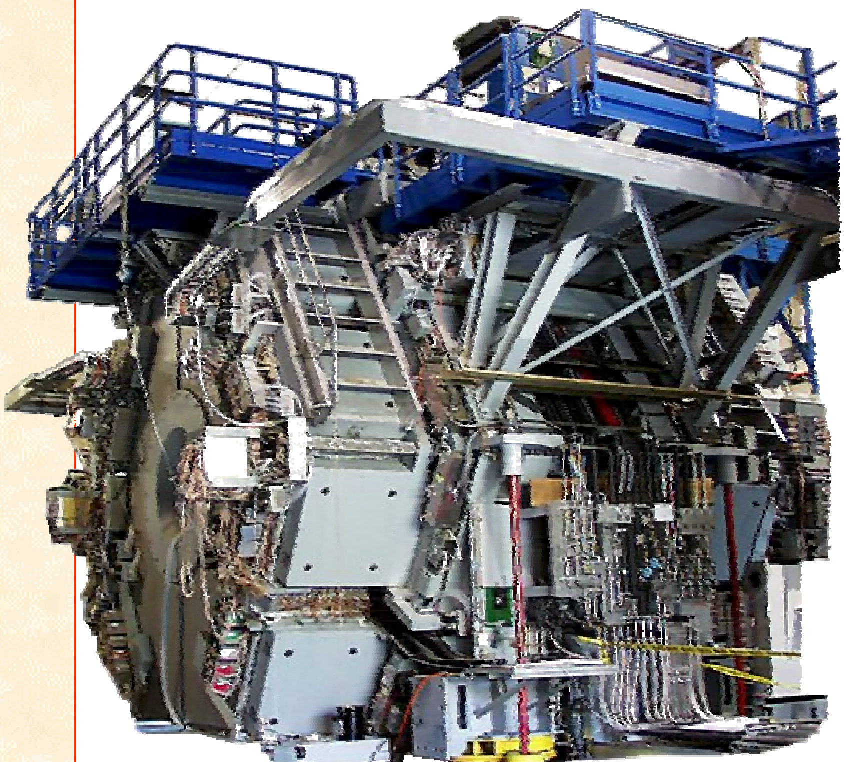
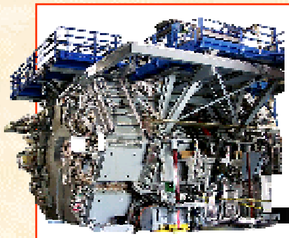
BABAR™ CP Results!



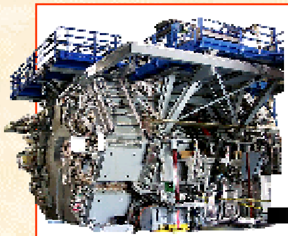
Stewart Smith
Princeton University
for the BABAR Collaboration

B Physics and ~~CP~~
Ise-Shima, Japan
February 19, 2001



Introduction

- Summary of 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
- Looking to the future
- Conclusion



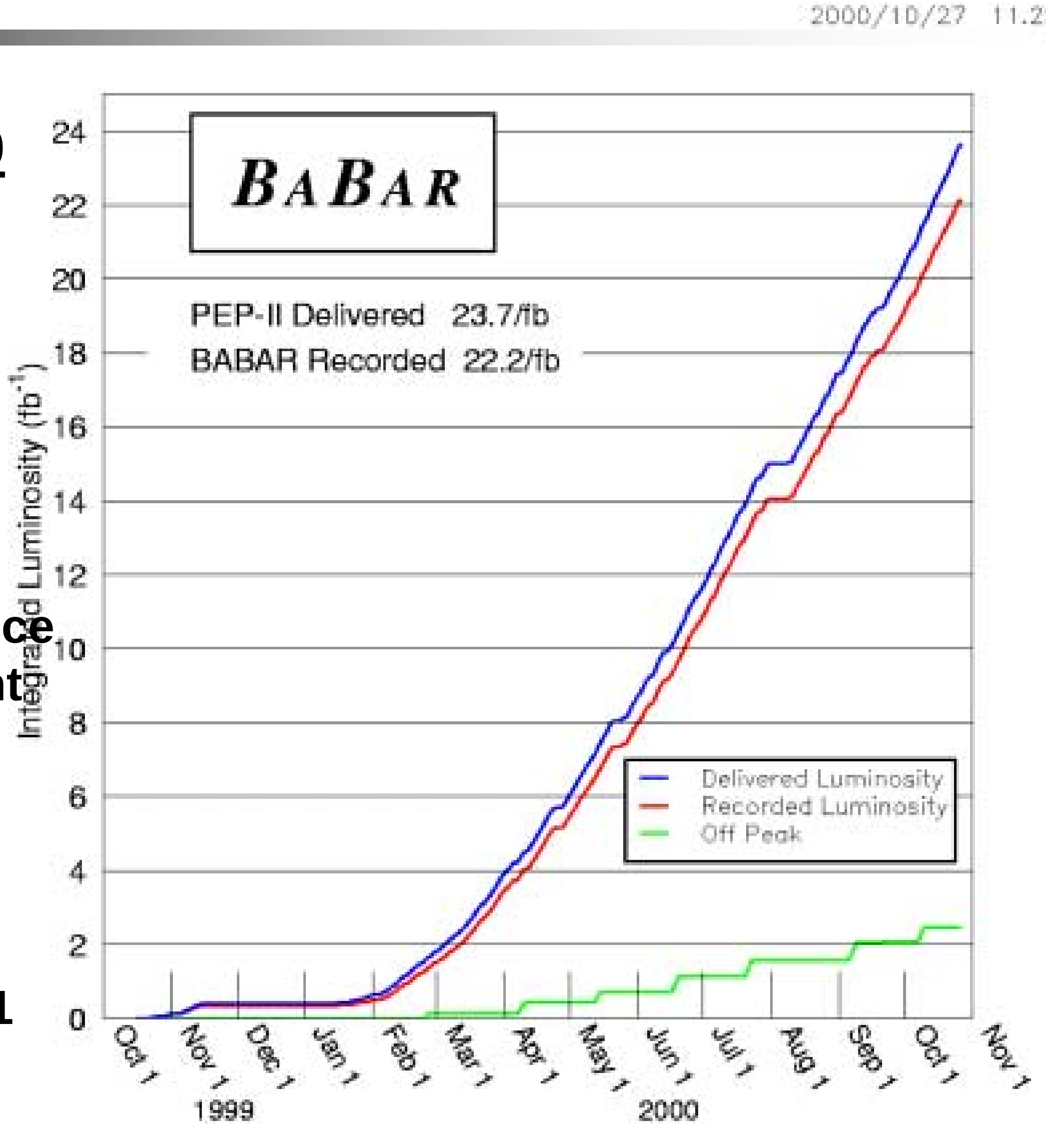
Year 2000/01 Operations

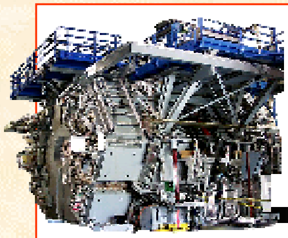
- **Running began Jan 2000**

  ~24 fb^{-1} total by Oct 31
  - **~21 fb^{-1} Υ(4S);**
  - **~3 fb^{-1} continuum**

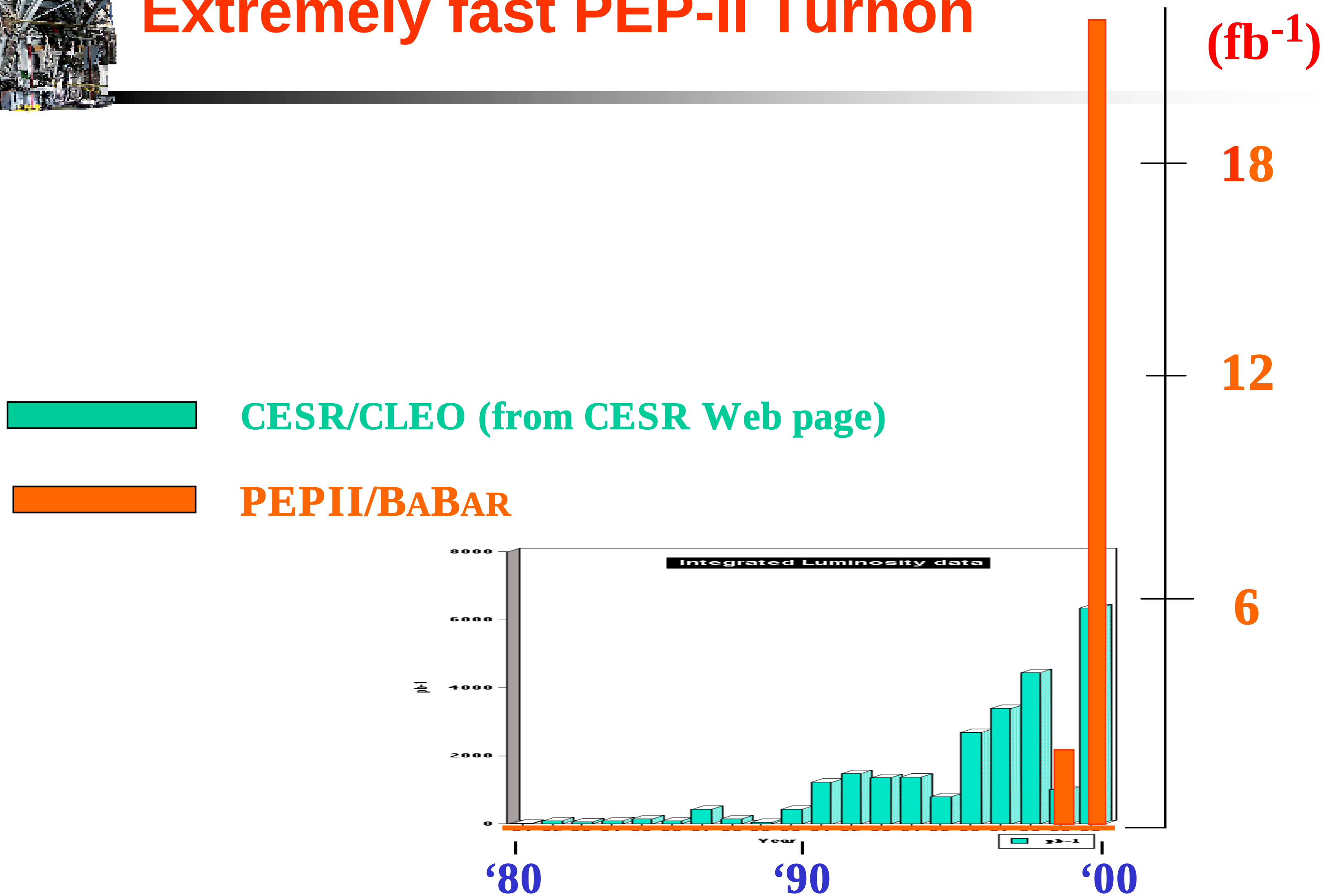
- **Shutdown Nov1 – Feb1**
  - **PEPII improvements**
  - **BaBar repair/maintenance**
  - **Computing development for 5 x 10^{33}**

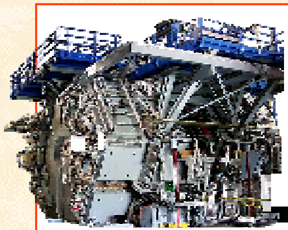
- **2001 Run is underway**
  - **Began 3 Feb**
  - **1.5 10^{33} As of 15 Feb**
  - **Expect ~40 fb^{-1} in CY '01**





Extremely fast PEP-II Turnon





Operations …

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

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

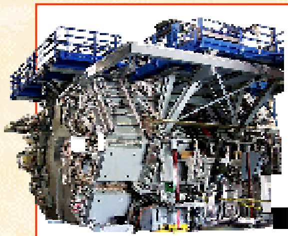
Preliminary
(~2% uncertainty)

- BaBar performed just fine at **3.2** $\times$ **10**^{33}
- This year we expect to reach **5** $\times$ **10**^{33}
- Luminosity profile - next few (calendar)years:

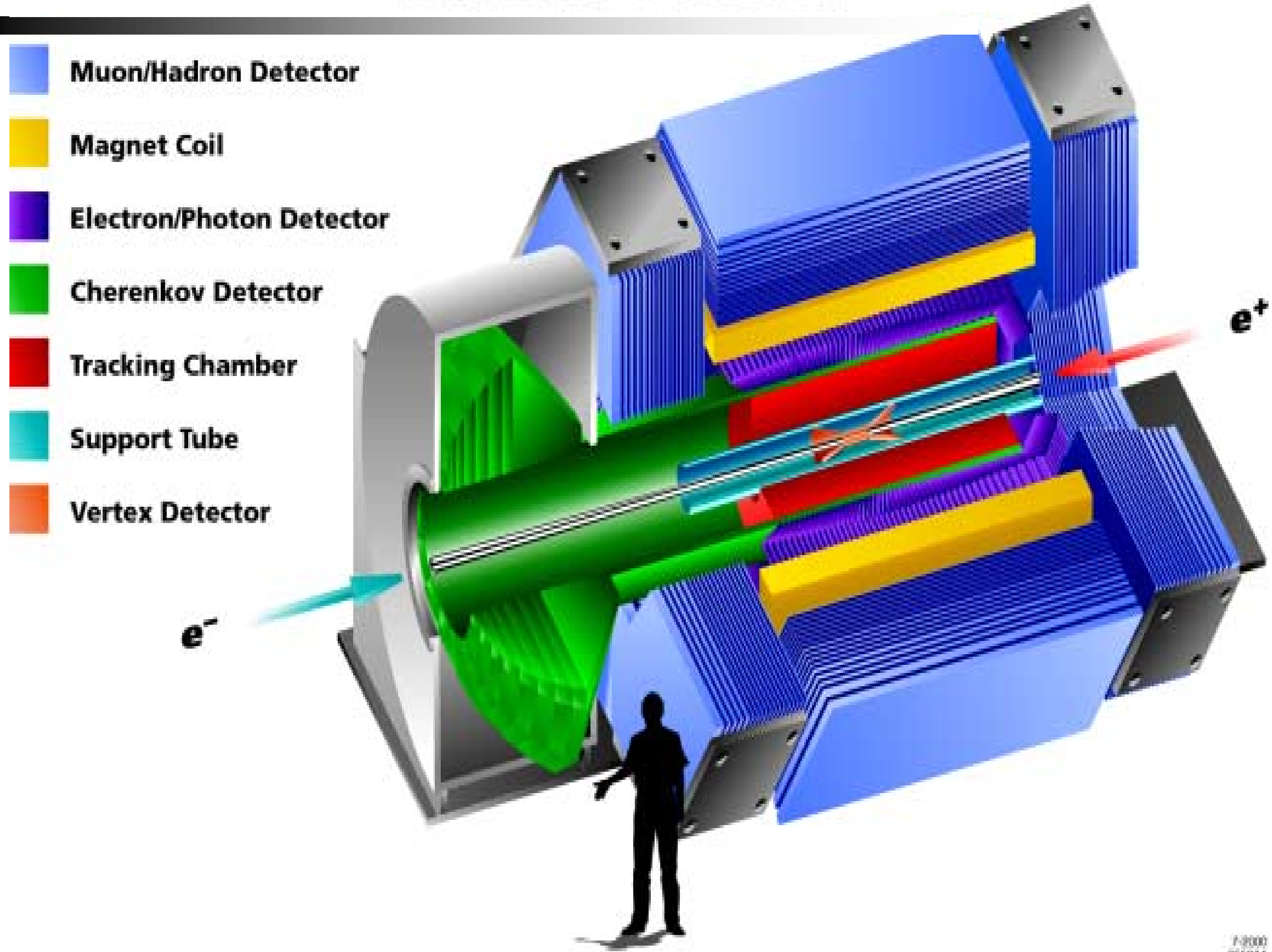
2000	2001	2002	2003	2004	2005	
25	43	80	110	130	180	fb^{-1}

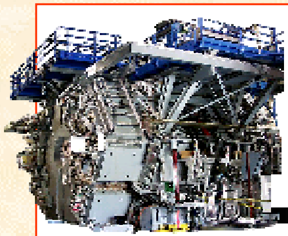
$\int$ Ldt $>$ 500 fb^{-1} by end of 2005

- **We're going to need it – life is hard.**



BaBar Detector





B^0-$\bar{B}^0$ Mixing and ~~CP~~

- Neutral *B* and $\bar{B}$ mix into mass eigenstates, oscillating at a frequency determined by Δm_B <u>Concezio Bozzi talks on BaBar mixing results at 0900 Thur.</u>

$$\frac{q}{p} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{2i\phi_M}$$

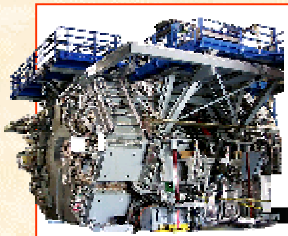
- **We define** $\lambda = \frac{q}{p}\frac{\bar{A}}{A}$, **where**

$$\bar{A} = \langle f \mid H \mid \bar{B}^0 \rangle$$
$$A = \langle f \mid H \mid B^0 \rangle$$

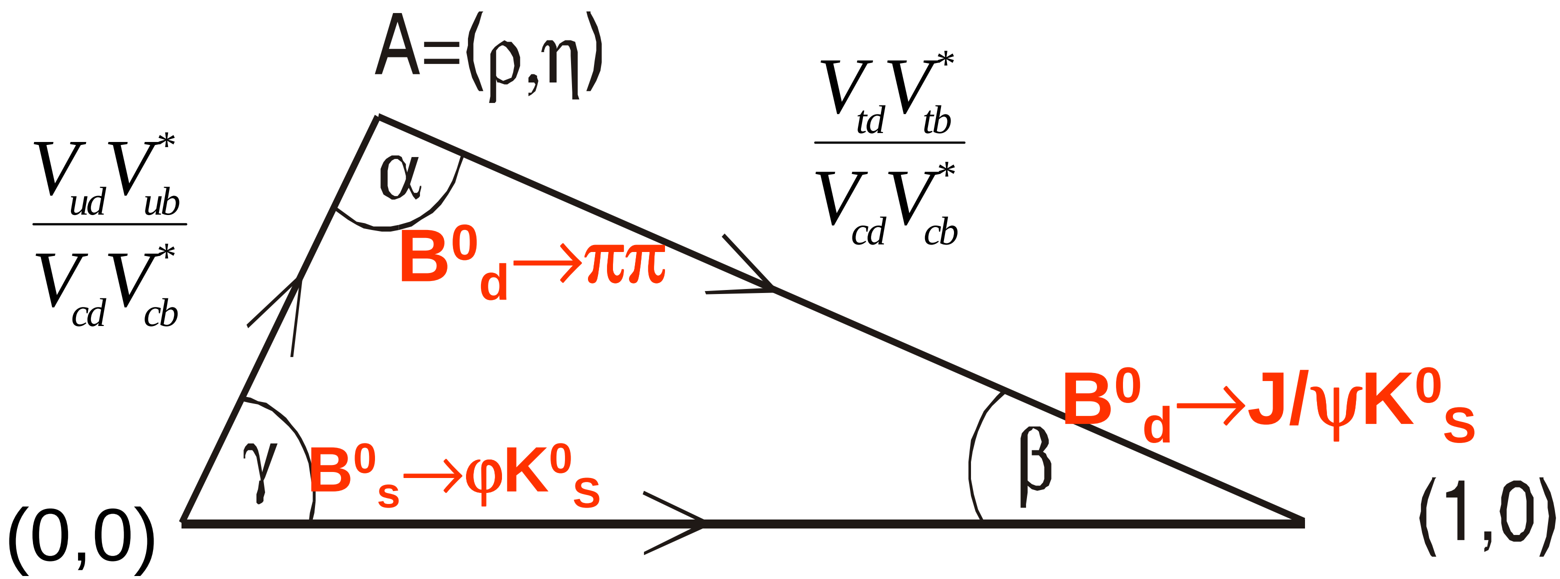
- **For a single decay amplitude with weak phase** ϕ_D

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

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

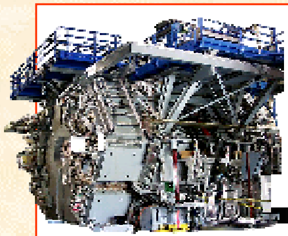


~~CP~~ in the SM –“The Triangle!”



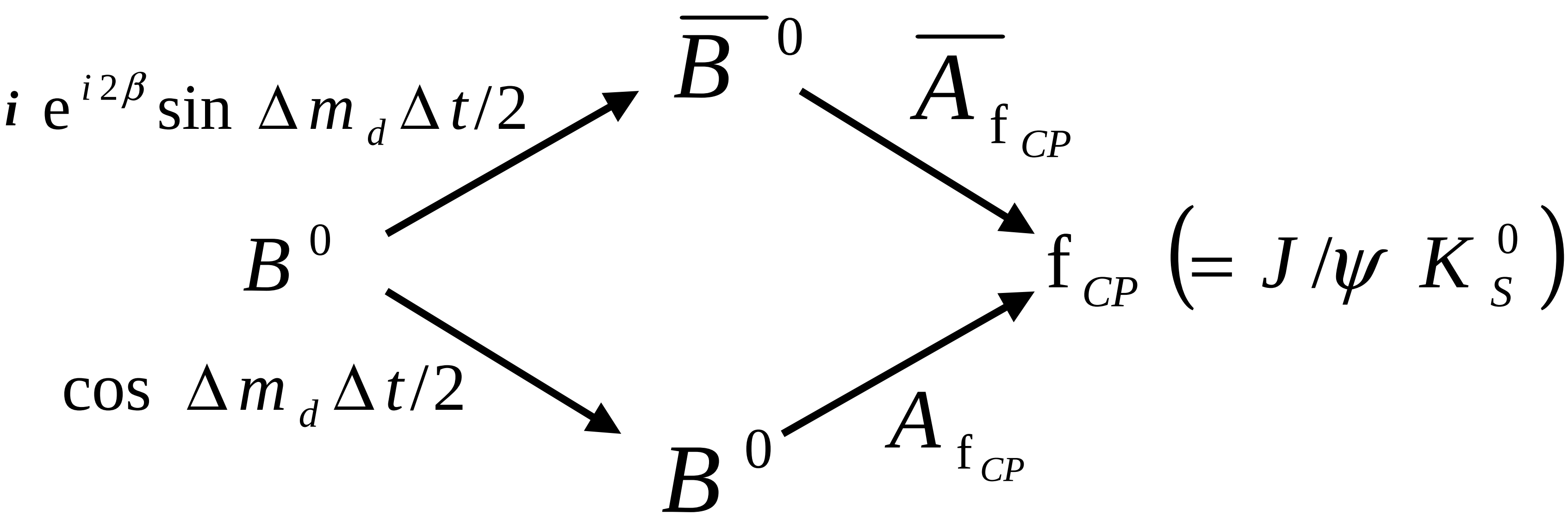
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

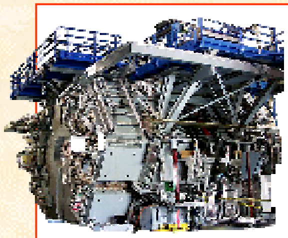
***CP*-violating Asymmetries in *B* decays directly measure phases α, β, and γ via– “no” hadronic uncertainties**



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

- The $\Upsilon(4S)$ decays into a *P*-wave $B^0\overline{B}^0$ state that evolves coherently till one of the *B*'s decays. The *B*'s are almost motionless in the $\Upsilon(4S)$ rest frame.
- We measure the interference between direct and mixed decays to a *CP* eigenstate



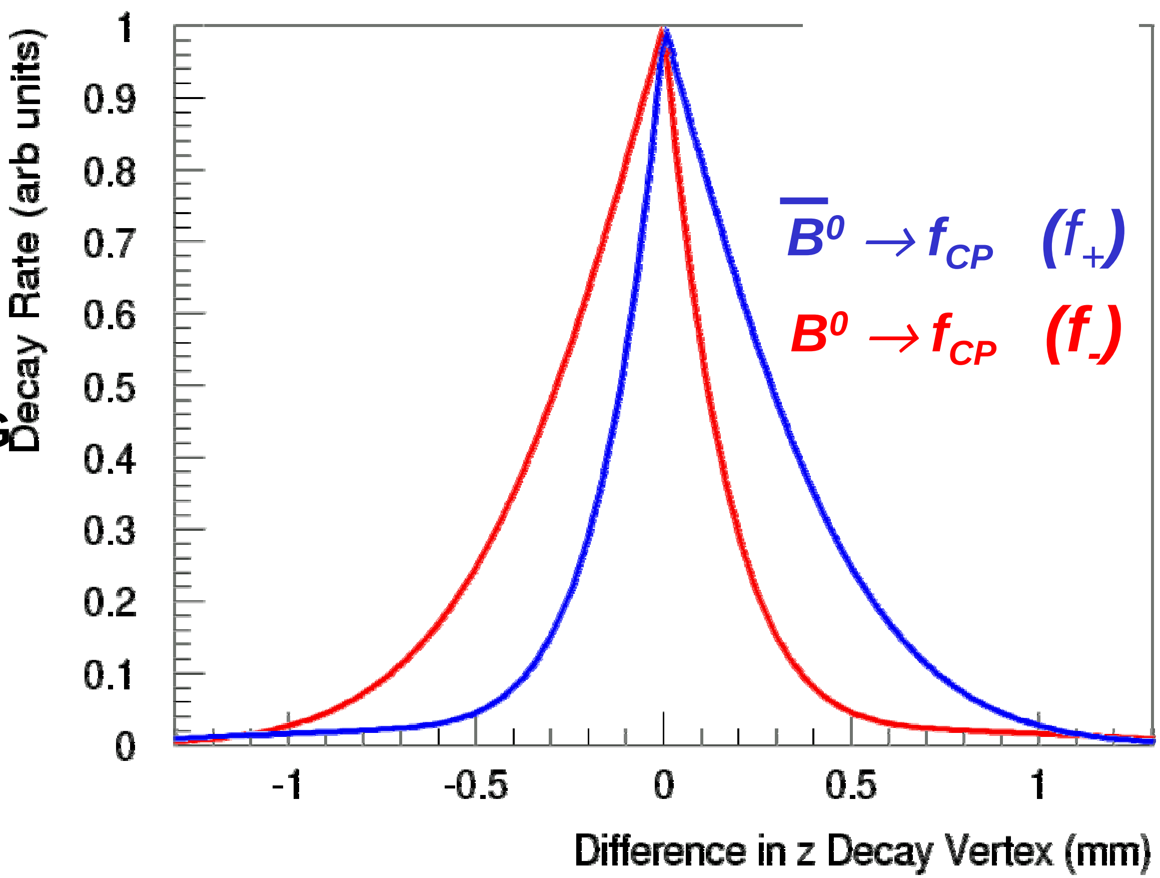


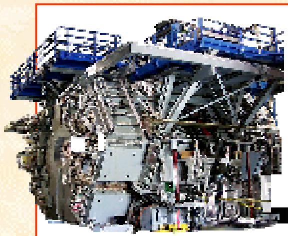
Decay-time Distributions

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

For a *tag* B^0 ($\overline{B}^0$) 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

- **For $b \rightarrow (c\bar{c})s$** $|\lambda|=1$ **and** $\mathrm{Im}\,\lambda = -\eta_f \sin 2\beta$

  $\beta = \arg\,[V_{cd}V_{cb}^{*}/\,V_{td}V_{tb}^{*}]$

- **We reconstruct the "gold / silver" CP eigenstates:**

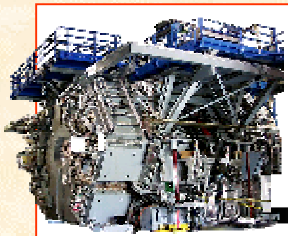
  $J/\psi K^0_S,\ \psi(2s)K^0_S \quad (\eta_f = -1)$

  $J/\psi K^0_L \quad (\eta_f = +1)$

- **t-dependent asymmetries:**

$$A_{CP}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \sin(\Delta m_{B^0}\Delta t)$$

$\int A_{CP}\,dt = 0 \Rightarrow$ Asymmetric *B* Factory!

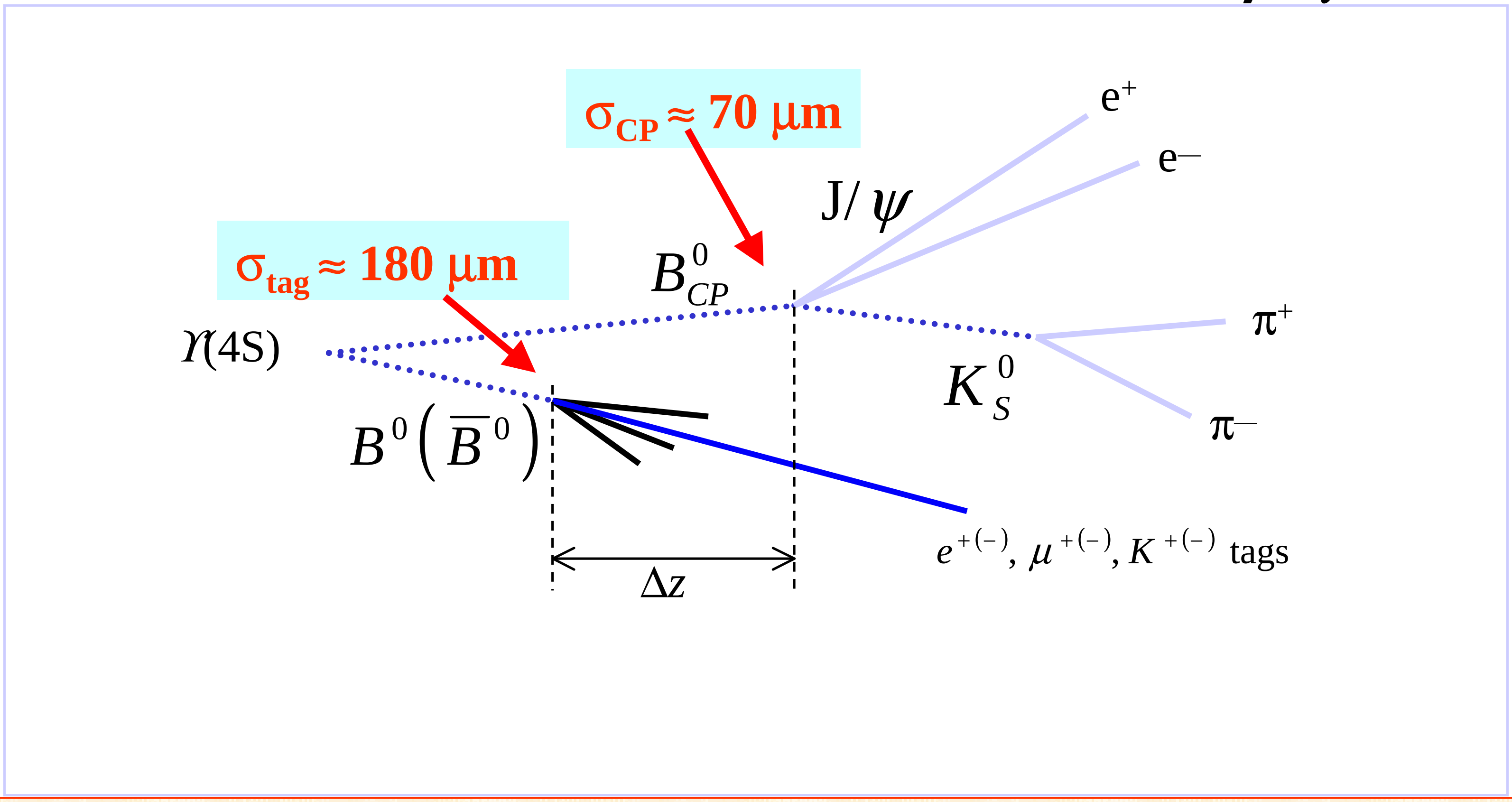


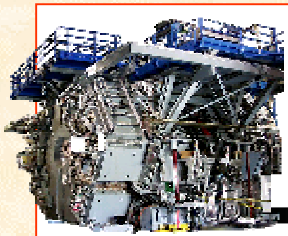
Measuring Δt at PEPII

- E^- = 9.0 GeV; E^+ = 3.1 GeV

Lorentz Boost $\Rightarrow$ $\beta\gamma$ **= 0.56**

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

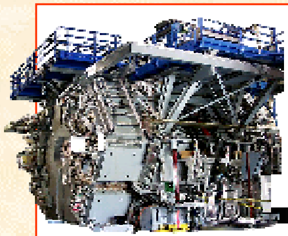




Overview of the Analysis

Fully reconstruct exclusive *B* decays to eigenstates of *CP* or flavour, and tag flavour of the other *B* in the event.

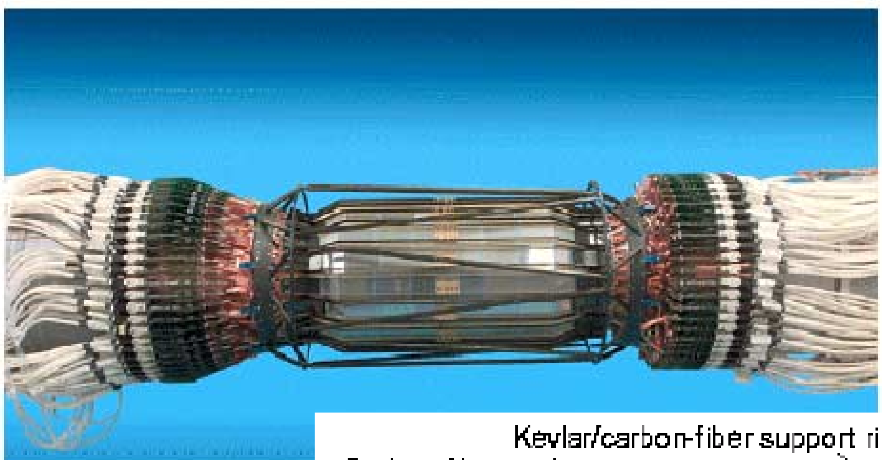
- Select B_{CP} candidates **(**$B^0 \rightarrow J/\psi K_s$ **,** *etc.)* and B_{flav} candidates **(**$B^0 \rightarrow D^* \; +$, *etc.)*
- Select B_{tag} events using, primarily, leptons and *K*'s from *B* hadronic decays, and determine the *B* flavour**.**
- Measure the mistag fractions w_i and determine 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**



Crucial Elements in A(Δt) measurement: I. Vertex Resolution

Even at PEP-II, *B*'s don't go very far! (≈ 250 **μm)**

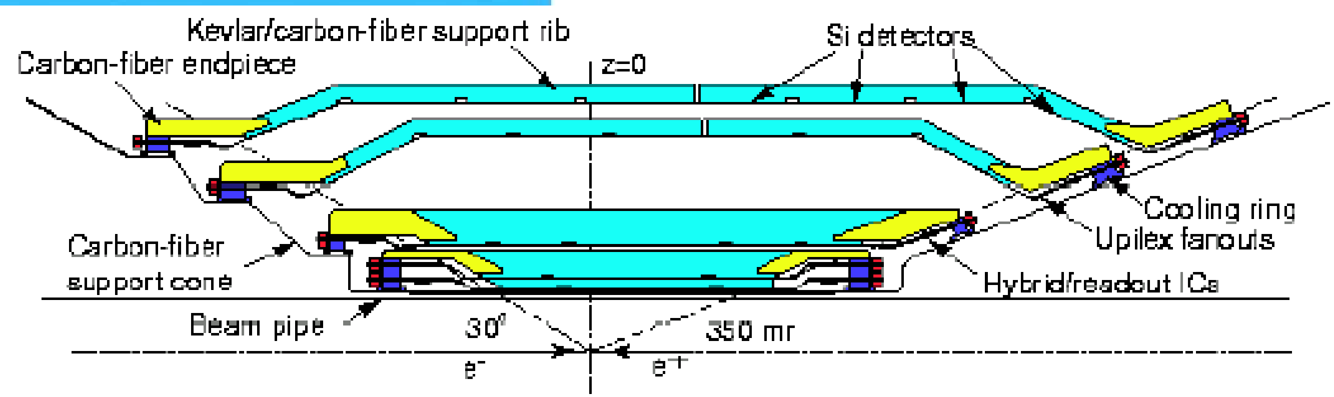
⇒ 5 Layer Silicon Vertex Tracker

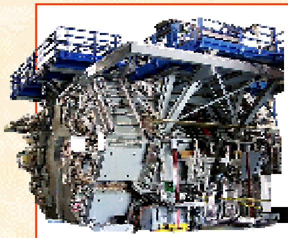


σ_z≈70 μm: reco'd *B*

180 μm: tagging *B*

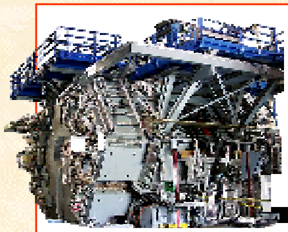
(rms for 99% of events)



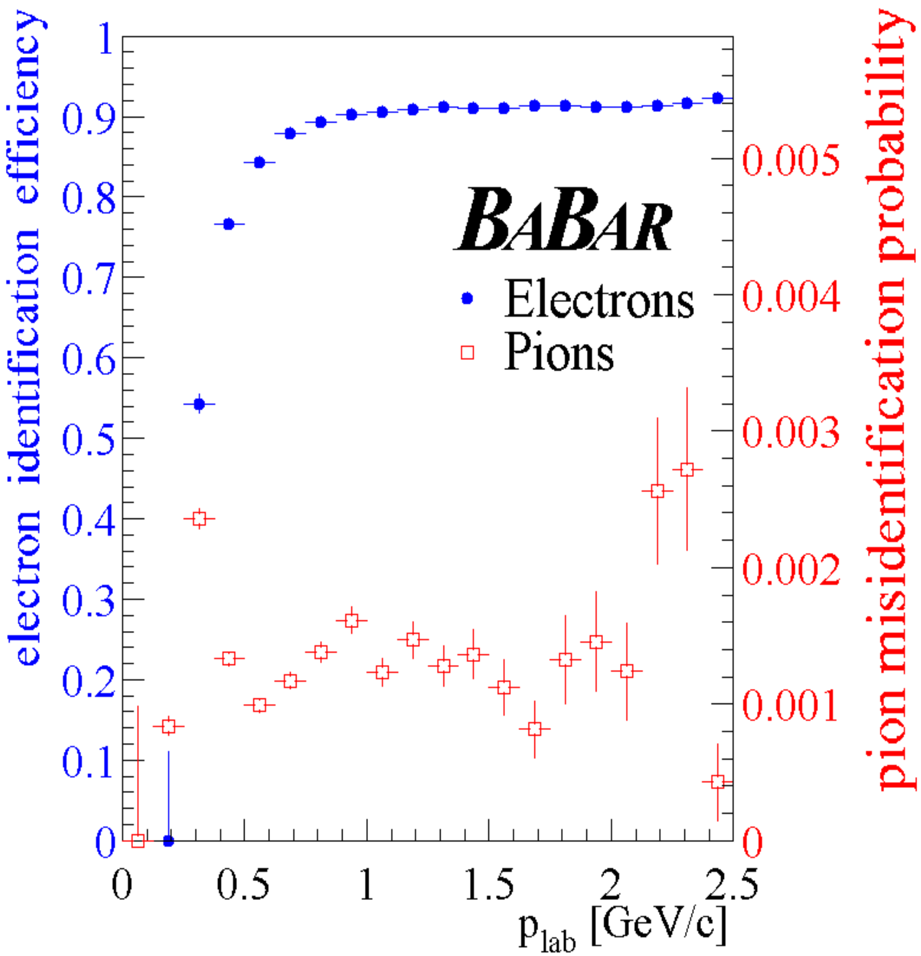


Crucial Elements in $A(\Delta t)$ measurement: II. Particle ID and Tagging

- J/ψ's are detected by their *ee* and $\mu\mu$ modes
- K_L modes are an important contributor to *CP* sample. K_L's are detected by their strong interaction debris in EMC and IFR
- The flavour of the tagging *B* decay is determined from its lepton and kaon content, and from slow pions from *D**'s



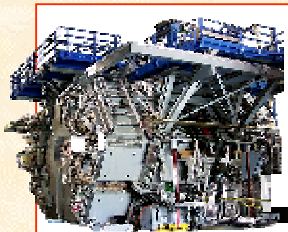
Particle ID: Electrons



- **Track matching in the EMC**
- **0.89 < E/P < 1.2**
- **EM shower shape requirements**
- **DCH d*E*/d*x* consistent with electron hypothesis**

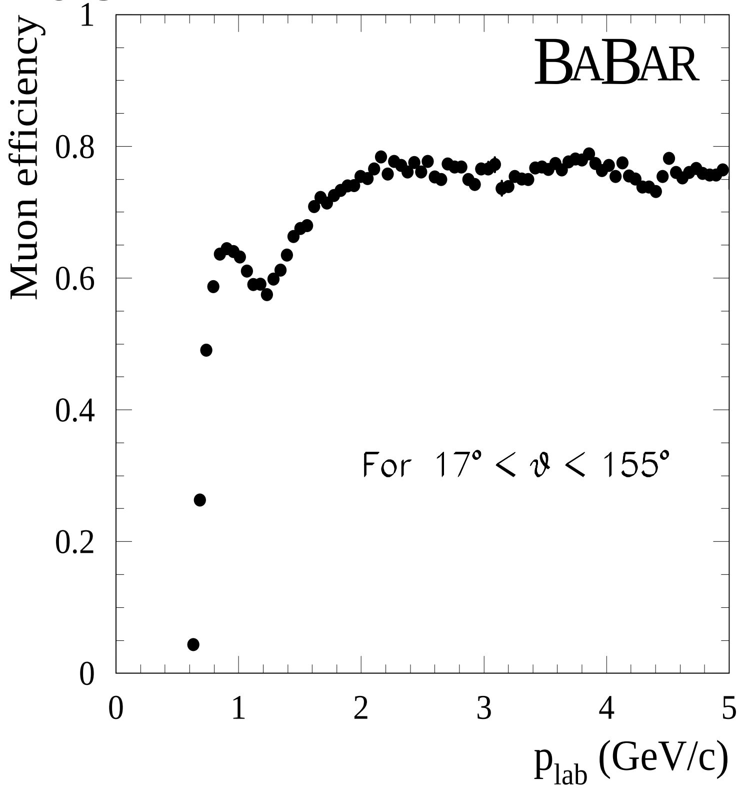
- **Efficiency and π misID probabilities determined from the data (Control Samples)**

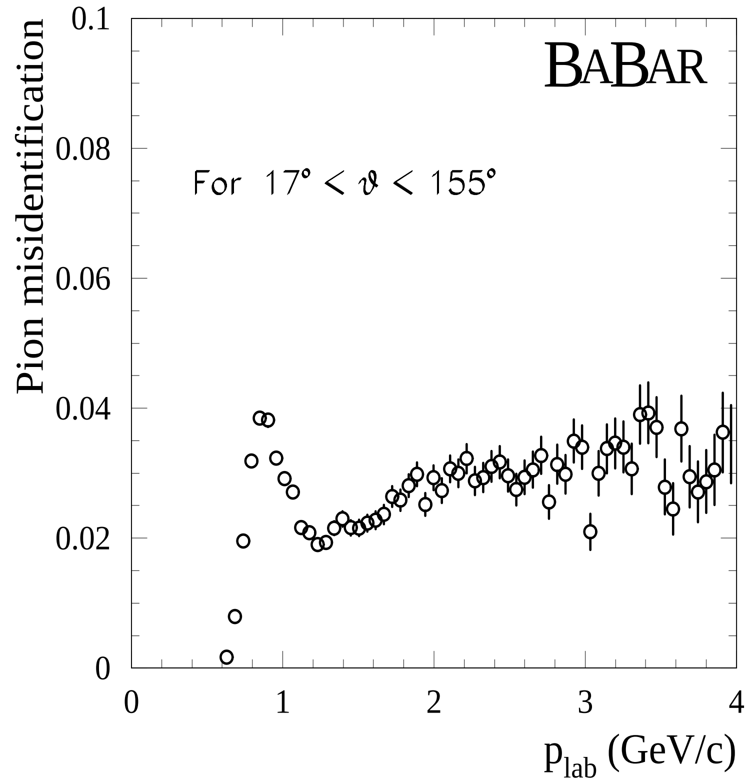
- **Typical Tight Electron selection: ~92% efficiency above 500 MeV, with 0.1% π misID**

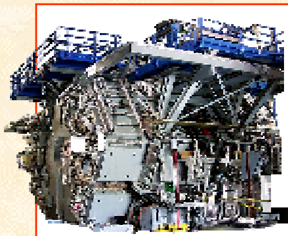


Particle ID: Muons

- 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

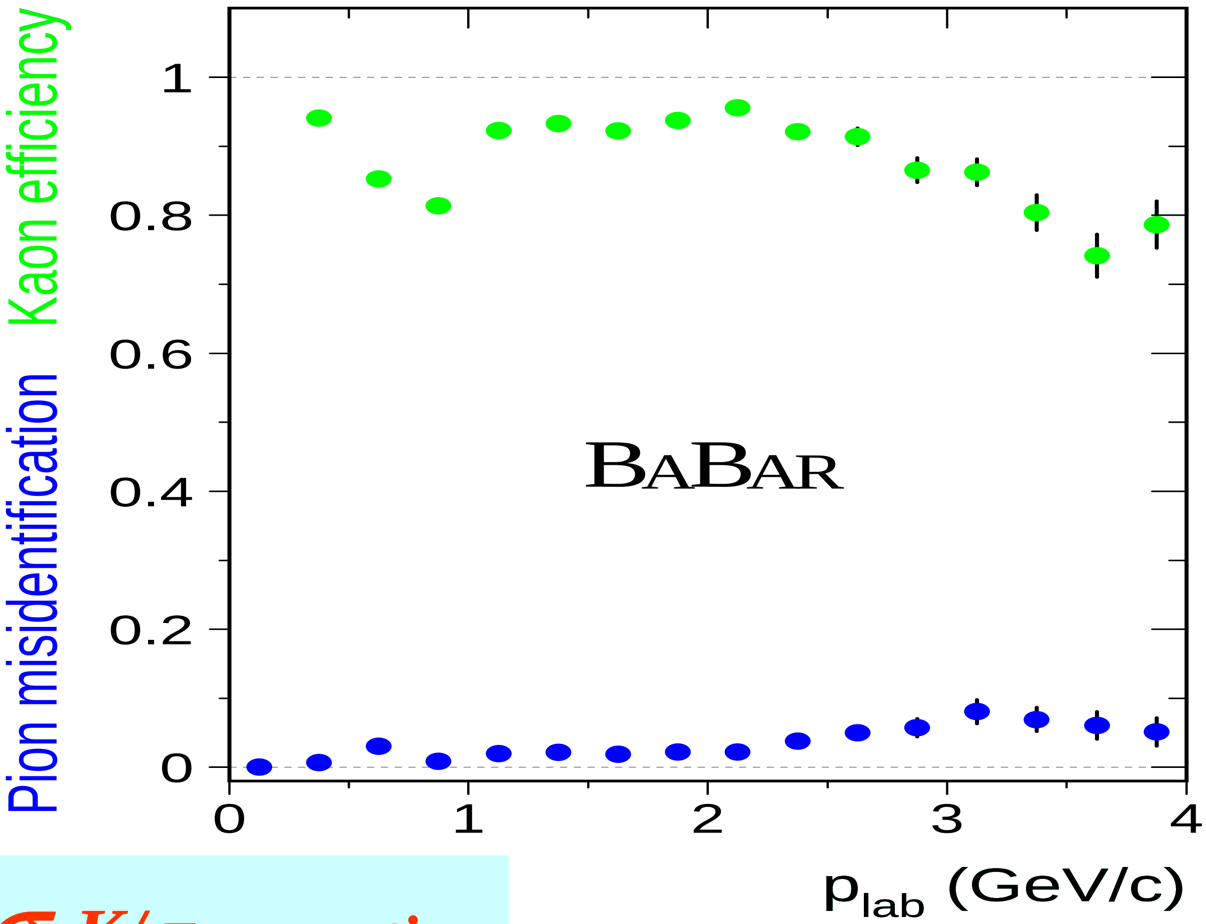




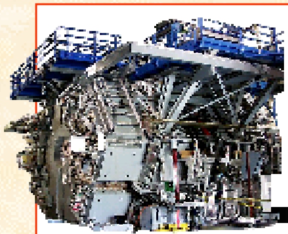


Particle ID: Kaons

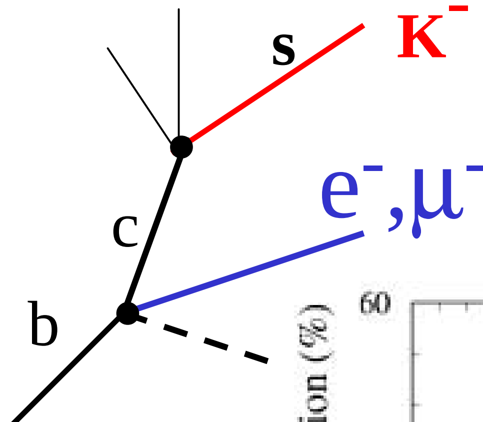
- ***dE/dx*** **from DCH and SVT**
- θ_c **from DIRC**



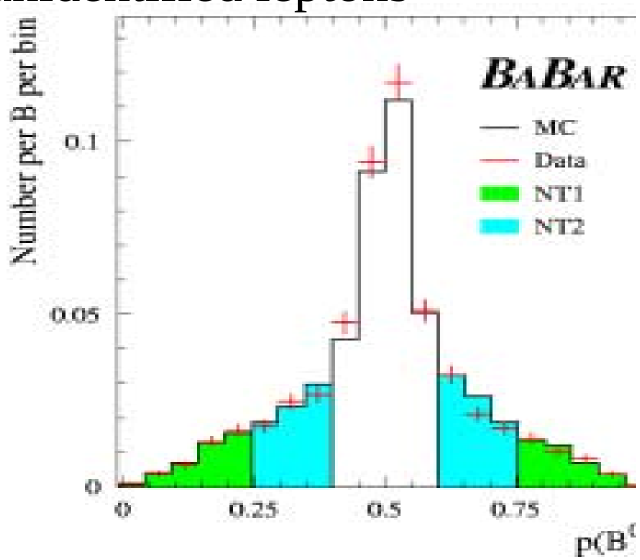
Better than 3 σ K/π separation for p_K > 250 MeV/c

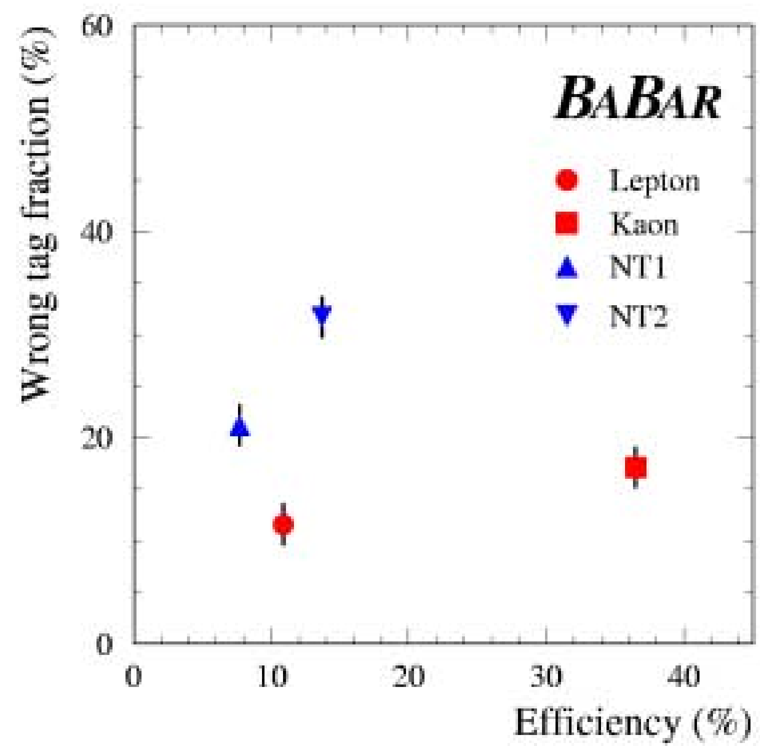


B Flavour-Tagging Categories

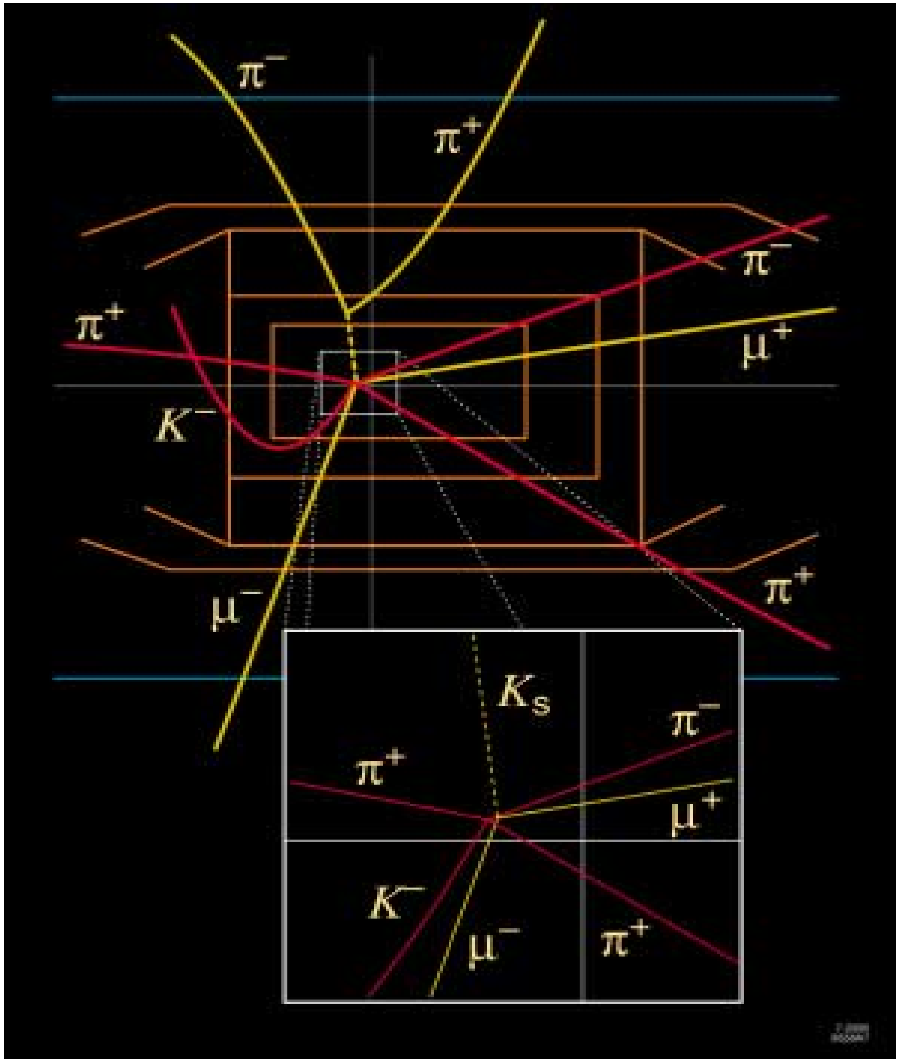


- **Leptons** ($l^- \rightarrow \bar{B}^0$ **tag**)
  - Electron P_{cm} >1.0 GeV/c
  - Muon P_{cm} >1.1 GeV/c
- **Kaons**
  - Σ Kaon Charge ≠ **0**
- **NT1,NT2 (neural net)**
  - slow pions (from ***D****)
  - Isolated unidentified leptons





An Event from the CP Sample



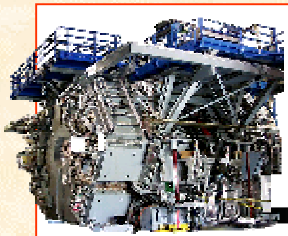
A candidate in the **Golden Mode**

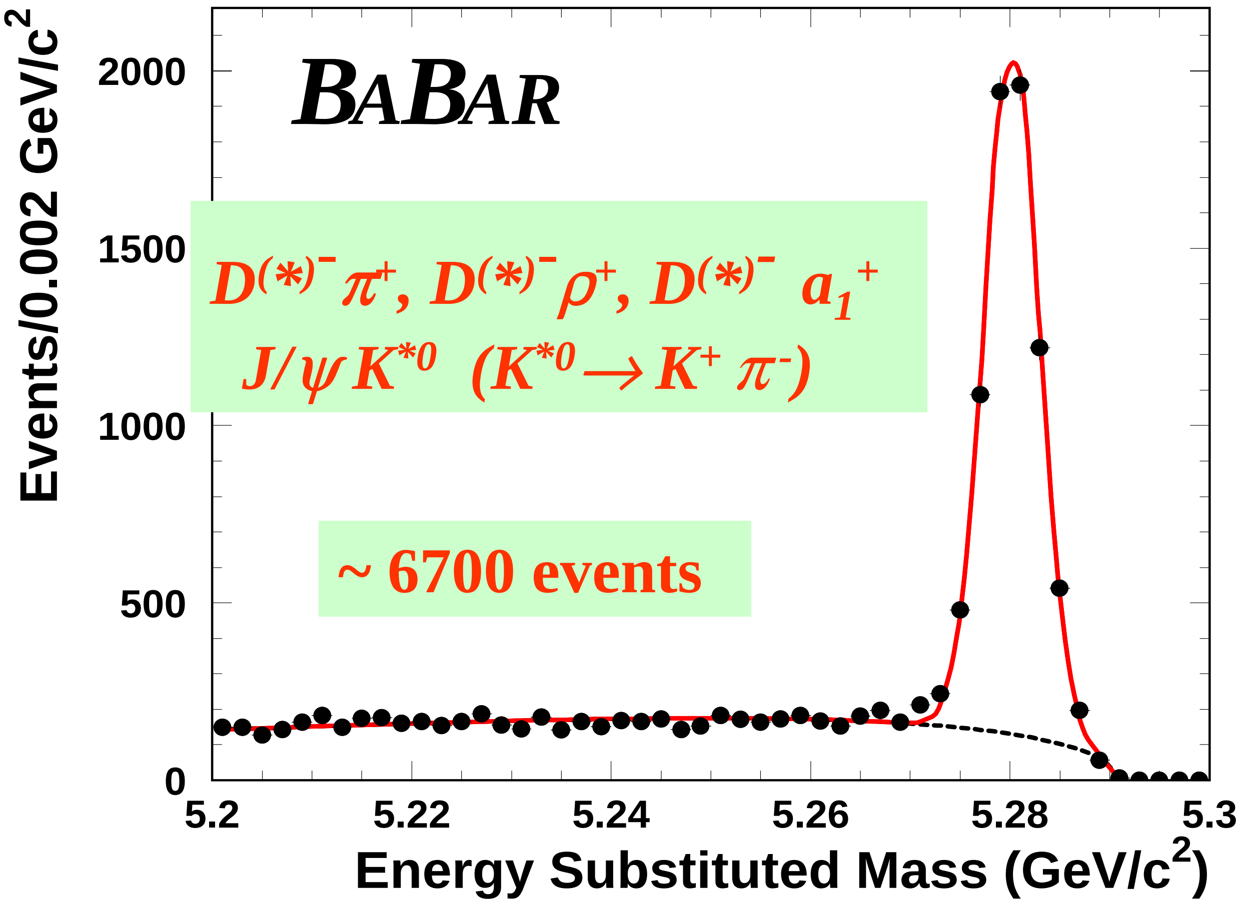
$$B^0_{CP} \rightarrow J/\psi K^0_S, \quad K^0_S \rightarrow \pi^+\pi^-$$

with: $J/\psi \rightarrow \mu^+\mu^-$

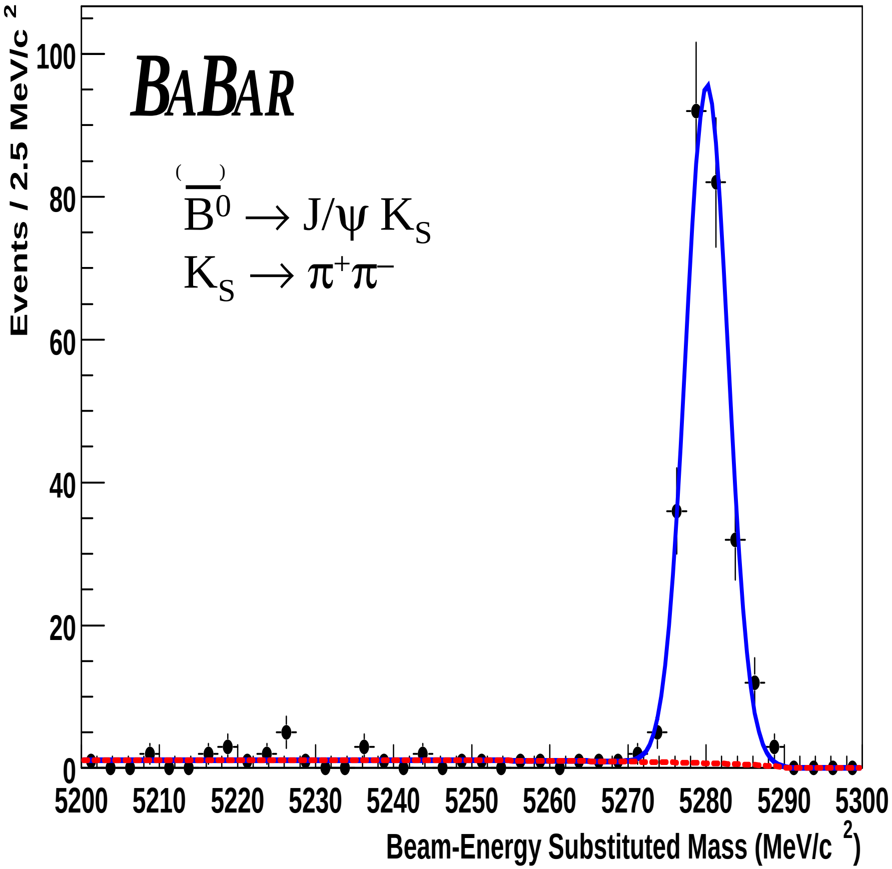
- A negative kaon is found in the decay products of the other ***B*** meson, which is therefore tagged as a $\overline{B}^0$
- **Δz is measured precisely, thanks to the Silicon Vertex Detector**

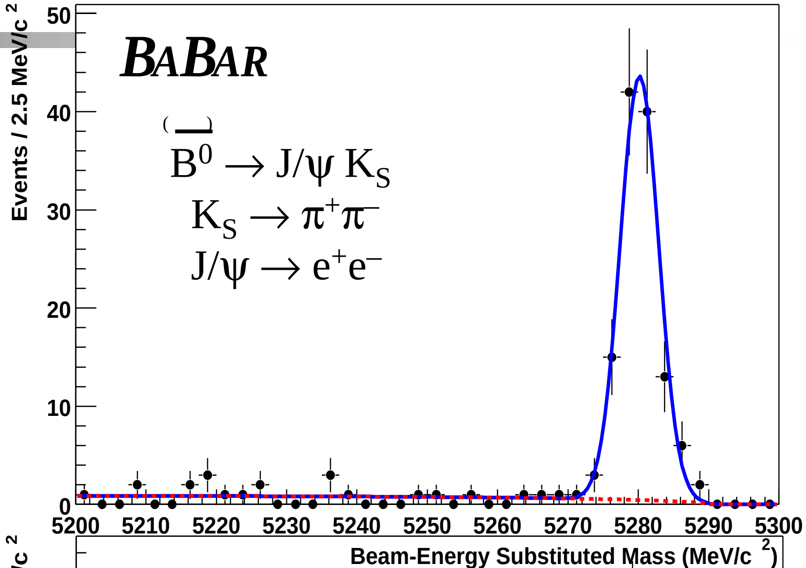
Reconstructed Hadronic B events for mixing and fitting (B_{flav} Sample)

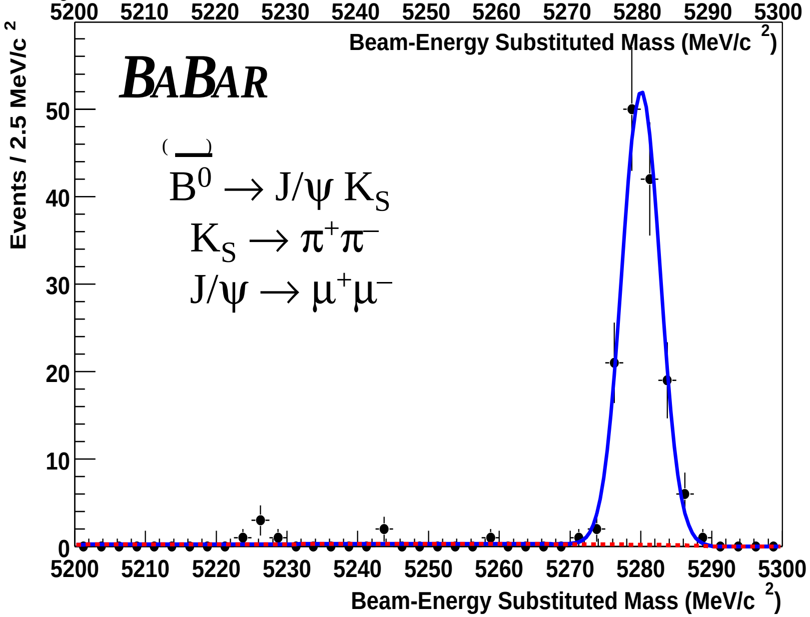


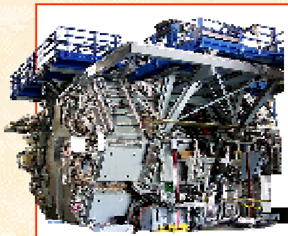


$B^0 \rightarrow J/\psi\ (K_s \rightarrow \pi^+\pi^-)$

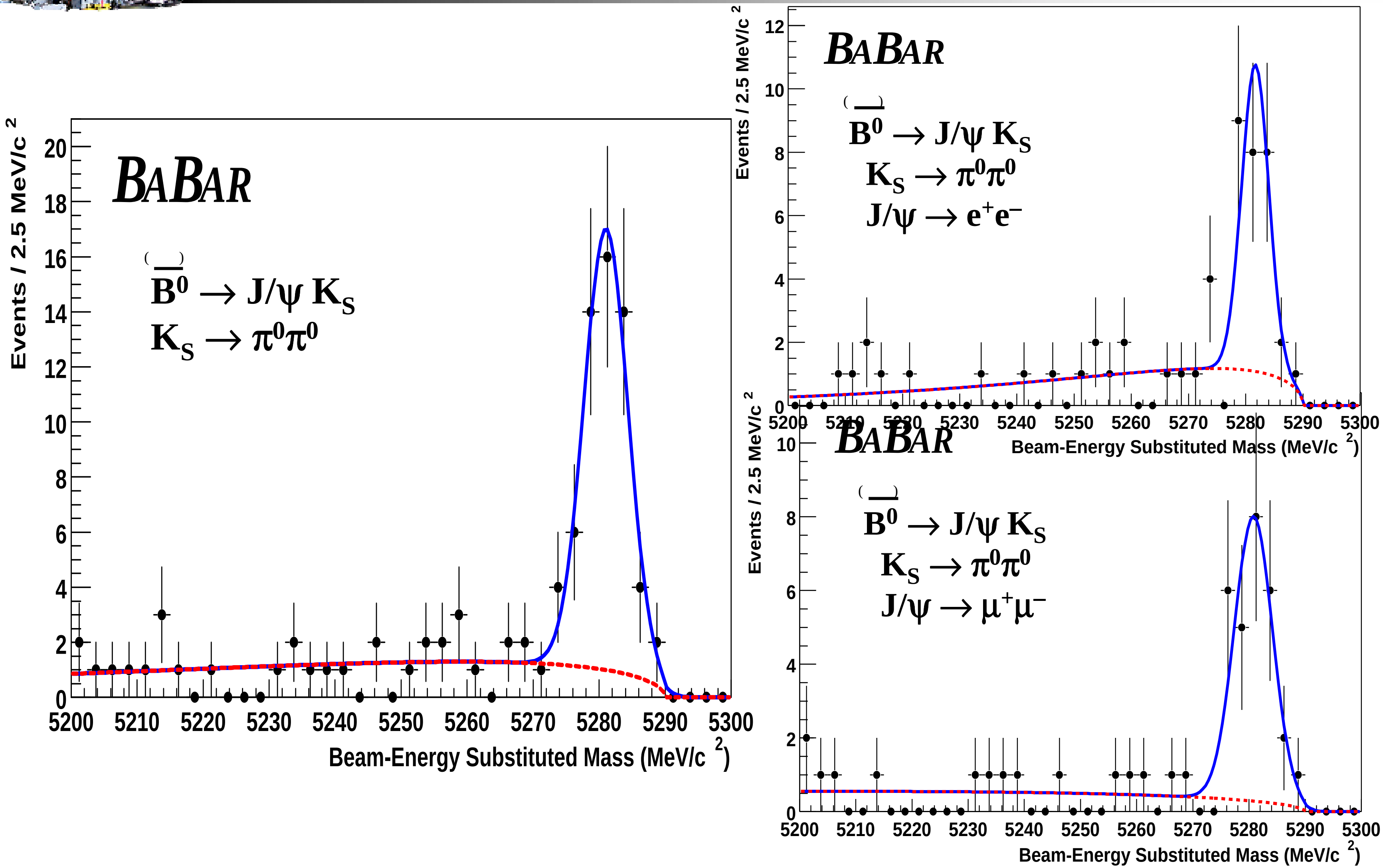


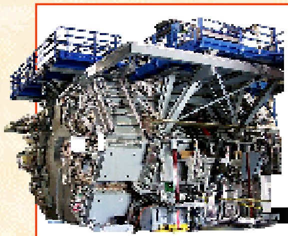




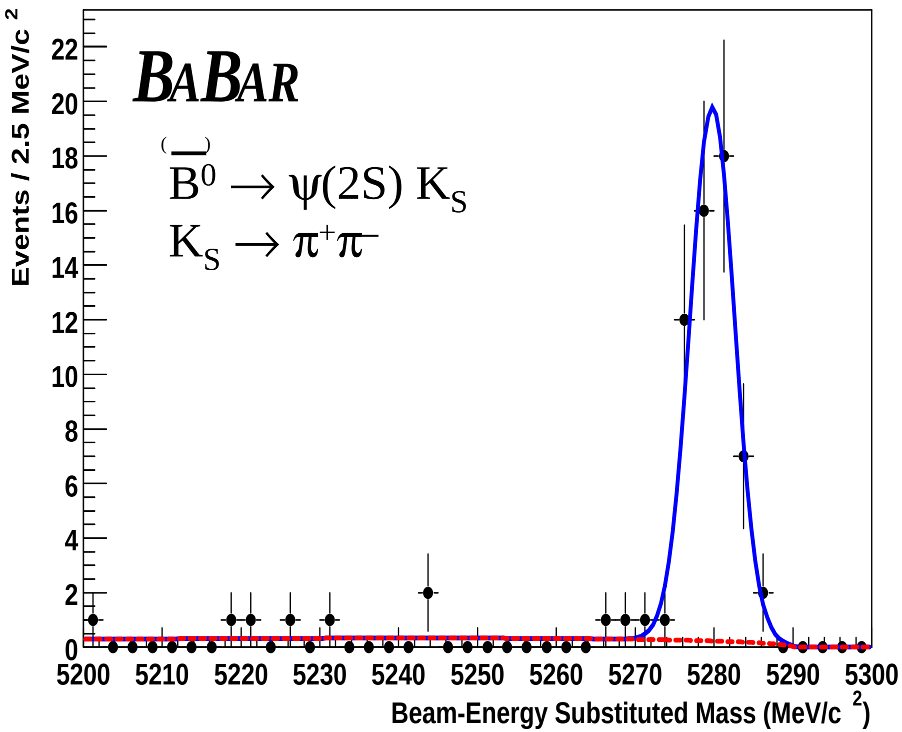


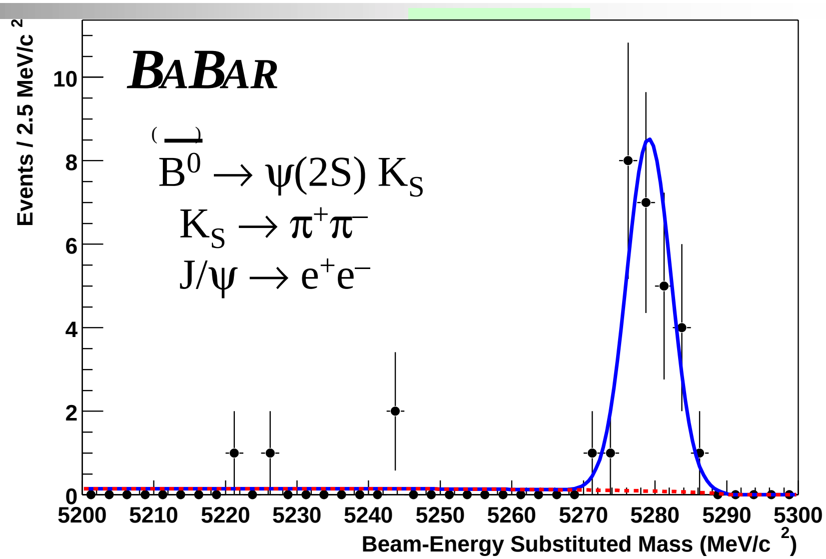
$B^0 \to J/\psi\,(K_s \to \pi^0\pi^0)$

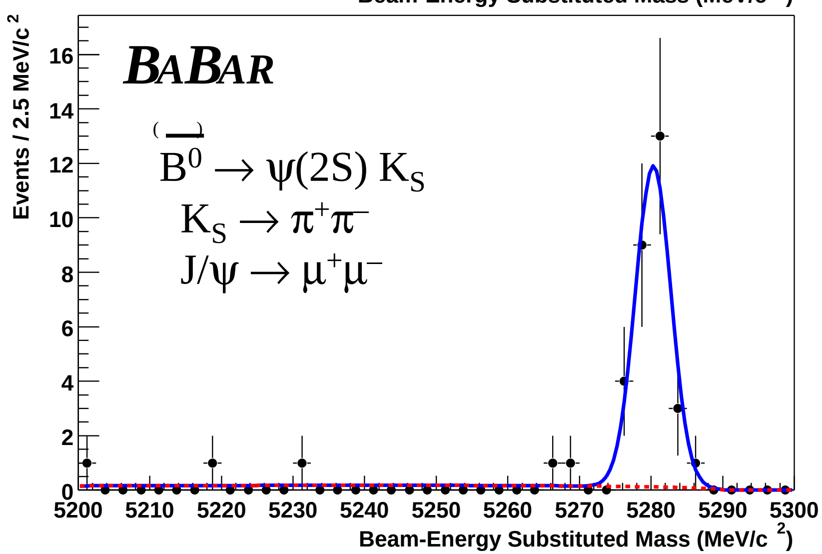




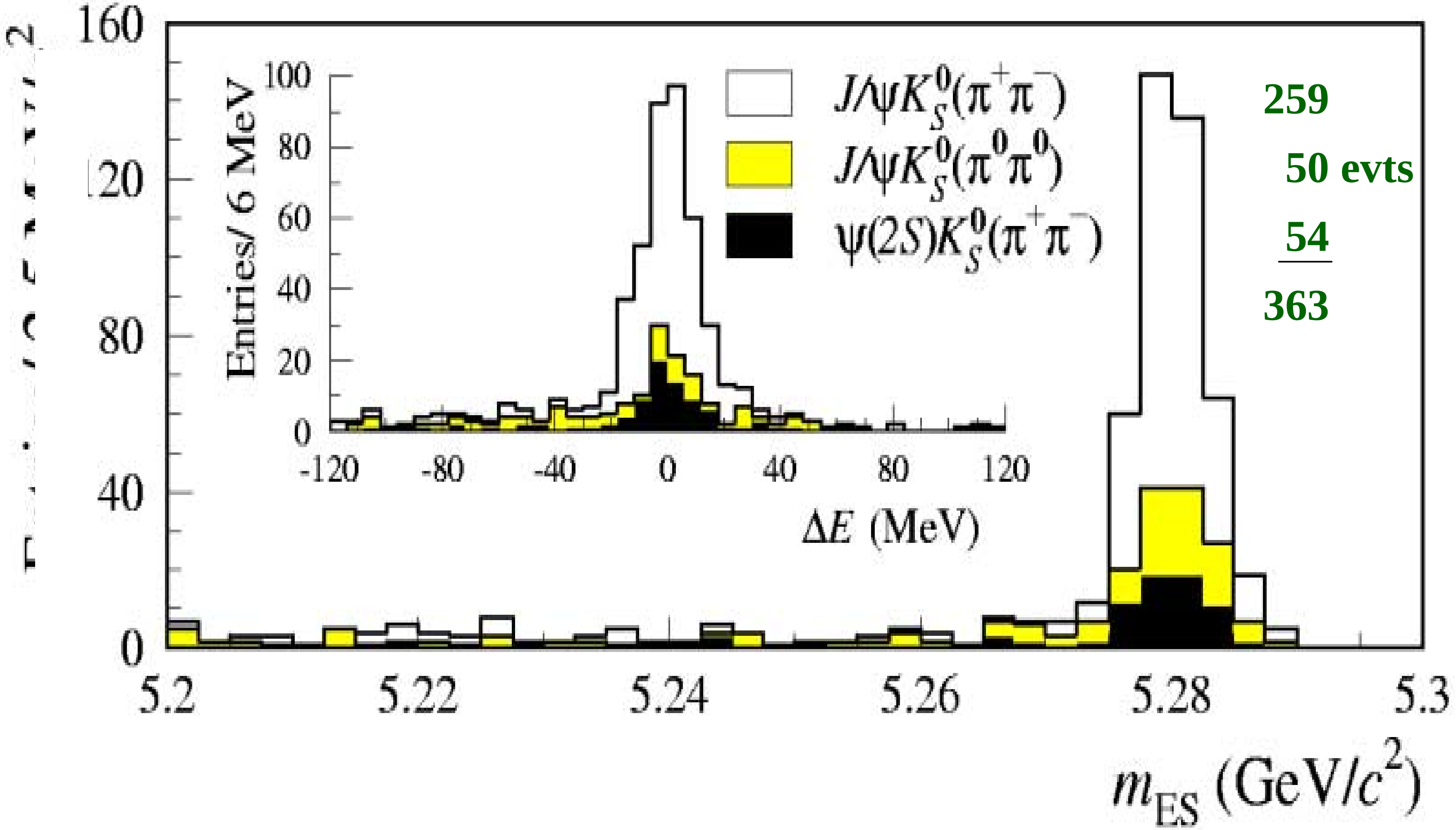
$\psi(2S)\ (K_S \rightarrow \pi^+\pi^-)$



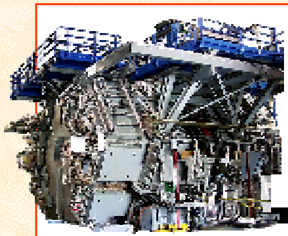




Final *CP* sample of K^0_S modes

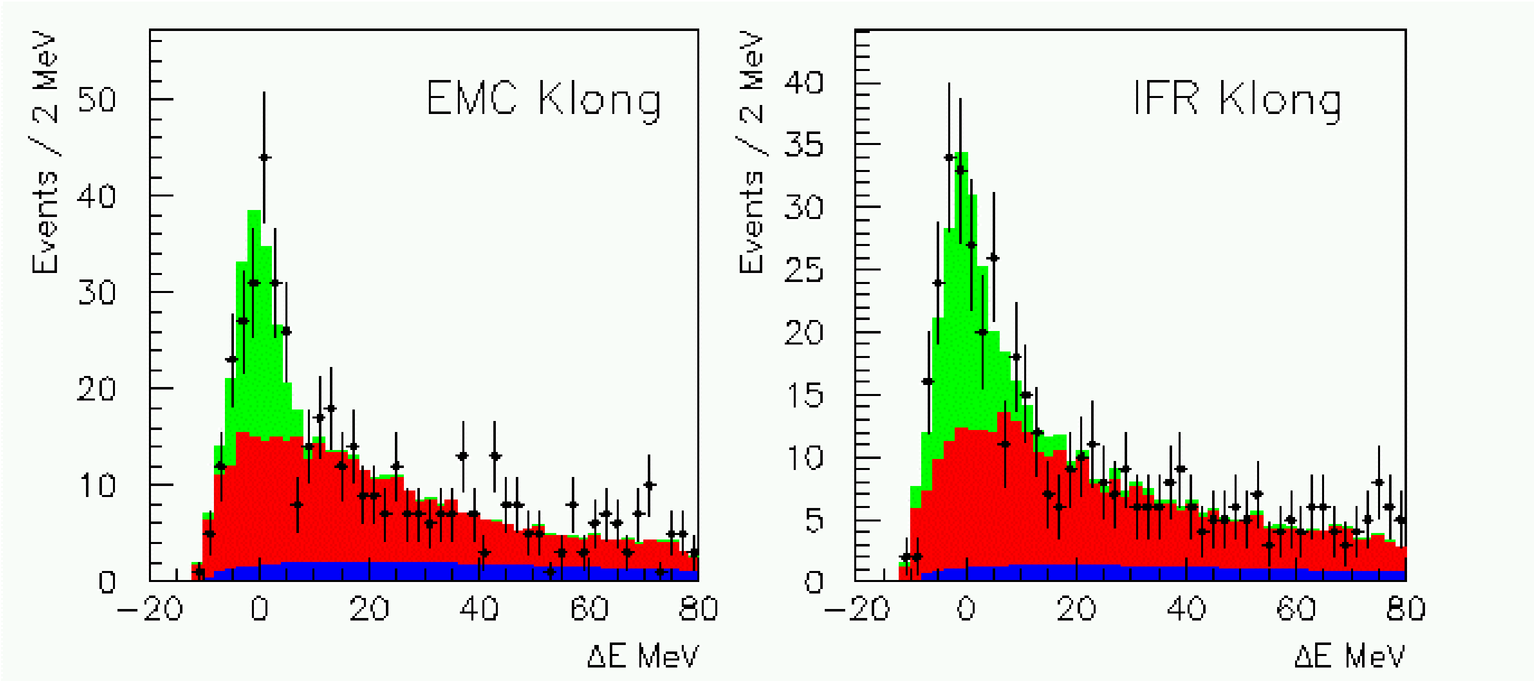


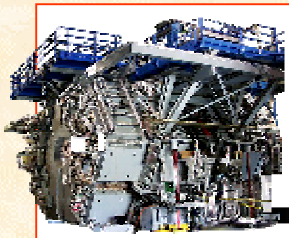
259
50 evts
54
363



$B^0 \rightarrow J/\psi K^0_L$ events in CY 2000 sample

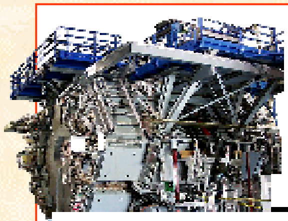
- K^0_L signaled by isolated clusters in IFR (>1 layer) and/or EMC (>200 MeV)
- K^0_L direction is combined with J/ψ momentum to reconstruct K^0_L energy
- ~ 205 total events above large background before tagging. Background shape, amount, and ***CP*** structure studied with Monte Carlo. (182 after tagging)





Likelihood analysis – global fit

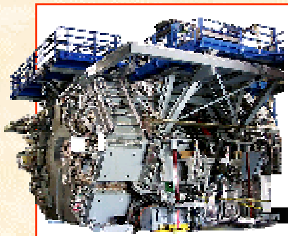
- Simultaneous fit to B_{CP} and B_{flav} samples for *sin 2β* (plus 34 parameters to characterize the detector and the data)
  - Signal Δt resolution function (9 parameters)
  - Signal dilutions and $B^0\ \overline{B}^0$ dilution differences (8 parameters)
  - Background $\boldsymbol{\Delta t}$ structure, resolution function, dilutions and *CP* content (17 parameters)
- Correlations between B_{CP} and B_{flav} are small
- Extract background parameters from:
  - m_{ES} sidebands for golden *CP* modes and B_{flav} modes
  - J/ψ sidebands and inclusive $B^0 \rightarrow J/\psi$ 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



Time (Δt) resolution function

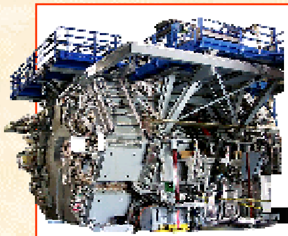
- **Sum of three Gaussians: Core (88%), Tail (11%), and Outliers (1%)**
- **Parameters determined from likelihood fit and other consistency checks**

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

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

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

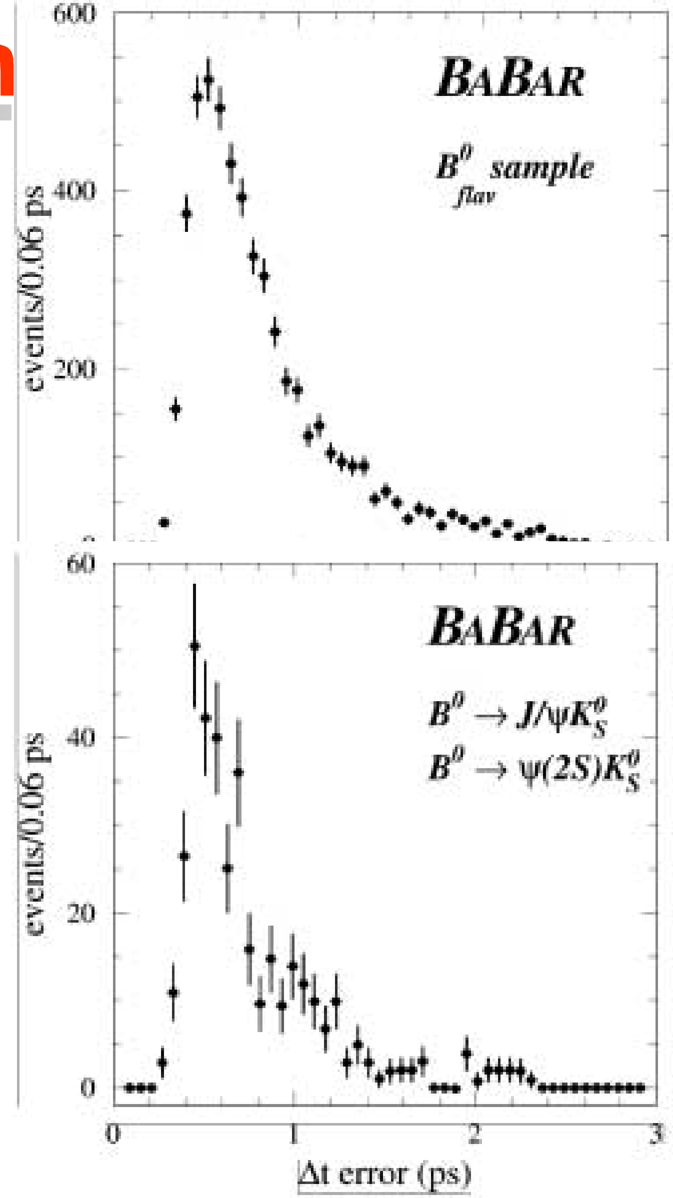
$$+ f_{\text{outlier}} \frac{\exp -\frac{1}{2}\left(\frac{\Delta t - \delta_{\text{outlier}} - \Delta t_{\text{true}}}{\sigma_{\text{outlier}}}\right)^2}{\sqrt{2\pi} \sigma_{\text{outlier}}}$$

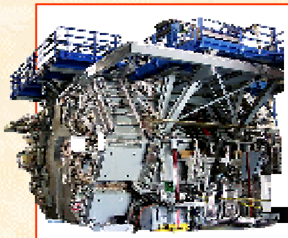


Fitted parameters in Δt resolution function

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
$\delta_{\mathrm{Core,Lepton}}$ (ps)	0.08 ± 0.10
$\delta_{\mathrm{Core,Kaon}}$ (ps)	-0.21 ± 0.05
$\delta_{\mathrm{Core,NT1}}$ (ps)	0.01 ± 0.10
$\delta_{\mathrm{Core,NT2}}$ (ps)	-0.18 ± 0.09
δ_{Tail} (ps)	-0.46 ± 0.38

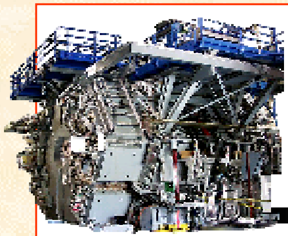




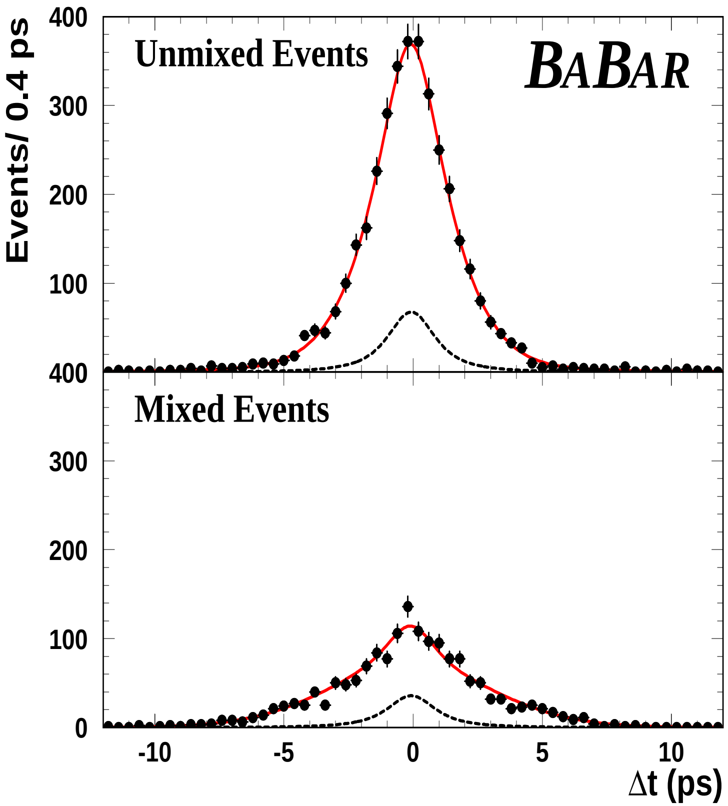
Cross checks on mistag fractions

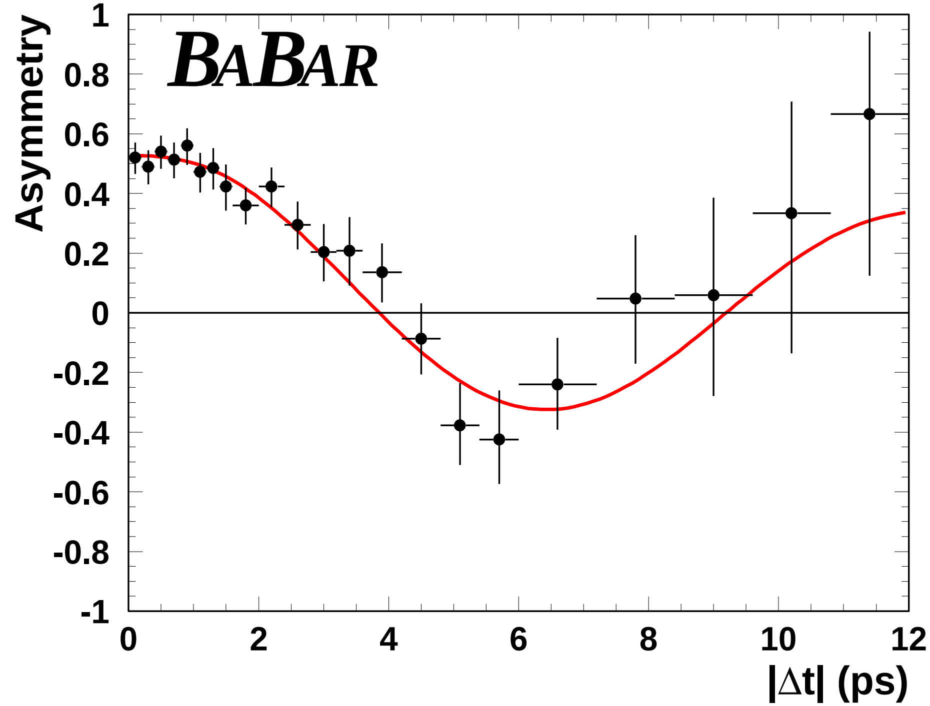
$B^0 \to D^{*-} l \nu$	B_{flav} sample
16,000 events	~5000 events

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



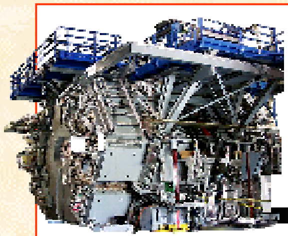
Δt distributions and oscillations for tagged hadronic B decays





Signal + bkgnd — Background

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

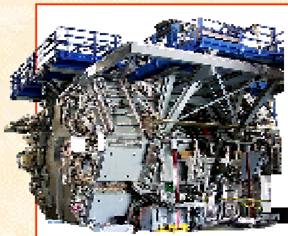


Breakdown of tagged *CP* events

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		



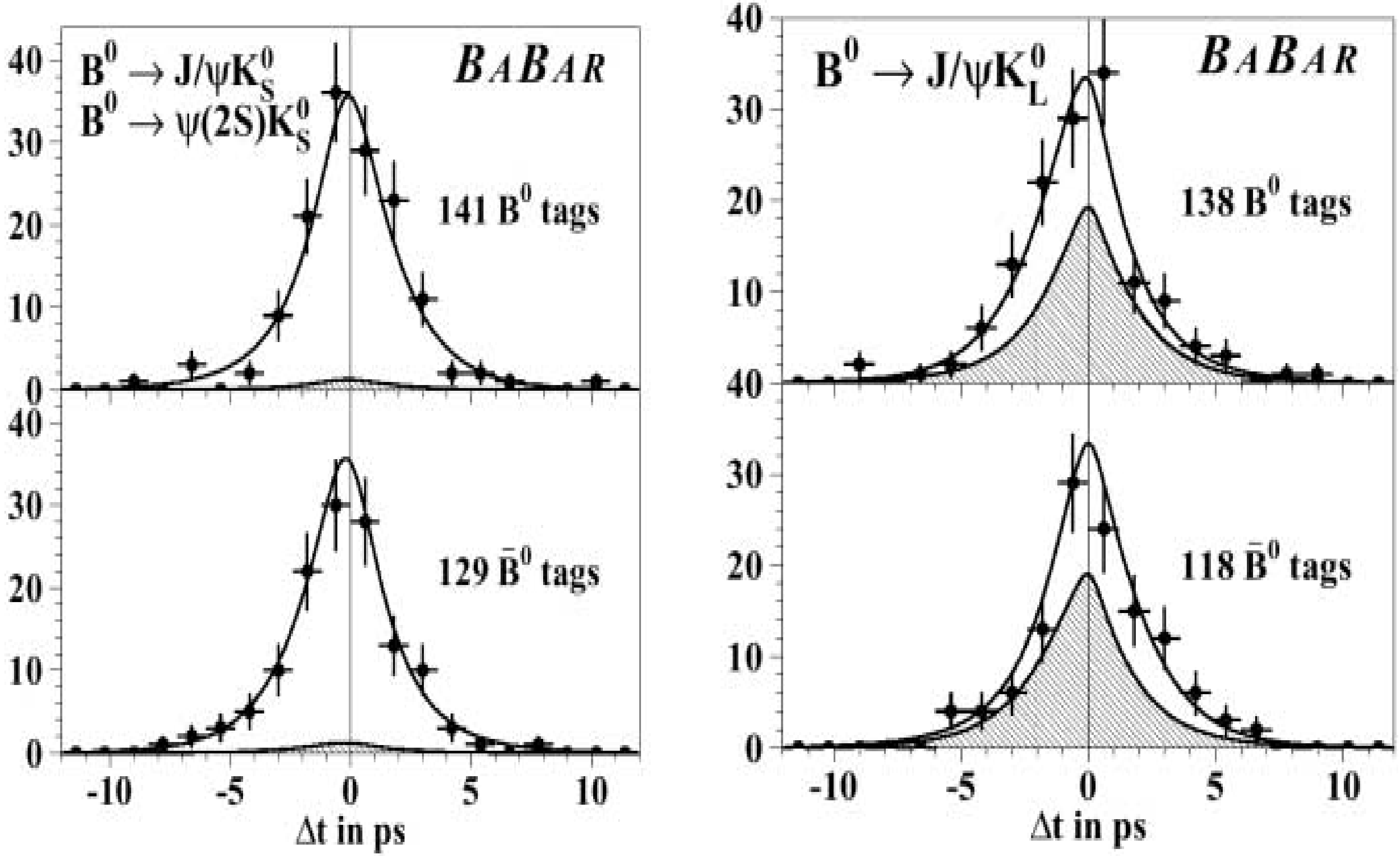
Breakdown (cont'd)

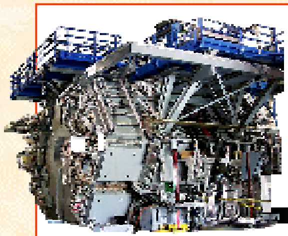
DECAY MODE

TAGGING CATEGORY

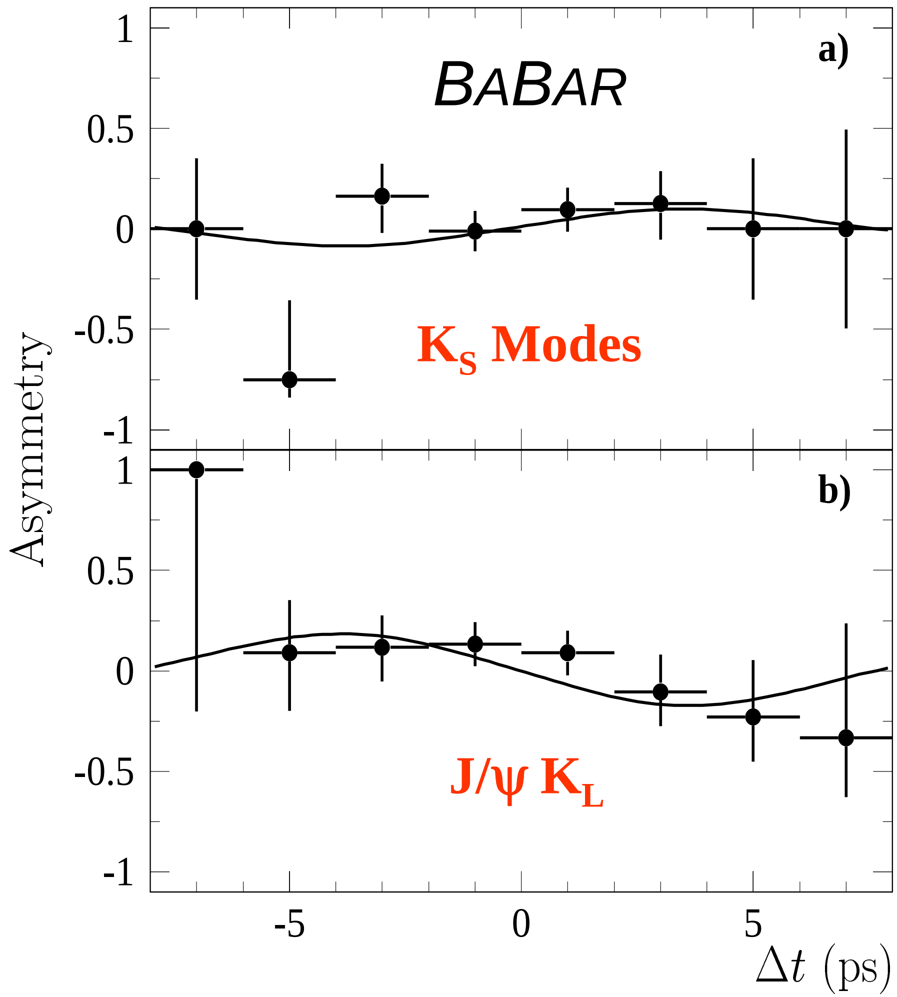
Tag	CP =1 modes			$J/\psi K_L^0$			Total		
	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot	B^0	$\overline{B}^0$	Tot
$e+K$	3	0	3	1	6	7	4	6	10
$\mu+K$	3	1	4	3	5	8	6	6	12
e	7	8	15	11	8	19	18	16	34
μ	5	7	12	5	6	11	10	13	23
Lepton	18	16	34	20	25	45	38	41	79
Kaon	80	76	156	70	60	130	150	136	286
NT1	13	15	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		

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





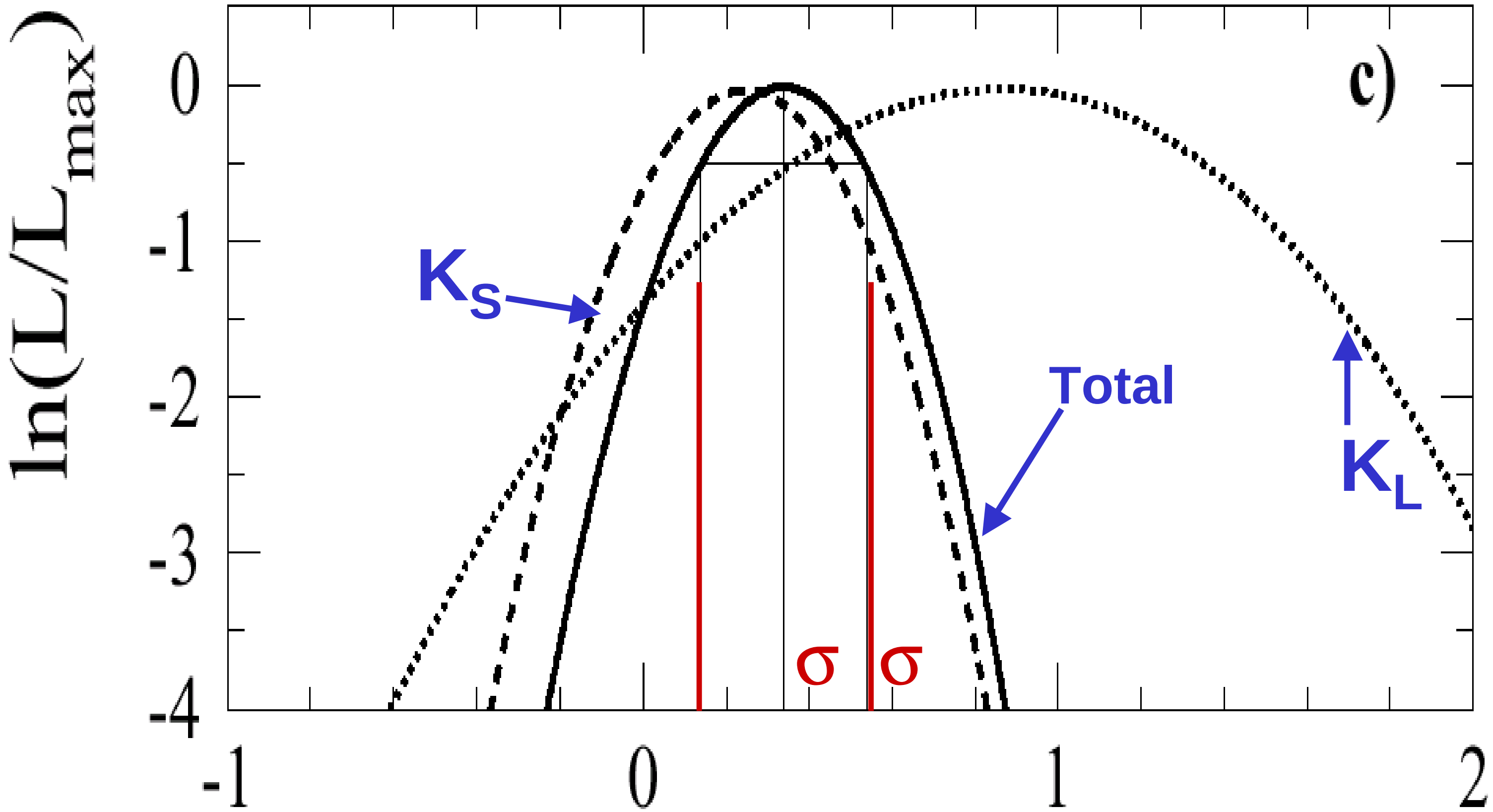
$A(\Delta t)$ vs Δt (Binomial Errors)



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

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

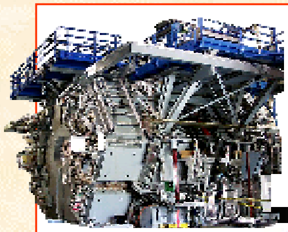
Log Likelihood vs *sin 2 β*

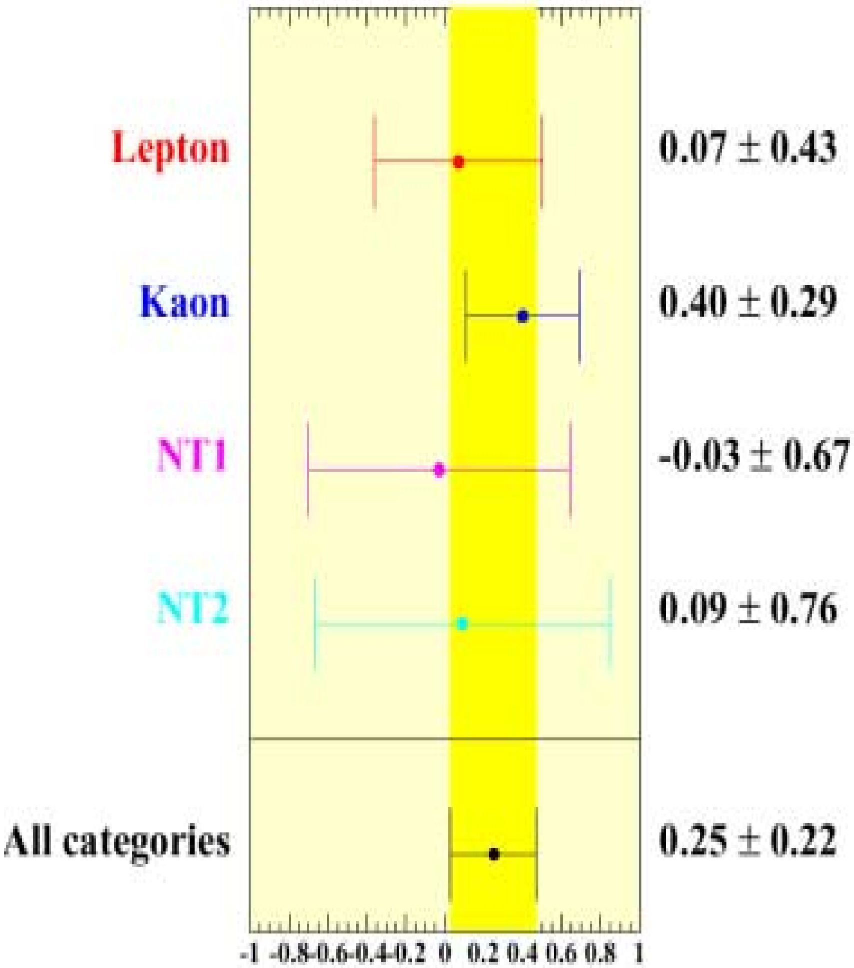


***sin 2 β* = 0.34 ± 0.20(stat) ± 0.05(sys)**

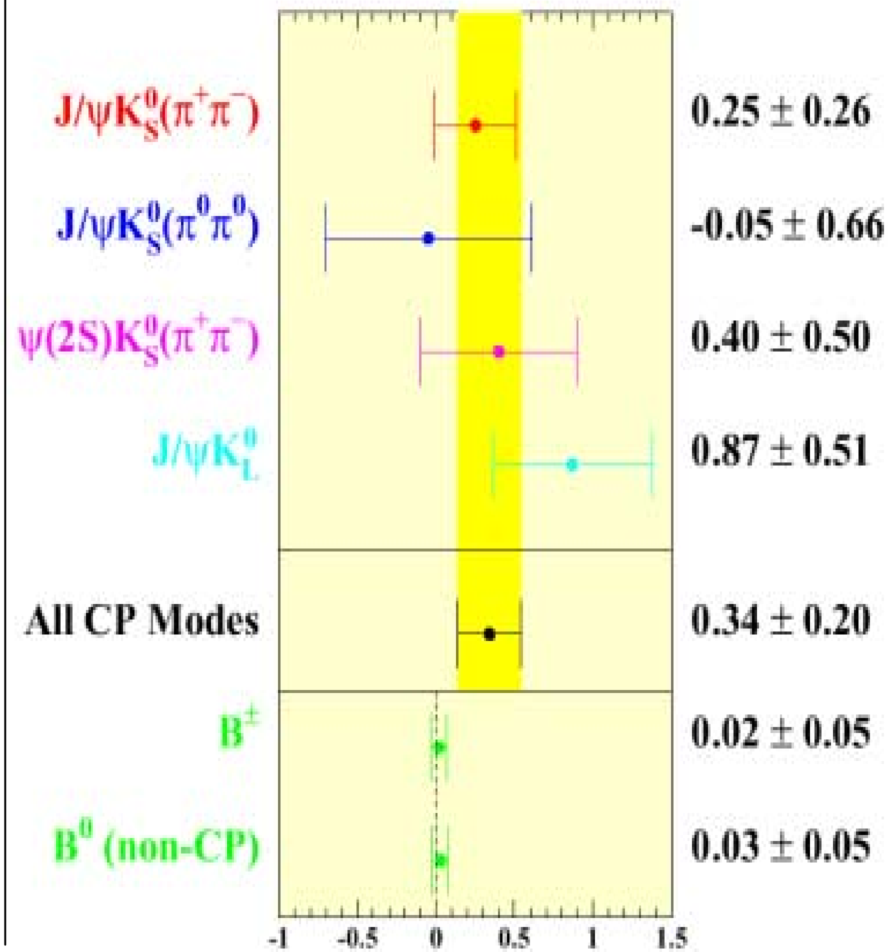
(MC study shows 60% prob. of obtaining worse fit.)

$\sin 2\beta$ for various parts of *CP* sample; crosschecks from B_{flav} and charged *B*' s

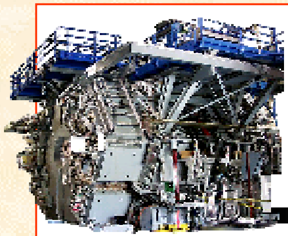




$\sin 2\beta$

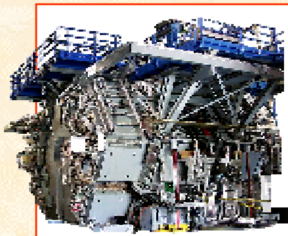


$\sin 2\beta$

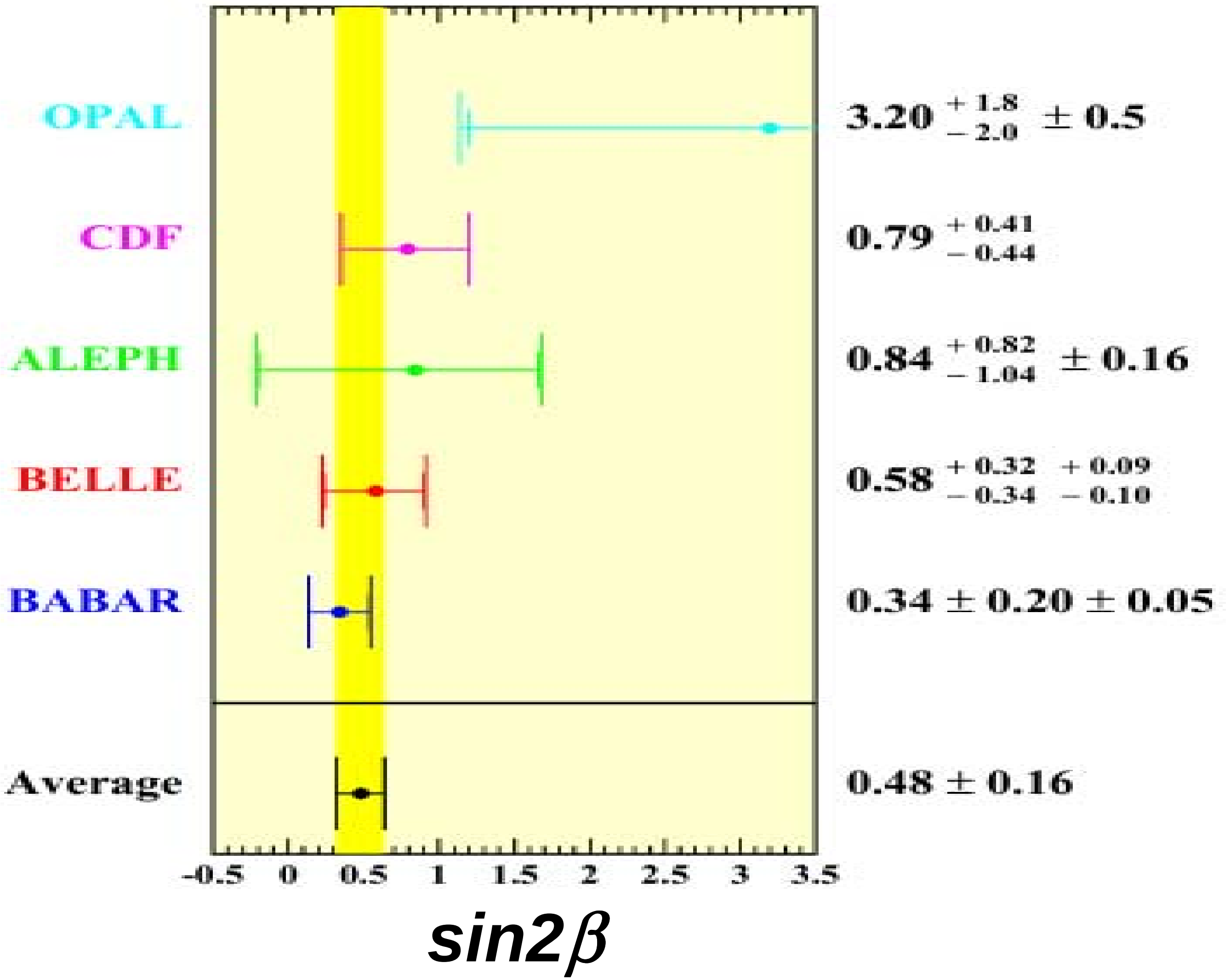


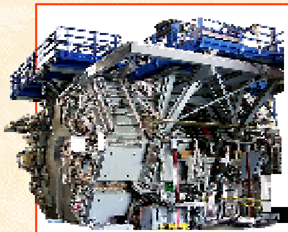
Systematic Effects

Systematic	$J/\psi\, K^0_S, \psi(2S) K^0_S$	$J/\psi\, K^0_L$	Full sample
Δt determination	0.04	0.04	0.04
$J/\psi\, K^0_S$, $\psi(2S) K^0_S$ back.	0.02	—	0.02
$J/\psi\, K^0_L$ back.	—	0.09	0.01
$J/\psi\, K^0_L$ 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

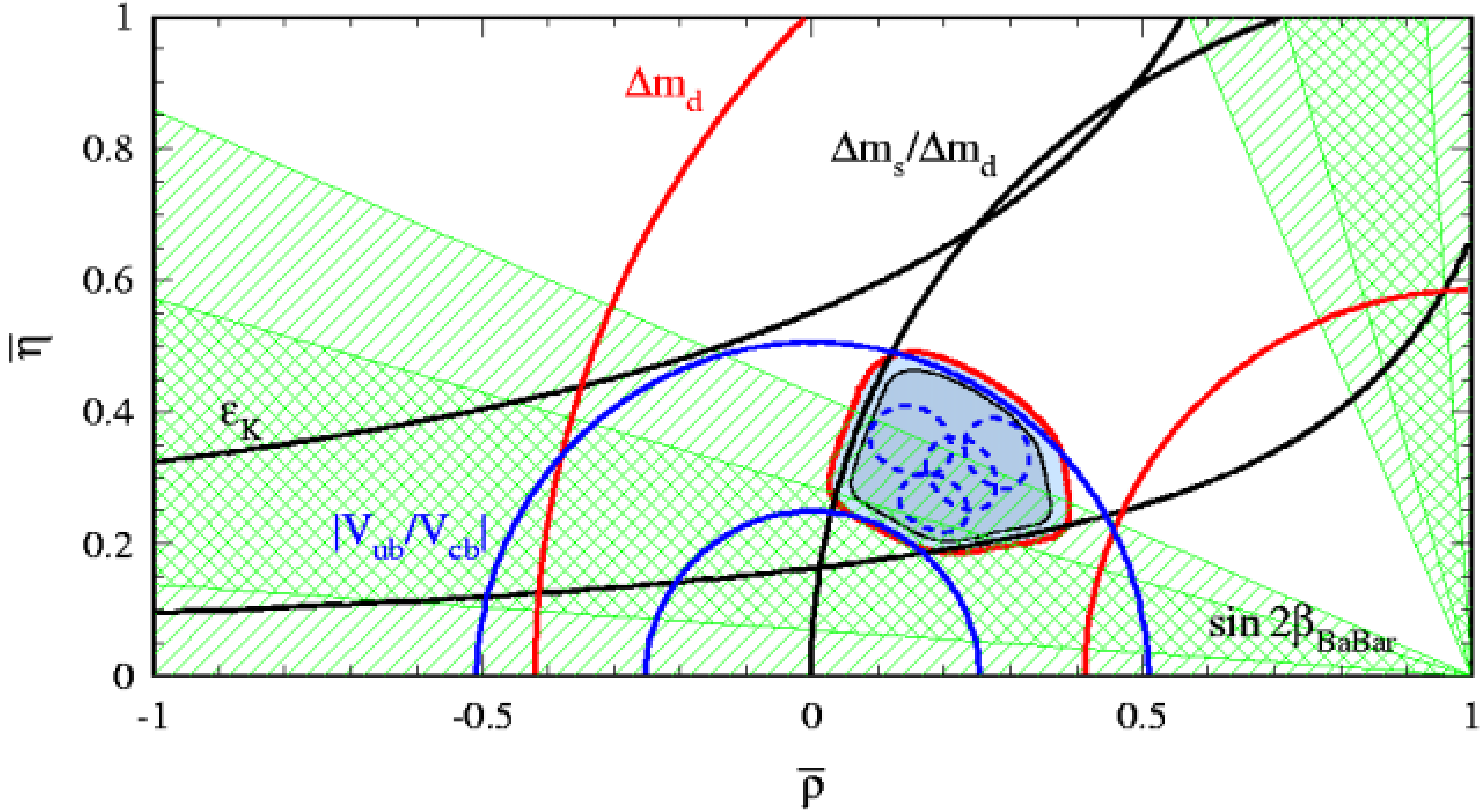


Time evolution of $sin2\beta$

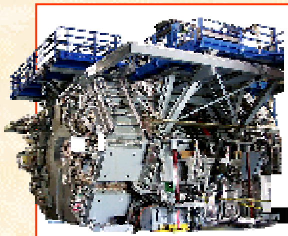




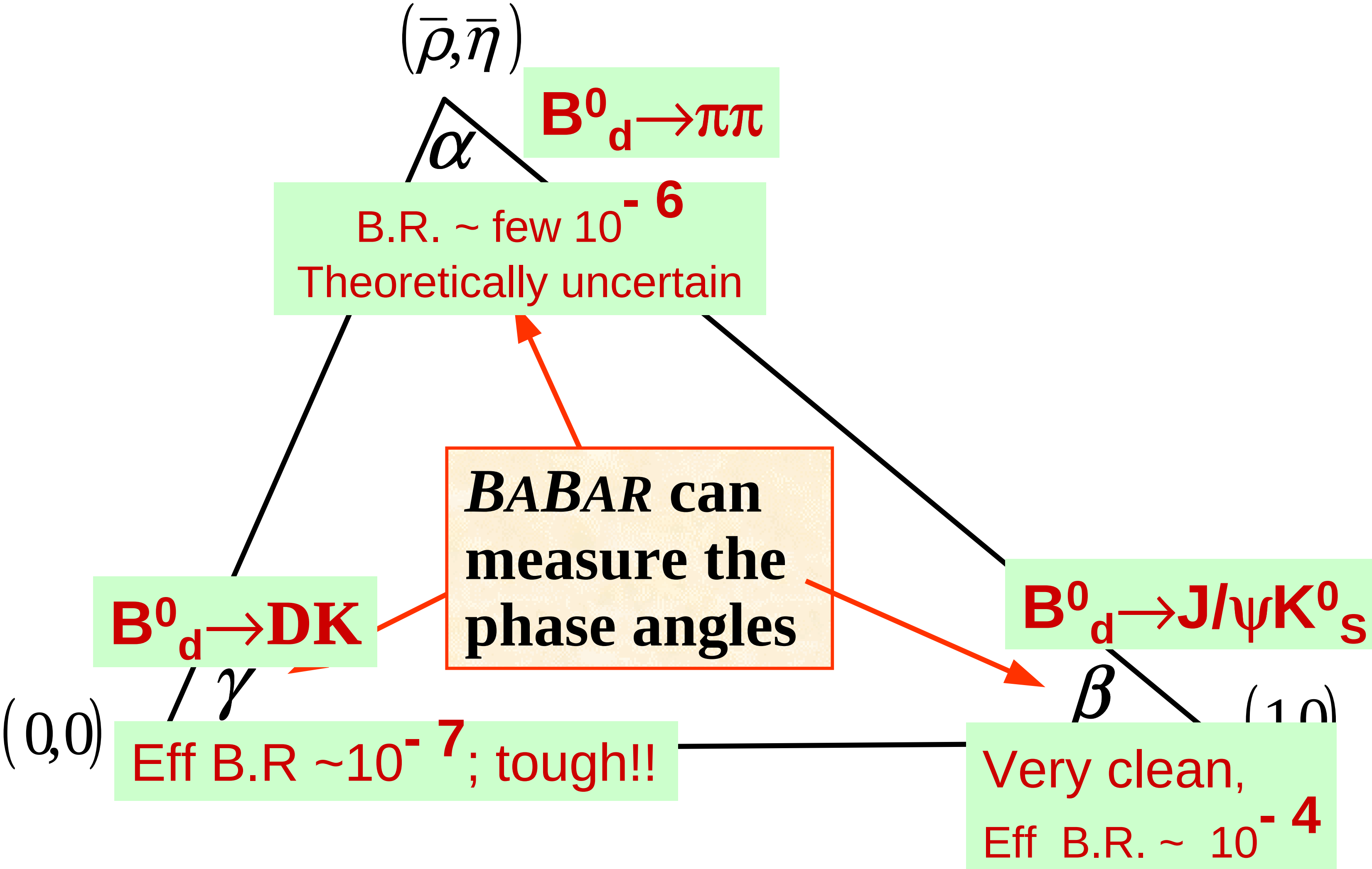
Constraints on Unitarity Triangle

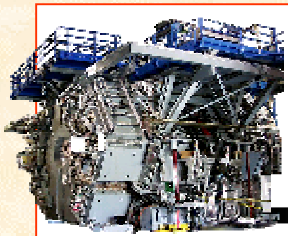


Allowed region (blue) is determined using theoretical inputs and fitting many experimental measurements

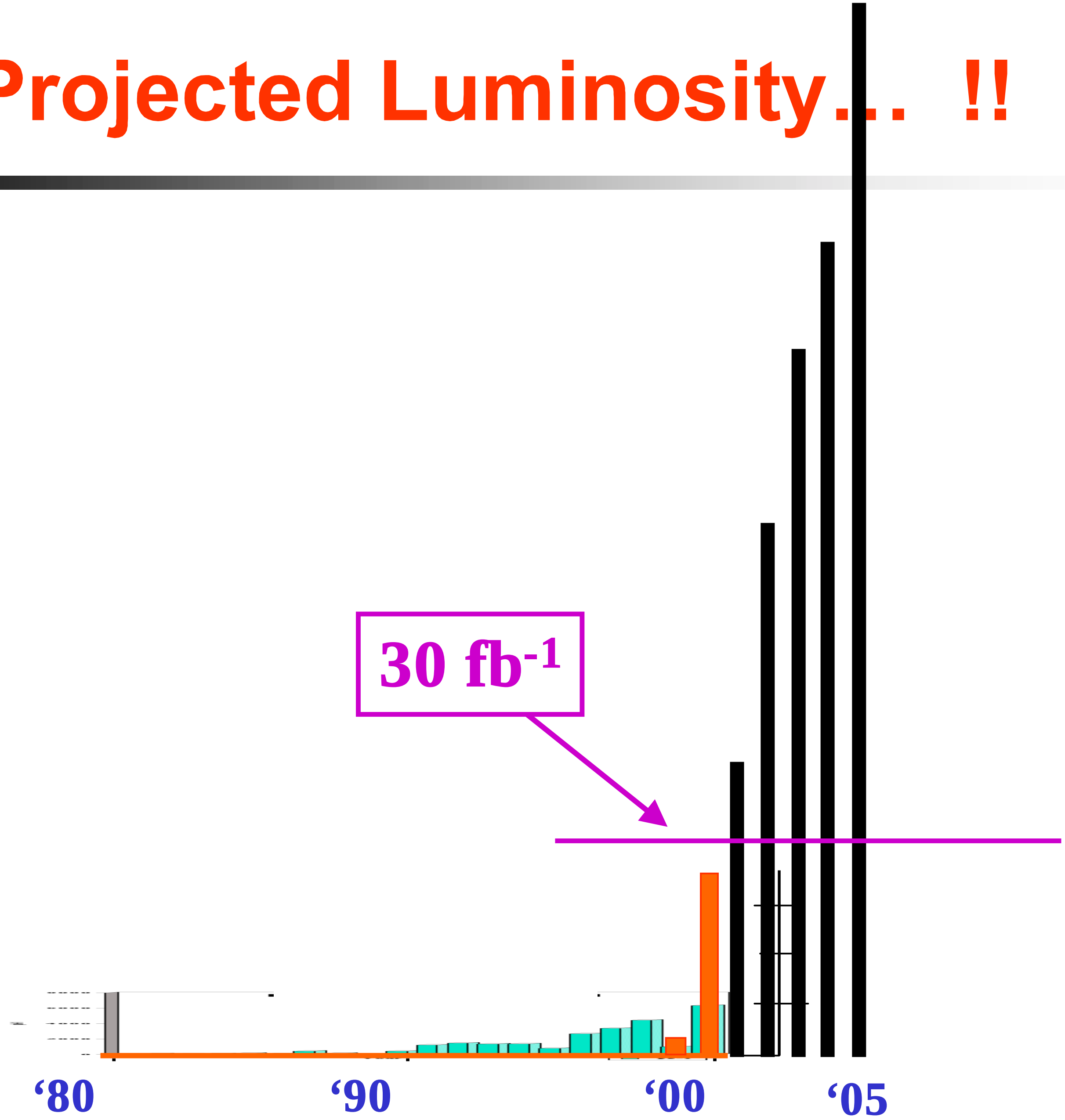


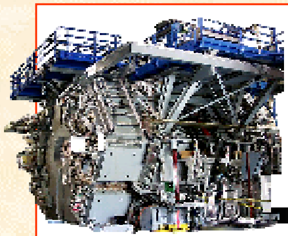
CP issues for BABAR





Projected Luminosity… !!





Conclusions

- PEP-II and BaBar are operating at or above design luminosity, and have dealt with ~25 fb^{-1} in 2000
- The detector is performing as designed, and the analysis teams are in full operation
- We have have made the most precise measurement to date of *sin 2β*, and many other analyses are underway
- We expect to more than double our data by the end of the run in August, and reduce the systematic effects to take full advantage of it.
- By 2005, we should accumulate ~ 500 fb^{-1}
  - Measure *sin 2α*, compare *sin 2β* in individual modes
  - Make serious measurements of direct *CP* violation and rare decays.