

Physics at *BABAR*

Christos Touramanis



THE UNIVERSITY
of LIVERPOOL

for the BABAR Collaboration

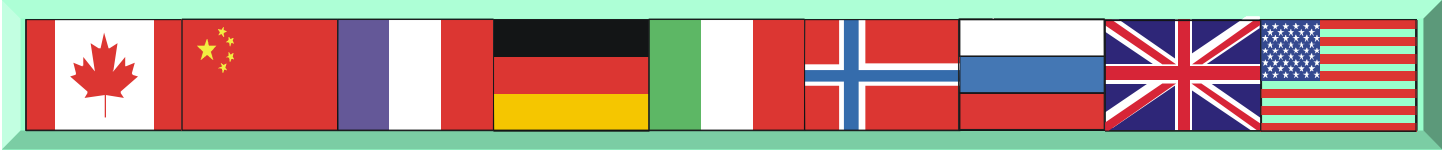
5th International Symposium on
Radiative Corrections

Carmel, September 11 2000



BABARTM

The *BABAR* collaboration



9 Countries
72 Institutions
554 Physicists

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U de Montréal
U of Victoria

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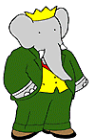
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Overview

- Physics programme
- PEP-II and BABAR
- Event reconstruction
- Selected preliminary measurements
- First CP results
- Conclusion-outlook



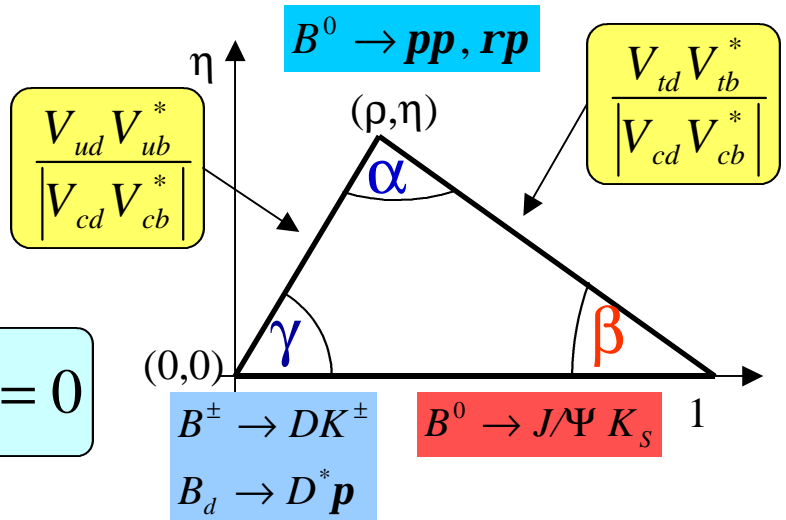
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CKM matrix, Unitarity Triangle, CP violation


 In the SM CP violation arises from the non-vanishing phase of the unitary CKM matrix

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



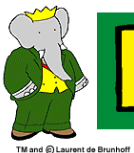
 Experimentally CP violation can be observed as time dependent decay rate asymmetry of CP conjugate processes, i.e. for a CP eigenstate f :

$$a_f(t) = \frac{R(B^0(t) \rightarrow f) - R(\bar{B}^0(t) \rightarrow f)}{R(B^0(t) \rightarrow f) + R(\bar{B}^0(t) \rightarrow f)}$$

 Independent measurements of $\sin(2\beta)$ with different theoretical and experimental systematics : $B^0 \rightarrow J/\psi K^0$ ($K_S \rightarrow \pi^+ \pi^- ; \pi^0 \pi^0 ; K_L$) ; $B^0 \rightarrow D^+ D^- ; D^* D^{*-} ; \phi K_S$

for $f = J/\psi K_S(K_L)$:

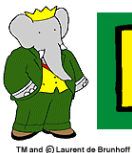
$$a_f(t) = (\pm 1) \sin(2\hat{\alpha}) \sin(\hat{\alpha} t)$$



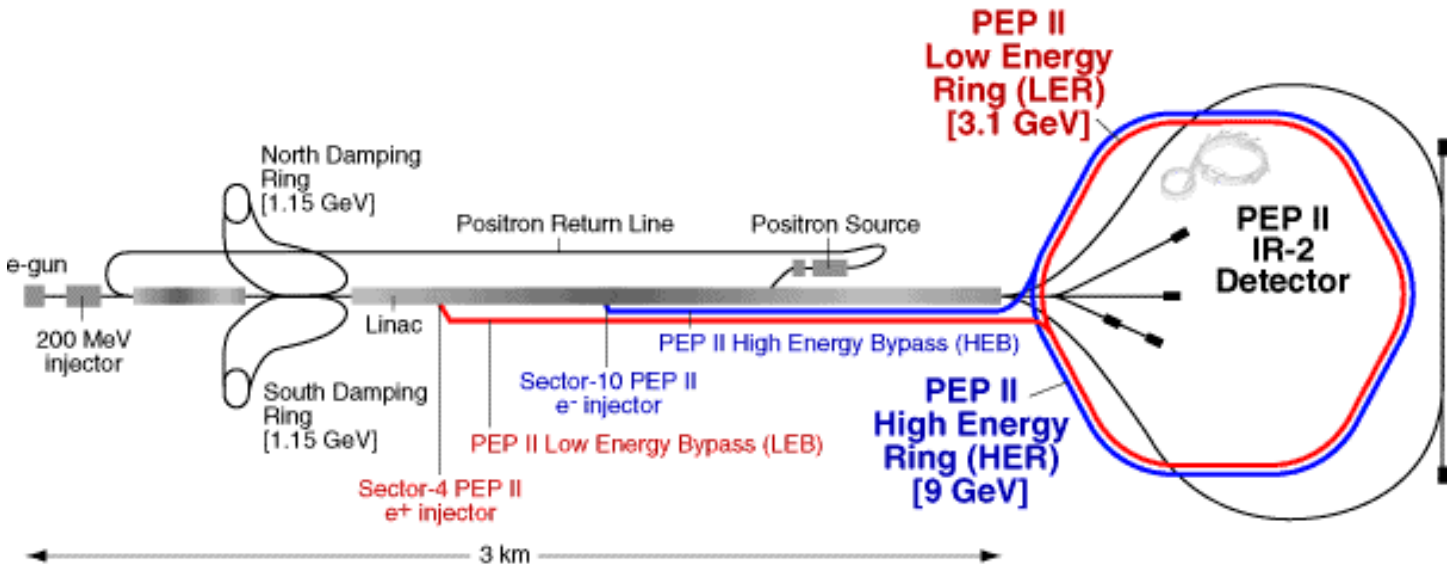
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The *BABAR* physics programme

- Main focus is B physics and in particular CP violation :
 - CP measurements : angles β , α and γ
- Determination of unitarity triangle sides through:
 - V_{ub} and V_{cb} : semileptonic B decays
 - V_{td} : B mixing (Δm)
- Above measurements allow to overconstrain the unitarity triangle and check for consistency between related observables => Stringent tests of the SM
- High statistics and broad access to the rich phenomenology of B sector allows BABAR to probe new physics at energy scales higher than the current reach of “direct search” experiments
- Furthermore, a rich non-B physics programme is accessible and ongoing in BABAR, covering charm, tau, two photon and QCD.



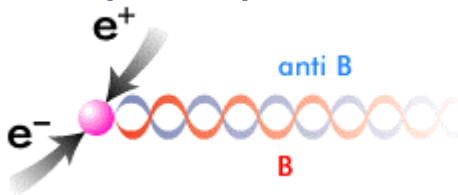
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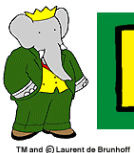
9 GeV e^- on 3.1 GeV e^+ :



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



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



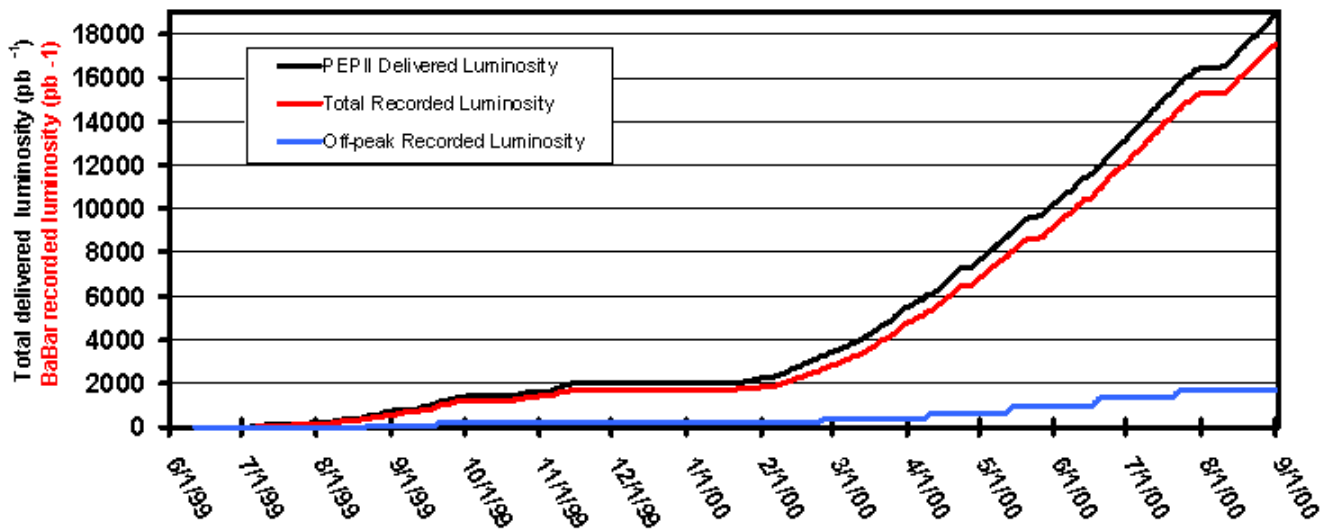
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SLAC B factory performance

- PEP-II top lumi : $2.4 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
(design 3.0×10^{33})
- Top 24h L : 150/pb (design 135)
- BABAR logging efficiency : >95%

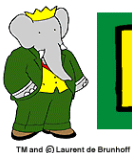
1 June 1999

31 August 2000



PEP-II delivered : 18.8/fb

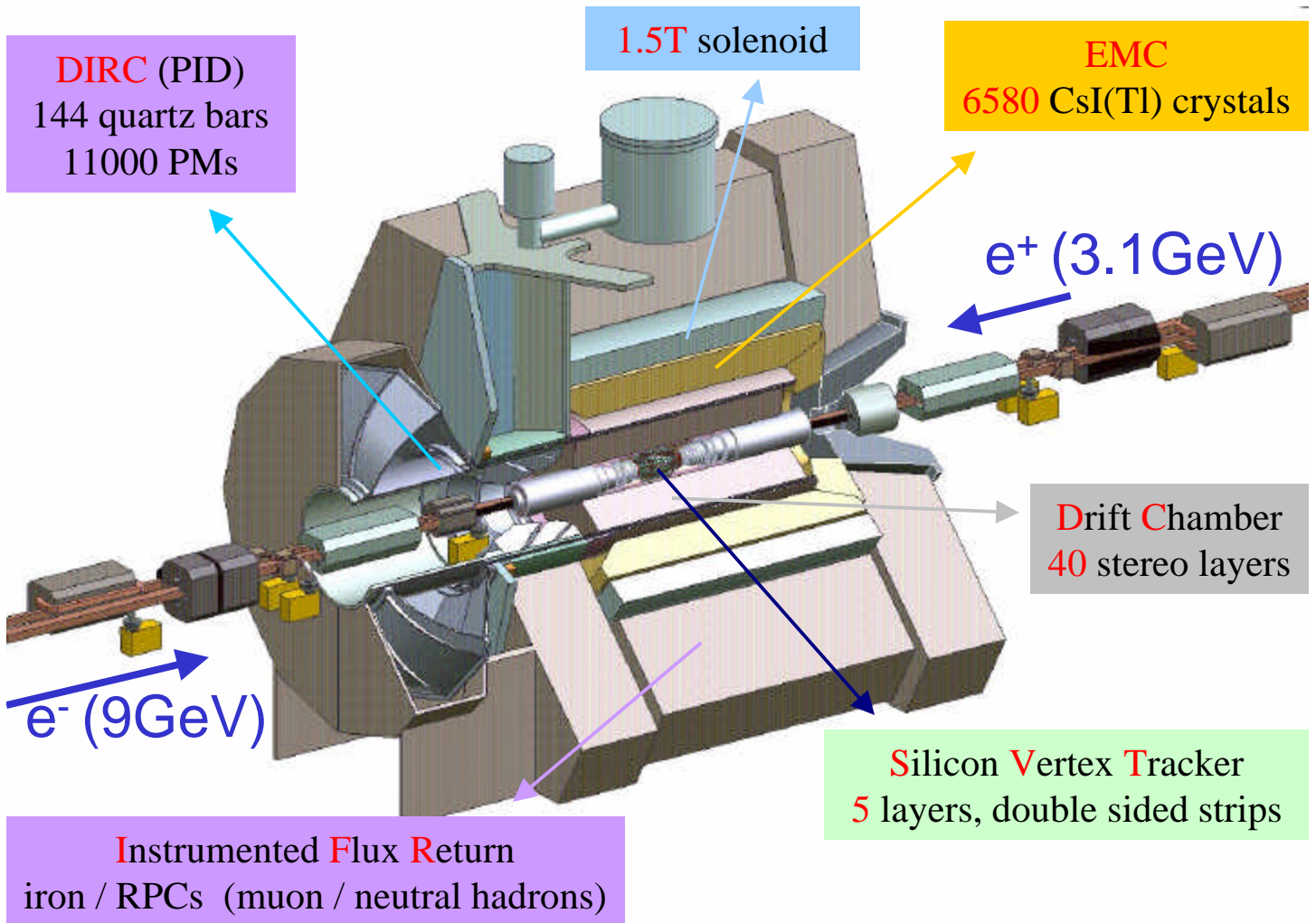
BABAR recorded : 17.5/fb (1.8/fb off peak)



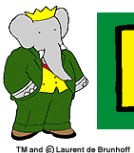
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Christos Touramanis RADCOR-2000

The BABAR detector

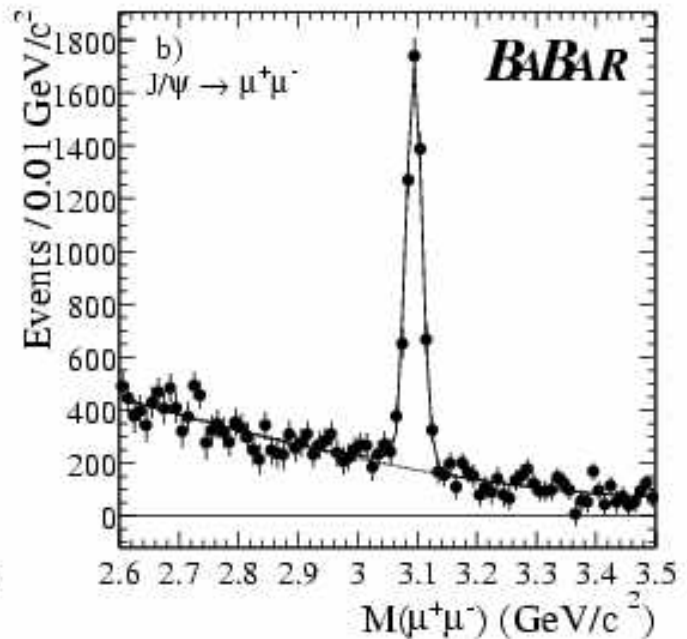
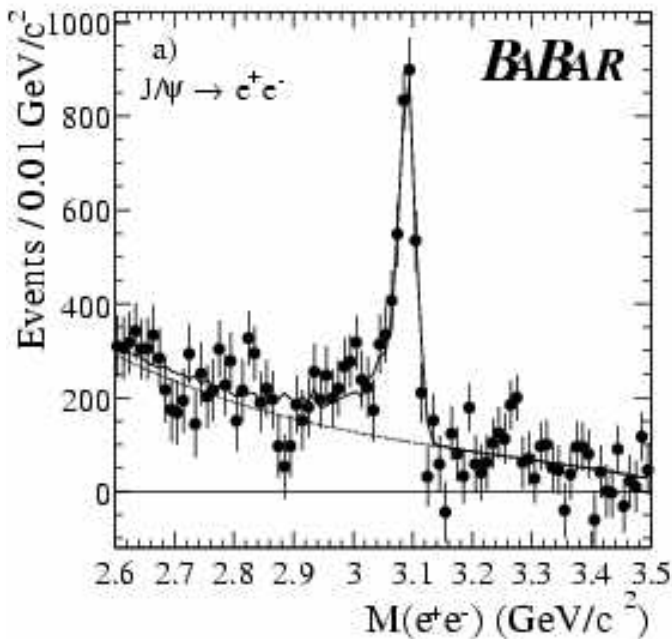


- Tracking : $\sigma(p_T)/p_T = 0.15\% \times p_T \oplus 0.45\%$
- DIRC : $K-\pi$ separation $>3.4\sigma$ for $P < 3.5 \text{ GeV}/c$



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Reconstruction quality(I)

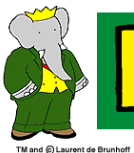
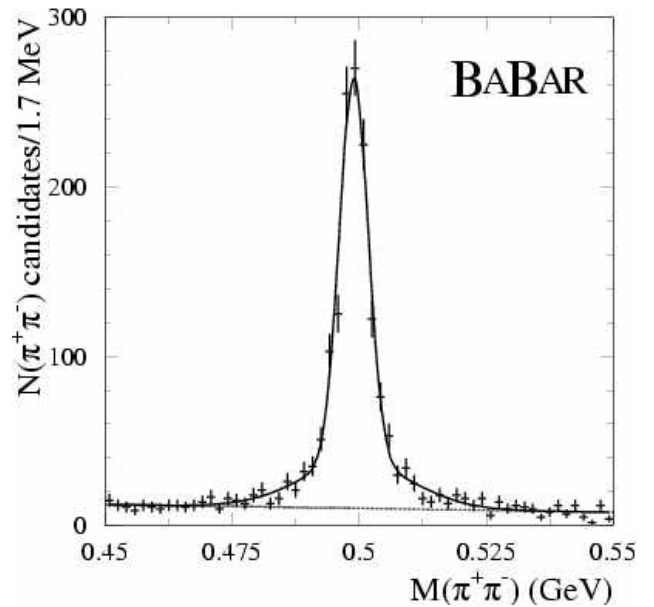


$J/\psi \quad \sigma = 13 \text{ MeV}/c^2$

$K_S \rightarrow \pi^+\pi^-$

$\sigma_1 = 2.8 \text{ MeV}/c^2 \quad (69\%)$

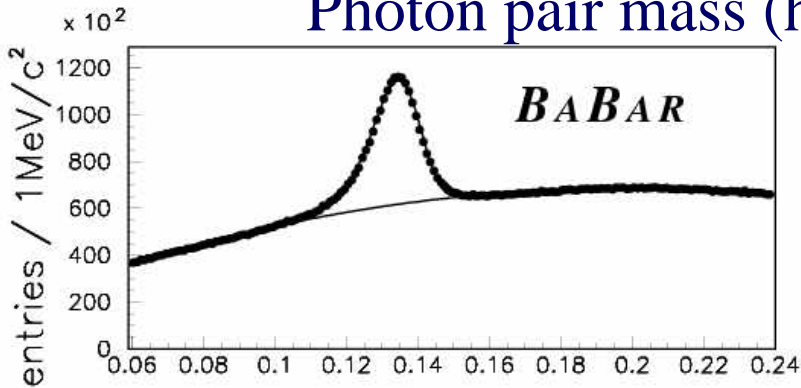
$\sigma_2 = 11 \text{ MeV}/c^2 \quad (31\%)$



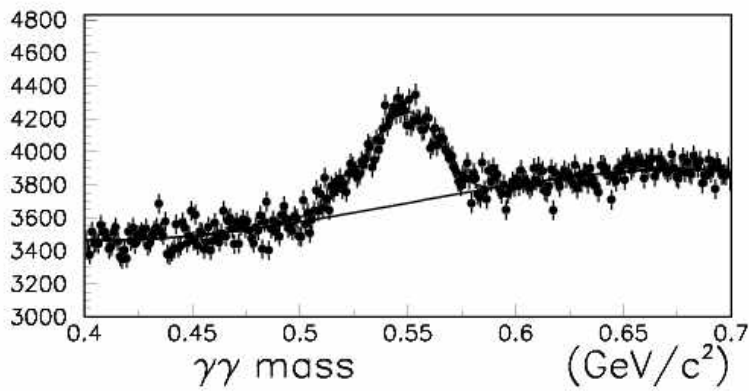
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Reconstruction quality(II)

Photon pair mass (hadronic events)

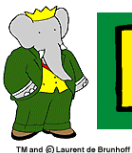
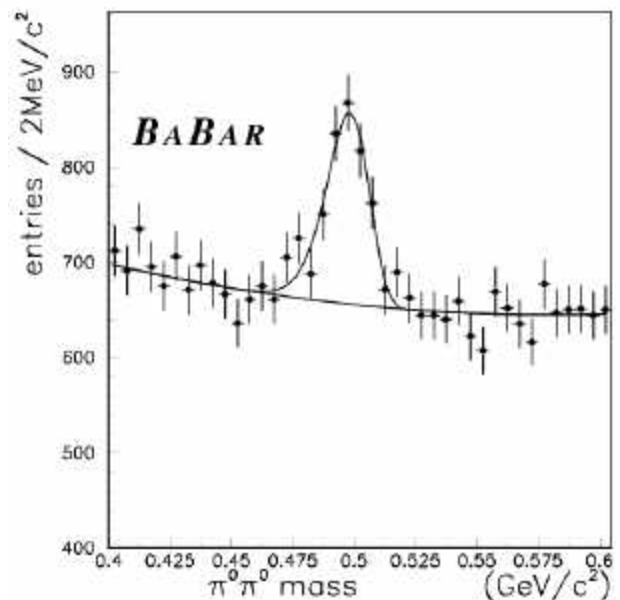


π^0 $\sigma = 6.9 \text{ MeV}/c^2$



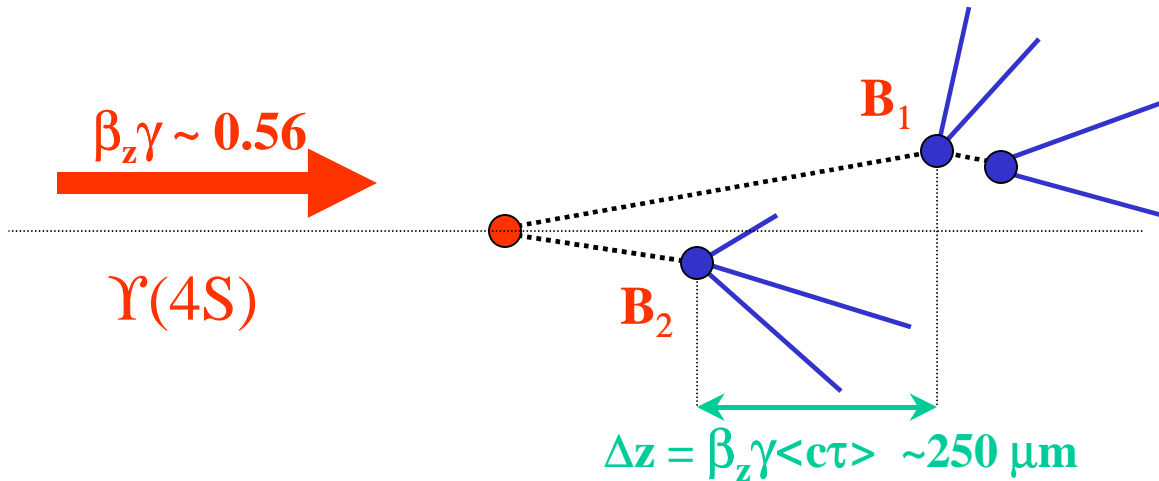
η $\sigma = 16 \text{ MeV}/c^2$

$K_S \rightarrow \pi^0 \pi^0$
 $\sigma = 10 \text{ MeV}/c^2$



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Y(4S) event reconstruction



Reco -> physics measurement & CP analysis input

- B_1 (incl,excl) : B decay fractions, kinematics ; signal purity (exclusive)
- B_1 (incl,semiexcl,excl), B_2 flav.tag, Δz : B lifetime, mixing ; tagging quality, Δz resolution
- B_1 (excl CP state), B_2 flav.tag, Δz : CP

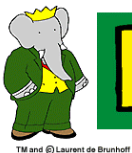
B Flavor Tagging :

- Primary Lepton
- Charged Kaon
- Neural Net (NT1, NT2)

Kinematic variables in exclusive reconstruction

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

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

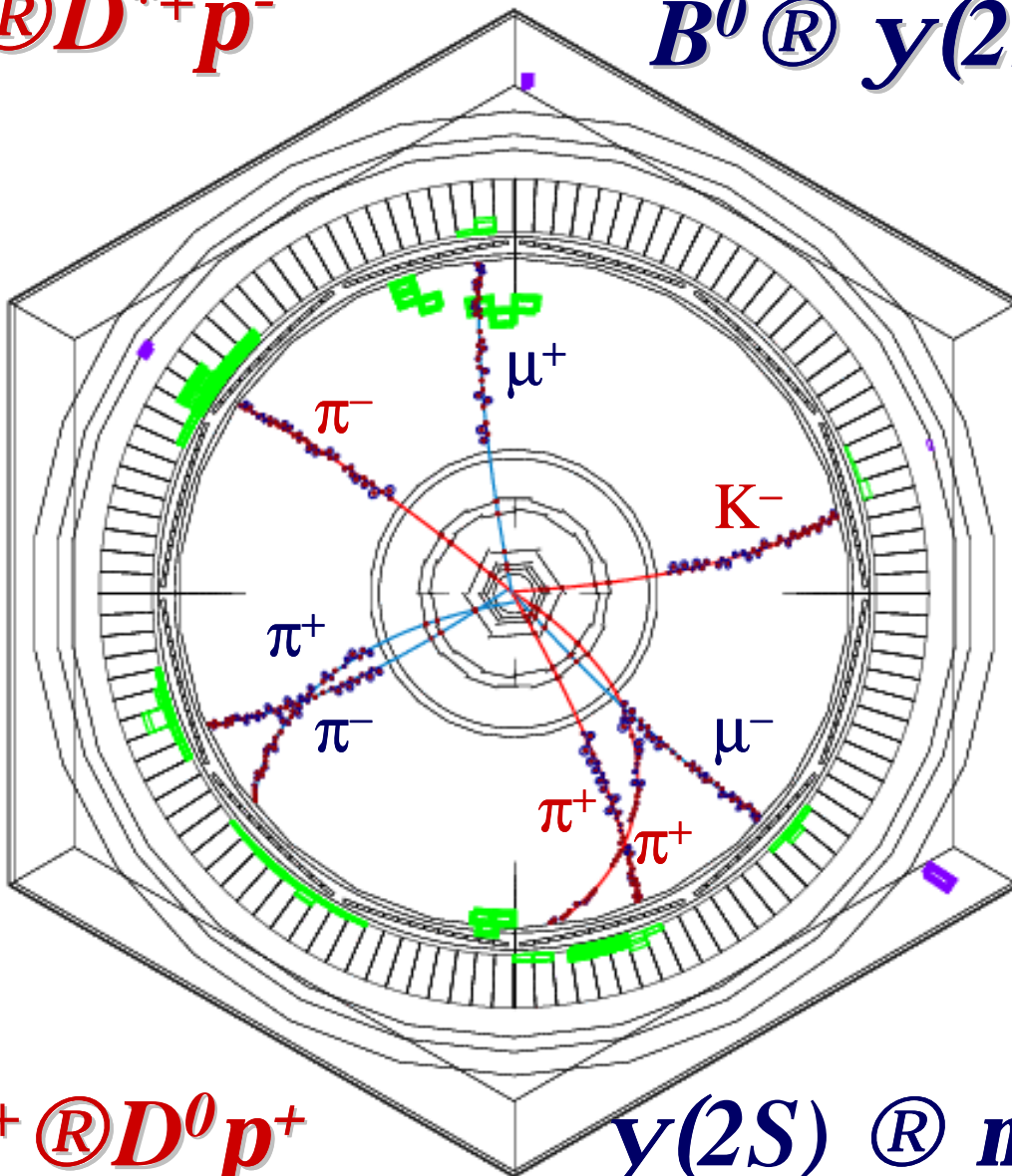


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Fully reconstructed $Y(4S)$ event

$\overline{B}^0 \textcircled{R} D^{*+} p^-$

$\overline{B}^0 \textcircled{R} \gamma(2S) K_s^0$



$D^{*+} \textcircled{R} D^0 p^+$

$\gamma(2S) \textcircled{R} m^+ m^-$

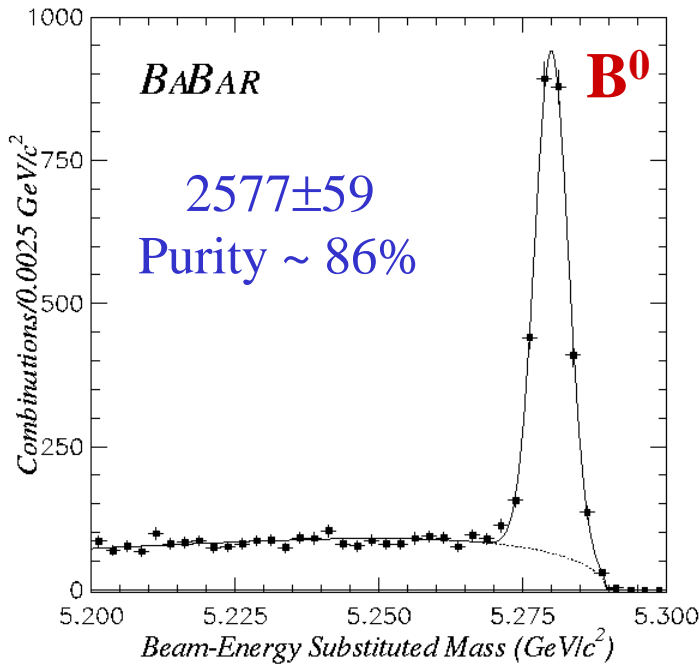
$D^0 \textcircled{R} K^- p^+$

$K_s^0 \textcircled{R} p^+ p^-$

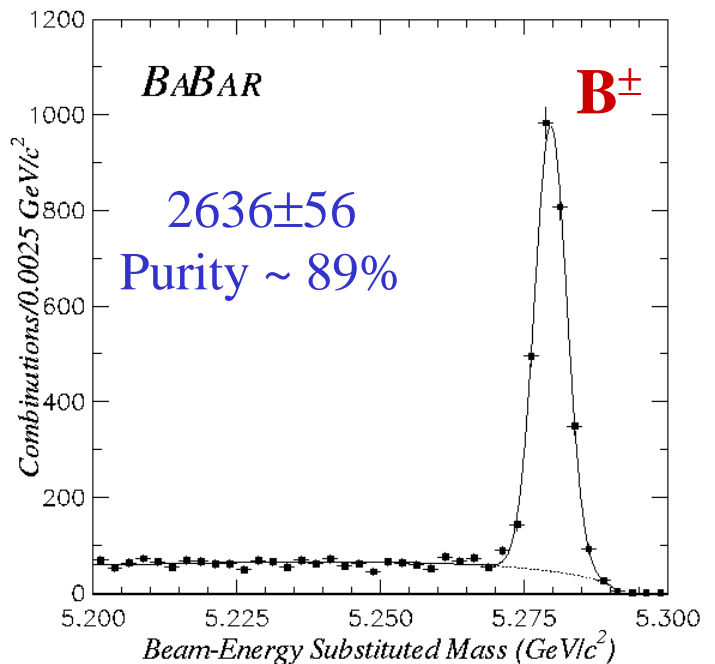


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Exclusive hadronic B sample



$B^0 @ D^{*-}p^+, D^{*0}r^+, D^{*0}a_1^+$
 $B^0 @ D^-p^+, D^-r^+, D^-a_1^+$
 $B^0 @ J/YK^{*0} (K^+p^-)$

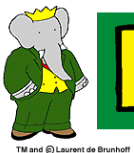


$B^- @ D^0p^-, D^{*0}p^-$
 $B^- @ J/YK^-, \gamma(2S)K^-$

Sample : 8.9 fb^{-1} on-resonance , 0.9 fb^{-1} off-resonance

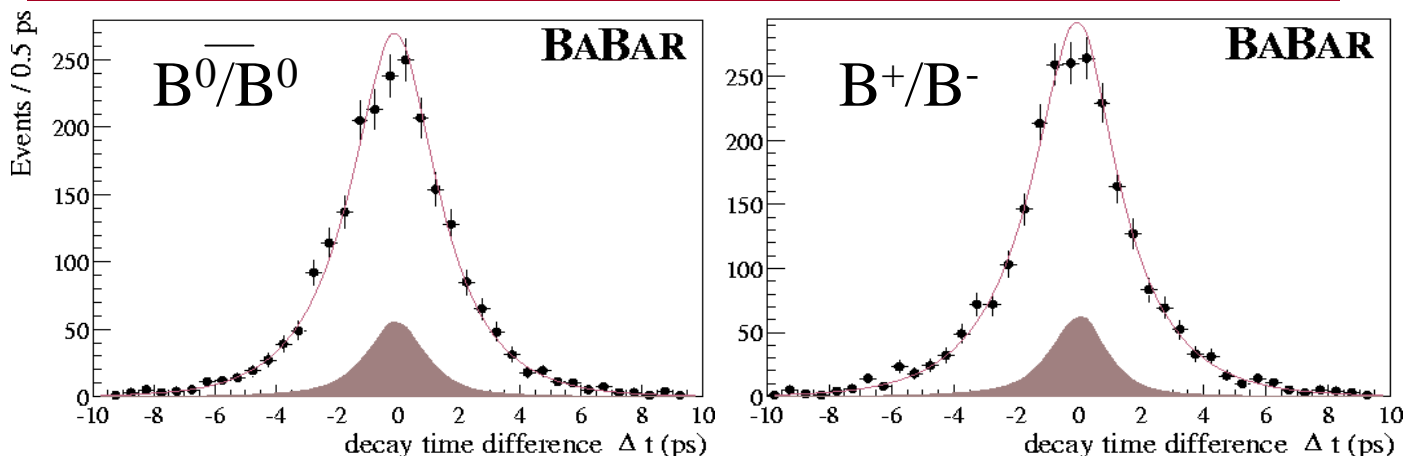
From these samples we measure :

- B^0, B^\pm lifetimes
- Δm (mixing) of neutral B
- Δz resolution and tagging performance for the $\sin(2\beta)$ measurement



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B lifetimes



- Determine z_{RECO} and z_{TAG} (the other B)
- Boost approximation : $\Delta t = \Delta z / c\langle\beta\gamma\rangle$
- Fit :
 - Maximum likelihood : $\Gamma e^{-\Gamma|\Delta t|} \otimes R(\Delta t; \mathbf{a})$
 - event-by-event error
- Resolution :
 - dominated by TAG side
 - Slight bias (0.2psec) from sec. decays
 - 3 gaussians

Preliminary result from 7.4 fb^{-1} on-resonance data:

$$\tau_{B^0} = 1.51 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (syst) ps}$$

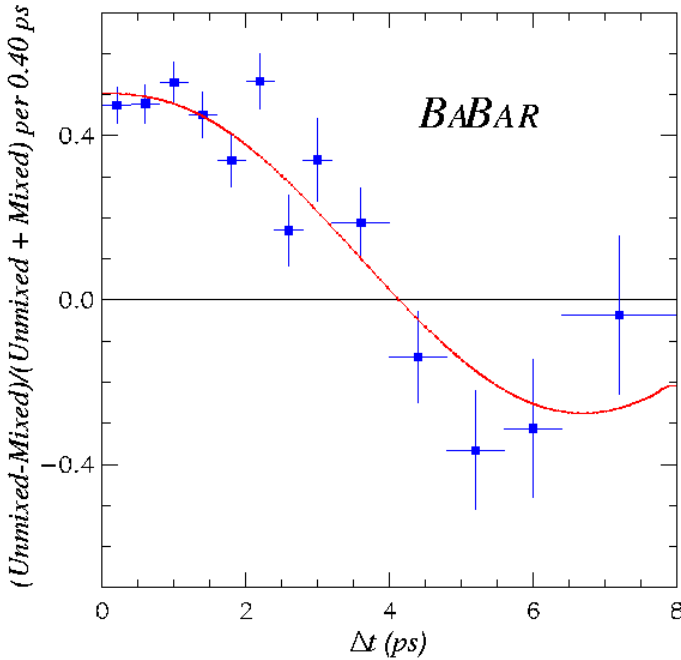
$$\tau_{B^+} = 1.60 \pm 0.05 \text{ (stat)} \pm 0.04 \text{ (syst) ps}$$

$$\tau_{B^+} / \tau_{B^0} = 1.065 \pm 0.044 \text{ (stat)} \pm 0.021 \text{ (syst)}$$



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B mixing



$$D \cos \Delta m_d \Delta t \otimes R(\Delta t; a)$$

Tagging efficiency

$$Q = \epsilon D^2, \quad D = 1 - 2w$$

D = Dilution

w : wrong tag fraction

ϵ : fraction of tagged events

Hadronic sample :

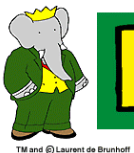
$$\Delta m_d = 0.516 \pm 0.031(\text{stat}) \pm 0.018(\text{syst}) \hbar \text{ ps}^{-1}$$

Semileptonic sample ($D^* l \nu$, 7517 events) :

$$\Delta m_d = 0.508 \pm 0.020(\text{stat}) \pm 0.022(\text{syst}) \hbar \text{ ps}^{-1}$$

Combined preliminary result :

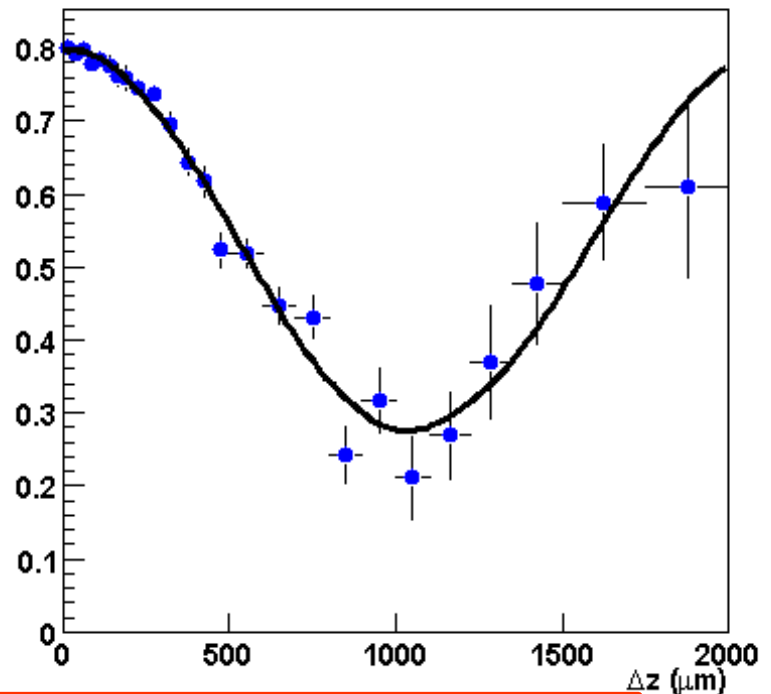
$$\Delta m_d = 0.512 \pm 0.017(\text{stat}) \pm 0.022(\text{syst}) \hbar \text{ ps}^{-1}$$



B mixing using dileptons

$$A(\Delta t) = \frac{N(\text{ }^+ \text{ }^-)(\Delta t) - N(\text{ }^\pm \text{ }^\pm)(\Delta t)}{N(\text{ }^+ \text{ }^-)(\Delta t) + N(\text{ }^\pm \text{ }^\pm)(\Delta t)}$$

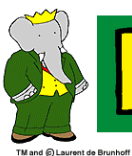
- **B Flavor**
=> sign of the direct lepton
- **Inclusive approach**
=> large BR (~4%)
- **Mixture of B⁰ and B[±]**
=> Fraction R fitted
- **Cascade leptons**
=> Mistag fraction fitted



$$A(\Delta t) = \frac{e^{-\Gamma^0|\Delta t|} \cos(\Delta m_B \Delta t) + R \cdot e^{-\Gamma^+|\Delta t|}}{e^{-\Gamma^0|\Delta t|} + R \cdot e^{-\Gamma^+|\Delta t|}}$$

Preliminary result from 7.7 fb⁻¹ on-resonance and 1.1 fb⁻¹ off-resonance data :

$$\Delta m_d = 0.507 \pm 0.015(\text{stat}) \pm 0.022(\text{syst}) \hbar \text{ ps}^{-1}$$



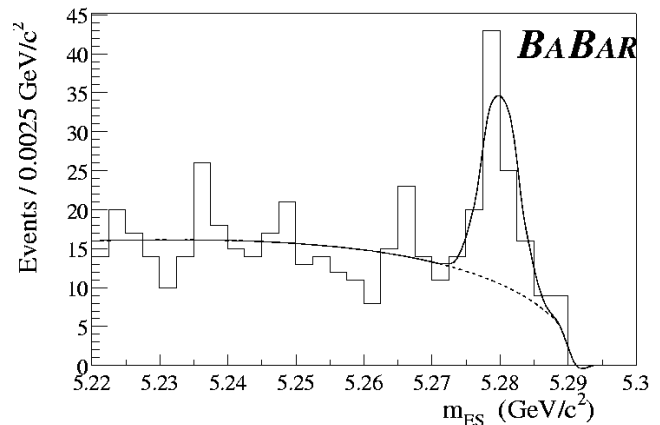
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Charmless 2-body decays

Cut based analysis, no PID

$$N(h^+h^-) = 67 \pm 11$$

(consistent with CLEO)

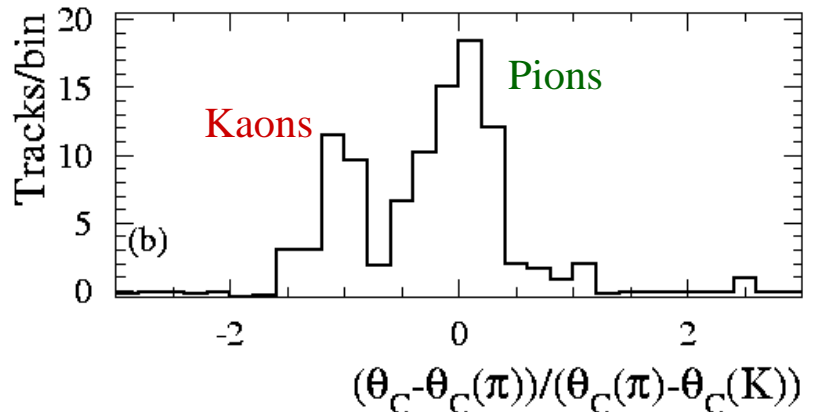


Kaon/pion content after sideband (m_{ES}) subtraction :

θ_C : Cerenkov angle in DIRC

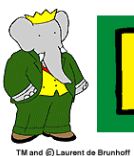
$\theta_C(\pi)$: expected angle, pion

$\theta_C(K)$: expected angle, Kaon



Preliminary result from likelihood fit (m_{ES} , ΔE , Fisher discriminant and K/ π PID) :

Mode	N_S	Stat. Sig. (σ)	$\mathcal{B} (10^{-6})$	CLEO
$\pi^+\pi^-$	29^{+8+3}_{-7-4}	5.7	$9.3^{+2.6+1.2}_{-2.3-1.4}$	$4.3^{+1.6}_{-1.4} \pm 0.5$
$K^+\pi^-$	38^{+9+3}_{-8-5}	6.7	$12.5^{+3.0+1.3}_{-2.6-1.7}$	$17.2^{+2.5}_{-2.4} \pm 1.2$
K^+K^-	$7^{+5}_{-4} (< 15)$	2.1	< 6.6	< 1.9

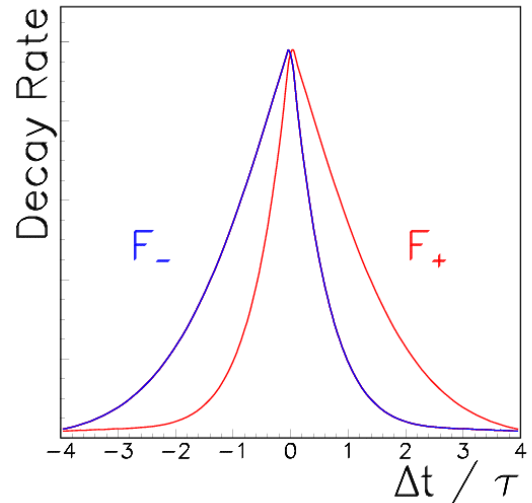


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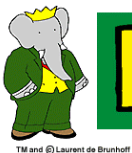
Measuring $\sin(2\beta)$

$$F_{\pm}(\Delta t) \propto \exp(-\Gamma\Delta t) (1 \pm \sin(2\beta) \sin(\Delta m\Delta t))$$

Decay rates (F_+, F_-) to CP eigenstate for (B^0, \bar{B}^0) tags
 [sin(2β) = 0.7, no detector effects]



- Select exclusive $B^0 \rightarrow$ CP eigenstate events
 ? Background fraction, type \Rightarrow exclusive studies
- Tag the flavor of the other B at decay time
 ? Dilution \Rightarrow mixing analysis
- Reconstruct the two B decay vertices and determine $\Delta t = \Delta z / \langle \beta \gamma \rangle$
 ? Resolution \Rightarrow lifetime analysis
- Unbinned max likelihood fit
 - ✓ event by event Δt error and outlier cut
 - ✓ Dilution dependent on tag type (lepton, kaon, NN)



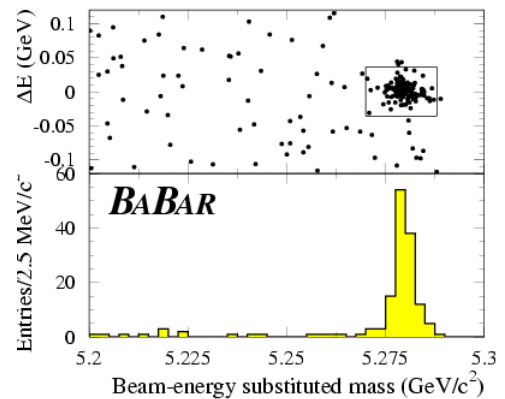
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The CP sample

$B^0 \rightarrow J/\Psi K_S (K_S \rightarrow \pi^+\pi^-)$

121 events

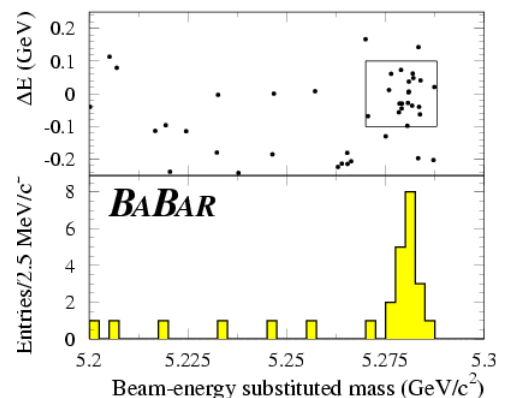
purity 96%



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

19 events

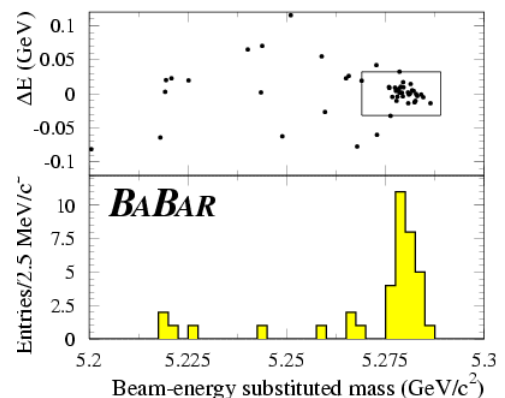
purity 91%



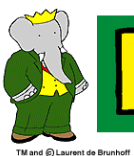
$B^0 \rightarrow \Psi(2S) K_S (K_S \rightarrow \pi^+\pi^-)$

28 events

purity 93%



Total : 168 fully reconstructed candidates



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Flavor tagging of the other B

Tagging categories (ranked) :

1. **Lepton** : Primary electron OR muon charge
2. **Kaon** (total) charge
3. **NT1** Neural Net (slow pion charge, "Jet Charge")
4. **NT2** same Neural Net, lower separation region

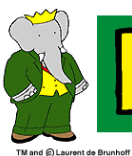
In presence of dilution factor **D** the CP and mixed/unmixed B decay rates become :

$$F_{\pm}(\Delta t) = \exp(-\Gamma\Delta t) (1 \pm \mathbf{D}\sin(2\beta)) \sin(\Delta m\Delta t)$$

$$F_{U,M}(\Delta t) = \exp(-\Gamma\Delta t) (1 \pm \mathbf{D}\cos(\Delta m\Delta t))$$

 We extract the tagging performance from the mixing analysis :

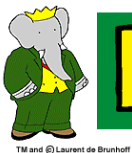
Tagging Category	ε (%)	w (%)	Q (%)
Lepton	11.2 ± 0.5	$9.6 \pm 1.7 \pm 1.3$	7.3 ± 0.3
Kaon	36.7 ± 0.9	$19.7 \pm 1.3 \pm 1.1$	13.5 ± 0.3
NT1	11.7 ± 0.5	$16.7 \pm 2.2 \pm 2.0$	5.2 ± 0.2
NT2	16.6 ± 0.6	$33.1 \pm 2.1 \pm 2.1$	1.9 ± 0.1
all	76.7 ± 0.5		27.9 ± 0.5



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Δt measurement

- CP side (fully reco'd) : σ_z 45-65 μm
(mode dependent)
- Tag side :
 - σ_z 125 μm
 - bias δ_z 25 μm (charm)
- Resolution extracted from lifetime measurement and verified on mixing :
 - Core : $\sigma = 0.6\text{ps}$; 75%
 - Tail : $\sigma = 1.8\text{ps}$
 - Outliers : $\sigma = 8\text{ps}$; 1%



$\sin(2\beta)$: precautions and checks



Blind Analysis

- $\sin(2\beta)$ fitted value and CP asymmetry in Δt distribution hidden to eliminate analyst's bias
- Event selection, tagging, vertexing fixed and studied blind
- Will revert to blind analysis for new data

Null CP asymmetry tests

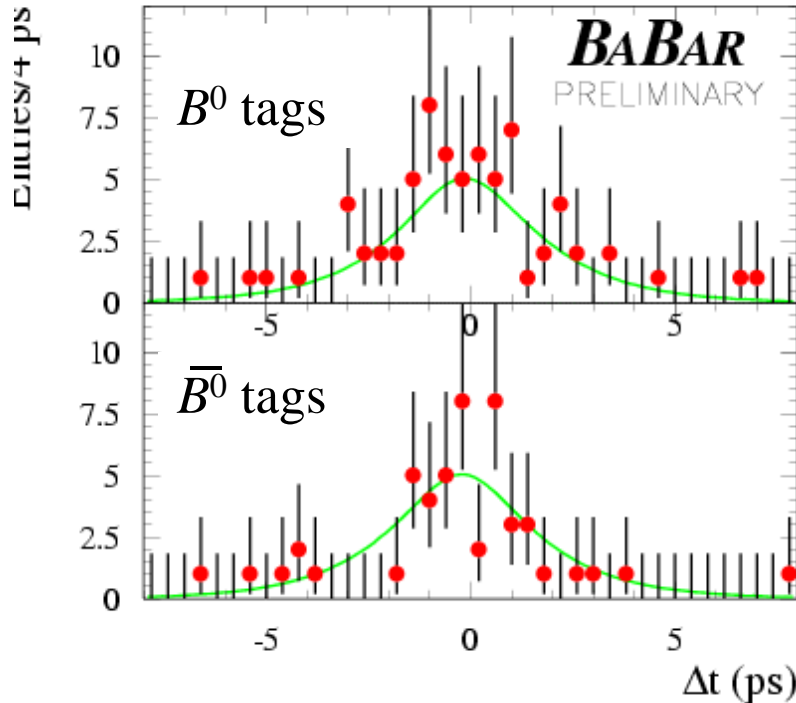
Sample	Apparent CP -asymmetry
Hadronic charged B decays	0.03 ± 0.07
Hadronic neutral B decays	-0.01 ± 0.08
$J/\psi K^+$	0.13 ± 0.14
$J/\psi K^{*0}$ ($K^{*0} \rightarrow K^+ \pi^-$)	0.49 ± 0.26



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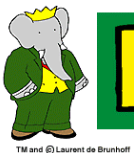
The $\sin(2\beta)$ fit

120 of 168 events tagged



$$\sin(2\beta) = 0.12 \pm 0.37(\text{stat}) \pm 0.09 (\text{syst})$$

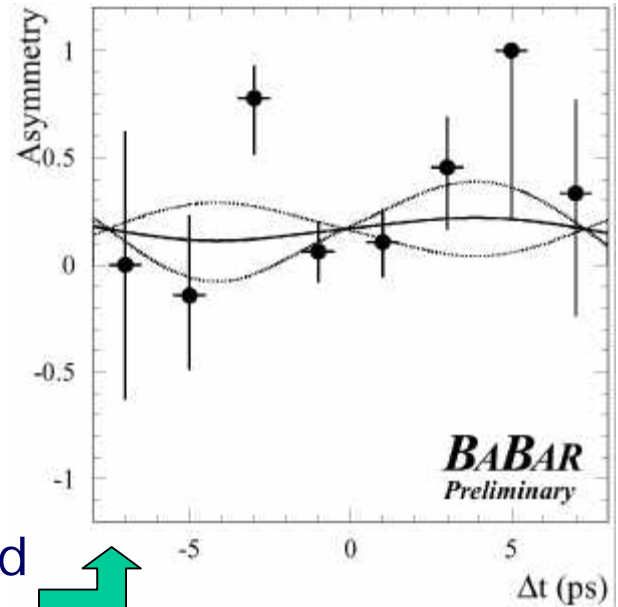
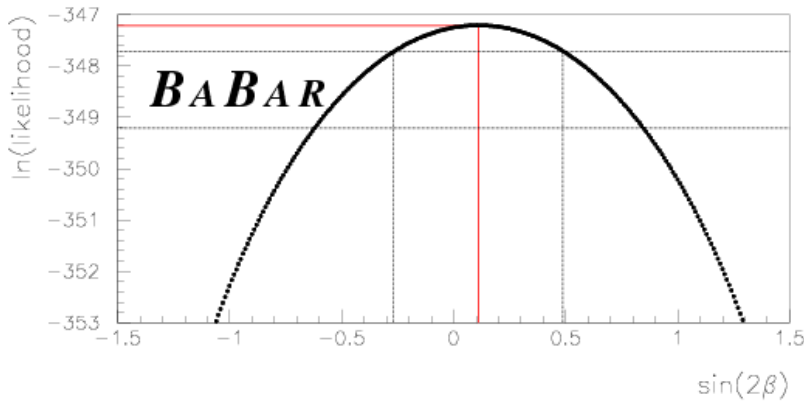
sample	$\sin 2\beta$
<i>CP</i> sample	0.12 ± 0.37
$J/\psi K_S^0$ ($K_S^0 \rightarrow \pi^+ \pi^-$)	0.10 ± 0.42
other <i>CP</i> events	0.87 ± 0.81
Lepton	1.6 ± 1.0
Kaon	0.14 ± 0.47
NT1	-0.59 ± 0.87
NT2	-0.96 ± 1.30



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Fit quality and systematic errors

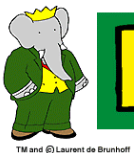
- Log likelihood function



- χ^2 for binned asymmetry and likelihood fit is 9.2 / 7



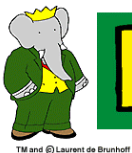
source of uncertainty	effect on $\sin 2b$
B^0 lifetime	0.012
Dm_d	0.015
Dz resolution, CP sample	0.019
Time resolution bias, CP sample	0.047
Mistag fraction measurement	0.059
Mistag difference in CP - non CP samples	0.050
Different mistag fractions for B^0 , anti- B^0	0.005
Background, CP sample	0.015
Total systematic uncertainty	0.091



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Conclusions and Outlook

- 👍 Impressive startup for PEP-II and BABAR:
 - 18.8fb⁻¹ delivered
 - 17.5fb⁻¹ recorded
 - 9fb⁻¹ analysed by July
- ✓ $\sin(2\beta) = 0.12 \pm 0.37_{\text{stat}} \pm 0.09_{\text{syst}}$
- ✓ many other interesting physics measurements already presented
- 🕒 Run until End October :: collect 25fb⁻¹
 - 😊 interesting $\sin(2\beta)$ measurement
 - 😊 and much more
 - in a few months



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