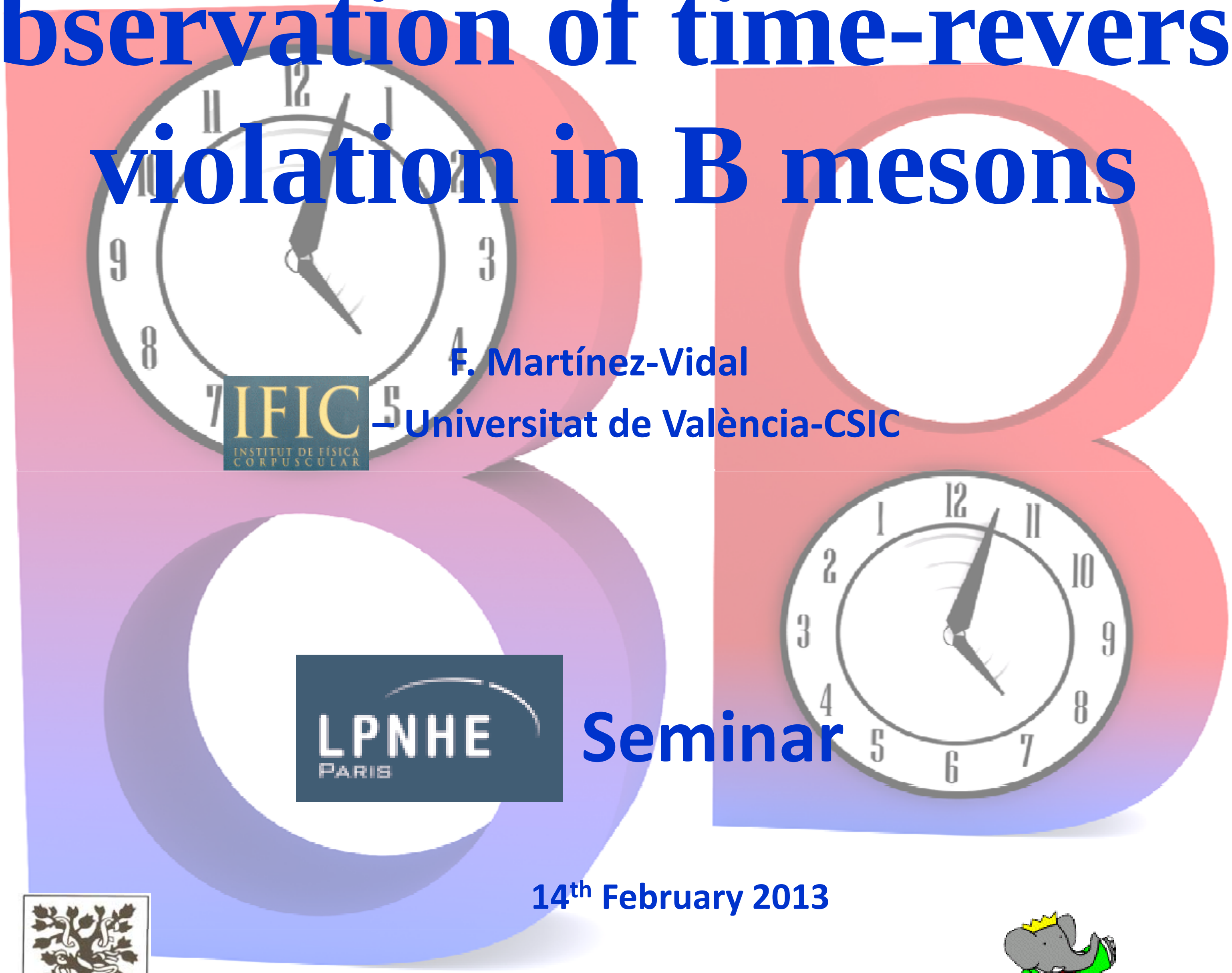
Observation of time-reversal violation in B mesons



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

LPNHE Paris Seminar

14th February 2013

Picture: 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

Physical Review Letters
moving physics forward

Physics 5, 129 (2012)

Viewpoint

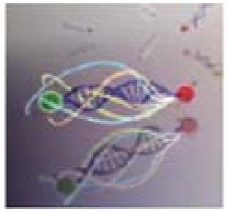
Particle Decays Point to an Arrow of Time

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

Published November 19, 2012

Physical Review Letters

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)]

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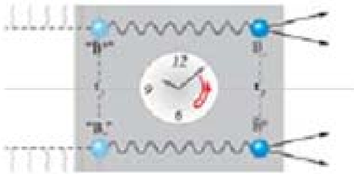
Physics: Particle Decays Point to an Arrow of Time

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)]

Read Article | More viewpoints

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

640 | NATURE | VOL 491 | 29 NOVEMBER 2012

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.

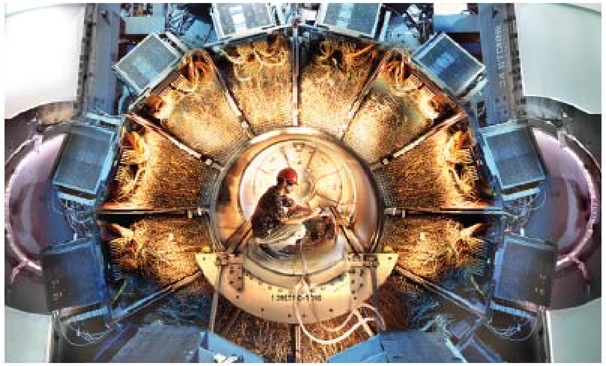
Sperm cells interacting with mutant *Arabidopsis* eggs that have faulty *ec1* genes failed to fuse, and the plant's pollen tubes continued to deliver sperm into the embryo sac. These results suggest that EC1 controls gamete fusion.

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

physics today

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

Bertram M. Schwarzschild

The Economist

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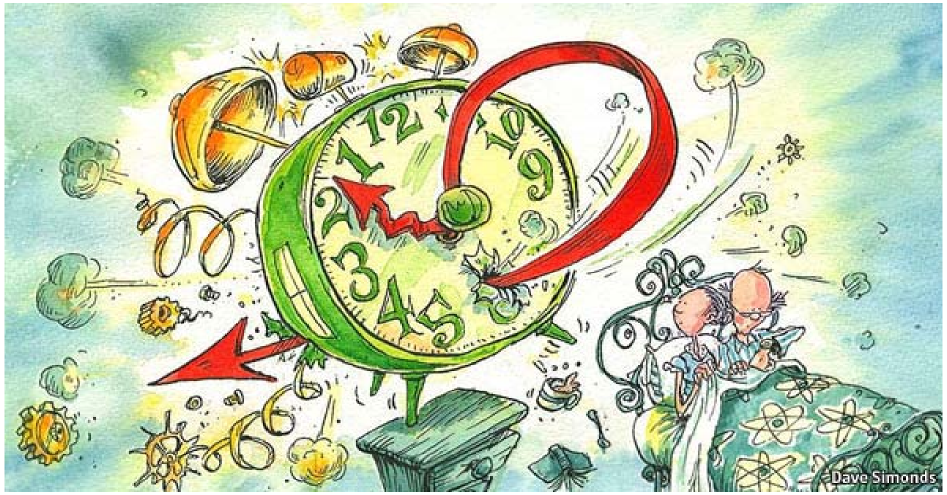
The arrow of time

Backward ran sentences...

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

Sep 1st 2012 | from the print edition



IOP A website from the Institute of Physics

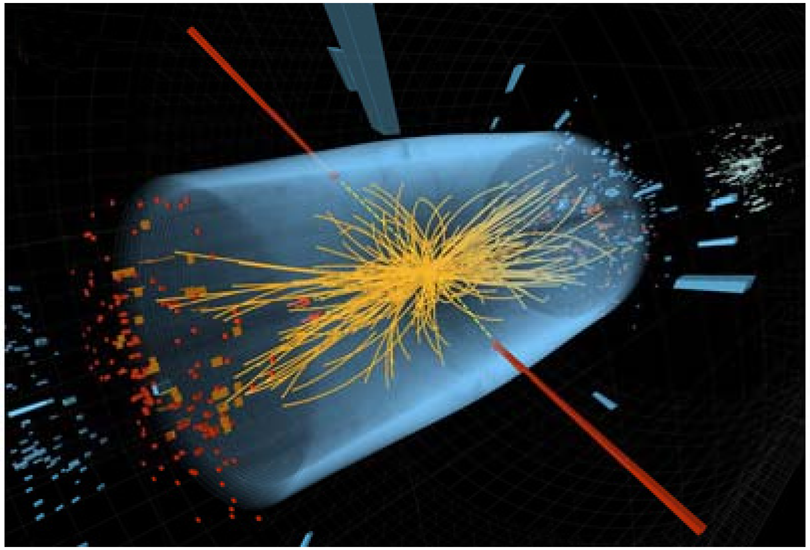
physicsworld.com

Physics World reveals its top 10 breakthroughs for 2012

Dec 14, 2012 11 comments

The *Physics World* award for the 2012 Breakthrough of the Year goes "to the ATLAS and CMS collaborations at CERN for their joint discovery of a Higgs-like particle at the Large Hadron Collider". Nine other research initiatives are highly commended and cover topics ranging from energy harvesting to precision cosmology

CERN discovers Higgs-like boson



One of many proton–proton collisions at CMS

Majorana fermions

"To Leo Kouwenhoven and colleagues at the Delft University of Technology and Eindhoven University of Technology for spotting the first evidence of the elusive Majorana fermion in a solid."

"Majorana fermions" are particles that are also their own antiparticles and were first proposed in 1937 by the Italian physicist Ettore Majorana. More recently, physicists have argued that Majorana-like quasiparticles could be lurking in materials with special topological properties. Now, Leo Kouwenhoven and colleagues have spotted the first hints of Majorana fermions at the interface between a topological superconductor and a semiconductor. Majorana fermions are expected to be impervious to environmental noise and therefore could prove useful in quantum computers.

Time-reversal violation

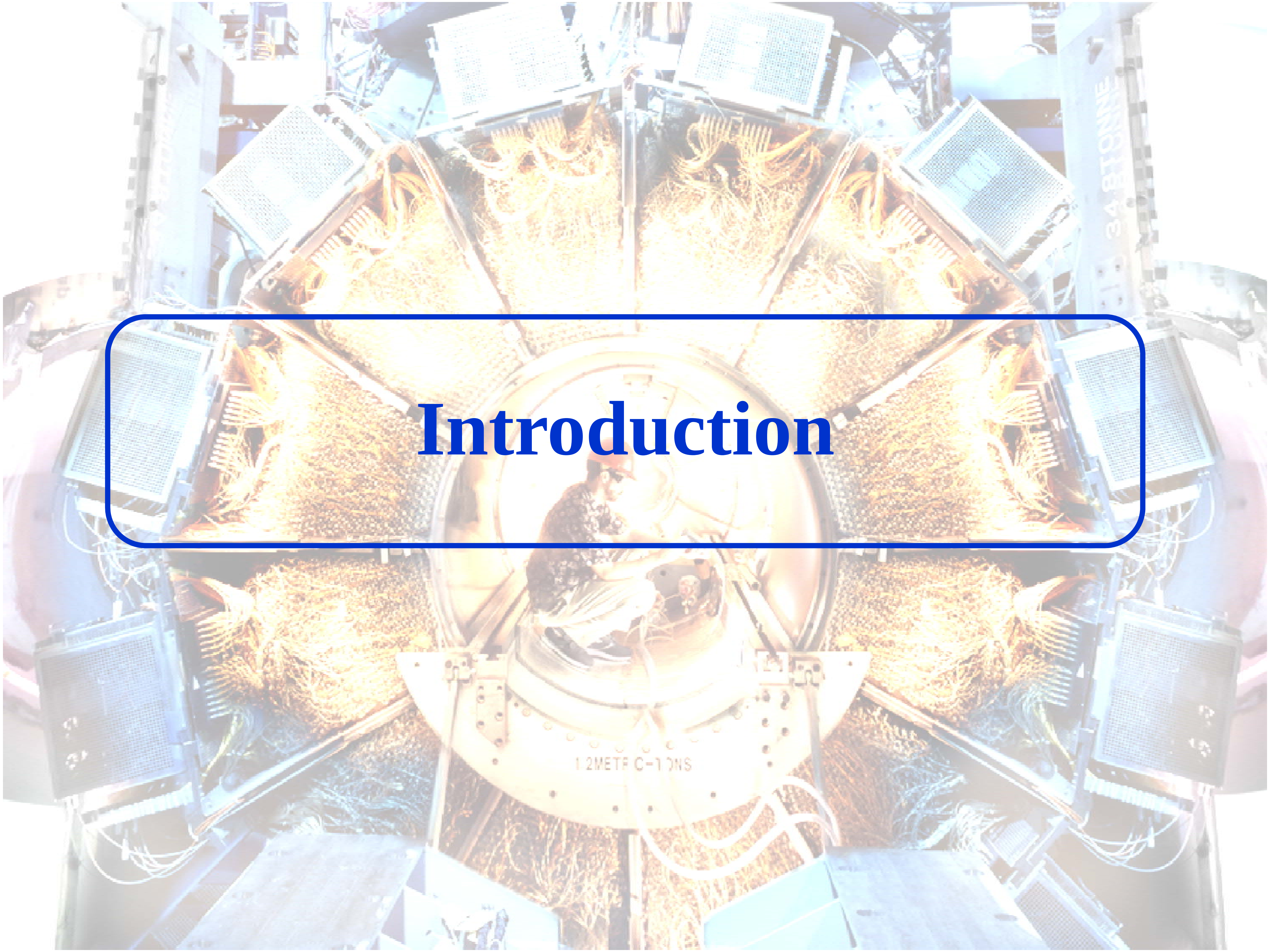
"To the BaBar collaboration for making the first direct observation of time-reversal violation by measuring the rates at which the B^0 meson changes quantum states."

Physicists have been waiting for almost 50 years for a direct observation of time-reversal (T) violation. Now, researchers analysing data obtained at the BaBar detector at the PEP-II facility at the SLAC National Accelerator Laboratory in California have done just that. The collaboration focused on transitions between the quantum states of the B^0 meson and found that the transition rates differed. While T-violation comes as no surprise, its direct experimental measurement is an important verification of quantum field theory.

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 → c+d) = P(c+d → 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 T asymmetry be directly observed, independently of CPV?

From complex *t* to fundamental T

- 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 "<u>arrow of time</u>"

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

The TIME'S ARROW is a property of ENTROPY alone
The ARROW OF TIME is NOT TIME REVERSAL VIOLATION

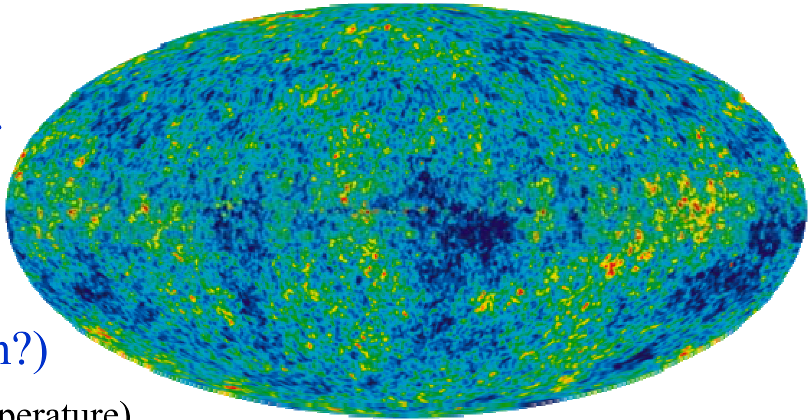
- How it is then possible to generate irreversibility from fundamental laws that are $t \to -t$ symmetric?
- T.D. Lee proposed the following example:
  - ✓ 1000 cars (particles) with fuel for 1000 km, departing from Paris in all directions
  - ✓ Single rule (fundamental law): <u>Drive straight away and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

From complex *t* to fundamental T (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
    - o "Highly difficult" to setup the initial conditions for reversed process matching the final condition of the original one
    - o "Random" nature of fundamental processes
  - ✓ Better to buy another one…

- Macroscopic *t* asymmetry is likely connected with the **Universe *t* asymmetry**
  - ✓ The Universe is expanding and accelerating

    $t \to -t$ asymmetry
  - ✓ Compatible with fundamental *t* symmetry of General Relativity (Lorentz symmetry)
  - ✓ Due to the initial (more ordered, less probable) condition of our Universe (inflation?)



Consistent with uniform average (same temperature) and its fluctuations in the CMB radiation map

From complex *t* to fundamental T (cont'd)

- In particle physics, decays are an example of time asymmetric process
  - ✓ Mismatch between $P \rightarrow 1+\ldots+n$ and $1+\ldots+n \rightarrow P$
  - ✓ It seems to prevent a fundamental test of T symmetry in unstable systems, just those where CP symmetry is known to be broken…

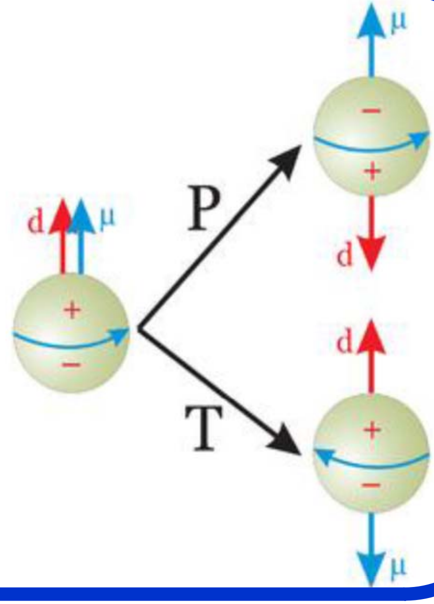
Alice: I simply must get through!
Doorknob: Sorry, you're much too big. Simply impassible.
Alice: You mean impossible?
Doorknob: No, impassible. Nothing's impossible.

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)

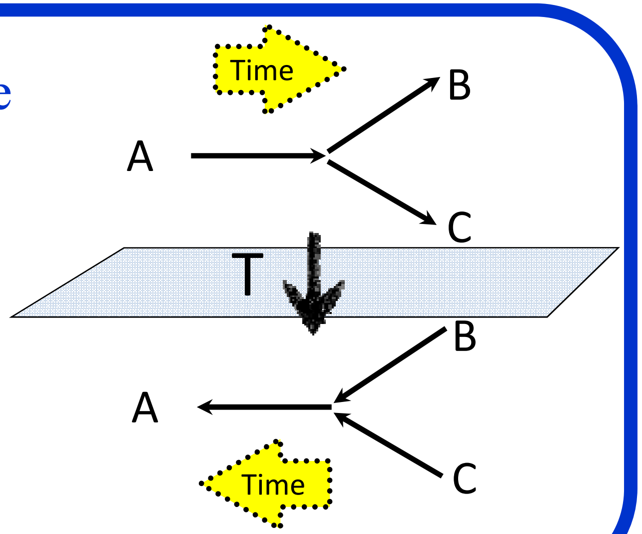
- ✓ Also violates parity, P
- ✓ EDM of the neutron or electron: PDGLive.org

  $d_n < 2.9 \times 10^{-26}$ 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
- ✓ <u>With stable particles</u>: $\nu_e \to \nu_\mu$ vs. $\nu_\mu \to \nu_e$ but needs future facility with a long baseline
- ➢ <u>With unstable particles</u>: 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

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

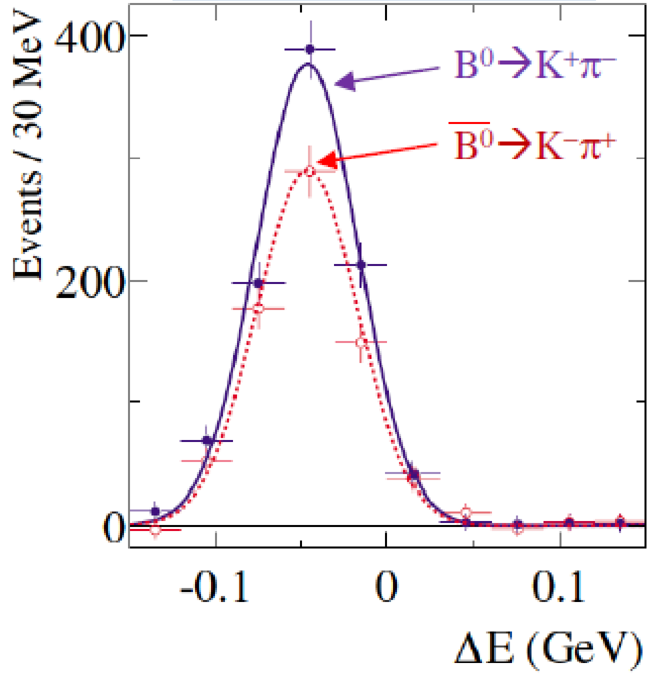
$$|A(\overline{B}^0 \to K^-\pi^+)|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos(-\Delta\varphi_{\text{weak}} + \Delta\delta_{\text{strong}})$$

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

  - ✓ 

  - ✓ Can we observe Kπ → B ?

PRL93, 131801 (2004)



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)

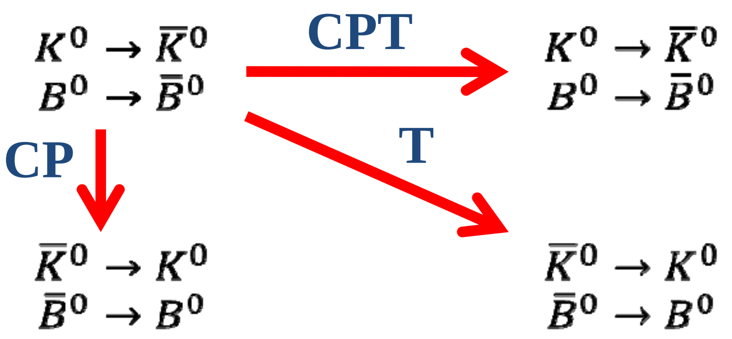
⇒ Impossible rather than "merely" unfeasible.

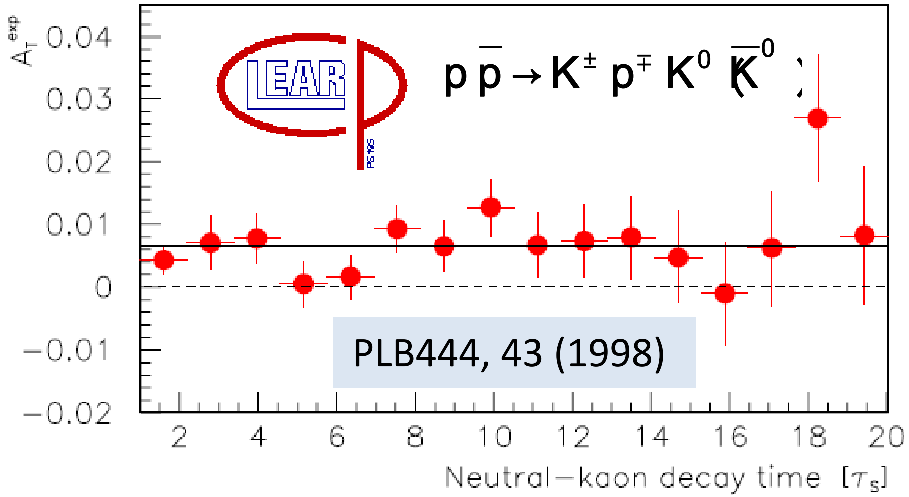
T violation in unstable systems (cont'd)

- Compare a → b vs. b → a in mixing processes

Kabir, PRD2, 540 (1970)

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





  - ✓ 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 at LEAR
  - ✓ 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

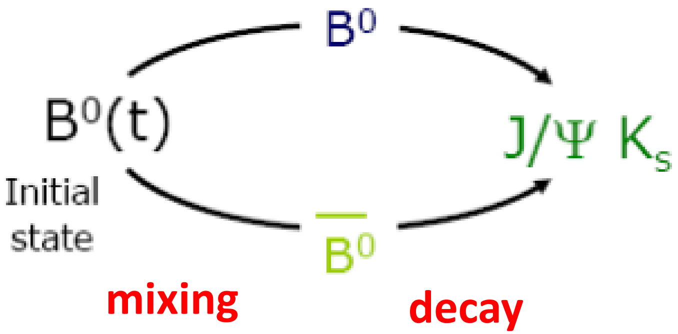
Gerber, Eur. Phys. Jour. C 35, 195 (2004)

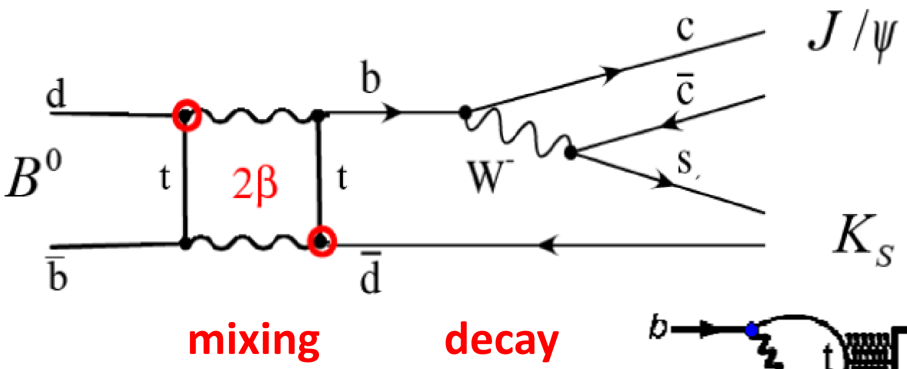
Alvarez-Gaume et al, Phys. Lett. B 458 (1999)

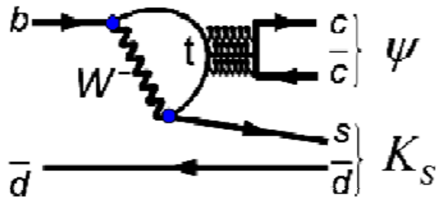
Wolfenstein, Int. Jour. Mod. Phys. E8, 501 (1999)

Test s of Conservation Laws, PDG, 2012

- 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 $\bar{B}^0 \to J/\Psi K_{S/L}$ ($\bar{b} \to \bar{c}c\bar{s}$) 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

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

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

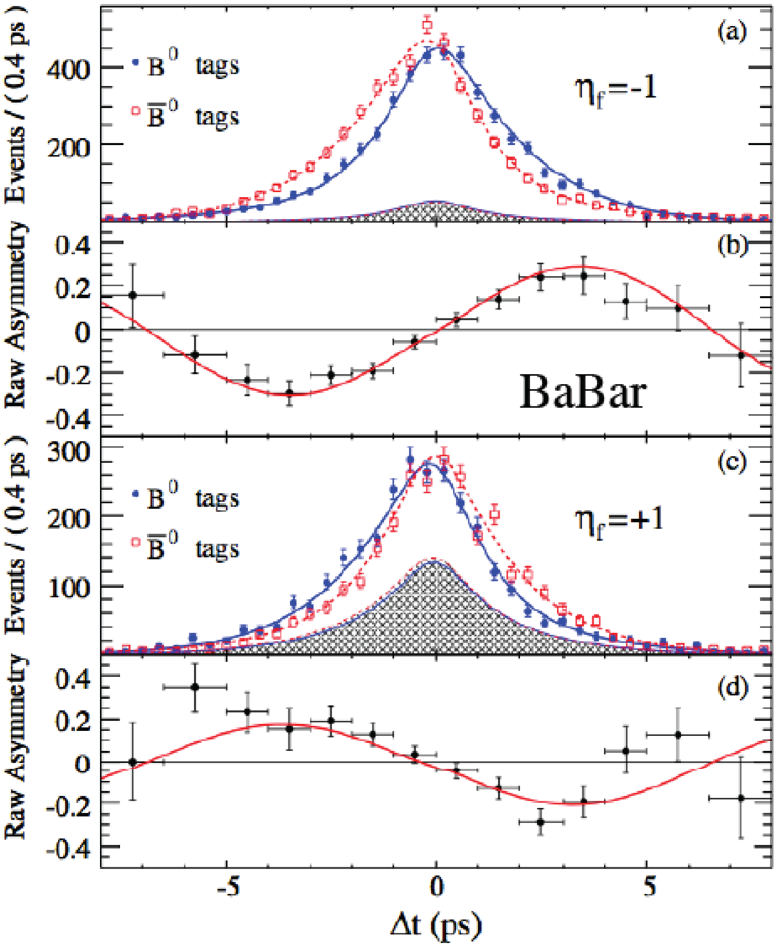
Within the SM and CKM:

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

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* ⇔ *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

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

- ✓ 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 $B\bar{B}$ 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 $t_2 > t_1$

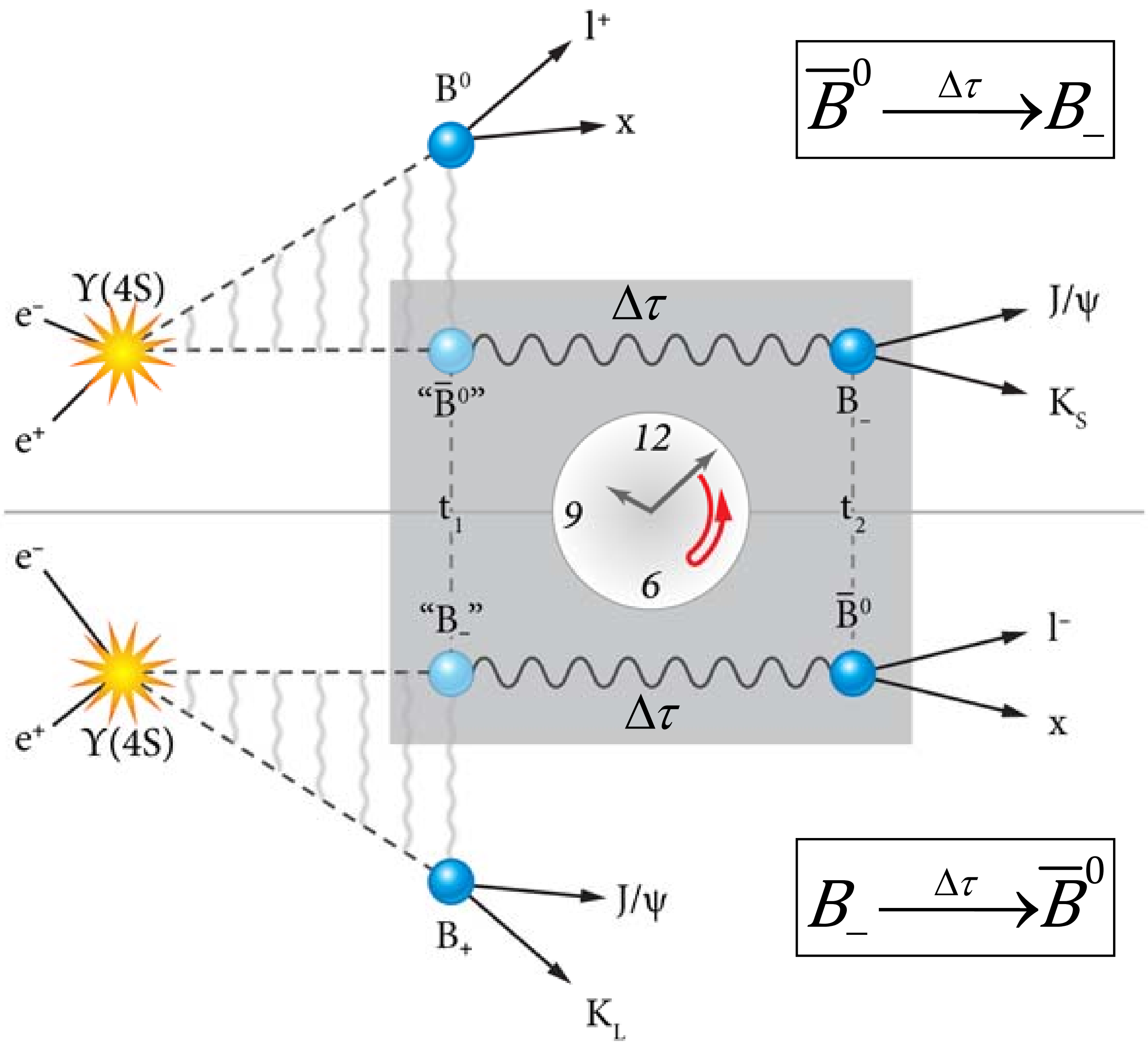
Flavor tag: e.g. B semileptonic decay to $l^+ X$ ($l^- X$) projects B^0 ($\bar{B}^0$) ⇒ $\bar{B}^0$ (B^0) tag

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)

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

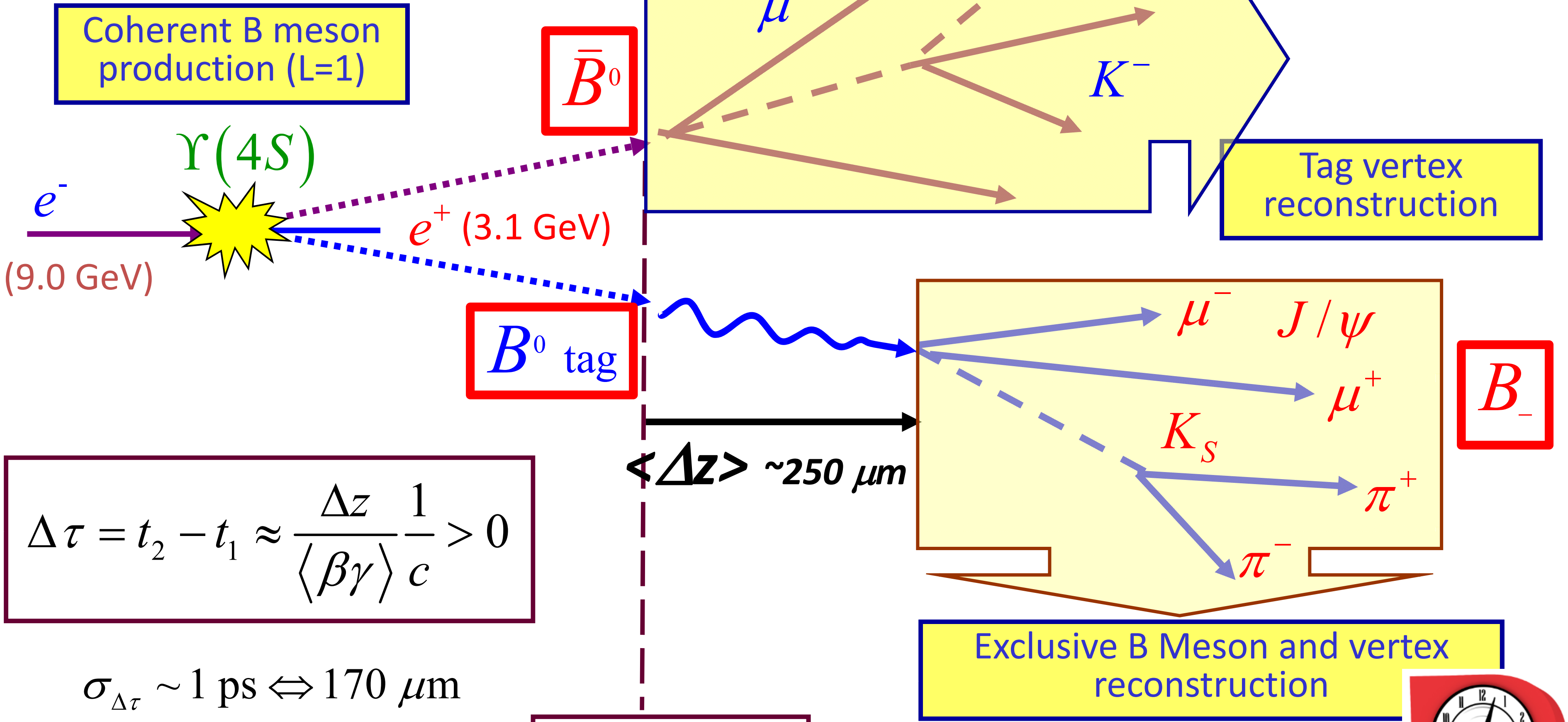


T mirror

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

T violation: experimental strategy at a B factory

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



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

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

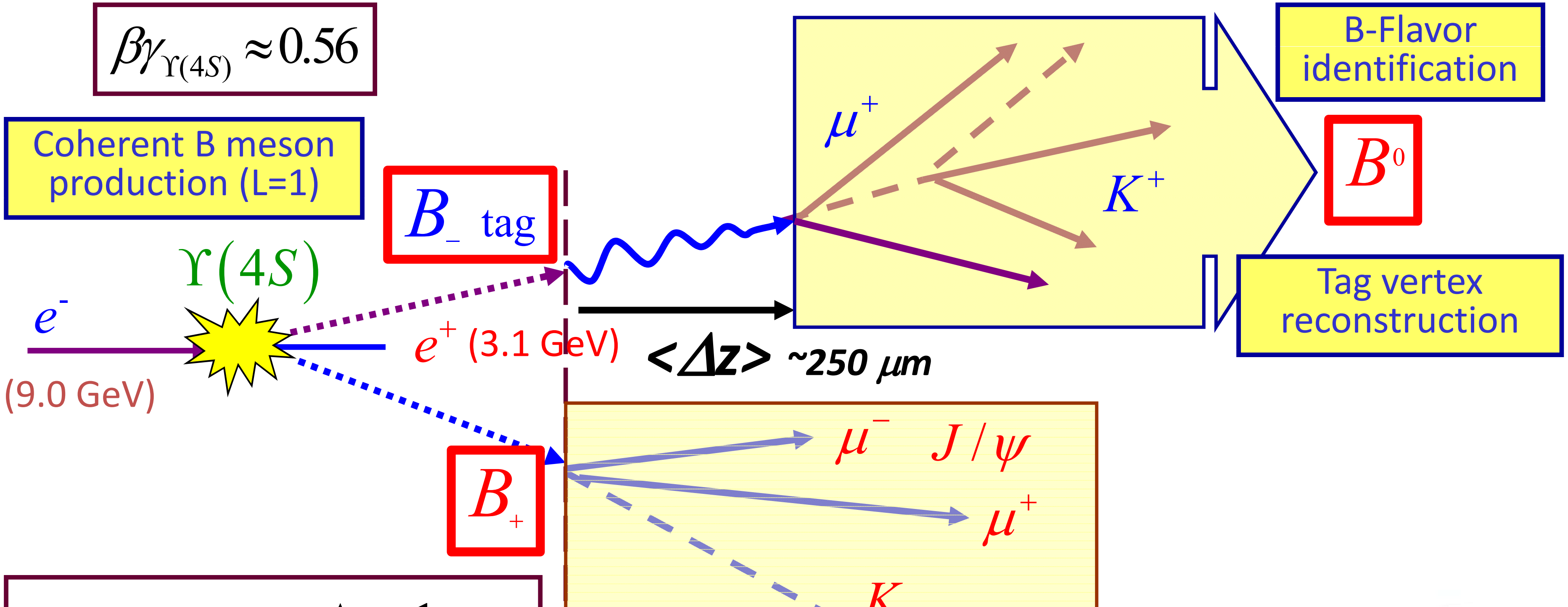
$$B^0 \xrightarrow{\Delta\tau} B_-$$

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

- ✓ calibrate tagging
- ✓ measure Δz resolution

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

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



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

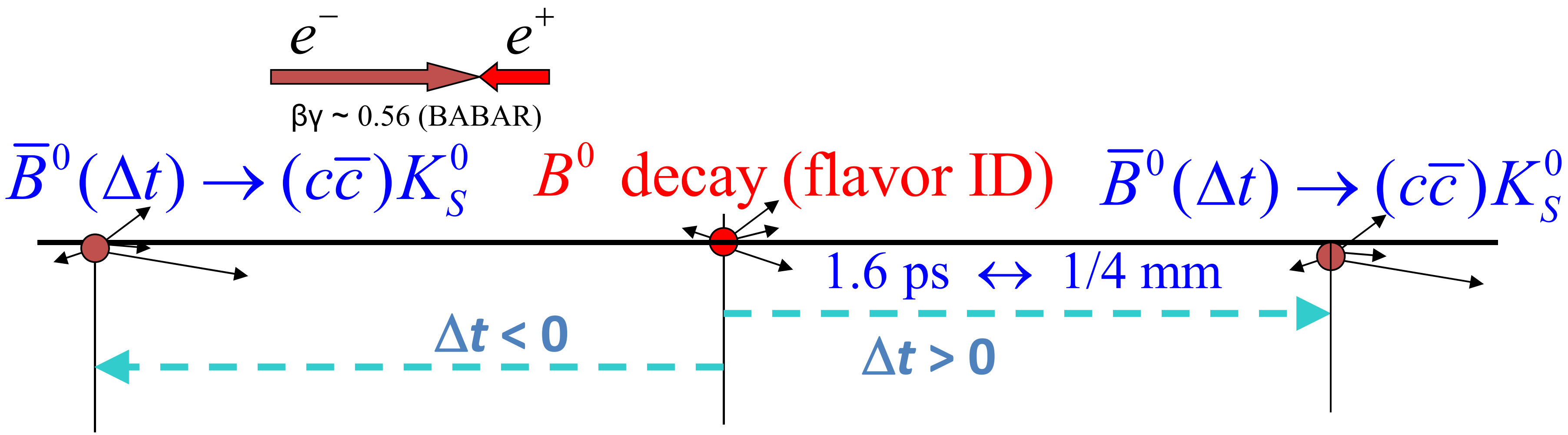
$$\sigma_{\Delta\tau} \sim 1 \text{ ps} \Leftrightarrow 170\ \mu\text{m}$$

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

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)



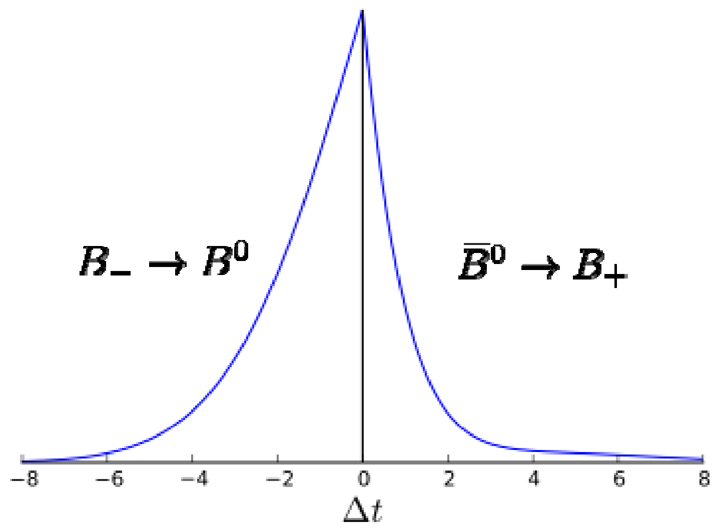
- ✓ At B factories, we define

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

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

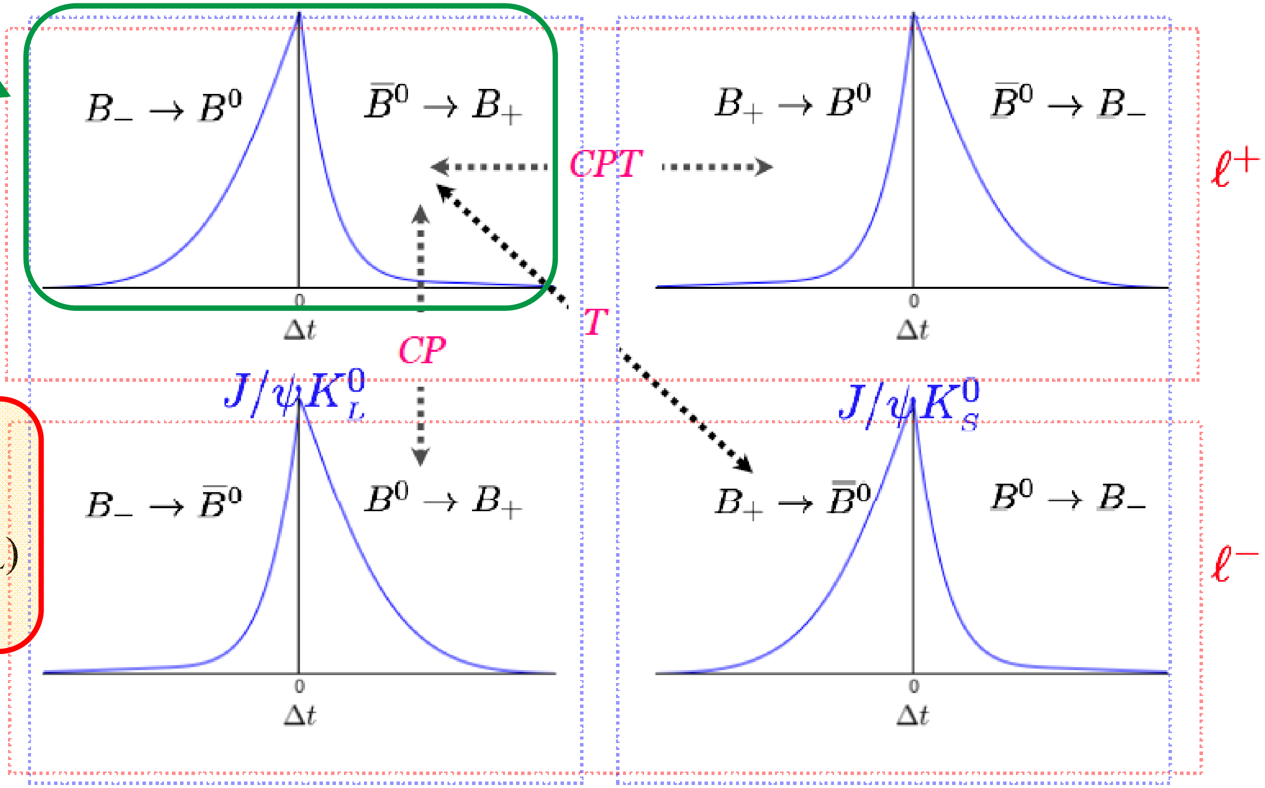
JHEP08 (2012) 064

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 ΔS± and ΔC±

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 ΔΓ=0

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

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

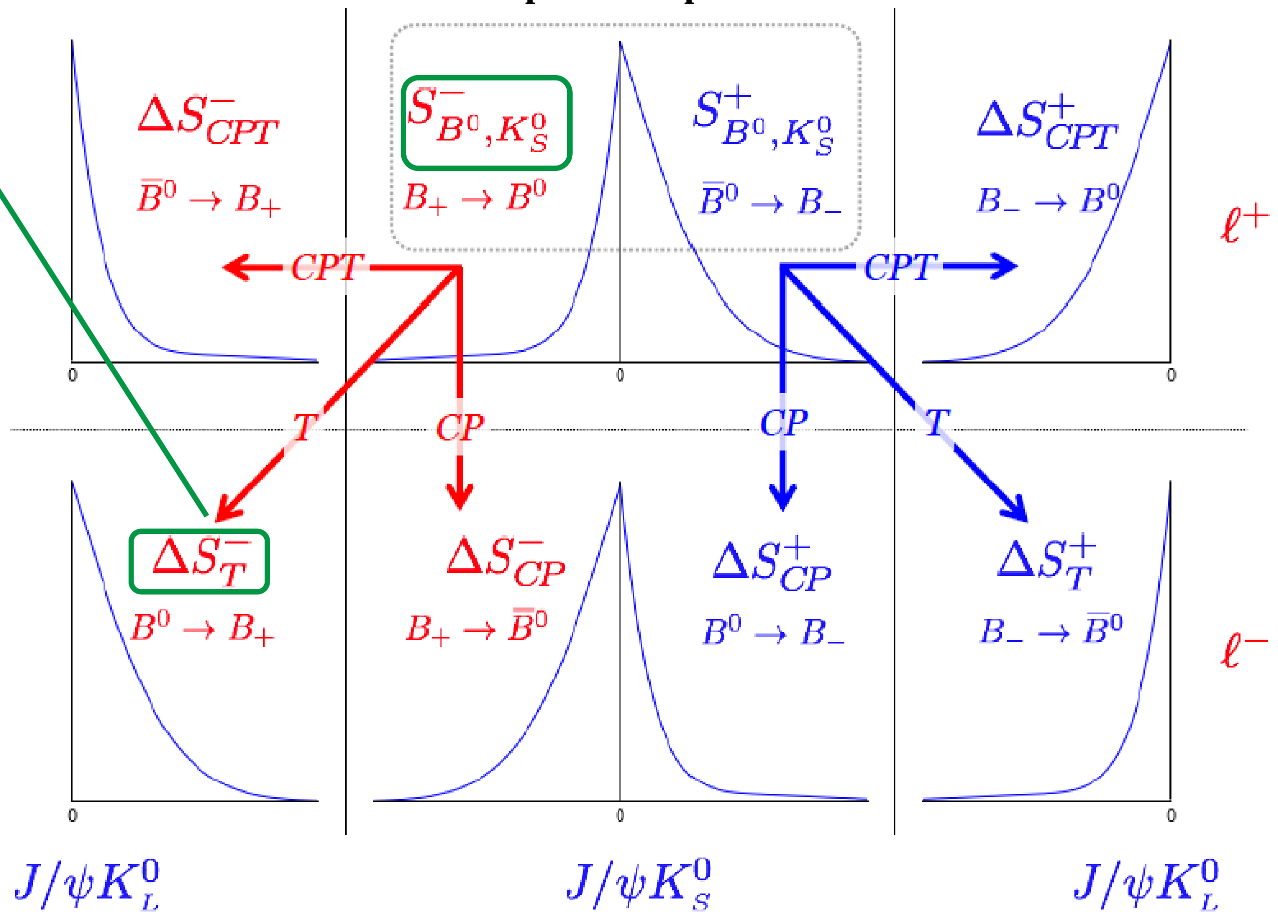
Parameter	≈
$\Delta S^+_{\mathrm{T}} = S^-_{\ell^-,K_L} - S^+_{\ell^+,K_S}$	−1.4
$\Delta S^-_{\mathrm{T}} = S^+_{\ell^-,K_L} - S^-_{\ell^+,K_S}$	1.4
$\Delta C^+_{\mathrm{T}} = C^-_{\ell^-,K_L} - C^+_{\ell^+,K_S}$	0.0
$\Delta C^-_{\mathrm{T}} = C^+_{\ell^-,K_L} - C^-_{\ell^+,K_S}$	0.0
$\Delta S^+_{\mathrm{CP}}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

For T violation

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

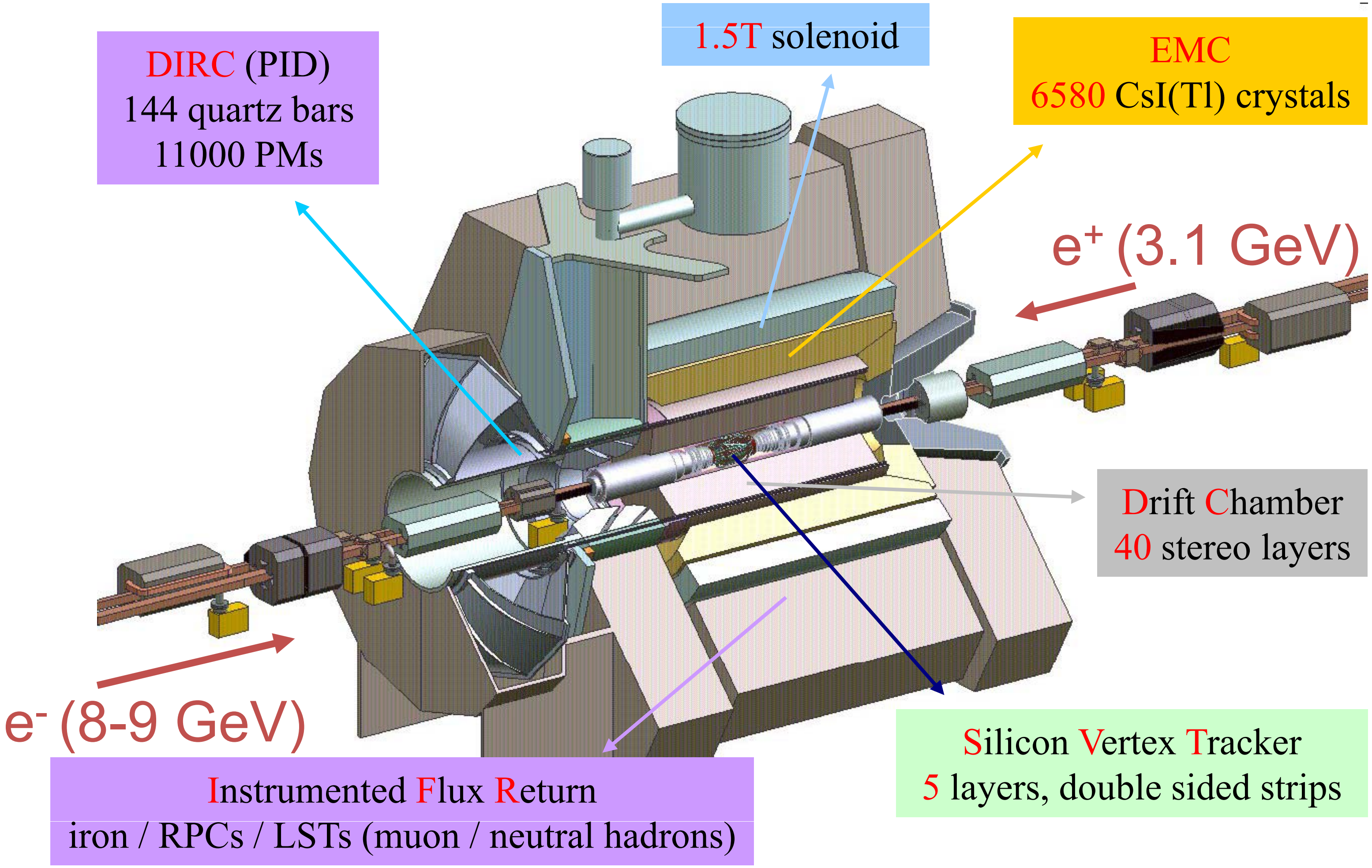
In decay $\Delta C^+_{\mathrm{T}} \neq 0$, $\Delta C^-_{\mathrm{T}} \neq 0$

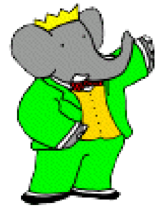
Reference processes/parameters



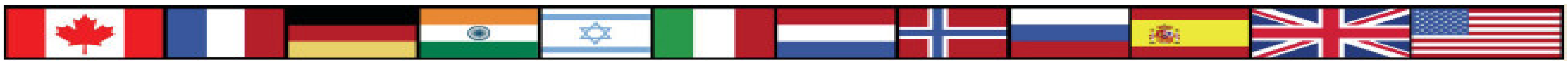
BaBar detector, data sample and fitting strategy

The BaBar detector



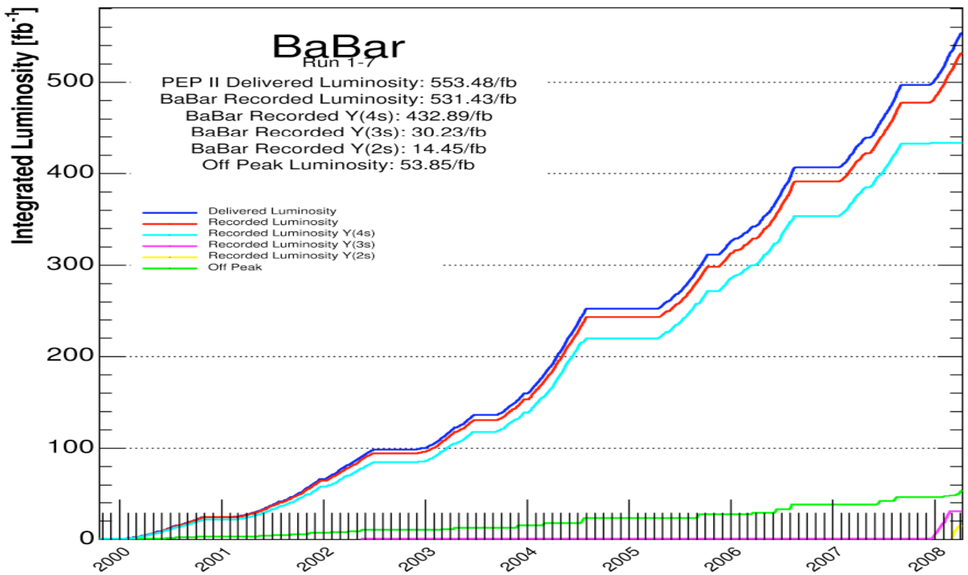


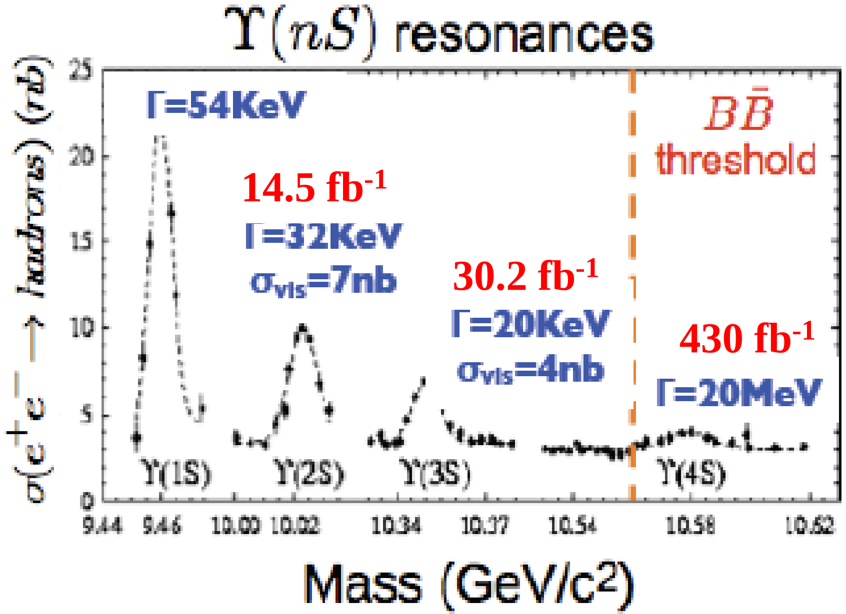
- Asymmetric B-factory at SLAC (DOE, Stanford): E_{cms} = 10.58 GeV $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L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



BaBar data set

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





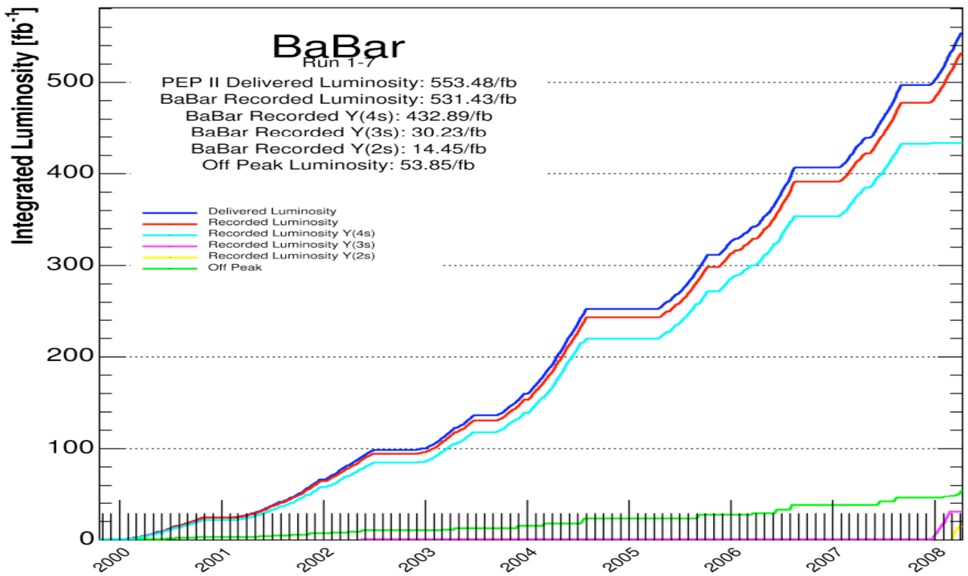
54 fb^{-1} Off-ϒ(nS)
4 fb^{-1} above ϒ(4S)

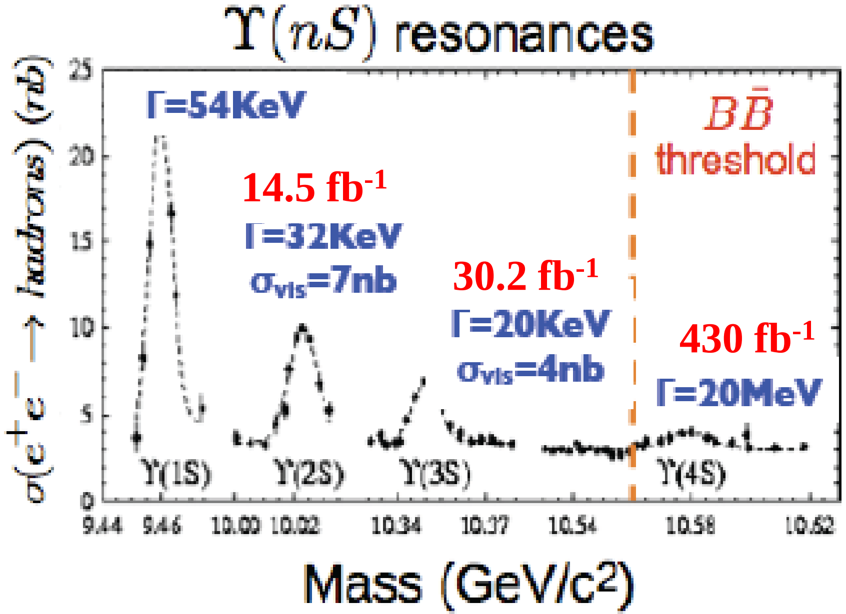
Final collisions 12:43pm, Monday 7 Apr 2008

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

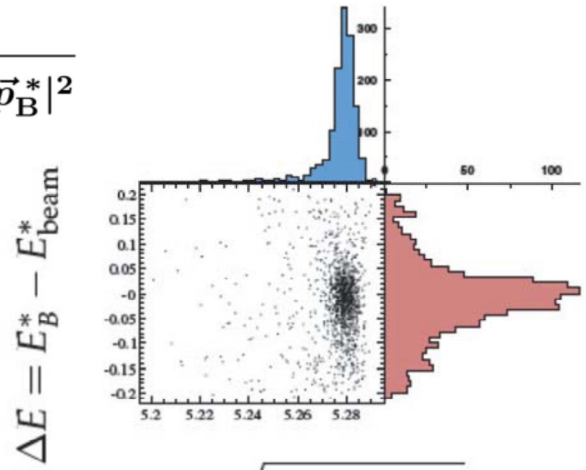
- ≈ 470×10^6 $B\bar{B}$ (0.5×Belle)
- ≈ 690×10^6 $c\bar{c}$
- ≈ 500×10^6 $\tau^+\tau^-$
- ≈ 121×10^6 ϒ(3S) (7×Belle+Cleo)
- ≈ 99×10^6 ϒ(2S) (0.5×Belle+Cleo)

Signal and backgrounds

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

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

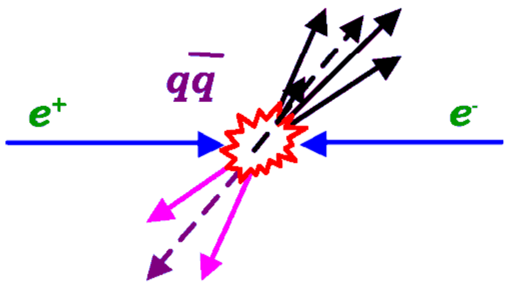
    $\sigma_{\Delta E} \sim \sigma_{E^*_B} \approx 10-50\ \mathrm{MeV}$
  - ✓ Energy difference $\Delta E = E^*_B - E^*_{\mathrm{beam}}$
  - ✓ Choose best B candidates based on masses of daughters

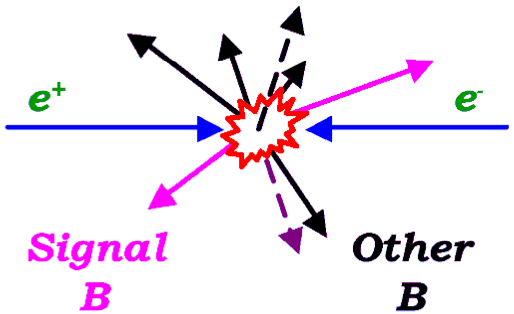


$m_{\mathrm{ES}} = \sqrt{E^*_{\mathrm{beam}} - p^{*2}_B}$

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

- 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

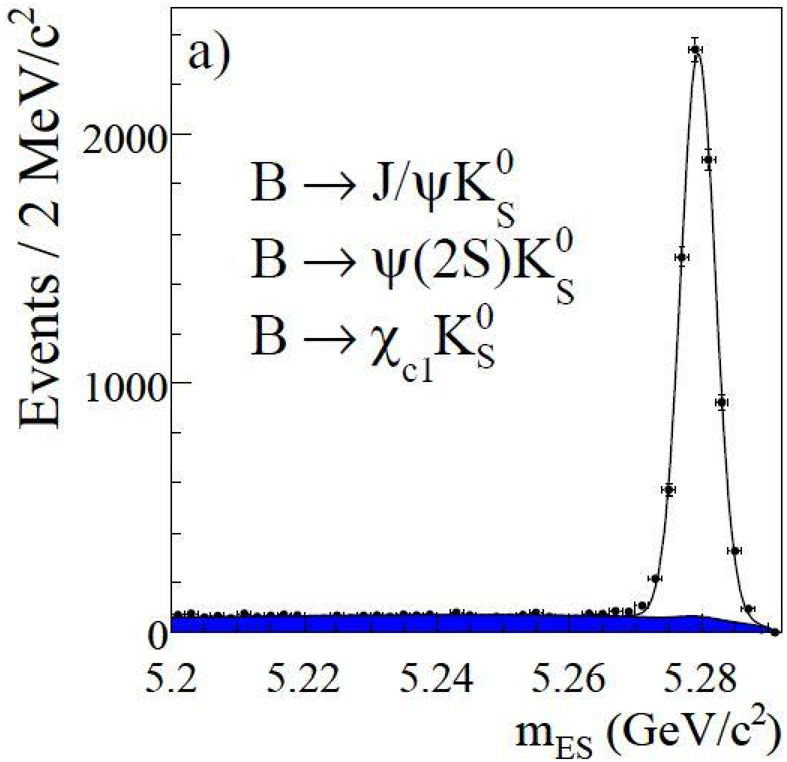




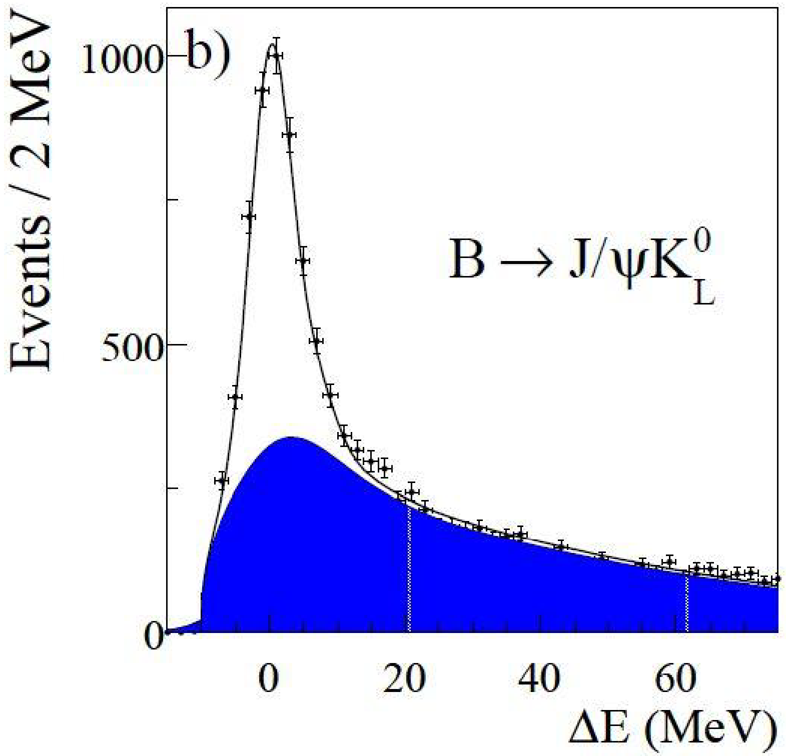
m_{ES} and ΔE for the signal sample

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)



7796 events, purity 87–96%



5813 events, purity ≈ 56%

Fitting strategy

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

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

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

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

Flavor tagged events (+)

$$+$$

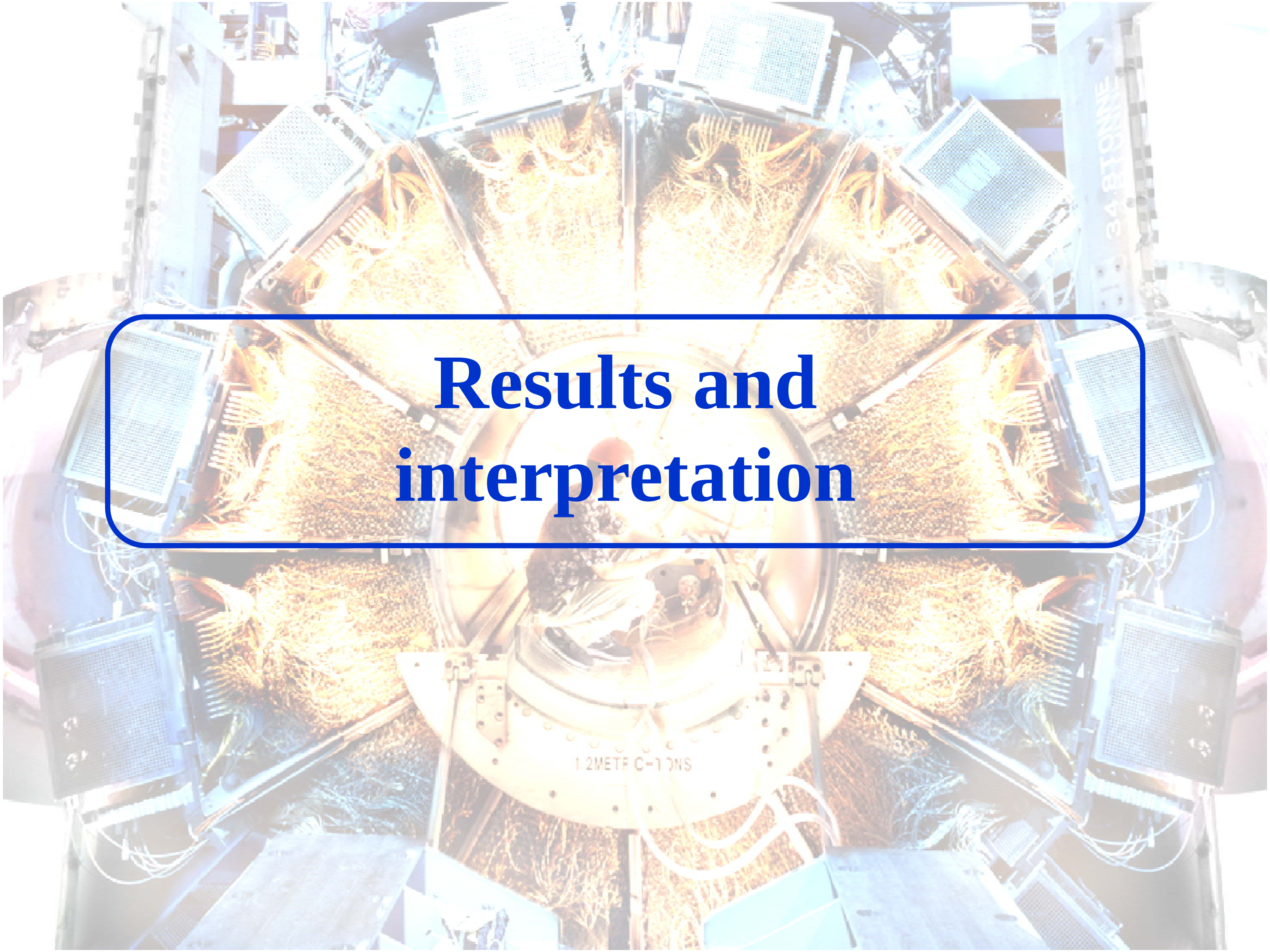
$$g^{-}_{\alpha,\beta}(-\Delta t_{true}) \times \mathrm{H}(-\Delta t_{true}) \otimes \Re(\delta t; \sigma_{\Delta t})$$

CP tagged events (–)

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

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

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

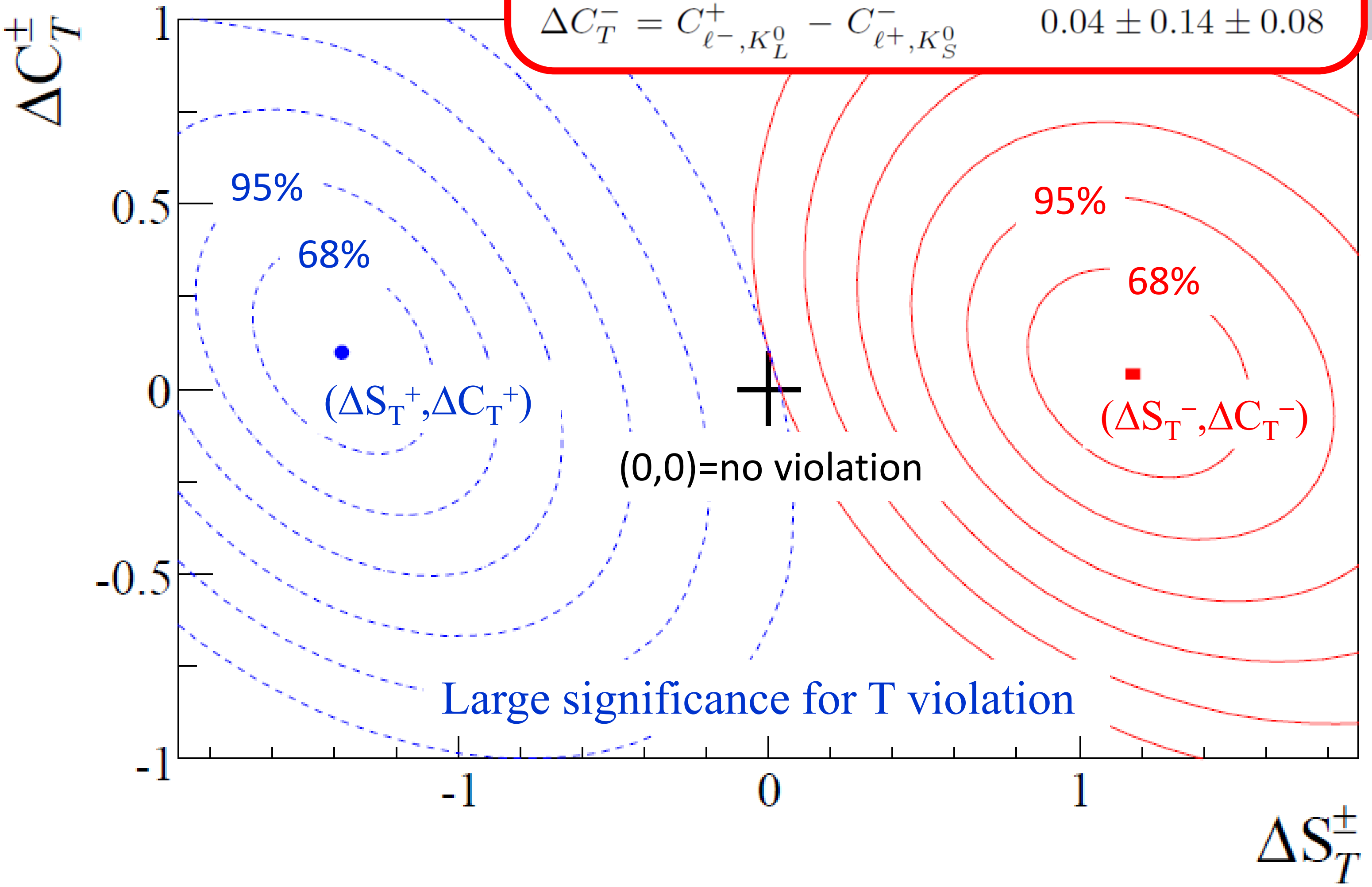


Results and interpretation

Results

T-violating parameters

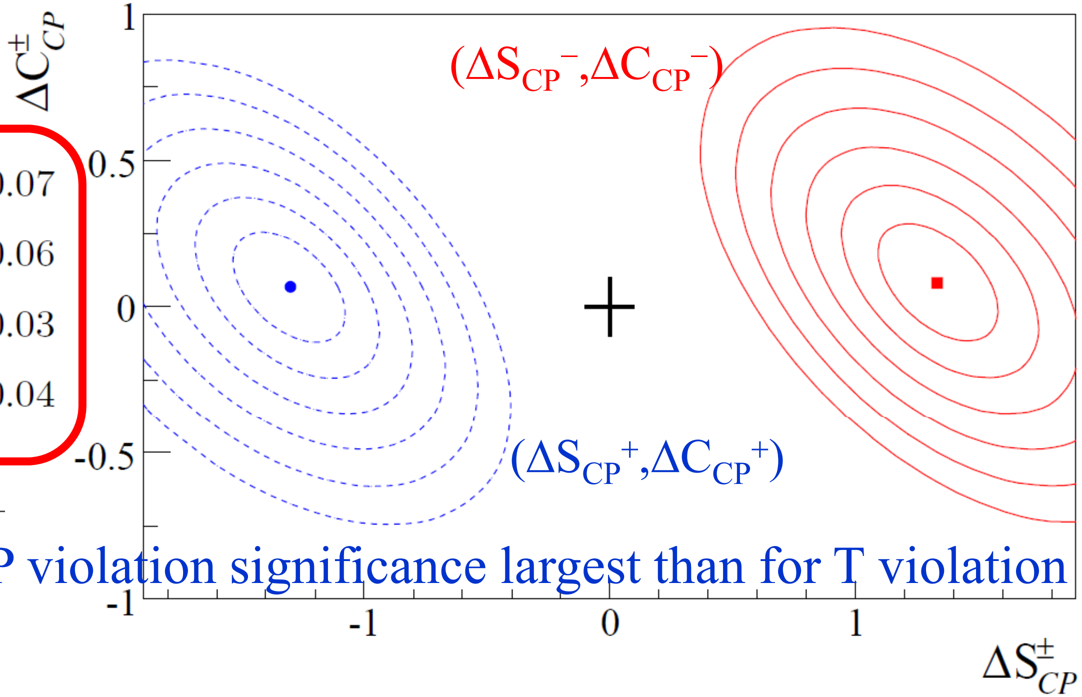
		expectation from canonical *CP*
$\Delta S_T^+ = S^-_{\ell^-,K_L^0} - S^+_{\ell^+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$	$-2\sin 2\beta$
$\Delta S_T^- = S^+_{\ell^-,K_L^0} - S^-_{\ell^+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$	$+2\sin 2\beta$
$\Delta C_T^+ = C^-_{\ell^-,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.10 \pm 0.14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



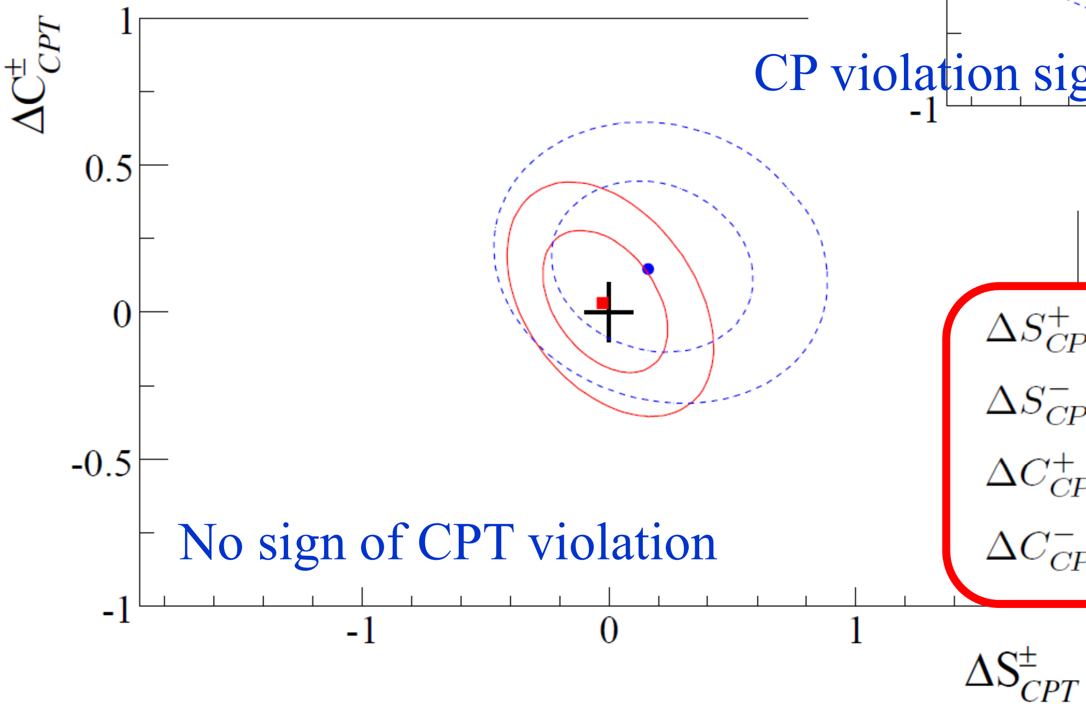
Results (cont'd)

CP-violating parameters

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



CP violation significance largest than for T violation



No sign of CPT violation

CPT-violating parameters

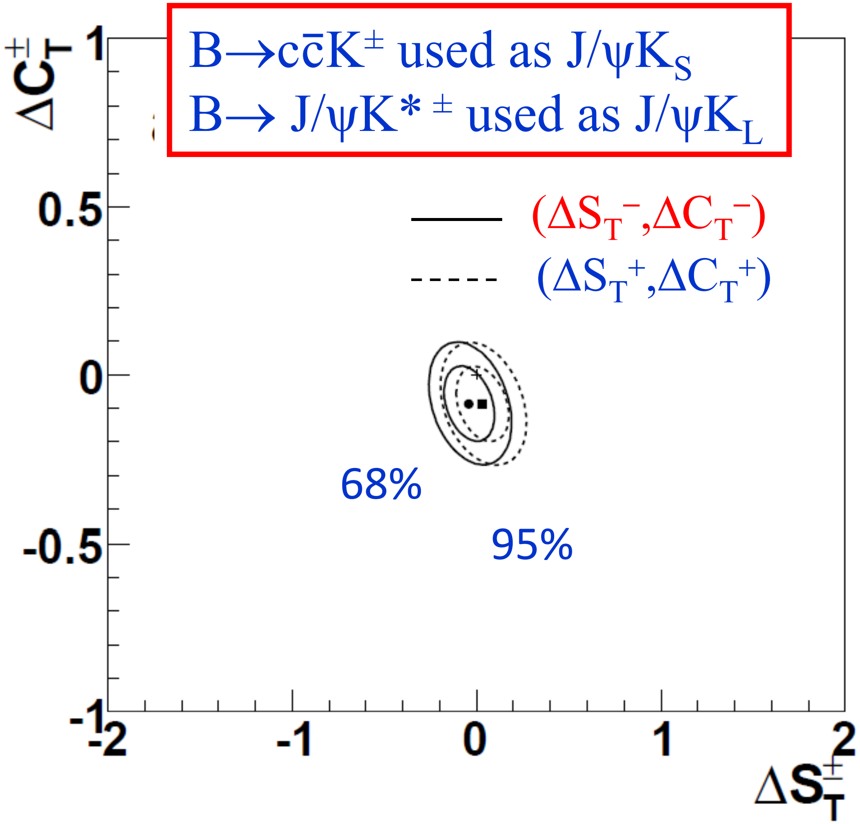
ΔS^{+}_{CPT}	$= S^{-}_{\ell+,K^0_L} - S^{+}_{\ell+,K^0_S}$	$0.16 \pm 0.21 \pm 0.09$
ΔS^{-}_{CPT}	$= S^{+}_{\ell+,K^0_L} - S^{-}_{\ell+,K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$
ΔC^{+}_{CPT}	$= C^{-}_{\ell+,K^0_L} - C^{+}_{\ell+,K^0_S}$	$0.14 \pm 0.15 \pm 0.07$
ΔC^{-}_{CPT}	$= C^{+}_{\ell+,K^0_L} - C^{-}_{\ell+,K^0_S}$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

Observed T violation as due to compensate CP violation

Cross checks

- Study using simulation data shows asymmetry parameters $\Delta S^{\pm}_{T}$, $\Delta C^{\pm}_{T}$ are unbiased and have Gaussian errors
- Studies of data segmented by running period or flavor 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

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

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

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

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

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

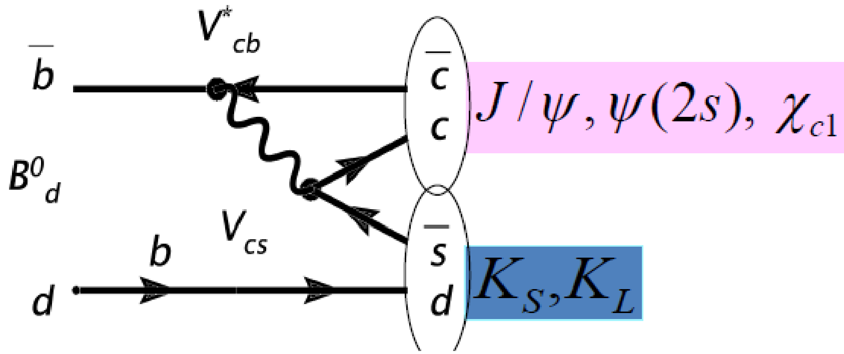
$$\text{if } |\beta| = 1$$

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

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

T-inv. constraints

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

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

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

- 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)

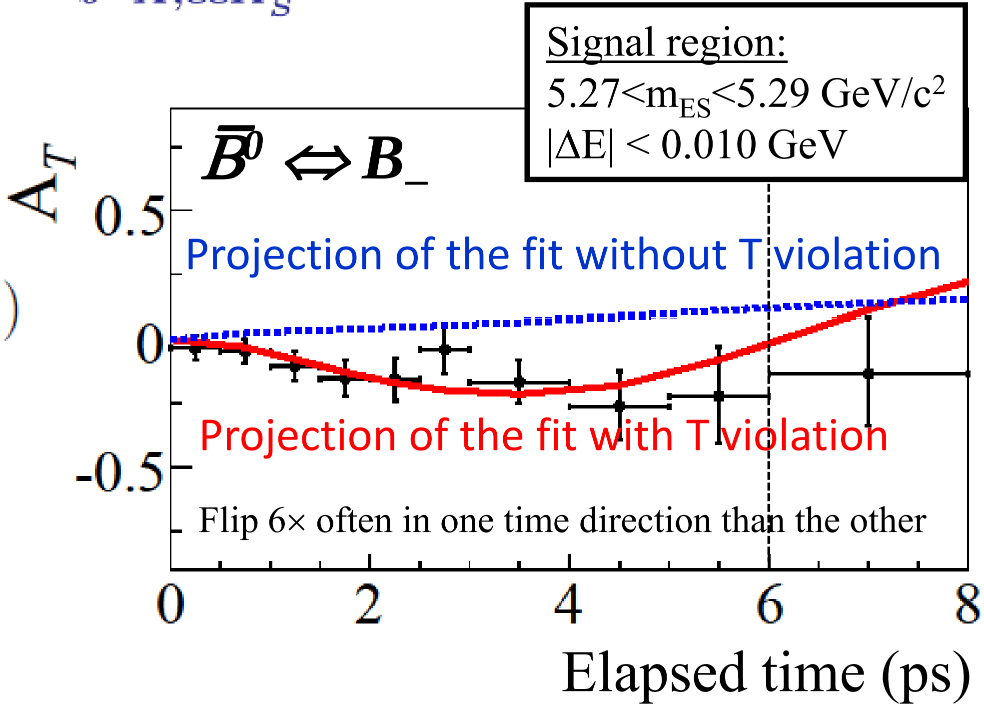
$$A_T(\Delta t) = \frac{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) - \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}{\mathcal{H}^-_{\ell^- X, J/\psi K^0_L}(\Delta t) + \mathcal{H}^+_{\ell^+ X, c\bar{c}K^0_S}(\Delta t)}$$

where

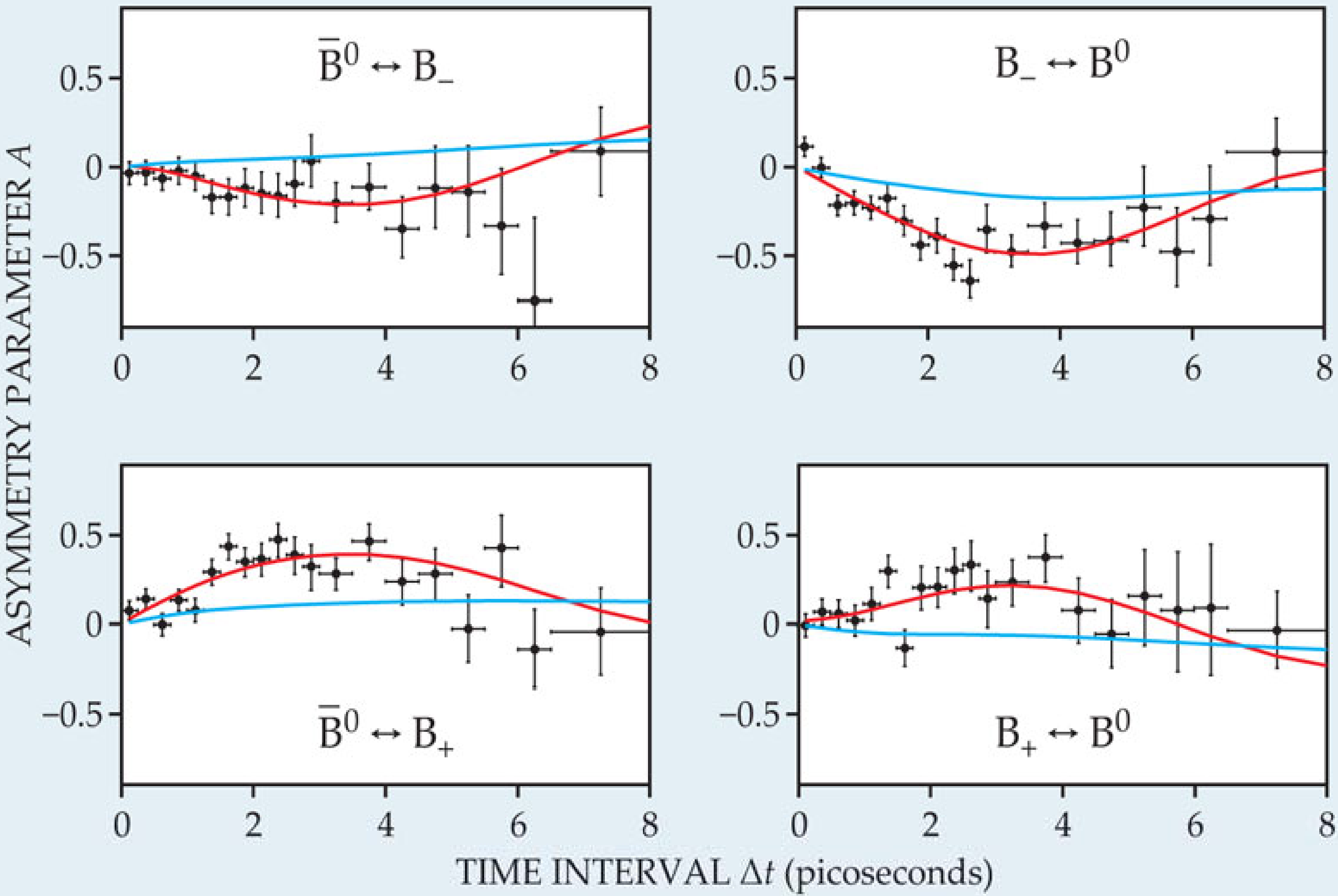
$$\mathcal{H}^\pm_{\alpha,\beta}(\Delta t) = \mathcal{H}_{\alpha,\beta}(\pm\Delta t) H(\Delta t)$$

- For perfect reconstruction, is

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

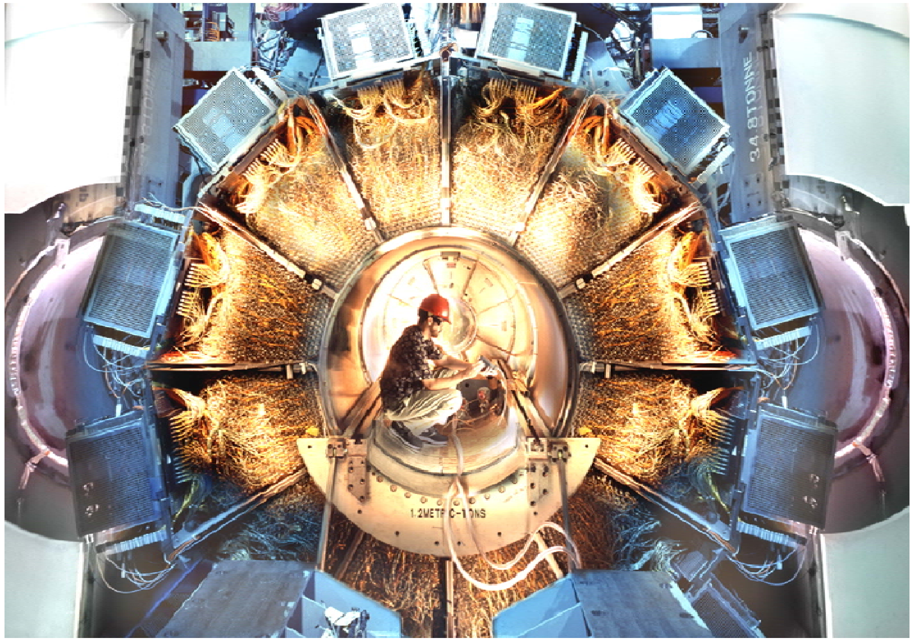


The four independent T asymmetries



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