Observation of the weak time's arrow in B mesons

F. Martínez-Vidal

IFIC – Universitat de València-CSIC

On behalf of the BABAR Collaboration

EP Seminar

18th December 2012

Picture: Greg Stewart, SLAC

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

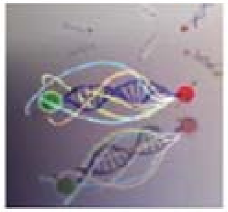
Authors
- General Information
- Submit a Manuscript
- Publication Rights
- Open Access
- Policies & Practices
- Tips for Authors
- Professional Conduct

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

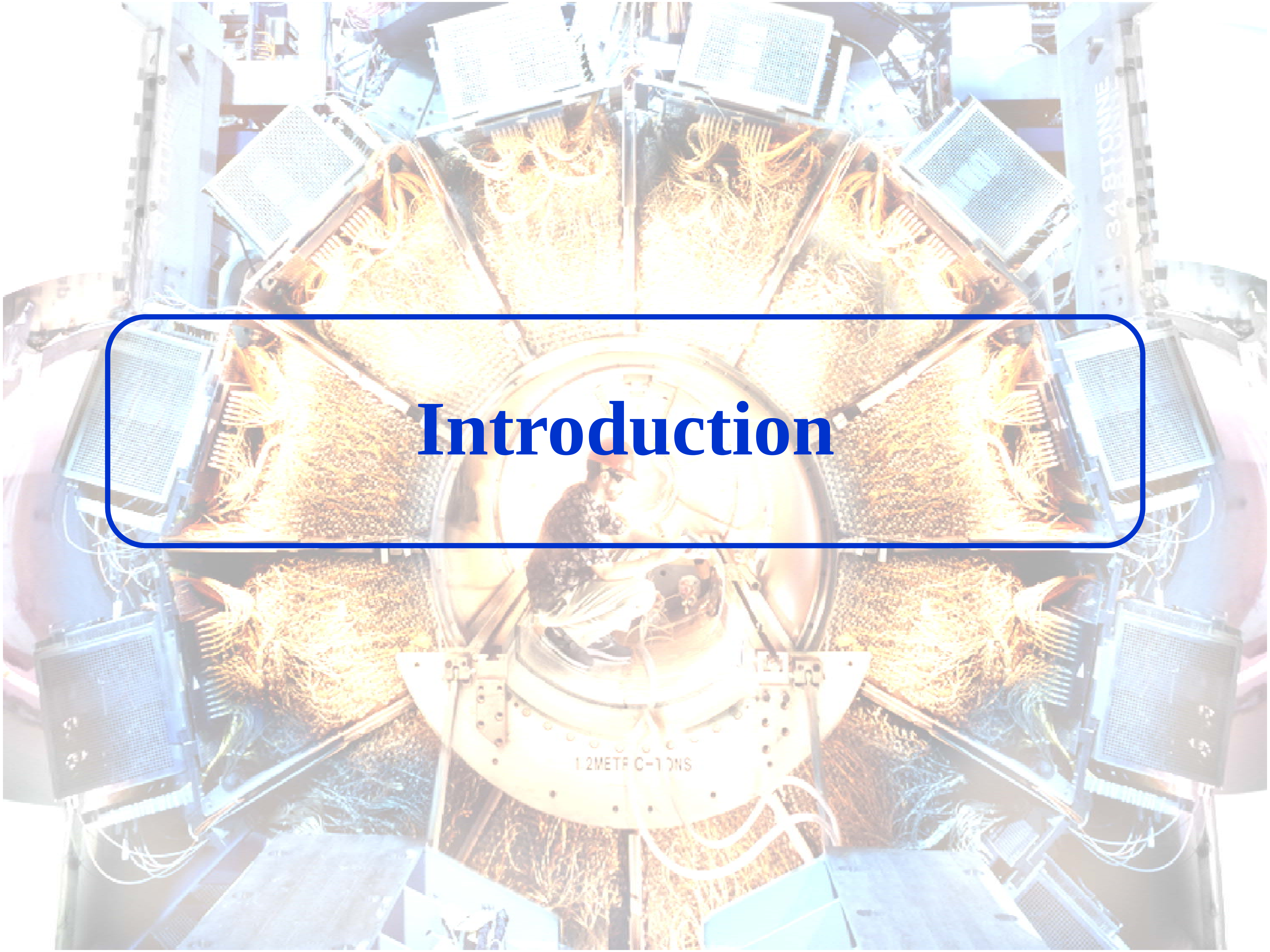
Michael Zeller
Department of Physics, Yale University, New Haven, CT 06520, USA

Published November 19, 2012

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

- ✓ Invariance under reversal of motion
- ✓ **Detailed balance** $P(a+b \rightarrow c+d) = P(c+d \rightarrow a+b)$

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

Macroscopic *t* asymmetries (cont'd)

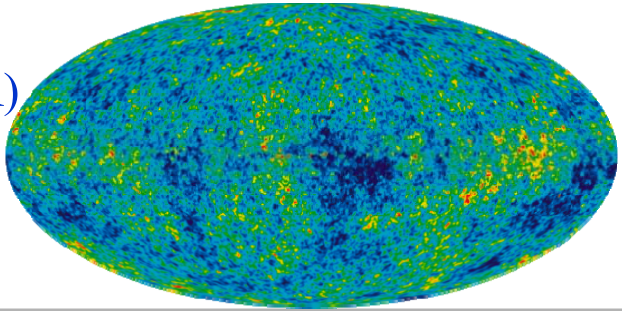
- The falling vase has trillions of trillions of particles and collisions
  - ✓ It is "highly improbable" that the vase returns to its original situation

  - ✓ Better to buy another one…
- <u>In particle physics, decays are an example of time asymmetric process</u>
  - ✓ Mismatch between P →1+…+n and 1+…+n → P
- Macroscopic *t* asymmetry is likely connected with the

Universe *t* asymmetry (expansion)

  - ✓ Compatible with T symmetry (Lorentz symmetry of GR)
  - ✓ Due to the initial (more ordered, less probable) condition of our Universe (inflation?)

~same temperature in the CBR map



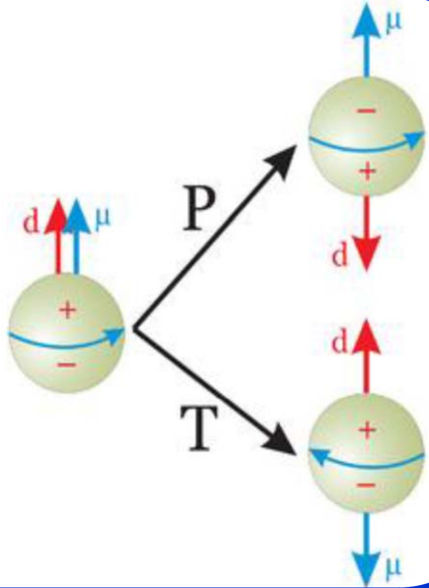
Scenarios for time reversal violation

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:

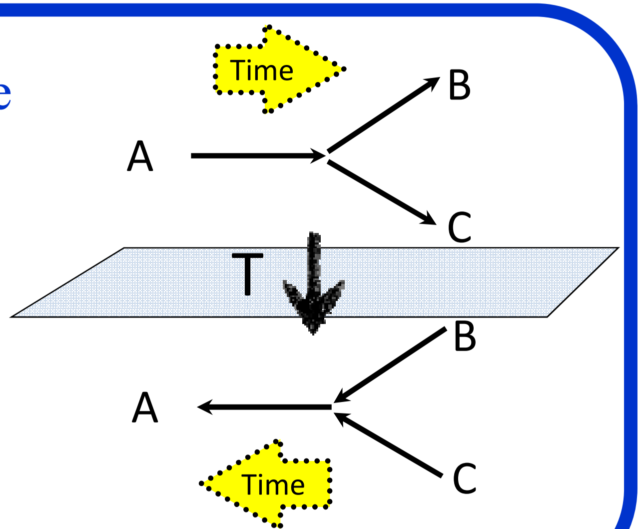
PDGLive.org

$d_n < 2.9 \times 10^{-26}$ *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

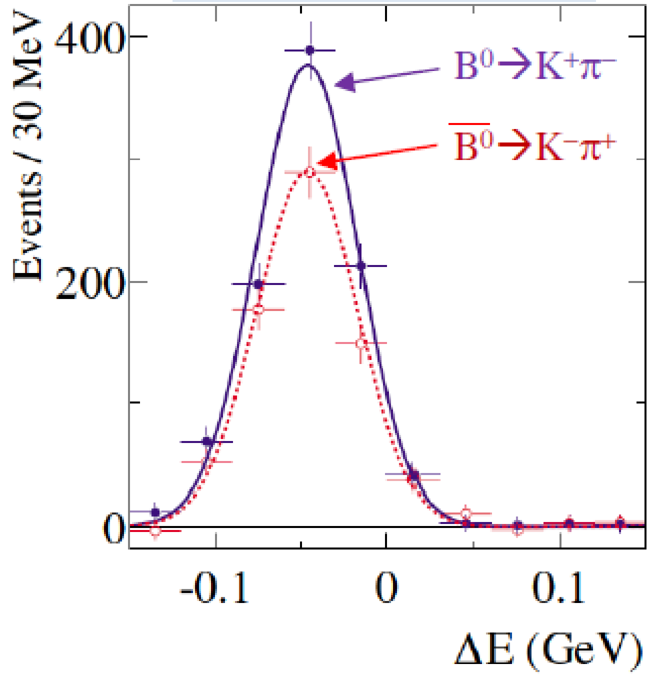
- Compare a → b vs. b → a in <u>decay</u> processes
  - ✓ B factories (BaBar and Belle) have observed large direct CP violation in B → Kπ

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

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

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

PRL93, 131801 (2004)



  - ✓ 

  - ✓ Can we observe Kπ → B ?

CP
- $B^0 \to K^+\pi^-$, R_1
- $\overline{B}^0 \to K^-\pi^+$, R_2

⟷ CPT ⟷

- $K^-\pi^+ \to \overline{B}^0$, R_1
- $K^+\pi^- \to B^0$, R_2

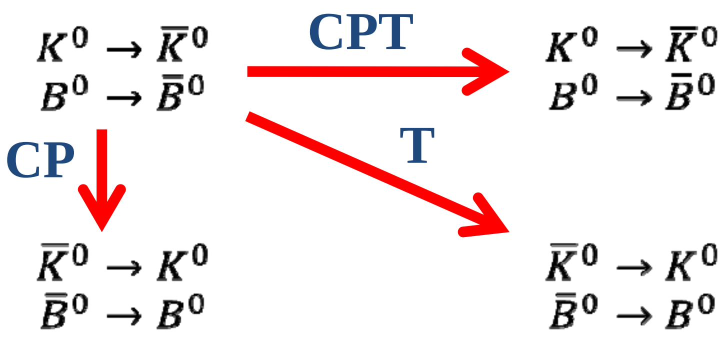
Preparation of the initial state difficult (unfeasible).

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)

$p\bar{p} \to K^{\pm}p^{\mp}K^0\bar{K}^0$

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

PLB444, 43 (1998)

  - ✓ This is the first direct evidence of T and CP violation
    - ✓ Via mixing and using semileptonic decays to tag kaons at decay time
    - ✓ Only detailed balance, no unitarity (Bell-Steinberger relations)
    - ✓ Some "controversy" in the interpretation of the observable

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

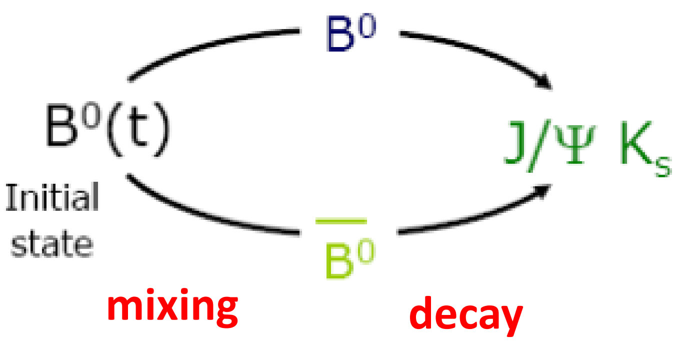
Alvarez-Gaume et al, Phys. Lett. B 458 (1999)

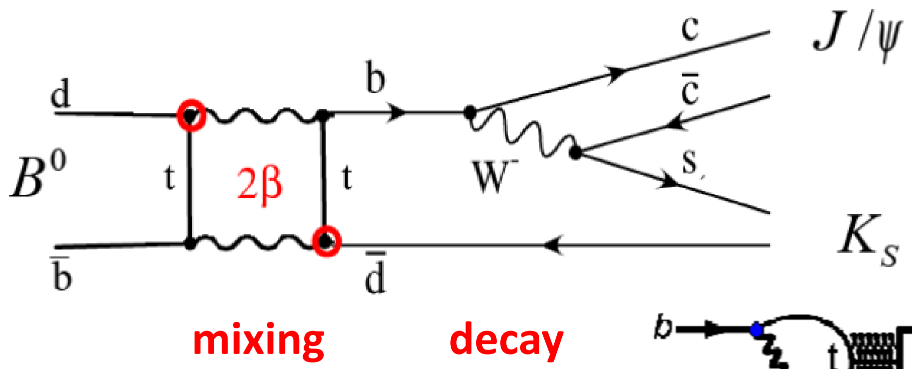
Wolfenstein, Int. Jour. Mod. Phys. E8, 501 (1999)

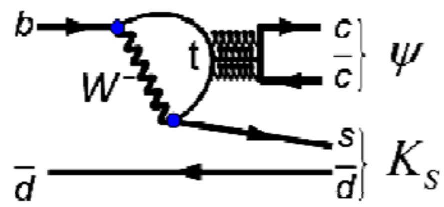
Test s of Conservation Laws, PDG, 2012

T violation in unstable systems (cont'd)

- Compare a → b vs. b → a in mixing+decay processes
  - ✓ B factories 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

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

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

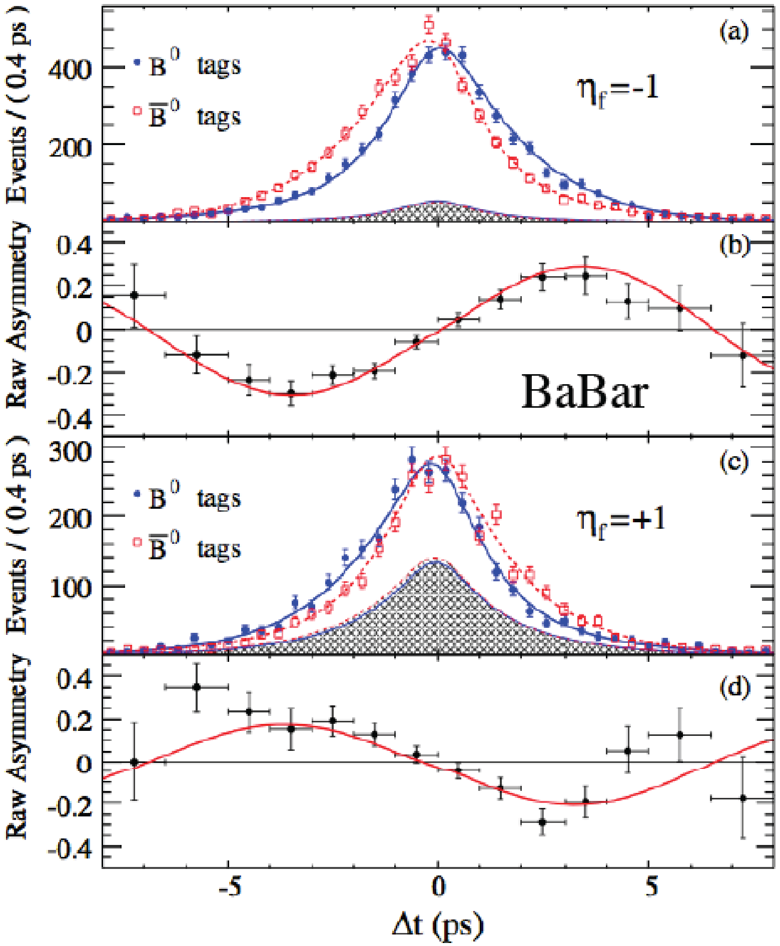
Within the SM and CKM:

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

CKM angle (V_{td})

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

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

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

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

CP asymmetry

Kobayashi and Maskawa awarded half of 2008 N.P.

Cannot be interpreted as T violation:

- ✓ Assumes CPT invariance and $\Delta\Gamma = 0$
- ✓ There is no test of detailed balance

(no exchanges $t \Leftrightarrow -t$ and *in* $\Leftrightarrow$ *out* states

How could we directly observe the large, expected T violation in this privileged system of Nature?

T violation and entanglement: strategy at a B factory

T violation and quantum entanglement

➢ Quantum (EPR) entanglement at B factories

Bernabeu & Bañuls, PLB464, 117 (1999)

Wolfenstein, Int. Jour. Mod. Phys. E8, 501 (1999)
Quinn, J. Phys. Conf. Ser. 171, 012001 (2009)

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

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

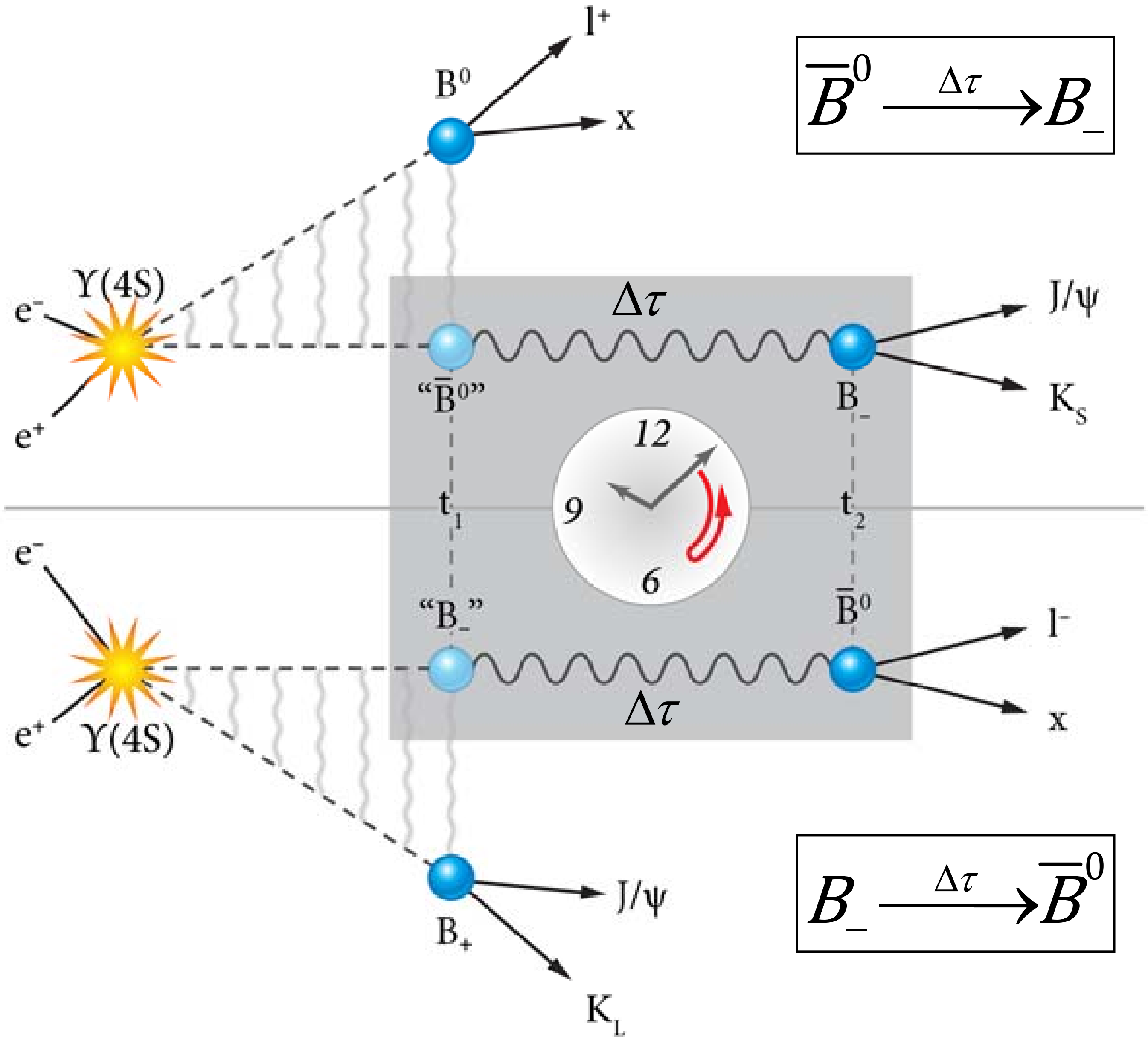
- ✓ ϒ(4S) is a $b\bar{b}$ state with $J^{PC} = 1^{--}$
- ✓ In the strong ϒ(4S) decay the created pair of B's inherit the ϒ(4S) quantum numbers
- ✓ B mesons are pseudo-scalars ⇒ the $B\overline{B}$ pair is in a P-wave state (antisymmetric state)
- ✓ The state of the 1st B to decay at t_1 dictates the 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 ($\overline{B}^0$) ⇒ $\overline{B}^0$ (B^0) tag

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



$$\overline{B}^0 \xrightarrow{\Delta\tau} B_-$$

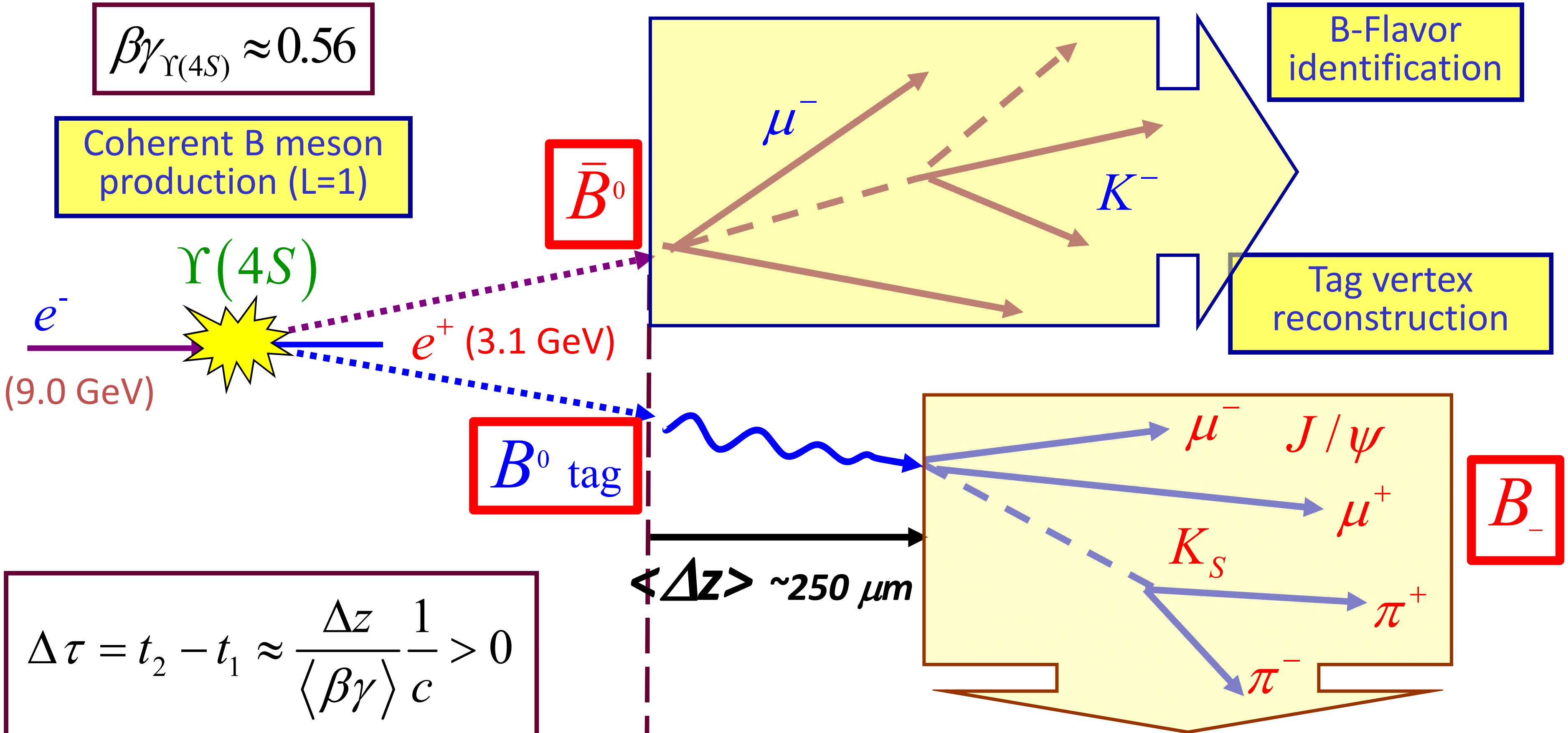
T mirror

$$B_- \xrightarrow{\Delta\tau} \overline{B}^0$$

T violation: experimental strategy at a B factory

$\beta\gamma_{\Upsilon(4S)} \approx 0.56$

Coherent B meson production (L=1)



$$\Delta\tau = t_2 - t_1 \approx \frac{\Delta z}{\langle\beta\gamma\rangle}\frac{1}{c} > 0$$

$$\sigma_{\Delta\tau} \sim 1\ \text{ps} \Leftrightarrow 170\ \mu\text{m}$$

$$B^0 \xrightarrow{\Delta\tau} B_-$$

Start the Clock

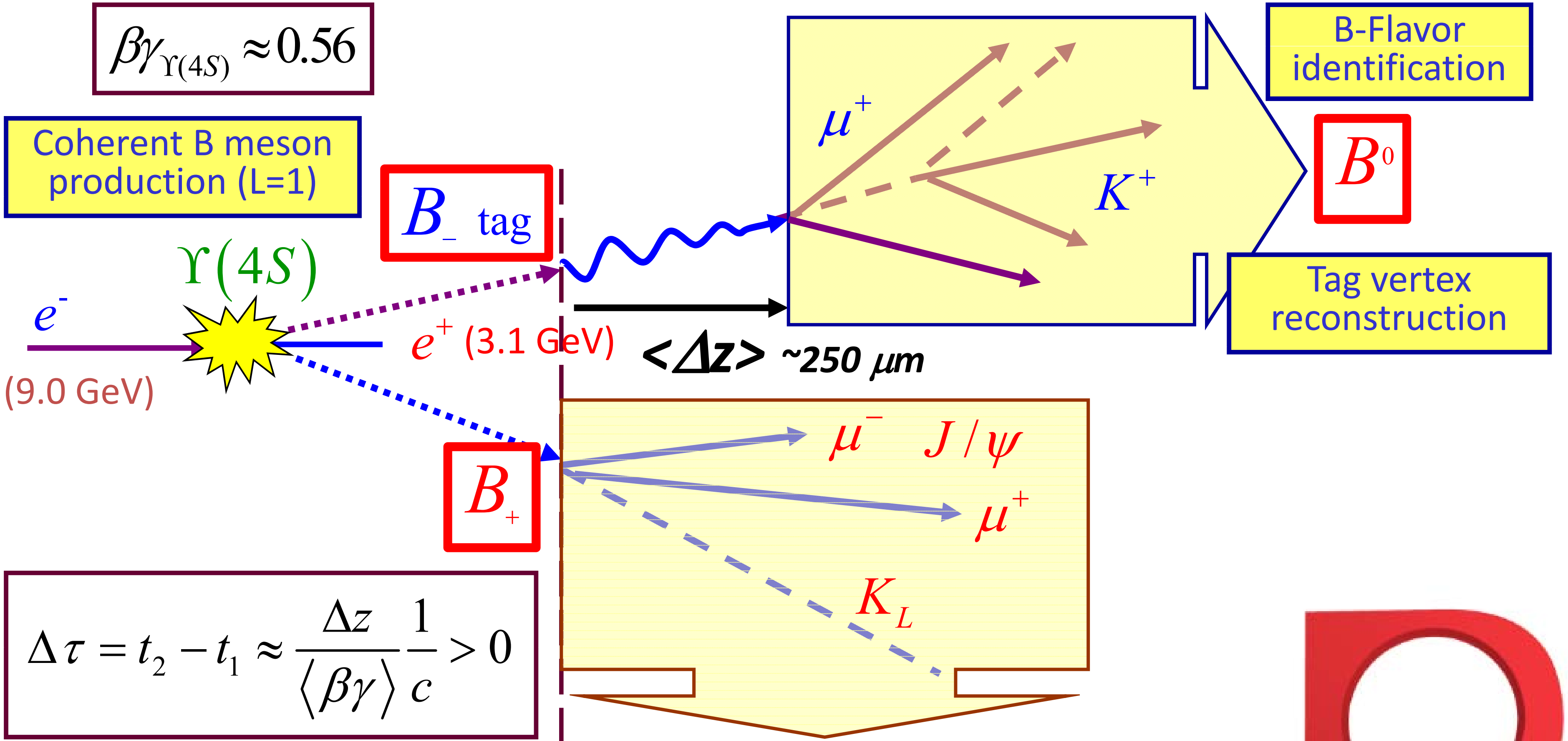
Exclusive B Meson and vertex reconstruction

High-statistics self-tagging "*B*-flavor" sample to

- ✓ calibrate tagging
- ✓ measure Δz resolution

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

$\beta\gamma_{\Upsilon(4S)} \approx 0.56$



$$\Delta\tau = t_2 - t_1 \approx \frac{\Delta z}{\langle \beta\gamma \rangle} \frac{1}{c} > 0$$

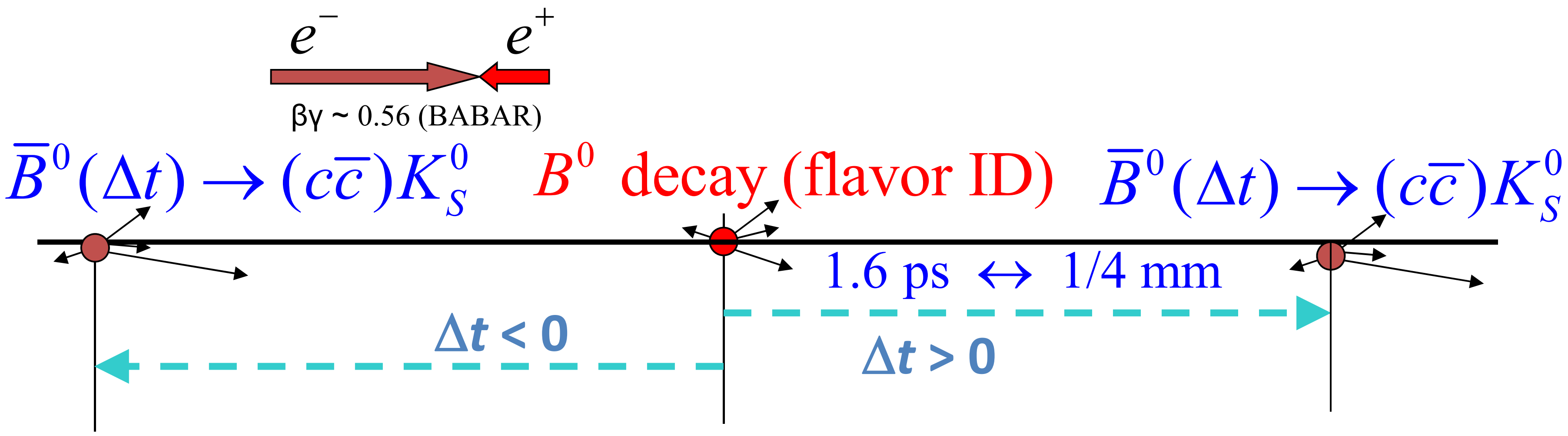
$$\sigma_{\Delta\tau} \sim 1 \text{ ps} \Leftrightarrow 170\ \mu\text{m}$$

$$B_- \xrightarrow{\Delta\tau} B^0$$

Start the Clock

High-statistics self-tagging "*B*-flavor" sample to
- ✓ calibrate tagging
- ✓ measure Δz resolution

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



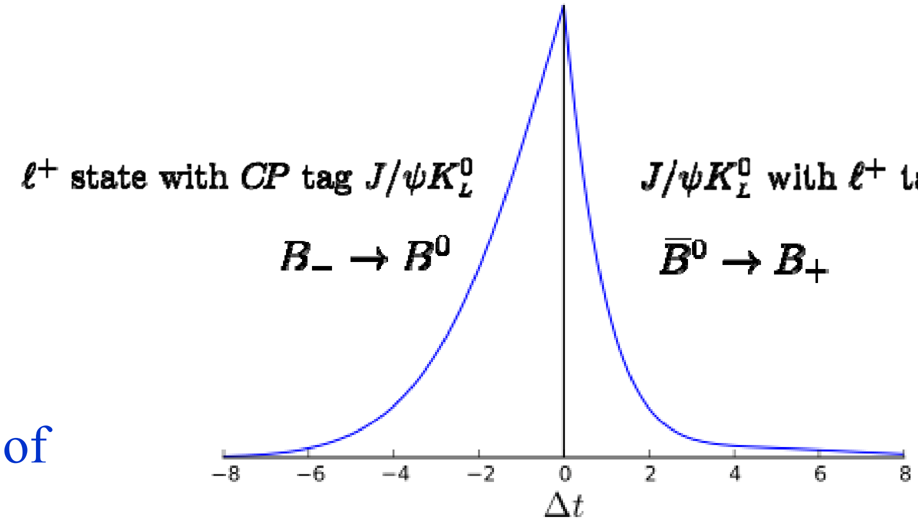
- ✓ At B factories, we define

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

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

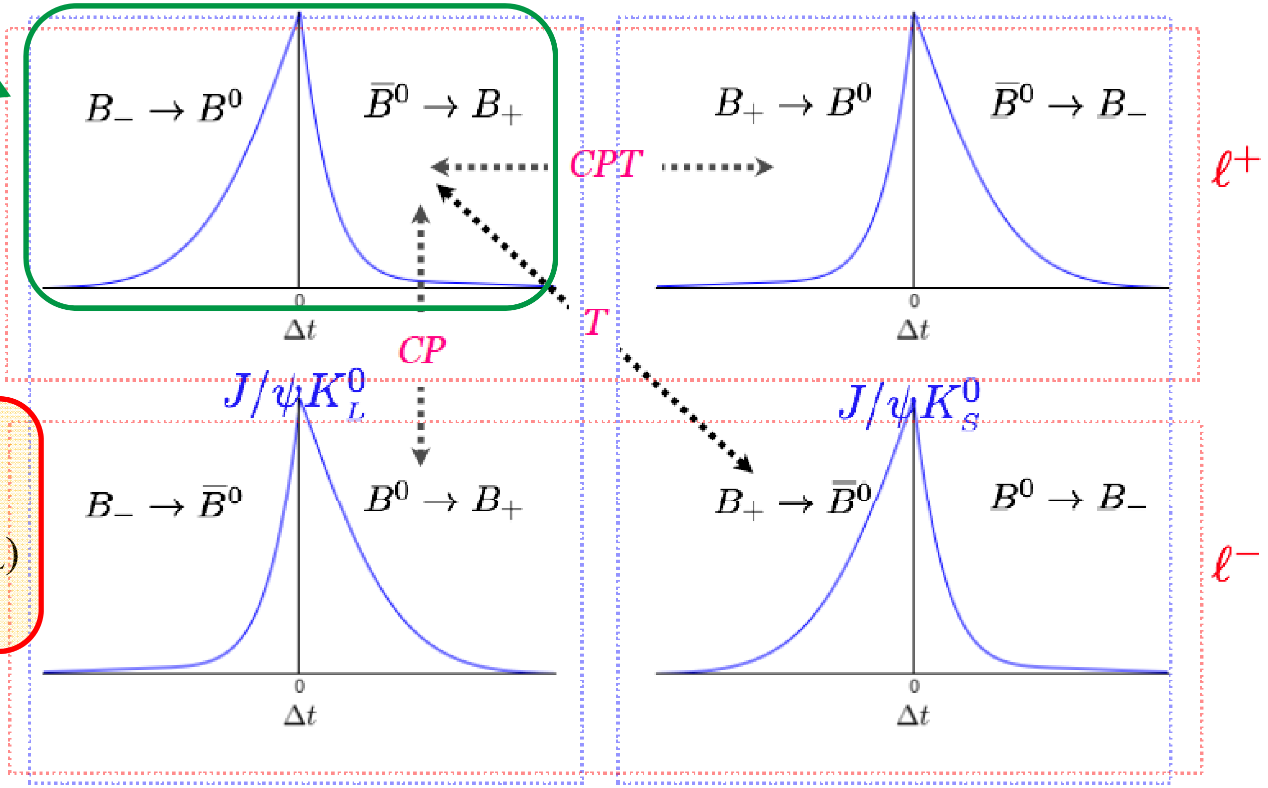
JHEP08 (2012) 064

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

…and similar for CP and CPT

(X,Y) is the reconstructed final states (flavor ID, CP reco'd)

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



T implies comparison of:
- ✓ Opposite Δt sign
- ✓ Different reco states (ψK_S v. ψK_L)
- ✓ Opposite flavor states

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

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

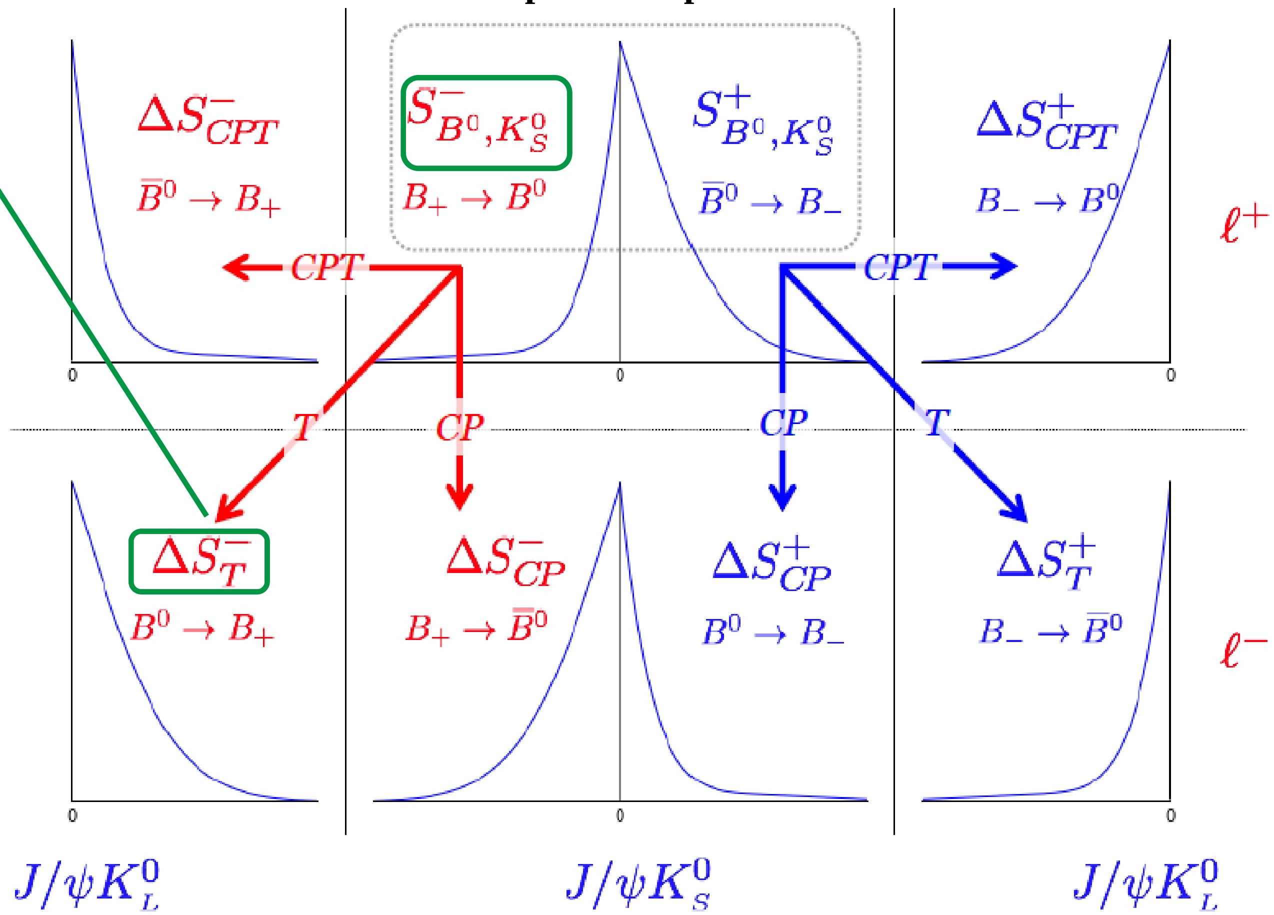
Assumes $\Delta\Gamma$=0

$$\Delta t = t_{CP} - t_{flav} = \begin{cases} +\Delta\tau & \text{for "flavor tag"} \\ -\Delta\tau & \text{for "CP tag"} \end{cases}$$

$$\alpha \in \{B^0, \bar{B}^0\}; \quad \beta \in \{K^0_S, K^0_L\}$$

Parameter	$\approx$
$\Delta S^+_{\mathrm{T}} = S^-_{\ell^-,K_L} - S^+_{\ell^+,K_S}$	-1.4
$\Delta S^-_{\mathrm{T}} = S^+_{\ell^-,K_L} - S^-_{\ell^+,K_S}$	1.4
$\Delta C^+_{\mathrm{T}} = C^-_{\ell^-,K_L} - C^+_{\ell^+,K_S}$	0.0
$\Delta C^-_{\mathrm{T}} = C^+_{\ell^-,K_L} - C^-_{\ell^+,K_S}$	0.0
$\Delta S^+_{\mathrm{CP}} = S^+_{\ell^-,K_S} - S^+_{\ell^+,K_S}$	-1.4
$\Delta S^-_{\mathrm{CP}} = S^-_{\ell^-,K_S} - S^-_{\ell^+,K_S}$	1.4
$\Delta C^+_{\mathrm{CP}} = C^+_{\ell^-,K_S} - C^+_{\ell^+,K_S}$	0.0
$\Delta C^-_{\mathrm{CP}} = C^-_{\ell^-,K_S} - C^-_{\ell^+,K_S}$	0.0
$\Delta S^+_{\mathrm{CPT}} = S^-_{\ell^+,K_L} - S^+_{\ell^+,K_S}$	0.0
$\Delta S^-_{\mathrm{CPT}} = S^+_{\ell^+,K_L} - S^-_{\ell^+,K_S}$	0.0
$\Delta C^+_{\mathrm{CPT}} = C^-_{\ell^+,K_L} - C^+_{\ell^+,K_S}$	0.0
$\Delta C^-_{\mathrm{CPT}} = C^+_{\ell^+,K_L} - C^-_{\ell^+,K_S}$	0.0

Reference processes/parameters



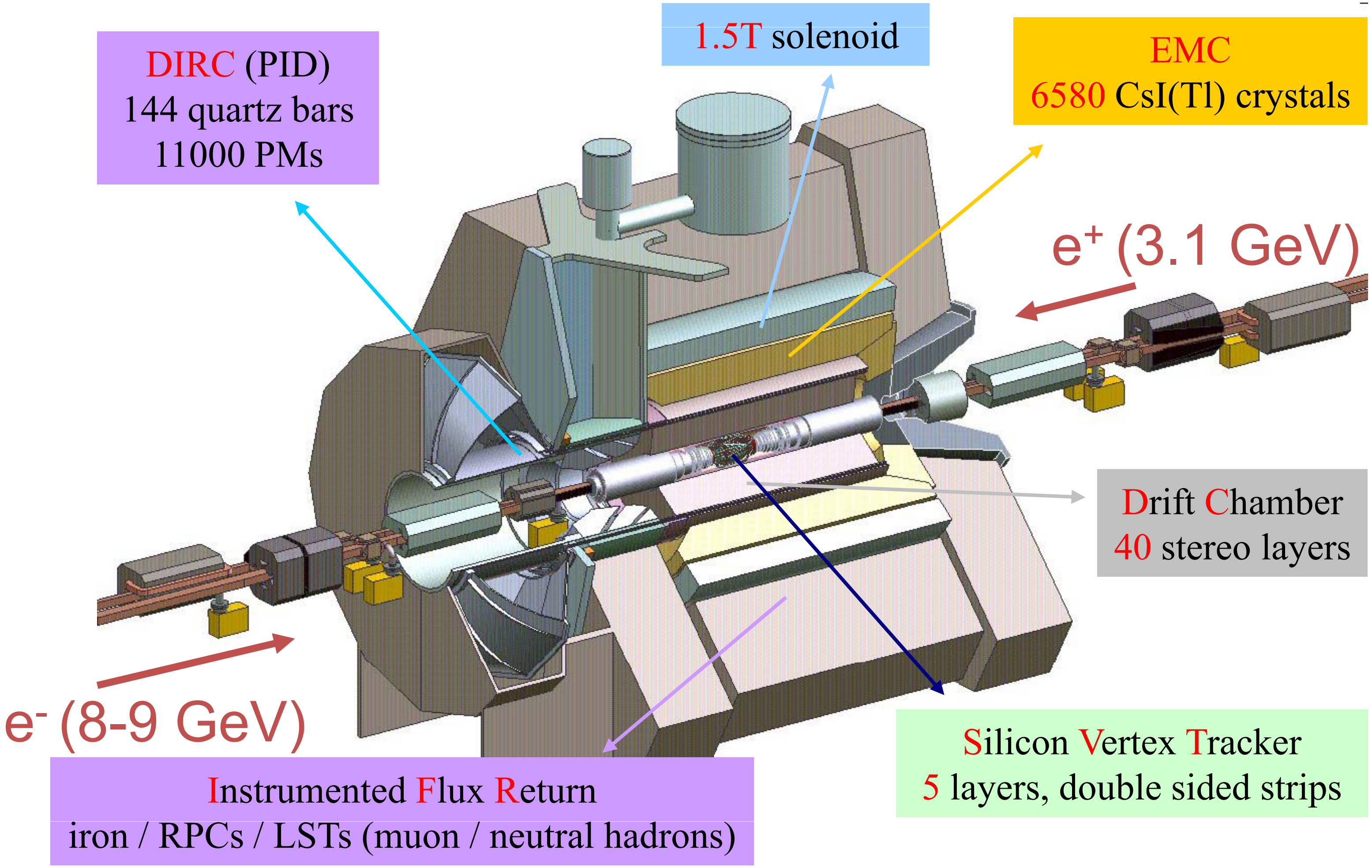
For T violation

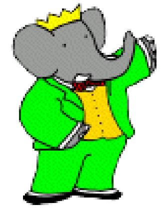
In interference $\Delta S^+_T \neq 0$, $\Delta S^-_T \neq 0$

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

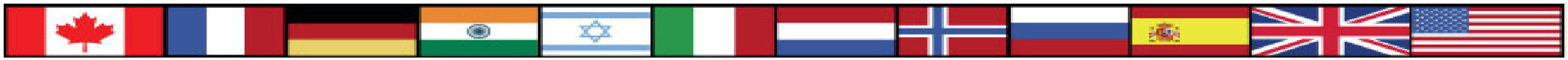
BaBar detector, data sample and fitting strategy

The BaBar detector



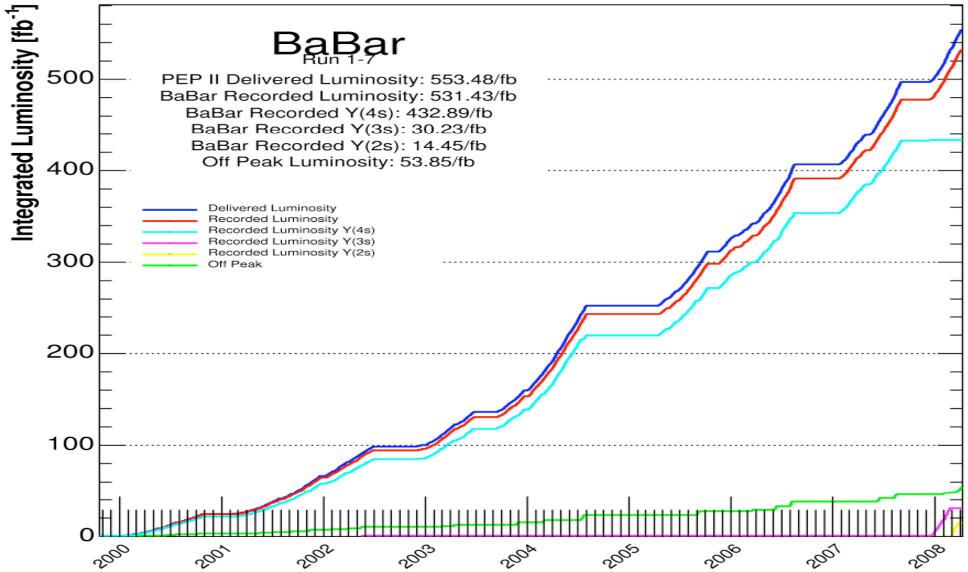


- Asymmetric B-factory at SLAC (DOE, Stanford): E_{cms} = 10.58 GeV $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle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



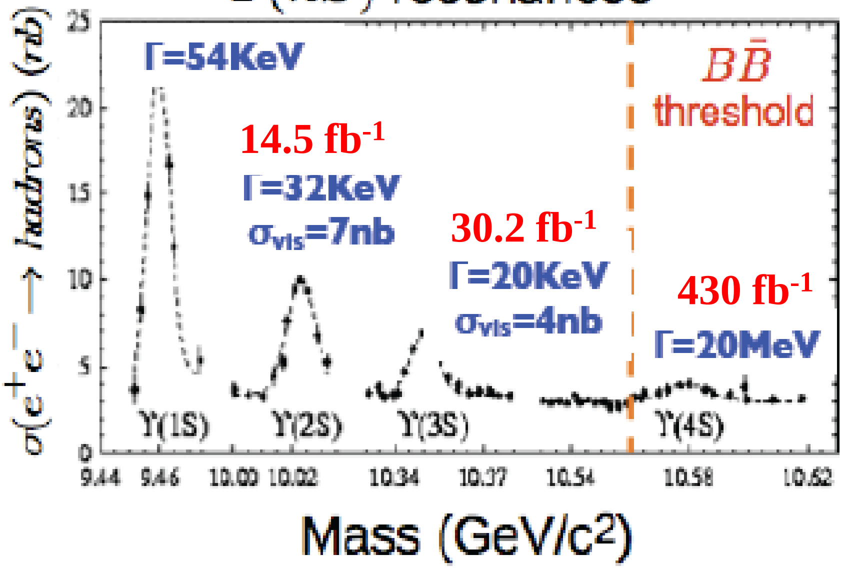
BaBar data set

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



Final collisions 12:43pm,
Monday 7 Apr 2008

$\Upsilon(nS)$ resonances

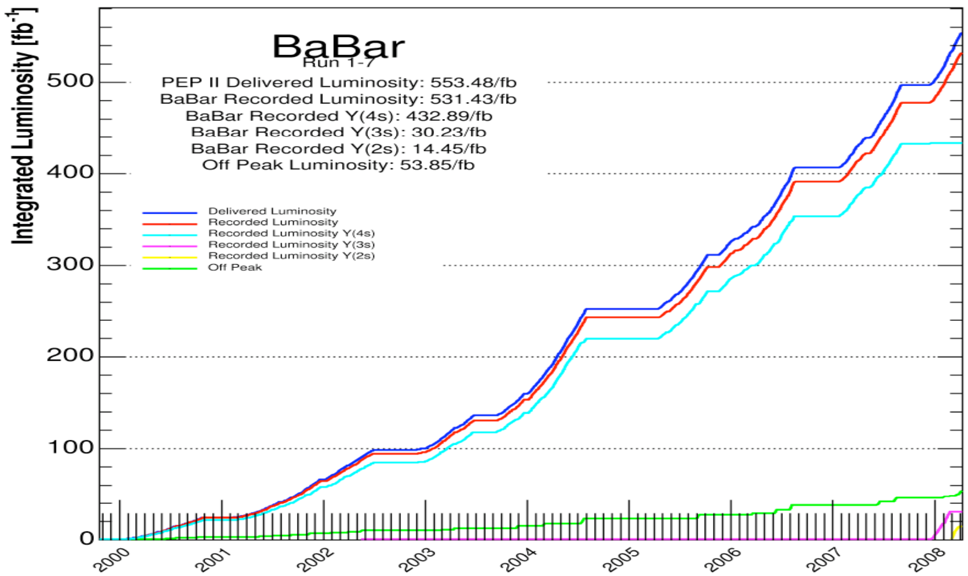


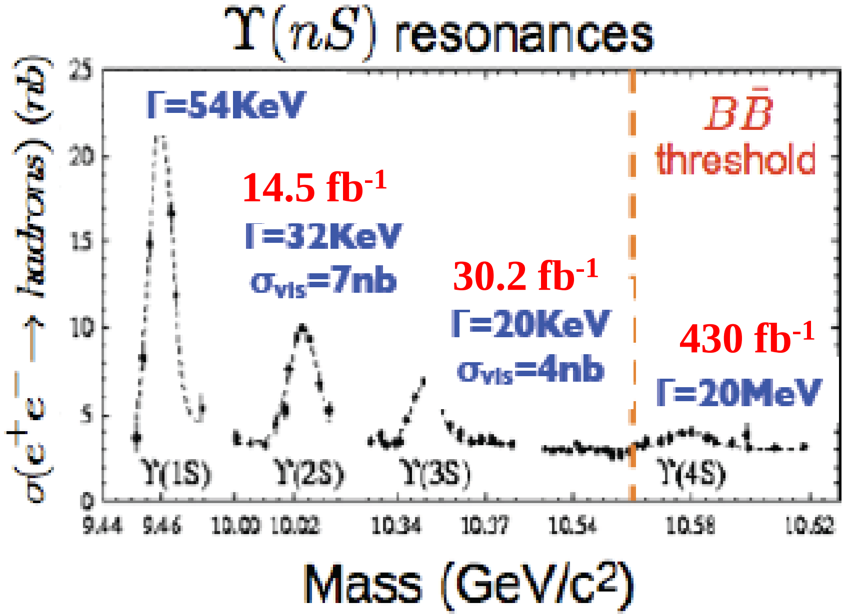
54 fb^{-1} **Off-Υ(nS)**
4 fb^{-1} **above Υ(4S)**

- ≈ 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)

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 $c\bar{c}K^\pm$, $J/\psi K^{*\pm}$	$B^+ \to J/\psi K^+$ $B^+ \to \psi(2S) K^+$ $B^+ \to J/\psi K^{*+}$

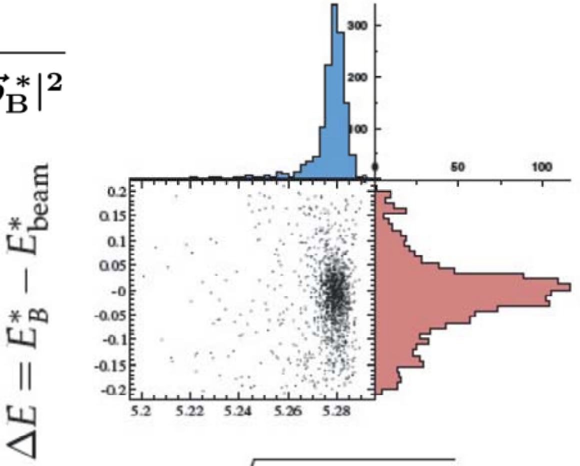
- $\approx 470\times10^6$ $B\bar{B}$ (0.5×Belle)
- $\approx 690\times10^6$ $c\bar{c}$
- $\approx 500\times10^6$ $\tau^+\tau^-$
- $\approx 121\times10^6$ Υ(3S) (7×Belle+Cleo)
- $\approx 99\times10^6$ Υ(2S) (0.5×Belle+Cleo)

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

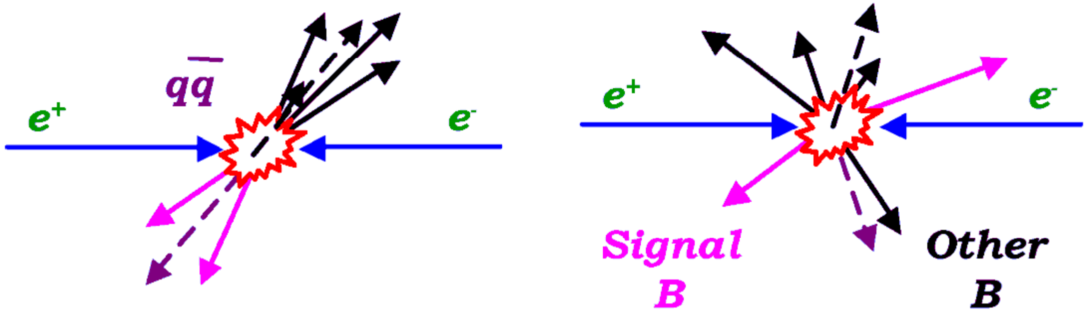
  - ✓ Energy difference $\Delta E = E^*_B - E^*_{beam}$
  - ✓ Choose best B candidates based on masses of daughters



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

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

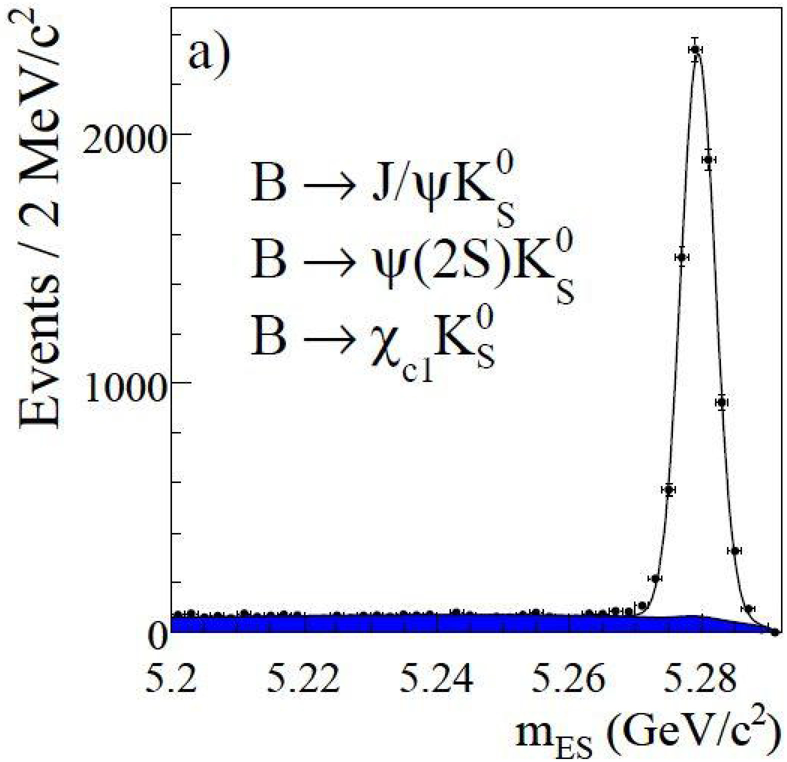
- Background rejection
  - ✓ Depends on B decay channel
  - ✓ Veto dangerous or significant backgrounds
  - ✓ Suppress continuum u, d, s backgrounds using angular distributions (B flight direction) and event shape variables



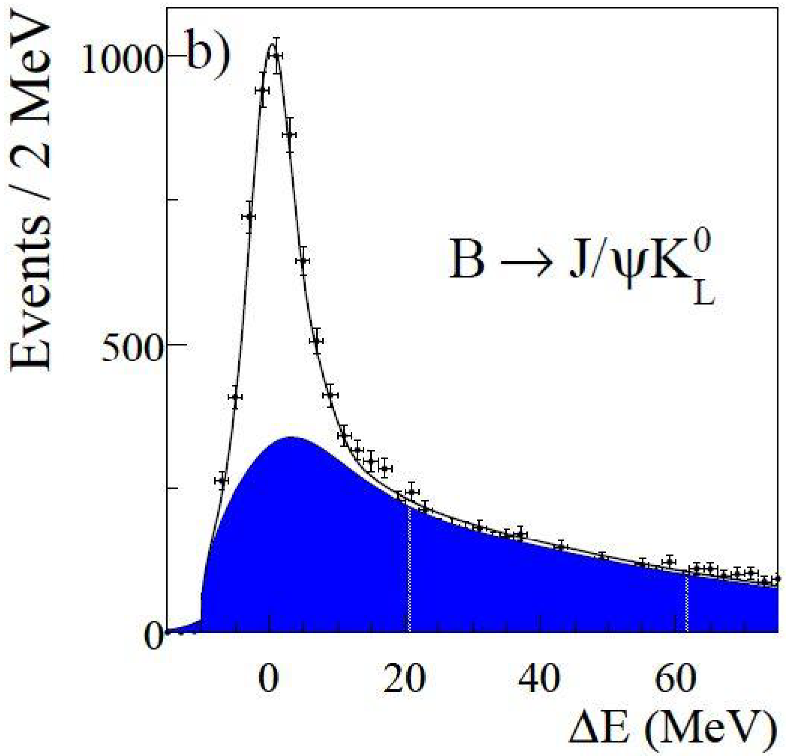
m_{ES} and ΔE for the signal sample

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)



7796 events, purity 87–96%



5813 events, purity ≈ 56%

Fitting strategy

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

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

- 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**

$$(\Delta t > 0, \Delta t < 0) \times (B^0, \bar{B}^0) \times (J/\psi K_S^0, J/\psi K_L^0)$$

- 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 (+)**

$$+$$

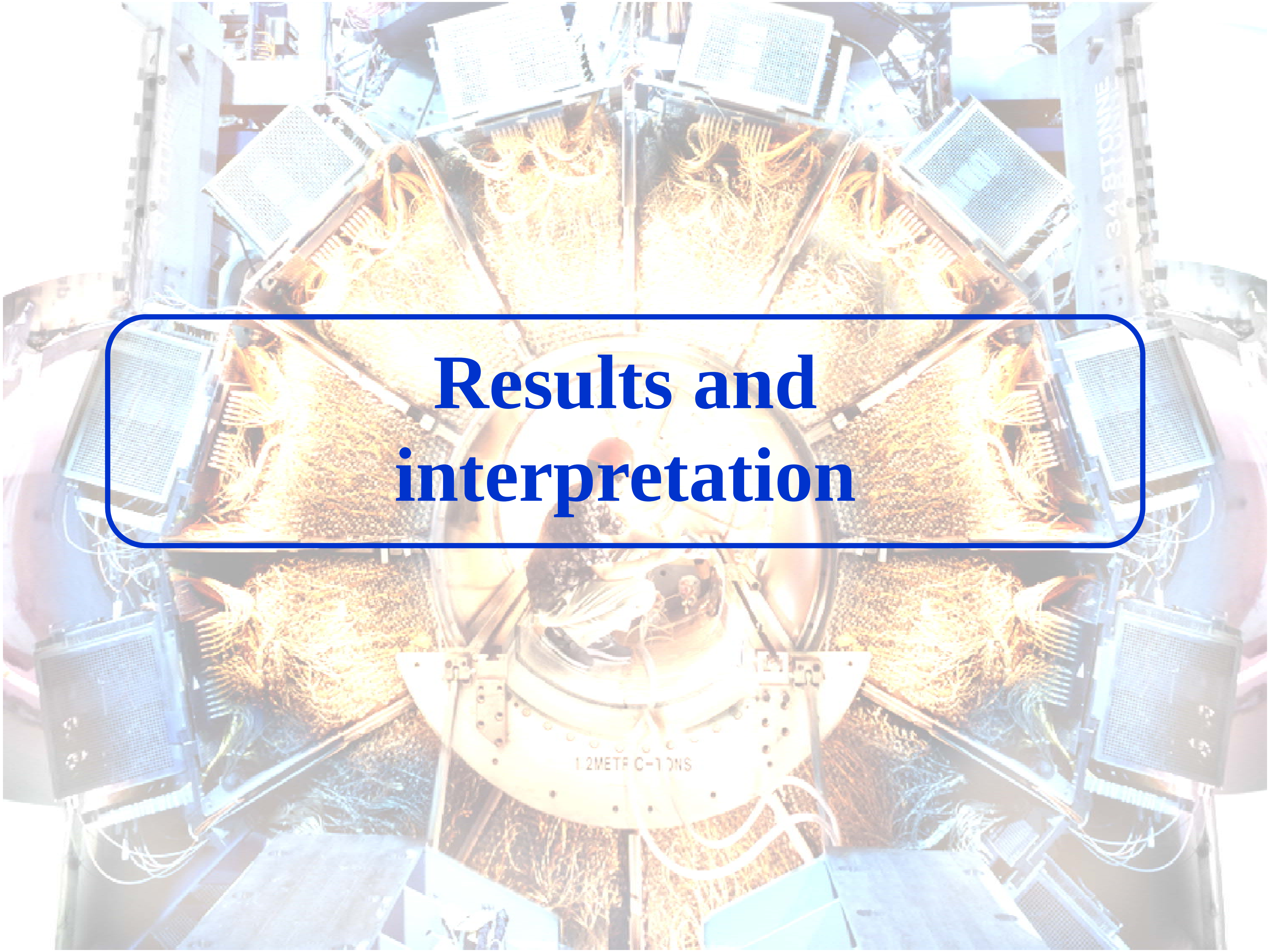
$$g^{-}_{\alpha,\beta}(-\Delta t_{true}) \times H(-\Delta t_{true}) \otimes \Re(\delta t; \sigma_{\Delta t})$$ **CP tagged events (–)**

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

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

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

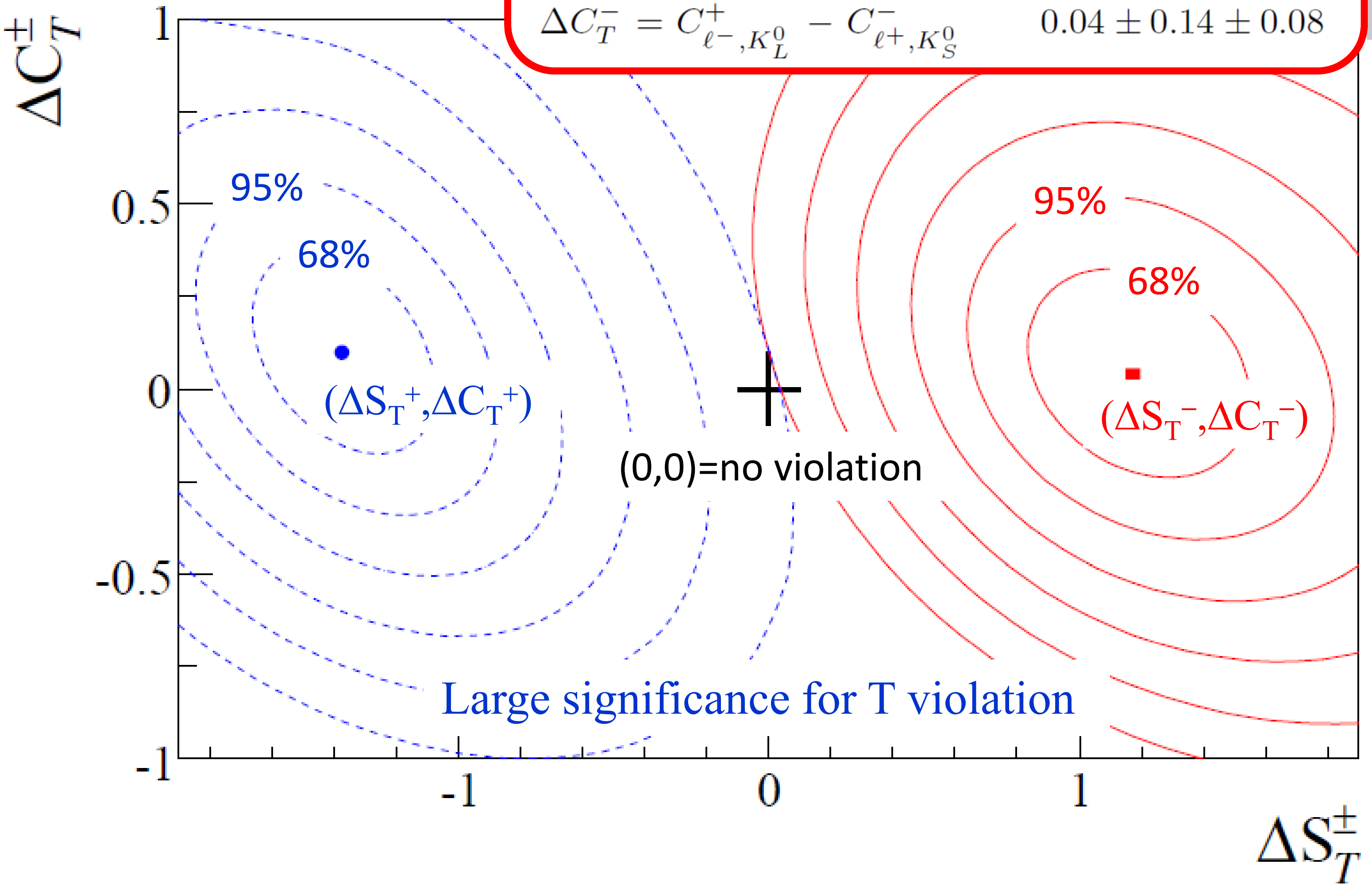
Results and interpretation



Results

T-violating parameters

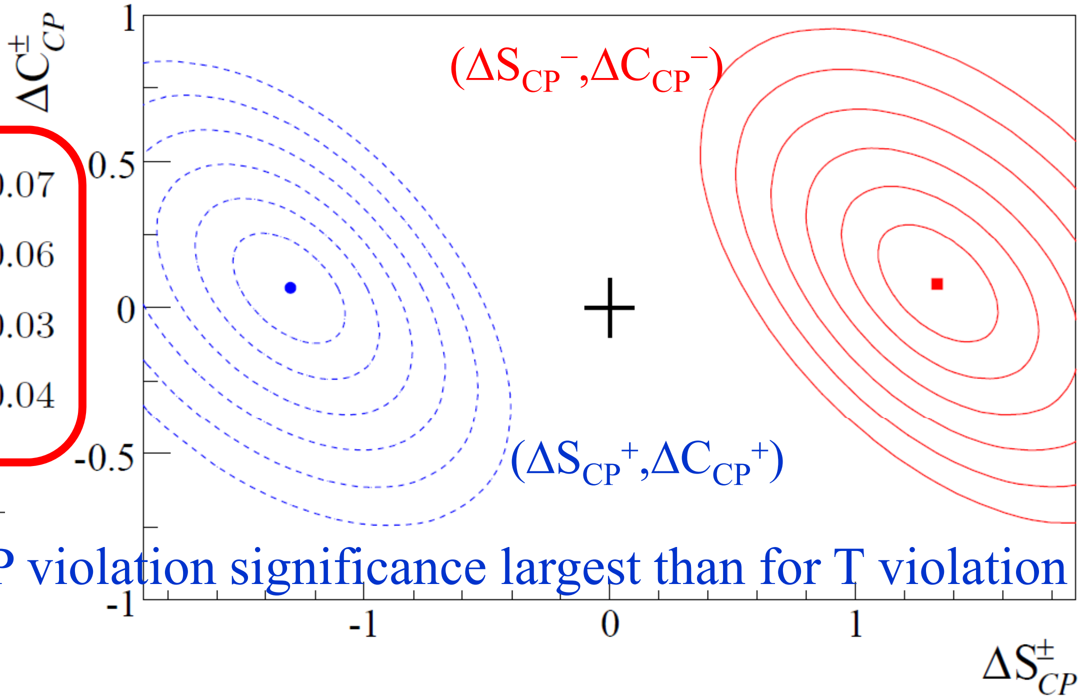
		expectation from canonical *CP*
$\Delta S_T^+ = S^-_{\ell-,K^0_L} - S^+_{\ell+,K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$	–2sin2β
$\Delta S_T^- = S^+_{\ell-,K^0_L} - S^-_{\ell+,K^0_S}$	$1.17 \pm 0.18 \pm 0.11$	+2sin2β
$\Delta C_T^+ = C^-_{\ell-,K^0_L} - C^+_{\ell+,K^0_S}$	$0.10 \pm 0.14 \pm 0.08$	0
$\Delta C_T^- = C^+_{\ell-,K^0_L} - C^-_{\ell+,K^0_S}$	$0.04 \pm 0.14 \pm 0.08$	0



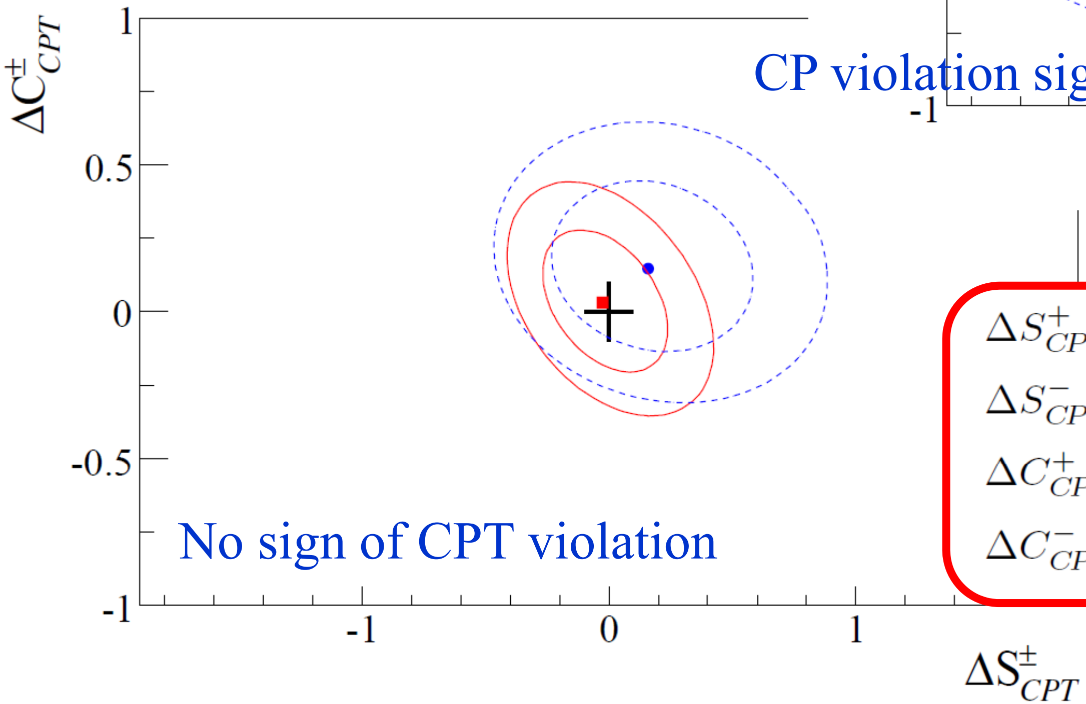
Results (cont'd)

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



No sign of CPT violation

CPT-violating parameters

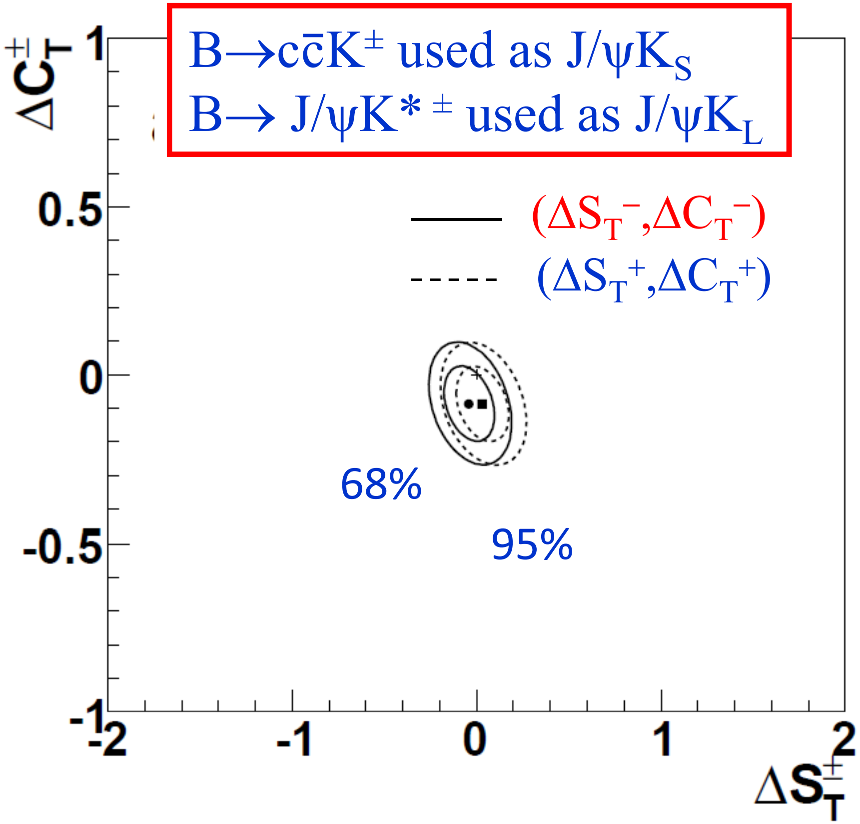
$\Delta S^+_{CPT} = S^-_{\ell^+,K^0_L} - S^+_{\ell^+,K^0_S}$	$0.16 \pm 0.21 \pm 0.09$
$\Delta S^-_{CPT} = S^+_{\ell^+,K^0_L} - S^-_{\ell^+,K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$
$\Delta C^+_{CPT} = C^-_{\ell^+,K^0_L} - C^+_{\ell^+,K^0_S}$	$0.14 \pm 0.15 \pm 0.07$
$\Delta C^-_{CPT} = C^+_{\ell^+,K^0_L} - C^-_{\ell^+,K^0_S}$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

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
ΔS_T^+	0.16 ± 0.09
ΔS_T^-	0.04 ± 0.09
ΔC_T^+	-0.02 ± 0.07
ΔC_T^-	-0.04 ± 0.07
ΔS_{CP}^+	0.04 ± 0.05
ΔS_{CP}^-	0.09 ± 0.05
ΔC_{CP}^+	-0.00 ± 0.05
ΔC_{CP}^-	0.04 ± 0.05
ΔS_{CPT}^+	0.03 ± 0.09
ΔS_{CPT}^-	-0.10 ± 0.08
ΔC_{CPT}^+	-0.16 ± 0.07
ΔC_{CPT}^-	-0.00 ± 0.07



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

Orthogonality of the B_+ and B_- states

JHEP08 (2012) 064

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

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

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

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

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

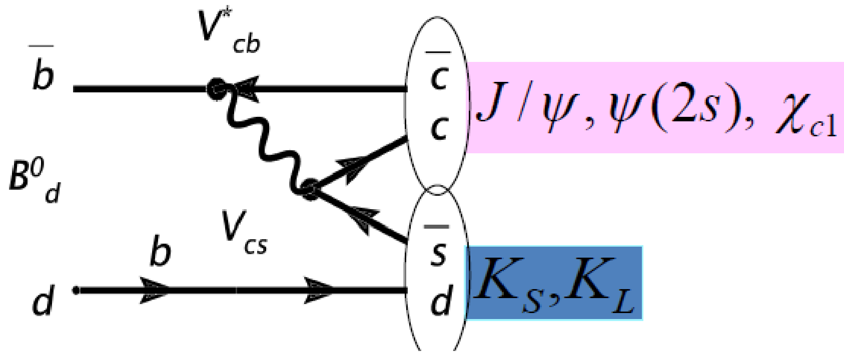
$$\textbf{if } |\beta| = 1$$

Orthogonality 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 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-$\overline{K}^0$ 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 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

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

T-inv. constraints

$$\Delta S_T^{\pm} = \Delta C_T^{\pm} = 0$$
$$\Delta S_{CP}^{\pm} = \Delta S_{CPT}^{\pm}$$
$$\Delta C_{CP}^{\pm} = \Delta C_{CPT}^{\pm}$$

- 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 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)

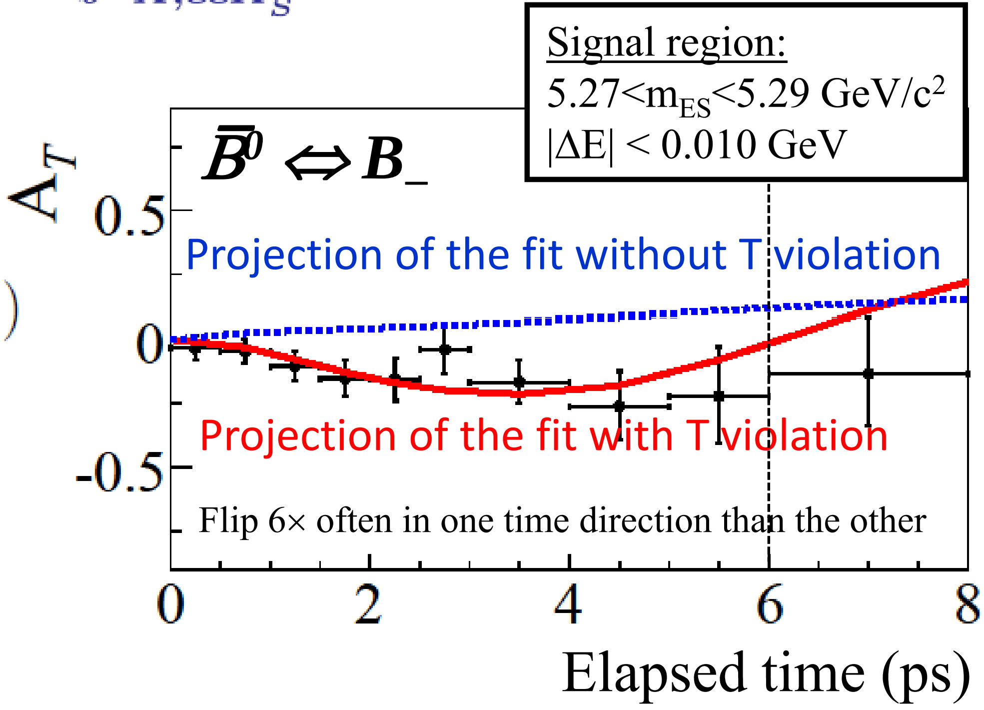
$$A_T(\Delta t) = \frac{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) - \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) + \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}$$

where

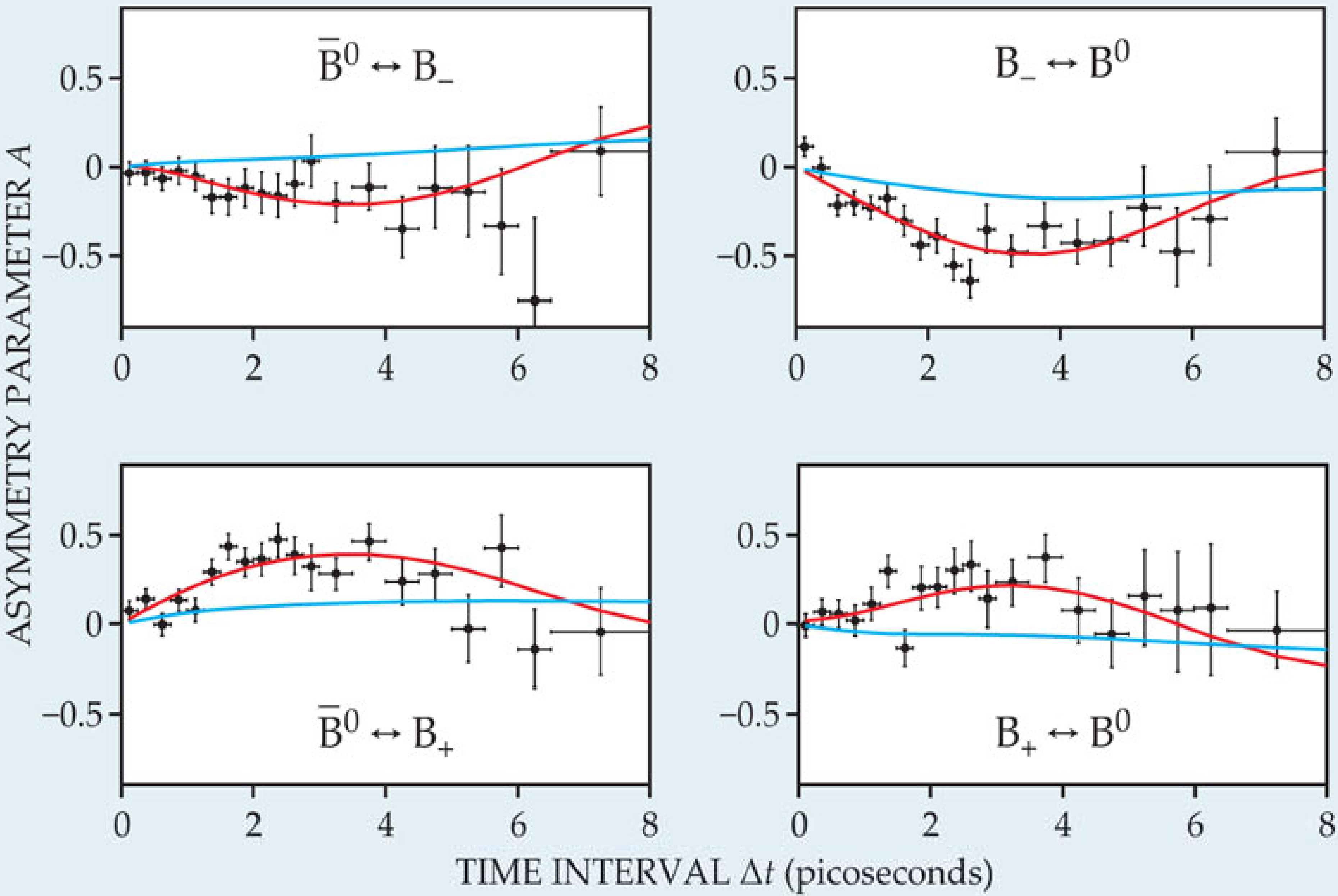
$$\mathcal{H}^{\pm}_{\alpha,\beta}(\Delta t) = \mathcal{H}_{\alpha,\beta}(\pm\Delta t) H(\Delta t)$$

- 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

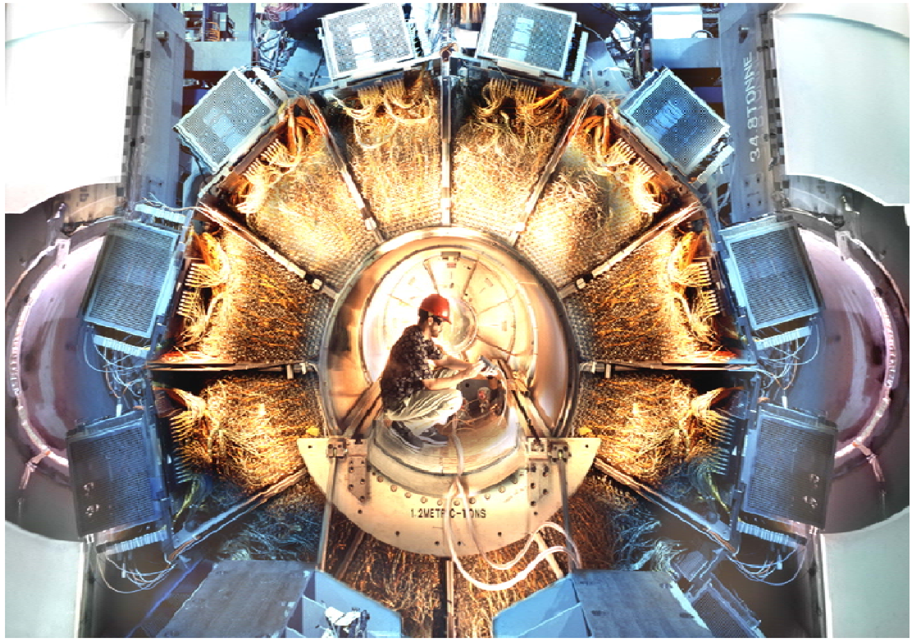


Summary

Summary

- BaBar has performed the first high significance (> 10σ) observation of large detailed balance breaking, through four different processes involving B meson states

$$\bar{B}^0 \Leftrightarrow B_- \qquad \bar{B}^0 \Leftrightarrow B_+$$
$$B_+ \Leftrightarrow B^0 \qquad B_- \Leftrightarrow B^0$$



- The observed breaking can uniquely be attributed to T non-invariance, without invoking CP violation or CPT invariance
- From these processes, non-zero T-violating parameters in the time evolution of neutral B mesons, arising from interference between mixing & decay, have been measured
- The results are consistent with CP-violating measurements obtained assuming CPT invariance
- They constitute direct observation of large T violation in the time evolution of any system, using processes related solely through time reversal


Thank you for your attention