Observation of CP violation in the B^0 system

with BABAR

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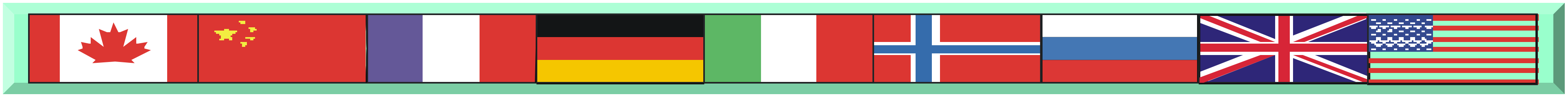
THE UNIVERSITY *of* LIVERPOOL

for the BABAR Collaboration

HEP2001 meeting, European Physical Society, Budapest, July 13 2001

The *BABAR* collaboration



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Overview

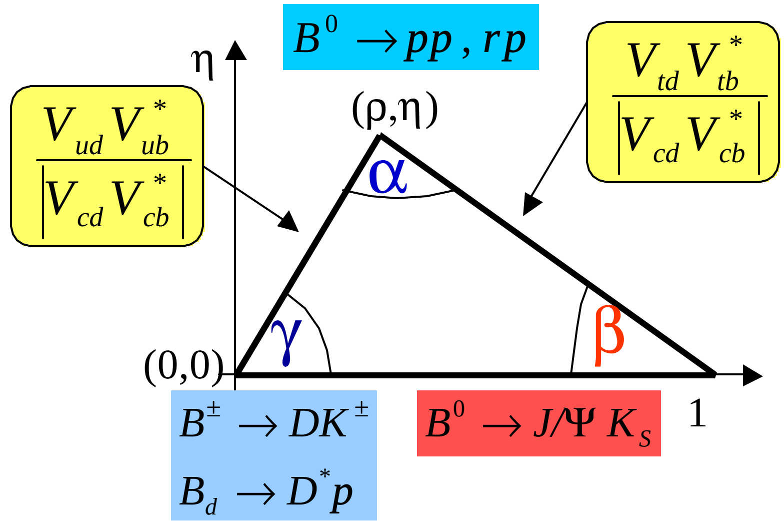
- Physics issues
- PEP-II and BABAR

- Dilepton B sample
  - mixing, CP/T violation
- Exclusive B sample
  - lifetimes, mixing
- Observation of CP violation, sin(2β)

- Conclusion

CP violation in the Standard Model

Unitarity triangle



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

A time dependent decay rate asymmetry between CP conjugate processes is a direct manifestation of CP violation

Asymmetry for B^0 -> J/$\psi K_S(K_L)$: $a_f(t) = (\pm 1)\sin(2\text{â})\sin(\text{Ä}mt)$

Main focus of the *BABAR* physics programme

- B physics, CP violation: angles **b** , **a** and **g**

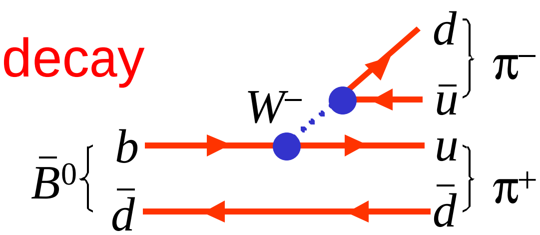
- Determination of unitarity triangle sides:
  - V_{ub} and V_{cb} : semileptonic B decays
  - V_{td} : B mixing (Δm)

- Stringent tests of the SM :
  - Overconstrain the unitarity triangle
  - check for consistency between related observables

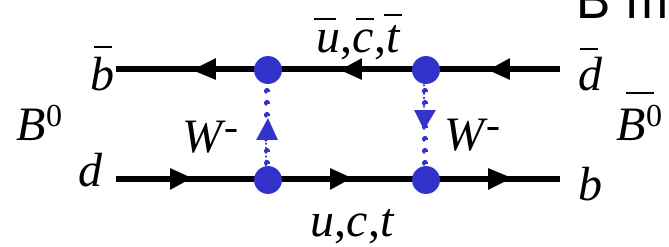
A word on CP violation

interfering amplitudes -> CP violating observables

B decay

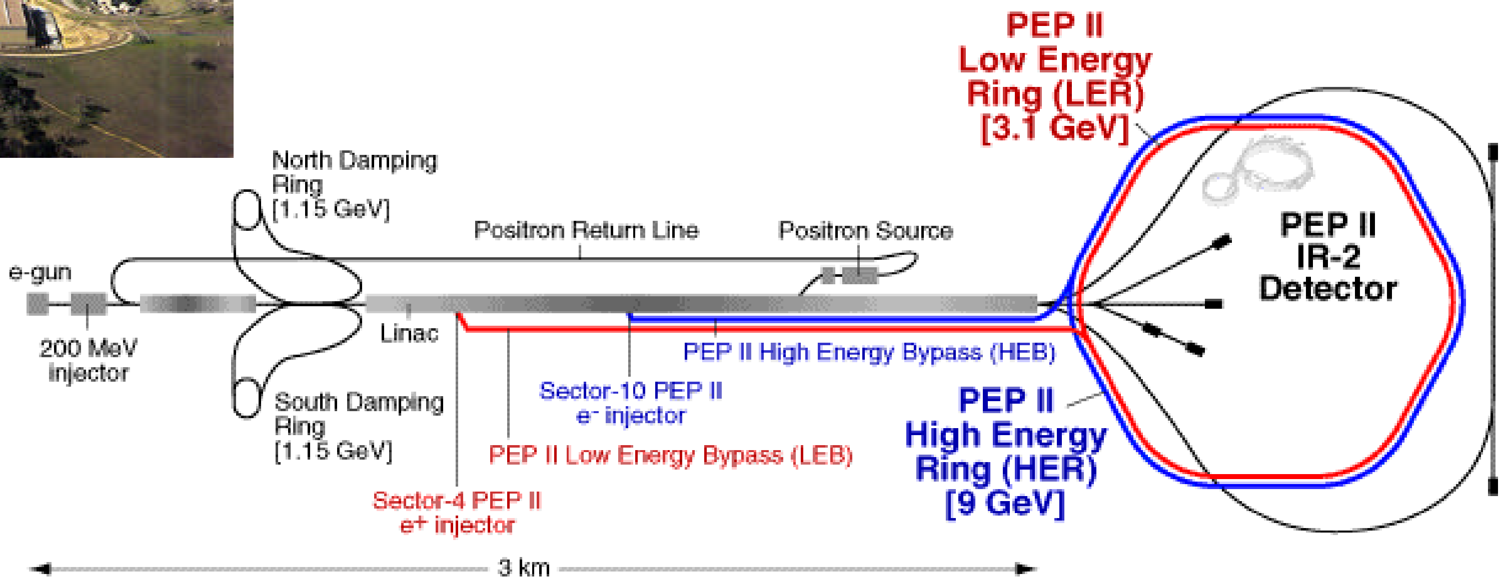


B mixing



Types of CP violation :

- Indirect
  - mixing amplitudes interference
  - A_T in this talk
- Direct
  - decay amplitudes interference
  - Sven Menke's talk
- CP violation in interference between mixing and decay
  - sin(2β) in this talk



9GeV e^- on 3.1GeV e^+ : $e^+e^- \rightarrow Y(4S) \rightarrow B^0\overline{B^0}$

- coherent neutral B pair production and decay (p-wave)
- boost of Y(4S) in lab frame : $\beta\gamma$=0.56

BABAR

SLAC B factory performance

- PEP-II top lumi:

$3.3x10^{33}cm^{-2}s^{-1}$ (design $3.0x10^{33}$)

- Top recorded 24h L:

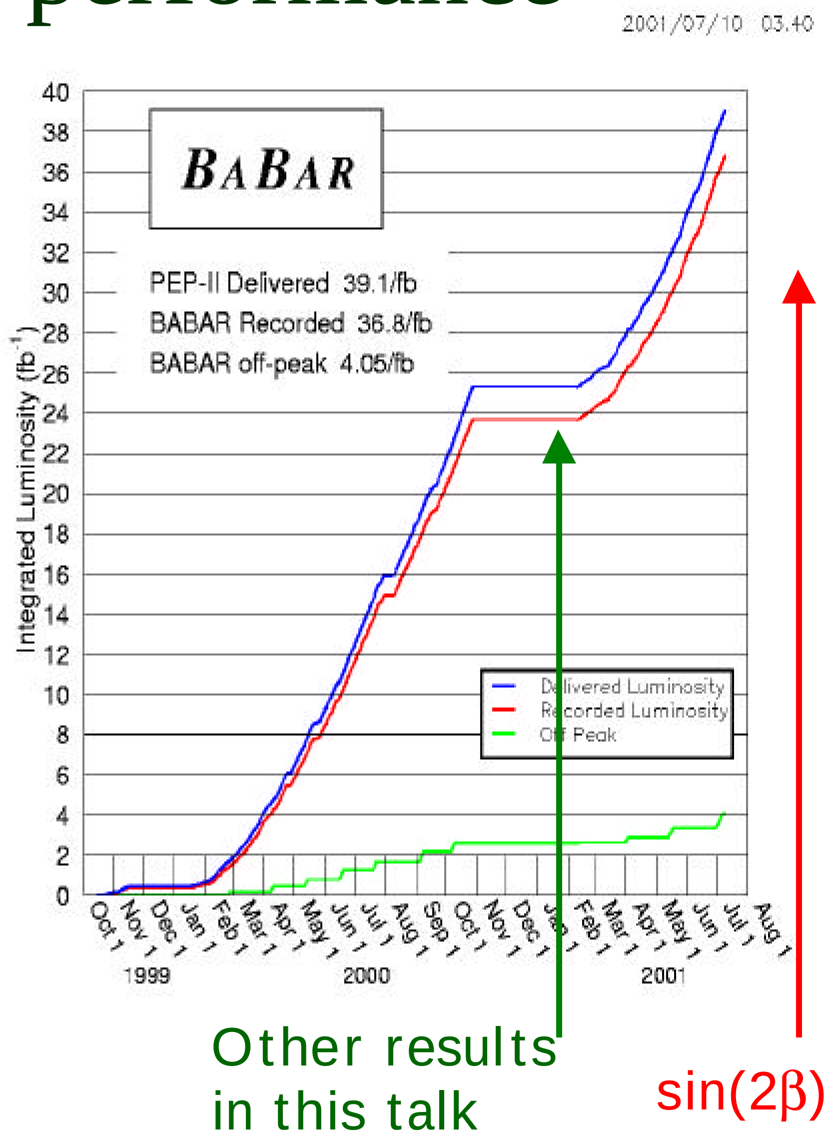
214/pb (design 135)

- BABAR logging efficiency:

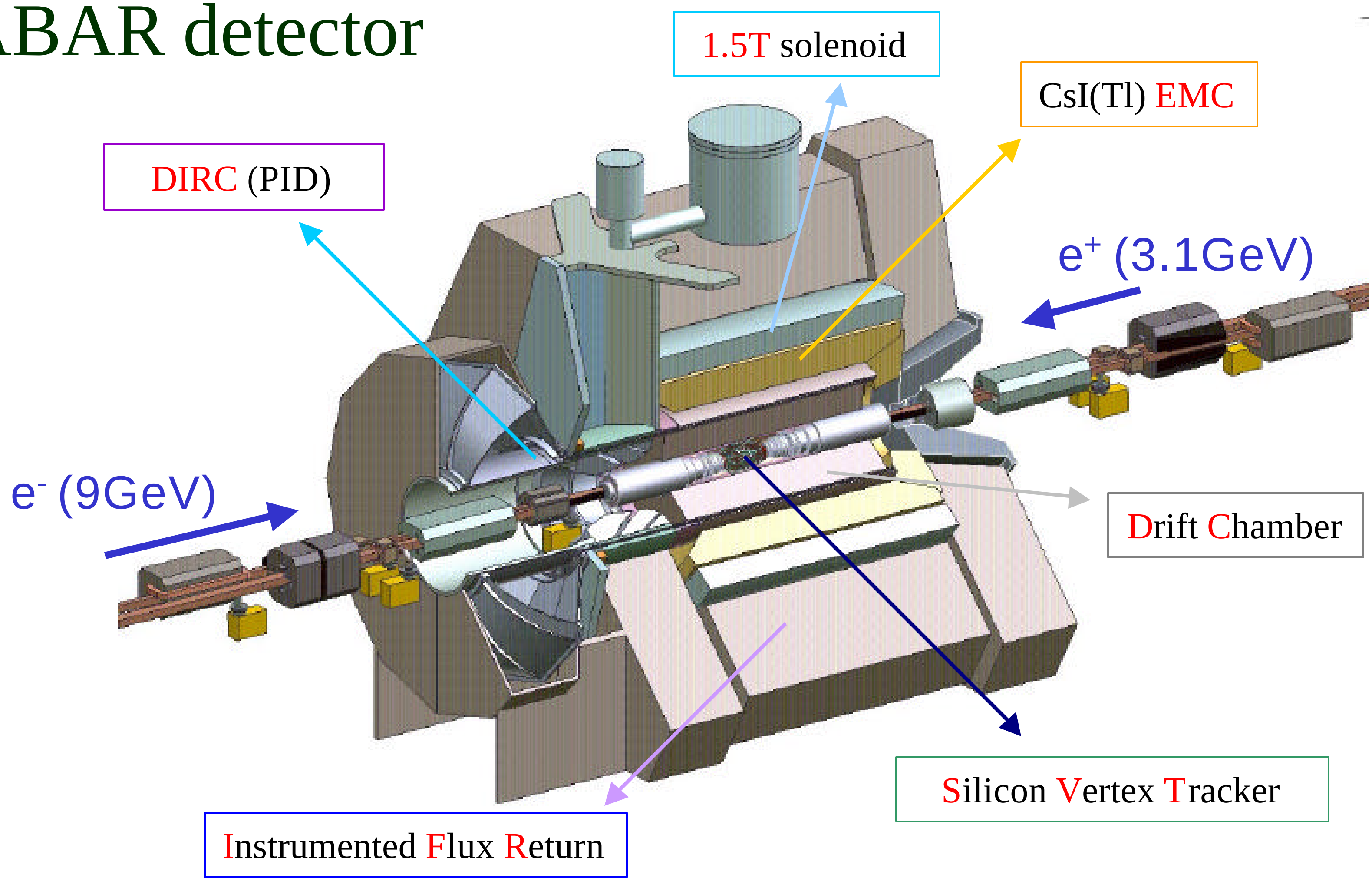
>96%

October 99 to 10 July 01 :

PEP-II delivered : 39.1/fb
BABAR recorded : 36.8/fb
(4.0/fb off peak)

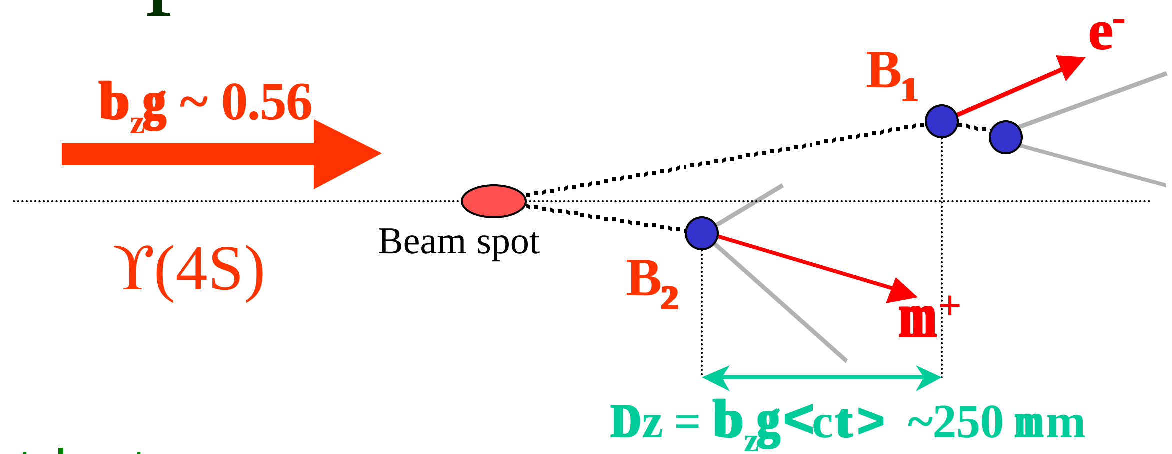


The BABAR detector



- SVT: 97% efficiency, 15μm z resol. (inner layers, perpendicular tracks)
- Tracking : $\sigma(p_T)/p_T = 0.15\% x p_T \oplus 0.45\%$
- DIRC : K-π separation >3.4σ for P<3GeV/c

Dilepton sample



- B Flavor: sign of direct lepton
- Event selection: PID (leptons), kinematics (NN)
- Δz: Closest approach of each lepton to beam spot in transverse plane

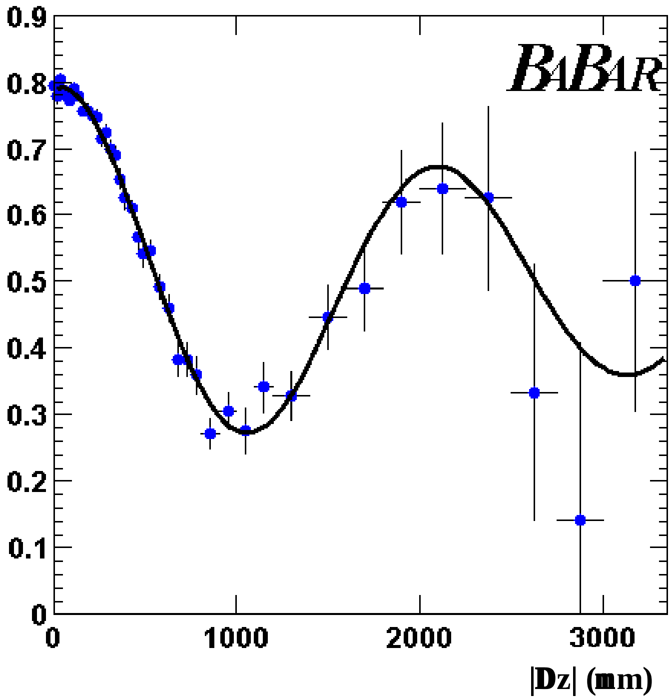
Mixing (Δm): $$A(\Delta t) = \frac{N(\ell^+\ell^-)(\Delta t) - N(\ell^\pm\ell^\pm)(\Delta t)}{N(\ell^+\ell^-)(\Delta t) + N(\ell^\pm\ell^\pm)(\Delta t)}$$

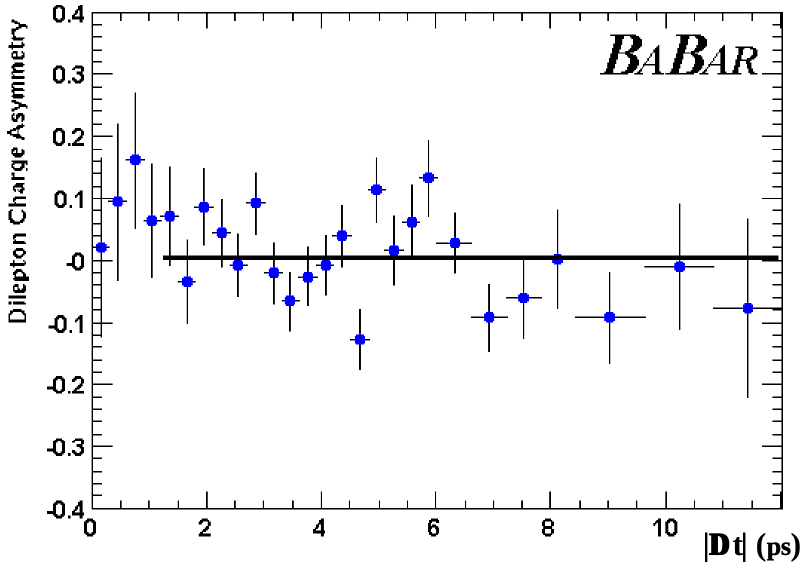
CP/T violation (ε_B): $$\mathrm{A_T}(\Delta t) = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} \approx \frac{4\mathrm{Re}(e)}{1+|e\ \ |^2}$$

Dilepton results, 20.7fb^{-1}

$\Delta m_d = 0.499 \pm 0.010_{stat} \pm 0.012_{syst}\ \hbar\ ps^{-1}$

Preliminary

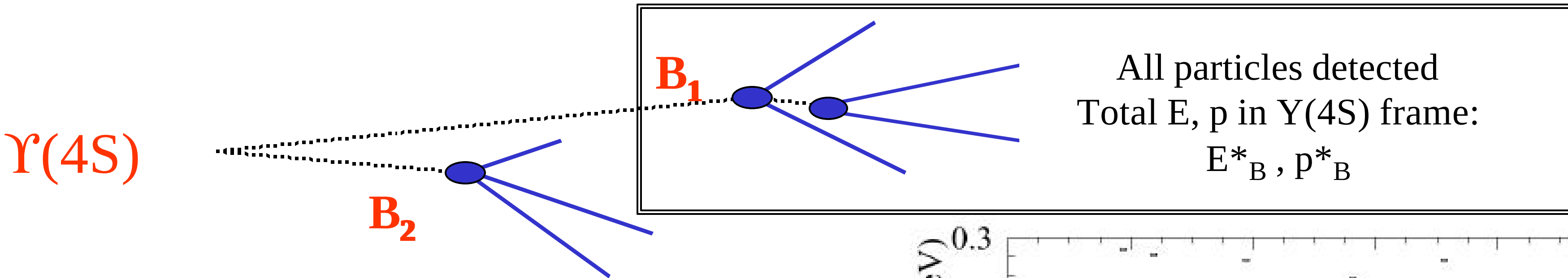




$Re(\varepsilon)/(1+|\varepsilon|^2) = (0.12 \pm 0.29 \pm 0.36)$ %

Preliminary; most precise measurement (no CPT assumption)

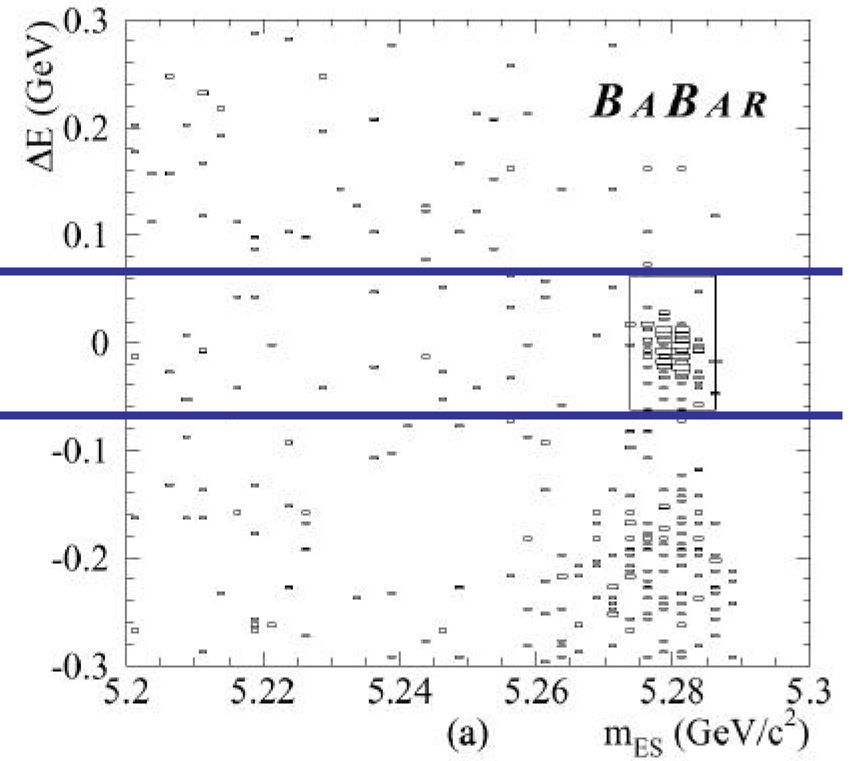
Exclusive B reconstruction

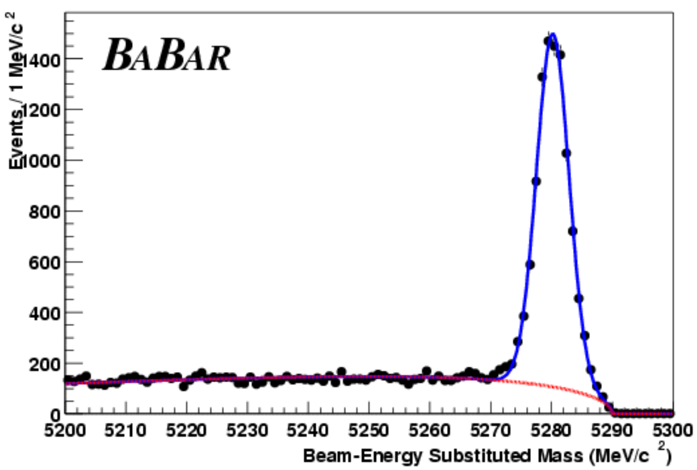


Kinematic variables:

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

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

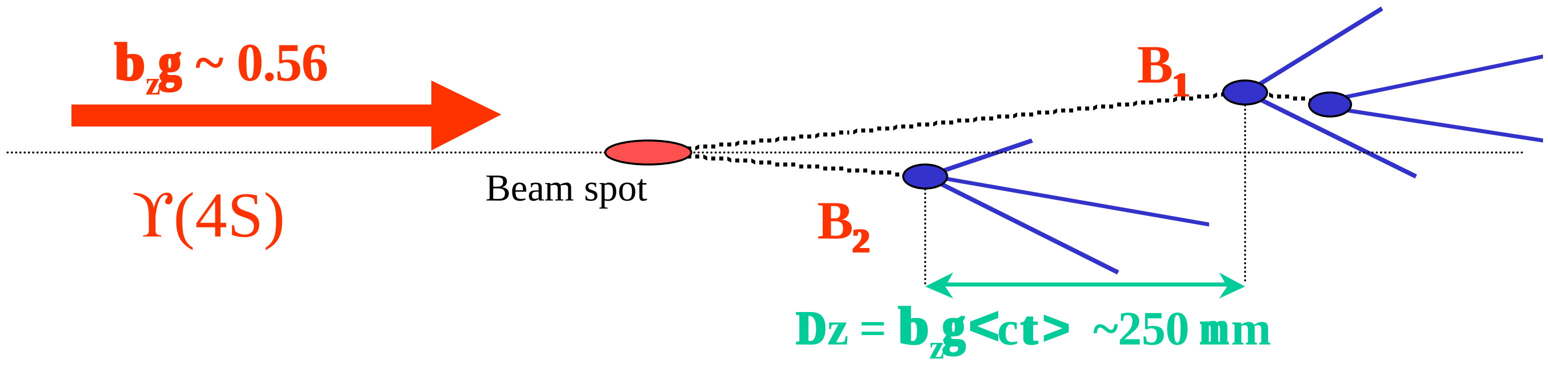




DE : s~15 MeV

m_{ES} : s~3MeV

Exclusive B sample use

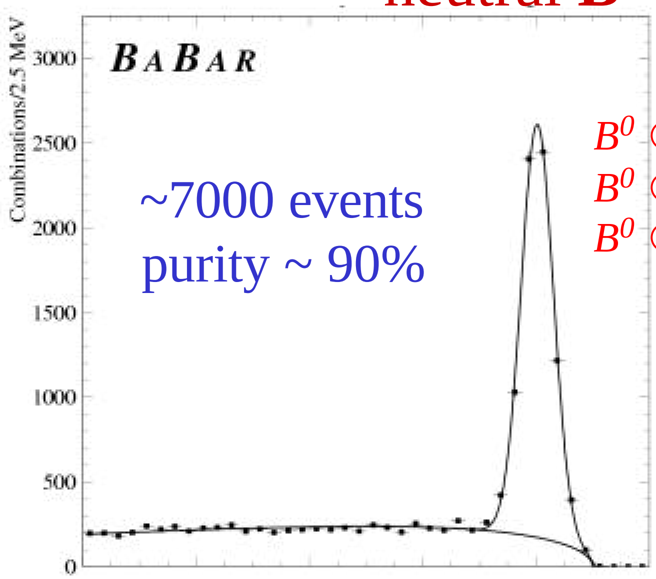


- B_1 exclusive reconstructed :
  - Known CP: B_{CP}
  - Known flavor: B_{FLAV}
- AND :
  - Δz : B lifetime
  - Δz, B_2 flavor :
    - mixing if $B_1 = B_{FLAV}$
    - CP if $B_1 = B_{CP}$

Exclusive hadronic B sample

20.7 fb^{-1} on-resonance (before tagging and vertexing)

neutral **B**



~7000 events
purity ~ 90%

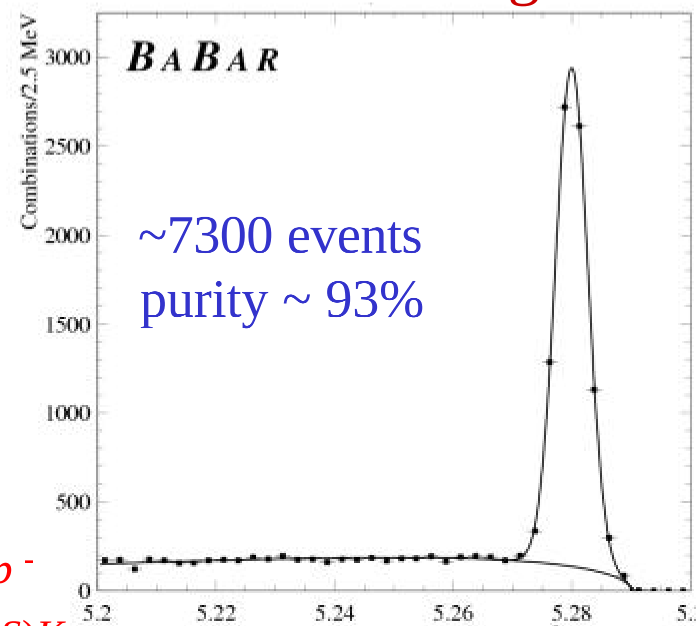
m_{ES} (GeV/c^2)

B^0 ® $D^{*-}p^+$, $D^{*-}r^+$, $D^{*-}a_1^+$

B^0 ® D^-p^+ , D^-r^+ , $D^-a_1^+$

B^0 ® $J/Y\ K^{*0}\ (K^+p^-)$

charged **B**



~7300 events
purity ~ 93%

B^- ® D^0p^- , $D^{*0}p^-$

B^- ® J/YK^- , $y(2S)K^-$

m_{ES} (GeV/c^2)

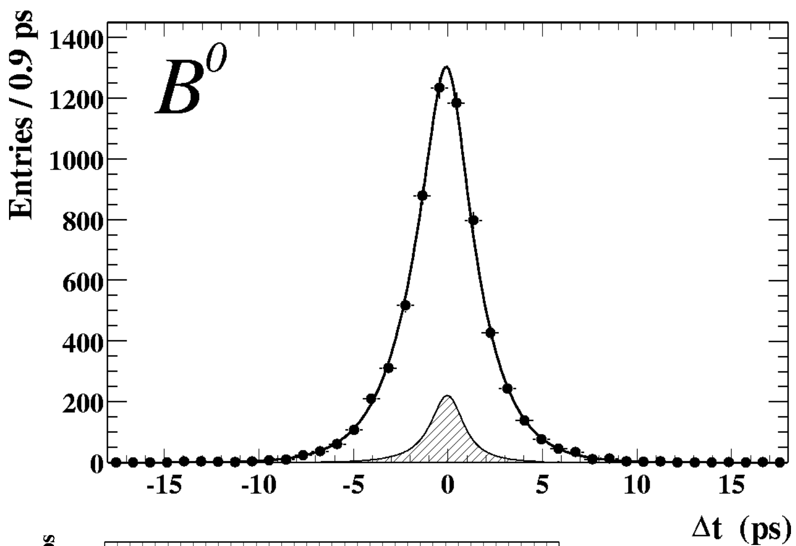
From these samples we measure:

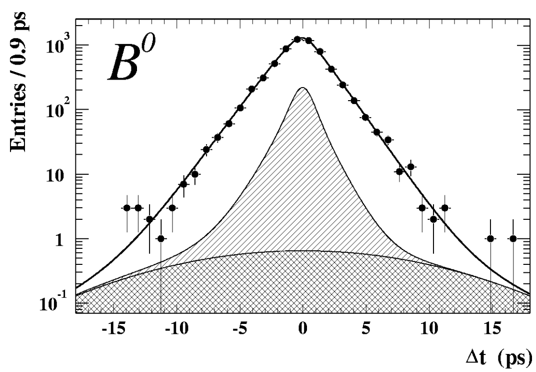
- B^0, B^+ lifetimes
- Δm (mixing) of neutral B
- Δz resolution and tagging performance for the sin(2β) measurement

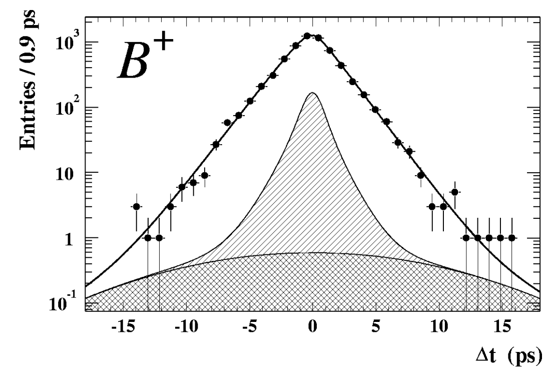
BABAR

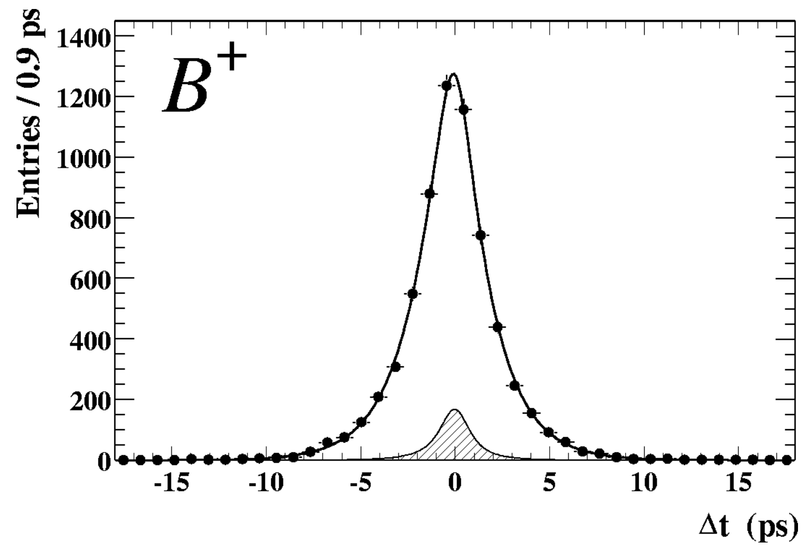
B lifetimes

- More precise than any published measurement
- From 20.7fb^{-1}, submitted to PRL







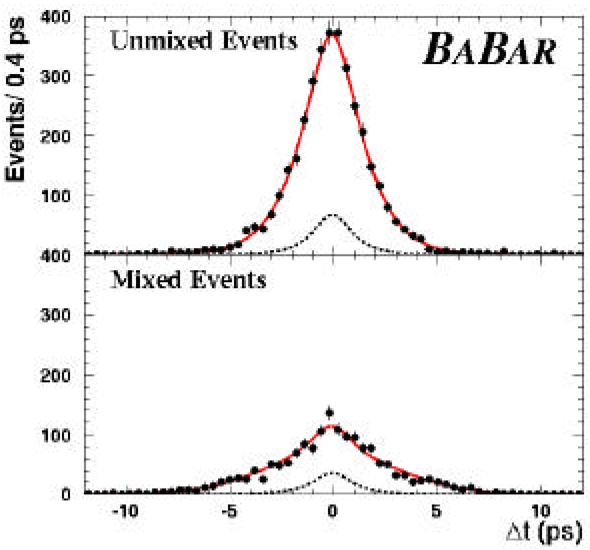


$t_{B0} = 1.546 \pm 0.032_{stat} \pm 0.022_{syst}$ ps

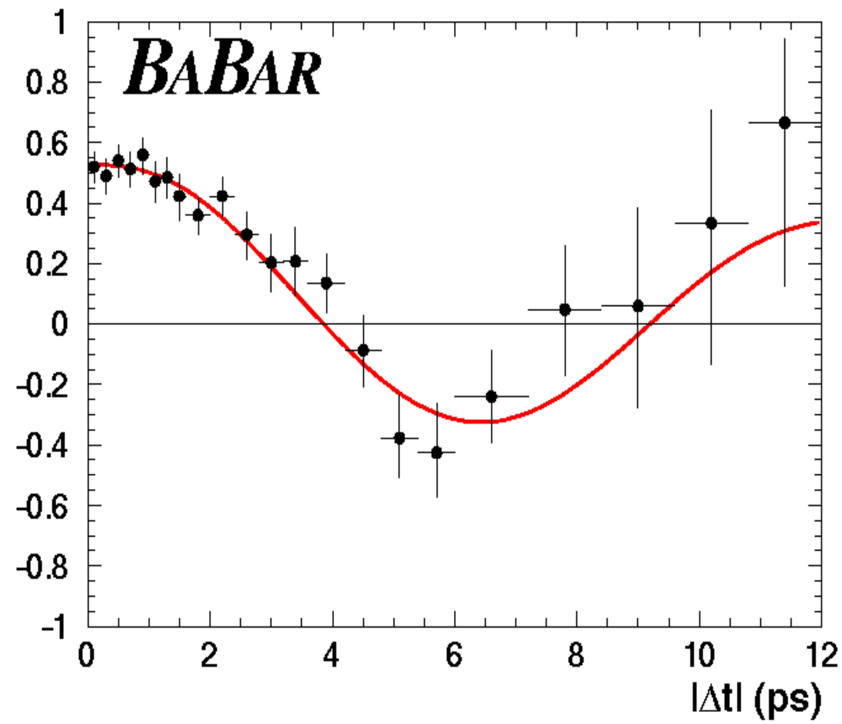
$t_{B+} = 1.673 \pm 0.032_{stat} \pm 0.023_{syst}$ ps

$t_{B+}/ t_{B0} = 1.082 \pm 0.026_{stat} \pm 0.012_{syst}$

B mixing



20.7 fb^{-1} on-resonance



$$A_{Mix}(t) = \frac{\Gamma(B^0 \to f_{flav}, t) - \Gamma(\overline{B}^0 \to f_{flav}, t)}{\Gamma(B^0 \to f_{flav}, t) + \Gamma(\overline{B}^0 \to f_{flav}, t)}$$

DcosDm$_d$ Dt ÄR(Dt;a)

<u>Tagging efficiency</u>

Q = εD^2 , D = 1-2*w*

D = Dilution

w : wrong tag fraction

ε : fraction of tagged events

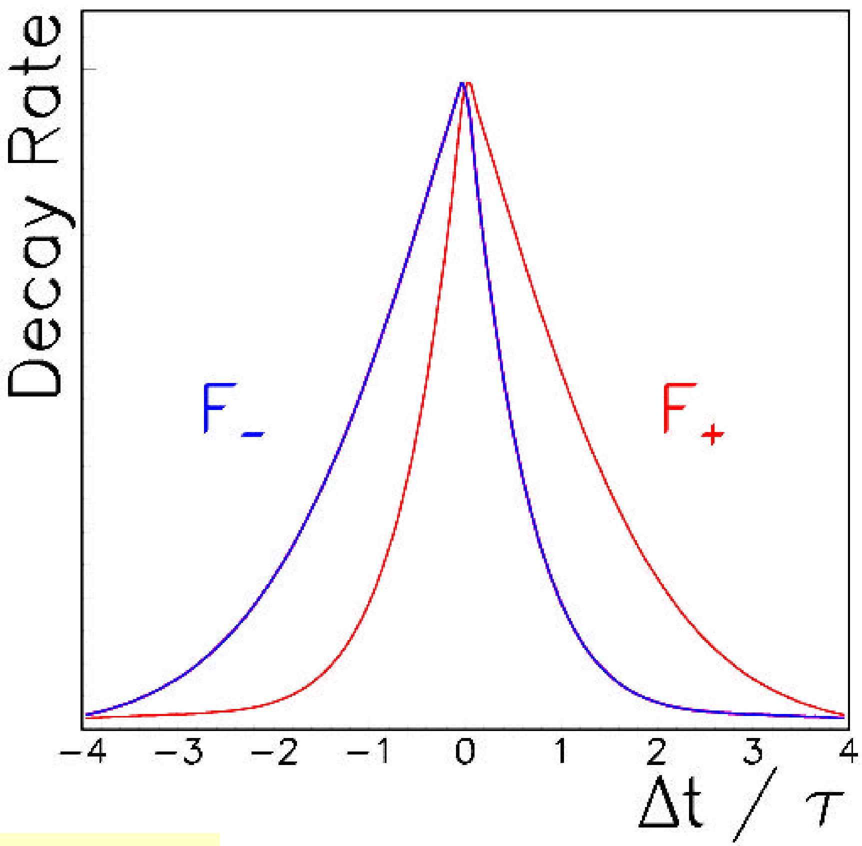
Preliminary: **Dm$_d$ = 0.519 ± 0.020(stat) ± 0.016 (syst) ħ ps^{-1}**

CP violation, sin(2β)

CP violation signature

Decay rates (F_+,F_-) for (B^0, $\overline{B^0}$) tags to a CP eigenstate (CP=η_f)

[sin(2β) = 0.7, perfect detector, no direct ~~CP~~]



$F_{\pm}(\Delta t) \sim \exp(-\Gamma|\Delta t|)\,(1 \pm \eta_f \sin(2\beta)\,\sin(\Delta m \Delta t))$

CP violation, experimental issues

What we need

- B^0 -> CP eigenstates sample (*backgrounds*)
- Flavor tag of the other B (*Dilution*)
- $\Delta t = \Delta z / \langle\beta\gamma\rangle$ (*decay vertices, resolution*)

sin(2β) extraction strategy

Unbinned max likelihood fit

- ✓ event by event Δt error
- ✓ Dilution dependent on tag type
- ✓ Simultaneous fit with B_{FLAV} sample

The current sin(2β) analysis

Data sample used

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

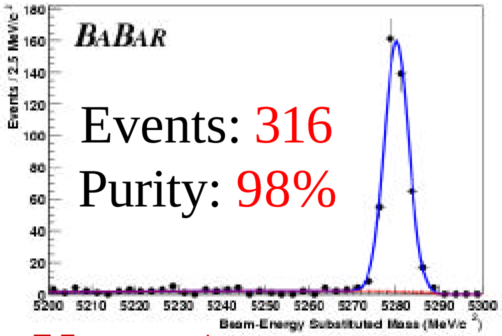
Improvements since last winter:

- 9×10^6 new BB events (in 2001)
- Improved tracking, K_S reconstruction
  - 30% more CP events per luminosity unit
- Better tracking system alignments, vertex reconstruction
  - 10% increase in sensitivity
- Optimized K_L selection for better sensitivity to sin(2β)
- New CP modes added

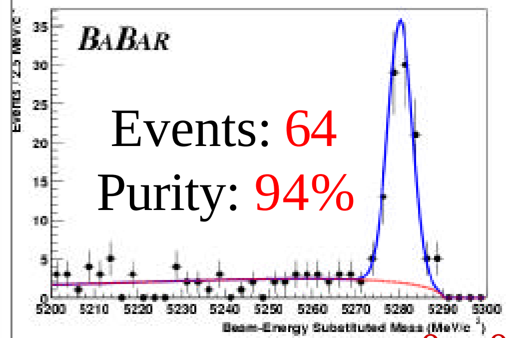
=> The statistical power of BABAR in sin(2β) has nearly doubled in the last 6 months !

The CP sample

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

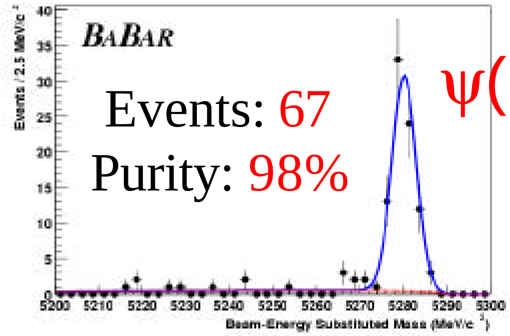


$K_S \to \pi^+ \pi^-$

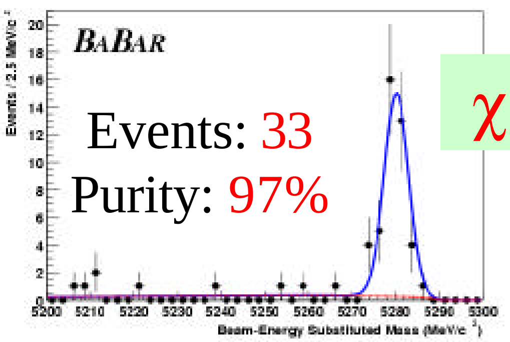


$J/\psi\ K_S$

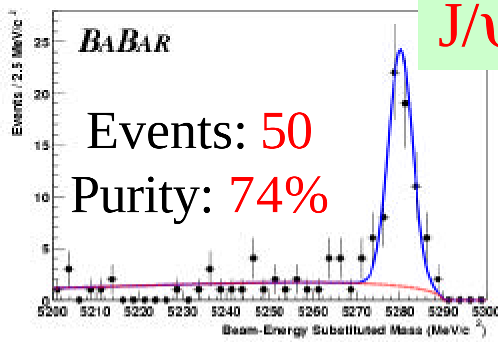
$K_S \to \pi^0 \pi^0$



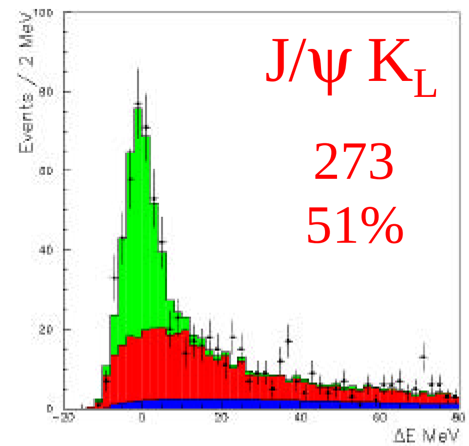
$\psi(2S)\ K_S$



$\chi_{c1}\ K_S$



$J/\psi\ K^*$



$J/\psi\ K_L$

Sample	tagged events	Purity	CP
[Jpsi, Psi(2S), chi_c1] 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%	

A word on JpsiK*

Jpsi $K^{*0}(K_S\pi^0)$ angular components:

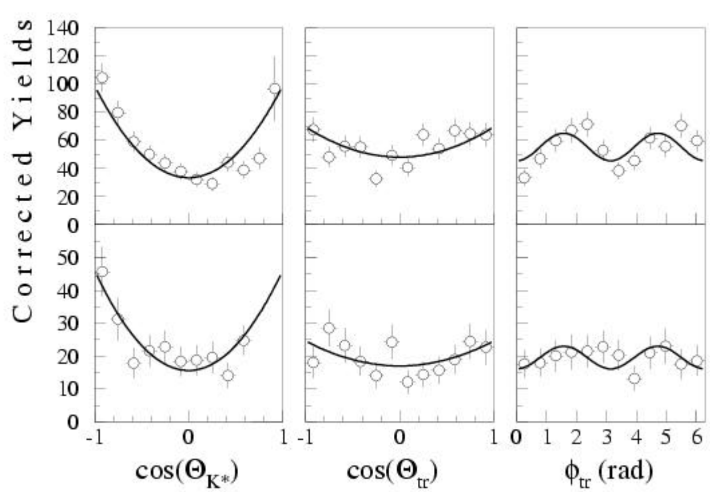
- $A_{||}$: CP = +1
- A_0 : CP = +1
- $A_\perp$: CP = -1 (define $R_\perp = |A_\perp|^2$)

-> CP asymmetry diluted by $D_\perp = (1 - 2R_\perp)$

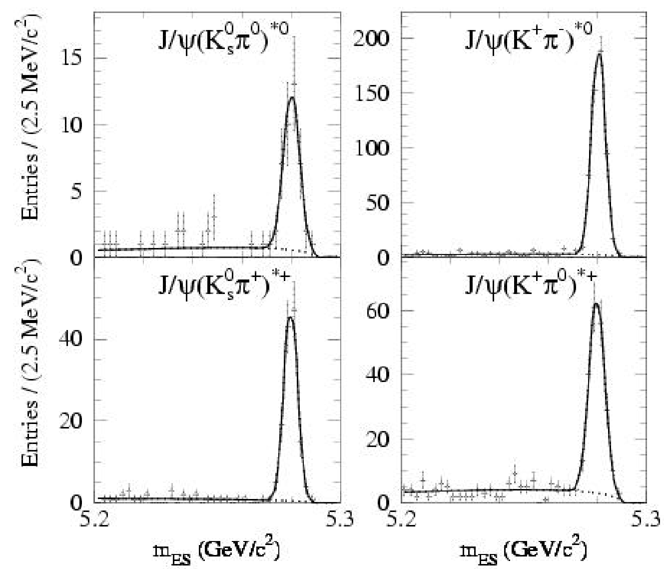
-> $R_\perp = (16.0 \pm 3.2 \pm 1.4)$ % (BABAR, submitted to PRL)

=> $\eta_f = 0.65 \pm 0.07$ (additional cuts)

Sample used in $R_\perp$ measurement (20.7 fb^{-1})



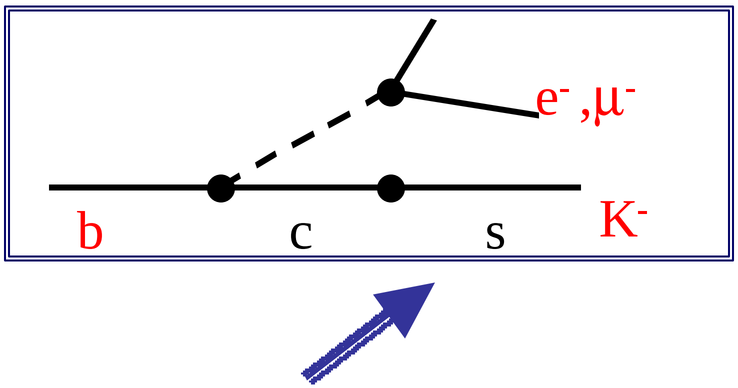
The angular fit



Flavor tagging of the other B

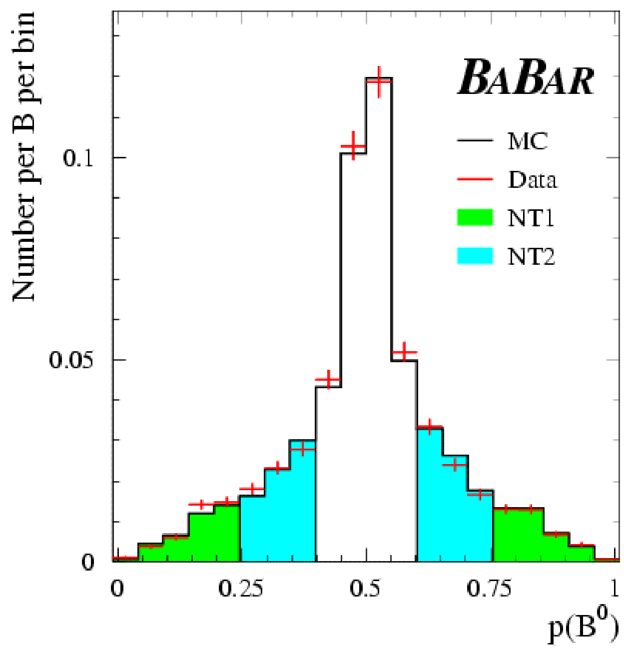
Tagging categories (ranked) :

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



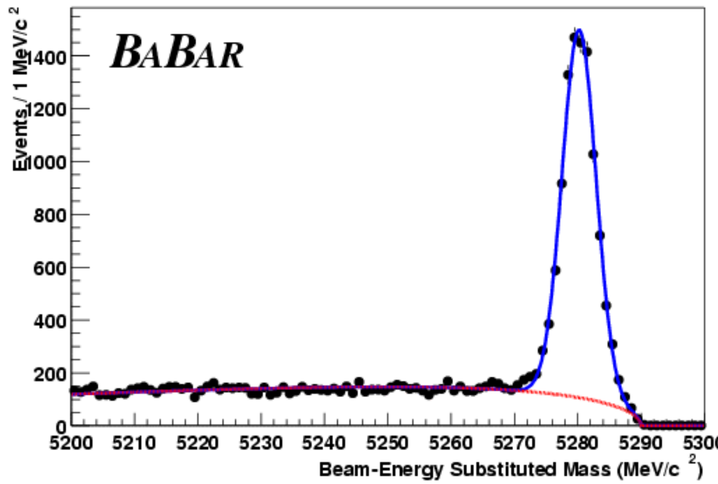
Lepton , Kaon tagging

NN tagging



Flavor tagging performance

B_{FLAV} sample, neutral B self-tagging final states: 7591 fully reconstructed, vertexed and tagged on other side => Tagging performance measurement



Tagging performance

$Q = \varepsilon D^2$, $D = 1\text{-}2w$

D = Dilution

w : wrong tag fraction

ε : fraction of tagged events

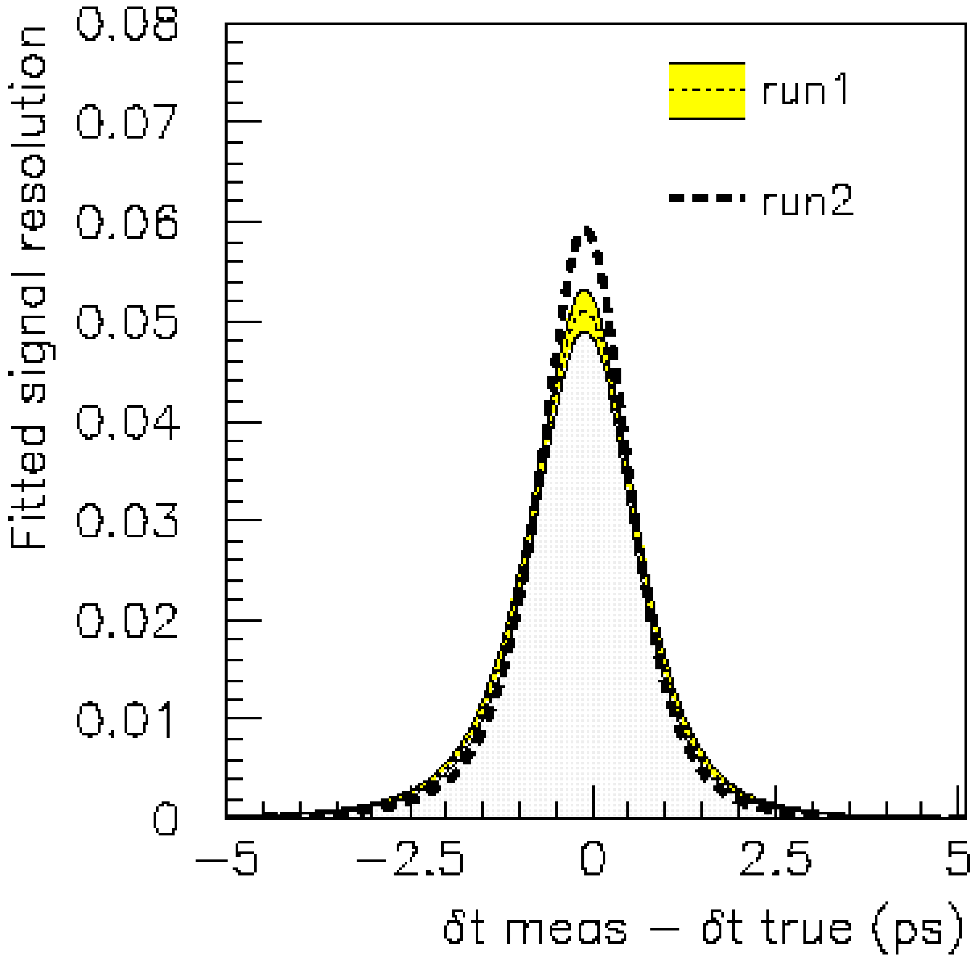
From final CP fit:

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*

Δt measurement

- Δt from $\Delta z = z_{CP} - z_{TAG}$
- Δz resolution:
  - CP side: ~60μm
  - Δz: ~180μm
  - Small charm bias (~20μm), correlated to the per event error
- 2001 data: improved alignment => resolution

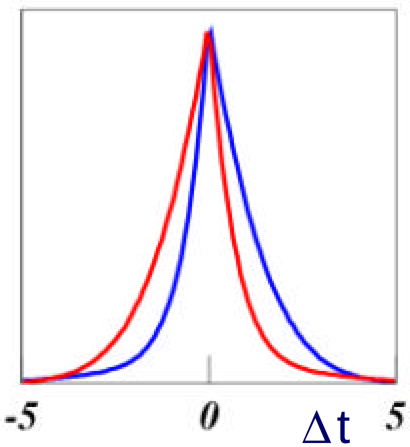
Fit results



Mistag and resolution in CP, Flavor samples

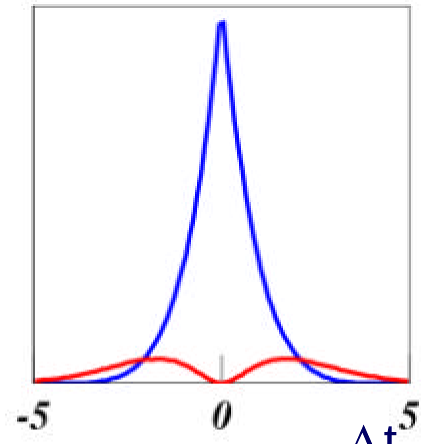
CP violation (CP sample)

Mixing (flavor sample)

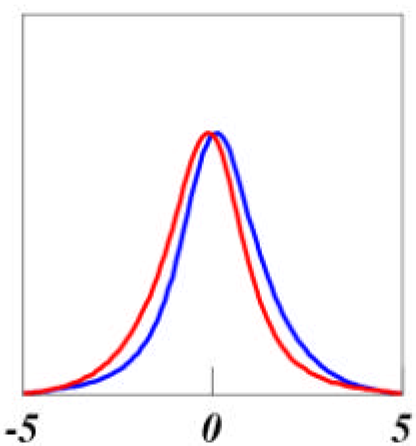


$F_{\pm}(\Delta t) \sim (1 \pm \sin(2\beta)\sin(\Delta m \Delta t))$

Ideal detector



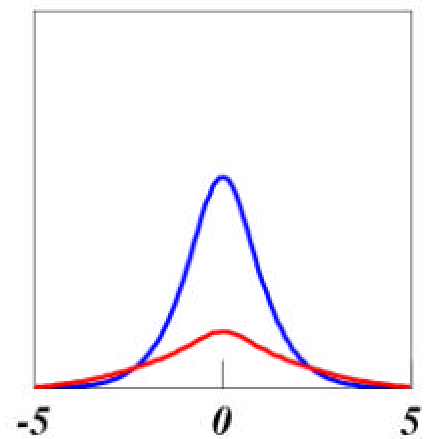
$F_{UM,MX}(\Delta t) \sim (1 \pm \cos(\Delta m \Delta t))$



$F_{\pm}(\Delta t) \sim (1 \pm D\sin(2\beta)\sin(\Delta m \Delta t)) \otimes R$

Realistic

tagging , resolution



$F_{UM,MX}(\Delta t) \sim (1 \pm D\cos(\Delta m \Delta t)) \otimes R$

Strong motivation to fit CP and Flavor samples together

The fit for sin(2β)

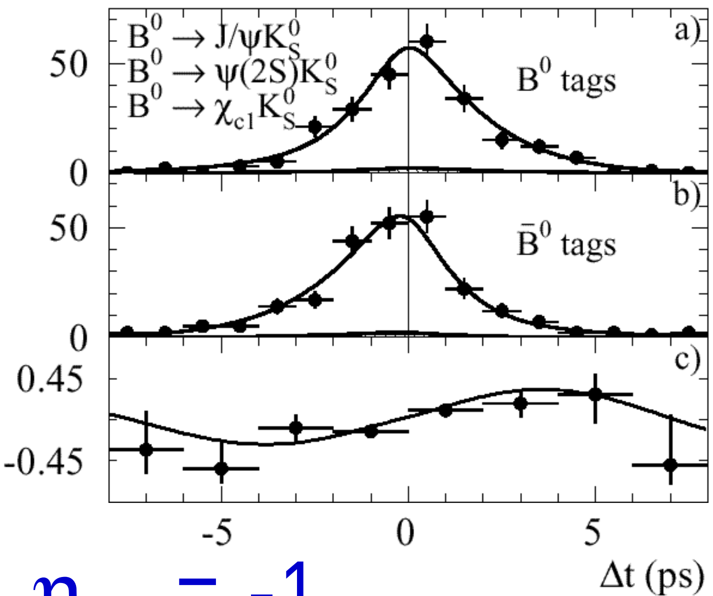
Combined likelihood for CP and FLAV samples

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*

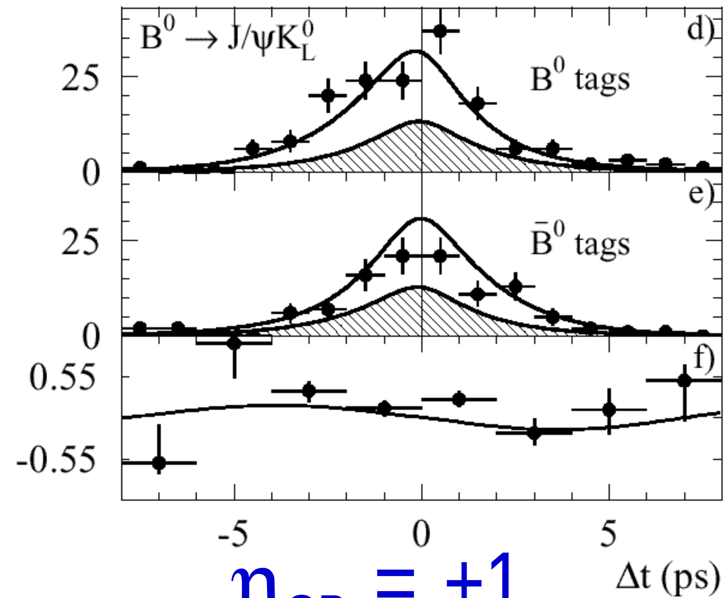
- Mistag, resolution determination dominated by large B_{FLAV} sample
- Background parameters from m_{ES} sidebands
- Largest sin(2β) correlation: 13% (any combination)
- B^0 Δm: fixed to 0.472 ps^{-1}
- B^0 lifetime: fixed to 1.548 ps

The sin(2β) result

sin(2b) = 0.59 ± 0.14$_{stat}$ ± 0.05$_{syst}$



η_{CP} = -1



η_{CP} = +1

CP violation in the B^0 system established : 4.1σ

Prob. of this result if CP is conserved : <3×10^{-5}

Same probability, CP=-1 modes only : <2×10^{-4}

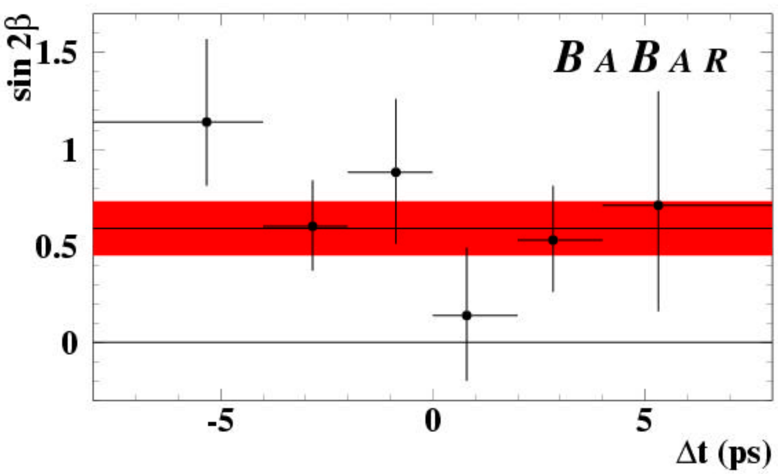
Most precise measurement

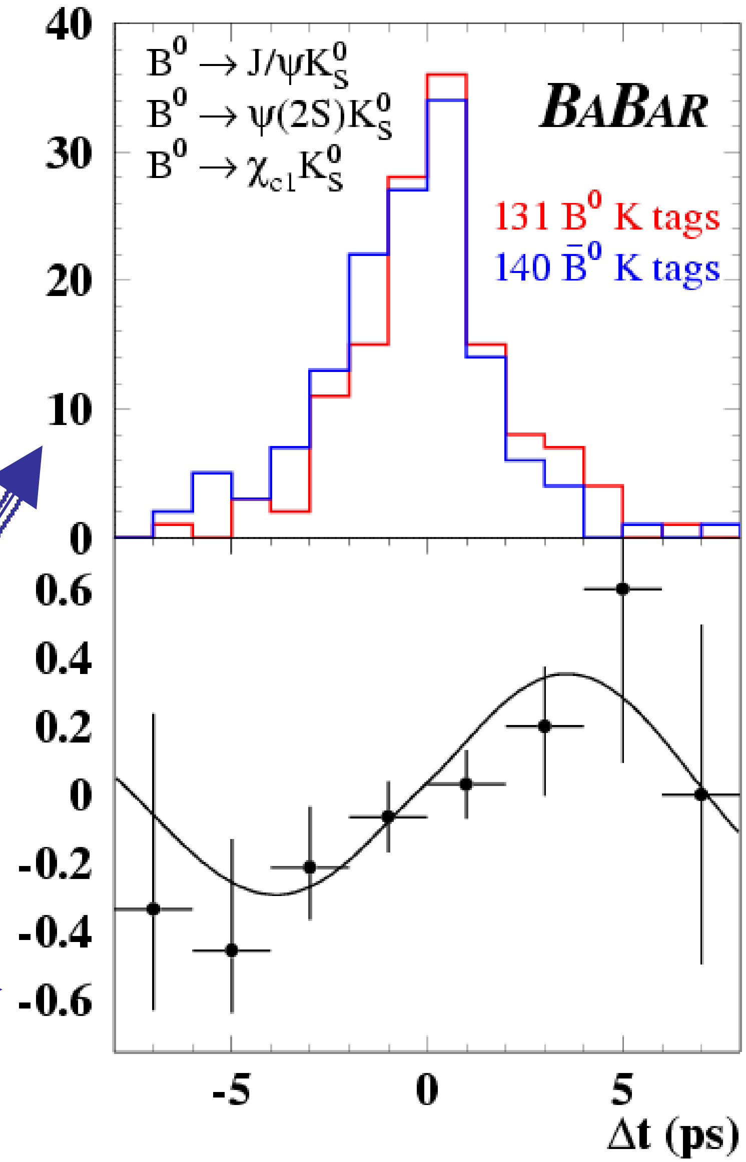
Submitted to PRL, July 5 (hep-ex/0107019)

BABAR

CP violation and sin(2β) in plots

All CP events: sin(2β) in Δt bins



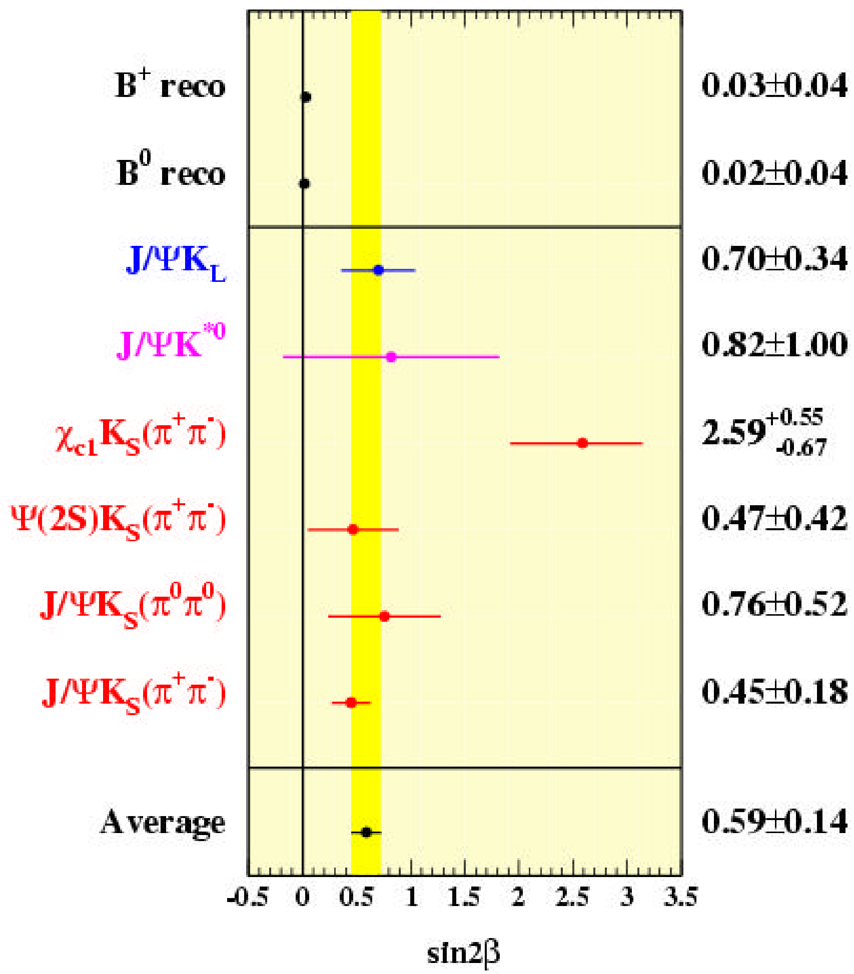


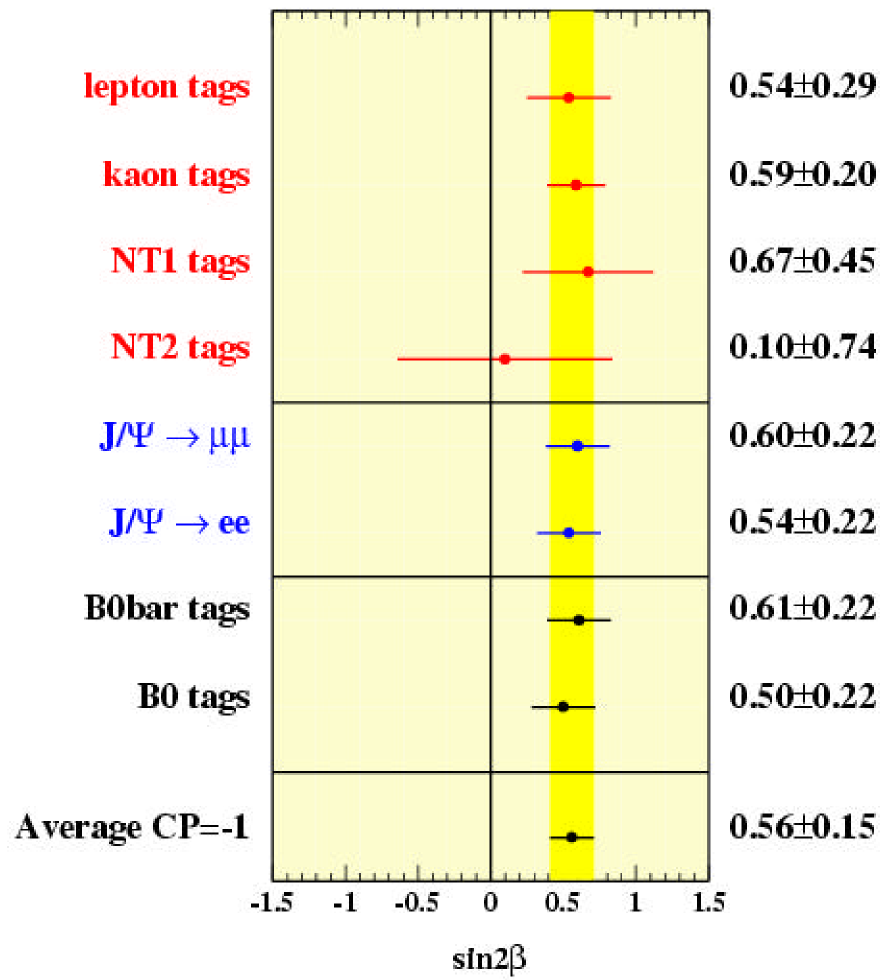
Decay rates

Raw asymmetry

CP=-1 modes, Kaon tags only

Sample consistency





Systematics etc

Main contributions to systematic error:

Source	error
Δt resolution function	0.03
Possible mistag difference (CP-FLAV samples)	0.03
Possible bgr CP asymmetry	0.02

- Prob. to get lower likelihood: 27% (MC)

- Blind analysis, Fit validations ......
- Different vertexing algorithms, PID, tagging methods tried

=> Our fit is well behaved and the result is stable

Direct CP violation

General expression for time dependent asymmetry:

$$A_{cp}(t) = \frac{-(1-|\lambda|^2)\cos\Delta m\,t \;+\; 2\,\mathrm{Im}\lambda\,\sin\Delta m\,t}{1+|\lambda|^2}$$

$$A_{cp}(t) = \mathrm{Im}\,\lambda \cdot \sin\Delta m\,t$$

When $|\lambda|=1$

in S.M. (no direct CP violation) :

$|\lambda| = 1$ :: $\mathrm{Im}(\lambda)$ -> $\sin(2\beta)$

Fit to the CP=-1 sample:

$|\lambda| = 0.93 \pm 0.09$ (stat.) $\pm$ 0.03 (sys.)

- No evidence for direct CP violation
- No shift in the "sin(2β)" value

Conclusions and Outlook

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

✓ CP violation in B system observed at 4.1σ

  ✓ First CP violation observation outside K^0 system

✓ Direct $\sin(2\beta)$ measurement in agreement with range implied by knowledge of CKM matrix elements

Plans:

- $\sin(2\beta)$ measurements with non-charmonium modes
- $100 fb^{-1}$ by next summer
- $500 fb^{-1}$ by 2005

Observations of CP violation:

⇒ 1964 in K mesons

⇒ 2001 in B mesons

Extra slide on the comparison of this result to our previous sin(2β) publication in early 2001

Run1 – Run2 comparison

mode	sin2β run1	N_{ev} run1	sin2β run2	N_{ev} run2	R_{ev}	Δ_{12}	R_{exp}
$J/\psi K^0_S$ $(\pi^+\pi^-)$	0.23 ± 0.24	305	0.72 ± 0.27	169	1.37	0.49 ± 0.36	1.19
$J/\psi K^0_S$ $(\pi^0\pi^0)$	0.13 ± 0.65	82	1.62 ± 0.74	42	1.26	1.49 ± 0.98	1.23
$\psi(2S)K^0_S$ $(\pi^+\pi^-)$	0.31 ± 0.49	64	1.16 ± 1.21	28	1.08	0.85 ± 1.31	0.61
$\chi_{c1}K^0_S$ $(\pi^+\pi^-)$	—	29	1.14 ± 1.25	17	1.44	—	—
$J/\psi K^{*0}$ $(K^0_S\pi^0)$	1.26 ± 1.22	60	0.15 ± 1.62	23	0.94	-1.11 ± 2.0	1.20
$J/\psi K^0_L$	0.71 ± 0.42	288	0.68 ± 0.58	142	1.21	-0.03 ± 0.72	1.03
$J/\psi K^0_S + \psi(2S)K^0_S$ $+J/\psi K^0_L$	0.32 ± 0.18	739	0.83 ± 0.23	381	1.27	0.51 ± 0.29	1.09
all	0.45 ± 0.18	816	0.82 ± 0.22	433	1.31	0.37 ± 0.29	1.12

Table 35: comparison between run1 and run2 results. Number of events are also compared. $R_{ev} = \frac{N_2\mathcal{L}_1}{N_1\mathcal{L}_2}$ is the ratio of the number of events per fb^{-1}, Δ_{12} is the difference between the two runs while $R_{exp} = \frac{\sigma_1}{\sigma_2}\sqrt{\frac{N_1}{N_2}}$

-> Change in central value ~1.8σ (uncorrelated)

Old data, new analysis, same channels used in the past