Latest time-dependent CP-violation results from BaBar

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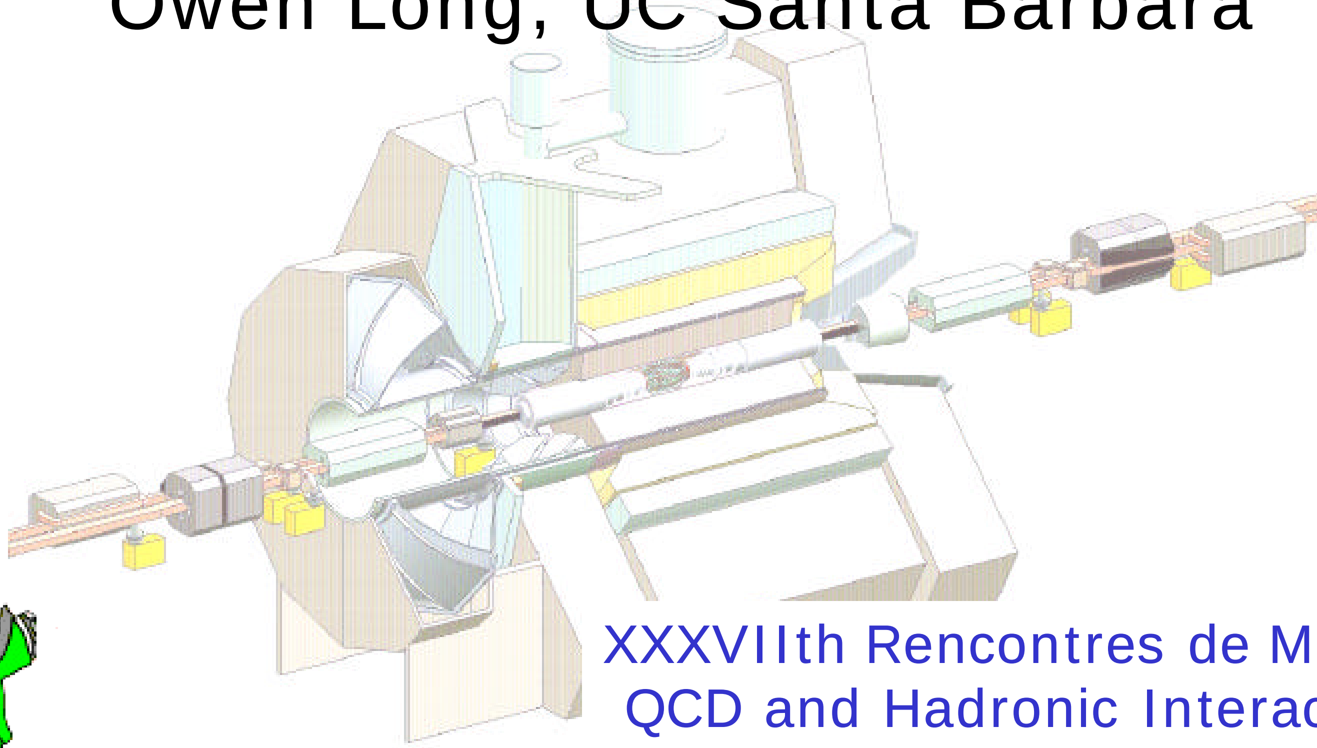

XXXVIIth Rencontres de Moriond
QCD and Hadronic Interactions
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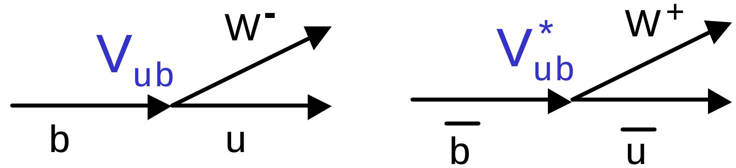
All results are preliminary

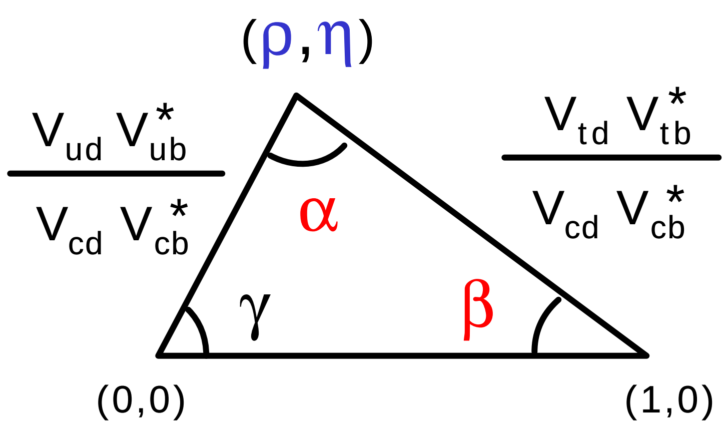
The CKM matrix

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.

Time-dependent CP asymmetries

$$A_{cp,f}(\Delta t) \equiv \frac{\Gamma(\overline{B^0}(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\overline{B^0}(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)}$$

$$A_{cp,f}(t) = S_f \;\sin \Delta m \Delta t - C_f \;\cos \Delta m \Delta t$$

Interference between mixing and decay produces a CP asymmetry that depends on the time difference between the B decays.

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f \equiv \frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}$$

General technique: fit for the sine and cosine coefficients in the time-dependent asymmetry.

Decay	Mode	$\lvert\lambda\rvert$	Imλ	Comments
$b \to c\bar{c}s$	$J/\Psi\ K_s$	1	$\sin 2\beta$	Single weak phase. *Theoretically clean*
$b \to c\bar{c}d$	$D^* D^{(*)}$	?	$\sin 2\beta$ if no penguin	Tree and penguin
$b \to u\bar{u}d$	$\pi^+\pi^-$	?	$\sin 2\alpha$ if no penguin	Tree and penguin

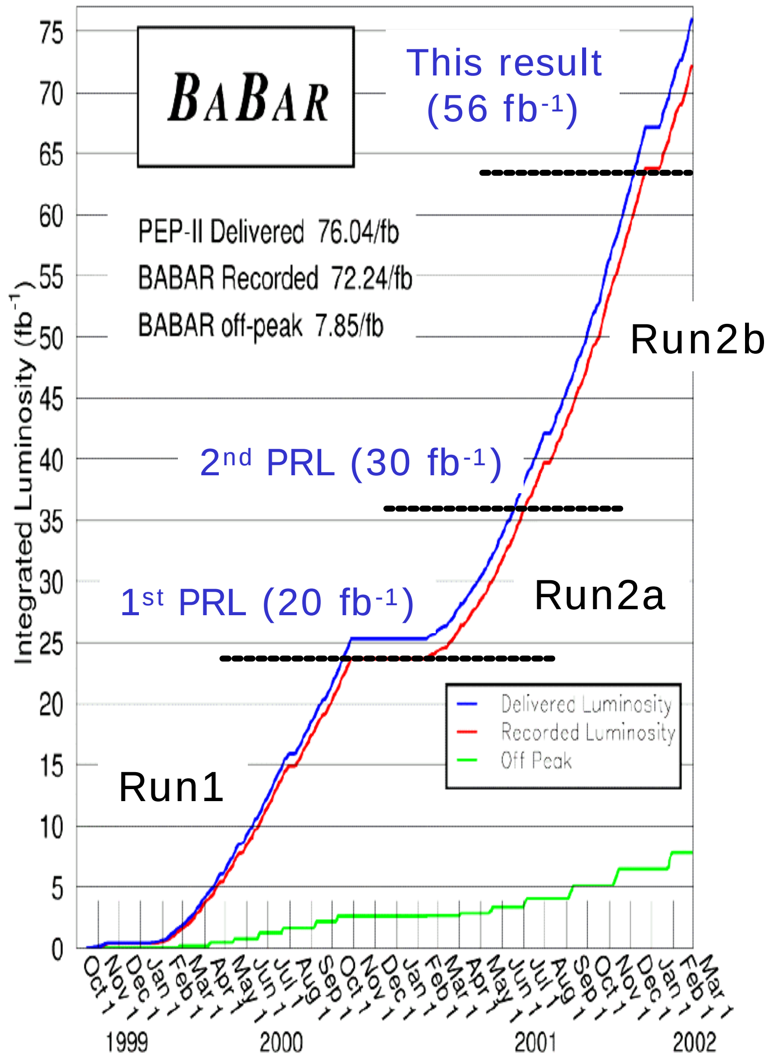
The PEP-II asymmetric e^+e^- storage ring

$E(e^-) = 9.0$ GeV, $E(e^+) = 3.1$ GeV

$\beta\gamma \cong 0.56$

	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**

This result: 56 fb^{-1} on-resonance.
62 million $B\bar{B}$ events.



The BaBar experiment

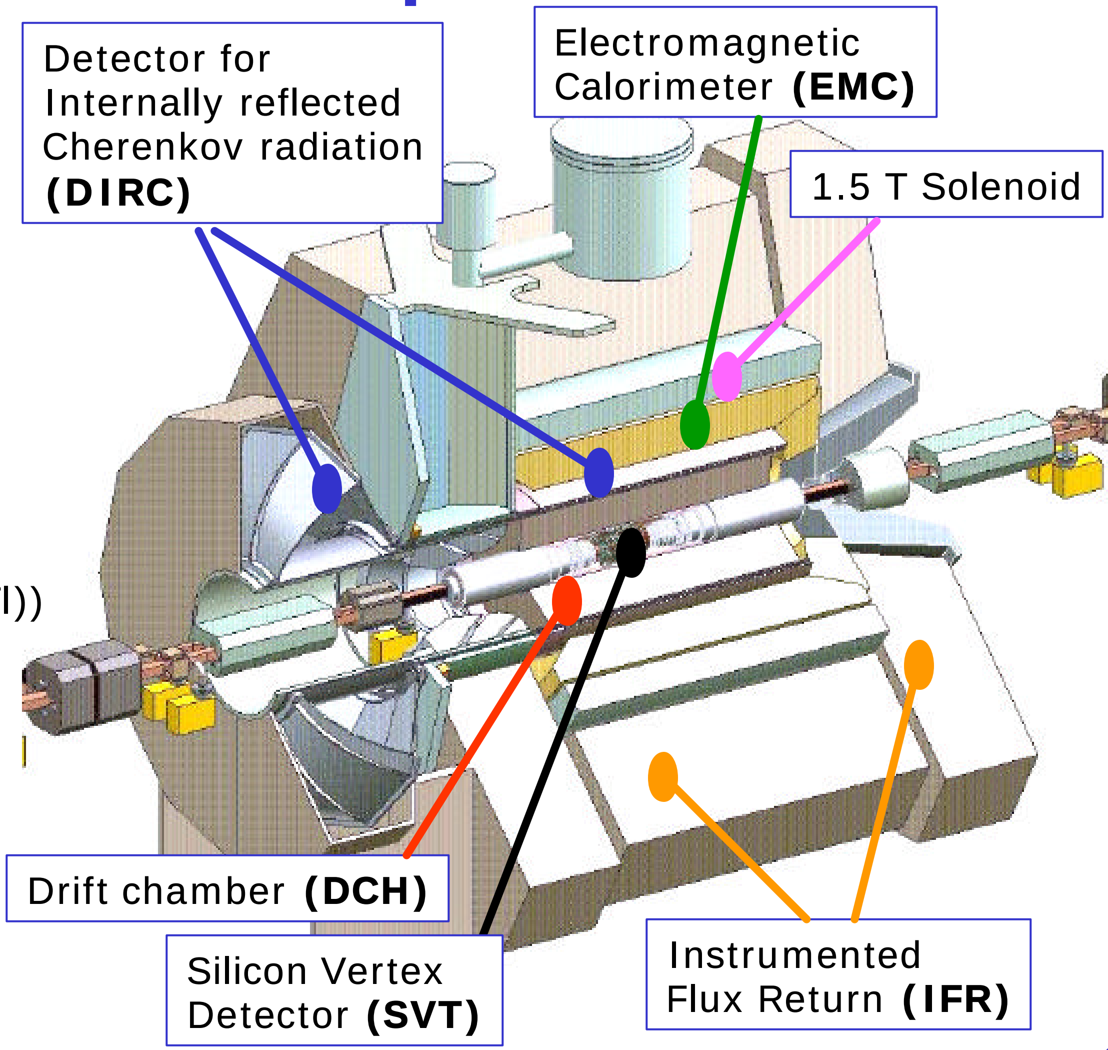
SVT: 5 layers double-sided Si. Crucial for measuring Δt.

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)



Changes in the sin2β analysis

Run1 data (20 fb^{-1}) were reprocessed

- Improved SVT internal alignment (better Δt measurement).
- More efficient tracking pattern recognition (K_s efficiency +20%).
- Improved DIRC alignment (better Cerenkov angle resolution, $K^{\pm}$ ID)

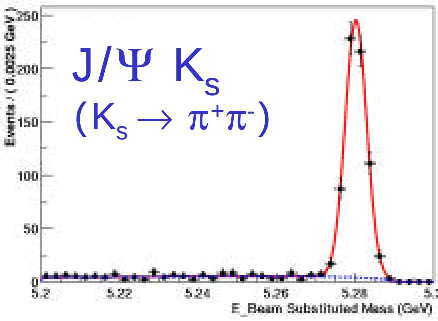
Improved kaon and muon PID algorithms

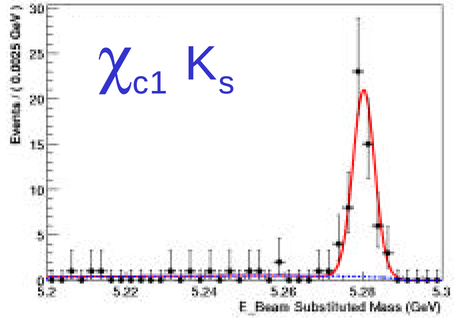
sin2β analysis improvements

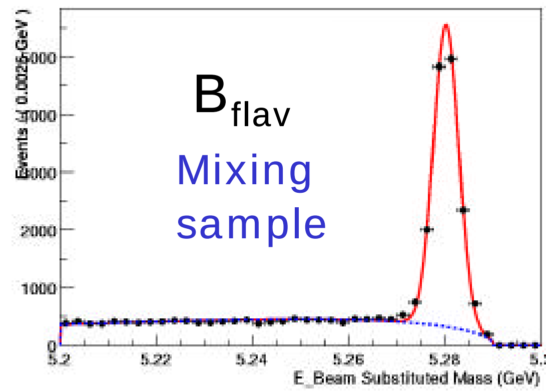
Decay Mode	Changes	Impact
J / Υ K_s	Wider K_s mass window	Eff. + 7% / Purity 98 % → 96 %
J / Υ K_L	Looser μ PID and π^0 veto	Eff. +15% / Purity 65 % → 58 %
J / Υ K^{*0}	Angular decomposition of L=0,1,2 Veto J/Ψ K^{*+} feed-accross	sin2β error 13% better FA reduced 60%. Eff. -3.5%

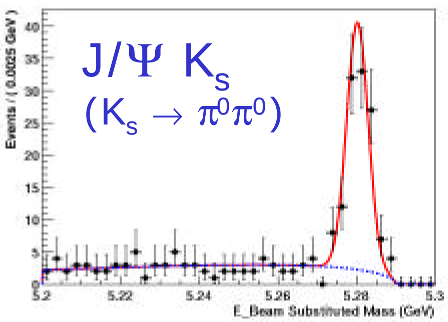
New measurements: $\eta_c K_s$, D^*D^* , D^*D

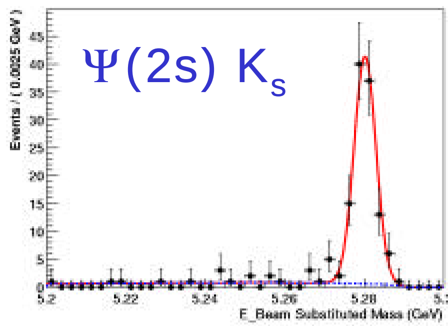
sin2β data samples

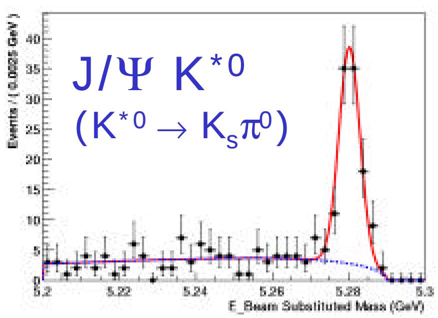


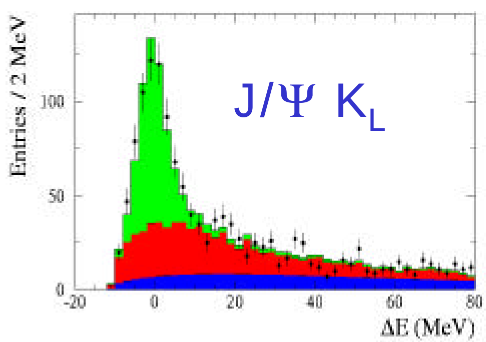










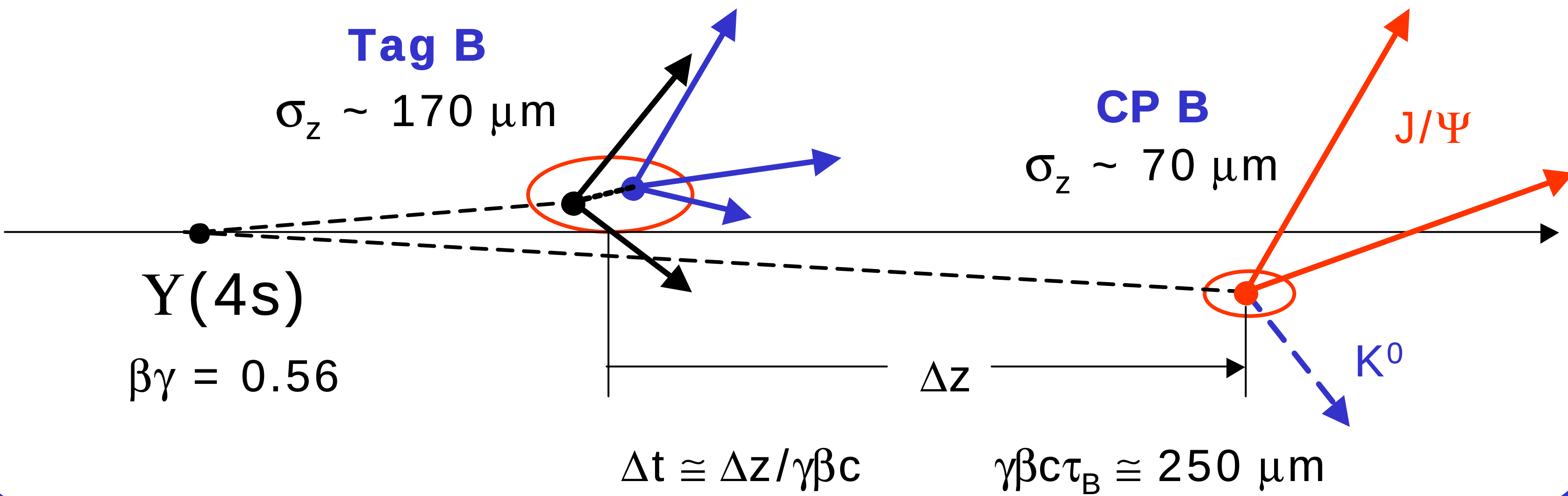


On-resonance integrated luminosity $56\ fb^{-1}$

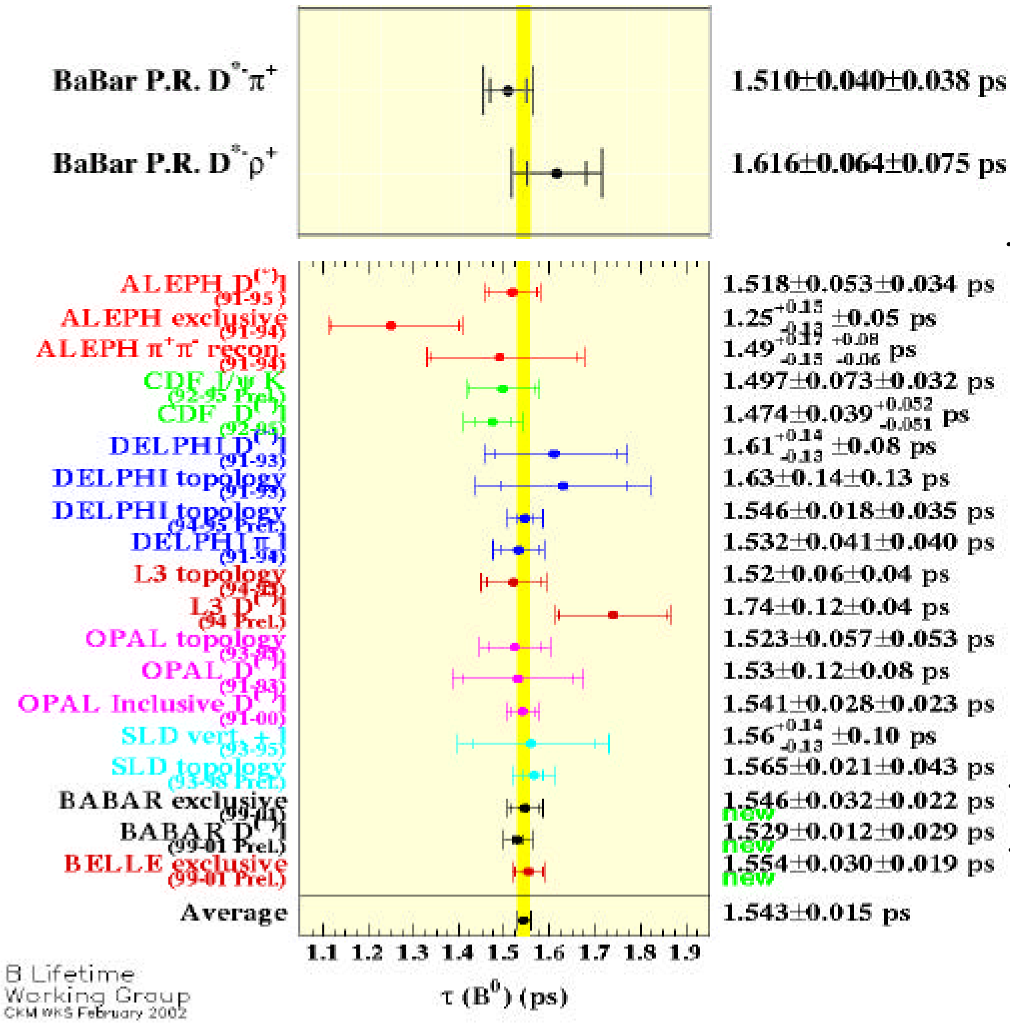
Mode	N_{tag}	Purity	CP
$(c\bar{c})K_s$	995	94%	-1
J/Ψ K_L	742	57%	+1
J/Ψ K^{*0}	113	83%	+0.68
All CP	**1,850**	**79%**	
Bflav	17,634	85%	Flav. ES

Measurement of Δt

- $J/\Psi \rightarrow l^+ l^-$ dominates in determination of CP vertex.
- Tracks not from CP B combined to form tag vertex.
  - Tracks with large χ^2 iteratively removed.
  - Long-lived particles (K_s , Λ) explicitly reconstructed.
  - Photon conversions ($\gamma \rightarrow e^+e^-$) removed.
- Vertex incorporates constraint from average beam position.
- Efficiency for CP sample 97 % (93% after $|\Delta t|<20$ ps, $\sigma_{\Delta t}<2.5$ ps)



BaBar B^0 lifetime measurements



New preliminary lifetime measurements using partial reconstruction.
(not in average)

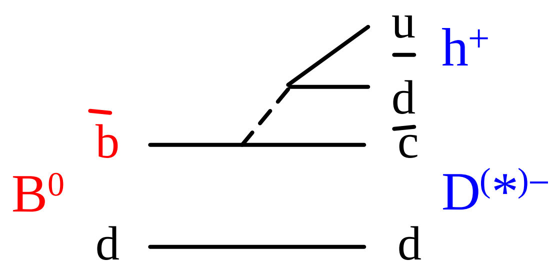
Lifetime measurements validate Δt measurement techniques

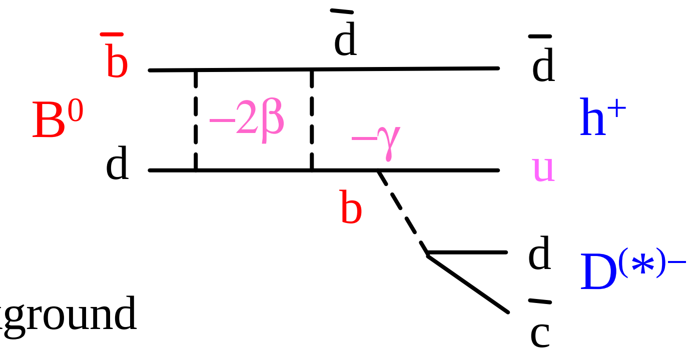
BaBar measurements published and submitted to PRL

Progress toward Measuring sin(2β+γ)

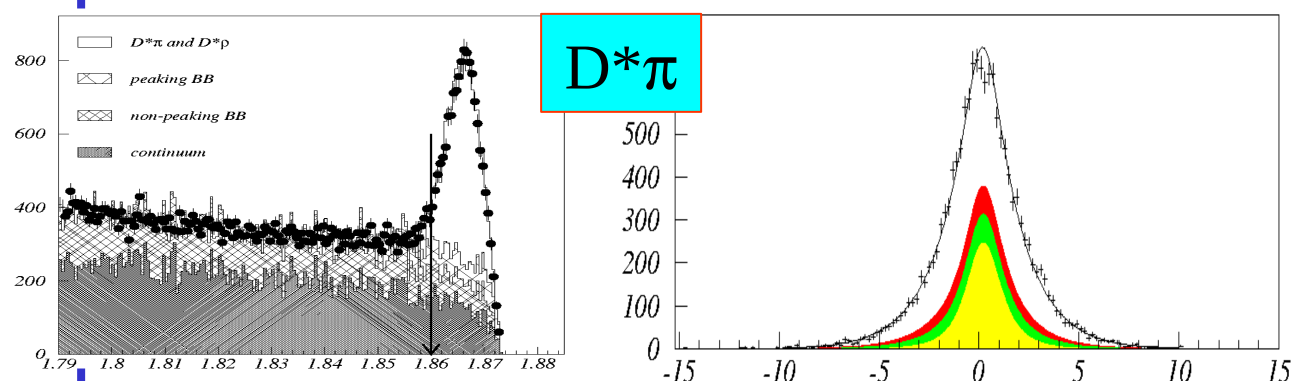
$B \to D^{(*)-} h^+$

$\quad \hookrightarrow \bar{D}^0 \pi_s^-$

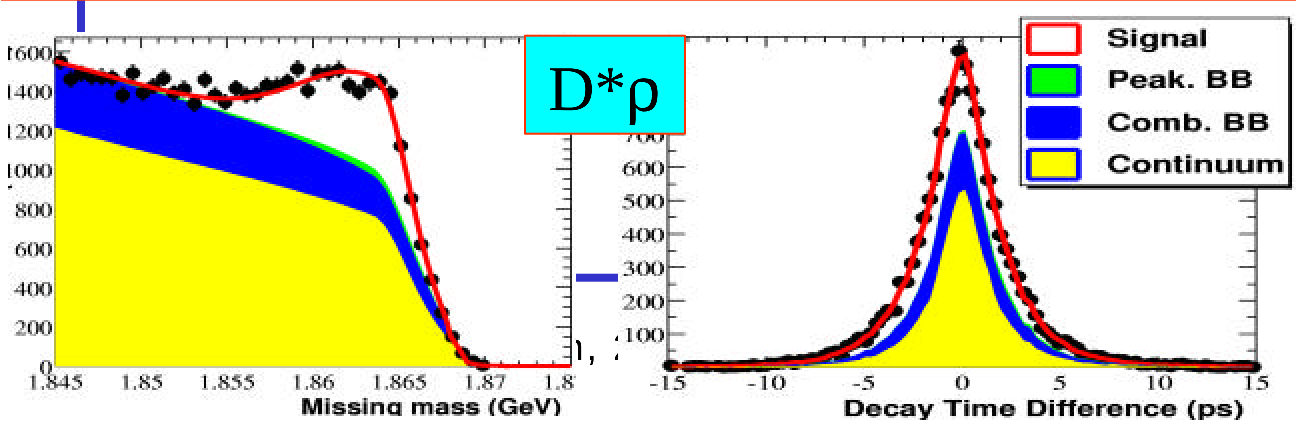




- Partial reconstruction → high statistics + high background
- Validation of time-dependent analysis with B^0 lifetime measurement



$\tau_{B^0} =$
$1.510 \pm 0.040 \pm 0.038$ ps



$\tau_{B^0} =$
$1.616 \pm 0.064 \pm 0.075$ ps

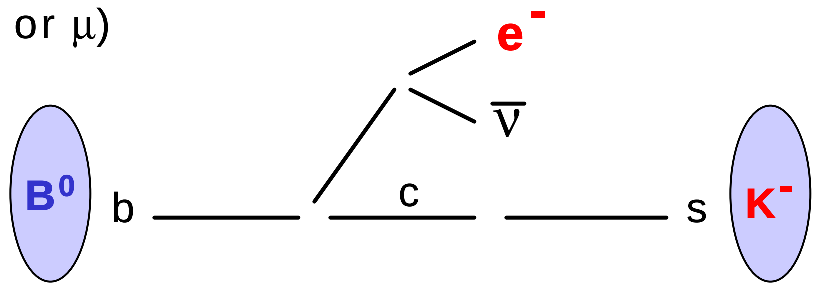
he BaBar collaboration

Flavor tagging

Flavor of CP B at $\Delta t=0$ inferred from decay products of other B in event.
Four hierarchical mutually exclusive categories (take the best available).

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

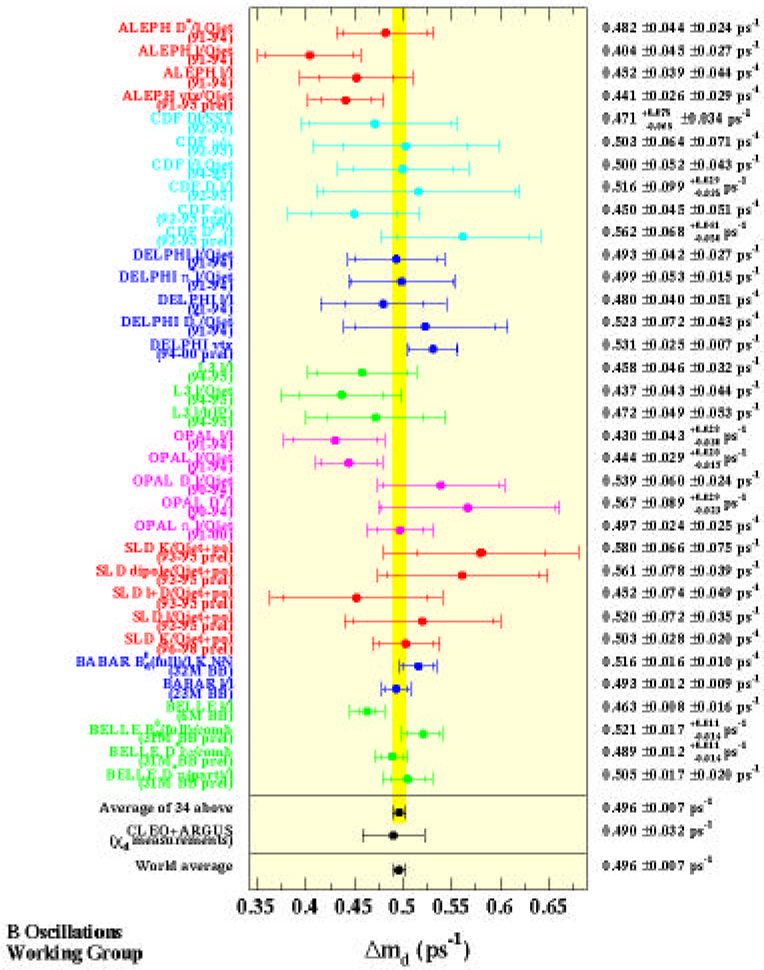
(NT1, NT2:) Bins of NN output. Slow $\pi^{\pm}$ from D^{*} and Unidentified leptons.



Tagging category	Efficiency ε (%)	Mistag fraction w (%)	B^0/B^0 diff. Δw (%)	$Q = \varepsilon(1-2w)^2$ (%)
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**			**25.1 ± 0.8**

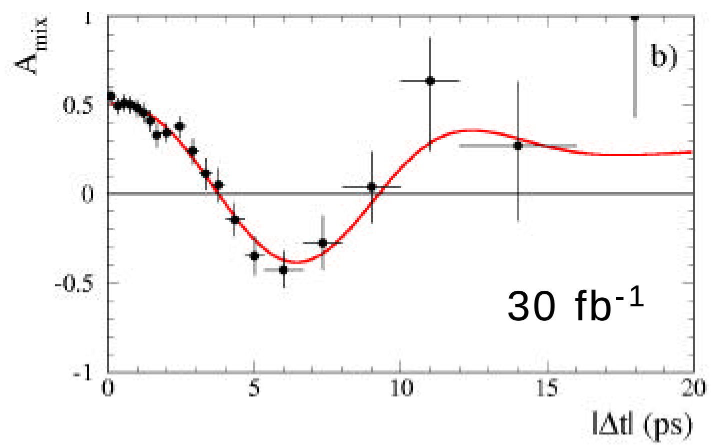
$\sigma(\sin 2\beta) \propto 1/\sqrt{Q}$

BaBar Δm_d measurements



BaBar mixing in hadronic B^0 decays

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

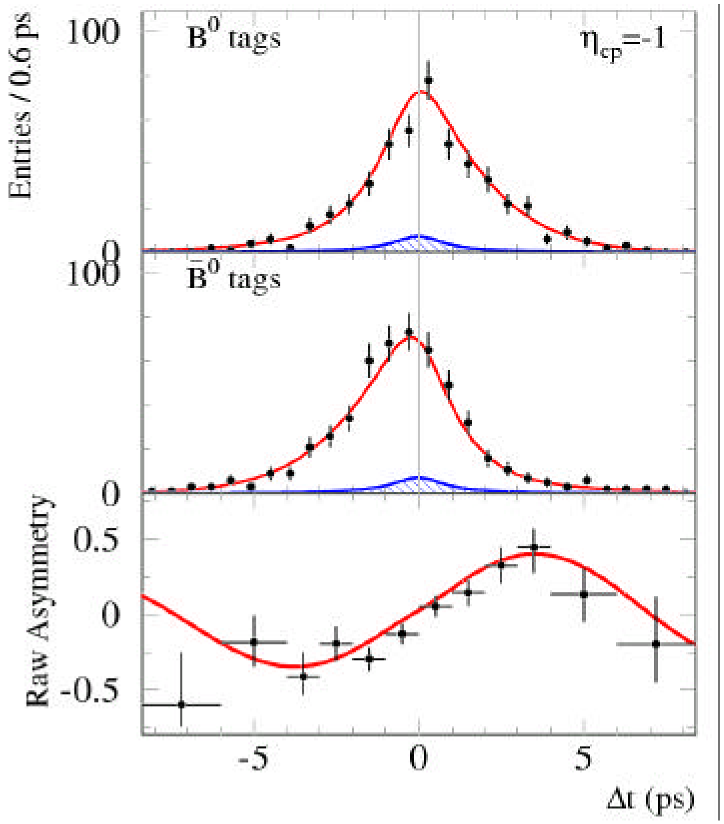


BaBar measurements

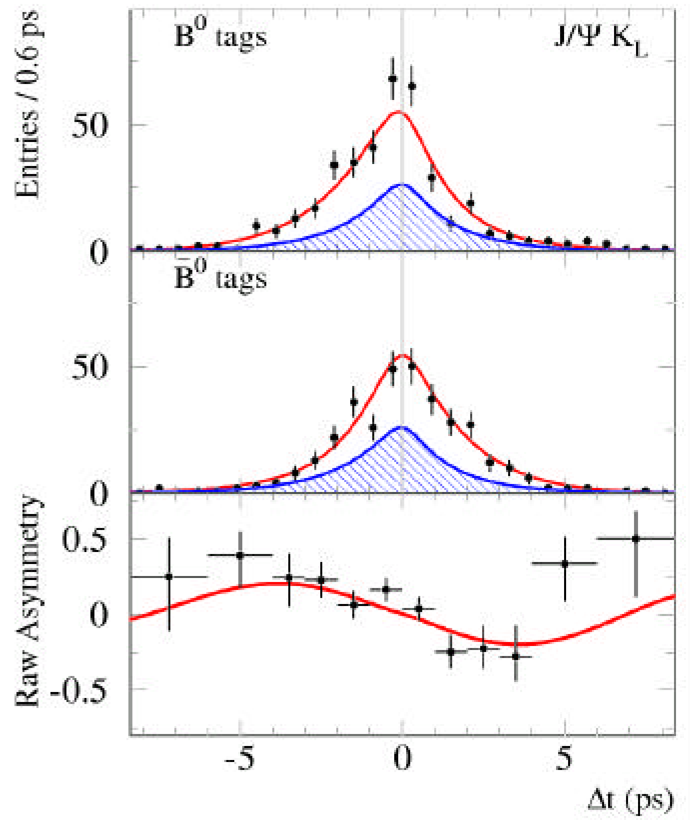
Mixing measurements validate time-dependent asymmetry measurement techniques.

CP asymmetry in CP –1 and +1 modes

$(c\bar{c})\ K_s$ CP = -1



$J/\Psi\ K_L$ CP = +1



Note: likelihood curves are normalized to the total number of tagged events, not B^0 and $\overline{B}^0$ separately.

$\sin 2\beta$ fit results

$\sin 2\beta$

$(c\bar{c})\ K_s$ CP = -1
$0.76 \pm 0.10 \pm 0.04$

$J/\Psi\ K_L$ CP = +1
$0.73 \pm 0.19 \pm 0.07$

All modes
0.75 ± **0.09** ± **0.04**
(stat) (syst)

Systematic errors

CP = -1 background	0.019
Δt resolution and detector effects	0.015
Δm_d and τ_B (PDG 2000)	0.014
Monte Carlo statistics	0.014
$J/\Psi\ K_L$ background	0.013
Signal mistag fractions	0.007
Total systematic error	0.04

Fit without $|\lambda|=1$ constraint (CP=-1 only)

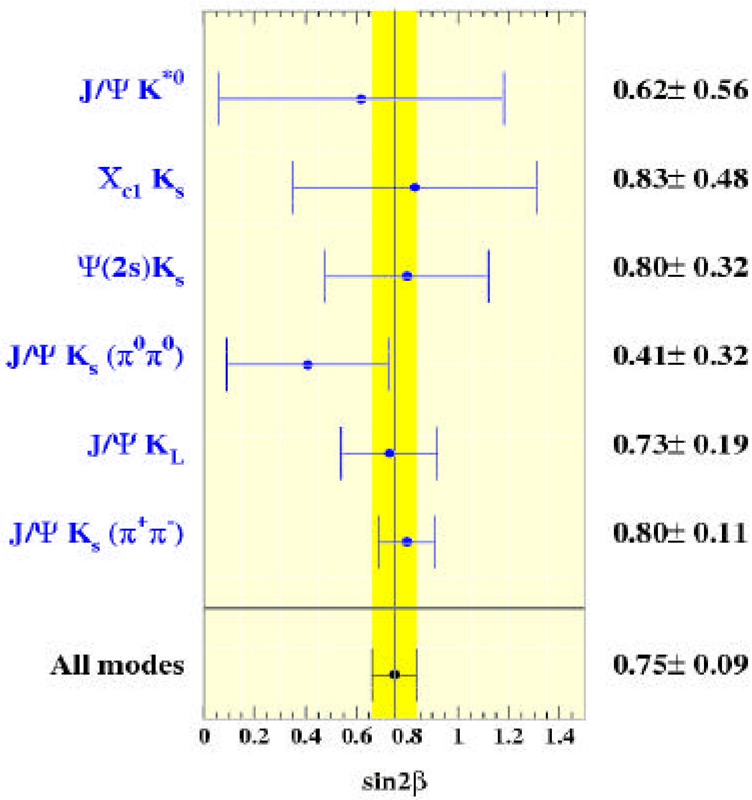
$|\lambda| = 0.92 \pm 0.06$ (stat) ± 0.03 (syst)

$\mathrm{Im}\lambda/|\lambda| = 0.76 \pm 0.10$

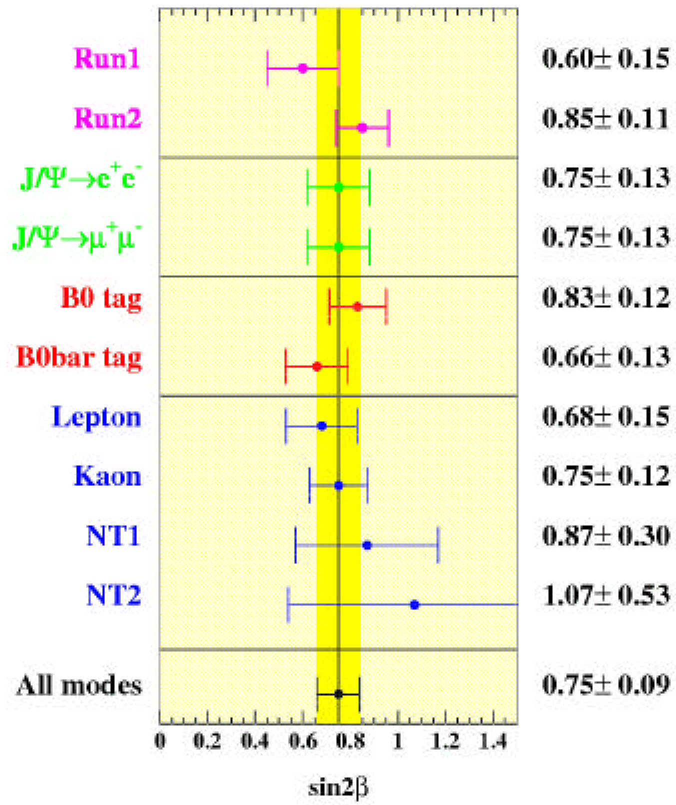
Analysis refinements responsible for 13% improvement in statistical error [compared to $\sigma(\sin 2\beta) = 0.14 \times \mathrm{sqrt}(30/56)$].

Cross checks

sin2β by decay mode



sin2β in sub-samples



Individual modes and sub-samples are all consistent.

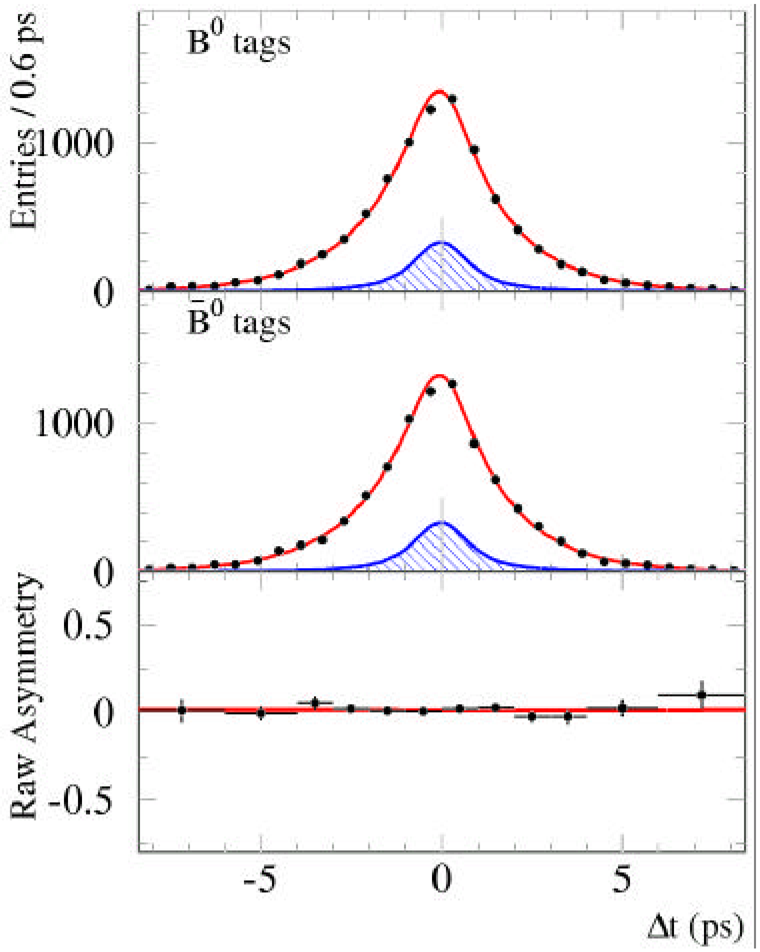
Crosscheck: fit B_{flav} sample as a CP sample

Check for bias in sin2β fit by treating B_{flav} (mixing) sample as if it were a CP sample.

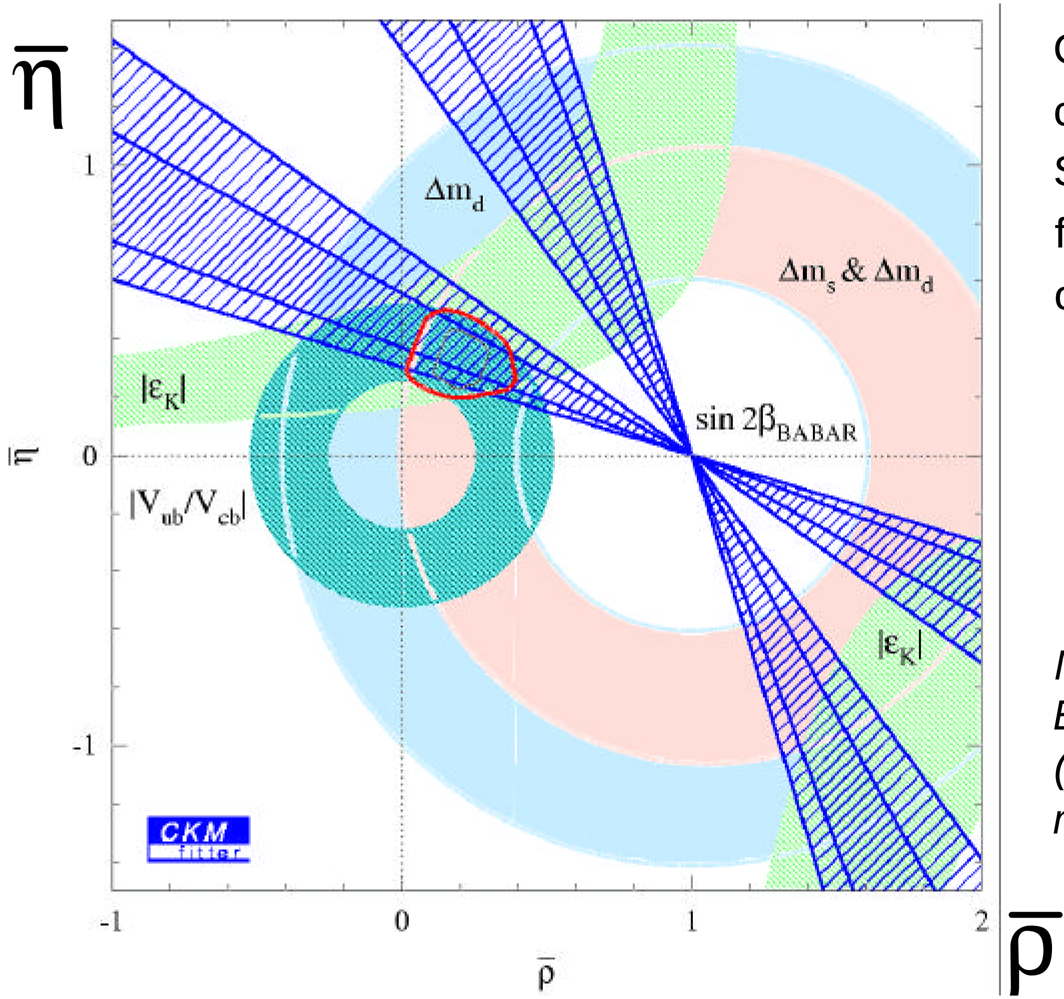
Expect no CP asymmetry.

See no CP asymmetry ☺.

A_{cp} = -0.004 ± 0.027



CKM interpretation



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

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

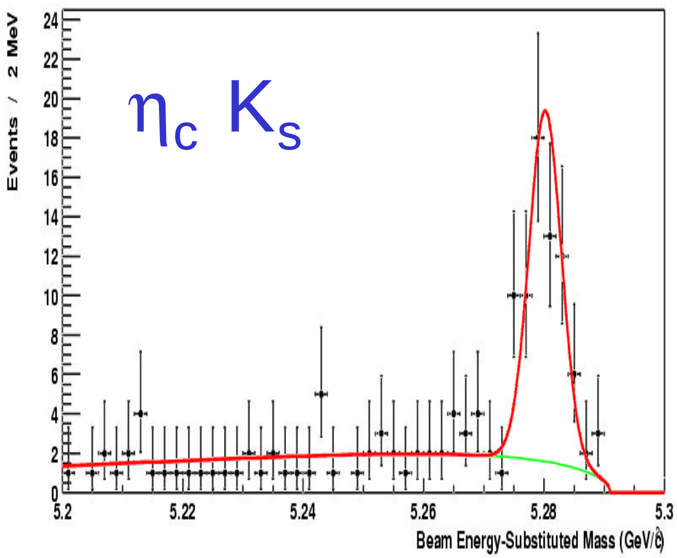
Method as in Höcker et al, Eur.Phys.J.C21:225-259,2001 (also other recent global CKM matrix analyses)

New sin2β measurement : η_c K_s

- Challenging high multiplicity final state: $\eta_c \to K_s K^{\pm}\pi^{\mp}$ and $K^+K^-\pi^0$.
- Another golden ($b \to c\bar{c}s$) mode.

Preliminary branching fraction measurement (run1 20 fb^{-1} only)

$Br(B^0 \to \eta_c K^0)$ x $Br(\eta_c \to KK\pi)$ = **(62 ± 16 ± 13) x 10^{-6}**



N_{tag} = 77 , Purity = 73%

sin2β = 0.43 ± 0.46 ± 0.08

Will be fully incorporated in the global sin2β by summer.

CP asymmetry in $b \to c\bar{c}d$ decays: $D^{*\pm}D^{*\mp}$ and $D^{*\pm}D^{\mp}$

- Weak phase for tree decay is same as for $b \to c\bar{c}s$ but watch out for penguins!
- D^*D^* is vector-vector decay (L=0,1,2) so mix of CP=+1 and –1.
- Fit for S_f and C_f (no penguin assumptions).

$$A_{cp,f}(t) = S_f \ \sin \Delta m \Delta t - C_f \ \cos \Delta m \Delta t$$

- Separate S_f and C_f for $D^{*+}D^-$ and $D^{*-}D^+$.

D^*D^*

$S = -\ 0.05 \pm 0.45 \pm 0.05$

$C = \ 0.12 \pm 0.30 \pm 0.05$

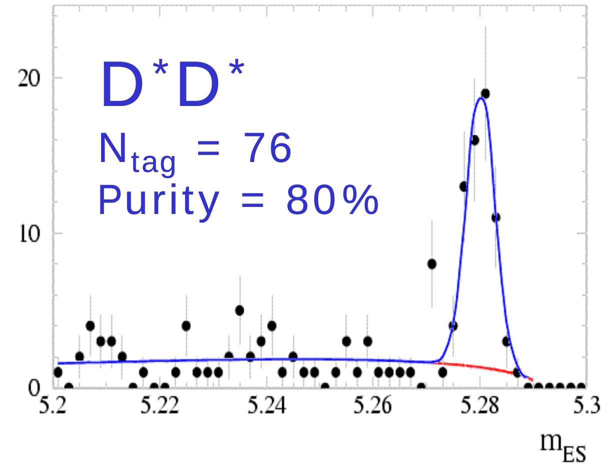
D^*D

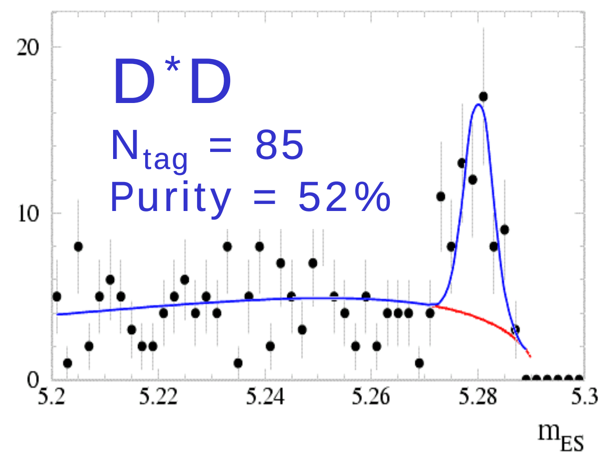
$S_{+-} = -\ 0.43 \pm 1.41 \pm 0.20$

$C_{+-} = \ 0.53 \pm 0.74 \pm 0.13$

$S_{-+} = \ 0.38 \pm 0.88 \pm 0.05$

$C_{-+} = \ 0.30 \pm 0.50 \pm 0.08$





Next step: angular analysis for D^*D^*

$B^0 \rightarrow h^+h^-$ analysis

CP asymmetry in $B^0 \rightarrow \pi^+\pi^-$ sensitive to $\sin 2\alpha$

Background almost entirely from the continuum (BB negligible)

- Cut on $|\cos\theta_s|$: signal flat , BG peaks near 1.
- Fisher discriminant F (energy cones) used in likelihood fit.

Maximum likelihood fit input

Sig/BG sep.	B kinematics : m_{es} and ΔE Fisher output : F
K/π separation	DIRC Cherenkov angles : θ_c^+ and θ_c^-
CP asymmetry	Δt and flavor tag

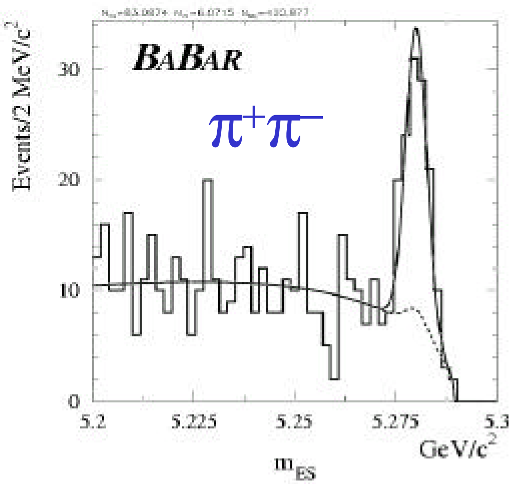
Fit for yield ($N_{\pi\pi}$, $N_{K\pi}$, N_{KK}) and $K^+\pi^-$ vs. $K^-\pi^+$ asymmetry ($A_{k\pi}$)

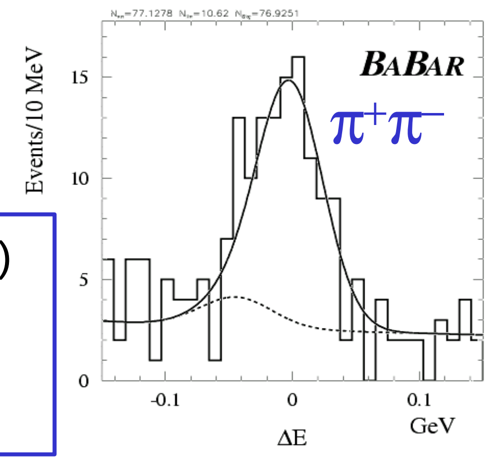
Use all events (No Δt or flavor tagging).

Fix yields, fit for $S_{\pi\pi}$ and $C_{\pi\pi}$ including Δt and flavor tagging.

$$A_{cp,\pi\pi}(t) = S_{\pi\pi}\ \sin \Delta m \Delta t - C_{\pi\pi}\ \cos \Delta m \Delta t$$

$B^0 \rightarrow \pi\pi$ and $K\pi$ branching fraction results





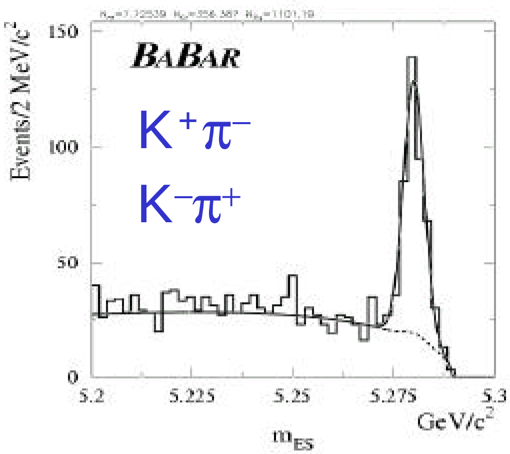
Branching fractions

in units of x 10^{-6}

$B(p^+p^-)$ = (5.4 ± 0.7 ± 0.04)

$B(K^+p^-)$ = (17.8 ± 1.1 ± 0.8)

$B(K^+K^-)$ < (1.1 , 90% C.L.)



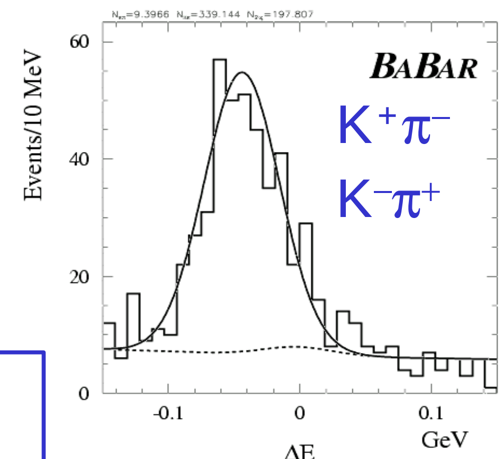
m_{es}

$K\pi$ asymmetry

$$A_{K\pi} \equiv \frac{N_{K^-\pi^+} - N_{K^+\pi^-}}{N_{K^-\pi^+} + N_{K^+\pi^-}}$$

A_{Kp} = -0.05 ± 0.06 ± 0.01

90% C.L. interval [-0.15, +0.05]



ΔE

Mixing/Lifetime Validation

- Measure B lifetime using $B^0 \rightarrow p^+p^-/K^\pm p^\mp$

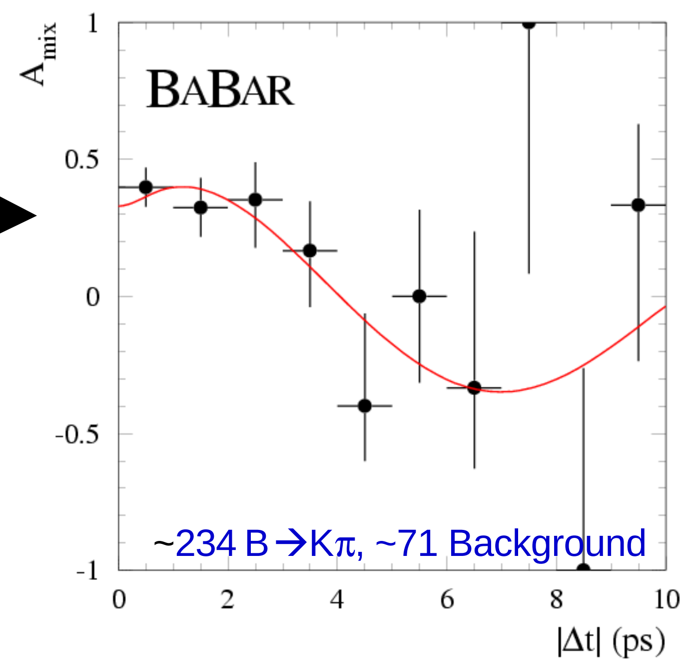
$$\Rightarrow t = 1.66 \pm 0.09\,\mathrm{ps}$$

- Measure Δm_d using $B^0 \rightarrow K^\pm p^\mp$

$$\Rightarrow \Delta m_d = 0.517 \pm 0.062\,\mathrm{ps}^{-1}$$

Cross-check

Select B→Kπ sample and plot the asymmetry between mixed/unmixed events.



$B^0 \rightarrow \pi^+\pi^-$ CP asymmetry results

Results of Δt – dependent fit

$$A_{cp,\pi\pi}(t) = S_{\pi\pi} \ \sin\Delta m\Delta t - C_{\pi\pi} \ \cos\Delta m\Delta t$$

S_{pp} = -0.01 ± 0.37 ± 0.07

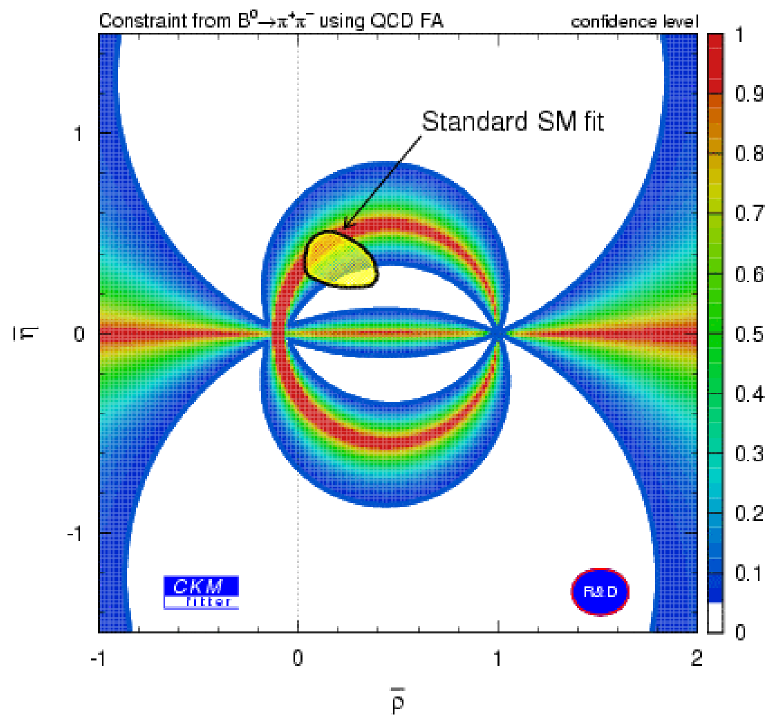
C_{pp} = -0.02 ± 0.29 ± 0.07

90% confidence intervals

S_{pp} = [-0.66,+0.62]

C_{pp} = [-0.54,+0.48]

Theoretical interpretation
of BaBar $S_{\pi\pi}$ result.
QCD factorization



Result is at the edge of the allowed region in the $\rho - \eta$ plane.

Summary and outlook

Several new results with 56 fb^{-1} of on-resonance data.

sin2b = 0.75 ± 0.09 (stat) ± 0.04 (syst)

Precision measurement consistent with other experimental constraints on the Standard Model.

First measurements of CP asymmetry in $b \to c\bar{c}d$ decays. Will eventually provide a valuable SM cross check.

CP asymmetry in $B^0 \to \pi^+\pi^-$

$\mathbf{S}_{pp}$ = -0.01 ± 0.37 ± 0.07

$\mathbf{C}_{pp}$ = -0.02 ± 0.29 ± 0.07

At the edge of the allowed region in the $\rho - \eta$ plane.

Will have more updates and measurements with ≈100 fb^{-1} this summer.