Observing directly the "weak arrow of time"

F. Martínez-Vidal
IFIC – Universitat de València-CSIC

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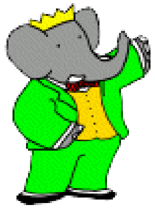

Outline

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  - ✓ Results
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  - ✓ The raw T asymmetries
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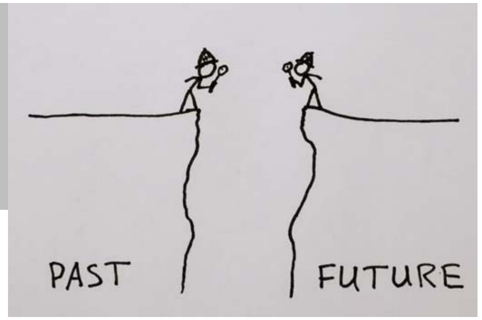
Introduction

Time reversal symmetries in the laws of Physics



- The dynamical laws of Physics have an intrinsic $t \to -t$ symmetry

Microscopic *t* symmetry, or T symmetry

- CP violation exists in the Standard Model or any extension of it
- All field theories with local Lorentz invariance have CPT symmetry
  - ✓ Straightforward connection between CP violation and T violation

- Observed weak CP violation in K and B mesons

T should be violated as well in weak interactions

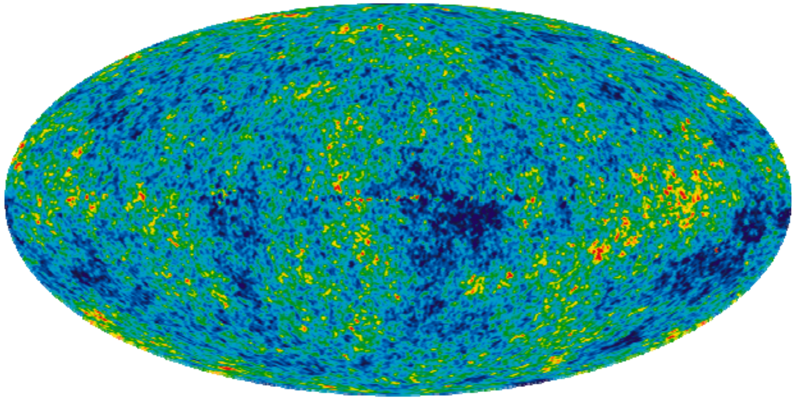
Can T violation be directly observed, independently of CP violation?

Universe and Macroscopic *t* asymmetries

- Effects in Physics $t \to -t$ asymmetric are not necessarily T violating

Universe *t* asymmetry

- ✓ The Universe is expanding, even accelerating
- ✓ Compatible with the *t* symmetry in the underlying laws of Physics (Lorentz symmetry of general relativity)
- ✓ Due to the initial conditions of our Universe (Inflation?)



- ✓ Consistent with uniform average (same temperature) and its fluctuations in the cosmic background radiation map

Macroscopic t asymmetry, or "arrow of time"

- ✓ Time is asymmetric with respect to the amount of order in an isolated system (Nature of Thermodynamics, Eddigton)

3000 BC to 2000 BC

?

- ✓ Probably connected with the Universe *t* asymmetry: the initial condition was improbable (more ordered)
- ✓ In particle physics, particle decays are an example of time asymmetric process:

Mismatch between

$P \to 1+\ldots+n$ and $1+\ldots+n \to P$

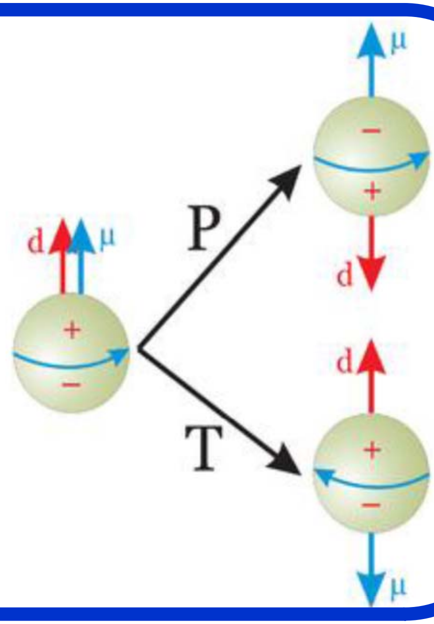
Scenarios for time reversal violation

Non-zero expected value of a T-odd observable for stationary, non-degenerate states, like the permanent electric dipole moment (EDM) of a particle (with spin)

- ✓ Also violates parity, P
- ✓ EDM of the neutron or electron:

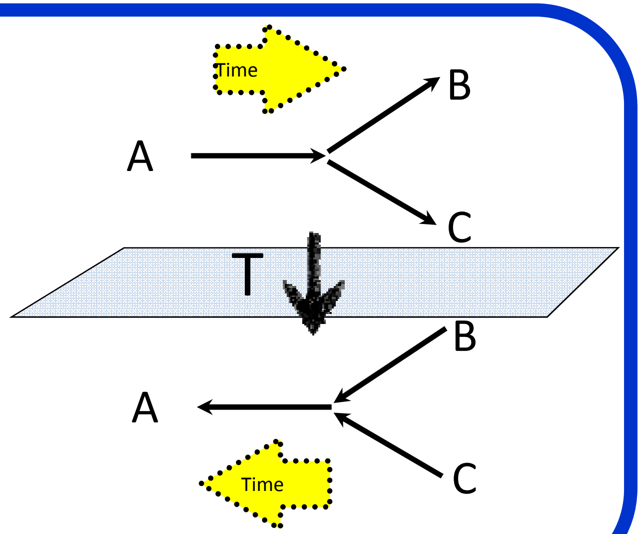
PDGLive.org

$d_n < 2.9 \times 10^{-26}$ e-cm; $d_e = (0.7 \pm 0.7) \times 10^{-26}$ e-cm



For a reaction a → b, P(a → b) ≠ P(b → a), once the initial conditions, namely a in one case and b in the other, have been precisely realized!

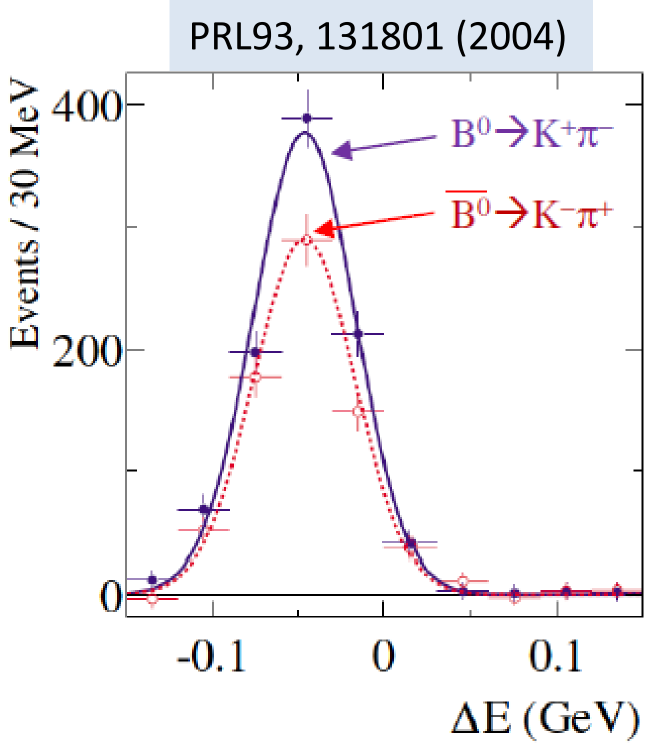
- ✓ Detailed balance when there are no spins
- ✓ With stable particles: $\nu_e \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_e$ but needs future facility with a long baseline
- ➢ With unstable particles: a→ decay products vs. decay products → a, very difficult or impossible



T violation in unstable systems

- Compare a → b vs. b → a in decay processes
  - ✓ BaBar and Belle have observed large direct CP violation in B → Kπ
  - ✓ 

  - ✓ Can we observe Kπ → B ?



CP $\left\{ \begin{array}{l} B^0 \to K^+\pi^-, R_1 \\ \bar{B}^0 \to K^-\pi^+, R_2 \end{array} \right.$ ⟵ CPT ⟶ $\left\{ \begin{array}{l} K^-\pi^+ \to \bar{B}^0, R_1 \\ K^+\pi^- \to B^0, R_2 \end{array} \right.$

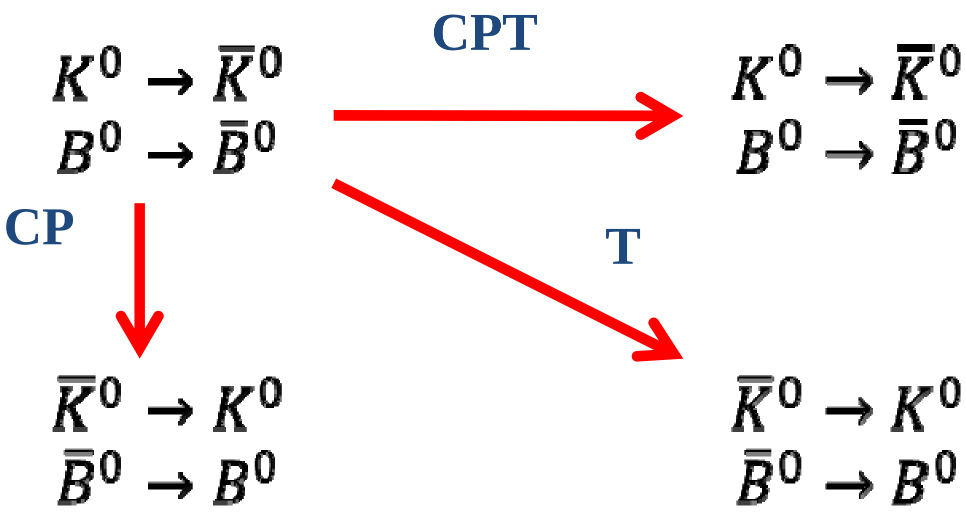
Preparation of the initial state difficult (unfeasible).

The strong process will swamp the feeble weak process, σ(Kπ→hadrons)>>σ(Kπ→B)

⇒ Impossible rather than "merely" unfeasible.

T violation in unstable systems (cont'd)

- Compare a → b vs. b → a in <u>mixing</u> processes
  - ✓ Mixing has been observed in K, B, and more recently in D neutral systems



Kabir, PRD2, 540 (1970)

- ✓ $K^0 \to \bar{K}^0$ vs. $\bar{K}^0 \to K^0$ asymmetry observed by CPLEAR, PLB444, 43 (1998)
- ✓ But, T and CP transformations lead to the same observation
  - o Can not distinguish T and CP

    e.g. Wolfenstein, PRL83, 911 (1999); Int. Jour. Mod. Phys. E8, 501 (1999)

  - o Not a direct observation of T violation [Wolfenstein, Quinn, Bernabeu]
- ✓ The flavor mixing asymmetry is independent of time and requires $\Delta\Gamma \neq 0$
  - o Various criticisms in the interpretation of this observable

Gerber, and references therein, Eur. Phys. Jour. C 35, 195 (2004)

T violation picture (from PDG)

e electric dipole moment		$<10.5 \times 10^{-28}$ $e$cm, CL = 90%
μ electric dipole moment		$(-0.1 \pm 0.9) \times 10^{-19}$ $e$cm
μ decay parameters		
transverse e^+ polarization normal to plane of μ spin, e^+ momentum		$(-2 \pm 8) \times 10^{-3}$
α'/A		$(-10 \pm 20) \times 10^{-3}$
β'/A		$(2 \pm 7) \times 10^{-3}$
Re(d_τ = τ electric dipole moment)		-0.220 to 0.45×10^{-16} $e$cm, CL = 95%
P_T in $K^+ \to \pi^0 \mu^+ \nu_\mu$		$(-1.7 \pm 2.5) \times 10^{-3}$
P_T in $K^+ \to \mu^+ \nu_\mu \gamma$		$(-0.6 \pm 1.9) \times 10^{-2}$
Im(ξ) in $K^+ \to \pi^0 \mu^+ \nu_\mu$ decay (from transverse μ pol.)		-0.006 ± 0.008
asymmetry A_T in K^0-$\overline{K}^0$ mixing		$(6.6 \pm 1.6) \times 10^{-3}$
Im(ξ) in $K^0_{\mu 3}$ decay (from transverse μ pol.)		-0.007 ± 0.026
$A_T(D^\pm \to K^0_S K^\pm \pi^+ \pi^-)$	[b]	$(-12 \pm 11) \times 10^{-3}$
$A_T(D^0 \to K^+ K^- \pi^+ \pi^-)$	[b]	$(1 \pm 7) \times 10^{-3}$
$A_T(D_s^\pm \to K^0_S K^\pm \pi^+ \pi^-)$	[b]	$(-14 \pm 8) \times 10^{-3}$
p electric dipole moment		$<0.54 \times 10^{-23}$ $e$cm
n electric dipole moment		$<0.29 \times 10^{-25}$ $e$cm, CL = 90%
$n \to p e^- \overline{\nu}_e$ decay parameters		
ϕ_{AV}, phase of g_A relative to g_V	[c]	$(180.018 \pm 0.026)^\circ$
triple correlation coefficient D	[d]	$(-1.2 \pm 2.0) \times 10^{-4}$
triple correlation coefficient R	[d]	0.008 ± 0.016
Λ electric dipole moment		$<1.5 \times 10^{-16}$ $e$cm, CL = 95%
triple correlation coefficient D for $\Sigma^- \to n e^- \overline{\nu}_e$		0.11 ± 0.10

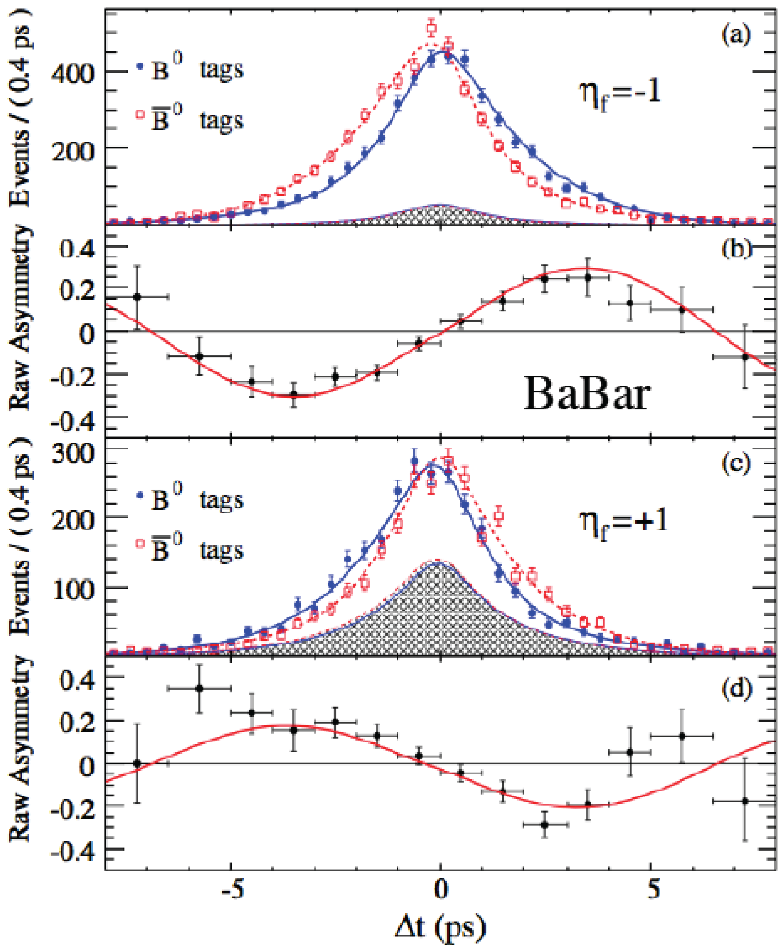
CPLEAR: PLB 444, 43 (1998)
Compares $K^0 \to \overline{K}^0$ with $\overline{K}^0 \to K^0$ Mixing rate.

- Related by T *and* CP.
- Not time-dependent.
- Various criticisms.

BABAR:
PRD(RC)81, 111103 (2010)
PRD(RC) 84, 031103 (2011)
Triple products

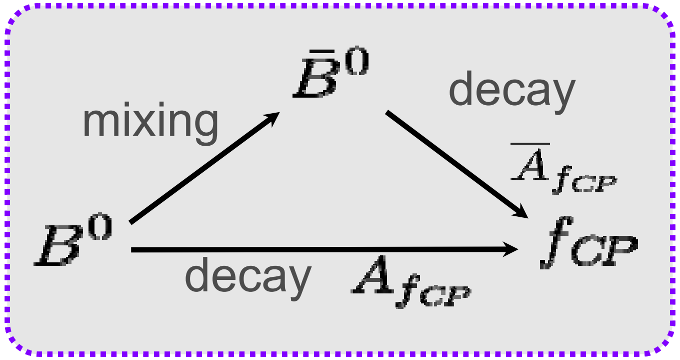
CP violation in mixing-decay interference

- Large CP violation observed in the interference between mixing and decay in B mesons, measured precisely with golden channels



$B^0 \to J/\psi K_S$ CP = -1

$B^0 \to J/\psi K_L$ CP = +1



$$g_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{(1 \mp \Delta w) \pm (1-2w) \times [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}.$$

Cannot be interpreted as T violation:

Assume CPT invariance and $\Delta\Gamma = 0$

No exchanges $t \Leftrightarrow -t$ and *in* $\Leftrightarrow$ *out* states

How could we directly observe T violation in this privileged system of Nature?

T violation and entanglement: strategy at a B factory

T violation and quantum entanglement

Bañuls & Bernabeu, PLB464, 117 (1999)

- Quantum (EPR) entanglement at B factories

$\Upsilon(4S)$ decay yields an entangled state of B mesons

$$|i\rangle = 1/\sqrt{2}\,[B^0(t_1)\overline{B}^0(t_2) - \overline{B}^0(t_1)B^0(t_2)]$$

NEW!

$$= 1/\sqrt{2}\,[B_+(t_1)B_-(t_2) - B_-(t_1)B_+(t_2)]$$

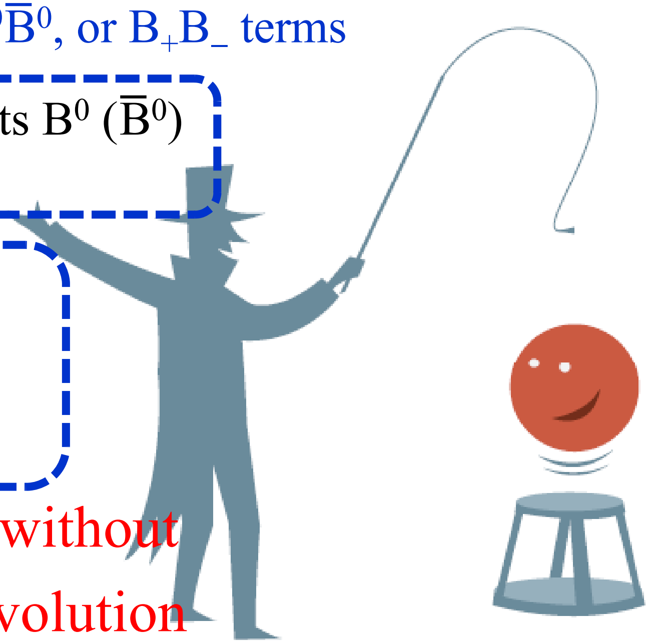
- ✓ Antisymmetric wave function (P-wave particle system)
- ✓ States 1 and 2 are defined by the time of their decay with $t_1 < t_2$
- ✓ Can be expressed in terms of any linear combination of flavor eigenstates
- ✓ Time evolution (including mixing) preserves only $B^0\overline{B}^0$, or B_+B_- terms

Flavor tag: e.g. B semileptonic decay to $l^+ X$ ($l^- X$) projects B^0 ($\overline{B}^0$)
$\Rightarrow$ $\overline{B}^0$ (B^0) tag

CP tag: B decay to $J/\psi K_L$ projects $B_+ \approx 1/\sqrt{2}\,[B^0 + \overline{B}^0]$
$\Rightarrow$ B_- tag ("CP-odd")

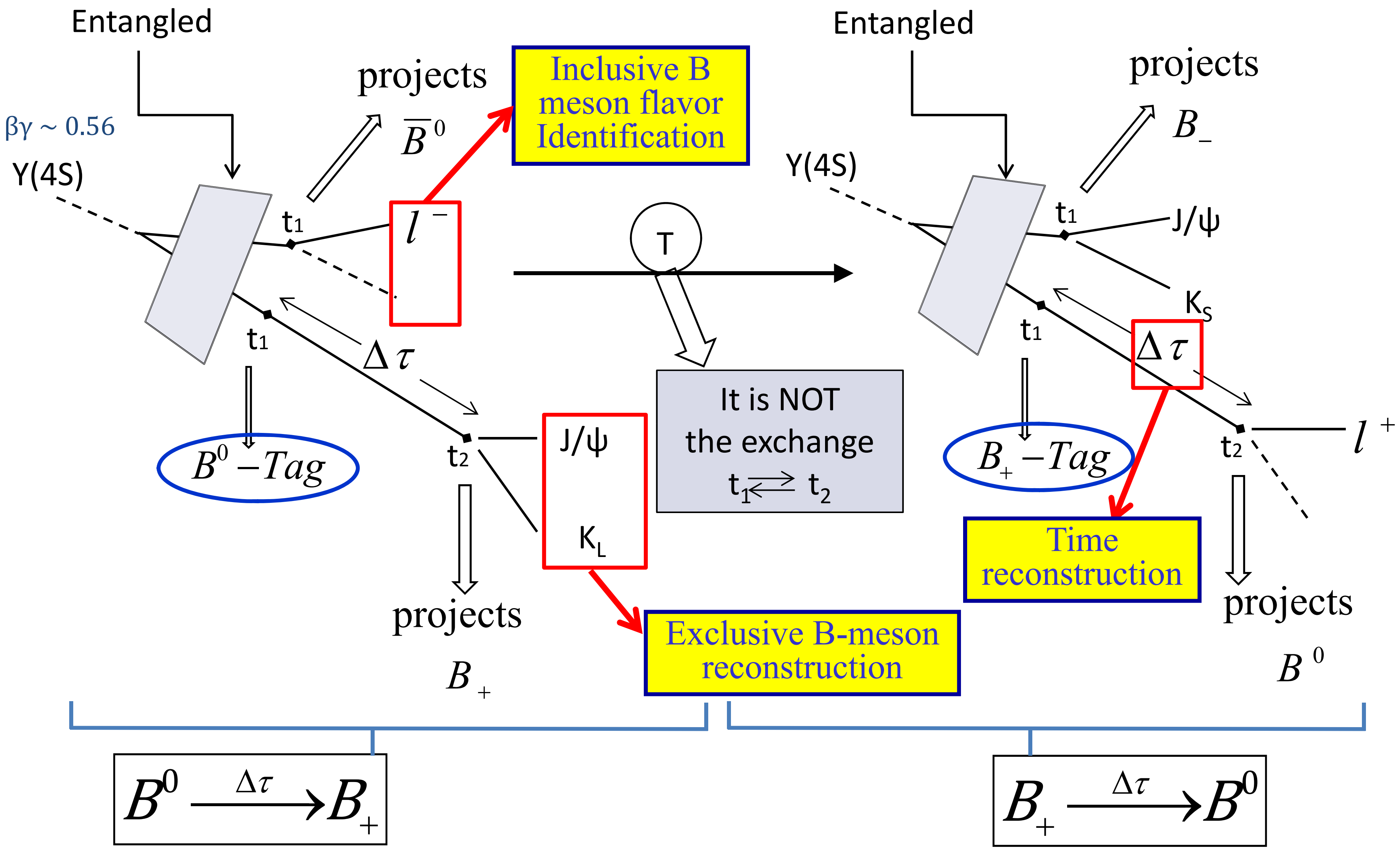
NEW!

B decay to $J/\psi K_S$ projects $B_- \approx 1/\sqrt{2}\,[B^0 - \overline{B}^0]$
$\Rightarrow$ B_+ tag ("CP-even")



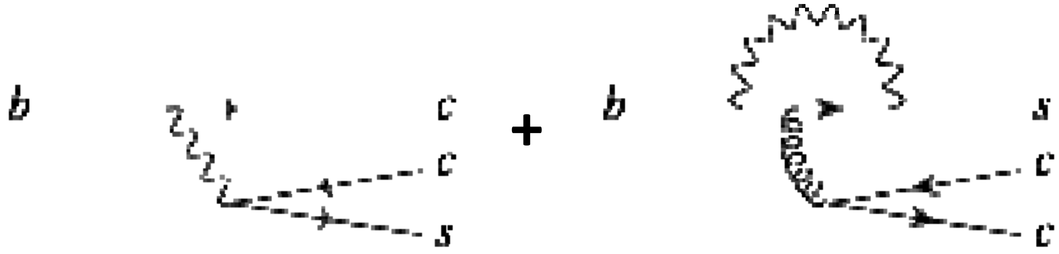
- Conclusion: ability to prepare a quantum state without destroying it ("tag") , and then study its time evolution

T violation: strategy at a B factory



T violation analysis at a glance

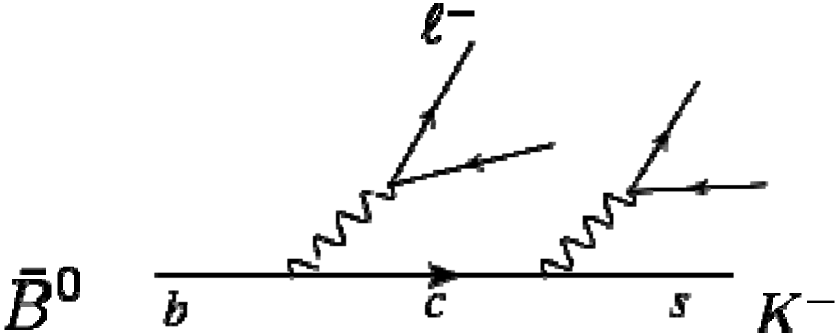
Completely reconstructed B



$B_- : J/\psi K^0_S$

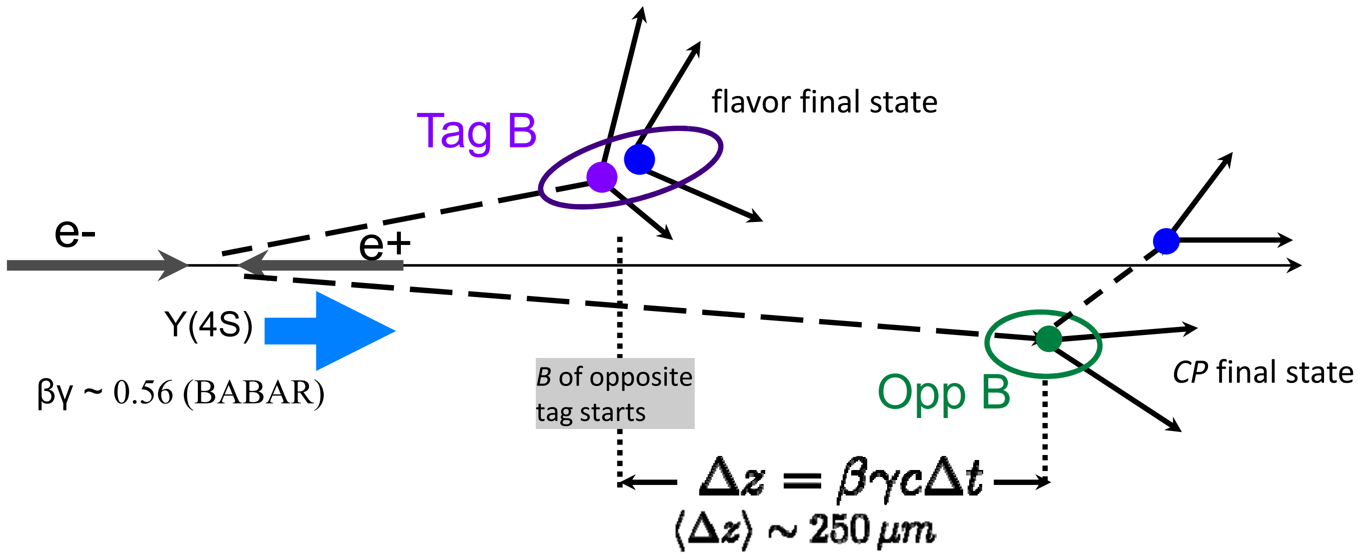
$B_+ : J/\psi K^0_L$

Inclusive reconstructed B: flavor identification (extract features to determine b or $\bar{b}$ quark content)



$\vert B^0\rangle = \vert\bar{b}d\rangle$	$\vert\bar{B}^0\rangle = \vert b\bar{d}\rangle$
ℓ^+	ℓ^-
K^+	K^-
etc.	etc.

T violation analysis at a glance (cont'd)

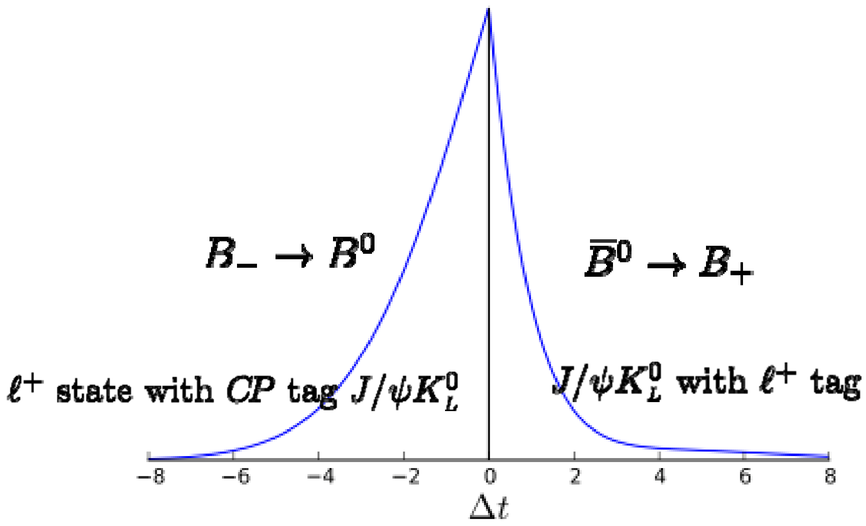


- ✓ In B factory CP violation canonical analysis, we define

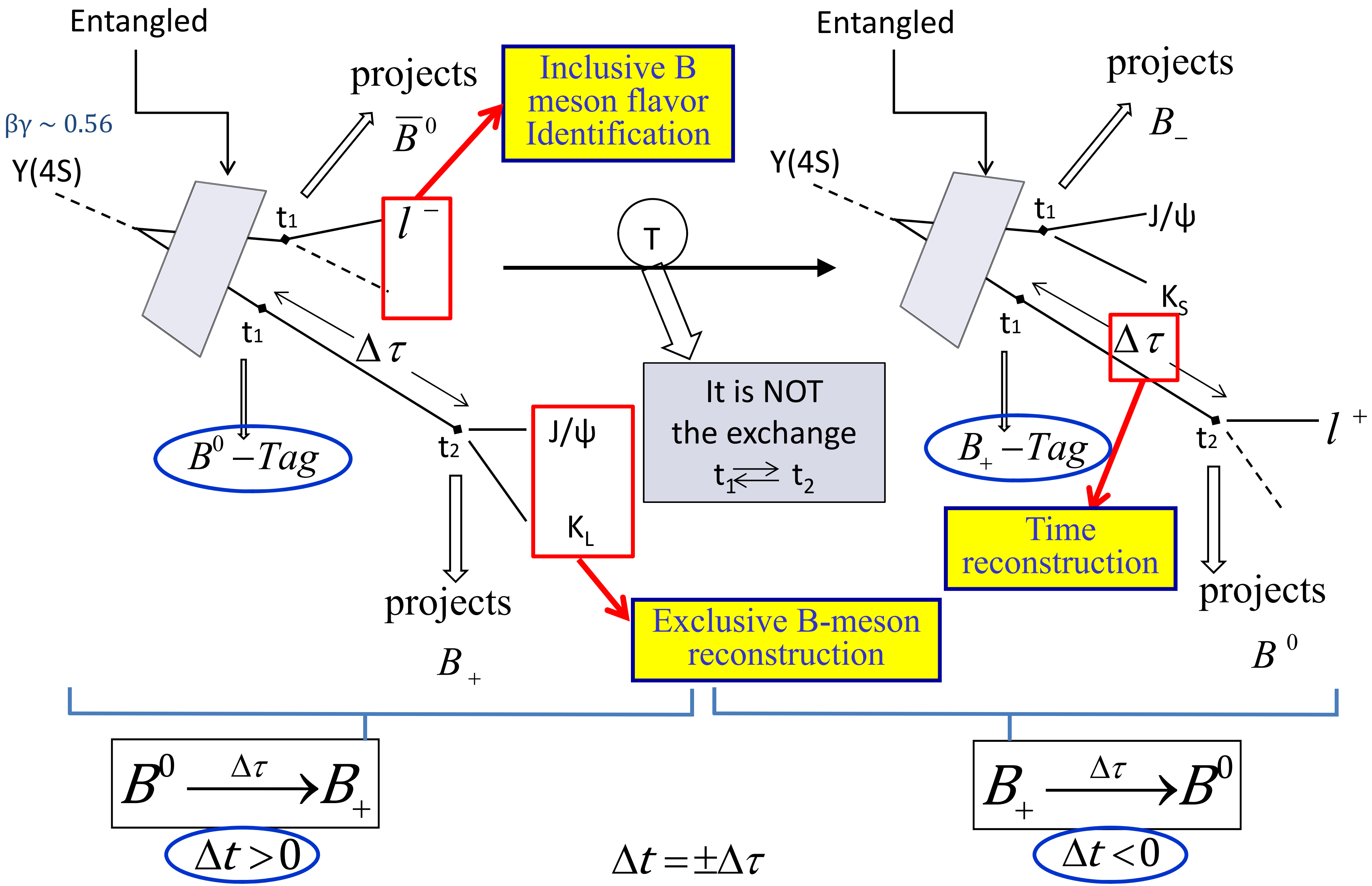
$$\Delta t = t_{CP} - t_{flav} \simeq \Delta z / \beta\gamma c$$

Signed decay time difference

- ✓ If Δt<0, we can exchange the roles of the two B's in above picture



T violation: strategy at a B factory



T-transformed processes

Define processes of interest and their T-transformed counterparts

JHEP08 (2012) 064

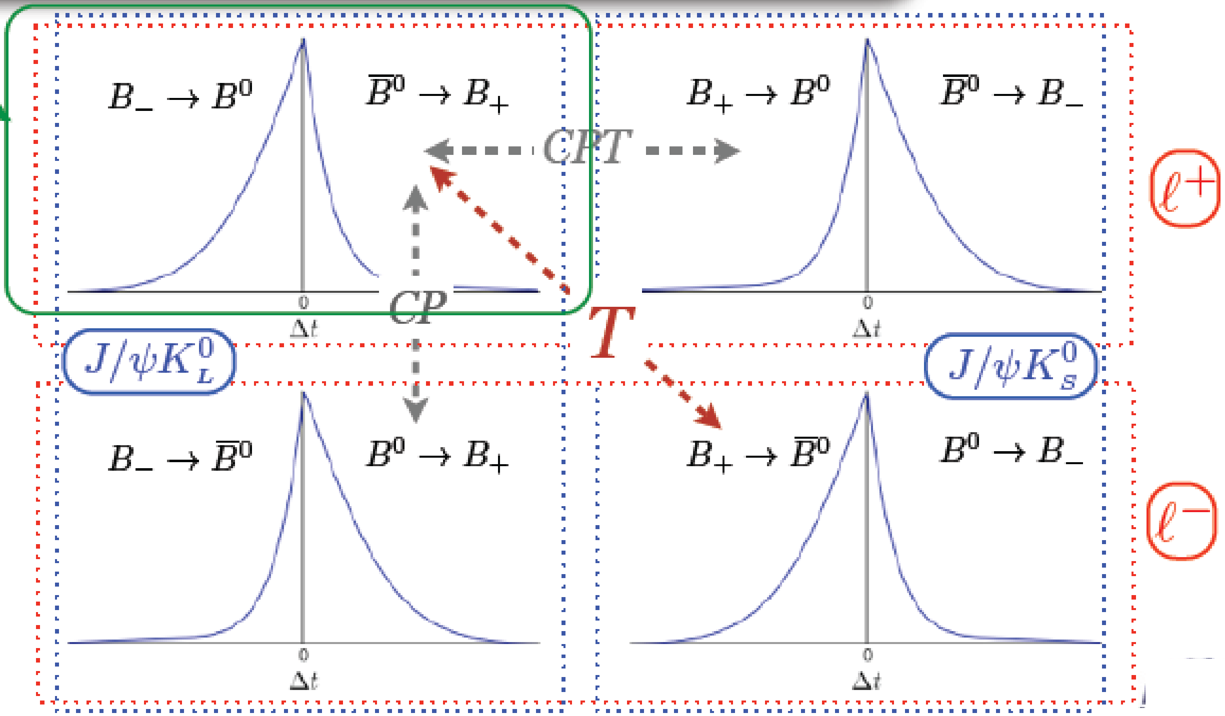
Reference (X,Y)		T-Transformed	
$B^0 \to B_+$	$(\ell^-, J/\psi K^0_L)$	$B_+ \to B^0$	$(J/\psi K^0_S, \ell^+)$
$B^0 \to B_-$	$(\ell^-, J/\psi K^0_S)$	$B_- \to B^0$	$(J/\psi K^0_L, \ell^+)$
$\overline{B}^0 \to B_+$	$(\ell^+, J/\psi K^0_L)$	$B_+ \to \overline{B}^0$	$(J/\psi K^0_S, \ell^-)$
$\overline{B}^0 \to B_-$	$(\ell^+, J/\psi K^0_S)$	$B_- \to \overline{B}^0$	$(J/\psi K^0_L, \ell^-)$

(X,Y) is the reconstructed final states (tag, reco.)

...and similar for CP, CPT

In total we can build:
- 4 independent T comparisons
- 4 independent CP comparisons
- 4 independent CPT comparisons

T implies comparison of:
1) Opposite Δt sign
2) Different reco states (ψK_S v. ψK_L)
3) Opposite flavor states (B^0 v. $\overline{B}^0$)



Signal parameters $\Delta S^{\pm}$ and $\Delta C^{\pm}$

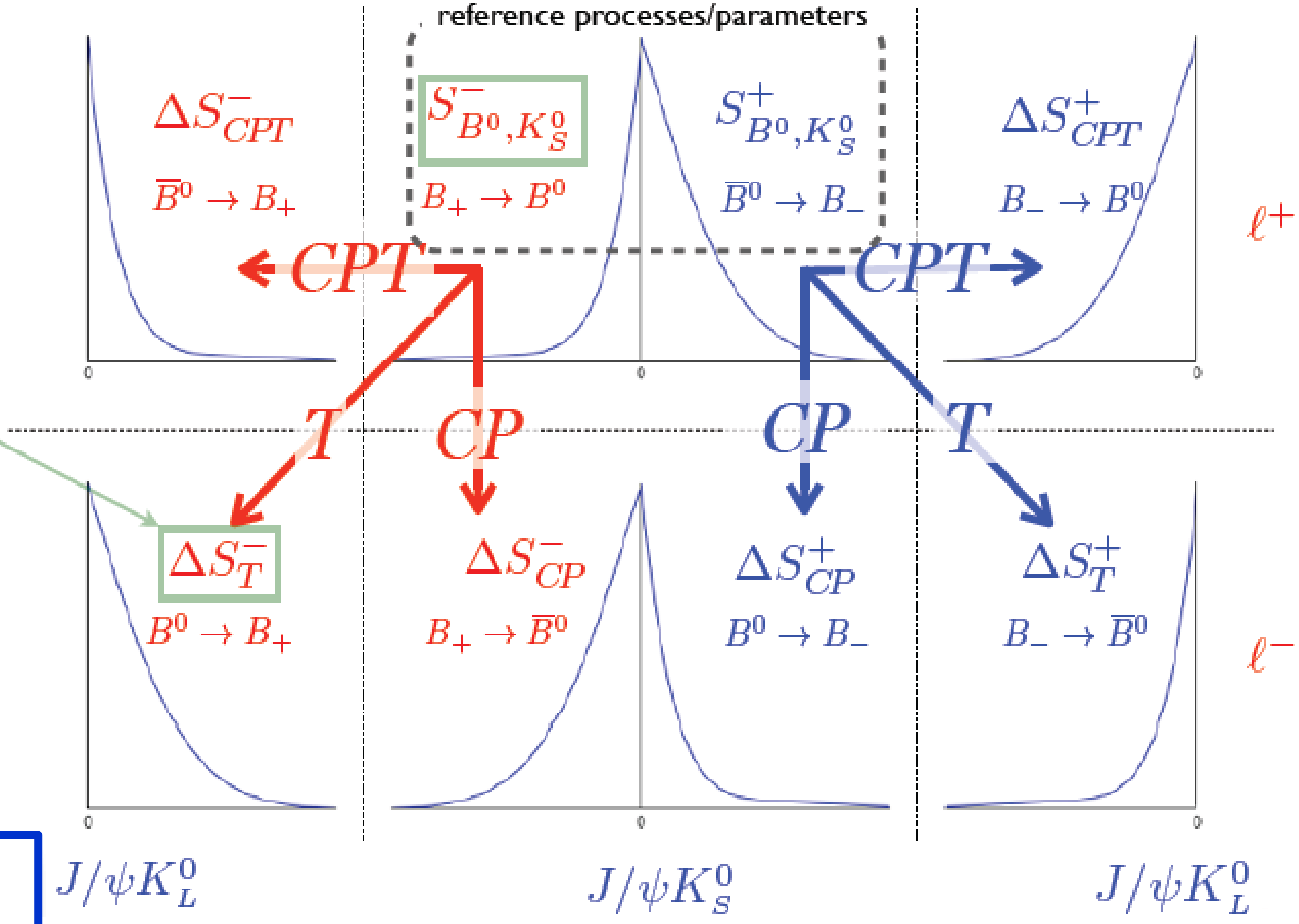
8 Signal PDFs: $g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)\}$

Assumes $\Delta\Gamma=0$

$$\Delta t = t_{CP} - t_{flav} = \begin{cases} +\Delta\tau \text{ for "flavor tag"} \\ -\Delta\tau \text{ for "CP tag"} \end{cases} \qquad \alpha \in \{B^0, \bar{B}^0\}; \quad \beta \in \{K^0_S, K^0_L\}$$

Prediction from CPV

Parameter	Value
$S^+_{B^0,K^0_S}$	0.7
$\Delta S^+_T = S^-_{\bar{B}^0,K^0_L} - S^+_{B^0,K^0_S}$	−1.4
$\Delta S^+_{CP} = S^+_{\bar{B}^0,K^0_S} - S^+_{B^0,K^0_S}$	−1.4
$\Delta S^+_{CPT} = S^-_{B^0,K^0_L} - S^+_{B^0,K^0_S}$	0.0
$S^-_{B^0,K^0_S}$	−0.7
$\Delta S^-_T = S^+_{\bar{B}^0,K^0_L} - S^-_{B^0,K^0_S}$	1.4
$\Delta S^-_{CP} = S^-_{\bar{B}^0,K^0_S} - S^-_{B^0,K^0_S}$	1.4
$\Delta S^-_{CPT} = S^+_{B^0,K^0_L} - S^-_{B^0,K^0_S}$	0.0
$C^+_{B^0,K^0_S}$	0.0
$\Delta C^+_T = C^-_{\bar{B}^0,K^0_L} - C^+_{B^0,K^0_S}$	0.0
$\Delta C^+_{CP} = C^+_{\bar{B}^0,K^0_S} - C^+_{B^0,K^0_S}$	0.0
$\Delta C^+_{CPT} = C^-_{B^0,K^0_L} - C^+_{B^0,K^0_S}$	0.0
$C^-_{B^0,K^0_S}$	0.0
$\Delta C^-_T = C^+_{\bar{B}^0,K^0_L} - C^-_{B^0,K^0_S}$	0.0
$\Delta C^-_{CP} = C^-_{\bar{B}^0,K^0_S} - C^-_{B^0,K^0_S}$	0.0
$\Delta C^-_{CPT} = C^+_{B^0,K^0_L} - C^-_{B^0,K^0_S}$	0.0



For T violation

In interference $\Delta S^+_T \neq 0$, $\Delta S^-_T \neq 0$

In decay $\Delta C^+_T \neq 0$, $\Delta C^-_T \neq 0$

Properties of the B_+ and B_- states

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- Let's call the state B_- as the one defined by the B decay to J/ψππ (J/ψK$_S$, K$_S$→ππ) [a pure CP-odd final state]
- $\tilde{B}_+$ is the state orthogonal to B_-, $\langle \tilde{B}_+ | B_- \rangle = 0$, defined by entanglement, thus cannot decay to J/ψππ, i.e., $\langle J/\psi\pi\pi | T | \tilde{B}_+ \rangle = 0$
- Since B_- and $\tilde{B}_+$ are linear combinations of flavor eigenstates,

$$\left|\tilde{B}_+\right\rangle = \tilde{N}_+\left[\left|B^0\right\rangle - \alpha\left|\bar{B}^0\right\rangle\right], \quad \left|B_-\right\rangle = N_-\left[\left|B^0\right\rangle + \delta\left|\bar{B}^0\right\rangle\right] \qquad \alpha = \frac{\langle J/\psi\pi\pi | T | B^0\rangle}{\langle J/\psi\pi\pi | T | \bar{B}^0\rangle}$$

$$\left\langle \tilde{B}_+ \middle| B_- \right\rangle = \tilde{N}_+ N_-\left[1-\alpha\delta\right] = 0 \Rightarrow \alpha\delta = 1 \Rightarrow \delta = \alpha^* \textbf{ if } |\alpha| = 1$$

- Analogously, the state B_+ is defined by the B decay to J/ψK$_L$ [a CP-even final state at $O(10^{-3})$],

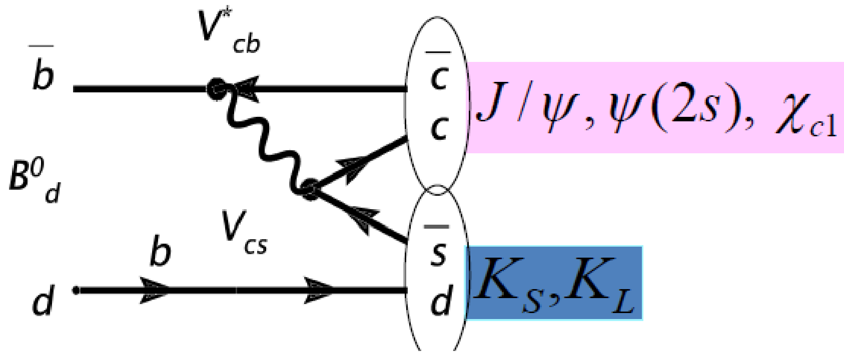
$$\left|\tilde{B}_-\right\rangle = \tilde{N}_-\left[\left|B^0\right\rangle - \beta\left|\bar{B}^0\right\rangle\right], \quad \left|B_+\right\rangle = N_+\left[\left|B^0\right\rangle + \beta^*\left|\bar{B}^0\right\rangle\right] \textbf{ if } |\beta| = 1 \qquad \beta = \frac{\langle J/\psi K_L | T | B^0\rangle}{\langle J/\psi K_L | T | \bar{B}^0\rangle}$$

Properties of the B_+ and B_- states (cont'd)

- $\tilde{B}_+$ and B_+ , and $\tilde{B}_-$ and B_- have to be the same states in order to define processes and their T-transformed counterparts, so $\beta = -\alpha^*$
- It then follows that B_+ and B_- are too orthogonal,

$$\langle B_+ | B_- \rangle = N_+ N_- \left[1 + \alpha^* \beta^* \right] = 0$$

- Property 1: B_+ and B_- are orthogonal linear combinations of flavor eigenstates, not necessarily defined through CP final states
- Property 2: B_+ and B_- states defined through the B decays to $J/\psi K_L$ and $J/\psi\pi\pi$ final states are orthogonal iff
  - ✓ We neglect the $J/\psi\pi\pi$ component in $J/\psi K_L$ final states, i.e. neglect CPV in K^0-$\bar{K}^0$ mixing, $O(10^{-3})$
  - ✓ $|\alpha|=|\beta|=1$, i.e., there is no direct CPV in the B decay to $J/\psi K^0$ (one single weak decay amplitude)

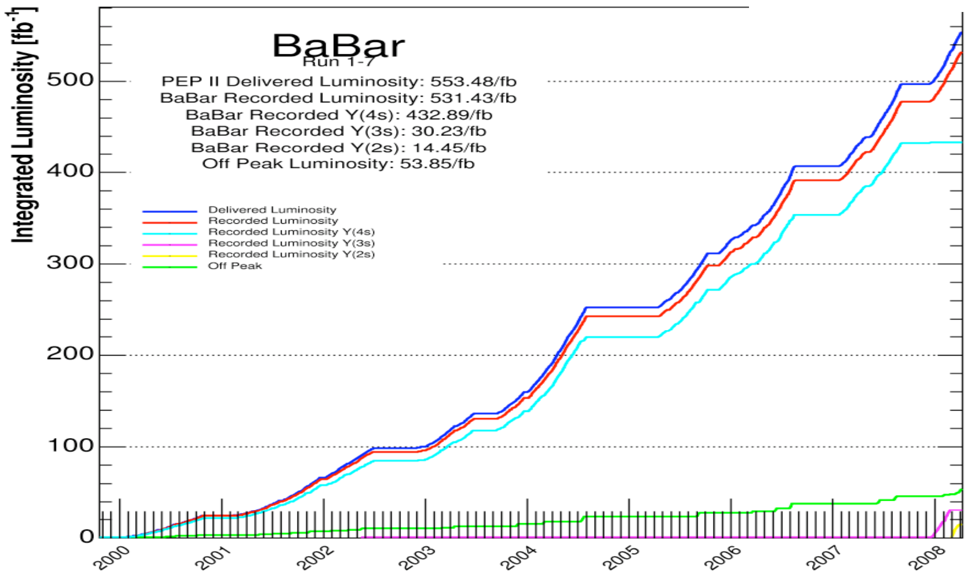


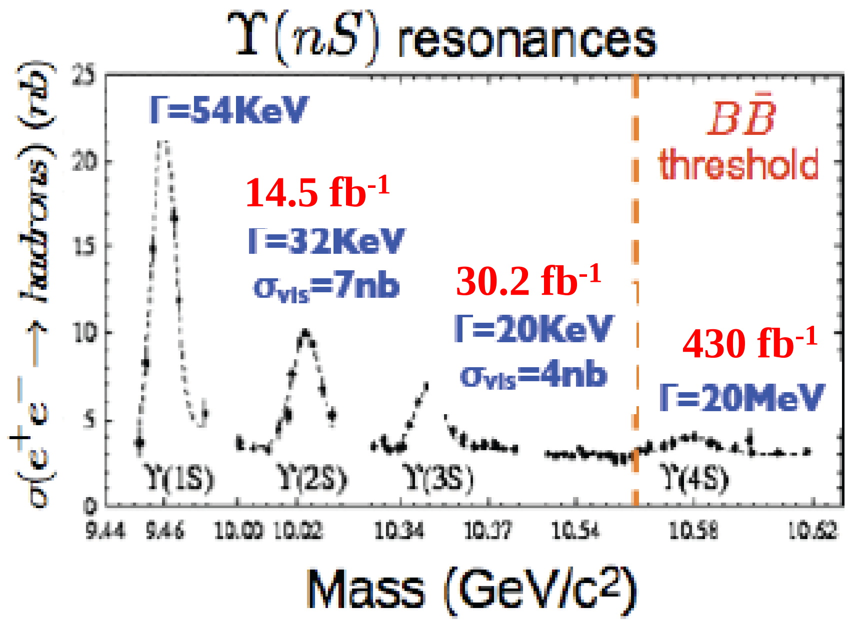
Next largest amplitude (λ^2) has same weak phase
Other CKM corrections are Cabibbo suppressed $O(\lambda^4)$

Data sample
and fitting strategy

BaBar data set

530 fb^{-1} recorded in the 9 years of operation





54 fb^{-1} Off-Υ(nS)
4 fb^{-1} above Υ(4S)

Reconstructed modes

signal sample

Category	Decay(s)
$c\bar{c}K^0_S$	$B^0 \to J/\psi K^0_S$ $B^0 \to \psi(2S) K^0_S$ $B^0 \to \chi_{c1} K^0_S$
$c\bar{c}K^0_L$	$B^0 \to J/\psi K^0_L$
$B_{\rm flav}$ (high statistics)	$B^0 \to D^* \pi(\rho, a_1)$ $B^0 \to J/\psi K^{*0}$
Control sample $c\bar{c}K^\pm$, $J/\psi K^{*\pm}$	$B^+ \to J/\psi K^+$ $B^+ \to \psi(2S) K^+$ $B^+ \to J/\psi K^{*+}$

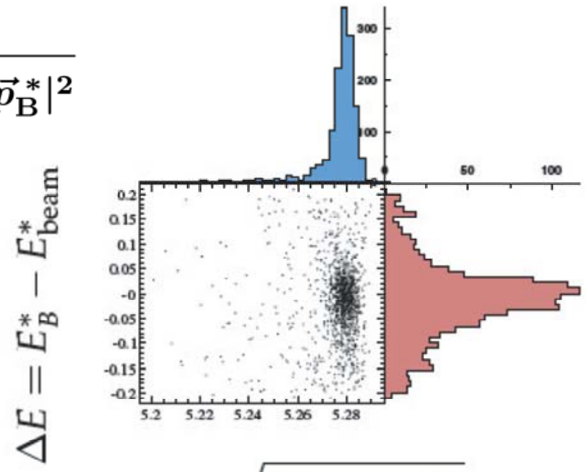
- ≈ 470×10^6 $B\bar{B}$ (0.5×Belle)
- ≈ 690×10^6 $c\bar{c}$
- ≈ 500×10^6 $\tau^+\tau^-$
- ≈ 121×10^6 Υ(3S) (7×Belle+Cleo)
- ≈ 99×10^6 Υ(2S) (0.5×Belle+Cleo)

Signal and backgrounds

- Select B candidates using
  - ✓ Beam-energy substituted mass $m_{ES} = \sqrt{{E^*_{beam}}^2 - |\vec{p}^*_B|^2}$

    where $E^*_B \to E^*_{beam}$ and $\vec{p}^*_B \approx 300\ \mathrm{MeV}/c$

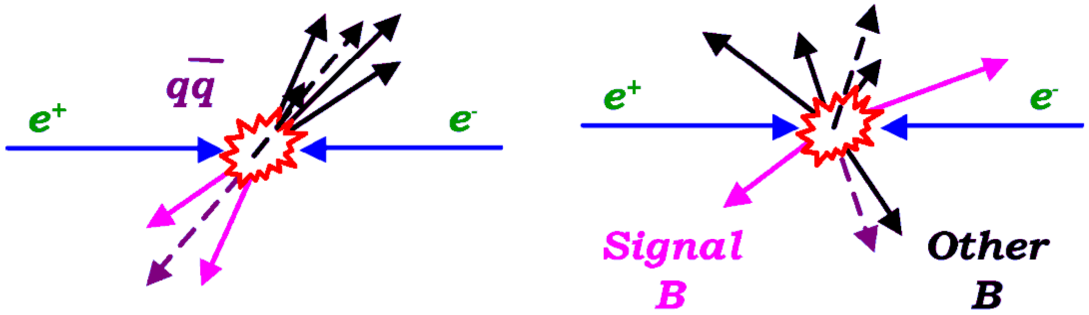
    $\sigma_{\Delta E} \sim \sigma_{E^*_B} \approx 10-50$ MeV
  - ✓ Energy difference $\Delta E = E^*_B - E^*_{beam}$
  - ✓ Choose best B candidates based on masses of daughters



$m_{ES} = \sqrt{E^*_{beam} - p^{*2}_B}$

$\sigma_{m_{ES}} \sim \sigma_{beam} \sim 2.7$ MeV

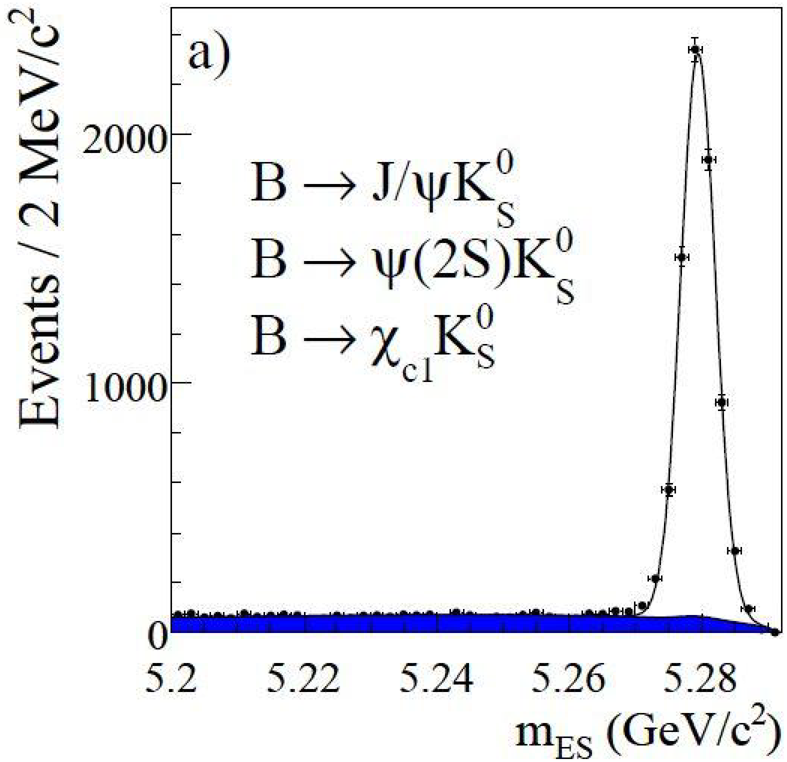
- Background rejection
  - ✓ Depends on B decay channel
  - ✓ Veto dangerous or significant backgrounds
  - ✓ Suppress continuum u, d, s backgrounds using angular distributions and event shape variables



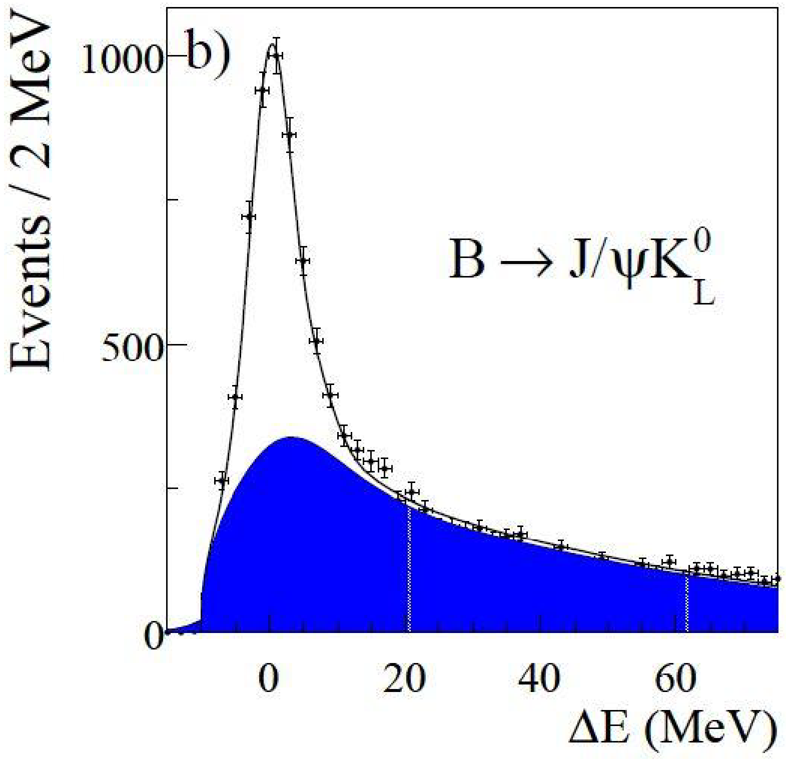
m_{ES} and ΔE for the signal sample

Identical sample to that used in our most recent (canonical) CP violation measurement with $B \to c\bar{c}K^{(*)0}$ events, but excluding $\eta_c K_S$ and $J/\psi K^{*0}(\to K_S \pi^0)$

PRD 79, 072009 (2009)



7796 events, purity 87–96%



5813 events, purity ≈ 56%

Fitting strategy

- Overall procedure very similar to that followed in the most recent CP violation study with $B \rightarrow c\bar{c}K^{(*)0}$ decays PRD 79, 072009 (2009)
- Use the B_{flav} sample to determine
  - ✓ Decay time difference resolution model and parameters
  - ✓ Wrong-flavor ID fractions

$$\Delta t = t_{CP} - t_{flav} = \pm \Delta \tau$$

Signed decay time difference

- Perform simultaneous, unbinned ML fit to the 4 signal samples

$$\underbrace{(B^0, \bar{B}^0)}_{\alpha} \times \underbrace{(J/\psi K_S^0, J/\psi K_L^0)}_{\beta}$$

  - ✓ Normalization is common for B^0, $\bar{B}^0$, and $\Delta t>0$ and $\Delta t<0$
  - ✓ But independent for $c\bar{c}K_S$ and $J/\psi K_L$
- Signal and background probabilities defined as a function of m_{ES} and ΔE
- Sample composition and time-dependent background description identical to the CP violation analysis
  - ✓ 11 parameters allow for possible T and CP violation in background
- But the signal model is quite different…
  - ✓ **Time ordering is the key!**

Fitting strategy: signal model

- Signal PDF

Step function — Resolution function — $\delta t = \Delta t - \Delta t_{\text{true}}$

$$H_{\alpha,\beta}(\Delta t) \propto g^{+}_{\alpha,\beta}(\Delta t_{true}) \times H(\Delta t_{true}) \otimes \Re(\delta t; \sigma_{\Delta t})$$

Flavor tagged events (+)

$$+$$

$$g^{-}_{\alpha,\beta}(-\Delta t_{true}) \times H(-\Delta t_{true}) \otimes \Re(\delta t; \sigma_{\Delta t})$$

CP tagged events (−)

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

- Fit has to unfold $\Delta t_{\text{true}}>0$ and $\Delta t_{\text{true}}<0$ events (mixed due to limited time resolution), to obtain **8 sets of S, C parameters**

$$(\Delta t > 0, \Delta t < 0) \times (B^0, \bar{B}^0) \times (J/\psi K^0_S, J/\psi K^0_L)$$

- Flavor misID fractions *w* (not shown here) dilute the S,C parameters by a factor (1-2*w*)
- In practice, we directly fit to the T-, CP- and CPT-violating parameters

  $\Delta S_T^{\pm}, \Delta C_T^{\pm}$ $\quad$ $\Delta S_{CP}^{\pm}, \Delta C_{CP}^{\pm}$ $\quad$ $\Delta S_{CPT}^{\pm}, \Delta C_{CPT}^{\pm}$

- In canonical CP violation studies (assume CPT and $\Delta\Gamma=0$), one single S, C set
  - ✓ In SM, S~ sin2β= 0.679±0.020 (HFAG winter'12) and C~0

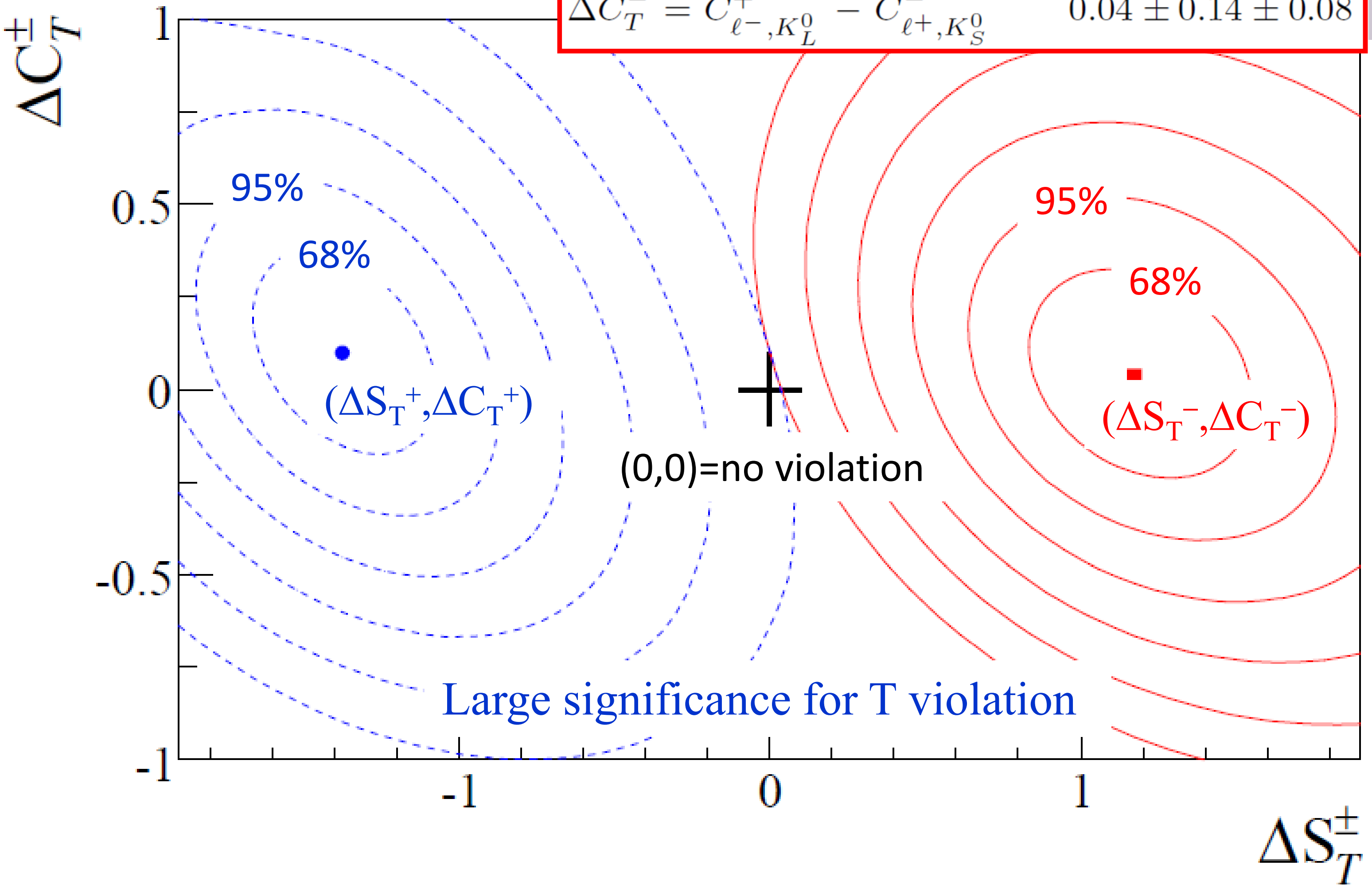
e.g. PRD 79, 072009 (2009)

Results and interpretation

Results

T-violating parameters

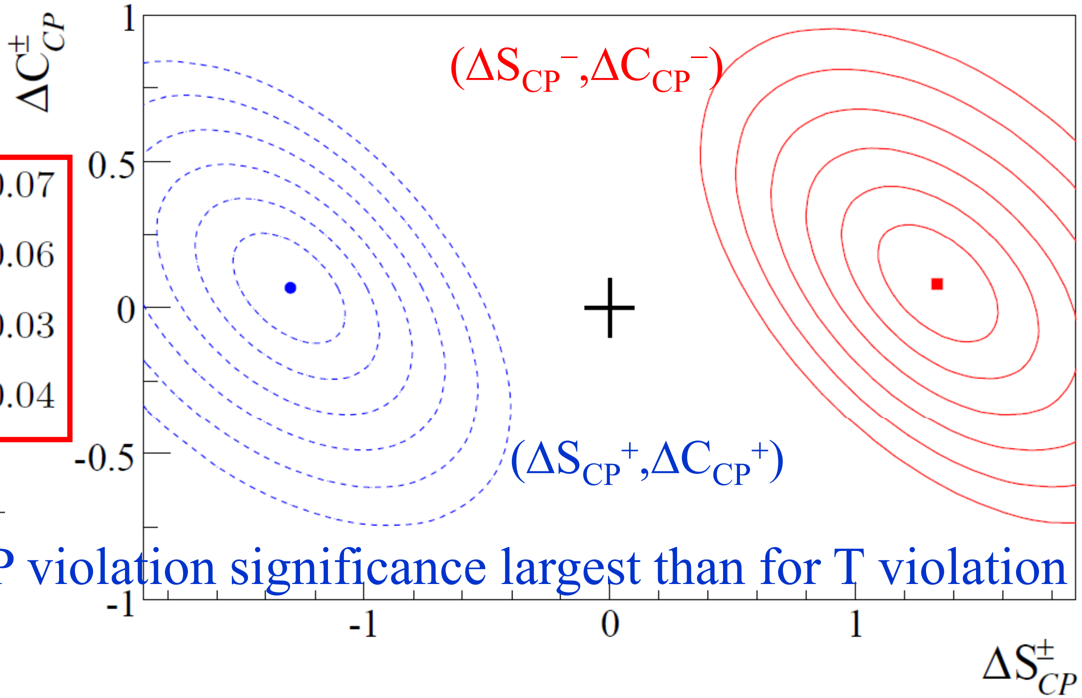
Parameter	Measurement	Expectation from canonical *CP*
$\Delta S_T^+ = S^-_{\ell-,K_L^0} - S^+_{\ell+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$	$-2\sin2\beta$
$\Delta S_T^- = S^+_{\ell-,K_L^0} - S^-_{\ell+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$	$+2\sin2\beta$
$\Delta C_T^+ = C^-_{\ell-,K_L^0} - C^+_{\ell+,K_S^0}$	$0.10 \pm 0.14 \pm 0.08$	0
$\Delta C_T^- = C^+_{\ell-,K_L^0} - C^-_{\ell+,K_S^0}$	$0.04 \pm 0.14 \pm 0.08$	0



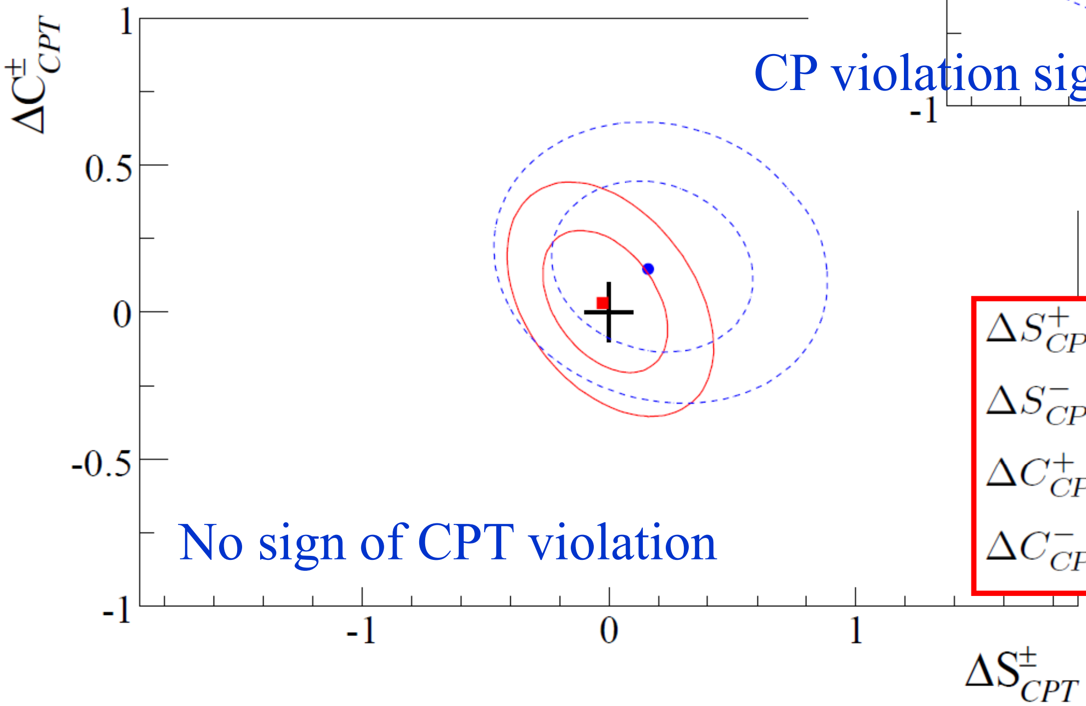
Results (cont'd)

CP-violating parameters

ΔS^{+}_{CP}	$= S^{+}_{\ell^-,K^0_S} - S^{+}_{\ell^+,K^0_S}$	$-1.30 \pm 0.11 \pm 0.07$
ΔS^{-}_{CP}	$= S^{-}_{\ell^-,K^0_S} - S^{-}_{\ell^+,K^0_S}$	$1.33 \pm 0.12 \pm 0.06$
ΔC^{+}_{CP}	$= C^{+}_{\ell^-,K^0_S} - C^{+}_{\ell^+,K^0_S}$	$0.07 \pm 0.09 \pm 0.03$
ΔC^{-}_{CP}	$= C^{-}_{\ell^-,K^0_S} - C^{-}_{\ell^+,K^0_S}$	$0.08 \pm 0.10 \pm 0.04$



CP violation significance largest than for T violation



No sign of CPT violation

CPT-violating parameters

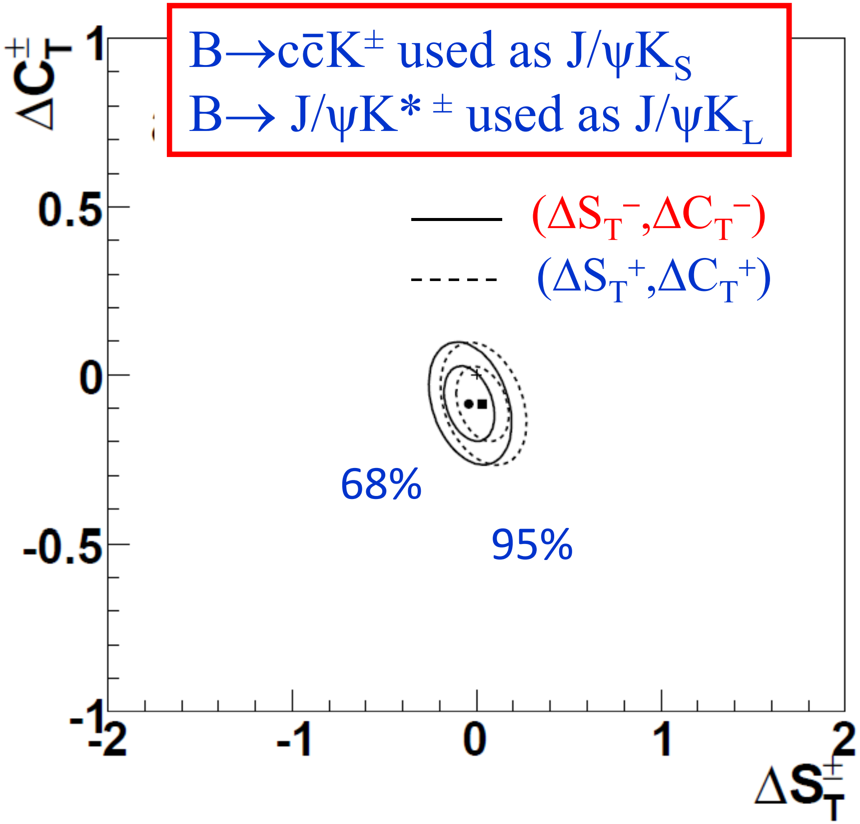
ΔS^{+}_{CPT}	$= S^{-}_{\ell^+,K^0_L} - S^{+}_{\ell^+,K^0_S}$	$0.16 \pm 0.21 \pm 0.09$
ΔS^{-}_{CPT}	$= S^{+}_{\ell^+,K^0_L} - S^{-}_{\ell^+,K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$
ΔC^{+}_{CPT}	$= C^{-}_{\ell^+,K^0_L} - C^{+}_{\ell^+,K^0_S}$	$0.14 \pm 0.15 \pm 0.07$
ΔC^{-}_{CPT}	$= C^{+}_{\ell^+,K^0_L} - C^{-}_{\ell^+,K^0_S}$	$0.03 \pm 0.12 \pm 0.08$

Observed T violation as due to compensate CP violation

Cross checks

- Study using simulation data shows asymmetry parameters $\Delta S^{\pm}_T$, $\Delta C^{\pm}_T$ are unbiased and have Gaussian errors
- Studies of data segmented by running period or flavor mode are consistent
- With appropriate constraints, obtain same S,C parameters as the latest BaBar CP violation study PRD 79, 072009 (2009)
- Fitting $B\to c\bar{c}K^{\pm}$ and $B\to J/\psi K^{*\pm}$ control samples yield asymmetry parameters consistent with zero

Parameter	Value
ΔC^-_{CP}	0.036 ± 0.050
ΔC^-_{CPT}	-0.0042 ± 0.068
ΔC^-_{T}	-0.0405 ± 0.073
ΔC^+_{CP}	-0.0044 ± 0.049
ΔC^+_{CPT}	-0.1586 ± 0.070
ΔC^+_{T}	-0.0237 ± 0.073
ΔS^-_{CP}	0.088 ± 0.054
ΔS^-_{CPT}	-0.1035 ± 0.083
ΔS^-_{T}	0.041 ± 0.089
ΔS^+_{CP}	0.041 ± 0.053
ΔS^+_{CPT}	0.030 ± 0.086
ΔS^+_{T}	0.155 ± 0.094



Systematic uncertainties

Systematic uncertainties are evaluated similarly as in our last CP analysis

Systematic source	ΔS_T^+	ΔS_T^-	ΔC_T^+	ΔC_T^-
Interaction region	0.011	0.035	0.02	0.029
Flavor misID probabilities	0.022	0.042	0.022	0.022
Δt resolution	0.030	0.050	0.048	0.062
$J/\psi\, K_L^0$ background	0.033	0.038	0.052	0.010
Background fractions and CP content	0.029	0.021	0.020	0.026
m_{ES} parameterization	0.011	0.002	0.005	0.002
Γ_d and Δm_d	0.001	0.005	0.011	0.008
CP violation for flavor ID categories	0.018	0.019	0.001	0.001
Fit bias	0.010	0.072	0.013	0.010
$\Delta\Gamma_d/\Gamma_d$	0.004	0.003	0.002	0.002
PDF normalization	0.013	0.019	0.005	0.004
Total	0.064	0.112	0.08	0.077

Effect of treating $c\bar{c}K_S$ and $J/\psi K_L$ as orthogonal states negligible

Significance of T violation

- Repeat the standard fit, applying constraints to the parameters for T-conjugate processes
- Difference in likelihood with the standard fit yields the significance of T violation

$$\Delta\chi^2 = -2\,(\ln L_{\rm NoTRV} - \ln L)$$
$$\Delta\nu = 8 \text{ degrees of freedom}$$

T-inv. constraints

$$\Delta S^{\pm}_{\rm T} = \Delta C^{\pm}_{\rm T} = 0$$
$$\Delta S^{\pm}_{\rm CP} = \Delta S^{\pm}_{\rm CPT}$$
$$\Delta C^{\pm}_{\rm CP} = \Delta C^{\pm}_{\rm CPT}$$

- CP and CPT significance can be estimated this way using appropriate constraints
- Include systematics variations in significance estimations

$$m_j^2 = -2\left[\ln L(q_j, o_j) - \ln L(p_0)\right]/s^2_{{\rm stat},j}$$

- Take max(m_j^2), scale significance by [1+max(m_j^2)]=1.61

Significance

	$-2\Delta \ln L$	Signif.
T	226	> 10 σ
CP	307	> 10 σ
CPT	5	0.33 σ

(Includes systematics)

Building raw T asymmetries

- Construct asymmetry for each of the four reference transitions

$$\overline{B}^0 \to B_- \qquad \overline{B}^0 \to B_+ \qquad B_+ \to B^0 \qquad B_- \to B^0$$

- For the 1st reference (and similarly for the other three)

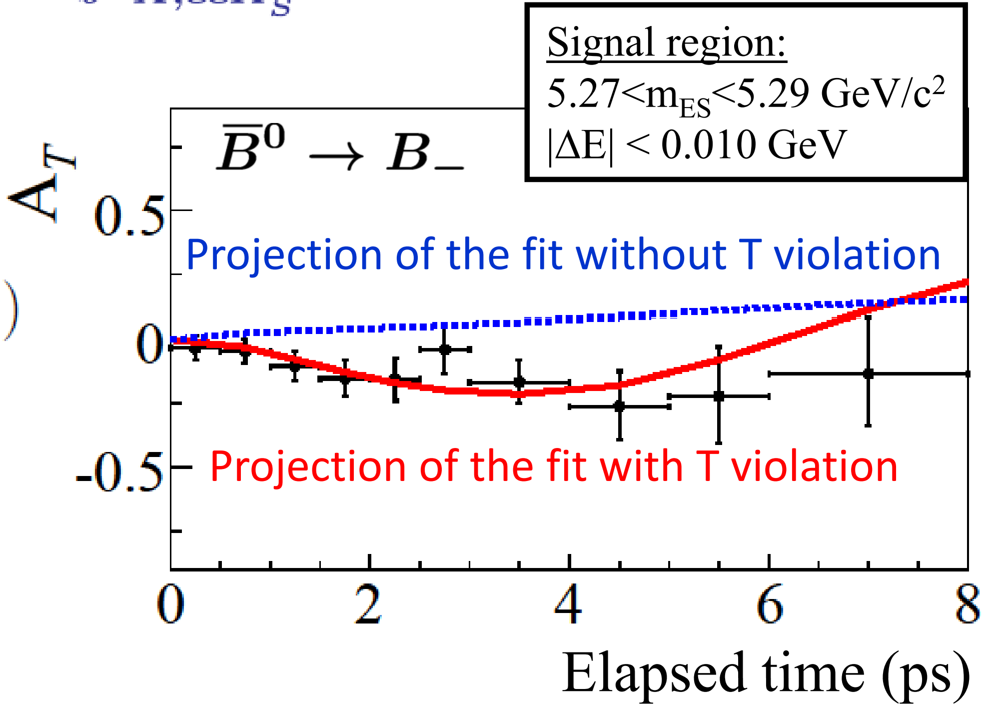
$$A_T(\Delta t) = \frac{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) - \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) + \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}$$

where

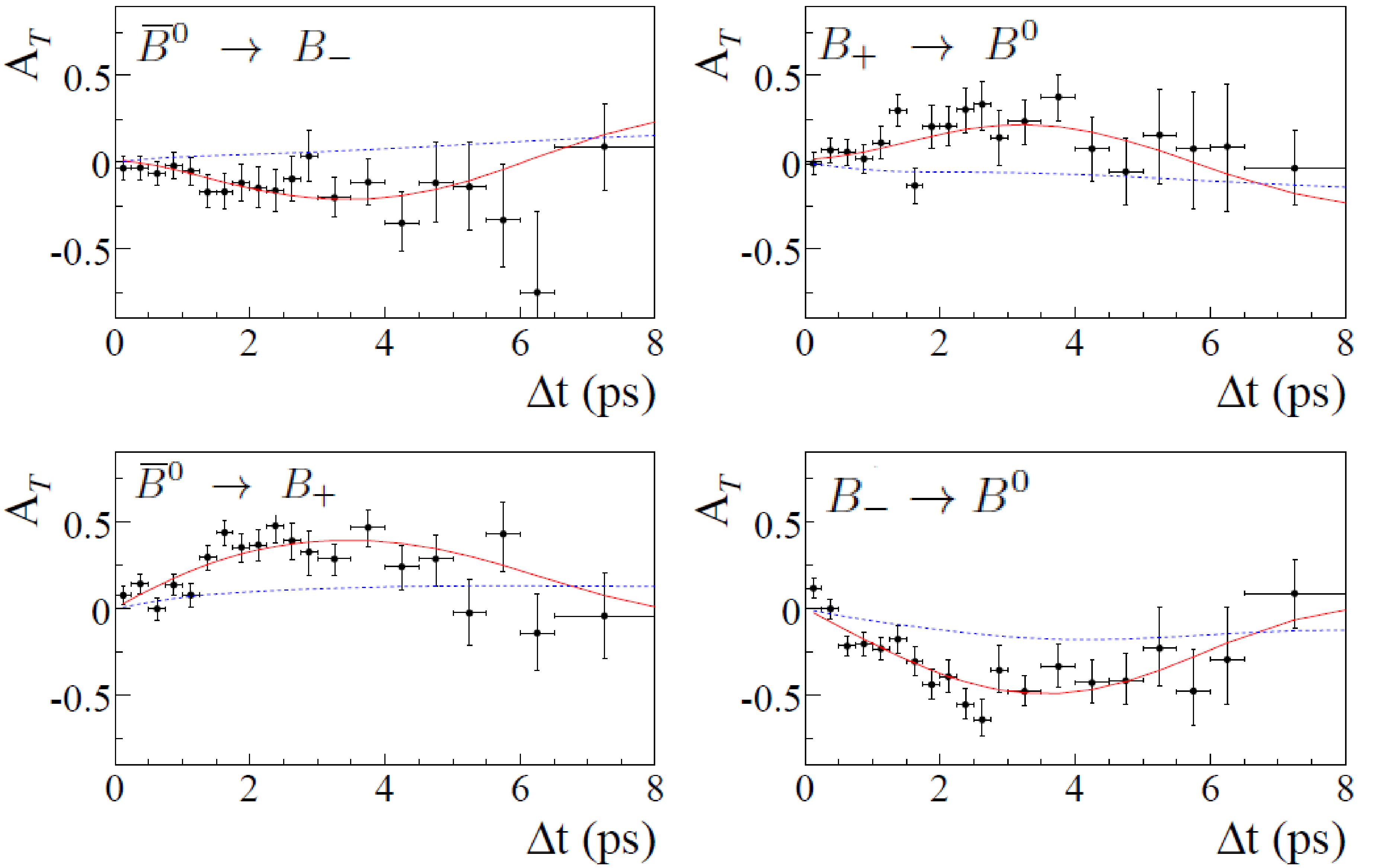
$$\mathcal{H}^\pm_{\alpha,\beta}(\Delta t) = \mathcal{H}_{\alpha,\beta}(\pm\Delta t)H(\Delta t)$$

- For perfect reconstruction, is

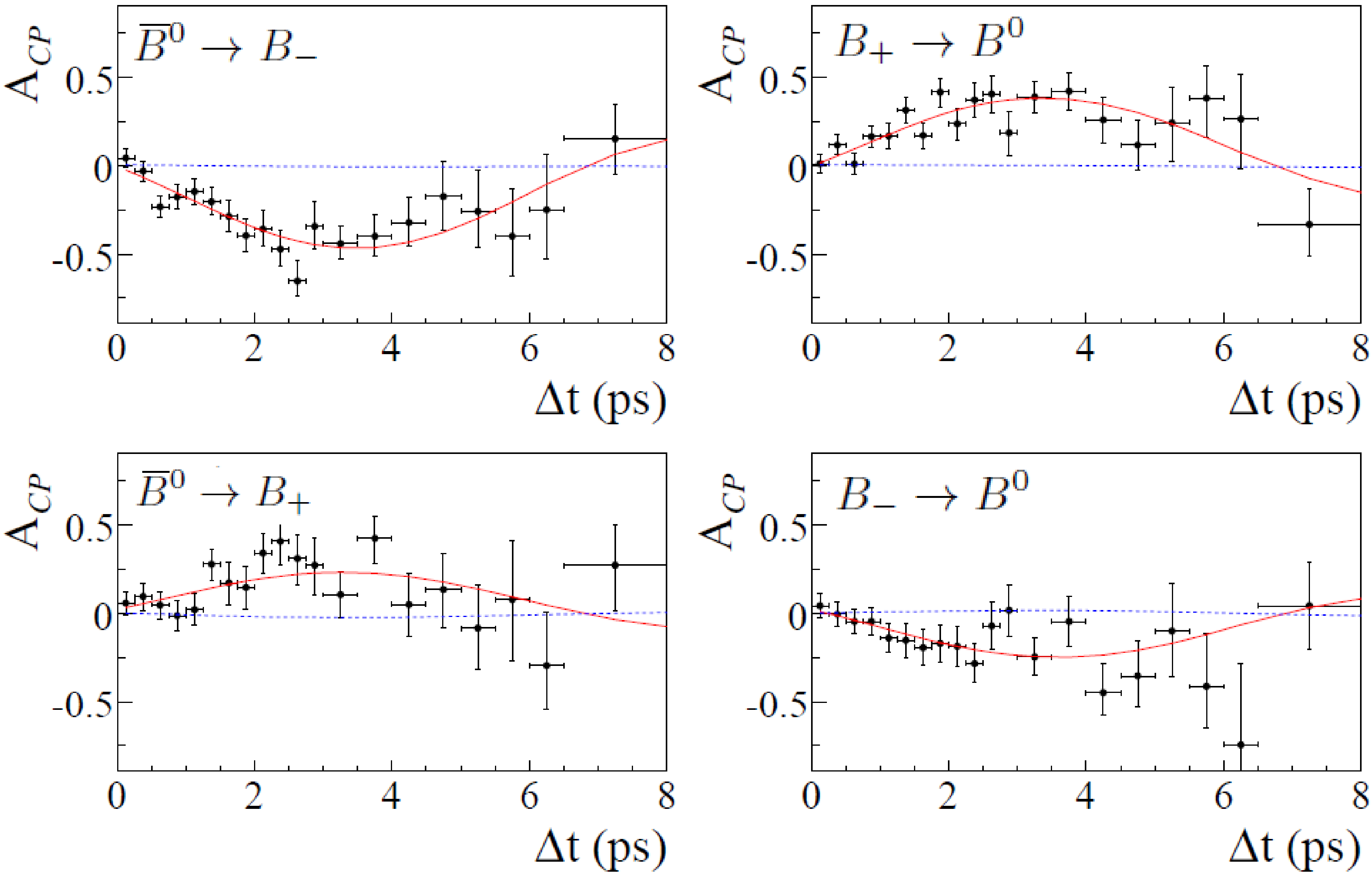
$$A_T(\Delta t) \approx \frac{\Delta C^+_{\mathrm{T}}}{2}\cos(\Delta m \Delta t) + \frac{\Delta S^+_{\mathrm{T}}}{2}\sin(\Delta m \Delta t)$$



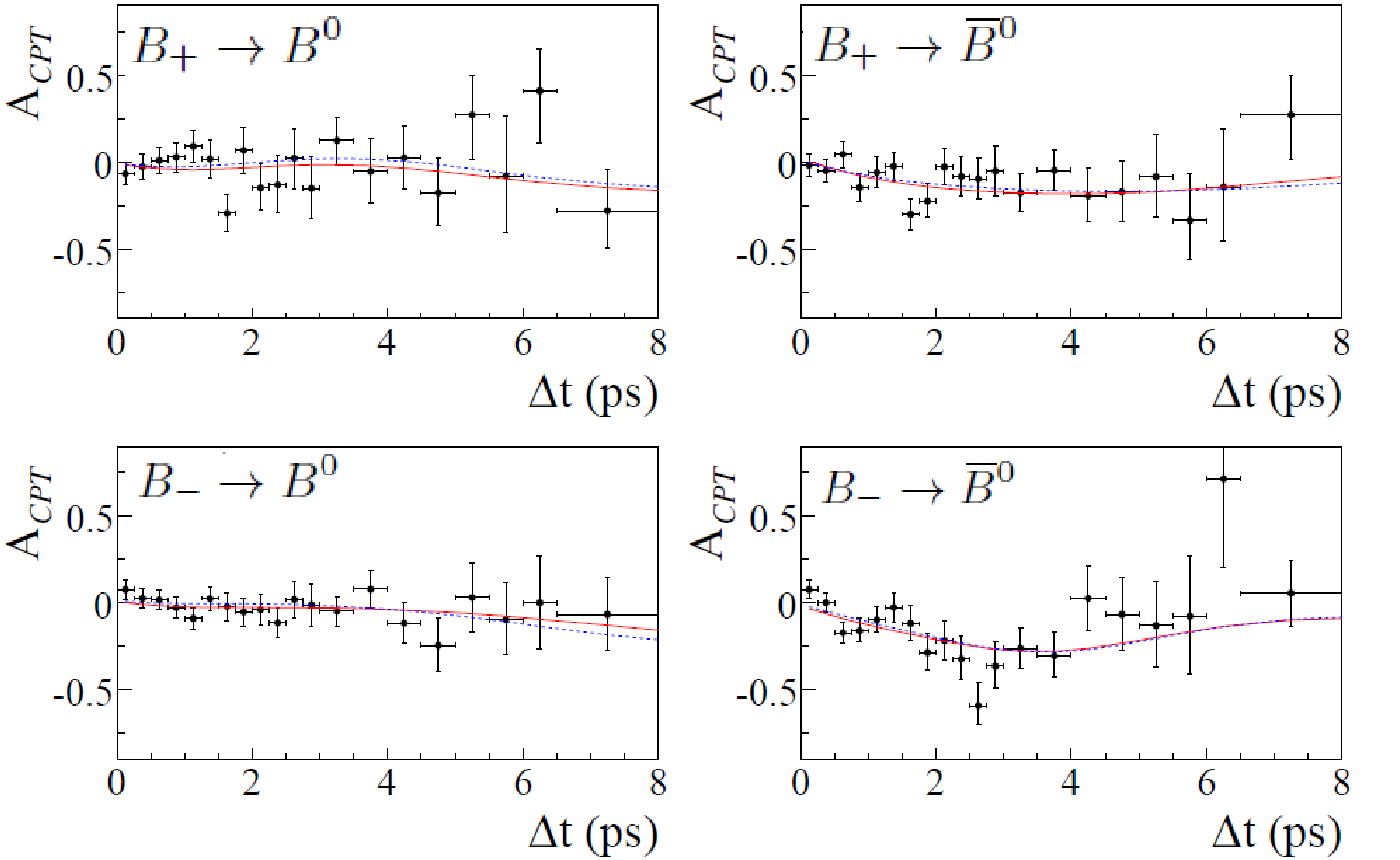
The four independent T asymmetries



The four independent CP asymmetries

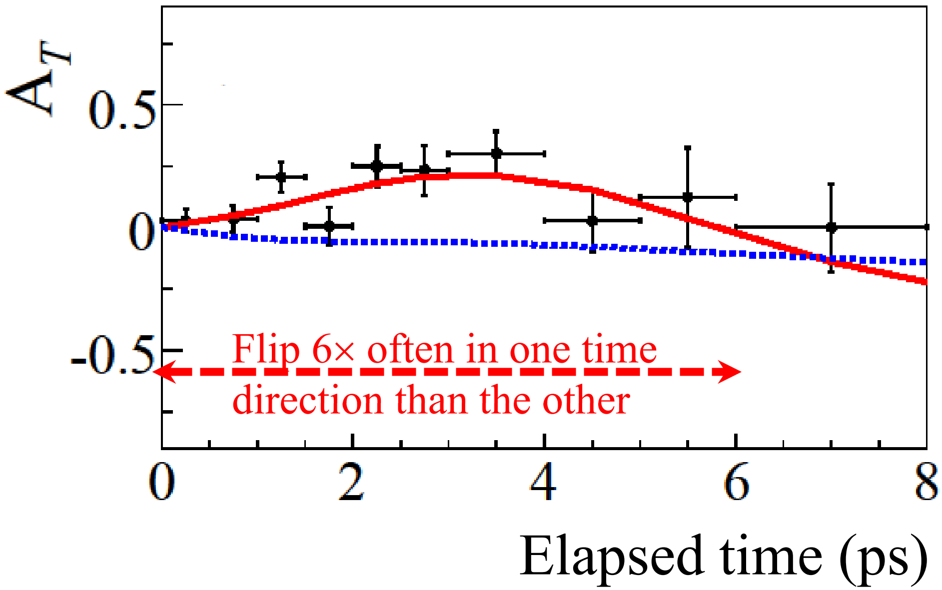


The four independent CPT asymmetries



Summary

Summary



- has measured for the first time T-violating parameters in the time evolution of neutral B mesons, by comparing conjugate processes that can only be achieved by T reversal, not CP
- This novel approach does not need CPT invariance to link T and CP violation
- The significance of the effect exceeds 10σ level
- The result is consistent with CP-violating measurements assuming CPT invariance
- This is the first direct observation of Time Reversal Violation, in any system, through processes that can only be related by a T transformation
- This somehow closes the cycle of the CPT theorem…

Summary

Paper (arXiv:1207.5832v3 [hep-ex]) is now in press

PHYSICAL REVIEW LETTERS

Observation of Time-Reversal Violation in the B^0 Meson System

J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] A. Palano,[3a,3b] G. Eigen,[4] B. Stugu,[4] D. N. Brown,[5] L. T. Kerth,[5] Yu. G. Kolomensky,[5] G. Lynch,[5] H. Koch,[6] T. Schroeder,[6] D. J. Asgeirsson,[7] C. Hearty,[7] T. S. Mattison,[7] J. A. McKenna,[7] R. Y. So,[7] A. Khan,[8] V. E. Blinov,[9] A. R. Buzykaev,[9] V. P. Druzhinin,[9] V. B. Golubev,[9] E. A. Kravchenko,[9] A. P. Onuchin,[9] S. I. Serednyakov,[9] Yu. I. Skovpen,[9] E. P. Solodov,[9] K. Yu. Todyshev,[9] A. N. Yushkov,[9] M. Bondioli,[10] D. Kirkby,[10] A. J. Lankford,[10] M. Mandelkern,[10] H. Atmacan,[11] J. W. Gary,[11] F. Liu,[11] O. Long,[11] G. M. Vitug,[11] C. Campagnari,[12] T. M. Hong,[12] D. Kovalskyi,[12] J. D. Richman,[12] C. A. West,[12] A. M. Eisner,[13] J. Kroseberg,[13] W. S. Lockman,[13] A. J. Martinez,[13] B. A. Schumm,[13] A. Seiden,[13] D. S. Chao,[14] C. H. Cheng,[14] B. Echenard,[14]

(The *BABAR* Collaboration)

(Received 24 July 2012)

Although CP violation in the B meson system has been well established by the B factories, there has been no direct observation of time-reversal violation. The decays of entangled neutral B mesons into definite flavor states (B^0 or $\bar{B}^0$), and $J/\psi K^0_L$ or $c\bar{c}K^0_S$ final states (referred to as B^+ or B^-), allow comparisons between the probabilities of four pairs of T-conjugated transitions, for example, $\bar{B}^0 \to B_-$ and $B_- \to \bar{B}^0$, as a function of the time difference between the two B decays. Using 468×10^6 $B\bar{B}$ pairs produced in $\Upsilon(4S)$ decays collected by the *BABAR* detector at SLAC, we measure T-violating parameters in the time evolution of neutral B mesons, yielding $\Delta S^+_T = -1.37 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$ and $\Delta S^-_T = 1.17 \pm 0.18(\text{stat}) \pm 0.11(\text{syst})$. These nonzero results represent the first direct observation of T violation through the exchange of initial and final states in transitions that can only be connected by a T-symmetry transformation.

Summary

Added bonus: article in The Economist (1st September)

A press release is now under review by SLAC and DOE, plan to release once the paper will be published online

Plan for an article in Physics Today

The Economist

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The arrow of time

Backward ran sentences...

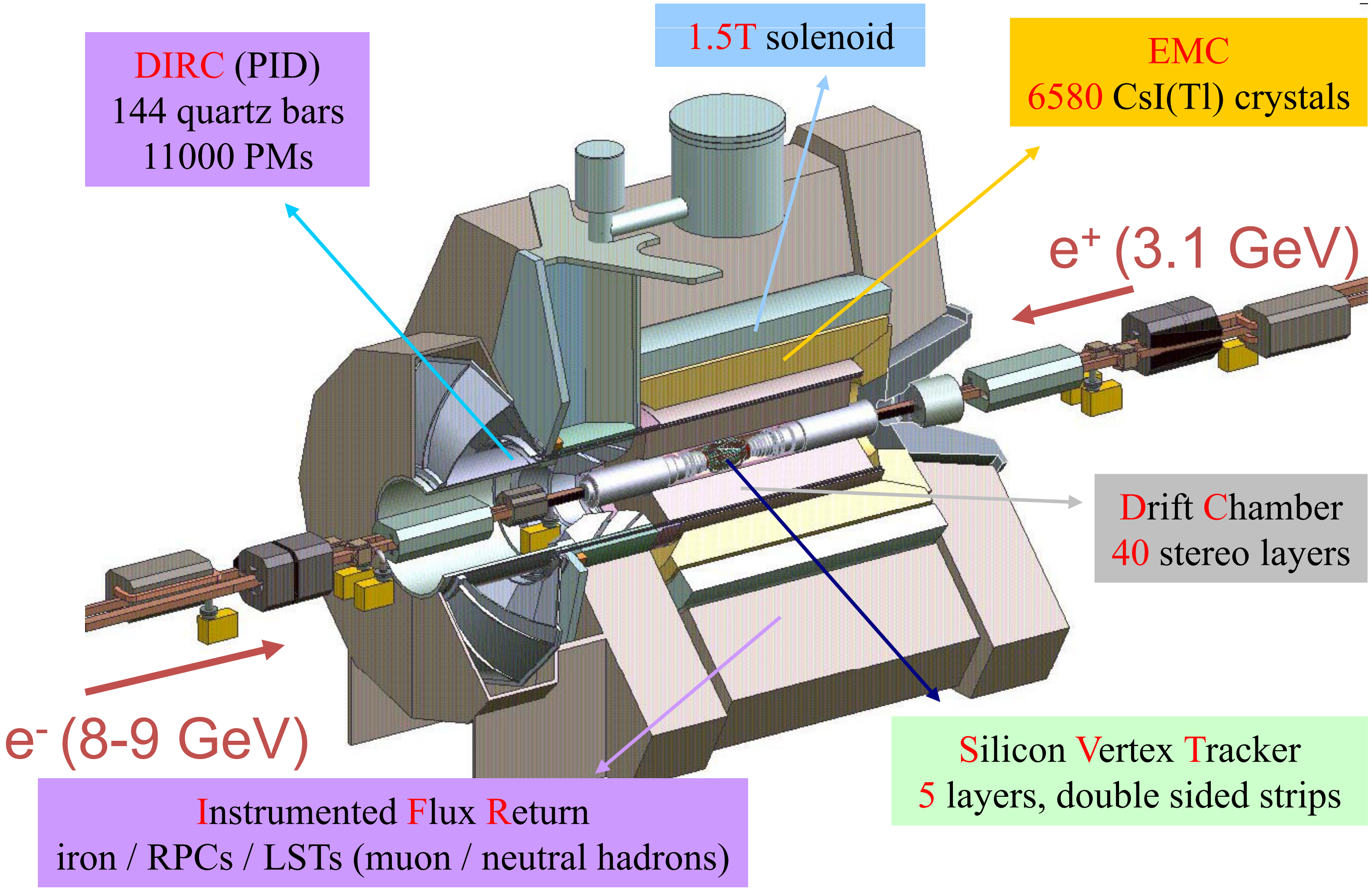
To the relief of physicists, time really does have a preferred direction

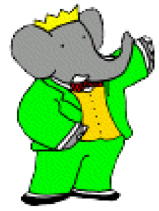
Sep 1st 2012 | from the print edition   Like 323   Tweet 62

http://www.economist.com/node/21561111

Thank you for your attention

The BaBar detector





- Asymmetric B-factory: E_{cms} = 10.58 GeV $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L identification. Very stable over the 9 years of operation