# Measurement of sin 2β by BaBar


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On Behalf of the BaBar Collaboration

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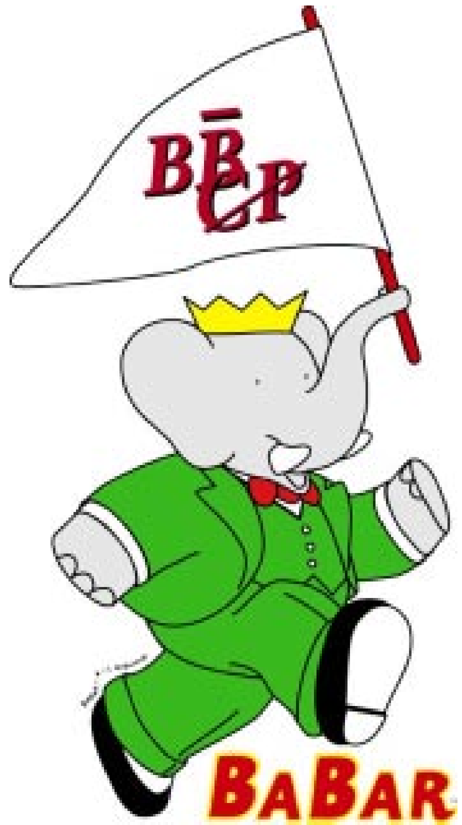


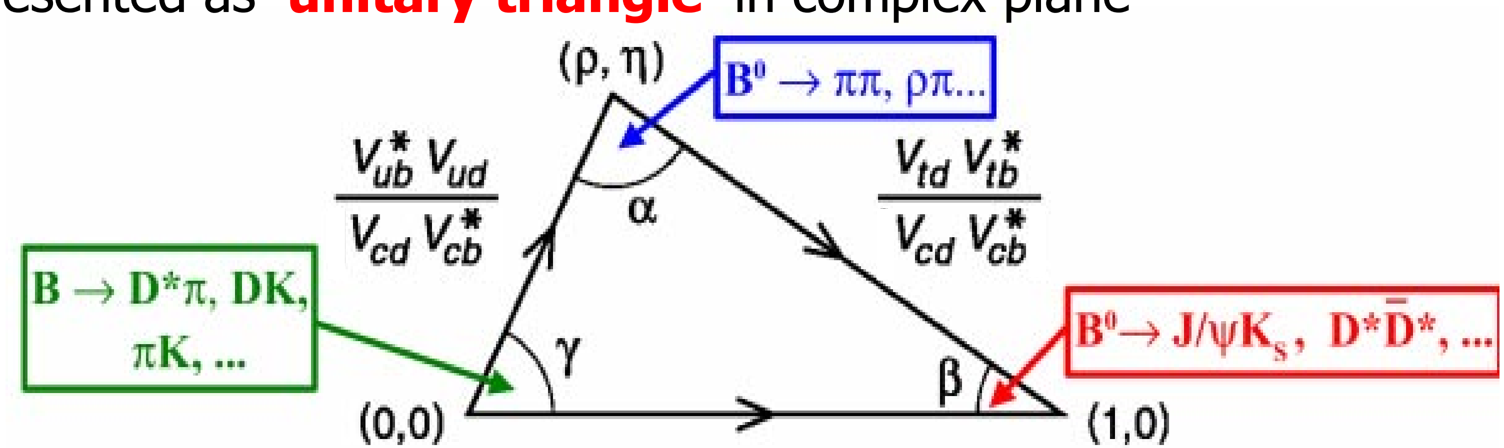
# CP violation in the Standard Model

CP violation arises from **single phase in CKM matrix**

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Unitarity of V implies eg. $\mathbf{V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0}$

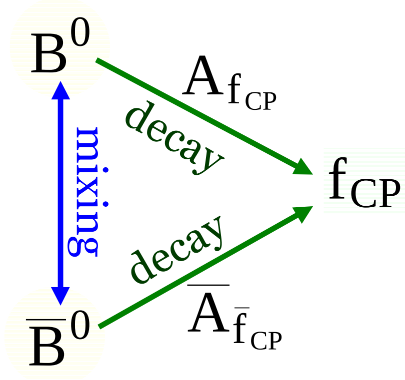
→ represented as **'unitary triangle'** in complex plane




***CP asymmetries in B⁰ decays give information on angles*** $\alpha, \beta, \gamma$ **!**

# ~~CP~~ in interference of mixing and decay

**Manifestation of CP violation in interference between decays with and without mixing**




$$\underbrace{\lambda_{f_{CP}} = \frac{q}{p}\cdot\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}}_{=|\lambda_{f_{CP}}|\,e^{-2i\varphi_{CP}}}$$

$$\boxed{\lambda_{f_{CP}} \neq \pm 1 \quad \Rightarrow \quad \mathrm{Prob}(\bar{B}^0_{phys}(t) \to f_{CP}) \neq \mathrm{Prob}(B^0_{phys}(t) \to f_{CP})}$$

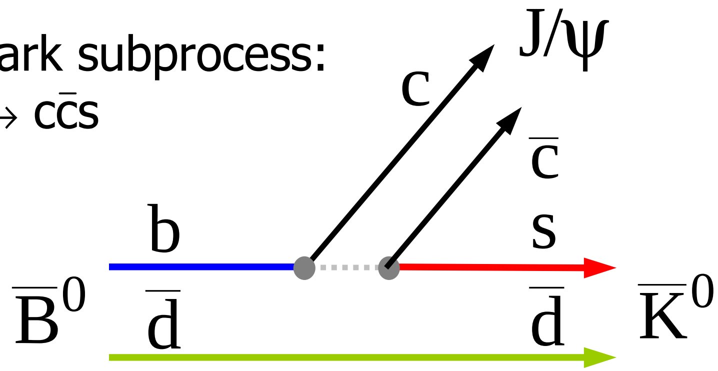
**Time-dependent CP asymmetry:**

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})}$$
$$= C_{f_{CP}} \cos(\Delta m_d t) + S_{f_{CP}} \sin(\Delta m_d t)$$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$
$$S_{f_{CP}} = \frac{-2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

# *Golden* mode: $B^0 \to J/\Psi\, K^0_S$

Quark subprocess:
$b \to c\bar{c}s$




$\bar{B}^0 \to J/\psi\, \bar{K}^0$
$B^0 \to J/\psi\, K^0$

**K⁰ mixing**

$B^0_{CP=-1} \to J/\psi K^0_S$
$B^0_{CP=+1} \to J/\psi K^0_L$

Single weak phase = no direct $\cancel{CP}$ $\Longrightarrow$ $|\lambda_{J/\psi K^0_{S,L}}| = 1$

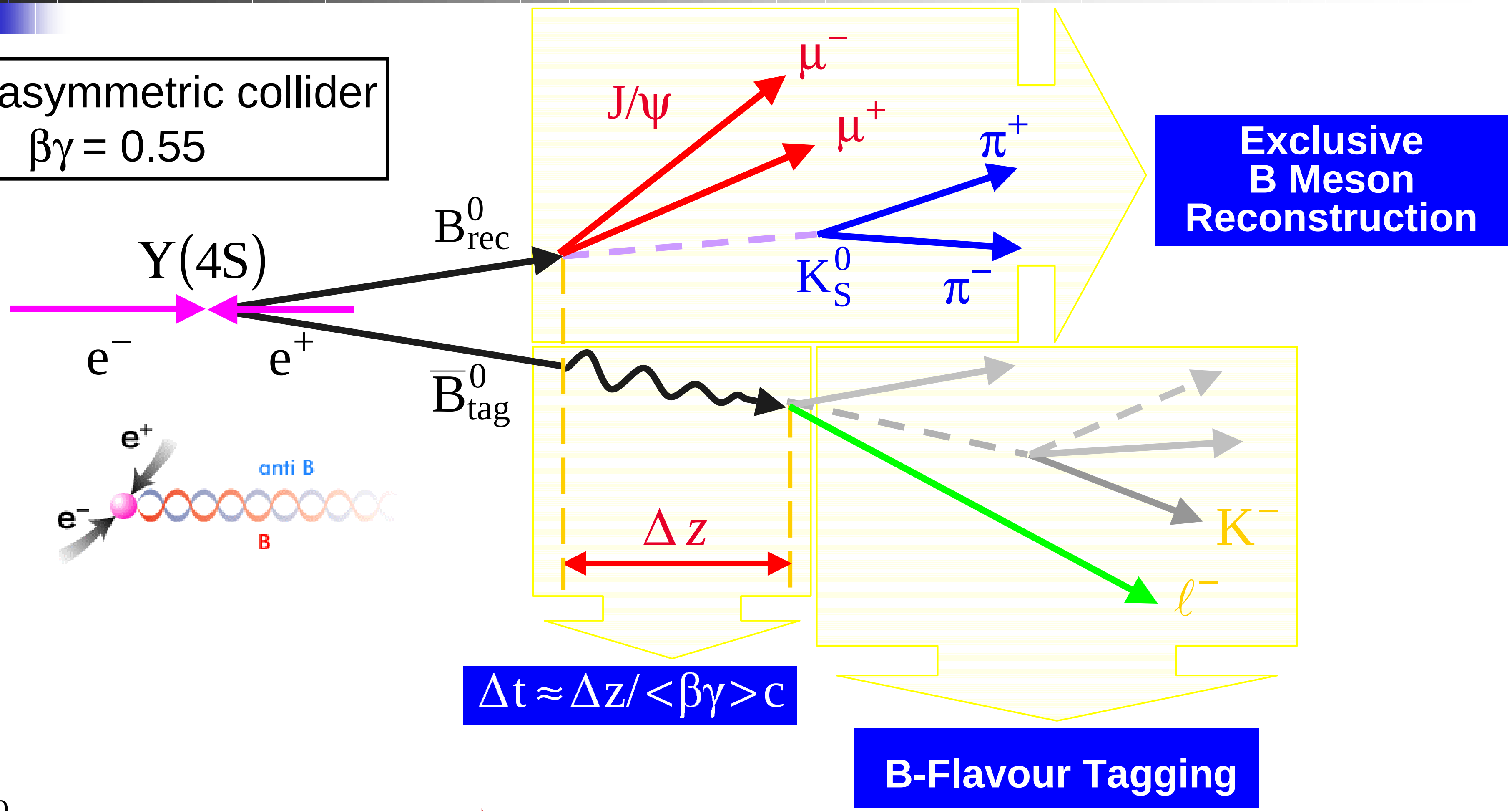
$$\boxed{A_{J/\psi K^0_{S,L}}(t) = -\eta_{J/\psi K^0_{S,L}} \sin 2\beta \sin(\Delta m_d t)}$$

$\eta_{CP}$ = -1 (+1) for $J/\psi\, K^0_{S(L)}$

- Theoretically clean way to measure sin2β
- Clear experimental signature
- Relatively large branching fraction

# Experimental technique

PEP-II asymmetric collider
$\beta\gamma = 0.55$

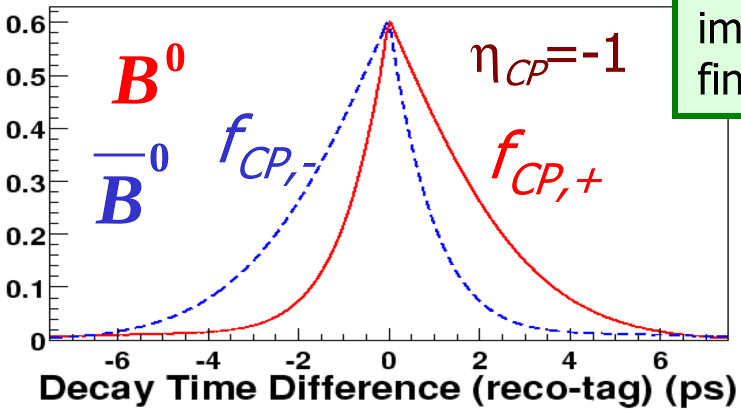


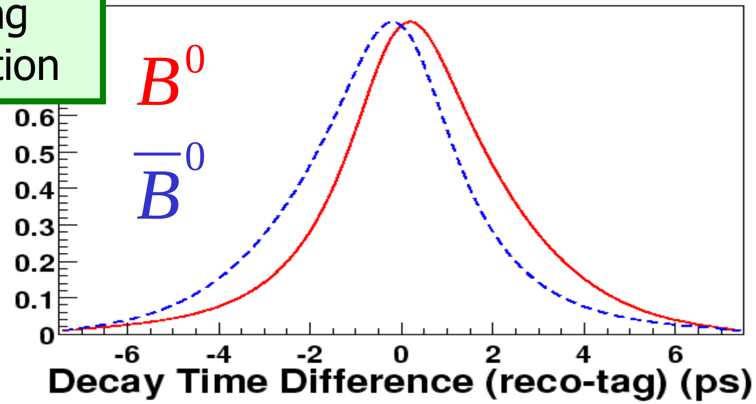

$B^0_{rec} = B^0_{CP}$ (CP eigenstates) ➡ CP analysis

$B^0_{rec} = B^0_{flav}$ (flavour eigenstates) ➡ lifetime, mixing analyses

# Expected decay time distributions

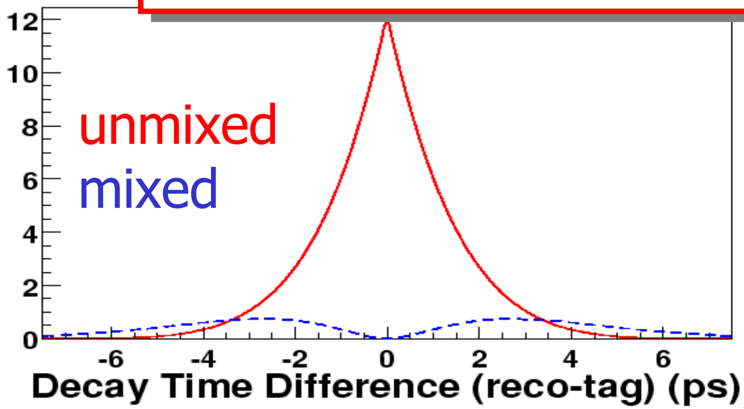
imperfect tagging
finite $\Delta z$ resolution

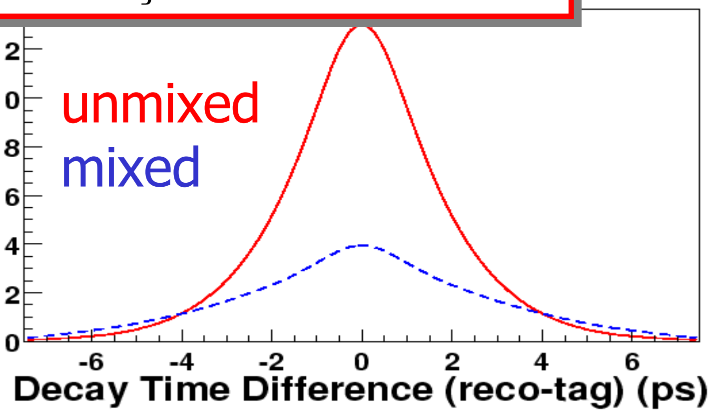


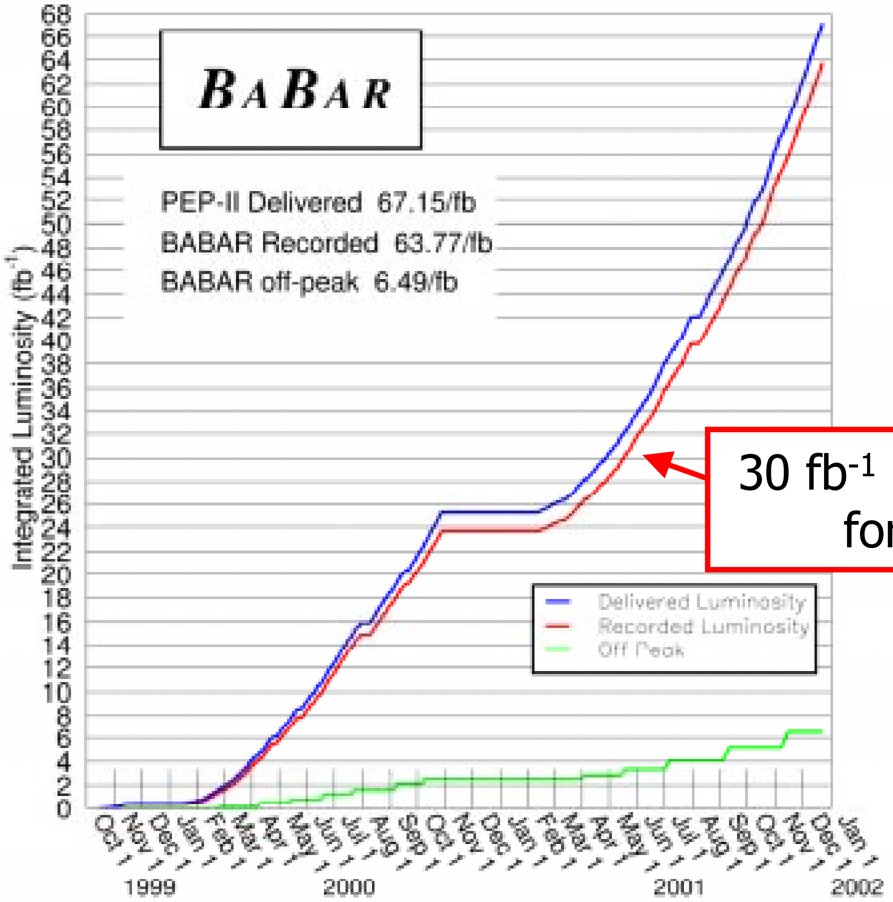

$$f_{CP,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{2\tau_{B_d}} \times \left(1 \mp \eta_{CP}\,(1-2\omega)\,\sin 2\beta .\sin(\Delta m_{B_d}\Delta t)\right) \right\} \otimes R(\Delta t)$$

$$f_{mix,\pm}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{2\tau_{B_d}} \times \left(1 \pm (1-2\omega)\cos(\Delta m_{B_d}\Delta t)\right) \right\} \otimes R(\Delta t)$$



# B factory performance



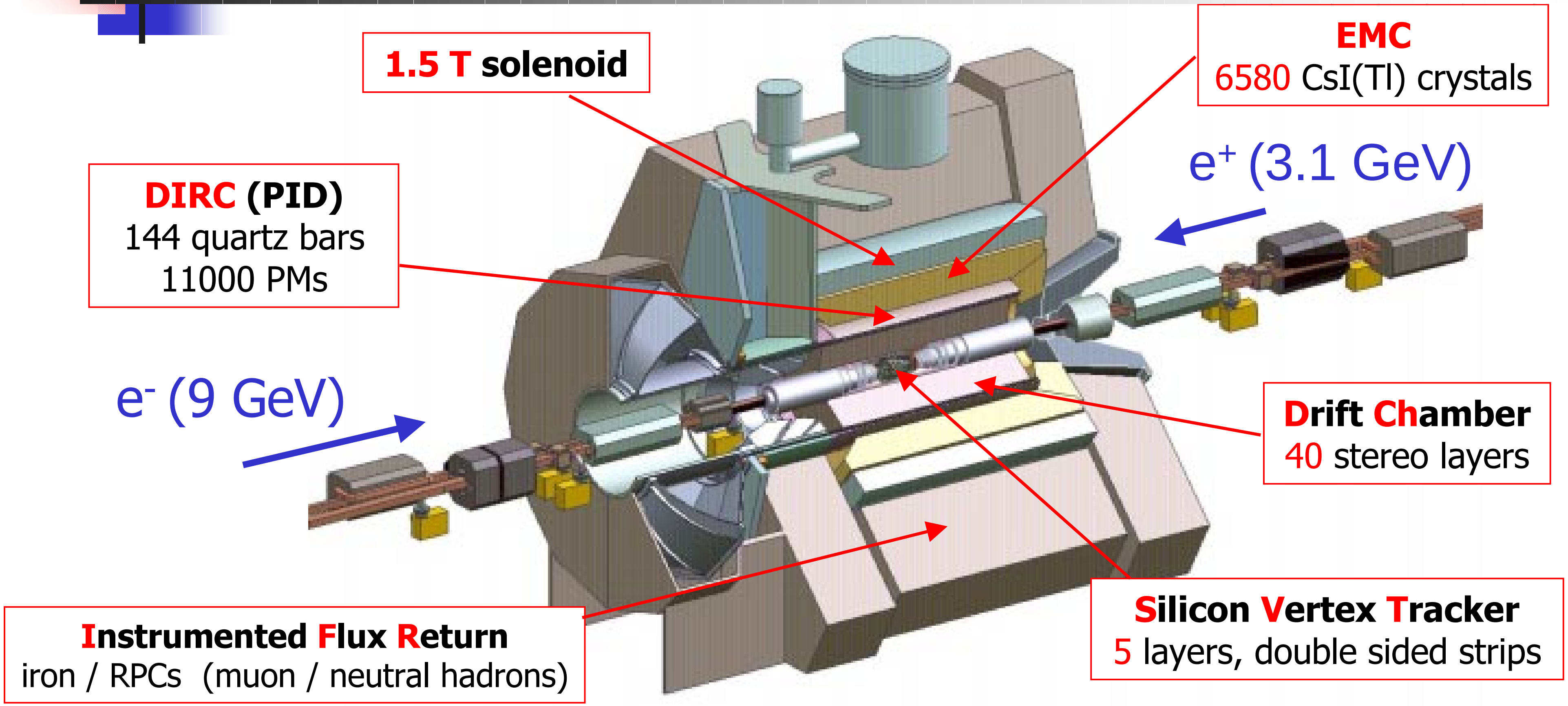

30 fb$^{-1}$ analysed for $\cancel{C}$P

October 99 January 1, 2002

- PEP-II top luminosity: 4.51 x $10^{33}$cm$^{-2}$s$^{-1}$ (design 3.0 x $10^{33}$)
- Top recorded L/24h: 309 pb$^{-1}$

PEP-II delivered: 67.2 fb$^{-1}$
BaBar recorded: 63.8 fb$^{-1}$
(incl. 6.5 fb$^{-1}$ off peak)

# The BaBar detector



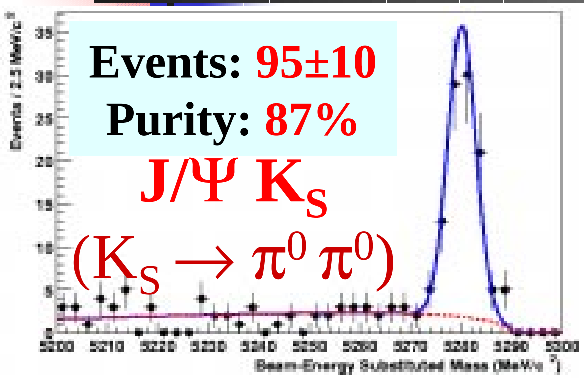

SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

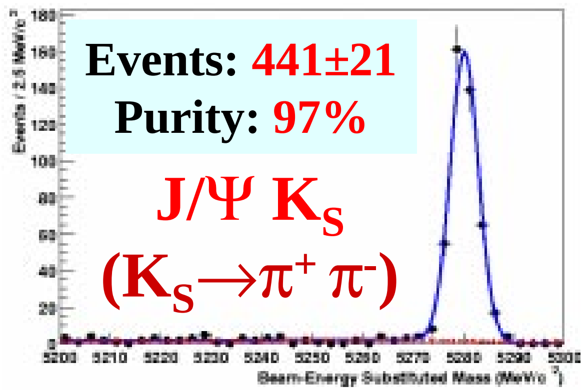
SVT+DCH: $\sigma(p_T)/p_T = 0.13\ \% \times p_T\ +\ 0.45\ \%$, $\sigma(z_0) = 65$ @ 1 GeV/c

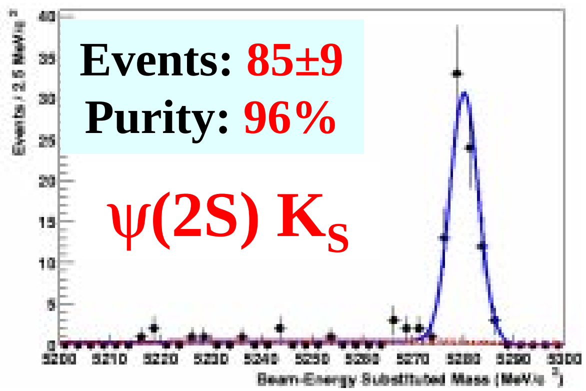
DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

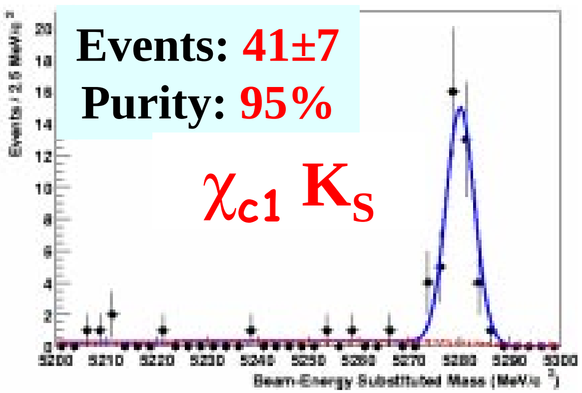
# Reconstructed B sample

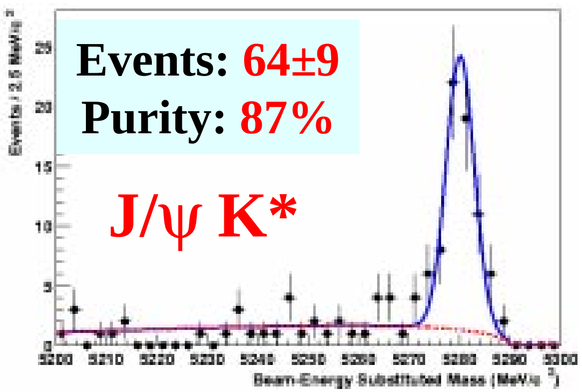


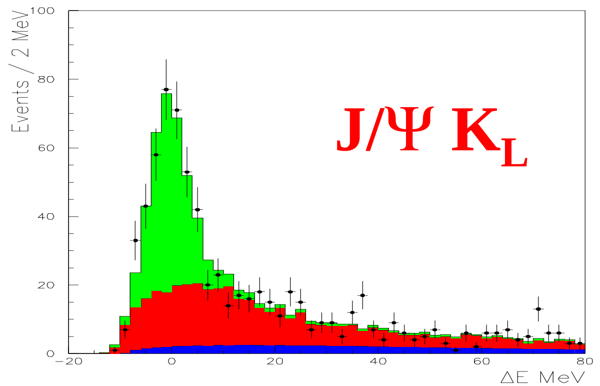



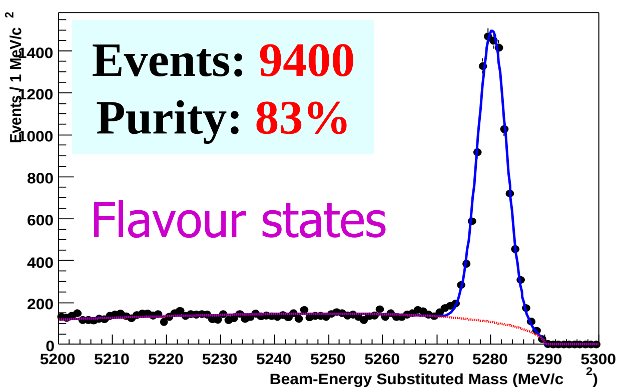

(plots before tagging)



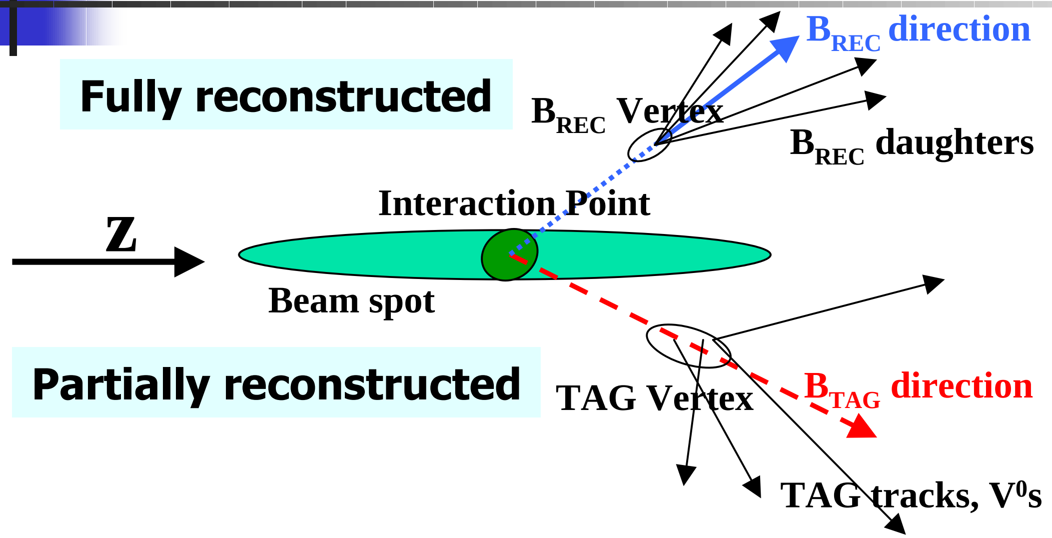




| CP sample after tagging | Tagged evts | Purity | *CP* |
|---|---|---|---|
| [J/ψ, ψ(2S), χ$_{c1}$] K$_S$ | 480 | 96% | -1 |
| J/ψ K$_L$ | 273 | 51% | +1 |
| J/ψ K*$^0$(K$_S$π$^0$) | 50 | 74% | mixed |
| **Full *CP* sample** | **803** | **80%** | |

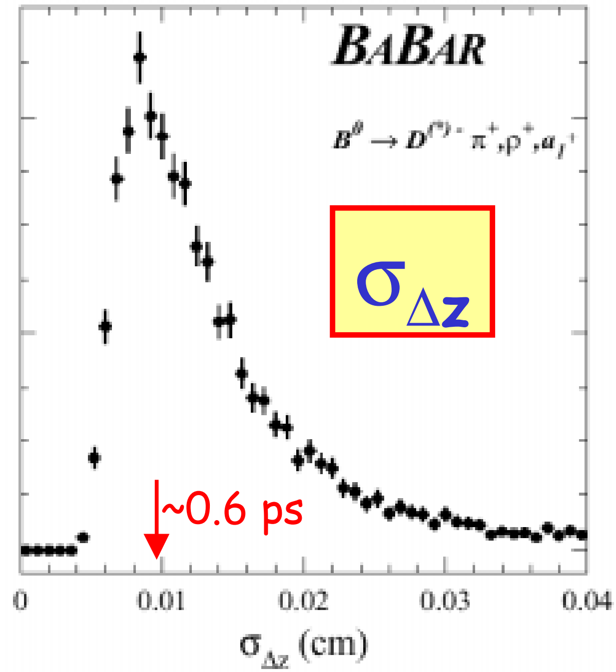


# Δt reconstruction and resolution




**$B_{TAG}$ vertex fit:**

- All tracks not in $B_{REC}$
- Direction of reconstructed $K_S$ and $\Lambda$'s
- $B_{TAG}$ direction constrained by $B_{REC}$ and beam spot information
- High $\chi^2$ tracks removed from fit (to reject charmed decays)

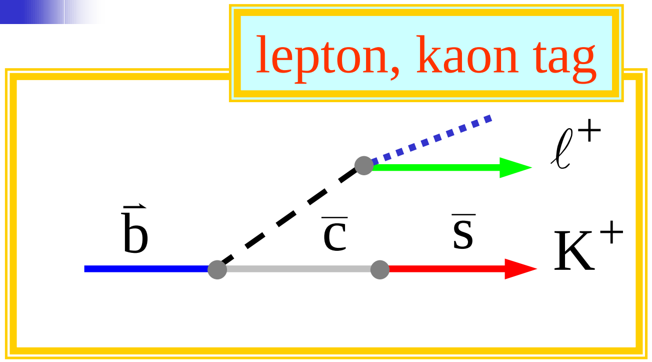



**High efficiency : 97%**
**Average resolution on** $\Delta z \sim 180\mu m$

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

Use per-event estimate $\sigma_{\Delta z}$ and empirical model (« resolution function ») to correct it.
Extract corresponding parameters (scale factors, biases) from data.

# Flavour tagging




Quality factor $Q = \varepsilon(1-2w)^2$

$\sigma(\sin 2\beta) \propto 1/\sqrt{Q}$

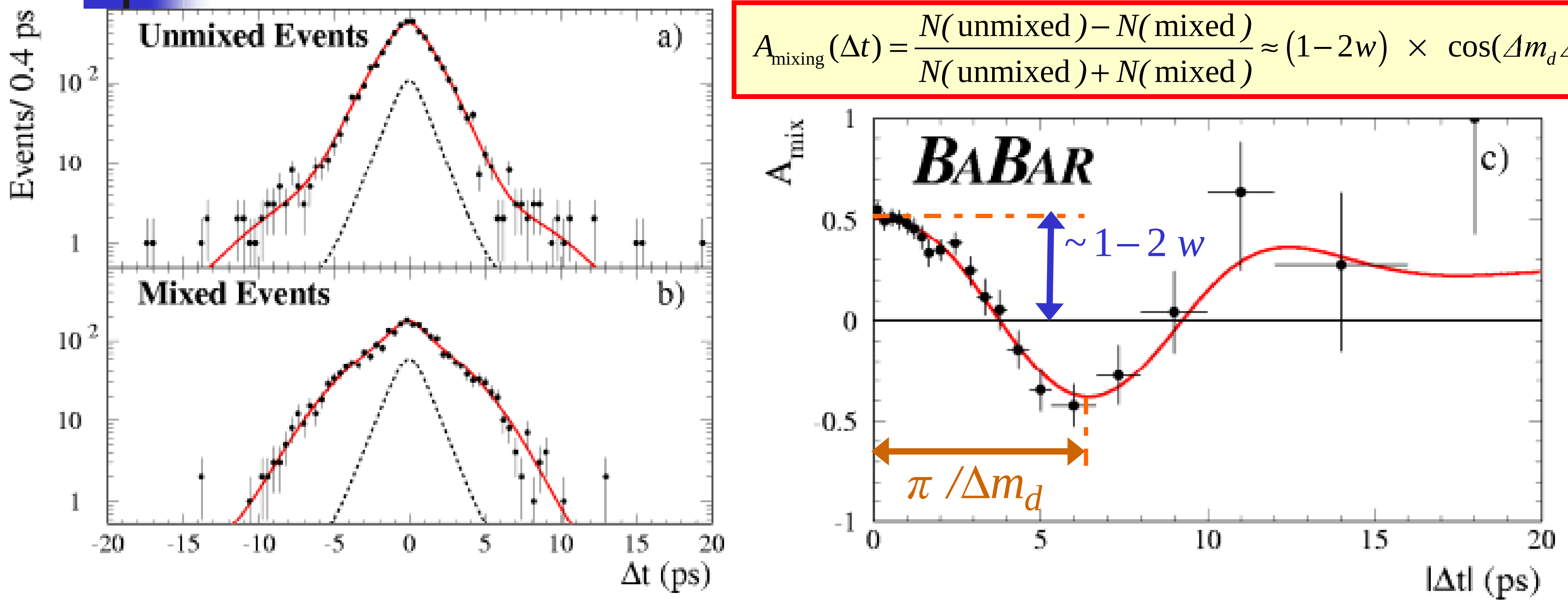
Hierarchy

| Category | Definition | efficiency | Q |
|---|---|---|---|
| ***Lepton*** | Charge of fastest electron (muon) with p*>1.0(1.1) GeV/c. | $10.9 \pm 0.4\%$ | $7.4 \pm 0.5\%$ |
| ***Kaon*** | Total charge of identified kaons | $35.8 \pm 0.5\%$ | $15.0 \pm 0.9\%$ |
| ***NT1*** | Neural Network | $7.8 \pm 0.3\%$ | $2.5 \pm 0.4\%$ |
| ***NT2*** | Neural Network | $13.8 \pm 0.3\%$ | $1.2 \pm 0.3\%$ |
| | **Total** | $68.4 \pm 0.7\%$ | $26.1 \pm 1.2\%$ |

NT1, 2 : unidentified leptons, soft pions from D*, momentum spectrum of B decay products

# Mixing analysis results

$$A_{\text{mixing}}(\Delta t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \approx (1-2w) \times \cos(\Delta m_d \Delta t)$$




$\Delta m_d$ **= 0.516 ± 0.016 (stat) ± 0.010 (syst) ps**$^{-1}$

hep-ex/0112044
submitted to Phys. Rev. Lett.

Also: Lifetime (PRL 87, 201803)

See E. Rosenberg 's talk at this workshop.

# sin $2\beta$ likelihood fit

- Global unbinned maximum likelihood fit to data:
  - **mistag rates**
  - **$\Delta t$ resolutions** } **Tagged flavour sample**
  - **sin$2\beta$** ← **Tagged CP sample**
- 44 parameters for mistag rates, $\Delta t$ resolution & backgrounds: floated to obtain an empirical description from data.

**Fit Parameters**

| | |
|---|---|
| sin$2\beta$ | 1 |
| Mistag rates for $B^0/\overline{B^0}$ tags | 8 |
| Signal resolution function | 16 |
| Empirical description of background $\Delta t$ | 20 |

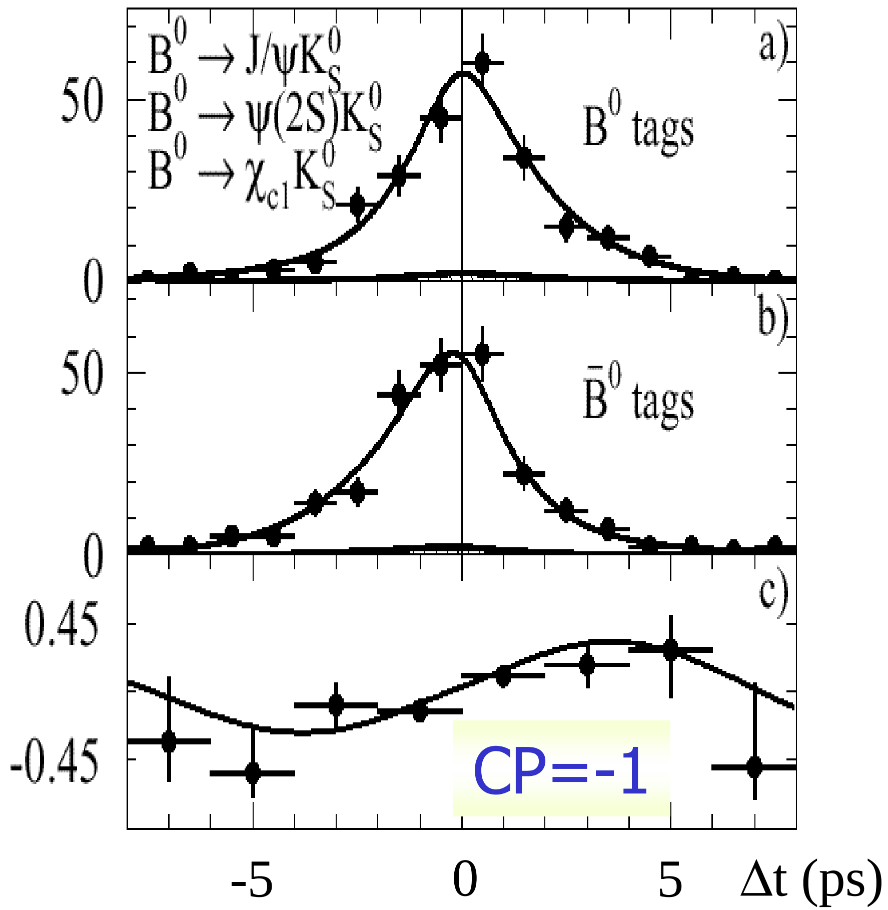
**Separate $\Delta t$ resolutions for two data-taking periods**

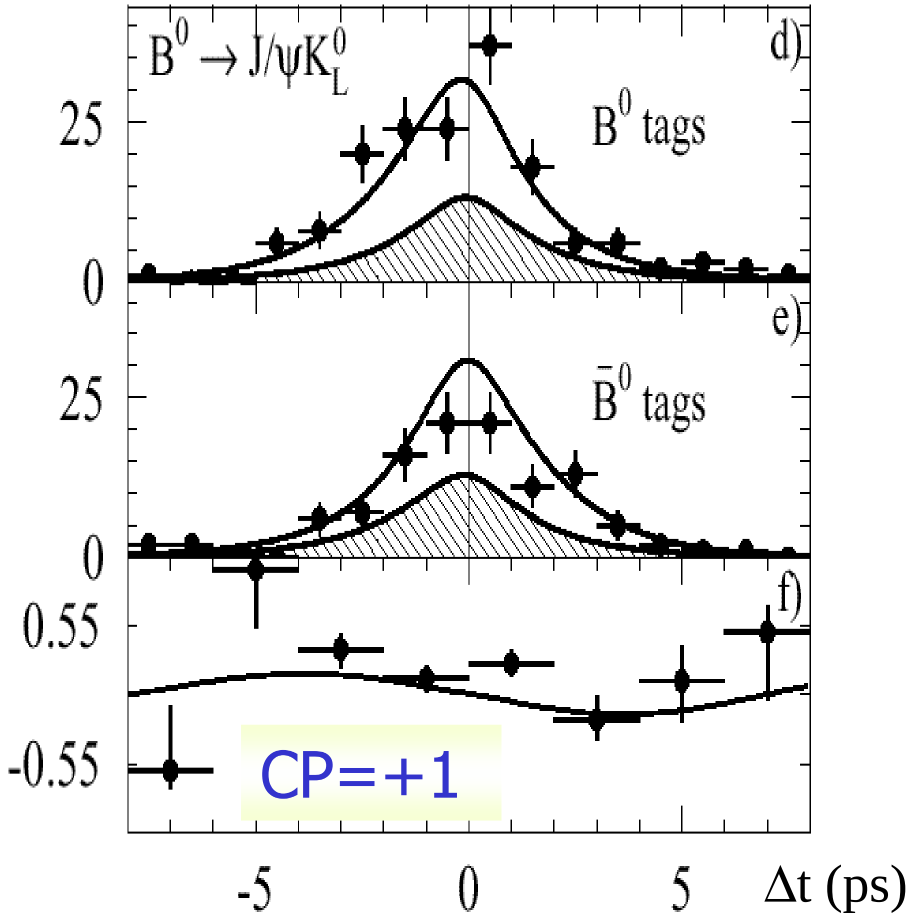
**$\tau_B$ = 1.548 ps fixed**
**$\Delta m_d$ = 0.472 ps$^{-1}$ fixed**

**Max correlation of sin($2\beta$) with any linear combination of the other parameters: 13%**

# sin 2β result: raw CP asymmetries

Compare raw asymmetries with results from ML fit




**sin2β = 0.56 ± 0.15$_{stat}$**

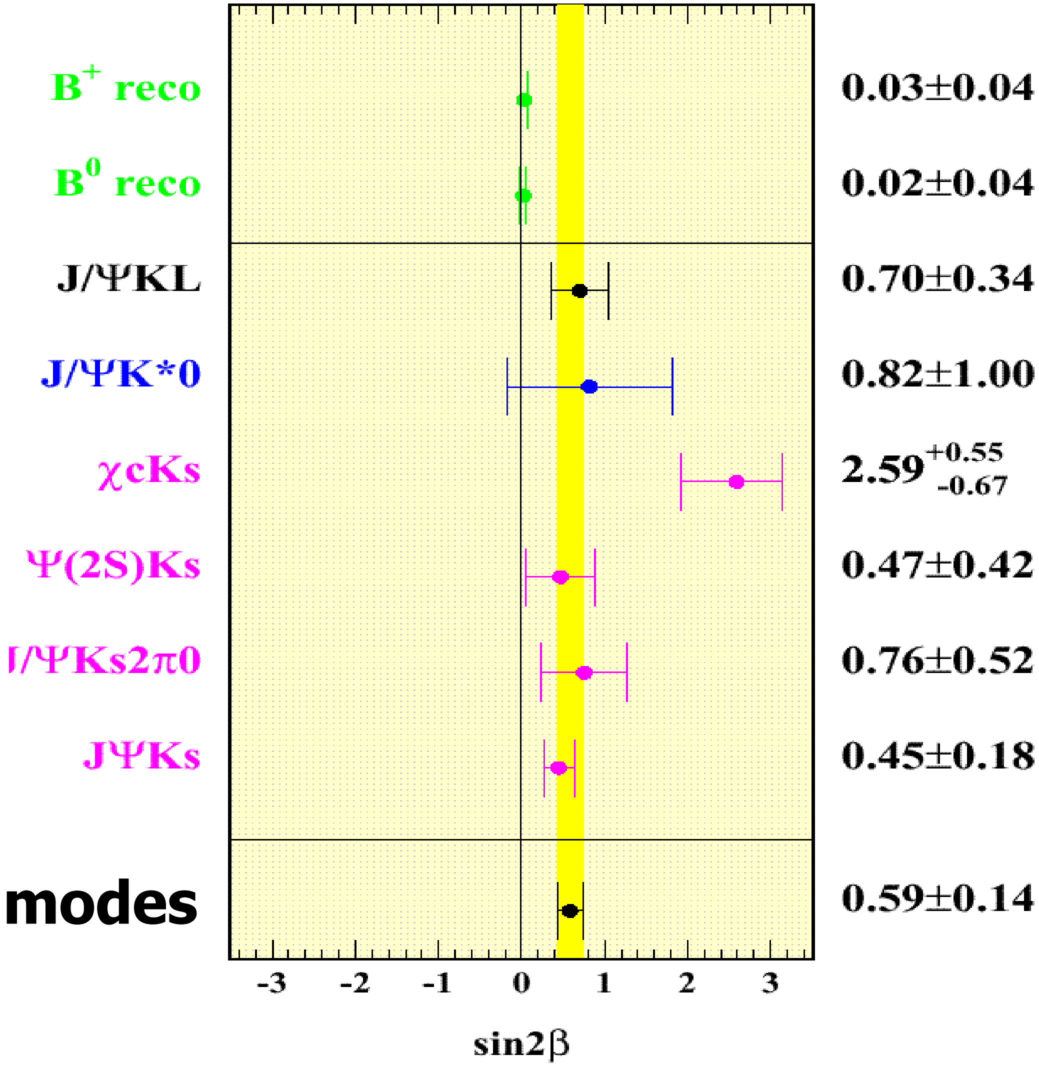
**sin2β = 0.70 ± 0.34$_{stat}$**

# sin 2β fit results

Cross-checks:
Null result in flavour samples

Consistency of CP channels $P(\chi^2) = 8\%$

Goodness-of-fit:
$P(L_{max}>L_{obs}) > 27\%$



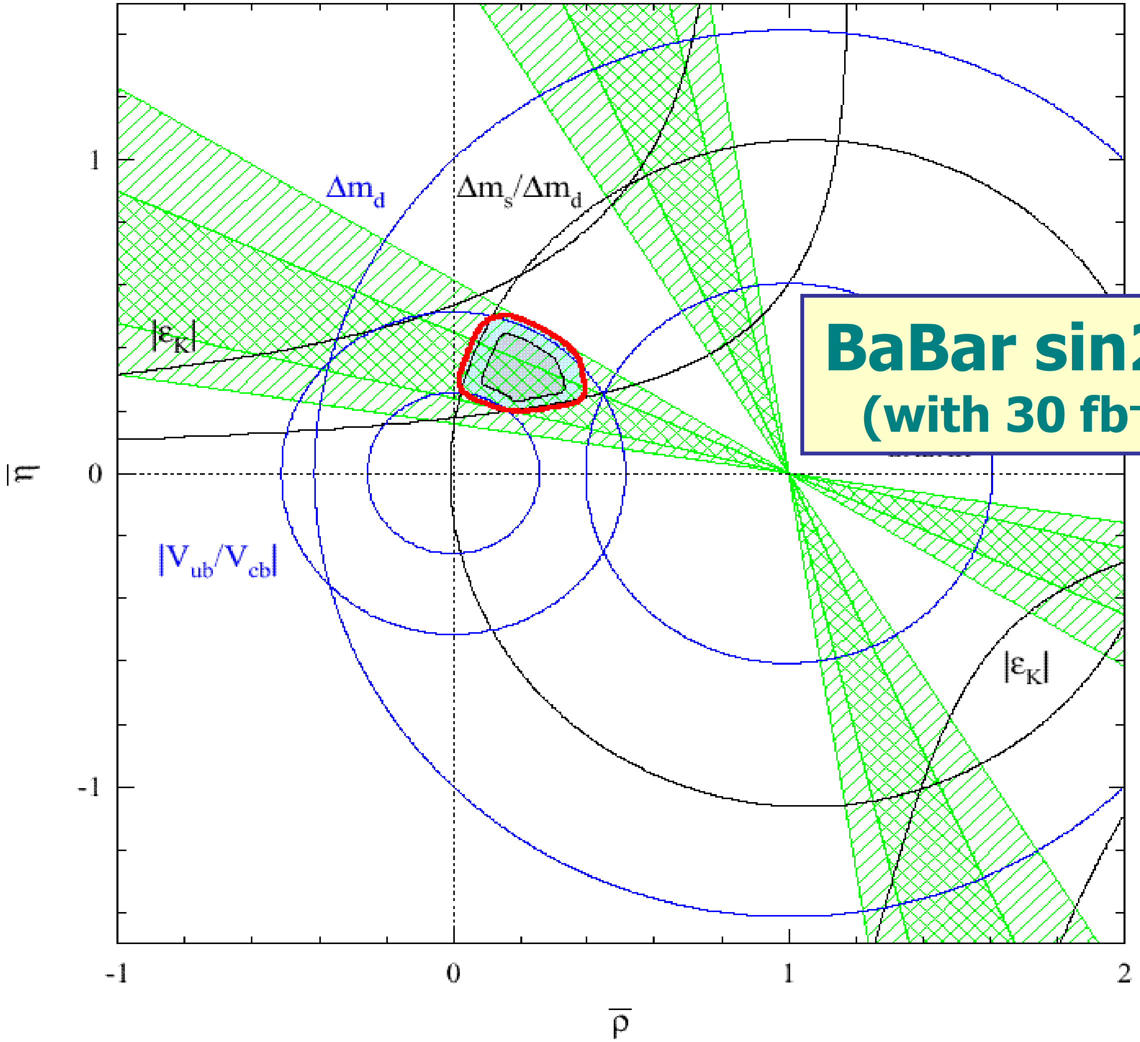

**$\sin(2\beta) = 0.59 \pm 0.14$**

# Systematic uncertainties

| Error | $K_S$ | $K_L$ | $K^{*0}$ | Total |
|---|---|---|---|---|
| Statistic | 0.15 | 0.34 | 1.01 | 0.14 |
| Systematic | 0.05 | 0.10 | 0.16 | 0.05 |

- Signal resolution and vertex reconstruction **0.03**
  - Resolution model, outliers, SVT residual misalignment
- Tagging **0.03**
  - possible differences between $B_{CP}$ and $B_{flavour}$ samples
- Backgrounds **0.02** (overall)
  - Signal probability, peaking background, CP content of background
  - Total 0.09 for $J/\Psi\ K_L$ channel; 0.11 for $J/\Psi\ K^{*0}$
- **Total = 0.05 for total sample**

# Interpretation of results




**BaBar sin2β**
**(with 30 $fb^{-1}$)**

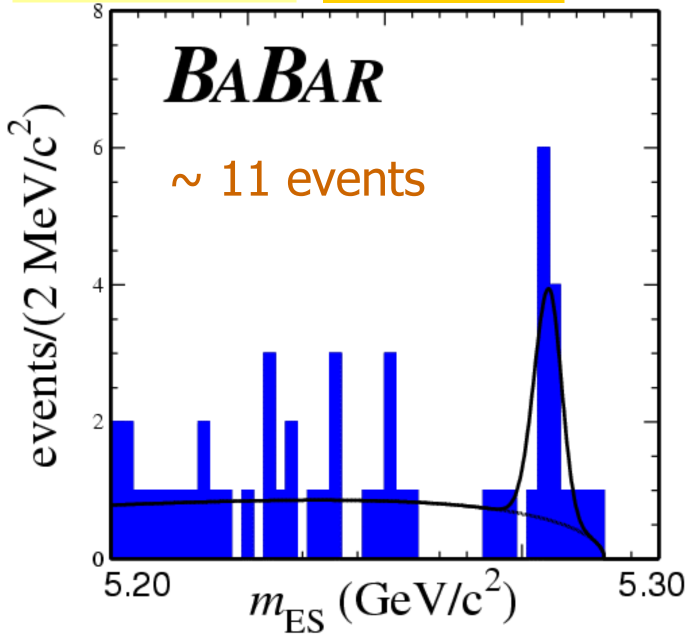
One solution for β is consistent with measurements of sides of Unitarity Triangle

*Method as in Höcker et al, hepex/0104062*
*(also other recent global CKM matrix analyses)*

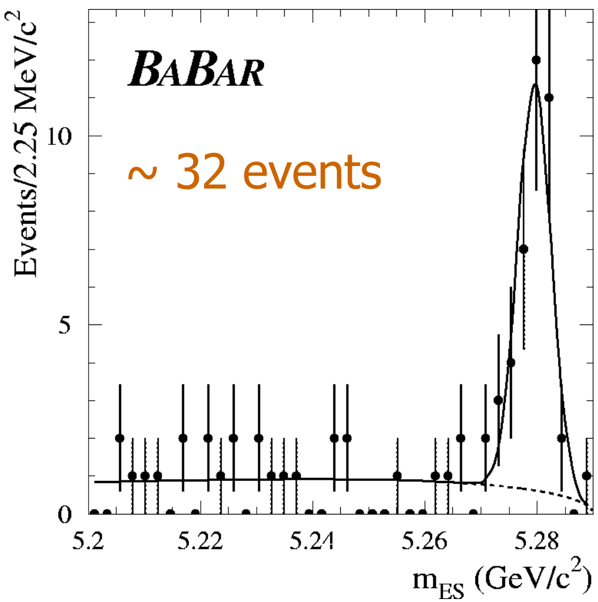
# Perspectives

**Golden modes:**
$\sigma(\sin 2\beta) \leq 0.08$ for 100 fb$^{-1}$ (next summer)
300 - 500 fb$^{-1}$ by 2005

$B^0 \to \phi K^0_S$ $\quad b \to s\bar{s}s$




$B^0 \to D^{*+}D^{*-}$ $\quad b \to c\bar{c}d$




← 21 fb$^{-1}$ →

New modes can potentially provide independent measurements of sin 2β:

- different quark processes
- various penguin contributions
- angular analyses for VV modes

# Conclusions

BaBar observes CP violation in the $B^0$ system at $4\sigma$ level

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

- PRL 87, 091801
- Detailed paper (hep-ex/0201020) submitted to Phys. Rev. D on January 10th

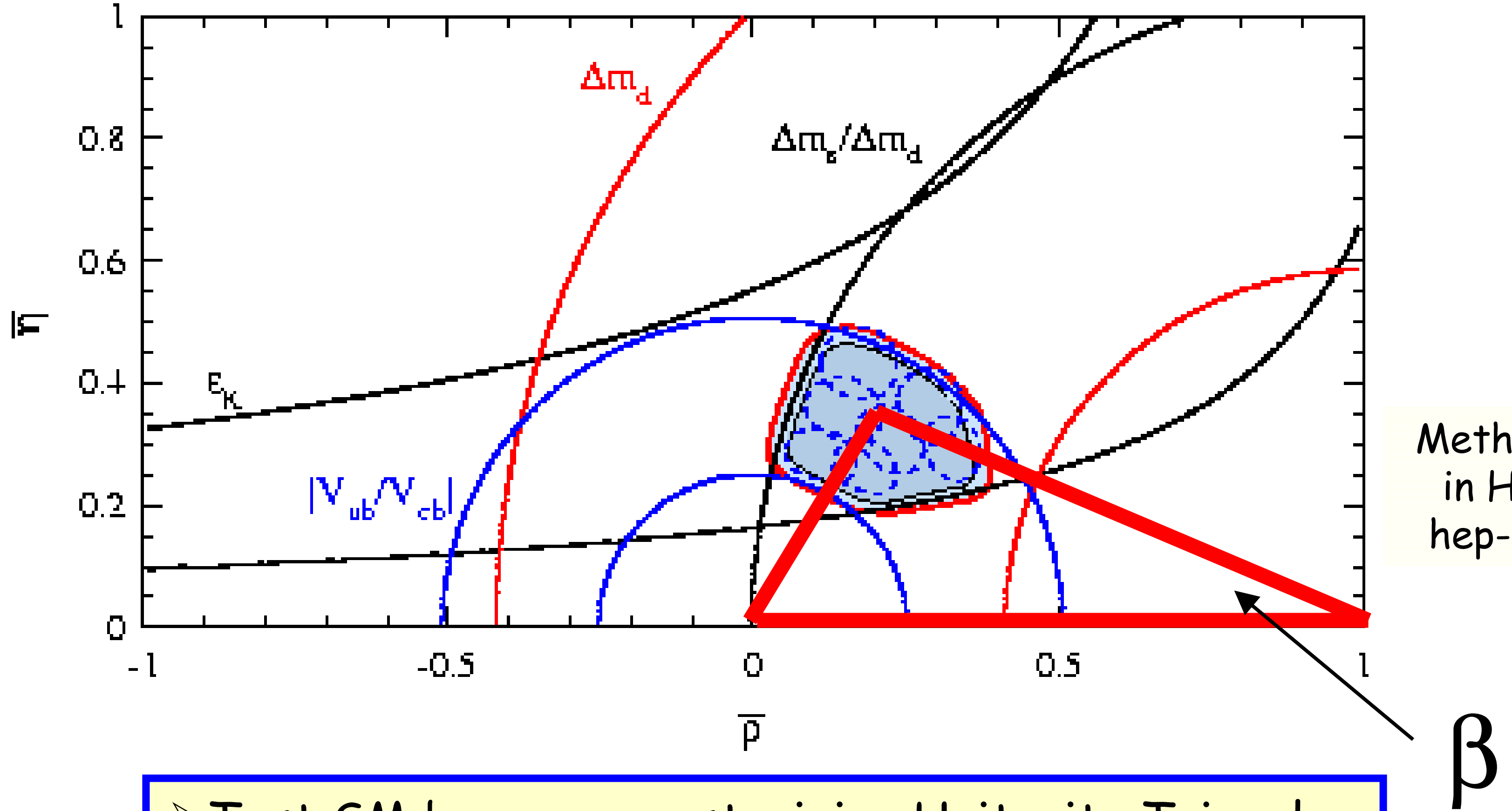
$\sin 2\beta$ will become a precision measurement:

$\sigma(\sin 2\beta) \leq 0.08$ with 100 $fb^{-1}$ (this summer)
300 - 500 $fb^{-1}$ by 2005

Test standard model by comparing $\sin 2\beta$ from different decay modes (different quark transitions, ...)

# Backup slides

# The unitarity triangle without CP violation measurements

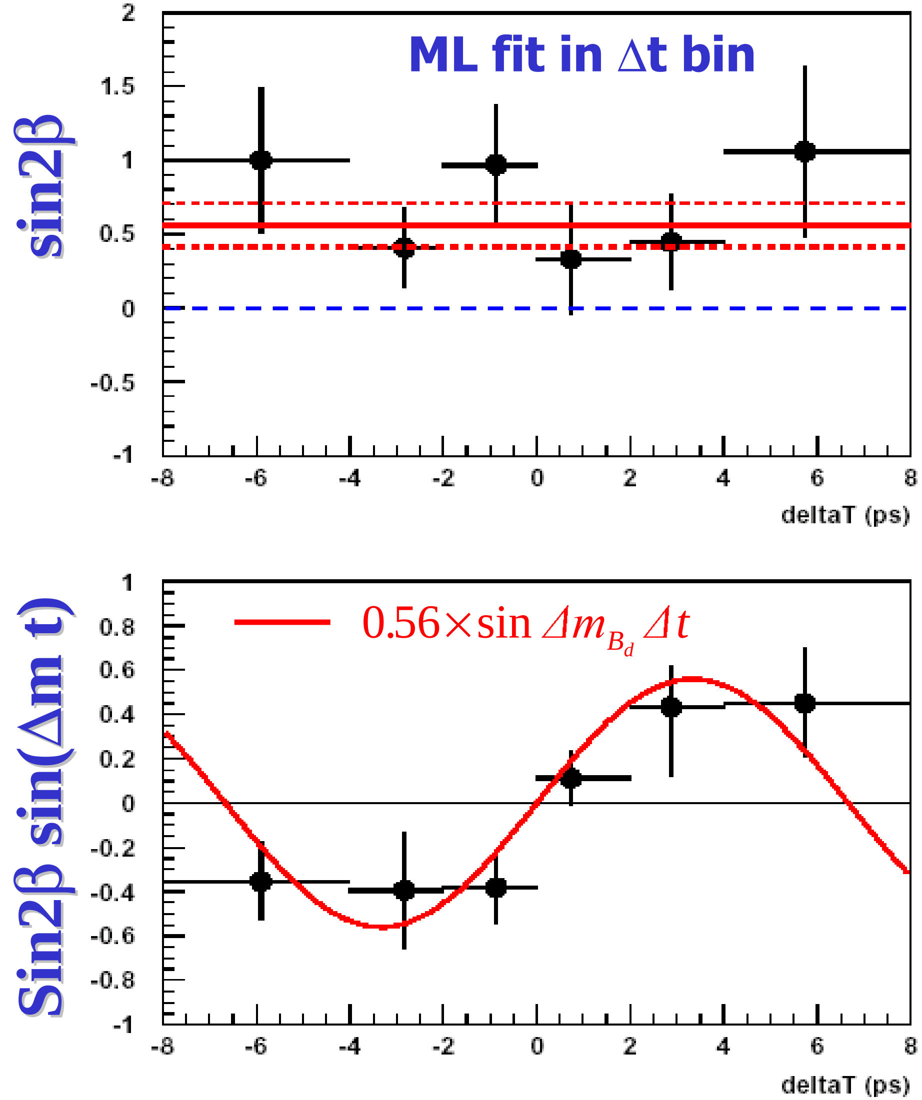



Method described in Höcker et al, hep-ex/0104062

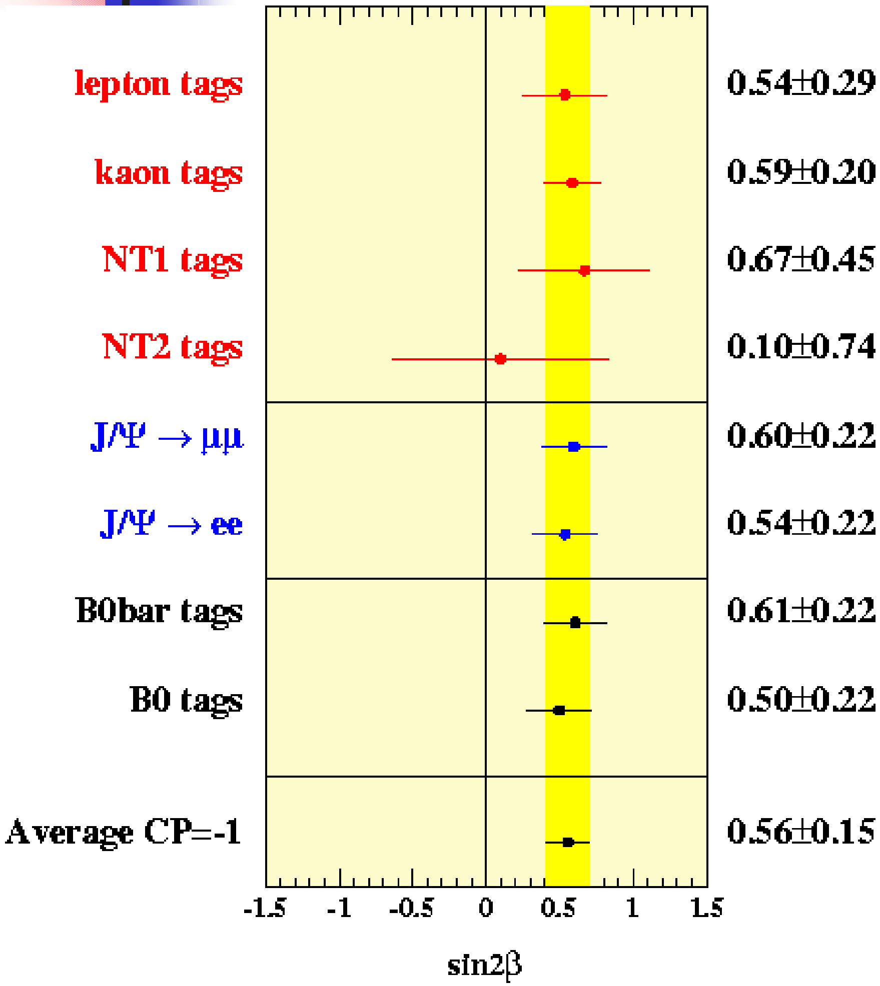
➢Test SM by over-constraining Unitarity Triangle with measurements of sides **and** angles

# "Corrected" CP asymmetries

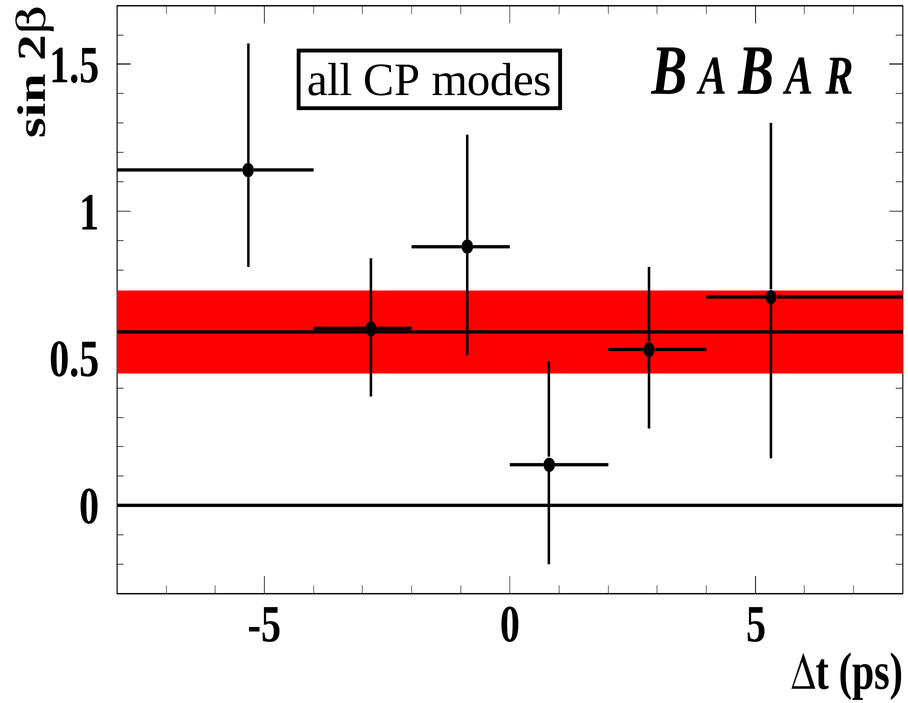
$$\eta_{CP} = -1 \text{ only}$$



# Consistency checks




sin(2β) vs. J/ψ decay mode, tagging category and flavour for η = -1 events




sin(2β) measured in several Δt bins

# Search for direct CP

If at least 2 amplitudes with a weak phase difference contribute

$|\lambda|$ might be different from 1

(tree amplitude and leading penguin amplitude for B→ $J/\psi\ K_S$ have same weak phase in SM)

$$A_{CP} = C_{f_{CP}} \cos \Delta m_d \Delta t + S_{f_{CP}} \sin \Delta m_d \Delta t$$

$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$S_{f_{CP}} = \frac{-2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

Probing new physics (only use $\eta_{CP}$=-1 sample that contains no $\cancel{CP}$ background)

$|\lambda|$ = 0.93 ± 0.09 (stat.) ± 0.03 (syst.)

No evidence of direct CP violation due to decay amplitude interference (coefficient of the “sine” term unchanged)

# Changes Run1 $\rightarrow$ Run2

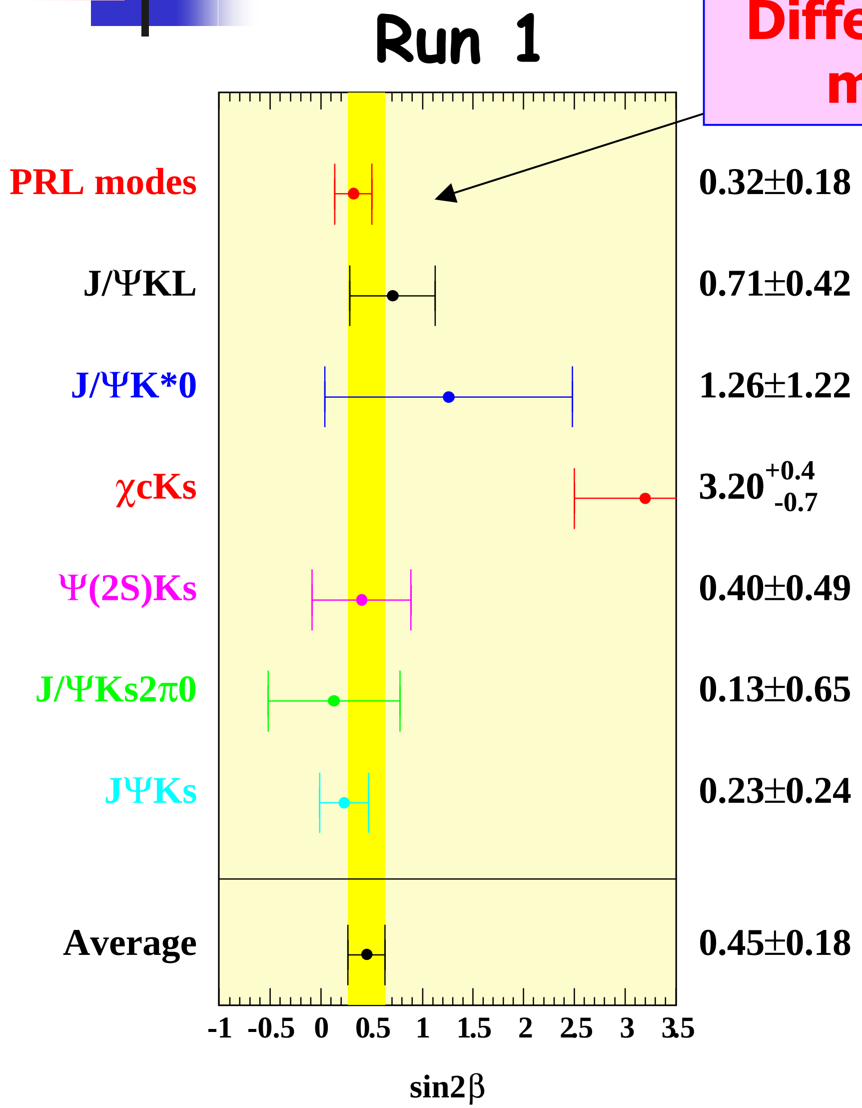
- First publication in March 2001

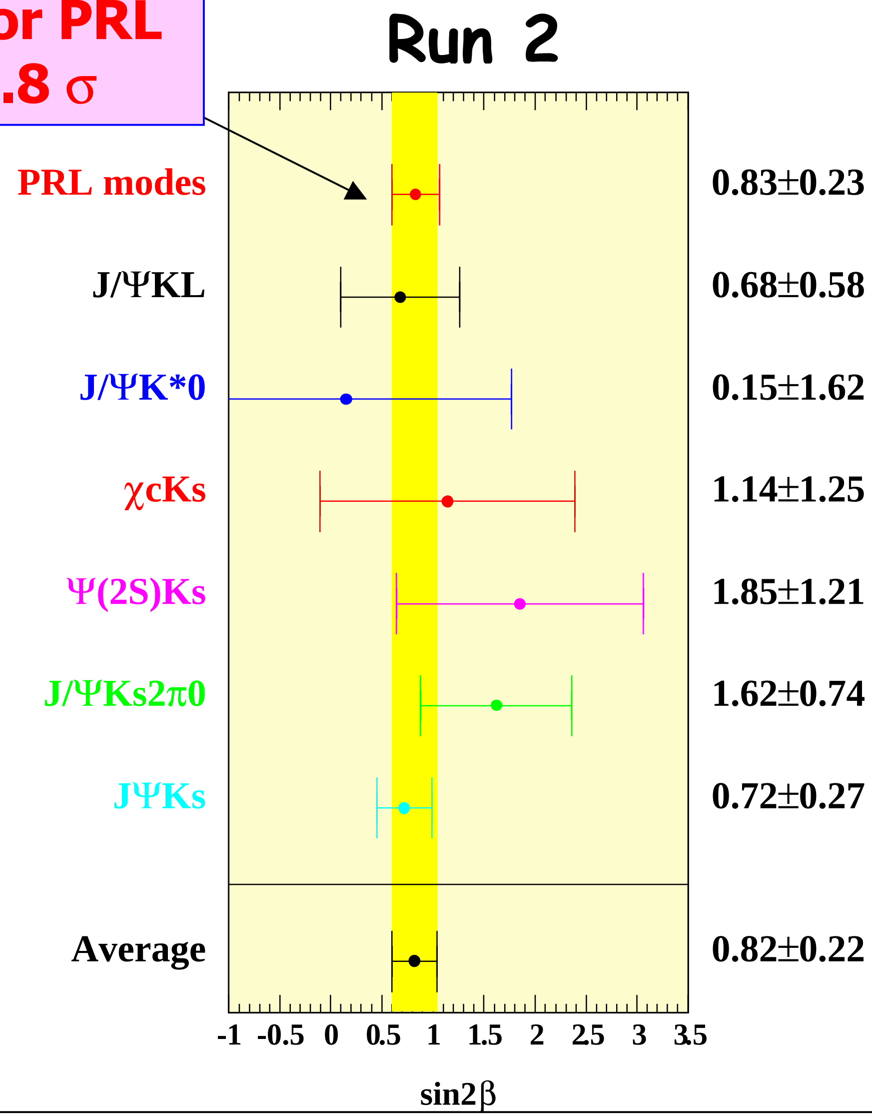
  $\sin(2\beta) = 0.34 \pm 0.20 \pm 0.05$ PRL 86 (2001) 2515

- Changes since then:
  - More data (run 2): **23 →32 $B\bar{B}$ pairs**
  - Improved reconstruction efficiency
  - Optimized selection criteria takes into account CP asymmetry of background in $J/\psi K_L$
  - Additional decay modes $\chi_{C1}K_S$ and $J/\psi K^{*0}$
  - Improved vertex resolution for reconstructed and tag B

# Run1/Run2 results

**Difference for PRL modes: 1.8 σ**

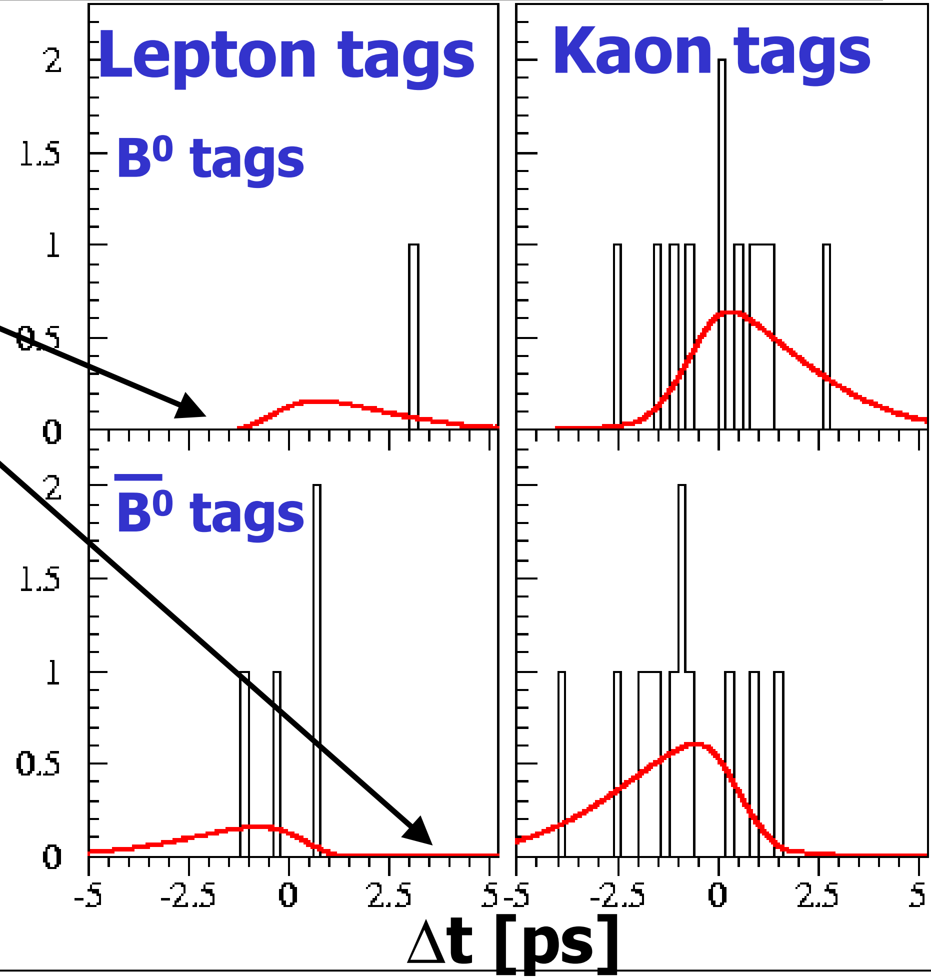


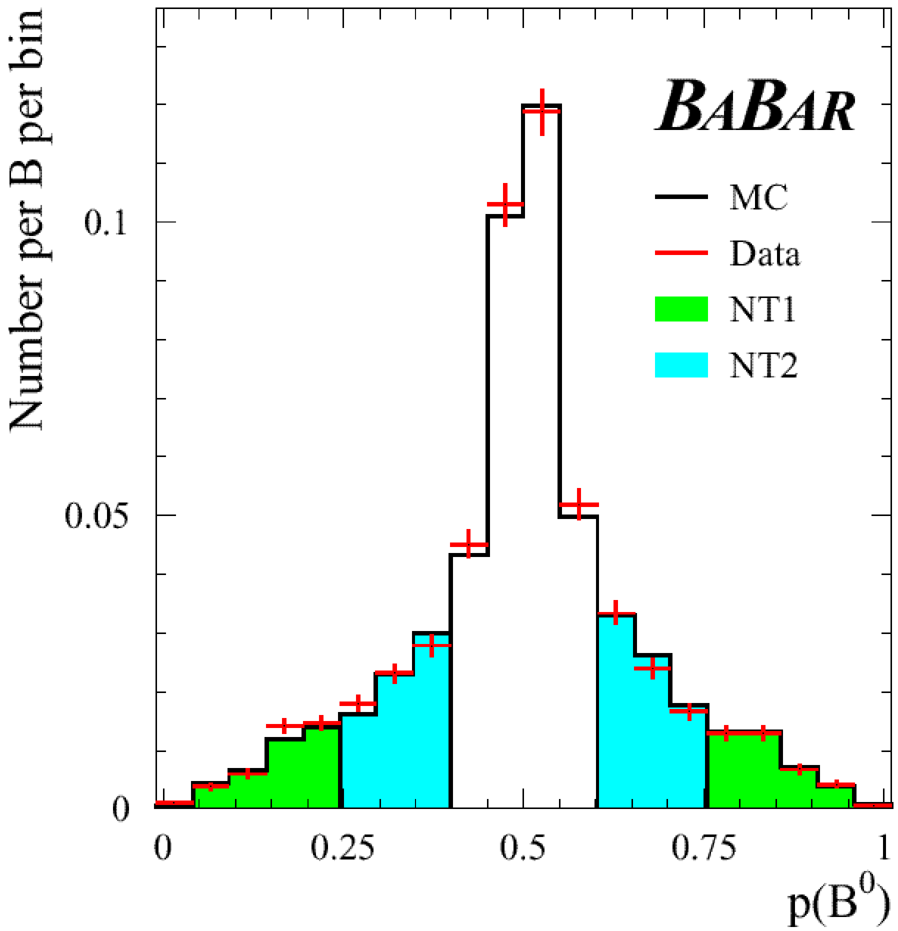
# Large sin 2β in $B^0 \to \chi_{c1} K^0_S$

$$f_{CP,\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\,\tau_B} \times \left(1 \pm \sin 2\beta \left(\mathbf{1\text{-}2\omega}\right) \sin(\Delta m_d \Delta t)\right)$$

- fit for $B^0/\overline{B}^0$ $\Delta t$ PDFs, not for $A_{CP}$
- accommodate large asymmetry with negative signal PDF (at $-(+)\pi/2\Delta m_d$ for $B^0(\overline{B}^0)$ tagged events)
- Possible , because
  - No events at these $\Delta t$ (eg. lepton tags)
  - Sum of signal + background PDFs positive (eg. Kaon tags)
- Note: a single lepton $B^0$-tag at $\Delta t = -\pi/2\Delta m$ would bring sin2β from 2.6 to $\sim 1/(1-2w_{lep}) \approx 1.1$
- Measure sin2β unbiased for low stat. samples and probability to obtain sin2β≥2.6 when true value 0.7 is 1-2%



# NT1, NT2



BABAR
MC
Data
NT1
NT2
Number per B per bin
0.1
0.05
0
0
0.25
0.5
0.75
1
$p(B^0)$