BaBar Results on CP Violation in the B Sector

TM and © Laurent de Brunhoff

Francesco Forti
INFN - Pisa

INFN Istituto Nazionale di Fisica Nucleare

On Behalf of the BaBar Collaboration

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, March 3-9 2002

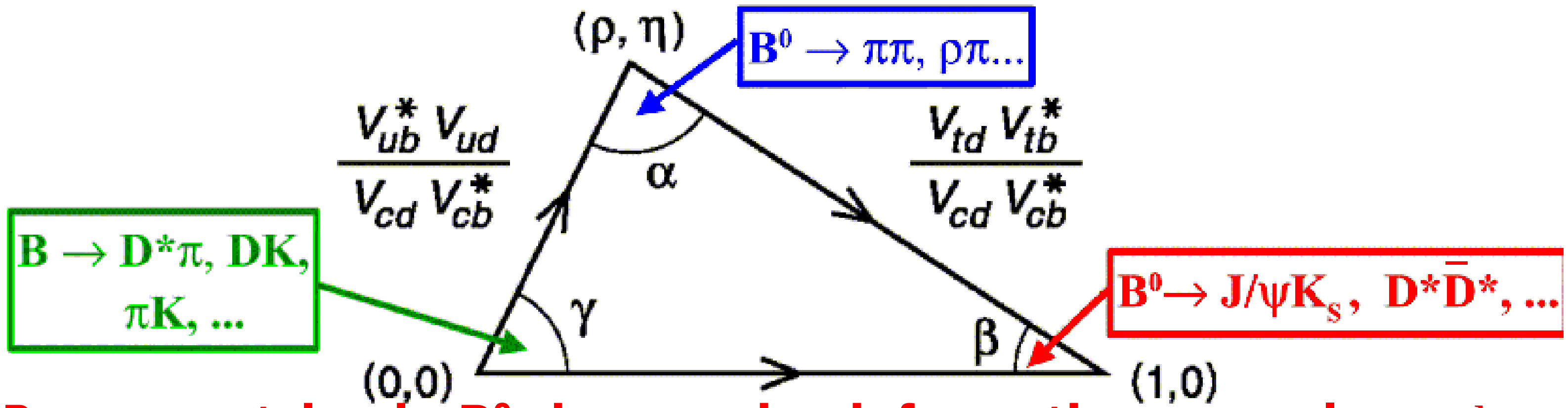
CP Violation in the Standard Model

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

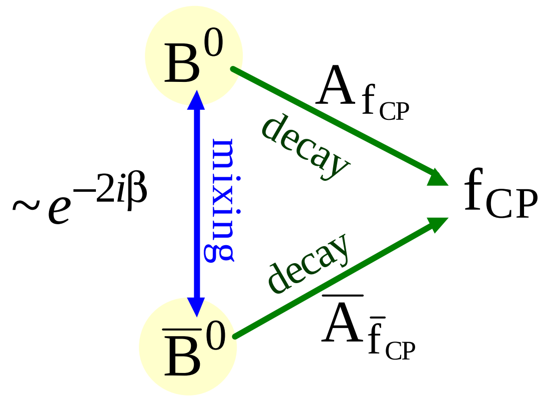
→ represented as **'unitarity triangle'** in complex plane



CP asymmetries in B⁰ decays give information on angles α, β, γ !

~~CP~~ from Interference of Mixing and Decay

A kind of CP violation results from interference between decays with and without mixing



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

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

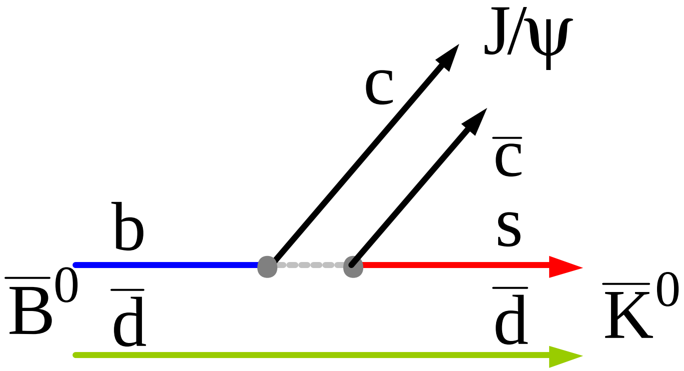
Time-dependent CP asymmetry:

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

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

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

Golden CP modes



$\overline{B}^0 \rightarrow J/\psi\, \overline{K}^0$
$B^0 \rightarrow J/\psi\, K^0$

K^0 mixing

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

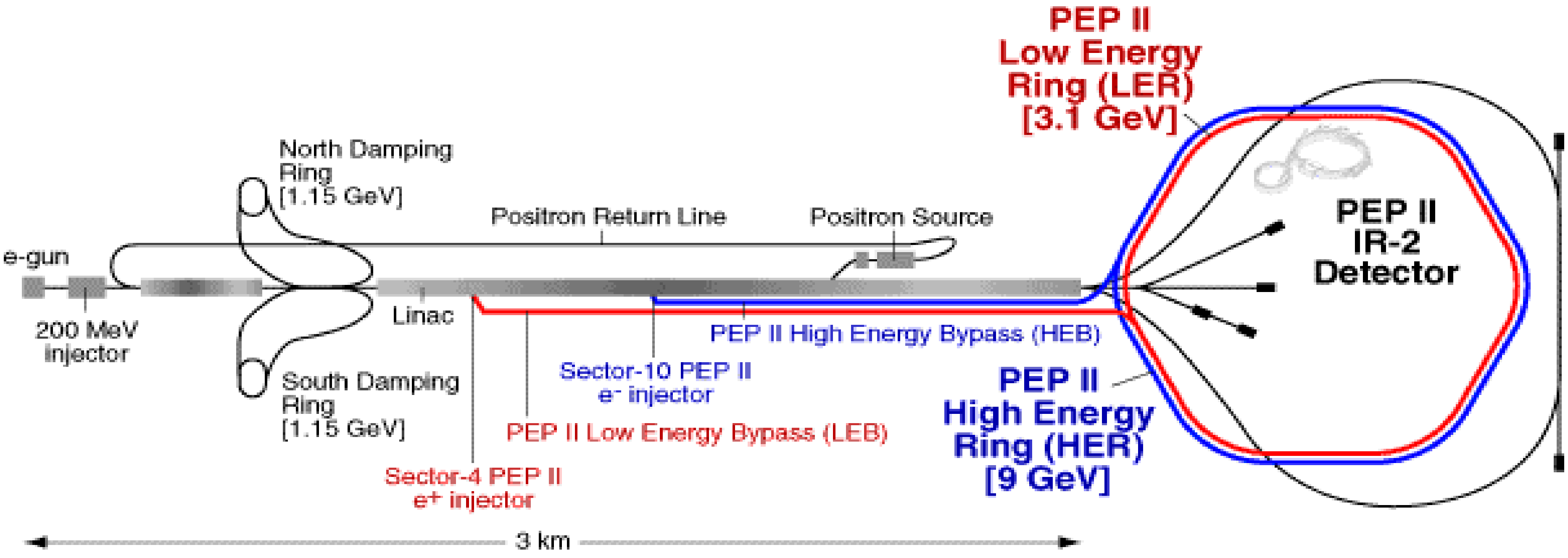
Single weak phase = no direct ~~CP~~ $\Longrightarrow$ $|\lambda_{J/\psi\, K^0_{S,L}}| = 1$

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

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

- Theoretically clean way to measure $\sin 2\beta$
- Clear experimental signature
- Relatively large branching fraction

PEP-II Asymmetric B Factory

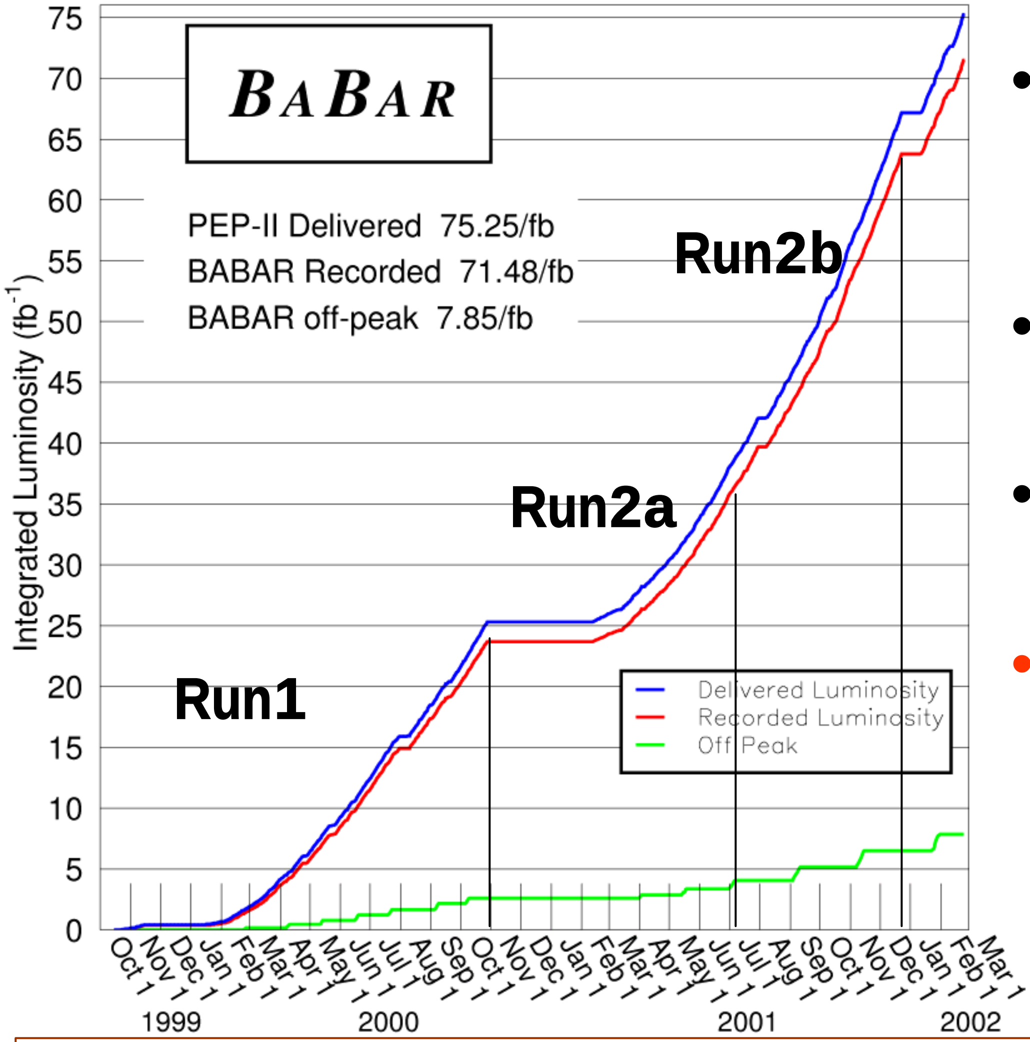


- **9 GeV e^- on 3.1 GeV e^+ :**

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

- U**(4S) boost in lab frame :** bg **= 0.55**

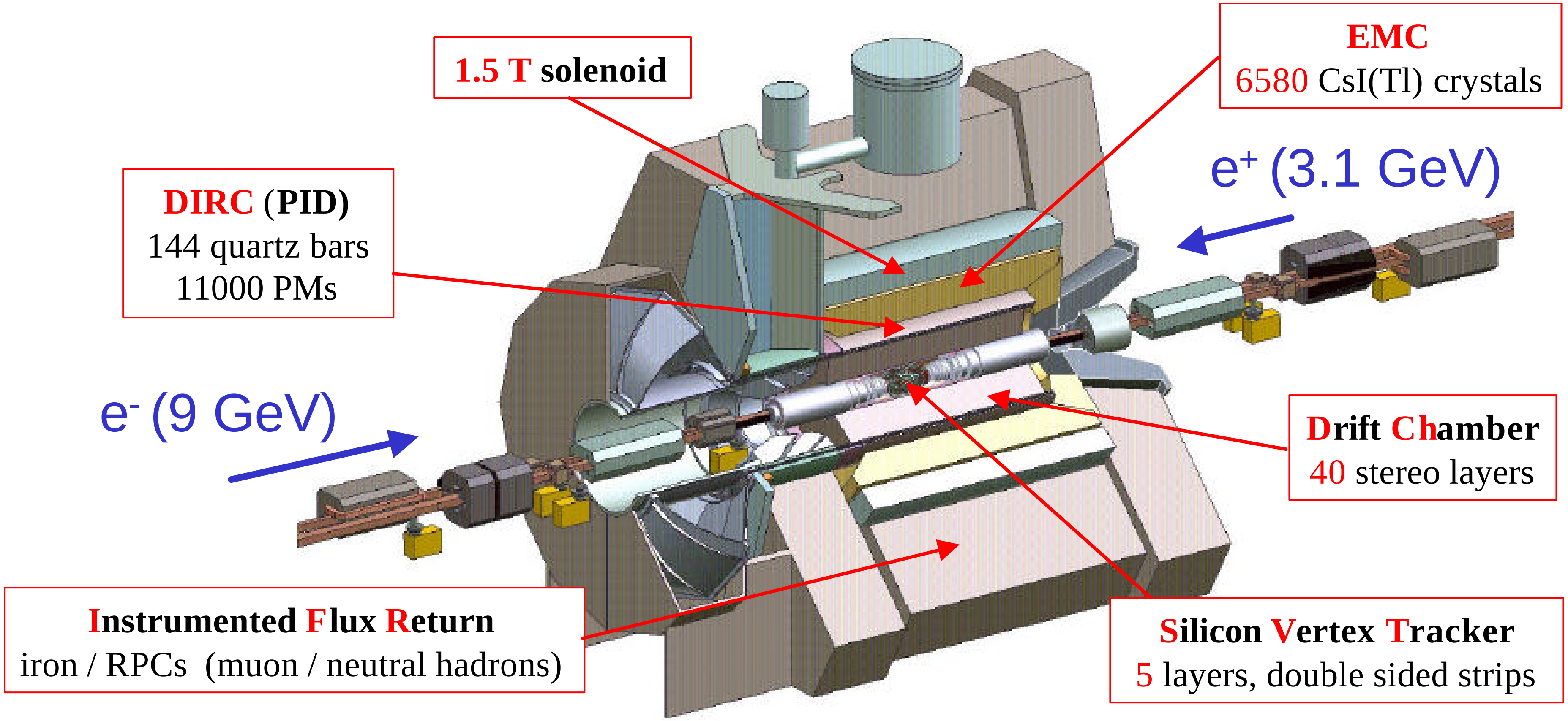
SLAC B Factory Performance



- PEP-II top luminosity: $4.51 \times 10^{33} cm^{-2}s^{-1}$ (design 3.0×10^{33})
- Top recorded L/24h: 303.4 pb^{-1}
- BABAR logging efficiency: > 96%
- Analysis Data samples
  - Run1 : 20.7 /fb
  - Run2a : 9.0 /fb
  - Run2b : 26.7 /fb
  - Total : 56.4 /fb

PEP-II delivered : 75.25 fb^{-1}
BABAR recorded : 71.48 fb^{-1} (incl.7.85 fb^{-1} off peak)

The BABAR Detector



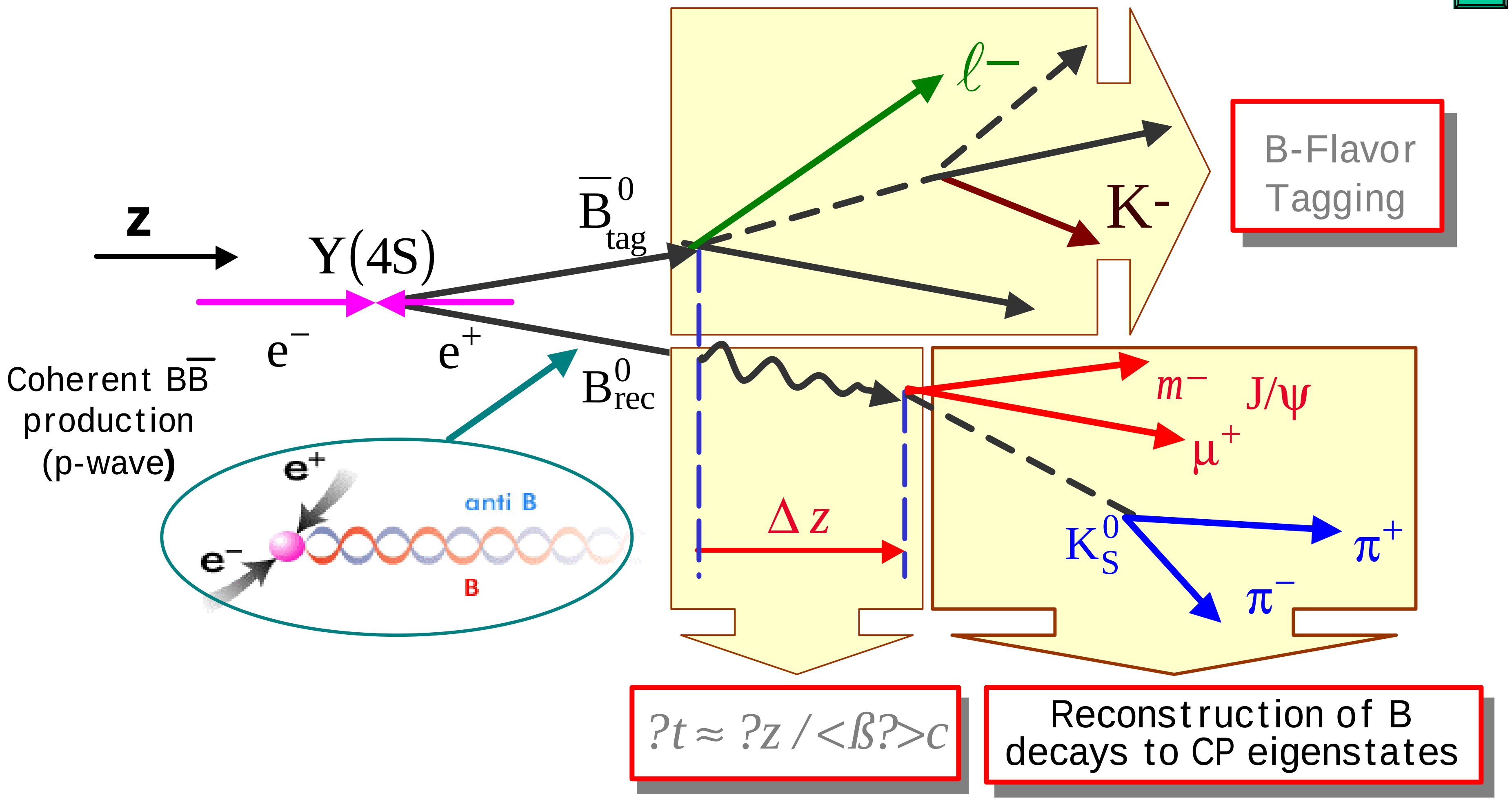
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

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

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

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

Analysis strategy

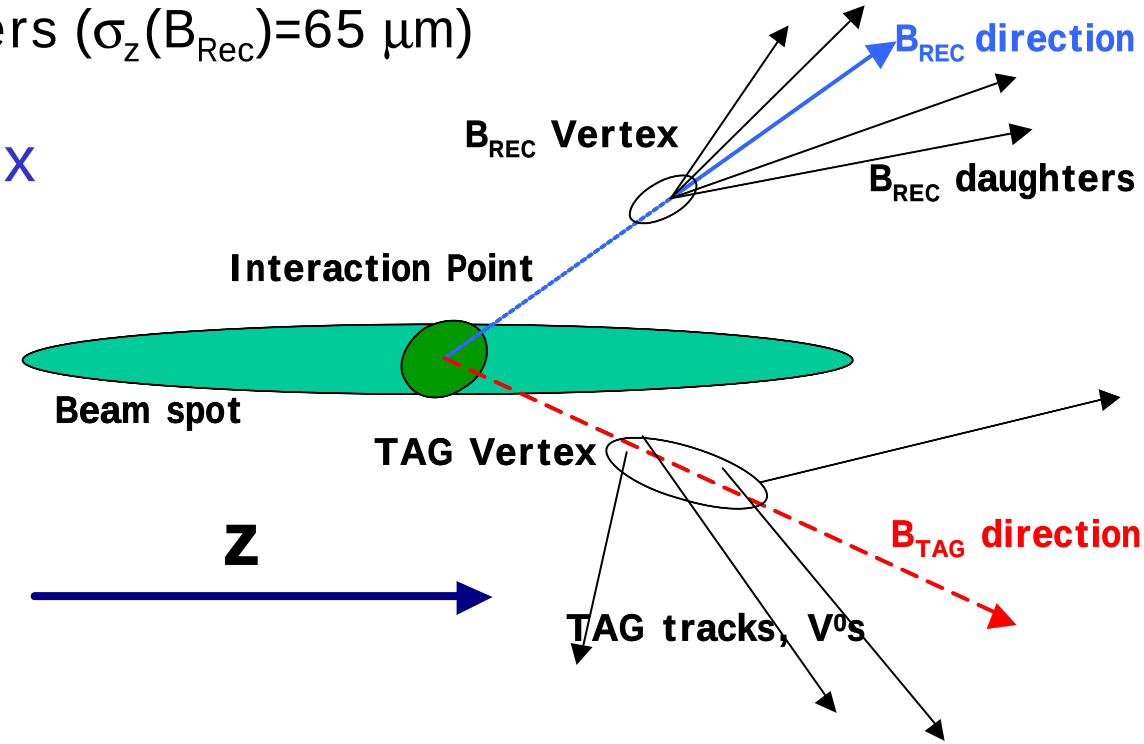


$B^0_{rec} = B^0_{CP}$ **(CP eigenstates)** ➡ **sin 2b**

$B^0_{rec} = B^0_{flav}$ **(flavor eigenstates)** ➡ **resolution, mistag rates**

Vertex and Δt Reconstruction

- Reconstruct B_{rec} vertex from
  - charged B_{rec} daughters ($\sigma_z(B_{Rec})$=65 μm)
- Determine B_{Tag} vertex from
  - charged tracks not belonging to B_{rec}
  - B_{rec} vertex and momentum
  - beam spot and $\Upsilon(4S)$ momentum

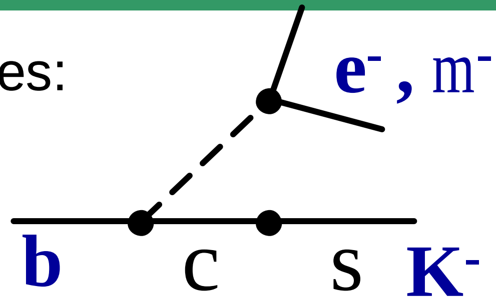


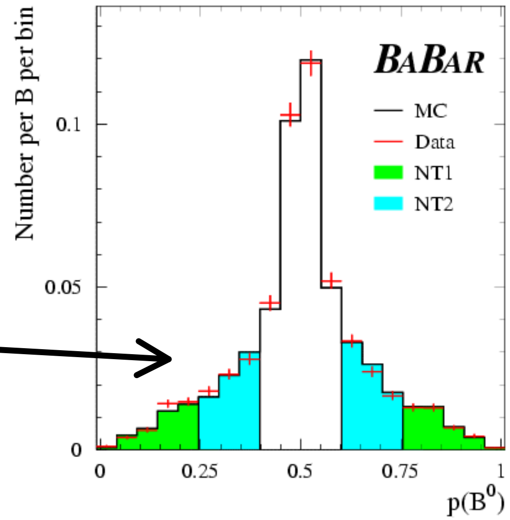
- High efficiency (93%) through inclusion of 1-prong tags
- Average Δz resolution is 180 μm ($\langle|\Delta z|\rangle = \beta\gamma c\tau$ = 260 μm) corresponding to a Δt resolution of 0.6 ps.
- Δt resolution function measured from data (B_{flav} sample)

B Flavor Tagging

Hierarchical tagging categories:

- Lepton – charge of lepton
- Kaon – net charge of kaon
- NT1 } exploit information from
- NT2 } soft π, unidentified l





Large B_{flav} sample provide tagging performance measurement:

Tagging category	Efficiency ε (%)	Mistag fraction w (%)	$\overline{B}^0/B^0$ diff. Δw (%)	Q = ε(1-2w)² (%)
Lepton	11.1 ± 0.2	**8.6 ± 0.9**	0.6 ± 1.5	7.6 ± 0.4
Kaon	**34.7 ± 0.4**	18.1 ± 0.7	-0.9 ± 1.1	14.1 ± 0.6
NT1	7.7 ± 0.2	22.0 ± 1.5	1.4 ± 2.3	2.4 ± 0.3
NT2	14.0 ± 0.3	37.3 ± 1.3	-4.7 ± 1.9	0.9 ± 0.2
ALL	67.5 ±0.5	s(sin2b) µ 1/ÖQ		**25.1 ± 0.8**

Changes in this analysis

Detector improvements

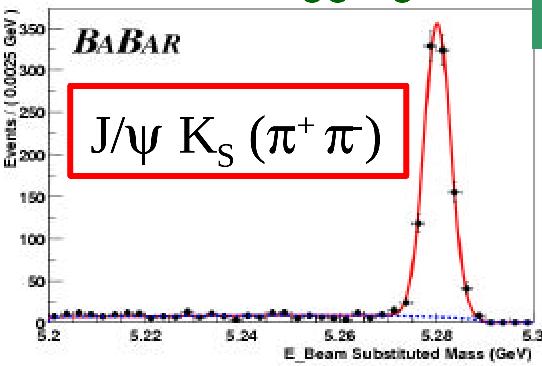
- Improved tracking impacts Δt resolution for reprocessed Run1 data:
  - Improved usage of the first SVT hit.
  - Improved SVT alignment
  - Improved track finder
  - Published Run2a data already had the improved tracking
- Improved PID impacts tagging
  - Better DIRC alignment and K selector
  - Better μ selector

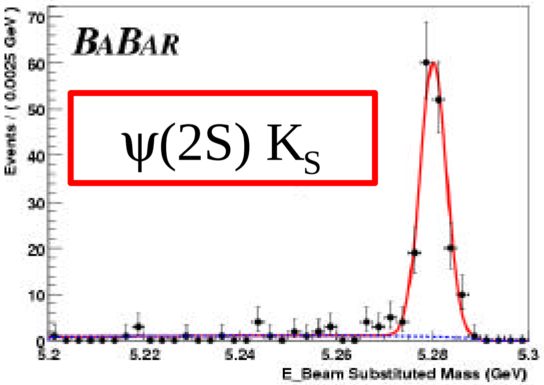
Analysis changes

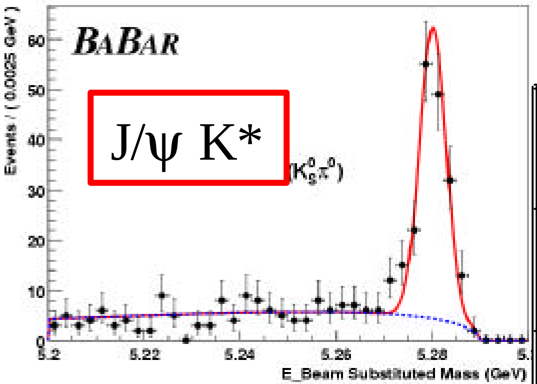
- Re-optimized selection criteria to improve yield
  - Wider K_S mass window results in 7% increase in $J/\psi\ K_S$ yield
  - Looser μid, π^0 veto results in 15% $J/\psi\ K_L$ yield with purity 60%→54%.
- $B^0 \rightarrow J/\psi\ K^{*0}$
  - Full angular analysis
  - Reduce feed-across by vetoing $B^+ \rightarrow J/\psi\ K^{*+}$ results in 60% background rejection with 0.5% signal loss.
- New D*D* result

The CP Sample

Before tagging:

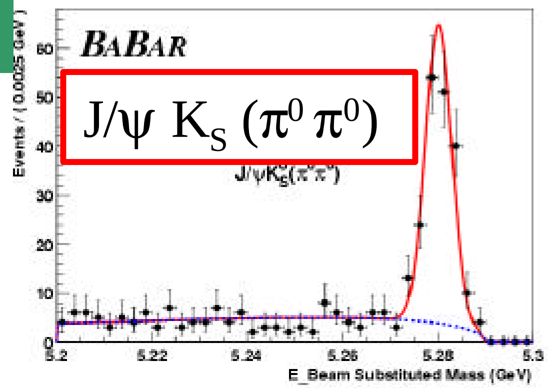


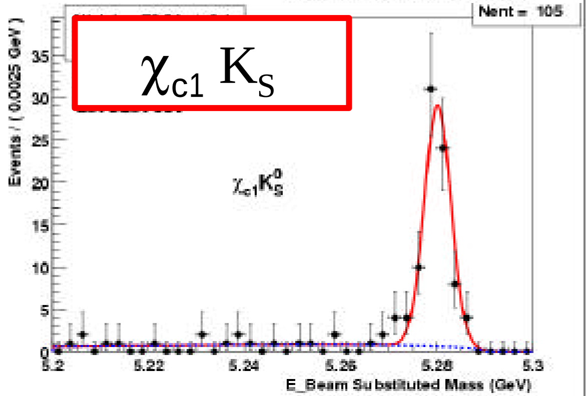




1999-2001 data

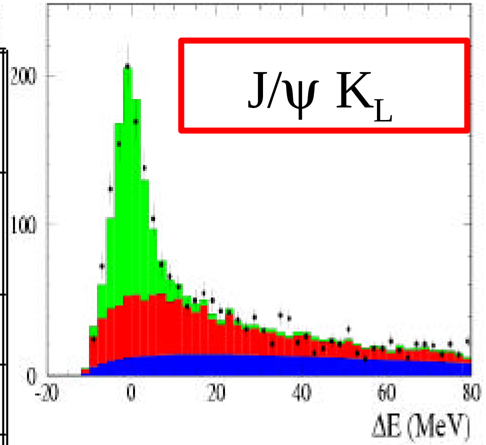
62 x 10^6 $B\overline{B}$ pairs,
56 fb^{-1} on peak





After tagging:

Sample	tagged events	Purity	*CP*
[J/ψ, $\psi(2S)$, χ_{c1}] K_S	995	94%	-1
$J/\psi\ K_L$	742	57%	+1
$J/\psi\ K^{*0}(K_S\pi^0)$	113	83%	mixed
Full *CP* sample	1850	79%	



sin2β Likelihood Fit

- Unbinned maximum likelihood fit to Δt distribution.
- Background is determined from M_{ES} fit (flat) or MC (peaking)
- B_{flav} sample → mistag rates and Δt resolution both for signal and for background
- Total of 34 parameters

CP PDF

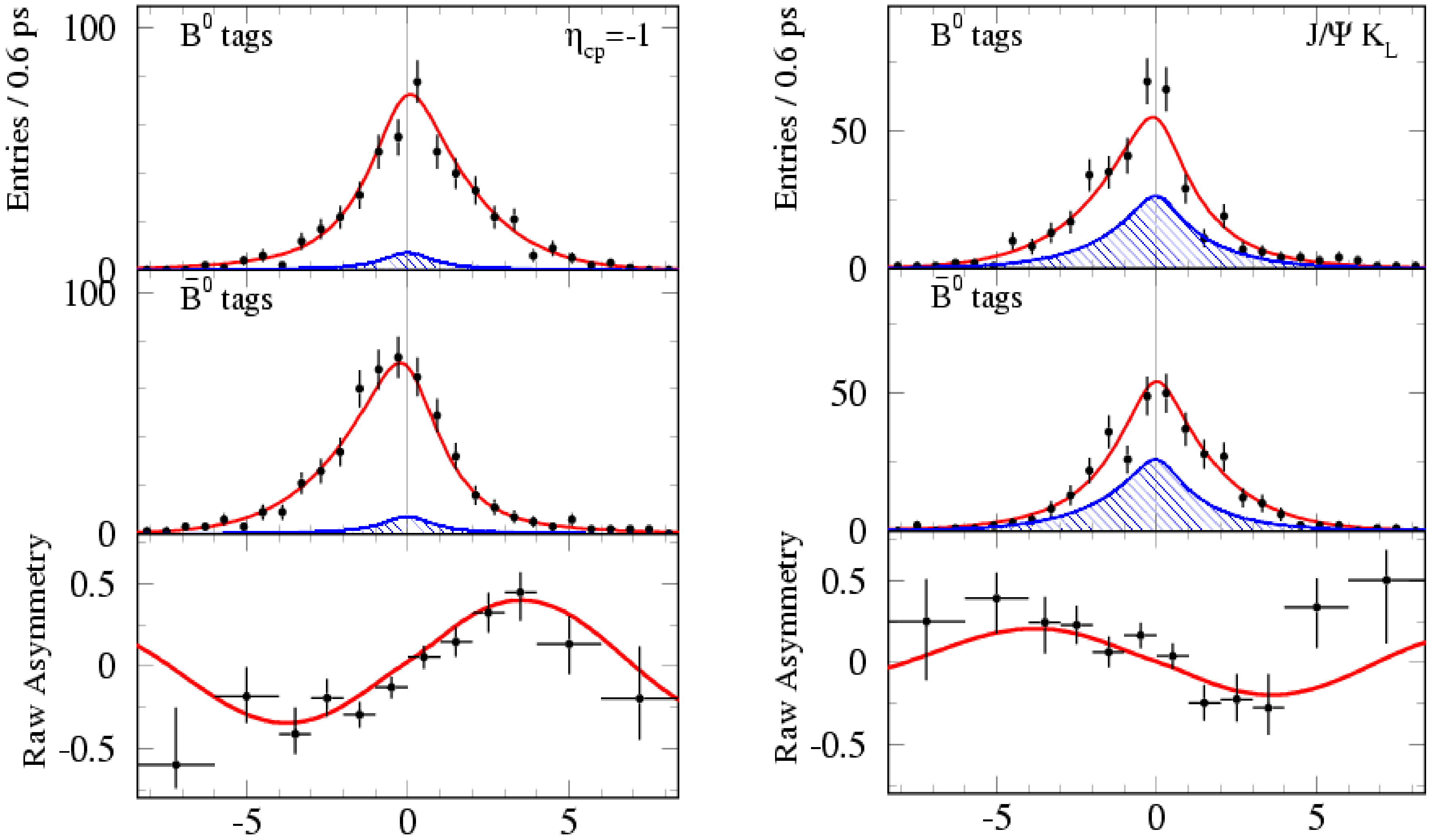
$$f_{CP,\pm}(?t)=\left\{\frac{e^{-|?t|/t_{B_d}}}{4\,t_{B_d}}\times\left(1\mp ?_f\ \sin 2\beta\left(\mathbf{1\text{-}2?}\right)\sin(?m_d\,?t)\right)\right\}\otimes \boldsymbol{R}$$

τ_B = 1.548 ps
Δm_d = 0.472 ps^{-1}
fixed

Mixing PDF

$$f_{mixing,\pm}(?t)=\left\{\frac{e^{-|?t|/t_{B_d}}}{4\,t_{B_d}}\times\left(1\pm\left(\mathbf{1\text{-}2?}\right)\cos(?m_d\,?t)\right)\right\}\otimes \boldsymbol{R}$$

CP asymmetries

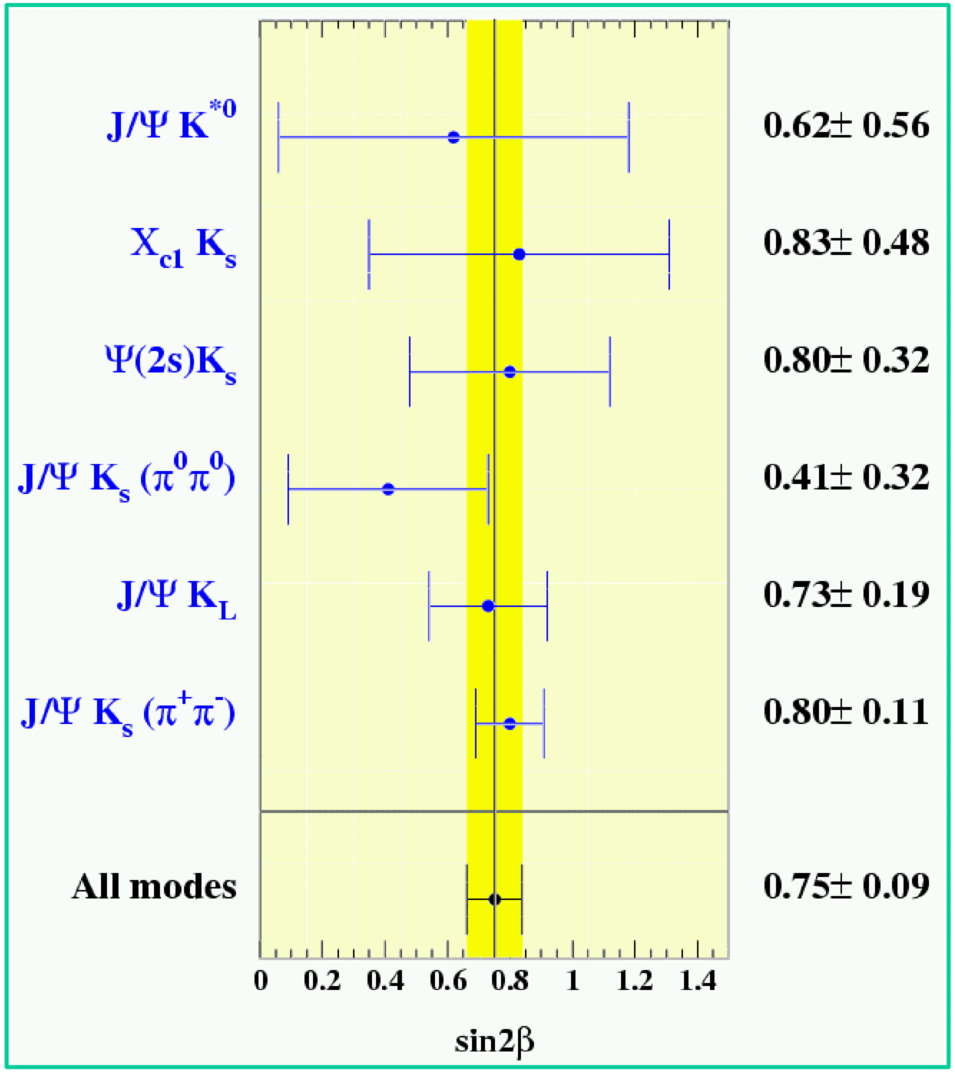


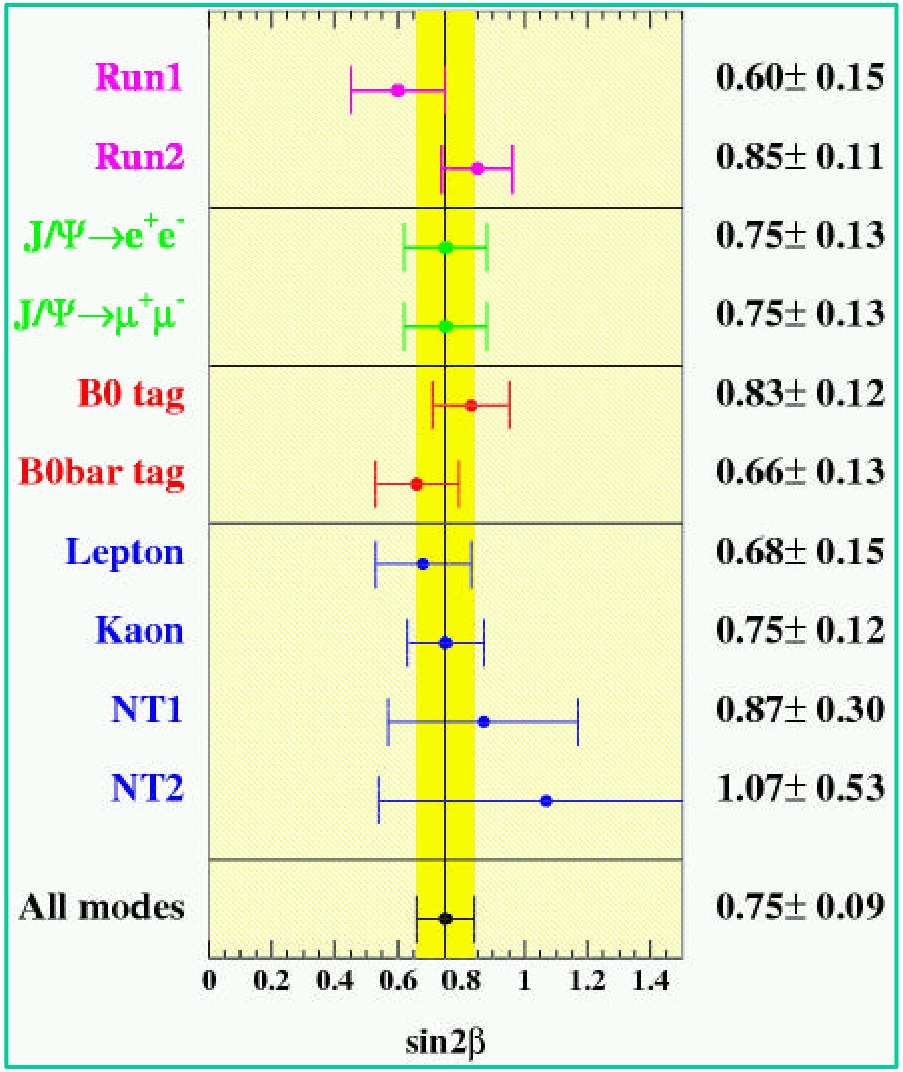
$$A_{CP} \approx (1-2w)\sin 2b \sin \Delta m \Delta t$$

$$A_{CP} \approx -(1-2w)\sin 2b \sin \Delta m \Delta t$$

sin2β fit results

$\sin 2\beta = 0.75 \pm 0.09\ (\text{stat}) \pm 0.04\ (\text{sys})$





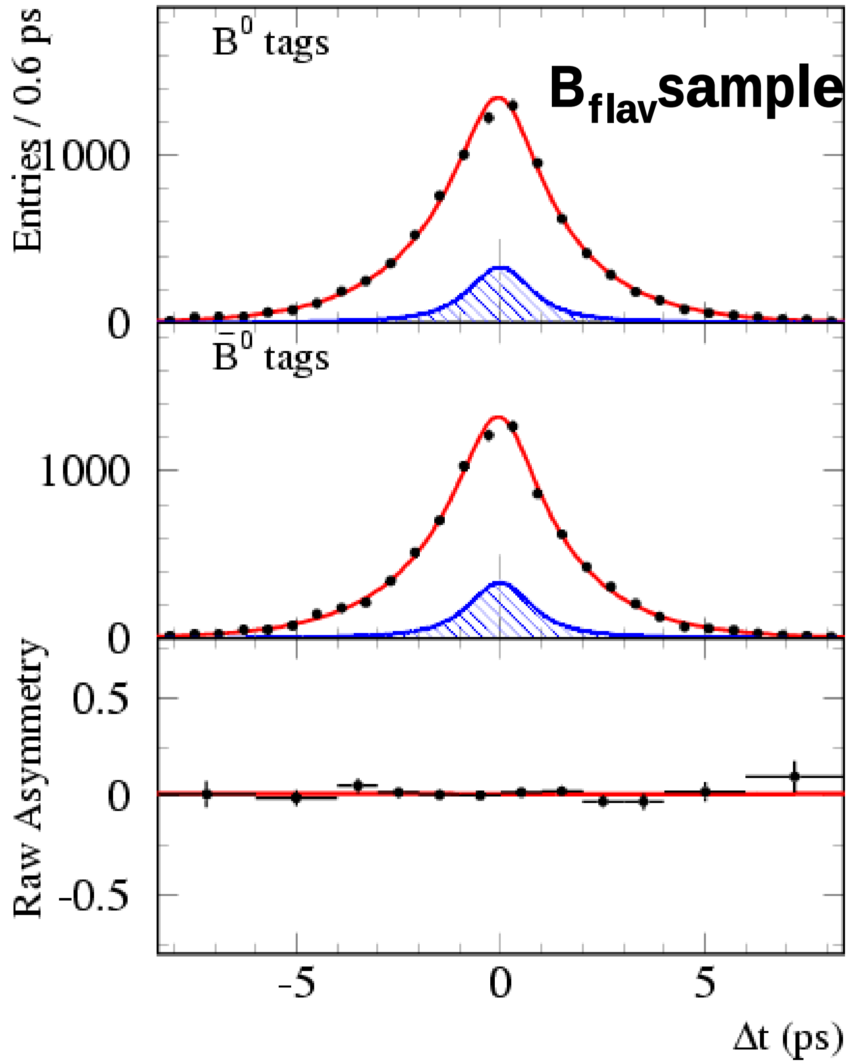
Systematic Errors

Error	K_S	K_L	K^{*0}	Total
Statistic	0.10	0.19	0.56	0.09
Systematic	0.04	0.07	0.10	0.04

- Signal resolution and vertex reconstruction **0.015**
  - Resolution model, outliers, SVT residual misalignment
- Tagging **0.007**
  - possible differences between B_{CP} and B_{flavor} samples
- Backgrounds **0.023** (overall)
  - Signal probability, peaking background, CP content of background
  - Total 0.05 for $J/\Psi\ K_L$ channel; 0.09 for $J/\Psi\ K^{*0}$
- Montecarlo correction (none applied) : **0.014**
- External parameters (Δm and τ_B) : **0.014**
- **Total = 0.04 for total sample**

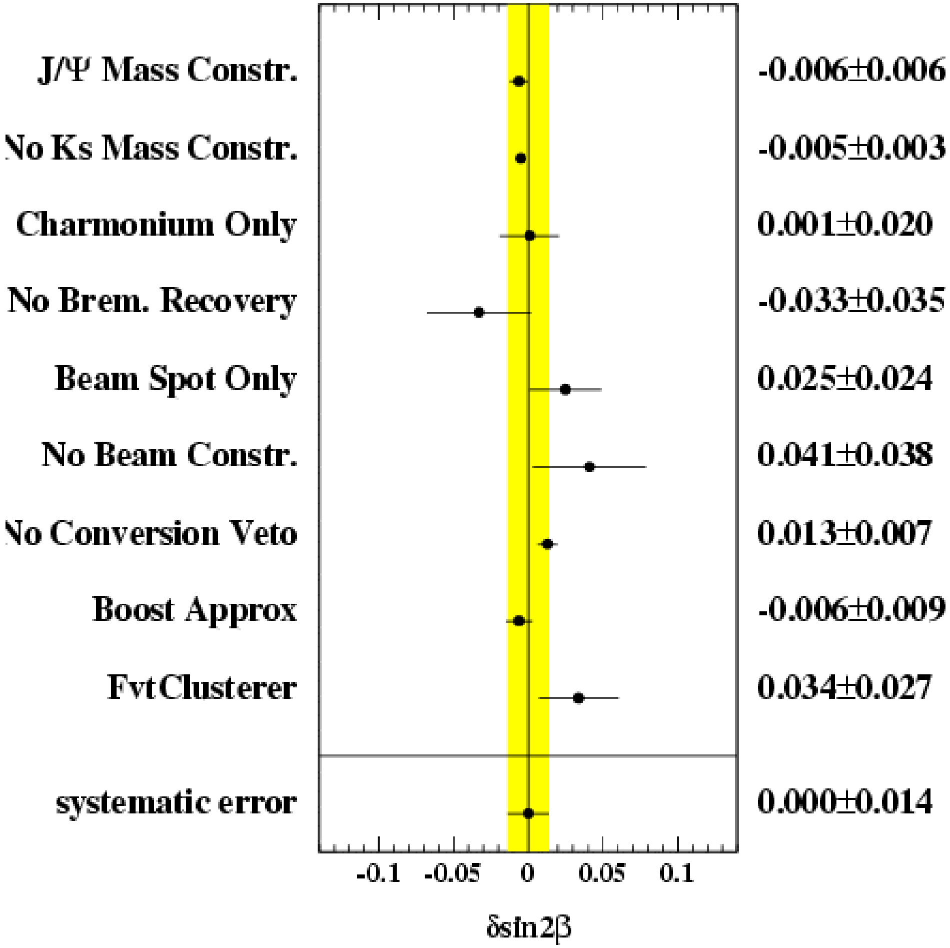
Cross checks

- No asymmetry on B_{flav} sample:
  $\sin 2\beta = -0.004 \pm 0.027$
- Full MC studies reproduce well the input value
- No mistag rate (w) dependence on Δt.
- Lifetime and mixing results



Cross checks II

- The sin2β variation when using alternative vertexing algorithms has been measured
  - Impose J/Ψ mass constraint
  - Remove Ks mass constraint
  - Charmonium only in CP vertex
  - No Bremsstrahlung recovery in J/Ψ→e+e-
  - Different ways of using the beam spot constraint
  - Use average boost to extract Δt from Δz w/out using $p(B_{rec})$.
  - Do not veto conversion pairs
  - Do not veto V^0s



- All the effects are compatible with the systematic error estimate

B^0 ® $D^{*+}D^{*-}$

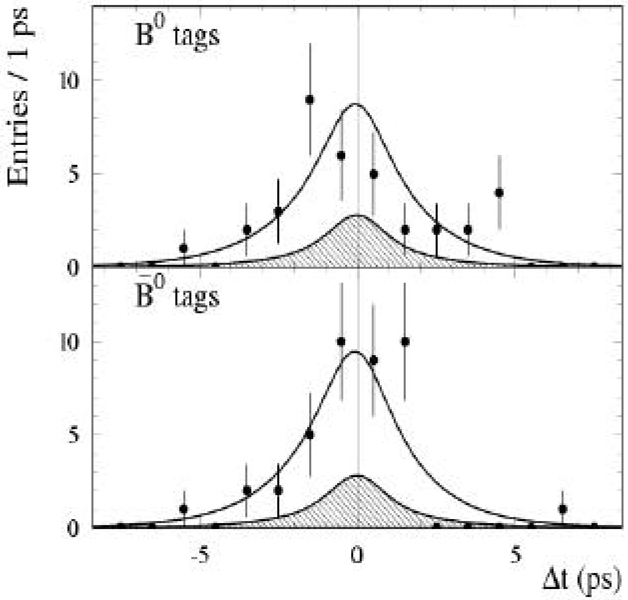
- Event reconstruction in $D^{*+} \rightarrow D^0\pi^+$ or $D^+\pi^0$(but not both D*'s in π^0).
- Motivation: can provide cross check for SM prediction
- Mixed CP: requires CP-odd fraction measurement. With 20/fb:

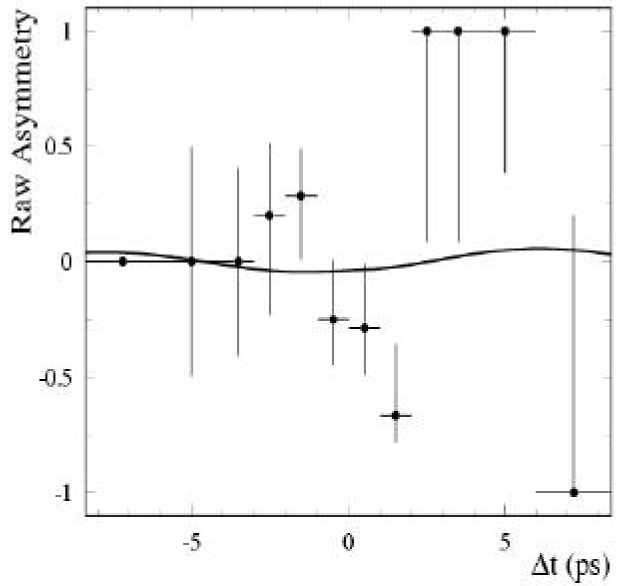
$$R_T = 0.22 \pm 0.18(stat) \pm 0.03(syst)$$

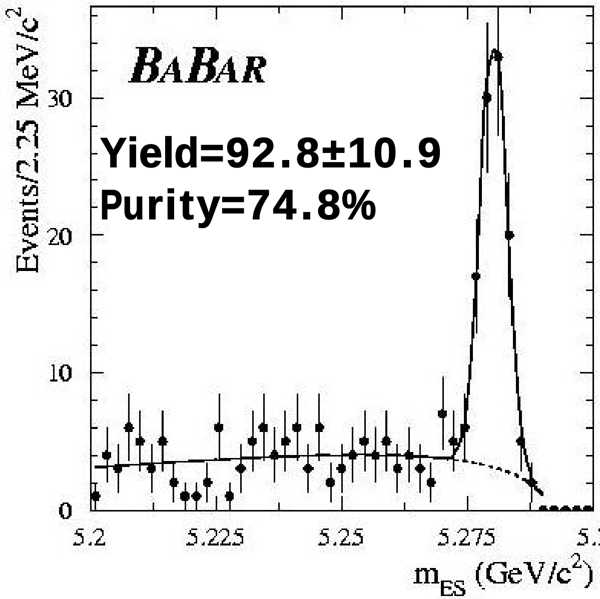
- With full sample we fit the sin $\Delta m \Delta t$ and cos $\Delta m \Delta t$ terms

$S = -0.05 \pm 0.45(stat) \pm 0.05(syst)$ $C = 0.12 \pm 0.30(stat) \pm 0.05(syst)$

- Disregarding penguin contributions $S = (1-2R_T)\sin 2\beta$







Other results

- Search for direct CP: float $|\lambda|$ in the η_{CP}=-1 sample

  $|\lambda|$ = 0.92 ± 0.06 (stat.) ± 0.03 (syst.)

  Im $\lambda/|\lambda|$ = 0.76 ± 0.10 (i.e. sin 2β)

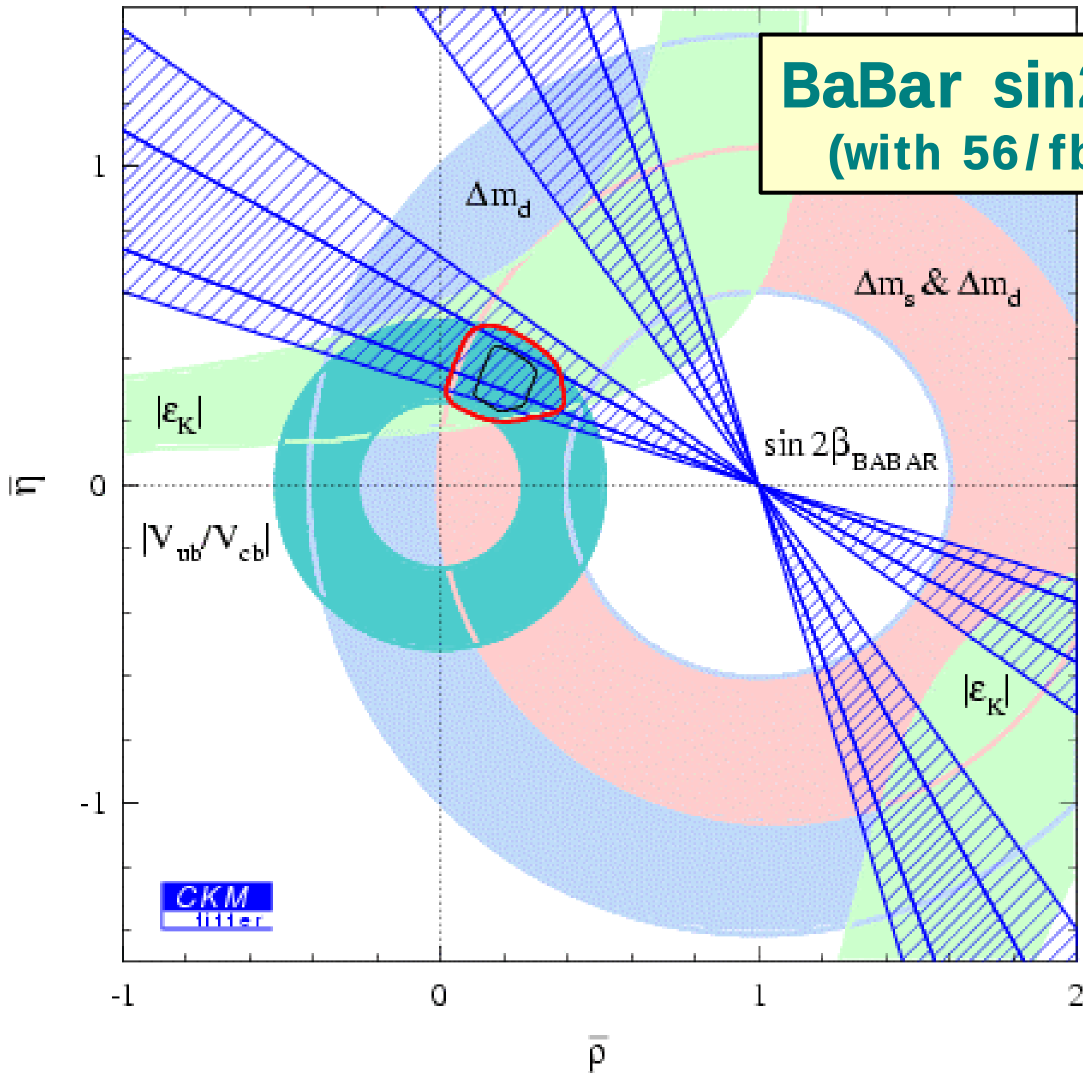
- Asymmetry in $B^0 \rightarrow \pi^+\pi^- / K^+\pi^-$ (30 /fb) (to be updated soon)

$$S(p^+p^-) = 0.03^{+0.53}_{-0.56}\,(stat) \pm 0.11\,(syst)$$

$$C(p^+p^-) = -0.25^{+0.45}_{-0.47}\,(stat) \pm 0.14\,(syst)$$

$$A_{CP}(K^{\pm}p^{\mp}) = -0.07 \pm 0.08\,(stat) \pm 0.02\,(syst)$$

The CKM triangle picture



BaBar sin2b
(with 56/fb)

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

Error on sin2β is dominated by statistics → will decrease ~1/√Luminosity

Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001 (also other recent global CKM matrix analyses)

Summary and outlook

- New measurement of CP violation in the B sector

  $\sin 2\beta$ = 0.75 ± 0.09 (stat) ± 0.04 (sys)

- $\sin 2\beta$ is beginning to be a precision measurement providing effective unitarity triangle constraints
- It is still statistically limited and will improve with the 100/fb expected by summer 2002
- Non-golden and rare decay modes begin to be accessible and will provide SM consistency checks.
- Stay tuned, exciting physics ahead.

====== Backup Slides =====

- Δt Resolution function
- sin2β Likelihood Fit parameters
- Mis-tagging and resolution
- $B^0 \to J/\psi\ K^*$
- Run1 data sample changes
- B Reco sample
- Lifetime and mixing

Δt Signal Resolution

- event-by-event $\sigma(\Delta t)$ from vertex errors
- Resolution Function (RF) – 2 models:
  - **Sum of 3 Gaussians** (mixing + CP analyses)

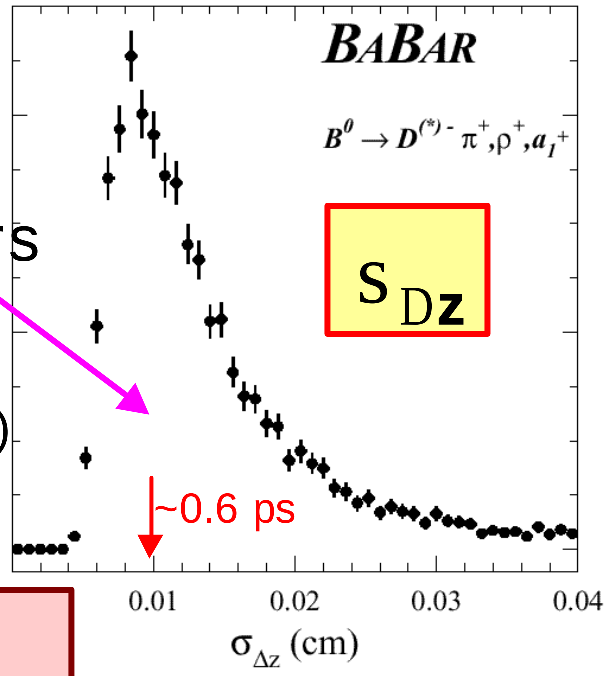
$$R = (1 - f_{tail} - f_{outlier})G(S_{core}\sigma_{\Delta t}, m_{core})$$
$$+ \quad f_{tail}G(S_{tail}\sigma_{\Delta t}, m_{tail})$$
$$+ \quad f_{outlier}G(\sigma_{outlier}, m_{outlier})$$

high flexibility

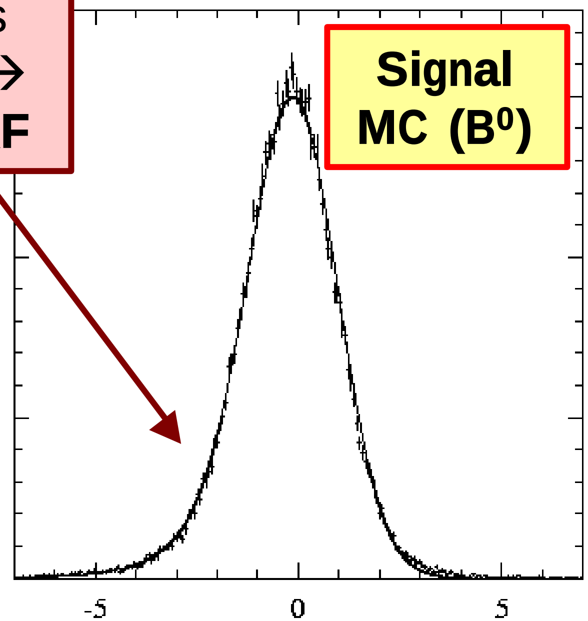
  - **Lifetime-like bias** (lifetime analysis)

$$R = (1 - f_{tail} - f_{outlier})G(S\sigma_{\Delta t}, m_{core} = 0)$$
$$+ \; f_{tail}G(S\sigma_{\Delta t}, m = 0) \otimes \exp(-\Delta t / S\tau_{bias})$$
$$+ \; f_{outlier}G(\sigma_{outlier}, m_{outlier})$$

small correlation with τ(B)



tracks from long-lived D's in tag vertex→ **asymmetric RF**



sin2β Likelihood Fit parameters

- Global unbinned maximum likelihood fit to data:
  - **Mistag rates, Δt resolutions** ← tagged flavor sample
  - sin(2β) ← tagged CP samples

Likelihood fit free parameters	
sin(2β)	1
Mistags (w, Δw)	8
Signal Δt resolution	8
Background time dependence	6
Background Δt resolution	3
Background mistags	8
TOTAL	*34*

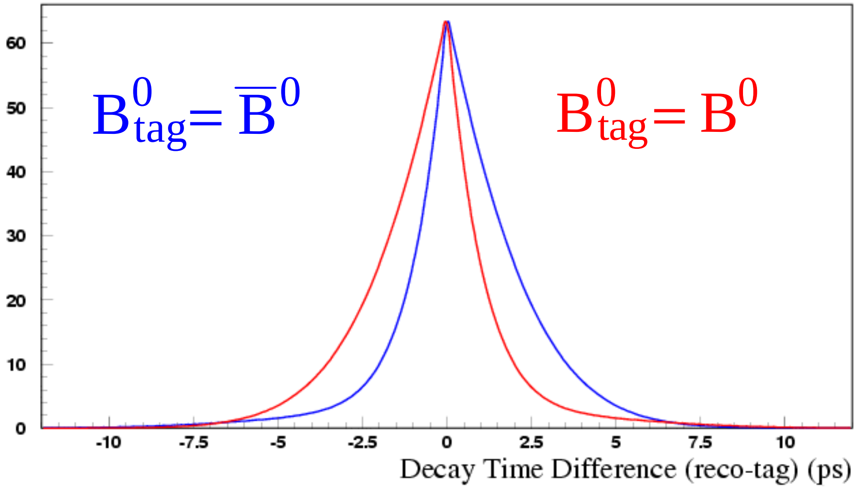
Global correlation coefficient for sin(2β) ρ = 13%

τ_B = 1.548 ps and Δm_d = 0.472 ps^{-1} fixed

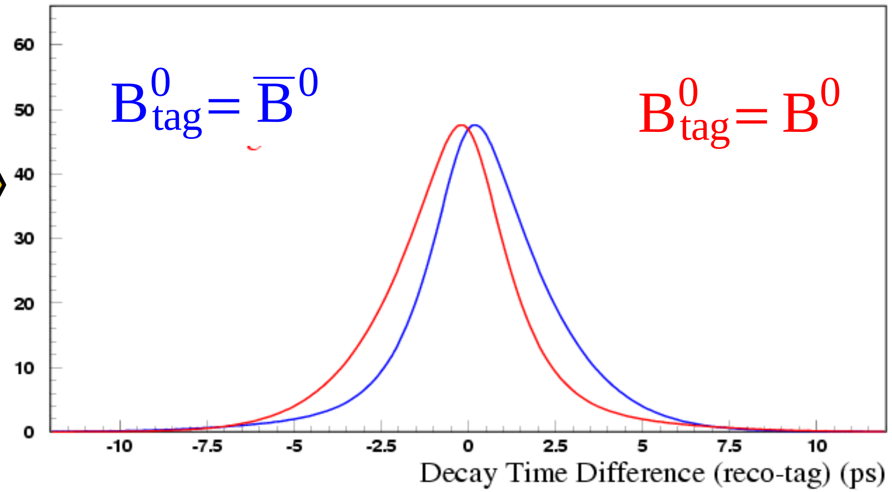
→ **determine Δt characteristics from data**

Mis-tagging and resolution

perfect
flavor tagging & time resolution



realistic
mis-tagging & finite time resolution



Measure mis-tagging probability w and Δt resolution function R with flavor eigenstate sample
→known mixing amplitude (=1) and large statistics

CP PDF

$$f_{CP,\pm}(?t) = \left\{ \frac{e^{-|?t|/t_{B_d}}}{4\,t_{B_d}} \times \left(1 \mp ?_f \,\sin 2ß \left(\mathbf{1\text{-}2?}\right) \sin(?m_d\, ?t)\right) \right\} \otimes \boldsymbol{R}$$

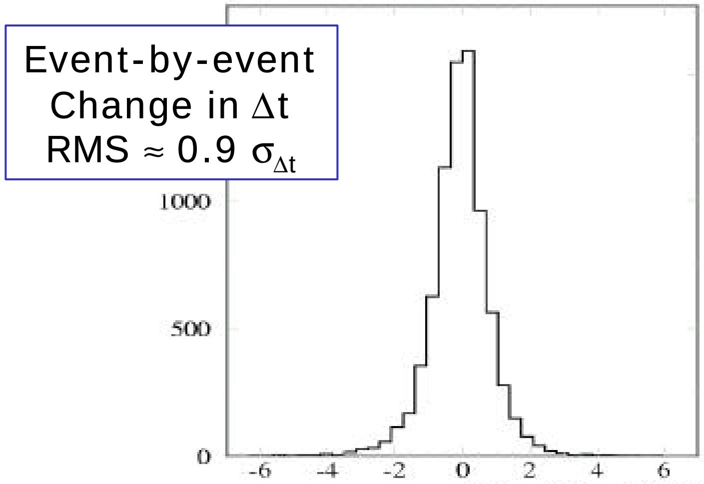
Mixing PDF

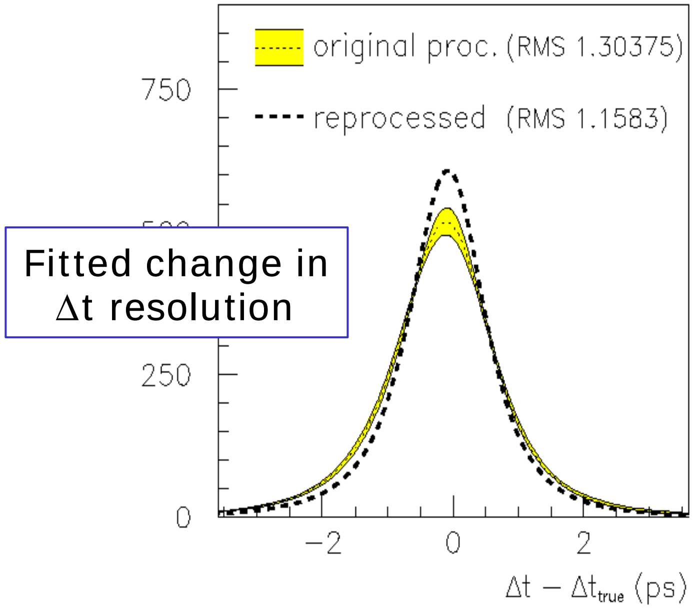
$$f_{mixing,\pm}(?t) = \left\{ \frac{e^{-|?t|/t_{B_d}}}{4\,t_{B_d}} \times \left(1 \pm \left(\mathbf{1\text{-}2?}\right) \cos(?m_d\, ?t)\right) \right\} \otimes \boldsymbol{R}$$

sin2β from the run1 data sample

Result	sin2β	Signal evts.	Purity
Old	0.49 ± 0.20	430	80%
New	0.60 ± 0.15	540	73%

Δm_d result stable
Old: 0.493 ± 0.024 ps^{-1}
New: 0.502 ± 0.023 ps^{-1}

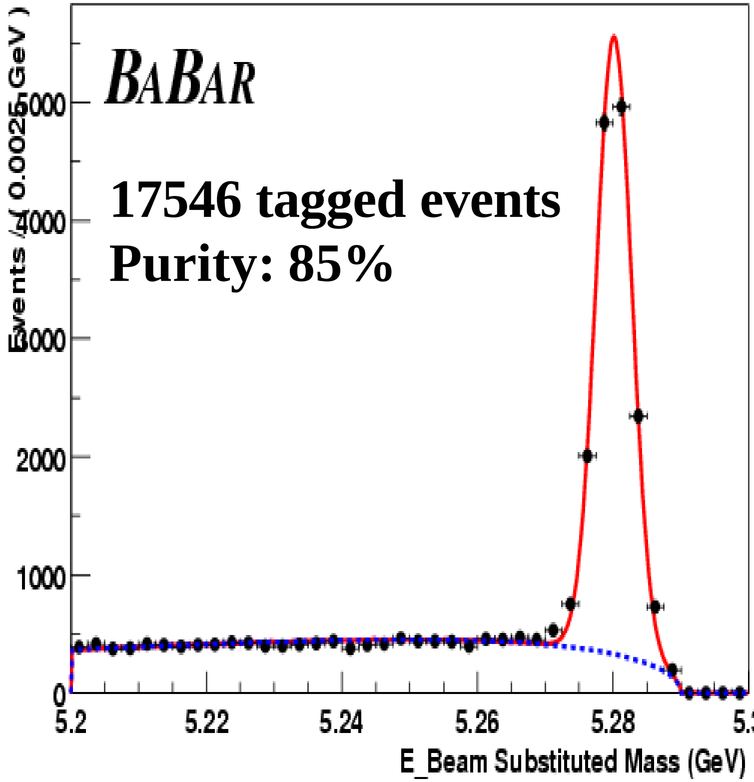




- Reprocessed data with significantly better SVT internal alignment.
- Event-by-event change in $\Delta t \approx 0.9\, \sigma_{\Delta t}$
- Fitted Δt resolution shows the improvement.
- Investigated change in sin2β in common events (old vs. reprocessed)
  - Estimated size of statistical spread of Δsin2β with toy MC, full MC, and data.
  - Change is about 2 sigma.

Samples of Fully-Reconstructed B^0 Decays

Flavor eigenstates B_{flav} for lifetime and mixing measurements



- Cabibbo-favored hadronic decays
  $b \to c\bar{u}d$ "Open Charm" decays

$$B^0 \to D^{(*)-} p^+ / ?^+ / a_1^+$$
$$B^- \to D^{(*)0} p^-$$

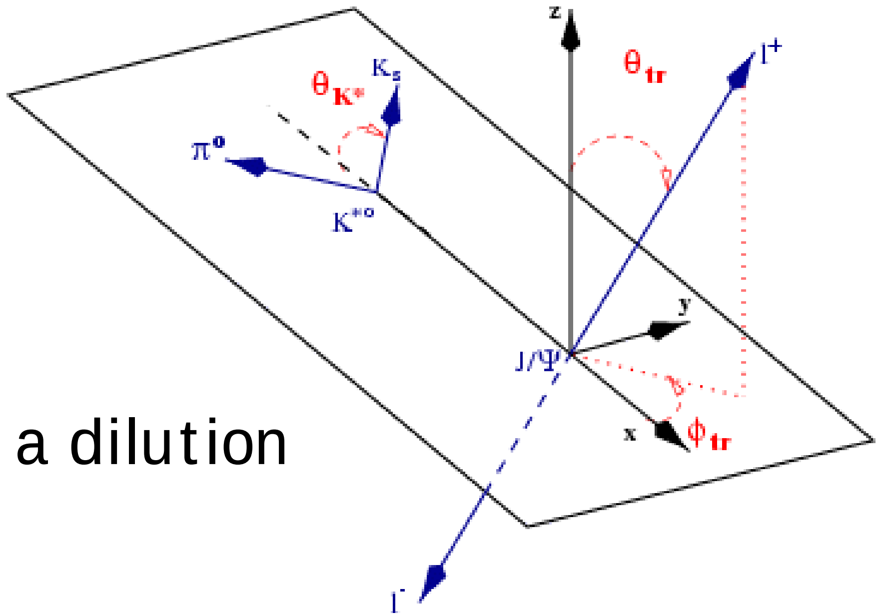
- Charmonium Decays $b \to (c\bar{c})s$

$$B^0 \to J/y\, K^{*0} (K^+ p^-)$$
$$B^+ \to J/y\, K^+,\ y(2S) K^+$$

$$m_{ES} = \sqrt{(E_{beam}^{cm})^2 - (p_B^{cm})^2}\ \text{[GeV]}$$

B^0 ® J/y K* angular analysis

- Different orbital angular momenta give mixed CP final states
- Three approaches to the fit, in order of increasing sensitivity (and complexity)
  - 1D : fit to Δt using the fraction of CP-odd (R_T) as a dilution
  - 2D : fit to Δt and θ_{tr}
  - 4D : full angular analysis



- 4D analysis is sensitive to $|\cos 2\beta|$

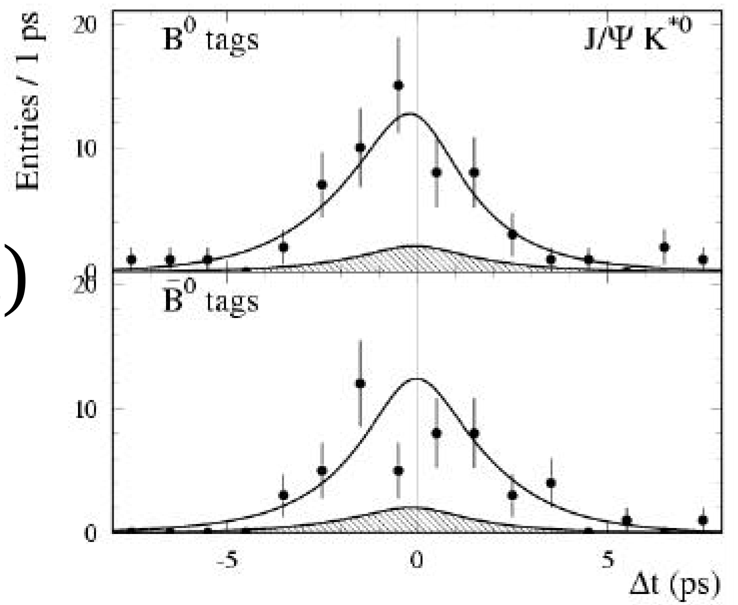
B^0 ® J/y K*

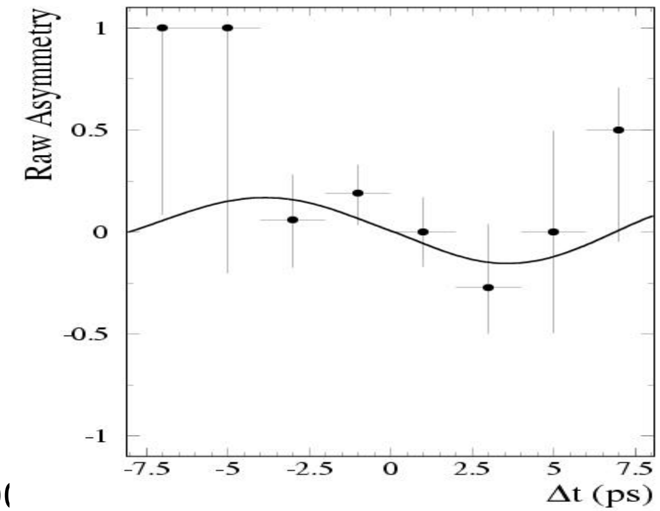
- From B^0 ® J/y K* full angular analysis we find

$$\cos 2b = -3.3^{+1.0}_{-0.6}(\text{stat}) \pm 0.7(\text{syst})$$

- The sign of cos2β cannot be measured because of strong phases in the transversity amplitudes.
- The effect seems large but it is statistical:

$$\left| \cos 2b - \sqrt{1 - \sin^2 2b} \right| = 2.2 s\,(\cos 2b)$$





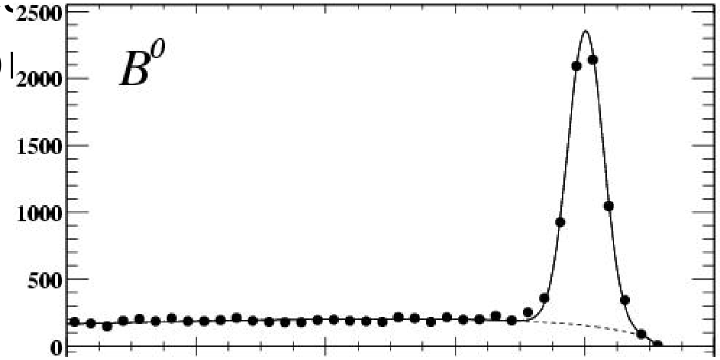
Lifetime with B reco

- Exclusively reconstruct in hadronic modes
  - $B^0 \rightarrow D(*)p/r/a_1$, $B^0 \rightarrow J/\psi K^{*0}$, likewise for B^+
  - Signal probability estimated from m_{ES} value
  - Background Δt parameters determined from sideband
- Lifetime measurements

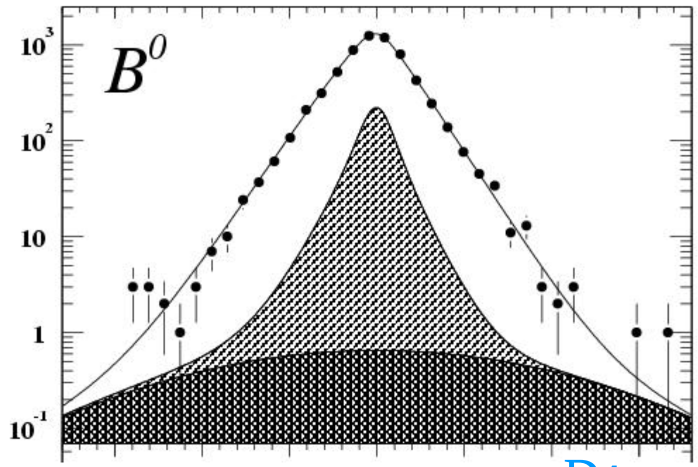
PRL 201803 (2001)

τ_{B0} = 1.546 ± 0.032 ± 0.022 ps
τ_{B+} = 1.673 ± 0.032 ± 0.023 ps
τ_{B0}/τ_{B+} = 1.082 ± 0.026 ± 0.012

  - Modeling of Δt outliers in resolution function is largest syst. uncertainty



Energy-substituted mass



Dt

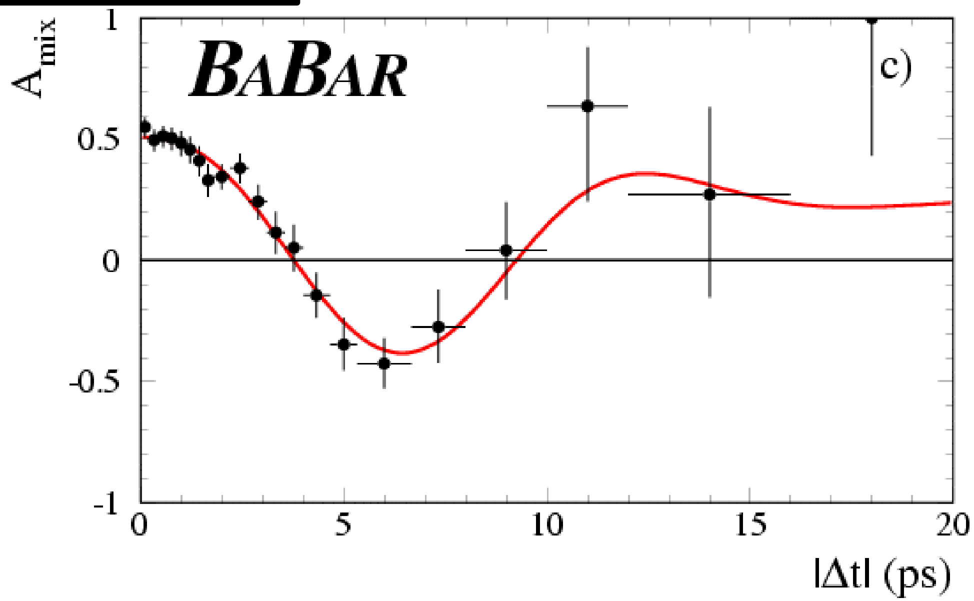
Mixing with B reco

- Mixing measurement uses 32 M $\overline{B}B$ pairs (29.7 fb^{-1})
  - Resolution model allows for differences between Run-1 and Run-2 vertexing and alignment w/ separate params.

Submitted to PRL (2001)

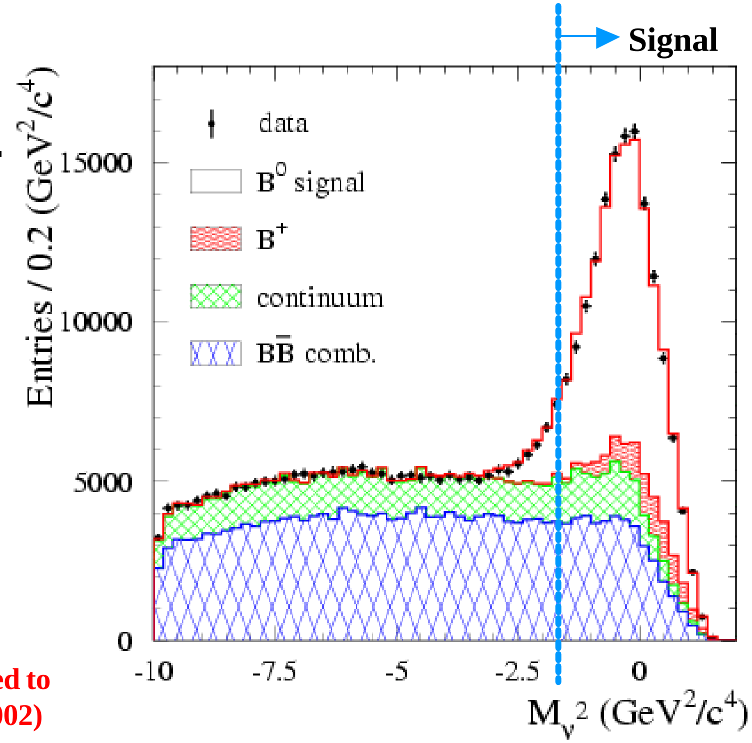
$$\Delta m_d = 0.516 \pm 0.016 \pm 0.010 \text{ ps}^{-1}$$

  - Largest syst. are
    - Varying B^0 lifetime w/in PDG errors
    - SVT alignment



Partial rec. with *D*lν*

- Select events with high *p* lepton and soft track consistent w/ π_{slow} from *D** decay
- Use π_{slow} direction to estimate D^* mom.
  - Compute neutrino inv. mass
- Lifetime measurement
  - Large sample →binned fit
  - Correction applied for bias due to D^0 daughter tracks outside π_{slow} cone



τ_{B0} = 1.529 ± 0.012 ± 0.029 ps

Submitted to PRL (2002)

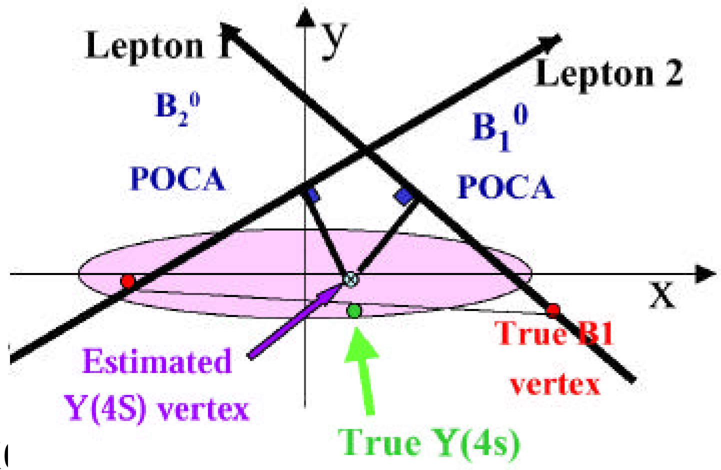
- Largest syst. is Δt resolution model

Lifetime with dileptons

- Select events with two high *p* leptons
  - Can inclusively reconstruct π_{slow} to select B^0 over B^+
- Fit (transverse) primary vertex with *l* tracks and beamspot
  - Use closest approach between each *l* track and this vtx to measure z
- Model includes contributions from
  - One or both leptons from *B* cascade decays
  - Semileptonic B^+ decays via D^{**}
- Preliminary lifetime result

$$\tau_{B0} = 1.557 \pm 0.028 \pm 0.027 \text{ ps}$$
$$\tau_{B+} = 1.655 \pm 0.026 \pm 0.027 \text{ ps}$$
$$\tau_{B0}/\tau_{B+} = 1.064 \pm 0.031 \pm 0.026$$

Preliminary



  - Largest systematics from res'n and bkg

Mixing with dileptons

- Very precise mixing measurement
  - Fraction of B^+ in the sample is also a fit parameter

    $\Delta m_d = 0.493 \pm 0.012 \pm 0.009\ ps^{-1}$ **Submitted to PRL (2001)**
  - Largest syst. are B^0 lifetime and resolution function param'zn