DIRECT OBSERVATION OF TIME REVERSAL VIOLATION

P. Villanueva-Pérez

IFIC – **Universitat de València-CSIC**

Marseille Seminar
11th February 2013

Selected for a Viewpoint in *Physics*

PRL **109**, 211801 (2012) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2012

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

Physical Review Letters
moving physics forward

APS Journals
Current Issue
Earlier Issues
About This Journal
Journal Staff
About the Journals
Search the Journals
APS Home
Join APS

Authors
> General Information
> Submit a Manuscript
> Publication Rights
> Open Access
> Policies & Practices
> Tips for Authors
> Professional Conduct

Referees
> General Information
> Submit a Report
> Update Your Information
> Policies & Practices
> Referee FAQ
> Advice to Referees

APS » Journals » Physical Review Letters

Physical Review Letters

Highlights | Editors' Suggestions | Recent Papers

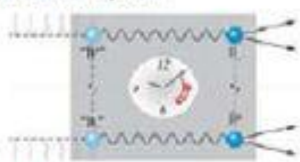
On the Cover

Fluorescent dyes spaced by short DNA strands probe Förster energy transfer in a controlled nanophotonic environment defined by a mirror. [Christian Blum, Niels Zijlstra, Ad Lagendijk, Martijn Wubs, Allard P. Mosk, Vinod Subramaniam, and Willem L. Vos, Phys. Rev. Lett. **109**, 203601 (2012)]

Read Article | More Covers

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)]

Read Article | More viewpoints

Physics

Physics 5, 129 (2012)

Viewpoint

Particle Decays Point to an Arrow of Time

Michael Zeller
Department of Physics, Yale University, New Haven, CT 06520, USA

Published November 19, 2012

- Concept→ M. C. Bañuls and J. B., PLB (1999), NPB (2000);
  - Scrutinized by L. Wolfenstein, IJMP (1999), H. Quinn, JPCS (2009); V. Rubakov; T. Nakada; F. Botella, …

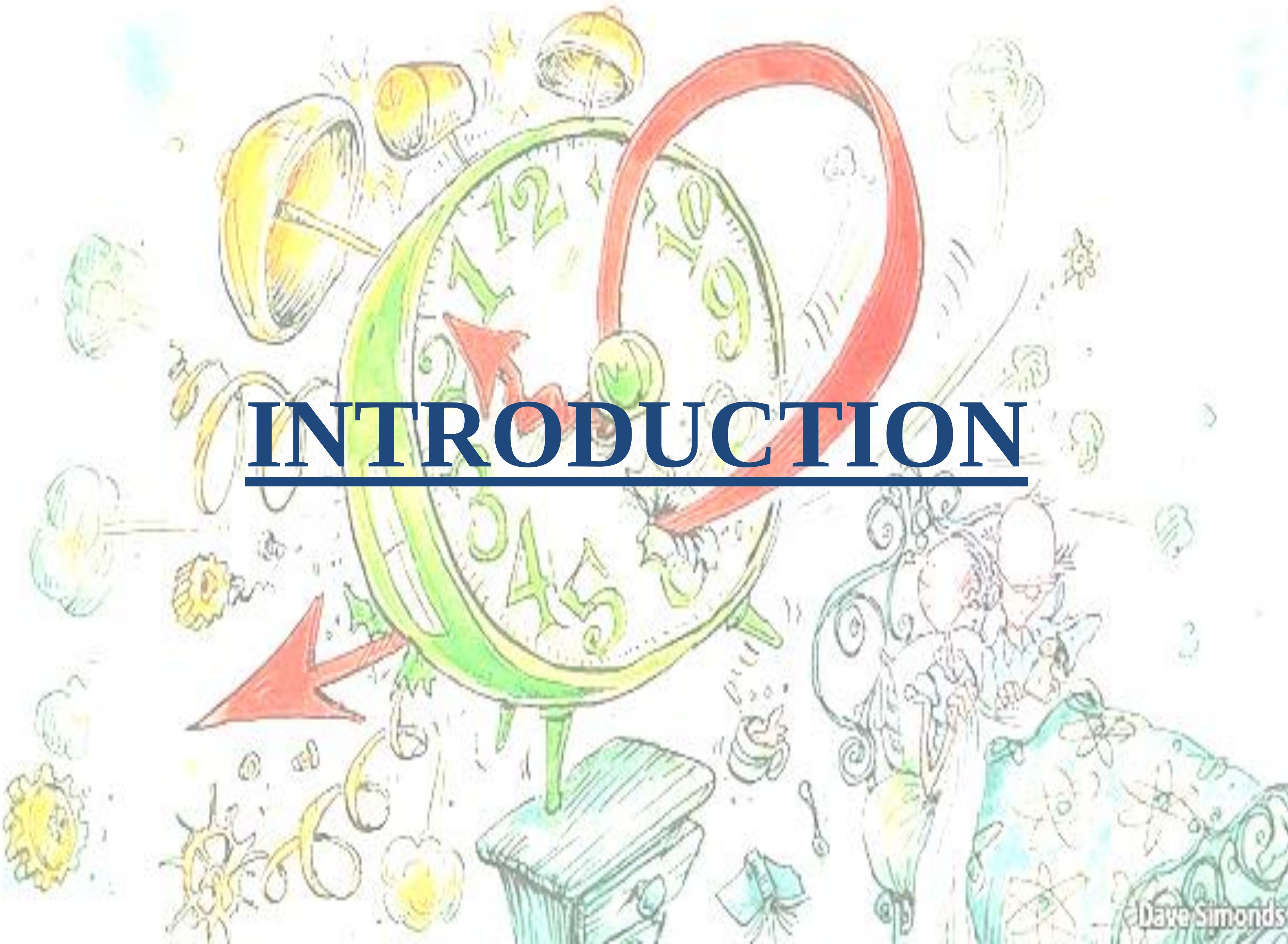
“it would appear to be a true TRV effect”

- Method, Definite Proposal and Simulation → J. B., F. Martínez-Vidal, P. Villanueva-Pérez, JHEP (2012).
- Experimental Result → BABAR Collaboration, PRL (2012), with View Point by Michael Zeller.
- Physics Today 65(11), 16 (2012).

Outline

- Introduction
  - Symmetries in the Laws of Physics
  - t-asymmetries vs. Time Reversal Violation
  - Time Reversal Violation searches
- T Violation through the entanglement
  - Time Reversal Violation in the evolution on the B-mesons
  - T-transformed processes
  - Signal parameters
- Data sample and fitting procedure
  - Data sample
  - Signal description and fitting strategy
- Results and interpretation
  - Summary of results
  - Cross checks and validation
- Conclusions

INTRODUCTION



Symmetries in the Laws of Physics

- Local Field Theories which are Lorentz invariant and Hermiticity→ CPT invariant
  - Connection CP ↔ T
- T-Violation exists in SM.
- T and CPT are described by ANTIUNITARY operators, introducing subtleties.
- As we have observed CP-violation. How do we observe T-violation?

T – Violation means Asymmetry under the interchange

- *in* ⇄ *out* states
- *t* ⇄ *-t*

- Discard odd effect under *t*↔*-t* not necessarily T-violating.
- t-asymmetries can occur in theories with exact T-symmetry.

Macroscopic *t* and time arrow

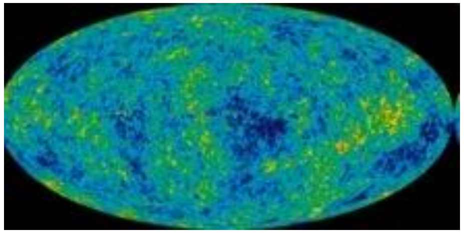
- Time cannot run backwards ⟶ *t*-asymmetry in complex systems.
- Nature of Thermodynamics ⟶ **The TIME ARROW is a property of ENTROPY alone**

  (Eddington)

E.g. A vase falls and breaks into pieces, but it is not possible that the vase flies back and returns to its original situation

The ARROW OF TIME is NOT TIME REVERSAL VIOLATION

- Universe *t*-asymmetry:



✓ The universe is expanding and accelerating

Asymmetry ⟶ $t \leftrightarrows -t$

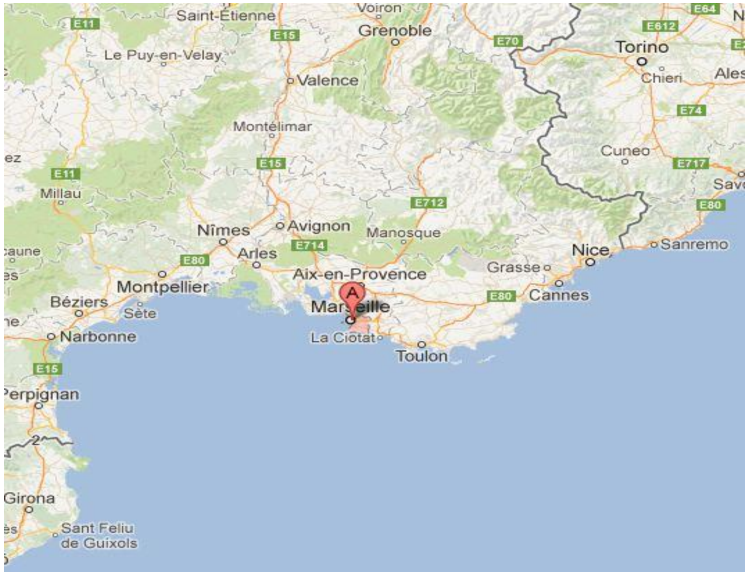
✓ This is perfectly compatible with laws of Physics being TR symmetric.

✓ *t*-asymmetry is due to initial condition of our Universe: inflation?

✓ Similar that in our Universe there is a privilege framework: CMB radiation

From complex *t to fumdamental* T

- T. D. Lee proposed the following example:
  - ✓ Imagine 1000 cars (particles) with fuel for 1000 km, departing from the city center of Marseille.
  - ✓ Single rule (fundamental law): Drive straight away and at each intersection (collisions), chose randomly.
  - ✓ After 500 km, they return.
  - ✓ The process is <u>time symmetric</u> only until the first intersection.
  - ✓ Macroscopic *t* (whole trip) vs. Microscopic *T* (until the first intersection).

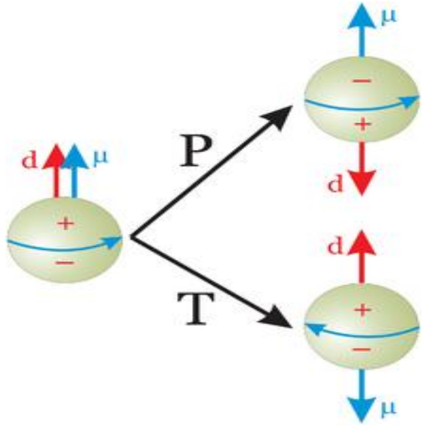


- Irreversibility character of P→1+…+n and 1+…+n→P is not related T-violation. In fact it looks like it prevents a real test of T-symmetry in unstable systems.

> Alice: I simply must get through!
> Doorknob: Sorry, you're much too big. Simply impassible.
> Alice: You mean impossible?
> Doorknob: No, impassible. Nothing's impossible.

Time Reversal Violation (TRV) in stable systems

- A non-zero value of a T-odd observable in a stationary state, e.g, dipole moment of an elementary particle or an atom.
  - It can be generated by either:



➢ Strong T-violation→ θ-term $\epsilon_{\mu\nu\varsigma\sigma}$ $F^{\mu\nu} F^{\varsigma\sigma}$ [Peccei & Quinn],
➢ Weak T- violation.

- In an oscillation a difference in the probability of a→b from b→a at a given time, P(a→b)(t)≠P(b→a)(t) , e.g., $\nu_e \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_e$ experiment proposed for the neutrino factories with muon storage ring.

TRV in unstable systems

- Key points:

A GENUINE and DIRECT evidence of TRV would mean an experiment that, considered by itself, clearly shows TRV INDEPENDENT of, and UNCONNECTED to, the results of CPV.

T – Violation means Asymmetry under the interchange
- ***in*** ⇄ ***out states*** → ***Experimentally tricky***
- ***t*** ⇄ ***-t***

- Possible searches

CP violation mechanisms		T violation mechanisms
• Decay • Mixing • Mixing×Decay	⟷ CPT	• Decay • Mixing • Mixing×Decay

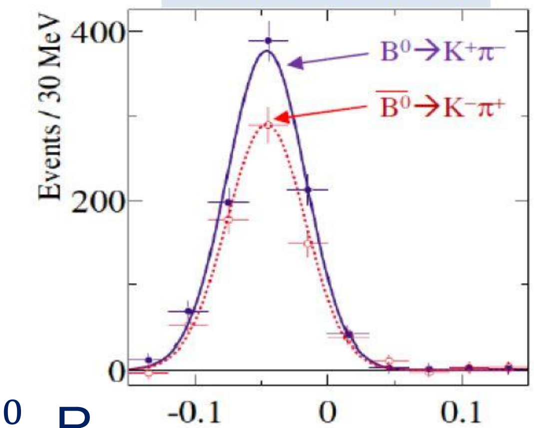
TRV searches in decays

- In this kind of searches we have to compare a→b vs. b→a in decay processes.
  - B factories (Belle and BaBar) have observed large direct CP violation in $B \to K\pi$

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

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

PRL93, 131801 (2004)



- Can we perform a T test through the decay?

CP:
$B^0 \to K^+\pi^-$, R$_1$
$\bar{B}^0 \to K^-\pi^+$, R$_2$

CPT ⟷

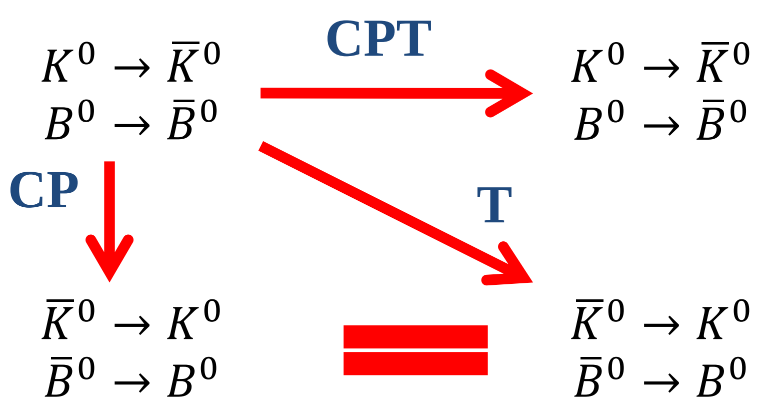
$K^-\pi^+ \to \bar{B}^0$, R$_1$
$K^+\pi^- \to B^0$, R$_2$

Unable to perform the T test:

- Preparation of the initial state.
- The strong processes will swamp the feeble weak processes.

TRV searches in mixing

- Mixing has been observed in *K*, *B*, and more recently in *D* neutral systems.



Kabir PRD2, 540 (1970)

  – This flavor mixing asymmetry is both T and CP violating (the two transformations lead to the same observation), and independent of time.
  – $\sim 4\sigma$ of $K^0 \to \bar{K}^0$ vs. $\bar{K}^0 \to K^0$ asymmetry

PLB 444, 43 (1998)

  – This is the first direct evidence of T and CP violation.
    - This result has arisen controversy in the literature

Gerber, Eur. Phys. Jour. C35, 195(2004)

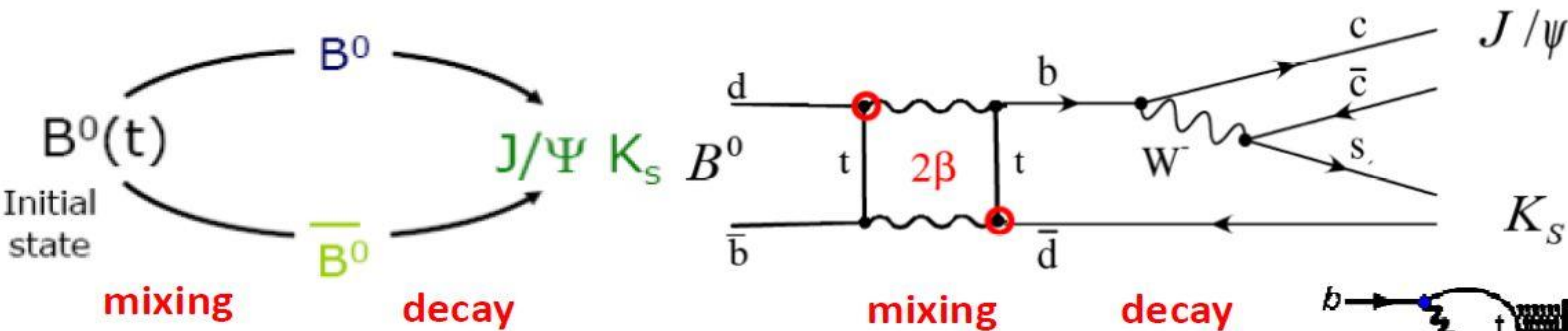
Wolfenstein, IJMP E8, 501 (1999)

Alvarez-Gaume et al, PLB 458 (1999)

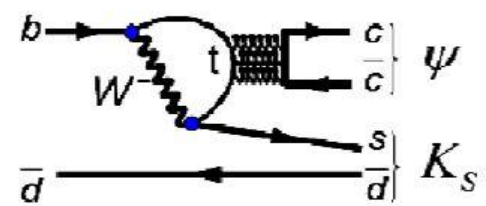
Test of Conservations Laws, PDG 2012

TRV searches in interference

- B-factories have observed large CP violation in interference between mixing+decays of $B^0 \to J/\psi K_{S/L}$ and $\bar{B}^0 \to J/\psi K_{S/L}$ this allows the determination of the CKM angle β.



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



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

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

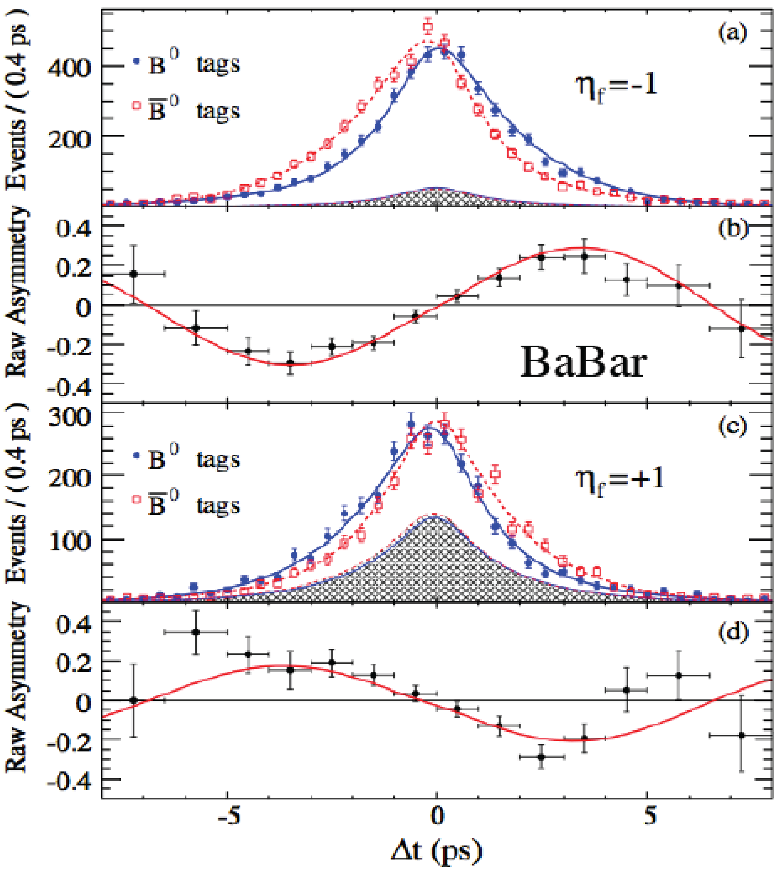
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \approx e^{-i2\beta}$$

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})

TRV searches in interference



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

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

$$A_{CP,f}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0 \to f}(\Delta t) - \Gamma_{B^0 \to f}(\Delta t)}{\Gamma_{\bar{B}^0 \to f}(\Delta t) + \Gamma_{B^0 \to f}(\Delta t)}$$

$$= S_f \sin(\Delta m \Delta t) - C_f \cos(\Delta m \Delta t)$$

CP asymmetry

Kobayashi and Maskawa awarded half of 2008 N.P.

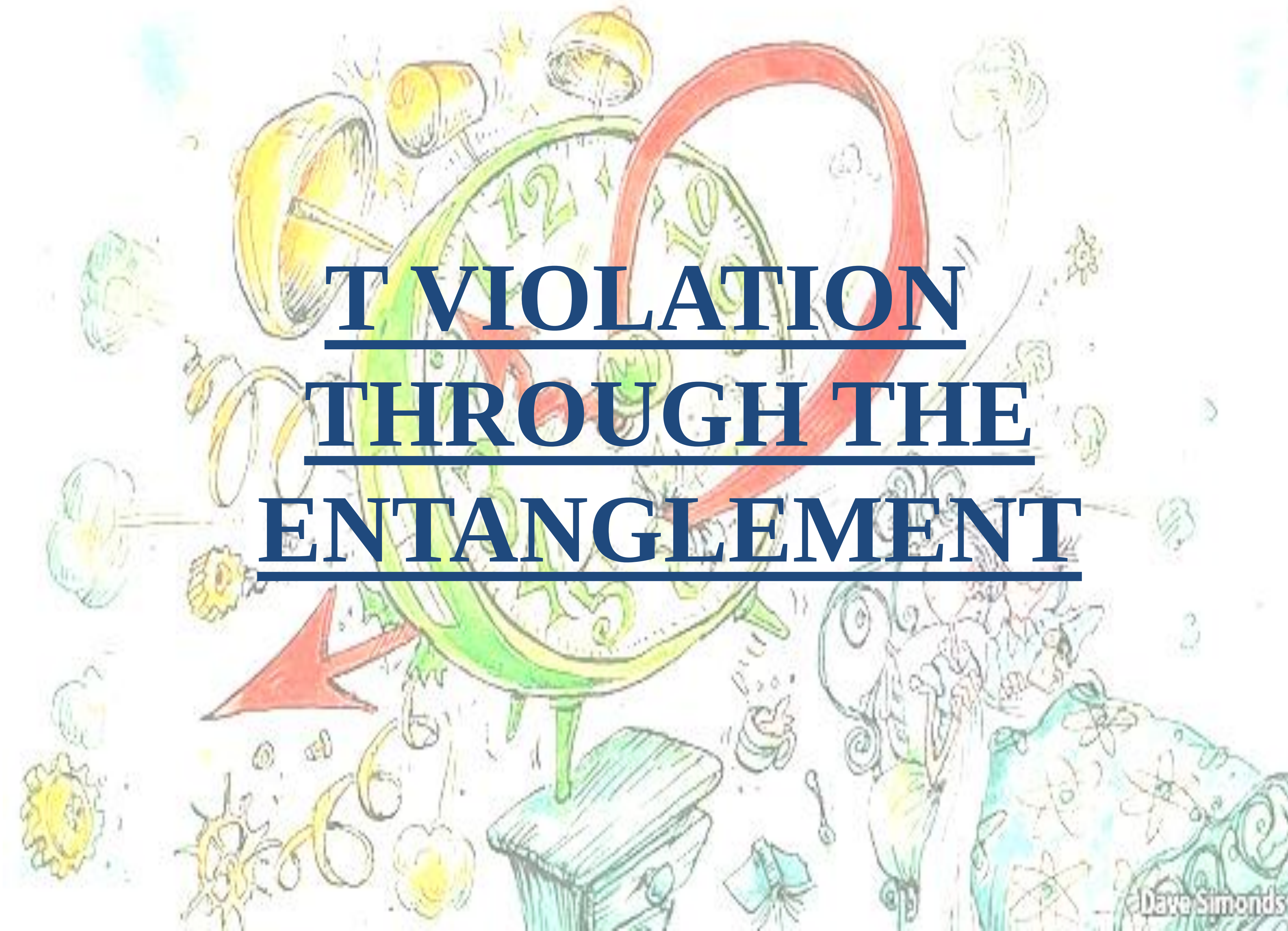
"impassible. Nothing's impossible".

CPV time dependent (TD) studies:

- There are no exchanges $t \leftrightarrow -t$ and $|in> \leftrightarrow |out>$.
- Assumes CPT invariance and $\Delta\Gamma = 0$.

How can we observe T violation in this privilege Nature system?

T VIOLATION THROUGH THE ENTANGLEMENT



The decay as a filtering measurement

ARISTOTELES "Virtue shines in the misfortunes"

- Quantum (EPR) entanglement at B-factories
  - The initial state can be written in any combination of B states

Bañuls & Bernabeu, PLB464, 117 (1999)

Υ(4S) decay yields an entangled state of *B* mesons

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

The INDIVIDUAL STATE of each neutral meson is NOT DEFINED BEFORE its collapse as a filter imposed by the observation of its orthogonal partner (TAG)

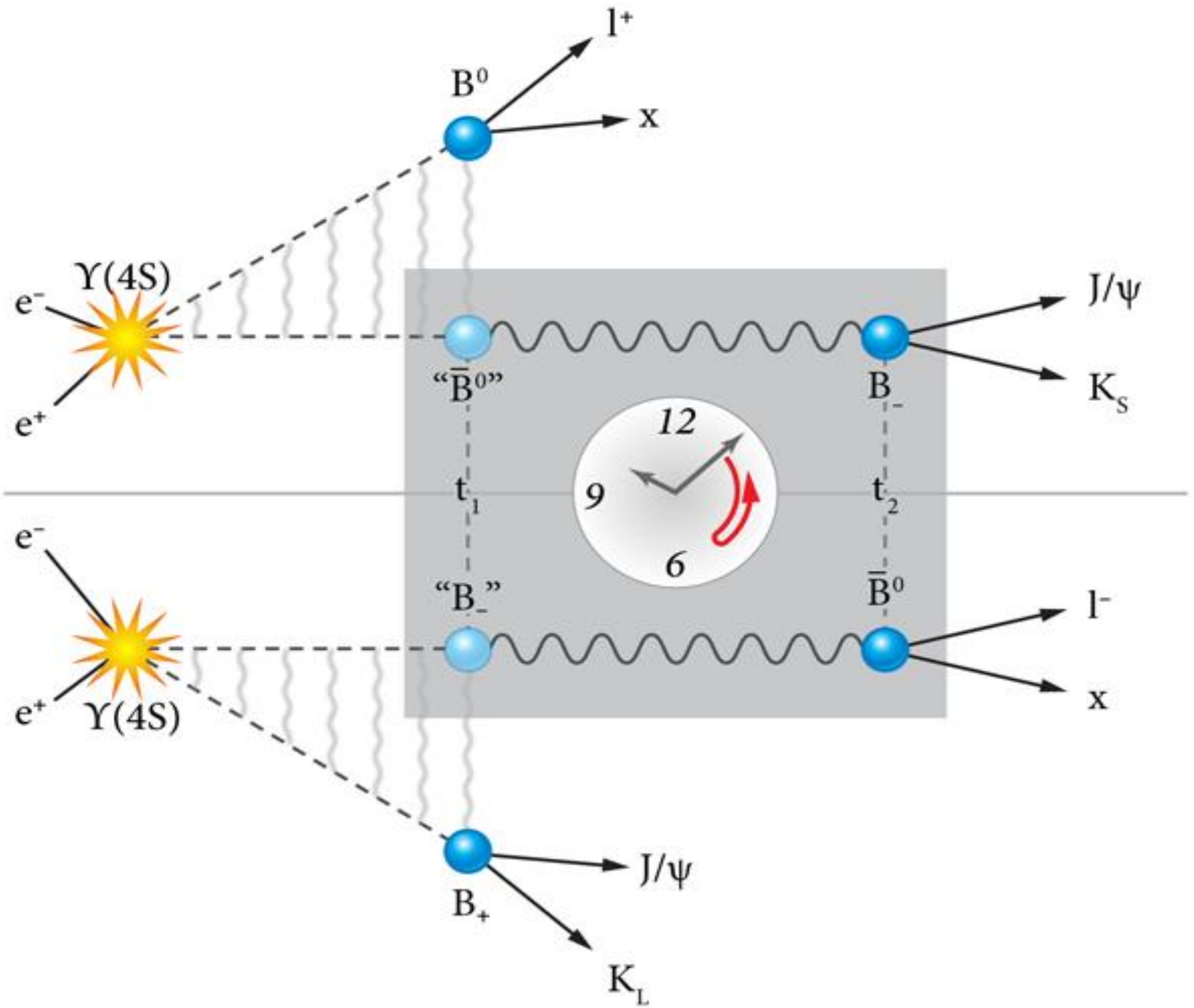
Flavor tag: e.g. B semileptonic decay to $l^+ X$ ($l^- X$) projects $B^0(\bar{B}^0) \Rightarrow \bar{B}^0(B^0)$ tag

CP tag: B_+ decay to $J/\psi K_L$ projects $\Rightarrow$ B_- tag ("CP-odd")
B_- decay to $J/\psi K_S$ projects $\Rightarrow$ B_+ tag ("CP-even")

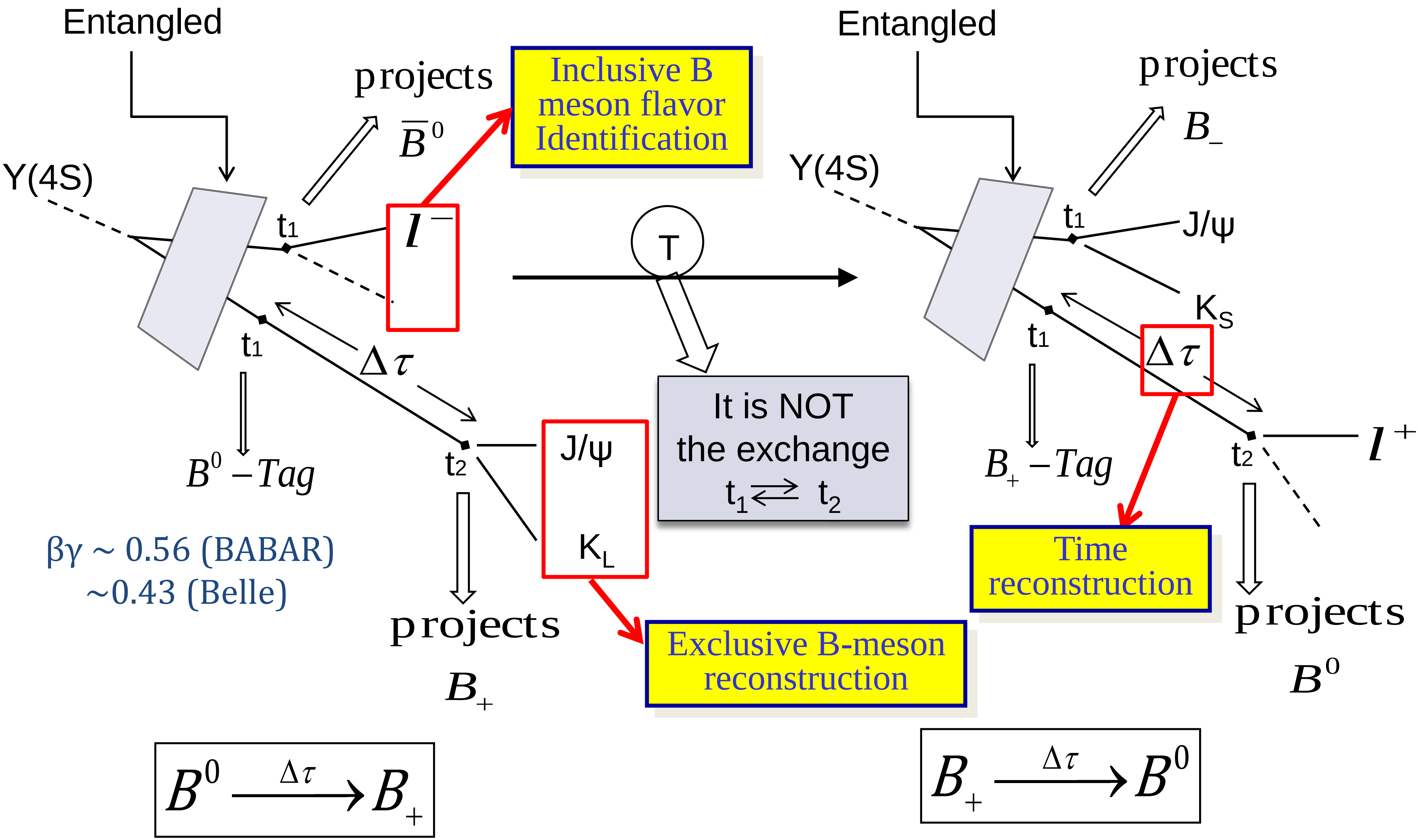
J. B., F. M-V, P. V-P, JHEP (2012).

B_+, B_- are not necesarilly CP-eigenstates of the neutral B-system, only under certain phase convention

TRV in the evolution of the B-meson



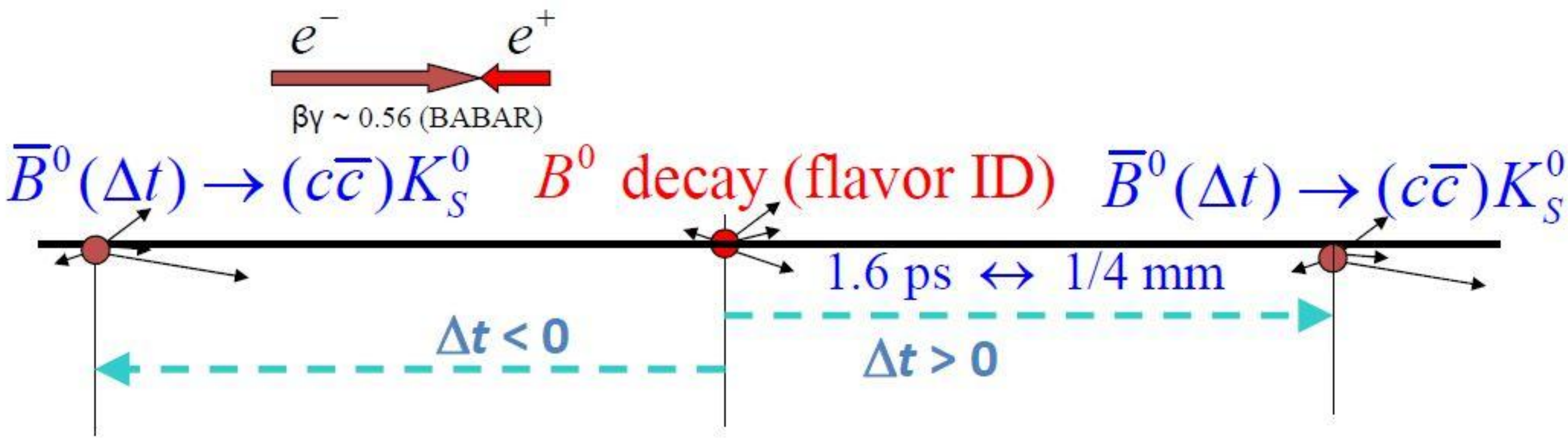
TRV in the evolution of the B-meson



$\Delta z = \beta\gamma c \Delta\tau$

$< \Delta z > \sim 250\mu m$ (BABAR), $200\mu m$ (Belle)

TRV in the evolution of the B-meson



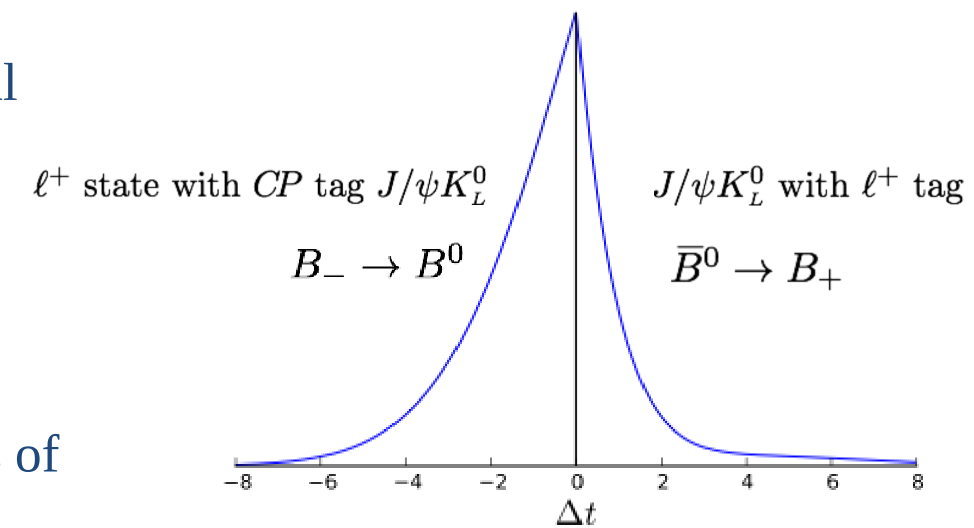
- In B factory CP violation canonical analysis, we define

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

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-conjugated processes

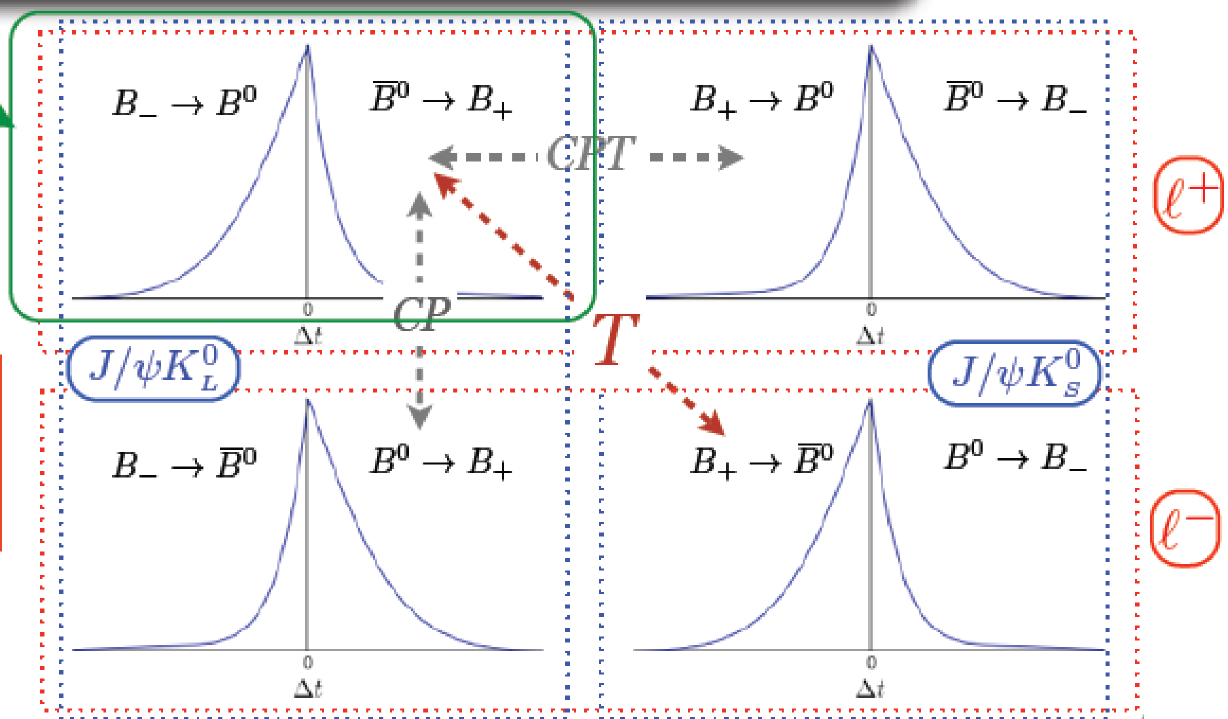
Define processes of interest and their T-transformed counterparts

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. $\overline{B}^0$)

Discard odd effect
t↔-t

Signal parameters

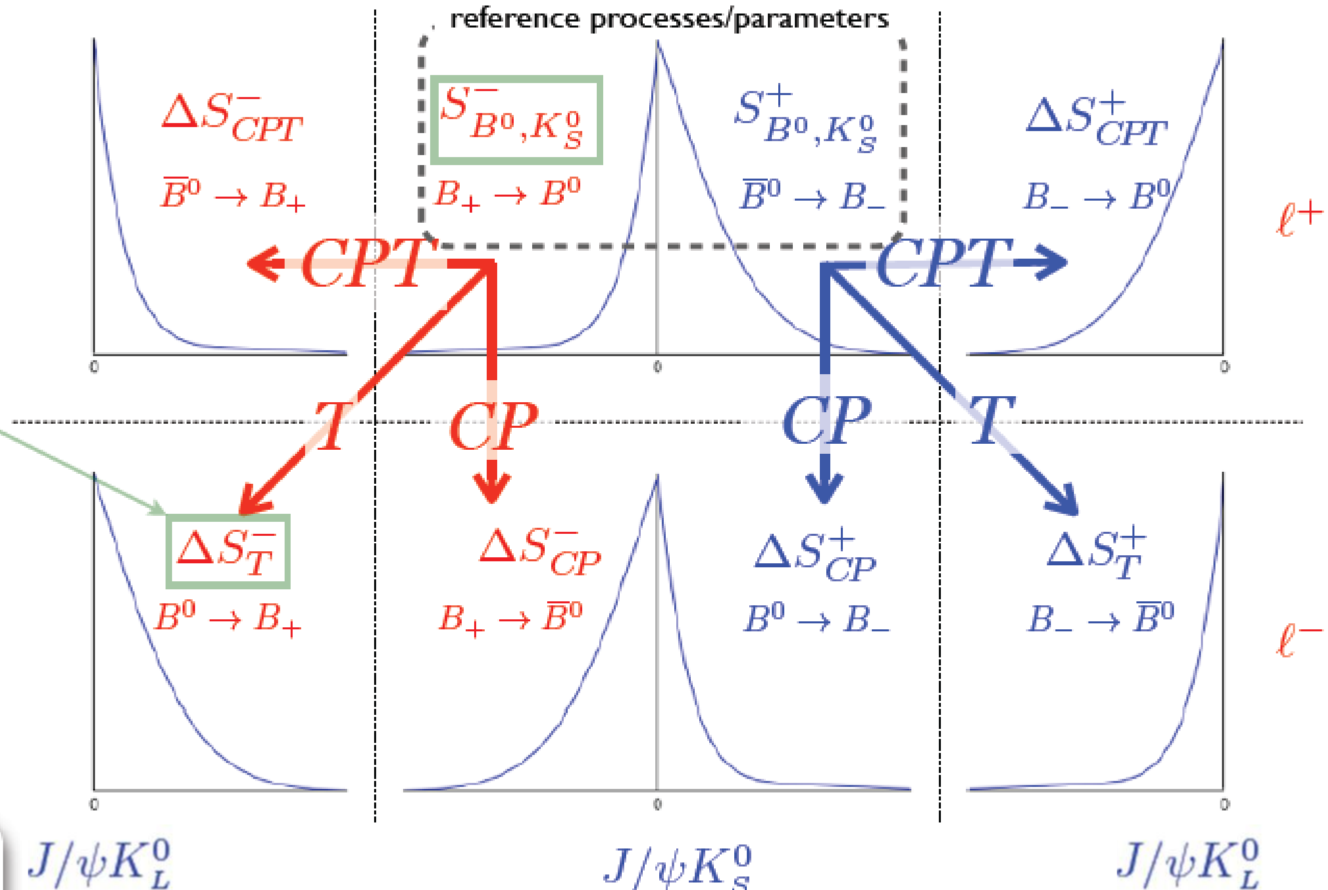
$$g^{\pm}_{\alpha,\beta}(\Delta\tau) \propto e^{-\Gamma\Delta\tau}\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)\}$$

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

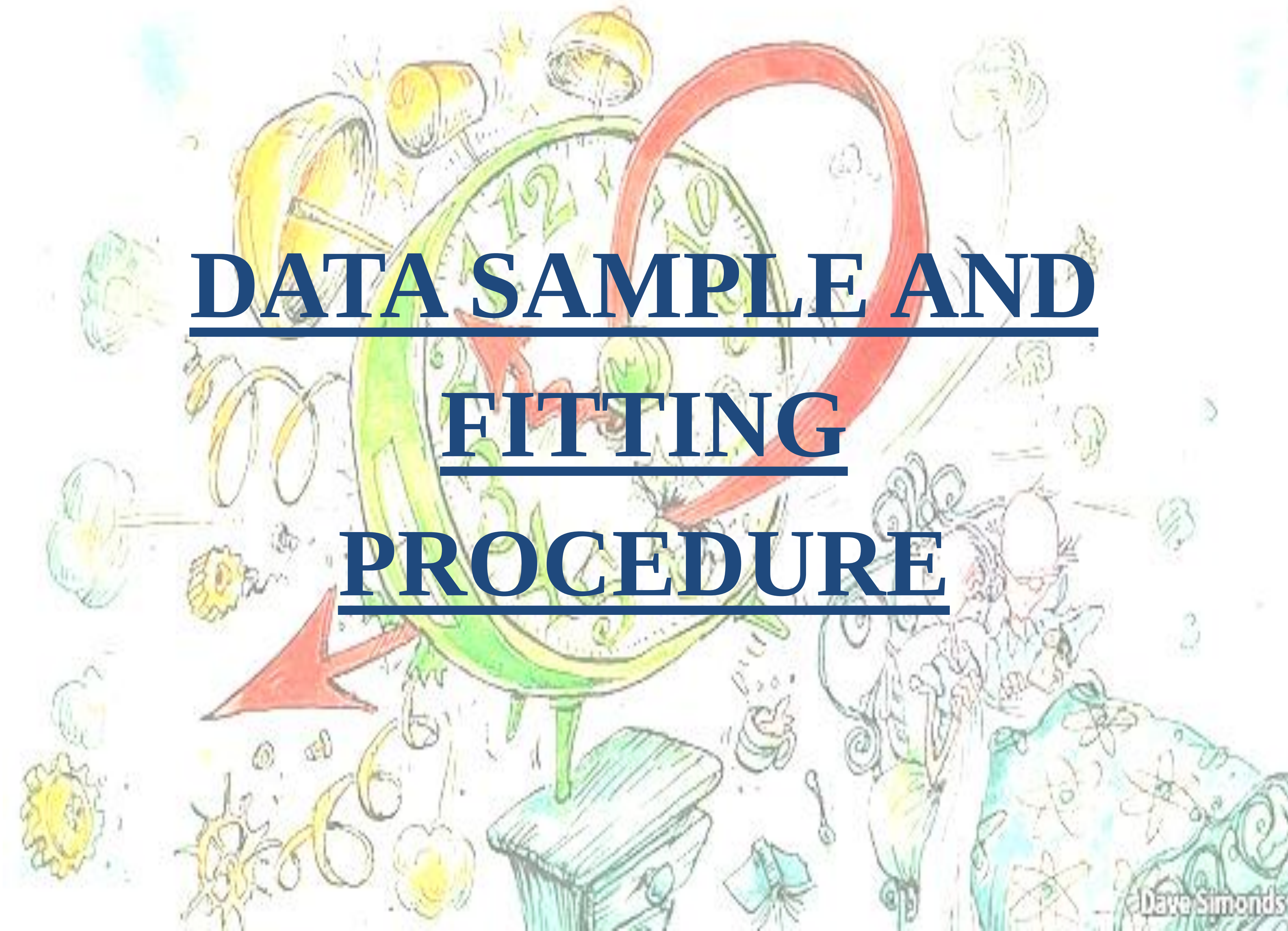


For T Violation

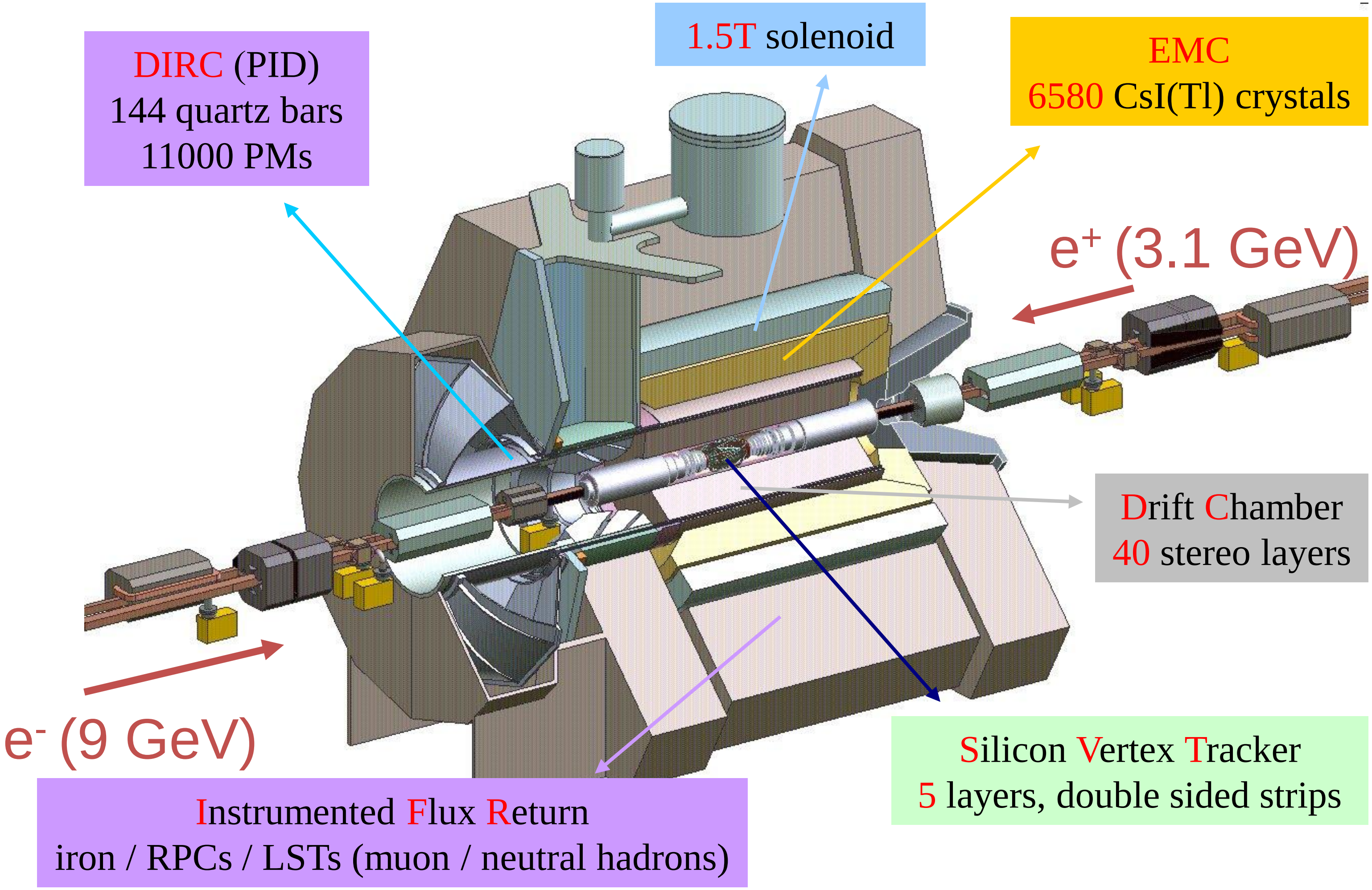
in the interference $\Delta S^{+}_{T} \neq 0$, $\Delta S^{-}_{T} \neq 0$

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

DATA SAMPLE AND FITTING PROCEDURE



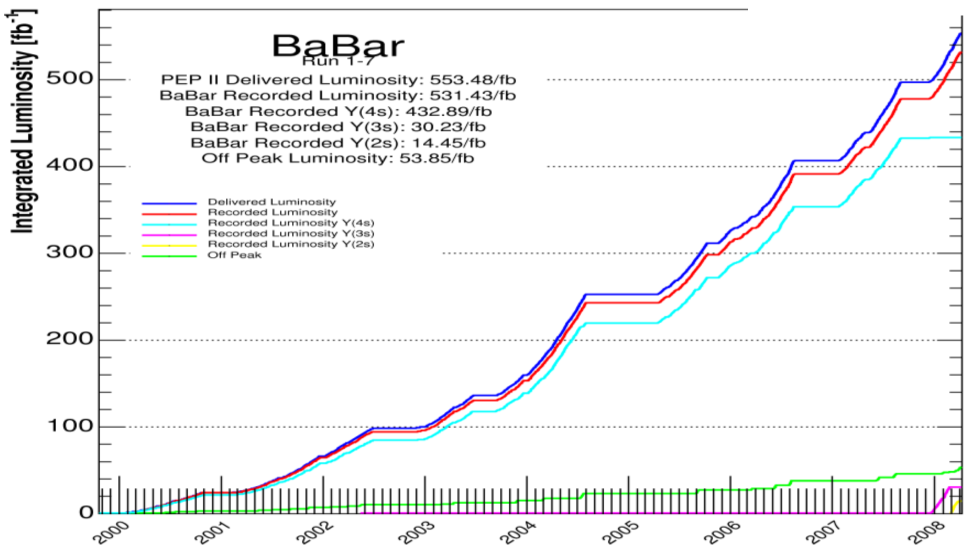
BaBar detector

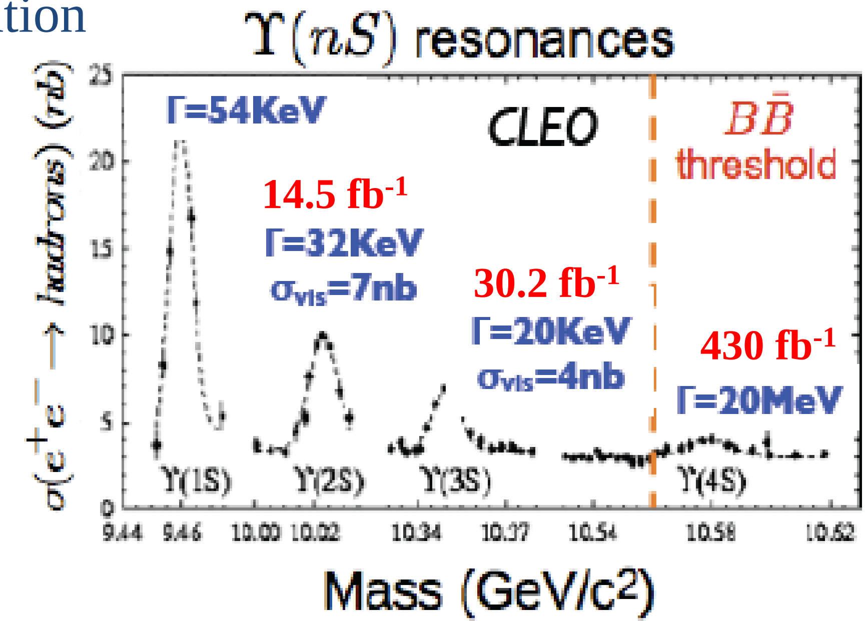


- Asymmetric B-factory: E_{cms} = 10.58 GeV $\quad e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L identification. Very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

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

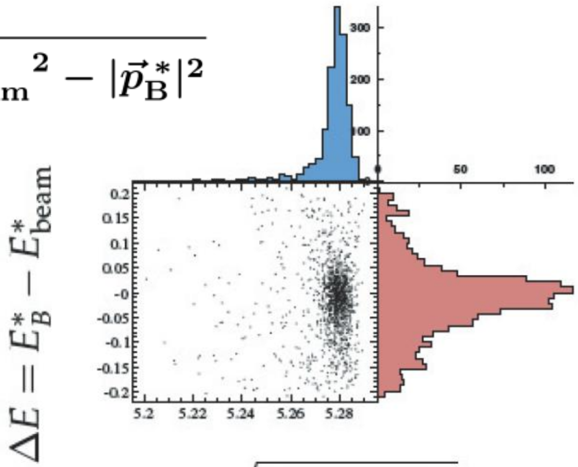
signal sample

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 BB (0.5×Belle)
- ≈ 690×10^6 cc
- ≈ 500×10^6 $\tau^+\tau^-$
- ≈ 1.2×10^8 Y(3S) (7×Belle+Cleo)
- ≈ 1.0×10^8 Y(2S) (0.5×Belle+Cleo)

BaBar data set

- 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 $\vec{p}^*_B \approx 300\ \mathrm{MeV}/c$
  - ✓ Energy difference $\Delta E = E^*_B - E^*_{beam}$
  - ✓ Choose best B candidates based on masses of daughters

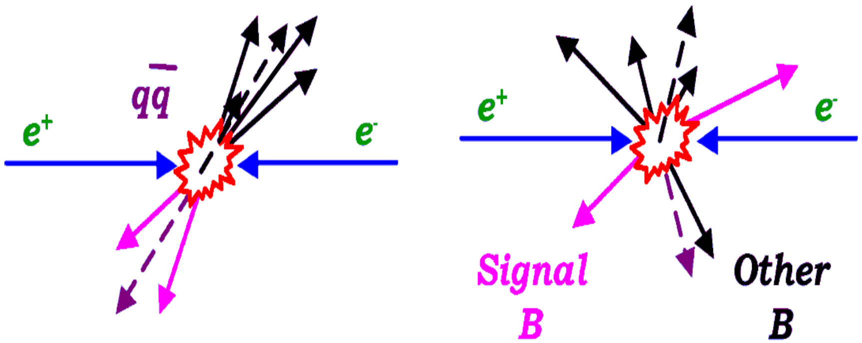


$m_{ES} = \sqrt{E^*_{beam} - p^{*2}_B}$

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

$\sigma_{\Delta E} \sim \sigma_{E^*_B} \approx 10 - 50\ \mathrm{MeV}$

- 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

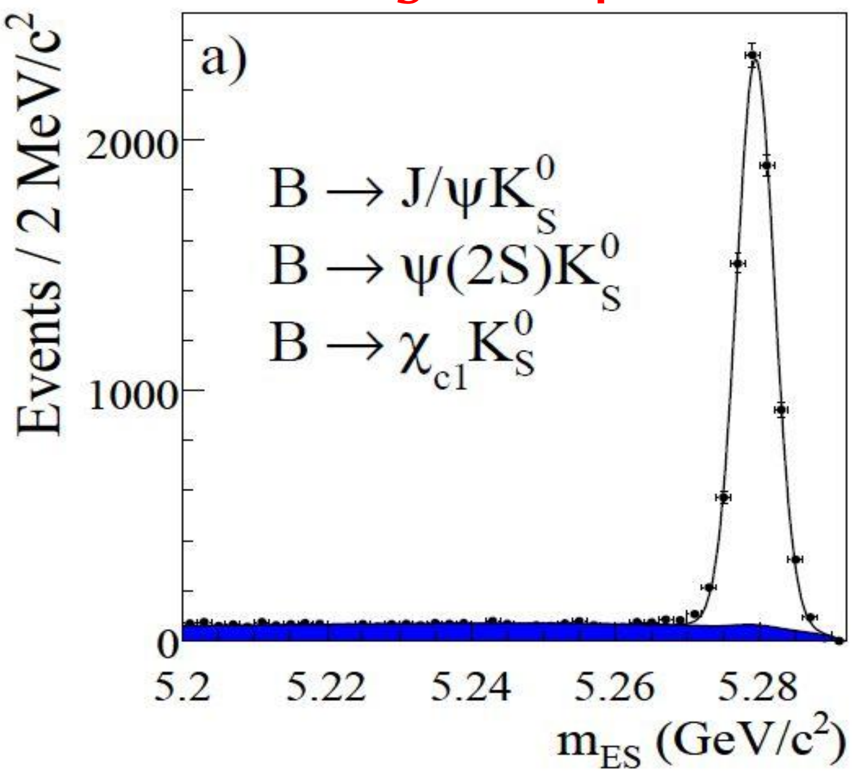


m_{ES} and ΔE for the signal sample

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 $J/\psi K^{*0}(\to K_S \pi^0)$

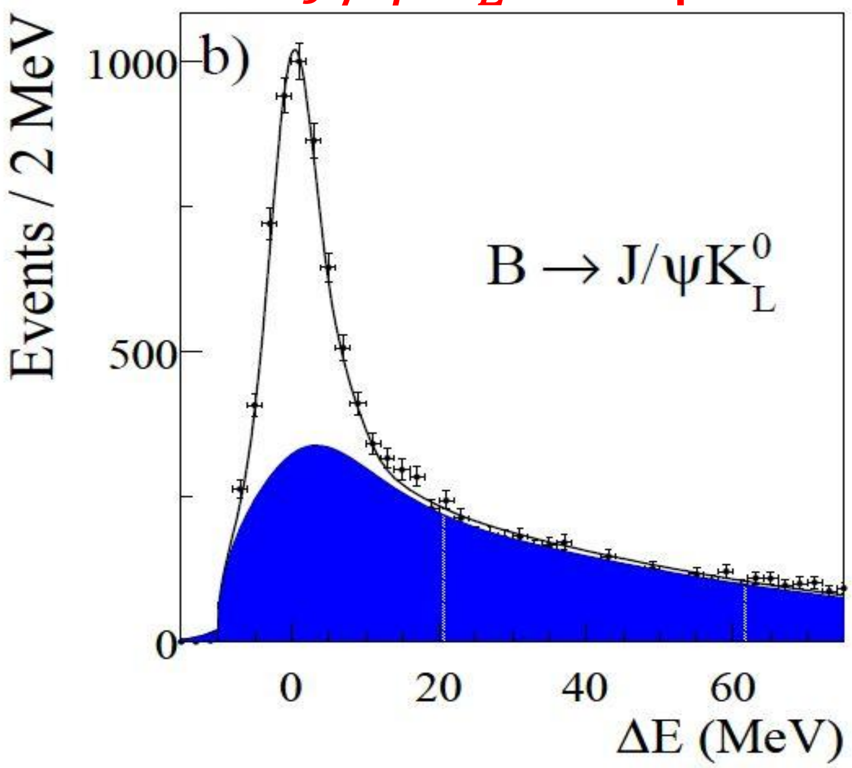
PRD 79, 072009 (2009)

$c\bar{c}K_S$ sample



7796 events
Purity: 87% to 96%

$J/\psi K_L$ sample



5813 events
Purity: ~56%

Fitting strategy

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

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

- 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**

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

- Signal PDF

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

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

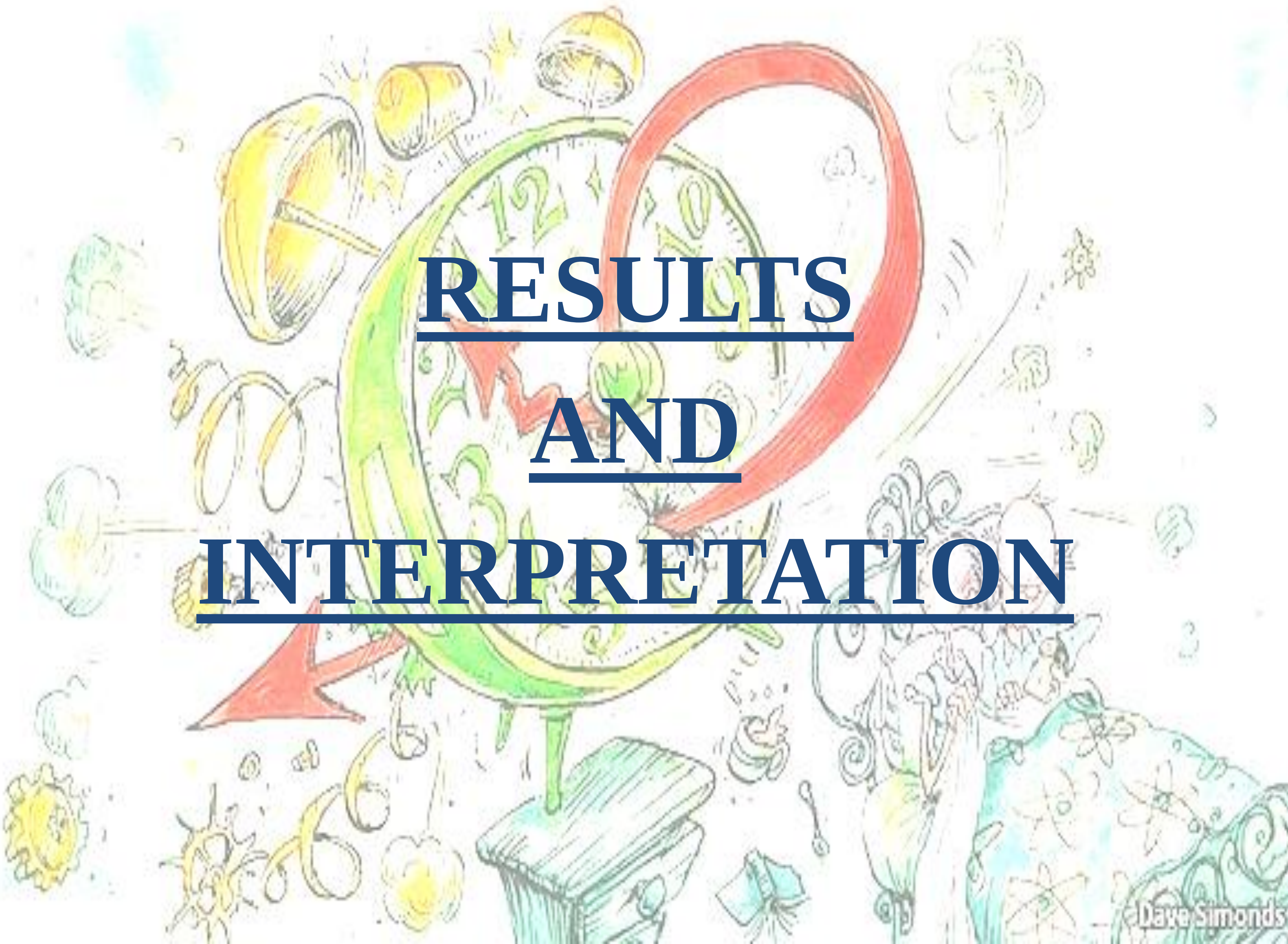
$$+\; g^{-}_{\alpha,\beta}(-\Delta t_{true}) \times \mathrm{H}(-\Delta t_{true}) \otimes \Re(\delta t; \sigma_{\Delta t})$$ **CP tagged events (−)**

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

- In practice, we directly fit to the T-, CP- and CPT-violating parameters

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

RESULTS AND INTERPRETATION

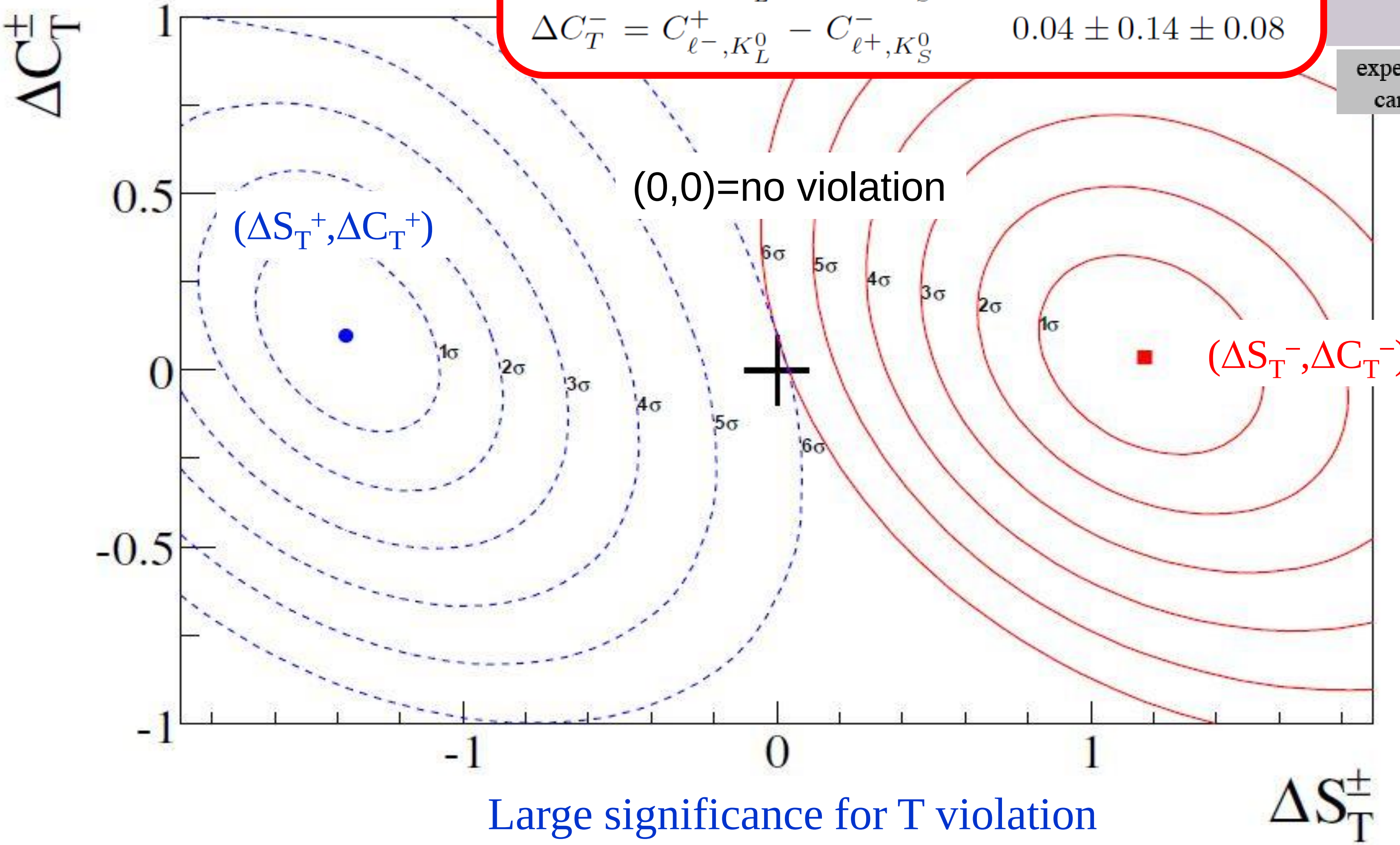


Fit results

	Parameter	Final result	SM expected val.
T	ΔS_T^+	$-1.37 \pm 0.14 \pm 0.06$	-1.4
T	ΔS_T^-	$1.17 \pm 0.18 \pm 0.11$	1.4
T	ΔC_T^+	$0.10 \pm 0.14 \pm 0.08$	$0.$
T	ΔC_T^-	$0.04 \pm 0.14 \pm 0.08$	$0.$
CP	ΔS_{CP}^+	$-1.30 \pm 0.11 \pm 0.07$	-1.4
CP	ΔS_{CP}^-	$1.33 \pm 0.12 \pm 0.06$	1.4
CP	ΔC_{CP}^+	$0.07 \pm 0.09 \pm 0.03$	$0.$
CP	ΔC_T^-	$0.08 \pm 0.10 \pm 0.04$	$0.$
CPT	ΔS_{CPT}^+	$0.16 \pm 0.21 \pm 0.09$	$0.$
CPT	ΔS_{CPT}^-	$-0.03 \pm 0.13 \pm 0.06$	$0.$
CPT	ΔC_{CPT}^+	$0.14 \pm 0.15 \pm 0.07$	$0.$
CPT	ΔC_{CPT}^-	$0.03 \pm 0.12 \pm 0.08$	$0.$
REF.	$S_{\ell^+,K_S^0}^+$	$0.55 \pm 0.09 \pm 0.06$	0.7
REF.	$S_{\ell^+,K_S^0}^-$	$-0.66 \pm 0.06 \pm 0.04$	-0.7
REF.	$C_{\ell^+,K_S^0}^+$	$0.01 \pm 0.07 \pm 0.05$	$0.$
REF.	$C_{\ell^+,K_S^0}^-$	$-0.05 \pm 0.06 \pm 0.03$	$0.$

T contours

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

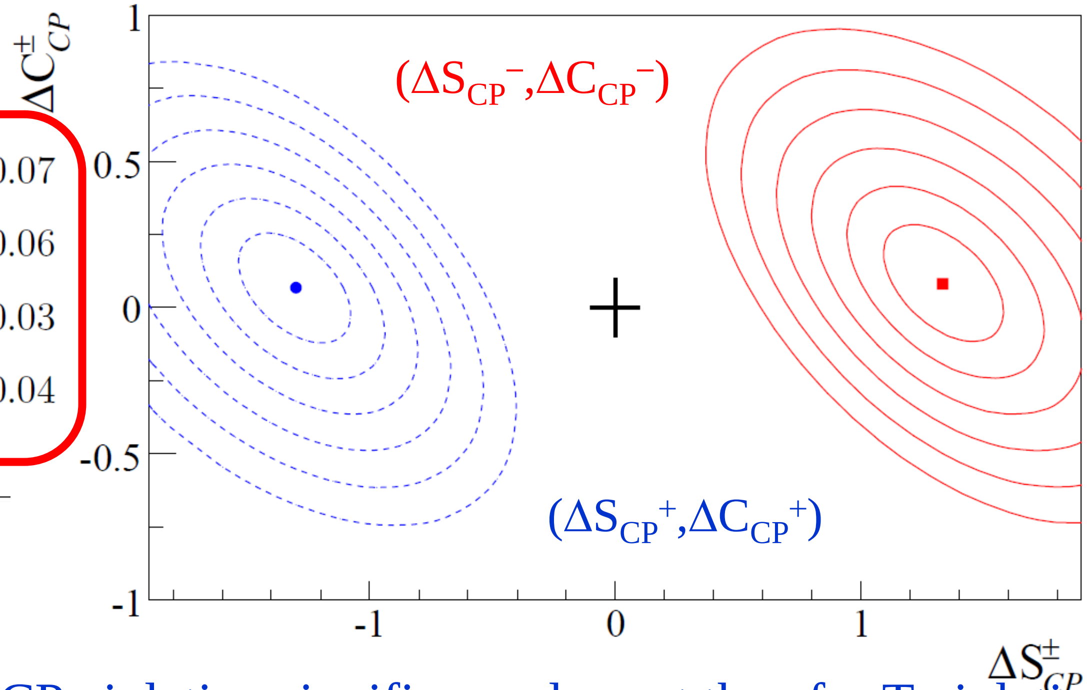


Large significance for T violation

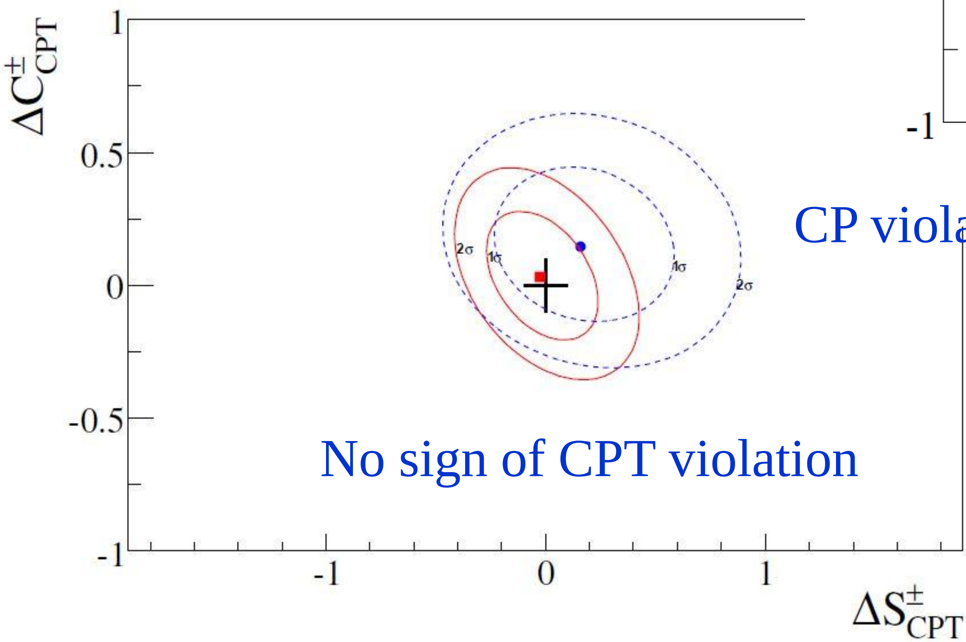
CP and CPT contours

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

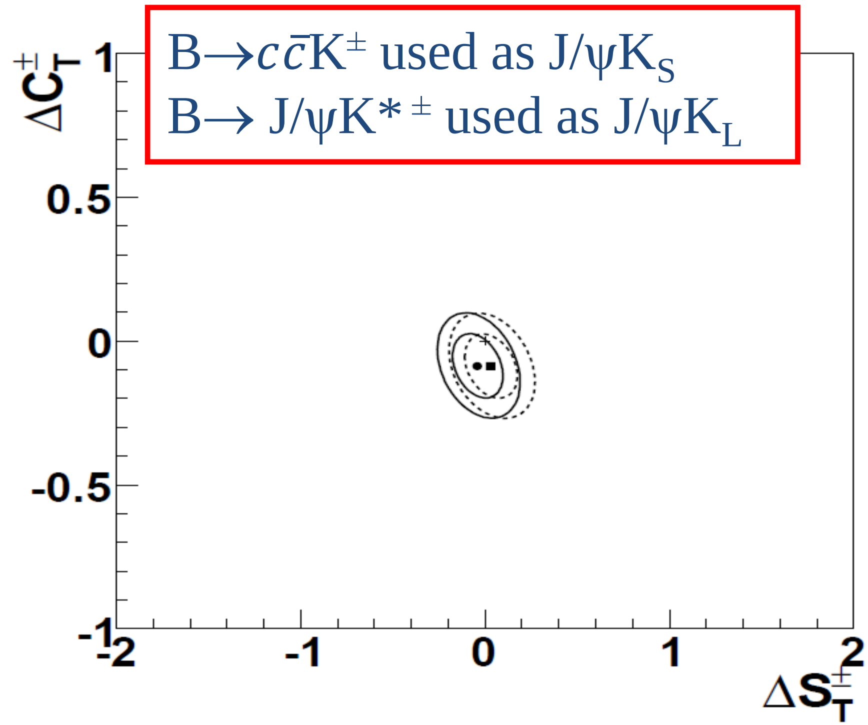
ΔS^{+}_{CPT}	$= S^{-}_{\ell+,K^0_L} - S^{+}_{\ell+,K^0_S}$	$0.16 \pm 0.21 \pm 0.09$
ΔS^{-}_{CPT}	$= S^{+}_{\ell+,K^0_L} - S^{-}_{\ell+,K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$
ΔC^{+}_{CPT}	$= C^{-}_{\ell+,K^0_L} - C^{+}_{\ell+,K^0_S}$	$0.14 \pm 0.15 \pm 0.07$
ΔC^{-}_{CPT}	$= C^{+}_{\ell+,K^0_L} - C^{-}_{\ell+,K^0_S}$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

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 category are consistent
- With appropriate constraints, obtain same S,C parameters as the latest BaBar CP violation study
- 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
$\Delta C^{-}_{\rm CP}$	0.036 ± 0.050
$\Delta C^{-}_{\rm CPT}$	-0.0042 ± 0.068
$\Delta C^{-}_{\rm T}$	-0.0405 ± 0.073
$\Delta C^{+}_{\rm CP}$	-0.0044 ± 0.049
$\Delta C^{+}_{\rm CPT}$	-0.1586 ± 0.070
$\Delta C^{+}_{\rm T}$	-0.0237 ± 0.073
$\Delta S^{-}_{\rm CP}$	0.088 ± 0.054
$\Delta S^{-}_{\rm CPT}$	-0.1035 ± 0.083
$\Delta S^{-}_{\rm T}$	0.041 ± 0.089
$\Delta S^{+}_{\rm CP}$	0.041 ± 0.053
$\Delta S^{+}_{\rm CPT}$	0.030 ± 0.086
$\Delta S^{+}_{\rm T}$	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
$m_{\rm ES}$ 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

Orthogonality of the B_+ and B_- states

- Let's call the state B_- as the one defined by the B decay to J/ψππ (J/ψK_S, $K_S \to \pi\pi$) [a pure CP-odd final state]

JHEP08 (2012) 064

- B_+ is the state orthogonal to B_-, $\langle B_+ | B_- \rangle = 0$, defined by entanglement, thus cannot decay to J/ψππ, i.e., $\langle J/\psi\pi\pi | T | B_+ \rangle = 0$
- Since B_- and B_+ are linear combinations of flavor eigenstates,

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

$$\langle B_+|B_-\rangle = N_+N_-\left[1-\alpha\delta\right] = 0 \Rightarrow \alpha\delta = 1 \Rightarrow \delta = \alpha^* \text{ if } |\alpha| = 1$$

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

$$|B_-\rangle = N_-\left[|B^0\rangle - \beta|\overline{B}^0\rangle\right], \quad |B_+\rangle = N_+\left[|B^0\rangle + \beta^*|\overline{B}^0\rangle\right] \qquad \beta = \frac{\langle J/\psi K_L|T|B^0\rangle}{\langle J/\psi K_L|T|\overline{B}^0\rangle}$$

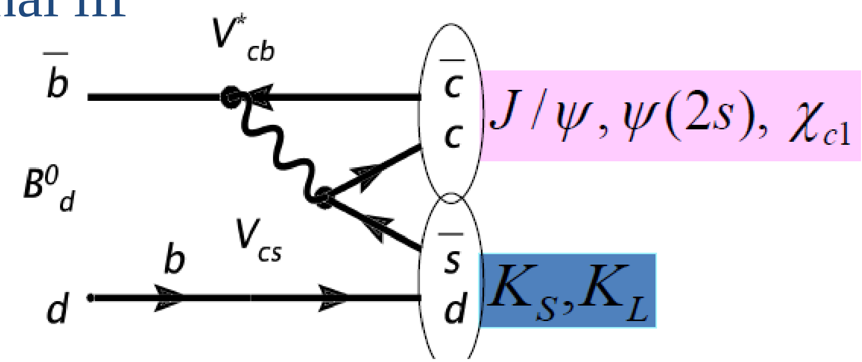
if $|\beta| = 1$

Orthogonality of the B_+ and B_- states

- B_+ and B_+ , and 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 also 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 strickly orthogonal iff
  - ✓ We neglect the $J/\psi\pi\pi$ component in $J/\psi K_L$ final states, i.e. neglect CPV in K^0-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 $O(\lambda^4)$

Significance determination

- 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

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

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

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

- 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 asymmetries

- Construct asymmetry for each of the four reference transitions

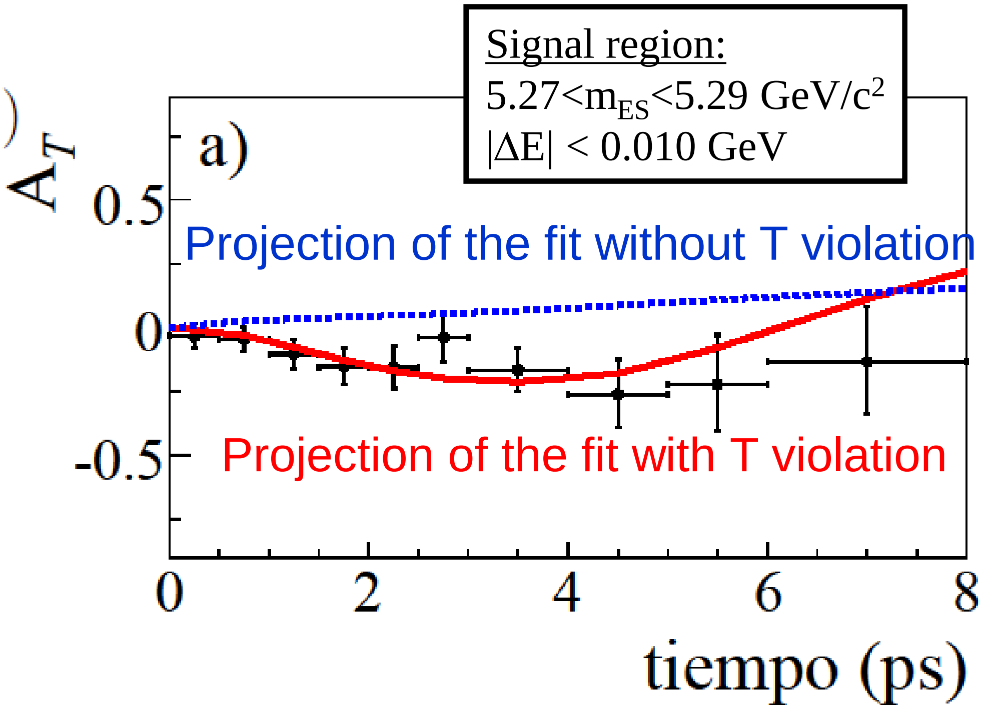
$$\overline{B}^0 \to B_- \qquad \overline{B}^0 \to B_+ \qquad B_+ \to B^0 \qquad B_- \to B^0$$

- 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

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

T raw asymmetries + significance

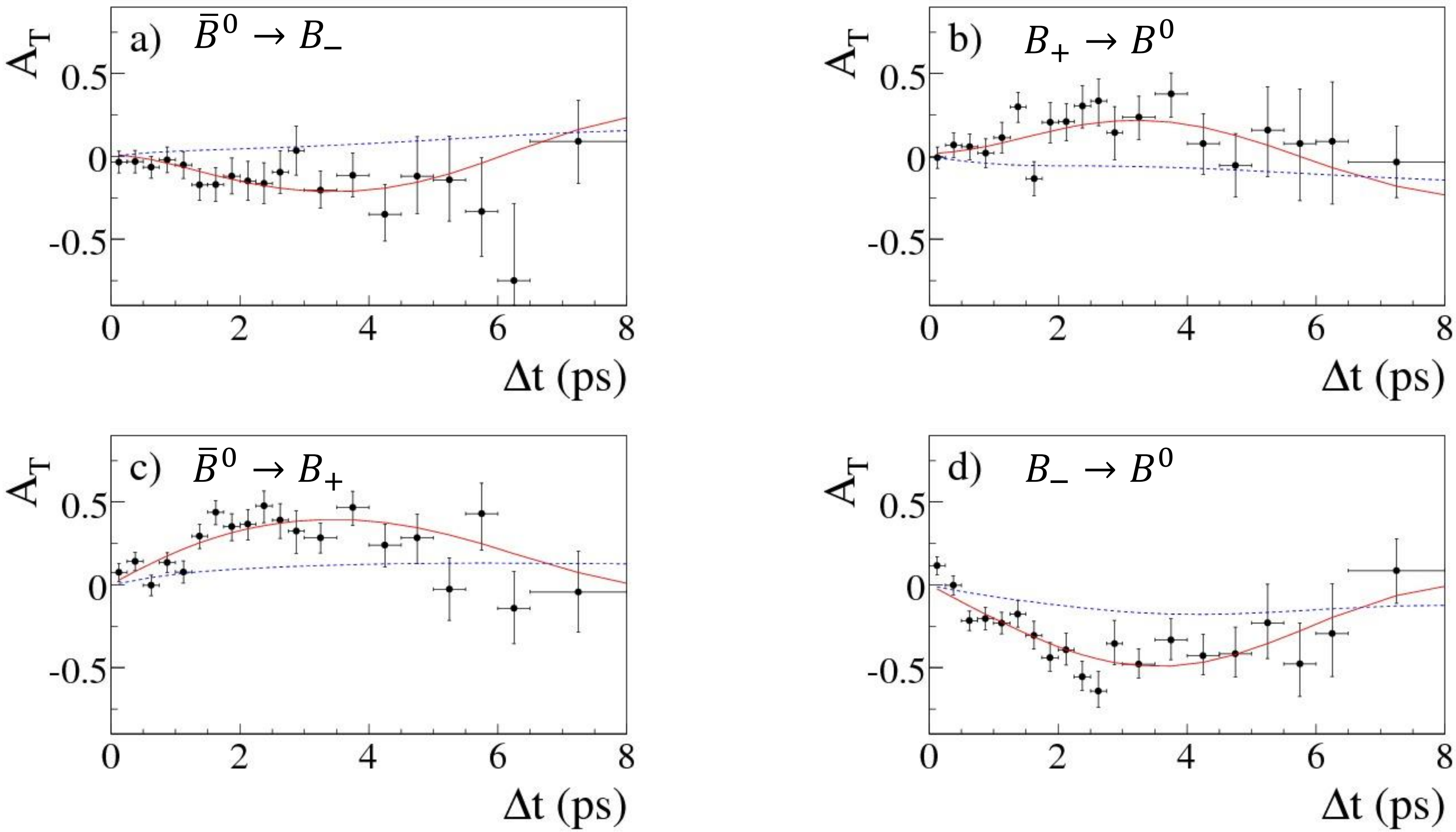
Significance test

$s^2_{NoT} = 226$ ⇒ 14σ

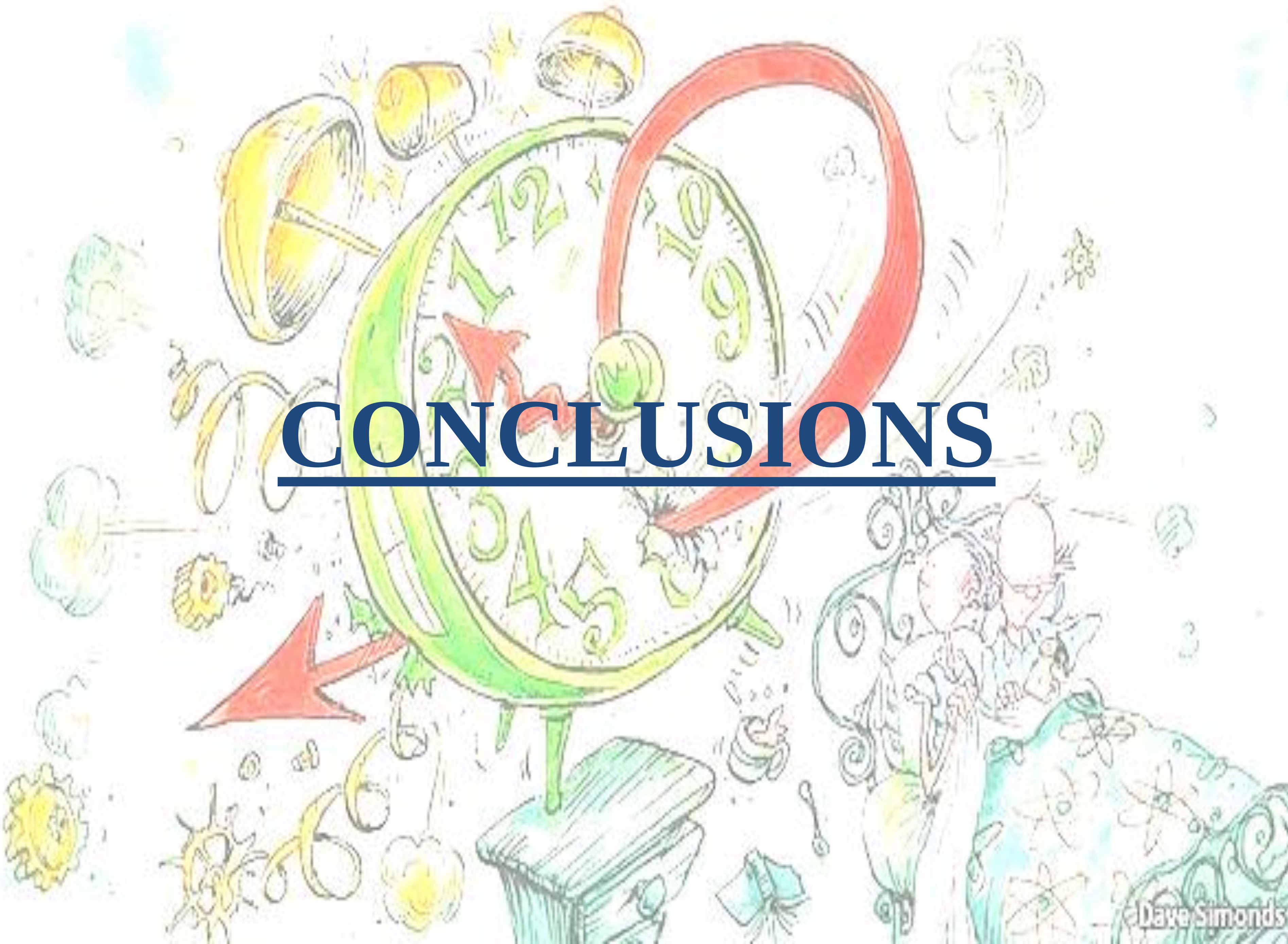
$s^2_{NoCP} = 307$ ⇒ 16.6σ

$s^2_{NoCPT} = 5$ ⇒ 0.33σ

Stat. and Syst. $\Delta\nu$=8



CONCLUSIONS



Conclusions

- Observed t-Asymmetries, like the Arrow of Time, are not T-violation.
  - Genuine TRV test requires: *t↔-t && in↔out states*
- EPR-entanglement at B offer a unique opportunity to test fundamental asymmetries.
- BaBar 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 , exploiting EPR entanglement.
- This observed effect can uniquely be attributed to TRV, without invoking CP violation or CPT invariance.
- The significance of the effect exceeds 10σ level.
- The result is consistent with CP-violating measurements if we assume CPT invariance.
- These measurements constitute the first direct observation of Time Teversal Violation, in any system, through processes that can only be related by a T transformation.

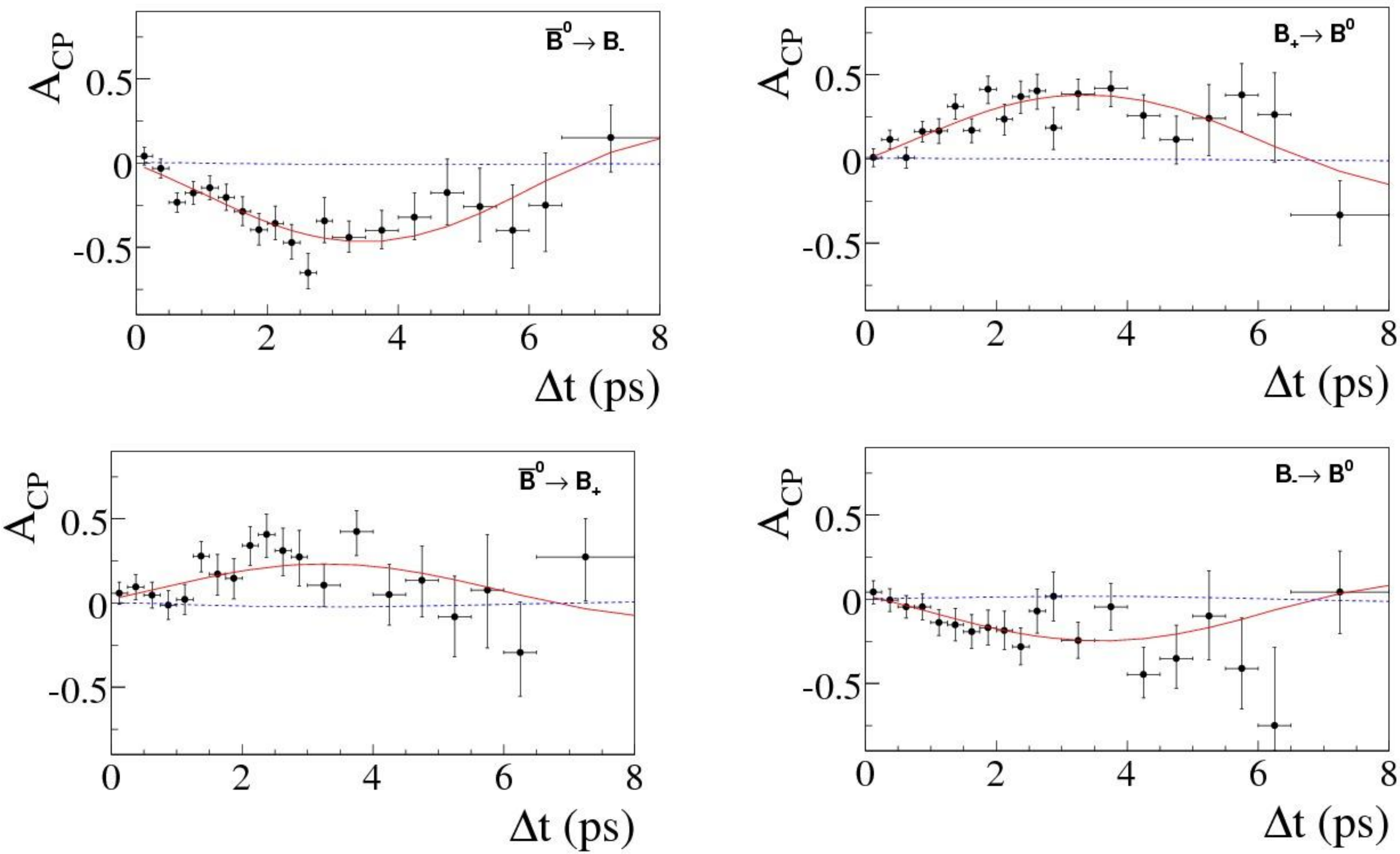

THANK YOU FOR YOUR ATTENTION

BACK-UP

CP raw asymmetries(CP Data Sample)

No CP violation
Experimental data

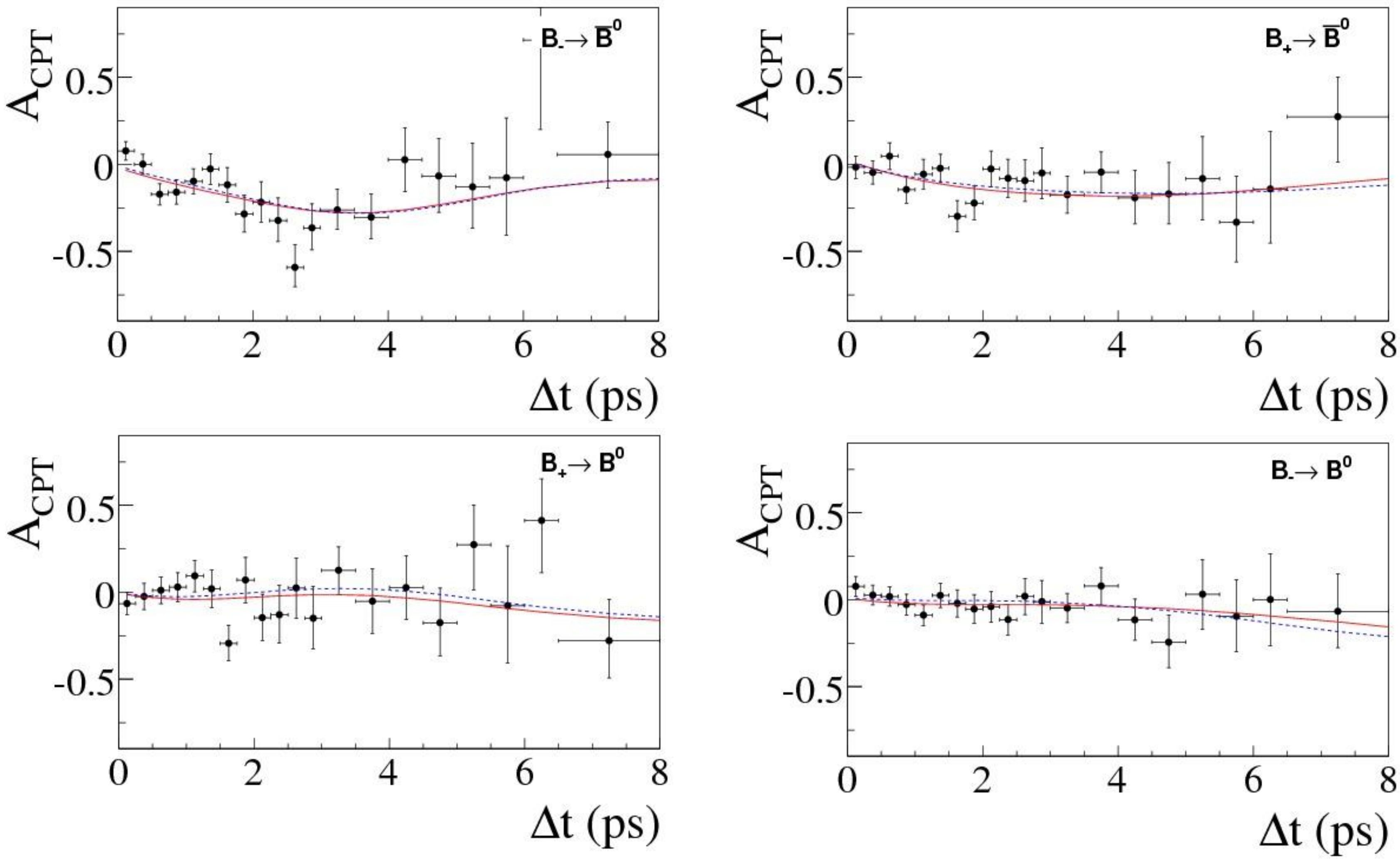
Signal region:
$5.27 < m_{ES} < 5.29$ GeV/c^2
$|E| < 0.010$ GeV



CPT raw asymmetries(CP Data Sample)

No CPT violation
Experimental data

Signal region:
$5.27 < m_{ES} < 5.29$ GeV/c^2
$|E| < 0.010$ GeV



The Economist

The arrow of time

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

Sep 1st 2012 | from the print edition

TIME seems to flow inexorably in one direction. Superficially, that is because things deteriorate with age—and this, in turn, is because there are innumerably fewer ways to arrange particles in an orderly fashion than in a jumbled mess. Any change in an existing arrangement is therefore likely to increase its disorder.
Dig a little deeper, though, and time's arrow becomes mysterious. A particle cannot, by itself, become………

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

Bertram M. Schwarzschild

November 2012, page 16

DIGITAL OBJECT IDENTIFIER

http://dx.doi.org/10.1063/PT.3.1774

Time's arrow in B mesons

SLAC NATL ACCELERATOR LAB.

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.

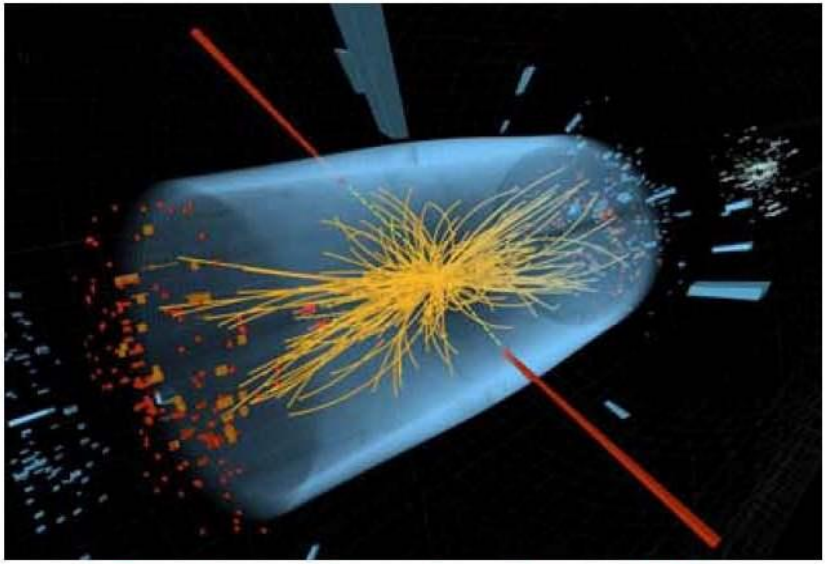
Phys. Rev. Lett. 109, 211801 (2012)

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

PHYSICS WORLD REVEALS ITS TOP BREAKTHROUGHS FOR 2012

http://physicsworld.com/cws/article/news/2012/dec/14/physics-world-reveals-its-top-10-breakthrough.

CERN discovers Higgs-like boson



One of many proton–proton collisions at CMS

Majorana fermions

Looking for Majorana fermions in a solid

Time-reversal violation

"To the BaBar collaboration for making the first direct observation of time-reversal violation by measuring the rates at which the B^0 meson changes quantum states."