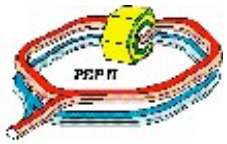


SLAC
NATIONAL ACCELERATOR LABORATORY

Recent Results on CP and T Violation in Hadronic B-meson Decays at BaBar

Tomo Miyashita
Caltech

Representing
The BaBar Collaboration
August 15, 2013


BABAR

Overview

α

- "Measurement of *CP*-violating asymmetries in $B^0 \to (\rho\pi)^0$ decays using a time-dependent Dalitz plot analysis"

Phys. Rev. D 88, 012003 (2013)

β

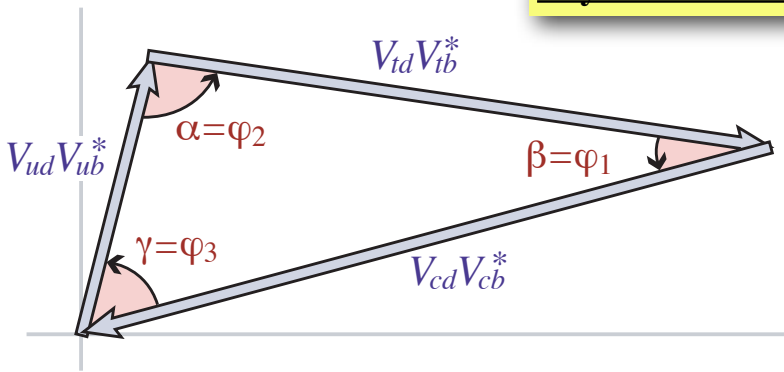
- "Measurement of the time-dependent *CP* asymmetry of partially reconstructed $B^0 \to D^{*+}D^{*-}$ decays" **Phys. Rev. D 86, 112006 (2012)**

γ

- "Obvservation of direct *CP* violation in the measurement of the CKM angle γ with $B^{\pm} \to D^{(*)}K^{(*)\pm}$ decays" **Phys. Rev. D 87, 052015 (2013)**

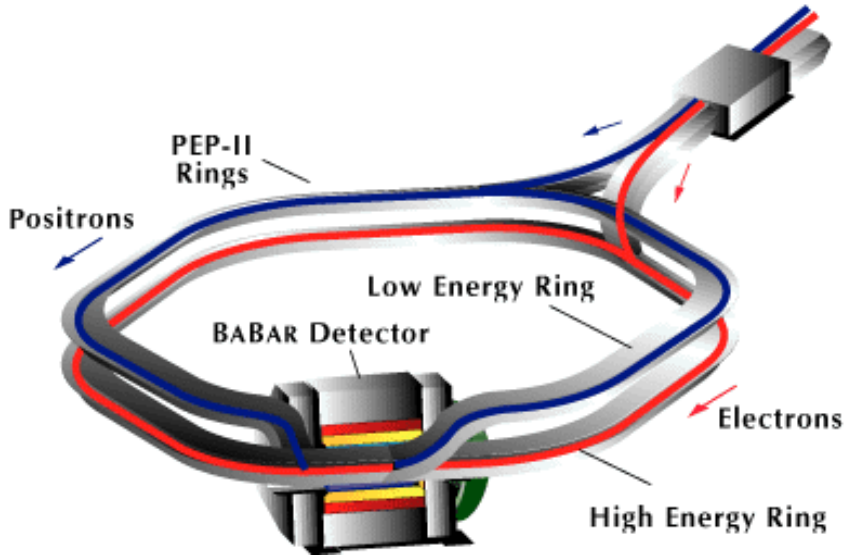
- "Observation of time reversal violation in the B^0 meson system"

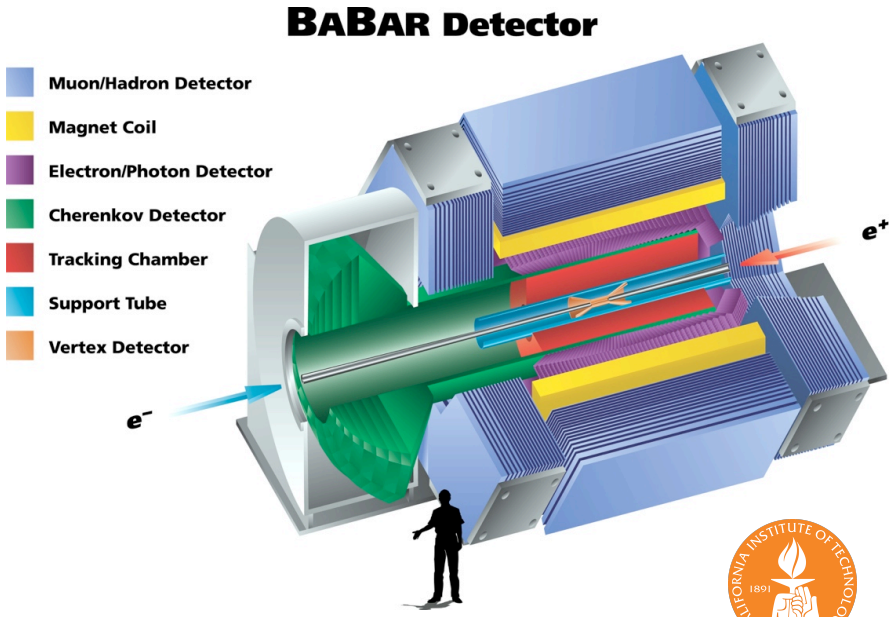
Phys. Rev. Lett. 109, 211801 (2012)



The BaBar Experiment

- Data collected by the BaBar detector at the PEP-II asymmetric-energy electron-positron collider at the SLAC National Accelerator Laboratory
- All analyses use the full dataset of ~ 430 fb^{-1} collected at the $\Upsilon(4S)$ resonance
  - Though some of the measurements used in the gamma combination only used a subset of the data
- Approximately 470×10^6 $B\overline{B}$ pairs

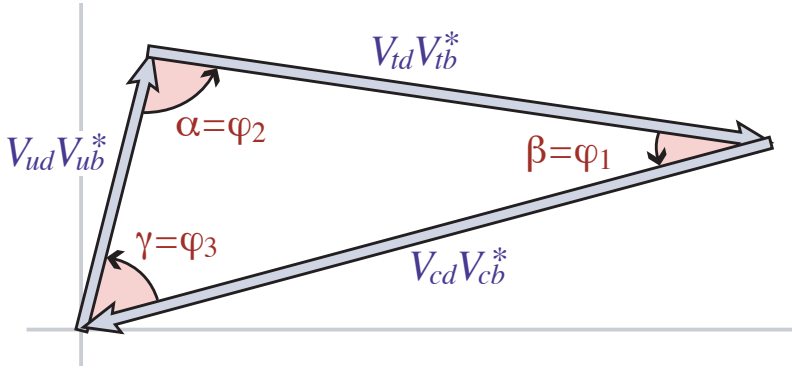




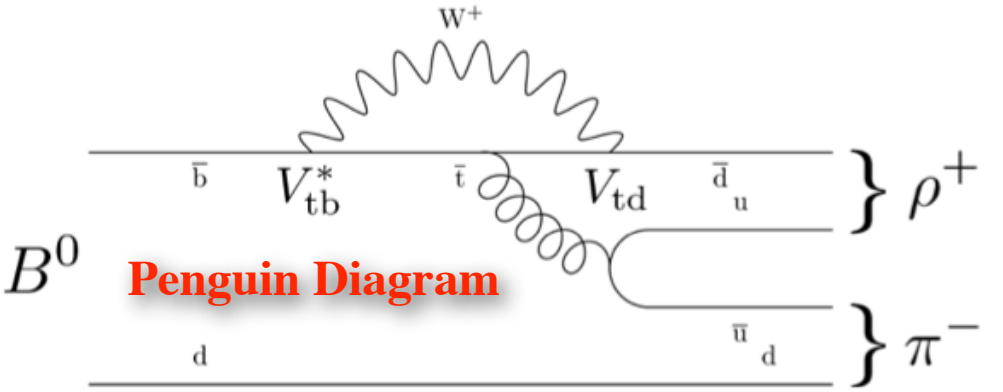
$B^0 \to \rho\pi$ CP Violation Analysis I

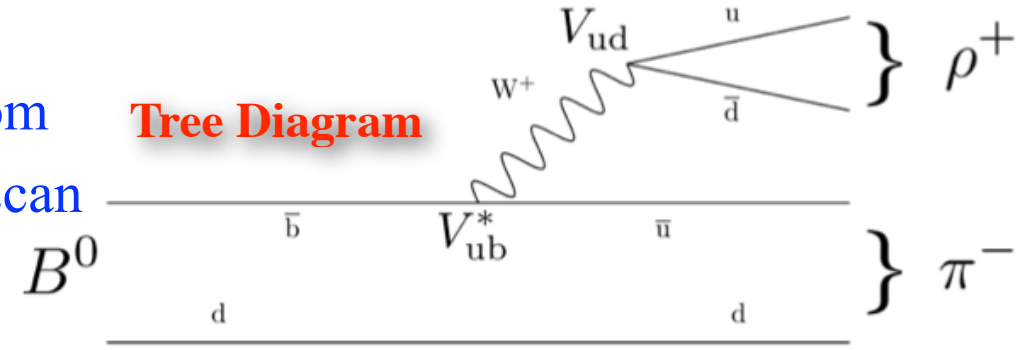
- $B^0 \to \pi^+\pi^-\pi^0$ time-dep *CPV* measurement

Phys. Rev. D 88, 012003 (2013)



- Dominated by $B^0 \to \rho^{\pm}\pi^{\mp}$
- Extensive update and reoptimization of a 2007 BaBar analysis*
- Extracts information about alpha, and other parameters
  - Interference between tree and penguin modes and decays w/ and w/o mixing provides sensitivity to alpha
- The use of a full Dalitz plot analysis reduces ambiguities found in analyses that ignore the interference regions
- Isospin relations allow information from charged B decays to be used in alpha scan





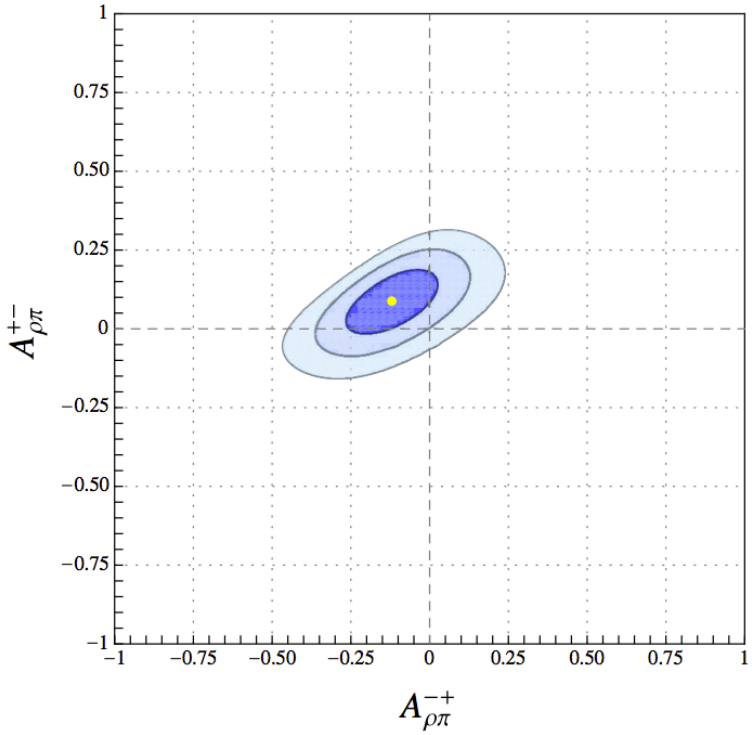
*Phys. Rev. D 76, 012004 (2007)

$B^0 \to \rho\pi$ CP Violation Analysis II

- Direct *CPV* asymmetries extracted in 2D scan:

$$\mathcal{A}_{\rho\pi}^{+-} \equiv \frac{\Gamma(\bar{B}^0 \to \rho^- \pi^+) - \Gamma(B^0 \to \rho^+ \pi^-)}{\Gamma(\bar{B}^0 \to \rho^- \pi^+) + \Gamma(B^0 \to \rho^+ \pi^-)} = 0.09^{+0.05}_{-0.06} \pm 0.04$$

$$\mathcal{A}_{\rho\pi}^{-+} \equiv \frac{\Gamma(\bar{B}^0 \to \rho^+ \pi^-) - \Gamma(B^0 \to \rho^- \pi^+)}{\Gamma(\bar{B}^0 \to \rho^+ \pi^-) + \Gamma(B^0 \to \rho^- \pi^+)} = -0.12 \pm 0.08^{+0.04}_{-0.05}$$



  - Origin (no direct *CPV*) is ~2σ from central value
  - Previous results:

BaBar 2007

$$\mathcal{A}_{\rho\pi}^{+-} = 0.03 \pm 0.07 \pm 0.04$$
$$\mathcal{A}_{\rho\pi}^{-+} = -0.32 \pm 0.16^{+0.09}_{-0.10}$$

Belle 2008

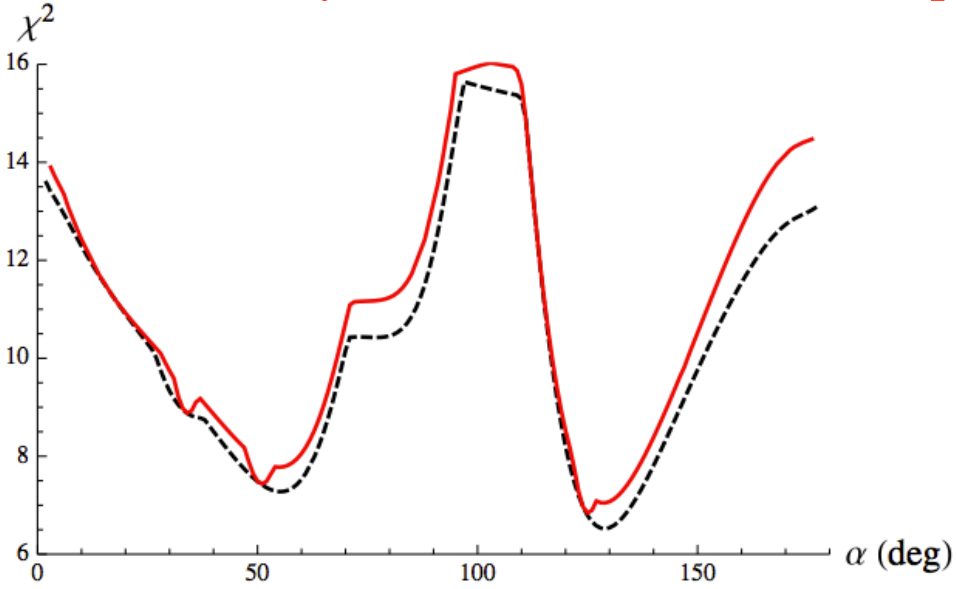
$$\mathcal{A}_{\rho\pi}^{+-} = 0.21 \pm 0.08 \pm 0.04$$
$$\mathcal{A}_{\rho\pi}^{-+} = 0.08 \pm 0.16 \pm 0.11$$

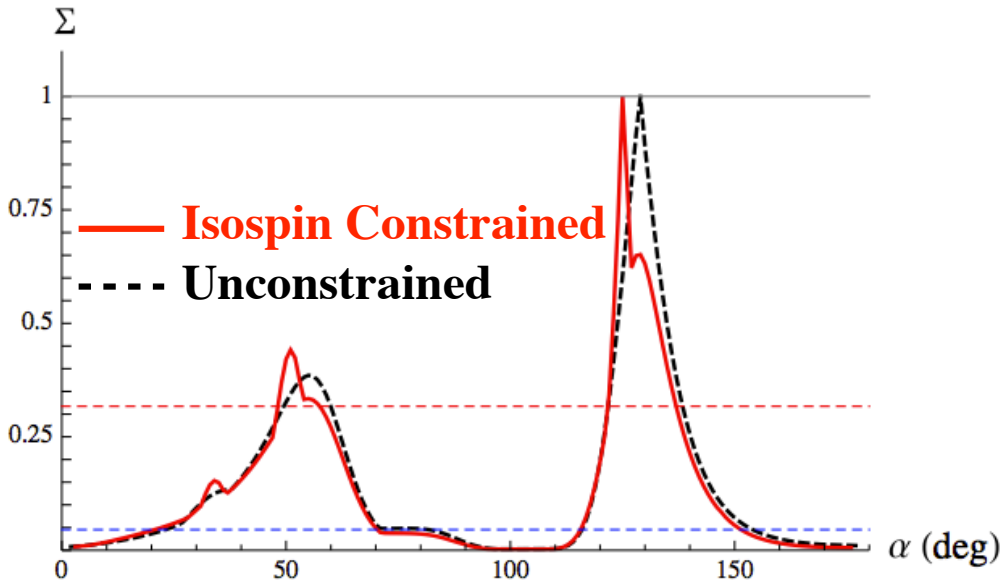
- The 26 physics parameters describing the $B^0 \to \rho\pi$ decay are extracted with, on average, 0.47 times the statistical uncertainties from the previous BaBar measurement

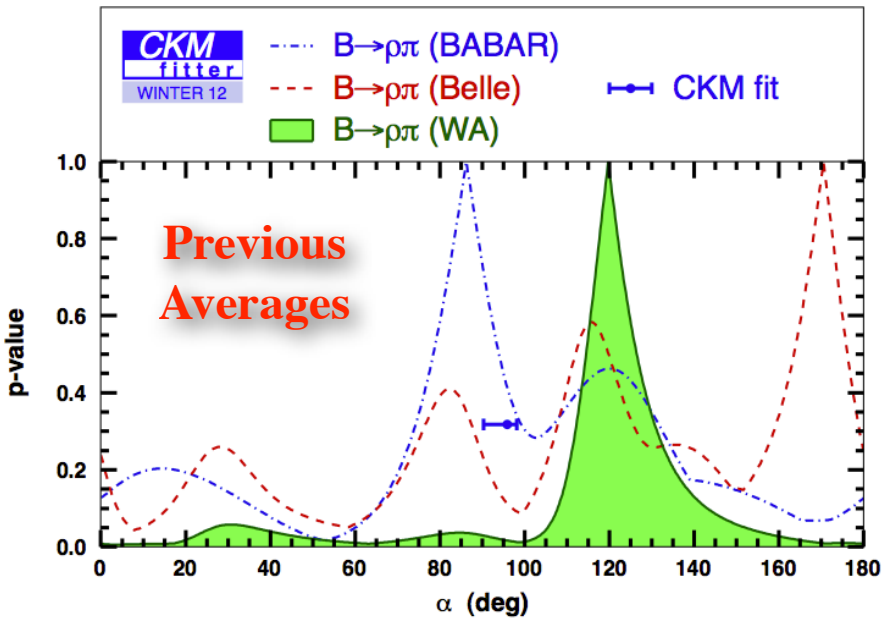
- Studies find that the 26 physics parameters are robustly extracted with our current statistical sensitivity

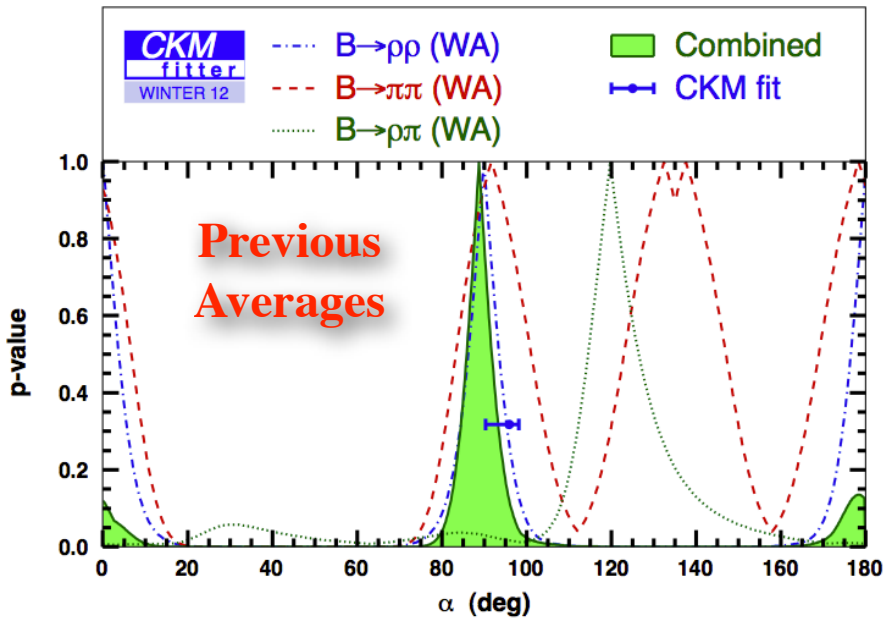
$B^0 \to \rho\pi$ CP Violation Analysis III

- We extract information about alpha from a chi2 scan
- Notably, studies reveal that the alpha scan is not robust with current statistics



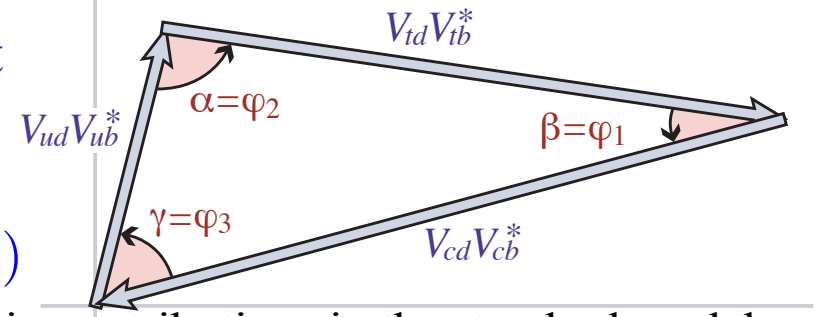






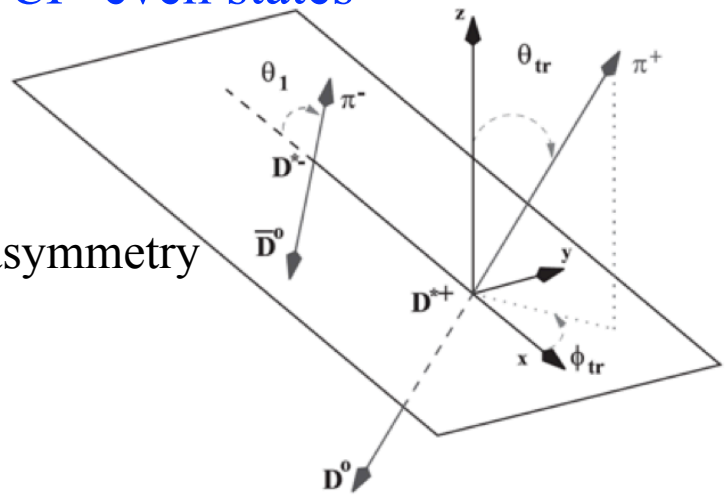
$B^0 \to D^{*+}D^{*-}$ CP Violation Analysis I

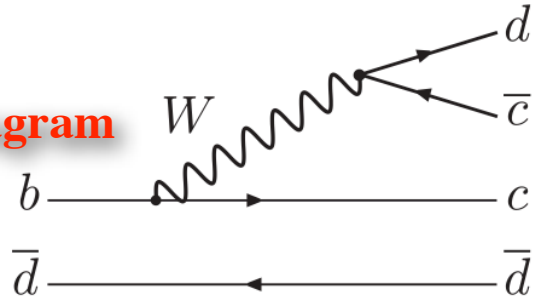
- $b \to c\bar{c}d$ time-dependent *CPV* measurement
- In the absence of penguin contribs, would yield same $\sin 2\beta$ as from $b \to c\bar{c}s$ $(J/\psi K)$
  - Only expect correction of a few % due to penguin contributions in the standard model
  - Large discrepancy between $\sin 2\beta$ in the two modes could indicate new physics
- Vector-Vector final state is a mixture of *CP*-odd and *CP*-even states
  - Need angular analysis to separate *CP* states
  - Using fully reconstructed events, BaBar and Belle have measured the *CP*-odd fraction $R_\perp$ and the time-dep *CP* asymmetry

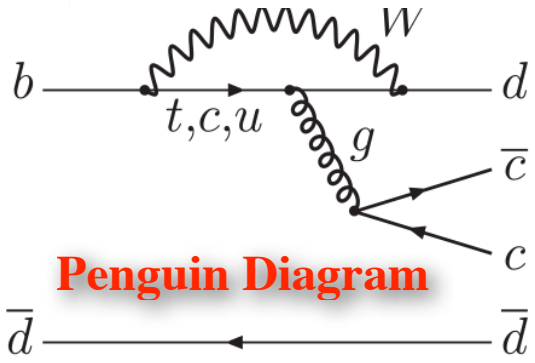


$$R_\perp = \frac{|A_\perp^0|^2}{|A_0^0|^2 + |A_\parallel^0|^2 + |A_\perp^0|^2}$$

CP=+1 for $A_\parallel$,A_0
CP=–1 for $A_\perp$

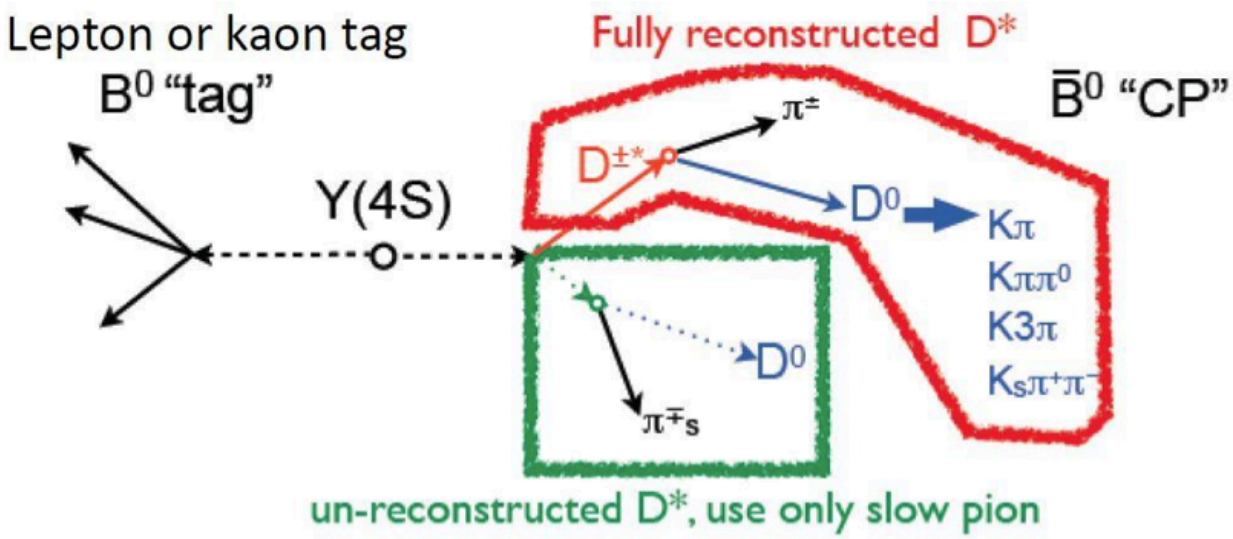






$B^0 \to D^{*+} D^{*-}$ CP Violation Analysis II

- Use partial reconstruction
  - One $D^*$is fully reconstructed from $D^* \to D^0 \pi$ where the D^0 decays to one of 4 modes
  - The fully reconstructed D^* is matched with a slow pion of opposite charge
  - The D^* candidate is selected if the kinematics are consistent with $B^0 \to D^* D^0 \pi$ where the D^0 is missing
  - Partial reconstruction provides ~5x the sig evts from a full reco, but with higher background and larger systematic errors
- The flavor of the other B meson is determined by either "lepton" or "kaon" tagging



$B^0 \to D^{*+}D^{*-}$ CP Violation Analysis III

- **Results:**
  - Combined parameters:

$$C = +0.15 \pm 0.09 \pm 0.05$$
$$S = -0.34 \pm 0.12 \pm 0.09$$

PDG 2012 WA
$\sin 2\beta = 0.679 \pm 0.020$

  - Neglecting penguin amplitudes:

$$S_+ = -S_-,\ C_+ = -C_-$$
$$C = C_+ \qquad S = S_+(1 - 2R_\perp)$$

$\Longrightarrow$

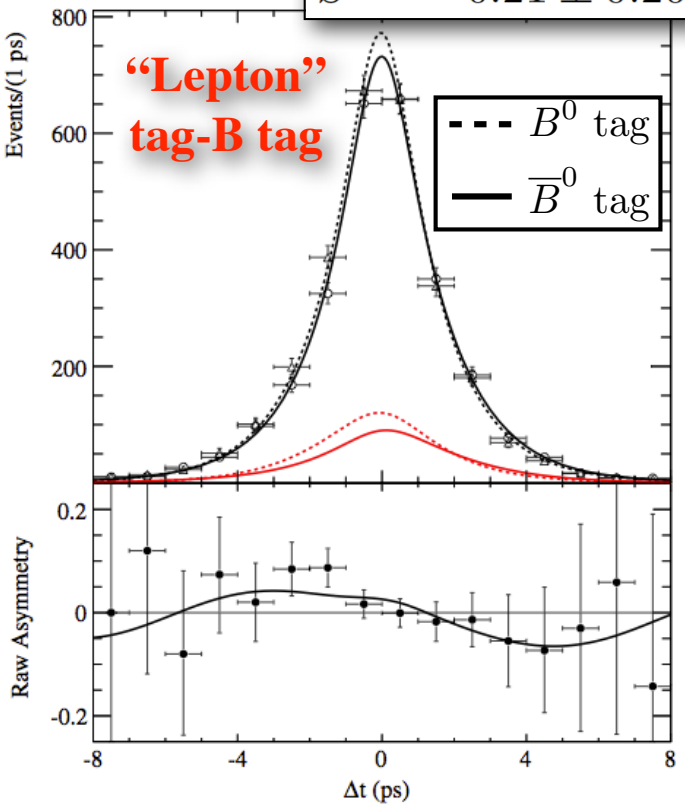
$$C_+ = +0.15 \pm 0.09 \pm 0.04$$
$$S_+ = -0.49 \pm 0.18 \pm 0.07 \pm 0.04$$

$S_+ \approx -\sin 2\beta$

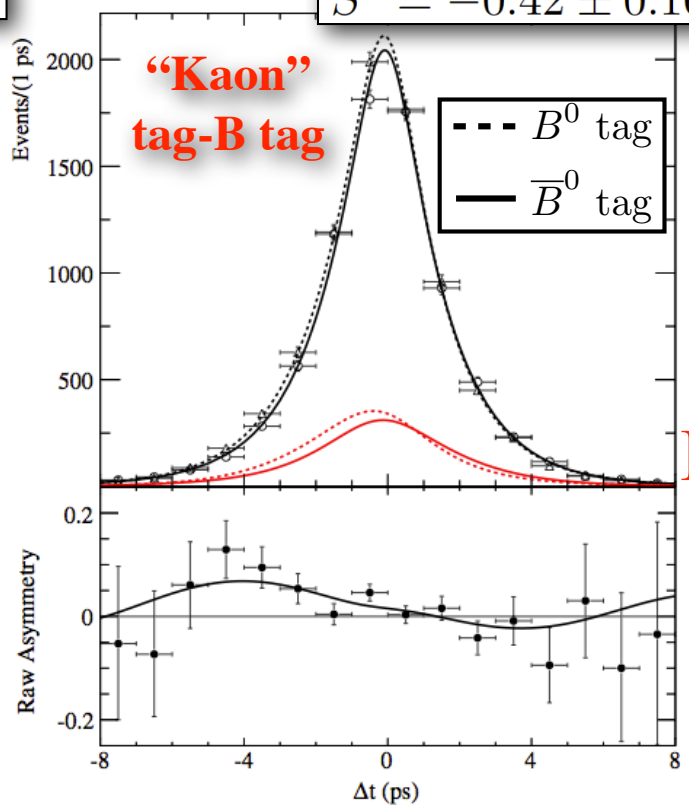
for $R_\perp = 0.158 \pm 0.029$*

*Phys. Rev. D 79, 032002 (2009)

$C = +0.20 \pm 0.15$
$S = -0.21 \pm 0.20$



$C = +0.12 \pm 0.11$
$S = -0.42 \pm 0.16$



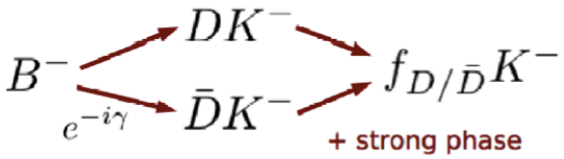
BaBar Full Reco*
$C_+ = +0.00 \pm 0.12 \pm 0.02$
$S_+ = -0.76 \pm 0.16 \pm 0.04$

Results are consistent with previous BaBar and Belle measurements

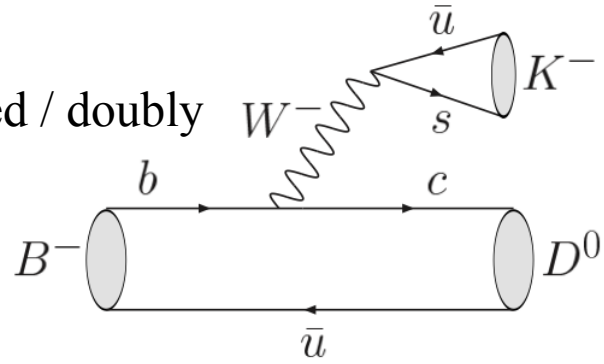
Overview of Gamma Measurement Methods

- Typically measure γ from interference between $B^- \to DK^-$ $(D \to f)$ and $B^- \to \overline{D}K^-$ $(\overline{D} \to f)$ where final state f is common to D and $\overline{D}$

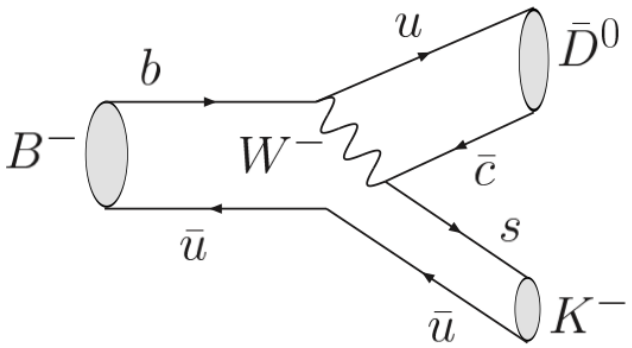
- Our gamma measurements are conveniently classified by the final state of the D meson:



- GLW Method **Phys. Rev. D 82, 072004 (2010)**
  - Reconstruct D from *CP* eigenstates (e.g., $D \to K^+K^-$, $D \to K_S\pi^0$)
- ADS Method **Phys. Rev. D 82, 072006 (2010)**
  - Use interference between decay chains involving Cabibbo-favored / doubly Cabibbo-suppressed D decays (e.g., $D \to K^-\pi^+$)
  - Enhanced interference, but poor statistics



- GGSZ Method (most precise) **Phys. Rev. Lett. 105, 121801 (2010)**
  - Use 3-body self-conjugate modes (e.g., $D \to K_S\pi^+\pi^-$)
  - Hadronic D-decay parameters vary across Dalitz Plot, aiding in gamma determination



Combined γ Measurement Using $B^{\pm} \to D^{(*)} K^{(*)\pm}$ I

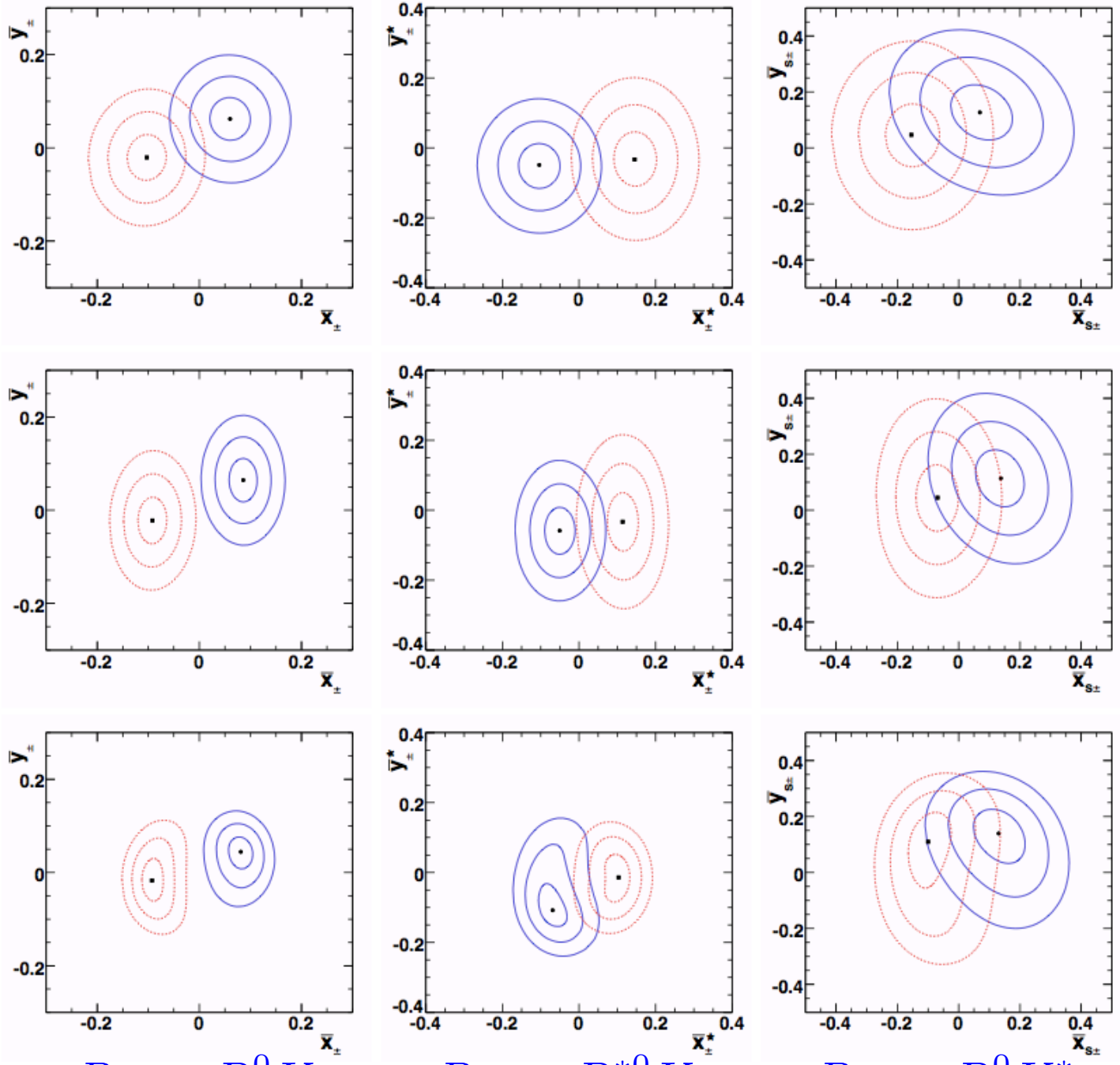
- Combination strategy
  - Parameterize likelihood shapes and convolve with systematic errors
  - Express GLW and ADS parameters in cartesian coordinates
  - Build global likelihood function from the product of partial likelihoods for GGSZ, GLW, and ADS measurements (and including external constraints for hadronic D parameters)
  - Maximize likelihood and extract best values of cartesian coordinates and D hadronic decay parameters
  - Plot projections of cartesian coordinates
  - Compute gamma

Combined γ Measurement Using $B^{\pm} \to D^{(*)} K^{(*)\pm}$ II

GGSZ

GGSZ + GLW

GGSZ + GLW + ADS



Combined γ Measurement Using $B^{\pm} \to D^{(*)}K^{(*)\pm}$ III

- Extraction of gamma
  - Transform cartesian coordinates into polar coordinates

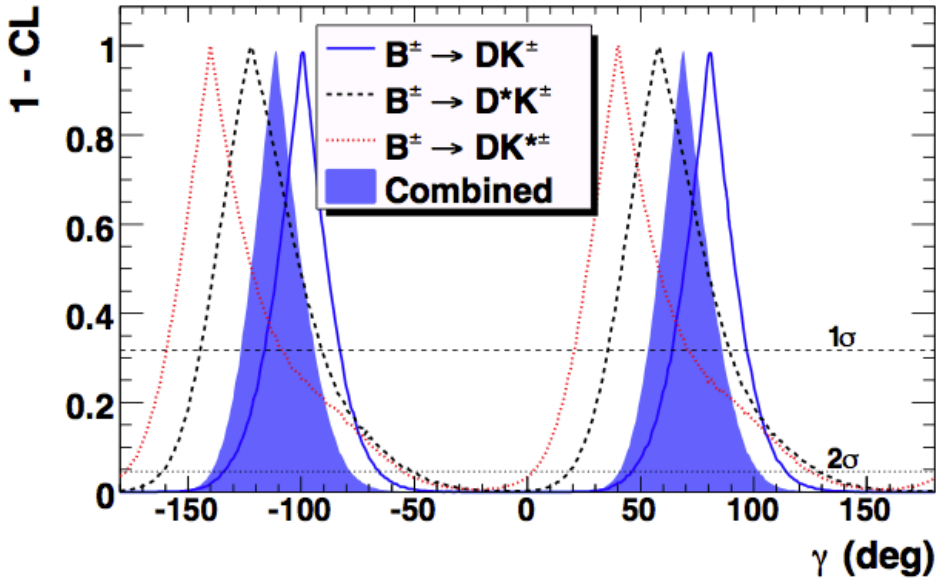
$$x_{\pm} = \mathrm{Re}[r_B e^{i(\delta_B \pm \gamma)}]$$
$$y_{\pm} = \mathrm{Im}[r_B e^{i(\delta_B \pm \gamma)}]$$

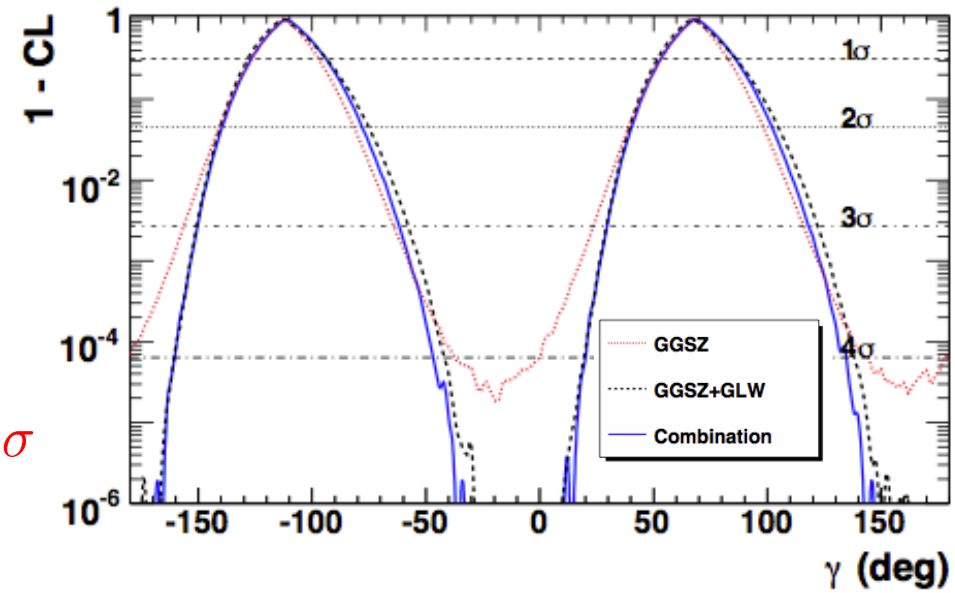
$$A(B^- \to D^0 K^-) = A_c e^{i\delta_c} \qquad r_B = A_u/A_c$$
$$A(B^- \to \bar{D}^0 K^-) = A_u e^{i(\delta_u - \gamma)} \qquad \delta_B = \delta_u - \delta_c$$

  - Use frequentist approach to obtain 1D confidence intervals in a scan of gamma

$$\chi^2(\gamma, \mathbf{u}) \equiv -2\Delta \ln \mathcal{L}(\gamma, \mathbf{u})$$
$$\equiv -2[\ln \mathcal{L}(\gamma, \mathbf{u}) - \ln \mathcal{L}_{\max}]$$

  - Change in chi2 is converted into 1-C.L. using Monte Carlo approach that accounts for non-gaussian behavior





- 5.9σ significance of *CP* violation (vs. 3.9σ for GGSZ only)
- Our 1σ and 2σ constraints have not improved, but our constraints are better at larger # of σ

$$\gamma = (69^{+17}_{-16})^{\circ}$$

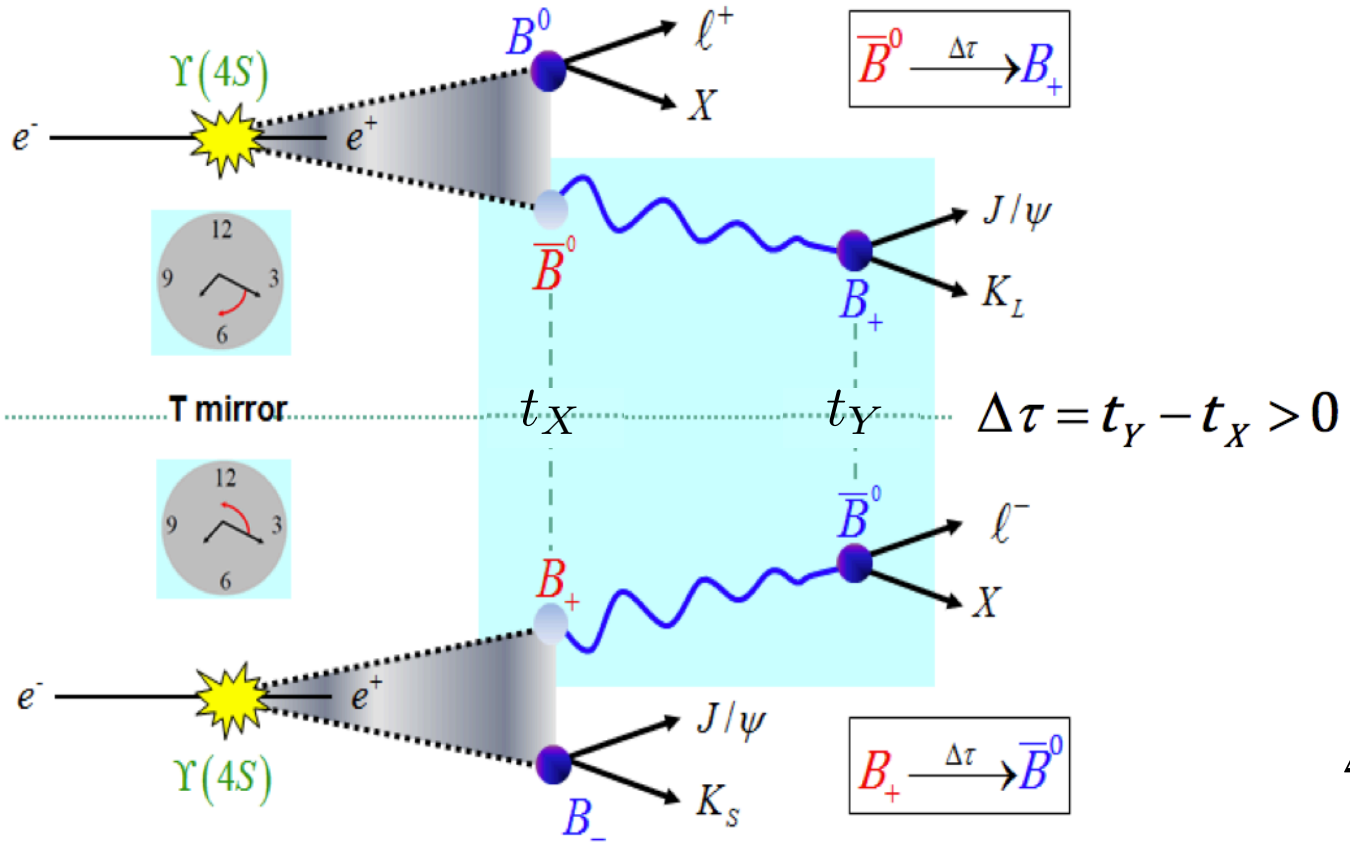
T Violation Measurement I

- Direct measurement of T violation independent of assumptions about *CPT*
- Takes advantage of the fact that B-mesons are produced as entangled pairs in $\Upsilon(4S)$ decays
  - Can be expressed in terms of either flavor-eigenstates, B^0 and $\overline{B}^0$, or the states B_+ and B_-
- The states B_+ and B_- are tagged by decays to $J/\psi K_L$ (*CP*-even) and $J/\psi K_S$ (*CP*-odd), respectively
- Flavor eigenstates can be tagged by semileptonic B decays to $\ell^+ X$ and $\ell^- X$
- Search for T violation by comparing rates for transitions between flavor and *CP* states with the rates for the time-reversed processes

$$A_T = \frac{P(a \to b) - P(b \to a)}{P(a \to b) + P(b \to a)}$$

T Violation Measurement II

- Example decay sequence:



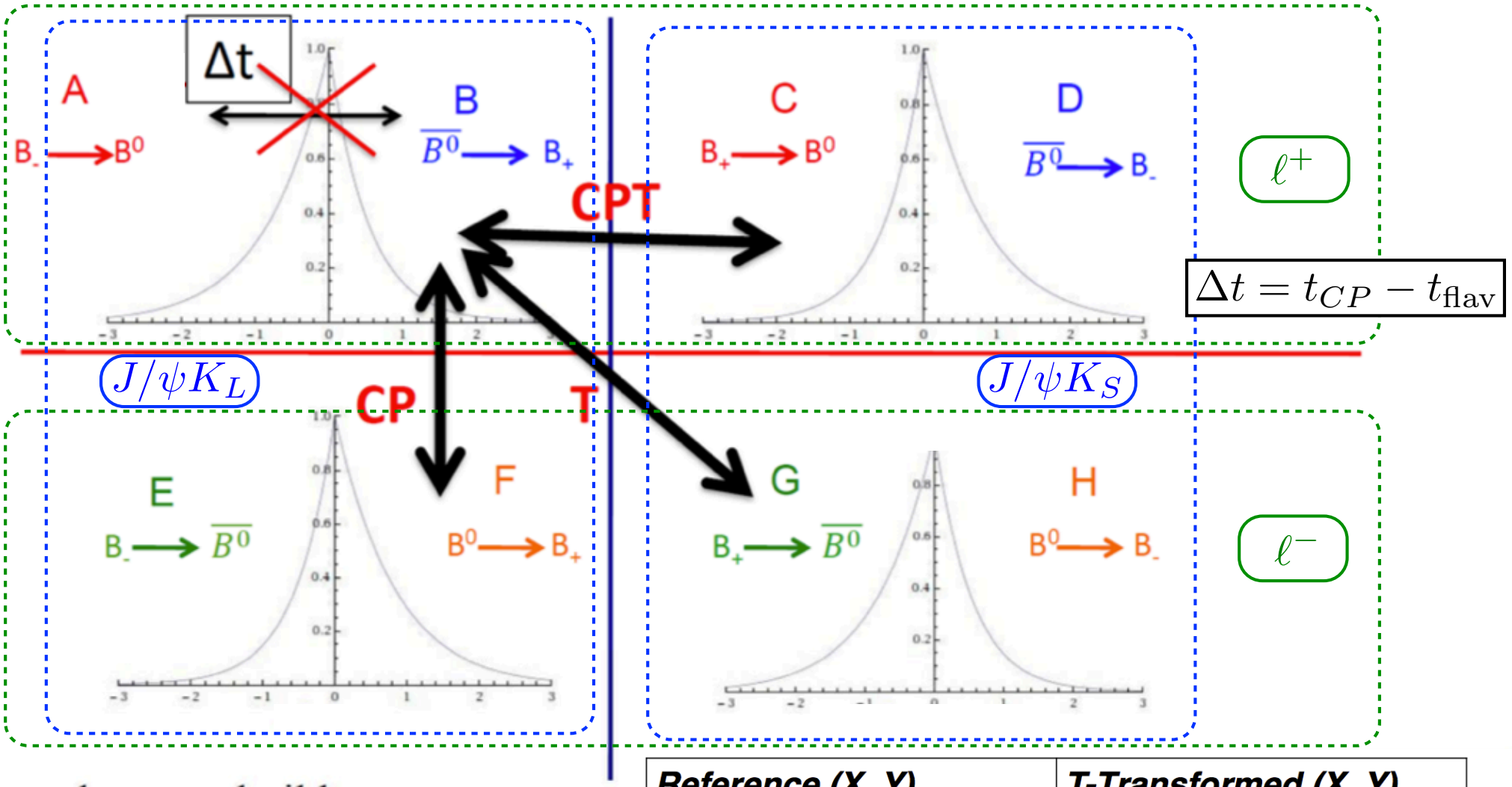
$$\Delta t = t_{CP} - t_{\text{flav}}$$

Reference (X, Y)	***T-Transformed (X, Y)***
$B^0 \to B_+$ $(l^-, J/\psi K_L)$	$B_+ \to B^0$ $(J/\psi K_S, l^+)$
$B^0 \to B_-$ $(l^-, J/\psi K_S)$	$B_- \to B^0$ $(J/\psi K_L, l^+)$
$\bar{B}^0 \to B_+$ $(l^+, J/\psi K_L)$	$B_+ \to \bar{B}^0$ $(J/\psi K_S, l^-)$
$\bar{B}^0 \to B_-$ $(l^+, J/\psi K_S)$	$B_- \to \bar{B}^0$ $(J/\psi K_L, l^-)$

Reference: Physical Process
(X,Y): Reconstructed Final States

B_+, B_- projected by $J/\psi K_L$, $J/\psi K_S$

T Violation Measurement III



In total we can build:

- 4 Independent T comparisons.
- 4 Independent CP comparisons.
- 4 Independent CPT comparisons.

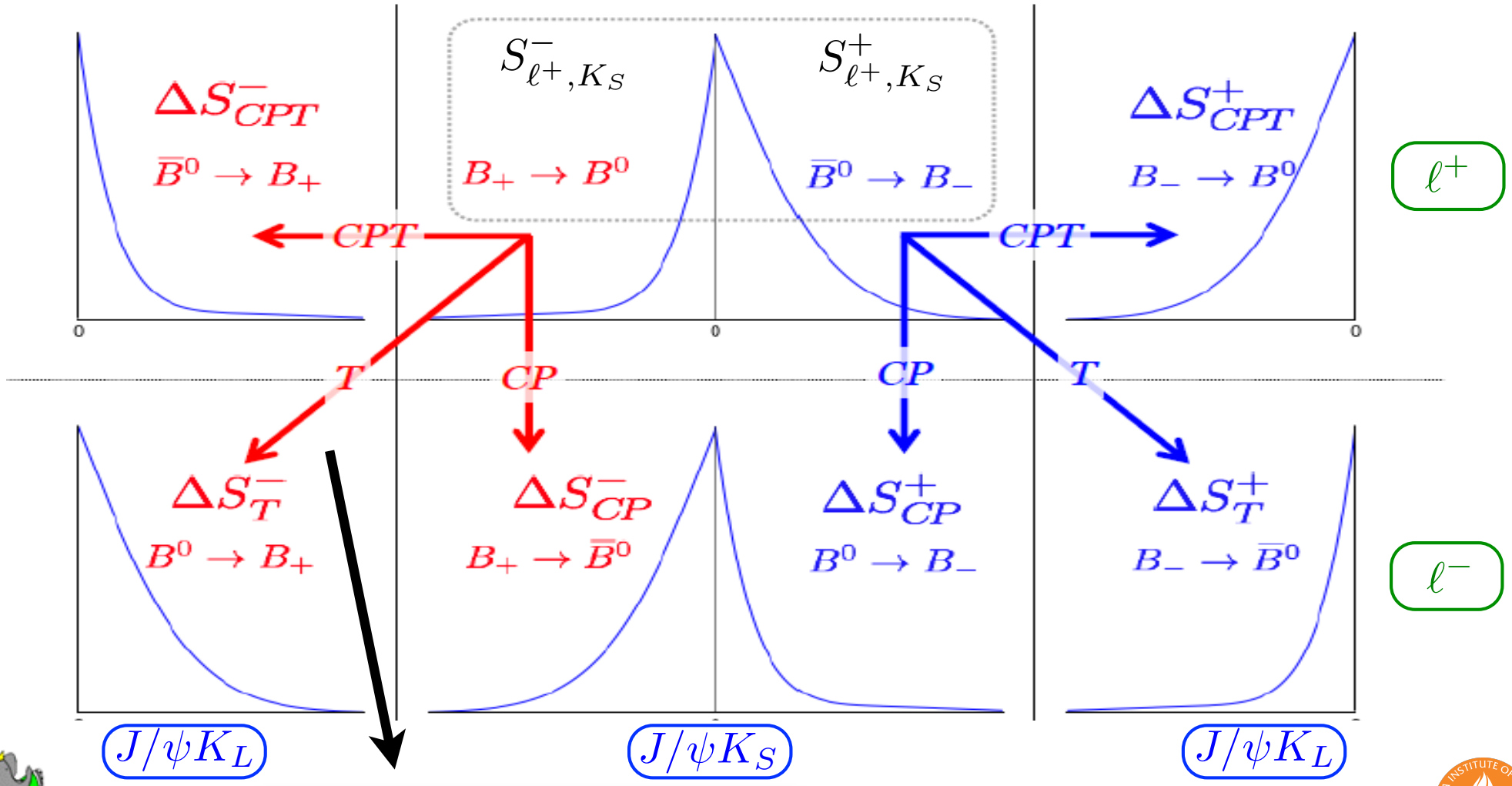
Reference (X, Y)	***T-Transformed (X, Y)***
$B^0 \to B_+$ (l^-, J/ψ K_L)	$B_+ \to B^0$ (J/ψ K_S, l^+)
$B^0 \to B_-$ (l^-, J/ψ K_S)	$B_- \to B^0$ (J/ψ K_L, l^+)
$\bar{B}^0 \to B_+$ (l^+, J/ψ K_L)	$B_+ \to \bar{B}^0$ (J/ψ K_S, l^-)
$\bar{B}^0 \to B_-$ (l^+, J/ψ K_S)	$B_- \to \bar{B}^0$ (J/ψ K_L, l^-)

T Violation Measurement IV

$\Delta t = t_{CP} - t_{\text{flav}}$

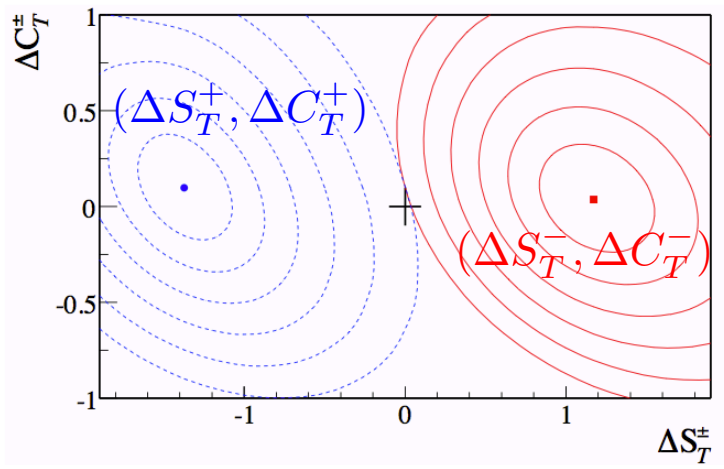
$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)\}$$

$\alpha \in \{\ell^+,\ \ell^-\}$, $\beta \in \{K_S,\ K_L\}$



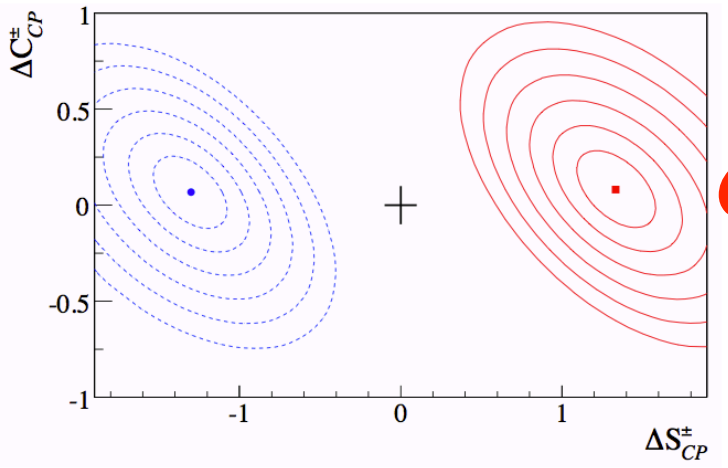
$$\Delta S^-_T = S^+_{\ell^-,K^0_L} - S^-_{\ell^+,K^0_S}$$

T Violation Measurement V

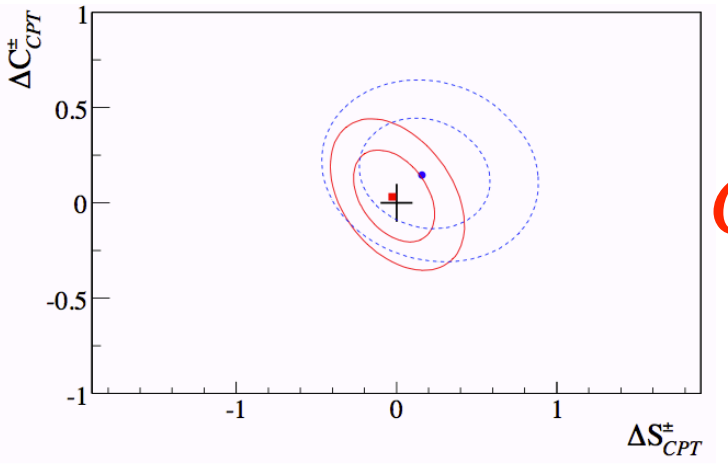


T

$$\Delta S_T^+ = S^-_{\ell^-,K^0_L} - S^+_{\ell^+,K^0_S} \qquad -1.37 \pm 0.14 \pm 0.06$$
$$\Delta S_T^- = S^+_{\ell^-,K^0_L} - S^-_{\ell^+,K^0_S} \qquad 1.17 \pm 0.18 \pm 0.11$$
$$\Delta C_T^+ = C^-_{\ell^-,K^0_L} - C^+_{\ell^+,K^0_S} \qquad 0.10 \pm 0.14 \pm 0.08$$
$$\Delta C_T^- = C^+_{\ell^-,K^0_L} - C^-_{\ell^+,K^0_S} \qquad 0.04 \pm 0.14 \pm 0.08$$



CP



CPT

- Significance of symmetry violation calculated from change in -2Δln(L) at best fit solution between fits w/ and w/o symmetry violation
- 8 degrees of freedom in fit

Symmetry	Change in -2Δ ln(L)	Significance of Violation
T	226	14 sigma
CP	307	17 sigma
CPT	5	0.3 sigma

Conclusions

- We have performed an update of our alpha measurement in $B^0 \to (\rho\pi)^0$ decays using the full BaBar dataset
  - Significantly, studies reveal that alpha is not robustly extracted with current statistical significance, though other physics parameters are robust
- A CPV analysis in the mode $B^0 \to D^{*+}D^{*-}$ using partial reconstruction has obtained results consistent with previous BaBar and Belle measurements
- By combining gamma measurements in various $B^{\pm} \to D^{(*)}K^{(*)\pm}$ modes, we have extracted $\gamma = (69^{+17}_{-16})^{\circ}$, consistent with SM predictions
- We have measured *T*-violating parameters in the time evolution of neutral *B* mesons and observed *T*-violation at 14 sigma significance
  - This is the first direct observation of *T* violation through the exchange of initial and final states connected only by *T*