CP Violation, Mixing and Lifetime Results from BaBar

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On behalf of the BaBar collaboration

Outline

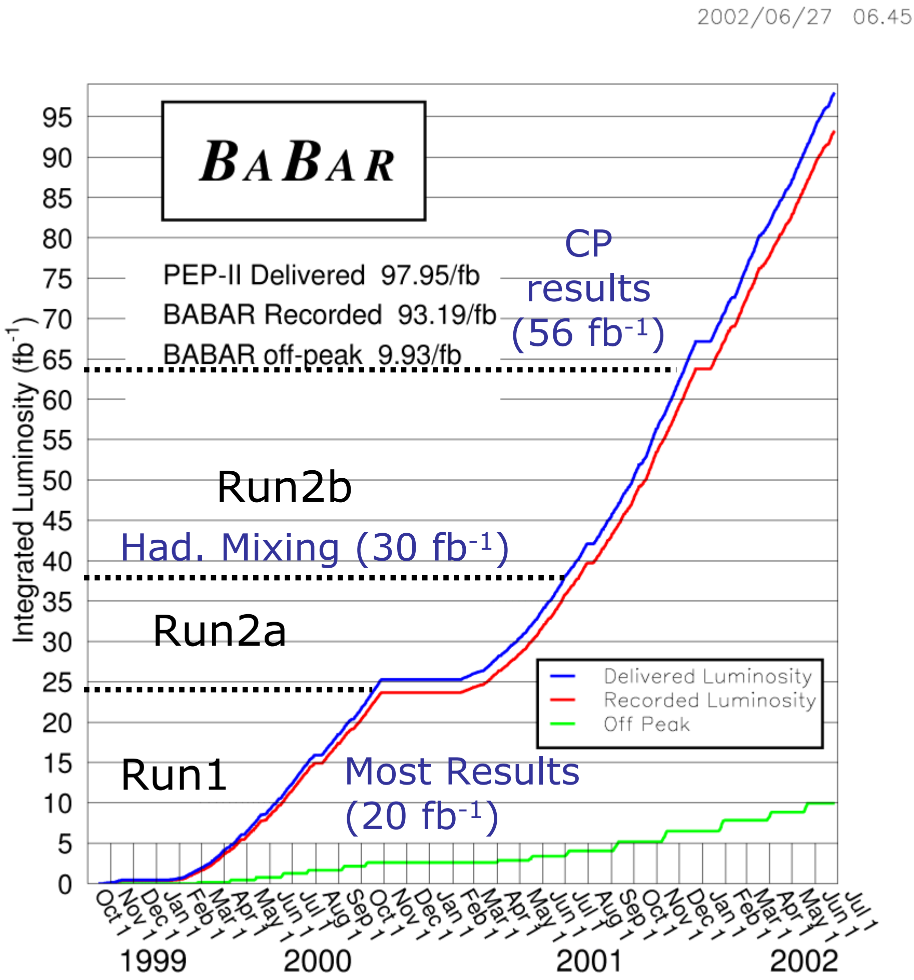
- Introduction
- Common tecniques
- Selected results for lifetime and mixing
- CP results:
  - Sin (2β)
  - Sin (2α)

The PEP-II asymmetric e^+e^- storage ring

Operates at the Y(4S) resonance

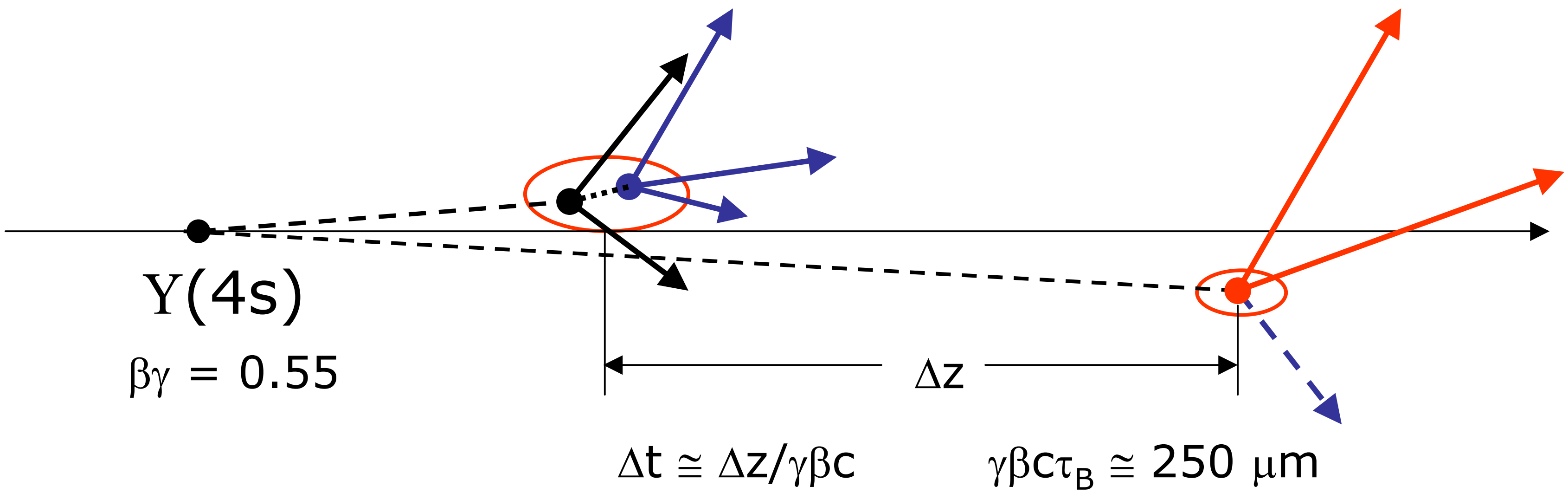
$\beta\gamma \cong 0.55$

	Design	Achieved
Luminosity ($cm^{-2}\ s^{-1}$)	3×10^{33}	**4.5** $\times 10^{33}$
Int. Lum / day (pb^{-1})	135	**303**
Int. Lum / month (fb^{-1})	3.3	**6.3**



B Time Distribution Measurements at BaBar

- Bs produced in pairs from the Υ(4s)
- Almost at rest in the centre of mass
- Boost of CM means we can measure flight time
- At Babar, we measure Δt (time between decay of the Bs)



The BaBar experiment

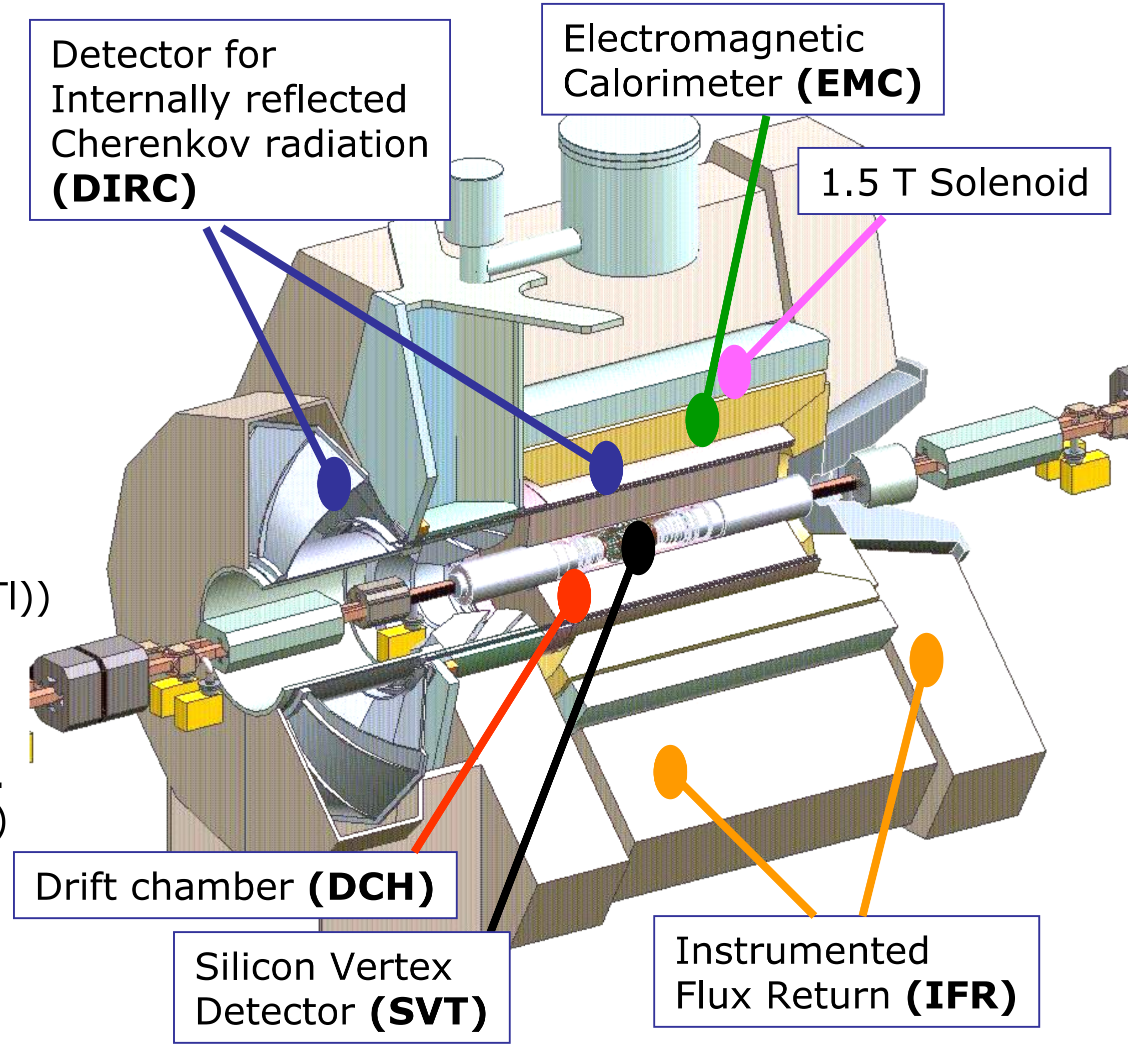
SVT: 5 layers double-sided Si. Crucial for measuring Δt.

DCH: 40 layers in 10 super-layers, axial and stereo.

DIRC: Array of precisely machined quartz bars. Excellent Kaon identification.

EMC: Crystal calorimeter (CsI(Tl)) Very good energy resolution. Electron ID, π^0 and γ reco.

IFR: Layers of RPCs within iron. Muon and neutral hadron (K_L)



Time Evolution of the B

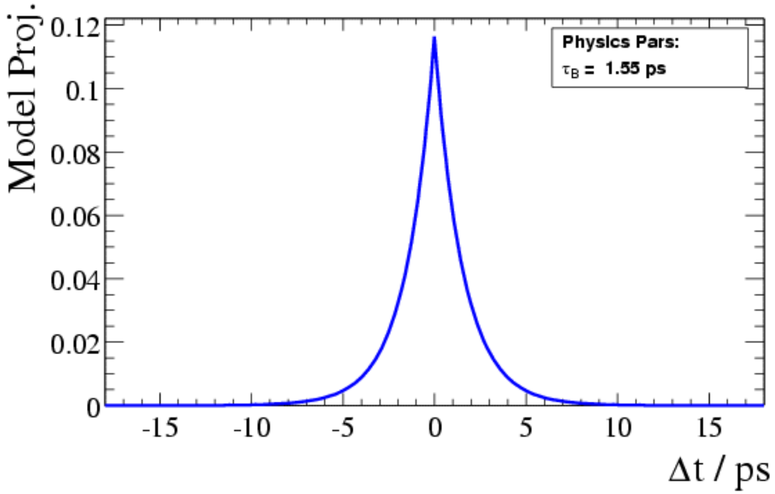
- For Charged B, evolution is just lifetime:

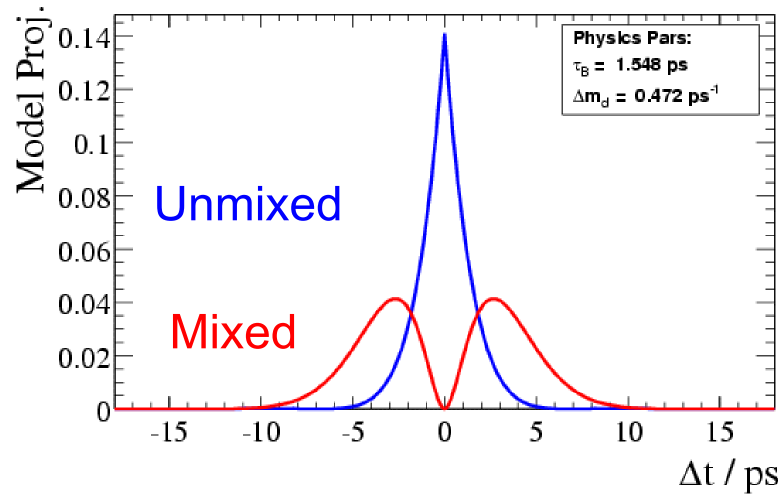
$$f_{B^{\pm}}(\Delta t) = \frac{1}{2\tau_{B^{+}}} e^{-\Delta t / \tau_{B^{+}}}$$

- For neutral B, mixing also plays a part, so when B flavour is known:

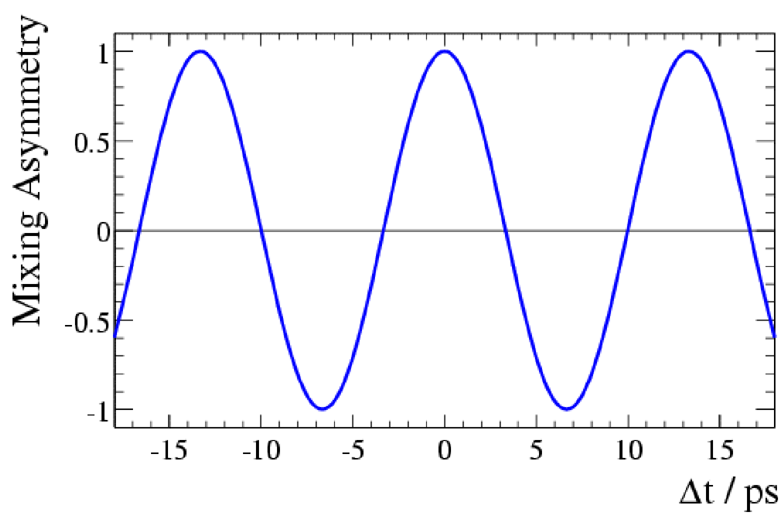
$$f_{\pm}(\Delta t) = \frac{1}{4\tau_{B^{0}}} e^{-\Delta t / \tau_{B^{0}}} \left(1 \pm \cos(\Delta m_d \Delta t)\right)$$

Time Distributions





$$A_{mixing}(\Delta t) = \frac{N_{unmix}(\Delta t) - N_{mix}(\Delta t)}{N_{unmix}(\Delta t) + N_{mix}(\Delta t)}$$
$$= \cos(\Delta m_d \Delta t)$$



Common Techniques

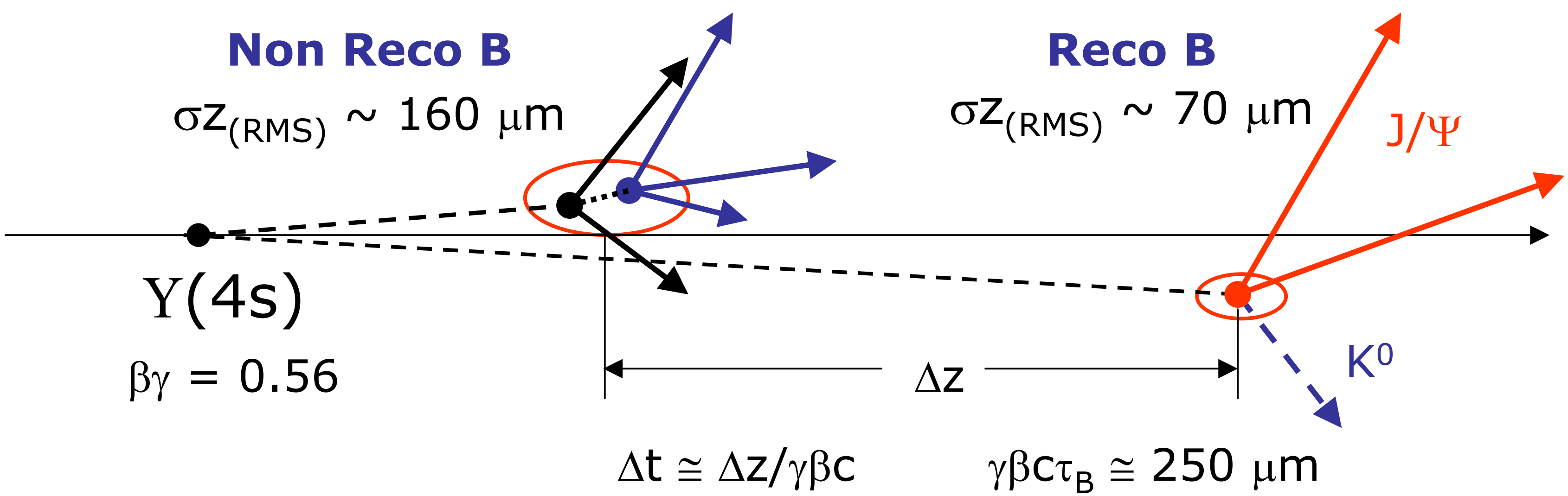
To measure time distributions:

- Suitable sample of events
  - Have to deal with background
- Measurement of Δt **(vertexing)**
  - Detector resolution
- Measurement of B flavour **(tagging)** for mixing and CP
  - Imperfect tagging: dilution

Measurement of Δt

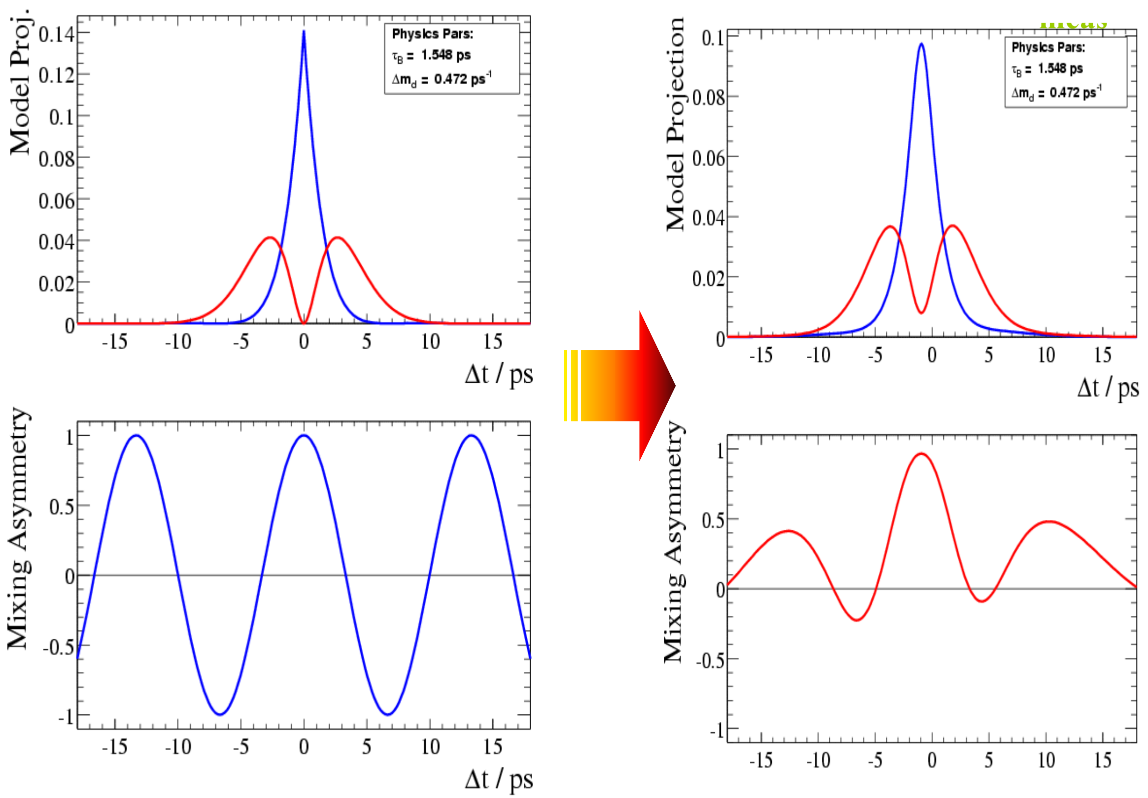
Tracks not from reconstructed B combined to form other vertex.

- Tracks with large χ^2 iteratively removed.
- Long-lived particles (K_s , Λ) explicitly reconstructed.
- Photon conversions ($\gamma \rightarrow e^+e^-$) removed.



Resolution function

- Δt dependant decay rate must be convoluted with resolution function



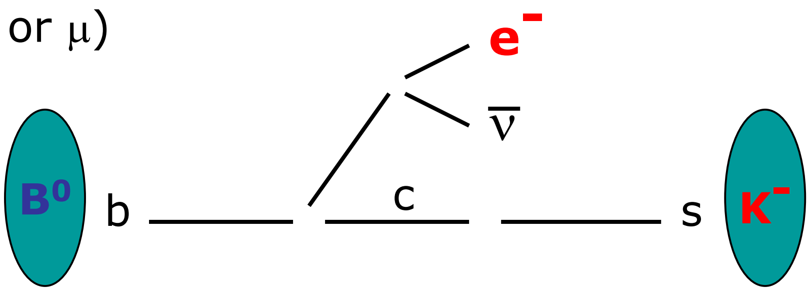
- Parameterised in terms of event by event error. Exact model depends on analysis.

Flavor tagging

Can infer flavour of reconstructed B at $\Delta t=0$ from decay products of other B.
Four hierarchical mutually exclusive categories (take the best available).

- Lepton: primary lepton charge (e or μ)
- Kaon: sum charge of $K^{\pm}$
- NT1
- NT2

(NT1, NT2:) Bins of NN output. Slow $\pi^{\pm}$ from D^{*} and Unidentified leptons.

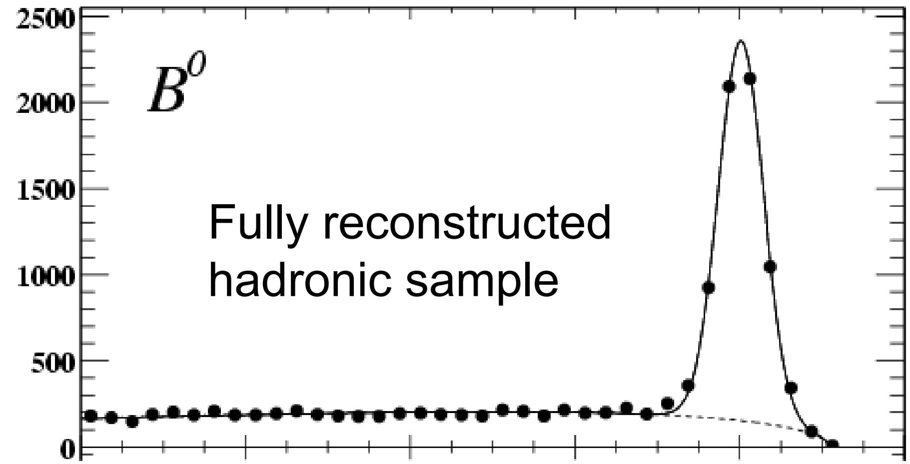


Tagging category	Efficiency ε (%)	Mistag fraction ω (%)	B^0/B^0 diff. $\Delta\,\omega$ (%)	Q = $\varepsilon(1\text{-}2w)^2$ (%)
Lepton	11.1 ± 0.2	**8.6 ± 0.9**	0.6 ± 1.5	7.6 ± 0.4
Kaon	34.7 ± 0.4	18.1 ± 0.7	-0.9 ± 1.1	**14.1 ± 0.6**
NT1	7.7 ± 0.2	22.0 ± 1.5	1.4 ± 2.3	2.4 ± 0.3
NT2	14.0 ± 0.3	37.3 ± 1.3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

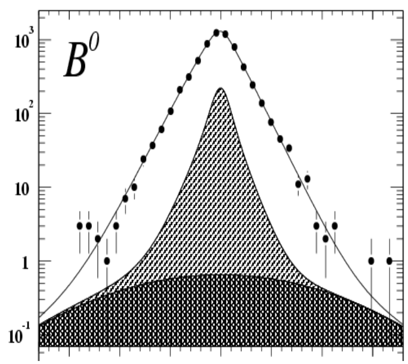
Lifetime and Mixing: Fully Reconstructed Hadronic

$B^0 \rightarrow D(^*)\pi/\rho/a_1$, $B^0 \rightarrow J/\psi K^{*0}$, likewise for B^+

- Lifetime
  - 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
  - – Resolution function is largest systematic uncertainty



Energy-substituted mass



Δt

- Mixing
  - 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
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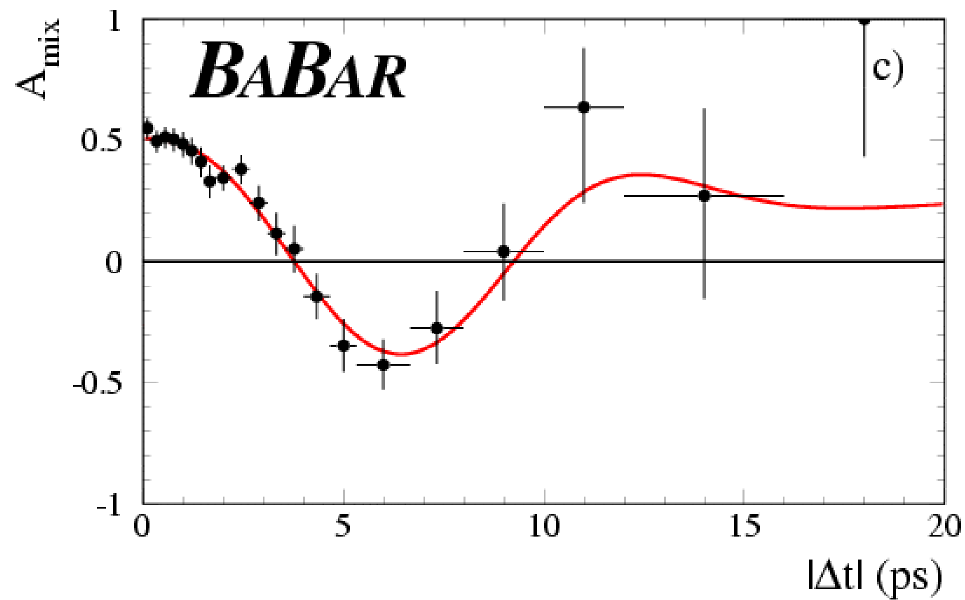
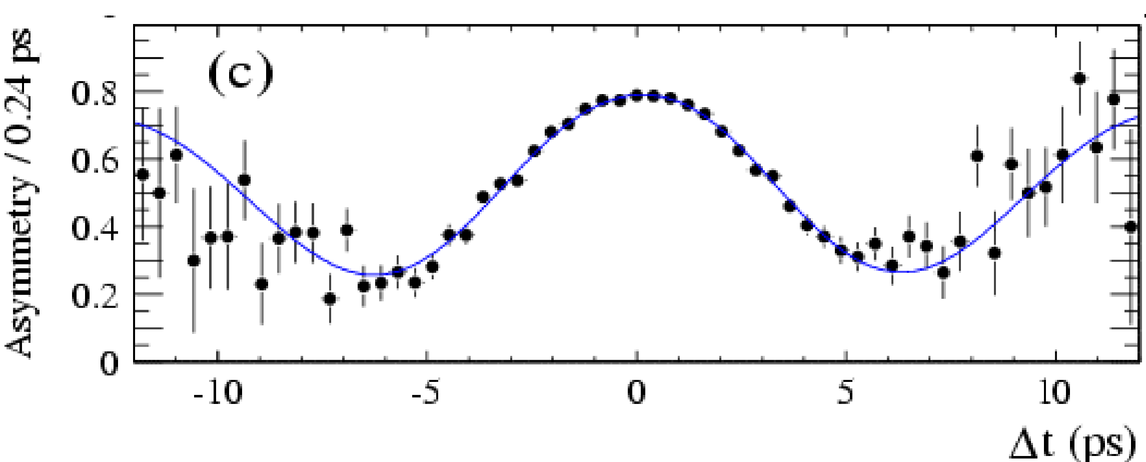


Lifetime and Mixing from other Samples

- Semileptonic, partially reconstructed Lifetime
  - τ_{B0} = 1.529 ± 0.012 ± 0.029 ps
  - Largest systematic: resolution model
- Hadronic partially reconstructed Lifetime
  - D*pi: τ_{B0} = 1.510 ± 0.040 ± 0.038 ps
  - D*rho: τ_{B0} = 1.616 ± 0.064 ± 0.075 ps
  - Largest syst. MC stats + BG



- Dilepton Lifetime

  Preliminary

  τ_{B0} = 1.557 ± 0.028 ± 0.027 ps

  τ_{B+} = 1.655 ± 0.026 ± 0.027 ps

  τ_{B0}/τ_{B+} = 1.064 ± 0.031 ± 0.026
  - Systematic dominated by resolution and background model
- Dilepton Mixing

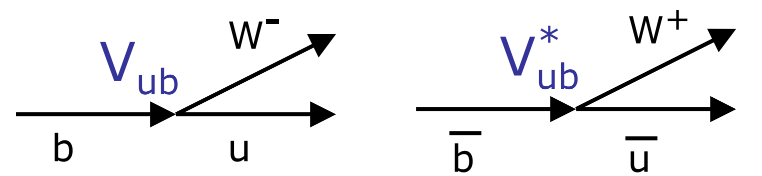
Δm_d = 0.493 ± 0.012 ± 0.009 ps^{-1}
  - Largest systematics:
    - B^0 lifetime
    - resolution function parameterization

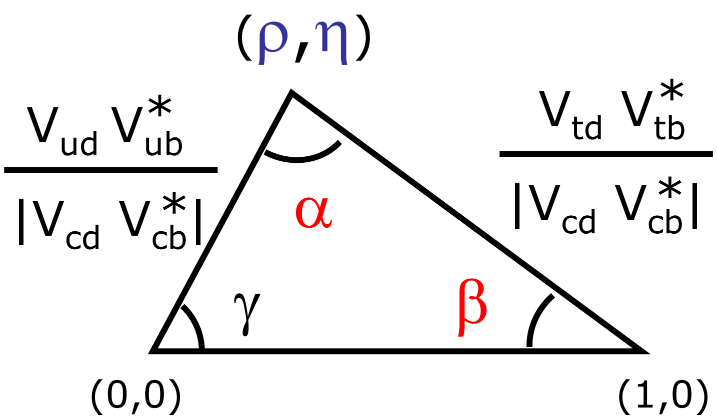
CP Violation in the B

The complex phase in the CKM quark mixing matrix provides the Standard model mechanism for CP violation in weak interactions.

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

Complex conjugate enters for CP conjugate process.





The Unitarity Triangle

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

CP asymmetries are sensitive to the angles of the triangle.

CP Time Distributions

- For a suitable final CP eigenstate, the decay rate to this final state is given by:

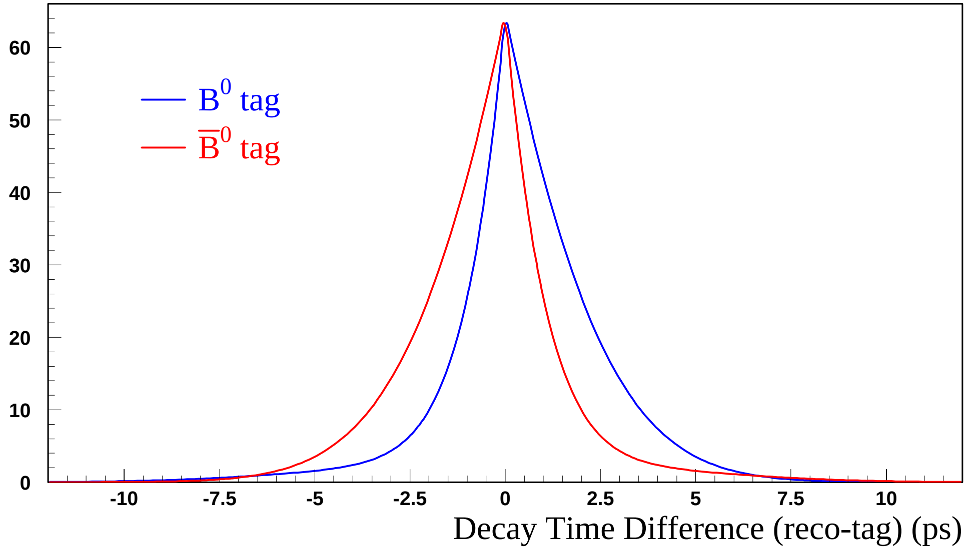
$$f_{CP,\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}(1+|\lambda|^2)} \times \left[\frac{1+|\lambda|^2}{2} \pm \mathcal{I}m\lambda \sin \Delta m_{B^0}\Delta t \mp \frac{1-|\lambda|^2}{2} \cos \Delta m_{B^0}\Delta t \right]$$

+/- is given by the B flavour ($B^0/\bar{B}^0$)
Δt is difference in decay time between Bs

$|\lambda| \neq 1$ => Direct CPV

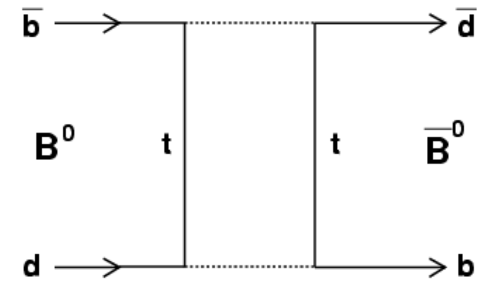
For J/ψ Ks *Im*λ = sin(2β)

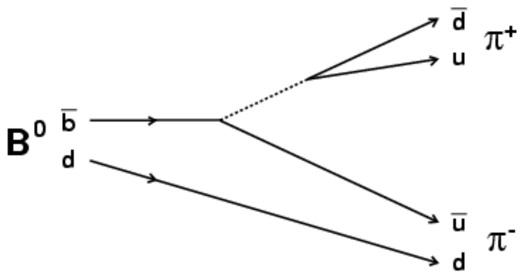
For π+π- *Im*λ ≈ sin(2α)

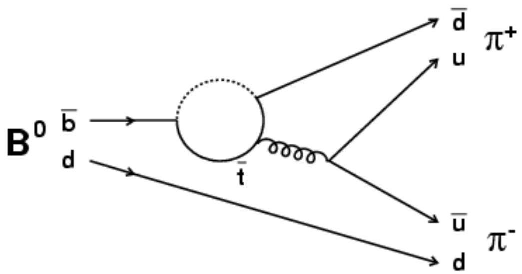


Trees and Penguins

- In appropriate modes, complex phase difference between decay and mixing => CP violation
- CP violation can also result when there is a complex phase between two decay diagrams: direct CP
- sin (2β) modes dominated by single tree diagram => direct measurement of angle, time distribution reduces to:
  - $e^{-(|\Delta t|/\tau_{B0})}/4\tau_{B0}(1 \pm \text{Sin}\, \Delta m_d\, \Delta t\ \text{Sin}\, 2\beta)$
- For Sin (2α) , both tree and penguin diagrams can be significant
  - $Im\lambda = \text{Sin}\,(2\alpha_{eff})$
  - $f(\Delta t) \sim 1 \pm S_{\pi\pi} \sin(\Delta m_d \Delta t) \mp C_{\pi\pi} \cos(\Delta m_d \Delta t)$
  - $S_{\pi\pi} = 2\text{Im}(\lambda)/(1+|\lambda|^2)$
  - $C_{\pi\pi} = (1-|\lambda|^2)/(1+|\lambda|^2)$



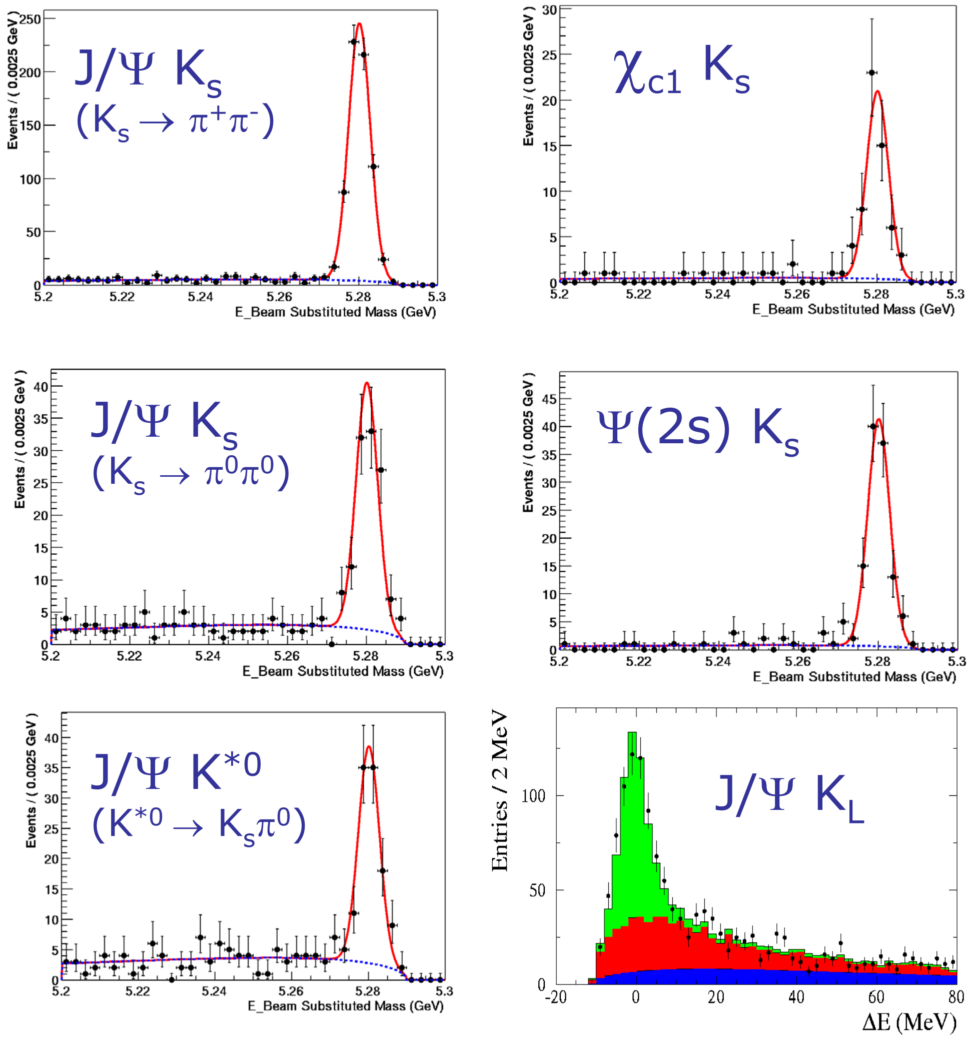




sin (2β)

- Uses Charmonium + Ks (Kl) sample
- Flavour tagging is needed to measure asymetry
  - Use fully reconstructed Hadronic sample to measure mistag rates: included in single fit sample
- This sample is free from Penguin polution: direct measurement of sin (2β)

sin2β CP data samples

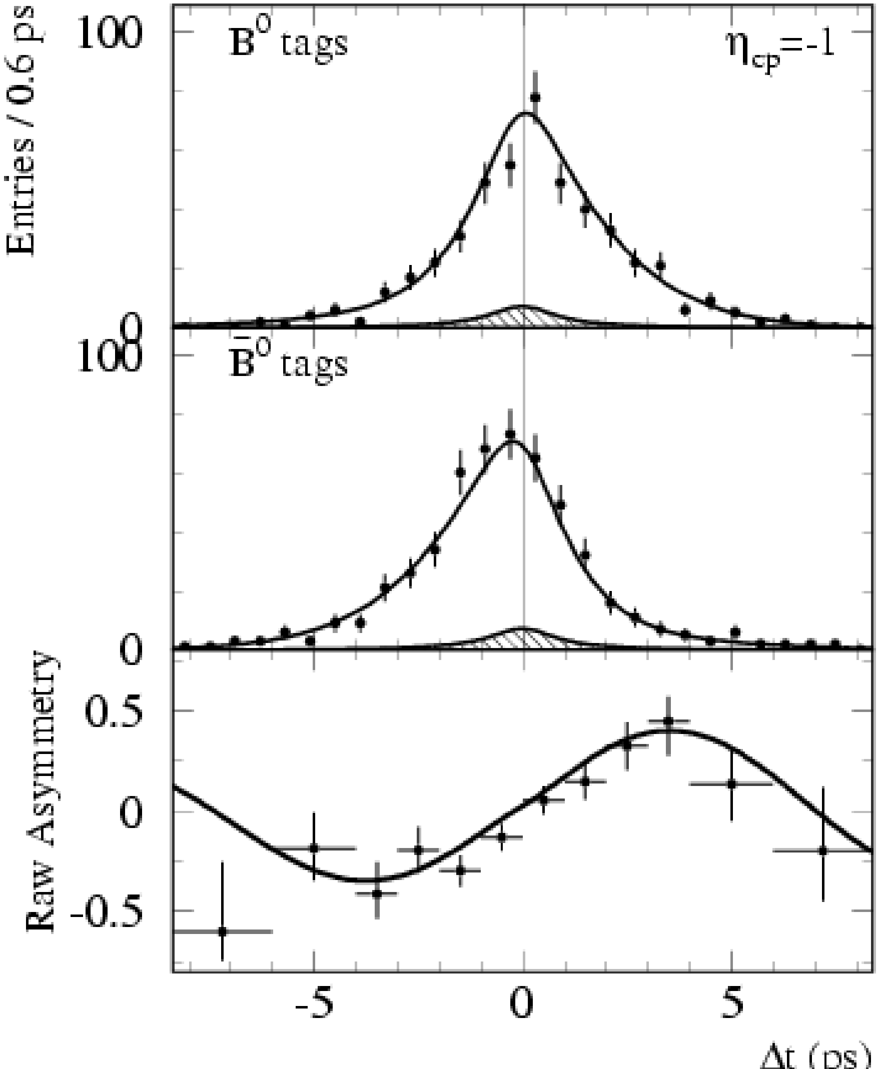


On-resonance integrated luminosity 56 fb^{-1}

Mode	N_{tag}	Purity	CP
(cc)K_s	995	94%	–1
J/Ψ K_L	742	57%	+1
J/Ψ K^{*0}	113	83%	+0.68
All CP	**1,850**	**79%**	

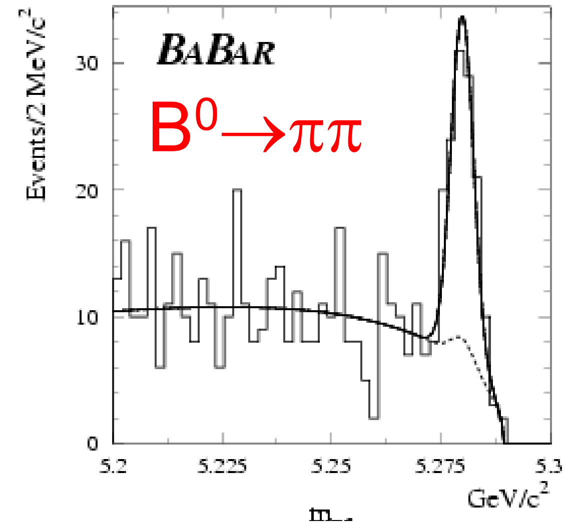
sin (2β) Result

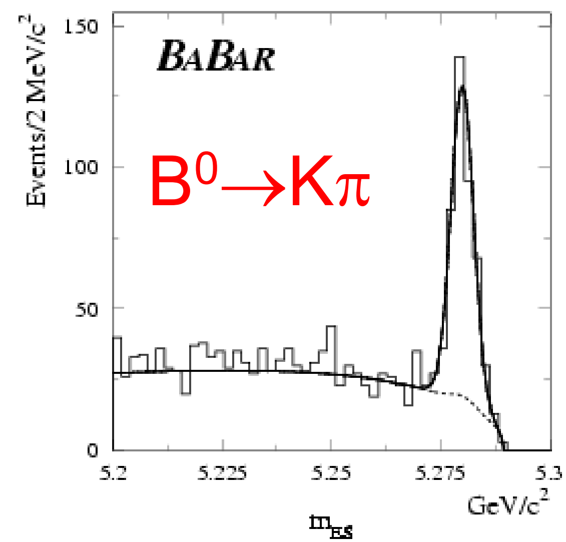
- Measurement of sin (2β) in the Charmonium modes with 56 fb^{-1}:
  - **sin (2β) = 0.75 ± 0.09 (stat) ± 0.04 (syst)**
- Systematics:
  - Uncertainty in Δm_d and B lifetime
  - Background properties
  - SVT misalignment



Sin(2α) (Preliminary)

- Very similar technique:
  - Simultaneous fit with hadronic sample for dilutions
- But:
  - Much higher background
  - Cannot assume Cosine term dissapears, indirect and direct CP
  - Must distinguish pipi and Kpi





Sin(2α) Results (Preliminary)

Analysis is done in two stages:

- First extract branching fractions for ππ, Kπ and KK and also the Kπ decay CP asymmetry $A_{k\pi}$ (Direct CP)

Mode	Yield (events)	Branching Fraction (10^{-6})	Kπ Asymmetry, $A_{K\pi}$
$B^0 \to \pi^+\pi^-$	124^{+16+7}_{-15-9}	$5.4 \pm 0.7 \pm 0.4$	
$B^0 \to K^+\pi^-$	$403 \pm 24 \pm 15$	$17.8 \pm 1.1 \pm 0.8$	$-0.05 \pm 0.06 \pm 0.01$
$B^0 \to K^+K^-$	< 15.6 (90% C.L.)	< 1.1 (90% C.L.)	

No significant direct CP violation seen in $B^0 \to K^+\pi^-$

90% C.L. $-0.14 < A_{K\pi} < 0.05$

Sin(2α) Results (Preliminary)

$S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$, $C_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$

No significant CP violation seen here

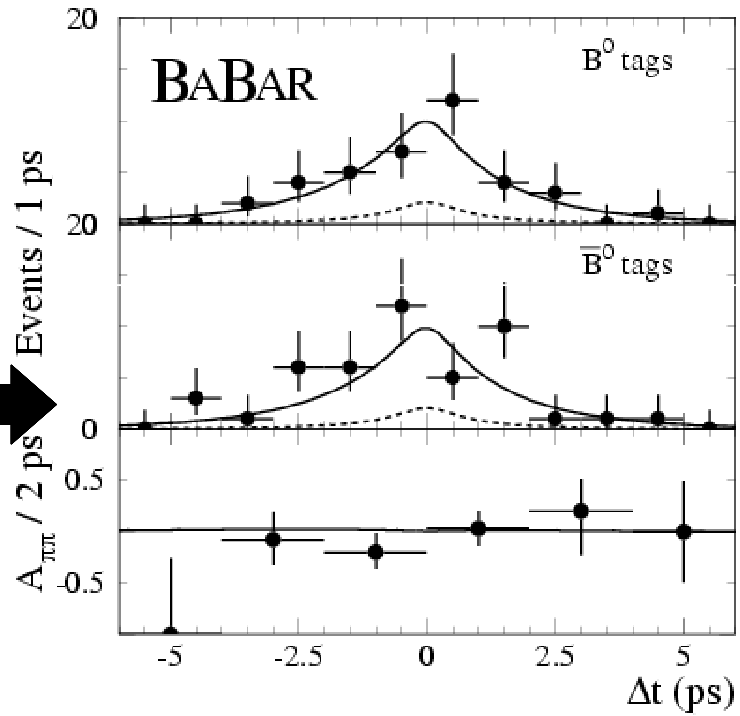
Predicted to be O(5%) – getting interesting

90% C.L.s : $-0.66 < S_{\pi\pi} < 0.62$, $-0.54 < C_{\pi\pi} < 0.48$

Main systematic:

K/π discrimination

Enhanced $B \to \pi\pi$ sample: Δt distributions and asymmetry between mixed and unmixed events.



Summary

- Many measurements of B lifetime and mixing
- sin (2β) is becoming a precision measurement
- Preliminary measurement of sin $(2\alpha_{eff})$

Backup Slides

Mes

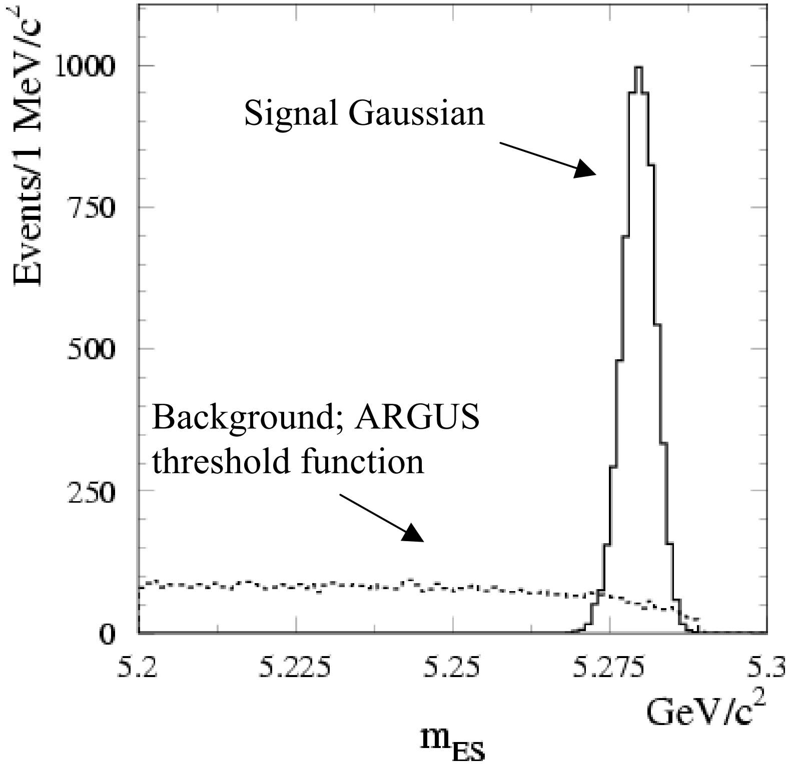
B candidate mass using beam "energy substitution"

$m_{ES} = \sqrt{(E_{beam}^2 - p_B^2)}$ in CM

Select $5.2 < m_{ES} < 5.3$ GeV/c^2

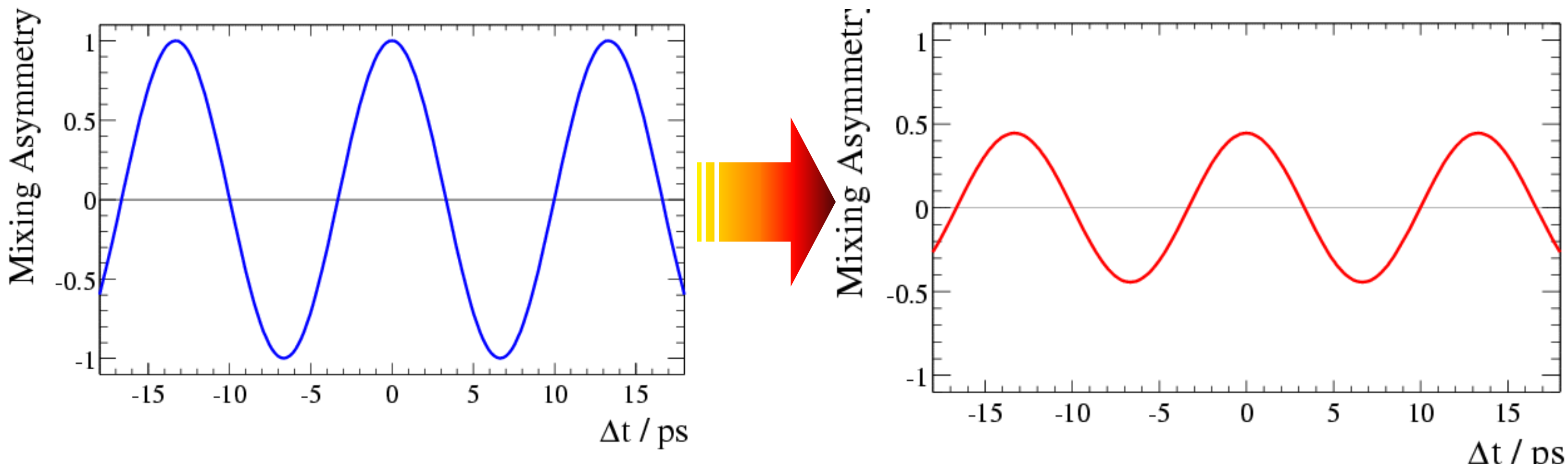
- Depends on reconstructed momentum of B candidate, $p_B \sim 325$ MeV
- Same for all signal modes
- Resolution dominated by beam energy uncertainty

□ $\sigma(m_{ES}) \sim 2.6$ MeV/c^2



Tagging dilution

- ‘Mistags’ dilute result



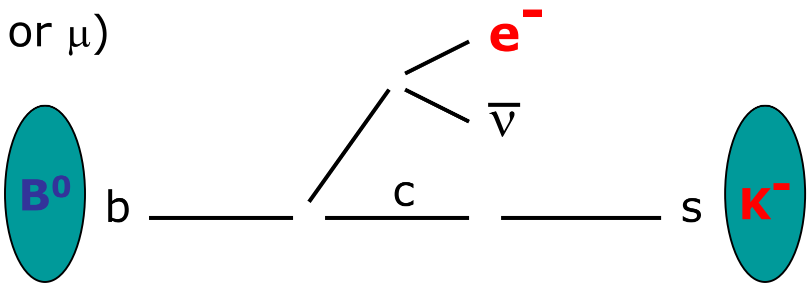
- Can extract dilution from mixing fits
- CP measurements require mixing fits to determine mistag

Flavor tagging

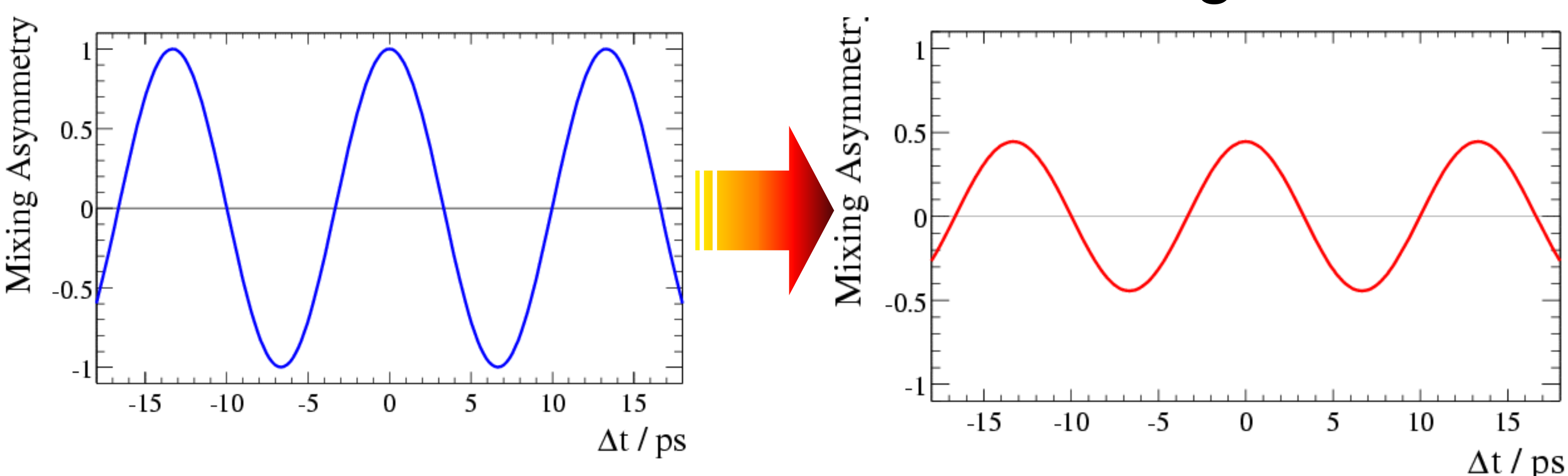
Flavor of Reconstructed B at Δt=0 inferred from decay products of other B.
Several methods are used:

- Lepton: primary lepton charge (e or μ)
- Kaon: sum charge of $K^{\pm}$
- Neural net:

  Slow p± and un-id-ed leptons.

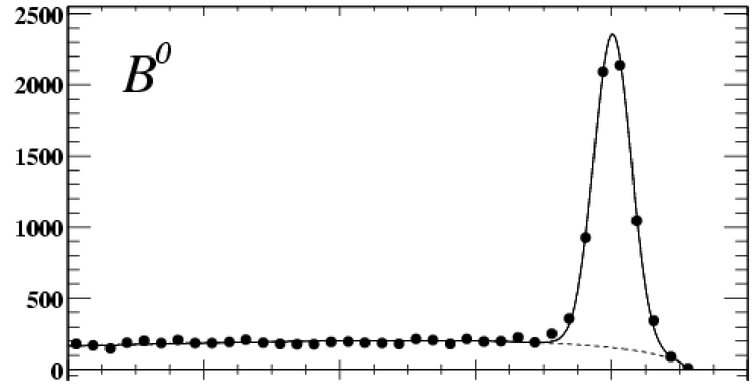


Tagging dilution:
Mistags can dilute result
Can fit for dilution in mixing

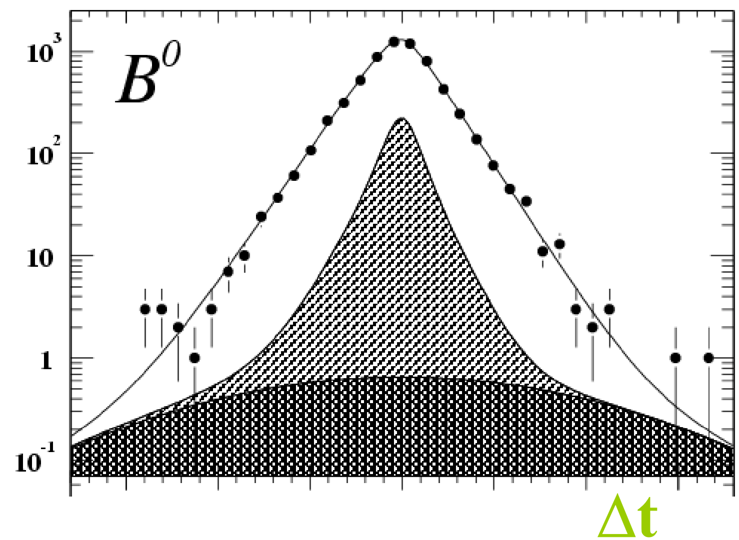


Hadronic B (full reco.)

- Exclusively reconstruct in hadronic modes
  - $B^0 \rightarrow D(*)\pi/\rho/a_1$, $B^0 \rightarrow J/\psi K^{*0}$, likewise for B^+
  - Signal probability taken from m_{ES} value
  - Sideband used to determine background Δt parameters.
- Lifetime measurements
  - 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

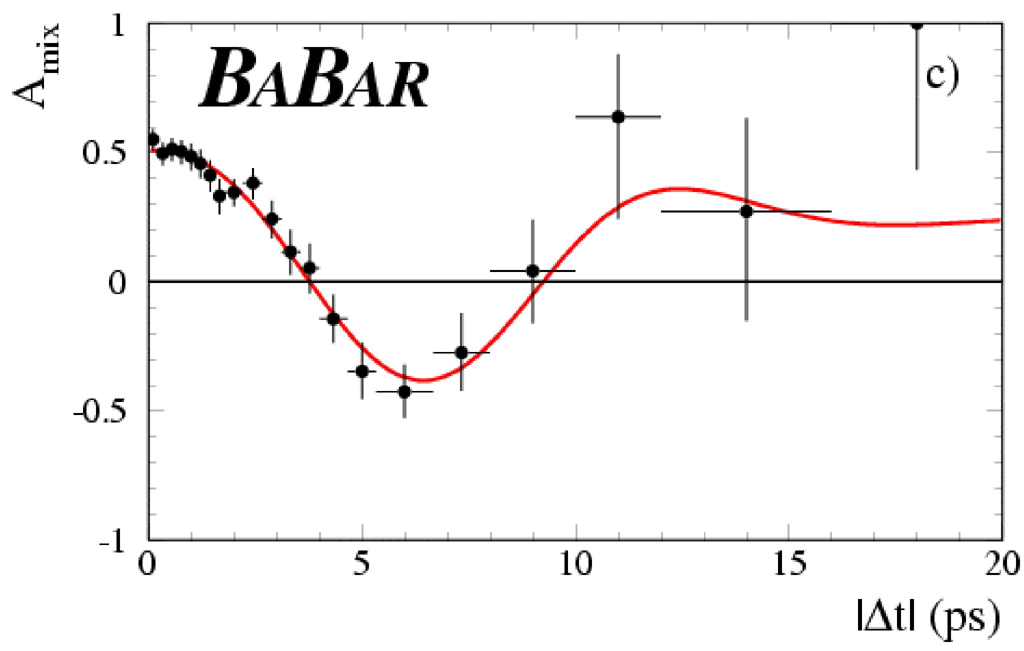


Energy-substituted mass



Hadronic B - Mixing

- Mixing measurement uses 32 M $B\overline{B}$ pairs (29.7 fb^{-1})
  - Resolution model allows for differences between Run-1 and Run-2 vertexing and alignment w/ separate params.
  - $\Delta m_d = 0.516 \pm 0.016 \pm 0.010\ ps^{-1}$
  - Largest syst. are
    - Varying B^0 lifetime w/in PDG errors
    - SVT alignment

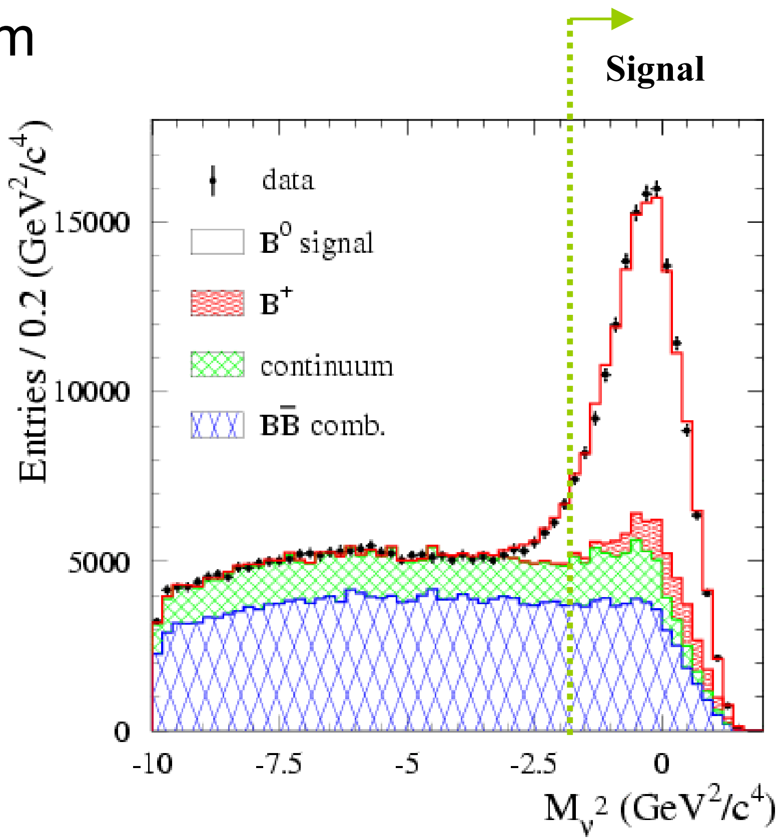


*D*lν* (Partial Reconstruction)

- Select events with high *p* lepton and soft track consistent with π_{slow} from *D** decay
- Estimate D^* momentum from π_{slow} direction
- Lifetime measurement
  - Large sample → binned fit
  - Bias due to D^0 daughter tracks outside π_{slow} cone, apply corectio

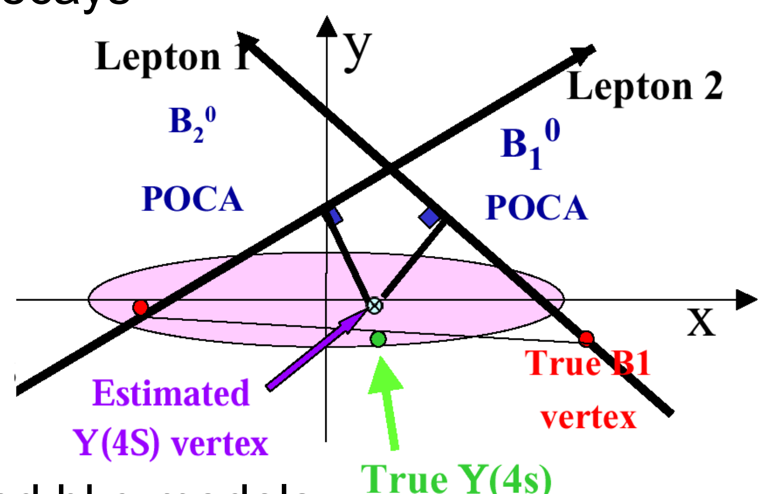
□ $\tau_{B0} = 1.529 \pm 0.012 \pm 0.029$ ps

  - Largest syst. is Δt resolution mod



Dileptons (inclusive reconstruction)

- 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
  - $\tau_{B0} = 1.557 \pm 0.028 \pm 0.027$ ps
  - $\tau_{B+} = 1.655 \pm 0.026 \pm 0.027$ ps
  - $\tau_{B0}/\tau_{B+} = 1.064 \pm 0.031 \pm 0.026$
  - Largest systematics from resolution and bkg models

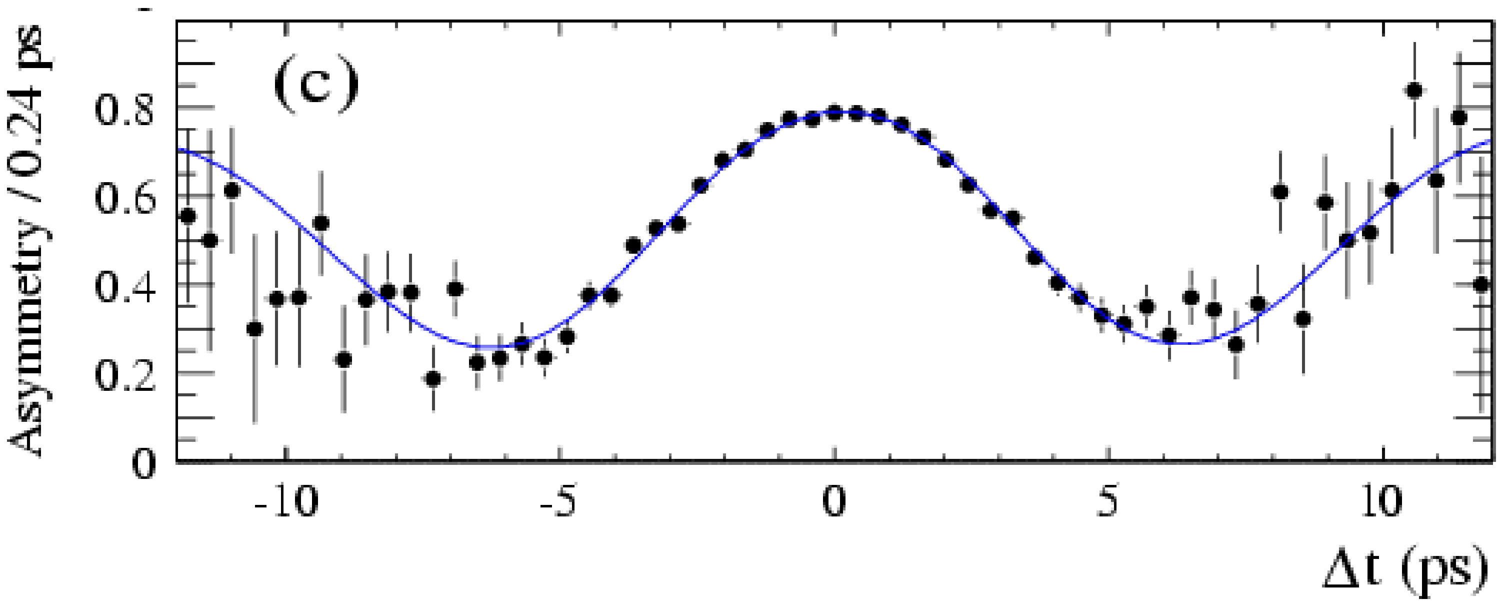


Dileptons - mixing

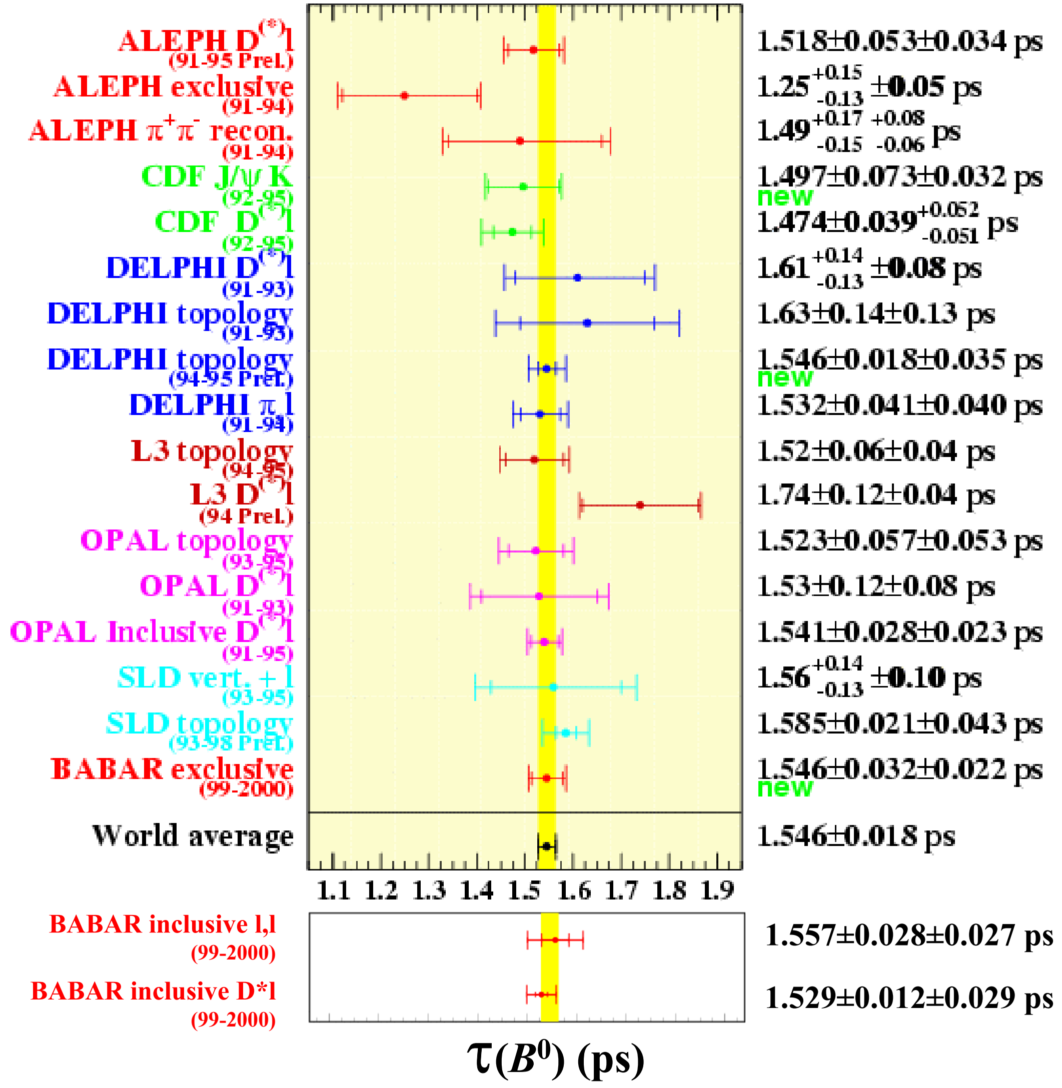
– Fraction of B^+ in the sample is also a fit parameter

 $\Delta m_d = 0.493 \pm 0.012 \pm 0.009$ ps^{-1}

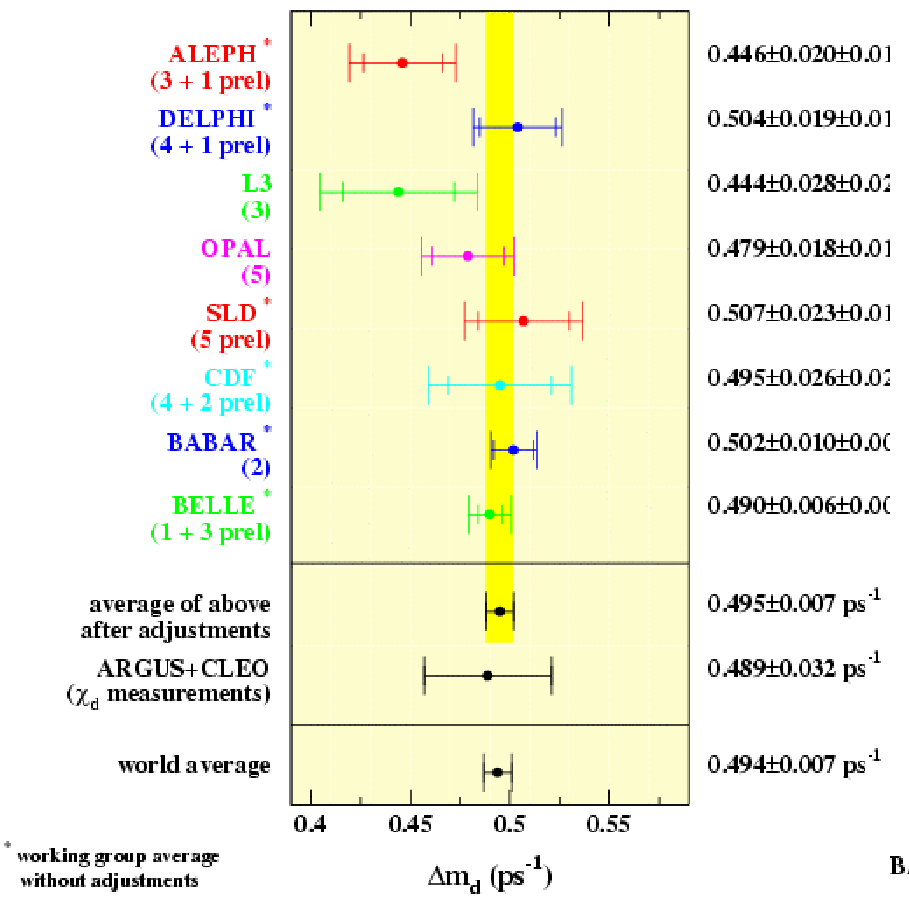
– Largest syst. are B^0 lifetime and resolution function parameterization.

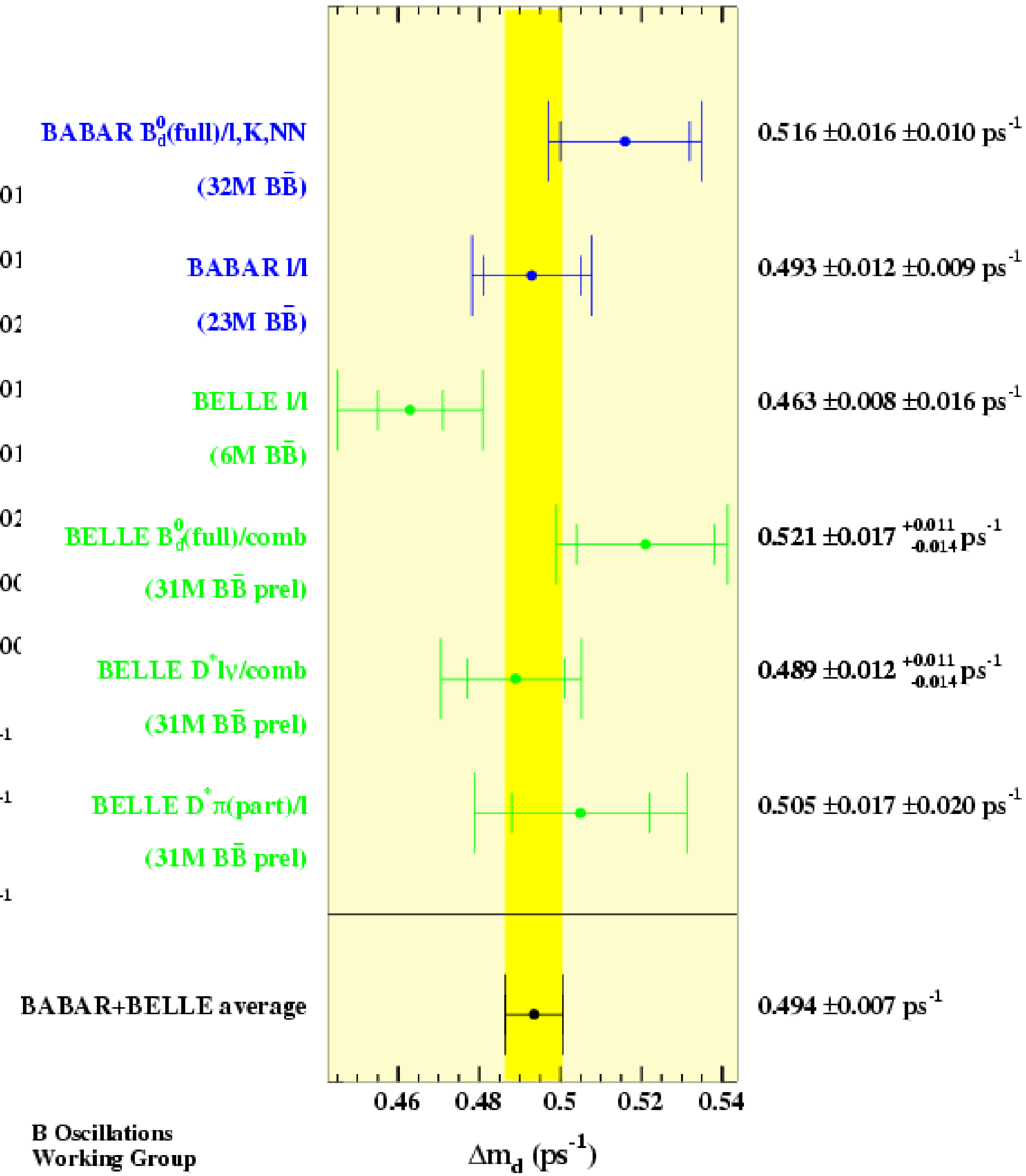


Summary of τ_{B0} measurements

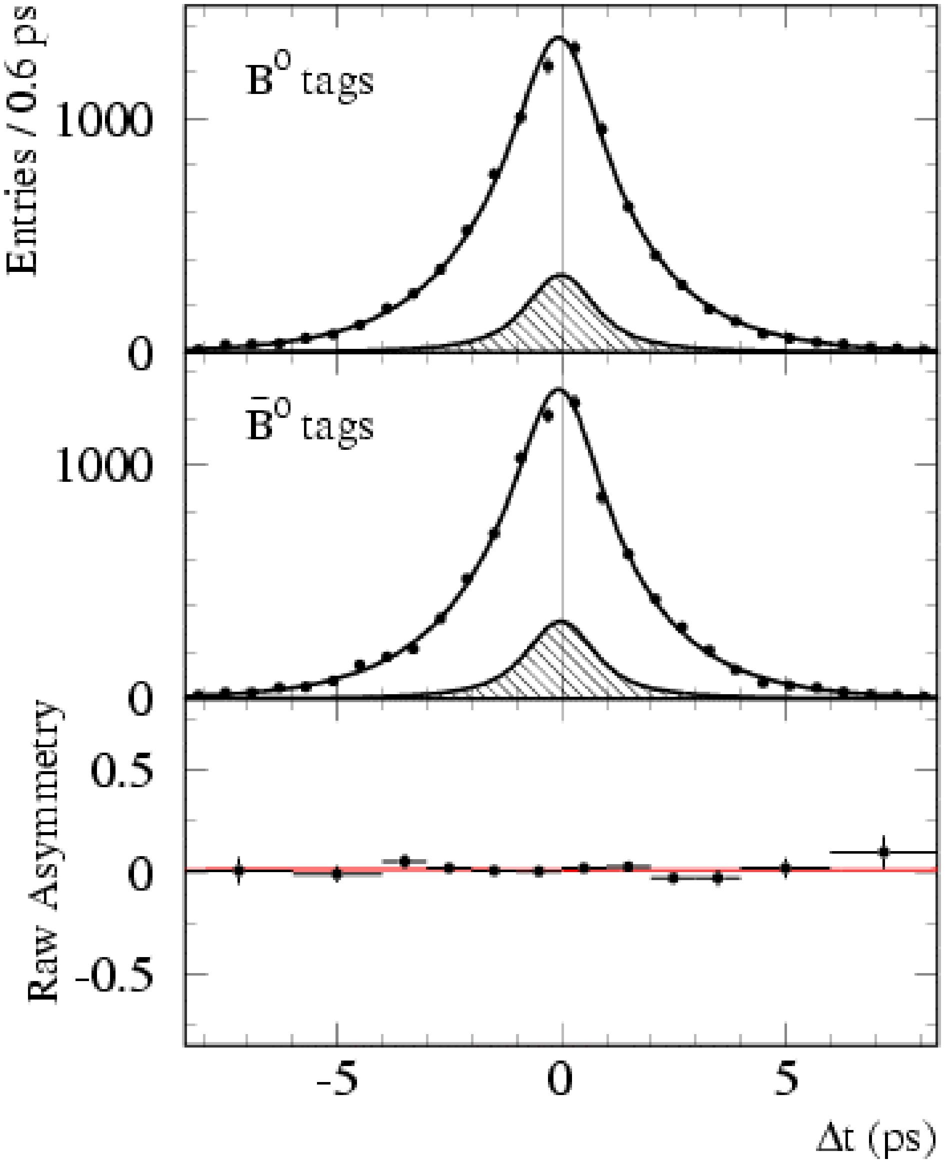


Summary of Δm_d measurements





Null Tests

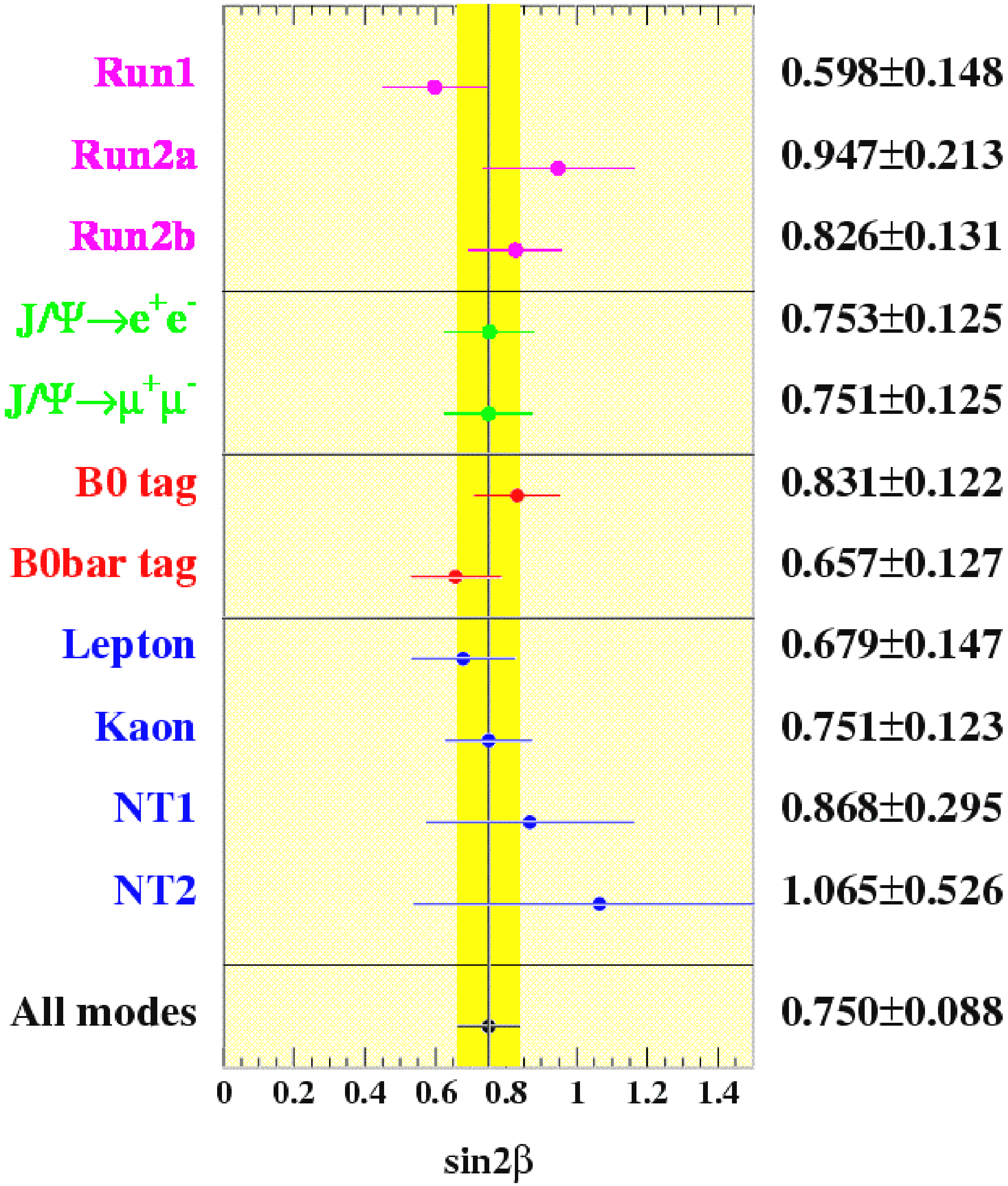


Large control samples available for the CP analysis:
No CP violation!

$\sin 2\beta = 0.00 \pm 0.03$

Sample	Sin2β
B^0 (no Charmonium)	-0.005 ± 0.028
B^+ (no Charmonium)	-0.014 ± 0.028
$J/\Psi\ K^{*+}$	-0.001 ± 0.093
B^+ (Charmonium)	-0.045 ± 0.080

Consistency Checks

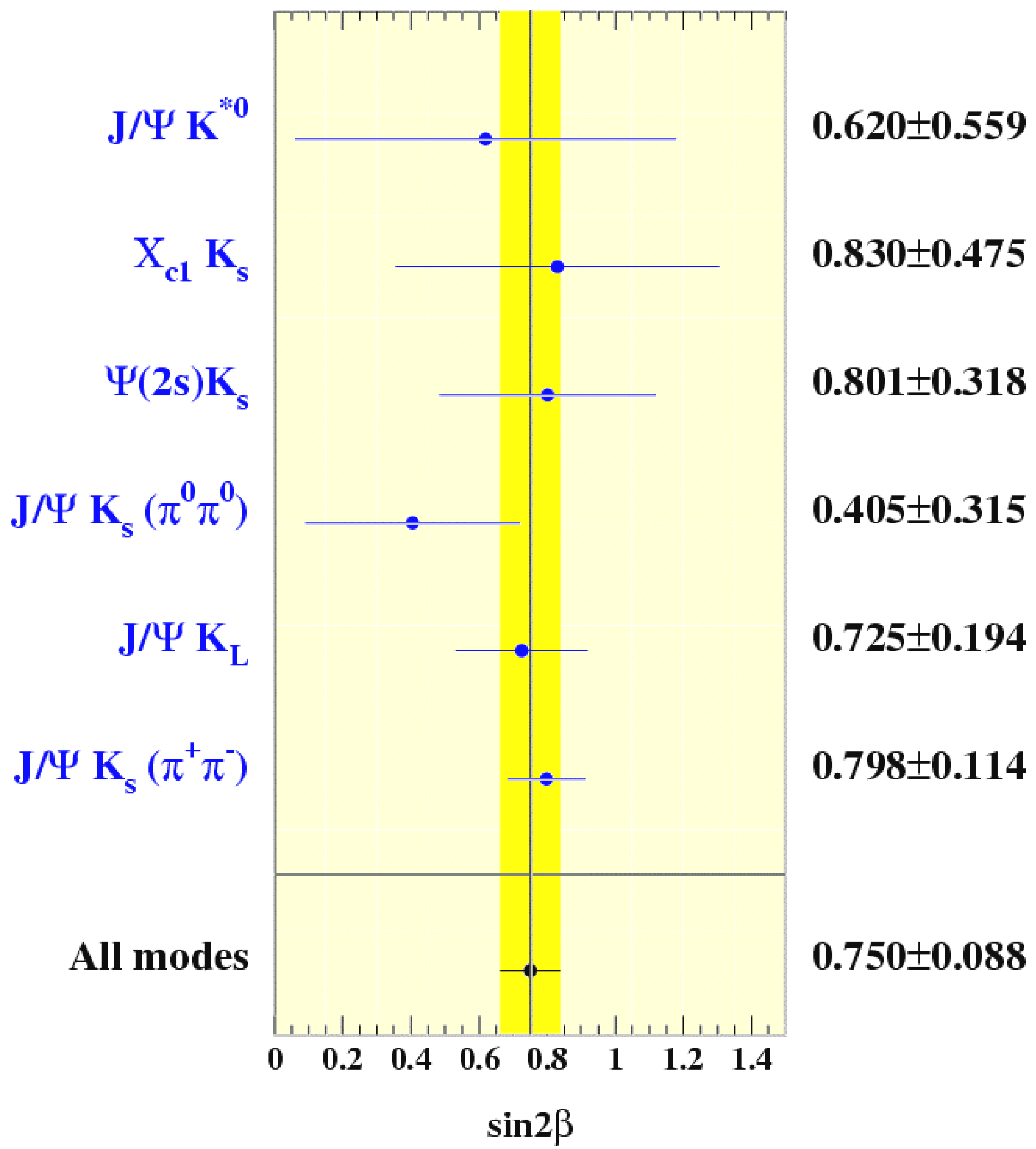


Sin2β Fit Results

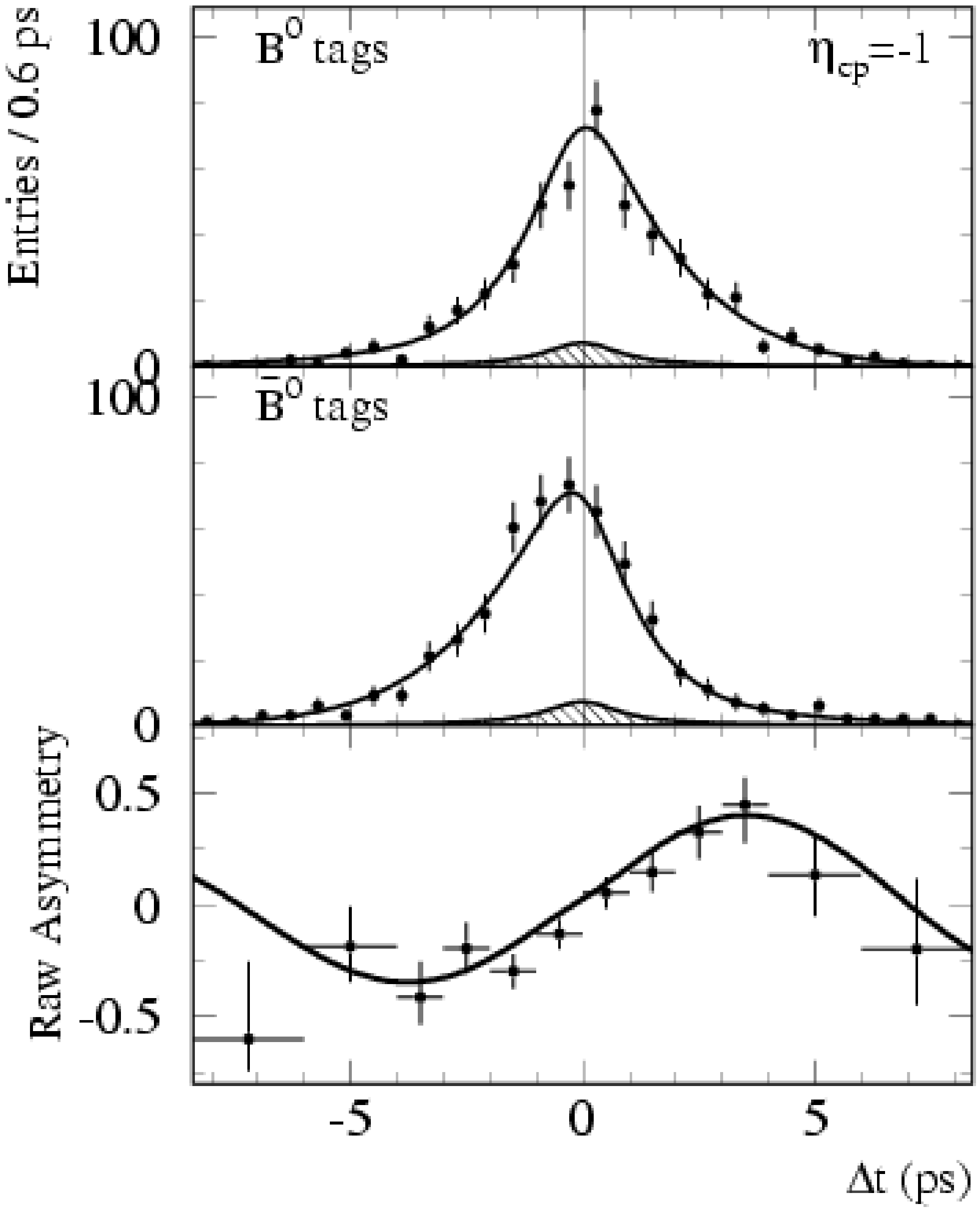
Consistency of CP channels $P(\chi^2) = 70\%$

The error is 13% better than expected from just increased luminosity

Goodness of fit: $P(L_{max} > L_{obs}) > \sim 50\%$



Golden Modes

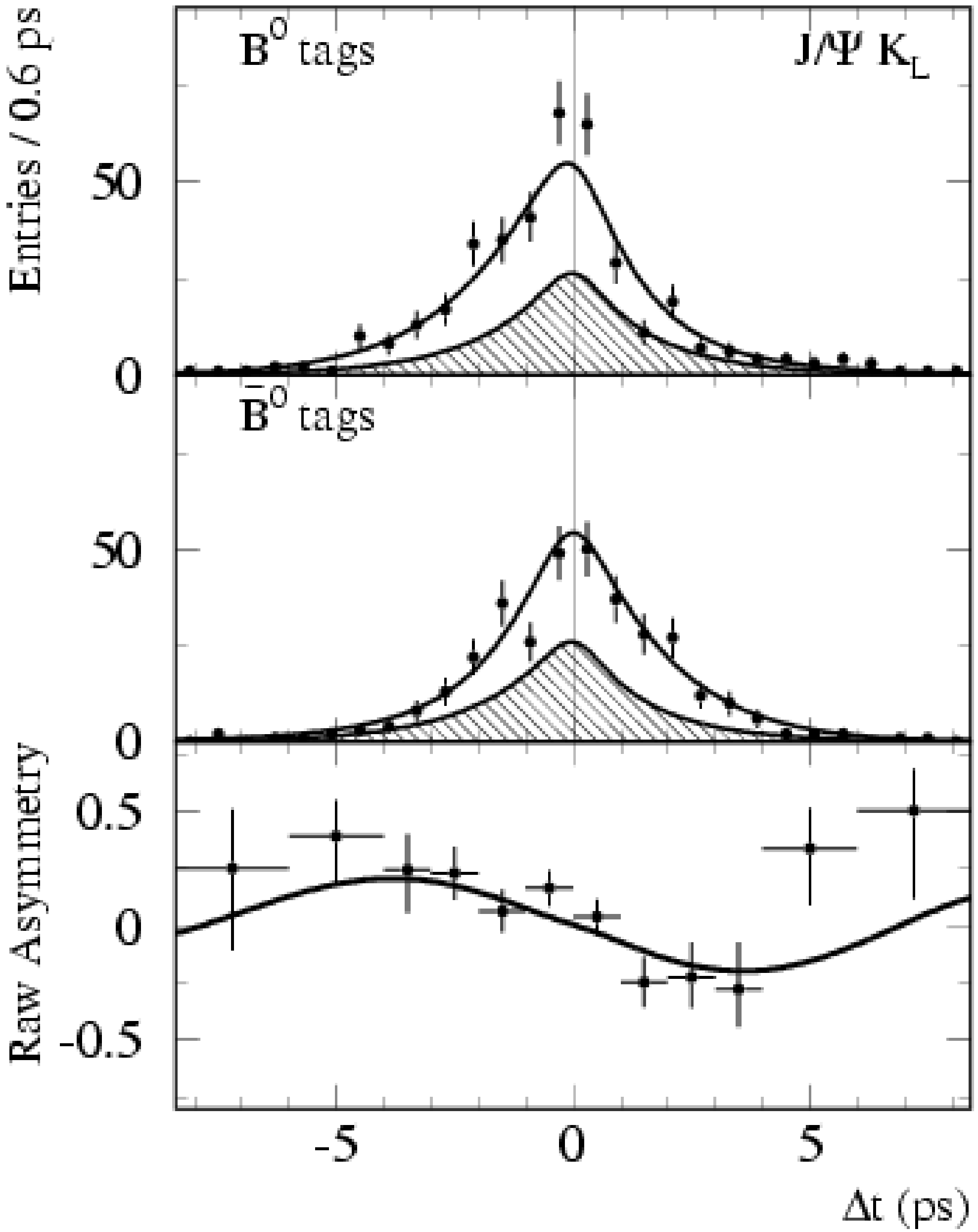


471 B^0 events

524 $\bar{B}^0$ events

$\sin 2\beta = 0.76 \pm 0.10$

J/psi K_L



392 B^0 events

350 $\bar{B}^0$ events

$\sin 2\beta = 0.73 \pm 0.19$

Extra bits: Measurement of |λ|

- In the nominal fit we do not allow for a direct CP violation term by fixing |λ| = 1

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

Amplitude ratio

Weak Phase

- The complete PDF including the direct CP term is

$$f_{\pm}(B \to f_{CP}, t) = \tfrac{\Gamma}{4} e^{-\Gamma\,|\Delta t|}\,[1 \pm C_{f_{CP}} \cos(\Delta m_d t) \mp S_{f_{CP}} \sin(\Delta m_d t)]$$

$$f_{+} : \overline{B}^0_{phys} \to f_{CP}$$

$$f_{-} : B^0_{phys} \to f_{CP}$$

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

- The fit when |λ| is floated yields

$$\frac{\mathrm{Im}\,\lambda_{f_{CP}}}{|\lambda_{f_{CP}}|} = 0.760 \pm 0.100$$

$$|\lambda_{f_{CP}}| = 0.925 \pm 0.064$$

Sin2β Likelihood Fit

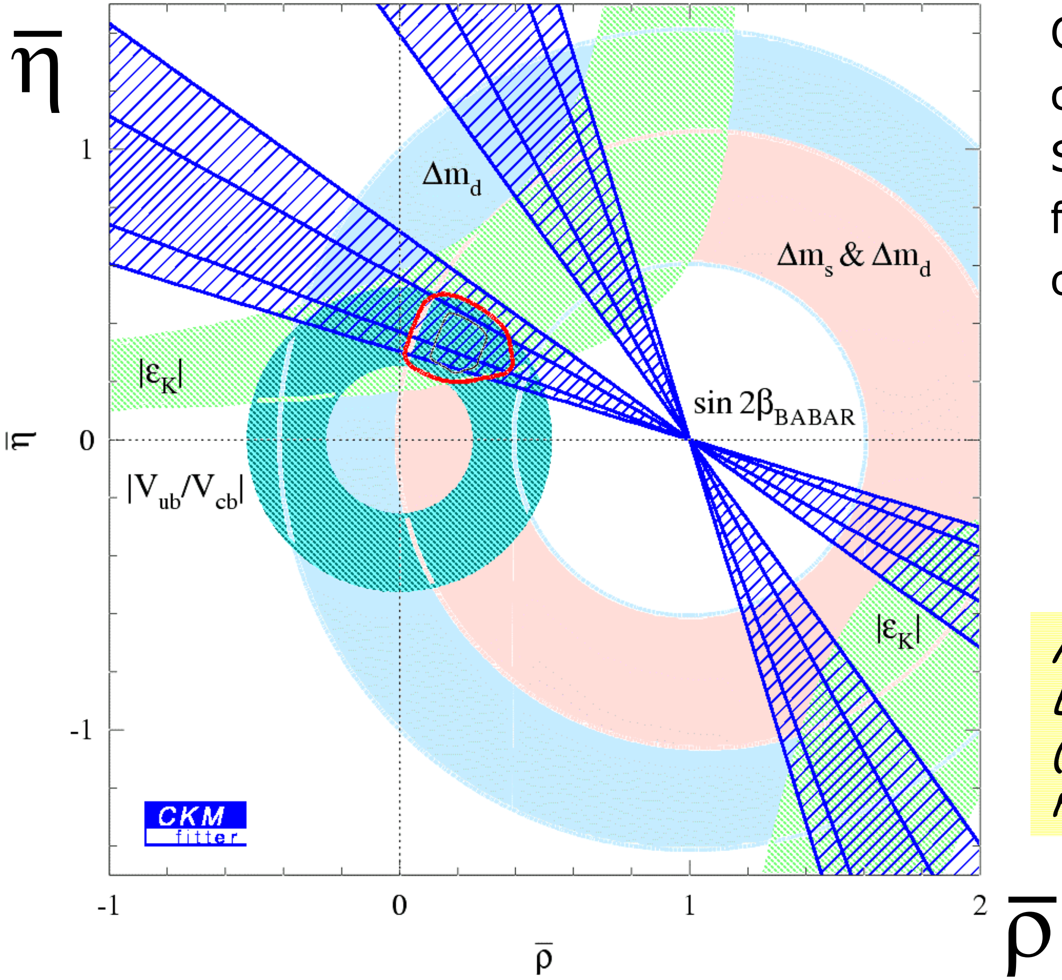
Combined unbinned maximum likelihood fit to Δt spectra of flavor and CP sample

sin2β	1	tagged CP samples
Signal Parameters:		
Dilutions	1*4=4	tagged flavor sample
ΔD for B^0 and $\overline{B^0}$ tags	1*4=4	
Signal resolution function	4+1*4=8	
Background Parameters:		
Dilutions	1*4=4	tagged flavor sample (BG)
ΔD for B0 and B0 tags	1*4=4	
Resolution function	3	
"Lifetime" of BG	1	
Fraction of prompt BG, Bflav sample	1*4=4	
Fraction of prompt BG, CP sample	1	tagged CP (BG)
TOTAL	34	

B lifetime fixed to the PDG value $\tau_B = 1.548$ ps

Mixing Frequency fixed to the PDG value $\Delta m_d = 0.472\ ps^{-1}$

CKM interpretation



Our sin2β measurement is consistent with current Standard Model constraints from measurements of other parameters.

$\bar{\rho} = \rho(1-\lambda^2/2)$
$\bar{\eta} = \eta(1-\lambda^2/2)$

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

Sin(2α) Time formalism

$\pi\pi$ general form allows for both tree and penguin:

- $f(\Delta t) \sim 1 \pm S_{\pi\pi} \sin(\Delta m_d \Delta t) \quad C_{\pi\pi} \cos(\Delta m_d \Delta t)$ for $B^0(B^0)$ tag
- $S_{\pi\pi} = 2\mathrm{Im}(\lambda)/(1+|\lambda|^2)$ and $C_{\pi\pi} = (1-|\lambda|^2)/(1+|\lambda|^2)$
- For pure tree, $\lambda = e^{i2\alpha}$ so $S_{\pi\pi} = \sin 2\alpha$ and $C_{\pi\pi} = 0$
- With some penguin contribution, $C_{\pi\pi} \neq 0$ and $S_{\pi\pi} = \sqrt{(1-C_{\pi\pi}{}^2)}\ \sin 2\alpha_{eff}$

$K\pi$ time dependence due to B^0 mixing:

- $f(\Delta t) \sim 1 \pm \cos(\Delta m_d \Delta t)$ for unmixed (mixed) B^0

KK general form similar to $\pi\pi$

Sin(2α) Branching fraction fit

Five input variables per event; assume independent (uncorrelated) PDFs for each:

- m_{ES}
- F
- ΔE
- θ_C^+
- θ_C^-

(m_{ES}, F, ΔE): Discriminate signal from background

(ΔE, θ_C^+, θ_C^-): Discriminate different signal modes

Eight fit parameters: four for signal, four for background

- $N(\pi^+\pi^-)$
- $N(K^+\pi^-)$
- $N(\pi^+K^-)$
- $N(K^+K^-)$

Fit directly for $N(K\pi)$ and $A_{K\pi}$:

$$N(K^+\pi^-) = N(K\pi)\ (1-A_{K\pi})/2$$

$$N(\pi^+K^-) = N(K\pi)\ (1+A_{K\pi})/2$$