# Observing directly the "weak arrow of time"

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IFIC – Universitat de València-CSIC

## IVICFA mini-Workshop

30th November 2012

*Picture Credit:*
*Greg Stewart, SLAC*

PRL 109, 211801 (2012) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2012

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

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(The *BABAR* Collaboration)

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 $468 \times 10^6$ $B\bar{B}$ 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.

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Physics

*Physics* 5, 129 (2012)

# Viewpoint

## Particle Decays Point to an Arrow of Time

**Michael Zeller**
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Published November 19, 2012

*An experiment studying B meson decays makes a direct observation of time-reversal violation without relying on assumed relationships with other fundamental symmetries.*

Subject Areas: **Particles and Fields**

**A Viewpoint on:**
**Observation of Time-Reversal Violation in the B0 Meson System**
J. P. Lees et al. (The BABAR Collaboration)
*Phys. Rev. Lett.* **109**, 211801 (2012) – Published November 19, 2012

tion found discrepancies in the decay rates. The asymmetry, which could only come from a $T$ transformation and not a $CP$ violation, was significant, being fourteen standard deviations away from time invariance. Thus the long wait for an unequivocal time-reversal violation in particle physics is finally over.

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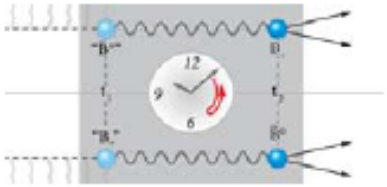
## *Physics:* Particle Decays Point to an Arrow of Time

**November 19, 2012**



An experiment studying *B* meson decays makes a direct observation of time-reversal violation without relying on assumed relationships with other fundamental symmetries.
[Viewpoint on Phys. Rev. Lett. **109**, 211801 (2012)]

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physics today

# Time-reversal asymmetry in particle physics has finally been clearly seen

Bertram M. Schwarzschild

Citation: Phys. Today **65**(11), 16 (2012); doi: 10.1063/PT.3.1774
View online: http://dx.doi.org/10.1063/PT.3.1774
View Table of Contents: http://www.physicstoday.org/resource/1/PHTOAD/v65/i11
Published by the American Institute of Physics.

search and discovery

## Time-reversal asymmetry in particle physics has finally been clearly seen

**Bedrock theory has insisted since 1964 that the weak interactions should look slightly different when the movie is run backwards.**

When it was discovered in 1957 that the weak interactions of elementary particles are not symmetric under the parity operation *P*, theorists retreated to the seemingly safe presumption that the combined operation *CP* remained an inviolate symmetry. (The charge-conjugation operation

B mesons quantum-entangled in such a way that, sometimes, the decay of one instantaneously fixes the state of its partner, perhaps a millimeter away. Having combed through all those B pairs, the international collaboration that ran the B factory's BaBar detector now reports the first clear, direct evi-

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## BaBar Experiment Confirms Time Asymmetry

Time's quantum arrow has a preferred direction, new analysis shows.

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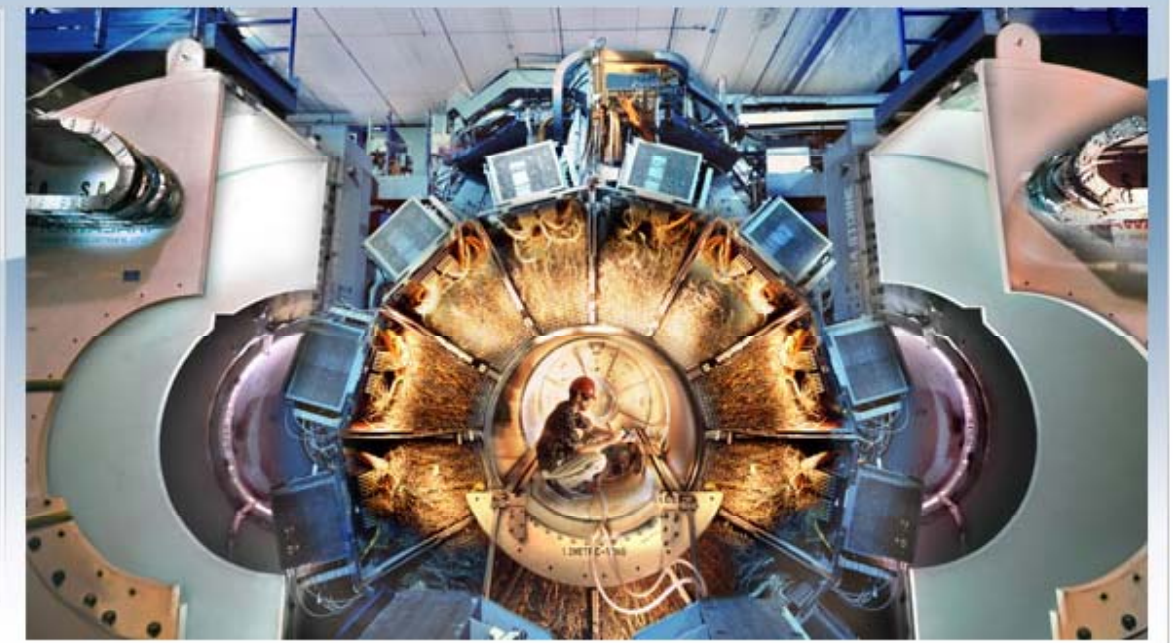
3 of 3



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# RESEARCH HIGHLIGHTS

*Selections from the scientific literature*

BOTANY

## Plant fertilization protein found

Fertilization in flowering plants is dependent on a protein that is secreted by the egg cell and activates incoming sperm.

Stefanie Sprunck at the University of Regensburg in Germany and her colleagues show that, in the model plant *Arabidopsis thaliana*, the arrival of sperm cells near the egg causes the release of a protein they call EGG CELL 1 (EC1). This triggers the redistribution of a second protein — one linked to fusion of the sex cells, or gametes — from inside the sperm to the sperm cell surface.

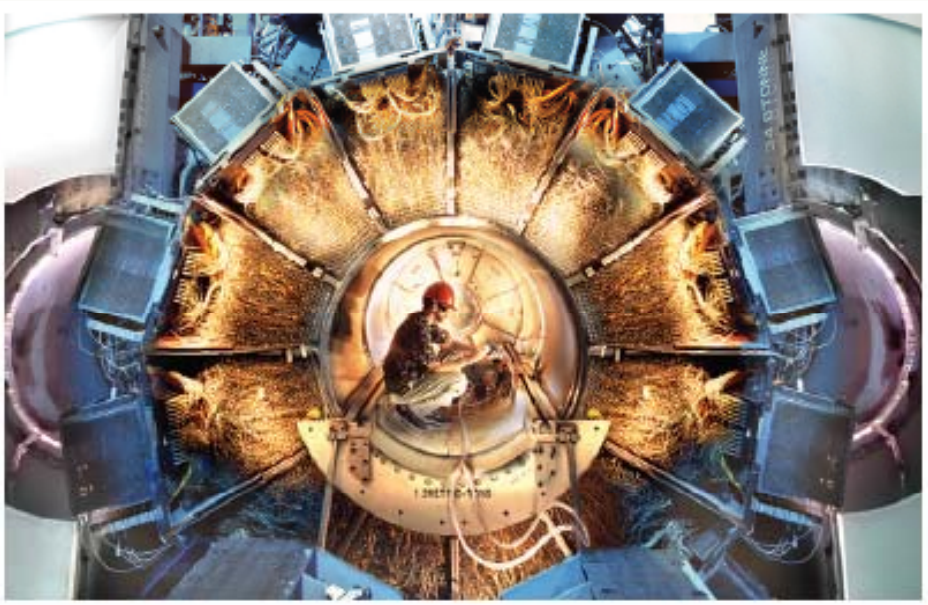
Sperm cells interacting with mutant *Arabidopsis* eggs that have faulty *ec1* genes failed to fuse, and the plant's pollen tubes continued to deliver sperm into the embryo sac. These results suggest that EC1 controls gamete fusion.

*Science* 338, 1093–1097 (2012)

CLIMATE CHANGE

## Carbon drop in snail shell shock

Free-swimming snails



SLAC NATL ACCELERATOR LAB.

PARTICLE PHYSICS

## Time's arrow in B mesons

A cornerstone of theoretical particle physics — the idea that not all processes run in the same way forwards in time as they do backwards — has been observed directly for the first time.

Members of the BaBar Collaboration trawled data from their experiment (pictured), which ran at the SLAC National Accelerator Laboratory in Menlo Park, California, from 1999 to 2008. The researchers identified B-meson decay chains that were time reversals of each other, and a comparison of the decay rates revealed a strong asymmetry. Earlier experiments have caught hints of time-reversal violation but failed to distinguish it clearly from violations of other fundamental symmetries.

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

**For a longer story on this research, see go.nature.com/258vei**



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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

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# Outline

- Introduction
  - ✓ Time reversal symmetries in the laws of Physics
  - ✓ Scenarios for T violation
  - ✓ T violation in unstable systems
- T violation and entanglement: strategy at a B factory
- Data sample and fitting strategy
  - ✓ The BaBar detector and data set
  - ✓ Signal and backgrounds
  - ✓ Fitting strategy
- Results and interpretation
  - ✓ Results
  - ✓ Cross checks and systematic uncertainties
  - ✓ Significance of T violation
  - ✓ The raw T asymmetries
- Summary

# Introduction

# Time reversal symmetries in the laws of Physics

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

**Microscopic *t* symmetry, or T symmetry**

  - ✓ T symmetry implies invariance under reversal of motion and detailed balance

$$\text{Prob}(\, a+b \rightarrow c+d \,) \;=\; \text{Prob}(\, c+d \rightarrow a+b \,)$$

Experimentally verified with high precision in certain nuclear reactions

- 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 this "weak arrow of time" be directly observed, independently of CPV?**

# Macroscopic *t* asymmetries

- All we know macroscopic (complex) systems cannot run backwards
  - ✓ E.g. A vase falls and breaks into pieces, but it is not possible that pieces of the group fly ordered forming the vase

**Macroscopic *t* asymmetry, or "arrow of time"**

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

- How it is then possible to generate irreversibility from fundamental laws that are the $t \rightarrow -t$ symmetric?
- T.D. Lee proposed the following example (adapted):
  - ✓ 1000 cars (particles) with fuel for 1000 km, departing from Valencia in all directions
  - ✓ Single rule (fundamental law): Drive straight away and at each intersection, chose randomly
  - ✓ After 500 km, they return (time reversal, or reversal of motion)
  - ✓ The process is time symmetric only until the first intersection

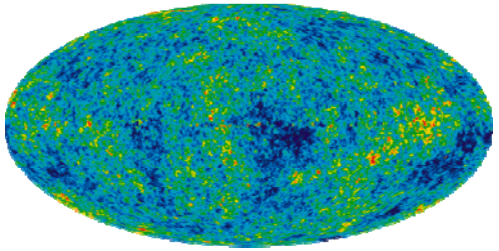
# Macroscopic *t* asymmetries (cont'd)

- The falling vase has trillions of trillions of particles and collisions
  - ✓ It is "highly improbable" that the vase returns to its original situation

  - ✓ Better to buy another one…
- In particle physics, decays are an example of time asymmetric process
  - ✓ Mismatch between $P \rightarrow 1+\ldots+n$ and $1+\ldots+n \rightarrow P$
- Macroscopic *t* asymmetry is probably connected with the Universe *t* asymmetry

**Universe *t* asymmetry**

The initial condition was improbable, more ordered (inflation?)

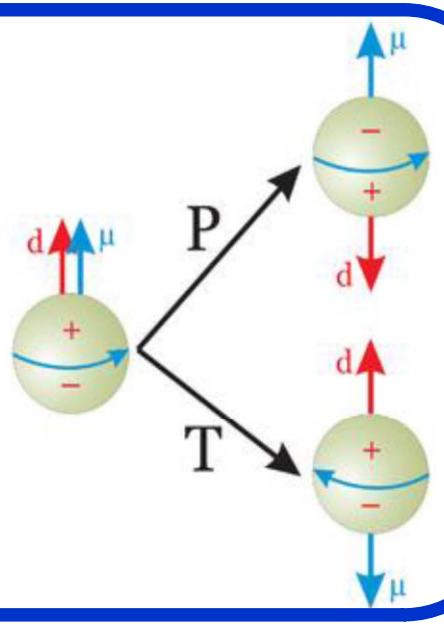


# Scenarios for time reversal violation

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)

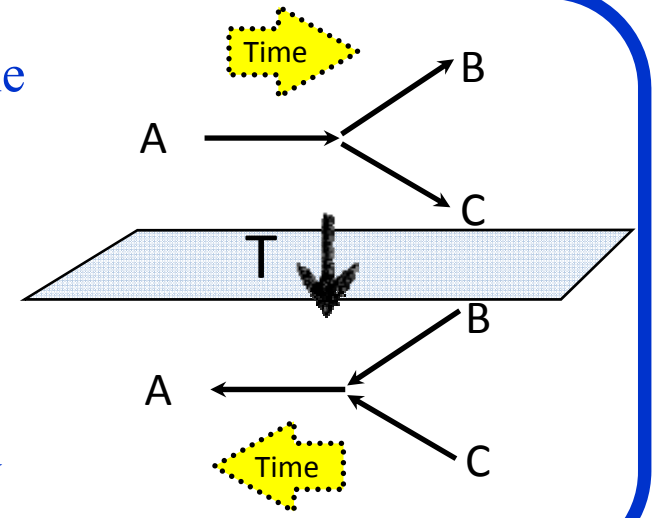
- ✓ Also violates parity, P
- ✓ EDM of the neutron or electron: PDGLive.org

$d_n < 2.9 \times 10^{-26}$ $e$-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: $\nu_e \to \nu_\mu$ vs. $\nu_\mu \to \nu_e$ 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

$$|A(B^0 \to K^+\pi^-)|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(\Delta\varphi_{weak} + \Delta\delta_{strong})$$

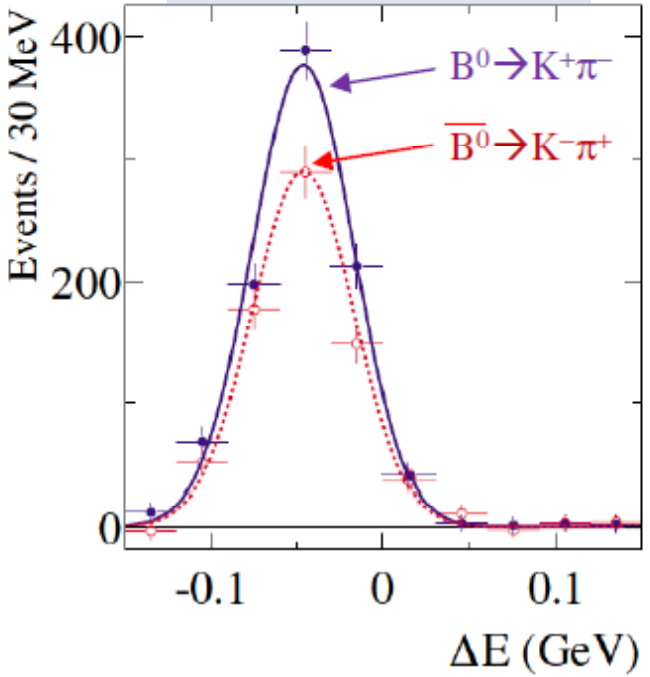
$$|A(\overline{B}^0 \to K^-\pi^+)|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(-\Delta\varphi_{weak} + \Delta\delta_{strong})$$

(Two paths to reach the same final state, and strong phases do not vanish)

  - ✓

  - ✓ Can we observe Kπ → B ?

PRL93, 131801 (2004)




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

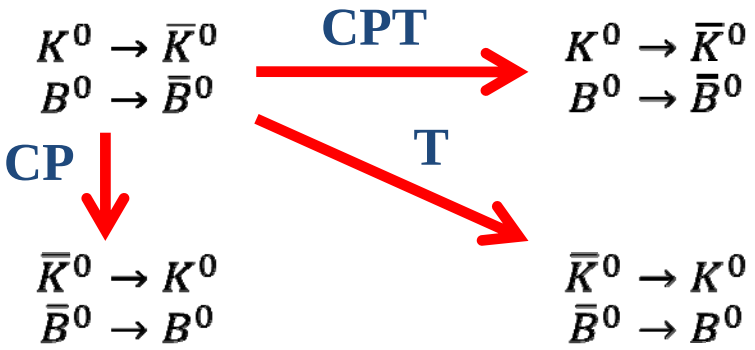
Preparation of the initial state difficult (unfeasible).

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)

  - ✓ Evidence (4σ) of $K^0 \to \bar{K}^0$ vs. $\bar{K}^0 \to K^0$ asymmetry by CPLEAR, PLB444, 43 (1998)
  - ✓ This flavor asymmetry is both T and CP violating (the two transformations lead to the same observation)

| $CPT$ | | $\not{CPT}$ | | |
|---|---|---|---|---|
| $CP, T$ | $\not{CP}, \not{T}$ | $\not{CP}, T$ | $CP, \not{T}$ | $\not{CP}, \not{T}$ |
| $= 0$ | $\neq 0$ | $= 0$ | $= 0$ | $\neq 0$ |

  - ✓ Is independent of time and ≈ requires $\Delta\Gamma \neq 0$ to be observed
  - ✓ Some "controversy" in the interpretation of the observable (formal analysis)

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

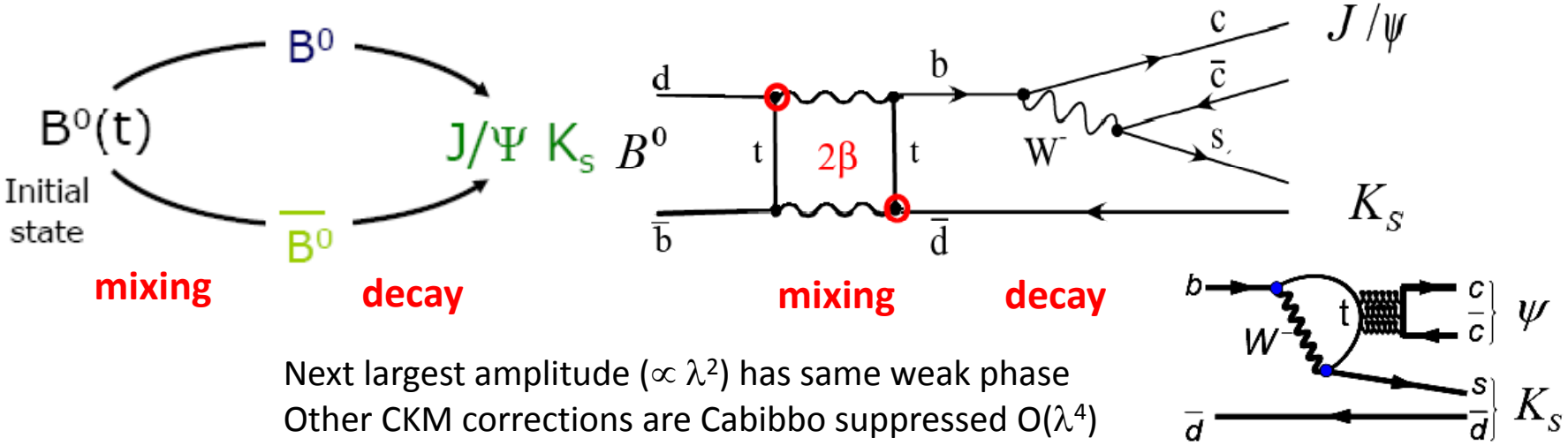
Wolfenstein, Int. Jour. Mod. Phys. E8, 501 (1999)

Alvarez-Gaume et al, Phys. Lett. B 458 (1999)

Test s of Conservation Laws, PDG, May 2010

# T violation in unstable systems (cont'd)

- Compare a → b vs. b → a in mixing+decay processes
  - ✓ BaBar and Belle have observed large CP violation in interference between mixing and decays of $B^0 \to J/\Psi K_{S/L}$ ($b \to c\bar{c}s$) and $B^0 \to J/\Psi K_{S/L}$ ($\bar{b} \to \bar{c}c\bar{s}$) final states (allows determination of CKM angle β)




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

  - ✓ The decay rate for a $B^0$ or $\bar{B}^0$ at initial time decaying to a CP final state *f* is

$$g_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1 \pm \left[-C_f \cos(\Delta m \Delta t) + S_f \sin(\Delta m \Delta t)\right]\right\}$$

Within the SM and CKM:

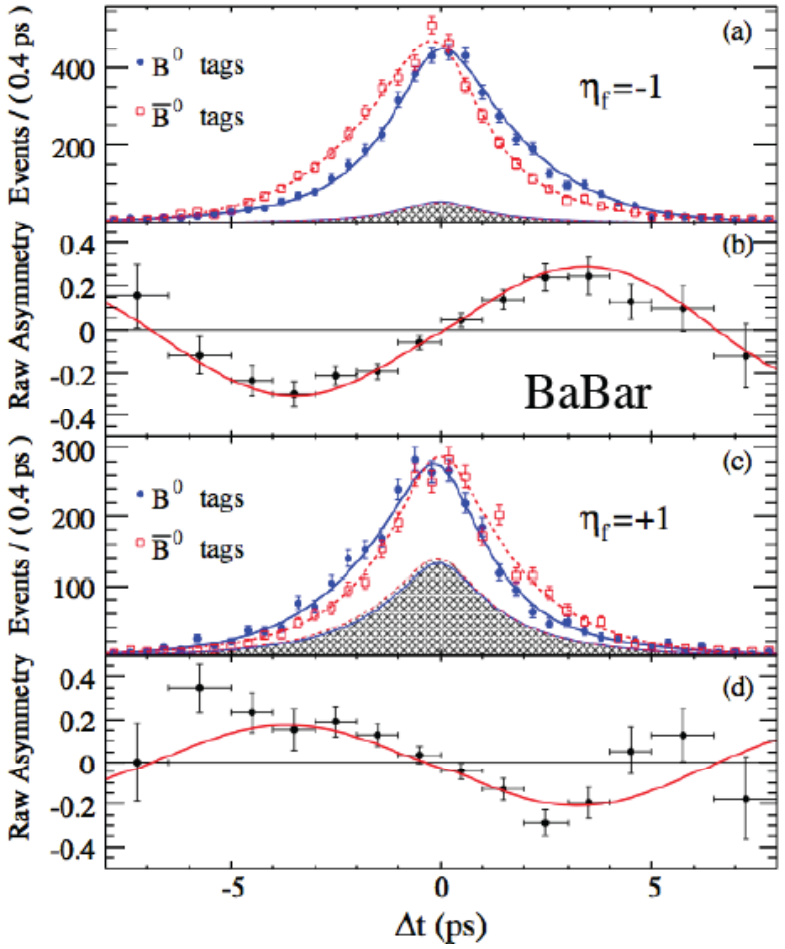
$$S_f = \frac{-2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2} \simeq -\eta_{f_{CP}} \sin 2\beta \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \simeq 0$$

CKM angle ($V_{td}$)

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$p/q \approx e^{-2i\beta}$$

# T violation in unstable systems (cont'd)




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

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

$$A_{CP,f}(\Delta t) \equiv \frac{\Gamma_{\overline{B}^0 \to f}(\Delta t) - \Gamma_{B^0 \to f}(\Delta t)}{\Gamma_{\overline{B}^0 \to f}(\Delta t) + \Gamma_{B^0 \to f}(\Delta t)} = S_f \sin(\Delta m \Delta t) - C_f \cos(\Delta m \Delta t)$$

CP asymmetry

***Kobayashi and Maskawa awarded half of 2008 N.P.***

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 picture (from PDG)

| | | |
|---|---|---|
| $e$ electric dipole moment | | $<10.5 \times 10^{-28}$ $e$cm, CL = 90% |
| $\mu$ electric dipole moment | | $(-0.1 \pm 0.9) \times 10^{-19}$ $e$cm |
| $\mu$ decay parameters | | |
| transverse $e^+$ polarization normal to plane of $\mu$ spin, $e^+$ momentum | | $(-2 \pm 8) \times 10^{-3}$ |
| $\alpha'/A$ | | $(-10 \pm 20) \times 10^{-3}$ |
| $\beta'/A$ | | $(2 \pm 7) \times 10^{-3}$ |
| Re($d_\tau$ = $\tau$ electric dipole moment) | | $-0.220$ to $0.45 \times 10^{-16}$ $e$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($\xi$) in $K^+ \to \pi^0 \mu^+ \nu_\mu$ decay (from transverse $\mu$ pol.) | | $-0.006 \pm 0.008$ |
| asymmetry $A_T$ in $K^0$-$\overline{K}^0$ mixing | | $(6.6 \pm 1.6) \times 10^{-3}$ |
| Im($\xi$) in $K^0_{\mu 3}$ decay (from transverse $\mu$ pol.) | | $-0.007 \pm 0.026$ |
| $A_T(D^\pm \to K^0_S K^\pm \pi^+ \pi^-)$ | [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 | | |
| $\phi_{AV}$, 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] | $0.008 \pm 0.016$ |
| $\Lambda$ electric dipole moment | | $<1.5 \times 10^{-16}$ $e$cm, CL = 95% |
| triple correlation coefficient $D$ for $\Sigma^- \to n e^- \overline{\nu}_e$ | | $0.11 \pm 0.10$ |

CPLEAR

**4σ evidence**

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

# T violation and entanglement: strategy at a B factory

# T violation and quantum entanglement

Bañuls & Bernabeu, PLB464, 117 (1999)

Wolfenstein, Int. Jour. Mod. Phys. E8, 501 (1999)

➢ Quantum (EPR) entanglement at B factories

Quinn, J. Phys. Conf. Ser. 171, 012001 (2009)

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

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

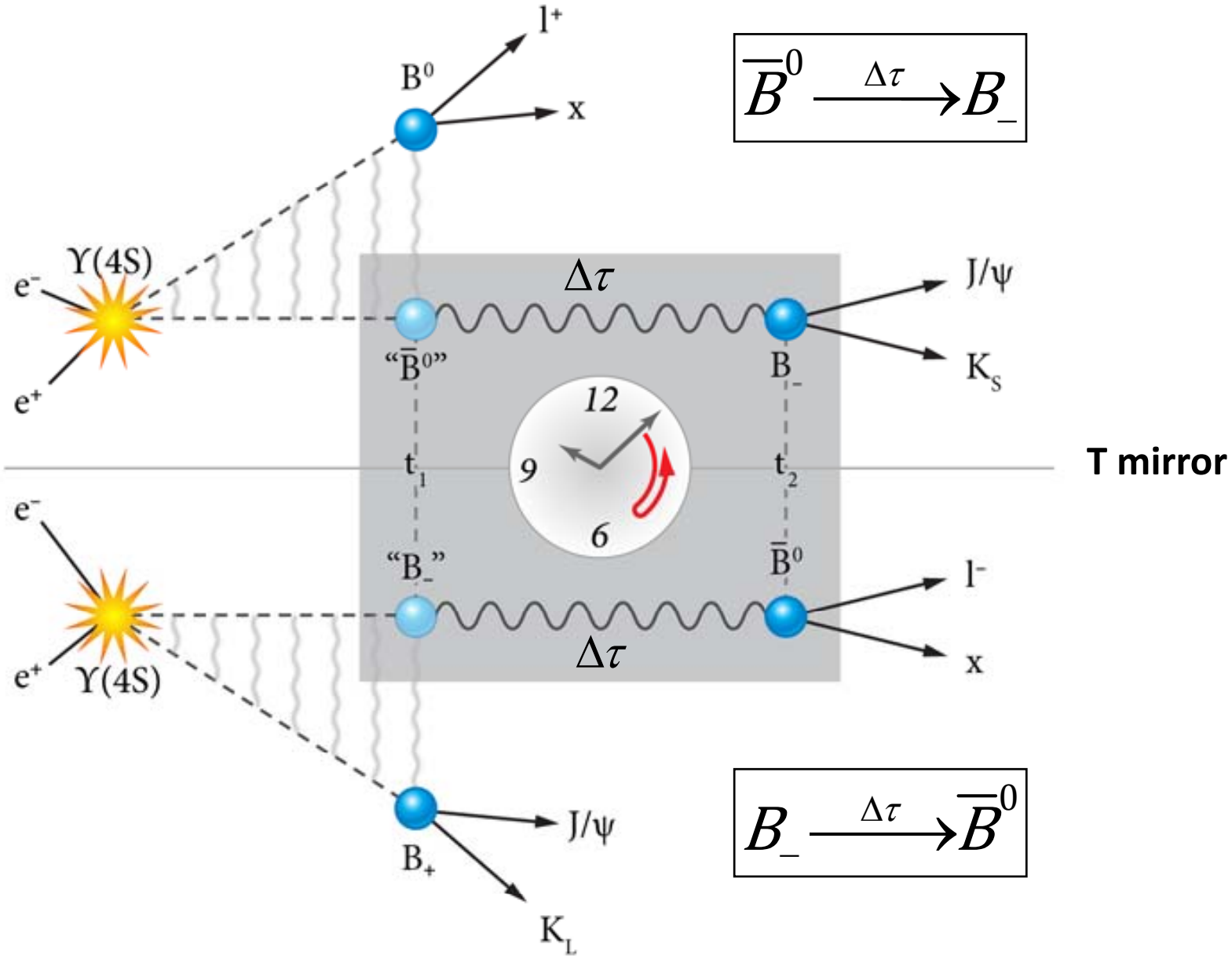
- ✓ $\Upsilon(4S)$ is a $b\bar{b}$ state with $J^{PC} = 1^{--}$
- ✓ In the strong $\Upsilon(4S)$ decay the created pair of B's inherit the $\Upsilon(4S)$ quantum numbers
- ✓ B mesons are pseudo-scalars ⇒ the $B\bar{B}$ pair is in a P-wave state (antisymmetric state)
- ✓ The state of the 1st B to decay at $t_1$ dictates the state of the other B, perhaps ~1 mm away, which decays afterwards at $t_2 > t_1$

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

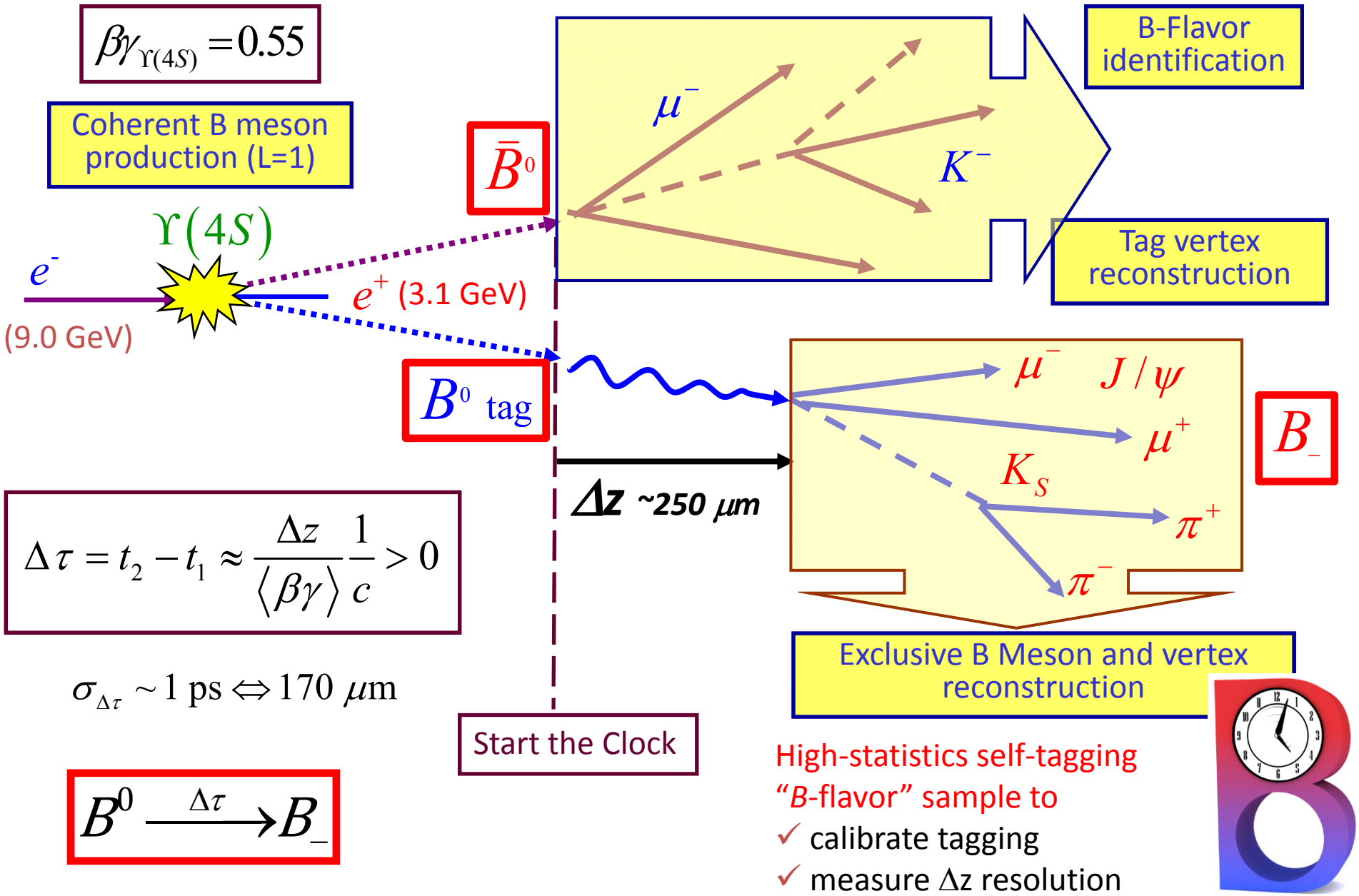
CP tag: B decay to $J/\psi K_L$ projects $B_+ \approx 1/\sqrt{2}\,[B^0 + \bar{B}^0]$ ⇒ $B_-$ tag ("CP-odd")
B decay to $J/\psi K_S$ projects $B_- \approx 1/\sqrt{2}\,[B^0 - \bar{B}^0]$ ⇒ $B_+$ tag ("CP-even")

**Ability to prepare a quantum state without destroying it ("tag"), and then study its time evolution**

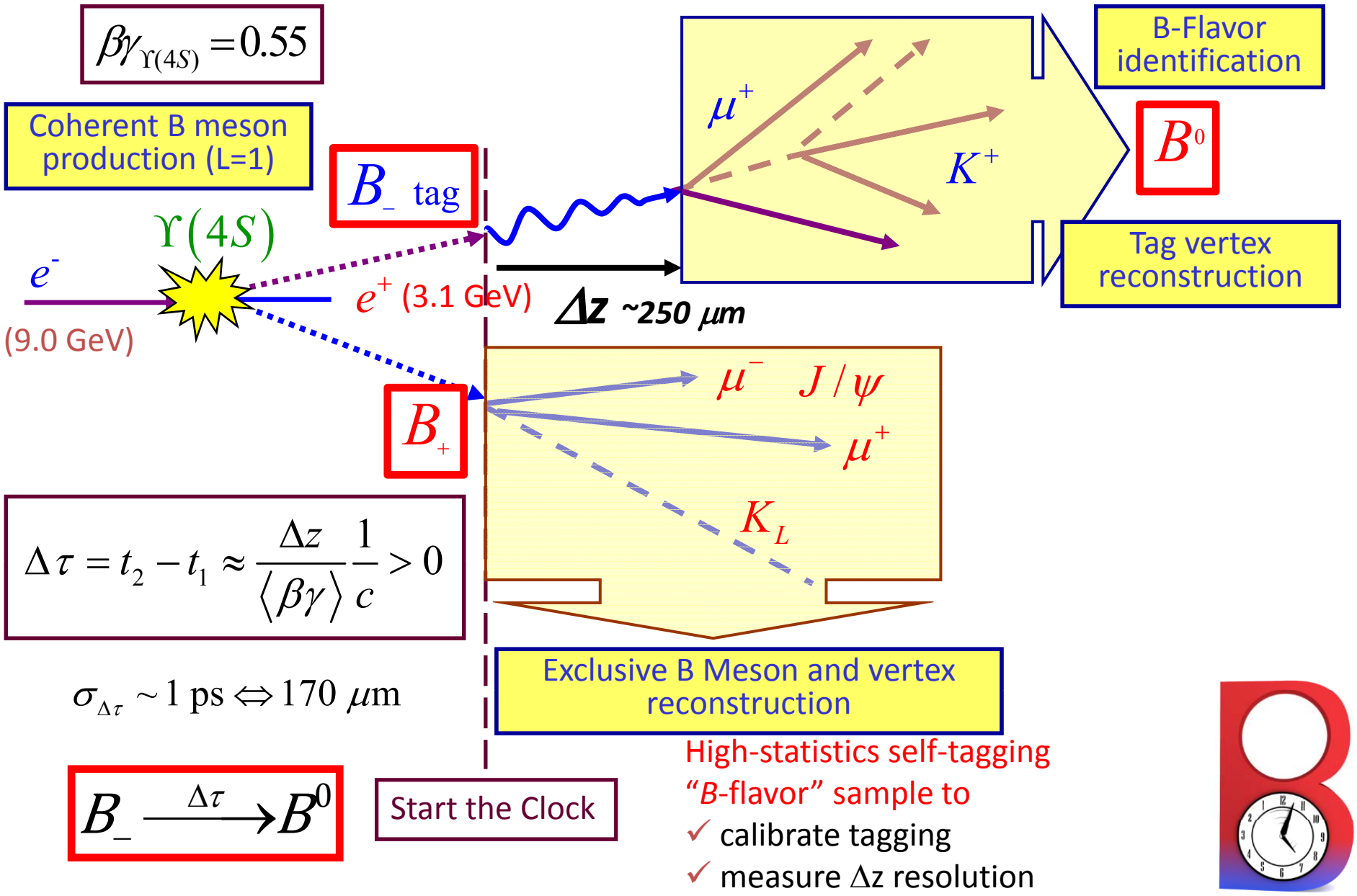
# T violation and quantum entanglement (cont'd)



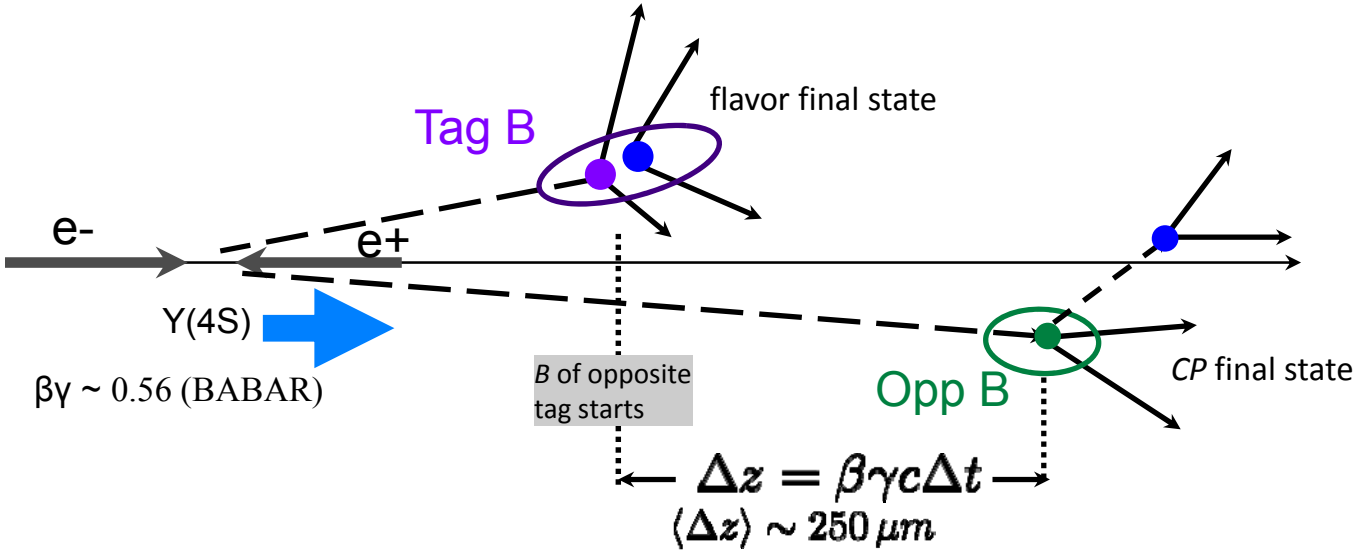
# T violation: experimental strategy at a B factory



# T violation: experimental strategy at a B factory (cont'd)



# T violation: experimental strategy at a B factory (cont'd)



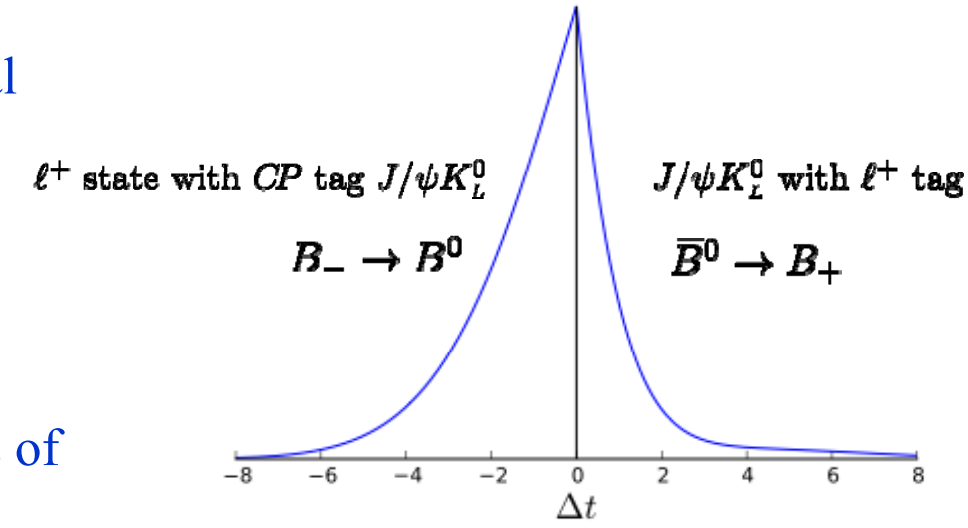

- ✓ In B factory CP violation canonical analysis, we define

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

Signed decay time difference

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

$$\Delta t = \pm \Delta \tau$$




Expected Δt distribution, e.g. $J/\psi K_L$, $l^+ X$

# T-transformed processes

## Define processes of interest and their T-transformed counterparts

JHEP08 (2012) 064

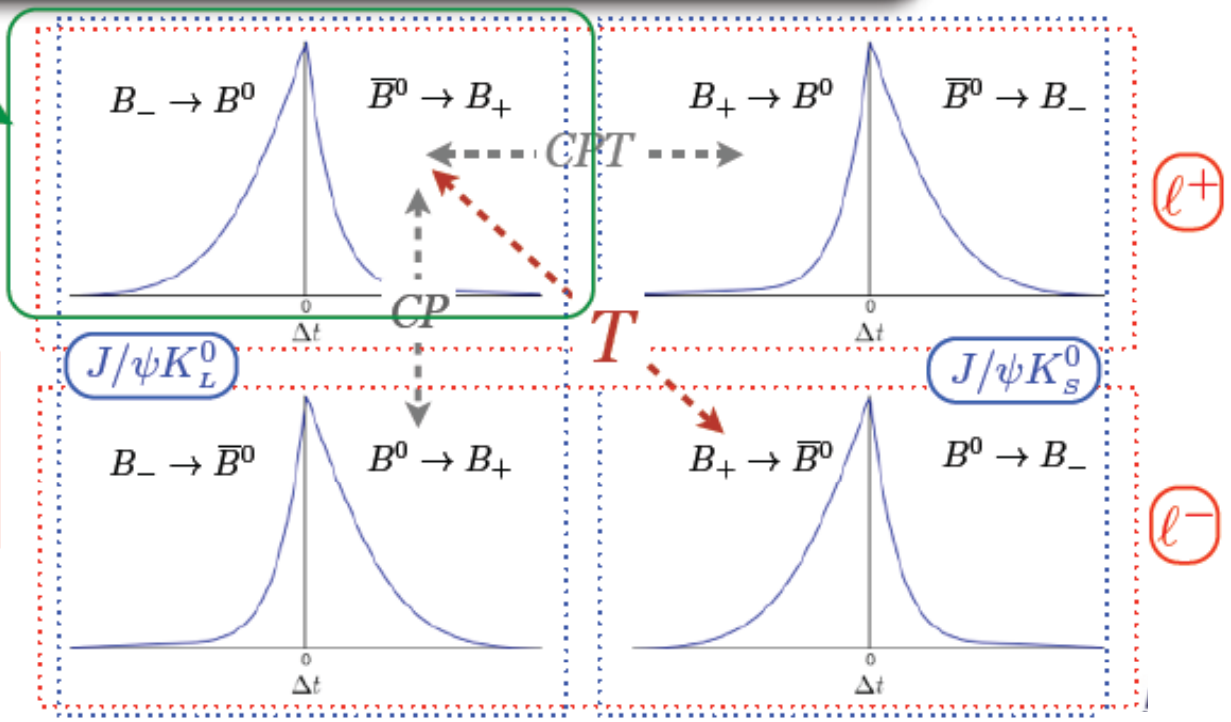
| Reference (X,Y) | | $T$-Transformed | |
|---|---|---|---|
| $B^0 \to B_+$ | $(\ell^-, J/\psi K^0_L)$ | $B_+ \to B^0$ | $(J/\psi K^0_S, \ell^+)$ |
| $B^0 \to B_-$ | $(\ell^-, J/\psi K^0_S)$ | $B_- \to B^0$ | $(J/\psi K^0_L, \ell^+)$ |
| $\overline{B}^0 \to B_+$ | $(\ell^+, J/\psi K^0_L)$ | $B_+ \to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

(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 $\Delta t$ sign
2) Different reco states ($\psi K_S$ v. $\psi K_L$)
3) Opposite flavor states ($B^0$ v. $\overline{B}^0$)



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

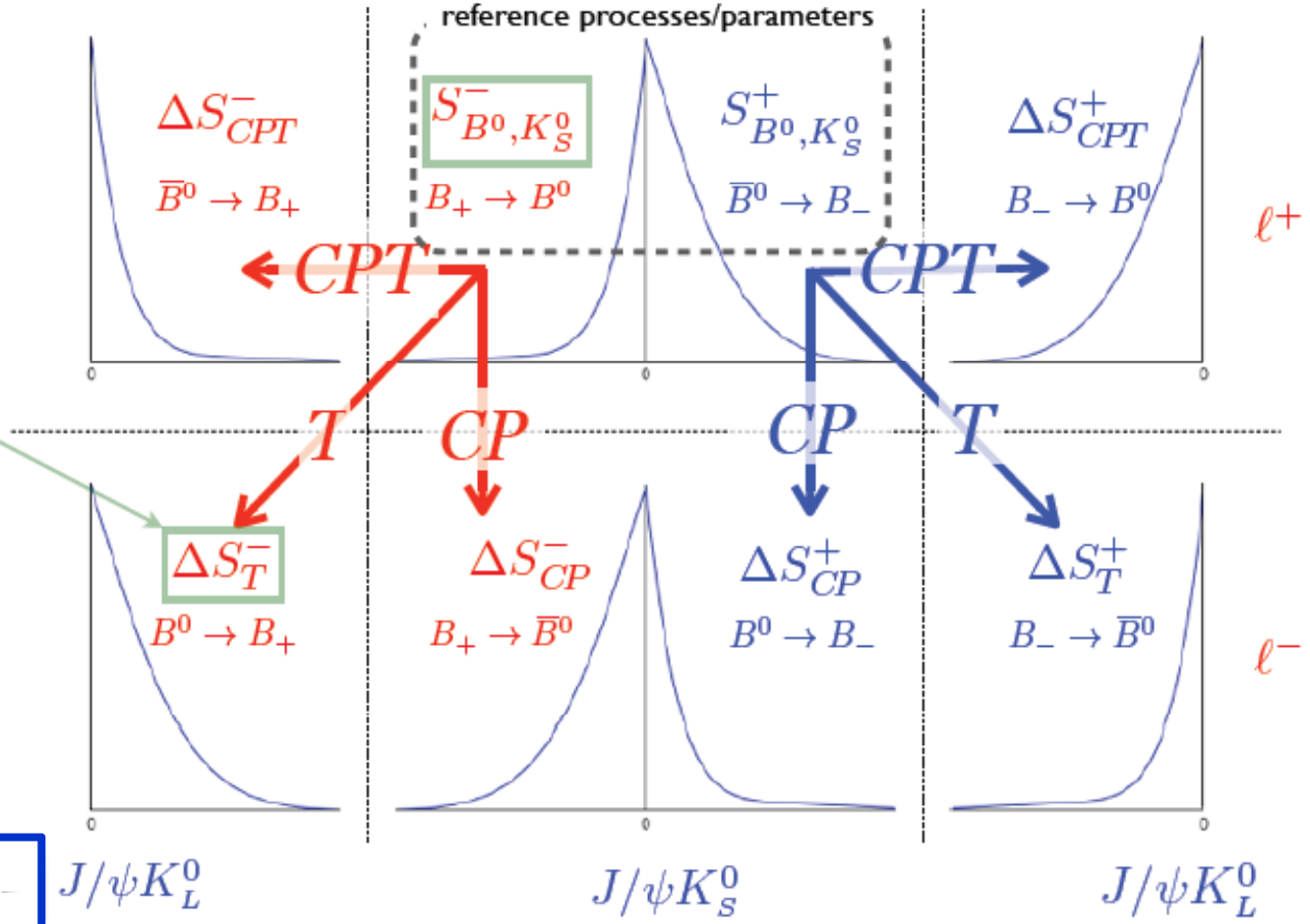
8 Signal PDFs: $g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)\}$

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 |



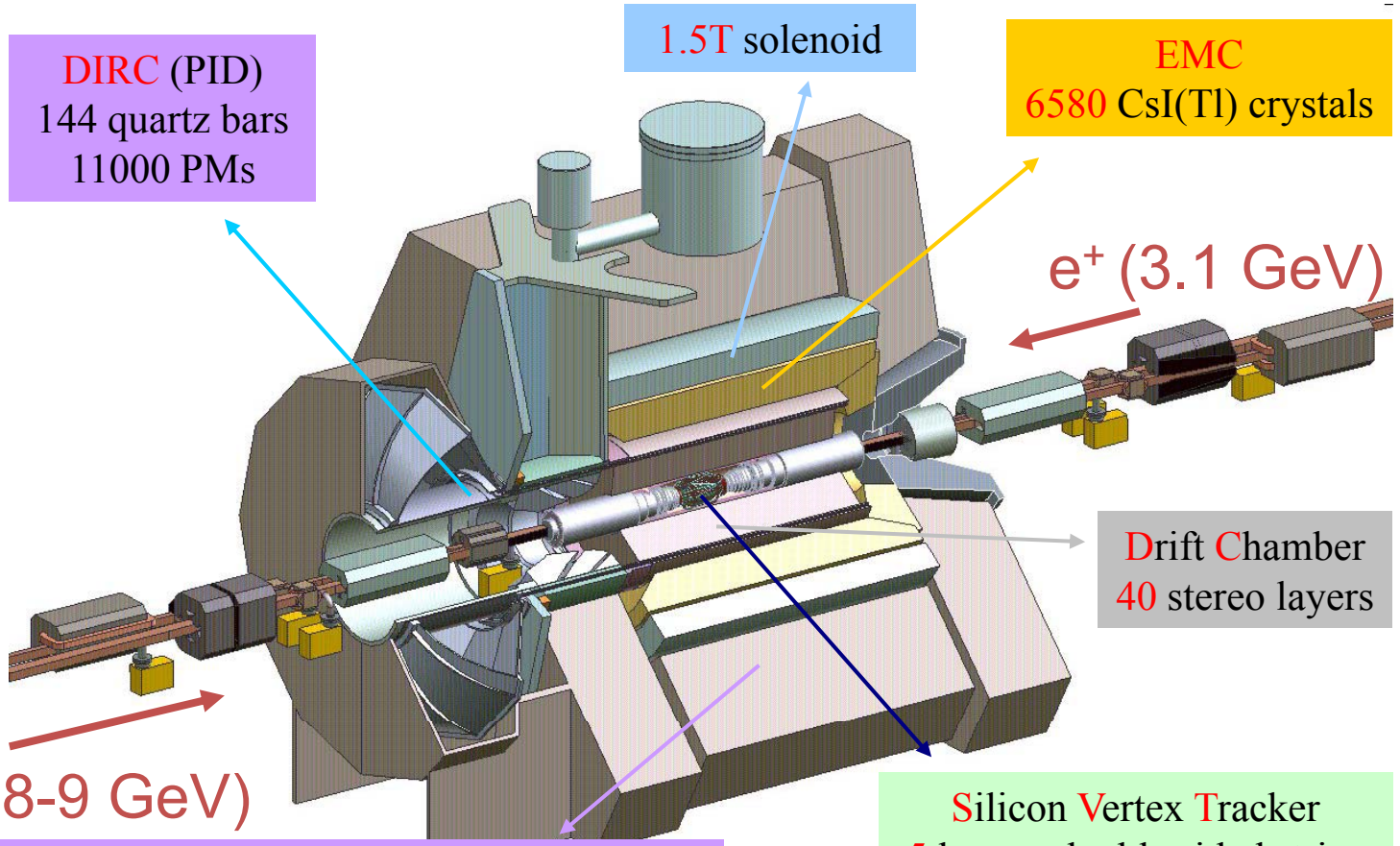

For T violation

In interference $\Delta S^{+}_{T} \neq 0$, $\Delta S^{-}_{T} \neq 0$

In decay $\Delta C^{+}_{T} \neq 0$, $\Delta C^{-}_{T} \neq 0$

# Data sample
# and fitting strategy

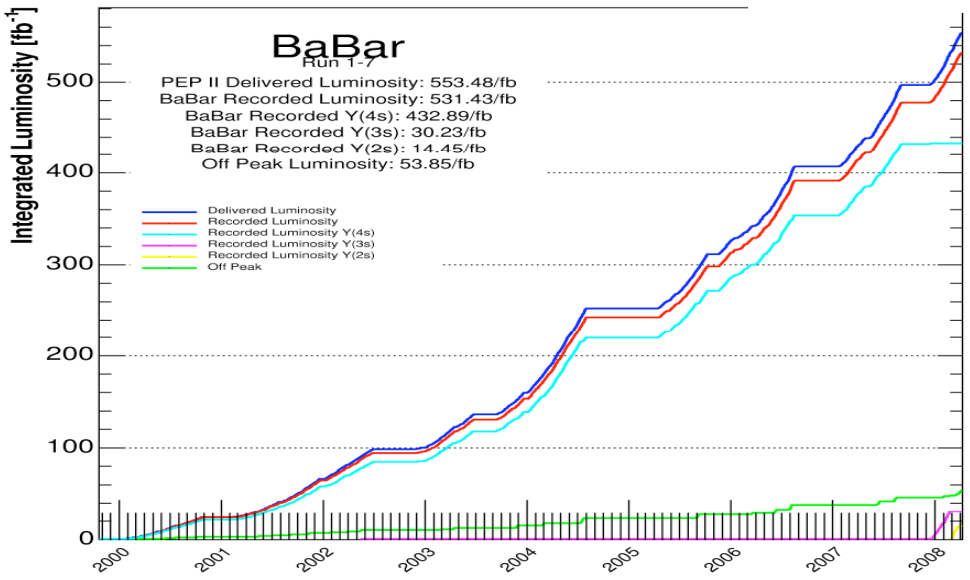
# The BaBar detector

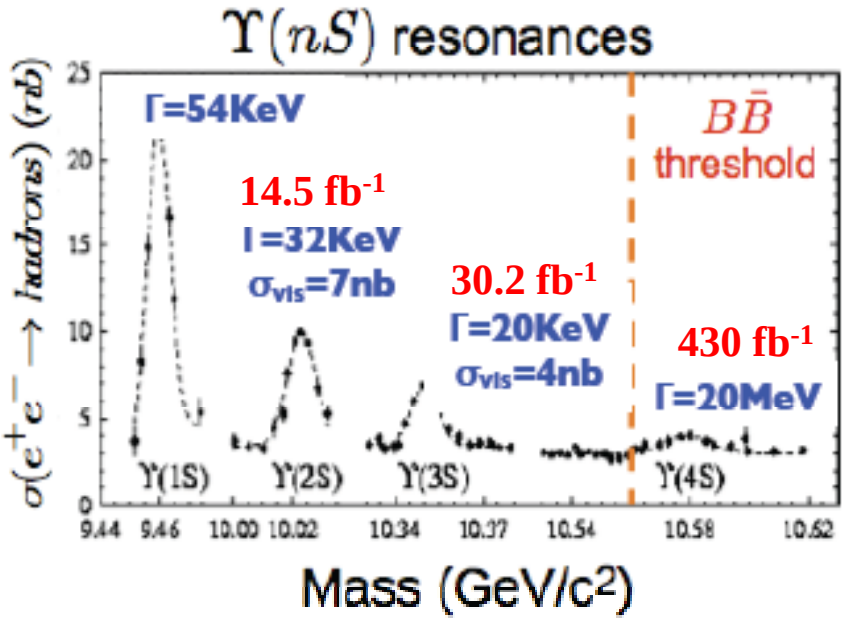



- Asymmetric B-factory at SLAC (DOE, Stanford): $E_{cms}$ = 10.58 GeV $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in $e^+e^-$ environment: precision tracking, photon/electron detection, particle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

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

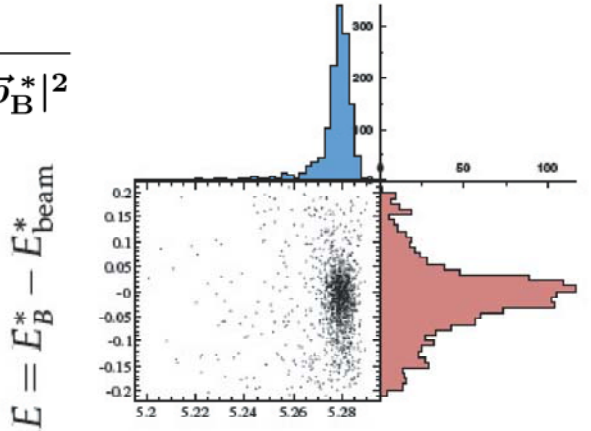
≈ 470×10$^6$ B$\bar{\rm B}$ (0.5×Belle)
≈ 690×10$^6$ c$\bar{\rm c}$
≈ 500×10$^6$ $\tau^+\tau^-$
≈ 121×10$^6$ Υ(3S) (7×Belle+Cleo)
≈ 99×10$^6$ Υ(2S) (0.5×Belle+Cleo)

# Signal and backgrounds

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

    where $E^{*}_{B} \to E^{*}_{\rm beam}$ and $\vec{p}^{\,*}_{B} \approx 300$ MeV/$c$

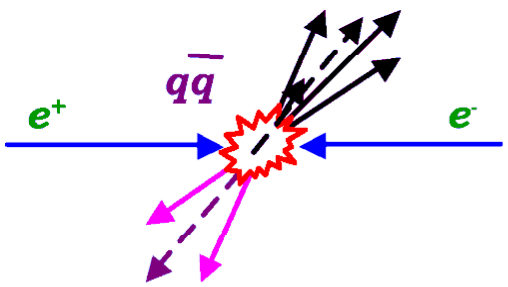
    $\sigma_{\Delta E} \sim \sigma_{E^{*}_{B}} \approx 10-50$ MeV
  - ✓ Energy difference $\Delta E = E^{*}_{B} - E^{*}_{\rm beam}$
  - ✓ Choose best B candidates based on masses of daughters

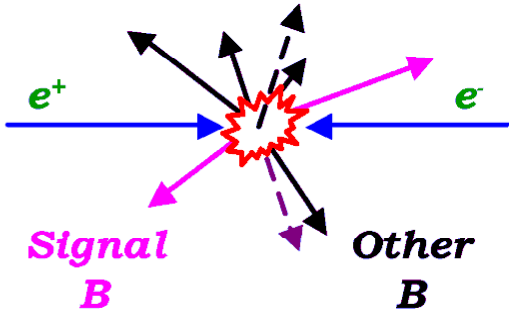



$m_{\rm ES} = \sqrt{E^{*}_{\rm beam} - p^{*2}_{B}}$

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

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

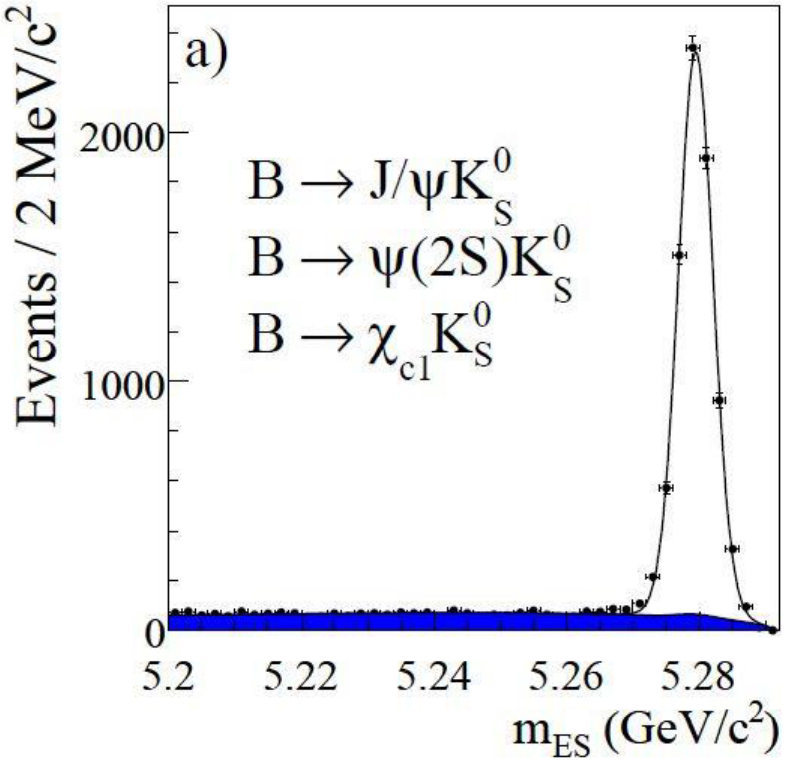


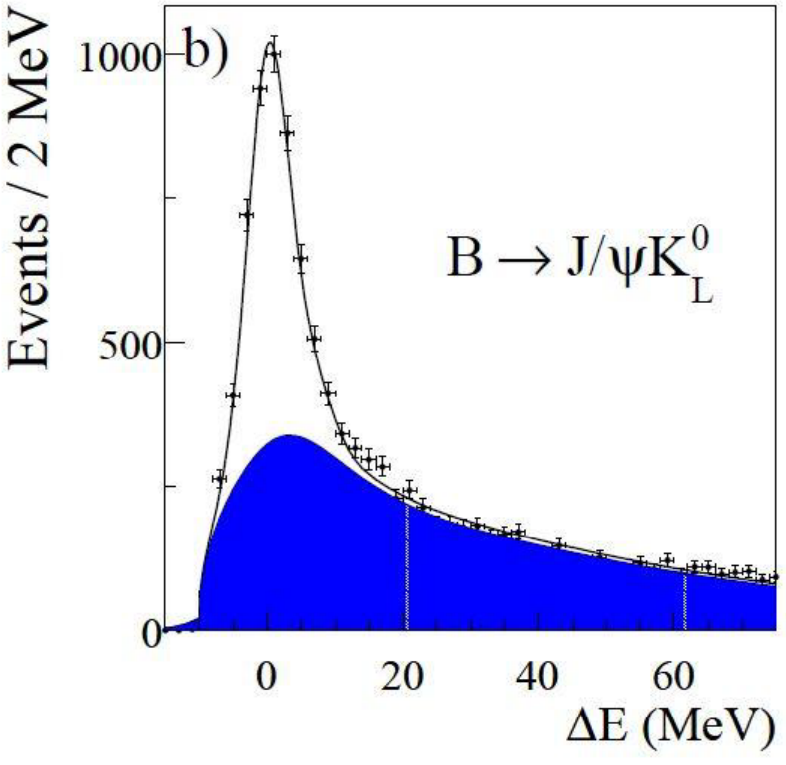
# $m_{ES}$ and $\Delta E$ for the signal sample

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 $B \to c\bar{c}K^{(*)0}$ 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

$$\underbrace{(B^0, \bar{B}^0)}_{\alpha} \times \underbrace{(J/\psi K^0_S, J/\psi K^0_L)}_{\beta}$$

  - ✓ 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 $\Delta E$
- 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  $\delta t = \Delta t - \Delta t_{\text{true}}$

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

$$+$$

$$g^{-}_{\alpha,\beta}(-\Delta t_{true}) \times \mathrm{H}(-\Delta t_{true}) \otimes \Re(\delta t;\sigma_{\Delta t})$$ **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 $\Delta t_{true}>0$ and $\Delta t_{true}<0$ 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

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

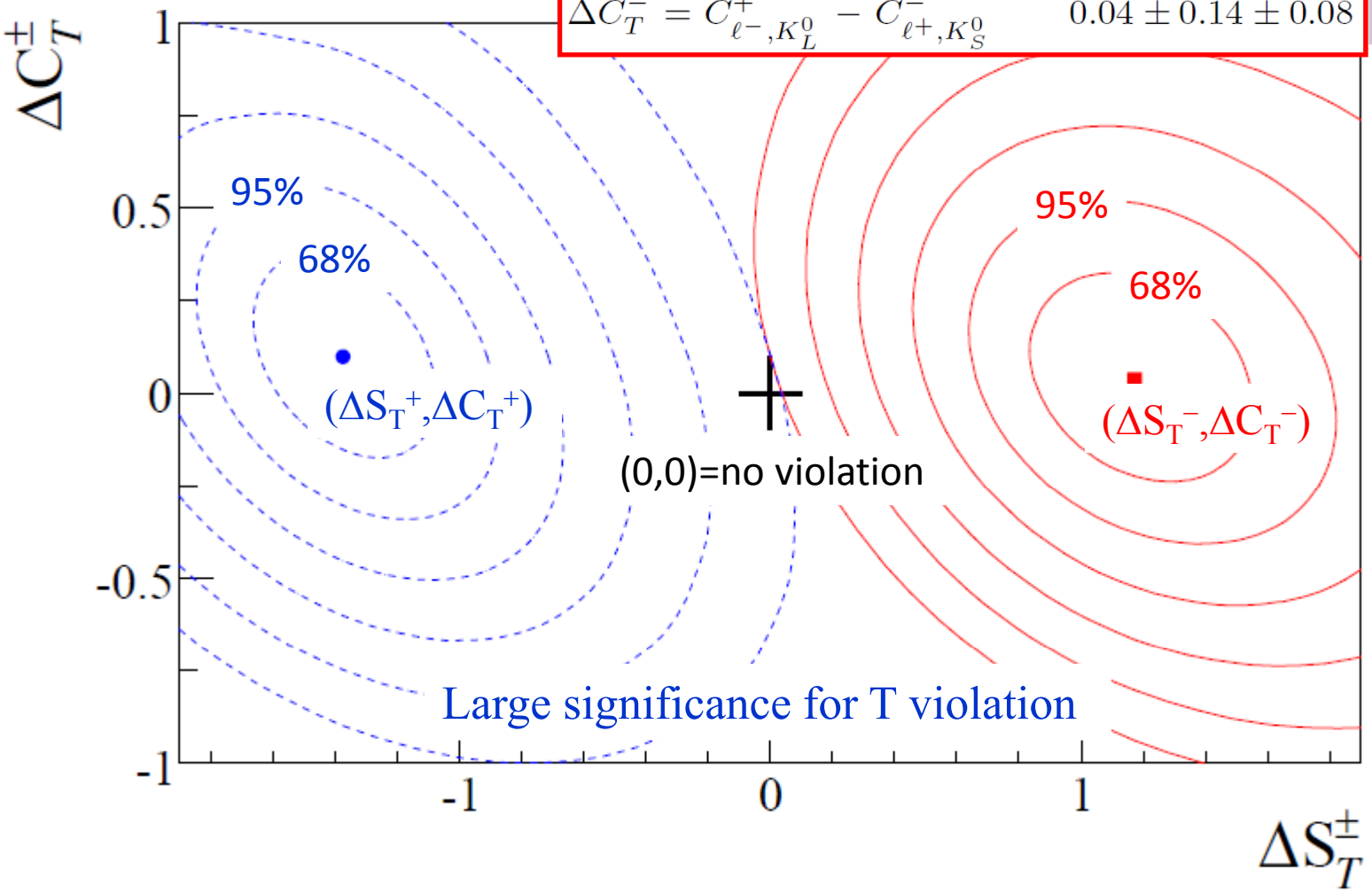
- In canonical CP violation studies (assume CPT and $\Delta\Gamma=0$), one single S, C set
  - ✓ In SM, S~ sin2β= 0.679±0.020 (HFAG winter'12) and C~0 e.g. PRD 79, 072009 (2009)

# Results and interpretation

# Results

T-violating parameters

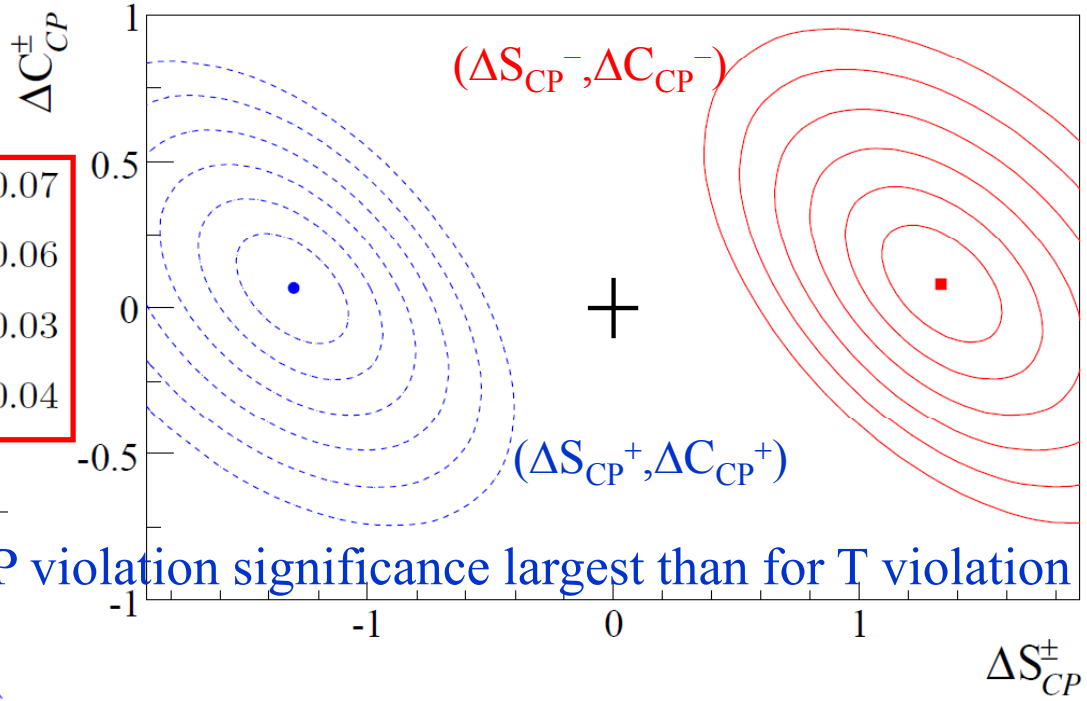
| | | |
|---|---|---|
| $\Delta S_T^+ = S^-_{\ell^-,K^0_L} - S^+_{\ell^+,K^0_S}$ | $-1.37 \pm 0.14 \pm 0.06$ | $-2\sin 2\beta$ |
| $\Delta S_T^- = S^+_{\ell^-,K^0_L} - S^-_{\ell^+,K^0_S}$ | $1.17 \pm 0.18 \pm 0.11$ | $+2\sin 2\beta$ |
| $\Delta C_T^+ = C^-_{\ell^-,K^0_L} - C^+_{\ell^+,K^0_S}$ | $0.10 \pm 0.14 \pm 0.08$ | 0 |
| $\Delta C_T^- = C^+_{\ell^-,K^0_L} - C^-_{\ell^+,K^0_S}$ | $0.04 \pm 0.14 \pm 0.08$ | 0 |
| | | expectation from canonical *CP* |



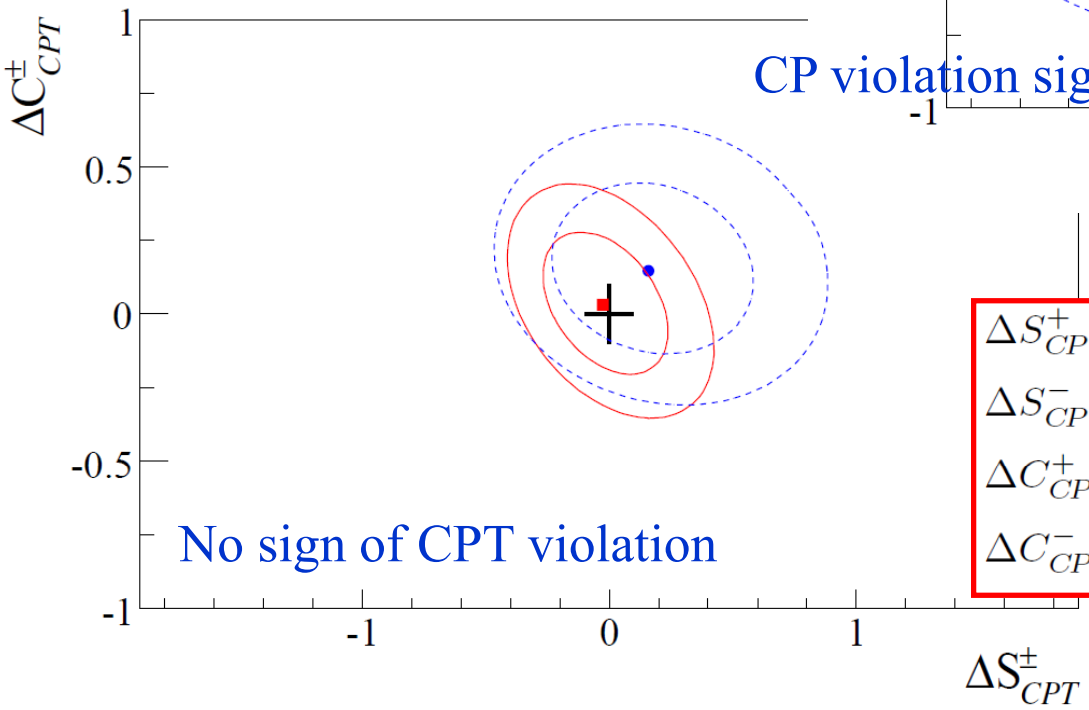
# Results (cont'd)

## CP-violating parameters

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




CP violation significance largest than for T violation




## CPT-violating parameters

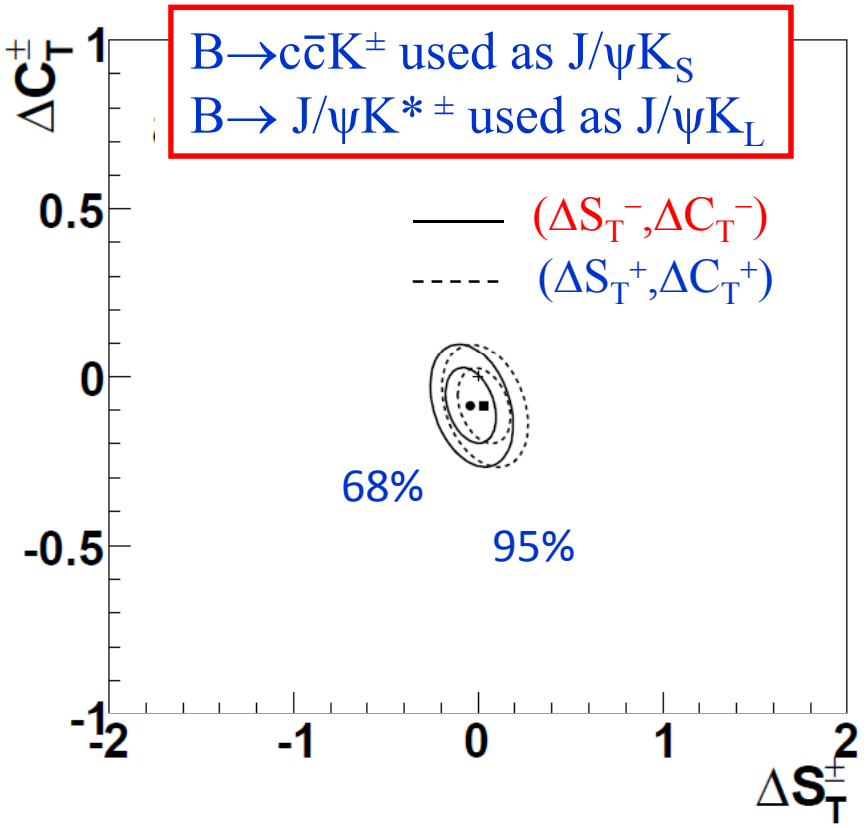
| | |
|---|---|
| $\Delta S^+_{CPT} = S^-_{\ell+,K^0_L} - S^+_{\ell+,K^0_S}$ | $0.16 \pm 0.21 \pm 0.09$ |
| $\Delta S^-_{CPT} = S^+_{\ell+,K^0_L} - S^-_{\ell+,K^0_S}$ | $-0.03 \pm 0.13 \pm 0.06$ |
| $\Delta C^+_{CPT} = C^-_{\ell+,K^0_L} - C^+_{\ell+,K^0_S}$ | $0.14 \pm 0.15 \pm 0.07$ |
| $\Delta C^-_{CPT}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

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 category 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 |
|---|---|
| $\Delta C^{-}_{CP}$ | $0.036 \pm 0.050$ |
| $\Delta C^{-}_{CPT}$ | $-0.0042 \pm 0.068$ |
| $\Delta C^{-}_{T}$ | $-0.0405 \pm 0.073$ |
| $\Delta C^{+}_{CP}$ | $-0.0044 \pm 0.049$ |
| $\Delta C^{+}_{CPT}$ | $-0.1586 \pm 0.070$ |
| $\Delta C^{+}_{T}$ | $-0.0237 \pm 0.073$ |
| $\Delta S^{-}_{CP}$ | $0.088 \pm 0.054$ |
| $\Delta S^{-}_{CPT}$ | $-0.1035 \pm 0.083$ |
| $\Delta S^{-}_{T}$ | $0.041 \pm 0.089$ |
| $\Delta S^{+}_{CP}$ | $0.041 \pm 0.053$ |
| $\Delta S^{+}_{CPT}$ | $0.030 \pm 0.086$ |
| $\Delta S^{+}_{T}$ | $0.155 \pm 0.094$ |



# Systematic uncertainties

Systematic uncertainties are evaluated similarly as in our last CP analysis

| Systematic source | $\Delta S_T^+$ | $\Delta S_T^-$ | $\Delta C_T^+$ | $\Delta C_T^-$ |
|---|---|---|---|---|
| Interaction region | 0.011 | 0.035 | 0.02 | 0.029 |
| Flavor misID probabilities | 0.022 | 0.042 | 0.022 | 0.022 |
| $\Delta t$ 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 |
| $m_{\rm ES}$ parameterization | 0.011 | 0.002 | 0.005 | 0.002 |
| $\Gamma_d$ and $\Delta m_d$ | 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

$$\begin{aligned} \Delta\chi^2 &= -2\left(\ln L_{\mathrm{NoTRV}} - \ln L\right) \\ \Delta\nu &= 8 \text{ degrees of freedom} \end{aligned}$$

**T-inv. constraints**

$$\Delta S_{\mathrm{T}}^{\pm} = \Delta C_{\mathrm{T}}^{\pm} = 0$$
$$\Delta S_{\mathrm{CP}}^{\pm} = \Delta S_{\mathrm{CPT}}^{\pm}$$
$$\Delta C_{\mathrm{CP}}^{\pm} = \Delta C_{\mathrm{CPT}}^{\pm}$$

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

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

- 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)

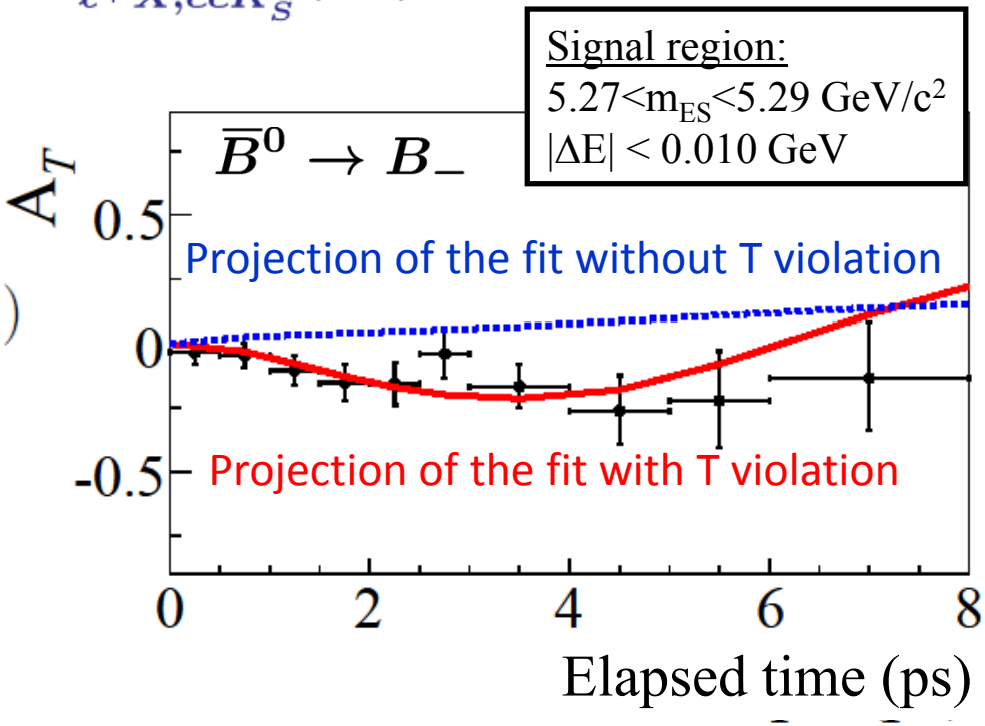
$$A_T(\Delta t) = \frac{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) - \mathcal{H}^+_{\ell^+ X, c\bar{c} K^0_S}(\Delta t)}{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) + \mathcal{H}^+_{\ell^+ X, c\bar{c} K^0_S}(\Delta t)}$$

where

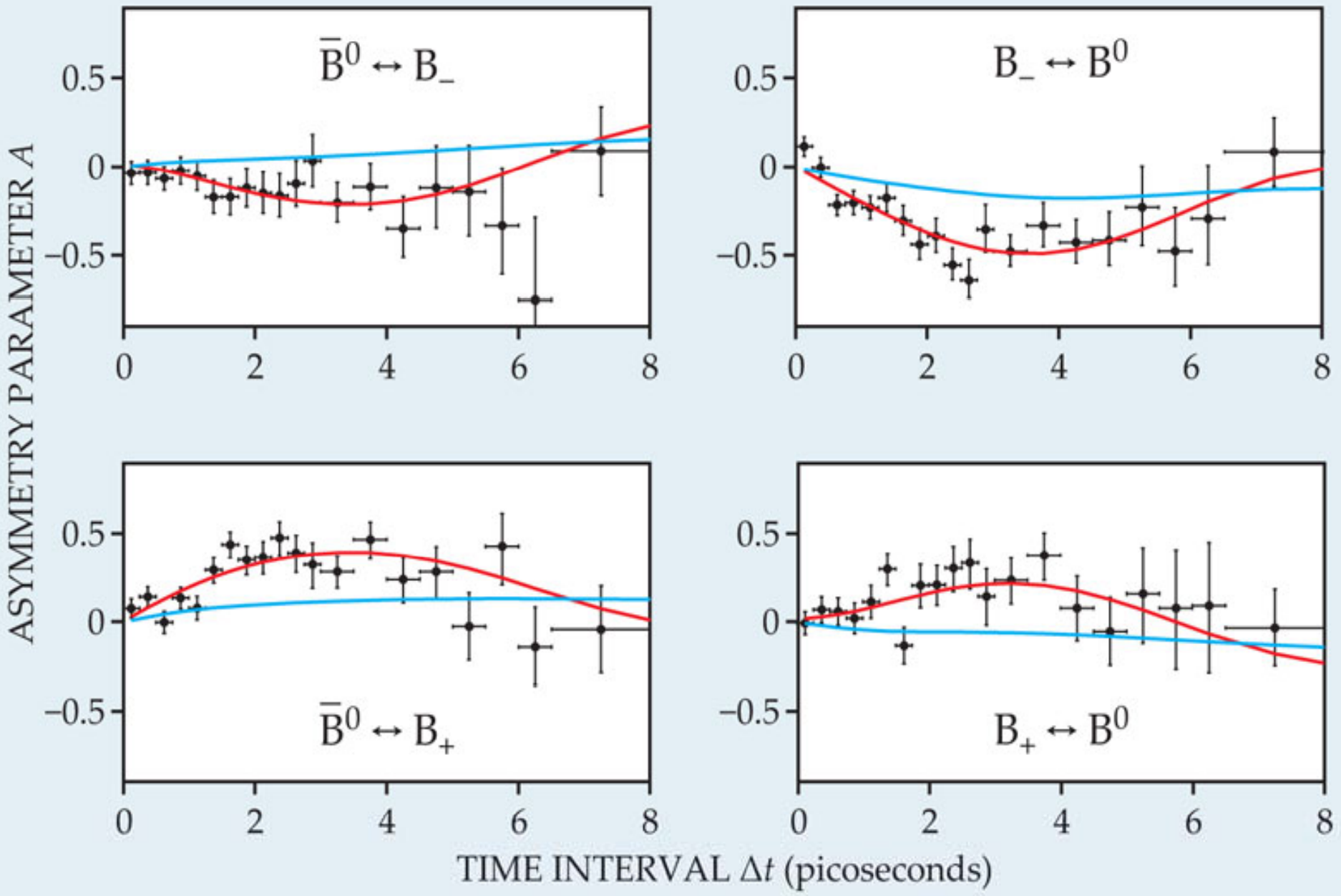
$$\mathcal{H}^{\pm}_{\alpha,\beta}(\Delta t) = \mathcal{H}_{\alpha,\beta}(\pm\Delta t) H(\Delta t)$$

- For perfect reconstruction, is

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



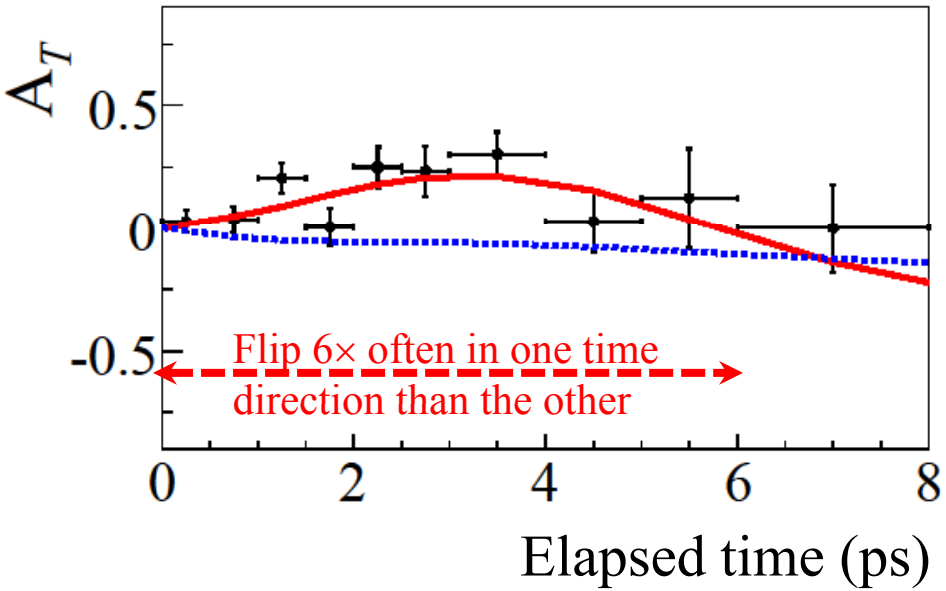
# The four independent T asymmetries



# 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, 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…

# Concluding remarks and acknowledgements

- This work has been the result of very close collaboration between theorists and experimentalists, mostly from IFIC
  - ✓ Many subtle aspects, both theoretical and experimental
  - ✓ And the motivating, strong enthusiasm of JOSE BERNABEU…

- The involvement of the BaBar Collaboration has been of fundamental importance for the success of the project, especially in the last steps

- The preparation of the Phys. Rev. Lett. manuscript was especially tough, having an involvement of the Collaboration as in very few others of the, as today, more than 500 papers published

- Very special thanks to PABLO VILLANUEVA PEREZ, the master piece of this project

**Thank you for your attention**