CP Violation at BaBar: sin2β

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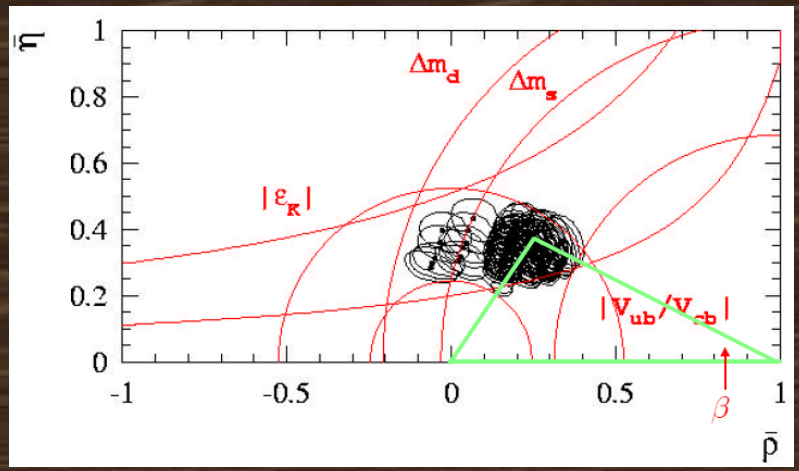
B-Factory Symposium
Stanford, 27 October 2008

CP Violation until 2000

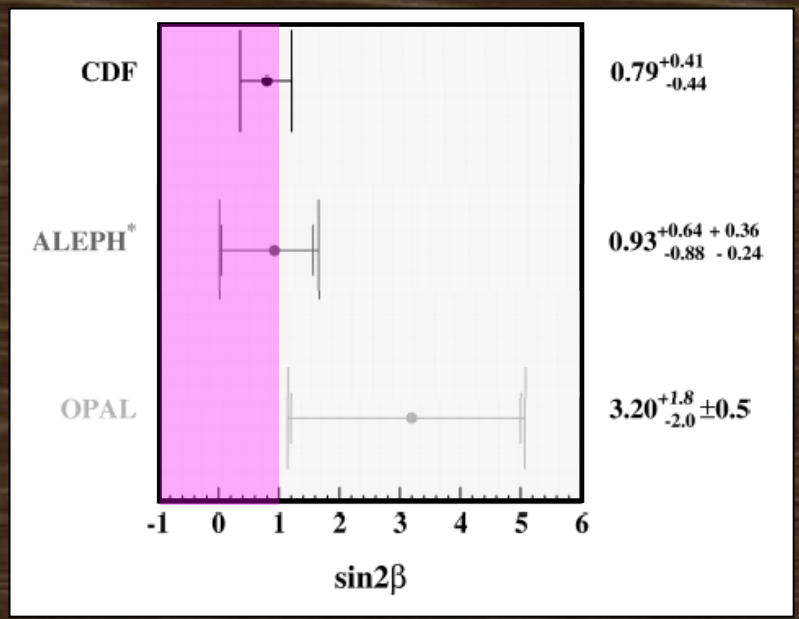
- First observation of CPV in kaon decays by Cronin, Fitch et al. (1964)
- Kobayashi and Maskawa provide mechanism for CPV (1973)
- Large CP asymmetries in B decays predicted by Bigi and Sanda (1980)
- Indirect sin2β measurements from unitarity constraints and direct measurements had poor precision
- Large CLEO sample of 10M $B\bar{B}$
  - CLEO had measured many B BRs, but no CPV measurements

Sin2β was BaBar's opportunity to provide an important new measurement with early data

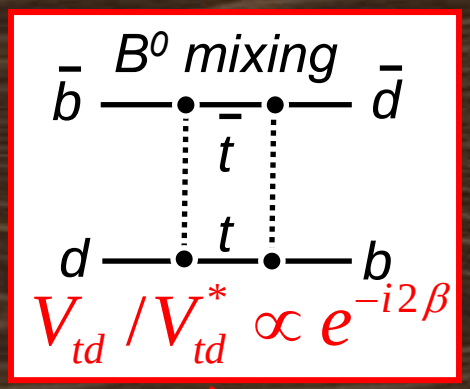
Unitarity Triangle in 2000

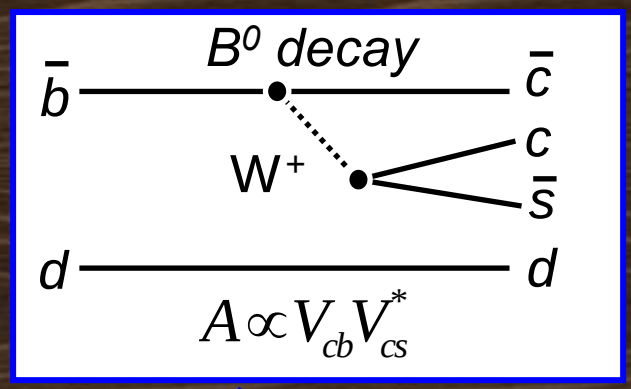


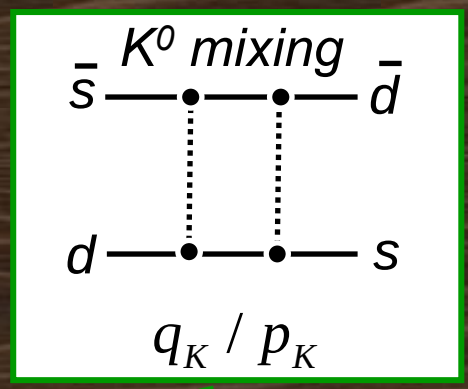
Early sin2β measurements (2000)



Sensitivity to sin2β







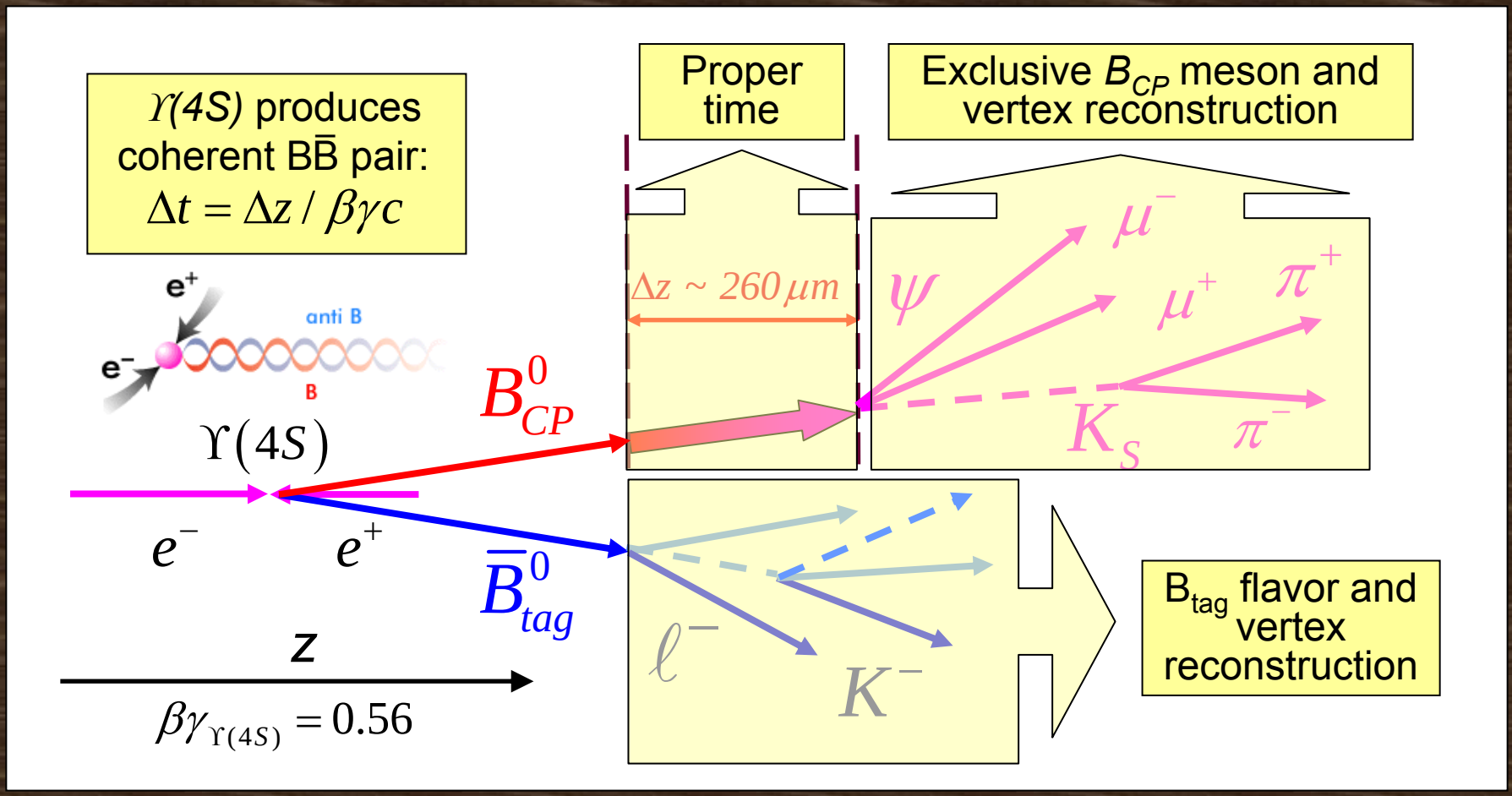
$$\lambda_{CP} = e^{-i2\beta}\frac{\bar{A}_{CP}}{A_{CP}} \cdot = -e^{-i2\beta}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}} = \eta_{CP}e^{-2i\beta}$$

$$S_{CP} \quad S_{CP} = \eta_{CP}\sin 2\beta \qquad C_{CP} = 0$$

$$\Gamma\left(B^0 \to J/\psi K_S^0\right) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1 - \sin 2\beta \sin(\Delta m \Delta t)\right] \quad C_{CP}\cos(\Delta m\Delta t)\Big]$$

$$\Gamma\left(\bar{B}^0 \to J/\psi K_S^0\right) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1 + \sin 2\beta \sin(\Delta m \Delta t)\right] \quad C_{CP}\cos(\Delta m\Delta t)\Big]$$

The sin2β Measurement



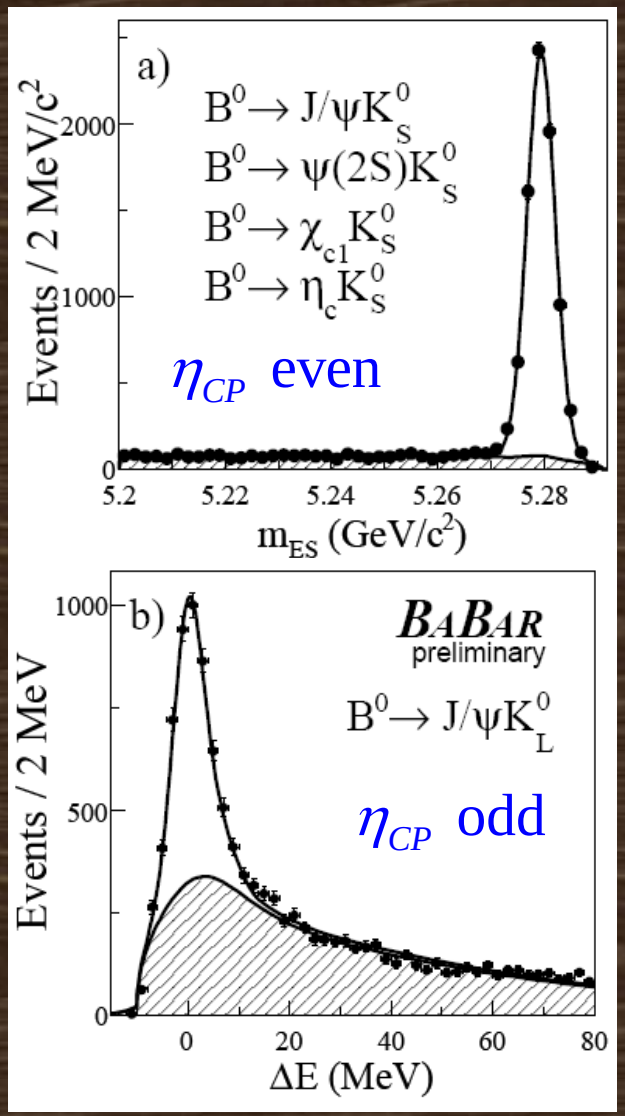
- Many novel techniques were necessary to measure sin2β
  - K_L reconstruction, Δt measurement, flavor tagging, multi-parameter likelihood fits, blind analysis method

The Golden sin2β Modes

- Theoretically clean in the Standard Model
  - $S_{J/\psi K}$ – sin2β ~ O(10^{-3})

Grossman, Kagan, Ligeti, PLB 538, 327 (2002)
Boos, Reuter, Mannel, PRD 70, 036006 (2004)
Ciuchini, Pierini, Silvestrini, PRL 95, 221804 (2005)
Li, Mishima, JHEP 0703, 009 (2007)

- Relatively large branching ratios and clean experimental signature
  - Small background levels
  - Now ~25 reconstructed and flavor-tagged B → (c$\bar{c}$)K CP decays per 10^6 B$\bar{B}$ events



BaBar, arXiv:0808.1903

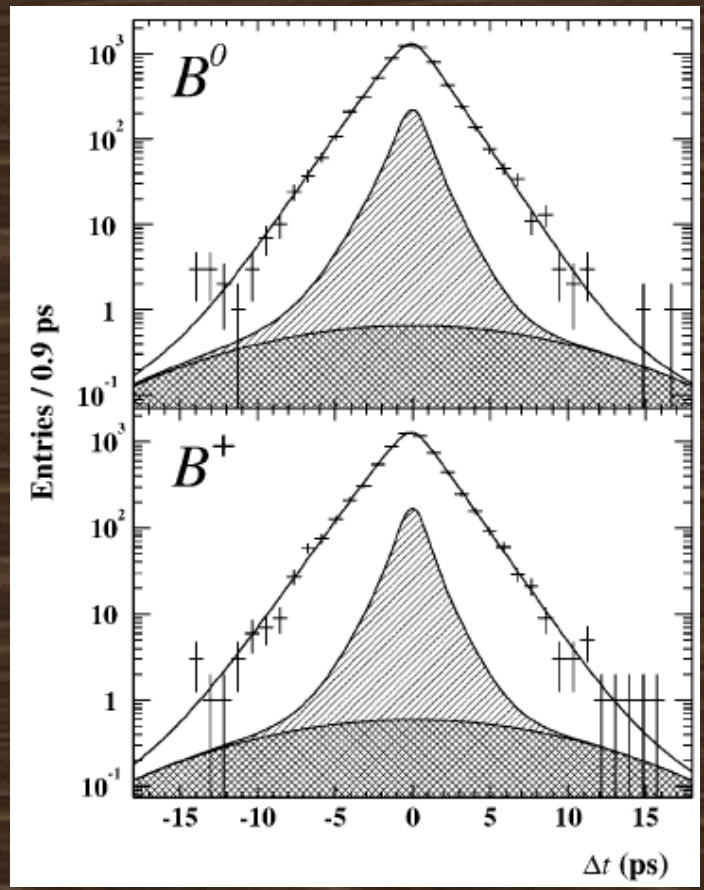
Δt Measurement and Resolution Function

- New proper time measurement technique
  - B production point (in z) is unknown at BaBar
  - We don't measure t, but Δt (which is distributed as a "two-sided exponential")
  - Need to disentangle resolution function from Δt distribution

- Δt resolution much more important for B lifetime measurement than for sin2β
  - Δt measurement dominated by *z* resolution of B_{tag} decay vertex ($\sigma_{\Delta t}$ ~ 1.1 ps)
  - τ_B ~ 1.5 ps, $\lambda_{B\text{-mixing}} = 2\pi / \Delta m$ ~ 12 ps
  - Sin2β only loosely correlated with resolution function

- Demonstrate understanding of resolution function with precision measurement of B lifetimes (2% error)
  - Use much larger sample of fully-reco'ed B decays to flavor final states (B_{flav})
  - Most precise B^+/B^0 lifetime ratio measurement at that time

BaBar, PRL 87, 201803 (2001)

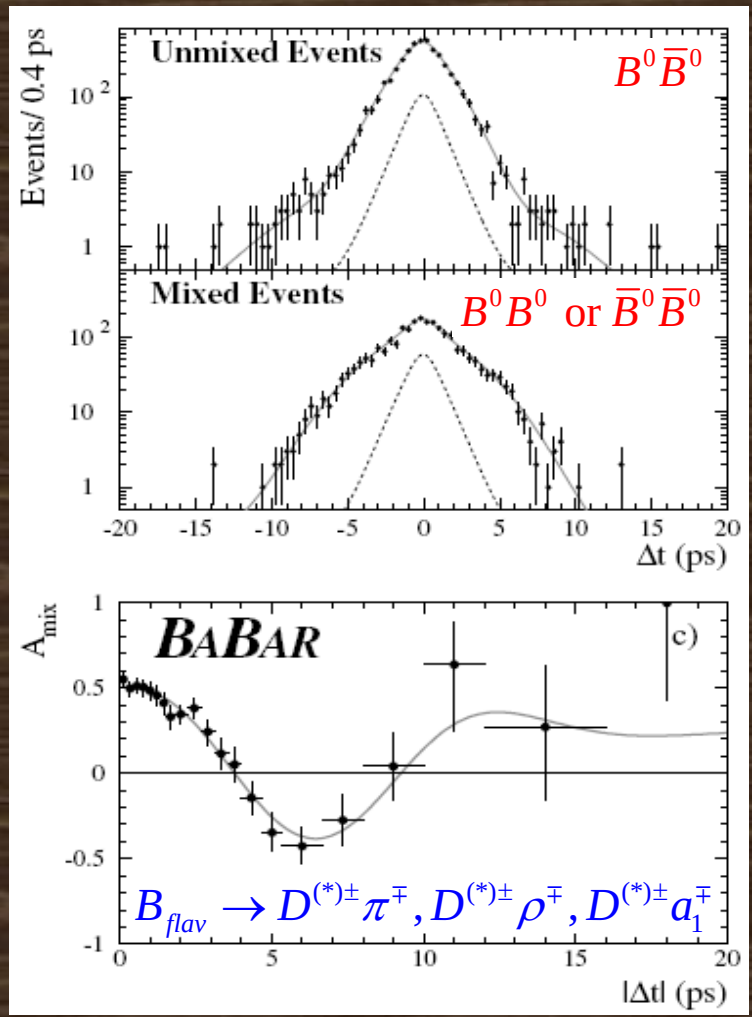


$$\tau_{B^0} = 1.546 \pm 0.032 \pm 0.022 \text{ ps},$$
$$\tau_{B^+} = 1.673 \pm 0.032 \pm 0.023 \text{ ps},$$
$$\tau_{B^+} / \tau_{B^0} = 1.082 \pm 0.026 \pm 0.012$$

B Flavor Tagging from B$\bar{B}$ Mixing

- Flavor of B_{tag} unambiguously defines flavor of B_{CP} at production
  - Determine flavor of B_{tag} from its charged decay products (l, K, high-p tracks and soft π)
  - Started out with conservative cut-based approach and slowly moved toward multivariate estimators
  - Effective tagging efficiency $\Sigma\ \varepsilon(1-2w)^2 \sim 30\%$
- Measure mis-tag rates w with B_{flav} sample
  - Mistag rates cannot be determined from B_{CP} sample, but did not want to rely on MC
  - Mistag rates in B_{flav} sample same as in B_{CP} sample, with known mixing amplitude (=1)
- Demonstrate tagging performance with precision measurement of B$\bar{B}$ mixing frequency (3.7%)
  - Together with BaBar's Δm from di-lepton analysis best measurement of Δm at that time

BaBar, PRL 88, 221802 (2001)



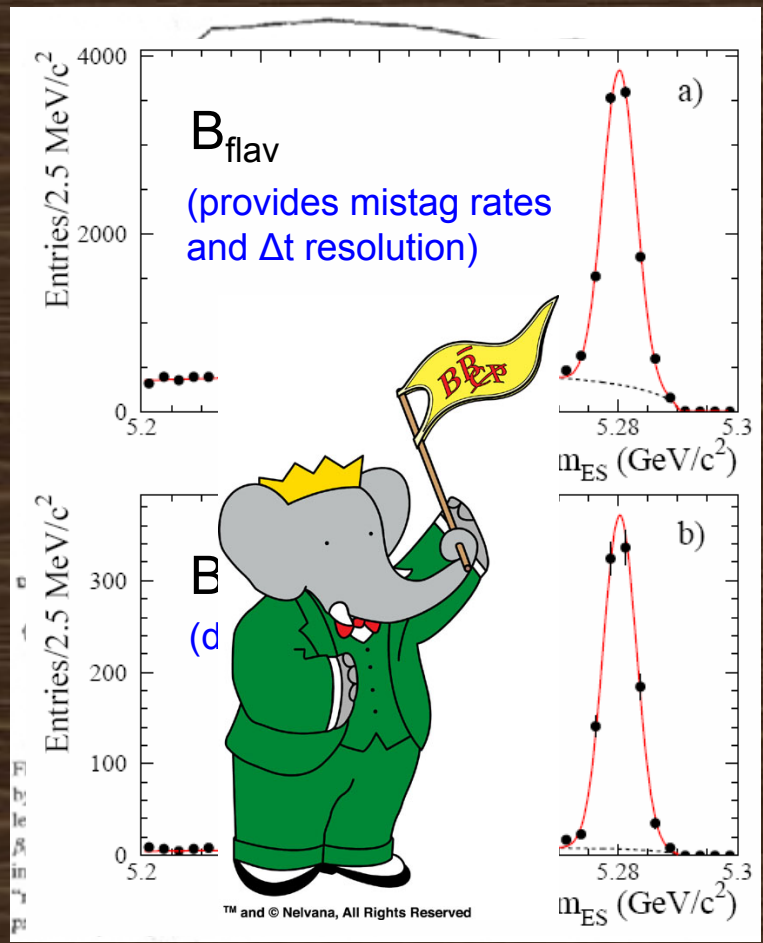
$$\Delta m_{B^0} = 0.516 \pm 0.016 \pm 0.010\ \text{ps}^{-1}$$

The Likelihood Fit

"I remember my friend Johnny von Neumann used to say, with four parameters I can fit an elephant, and with five I can make him wiggle his trunk." Enrico Fermi (1953)

- Extract sin2β with simultaneous unbinned likelihood fit to Δt spectra of B_{CP} and B_{flav} samples
  - 35 fit parameters for first paper
    - Determination of common parameters (mistag rates, Δt resolution) dominated by much larger B_{flav} sample
    - Only sin2β dominated by B_{CP} sample
- Very small total correlation between sin2β and other parameters (<10%)

Need at least 30 parameters to fit something that resembles an elephant!



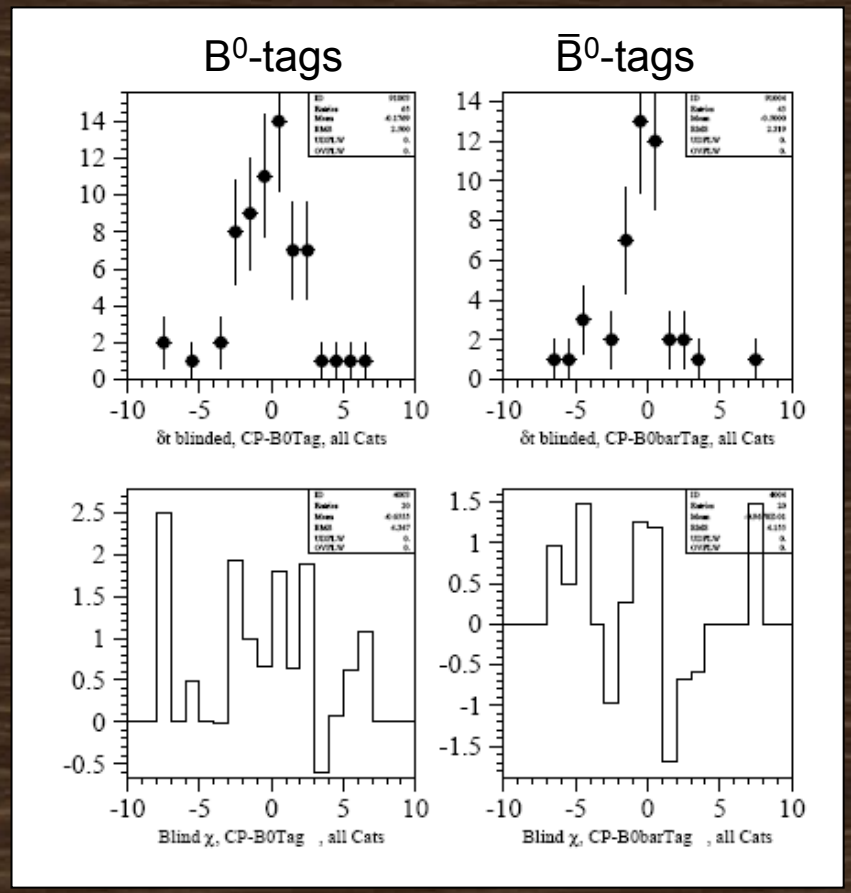
BaBar, PRD 66, 032003 (2002)

Wells J, "Least squares fitting of an elephant", Chemtech February (1975)

Blind Analysis

- Avoid possible experimenter's bias
  - e.g. towards the standard model prediction
- Sin2β measurement well suited for blind analysis
  - Value and sign of sin2β in fit are hidden
  - Apparent asymmetry in Δt distribution for B^0 and $\bar{B}^0$-tagged events are hidden
  - Systematic uncertainties are estimated before unblinding
- BaBar established a culture of removing experimenter's bias whenever possible
  - BaBar's CP asymmetry, mixing and lifetime analyses have been blinded in a similar way
  - Branching ratio measurements use "hidden signal box", etc.

The first look at blinded sin2β data (July 10, 2000)



$$\sin 2\beta(blind) = 1.22 \pm 0.37$$

Towards the First Result

- First public sin2β result targeted for ICHEP 2000 conference in Osaka (July 27- Aug 2)

- Elba BaBar meeting (May 28-31)
  - Defined the Elba flavor tagger
    - Hybrid tagger with 4 categories (lepton, kaon + 2 NN)
  - First measurement of mistag rates with B_{flav} sample presented on 3.7/fb
- SLAC BaBar meeting (July 10-13)
  - Tagging performance measured in data, Δm competitive with world's best measurement
  - First blinded CP fit on 8/fb (statistical error larger than expected, 5% probability)
- Last 2 weeks
  - Last 1/fb added on July 15
  - Unblinding of sin2β on July 17
  - Final Osaka paper (BAD 44) on July 25

- Sin2β result presented at ICHEP on July 31

Time	*Activity*	*datasample*
Elba	Extract collections of charged B's/ fully exclusive B0	2.8 fb-1
Elba to june 13th	Setup hbooks/comis for all charged B's and exclusive B0	"
"	Extract CP events (3 modes)	"
"	• Reconcile differences between TagMix analyses • Understand data/MC differences in tagging • choose 2 taggers and agree on TagMix strategy • Agree upon D*lnu selection	"
June 13th	Tag ε,w, Vertexing studies on Charged B's	"
June 13th	Freeze and QA data sample for the 27th	~6fb-1
June 13th to 27th	• Extract D*lnu collections • New ntuple production	~6 fb-1
June 27th	• CP fitting on non CP modes • Blind sin2b fit on data • Freeze and QA data sample for Osaka • CP fitting on JpsiK+	"
June 27th to CollMtg	Detailed sin2b systematics	~8fb-1
27thJune-CollMtg	• Finalize TagMix Paper • Finalize sin2b Paper	~8fb-1
CollMtg (10-13 Jul)	• Show complete blind analysis • Freeze analysis • [stop db sweeps/outages?]	~8fb-1
During Coll Mtg	Unblind analysis	"
July 25th	Practice talk for Osaka and go on VACATION !	"

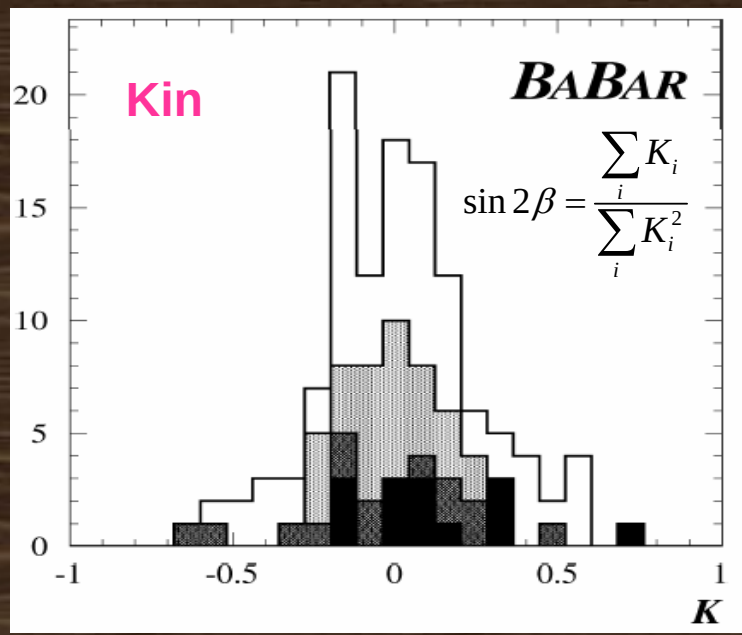
Validations, Validations, Validations, …

- Monte Carlo Studies
  - Parametrized MC and full simulation with various sin2β values
- Null-tests for CP asymmetries in B_{flav} and B^+ control samples
- 10 alternative B vertex fit configurations
- 3 independent fitting packages
- Alternative extraction of mistag rates
  - time-integrated method in optimized Δt interval (Single-Bin method)
- Alternative extraction of sin2β with Kin

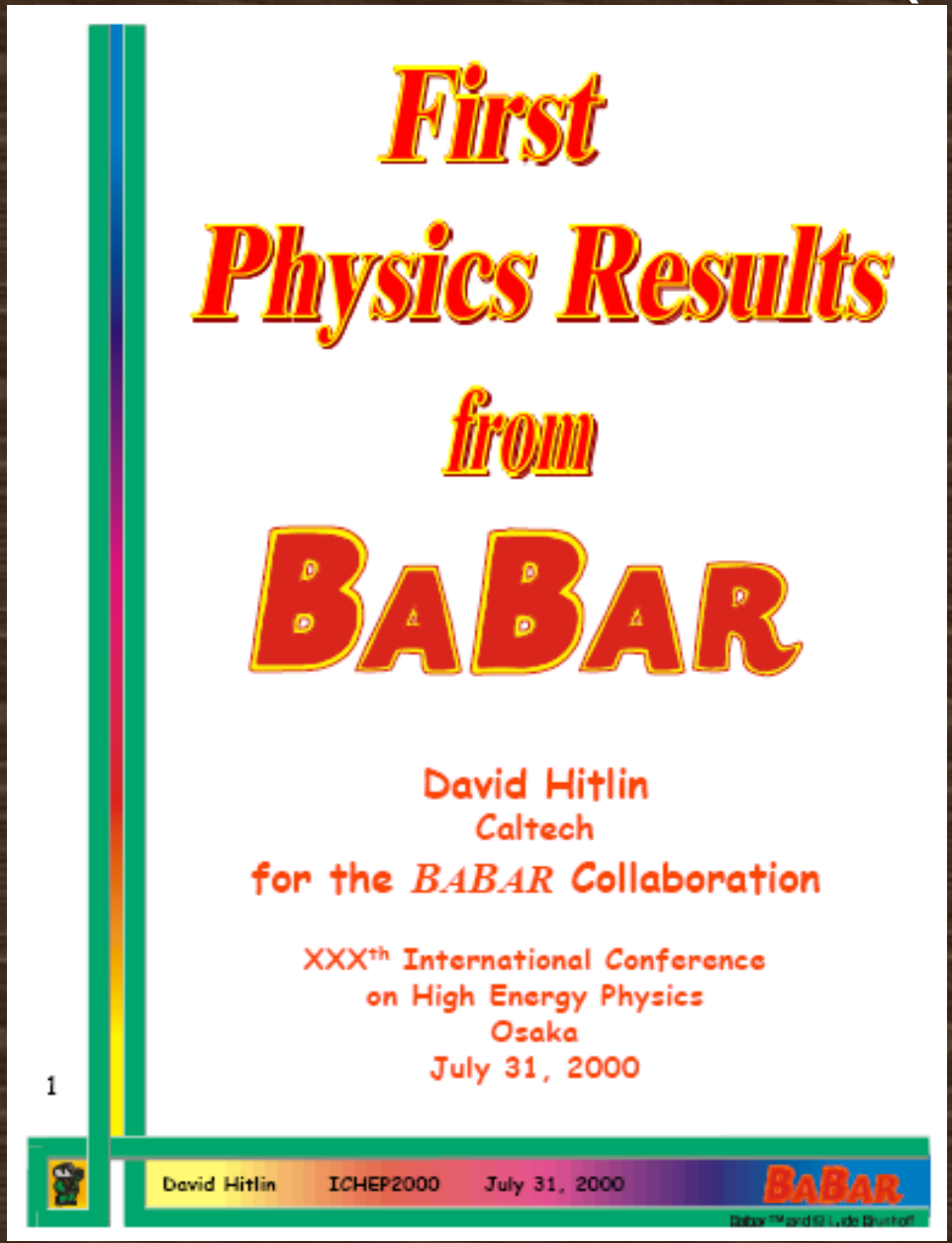
$$K \sim -\eta_{CP} \sin(\Delta m \Delta t)$$

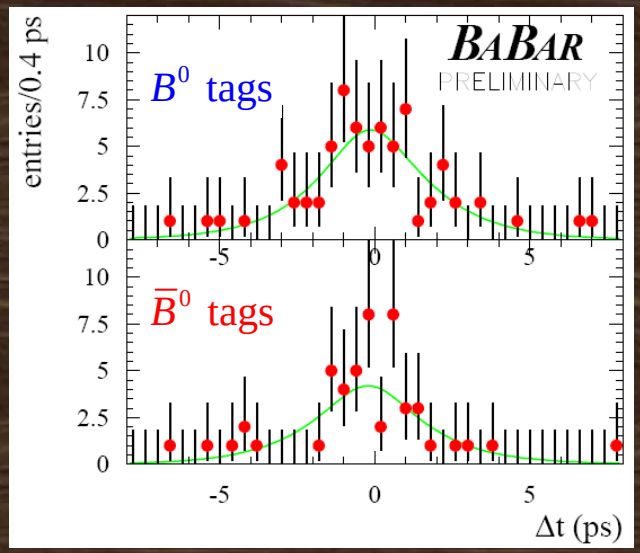
- Full measurements of τ_B and Δm

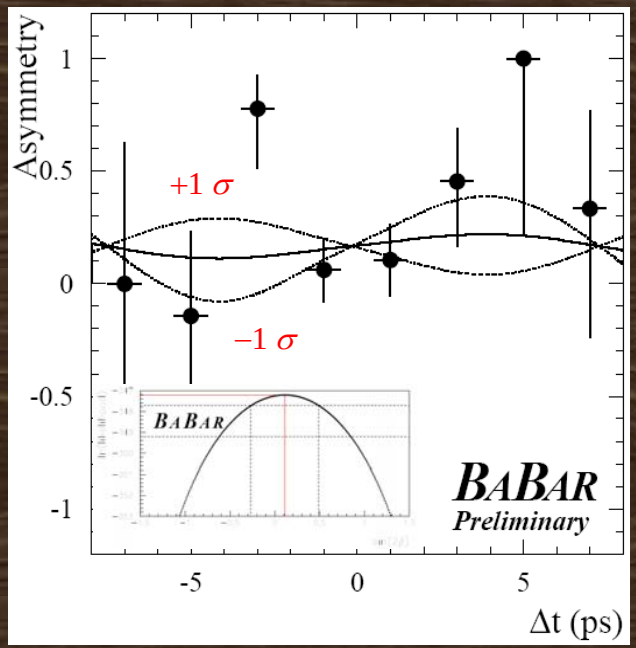
Sample	Apparent CP-asymmetry
Hadronic charged B decays	0.03 ± 0.07
Hadronic neutral B decays	-0.01 ± 0.08
$J/\psi K^+$	0.13 ± 0.14
$J/\psi K^{*0}$ $(K^{*0} \to K^+\pi^-)$	0.49 ± 0.26



ICHEP 2000 (Osaka)







BaBar, hep-ex/0008048

BaBar's First Paper

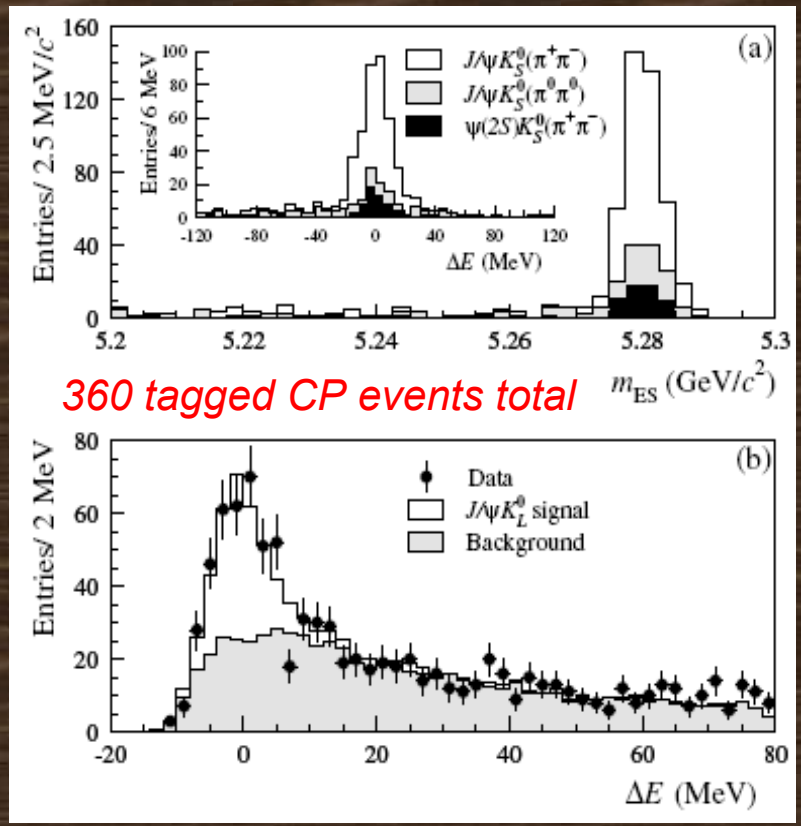
VOLUME 86, NUMBER 12 PHYSICAL REVIEW LETTERS 19 MARCH 2001

Measurement of *CP*-Violating Asymmetries in B^0 Decays to *CP* Eigenstates

- BaBar's sin2β result published on March 19, 2001 in PRL 86, 2518 (2001)
  - Back-to-back with Belle's sin2β paper
- Improvements to analysis since ICHEP
  - Reblinded after ICHEP
  - Doubled the data sample to 23M $B\bar{B}$s
  - Added $B \rightarrow J/\psi\, K^0_L$ mode
  - Combined likelihood fit to B_{CP} and B_{flav} samples with 35 free parameters
- Sin2β is slowly going up…

$$\sin 2\beta = 0.34 \pm 0.20 \pm 0.05$$

$$|\lambda| \text{ consistent with } 1$$

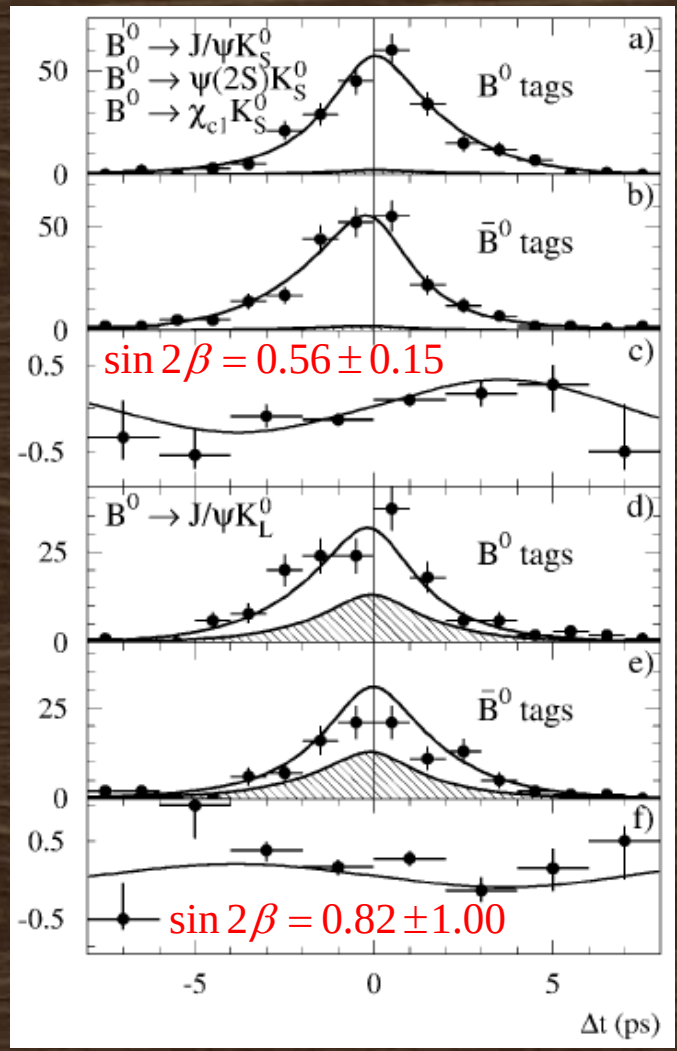


VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Observation of CP Violation in the B^0 Meson System

- Submitted to PRL on July 5, 2001
  - Belle submitted 14 days later, published back-to-back
- Analysis improvements doubled sensitivity
  - 40% more data added
  - Improved track and K^0_S reconstruction
  - Added $B \to J/\psi\, K^{0*}$ and $B \to X_{c1}\, K^0_S$ modes
  - Better SVT alignment and vertex reconstruction
- 2nd most cited BaBar physics paper

$$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05 \quad (4.1\sigma)$$
$$|\lambda| = 0.93 \pm 0.09 \pm 0.03$$



BaBar, PRL 87, 091801 (2001)

Towards a precision measurement

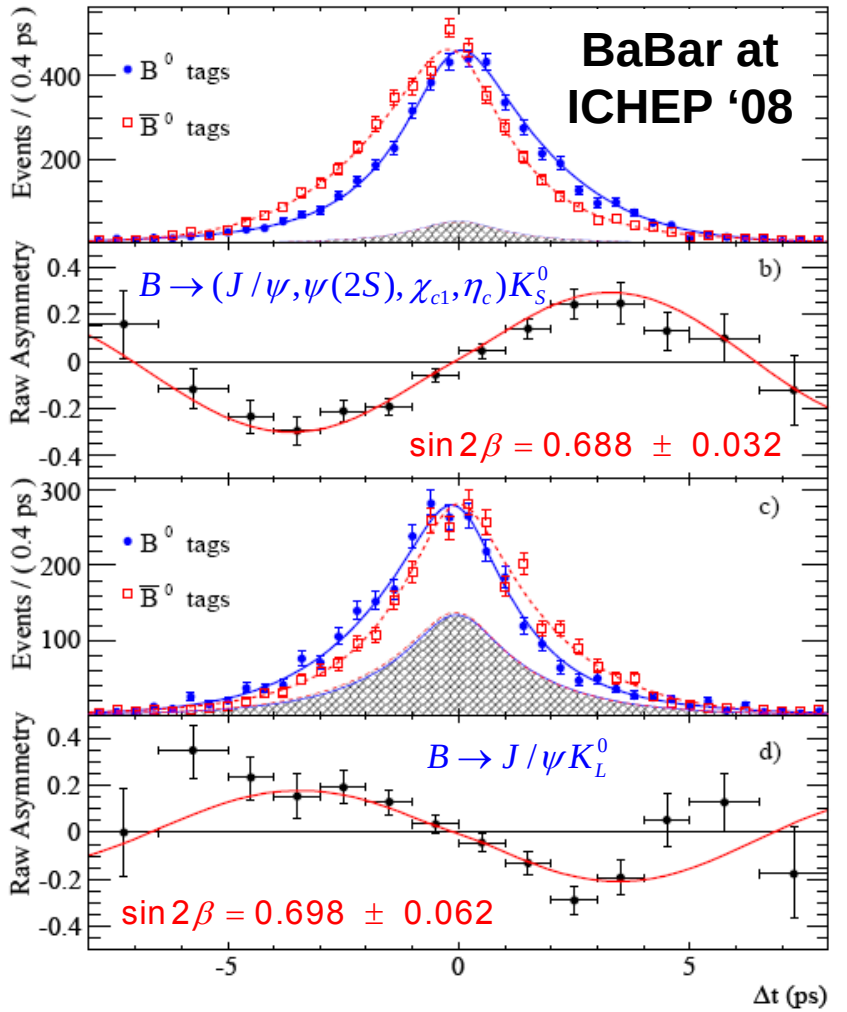
- 3 more BaBar sin2β PRLs and 2 PRDs
  - "The" sin2β PRD [PRD 66, 032003('01)]
    - Longest BaBar paper with 54 pages
  - Run 1+2 paper [PRL 89, 201802 ('02)]
    - 3rd most cited BaBar paper
  - Run 1-4 paper [PRL 94, 161803 ('05)]
  - Run 1-5 paper [PRL 99, 171803 ('07)]
  - Final sin2β result on full data set [arXiv:0808.1903, to be subm. to PRD]

- BaBar's sin2β measurement benefited from continuously improving the analysis for each publication
  - Tagging, samples, systematics,….

- After some up's and down's BaBar and Belle have converged on sin2β

$$\sin 2\beta = 0.671 \pm 0.024$$
$$C = 0.005 \pm 0.020$$

sin2β HFAG World Average

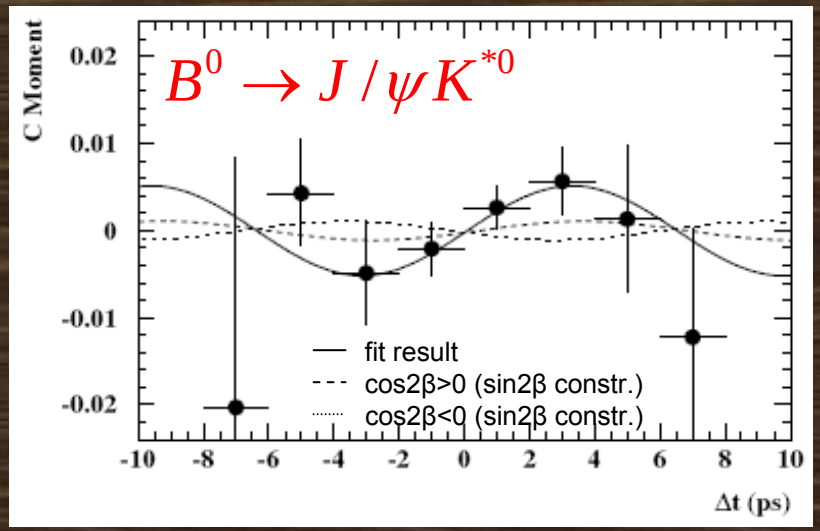


$$\sin 2\beta = 0.691 \pm 0.029 \pm 0.014$$
$$C = 0.026 \pm 0.020 \pm 0.016$$

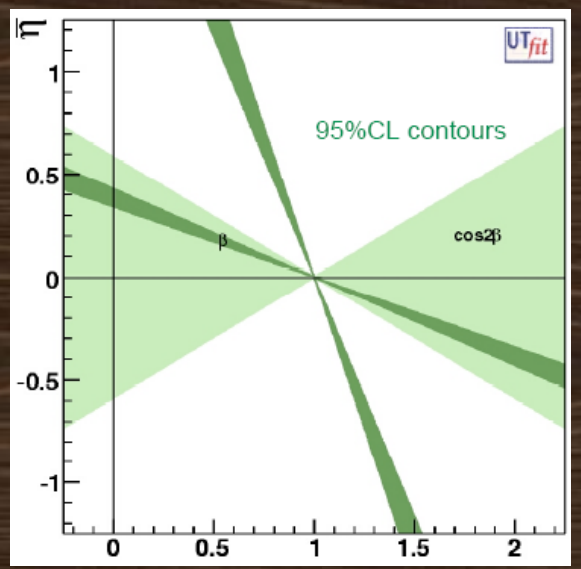
Removing the 90°–β Ambiguity

- The sign of cos2β resolves the 90°–β ambiguity in sin2β
- Interference terms between CP-odd and CP-even amplitudes in B decays to three-body or VV final states are sensitive to cos2β

BaBar, PRD 71, 032005 (2005)

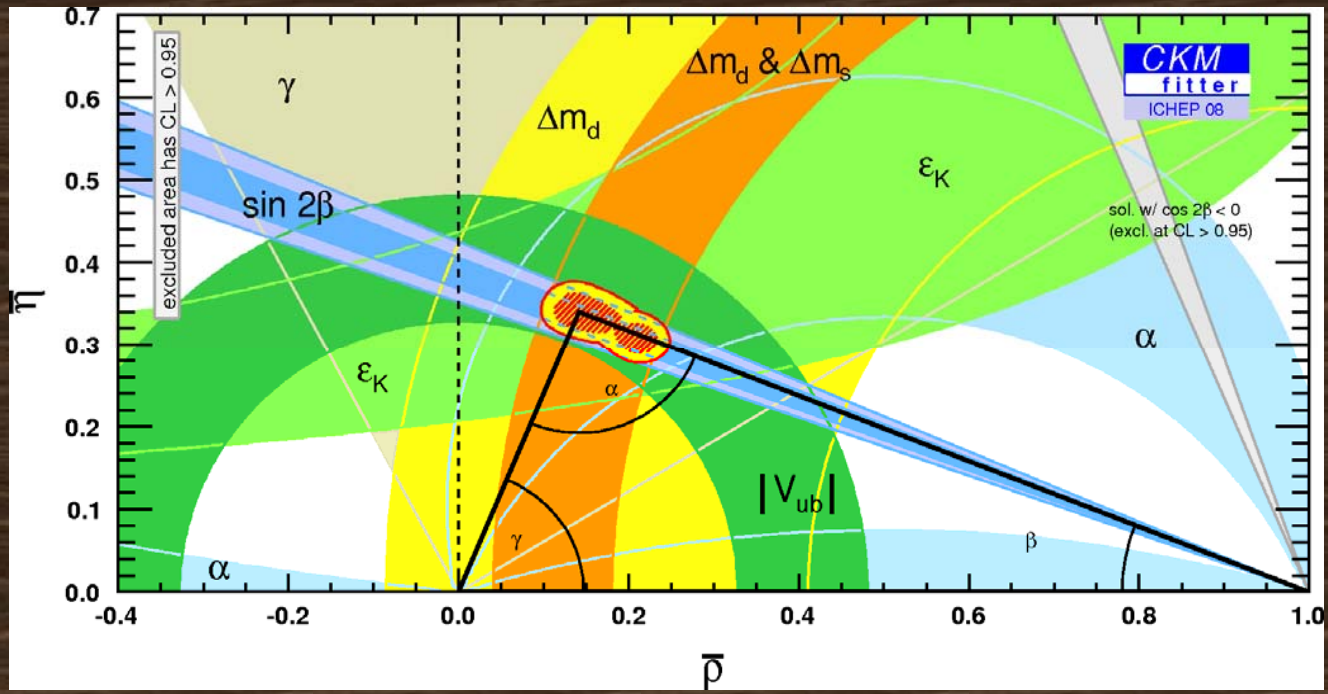


$B^0 \to J/\psi K^{*0}$ [BABAR, PRD 71, 032005 (2005)]: $\cos 2\beta > 0$ @ 89% C.L.
$B^0 \to D^{(*)0}_{K^0_S\pi^+\pi^-} h^0$ [BABAR, PRL 99, 231802 (2007)]: $\cos 2\beta > 0$ @ 86% C.L.
$B^0 \to D^{*+} D^{*-} K^0_S$ [BABAR, PRD 74, 091101 (2006)]: $\cos 2\beta > 0$ @ 94% C.L.
$B^0 \to K^+ K^- K^0_S$ [BABAR, arXiv:0808.0700 (2008)]: $\cos 2\beta > 0$ @ 4.8σ



cos2β < 0 solutions excluded: β = (21.1 ± 0.9)°

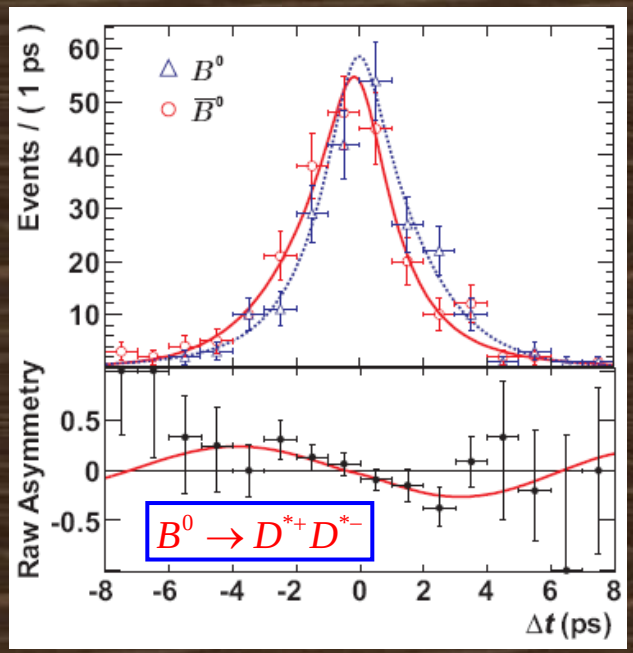
Impact on the Standard Model



- Sin2β is now the most precise constraint on the apex of the Unitarity Triangle
  - Contrary to the sides sin2β is still limited by statistics
- Sin2β serves as a benchmark for other "β" measurements from decays sensitive to New Physics (e.g. hadronic-penguins) and the sides and other angle measurements

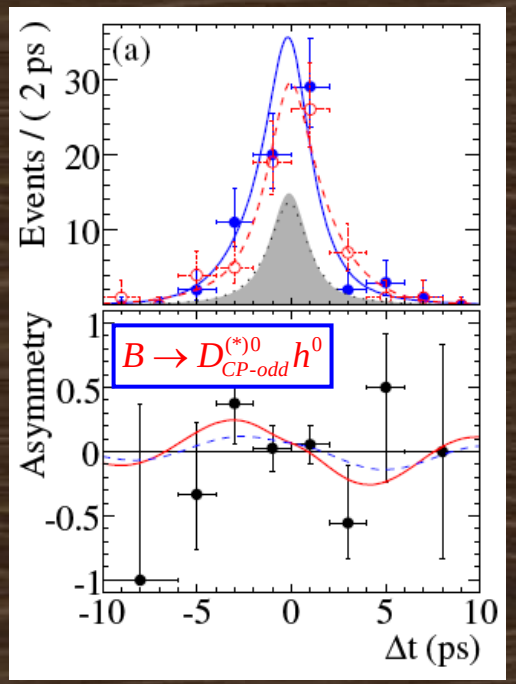
Searching for New Physics:

Sin2β in Cabibbo-suppressed Tree Decays



Large discrepancies from S = -sin2β in these modes could indicate evidence for new physics

All CP measurements are consistent with the Standard Model prediction



BaBar, arXiv 0808.1866, submitted to PRD

$S_{D^{*+}D^{*-}} = -0.70 \pm 0.16 \pm 0.03$	$S_{D^{*+}D^{-}} = -0.62 \pm 0.21 \pm 0.03$
$C_{D^{*+}D^{*-}} = +0.05 \pm 0.09 \pm 0.02$	$S_{D^{+}D^{*-}} = -0.73 \pm 0.23 \pm 0.05$
$S_{D^{+}D^{-}} = -0.63 \pm 0.36 \pm 0.05$	$C_{D^{*+}D^{-}} = +0.08 \pm 0.17 \pm 0.04$
$C_{D^{+}D^{-}} = +0.07 \pm 0.23 \pm 0.03$	$C_{D^{*}D^{*-}} = +0.00 \pm 0.17 \pm 0.03$

BaBar, PRL 99, 081801 (2007)

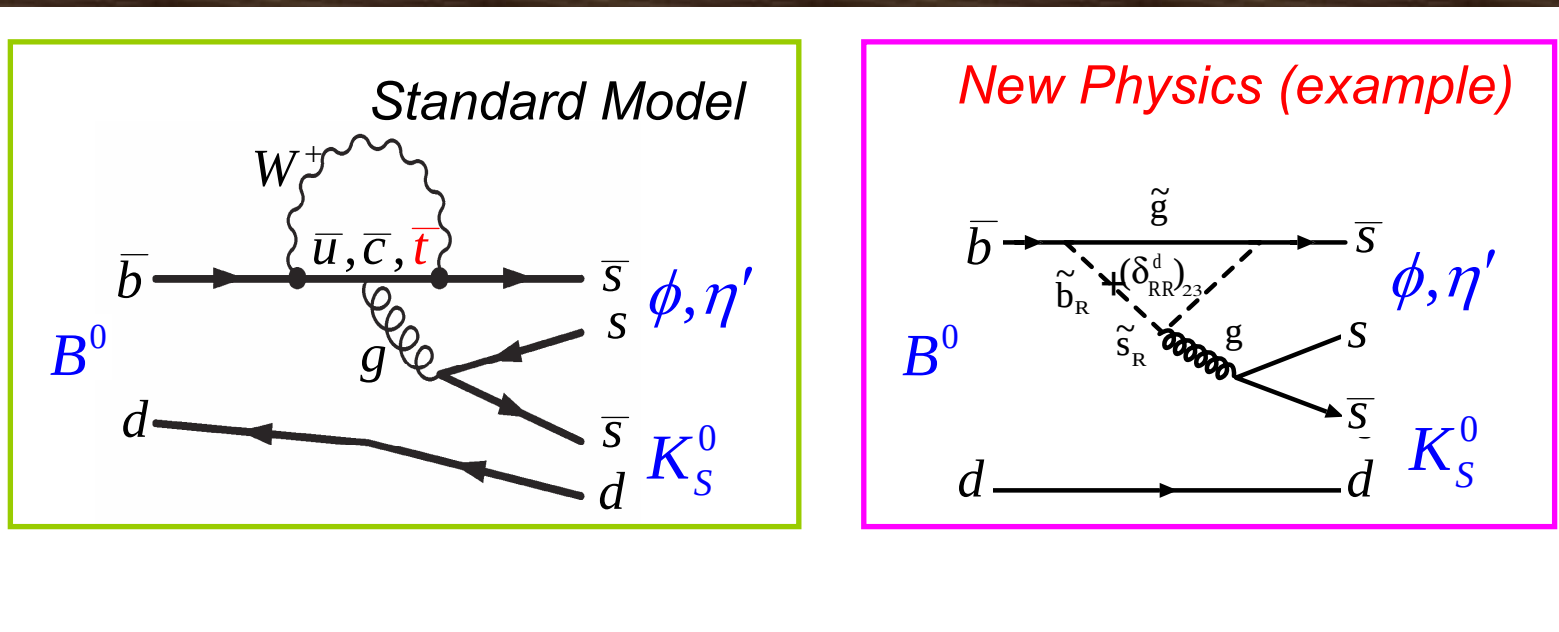
$$S_{D^{(*)0}_{CP}h^0} = -0.56 \pm 0.23 \pm 0.05$$
$$C_{D^{(*)0}_{CP}h^0} = -0.23 \pm 0.16 \pm 0.04$$

BaBar, PRL 101, 021801 (2008)

$$S_{J/\psi\pi^0} = -1.23 \pm 0.21 \pm 0.04$$
$$C_{J/\psi\pi^0} = -0.20 \pm 0.19 \pm 0.03$$

Searching for New Physics:
Sin2β in loop-dominated Decays

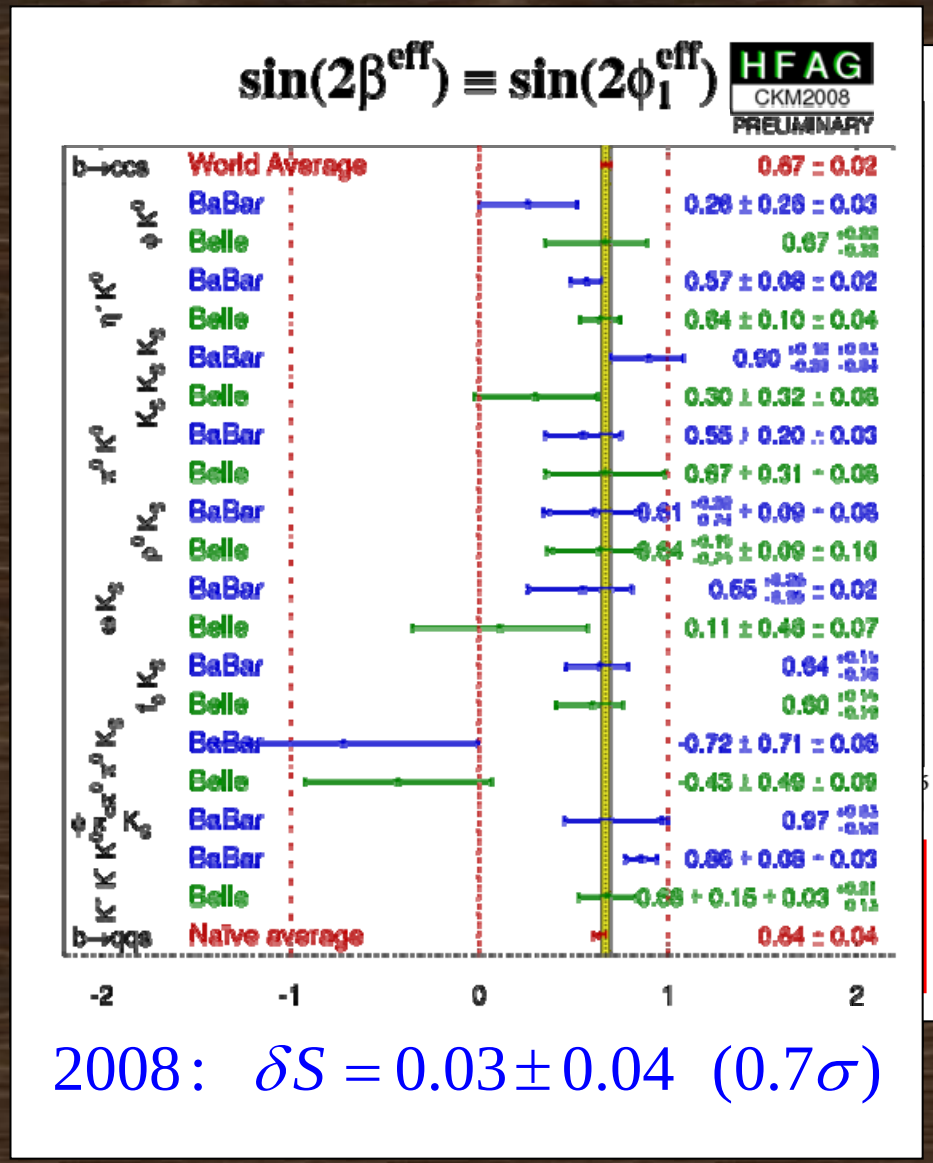
- Rare decays mediated by heavy virtual particles can receive contributions from New Physics



- CP violating amplitudes of such decays predicted by the Standard Model could differ from actual observations

CP Asymmetries in Penguin Decays

- Measured S_{CP} in many penguin-dominated modes and compared to sin2β measured in $B^0 \to (c\bar{c})K$
- Most significant difference in "naïve" penguin average reached in 2004
- More precise measurements have decreased the significance of δS below 1σ
  - Some measurements come now from complicated 3-body time-dependent Dalitz analyses
  - S_{CP} in charmless penguin modes is still a good place to look for new physics, but no evidence with BaBar statistics



$$2008: \quad \delta S = 0.03 \pm 0.04 \quad (0.7\sigma)$$

Conclusions

- Sin2β measurements by the B-factories established CP violation in the B system
  - Confirmed CKM mechanism as dominant source for CP violation in quark mixing
- Sin2β analysis had a large impact on the whole BaBar physics analysis program
  - Pioneered the time-dependent analysis techniques
    - Flavor tagging, vertex and Δt reconstruction
    - Many-parameter likelihood fits, blind analysis techniques
- High standards imposed on sin2β measurement laid the foundation for the quality, thoroughness and conservatism that is maintained until today in BaBar's analysis program and review process