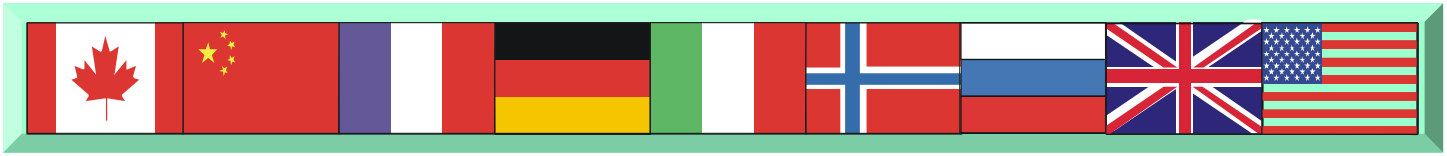
CP Violation in the B^0 Meson System with BaBar

James Weatherall

for the BaBar Collaboration

The Legacy of LEP and SLC

Siena, October 9th 2001



The BaBar Collaboration

9 Countries
72 Institutions
554 Physicists

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U de Montréal
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LPNHE des Universités Paris 6/7
Ecole Polytechnique
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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

Talk Overview

- CP violation with BABAR
  - Machine,detector,physics principles
- Measurement of sin2β (includes mixing)
- Results on asymmetries in $B^0 \to \pi^+\pi^-$ decays
  - Towards sin2α
- Summary

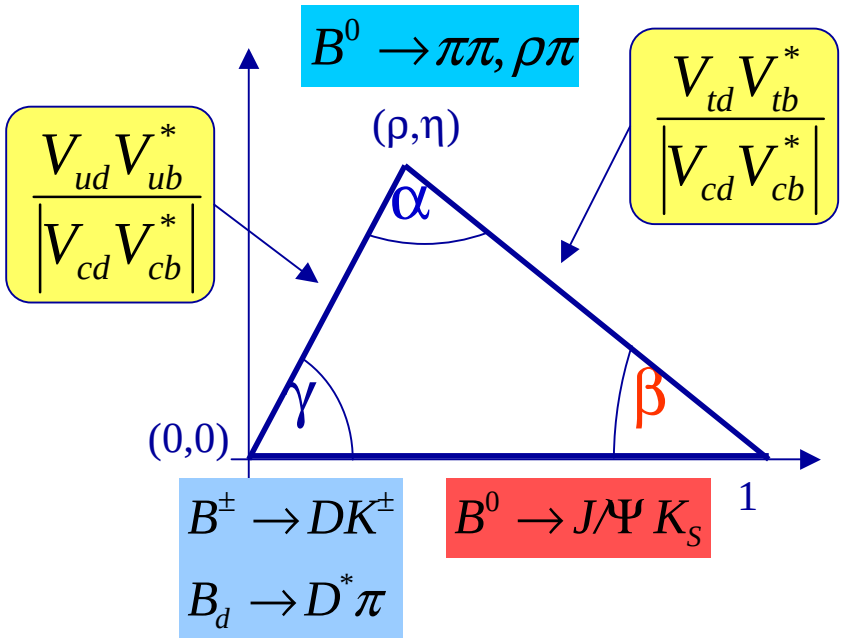
CP Violation in the Standard Model

The Unitarity Triangle

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

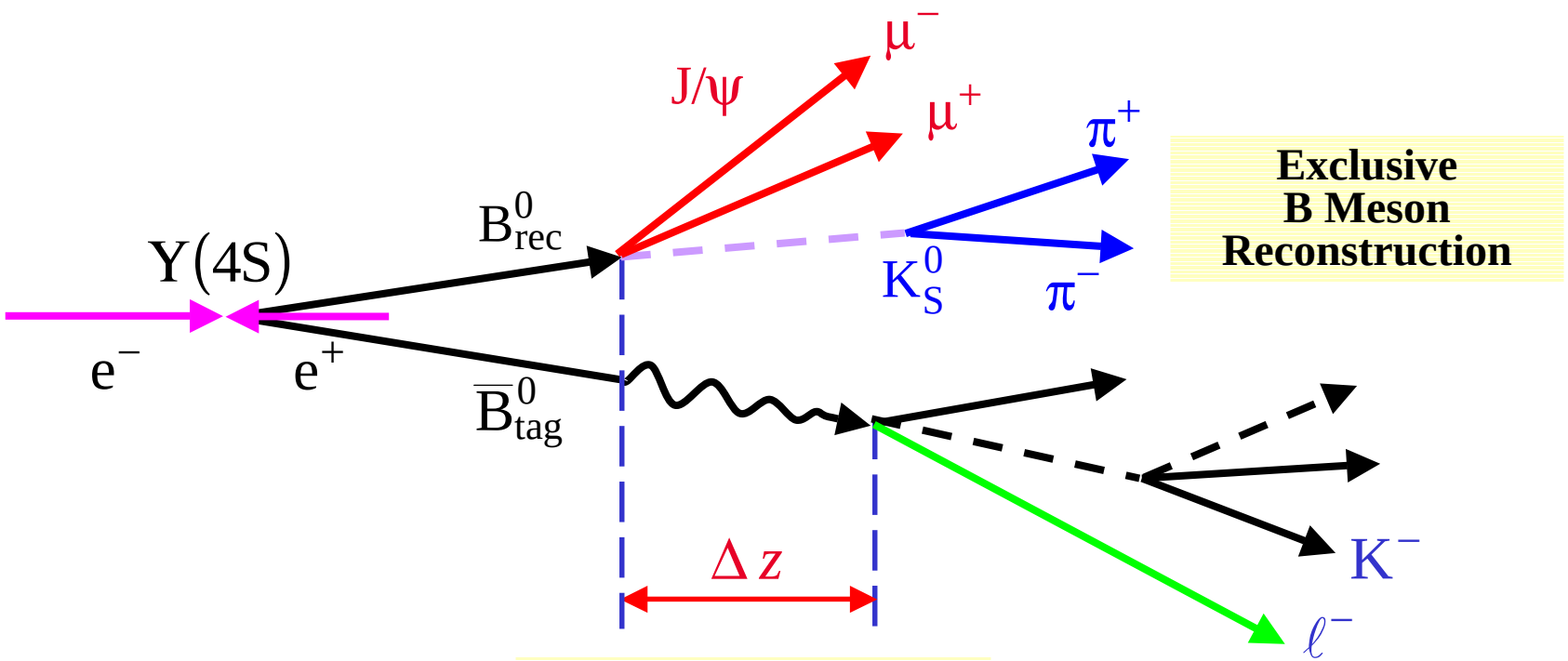
β measured through time dependent decay rate asymmetries in b -> ccs decays such as B^0 -> J/ψ Ks

$$a_f(t) = (\pm 1)\sin(2\beta)\sin(\Delta m t)$$



CP Asymmetry in B^0 -> J/ψ Ks

Interference between decays (to CP eigenstate) with and without mixing produces asymmetry in Δt

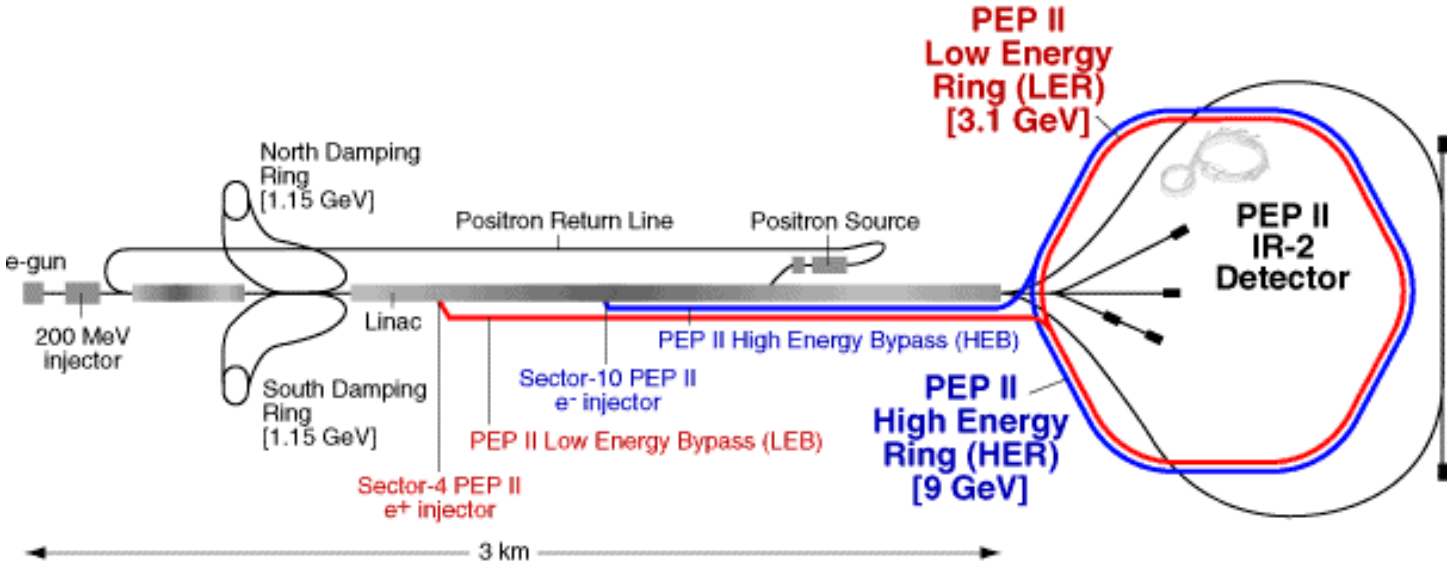


Exclusive B Meson Reconstruction

$\Delta t \approx \Delta z / \langle\beta\gamma\rangle c$

B-Flavor Tagging

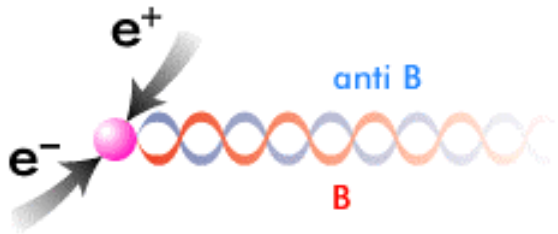
PEP-II



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

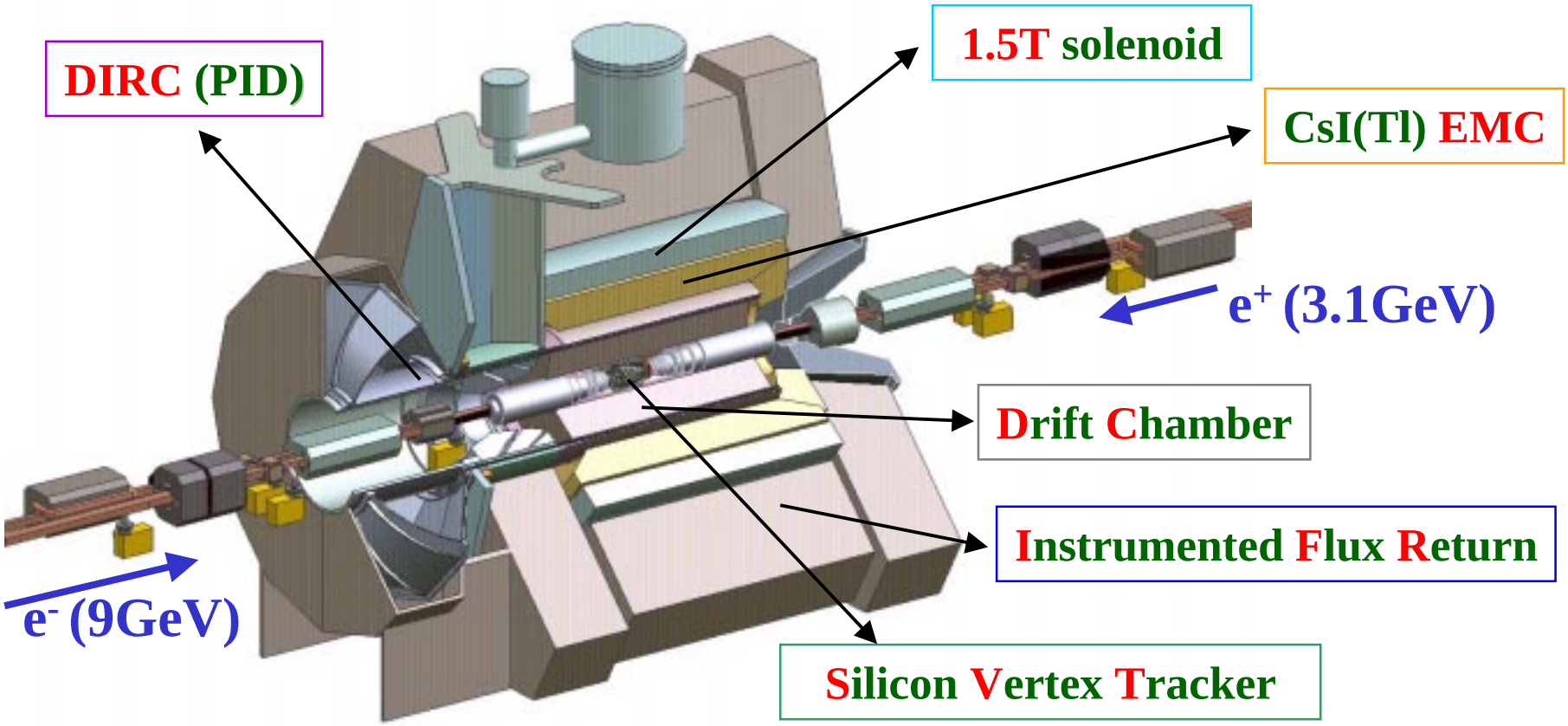
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B^0}$$

- coherent neutral B pair production and decay (p-wave)



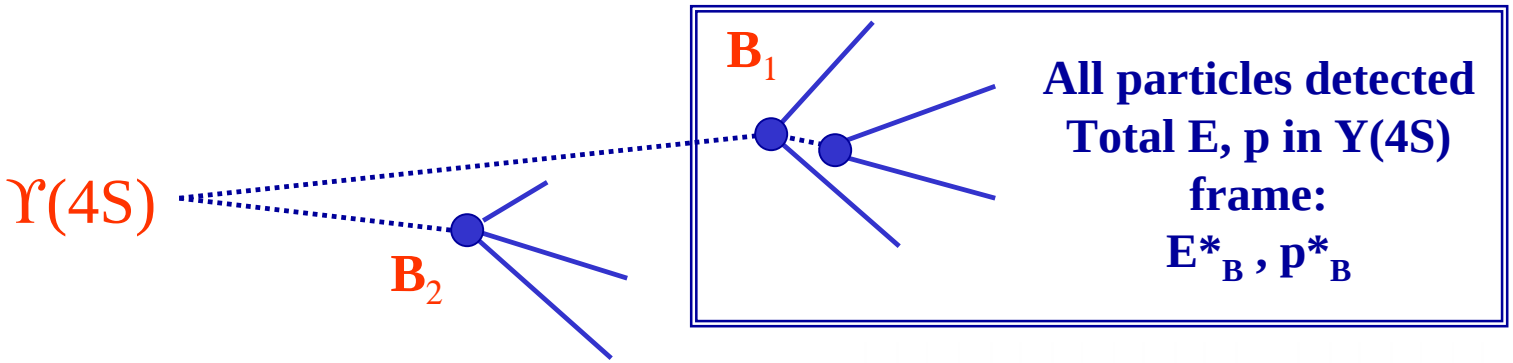
- boost of Υ(4S) in lab frame : $\beta\gamma$=0.56

The BaBar Detector



- SVT: 97% efficiency, 15μm z resol. (inner layers, perpendicular tracks)
- Tracking : $\sigma(p_T)/p_T = 0.13\% P_T + 0.45\%$
- DIRC : K-π separation >3.4σ for P<3.5GeV/c
- EMC: $\sigma_E/E = 2.3\% E^{-1/4} \oplus 1.9\%$

Exclusive B Reconstruction

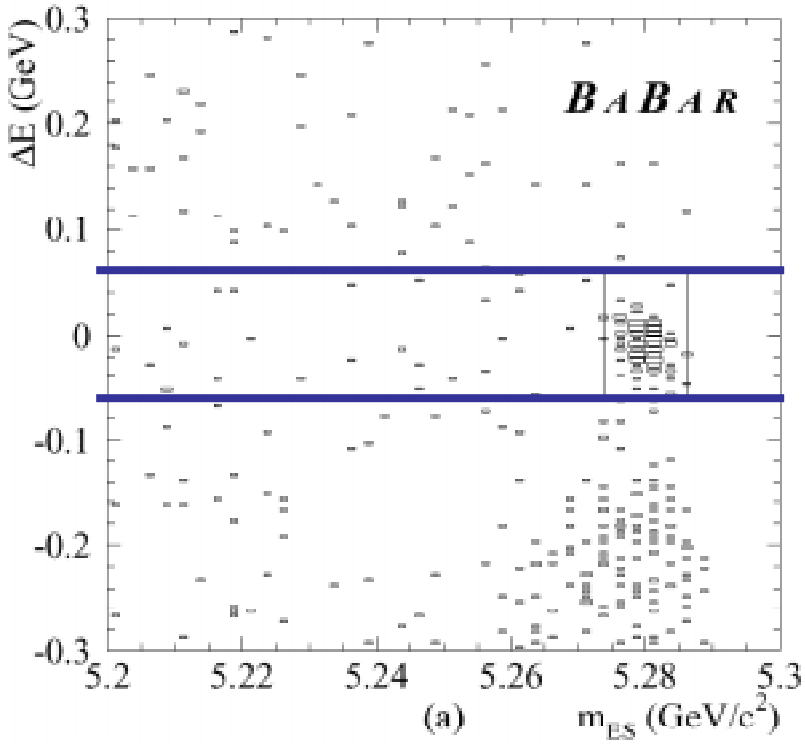


$$\Delta E = E^*_B - \sqrt{s} / 2$$

$$m_{ES} = \sqrt{(s/4 - p^{*2}_B)}$$

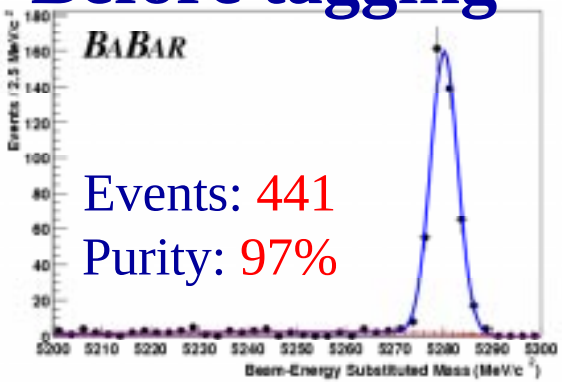
ΔE : σ~15 MeV

m_{ES} : σ~3MeV



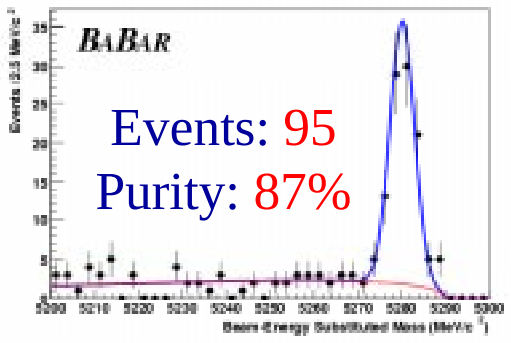
B^0->CP Sample

Before tagging

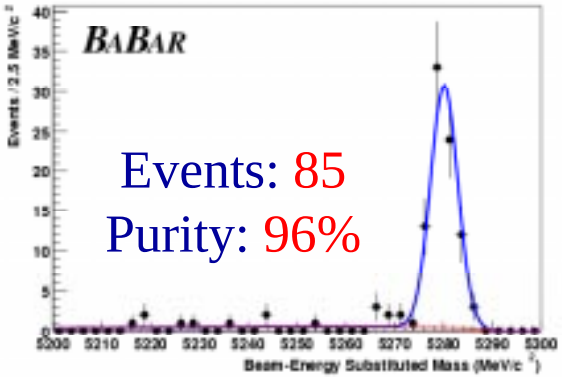


$J/\psi\ K_S$

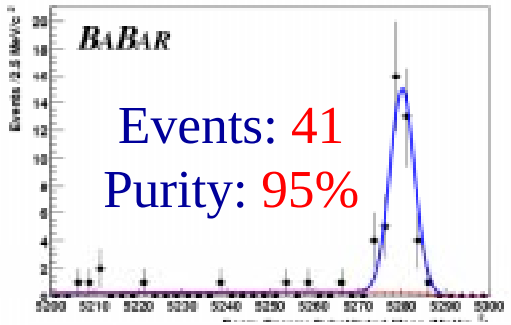
$K_S \to \pi^+\pi^-$ $K_S \to \pi^0\pi^0$



$\psi(2S)\ K_S$

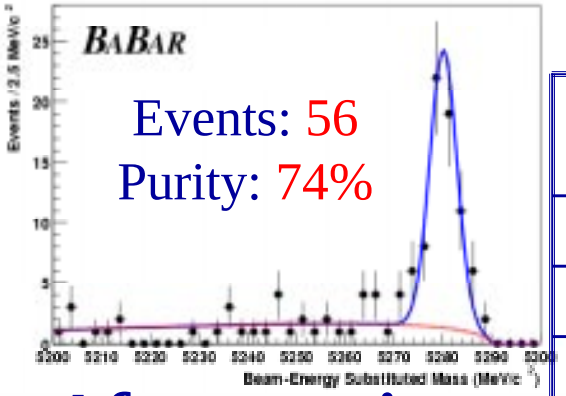


$\chi_{c1}\ K_S$



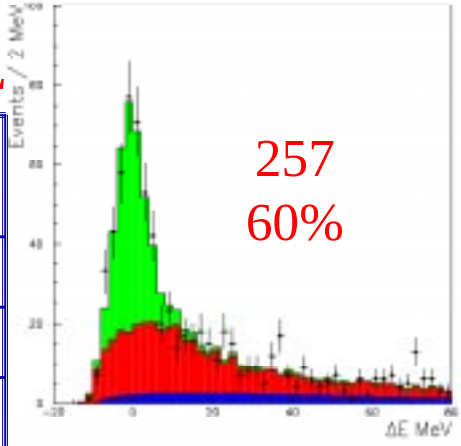
1999-2001 data :
32×10^6 BB pairs
$29\,fb^{-1}$ on peak

$J/\psi\ K^*$



After tagging

$J/\psi\ K_L$

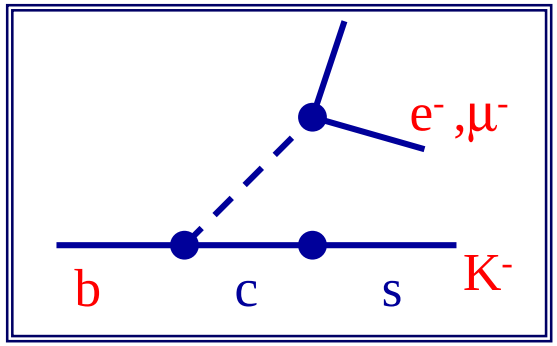


Sample	tagged events	Purity	CP
[charmonium] K_S	480	96%	-1
Jpsi K_L	273	51%	+1
Jpsi $K^{*0}(K_S\pi^0)$	50	74%	mixed
Full CP sample	803	80%	

B-Flavour Tagging

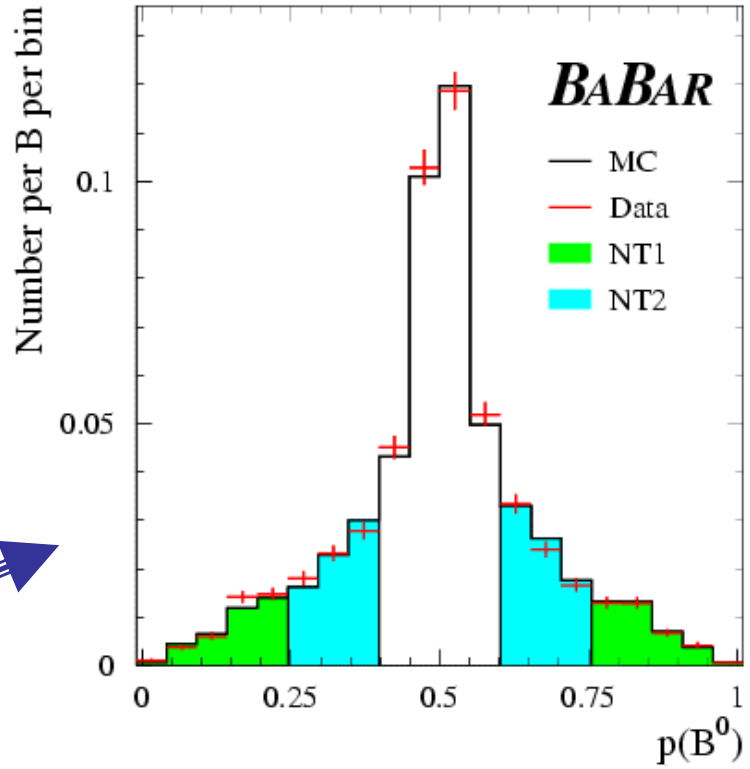
Ranked Categories:

- **Lepton – charge of fastest electron or muon**
- **Kaon – Net charge of identified kaons ≠ 0**
- **NT1/NT2 – Neural Net (slow pions, "Jet Charge"). Different cuts on NN output**



Lepton , Kaon tagging

NN tagging



Flavour Tagging Performance

Sample of B decays to self-tagging modes, B_{FLAV}, used for measurement of tagging performance: $Q_i = \varepsilon_i D_i^2$, $D_i = 1\text{-}2w_i$

D_i = Dilution, w_i = wrong tag fraction

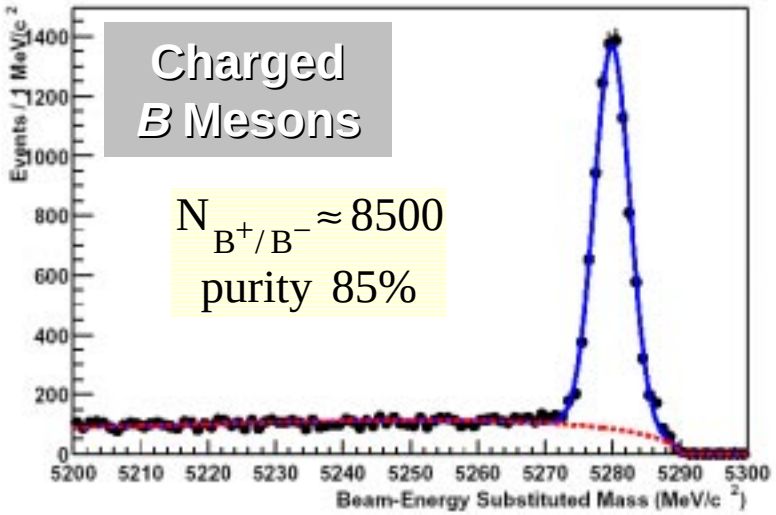
ε_i = fraction of events that were tagged

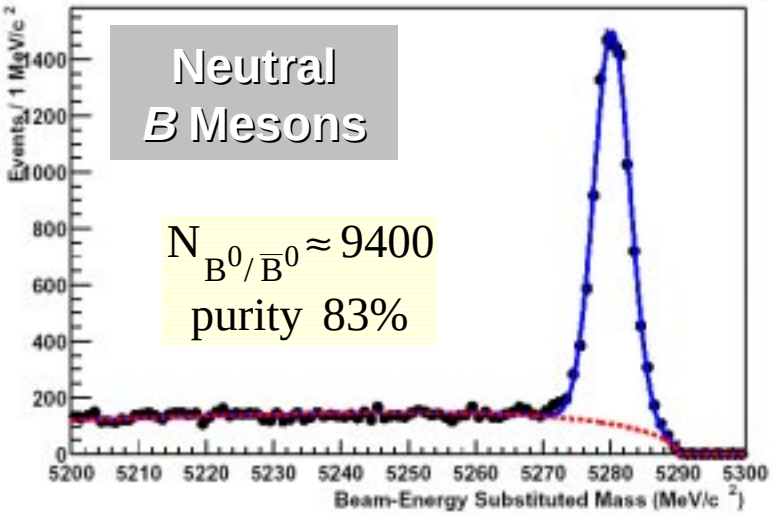
Tagging category	ε (%)	w(%)	Q (%)
Lepton	10.9 ± 0.3	8.9 ± 1.3	7.4 ± 0.5
Kaon	35.8 ± 0.5	17.6 ± 1.0	15.0 ± 0.9
NT1	7.8 ± 0.3	22.0 ± 2.1	2.5 ± 0.4
NT2	13.8 ± 0.3	35.1 ± 1.9	1.2 ± 0.3
ALL	68.4 ± 0.7		*26.1 ± 1.2*

B_{FLAV} Sample of Fully-reco'd B Decays

States with definite flavour for measurement of lifetimes, mixing and Δz resolution and tagging performance for $\sin 2\beta$ measurement

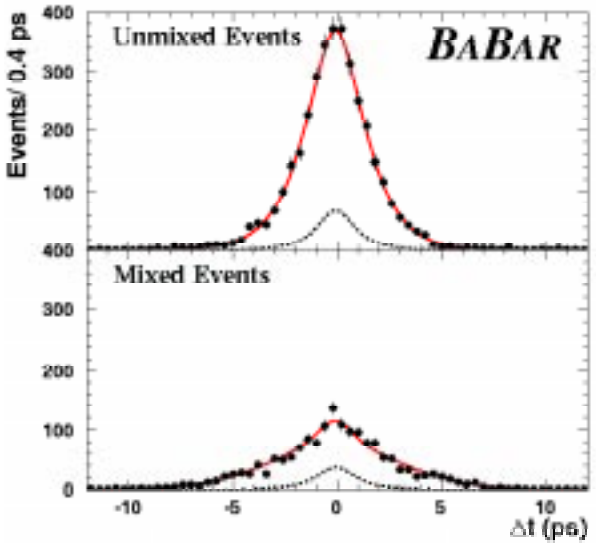
Cabibbo favoured "open charm" decay: e.g. $B^0 \rightarrow D^{(*)-}\pi^+/\rho^+/a_1^+$
Charmonium decays: e.g. $B^+ \rightarrow J/\psi\, K^+$

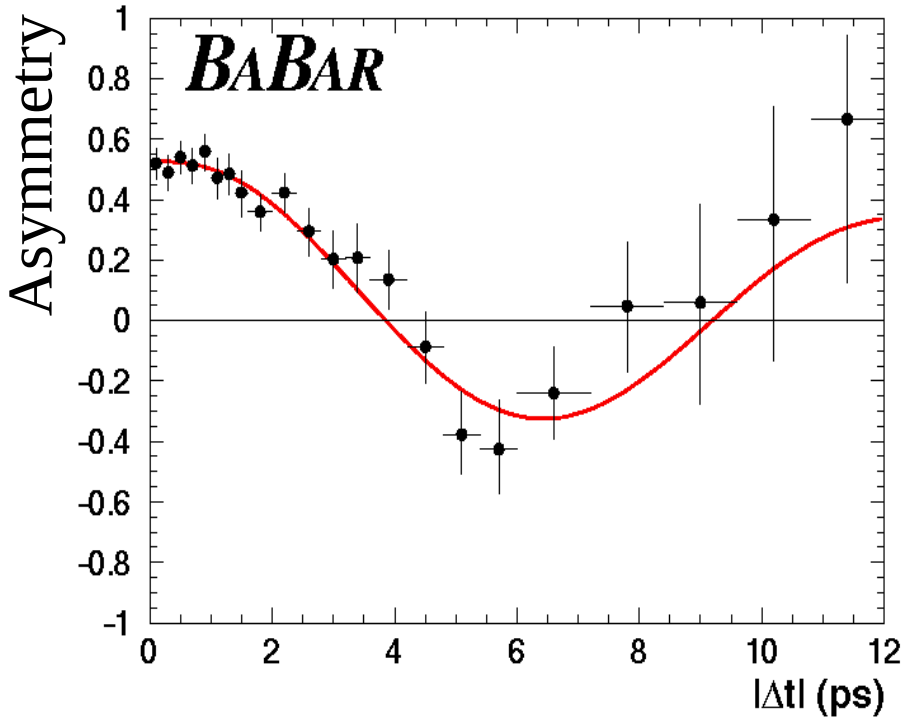




Mixing Measurement with B_{FLAV} Sample

20.7 fb^{-1} on-resonance



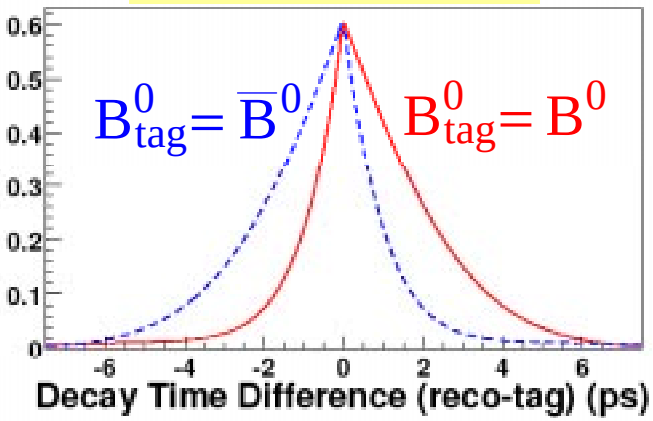


$$A_{mixing}(\Delta t) \approx (1-2w)\cos(\Delta m_d \Delta t)$$

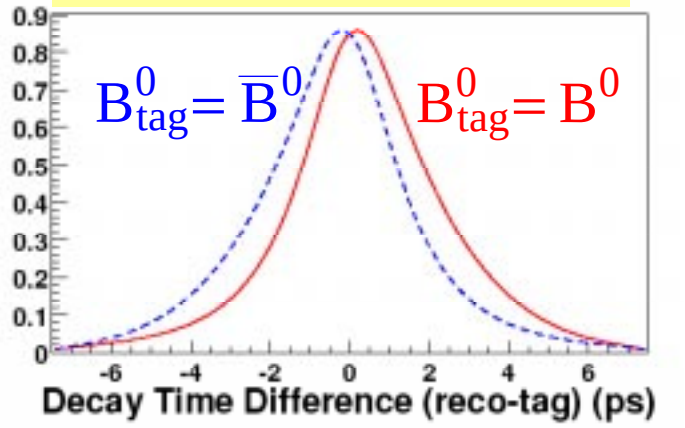
$$\Delta m_d = 0.519 \pm 0.020(stat) \pm 0.016\ (syst)\ \hbar\ ps^{-1}$$

CP Violation Time Distributions

perfect
flavor tagging &
time resolution



realistic
mis-tagging probability &
finite time resolution



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

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

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

Mixing & CP Time evolution

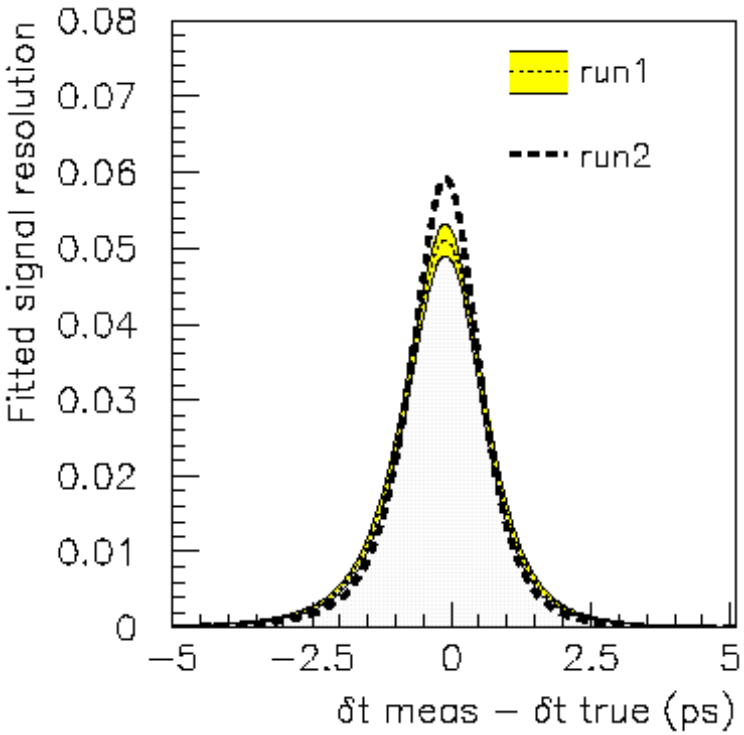
same mis-tagging probability ω

and time-resolution function $R(\Delta t)$

Likelihood Fit for sin2β

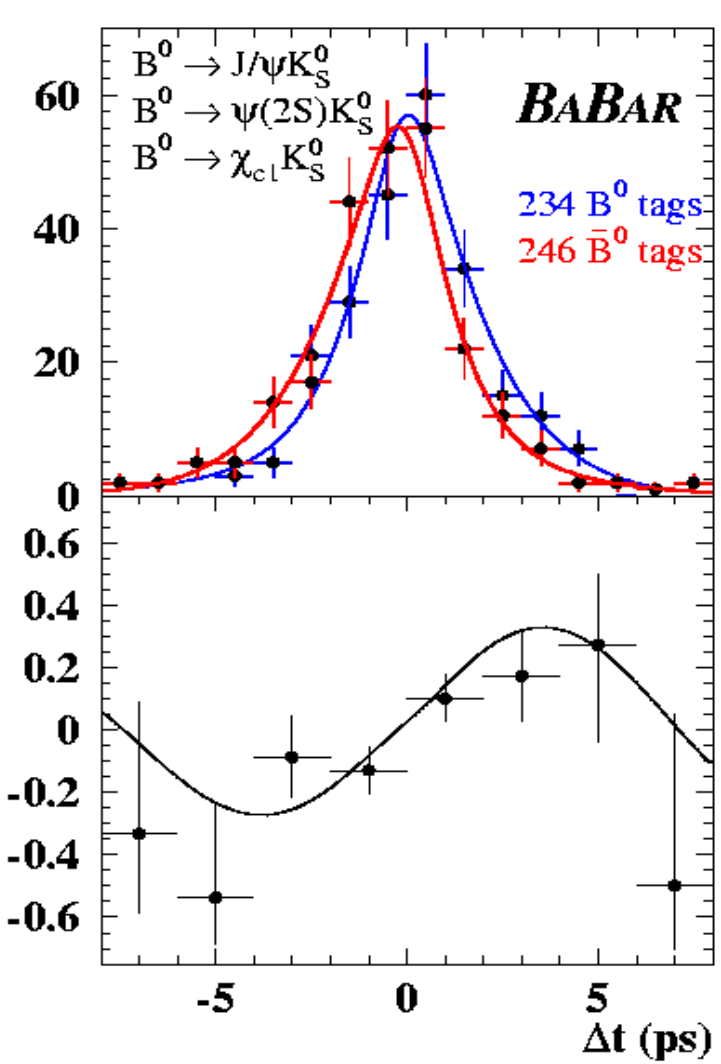
- Fit data with global, unbinned maximum likelihood including:
  - Mistag fractions, Δt resolutions (B_{FLAV} sample)
  - sin2β (tagged sample of CP eigenstate events)
- Total of 44 parameters embody mistag rates, resolution function and backgrounds

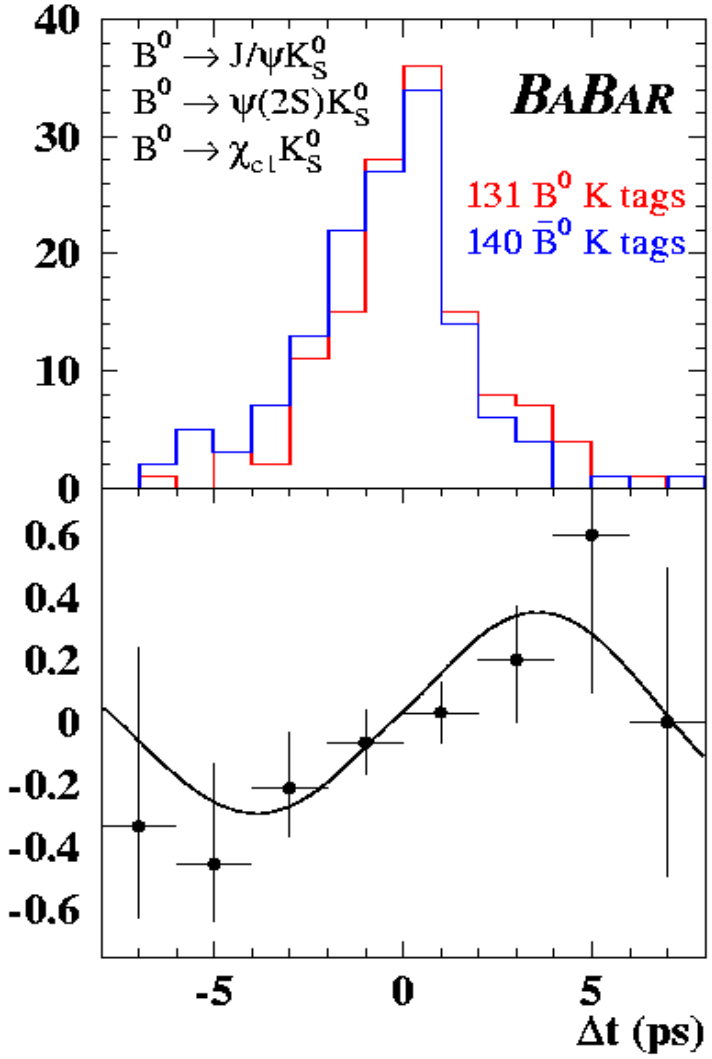
effect	Free params
sin(2β)	1
Mistags (avg, delta B^0 - antiB^0)	8
Signal Δt resolution (run1, run2)	16
Background time dependence	9
Background Δt resolution	3
Background mistags	8
TOTAL	*45*



The sin2β Result

$$\sin(2\beta) = 0.59 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$$





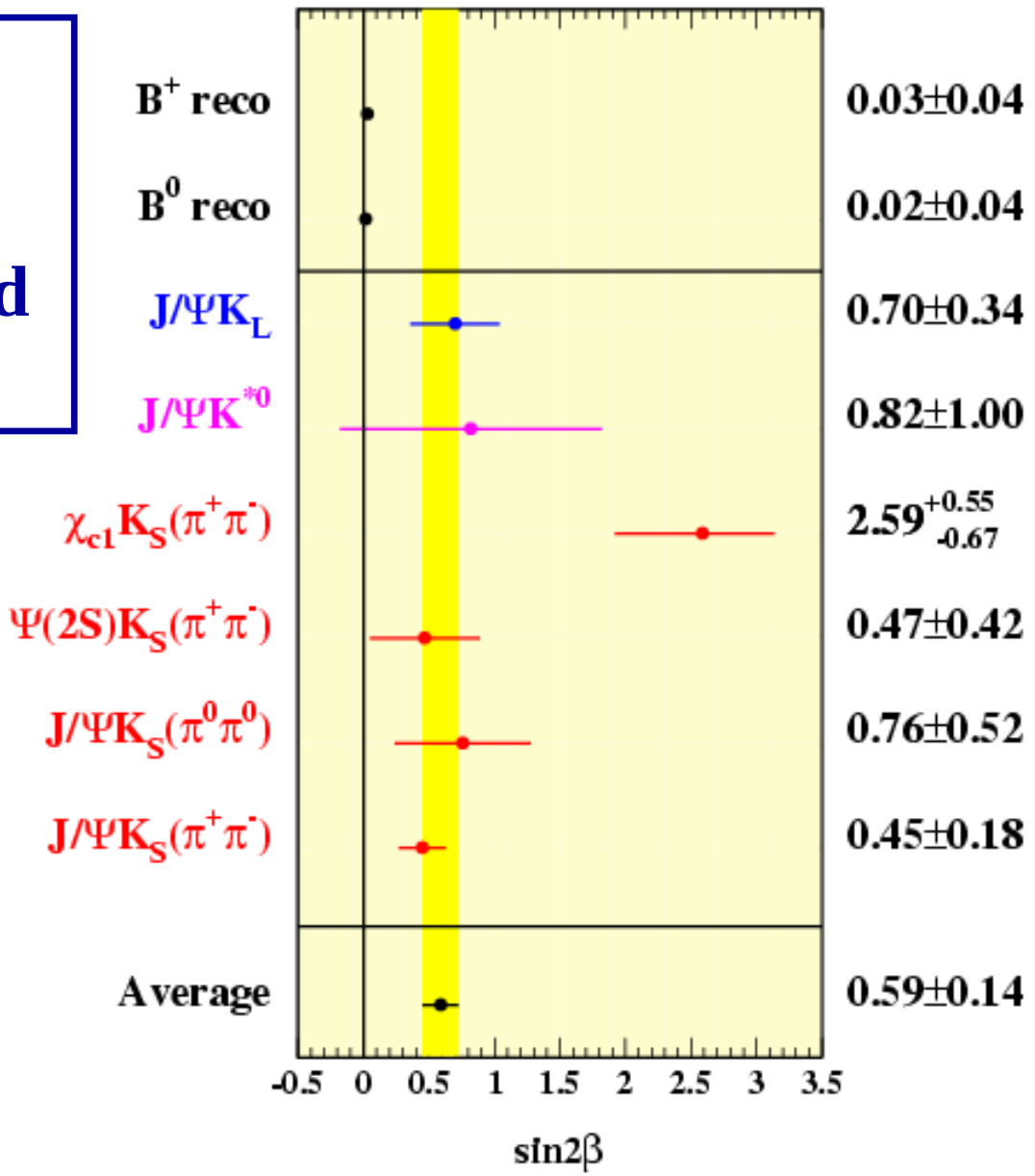
Mode by Mode Breakdown

P(0.59) if CP conserved: $< 3\times10^{-5}$

P(0.59) if CP conserved ($\eta_{CP}= -1$): $< 2\times10^{-4}$

Prob($L<L_{MEAS}$) = 27%

Result submitted to PRL, July 5 (hep-ex/0107019)

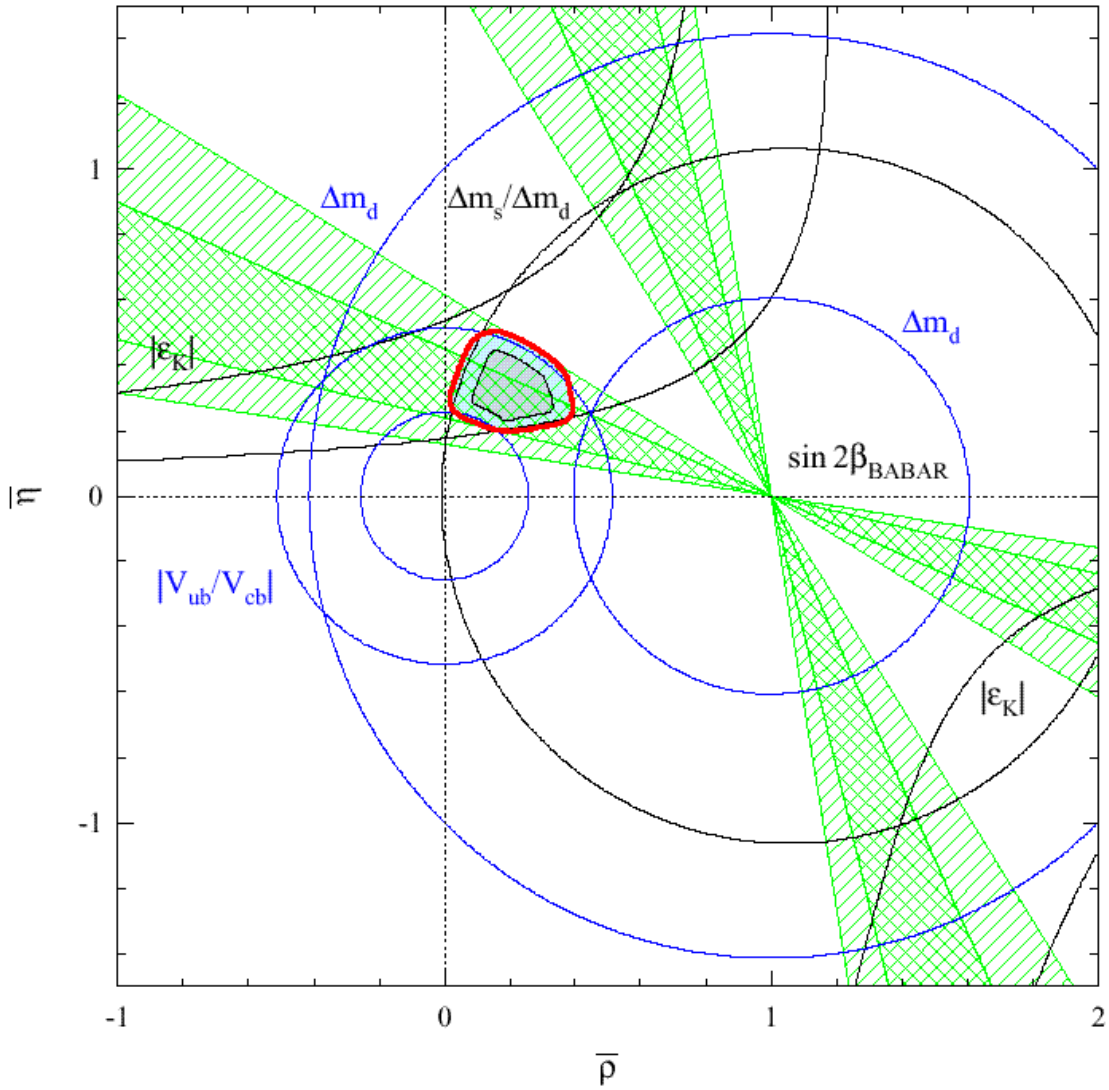


Systematic Errors

- Resolution function for $\Delta t = 0.03$
  - Residual uncertainties in SVT alignment
- Mistag fraction differences B_{CP} versus B_{FLAV} samples = 0.03
- Background in selected CP events = 0.02
  - Level, composition and CP asymmetry

	K_S	K_L	K^{*0}	Full
Total Sys	0.049	0.104	0.162	0.049
Total Stat	0.151	0.340	1.01	0.137

The Global CKM Picture



Consistent with the SM but more data needed to be sure

Following Höcker et al, hep-ex/0104062 (many other recent global CKM matrix analyses)

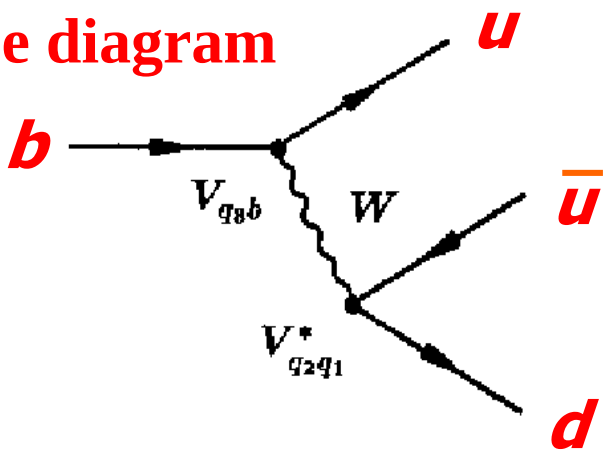
sin2α from $B^0 \to \pi^+\pi^-$ Decays

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

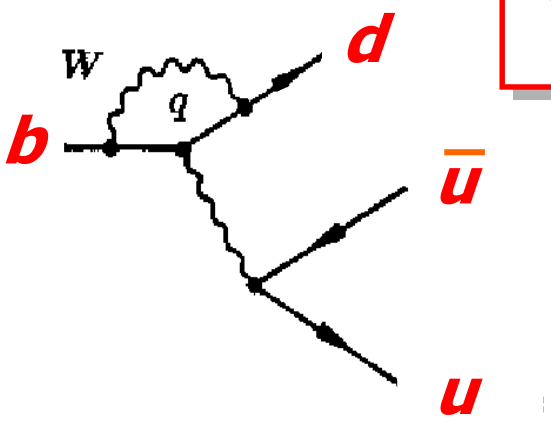
$$f_{\pm}(\Delta t) = \frac{e^{(-\Delta t/\tau)}}{4\tau}[1 \pm S_f \sin(\Delta m_d \Delta t) \mp C_f \cos(\Delta m_d \Delta t)]$$

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

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

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

Results from $B^0 \to \pi^+\pi^-$ (with 30fb^{-1})

- Simultaneous ML fit to BRs and CP coeffs:
  - 8 event types (sig+bg: $\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, K^+K^-)
  - Discriminating variables (m_{ES}, ΔE, F,θ_c^1,θ_c^1,Δt)
  - Mistags and resolution function from sin2β analysis
  - Resolution function for background from sidebands

Preliminary Results

(65 ππ and 217 Kπ events)

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

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

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

Summary

- We have observed CP violation in the B^0 system at the 4σ level
  - $\sin(2\beta)=0.59\pm0.14\pm0.05$
- First measurement with $B^0 \rightarrow \pi^+\pi^-$ also presented measurement possible but more data needed
- This is only the start of a long road…
  - More data for greater precision and comparison of channels
  - Start to really test the Standard Model
- Anticipate data set of 100 fb^{-1} by next summer
  - $\sin2\beta$ known to better than 0.1
  - $B^0 \rightarrow \pi^+\pi^-$ asymmetry measured to ≈ 0.3

Backup slides…

The current sin2β analysis

29fb^{-1} on resonance => 32×10^6 $B\bar{B}$ pairs (1999-2001)

Improvements since last winter

- Enhanced tracking, Ks reconstruction
  - 30% more CP events per unit luminosity
- Improved vertex reconstruction and knowledge of tracking system alignment
  - Sensitivity increased by 10%
- J/ψ K_L selection optimized for added sensitivity to sin2β
- Added new modes (J/ψ $K^*(Ks\pi^0)$, χ_{c1} Ks)

The Δt Resolution Function

Resolution dominated by B_{tag} vertex reconstruction

Biases scale with per-event error

$$\mathcal{R}(\delta_t;\hat{a}) = \sum_{k=1}^{2} \frac{f_{\mathrm{core,tail}}}{\sigma_{\mathrm{core,tail}}\sqrt{2\pi}} \exp\left(-\frac{(\delta_t-\delta_{\mathrm{core,tail}})^2}{2\sigma_{\mathrm{core,tail}}}\right) + \frac{f_{\mathrm{outlier}}}{\sigma_{\mathrm{outlier}}\sqrt{2\pi}} \exp\left(-\frac{\delta_t^2}{2\sigma_{\mathrm{outlier}}{}^2}\right).$$

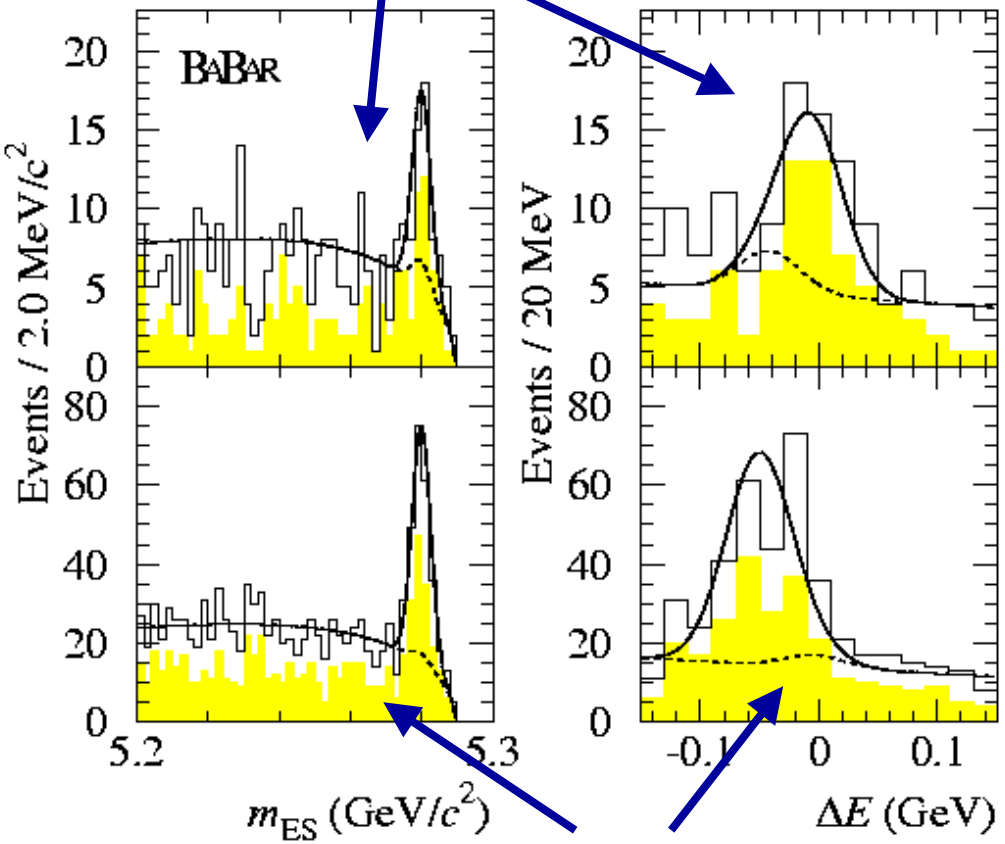
Fixed to 8ps with no offset, accounts for <1% of events

Scaled by per-event error

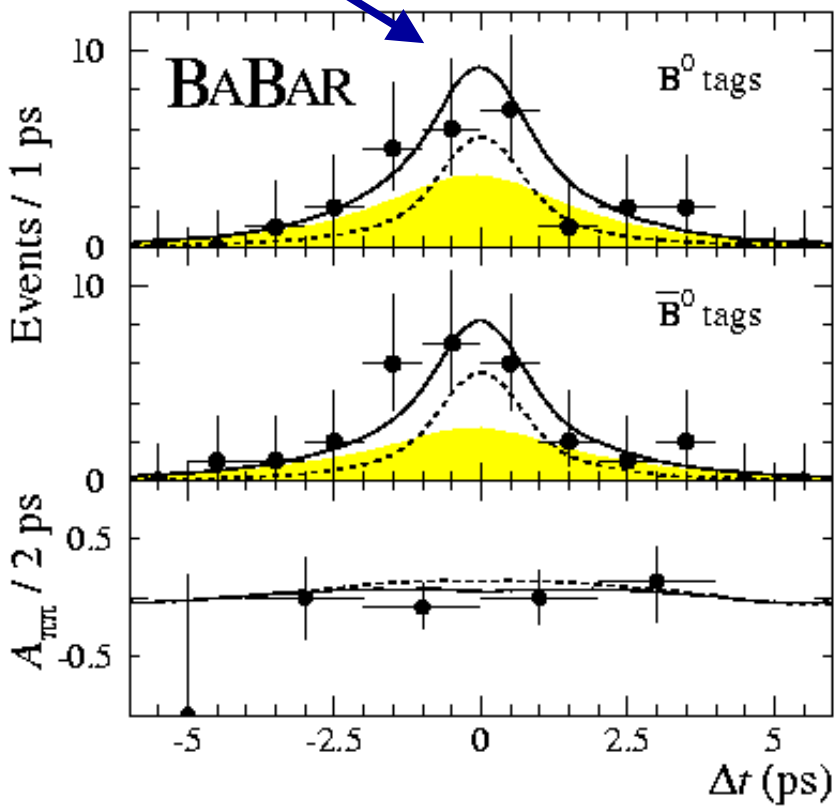
B → ππ/Kπ Data Sample and Results

$\pi^+\pi^-$

Δt for $\pi^+\pi^-$ enriched sample



$K^+\pi^-$

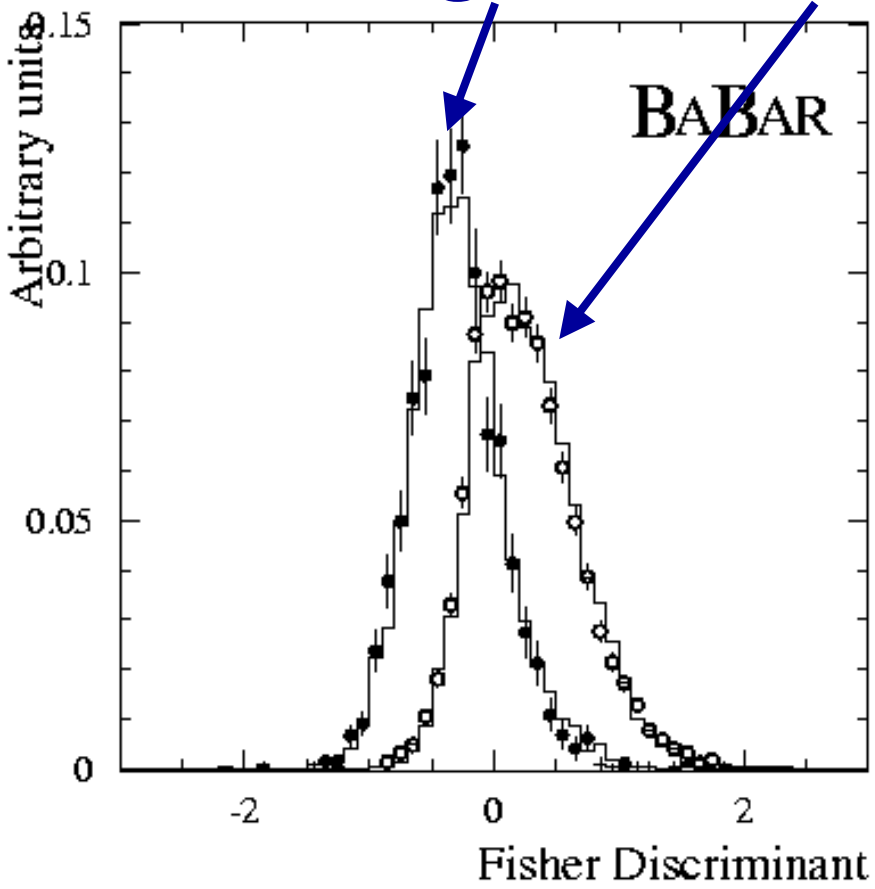


Discriminating Variables for ππ/Kπ Fits

$$\mathcal{F} = \sum_{i=1}^{9} \alpha_i x_i$$

Where the α_i are tuned for signal/BG separation

Fisher for signal and BG



Θ_c for π/K samples