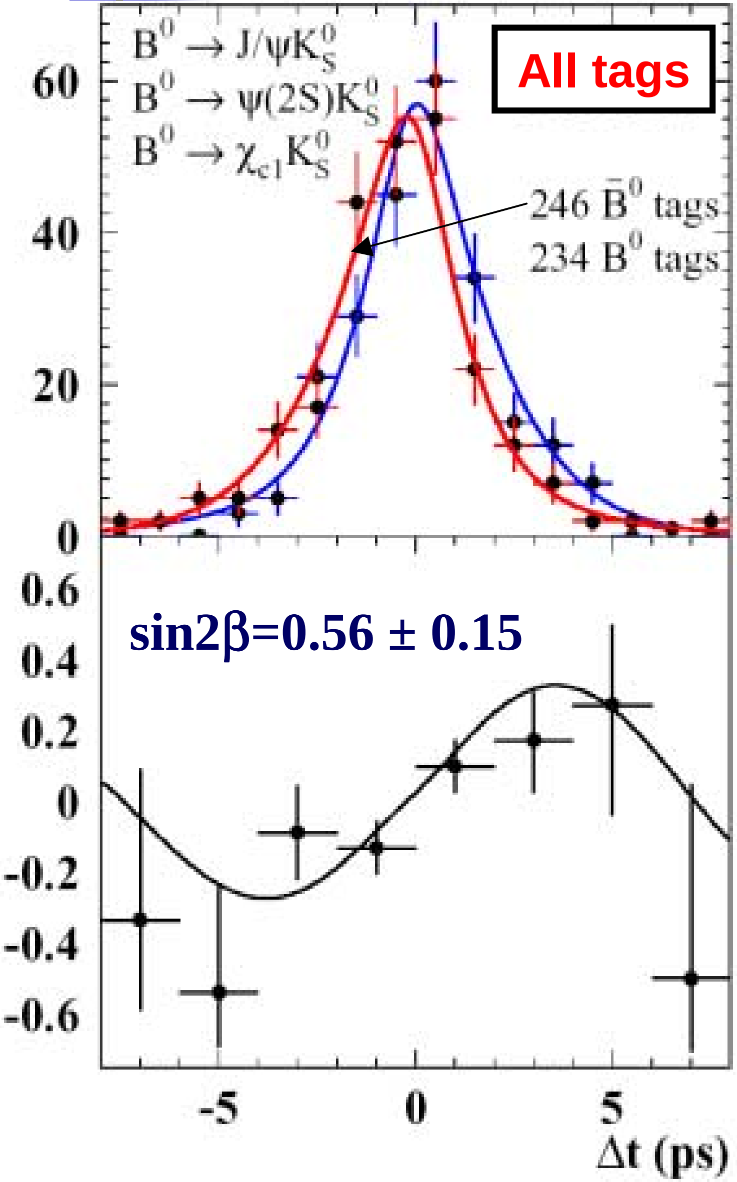
– *The amplitude in the asymmetry $A_{CP}(\Delta t)$ was hidden by arbitrarily flipping its sign and by adding an arbitrary offset*

– *The CP asymmetry in the Δt distribution was hidden by multiplying Δt by the sign of the tag and by adding an arbitrary offset*

– *The blind aproach allows systematic studies of tagging, vertex resolution and their correlations to be done while keeping the value of sin2β hidden*

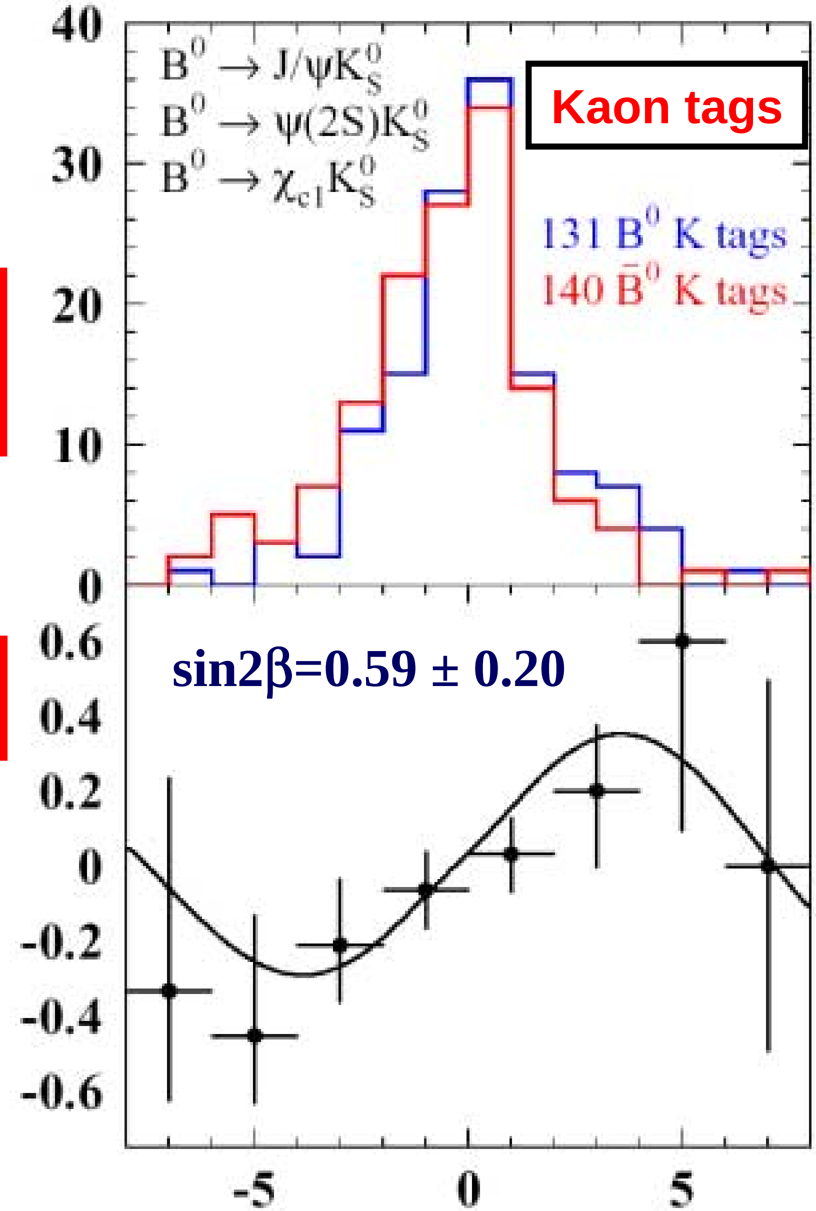
– *The result was unblinded 1 week before public announcement this summer!*

Raw CP Asymmetry in Clean Charmonium Modes

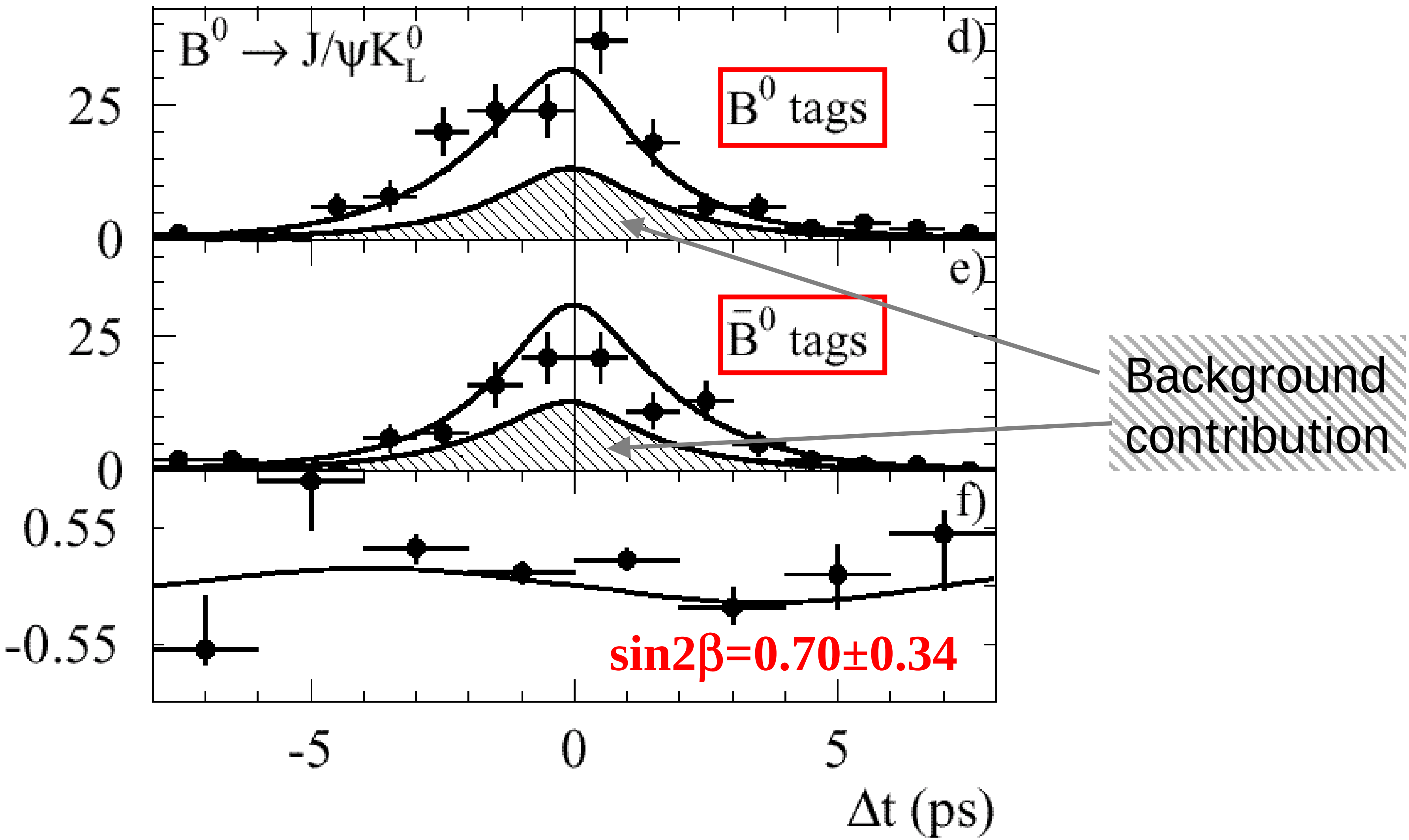


η_f = -1 events

Raw A_{CP}



Raw CP Asymmetry for ψ K_L



Sin2β Results

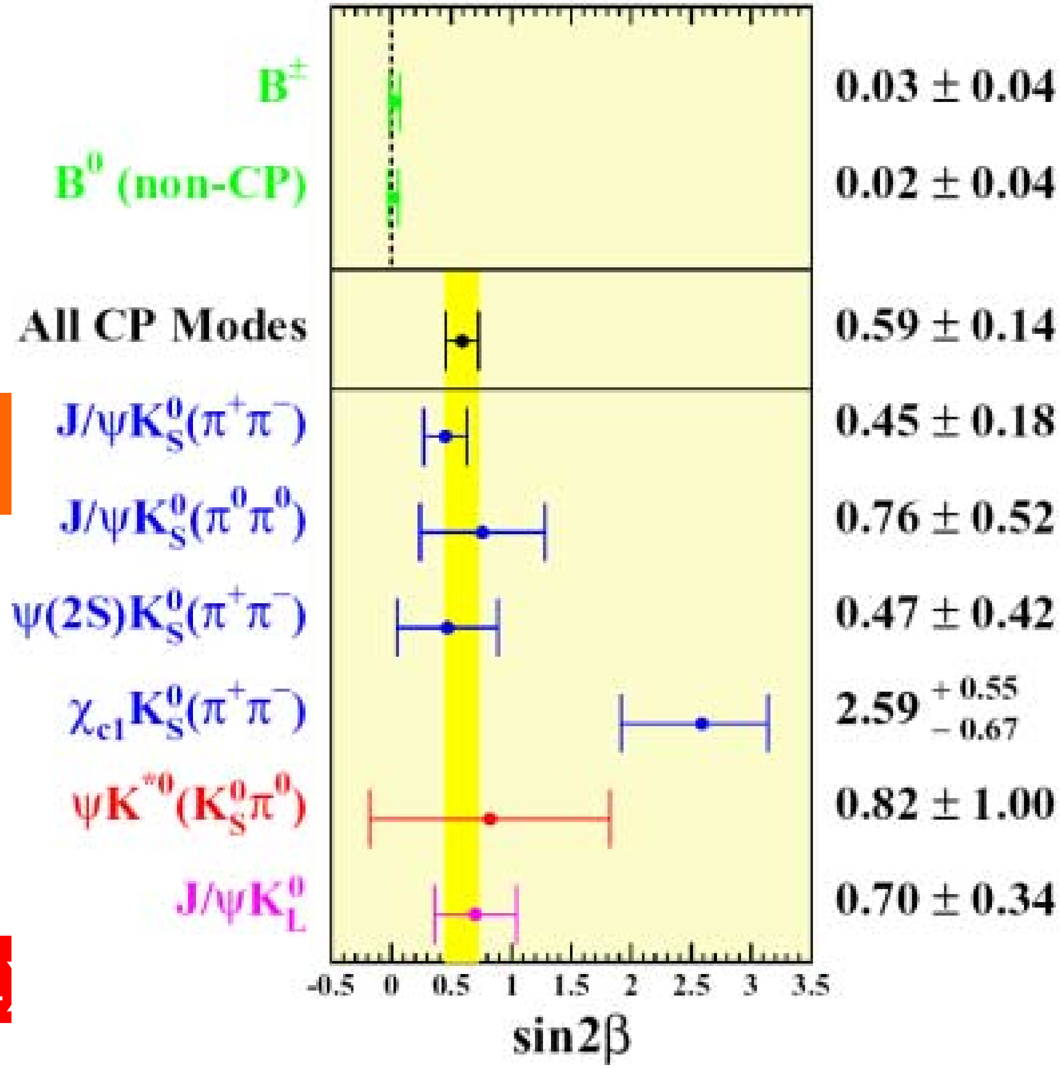
Calibration:
Null result in flavor samples

Combined fit to all modes

$\sin 2\beta = 0.59 \pm 0.14$

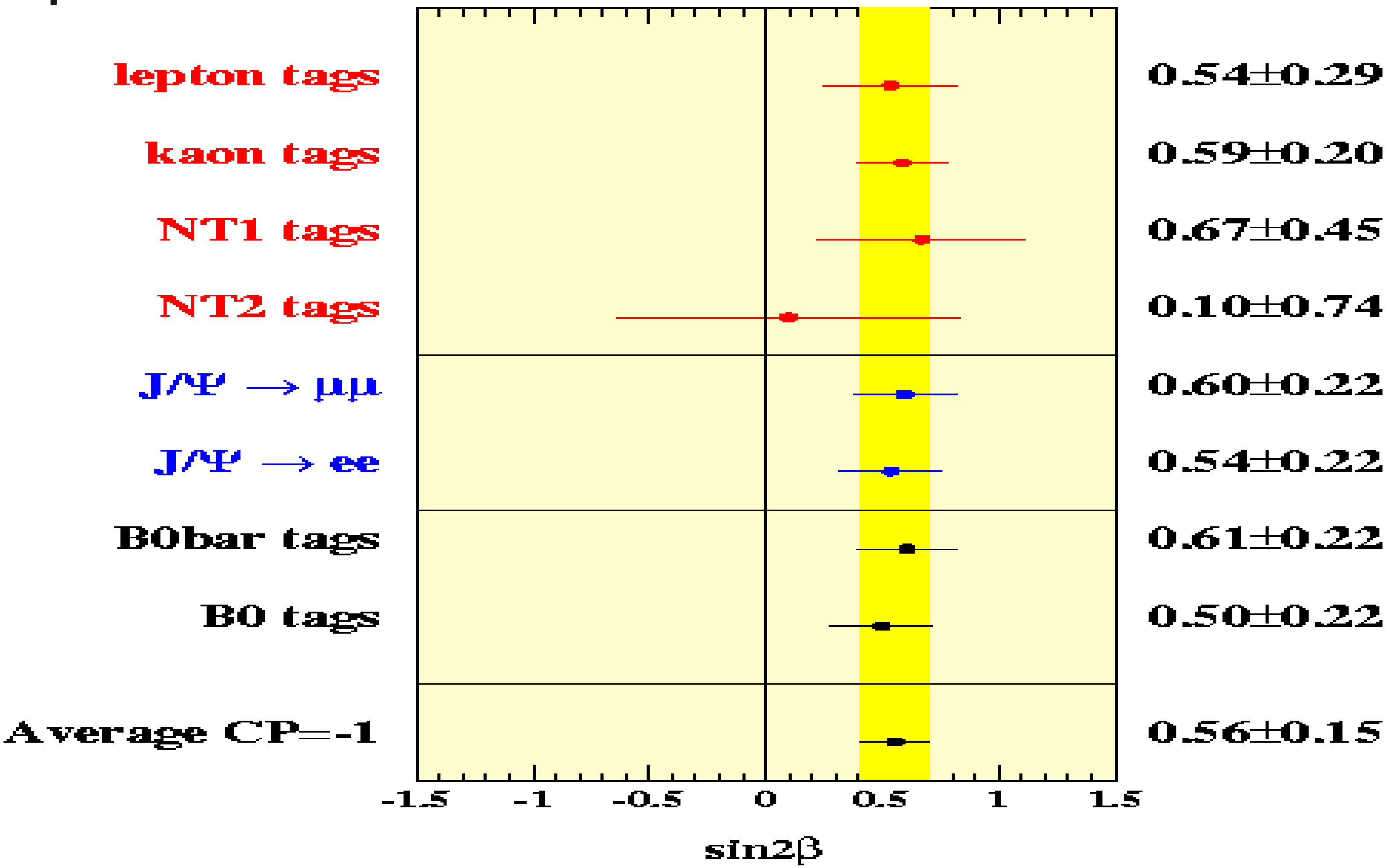
Consistency of CP channels $P(\chi^2) = 8\%$

Goodness of fit (CP Sample): $P(L_{max}>L_{obs}) > 27\%$



Phys. Rev. Lett. **87** 091801 (2001)

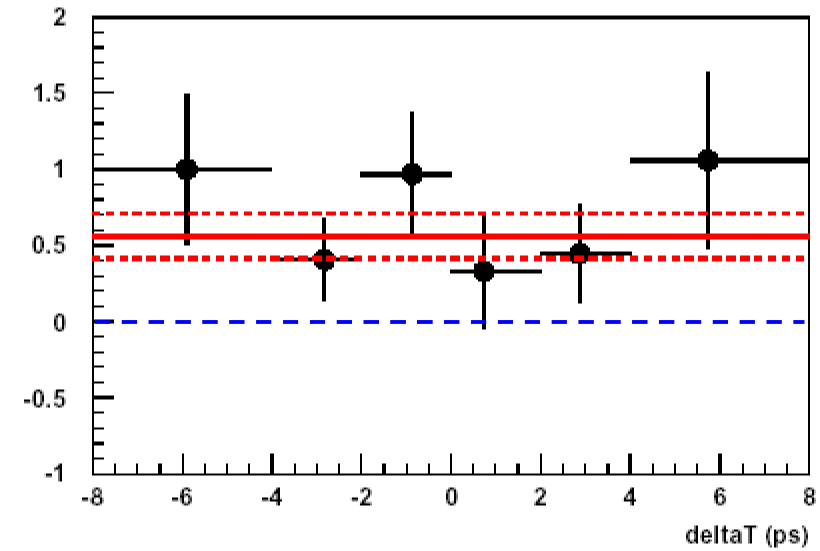
Consistency Checks



sin2β vs. ψ decay mode, tagging category and flavor for η = -1 events

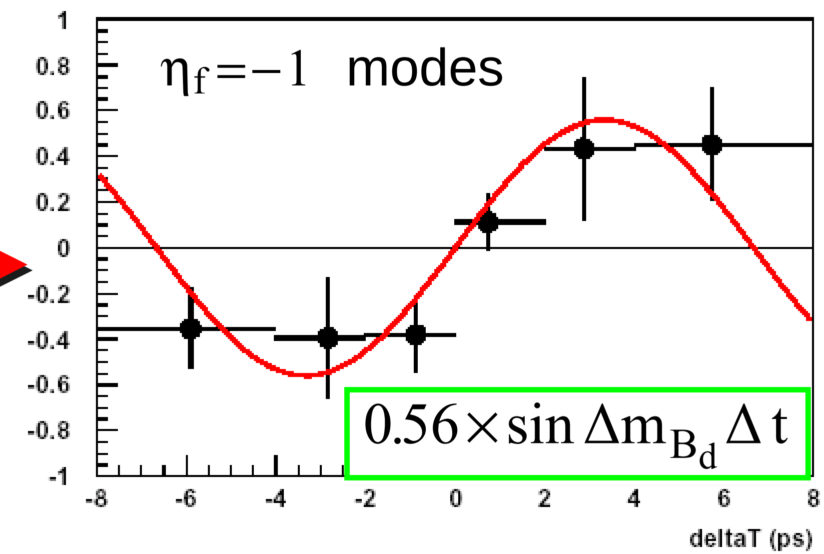
CP Asymmetry Corrected For B Oscillation

Sin 2β value, fitted in bins of Δt



sin 2β, fitted in bins of Δt
and multiplied by sin(Δm Δt)

$$A_{CP}(t) = \sin 2\beta \, \sin(\Delta m_d t)$$



Major Sources of Systematic Error in Sin2β

Measurement is Statistics Dominated

Error/Sample	K_S	K_L	K^{*0}	Total
Statistical	0.15	0.34	1.01	0.14
Systematic	0.05	0.10	0.16	0.05

- Signal resolution and vertex reconstruction ± 0.03
  - *Resolution model, outliers, residual misalignment of the Silicon Vertex Detector*
- Flavor Tagging ± 0.03
  - *possible differences between B_{CP} and B_{flavor} samples*
- Background Characterization: ± 0.02 (overall)
  - *Signal probability, fraction of B^+ background in the signal region, CP content of background*
  - *Total 0.09 for ΨK_L channel; 0.11 for ΨK^{*0}*
- Total Systematic Uncertainty: ± 0.05 for total sample

Search for Direct CP Violation

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

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

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

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

To probe new physics
(only use $\eta_{CP}=-1$ sample that contains no CP background)

$|\lambda| = 0.93 \pm 0.09$ (stat) ± 0.03 (syst)

No evidence of direct CP violation due to decay amplitude interference (S_{CP} unchanged in Value)

CP violation in $B^0 \to \pi^+\pi^-$ decays

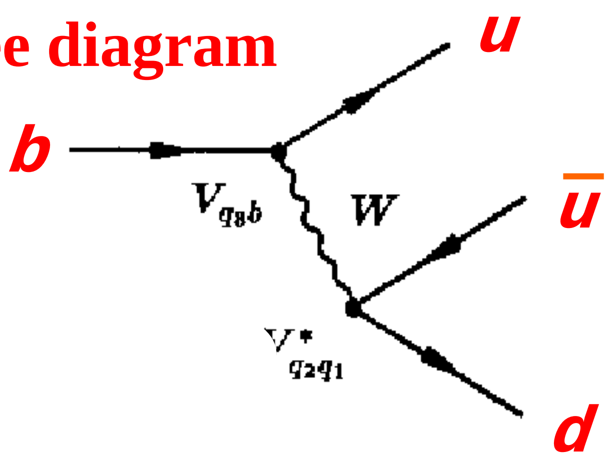
Decay distributions $f_+(f_-)$ when tag = $B^0(\bar{B}^0)$

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

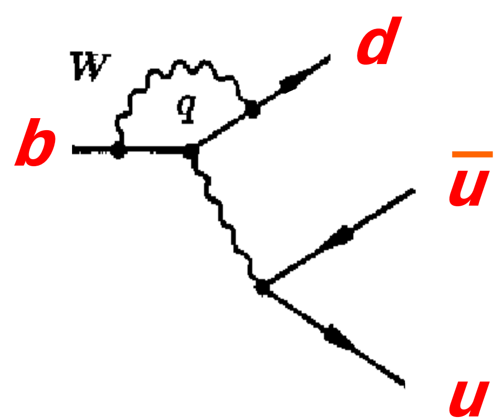
$$S_f = \frac{2\,\mathrm{Im}(\lambda)}{1+|\lambda|^2}$$

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

tree diagram



penguin diagram



For single weak phase

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

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

For additional weak phase

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

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

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

$B \to \pi^+\pi^-/K^+\pi^-$ Likelihood Fit

Simultaneous extended Maximum Likelihood fit to the BRs and CP asymmetries:

- 8 event samples (Signal and Bkg: $\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, K^+K^-) measure also direct CP violation in charge asymmetry

$$A = N(K^-\pi^+) - N(K^+\pi^-) / N(K^-\pi^+) + N(K^+\pi^-)$$

  - Discriminating variables (m_{ES}, ΔE , *Fisher,* Cherenkov angles, Δt)
  - Mistag rates and Δt signal resolution function same as in $\sin 2\beta$ fit (uses also untagged events to improve BR measurements)
  - Δm_d, B^0 lifetime fixed
  - Empirical background parameters determined from m_{ES} sidebands

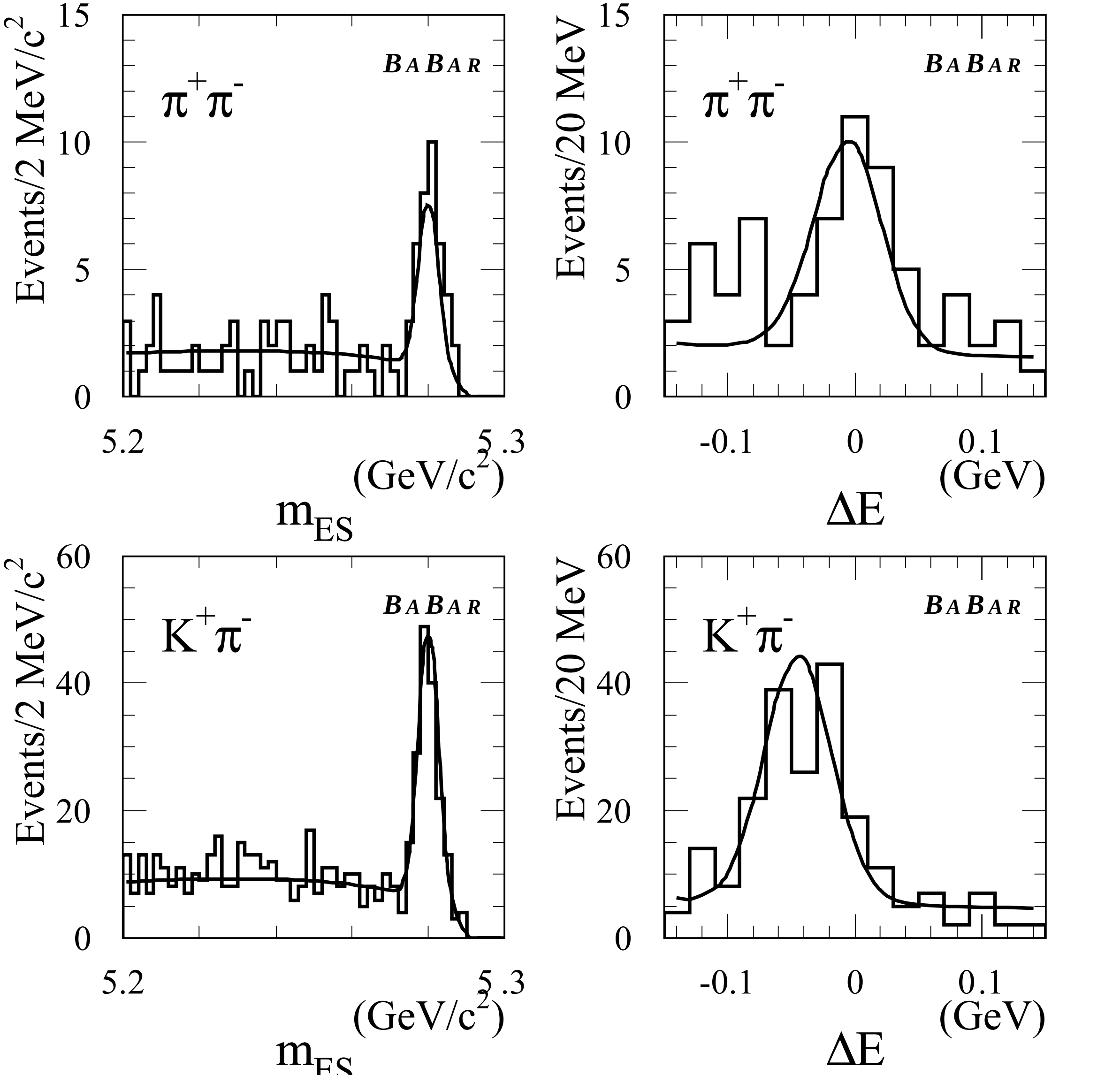
CP Sample $B^0 \to \pi^+\pi^-$

For Illustration purposes:
Events after likelihood ratio cuts

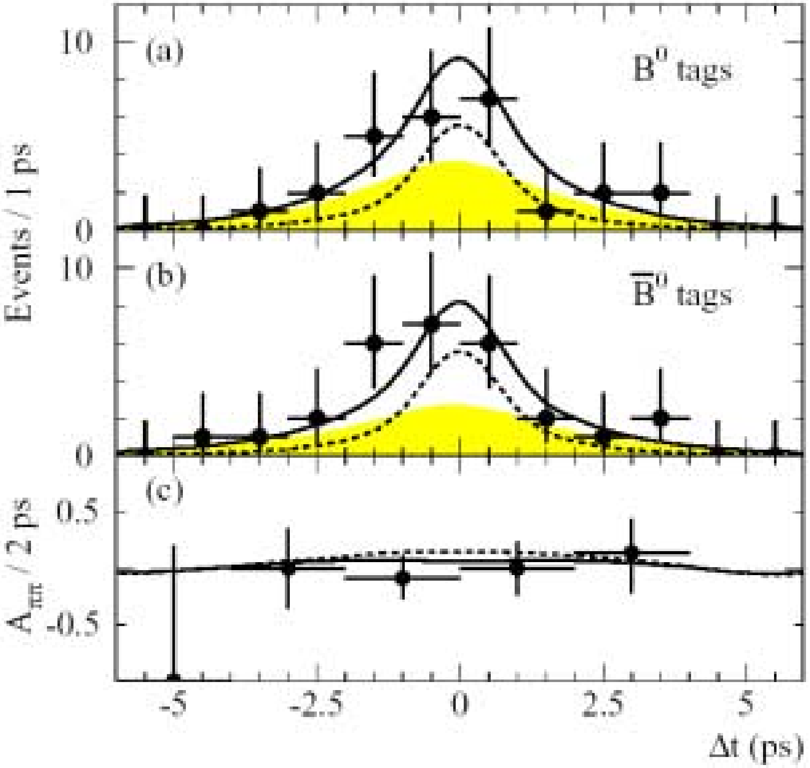
L= 30.4 fb^{-1}

Total Yields (fit):

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



CP Asymmetry and Fit Results



Preliminary Results

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

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

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

First measurement

- *compatible with no CP Violation*
- *Statistics limited*
- *Need ~500/fb for σ(Sππ) ~0.10*

Summary and Outlook

- BABAR has observed CP violation in the B^0 system at 4.1σ level

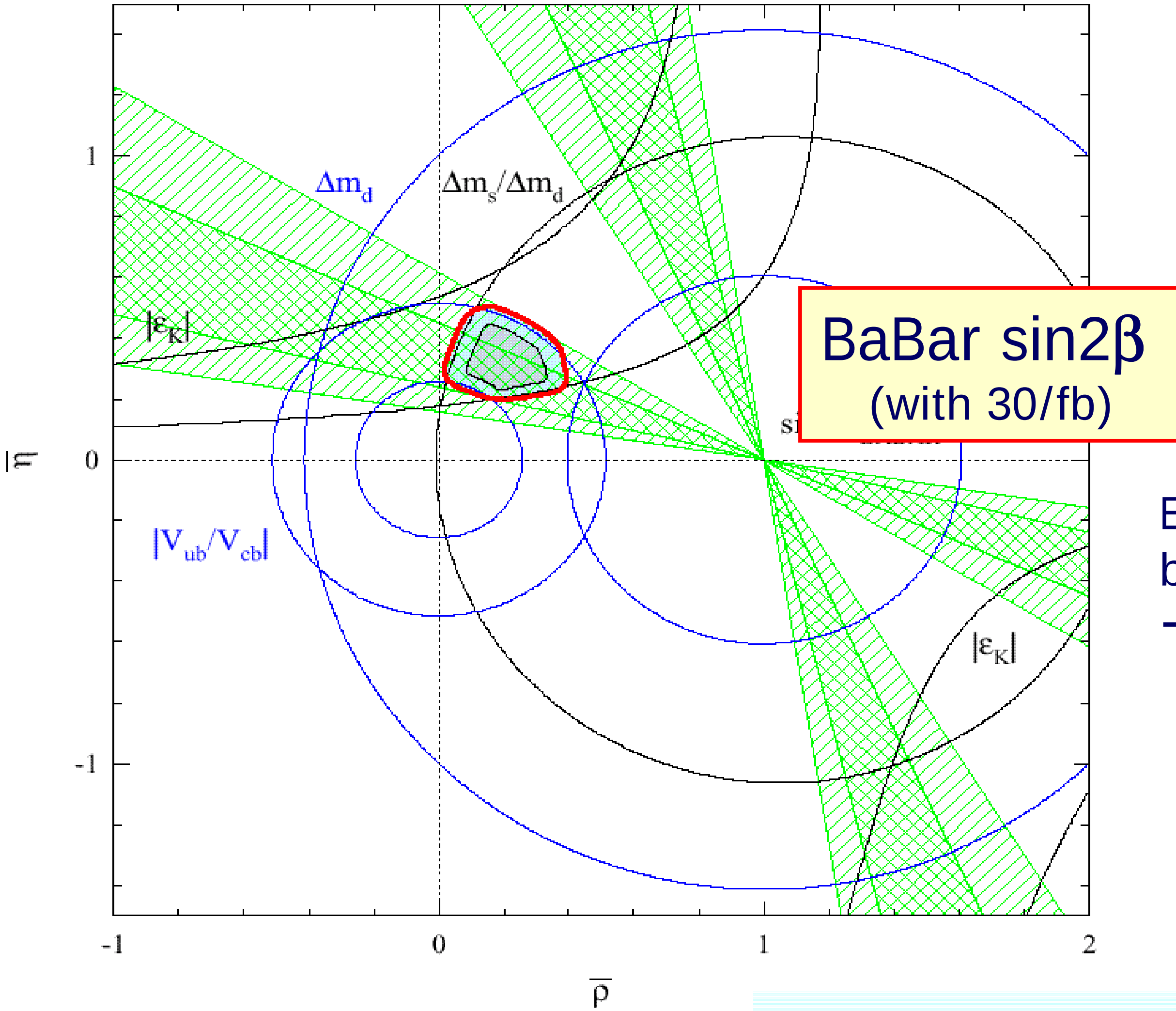
$$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05$$

  - Probability to observe an equal or larger value if no CP violation exists is $< 3 \times 10^{-5}$
  - Corresponding probability for the $\eta_{CP} = -1$ modes only is $< 2 \times 10^{-4}$

- New precision measurements of B^0/B^+ lifetimes and $B^0 B^0$ Oscillation frequency Δm_d

$$\tau_0 = 1.546 \pm 0.032 \pm 0.022 \text{ ps}$$
$$\tau_\pm = 1.673 \pm 0.032 \pm 0.022 \text{ ps}$$
$$\tau_0 / \tau_\pm = 1.082 \pm 0.026 \pm 0.011$$
$$\Delta m_d = 0.519 \pm 0.020 \pm 0.016 \hbar \text{ ps}^{-1}$$

The Unitarity Triangle and This Measurement



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

Error on sin2β is dominated by statistics
→ will decrease as

$$\propto \frac{1}{\sqrt{\text{Luminosity}}}$$

Example: Höcker et al, hep-ph/0104062
(also other recent global CKM matrix analyses)

Success and Embarassment

- The agreement of measured sin2β with Standard Model prediction suggests that the B_d mixing phase ϕ_d is indeed due to the phase of the CKM element V_{td}
- Like for the EW precision data, the lack of deviations from the CKM mechanism leaves us with a puzzle
  - *CKM does not explain baryon asymmetry*
  - *All extensions of the SM contain many new CP violating parameters, e.g. minimal unconstrained SUSY has 43 new CP phases!*
- Does this mean that the non-standard CP violating effect are decoupled just like New Physics in the EWSB sector appears to be decoupled ??
- Further searches for probably small deviations from CKM with more precise diverse measurements to come!

Summary and Outlook (cont.)

- First measurement of time-dependent CP asymmetry in rare B decay mode $B \to \pi^+\pi^-$

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

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

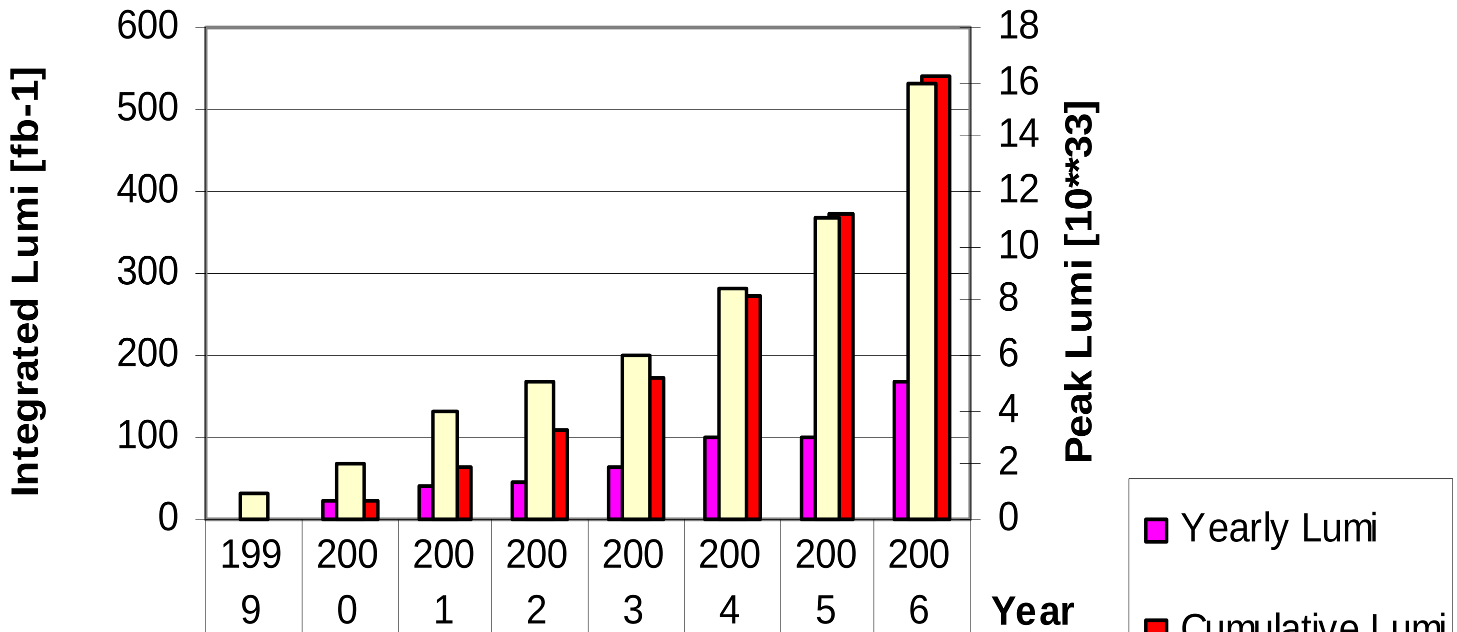
- The study of CP violation in the B system has started:
  - sin2β will very soon become precision measurement (i.e. unitarity triangle constraints will be limited by other CKM parameters)
  - Need to compare sin2β from different decay modes to test standard model
- With anticipated 100 fb^{-1} by next summer, error on sin2β will be ±0.08, error on asymmetry of $B \to \pi^+\pi^-$ will be ±0.3 !

More to come ....

- V_{cb} and V_{ub} from inclusive semi-leptonic B decays
- CP violating effects in rare B decays
  - $\sin 2\beta_{\phi k}$ =? $\sin 2\beta_{\psi k}$ — $b \rightarrow$ sss penguins
  - $A_{CP}(B \rightarrow X_s \gamma)$ =? 0 — radiative penguins
  - $\gamma_{\pi\kappa}$ =? γ_{tree} — penguin vs tree
- New physics in $B \rightarrow K\, l^+ l^-$
- New Physics in D (and K) decays
  - D mixing
  - Charm weak decays
  - (Rare K decays, $K \rightarrow \pi \nu \nu$)
- CP violation without flavor violation ?

Luminosity Plans for BABAR & PEP II

Expect >500 fb^{-1} By 2006



	1999	2000	2001	2002	2003	2004	2005	2006
Yearly Lumi	2	23	40	45	62	100	100	170
Cumulative Lumi	2	25	65	110	172	272	372	542
Peak Lumi	1	2	4	5	6	8.5	11	16