BaBar Measurements of CP Violation, Mixing and Lifetimes of B Mesons

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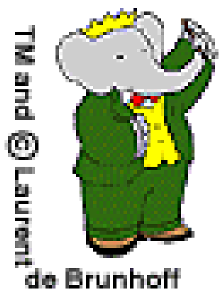

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Outline

- CP Violation, CKM Matrix and the Unitarity Triangle
- Observation of CP Violation in the interference of Decay and Mixing ⇒ Sin2β
  - The PEP-II B Factory & The BaBar Detector
  - The three linked steps towards the sin2β measurement
    - B Lifetime
    - B Mixing (⇒ digression on dileptons…)
    - CP Asymmetry
- The way forward : Summary and Outlook

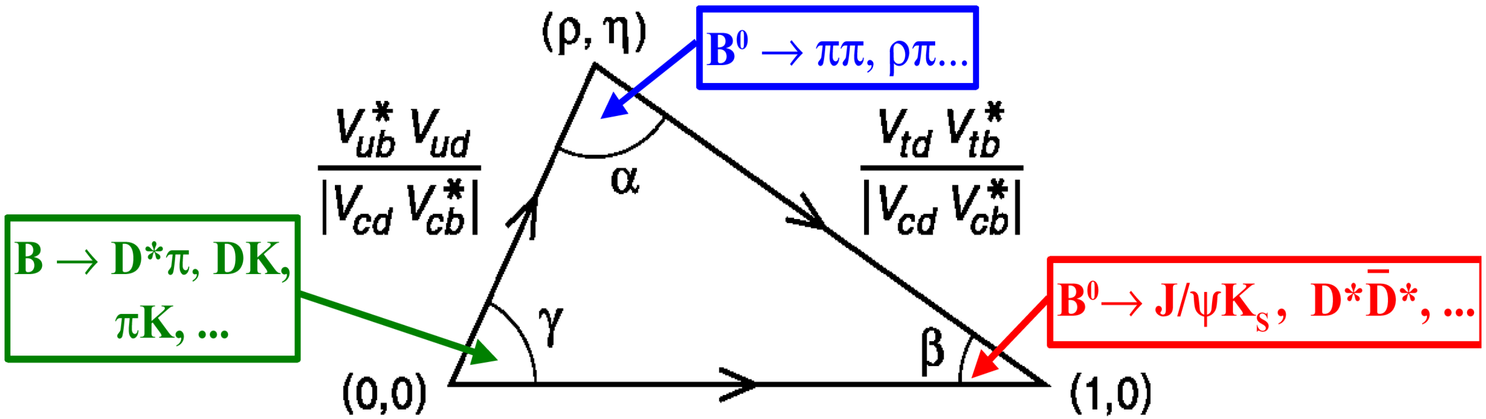
CP violation in the Standard Model

CP violation arises from **single phase in CKM matrix**

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

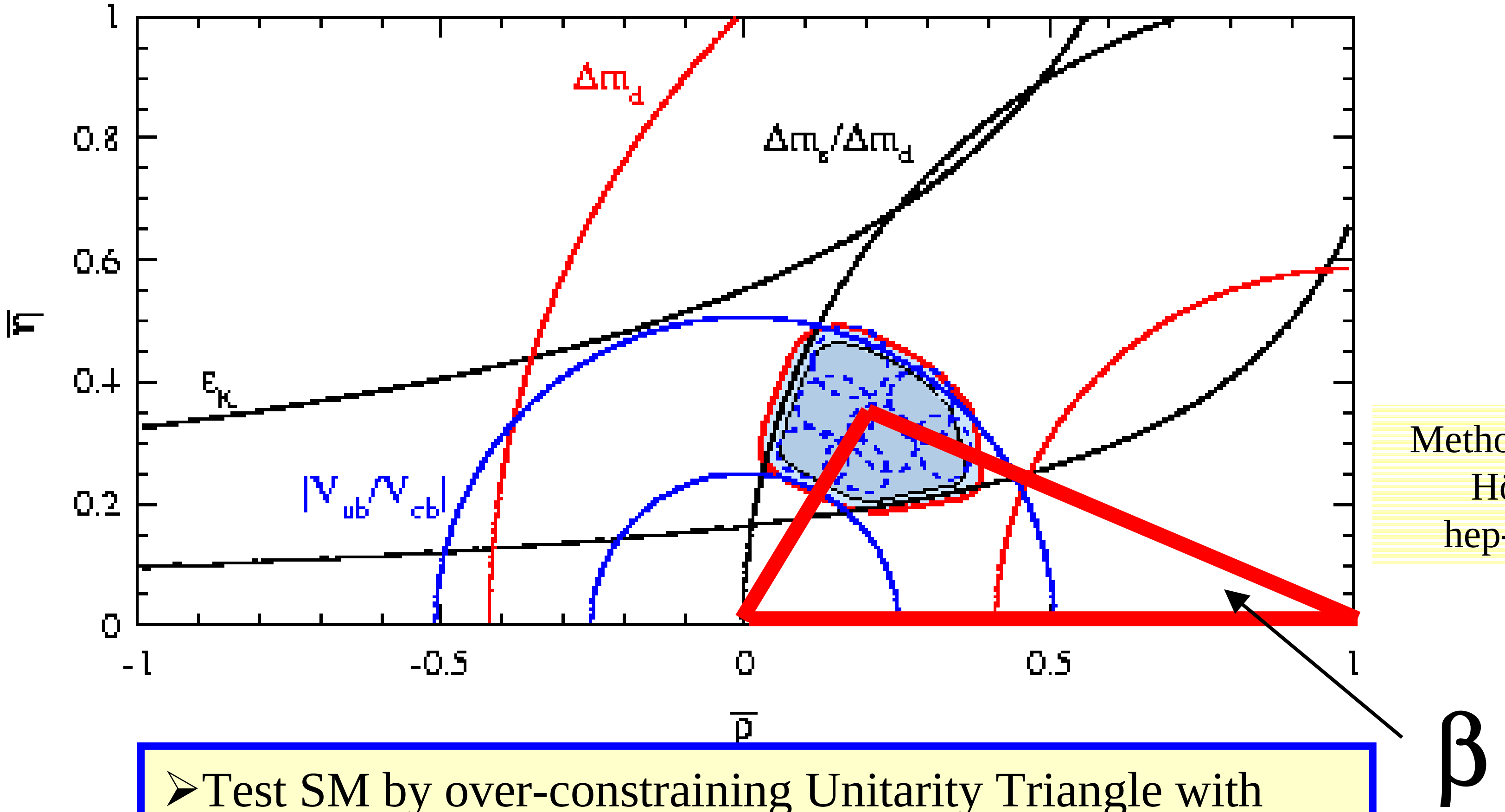
Unitarity of V implies eg. $\mathbf{V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0}$

→ represented as **'unitary triangle'** in complex plane



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

The Unitarity Triangle without CP Violation Measurements

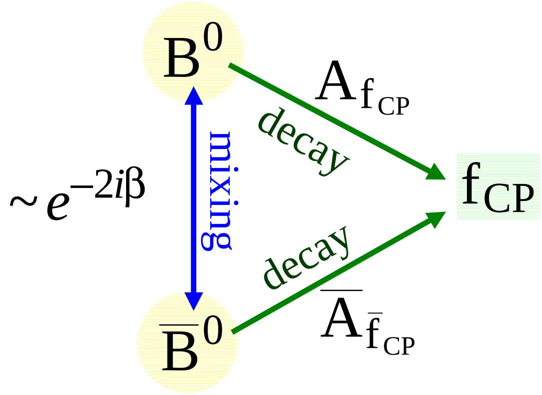


Method described in Höcker et al, hep-ex/0104062

➢Test SM by over-constraining Unitarity Triangle with measurements of sides **and** angles

$\not{C}P$ from Interference of Mixing and Decay

CP violation results from interference between decays with and without mixing



$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = |\lambda_{f_{CP}}| e^{-2i\varphi_{CP}}$$

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

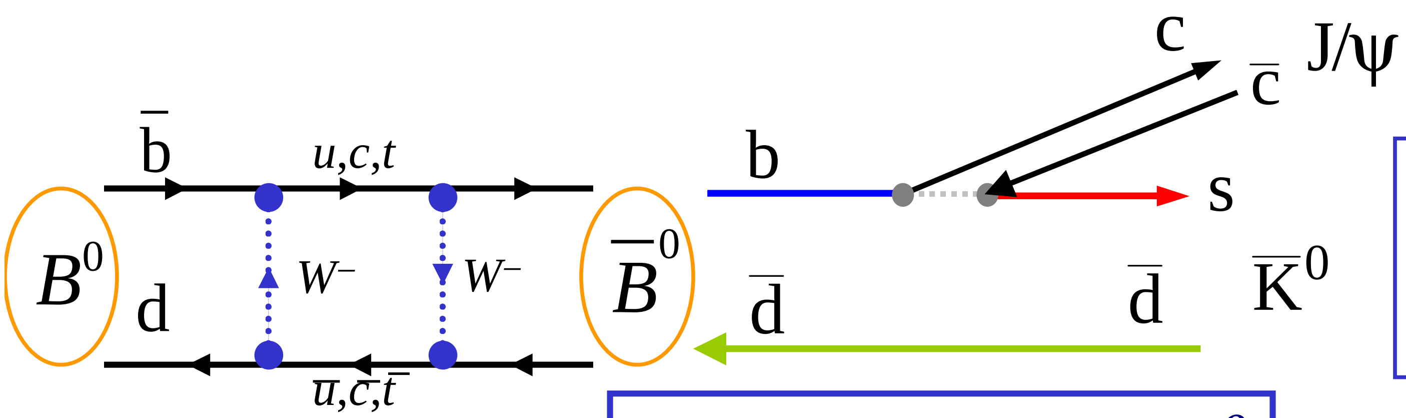
Time-dependent CP asymmetry:

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

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

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

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



K0 mixing

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

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

- Theoretically clean mode to measure sin2β
- 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"

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

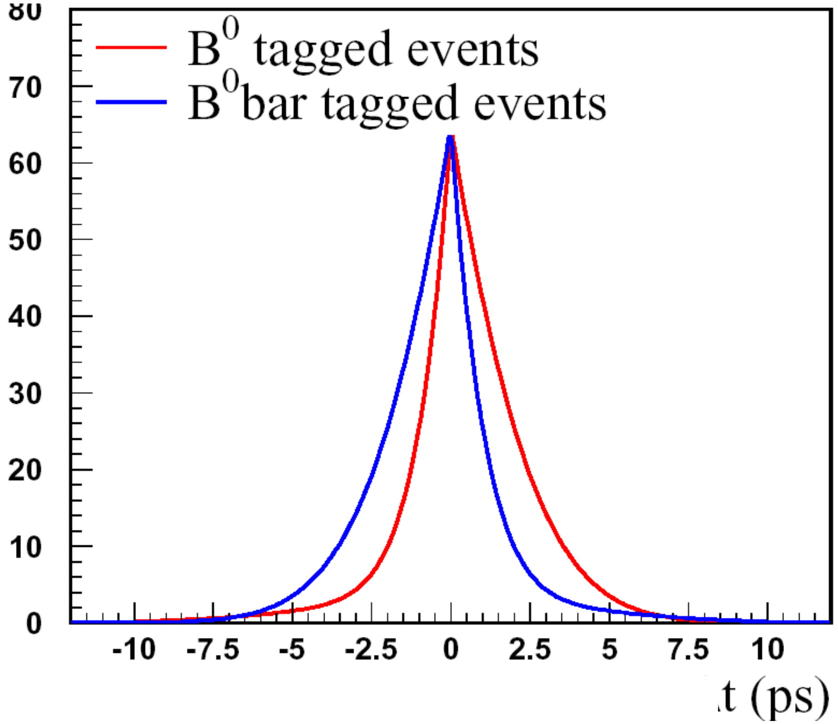
Decay Time Distribution in B $\rightarrow f_{CP}$

$$f_+ : \overline{B}^0_{phys} \rightarrow f_{CP}$$

$$f_- : B^0_{phys} \rightarrow f_{CP}$$

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

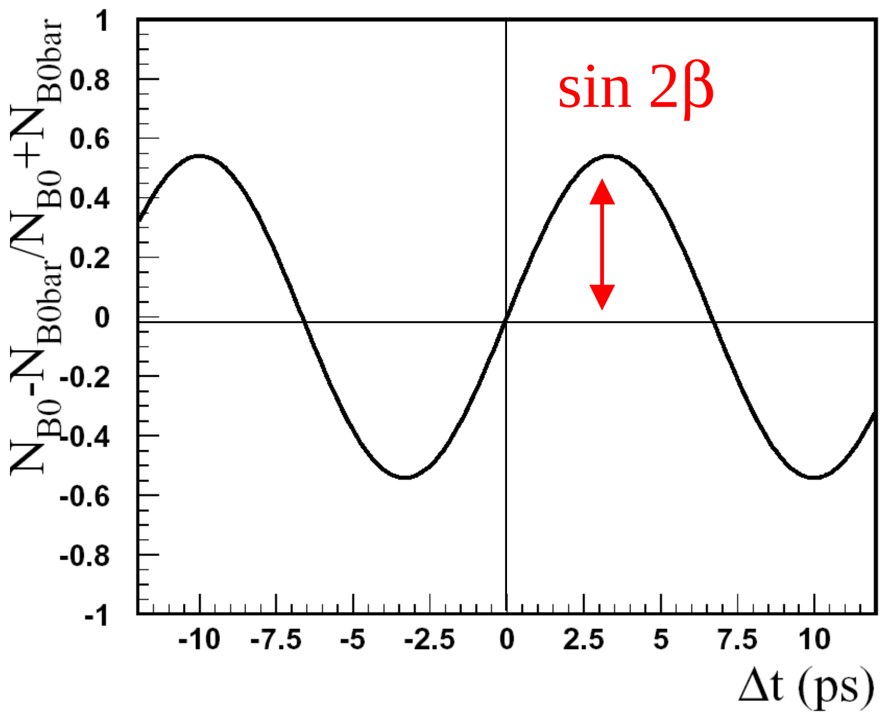
Decay Time Evolution & A_{CP} for $B^0 \to J/\psi K^0_S$



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

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

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



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Exptal Requirements For CPV Measurement

- BR ($B \rightarrow f_{CP}$) ~ 10^{-4} $\Rightarrow$ Need to record and reconstruct a large # of B Mesons
- Determine the flavor of the initial B meson to separate B^0 from $\overline{B}^0$ (B Flavor Tagging)
- Define and measure a 'time' in order to study the time-dependent asymmetry
  - B Mesons must travel a measurable distance before decaying
  - Vertex Reconstruction: A high precision tracking system to measure the distance between the B decay points

BaBar Detector @ PEP-II B Factory as example

The Asymmetric Energy Collider@Y(4S):PEPII

Cleanest source of B^0 mesons: $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$ at $\sqrt{s} = 10.58\ GeV$

$$\sigma_{Y(4S)} \approx 1.05\,nb$$

$$(24\%\ \text{of}\ \sigma_{had})$$

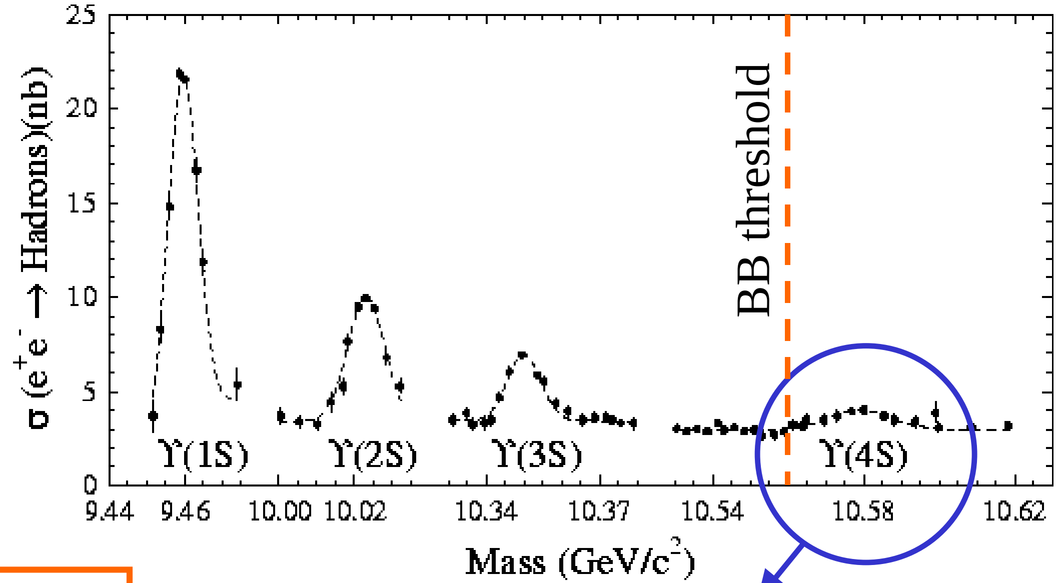
The Y(4S) B^0B^0 system evolves coherently until one of the B^0 mesons decays, so:

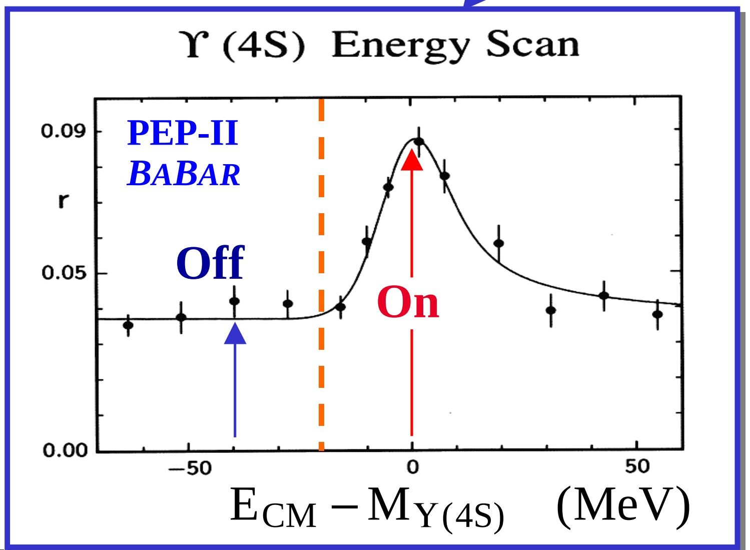
$$A_{CP}(t) \rightarrow A_{CP}(\Delta t) \propto \sin(\Delta m_{B_d} \Delta t)$$

Δt : proper time difference between the two B decays

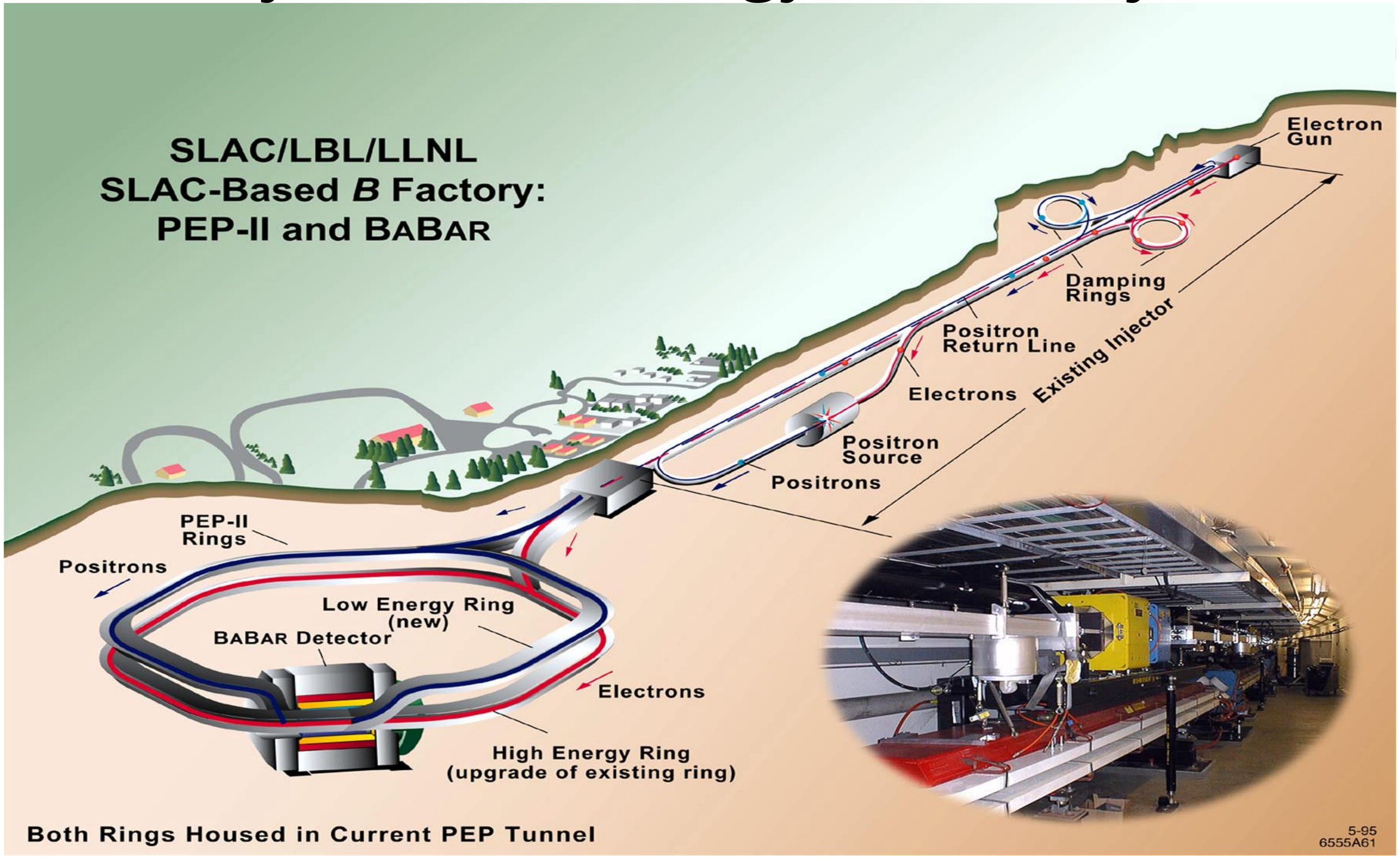
$A_{CP}(\Delta t)$ integrates to zero over all Δt

Study of CPV ➡ measure of Δt





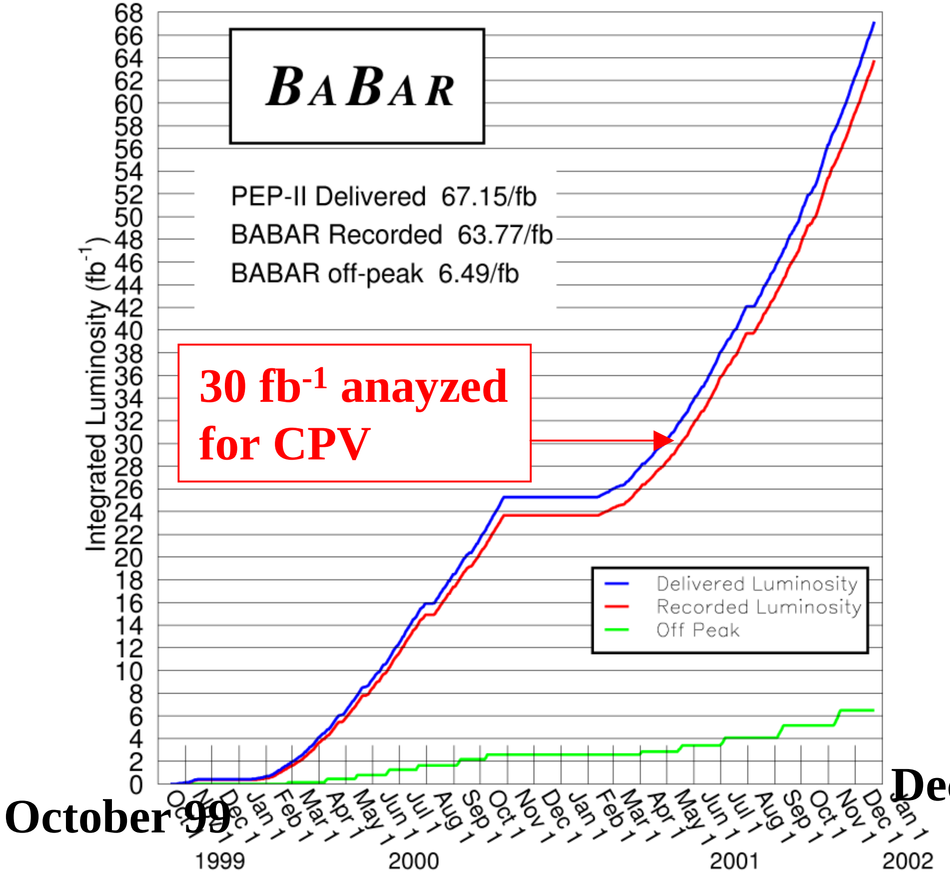
PEP-II Asymmetric Energy B-Factory at SLAC



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

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

PEP-II Performance Has Been Spectacular !



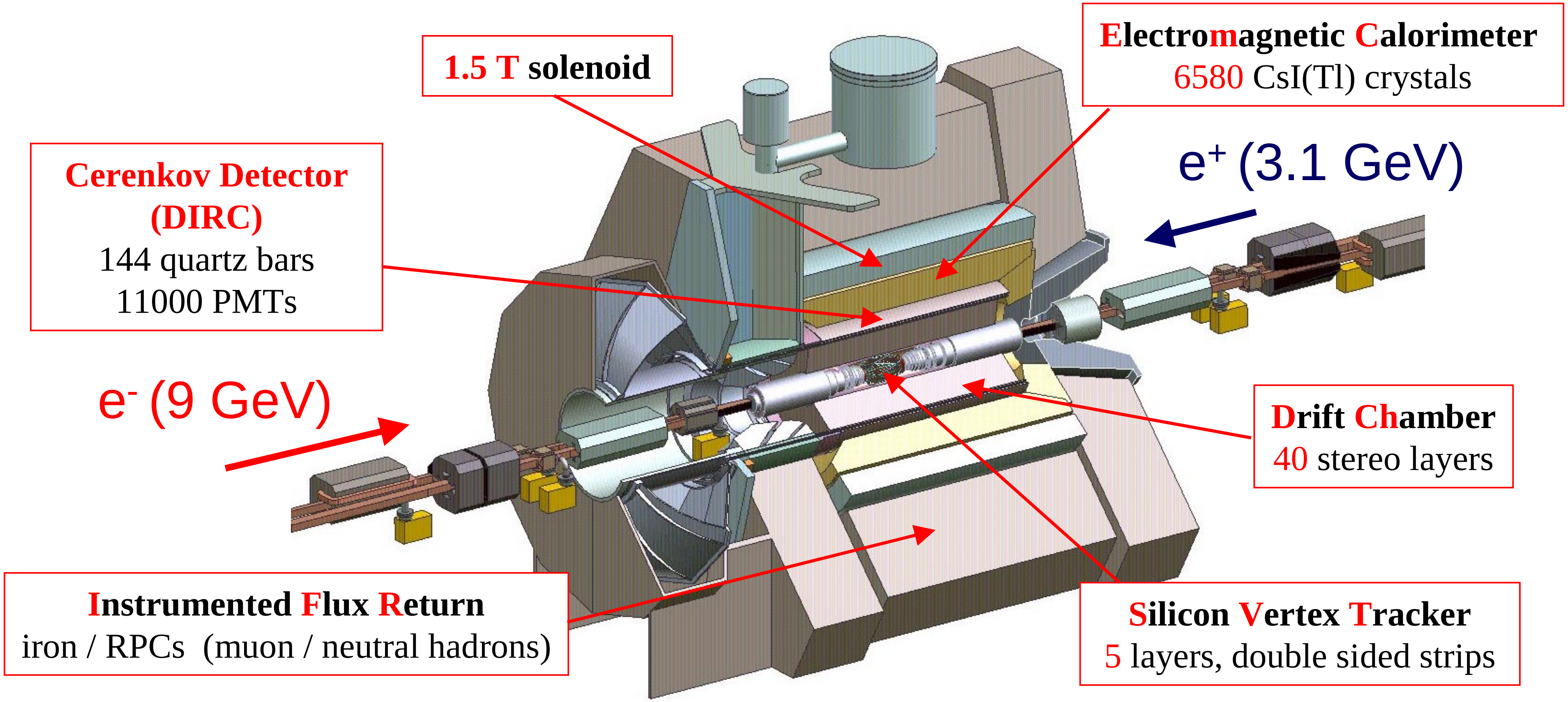
- PEP-II top luminosity:
  4.513 x 10^{33} cm^{-2}s^{-1}
  (design: 3.0 x 10^{33})
- Top recorded Lumi/month: 6.35 fb^{-1}
- Top recorded Lumi/week: 1.76 fb^{-1}
- Top recorded Lumi/24hr: 303 pb^{-1}
- Top recorded Lumi/8hr: 105 pb^{-1}
- BaBar logging efficiency: >96%

PEP-II delivered: 67.15 fb-1

BaBar recorded: 63.77 fb-1 (including 5.49 fb-1 off-peak)

120 million B's recorded, being analysed!

The BaBar Detector



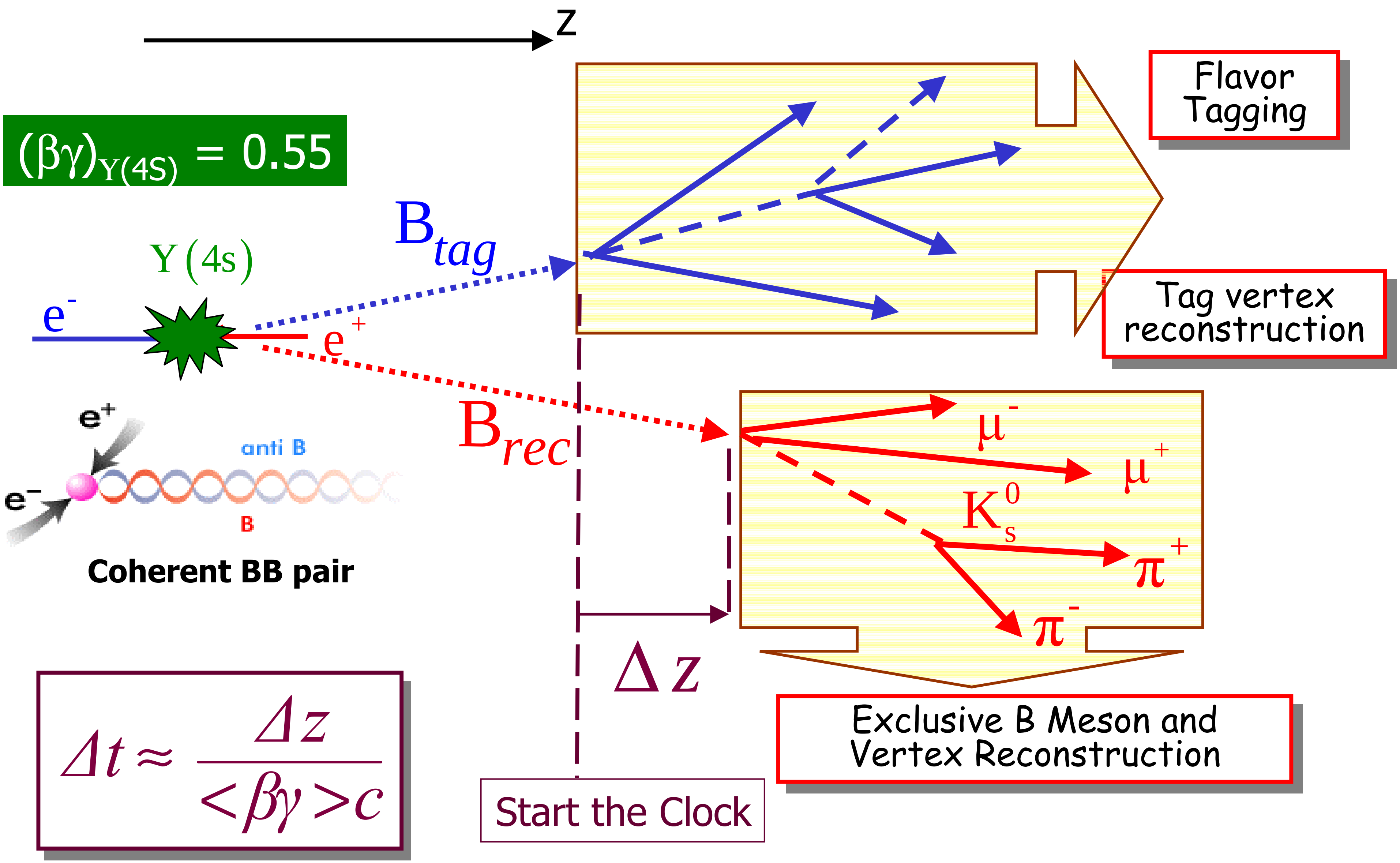
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

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

B Event Topology at the Boosted Υ(4S)



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

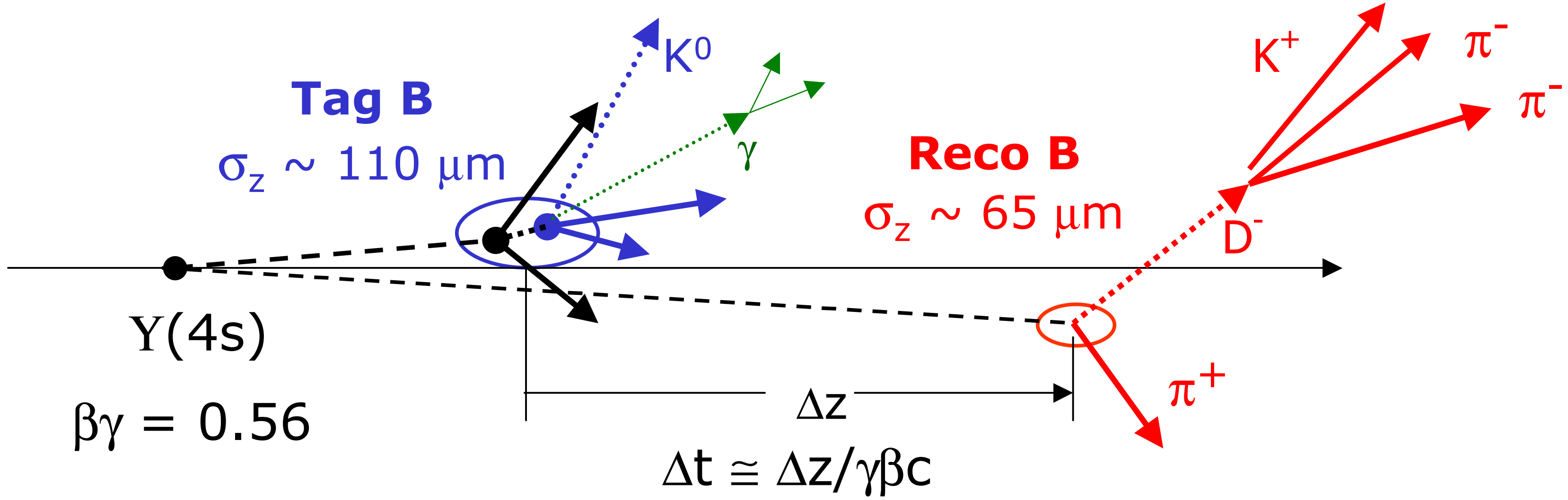
Sin2β Analysis Strategy

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

Higher precision ↑ | Increasing complexity ↓

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

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**

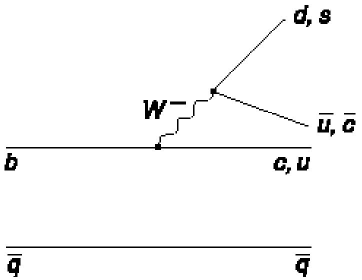
4. **compute the proper time difference Δt**
5. **Fit the Δt spectra**

Fully-Reconstructed Hadronic B Decay sample

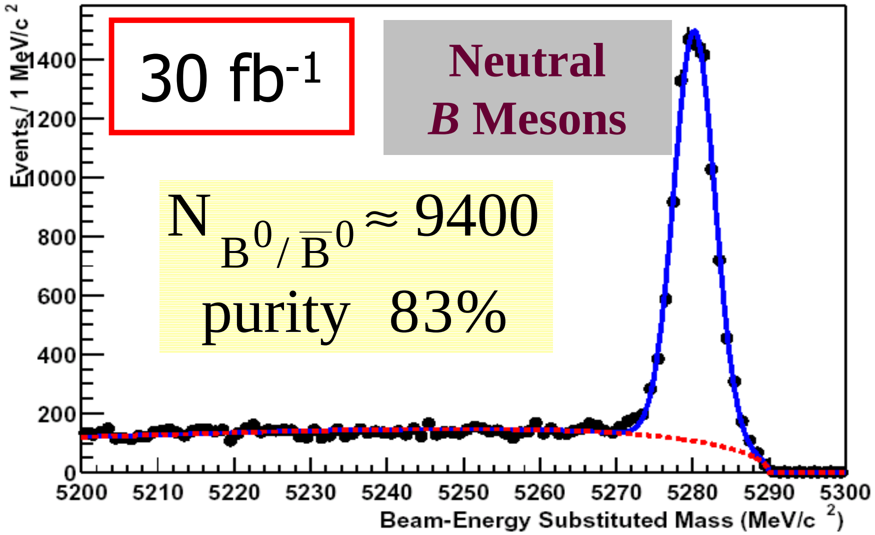
Flavor Eigenstates B_{flav} : for lifetime and mixing measurements

Self-tagging hadronic decays

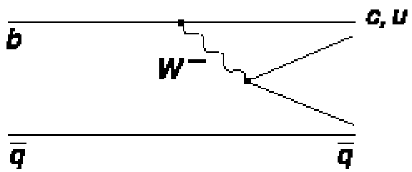
$b \rightarrow c\bar{u}d$ "Open Charm" decays

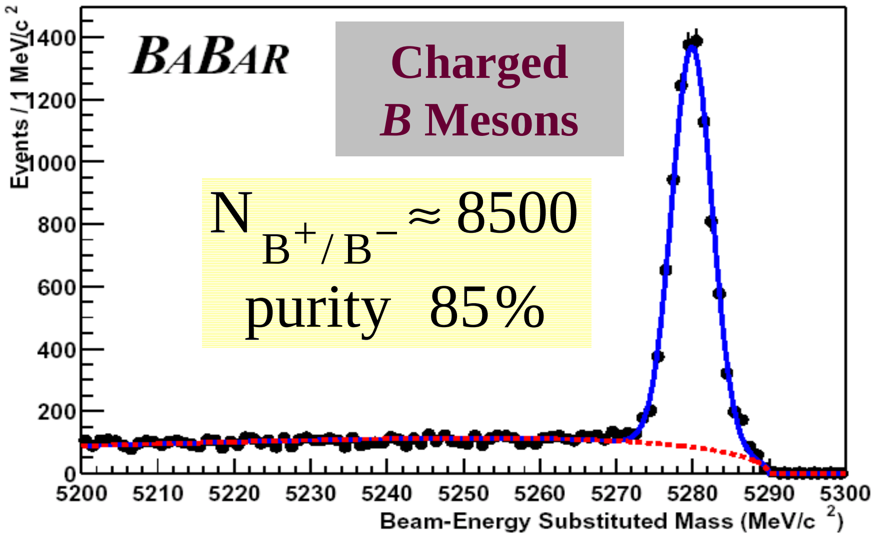


$$B^0 \rightarrow D^{(*)-}\pi^+/\rho^+/a_1^+$$
$$B^- \rightarrow D^{(*)0}\pi^-$$



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



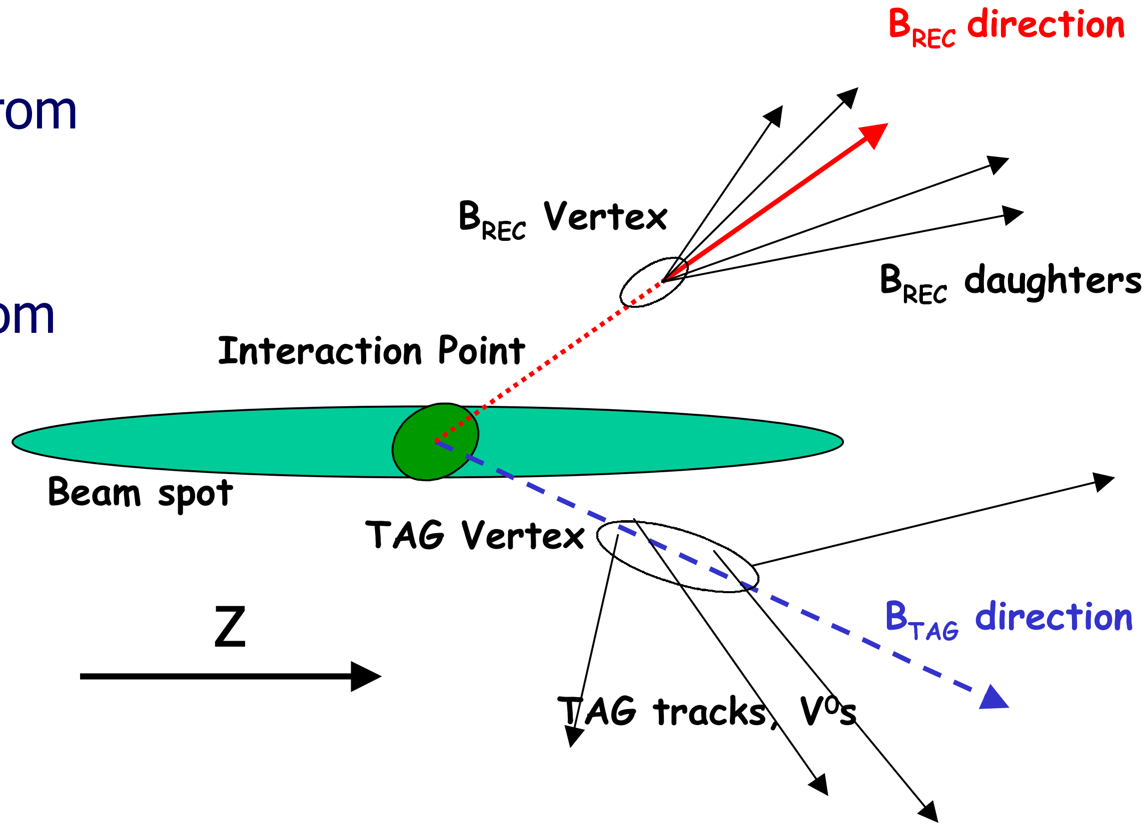


$$B^0 \rightarrow J/\psi K^{*0}(K^+\pi^-)$$
$$B^+ \rightarrow J/\psi K^+,\ \psi(2S)K^+$$

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

Recoil (Tag) side Vertex and Δz 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 μm)
- Δt resolution function characterized from data

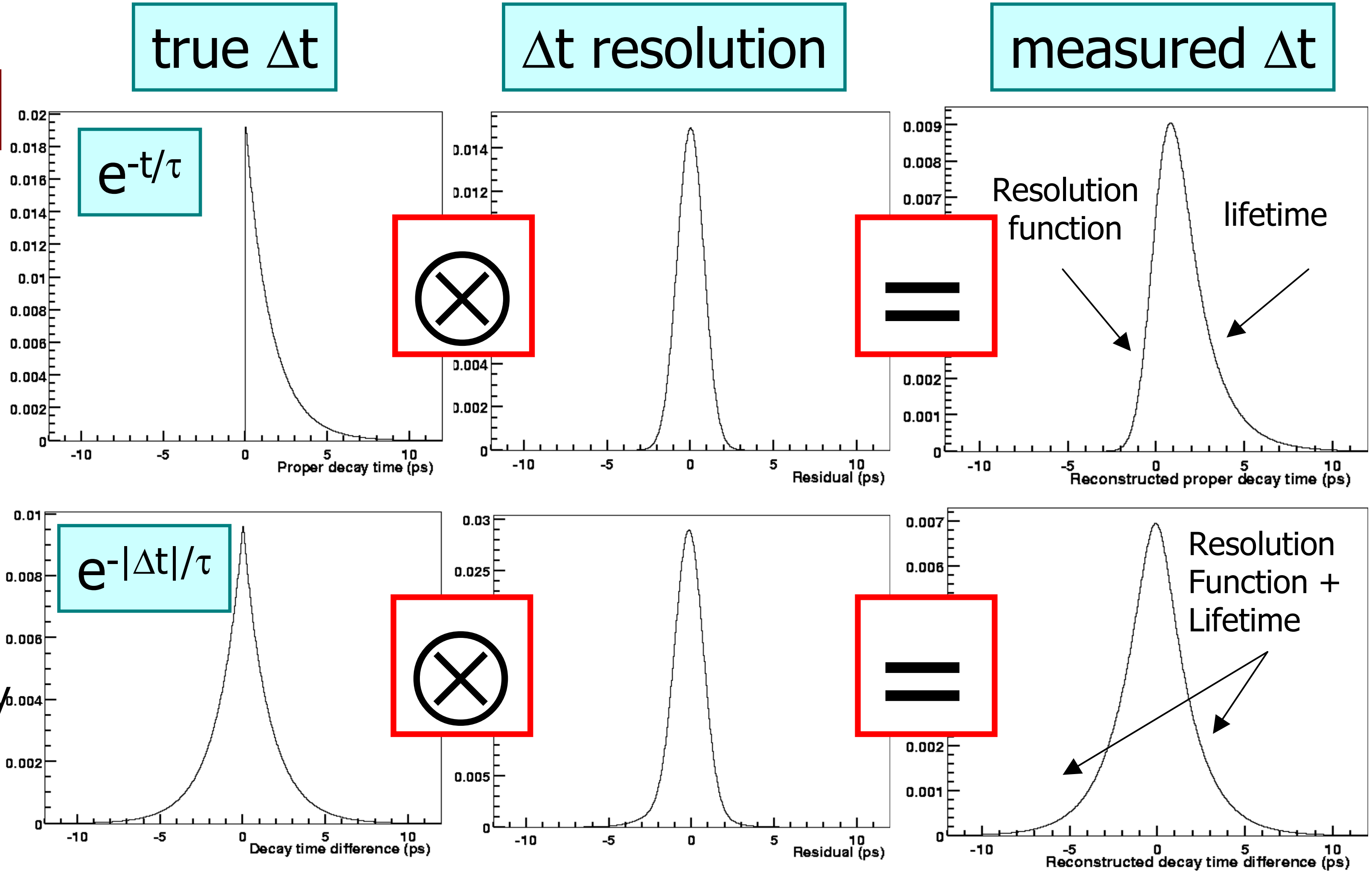
τ_B Measurement at Boosted $\Upsilon(4S)$: Unique

LEP/CDF

B production point known eg. from beam spot

BaBar

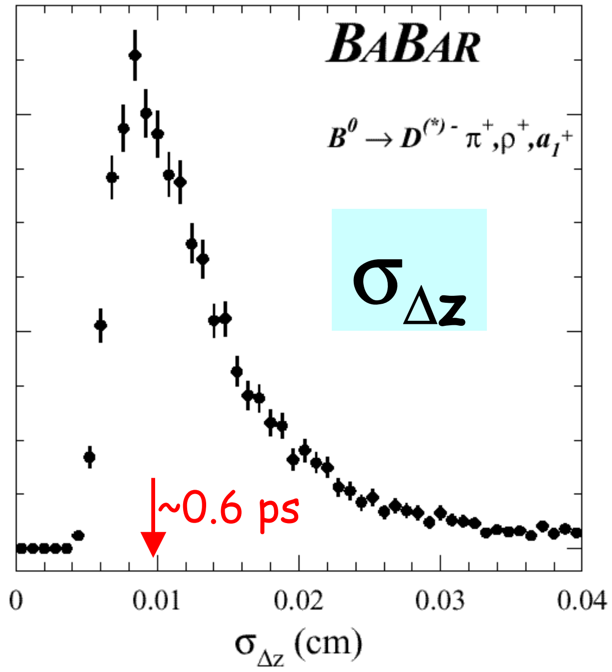
Either B_{rec} or B_{tag} can decay first (this analysis)



Need to disentangle resolution function from physics

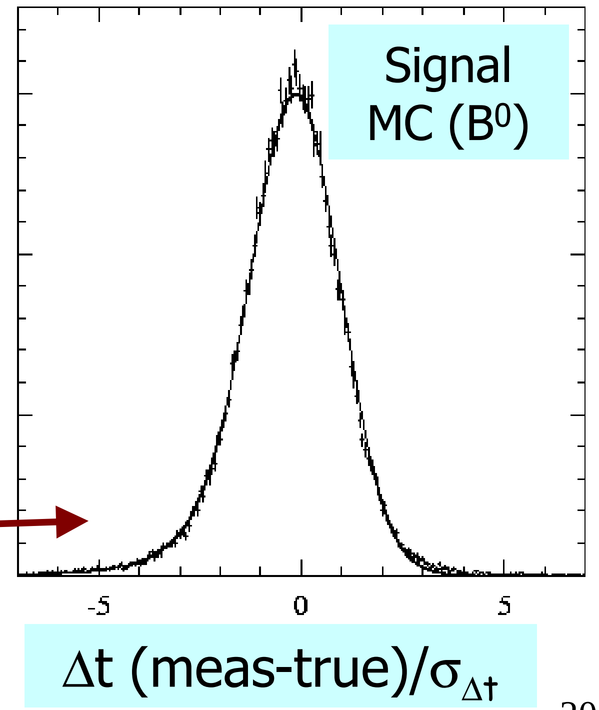
Δt Resolution Function

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



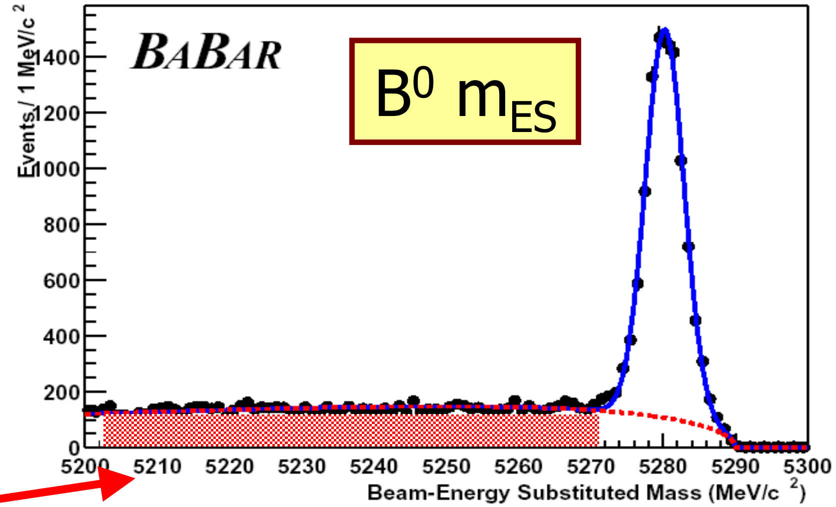
$$R = (1 - f_{tail} - f_{outlier})G(S\sigma_{\Delta t}, \mu_{core} = 0)$$
$$+ \ f_{tail}G(S\sigma_{\Delta t}, \mu = 0) \otimes \exp(-\Delta t / \sigma_{\Delta t}\tau_{bias})$$
$$+ \ f_{outlier}G(\sigma_{outlier}, \mu_{outlier})$$

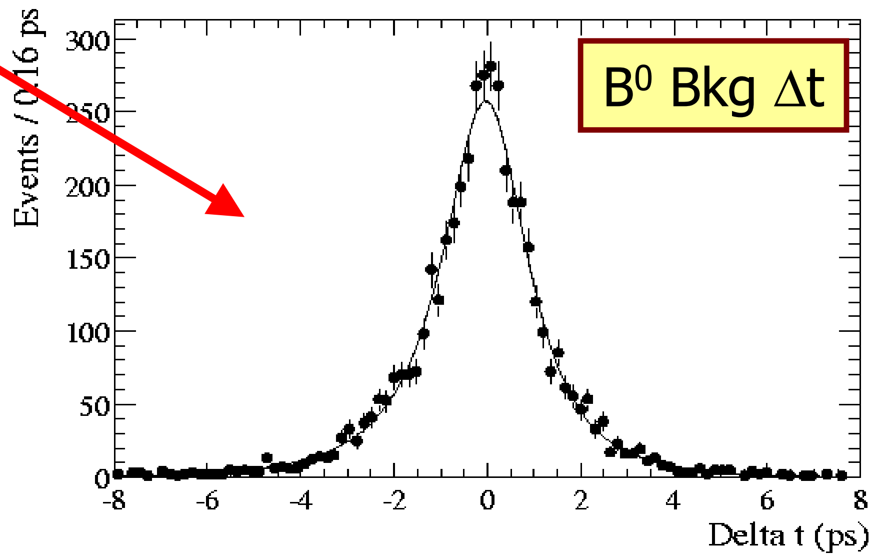
tracks from long-lived D's
in tag vertex
asymmetric Resolution Function



B Lifetime Likelihood Fit

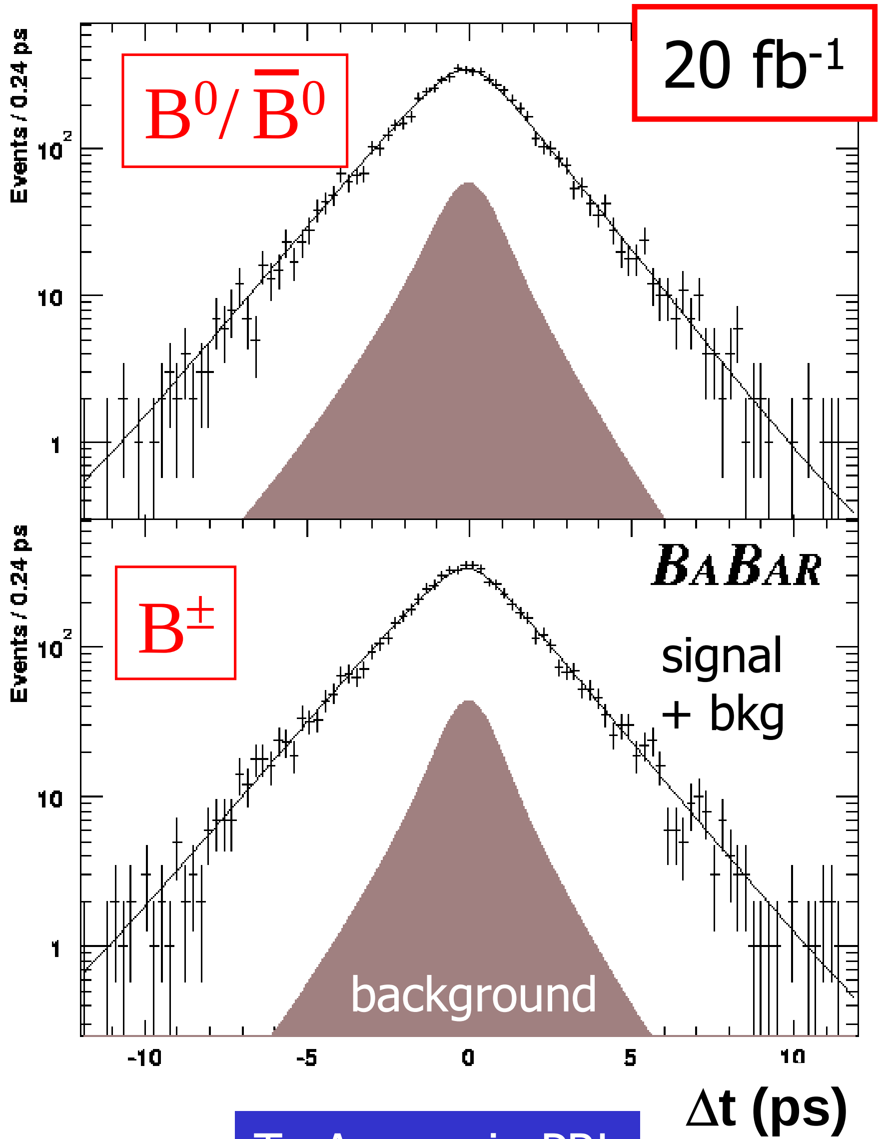
- Simultaneous unbinned maximum likelihood fit to B^0/B^+ samples
- Use data to extract the properties of background events
  - Mass distribution provides the signal probability
  - Use the events in the sideband (m_{ES} < 5.27) to determine the Δt structure of the background events under the signal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





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

B Lifetime Results:Calibrating The BaBar Clock



To Appear in PRL

$\tau_0 = 1.546 \pm 0.032 \pm 0.022$ ps

PDG: 1.548 ± 0.032 ps

$\tau_\pm = 1.673 \pm 0.032 \pm 0.022$ ps

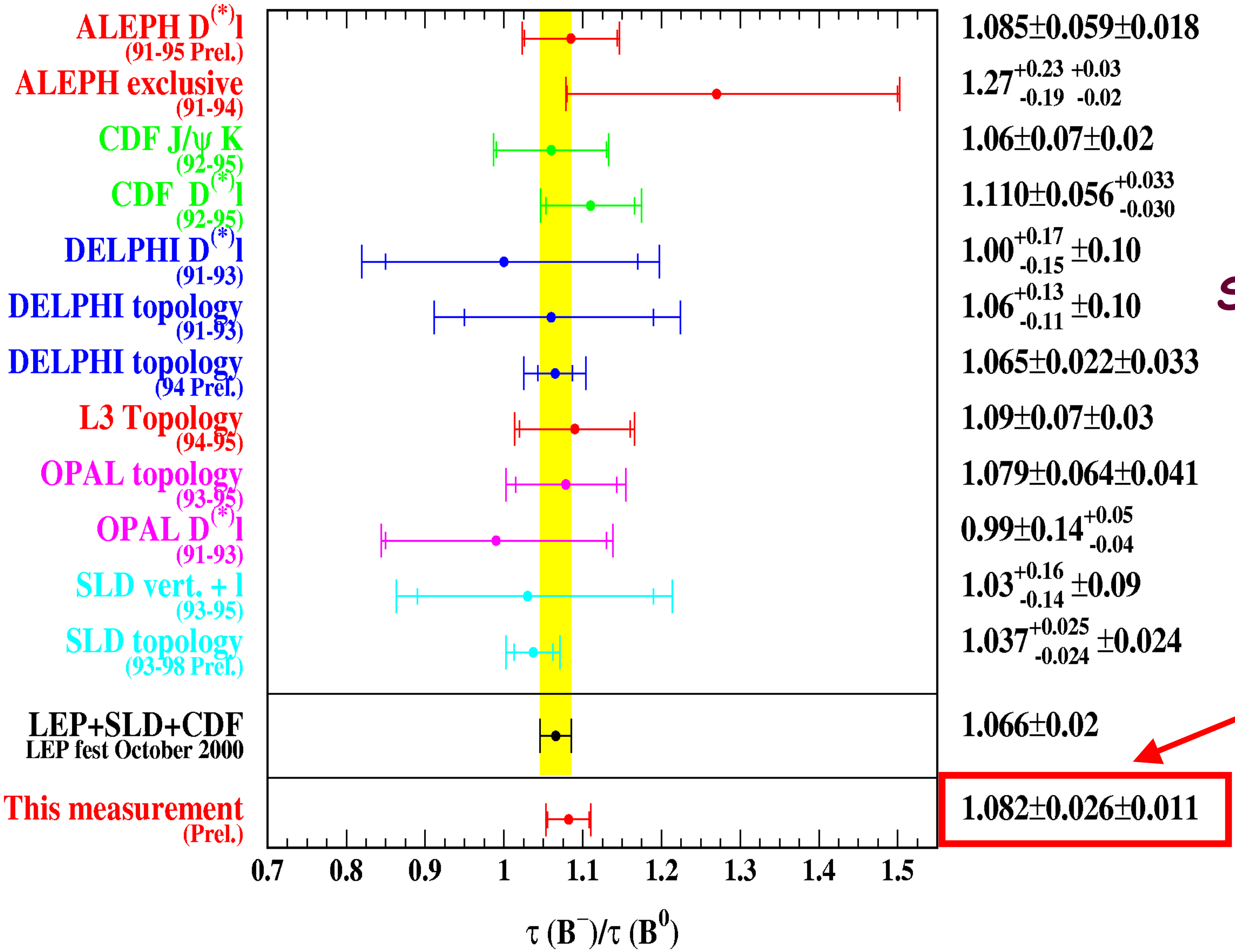
PDG: 1.653 ± 0.028 ps

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

PDG: 1.062 ± 0.029

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

Comparison of Lifetime Ratio Measurements



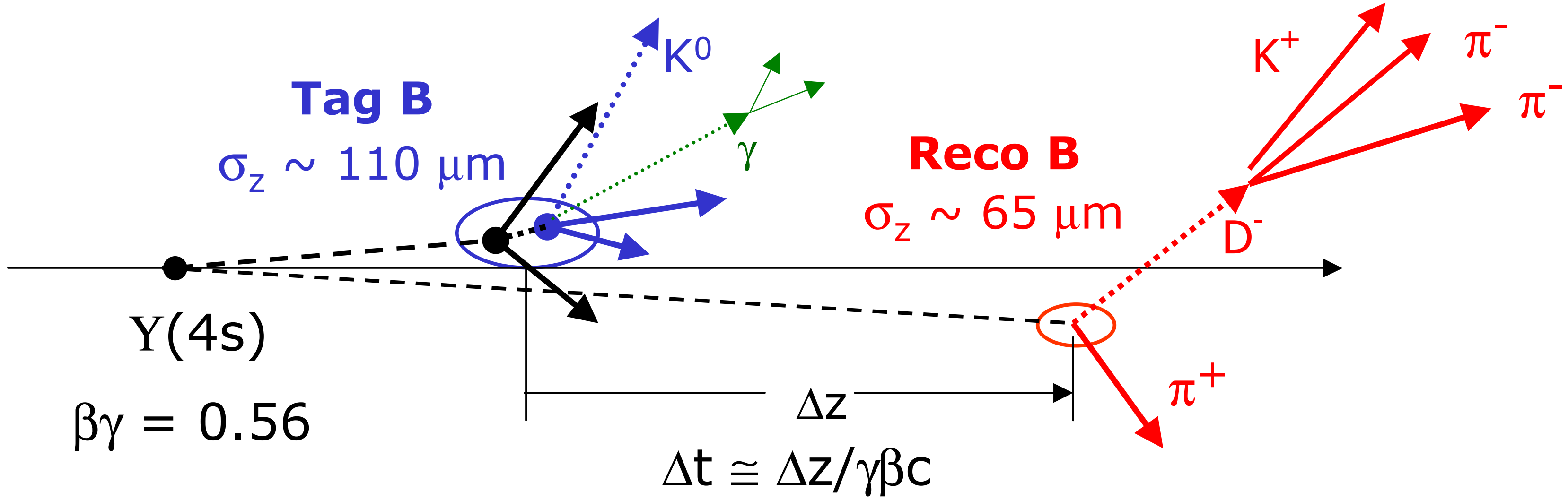
Systematic error 1% in B^+/B^0 lifetime ratio

Single most precise measurement

Sin2β Analysis Strategy (Part II)

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-Asymmetries	• Reconstruction of neutral B mesons in CP eigenstates (+ a + b + c)

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



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

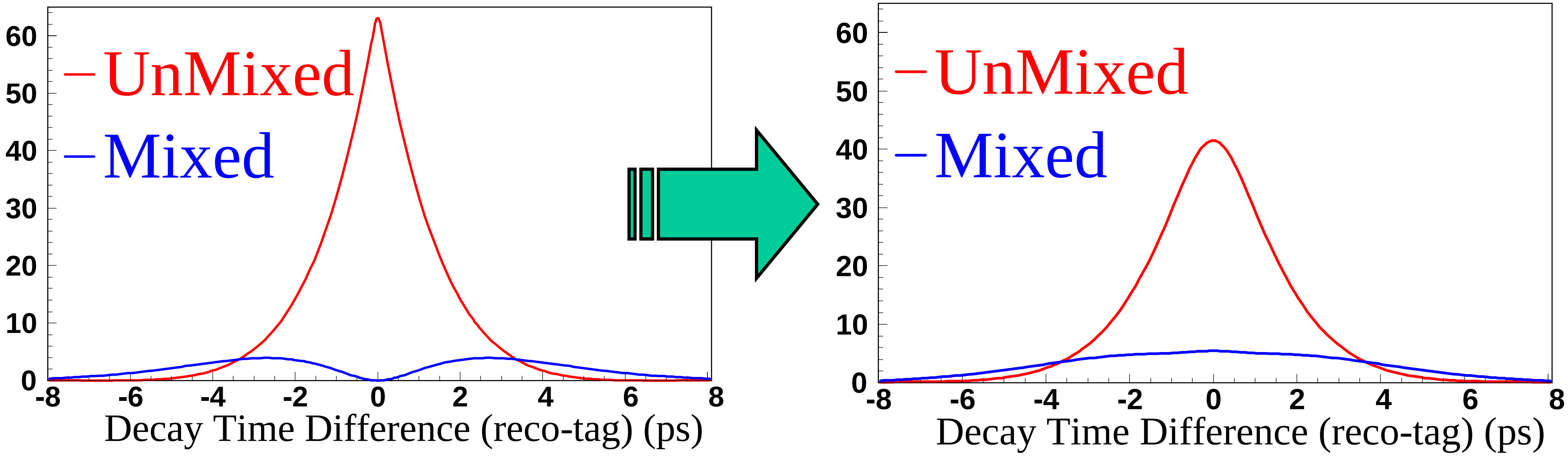
1. Fully reconstruct one B meson in flavor eigenstate (B_{REC}) ✓
2. Reconstruct the decay vertex ✓

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

Δt Spectrum of Mixed and Unmixed B Events

perfect
flavor tagging & time resolution

realistic
mis-tagging & finite time resolution



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

w: the fraction of wrongly tagged events

Δm_d: oscillation frequency

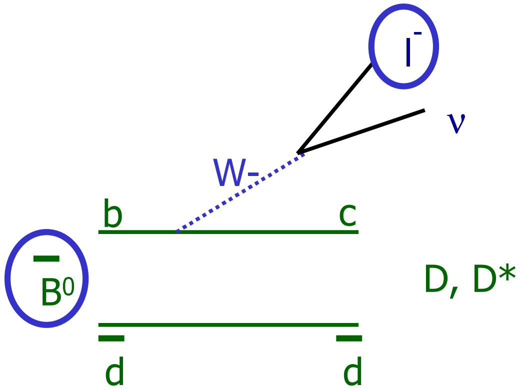
Unmixed: $B^0_{flav}\bar{B}^0_{tag}$ *or* $\bar{B}^0_{flav}B^0_{tag}$

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

B Flavor Tagging Methods

Hierarchical Tagging Categories

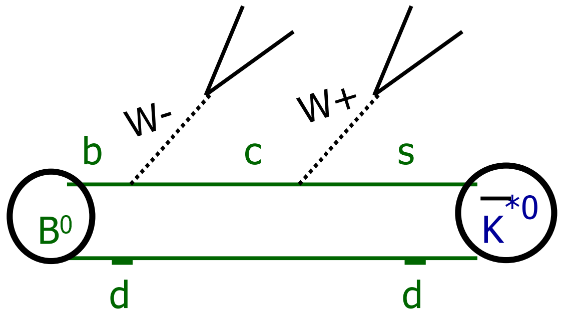
For electrons, muons and Kaons use the charge correlation



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

$l^+ \rightarrow B^0$

Lepton Tag



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

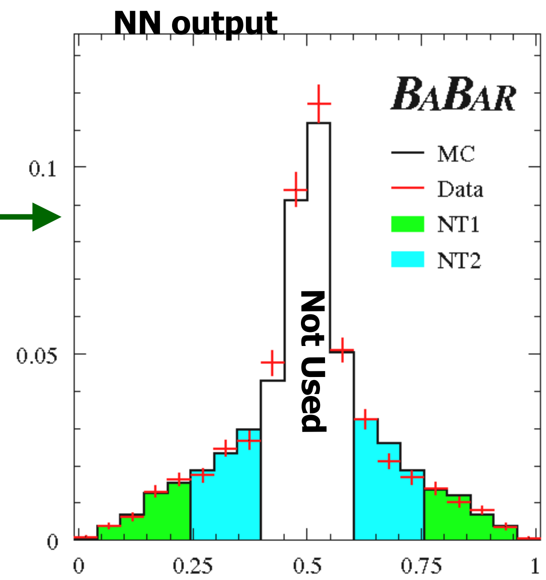
$\sum_{kaons} Q > 0 \Rightarrow B^0$

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*)

B Flavor Tagging Performance Using B Mixing

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

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

Highest "efficiency"

The error on sin2β the quality factor Q

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

Smallest mistag fraction

Δt Resolution Function

$$R(\delta\Delta t) = (1 - f_{tail} - f_{outl}) \cdot G_{core}(\delta\Delta t, S_{core}, \delta_{core,i}) \leftarrow \text{Core}$$

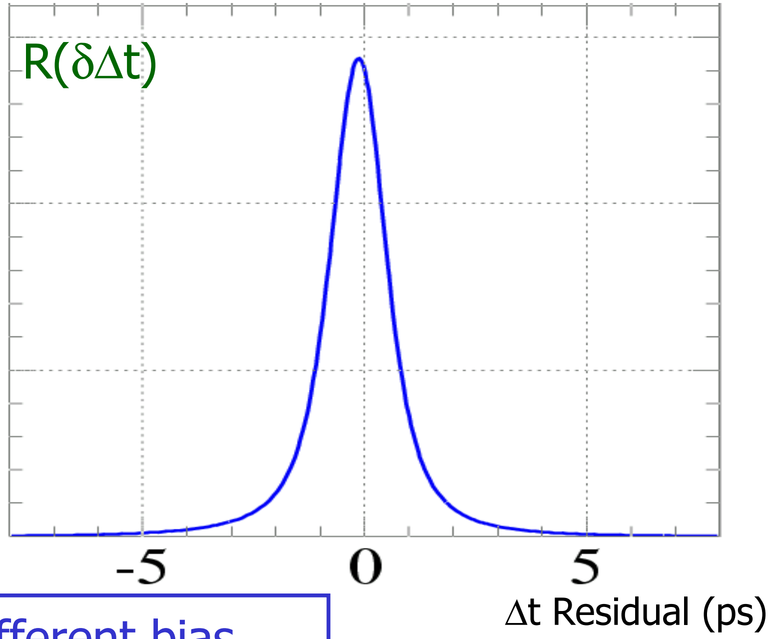
$$+ f_{tail} \cdot G_{tail}(\delta\Delta t, S_{tail}, \delta_{tail}) \leftarrow \text{Tail}$$

$$\text{Outlier} \rightarrow + f_{outl} \cdot G_{outl}(\delta\Delta t, \sigma_{outl} = 8\,ps, \delta_{outl} = 0)$$

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

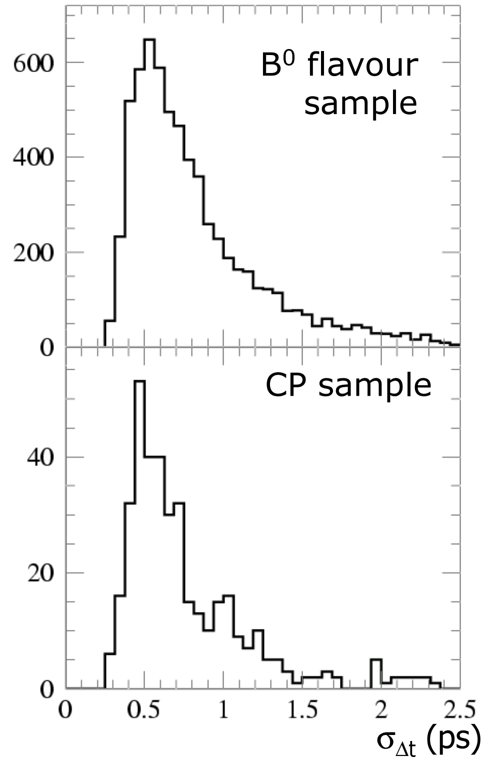
$$\sigma_{tail} = S_{tail} \cdot \sigma_{\Delta t}^{evt}$$

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



Mixing Likelihood Fit

Unbinned maximum likelihood fit to flavor-tagged neutral B sample

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

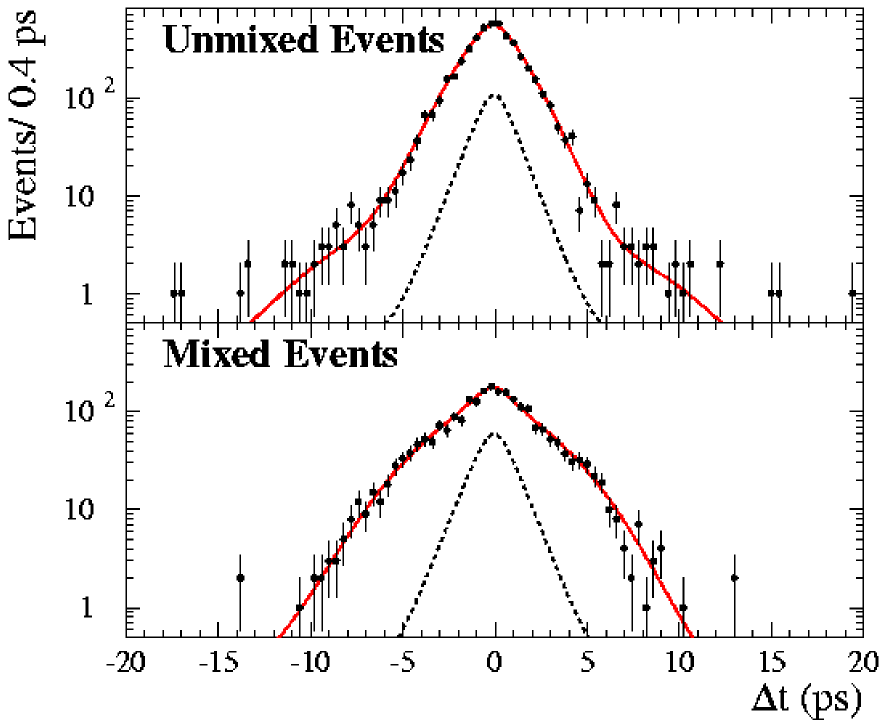
Fit Parameters

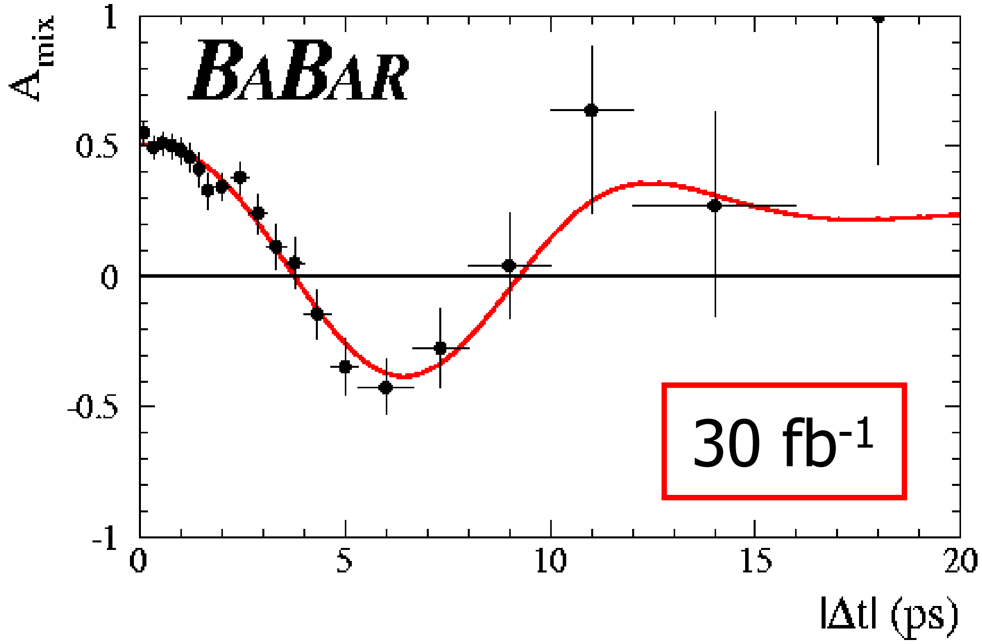
Δm_d	1
Mistag fractions for B^0 and $\overline{B}^0$ tags	8
Signal resolution function(scale factor,bias,fractions)	9
Empirical description of background Δt	16
B lifetime fixed to the PDG value	τ_B = 1.548 ps

34 total free parameters ⇒ All Δt parameters extracted from data

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

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

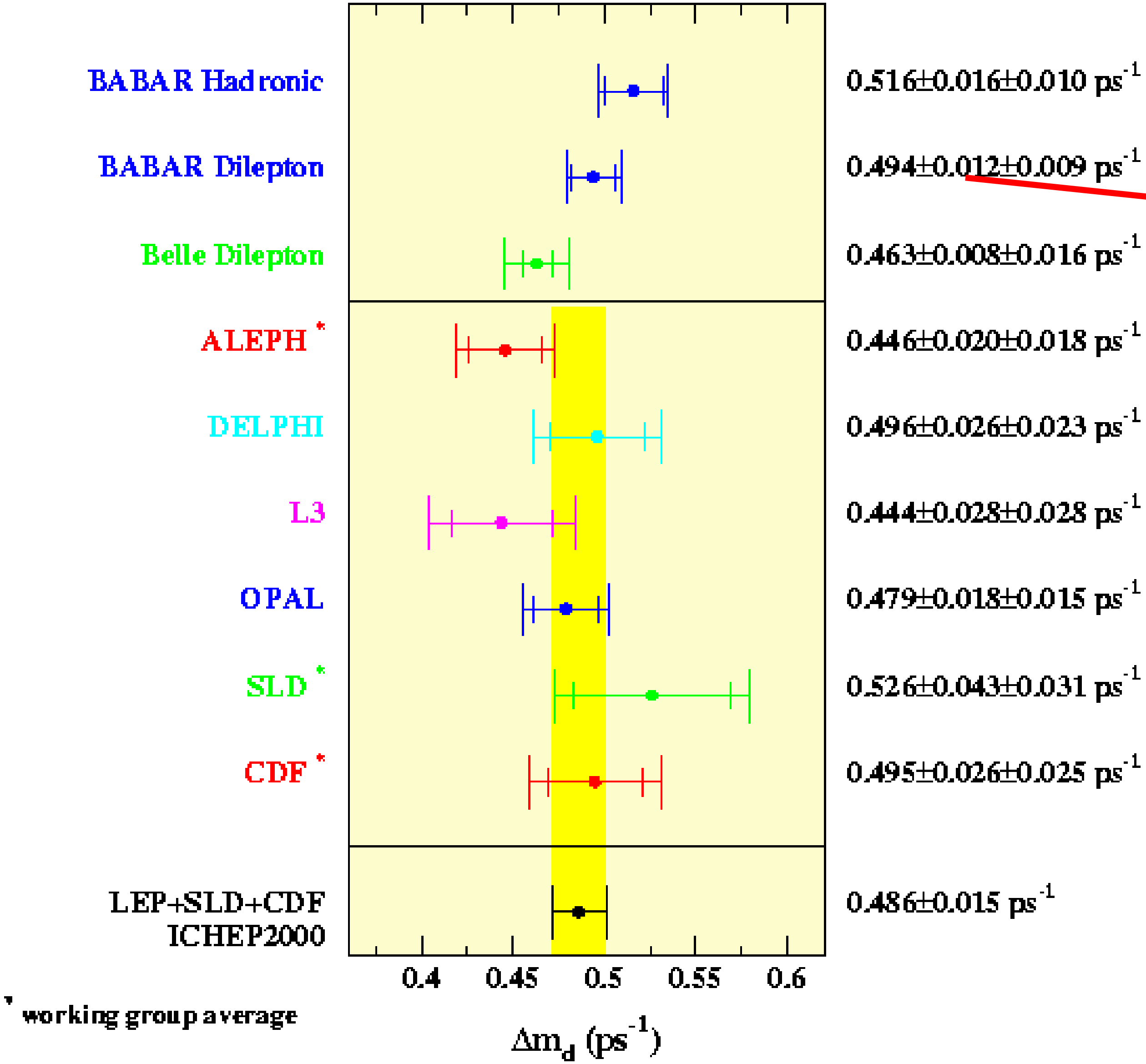




$\Delta m_d = 0.516 \pm 0.016\ (\text{stat}) \pm\ 0.010\ (\text{syst})\ \hbar\ ps^{-1}$

hep-ex/0112044

Δm_d Measurements in Comparison

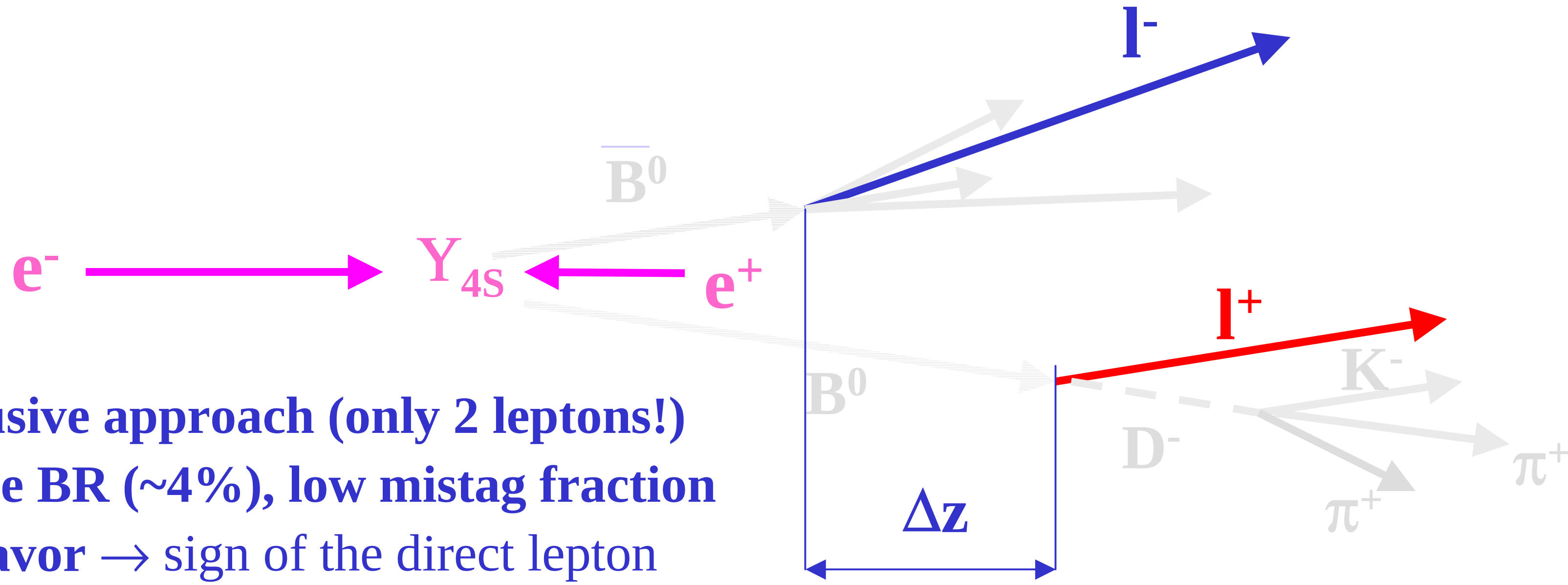


hep-ex/0112044

hep-ex/0112045
see next slides

Each of them is the average of several measurements

The Dilepton Way to mixing and CPV

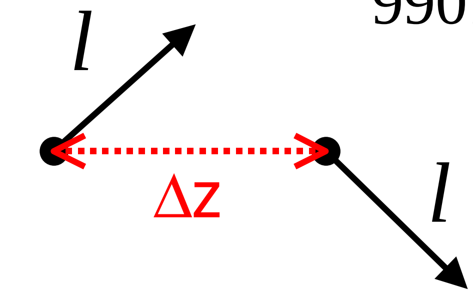


- **Inclusive approach (only 2 leptons!)**
- **Large BR (~4%), low mistag fraction**
- **B Flavor** $\rightarrow$ sign of the direct lepton
- **B^0 and $B^\pm$ admixture**
- **Efficient Neural Network event selection**
- **Very accurate description of the residual background**
- $\Delta z \rightarrow$ **points of closest approach of the leptons to the beam spot in transverse plane**
- **Extraction of Δm from time evolution: $e^{-\Gamma|\Delta t|}\,[1\pm\cos(\Delta m \Delta t)]$**
- **Study of CPV in mixing from charge asymmetry of same sign leptons:**

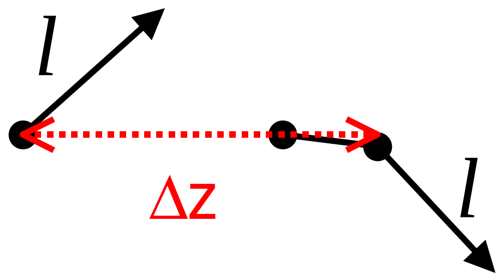
$$A_T=(N_{l^+l^+} - N_{l^-l^-})/(N_{l^+l^+} + N_{l^-l^-}) \sim {}^{4Re(\varepsilon)}/_{1+|\varepsilon|^2}$$

Dileptons: sample composition

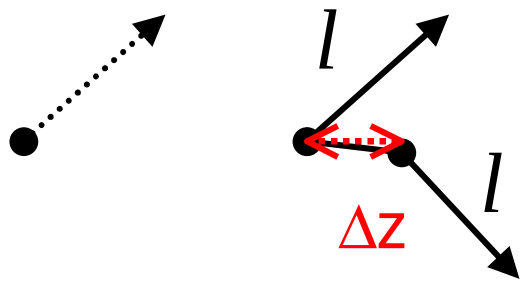
99010 events selected in 20.7 fb^{-1}



- Direct leptons (~78%)
  - sensitive to mixing (!)
  - B-lifetime component

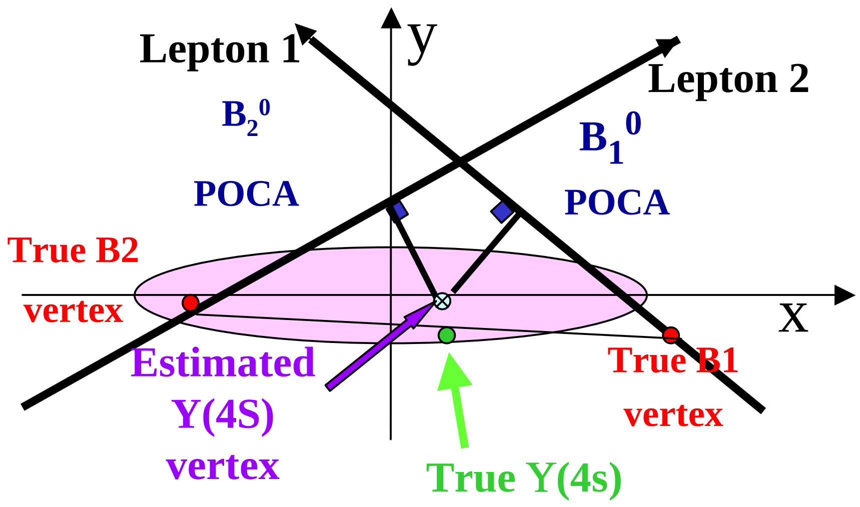


- Opposite-B cascade (OBC) leptons (~7%)
  - sensitive to mixing, but
  - source of mistag (~100%)
  - extra-lifetime due to charm decay
    (B-lifetime + effective lifetime from charm)



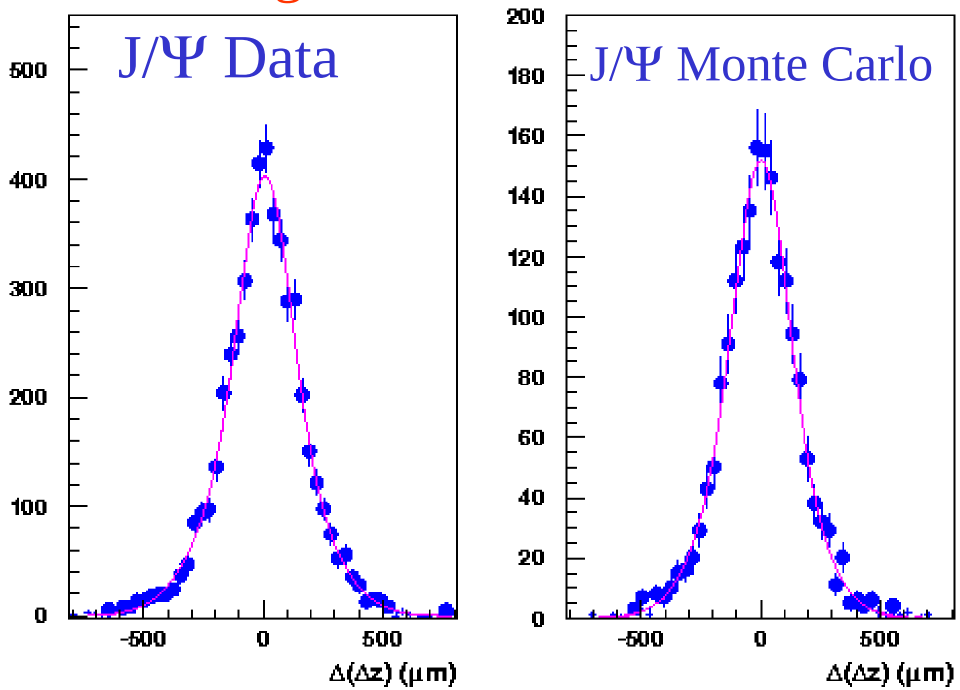
- Same-B cascade (SBC) leptons (~5%)
  - not sensitive to mixing
  - source of opposite-sign leptons only
  - effective lifetime from charm
- Misidentified leptons (~5%):
  - same topologies (and resolution function) as above
  - extra mistag to be taken into account
- Continuum (~5%): fit off-resonance data

Dilepton Mixing: Δt measurement



Δz = z difference of the point of closest approach (POCA) of the tracks to a Y(4S) vertex, estimated with the 2 leptons and a beam spot constraint

Agreement within 10%



- Δz resolution function determined with MC and cross-checked with J/Ψ.
- Resolution model: 3 gaussians
  - Narrow Gaussian : 85μm (64.8%)
  - Wide Gaussian : 160μm (35.5%)
  - Outlier Gaussian : 630μm (0.7%)
- Boost approximation:

$$\Delta t = \Delta z / (c < \beta\gamma >)$$

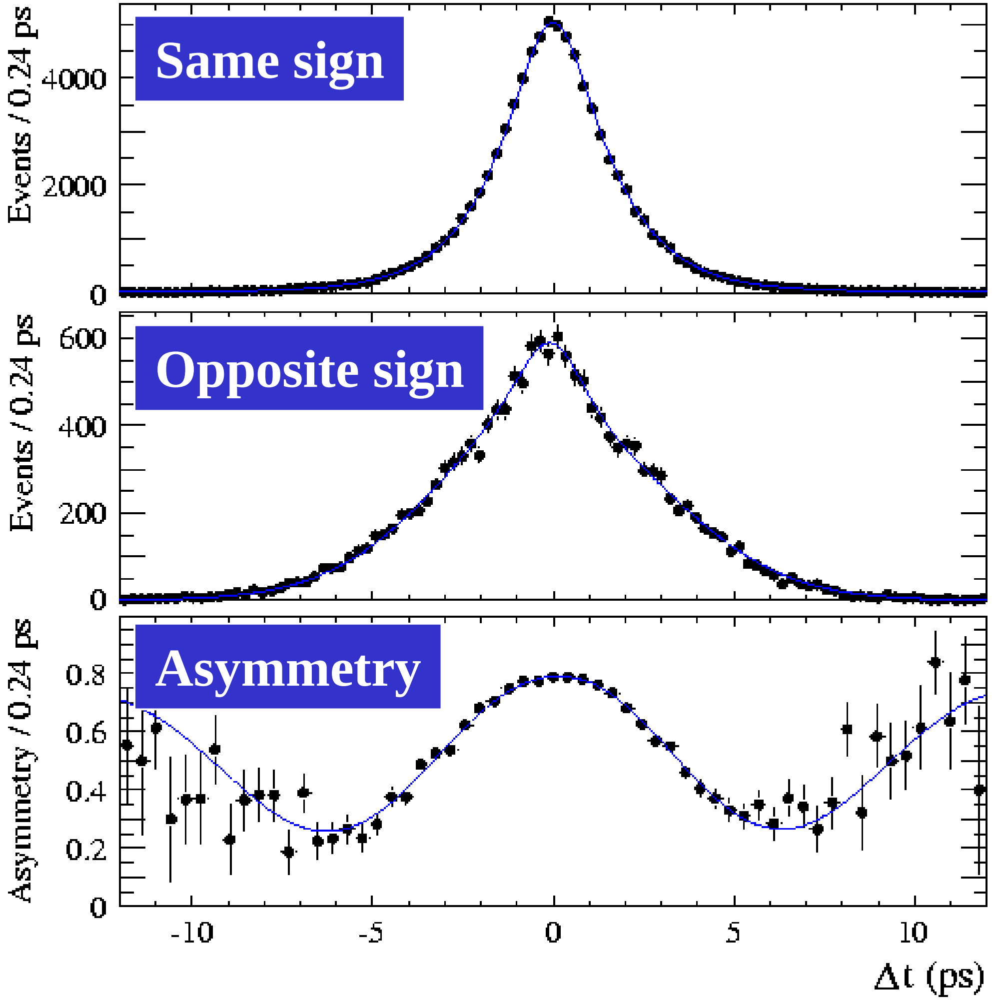
Dilepton mixing results

$\Delta m_d = 0.493 \pm 0.012 \pm 0.009\ ps^{-1}$

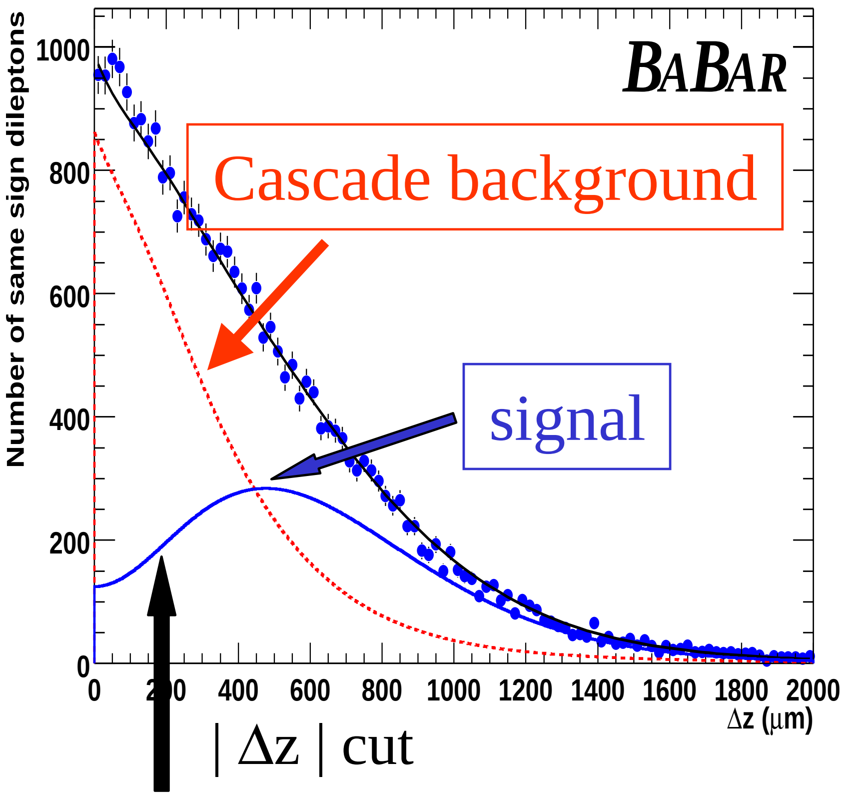
Most precise single measurement!

1% correction due to the time dependence of the resolution function

Systematics dominated by:
- B meson lifetimes (0.0064)
- time dependence of resolution function and cascade resolution + lifetimes (0.0050)



CPV with dileptons: Background reduction



Almost all background comes from cascade leptons from B+ or unmixed B0

Cut at 200μm
Correct for background dilution by weighting in bins of |Δz|

$$A_T^{mes}(\Delta t) = A_T(\Delta t) \cdot \frac{S(\Delta t)}{S(\Delta t) + B(\Delta t)}$$

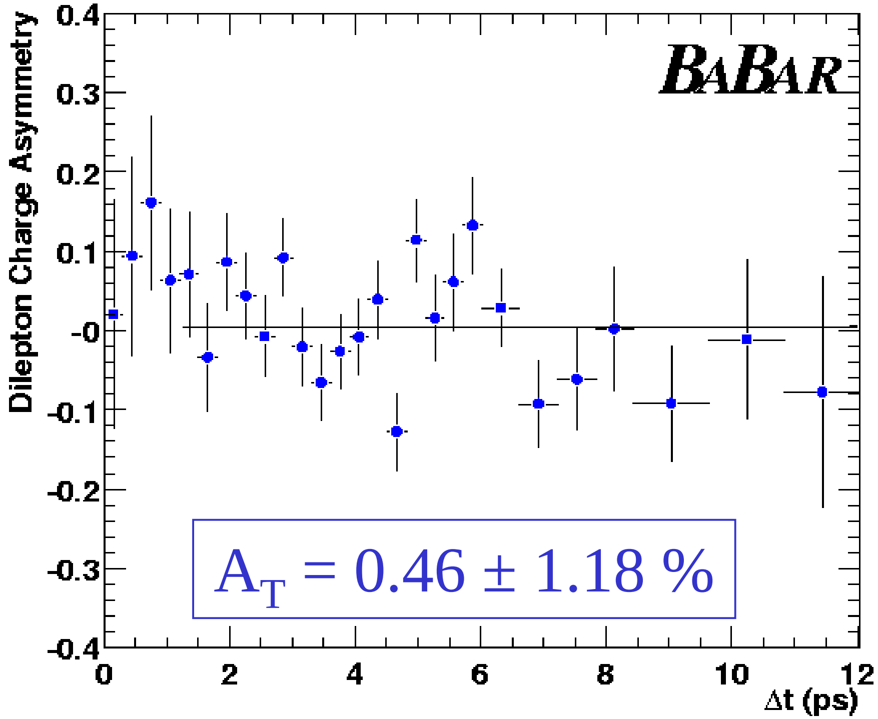
Neglect background asymmetry
⇒ small systematics

20381 events in 20.7 fb-1

CPV with dileptons: results

Corrected for charge asymmetries in the detection (particle ID, tracking)

Most precise single measurement!

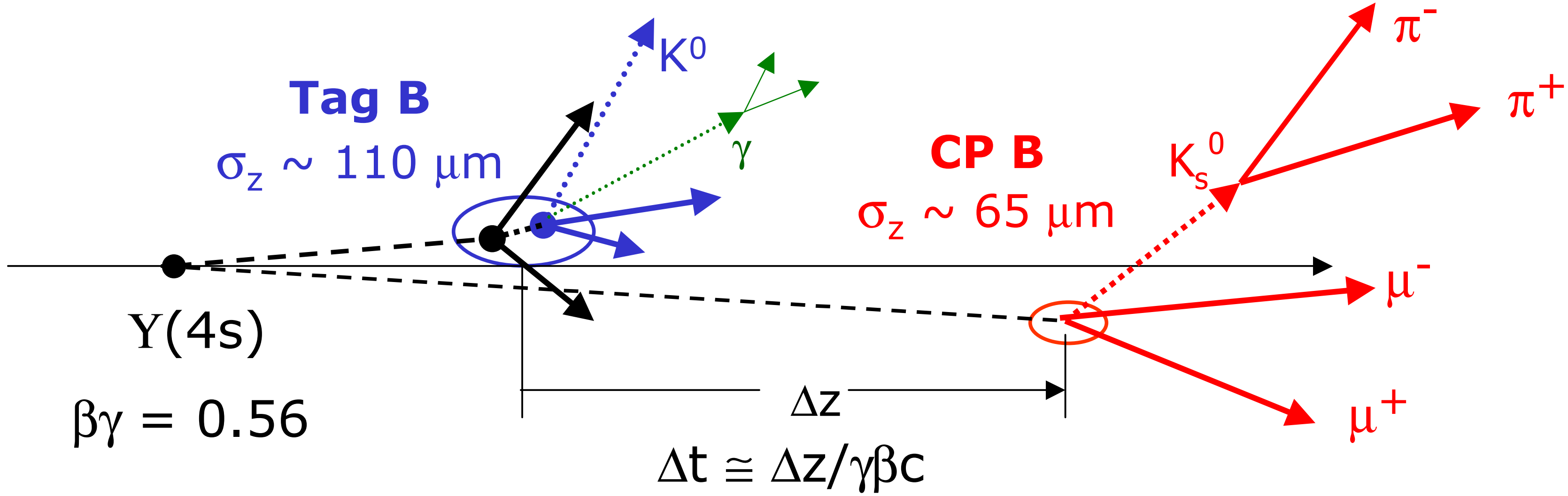


$$\mathrm{Re}(\varepsilon)/_{1+|\varepsilon|^2} = 0.11 \pm 0.29 \pm 0.36\ \%, \text{ or}$$

$$|q/p| = 0.998 \pm 0.006 \pm 0.007$$

Systematics dominated by charge asymmetries in the detector

Measurement of CP Asymmetry : Sin2β

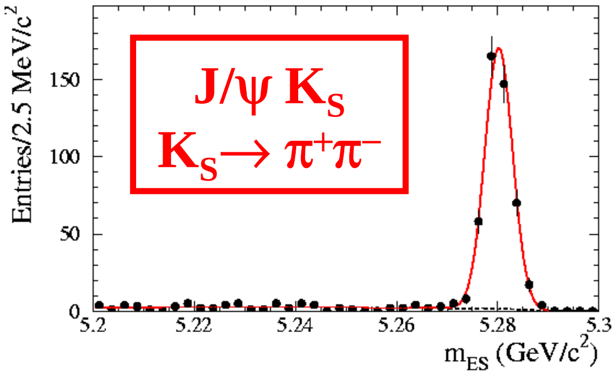


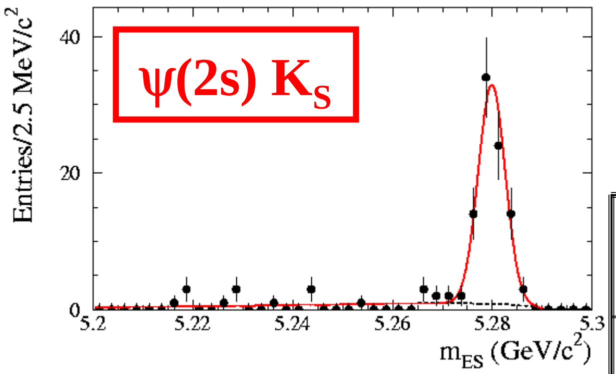
3. Reconstruct Inclusively the vertex of the "other" B meson (B_{TAG}) ✓
4. Determine the flavor of B_{TAG} to separate Mixed and Unmixed events ✓

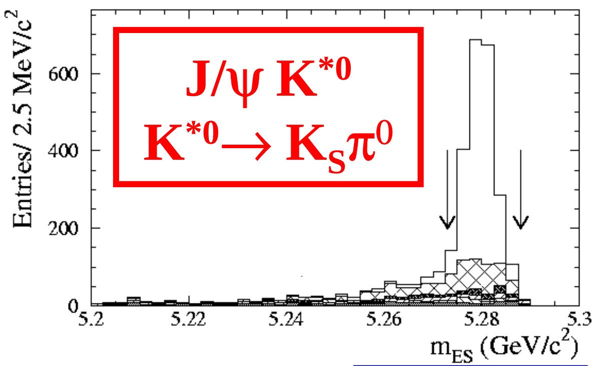
1. Fully reconstruct one B meson in CP eigenstate (B_{CP})
2. Reconstruct the decay vertex ✓

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

The fully Reconstructed CP Sample



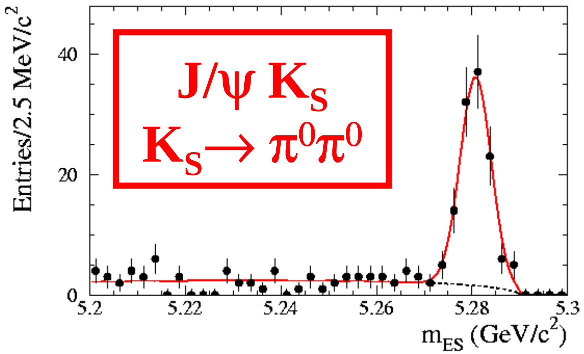


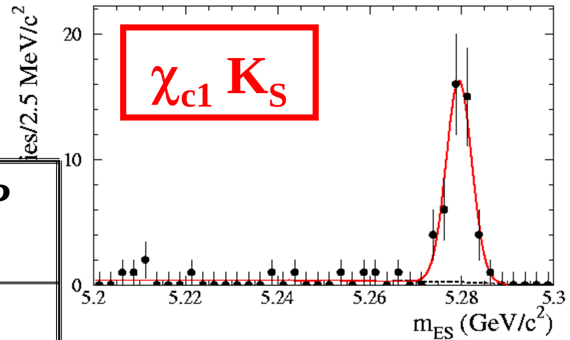


$m_{ES} = \sqrt{(E^{cm}_{beam})^2 - (p^{cm}_B)^2}$

Before tagging requirement

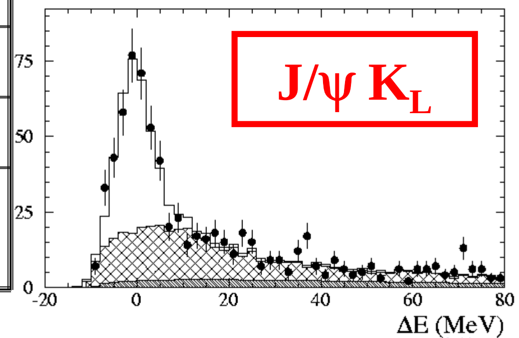
1999-2001 data
32 x 10^6 $B\bar{B}$ pairs
29 fb^{-1} on peak





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

After flavor tagging

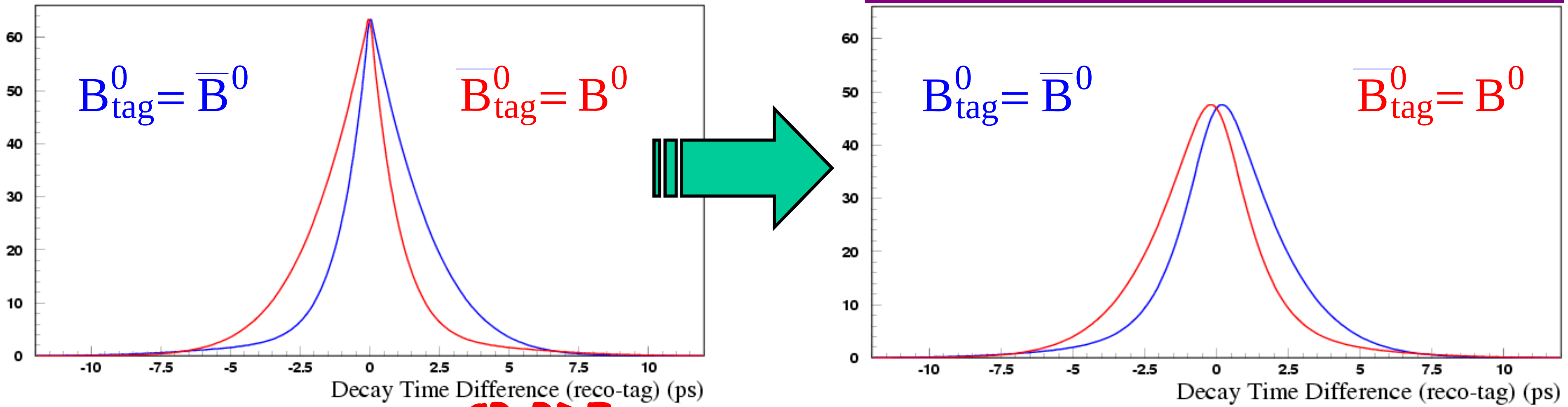


$\Delta E = E_{J/\psi} + E_{K_L} - E^{cm}_{beam}$

Δt Spectrum of CP Events

perfect
flavor tagging & time resolution

realistic
mis-tagging & finite time resolution



CP PDF

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

Mistag fractions w

And

Resolution function R

determined from the flavor sample

Mixing PDF

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

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	tagged flavor sample
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%

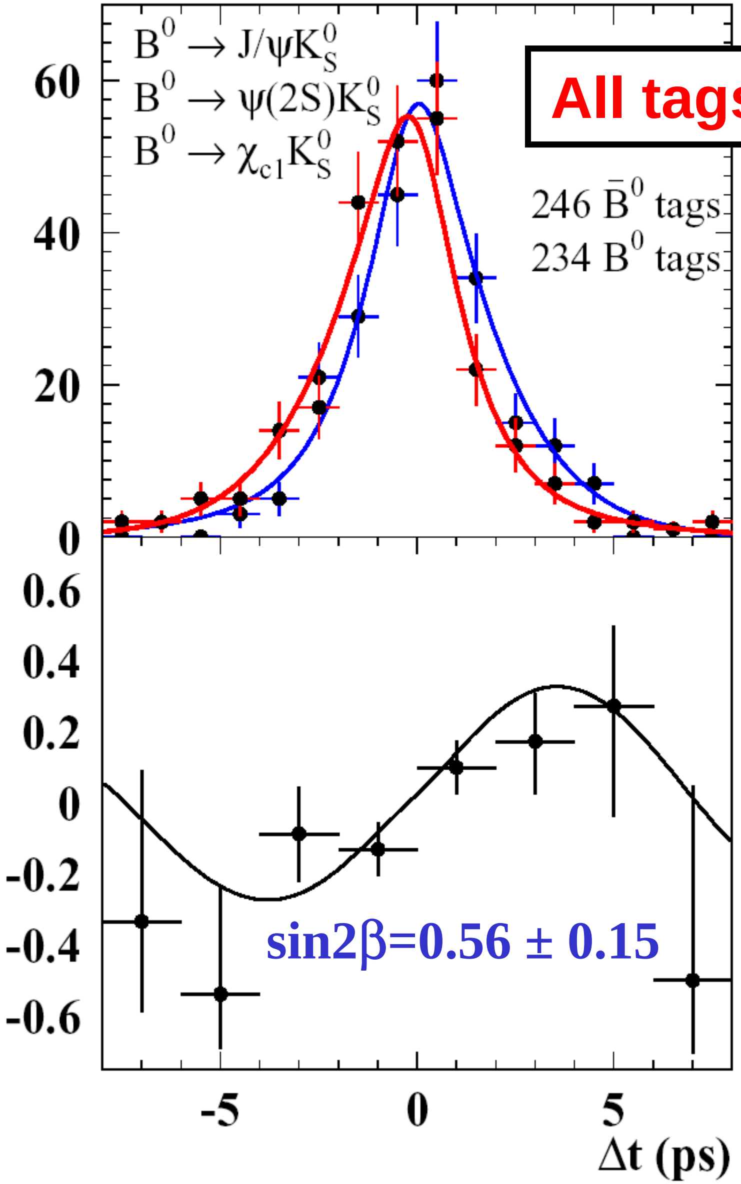
Different Δt resolution function parameters for Run1 and Run2

45 total free parameters ⇒

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

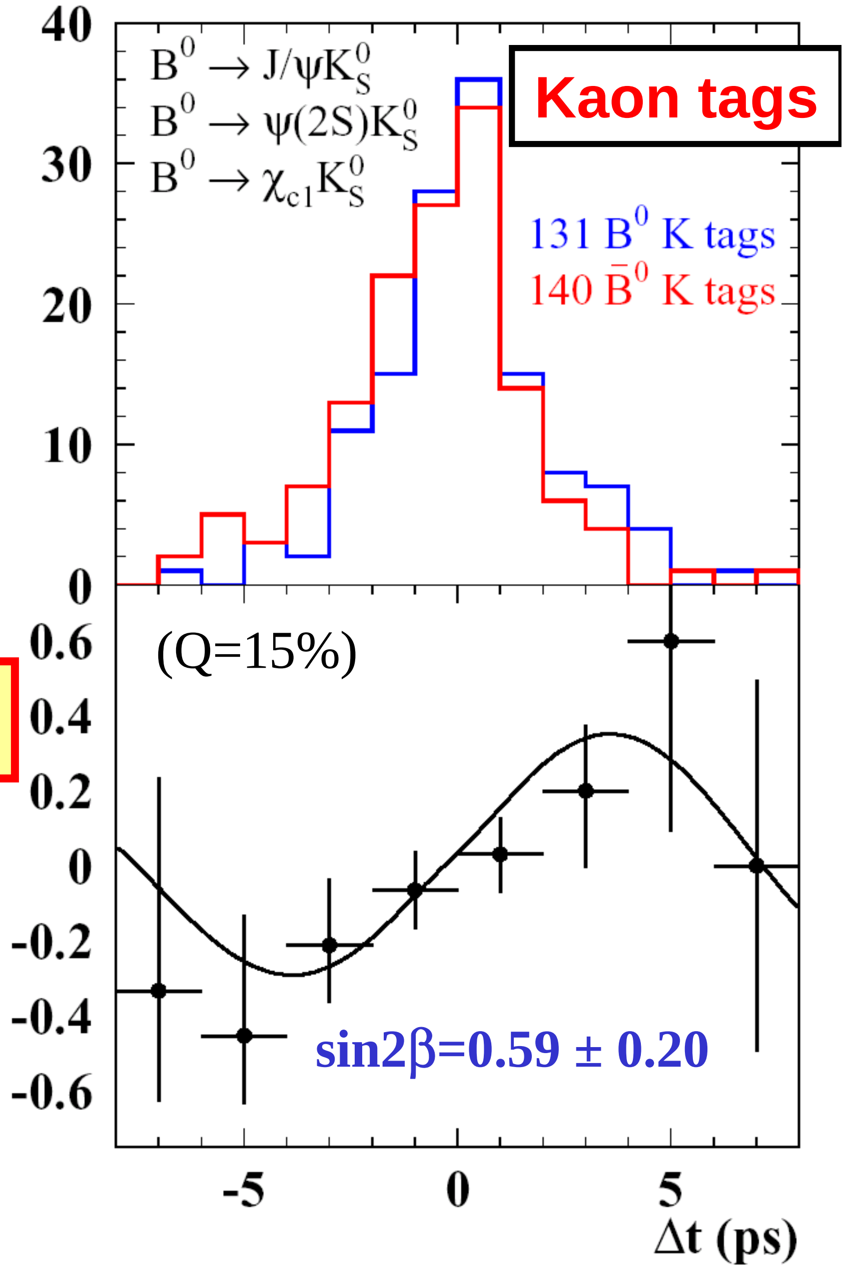
Raw Asymmetries

$$A_{CP}(\Delta t) \approx (1-2w) \times \sin(2\beta) \times \sin(\Delta m_d \, \Delta t)$$

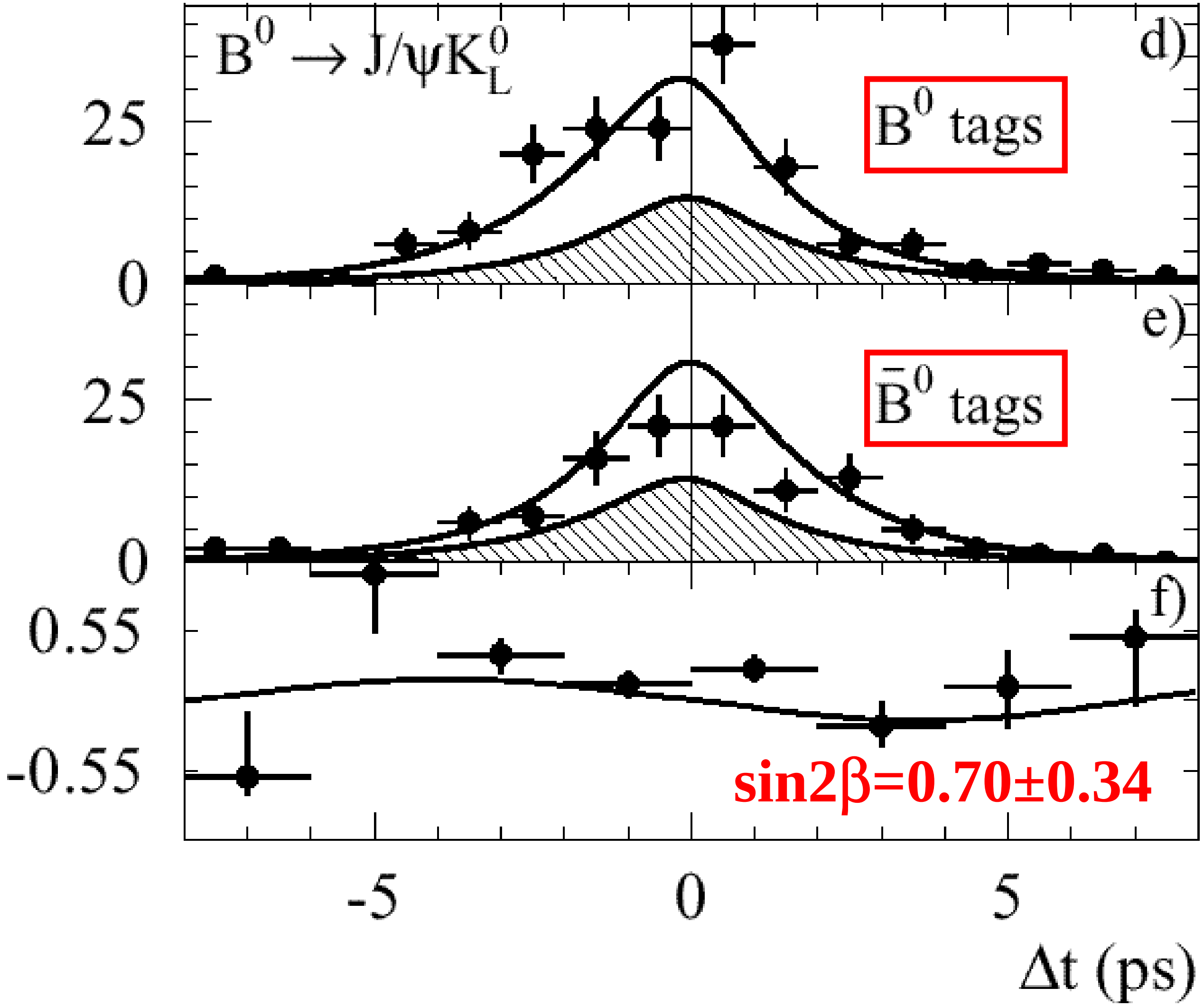


$\eta_f = -1$ events

Raw A_{CP}



J/Ψ K_L Δt Distributions



Raw A_{CP}

Fit projections are from global fit to all CP samples

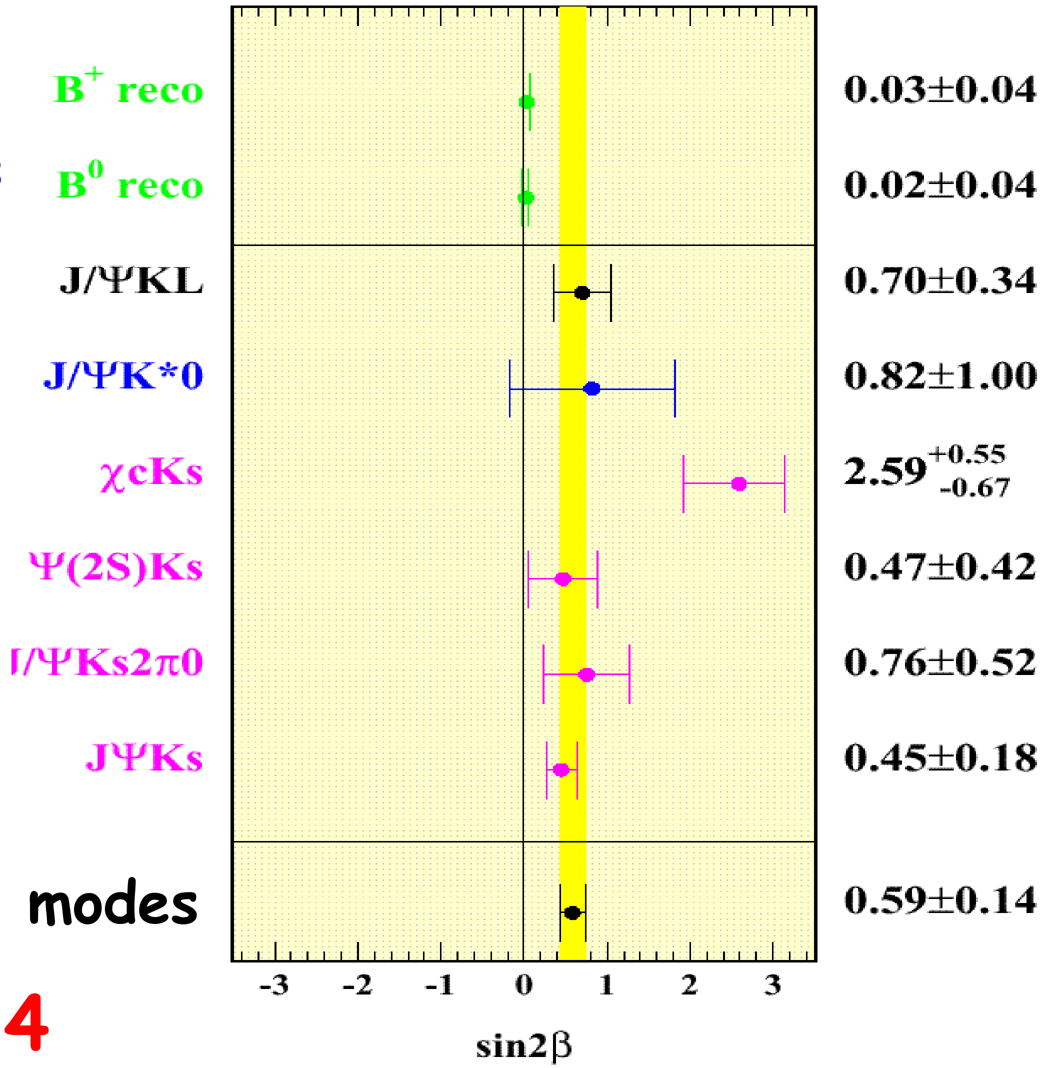
sin2β Fit Results

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

Cross-checks:
Null result in flavor samples

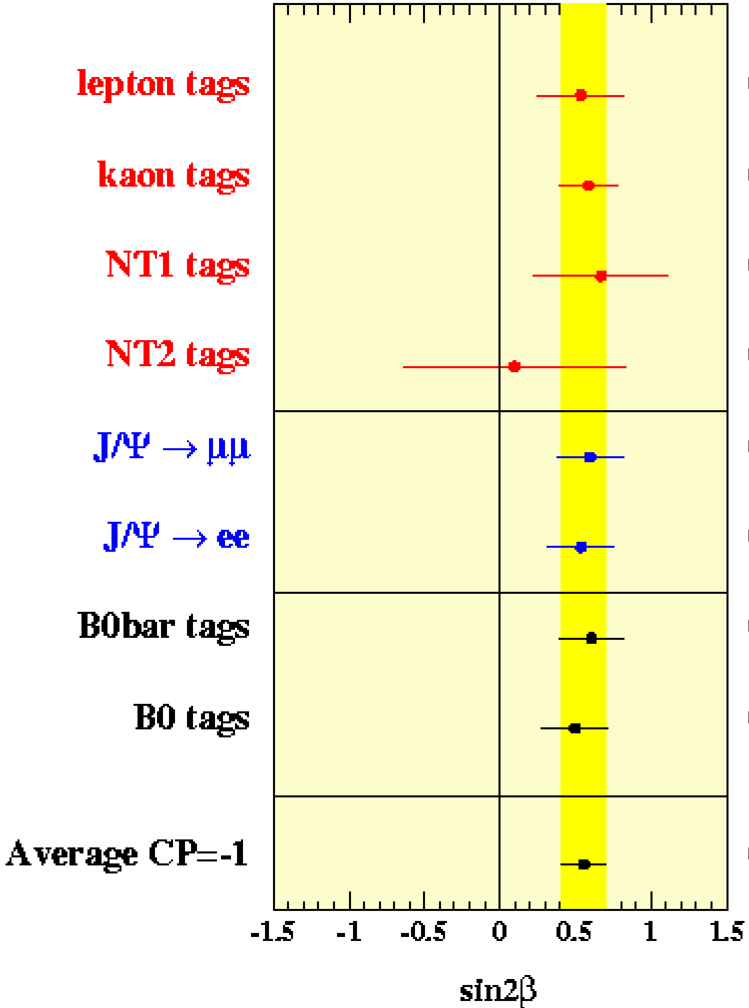
Consistency of CP channels $P(\chi^2) = 8\%$

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

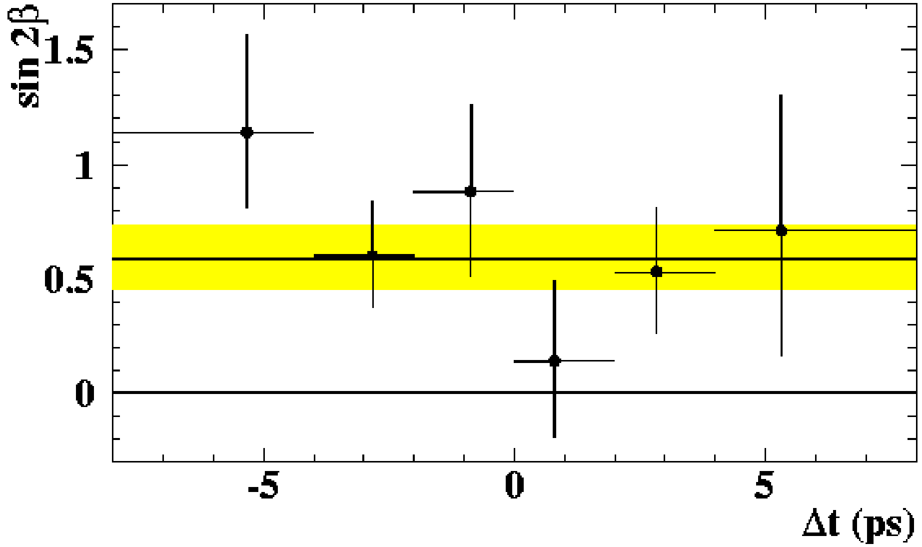


$\sin(2\beta) = 0.59 \pm 0.14$

Sin2b in various sub-samples



sin(2β) vs. J/ψ decay mode and tagging category and flavor for $\eta = -1$ events

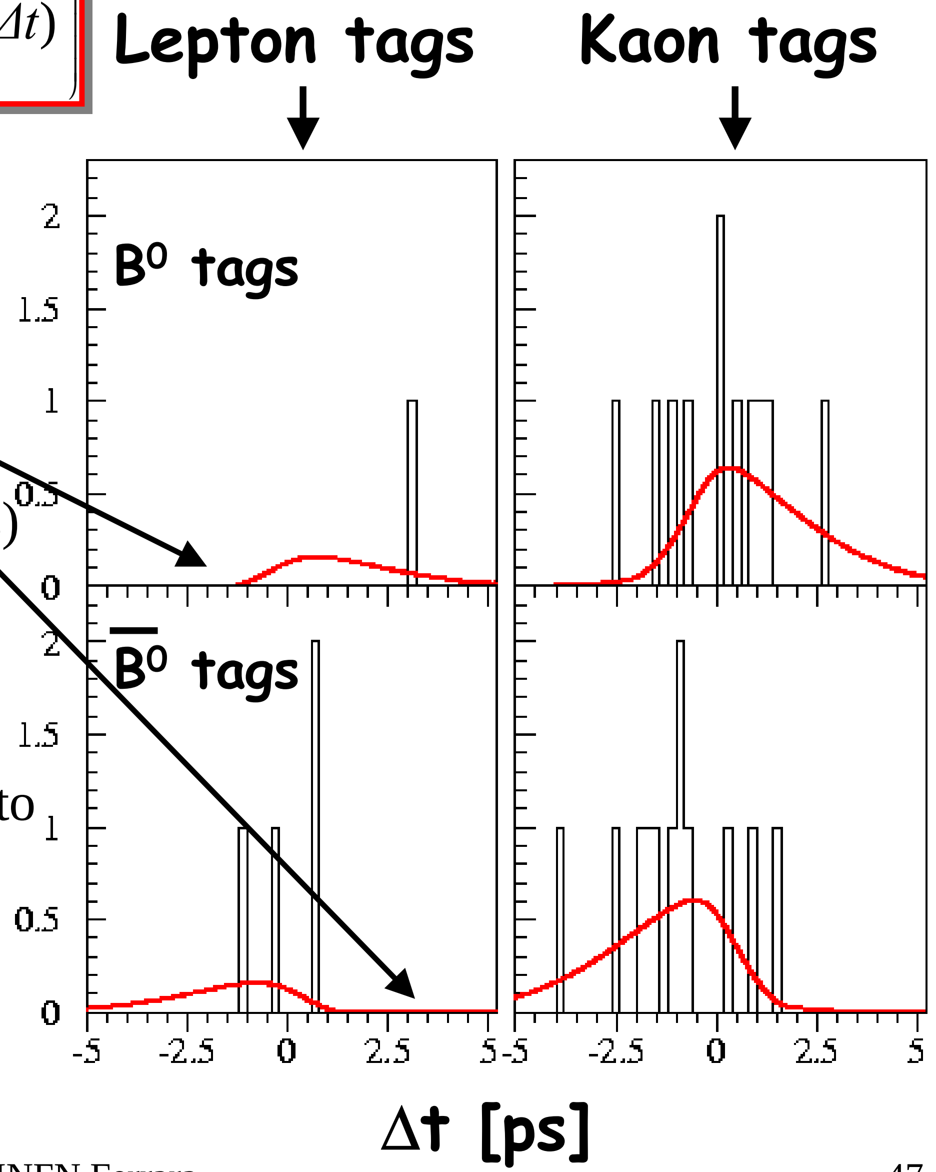


sin(2β) measured in several Δt bins

Large sin2β in $B^0 \rightarrow \chi_{C1} K_S$

$$f_{CP,\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \times \left(1 \pm \sin 2\beta \left(\mathbf{1\text{-}2\omega}\right) \sin(\Delta m_d \Delta t)\right)$$

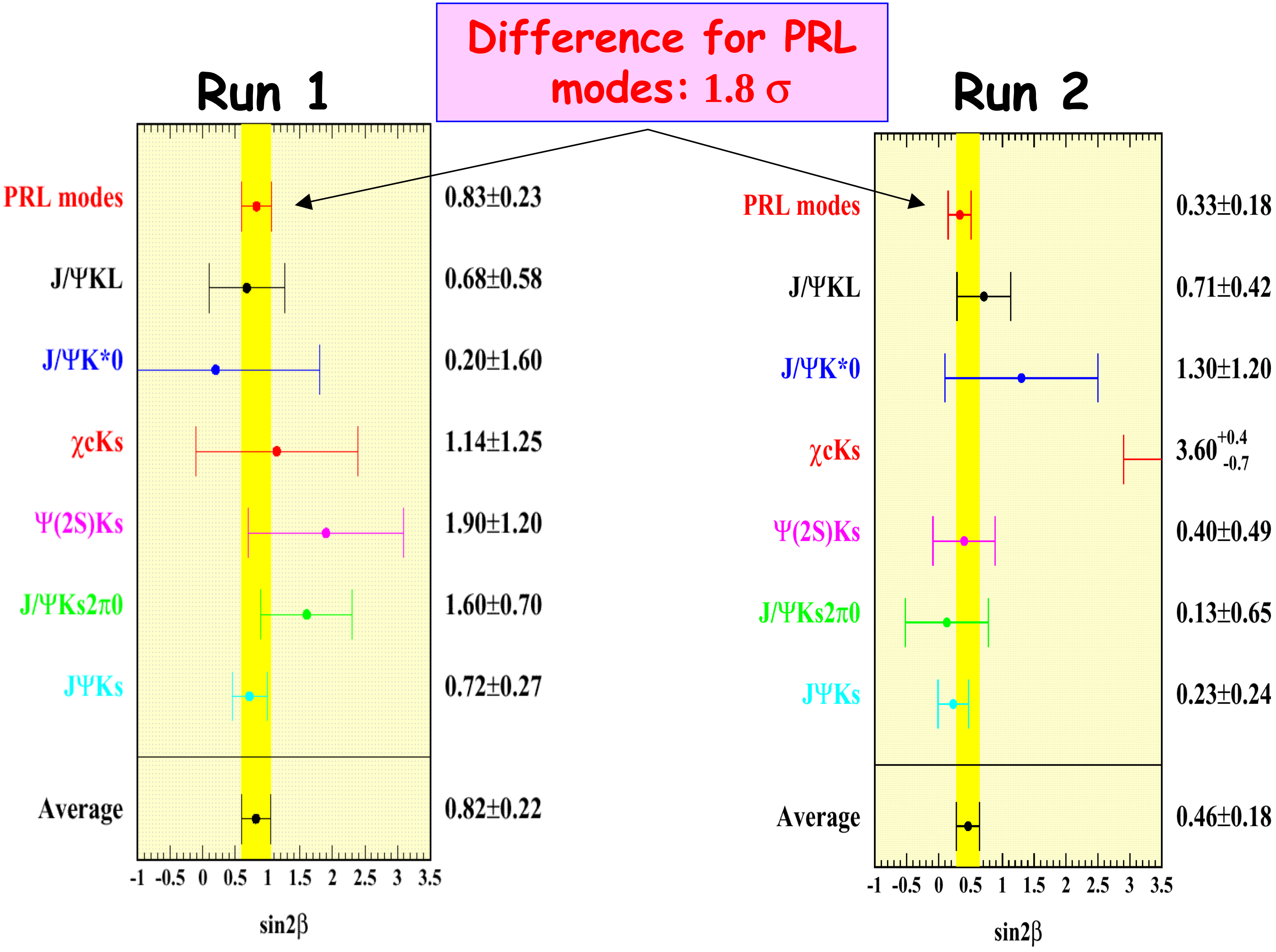
- fit for $B^0/\bar{B}^0$ Δt PDFs, not for A_{CP}
- accommodate large asymmetry with negative signal PDF (at -(+)π/2Δm_d for $B^0(\bar{B}^0)$ tagged events)
- Possible , because
  - No events at these Δt (eg. lepton tags)
  - Sum of signal + background PDFs positive (eg. Kaon tags)
- Note: a single lepton B^0-tag at Δt = -π/2Δm would bring sin2β from 2.6 to ~$1/(1-2w_{lep}) \approx 1.1$
- Measure sin2β unbiased for low stat. samples and probability to obtain sin2β>2.6 when true value 0.7 is 1-2%



Run1→Run2 Changes/Results

- First publication in March 2001
  $\sin(2\beta) = 0.34 \pm 0.20 \pm 0.05$ PRL 86 (2001) 2515
- Changes since then:
  - More data (run 2): **23 →32 $B\bar{B}$ pairs**
  - Improved reconstruction efficiency
  - Optimized selection criteria takes into account CP asymmetry of background in $J/\psi K_L$
  - Additional decay modes $\chi_{C1}K_S$ and $J/\psi K^{*0}$
  - Improved vertex resolution for reconstructed and tag B

Run 1 / Run 2 Results



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 J/Ψ K_L channel; 0.11 for J/Ψ K^{*0}
- Total Systematic Uncertainty: → 0.05 for total sample

Search for Direct CP

If at least 2 amplitudes with a weak phase difference contribute

$|\lambda|$ might be different from 1

(tree amplitude and leading penguin amplitude for B→ $J/\psi\ K_S$ have same weak phase in SM)

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

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

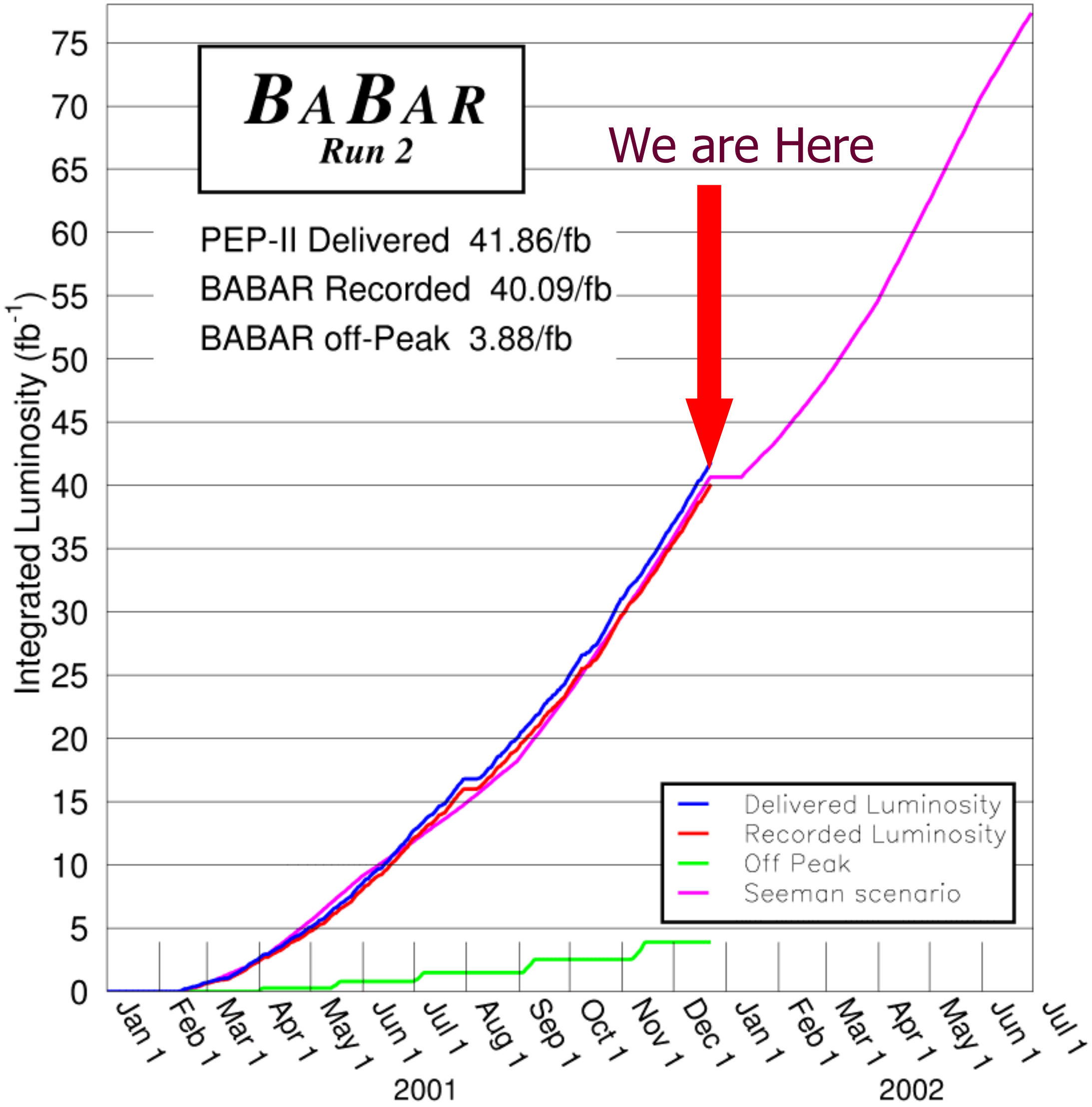
$$S_{f_{CP}} = \frac{-2 \, \mathrm{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

Probing new physics (only use η_{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 (coefficient of the "sine" term unchanged)

Luminosity Projection to Summer 2002

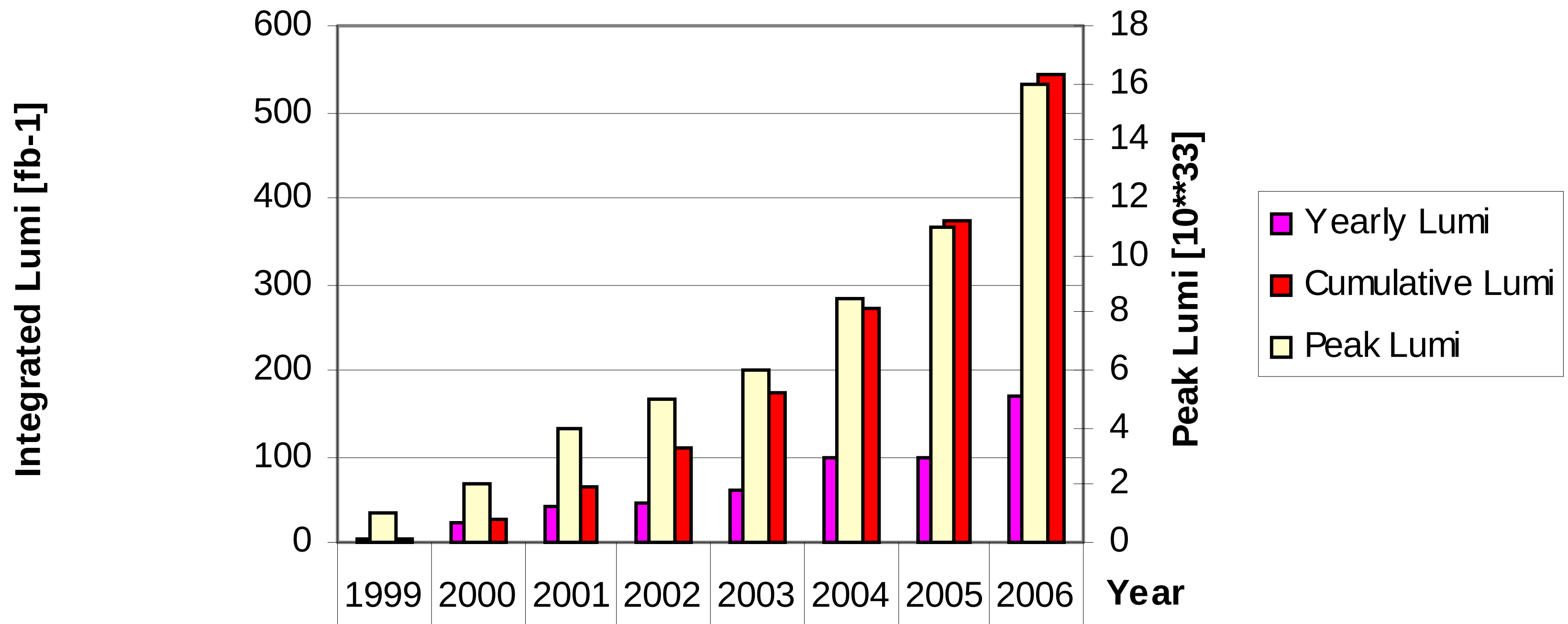


Project 100 fb^{-1} by Jun 2002

Hope to analyze Data very Quickly As demonstrated Already

Luminosity Plans for BABAR & PEP II

Expect 550 fb^{-1} By 2006



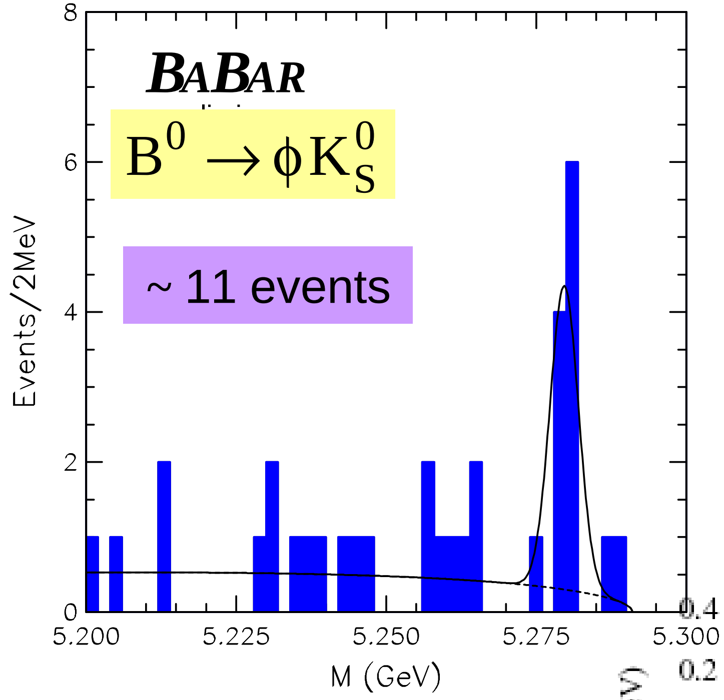
	1999	2000	2001	2002	2003	2004	2005	2006
Yearly Lumi	2	23	40	45	62	100	100	170
Cumulative Lumi	2	25	65	110	172	272	372	542
Peak Lumi	1	2	4	5	6	8.5	11	16

Prognostications on Future Sin2β Precision

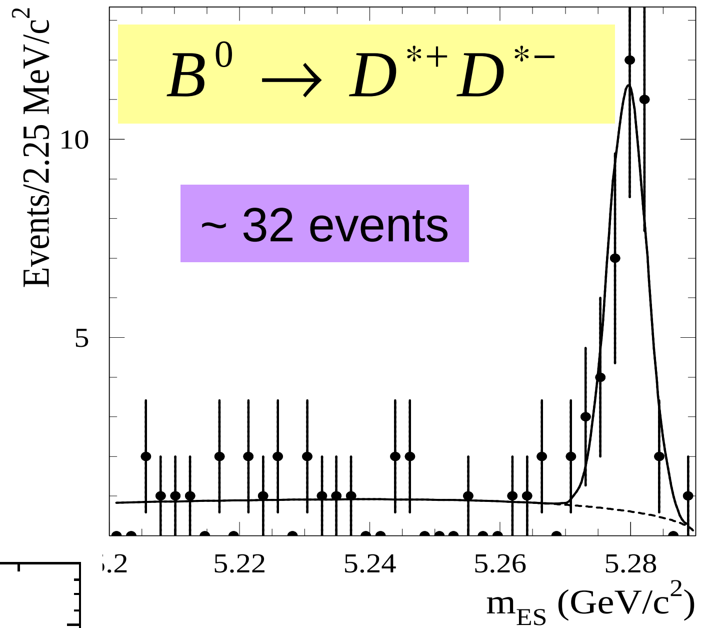
- In the Charmonium Modes
  - Add more sub-modes “drops in the bucket” :
    - Select $\Psi\rightarrow$ hadrons, not just $\Psi\rightarrow e^+ e^-$ or $\mu^+ \mu^-$,
    - smarter event selection (bremstrahlung recovery)
    - Expect for charmonium modes: ➡ $\sigma_{\sin 2\beta} \leq 0.08$ for $100\ fb^{-1}$
  - Add new CP modes :
    - $b\rightarrow s s\bar{s} \Rightarrow B \rightarrow \phi K_S$ ➡ $\sigma_{\sin 2\beta} \leq 0.25$ for $500\ fb^{-1}$
      - Compare with sin2β from $b\rightarrow c\bar{c}s$
    - Cabibbo Suppressed $B \rightarrow \Psi\pi^0$ ➡ $\sigma_{\sin 2\beta} \leq 0.23$ for $500\ fb^{-1}$
      - Look for difference in sin2β measured from $b\rightarrow c\bar{c}s$
        - » bound u-quark penguin pollution
    - Cabibbo suppressed $b\rightarrow c\bar{c}d \Rightarrow B \rightarrow D^{(*+)}\ D^{(*-)}$
      - May contain (small but unknown) penguin pollution
        - » D*D* mode requires angular analysis (in progress)

New Modes for "Sin2β": 20 fb^{-1}

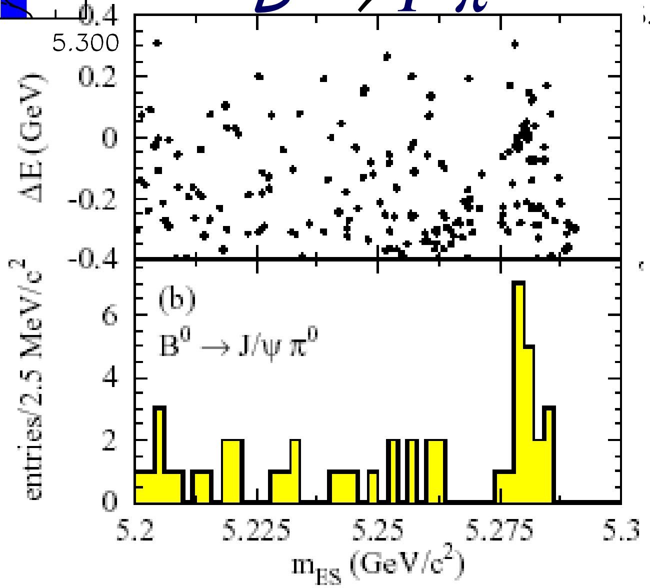
$b \rightarrow s\bar{s}s$



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

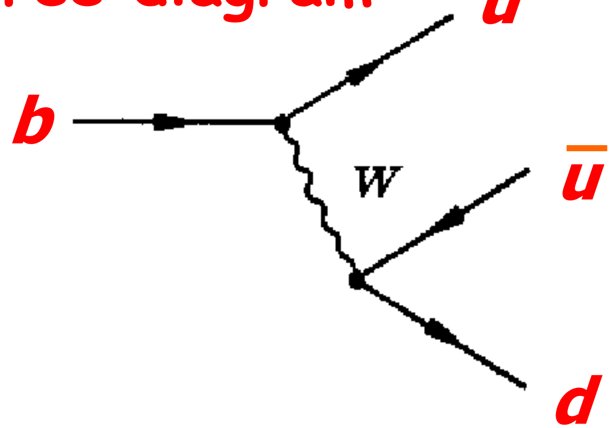


$B \rightarrow \Psi\ \pi^0$

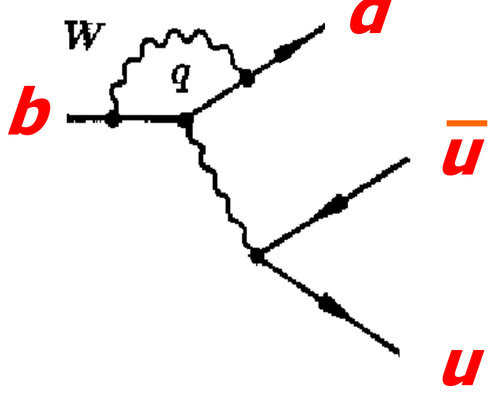


CP Violation in $B^0 \to \pi^+\pi^-$ Decays

tree diagram



penguin diagram



Weak phase (only tree diagram)

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

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

Additional phase from penguin diagram

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

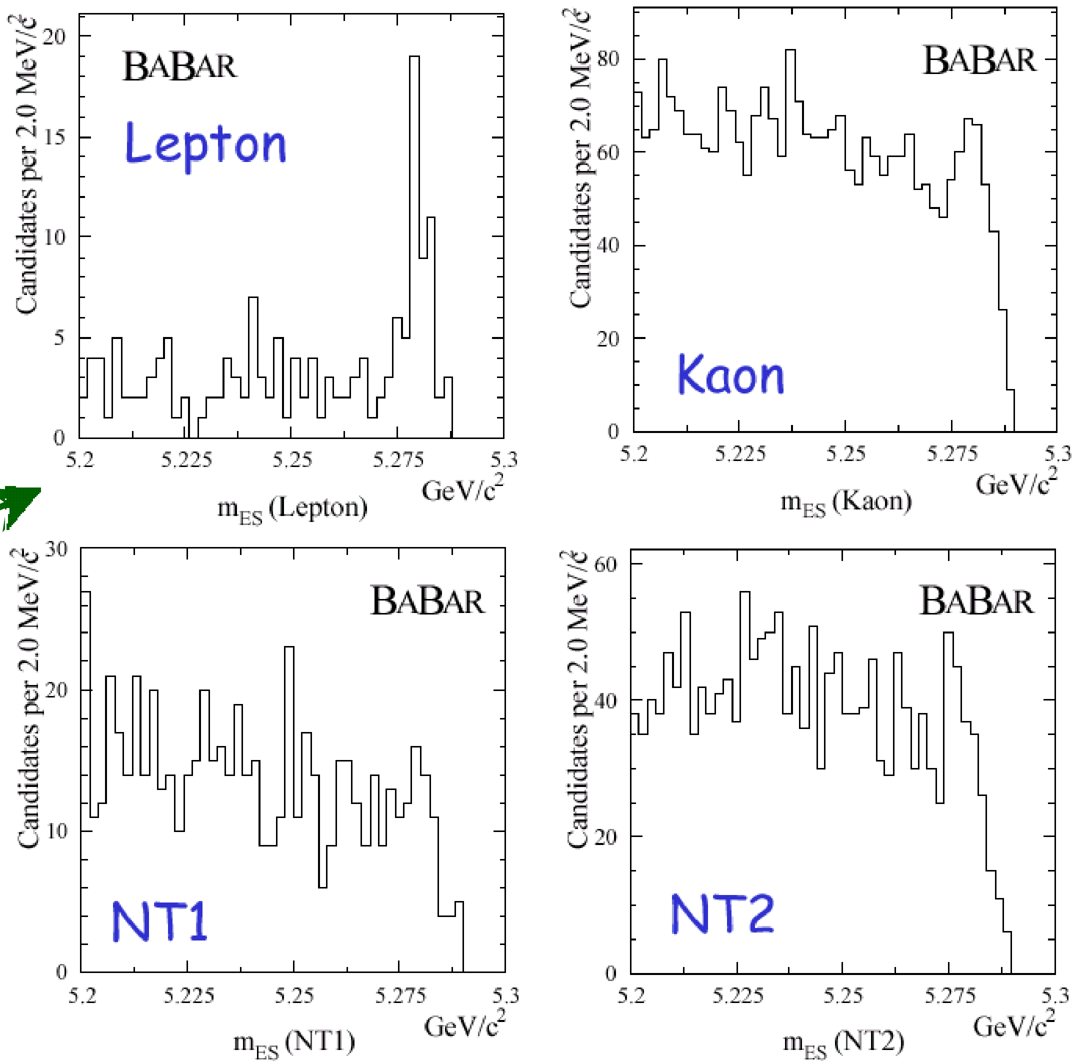
$$C_{\pi\pi} \neq 0,\ S_{\pi\pi} = \sin 2\alpha_{eff}$$

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

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

$B \rightarrow \pi^+\pi^-, K^+\pi^-, K^+K^-$ Data Sample

Likelihood Analyis with **high reconstruction efficiency:**
Loose selection criteria yield 9741 two-prong candidates in 30.4 fb^{-1}
(includes 97% background, almost entirely from continuum)



sum of $\pi^+\pi^-/K^+\pi^-$ m_{ES} distributions by tagging category (particle ID used in likelihood fit for $\pi\pi/K\pi$ separation)

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

- Simultaneous extended ML fit to the BRs and CP asymmetries:
  - 8 event types (Sig 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
- With 30.4 fb^{-1}:

$$65 \pm^{12}_{11} \pi^+\pi^-,\ 217\pm18\ K^+\pi^-,\ 4.3 \pm^{6.3}_{4.3} K^+K^-$$

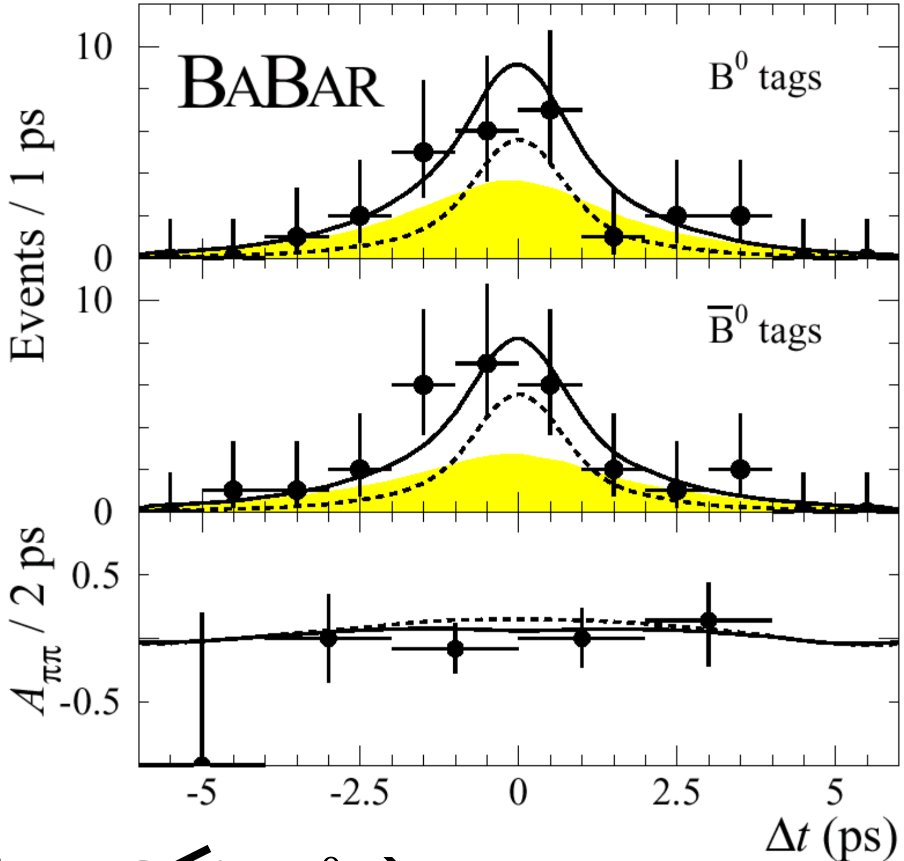
$B^0 \rightarrow \pi^+\pi^-$ Asymmetry Result

hep-ex/0110062

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

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

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



- Measurement compatible with no ~~CP~~ in $B^0 \rightarrow \pi^+\pi^-$
- Statistically limited due to small branching fraction
- Need ~500/fb for $\sigma(S_{\pi\pi})$ ~ 0.10-0.15

Summary and Outlook

- New precision measurements of B^0/B^+ lifetimes and $B^0\overline{B}^0$ mixing frequency Δm_d

$$\tau_0 = 1.546 \pm 0.032 \pm 0.022 \text{ ps}$$
$$\tau_\pm = 1.673 \pm 0.032 \pm 0.022 \text{ ps}$$
$$\tau_0/\tau_\pm = 1.082 \pm 0.026 \pm 0.011$$
$$\Delta m_d = 0.516 \pm 0.016 \pm 0.010 \text{ ps}^{-1} \text{ (hadronic)}$$
$$\Delta m_d = 0.493 \pm 0.012 \pm 0.009 \text{ ps}^{-1} \text{ (dileptons)}$$

- Measurement of flavor-tagged, time-dependent B decays at asymmetric B factory has become established technique
- BaBar observes CP violation in the B^0 system at 4σ level

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

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

Summary and Outlook (cont.)

- Best measurement of CPV in mixing:

$$|q/p| = 0.998 \pm 0.006 \pm 0.007$$

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

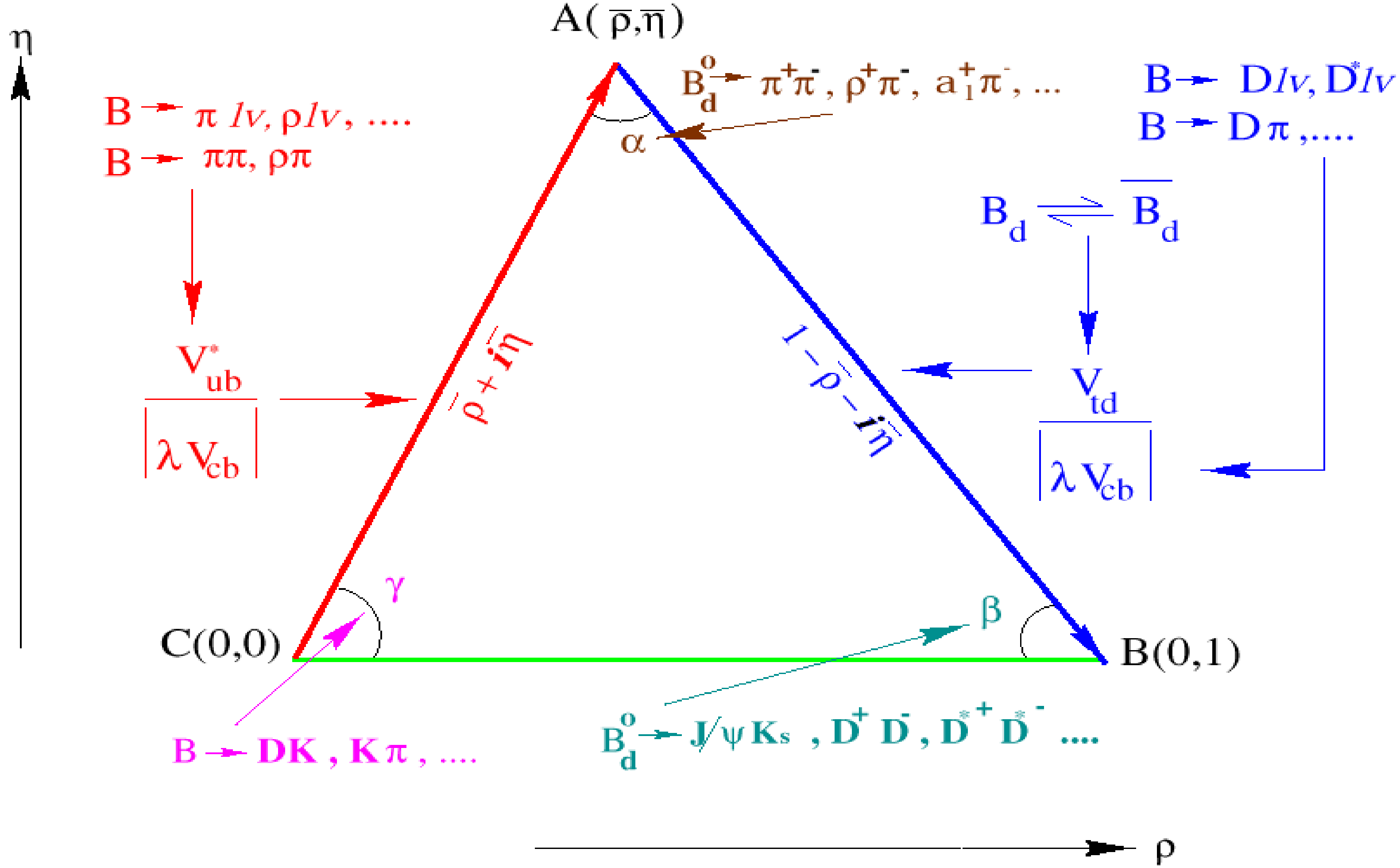
$$S(\pi^+\pi^-) = 0.03^{+0.53}_{-0.56}\,(stat) \pm 0.11\,(syst)$$

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

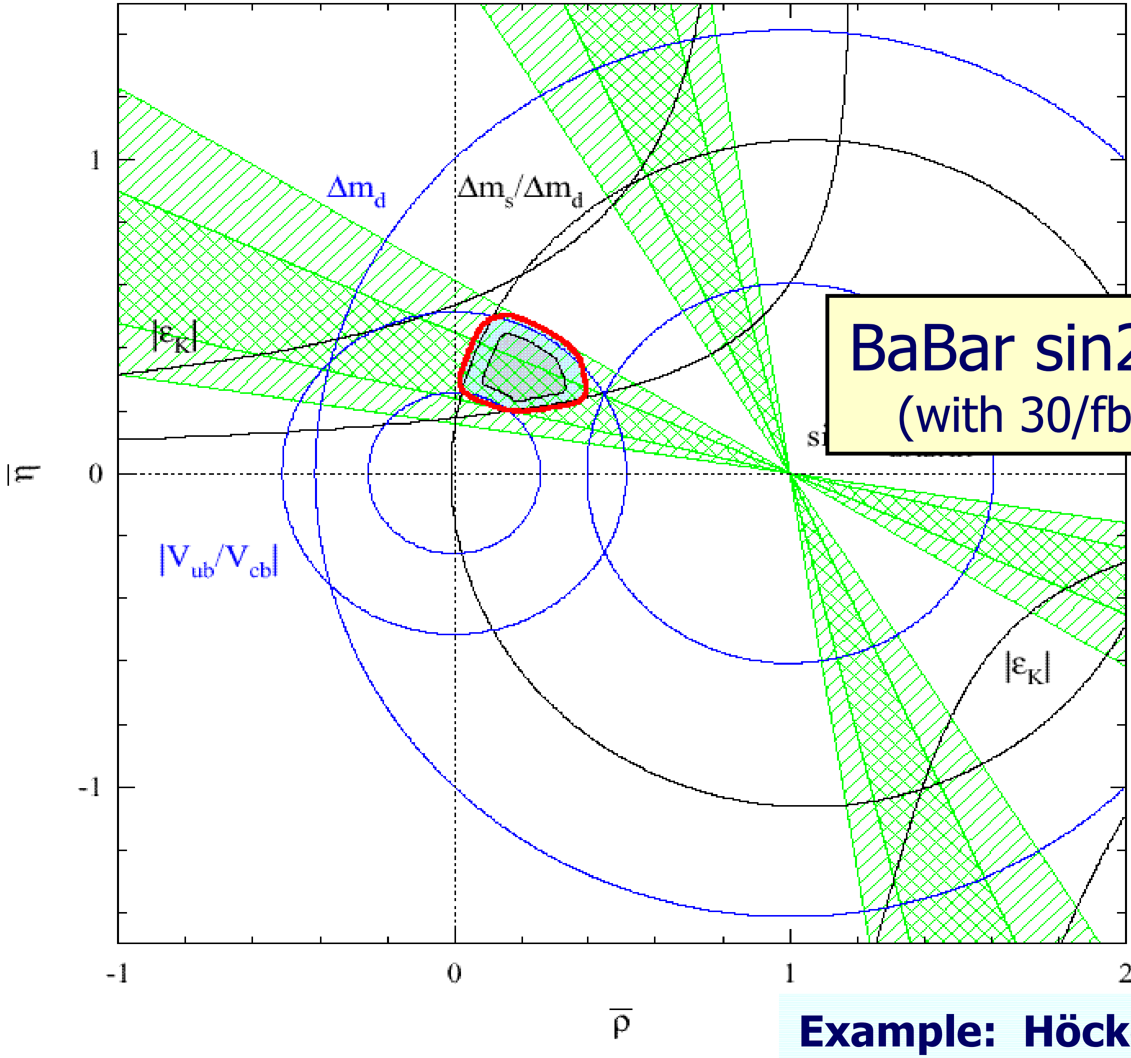
- The study of CP violation in the B system has started:
  - sin(2β) will very soon become precision measurement (→ unitarity triangle constraints will be limited by other CKM parameters)
  - Need to compare sin(2β) from different decay modes to test standard model
- With anticipated 100 fb^{-1} by next summer, error in sin(2β) will be 0.08 and for the asymmetry in $B \rightarrow \pi^+\pi^-$ error will be ~0.3

BaBar Aim : Multiple Measurements and Tests to Overconstrain the Unitarity Triangle

Sin2β is just one focus of BaBar: Work in progress on Many Fronts
An Exciting era of B physics in Progress !



The Unitarity Triangle and This Measurement



BaBar sin2β
(with 30/fb)

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

Error on sin2β is dominated by statistics
→ will decrease as

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

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