$B^0\overline{B}^0$ Oscillations and sin2β at BABAR

David Nathan Brown

Lawrence Berkeley National Laboratory

Representing the BABAR Collaboration

Outline

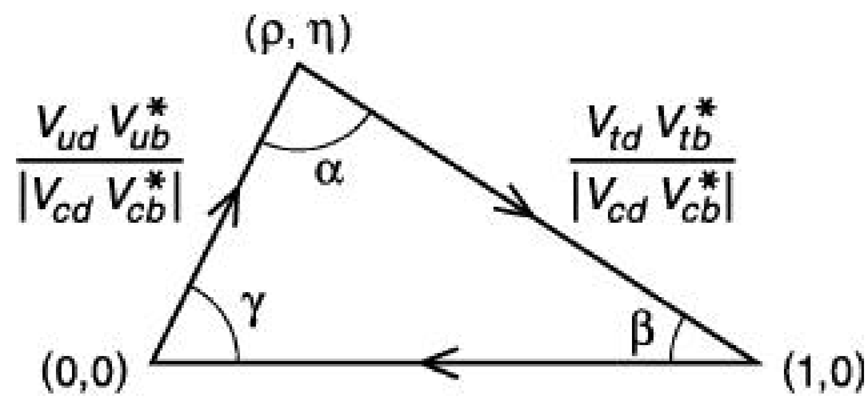
- $B^0\overline{B}^0$ **mixing and CP in the Standard Model**
- **BABAR and PEPII**
- **Event sample**
- **Analysis procedure**
  - **Signal channel selection**
  - **Flavor tagging**
  - **Time measurement resolution modeling**
  - **Fitting**
- **Results**
  - Δm_{B^0}
  - $\sin 2\beta$
- **Systematic error estimation**
- **Conclusions**

Quark mixing in the Standard Model

Quark electroweak doublets are composed of mass eigenstate mixtures given by a mixing matrix.

$$\begin{bmatrix} d \\ s \\ b \end{bmatrix}'_{EW} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}_{CKM} \times \begin{bmatrix} d \\ s \\ b \end{bmatrix}_{Mass}$$

Unitarity of the mixing matrix can be shown graphically as a triangle.

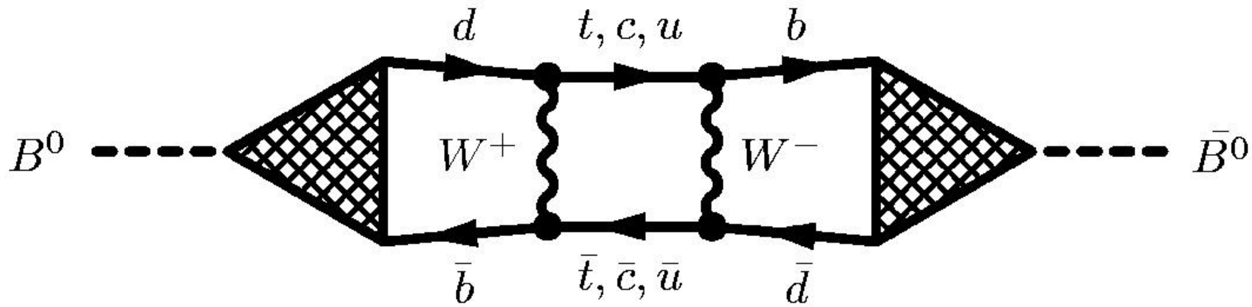


Non-zero triangle area (α,β, or γ != 0) implies CP violation

A ‘triangle’ which doesn’t close implies non-SM physics

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

$B^0 \overline{B}^0$ mixing can proceed through EW box diagrams

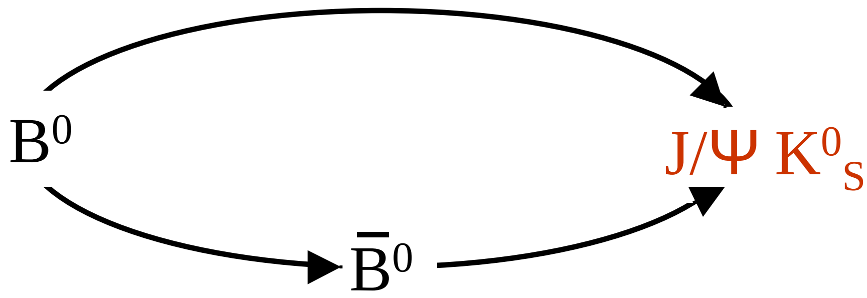


$$f_{\text{Mixing},\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \times \left[1 \pm \cos \Delta m_{B^0} \Delta t\right]$$

Δm_{B^0} is sensitive to $|V_{td}V_{tb}^*|$

CP Violation via Mixing Interference

Interference between mixed and unmixed B_0 decays to CP eigenstates induces a time and flavor-dependent rate



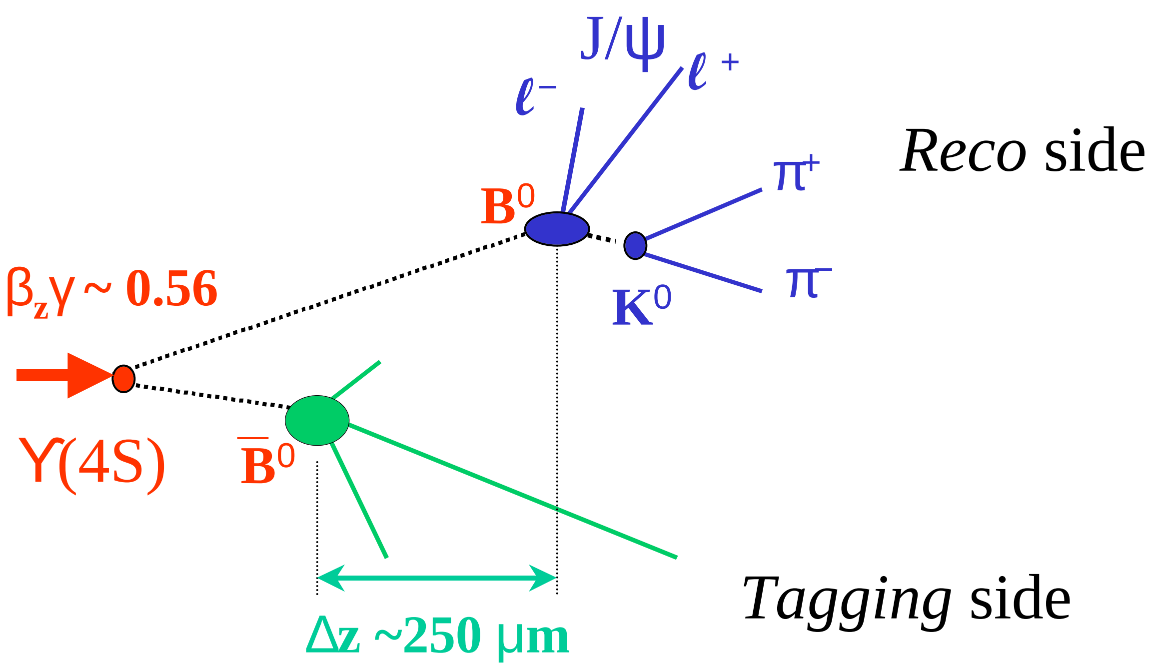
$$f_{CP,\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times [1 \pm \sin 2\beta \sin \Delta m_{B^0} \Delta t]$$

Flavor-specific rate vs time depends on sin2β

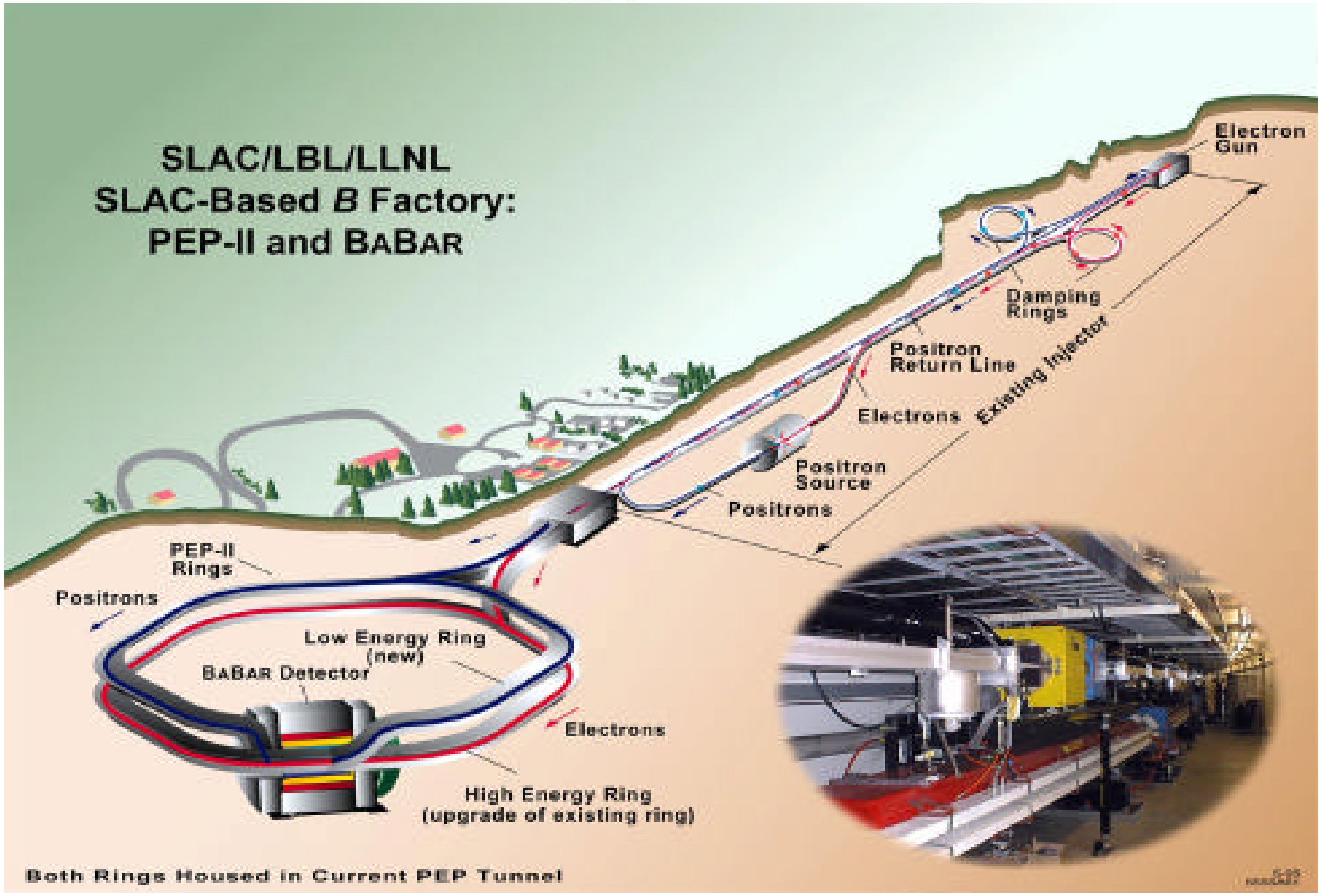
CP and Mixing at the Υ(4S)

Υ(4S) $\to$ $B^0 \bar{B}^0$ proceeds via coherent P-wave. Tagging the flavor of one B at decay determines the flavor of the other at that instant.

By boosting the Υ(4S) the decay time difference becomes observable.

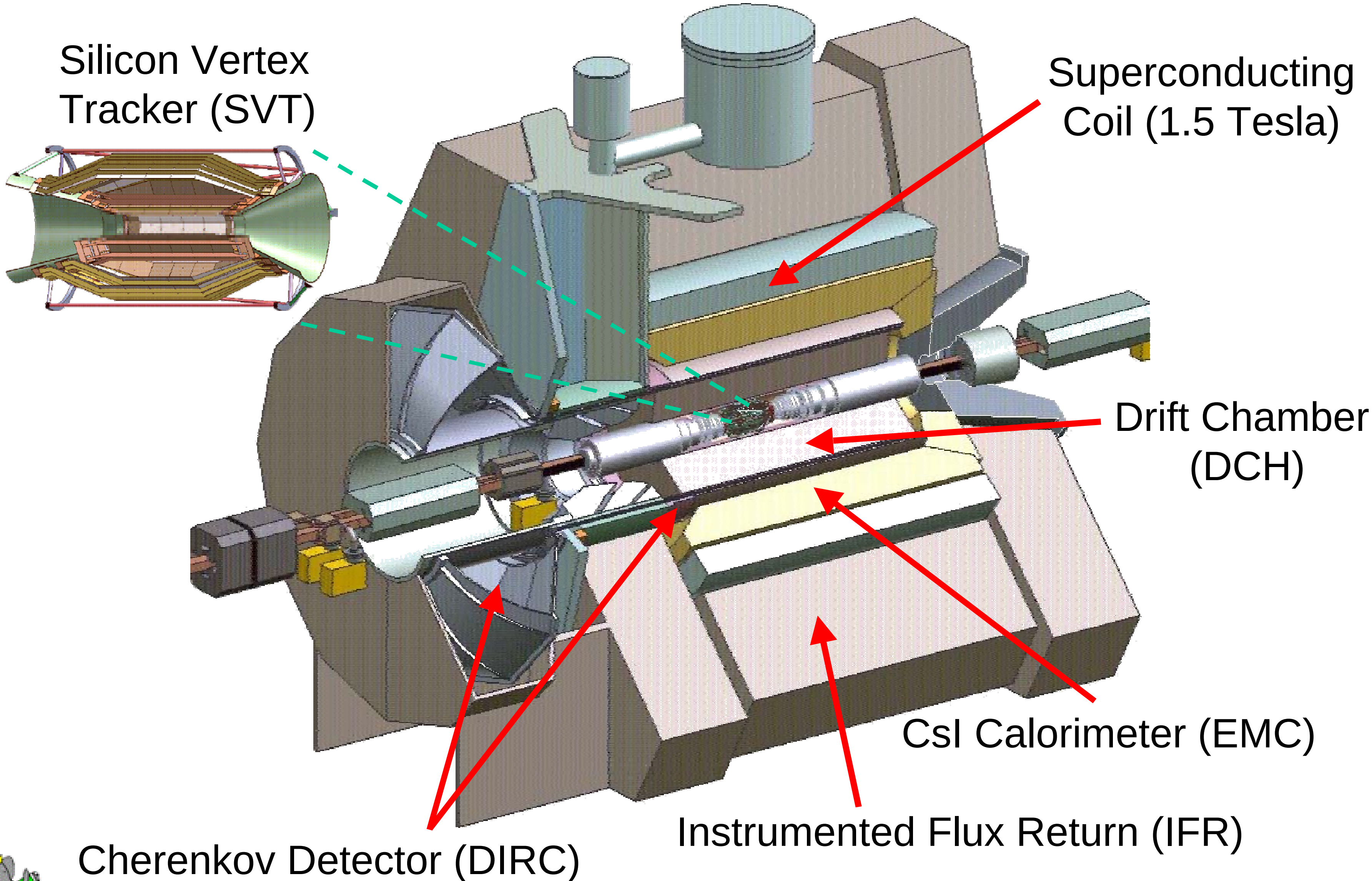


PEPII at SLAC

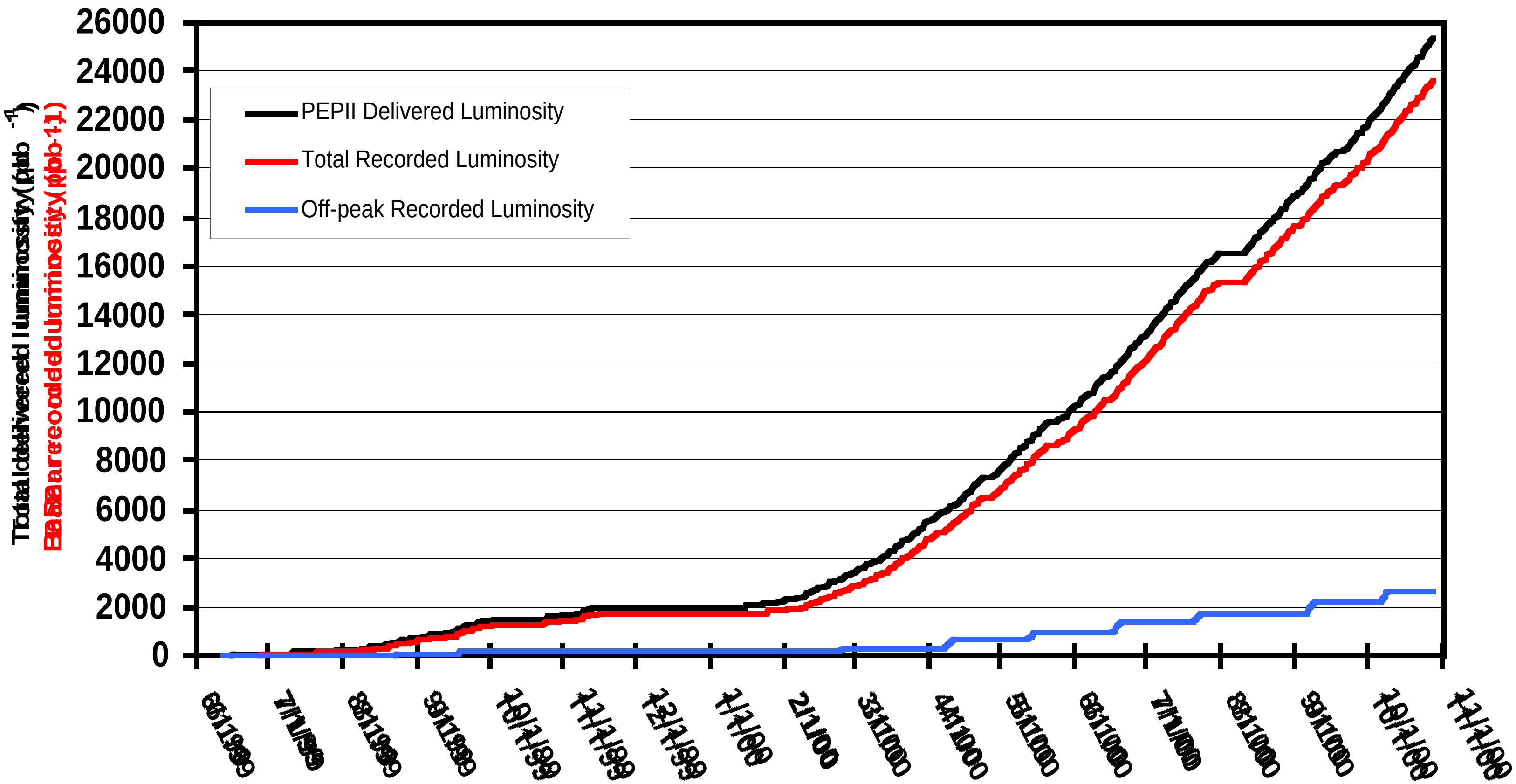


3.1 GeV e^+ → Υ(4S) ← 9 GeV e^-

The BaBar Detector



The BaBar Data Sample

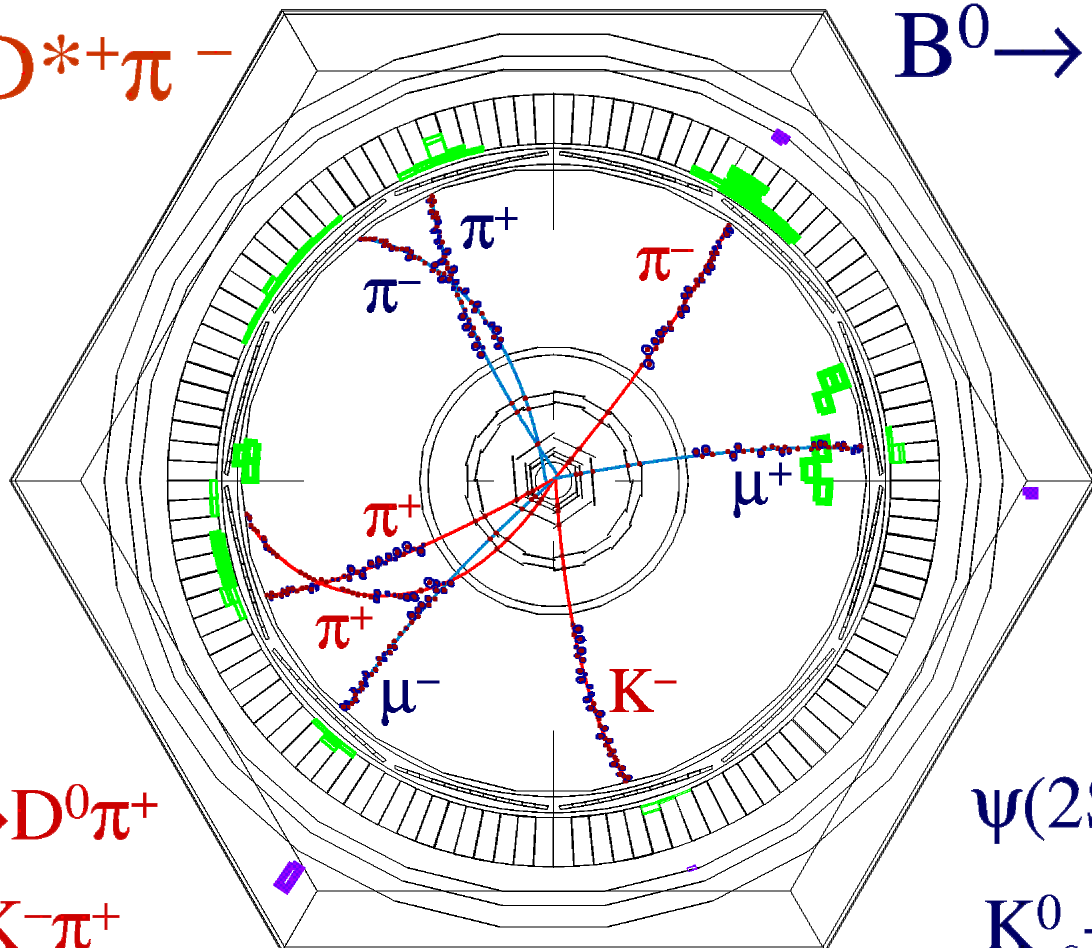


23 Million $B^0 \overline{B}^0$ pairs recorded

A Fully-Reconstructed $\Upsilon(4S)$ $B^0\bar{B}^0$ Event

$\bar{B}^0 \rightarrow D^{*+}\pi^-$

$B^0 \rightarrow \psi(2S)K^0_s$



$D^{*+} \rightarrow D^0\pi^+$

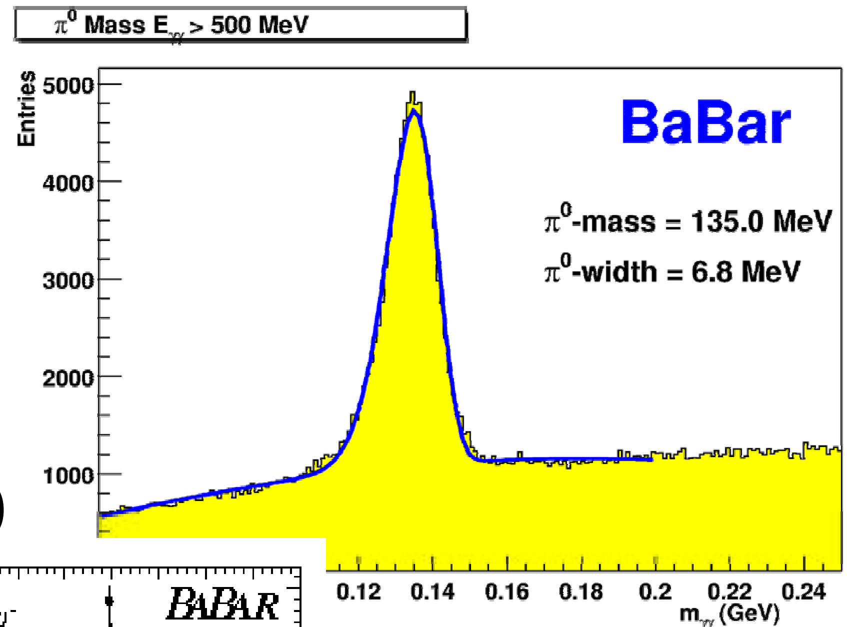
$D^0 \rightarrow K^-\pi^+$

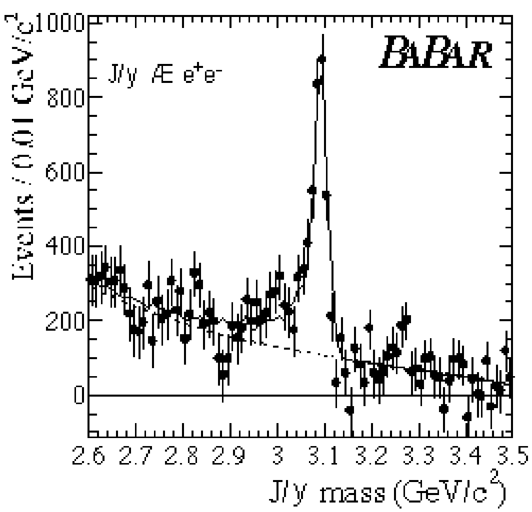
$\psi(2S) \rightarrow \mu^+\mu^-$

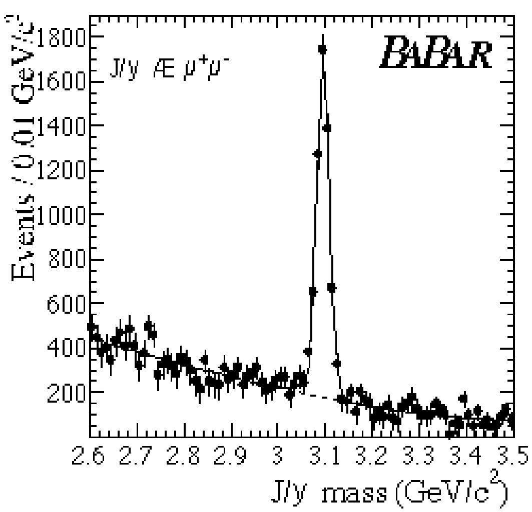
$K^0_s \rightarrow \pi^+\pi^-$

Event Reconstruction

- **‘Stable’ particle reconstruction**
  - **Tracking**
    - dE/dx and DIRC PID
    - Vertexing (k_s, ψ, B^0)
  - **$e^\pm$ and $\mu^\pm$ in EMC and IFR**
  - **Neutrals in EMC and IFR**
- Υ(4S)   **$B\bar{B}$ selection**
  - **Event shape cuts (FW, thrust)**

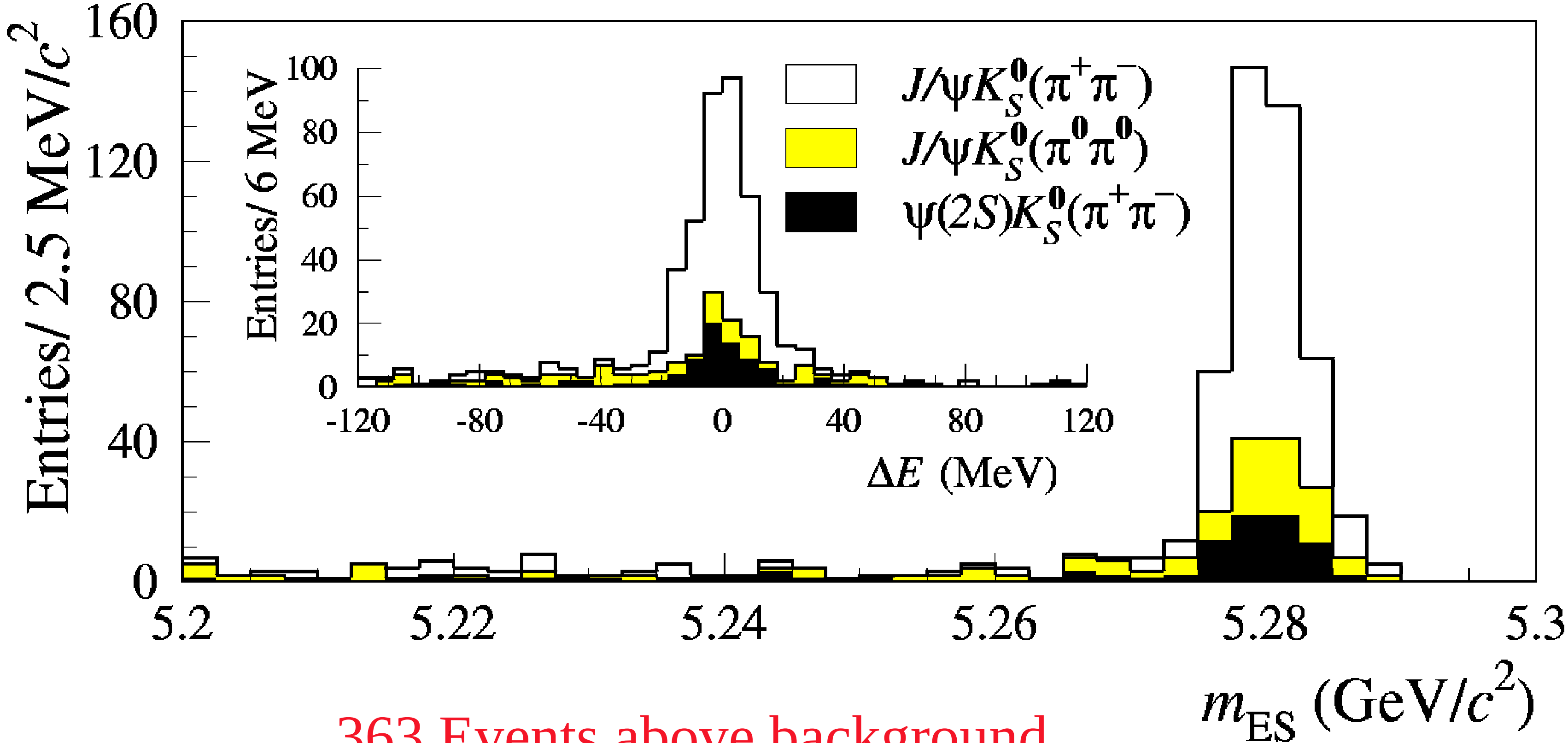






$J/\psi\ K_s$ and $\psi(2s)\ K_s$ Reconstruction

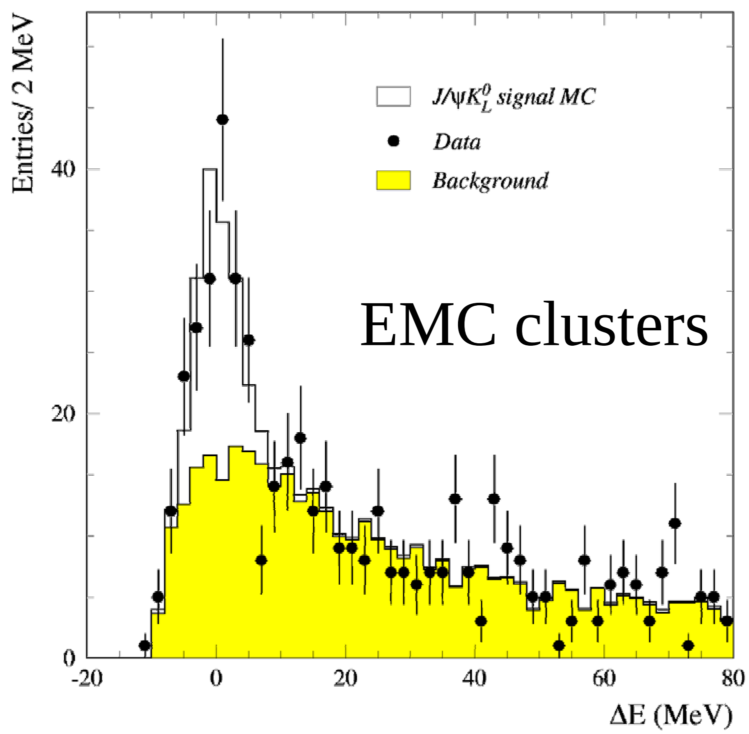
$$\Delta E = E_B - E_{beam}\Big|_{CM} \quad m_{ES} = \sqrt{E^2{}_{beam} - P^2{}_B}\Big|_{CM}$$

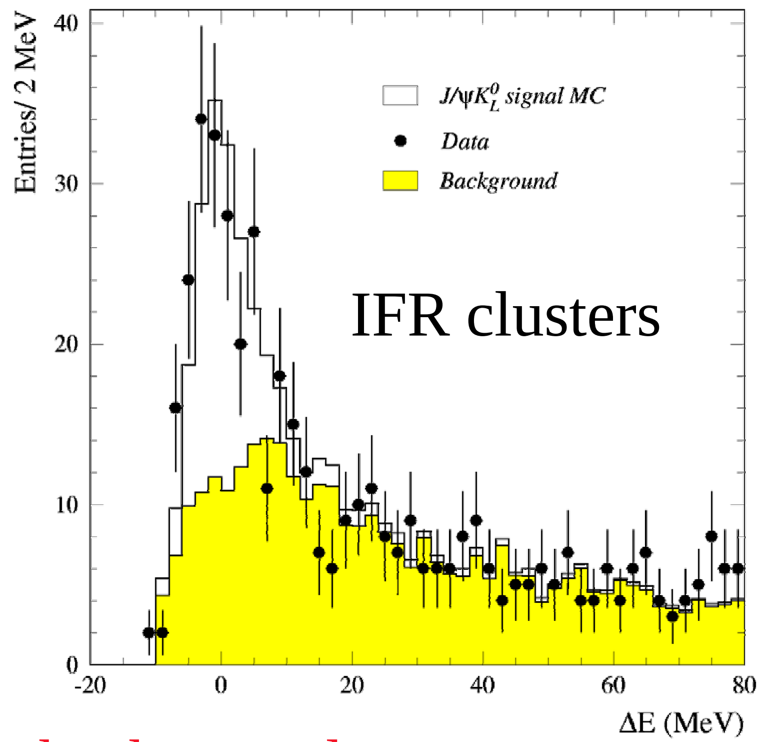


363 Events above background

J/ψ K_L Reconstruction

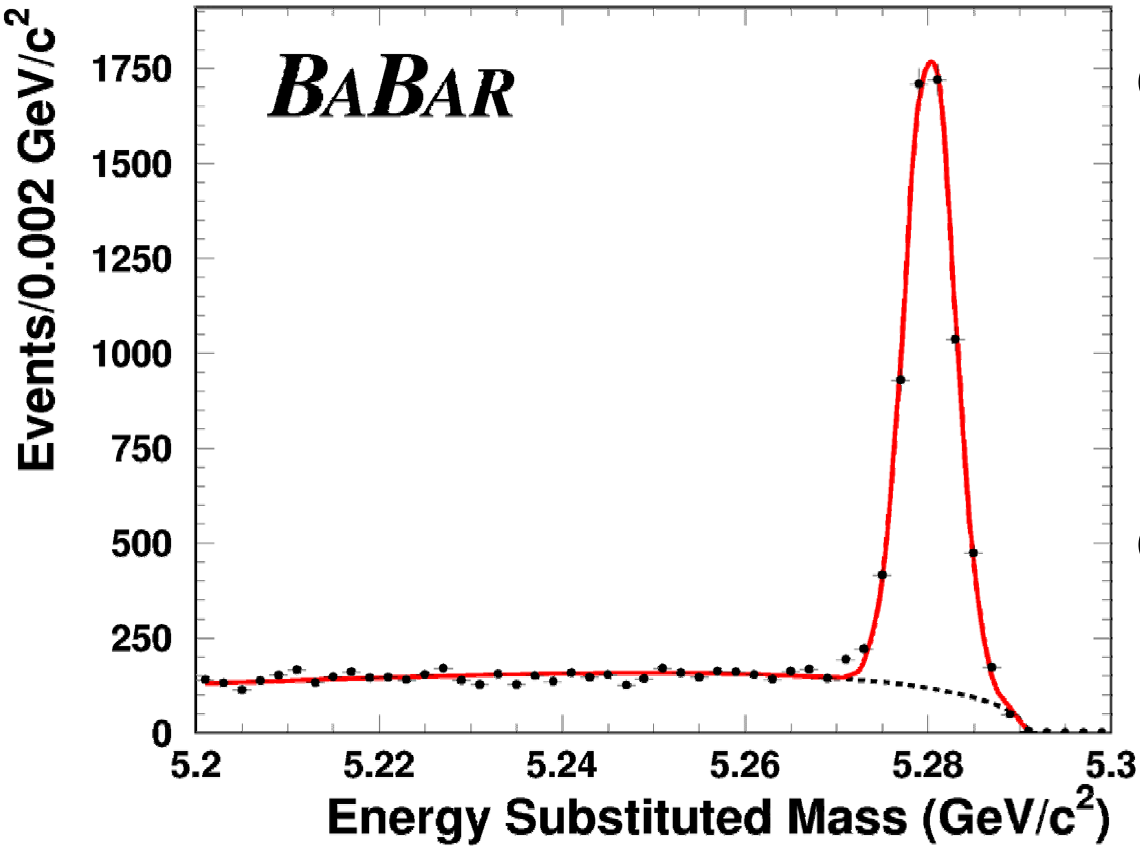
- **K_L are found in EMC and IFR**
  - **Cluster with no associated track**
  - **Inconsistent with π^0 or γ**
- **B^0 mass used to reconstruct candidates (no cut)**





182 Events above background

Hadronic (non-CP) B^0 Reconstruction



- **B^0 $D^{(*)-}$ $(\pi,\rho,a_1)^+$**
  - **D^- $K^-\pi^+\pi^+, K^0\pi^-$**
  - **D^0 $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K^0\pi^-\pi^+$**
  - **D^{*-} $D^0\pi^-$**
- **B^0 J/ψ K^{*0}**
  - **K^{*0} $K^-\pi^+$**

4637 Events above background (CP fit)

6368 Events above background (Δm_{B^0} fit)

Flavor Tagging

- **Tags are assigned hierarchically**
  - **Leptons from semi-leptonic decay (b c W^-, W^- eν_e)**
  - **Kaons From Cabibo-favored hadronic cascade (b c s)**
  - **Neural net (1 and 2)**
    - Low-momentum leptons, soft pions, additional kaons
- **Efficiency and mistag rates are determined from B^0 decays**
  - **Parameters in sin2β, Δm_{B^0} Likelihood fits**
  - **Cross-checked with B^0 $D^*\ell\nu$**

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

ε = efficiency

w = mistag rate

Q = ε (1-2w)^2

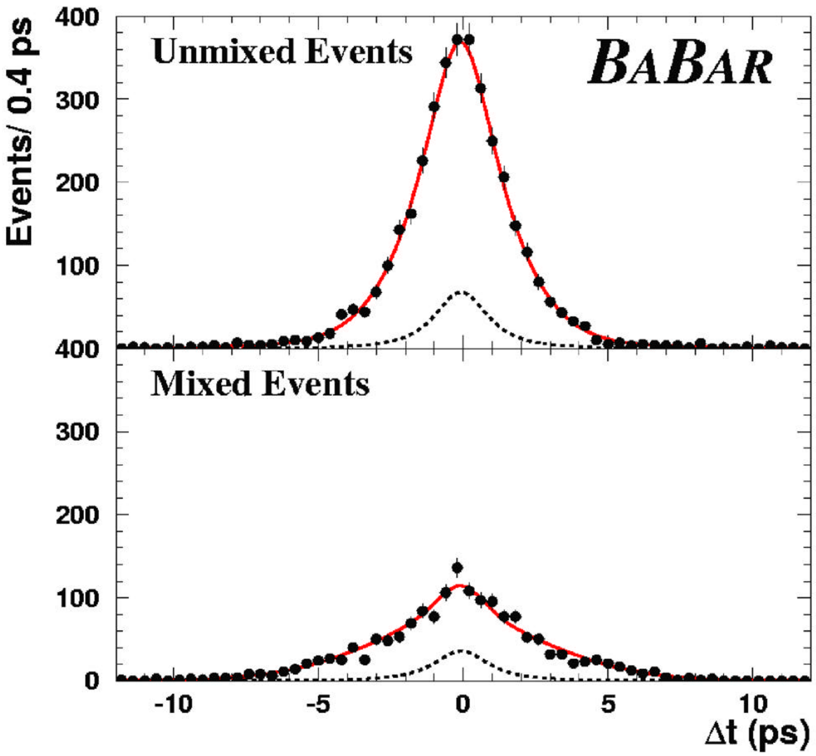
Δt Resolution

- **$\Delta t \approx \Delta z/\beta\gamma c$**
- **Δz from vertex difference**
  - **Tag B^0 z resolution ~180 μm**
  - **Signal B^0 z resolution ~70 μm**
- **Resolution modeled with 3 Gaussians**
  - **Core,Tail, and Outliers**
  - **σ scaled to vertex error estimate (core and tail)**
  - **Shifts from 0 allowed (charm vertex flight)**
- **Fit Parameters in sin2β, Δm_{B^0} Likelihood fits**

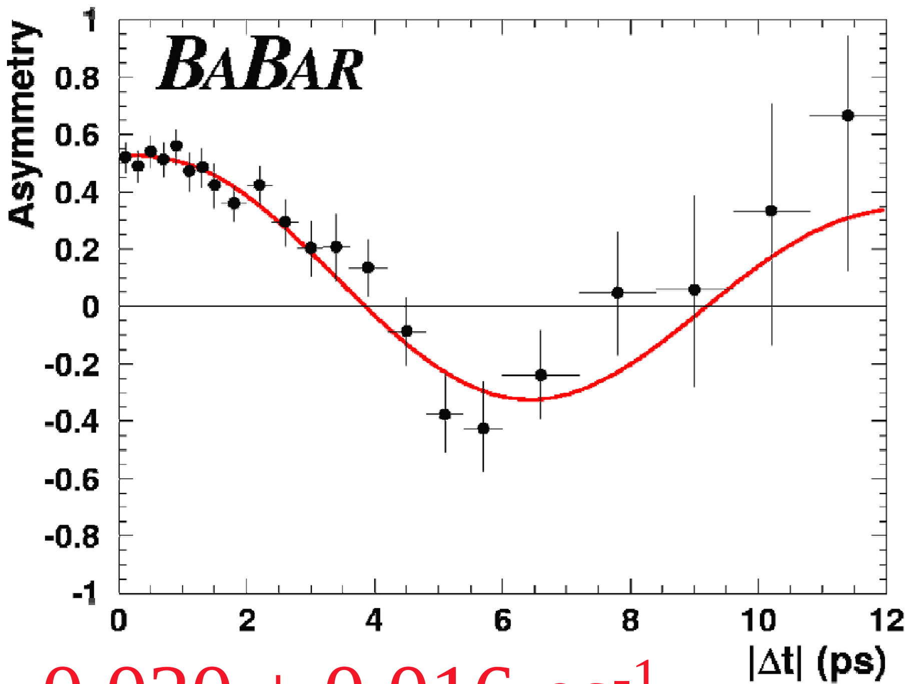
Parameter	Value
$S_{\rm Core}$	1.1 ± 0.1
$S_{\rm Tail}$	3.8 ± 0.9
$f_{\rm Tail}$ (%)	11 ± 5
$f_{\rm Outlier}$ (%)	0.8 ± 0.5
$\delta_{\rm Core,Lepton}$ (ps)	0.08 ± 0.10
$\delta_{\rm Core,Kaon}$ (ps)	0.21 ± 0.05
$\delta_{\rm Core,NT1}$ (ps)	0.01 ± 0.10
$\delta_{\rm Core,NT2}$ (ps)	-0.18 ± 0.09
$\delta_{\rm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

$B^0 \bar{B}^0$ Mixing Result (Preliminary)

- **Fit for Δm_{B^0} + 33 parameters for tagging effects and Δz resolution for signals and backgrounds**

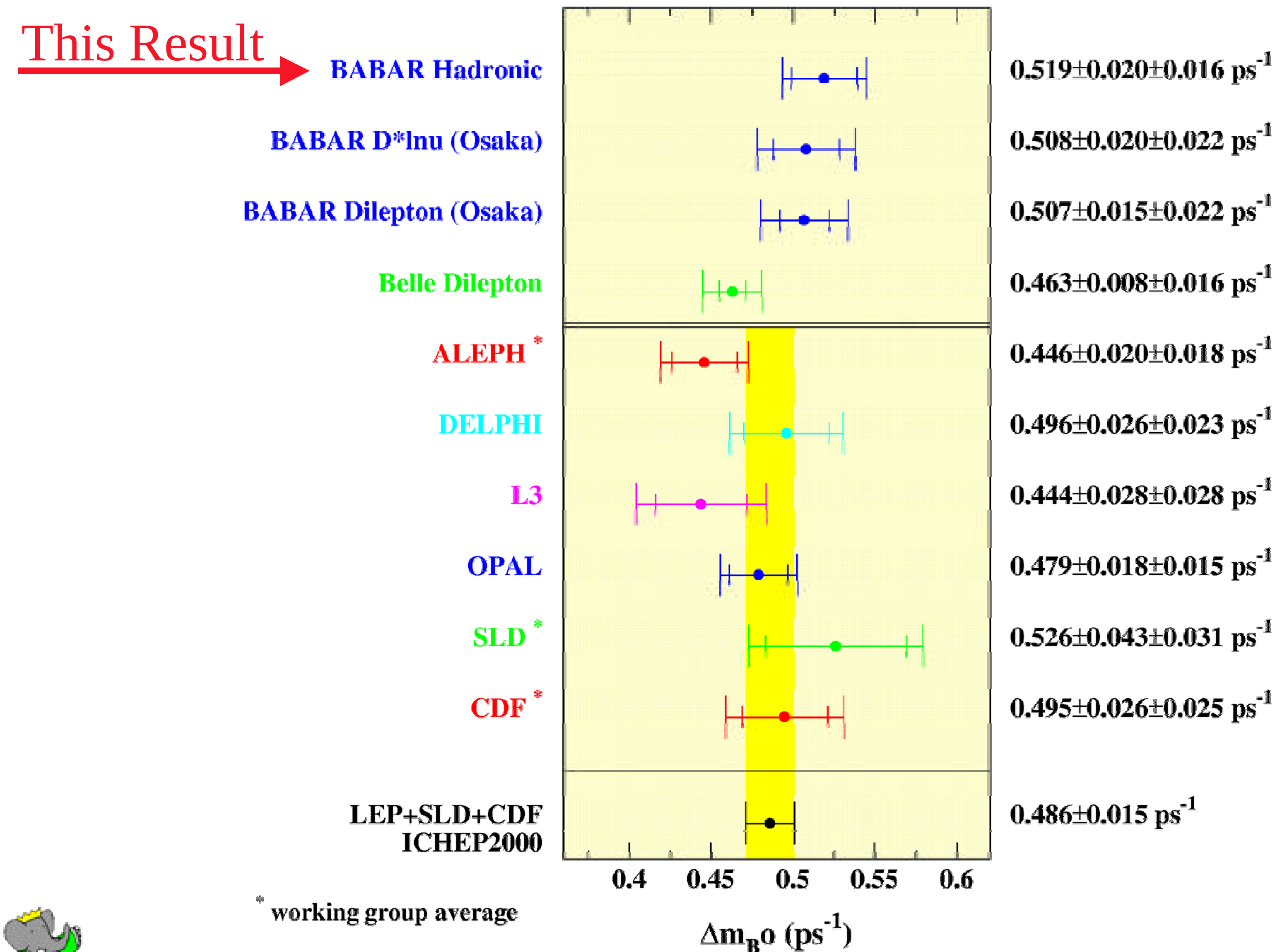


$$A_{mixing} \equiv \frac{f(\text{unmixed}) - f(\text{mixed})}{f(\text{unmixed}) + f(\text{mixed})} = \cos(\Delta m_{B^0} \Delta t)$$

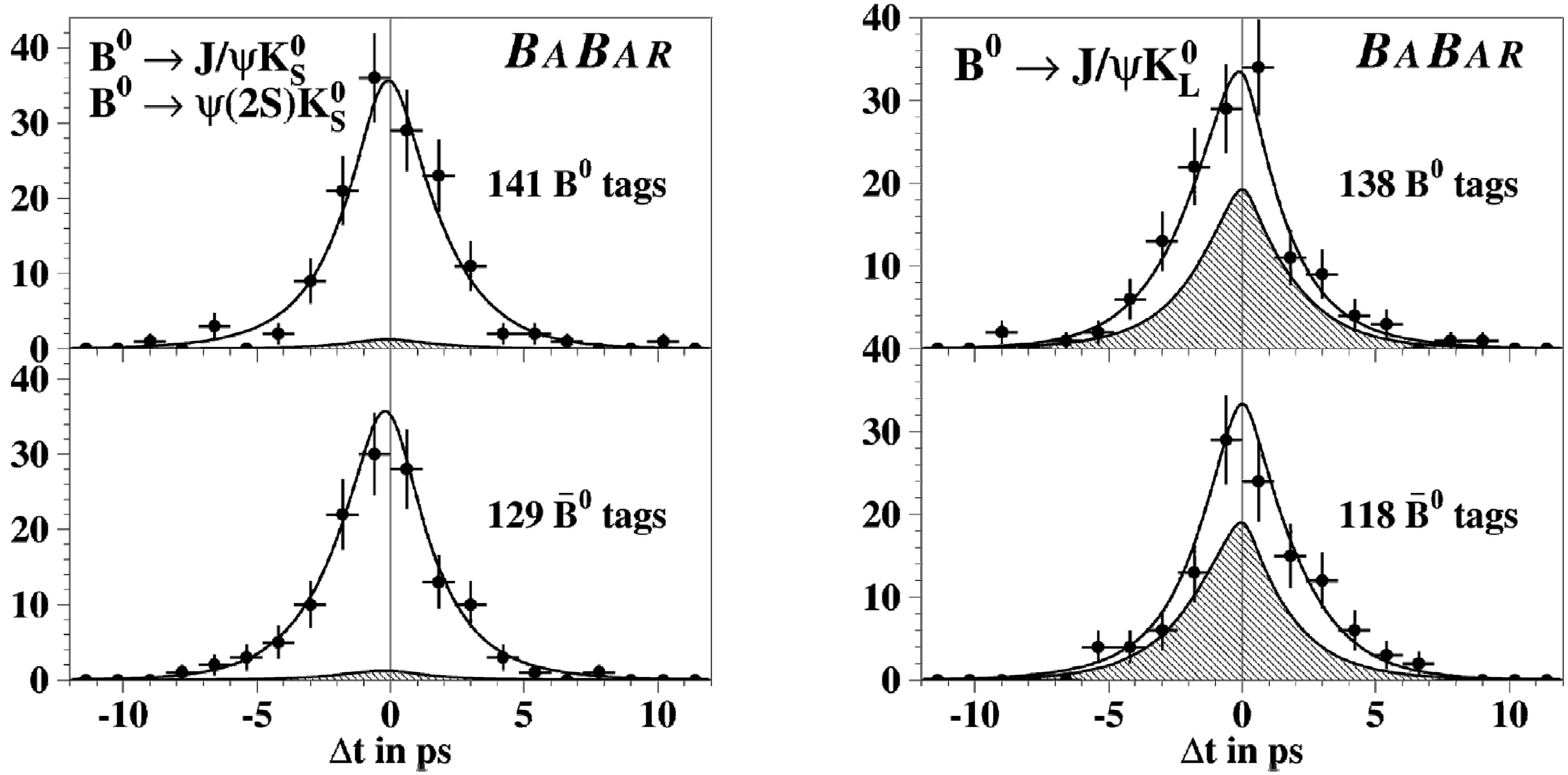


$$\Delta m_{B^0} = 0.519 \pm 0.020 \pm 0.016 \text{ ps}^{-1}$$

Comparison with Other Results



CP Rates by Mode and Tag

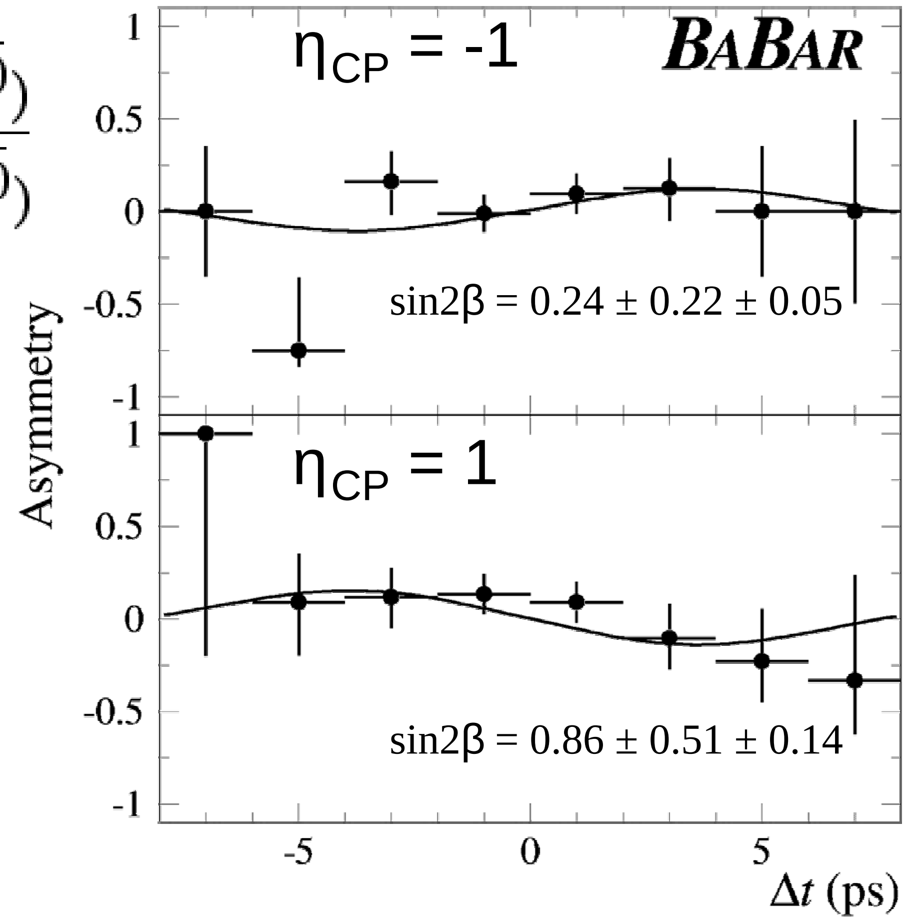


sin2β Extraction

$$A_{CP} = \frac{f(tag = B^0) - f(tag = \overline{B^0})}{f(tag = B^0) + f(tag = \overline{B^0})}$$

$$= -\eta_{CP} \sin 2\beta \sin \Delta m_{B^0} \Delta t$$

- **Fit for sin2β + 33 parameters for tagging effects and Δz resolution for signals and backgrounds**



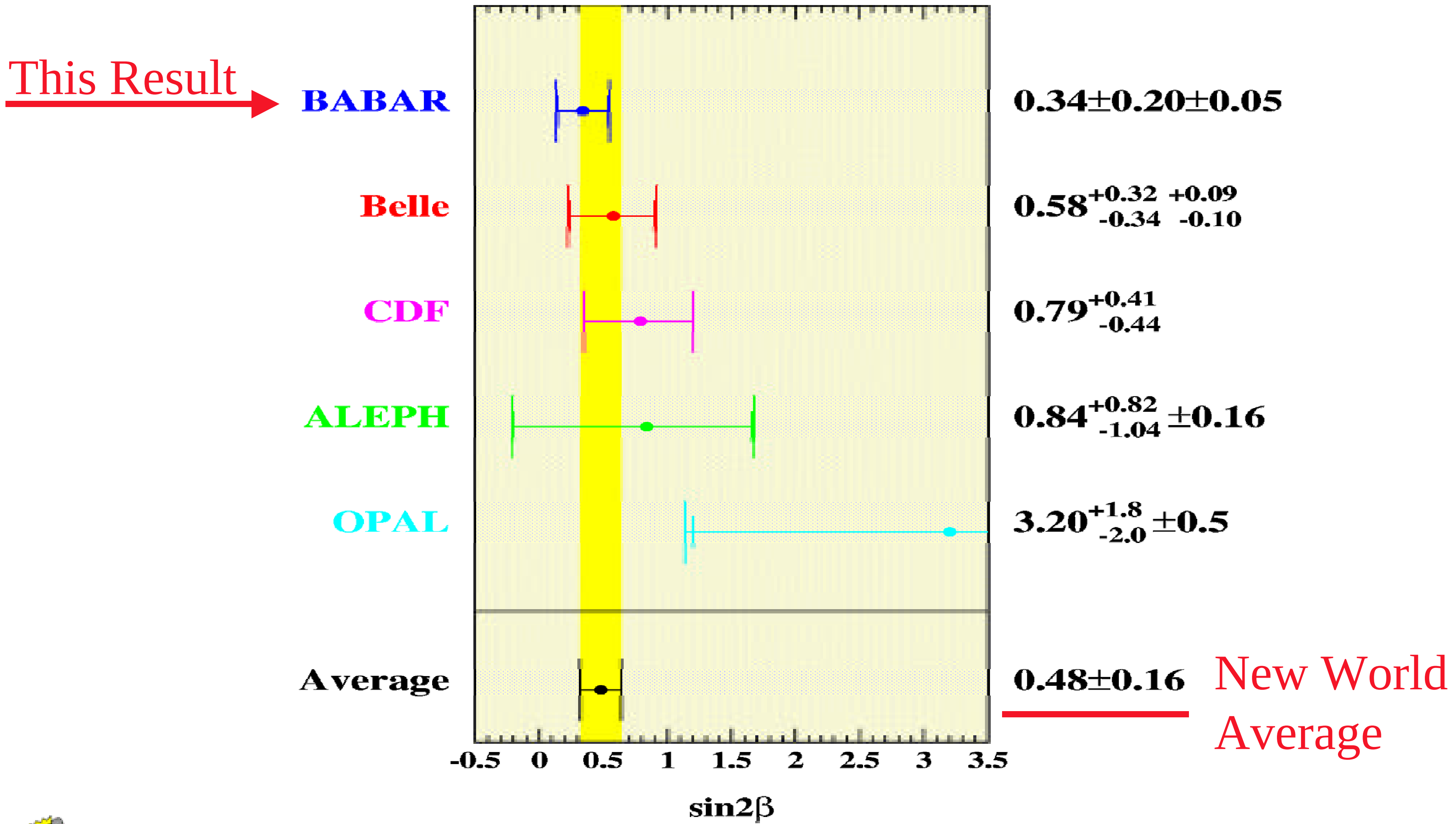
$$\sin(2\beta) = 0.34 \pm 0.20 \pm 0.05$$

Systematic Errors and Cross-Checks

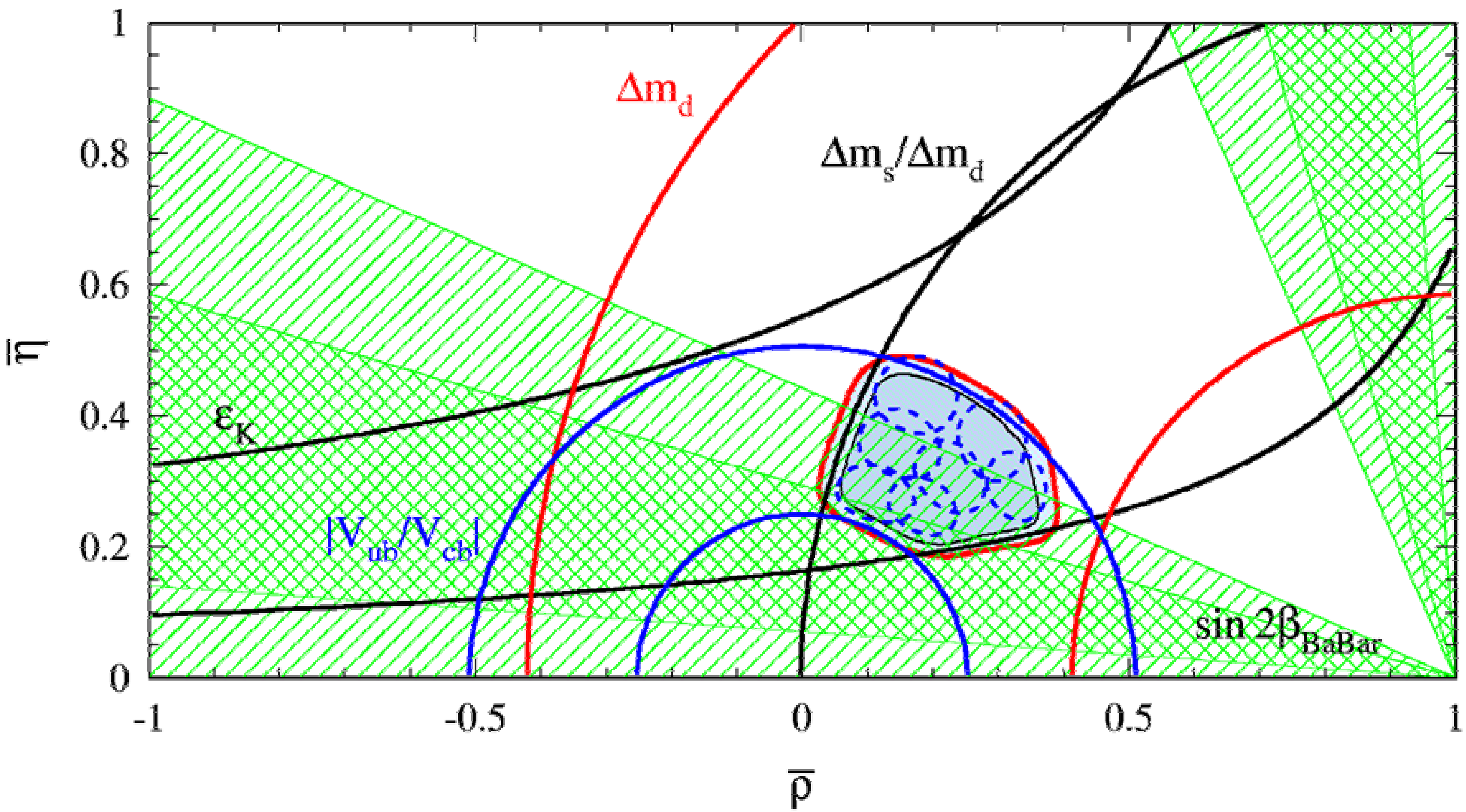
Systematic	$J/\psi K^0_S, \psi(2S) K^0_S$	$J/\psi K^0_L$	Full sample
Δt determination	0.04	0.04	0.04
$J/\psi K^0_S$, $\psi(2S) K^0_S$ back.	0.02	—	0.02
$J/\psi K^0_L$ back.	—	0.09	0.01
$J/\psi K^0_L$ Sig. fraction	—	0.10	0.01
τ_{B^0}	0.01	0.01	< 0.01
Δm_{B^0}	0.01	< 0.01	0.01
Other	0.01	0.01	0.01
Total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

- **No significant differences are seen dividing sample by tagging mode, signal mode, decay mode, …**
- **No significant direct CP violation**
- **No CP asymmetry in fits to $B^{\pm}$ samples**

Comparison with Other Results



CKM Constraints



$V_{ub} \approx A\lambda^3(\rho\text{-}i\eta)$ (Wolfenstein parameterization)

Conclusions

- **BaBar has measured Δm_{B^0} and sin2β in ~21 fb^{-1} of recorded Υ(4S) decays**
  - **Most precise single measurement of sin2β**
  - **Consistent with other measurements and world average**
  - **World average sin2β is now 3 σ away from 0**
- **BaBar is running again since February 1**
  - **0.6 fb^{-1} recorded so far**
  - **Peak luminosity ~$1 \times 10^{33}/cm^2 s$**
  - **We expect an additional ~30 fb^{-1} of data by August**

Mixing and sin2β measurements are done with the same strategy: do a global fit to all the events that can carry information:

Mixing : tagged flavour eigenstates

sin2β : tagged flavour and CP eigenstates

We float in the fit as many parameters as possible

parameter	#params	Sensitive evts	
sin2β	1	CP	Only in CP fit
ΔM_d	1	flavour	Only in mixing
w & Δw	8	flavour	
Δt resolution	9	flavour and CP	
Background τ	6	sidebands	
Background w	8	sidebands	
Background Δt	3	sidebands	

Biggest correlation with sin2β 7.6%

$J/\Psi K_L$ composition

	Fraction(%)	EMC	IFR
	signal	40.3	50.7
Inclusive J/Ψ MC	$J/\Psi K^{*0}(K_L\pi^0)$	9.1	9.9
Inclusive J/Ψ MC	$J/\Psi K^{*+}(K_L\pi^+)$	14.4	16.9
Inclusive J/Ψ MC	$J/\Psi K_s(\pi^0\pi^0)$	6.4	2.1
Inclusive J/Ψ MC	Other- J/Ψ	29.8	20.4
J/Ψ sidebands	Non- J/Ψ	6.3	4.4