THE UNIVERSITY of LIVERPOOL

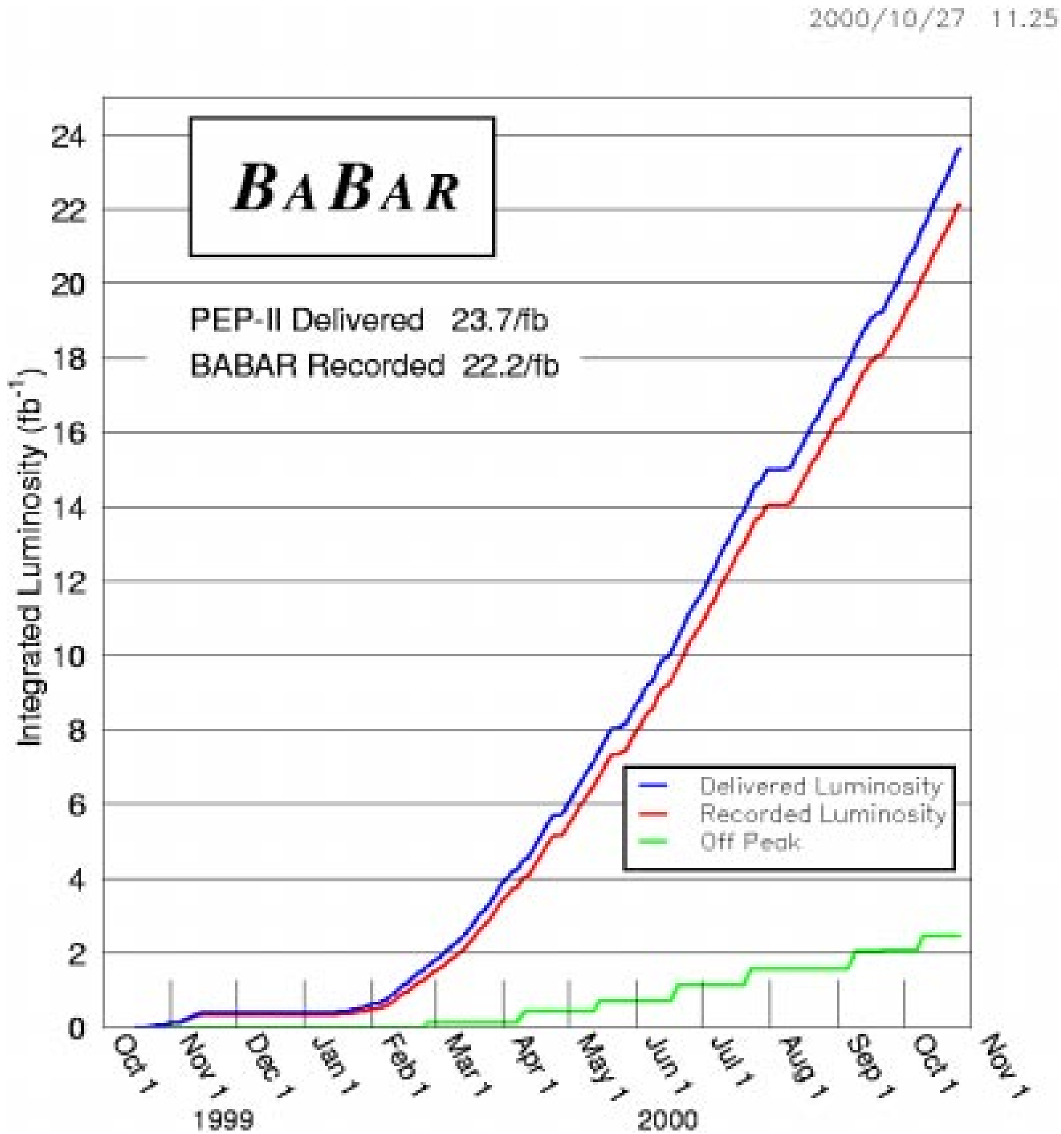
sin 2β at BaBar

BABAR

Introduction

- PEP−II/BaBar performance
- Basics of measuring *CP* violation at an asymmetric *B* Factory
- Details of the data sample and analysis
- Extracting *sin 2*β
- Cross−checks and error analysis
- The future
- Conclusions

Year 2000/01 Operations



Operations …

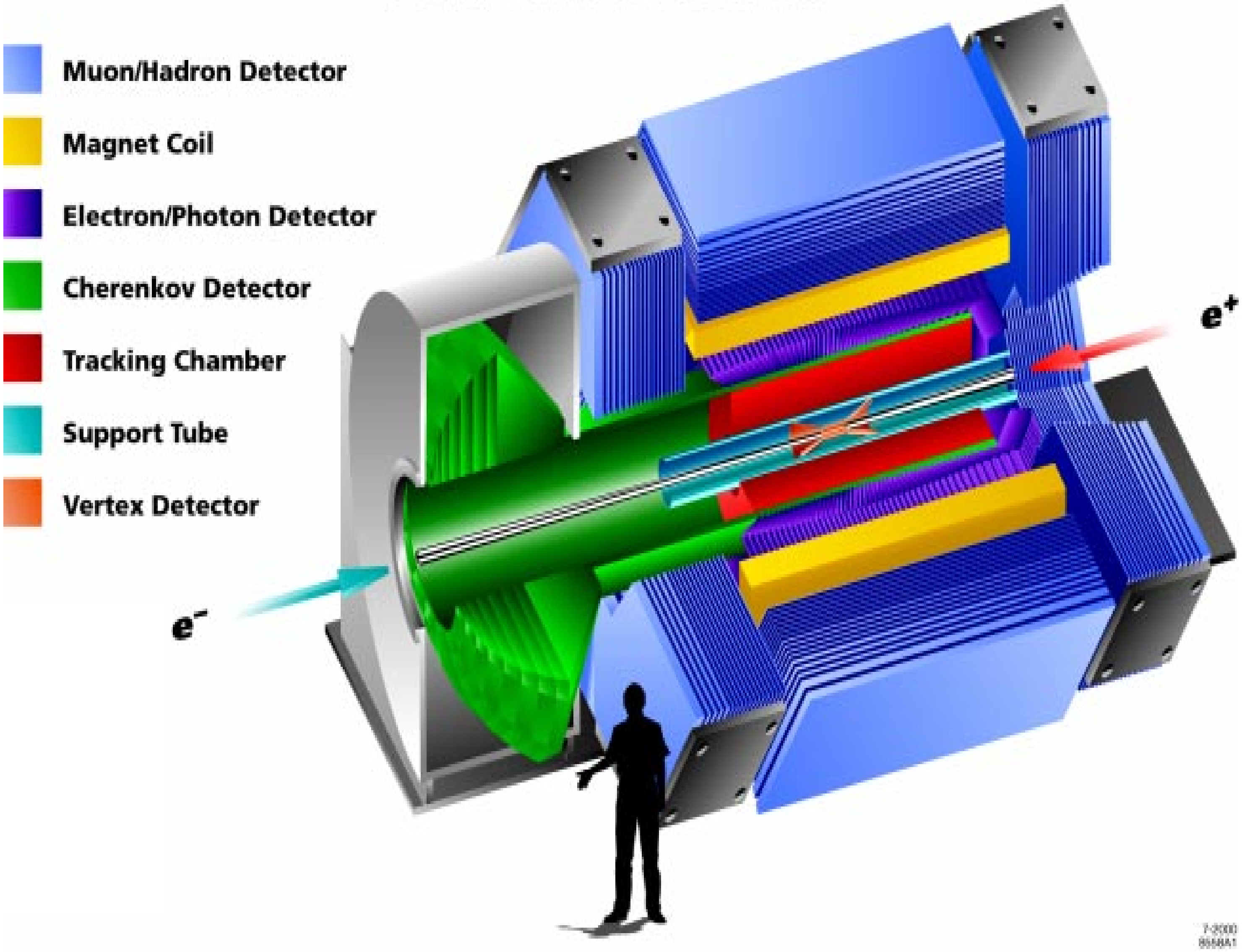
- By end of 2000 run, peak & <u>*average*</u> luminosity were above design and climbing:

DESIGN:	ACHIEVED:
3.0 nb^{-1}/s	**3.28**
135 pb^{-1}/d	**184**
~**0.80** fb^{-1}/w	**1.03**
~**3.3** fb^{-1}/m	**3.8**

Preliminary
(~2% uncertainty)

- BaBar performed fine at **3.2×10^{33} cm^{-2}s^{-1}**
- This year expect to reach **5×10^{33} cm^{-2}s^{-1}**

BABAR Detector



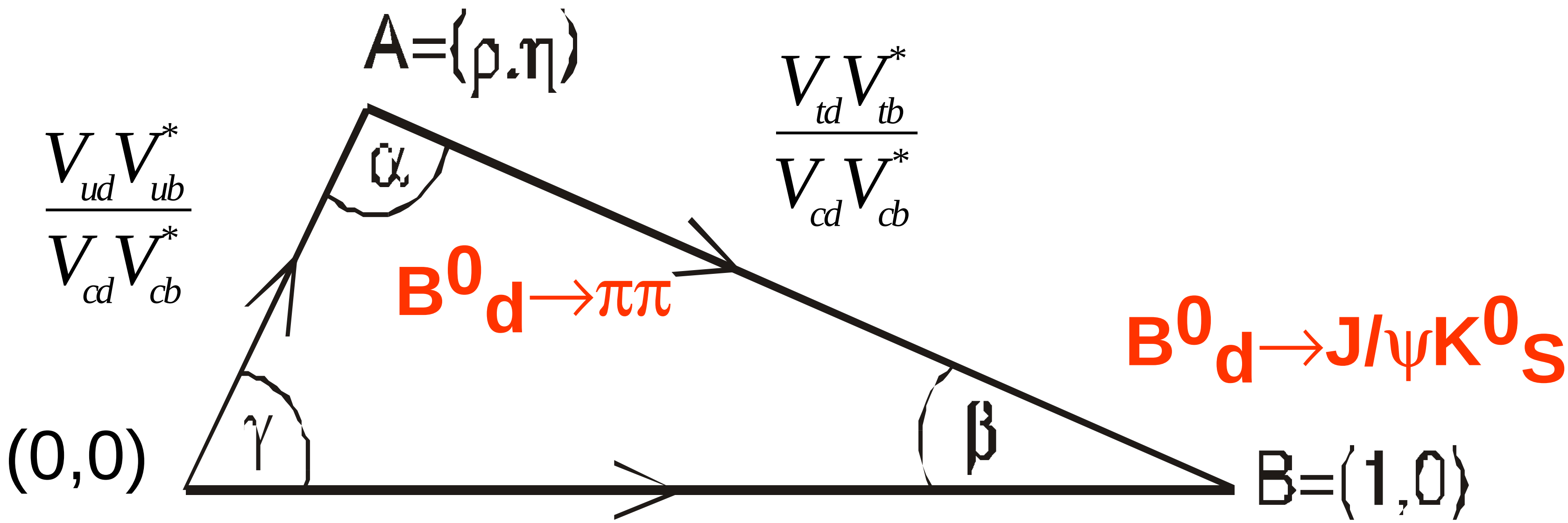
CP Violation

- First observed in K^0_l decay in 1964
- Difficult to relate observed asymetries to parameters of Standard (or other) model
- B sector promises "large" CP violation that can be used as test of models
- In SM, interactions of quarks described by CKM matrix

$$
\begin{array}{c} \\ u \\ c \\ t \end{array}
\begin{array}{ccc} d & s & b \\ \end{array}
$$

	d	s	b
u	V_{ud}	V_{us}	V_{ub}
c	V_{cd}	V_{cs}	V_{cb}
t	V_{td}	V_{ts}	V_{tb}

The Unitary Triangle



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

***CP*–violating Asymmetries in *B* decays directly measure phases α, β, and γ**

~~CP~~ in interference between mixing and decay

- CP violation could manifest in decay, mixing or interference between decays with and without mixing
  - e.g. Neutral B decays into final CP eigenstates
    - $B^0 \rightarrow f_{cp}$
    - $B^0 \rightarrow \overline{B}^0 \rightarrow f_{cp}$
- We use "golden" and "silver" CP eigenstates
  - $B^0 \rightarrow J/psi\ K^0s$, $B^0 \rightarrow Psi(2S)\ K^0s$,
  - $B^0 \rightarrow J/psi\ K^0l$

CP physics at the $\Upsilon(4S)$

- PEP II operates at the $\Upsilon(4S)$. $\Upsilon(4S)$ decays into P–wave $B^0 \bar{B}^0$ state that evolves coherently till one of the B's decays
- Remaining B^0 continues to oscilate until it too decays.

Decay–time Distributions

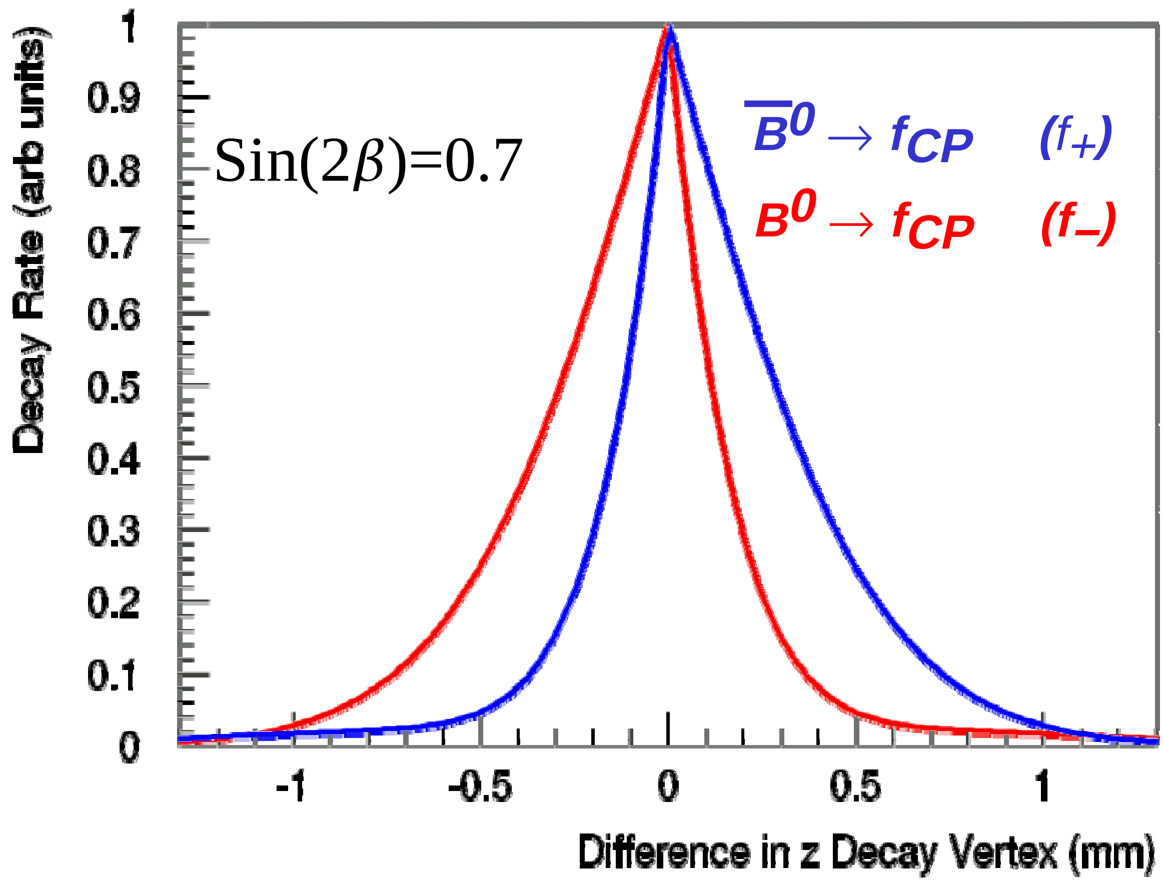
$$f_{CP,\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\,\tau_{B^0}} \times \left[1 \pm \mathcal{I}m\,\lambda \sin \Delta m_{B^0} \Delta t\right]$$

When a given B^0 ($\overline{B}^0$) is known to have decayed at time t_{TAG}, the time distribution of the *other* meson into a *CP* eigenstate at time

$\Delta t = t_{CP} - t_{TAG}$

is given by

f_+ (f_-)



Time−dependent Asymmetries

- **t−dependent asymmetry:**

$$\int A_{CP}\, dt = 0$$

- $$A_{cp} = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)}$$

$$= -\eta_f \sin(2\beta)\ \sin(\Delta m_{B^0} \Delta t)$$

- **We reconstruct the "gold/silver" CP eigenstates**
  - $J/\psi K_S$, $\psi(2s)K_S$ $(\eta_f = -1)$
  - $J/\psi K_L$ $(\eta_f = +1)$

How to measure Sin2β

- Select B_{CP} candidates **(**$B^0 \rightarrow J/\psi\ K_S$ **,** *etc.)*
- Tag flavour of other B using (primarily) leptons and K's.
- Measure the mistag fractions w_i and determine

  the dilutions $(D_i = 1 - 2w_i)$
- Measure ΔZ between B_{CP} and B_{tag} to determine the signed time difference Δt between the decays
- **Determine the resolution function for Δt**

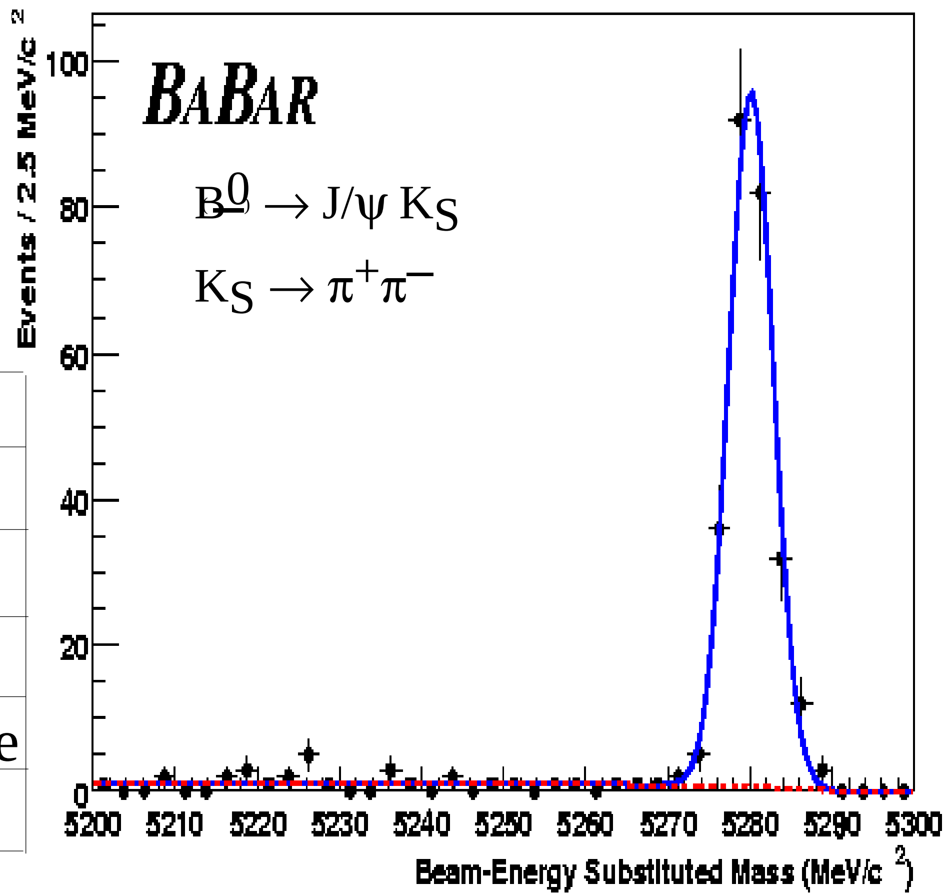
Event Selection

- Three different CP eigenstates used for measurement:
  - $B^0(B^0)$-> J/ψ Ks
    - (Ks->$\pi^+ \pi^-$ and Ks->$\pi^0 \pi^0$)
  - $B^0(B^0)$-> Psi'(2S) Ks
  - $B^0(B^0)$-> J/psi Kl

$B^0 \to J/\psi\ (K_S \to \pi^+\pi^-)$

BR($B^0 \to J/\psi\ (K_S \to \pi^+\pi^-$, $J/psi \to ll$)) $\sim 7 \times 10^{-5}$

Cut	ee	mumu
$Mass_{J/psi}$	2.95−3.14	3.06−3.14
$Mass_{Ks}$	0.489−0.507	
Cos $theta_{hel}$	<0.8	<0.9
PID	1 Tight	1mip+1loose
Ks^0_s flt.	>1mm	

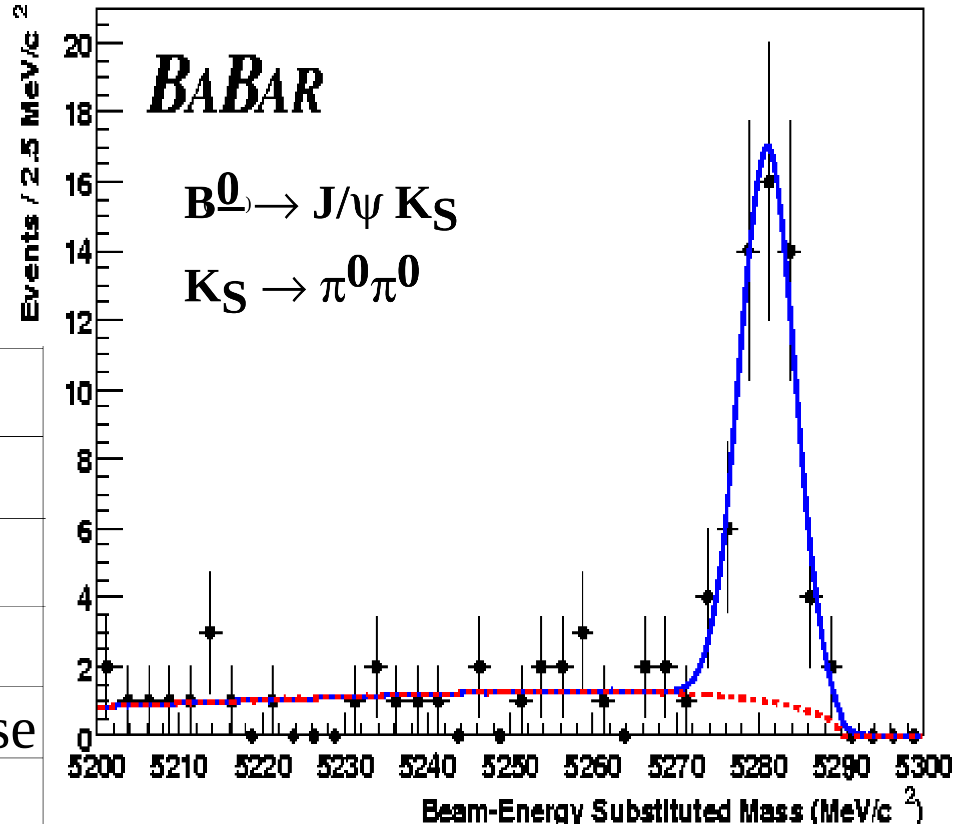


292 Events before tagging.

$B^0 \rightarrow J/\psi\ (K_S \rightarrow \pi^0\pi^0)$

BR($B^0 \rightarrow J/\psi\ \ (K_S \rightarrow \pi^0\pi^0$, $J/psi->ll$)) $\sim 3 \times 10^{-5}$

Cut	ee	mumu
$Mass_{J/psi}$	2.95−3.14	3.06−3.14
$Mass_{Ks}$	0.489−0.507	
$Cos\ theta_{hel}$	<0.8	<0.9
PID	1 Tight	1mip+1loose
Ks^0_s flt.	>1mm	



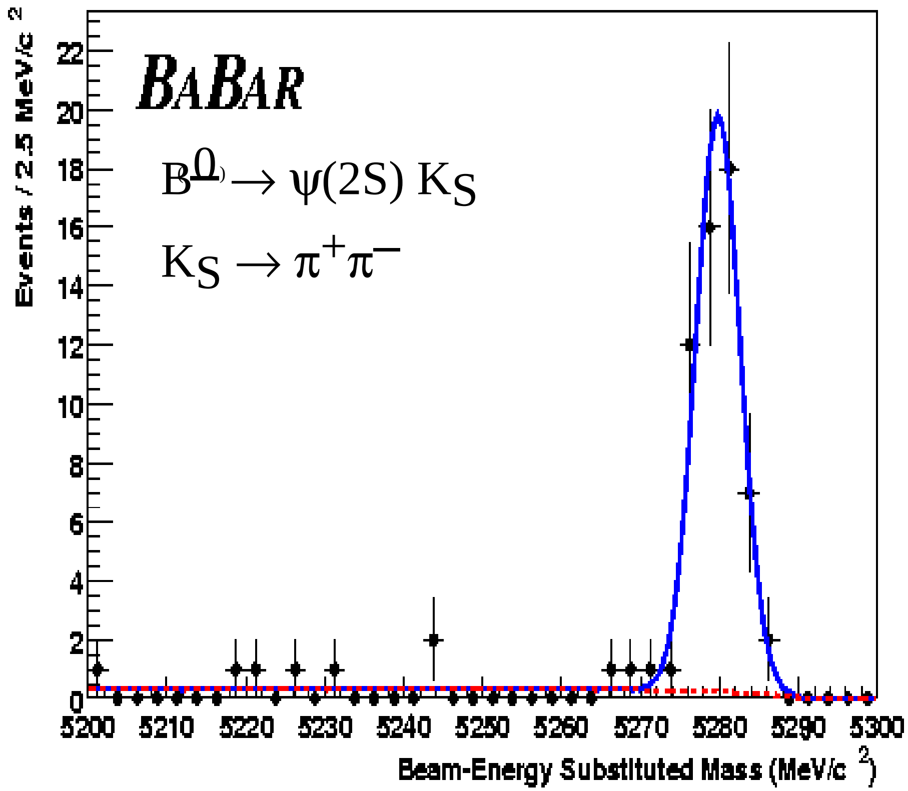
65 Events before tagging

$\psi(2S)$ $(K_S \to \pi^+\pi^-)$

BR($B^0 \to \psi(2S)$ $(K_S \to \pi^+\pi^-$, $\psi(2S) \to J/\psi\ \pi^+\pi^-$(J/psi->ll) **or** $\psi(2S) \to ll$))

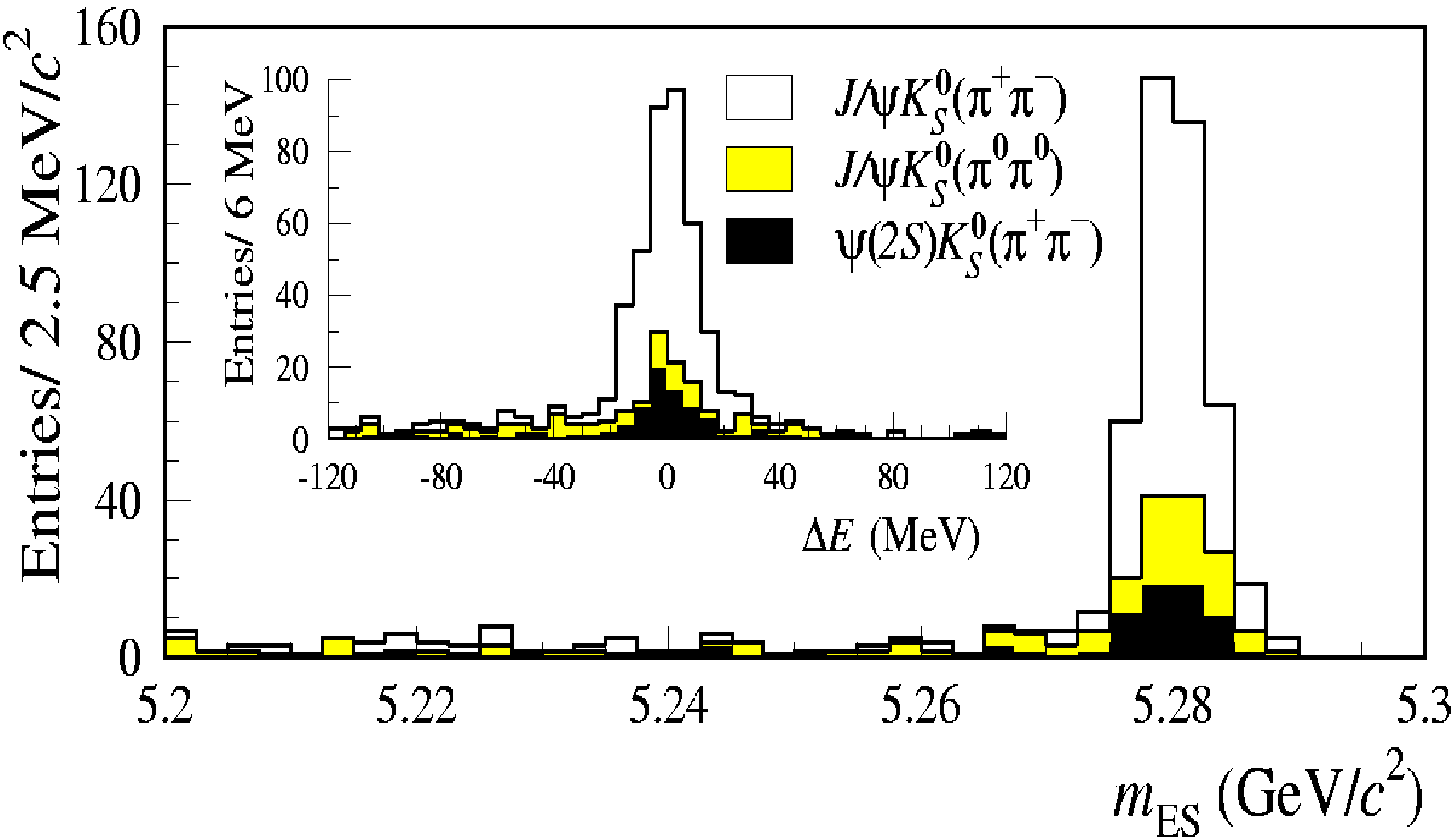
$\sim \times 10^{-5}$

Cut	ee	mumu
Mass$_{J/psi}$	2.95−3.14	3.06−3.14
Mass$_{Ks}$	0.489−0.507	
Cos θ_{hel}	<0.8	<0.8
Cos θ_{thrust}	<0.9	<0.9
PID	Vl+T	Vl+T
Ks^0_s flight	>1mm	
Mass diff	0.574−0.604	
Mass$_{psi(2S)}$	3.44−3.74	3.64−3.74



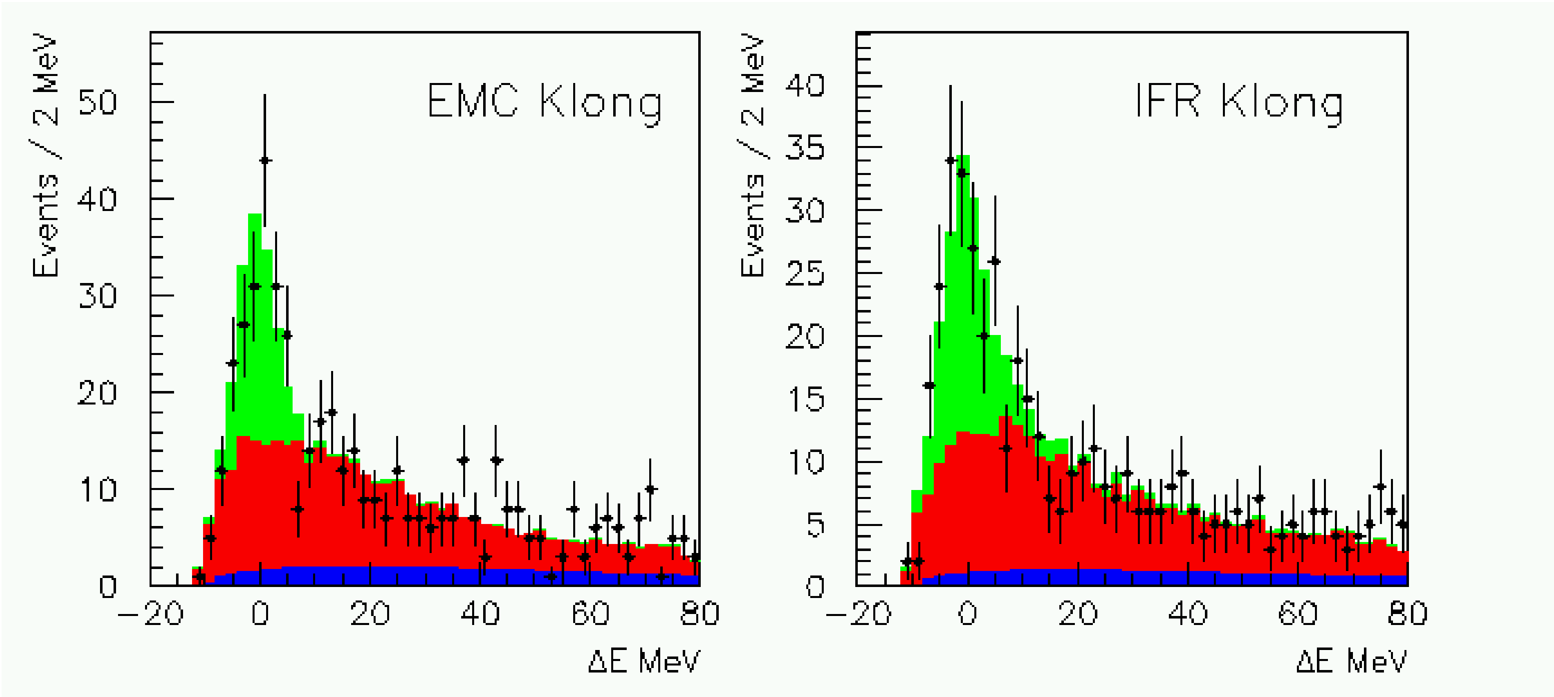
63 Events before tagging

Final *CP* sample of K^0_S modes



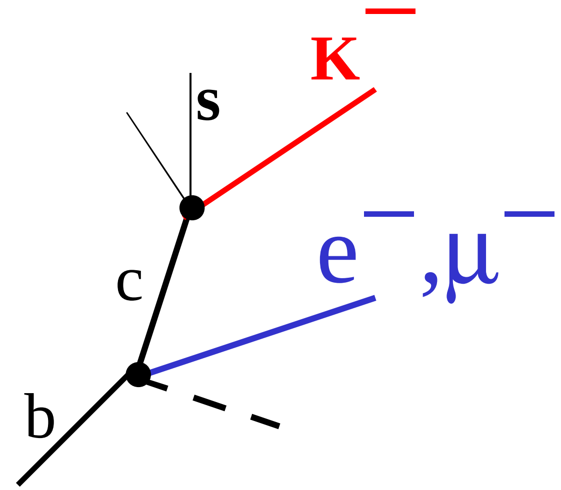
$B^0 \rightarrow J/\psi \, K^0_L$

- K^0_L signaled by isolated clusters in IFR and/or EMC
- K^0_L direction is combined with J/ψ momentum to reconstruct K^0_L energy
- ~ 205 total events above large background (before tagging). Background shape, amount, and ***CP*** structure studied with Monte Carlo. (182 after tagging)

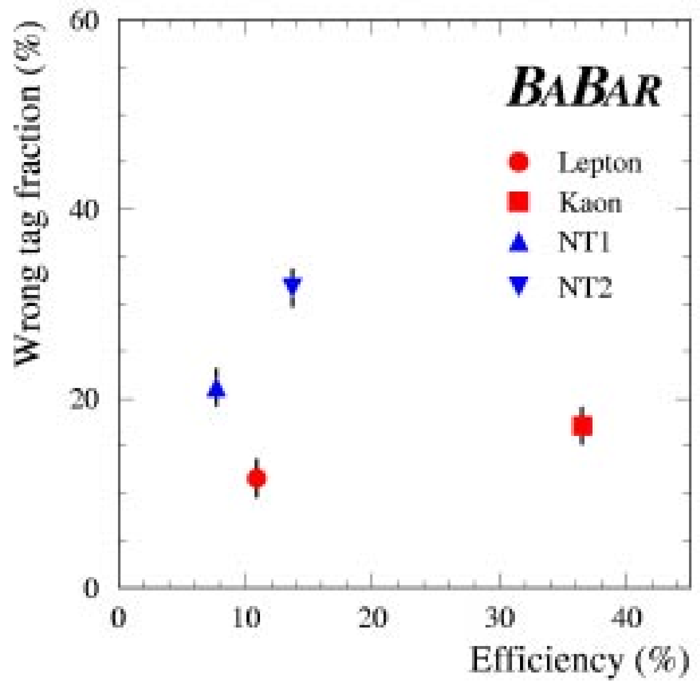


B Flavour–Tagging Categories

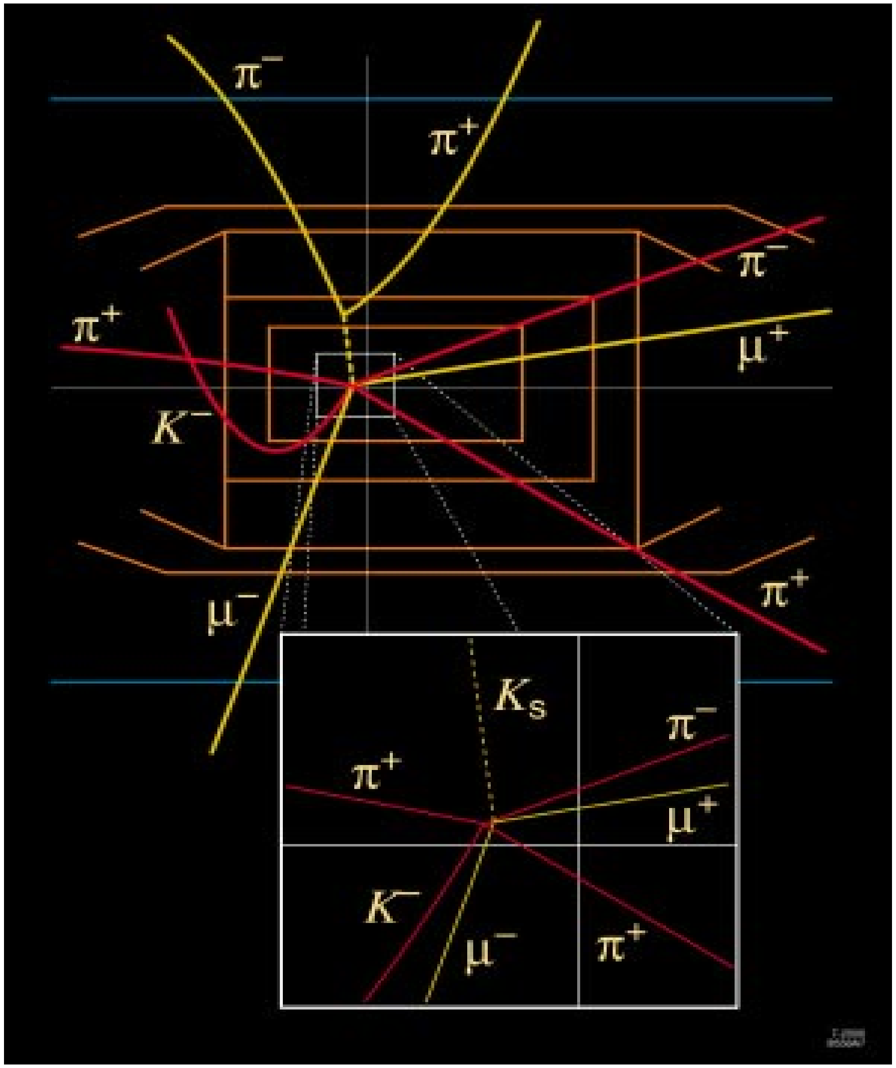
- **Leptons** ($\ell^- \Longrightarrow \bar{B}^0$ **tag**)
  - Electron $P_{\mathbf{cm}}$ >1.0 GeV/c
  - Muon $P_{\mathbf{cm}}$ >1.1 GeV/c



- **Kaons**
  - Σ Kaon Charge ≠ **0**
- **NT1,NT2 (neural net)**
  - slow pions (from ***D****)
  - Isolated unIDed leptons



An Event from the CP Sample



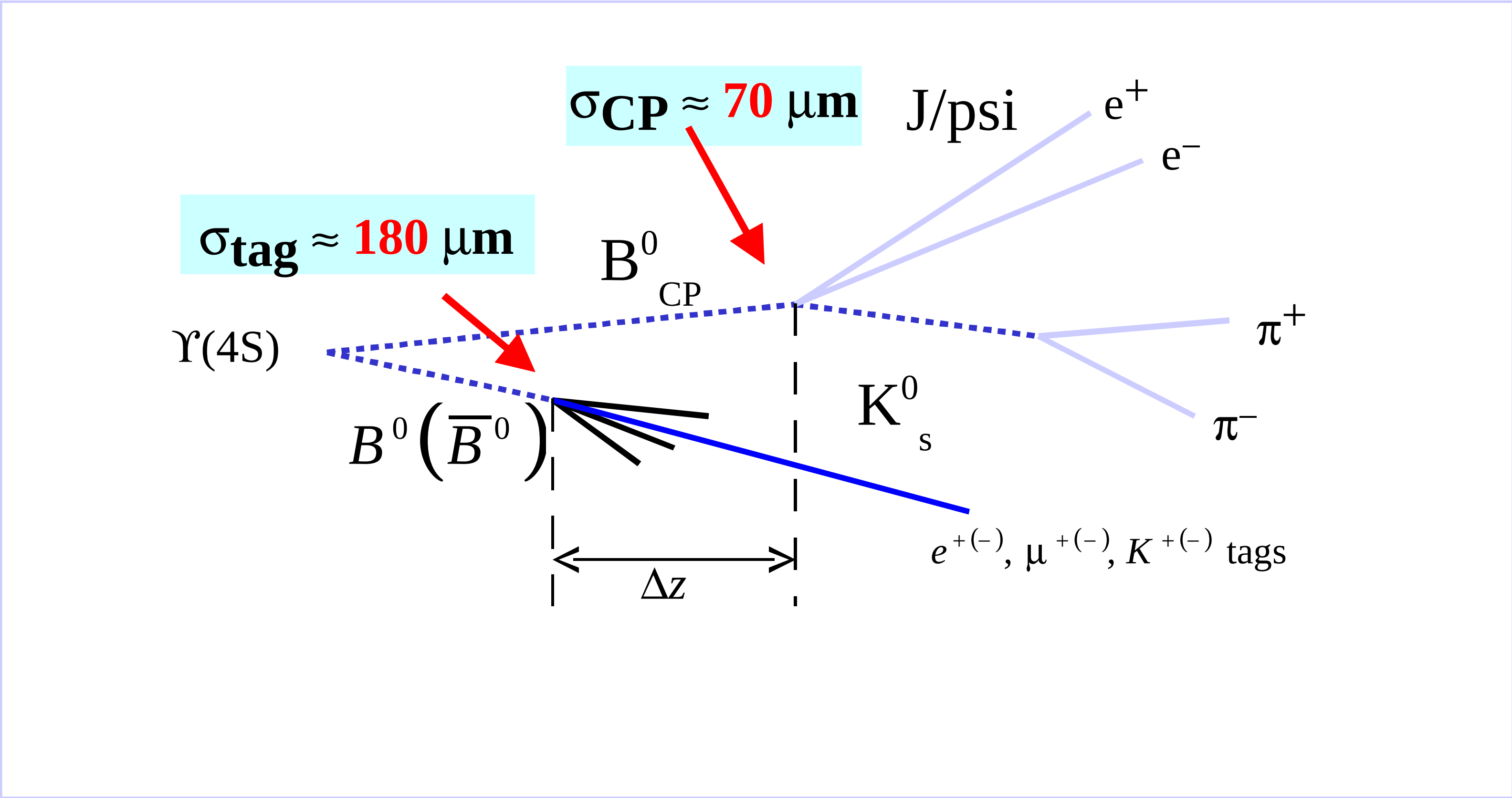
A $B^0 \rightarrow J/\psi$ $(K_S \rightarrow \pi^+\pi^-$, *J/psi−>ll*) event

- A negative kaon is found in the decay products of the other ***B*** meson, which is therefore tagged as a $\bar{B}^0$
- **Δz is measured precisely, thanks to the Silicon Vertex Detector**

Measuring Δt at PEPII

E_{e-} = 9.0 GeV, E_{e+} = 3.1 GeV

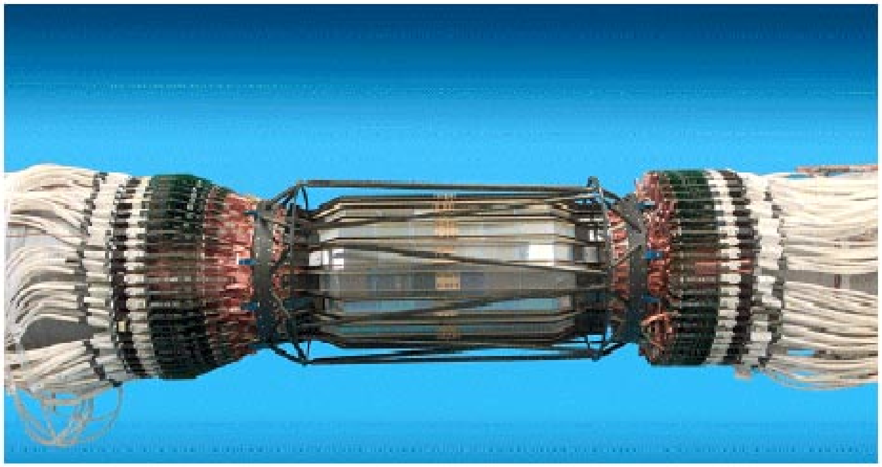
Lorentz boost BetaGamma = 0.56



Vertex Resolution: the SVT

Even at PEP−II, *B*'s don't go very far! (≈ 250 μ**m)**

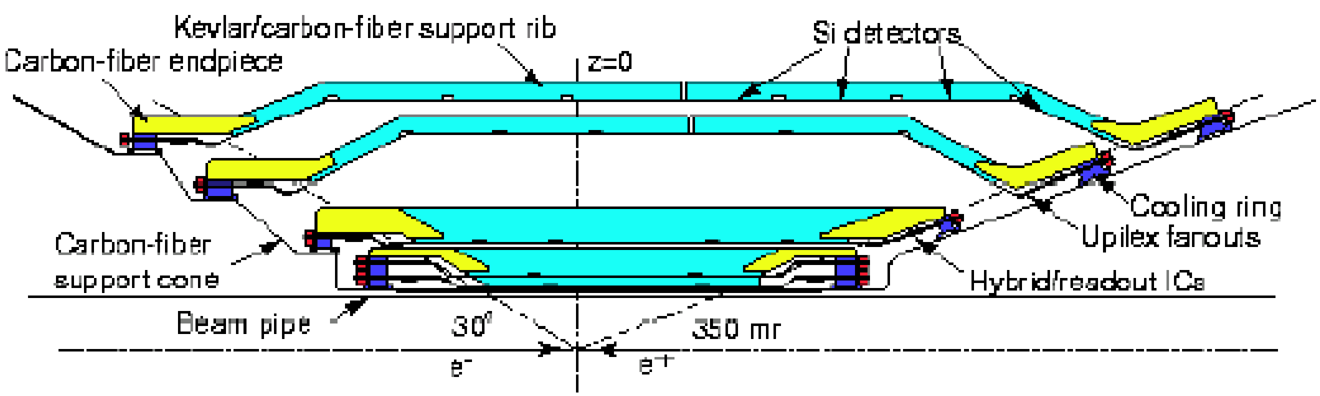
⇒ 5 Layer Silicon Vertex Tracker



$\sigma_Z \approx$ 70 μm: reco'd *B*

180 μm: tagging *B*

(rms for 99% of events)



Reconstructed Hadronic B events (mixing and fitting)

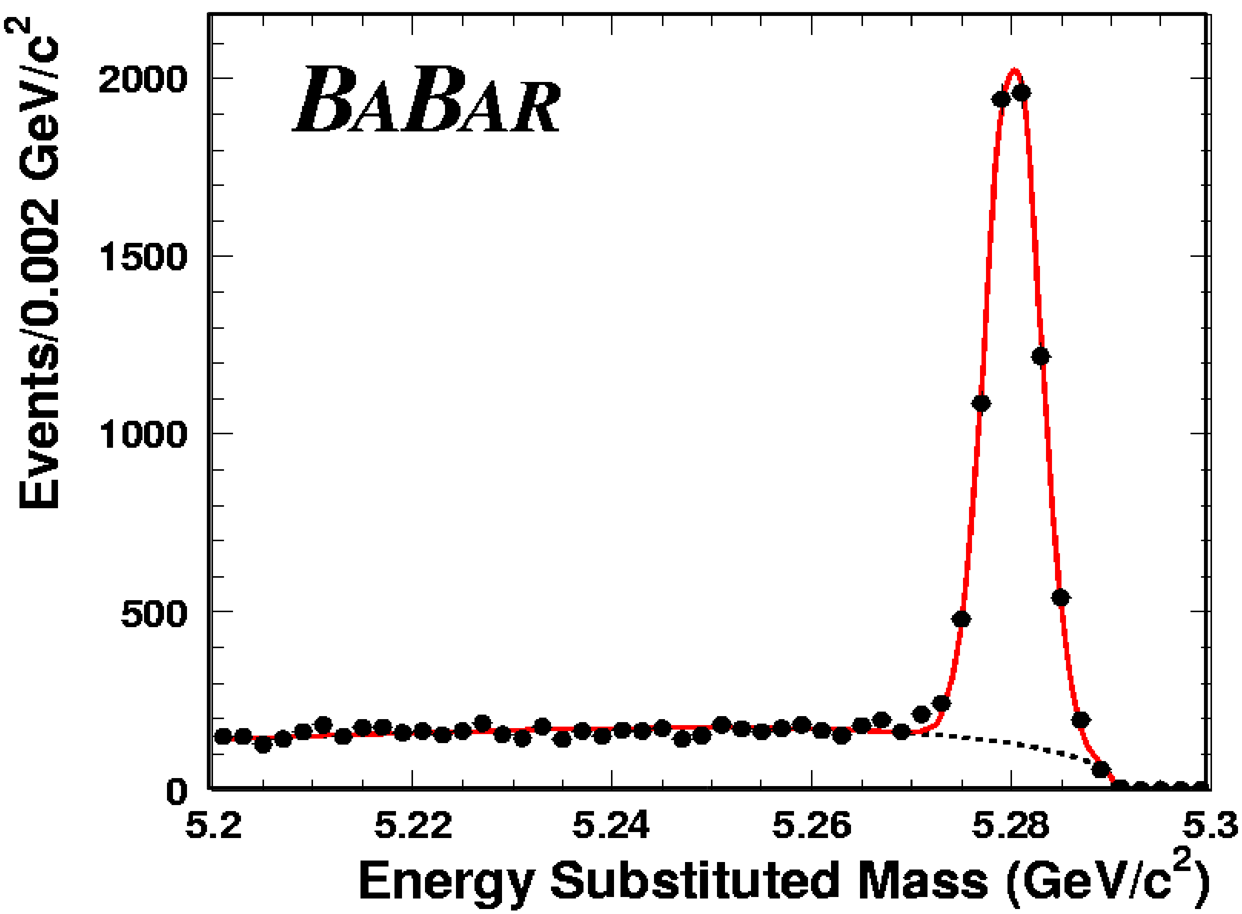
$D^{(*)-}\pi^+$

$D^{(*)-}\rho^+$

$D^{(*)-}a_1^+$

$J/\psi\ K^{*0}$

$(K^{*0}\rightarrow K^+\pi^-)$



Likelihood analysis – global fit

- Simultaneous fit to B_{CP} and B_{flav} samples for *sin 2*β (plus 34 parameters to characterize the detector and the data)
  - Signal Δt resolution function (9 parameters)
  - Signal dilutions and B^0 $\overline{B}^0$ dilution differences (8 parameters)
  - Background Δt structure, resolution function, dilutions and *CP* content (17 parameters)

Likelihood analysis – global fit

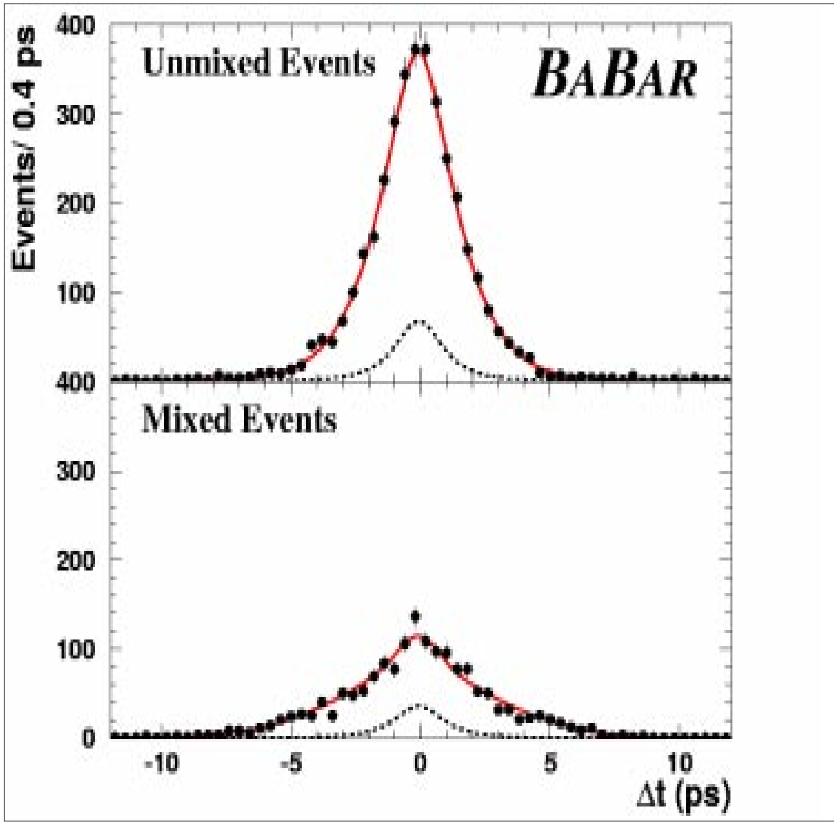
- Correlations between B_{CP} and B_{flav} are small
- Extract background parameters from:
  - $m_{\mathbf{ES}}$ sidebands for golden CP modes and B_{flav} modes
  - J/ψ sidebands and inclusive $B^0 \to J/\psi$ monte carlo for K^0_L modes

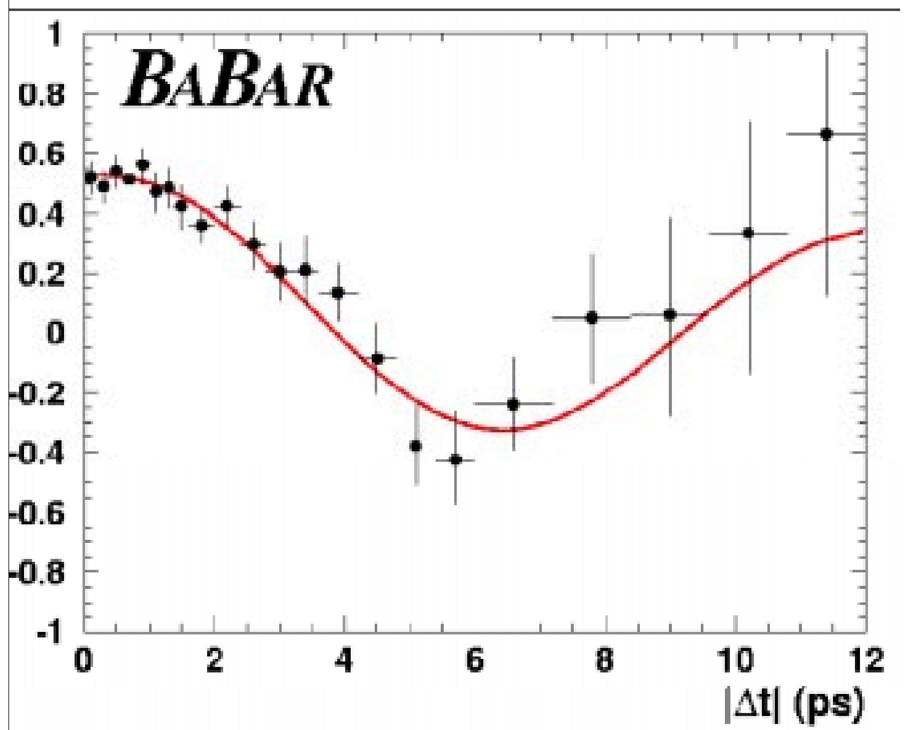
Mistag fractions w_i and effective efficiencies Q_i

- **Determined from data via likelihood fit**
- $Q_i = \varepsilon_i (1-2w_i)^2$ **is the effective tagging efficiency**

Tag Category	$\varepsilon(\%)$	$w(\%)$	$Q(\%)$
Lepton	10.9 ± 0.4	11.6 ± 2.0	6.4 ± 0.7
Kaon	36.5 ± 0.7	17.1 ± 1.3	15.8 ± 1.3
NT1	7.7 ± 0.4	21.2 ± 2.9	2.6 ± 0.5
NT2	13.7 ± 0.5	31.7 ± 2.6	1.8 ± 0.5
Total	68.9 ± 1.0		26.7 ± 1.6

Δt distributions and oscillations for tagged hadronic B decays

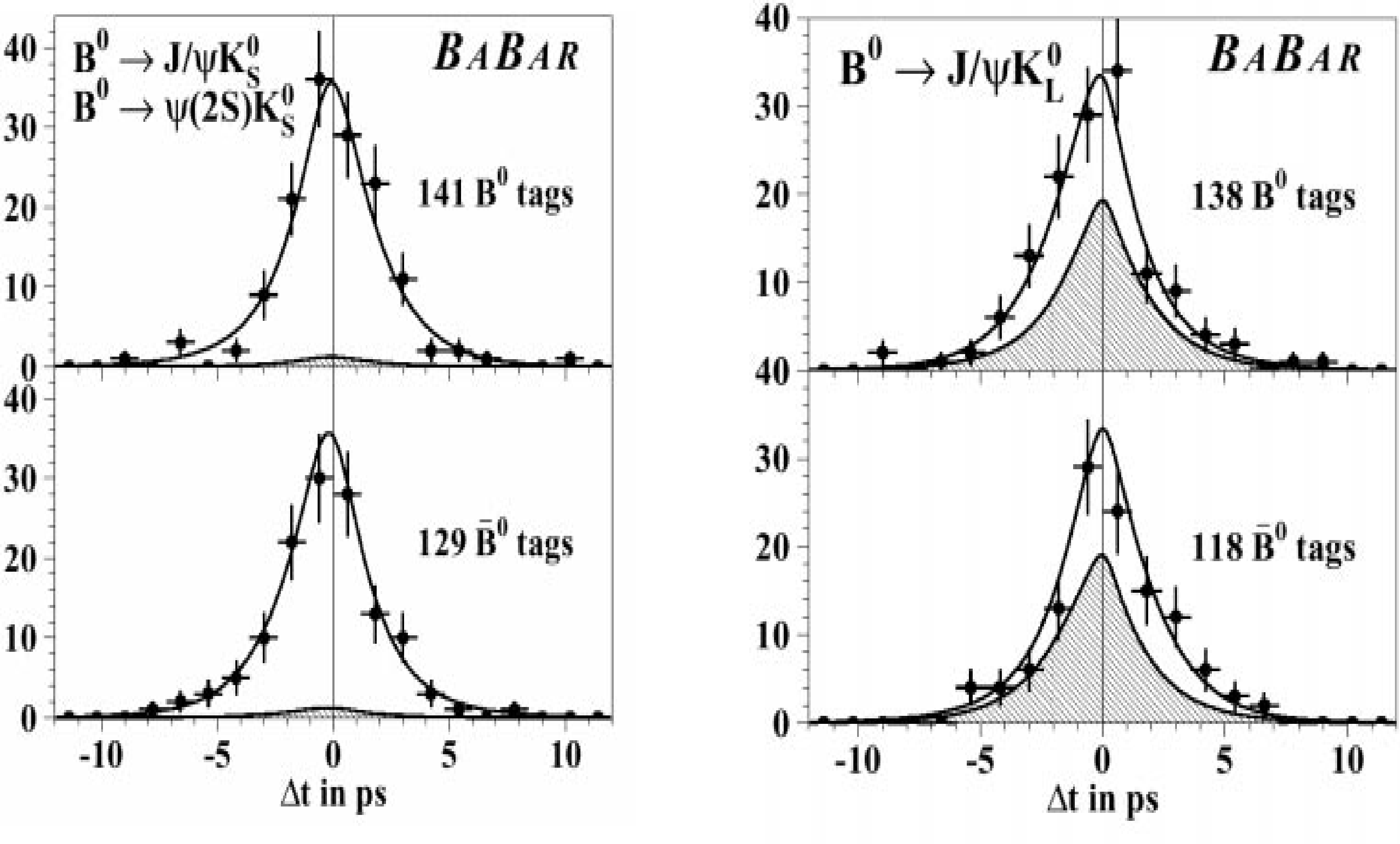




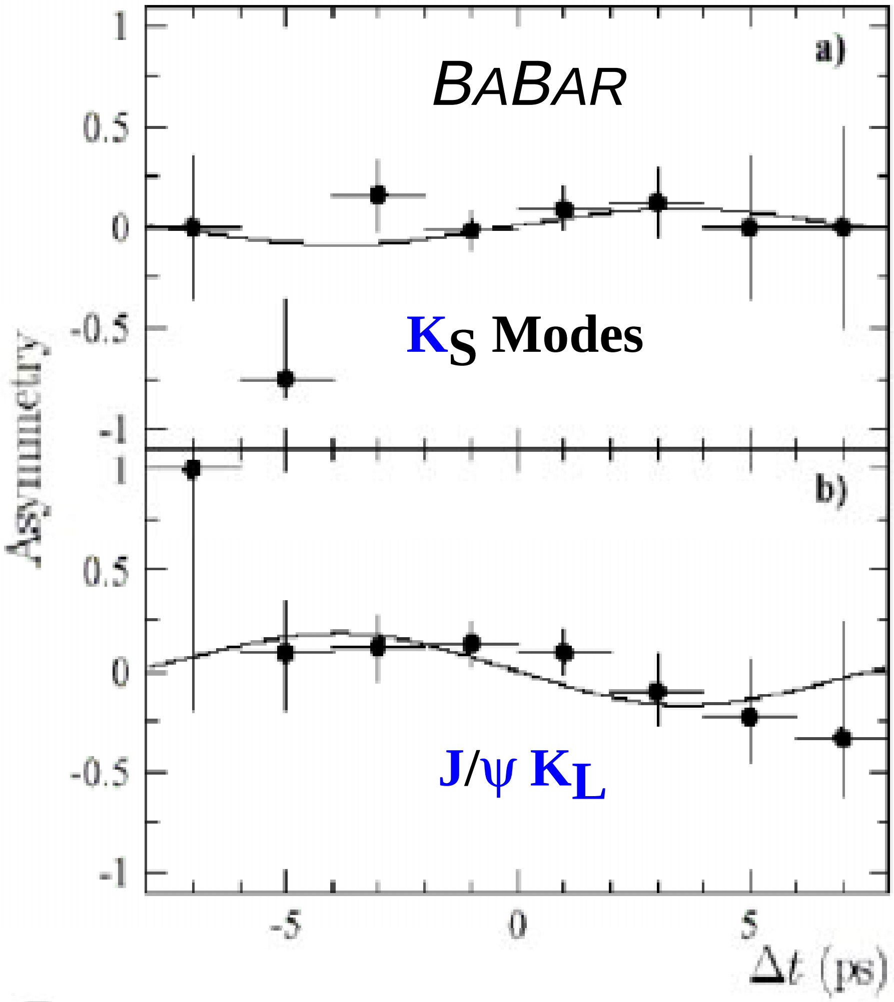
Signal + bkgnd   Background

$$\Delta m_{B0} = 0.519 \pm 0.020 \pm 0.016\ \hbar\ \mathrm{ps}^{-1}$$

CP Sample: Δt distributions for tagged K^0_S and K^0_L events



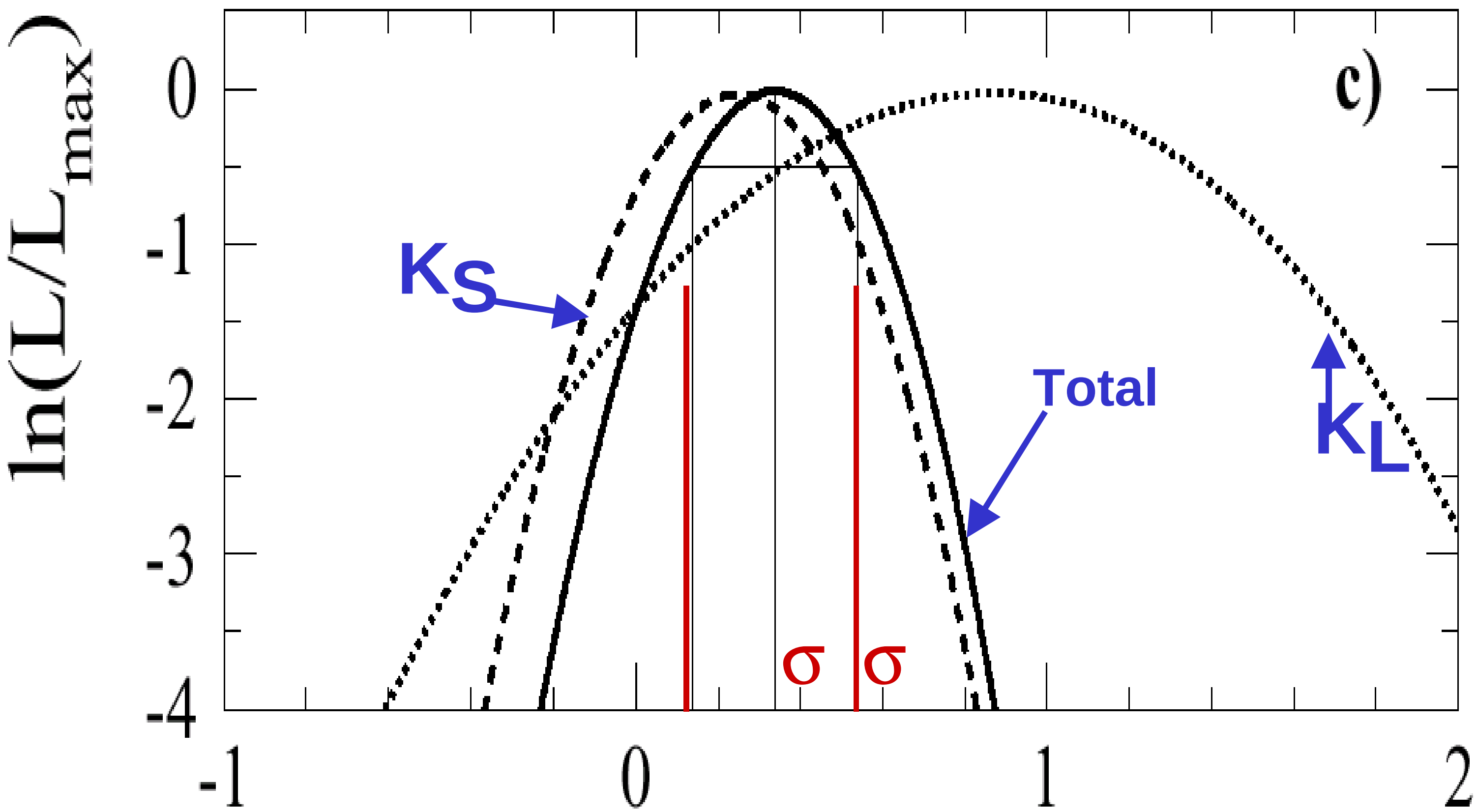
$A(\Delta t)$ *vs* Δt (Binomial Errors)



$\sin 2\beta = 0.25 \pm 0.22$ (stat)

$\sin 2\beta = 0.87 \pm 0.51$ (stat)

Log Likelihood vs *sin 2* β

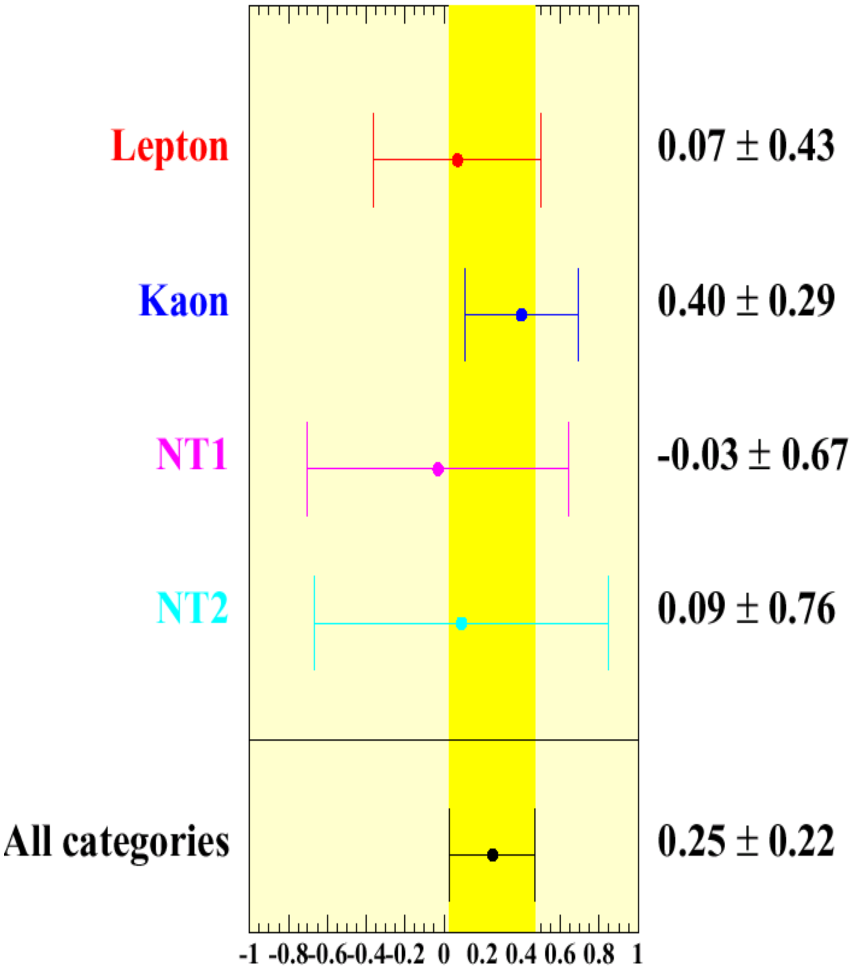


$\mathbf{\textit{sin 2}\ \beta = 0.34 \pm 0.20(stat) \pm 0.05(sys)}$

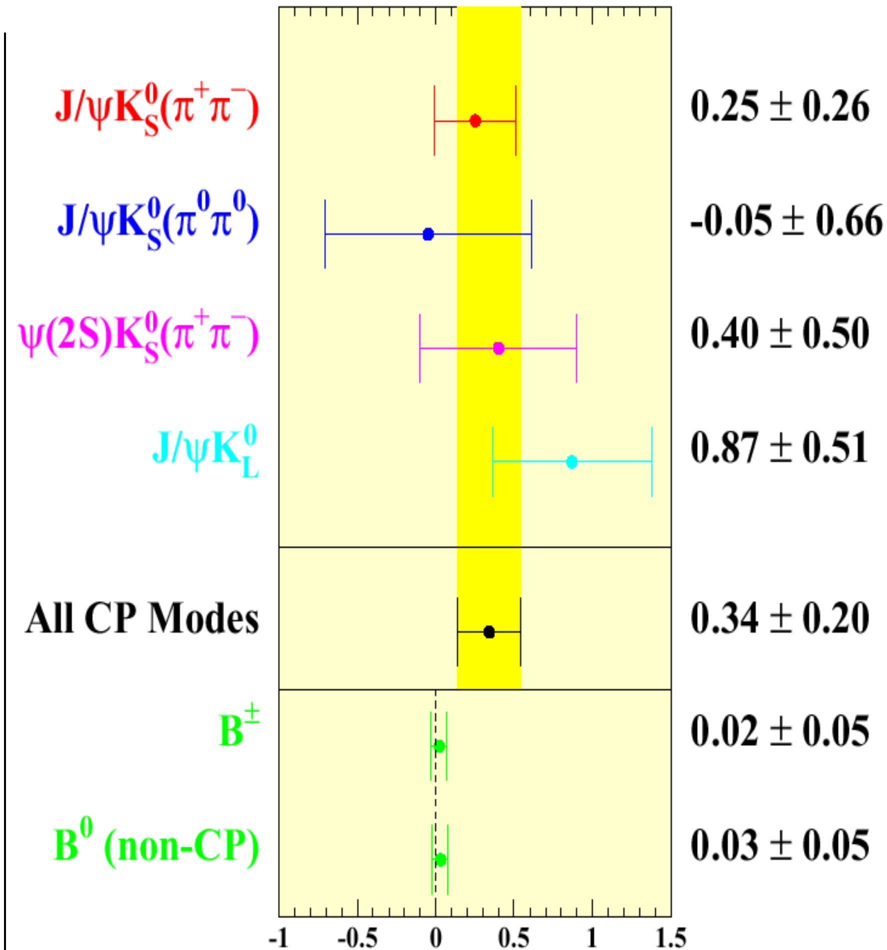
Systematic Effects

Systematic	$J/\psi K_S^0, \psi(2S) K_S^0$	$J/\psi K_L^0$	Full sample
Δt determination	0.04	0.04	0.04
$J/\psi K_S^0$, $\psi(2S) K_S^0$ back.	0.02	—	0.02
$J/\psi K_L^0$ back.	—	0.09	0.01
$J/\psi K_L^0$ Sig. fraction	—	0.10	0.01
τ_{B^0}	0.01	0.01	< 0.01
Δm_{B^0}	0.01	< 0.01	0.01
Other	0.01	0.01	0.01
Total	0.05	0.14	0.05

*sin2*β for various parts of *CP* sample; crosschecks from *B*flav and charged *B*' s

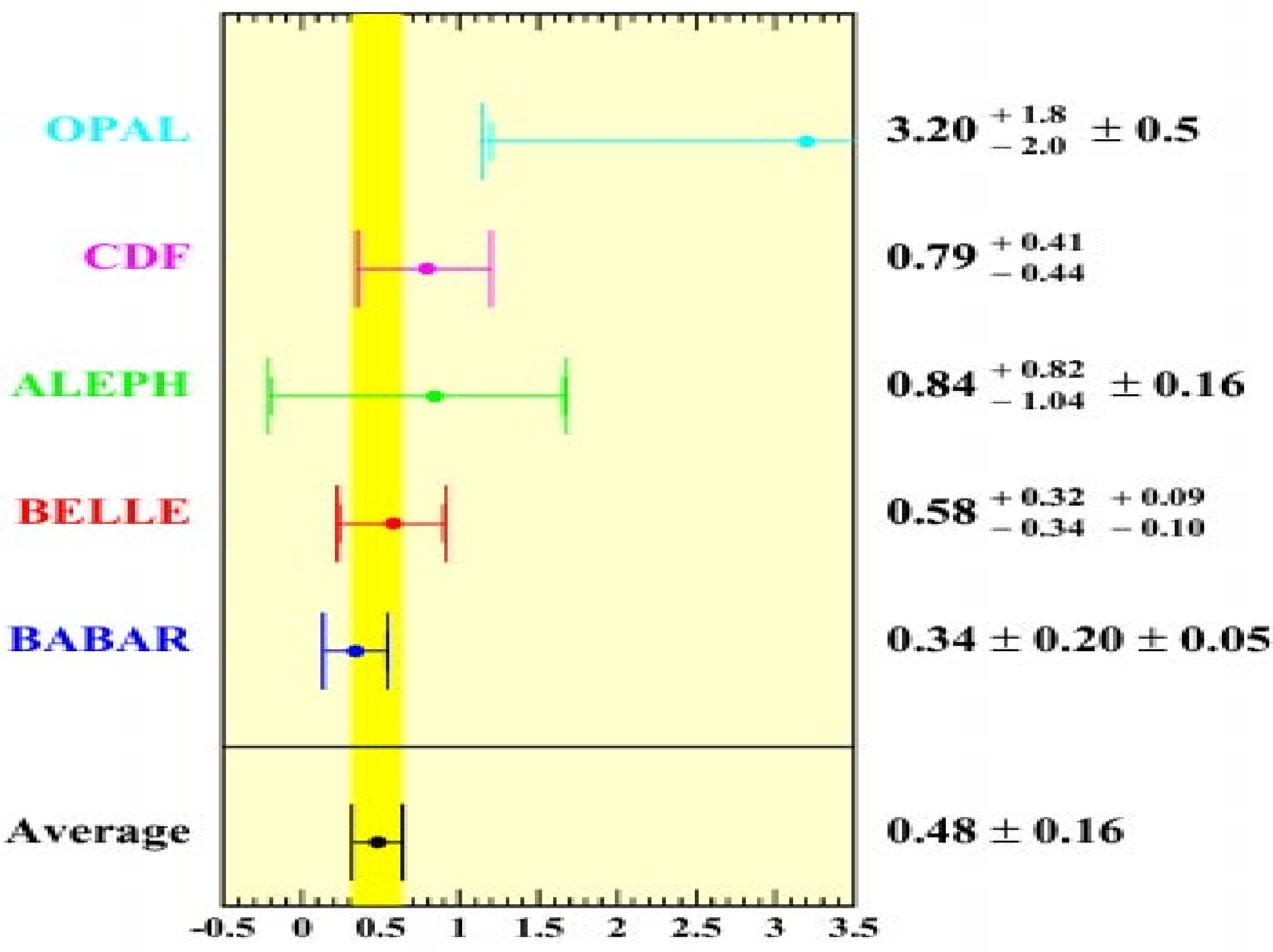


*sin2*β(*Golden*)



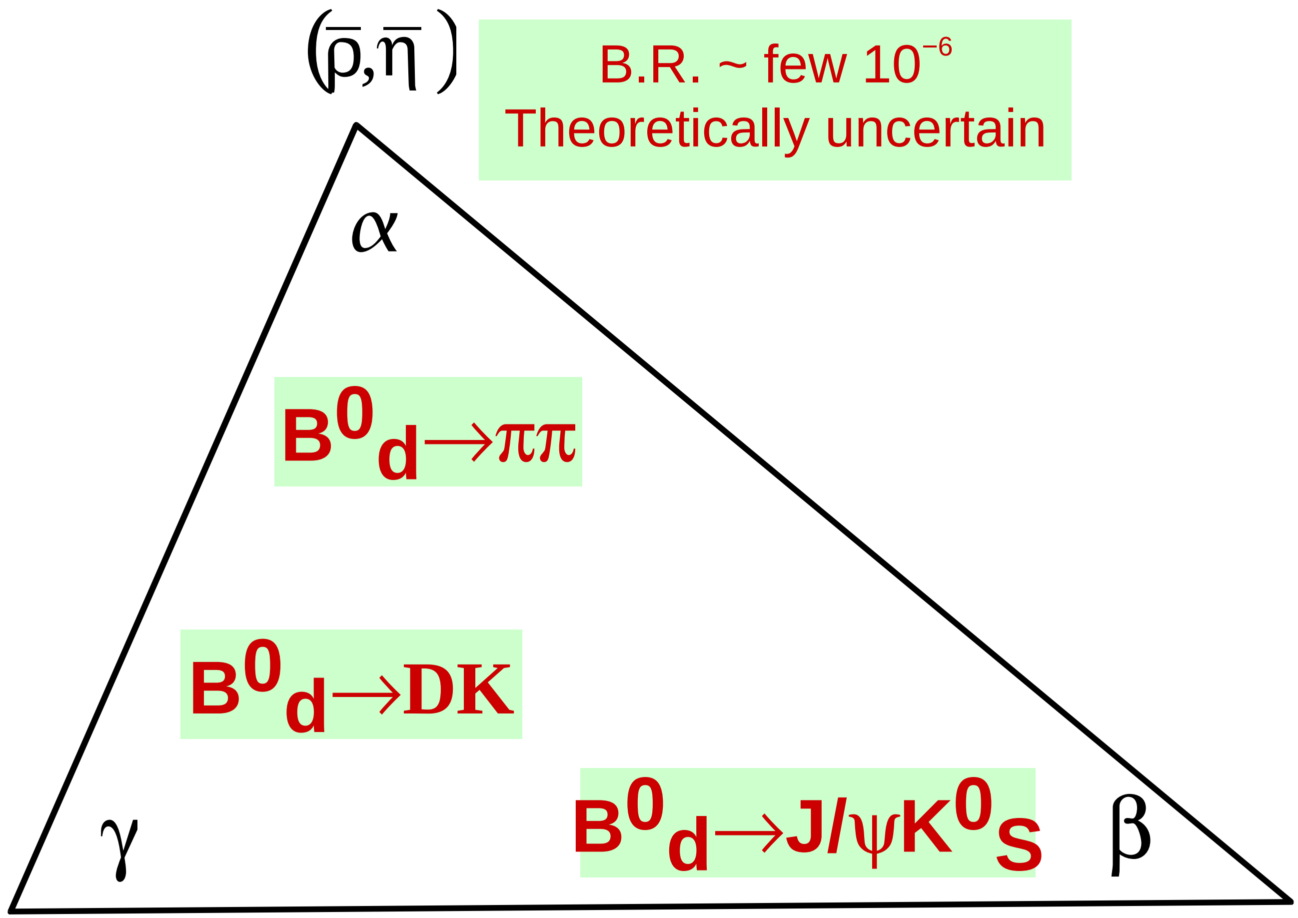
*sin2*β

Comparison to other experiments



Sin2β

~~CP~~ issues for BABAR

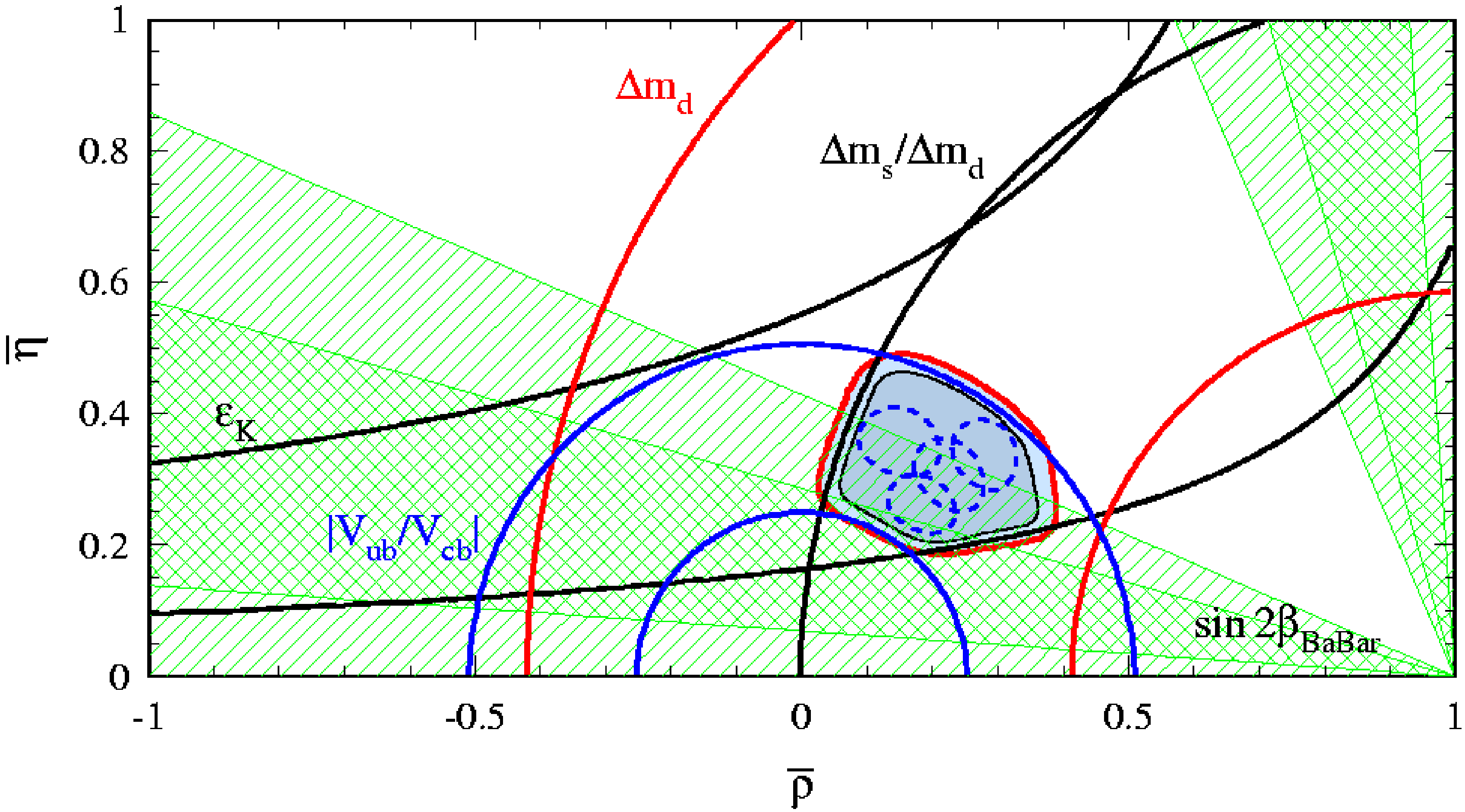


B.R. ~ few 10^{-6}
Theoretically uncertain

Eff B.R ~10^{-7} (difficult)

Very clean,
Eff B.R. ~ 10^{-4}

Constraints on Unitarity Triangle



Allowed region (blue) is determined using theoretical inputs and fitting many experimental measurements

The Future

Luminosity profile − next few years:

2000	2001	2002	2003	2004	2005
25	43	80	110	130	180 fb^{-1}

$\int$ Ldt $>$ 500 fb^{-1} by end of 2005

(~4.5 10^8 $B\bar{B}$ pairs)

Conclusions

- PEP−II and BaBar $\geqslant$ design luminosity
- ~25 fb^{-1} in 2000
- Most precise measurement of *sin 2*β
- Many other analyses underway
- By 2005, will accumulate ~ 500 fb^{-1}
  - Measure *sin 2*α
  - Compare *sin 2*β in individual modes
  - Make serious measurements of direct *CP* violation and rare decays

B^0–$\overline{B}^0$ Mixing and ~~*CP*~~

- Neutral *B* and $\overline{B}$ mix into mass eigenstates, oscillating at a frequency determined by Δm_B

- **We define** $\lambda = \frac{q}{p}\frac{\overline{A}}{A}$ **, where :**

$$\frac{q}{p} = \frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}} = e^{2i\phi_M} \qquad \overline{A} = \langle f \mid H \mid \overline{B^0}\rangle \qquad A = \langle f \mid H \mid B^0\rangle$$

- **For a single decay amplitude with weak phase**

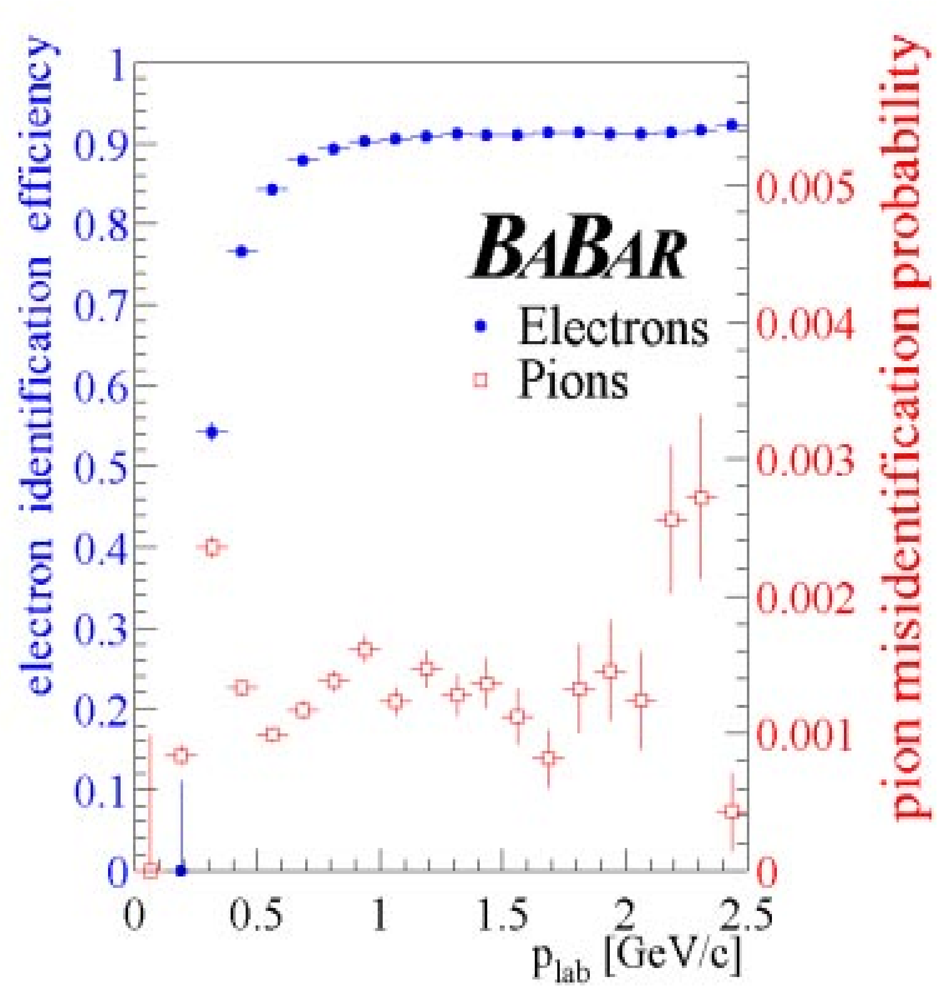
$$\mathbf{Im}\,\lambda = \sin 2(\phi_M - \phi_D)$$

- **Leads to *CP*–violating asymmetries interpretable by the Standard model**

CP physics at the Υ *(4S)*

- PEP II operates at the Υ*(4S)*. Υ*(4S)* decays into *P*−wave B^0 $\overline{B}^0$ state that evolves coherently till one of the *B*'s decays
- Mixing governed by single phase $q/p = e^{2i\phi m}$
  - (q,p coefficients of B in Mh, Ml)
- Amplitudes for decays to CP eigenstate f are:
  - $A = \langle f \mid H \mid B^0 \rangle$, $\overline{A} = \langle f \mid H \mid \overline{B}^0 \rangle$
- Define $\lambda = q/p \cdot \overline{A}/A$
  - ($|\lambda| = 1$ for interference mixixng/decay)
- When single weak phase dominates decay:
  - $\overline{A}/A = e^{-2i\phi D}$
- *Therefore there is a CP asymetry proportional to* $Sin2(\phi m - \phi D)$

Particle ID: Electrons



- Track matching in the **EMC**
- **0.89 < E/P < 1.2**
- **DCH d*E*/d*x***

- **Efficiency and π misID from Control Samples**
- **Tight Electron selection:**

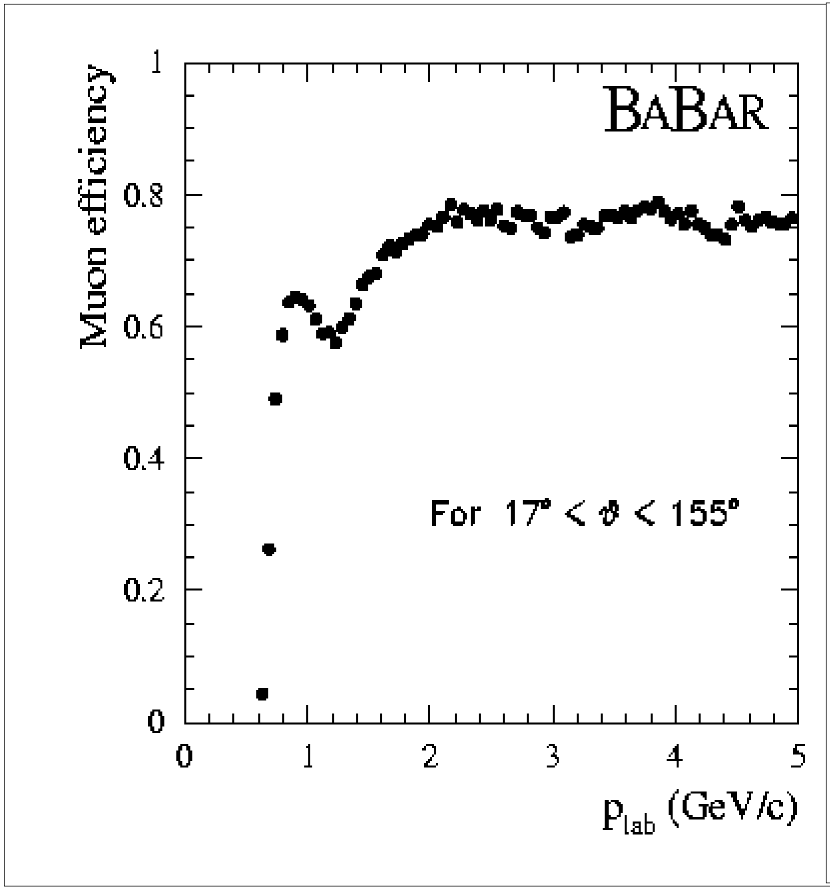
  ~92% efficiency

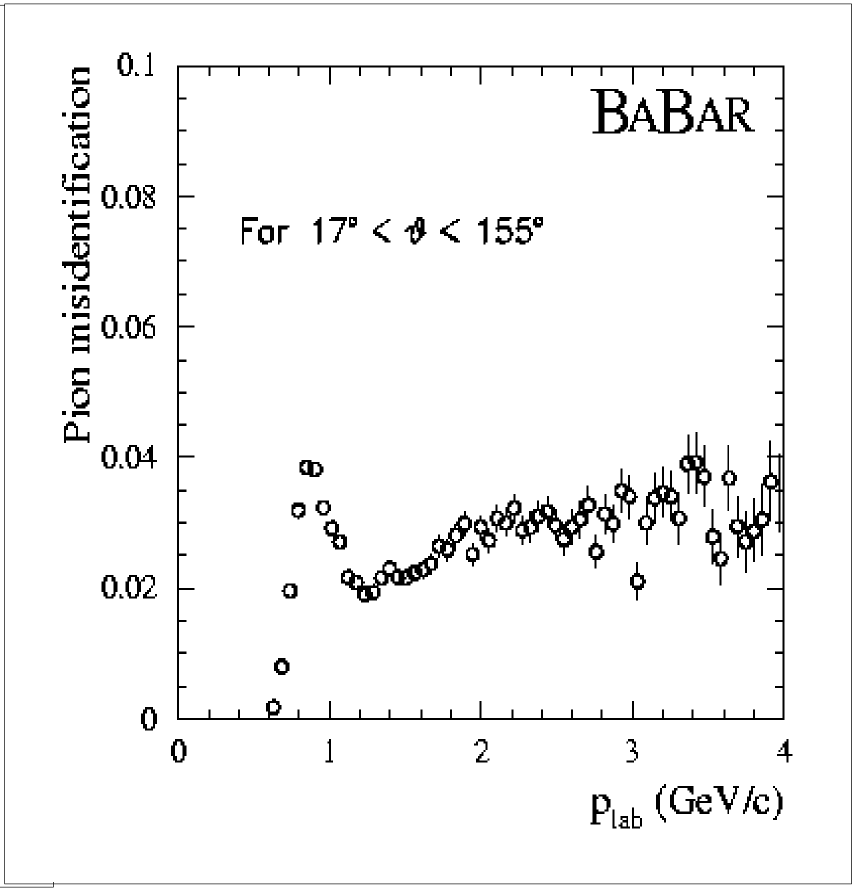
  0.1% π misID

  (>500 MeV)

Particle ID: Muons

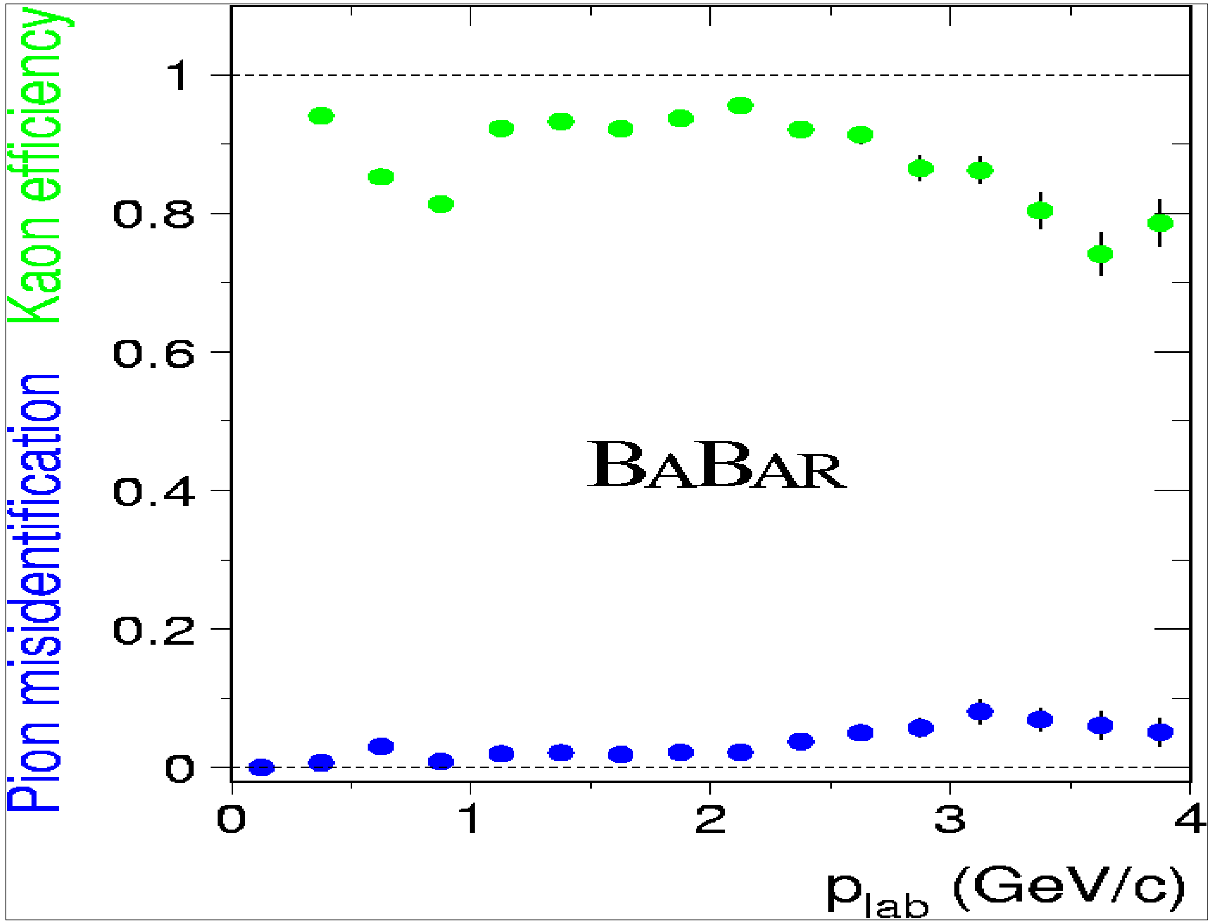
- Cut on # interaction lengths and difference from that expected for a μ track
- IFR hit pattern rejects hadron showers
- consistent with a MIP in the EMC
- Typical Tight Muon selection: ~75% efficiency above 1.5 GeV, with ~3% pion mis ID





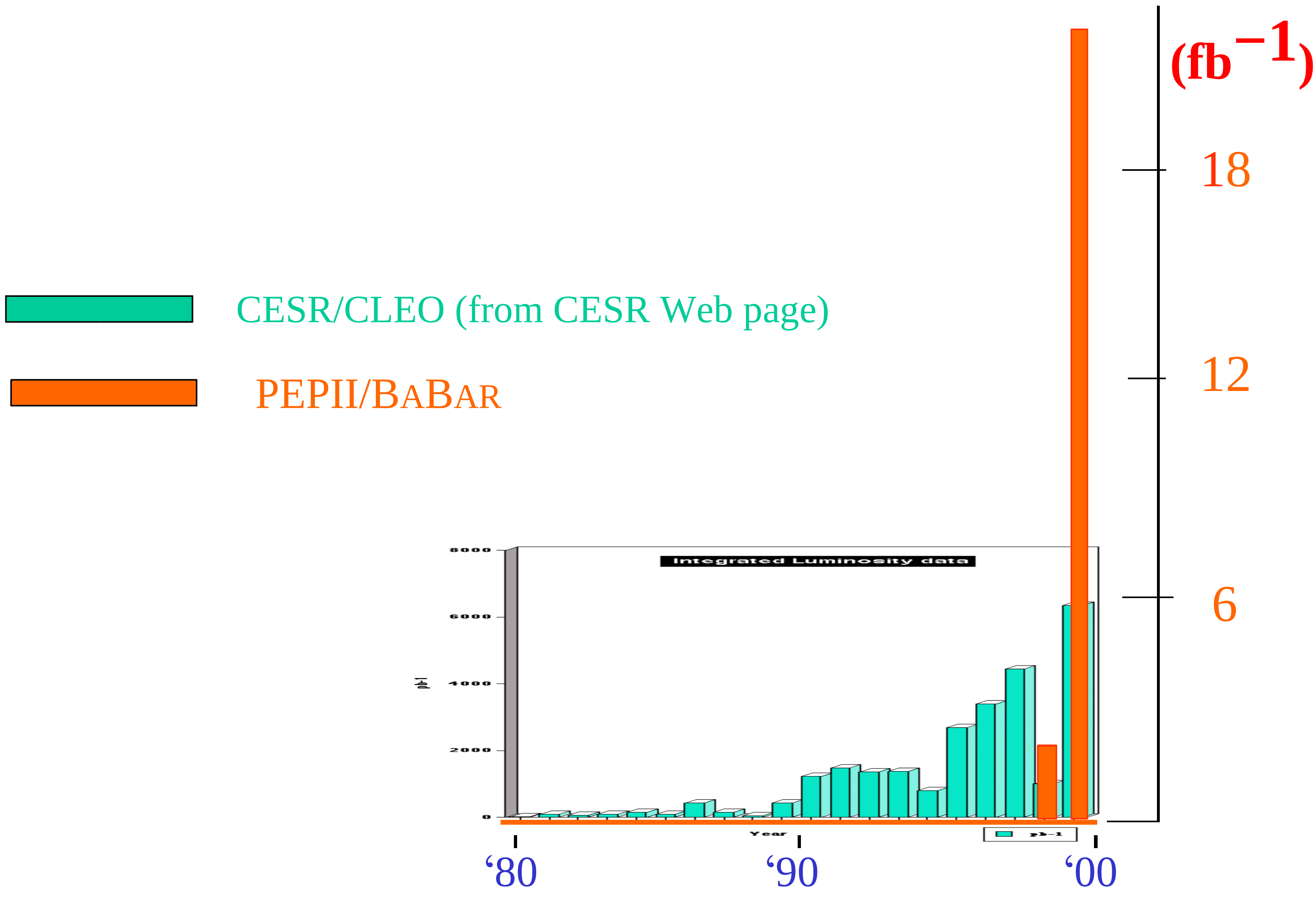
Particle ID: Kaons

- ***dE/dx*** **from DCH and SVT**
- θ_C **from DIRC**

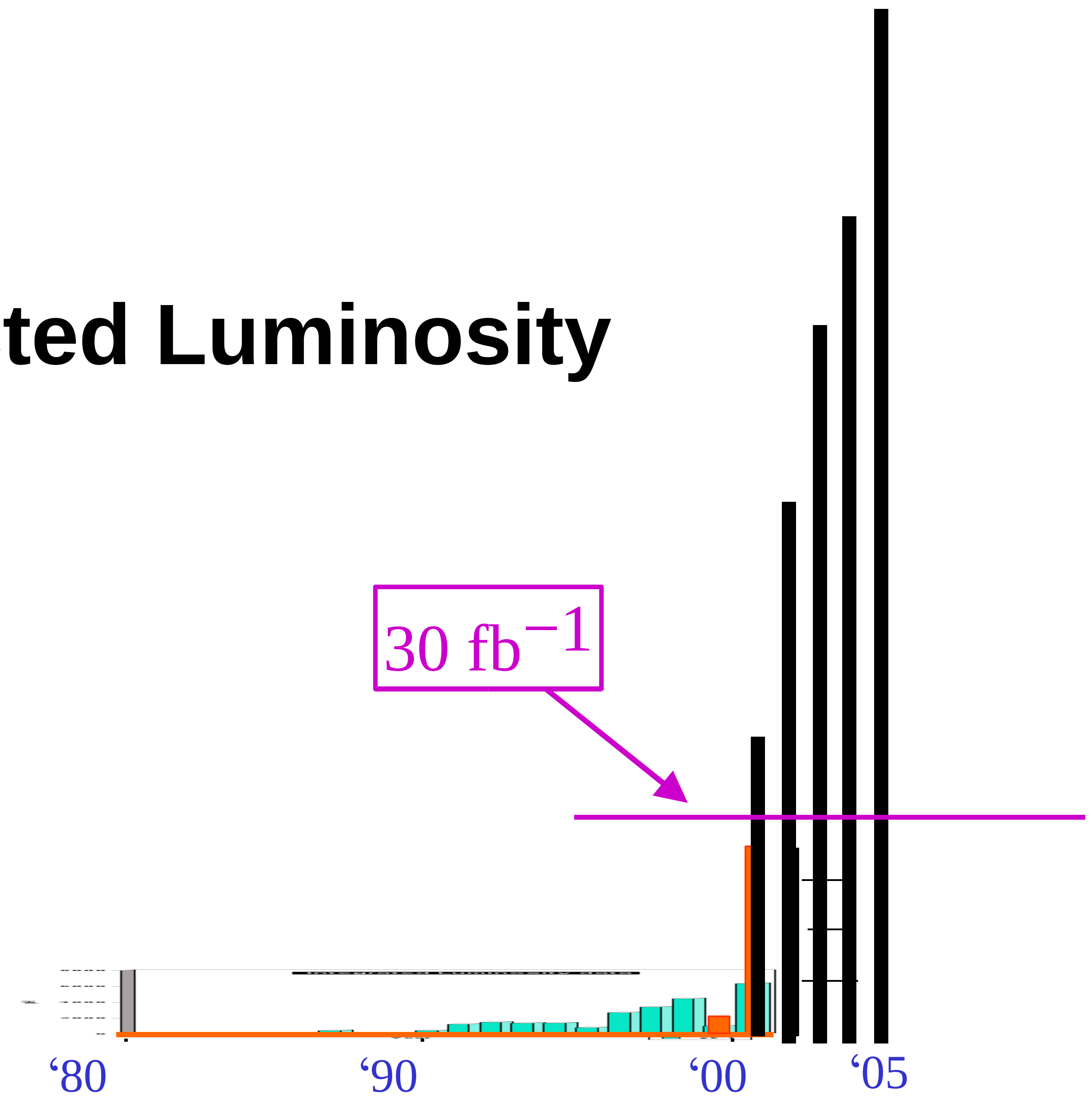


Better than 3 σ *K/π* separation for p_K > 250 MeV/c

Extremely fast PEP–II Turnon



Projected Luminosity



Cross checks on mistag fractions

$B^0 \rightarrow D^{*-}\, l\, \nu$
16,000 events

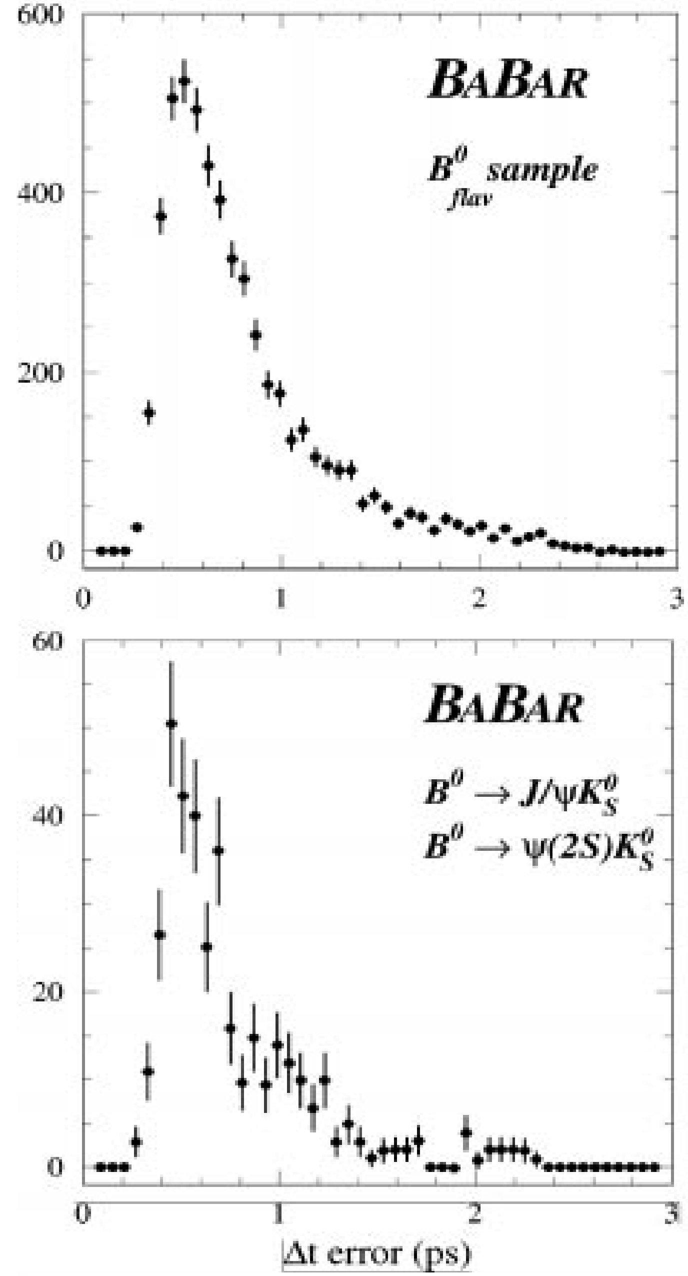
$B_{\mathbf{flav}}$ sample
~5000 events

Parameter	one bin	One bin hadronic	Global likelihood fit
***w* [Lepton]**	**0.108 ± 0.013**	**0.116 ± 0.021**	0.116 ± 0.020
***w* [Kaon]**	**0.180 ± 0.009**	**0.176 ± 0.014**	0.171 ± 0.013
***w* [NT1]**	**0.216 ± 0.019**	**0.197 ± 0.030**	0.212 ± 0.029
***w* [NT2]**	**0.364 ± 0.016**	**0.323± 0.027**	0.317 ± 0.026
Q	0.255 ± 0.017	0.264 ± 0.018	0.267 ± 0.017

Fitted parameters in Δt resolution function

Fitted for B_{CP} and B_{flav} samples together

Parameter	Value
S_{Core}	1.1 ± 0.1
S_{Tail}	3.8 ± 0.9
f_{Tail} (%)	11 ± 5
f_{Outlier} (%)	0.8 ± 0.5
$\delta_{\text{Core,}\texttt{Lepton}}$ (ps)	0.08 ± 0.10
$\delta_{\text{Core,}\texttt{Kaon}}$ (ps)	-0.21 ± 0.05
$\delta_{\text{Core,}\texttt{NT1}}$ (ps)	0.01 ± 0.10
$\delta_{\text{Core,}\texttt{NT2}}$ (ps)	-0.18 ± 0.09
δ_{Tail} (ps)	-0.46 ± 0.38



Time (Δt) resolution function

- **Sum of three Gaussians: Core (88%), Tail (11%), and Outliers (1%)**
- **Parameters determined from likelihood fit and other consistency checks**

$$\mathcal{R}_{\rm reso}(\Delta t, \Delta t_{\rm true}, \sigma_{\Delta t} | f_{\rm tail}, f_{\rm outlier}, S_{\rm core}, \delta_{\rm core}, S_{\rm tail}, \delta_{\rm tail}, \sigma_{\rm outlier}) =$$

$$(1 - f_{\rm tail} - f_{\rm outlier}) \frac{\exp -\frac{1}{2}\left(\frac{\Delta t - \delta_{\rm core} - \Delta t_{\rm true}}{S_{\rm core}\sigma_{\Delta t}}\right)^2}{\sqrt{2\pi} S_{\rm core}\sigma_{\Delta t}}$$

$$+ f_{\rm tail} \frac{\exp -\frac{1}{2}\left(\frac{\Delta t - \delta_{\rm tail} - \Delta t_{\rm true}}{S_{\rm tail}\sigma_{\Delta t}}\right)^2}{\sqrt{2\pi} S_{\rm tail}\sigma_{\Delta t}}$$

$$+ f_{\rm outlier} \frac{\exp -\frac{1}{2}\left(\frac{\Delta t - \delta_{\rm outlier} - \Delta t_{\rm true}}{\sigma_{\rm outlier}}\right)^2}{\sqrt{2\pi}\sigma_{\rm outlier}}$$

Breakdown of tagged *CP* events

DECAY MODE

TAGGING CATEGORY

Tag	$J/\psi K_S^0\ (\pi^+\pi^-)$			$J/\psi K_S^0\ (\pi^0\pi^0)$			$\psi(2S)K_S^0$			Total		
	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot
$e+K$	2	0	2	0	0	0	1	0	1	3	0	3
$\mu+K$	1	0	1	0	1	1	2	0	2	3	1	4
e	5	5	10	1	1	2	1	2	3	7	8	15
μ	3	6	9	0	0	0	2	1	3	5	7	12
Lepton	11	11	22	1	2	3	6	3	9	18	16	34
Kaon	54	54	108	14	11	25	12	11	23	80	76	156
NT1	10	12	22	1	1	2	2	2	4	13	15	28
NT2	18	18	36	8	3	11	4	4	8	30	25	55
Total tag	93	95	188	24	17	41	24	20	44	141	132	273
No tag	76			20			13			109		
Tag ε (%)	71±3			67±6			77±6			71±2		

Breakdown (cont'd)

DECAY MODE

TAGGING CATEGORY

Tag	CP =1 modes			$J/\psi K_L^0$			Total		
	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot
$e+K$	3	0	3	1	6	7	4	6	10
$\mu+K$	3	1	4	3	5	8	6	6	12
e	7	8	15	11	8	19	18	16	34
μ	5	7	12	5	6	11	10	13	23
Lepton	18	16	34	20	25	45	38	41	79
Kaon	80	76	156	70	60	130	150	136	286
NT1	13	15	28	16	6	22	29	21	50
NT2	30	25	55	32	27	59	62	52	114
Total tag	141	132	273	138	118	256	279	250	529
No tag	109			130			239		
Tag ε (%)	71±2			66±2			69±2		