Direct Measurement of Time-Reversal Asymmetry at *BABAR*

Chih-hsiang Cheng
Caltech

on behalf of BABAR Collaboration

Brookhaven Forum
BNL, 2013/05/01–03

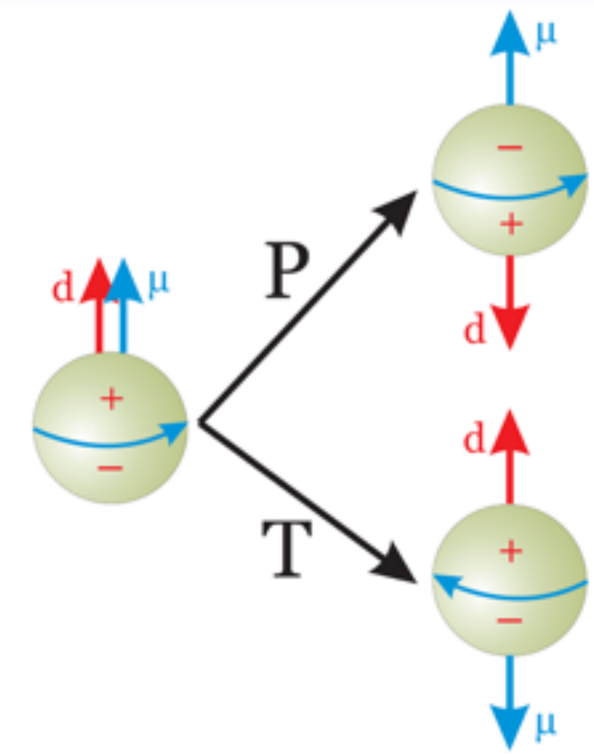
Time-reversal symmetry

- Laws of physics have an intrinsic, microscopic $t \to -t$ symmetry *if* they are
  - ✦ invariant under reversal of motion ($\boldsymbol{v} \to -\boldsymbol{v}$, exchange of in and out states),
  - ✦ balanced in detail: $P(\mathrm{a+b} \to \mathrm{c+d}) = P(\mathrm{c+d} \to \mathrm{a+b})$.

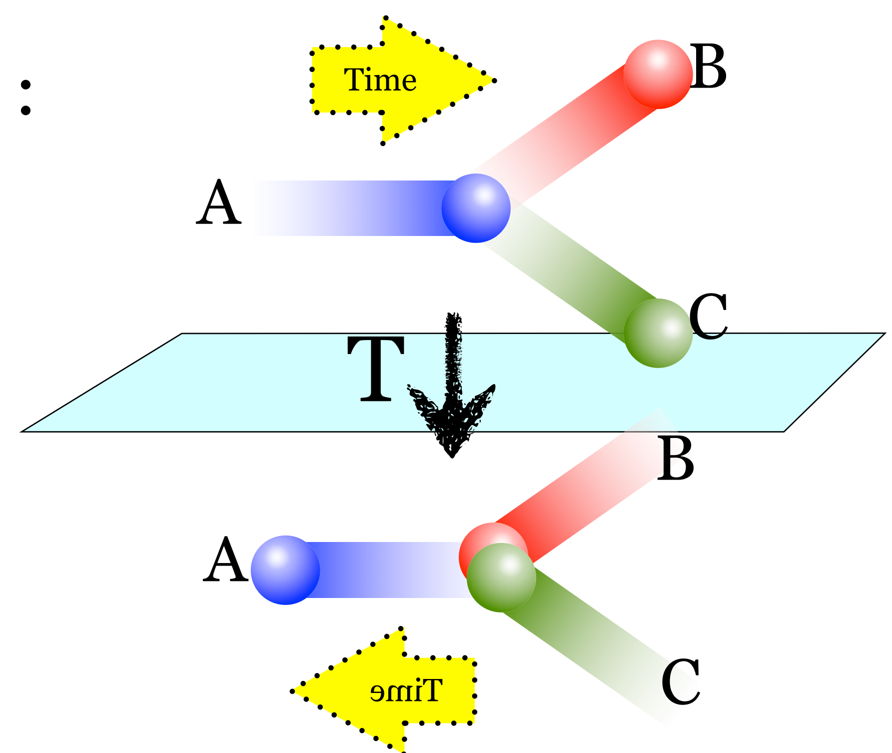
- It is *not* about the arrow of time
  - ✦ *T* asymmetry of a macroscopic state
  - ✦ nature of thermodynamics

Scenarios of time-reversal violation

- A permanent electric dipole moment (EDM) of a particle (with a spin) violates *T*-reversal symmetry (as well as parity). No evidence has been observed yet.



- Difference in time-reversed processes: $P(|i\rangle \rightarrow |f\rangle)$ vs. $P(|f\rangle \rightarrow |i\rangle)$
  - ✦ $\nu_e \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_e$: stable system, but needs future facility with a long baseline.
  - ✦ $|i\rangle \rightarrow |\text{decay product}\rangle$ vs. $|\text{decay product}\rangle \rightarrow |i\rangle$: unstable system, often very difficult to prepare the initial state of time-reversed process.

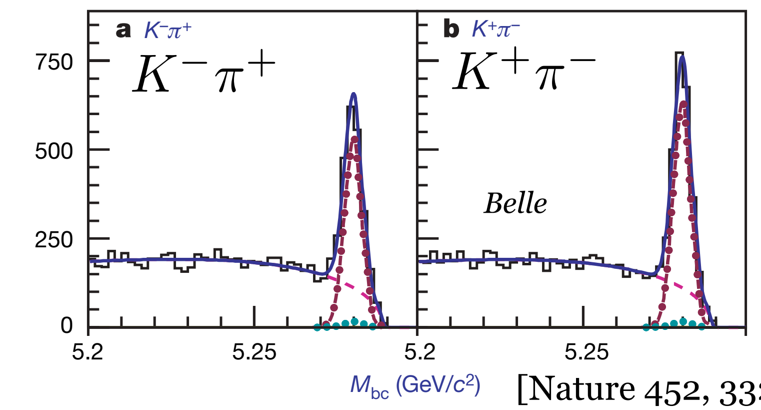


- Assume *CPT* invariance, observing *CP* asymmetry indicates *T* violation.
  - ✦ *CP* violation is established in neutral kaon and bottom mesons.

T violation in meson decays

- Can we search for T violation in known CP-violating processes?
  - ✦ Search in decay

CP $\left\{ \begin{array}{l} B^0 \to K^+\pi^-, \mathrm{R}_1 \\ \bar{B}^0 \to K^-\pi^+, \mathrm{R}_2 \end{array} \right.$ ⟷ CPT ⟷ $\left\{ \begin{array}{l} K^-\pi^+ \to \bar{B}^0, \mathrm{R}_1 \\ K^+\pi^- \to B^0, \mathrm{R}_2 \end{array} \right.$

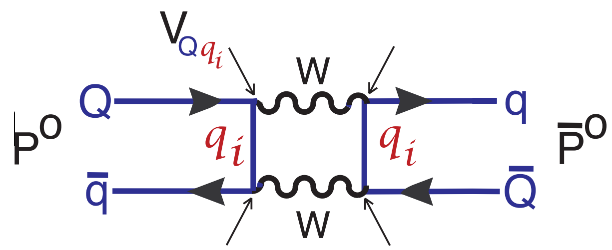


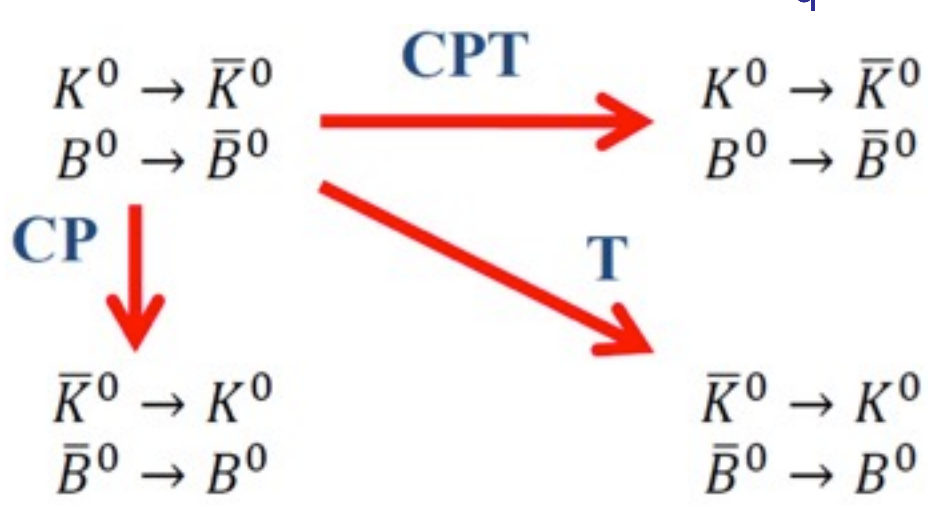
[Nature 452, 332]

Unable to perform the T test:

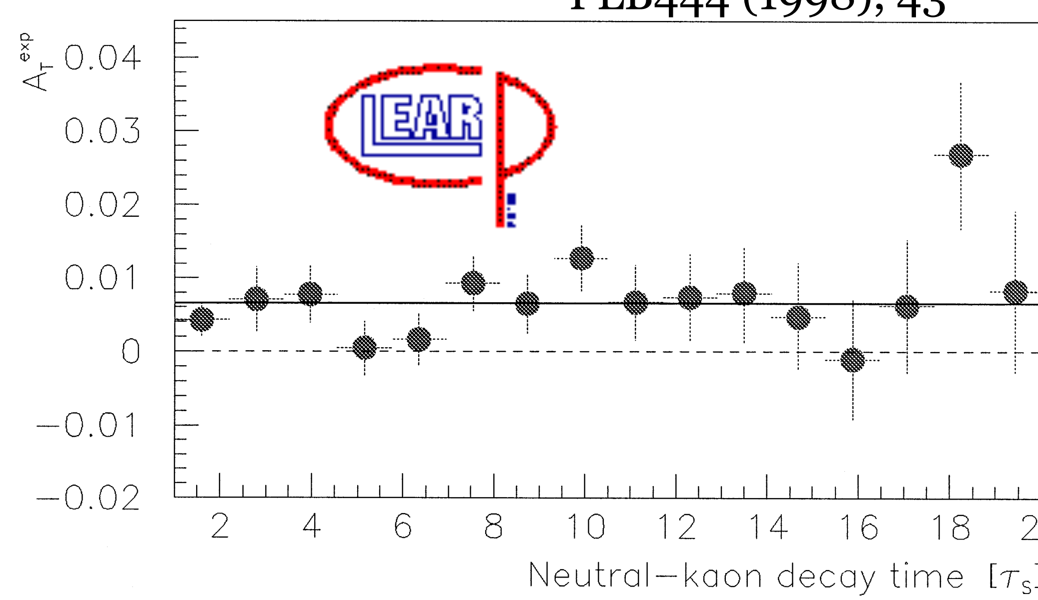
- Preparation of the initial state.
- The strong processes will swamp the feeble weak processes.

  - ✦ Search in mixing





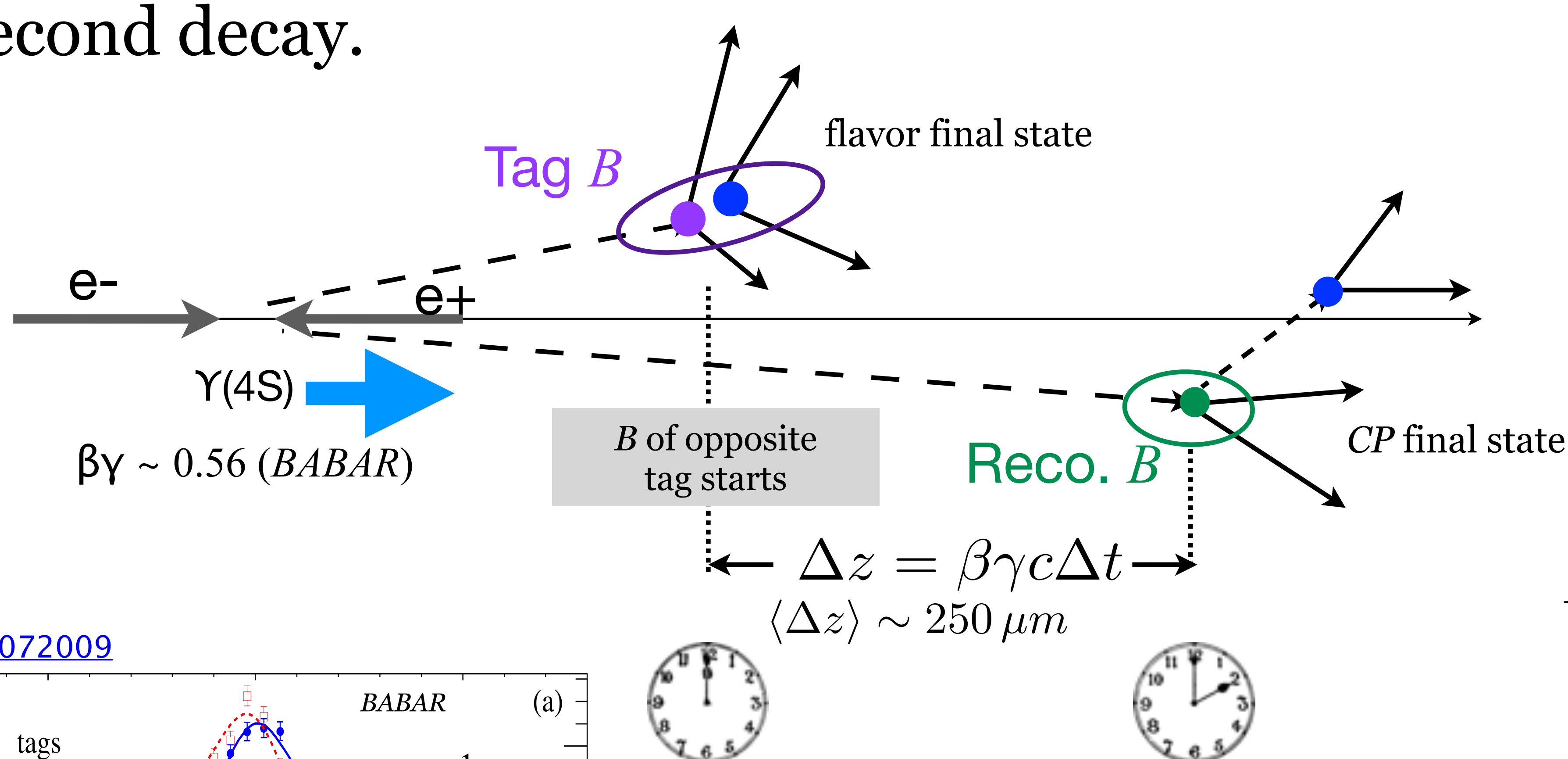
PLB444 (1998), 43

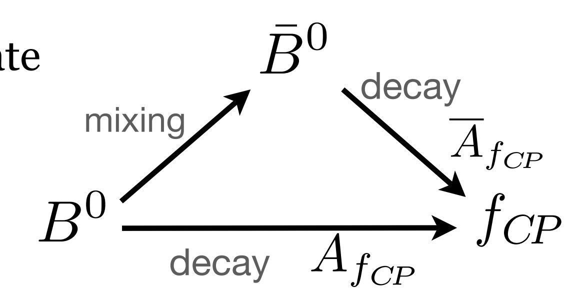


$$\left\langle \frac{R(\bar{K}^0_{t=0} \to e^+\pi^-\nu_{t=\tau}) - R(K^0_{t=0} \to e^-\pi^+\bar{\nu}_{t=\tau})}{R(\bar{K}^0_{t=0} \to e^+\pi^-\nu_{t=\tau}) + R(K^0_{t=0} \to e^-\pi^+\bar{\nu}_{t=\tau})} \right\rangle = (6.6 \pm 1.3_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}) \times 10^{-3}$$

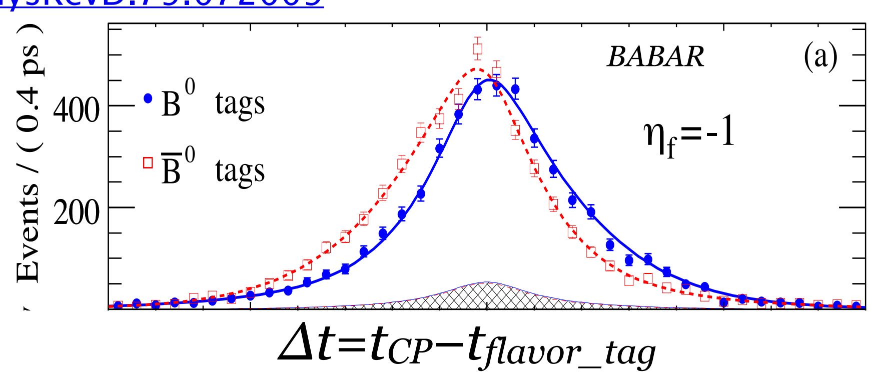
CP in mixing/decay interference

- Υ(4S) decays to a pair of B mesons in a coherent L=1, antisymmetry quantum state. $|i>= 1/\sqrt{2}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)]$
- Once one B decays to a basis state, the other collapses to the orthogonal state. So the first decay "tags" the initial state of the second decay.





PhysRevD.79.072009



$$\Gamma(B^0 \to f_{CP})(t) \neq \Gamma(\overline{B}^0 \to f_{CP})(t)$$

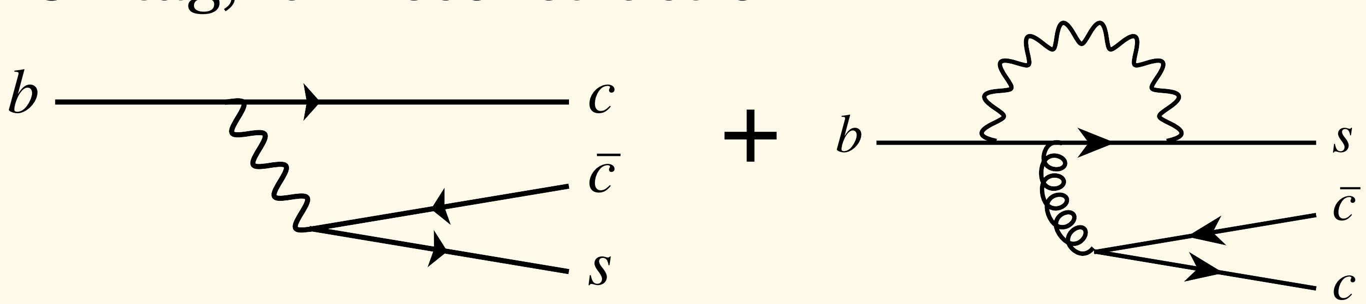
Take advantage of entangled quantum state

- The basis can be projected by *CP* states as well

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

  - ✦ B meson can start in B_+ or B_- state at t=0. 

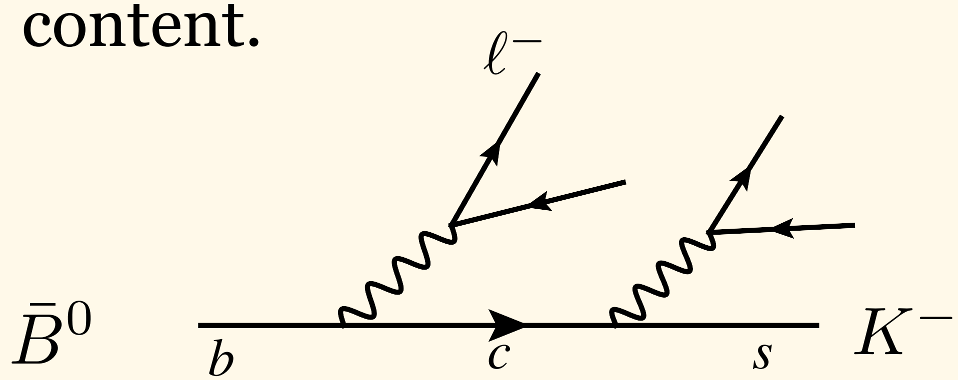
- *CP* tag, full reconstruction



$B_- : J/\psi K_S^0$

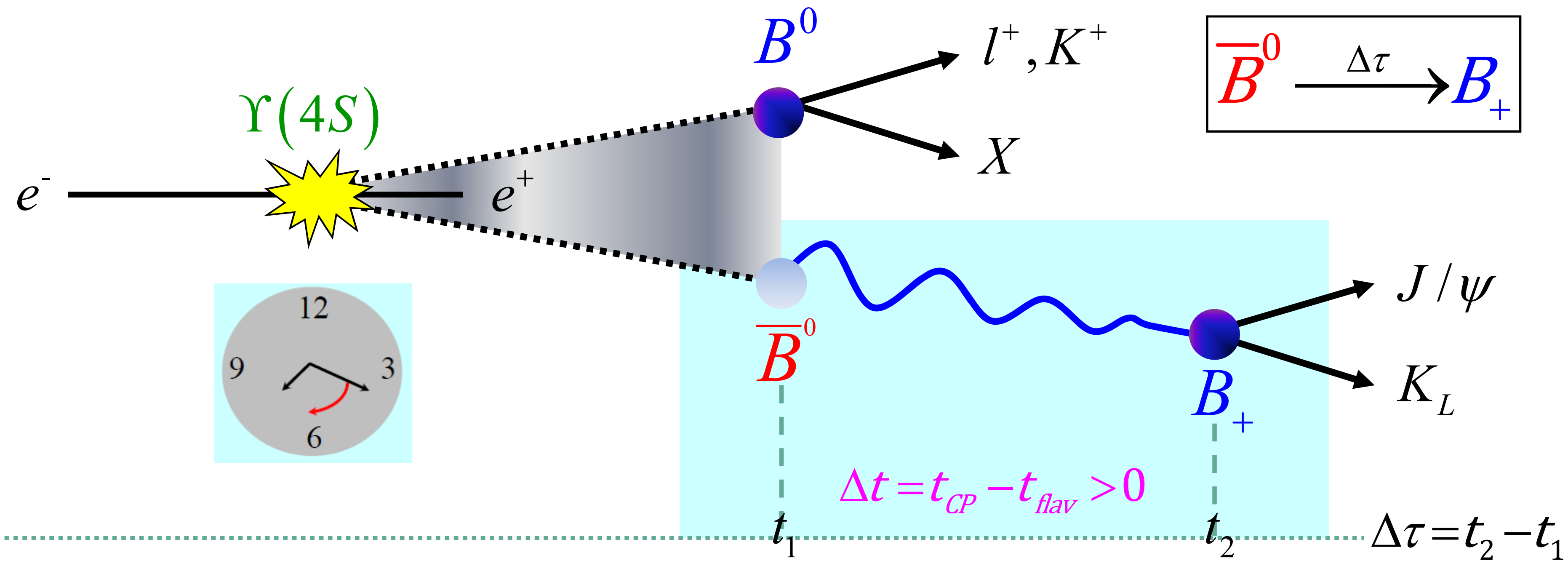
$B_+ : J/\psi K_L^0$

- Flavor tag, inclusive reconstruction; extract features to determine *b*-quark content.



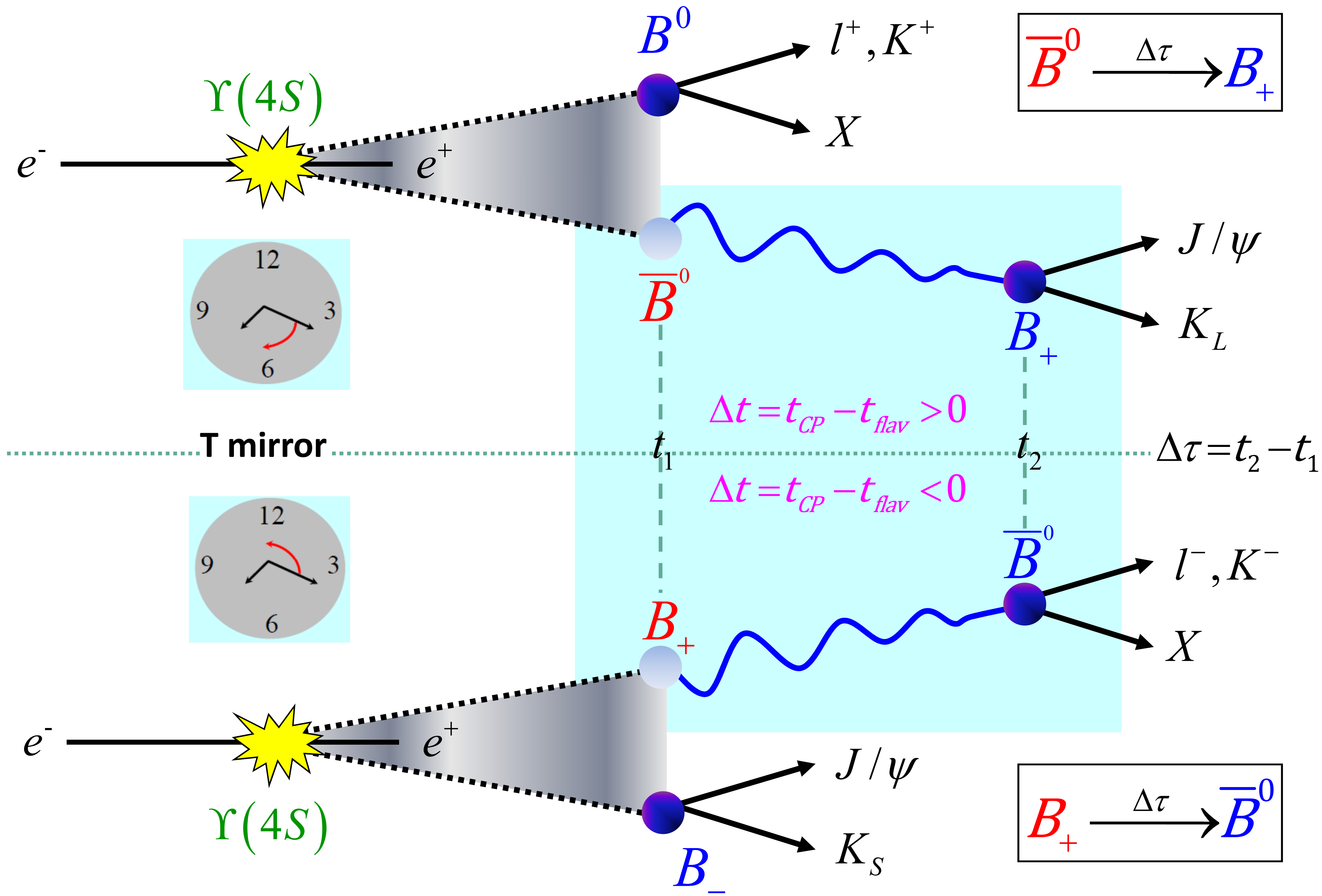
$\vert B^0\rangle = \vert\bar{b}d\rangle$	$\vert\bar{B}^0\rangle = \vert b\bar{d}\rangle$
ℓ^+	ℓ^-
K^+	K^-
etc.	etc.

T reversal



B^0
l^+, K^+
X
$\Upsilon(4S)$
e^-
e^+
12
9
3
6
$\overline{B}^0$
J/ψ
K_L
B_+
$\Delta t = t_{CP} - t_{flav} > 0$
t_1
t_2
$\Delta\tau = t_2 - t_1$
$\overline{B}^0 \xrightarrow{\Delta\tau} B_+$

T reversal



B^0
l^+, K^+
X
$\Upsilon(4S)$
e^-
e^+
$\overline{B}^0 \xrightarrow{\Delta\tau} B_+$
J/ψ
K_L
$\overline{B}^0$
B_+
$\Delta t = t_{CP} - t_{flav} > 0$
T mirror
t_1
t_2
$\Delta\tau = t_2 - t_1$
$\Delta t = t_{CP} - t_{flav} < 0$
$\overline{B}^0$
l^-, K^-
X
B_+
e^-
e^+
J/ψ
K_S
$\Upsilon(4S)$
B_-
$B_+ \xrightarrow{\Delta\tau} \overline{B}^0$
12
9
3
6

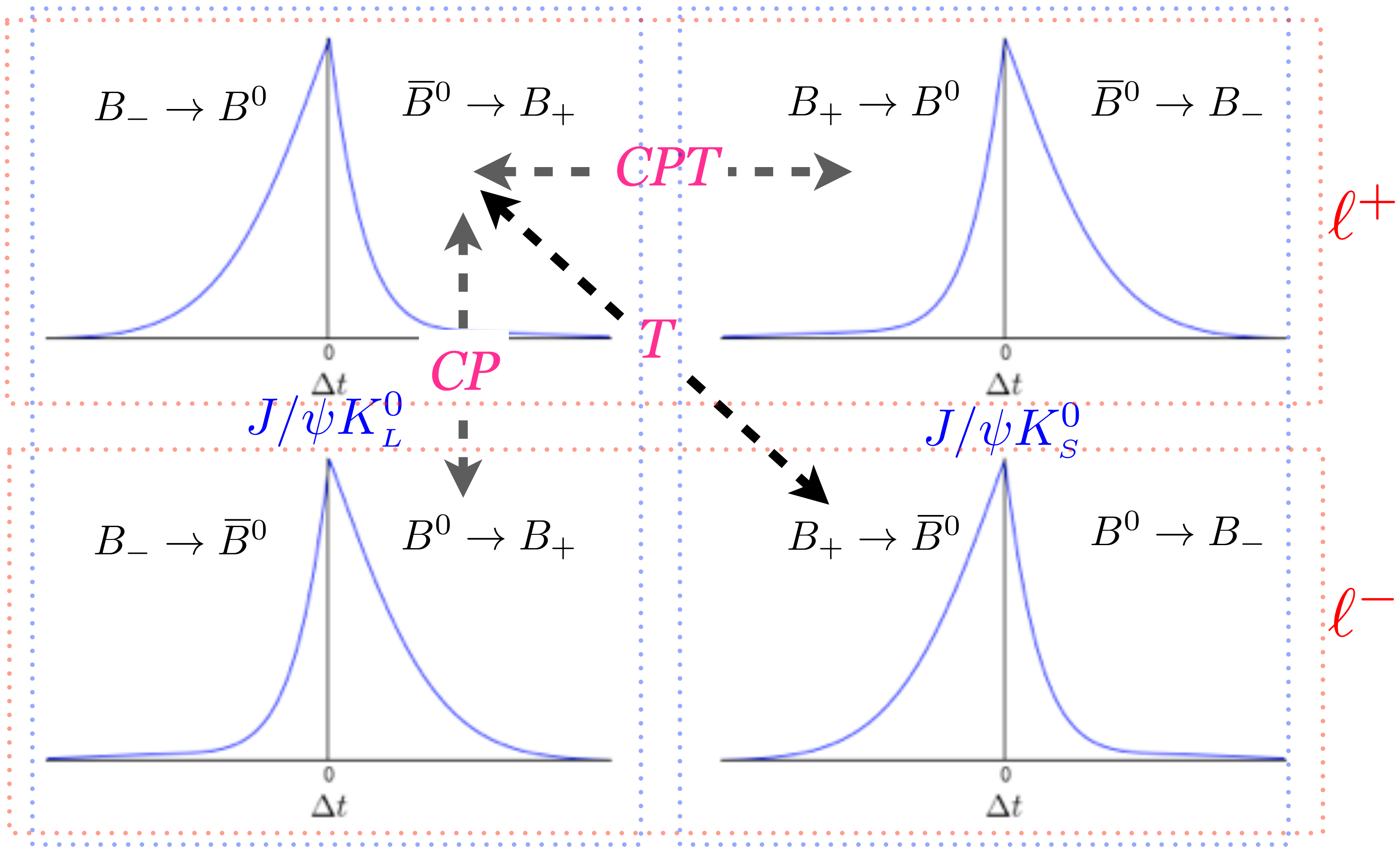
T-reversal processes

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

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

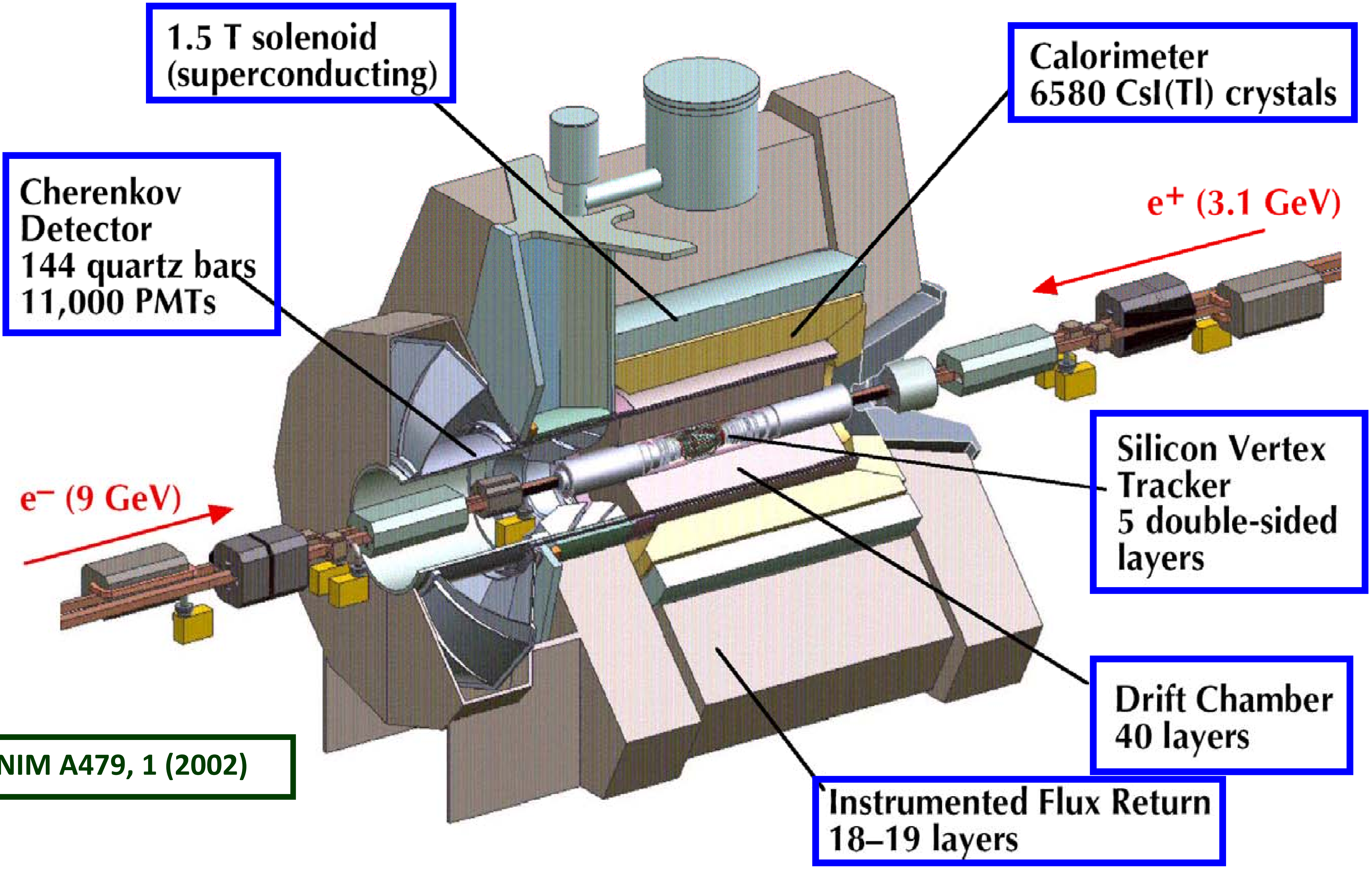
(X,Y) is the reconstructed final states (tag, reco.)

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



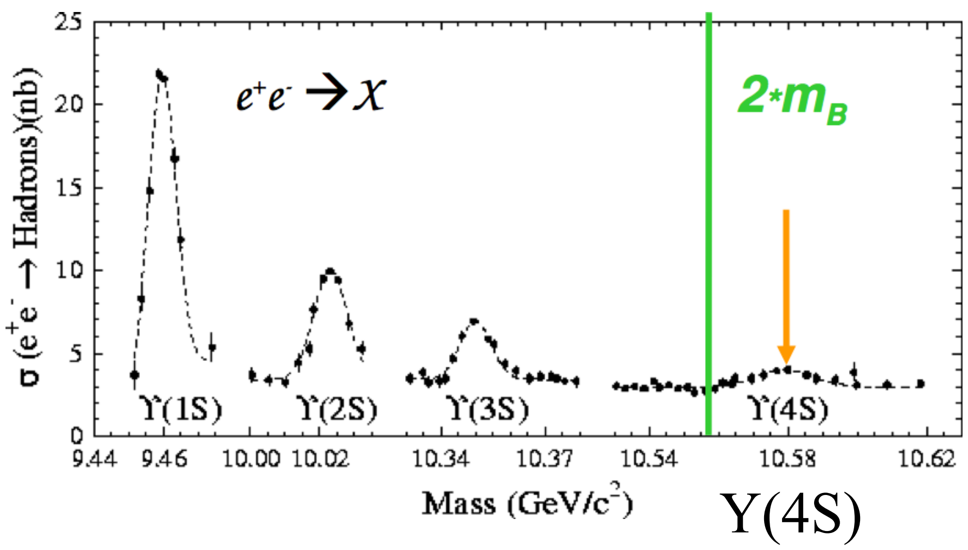
T implies comparison of:
1) Opposite Δt sign
2) Different reco states (ψK_S v. ψK_L)
3) Opposite flavor states (B^0 v. $\overline{B}^0$)

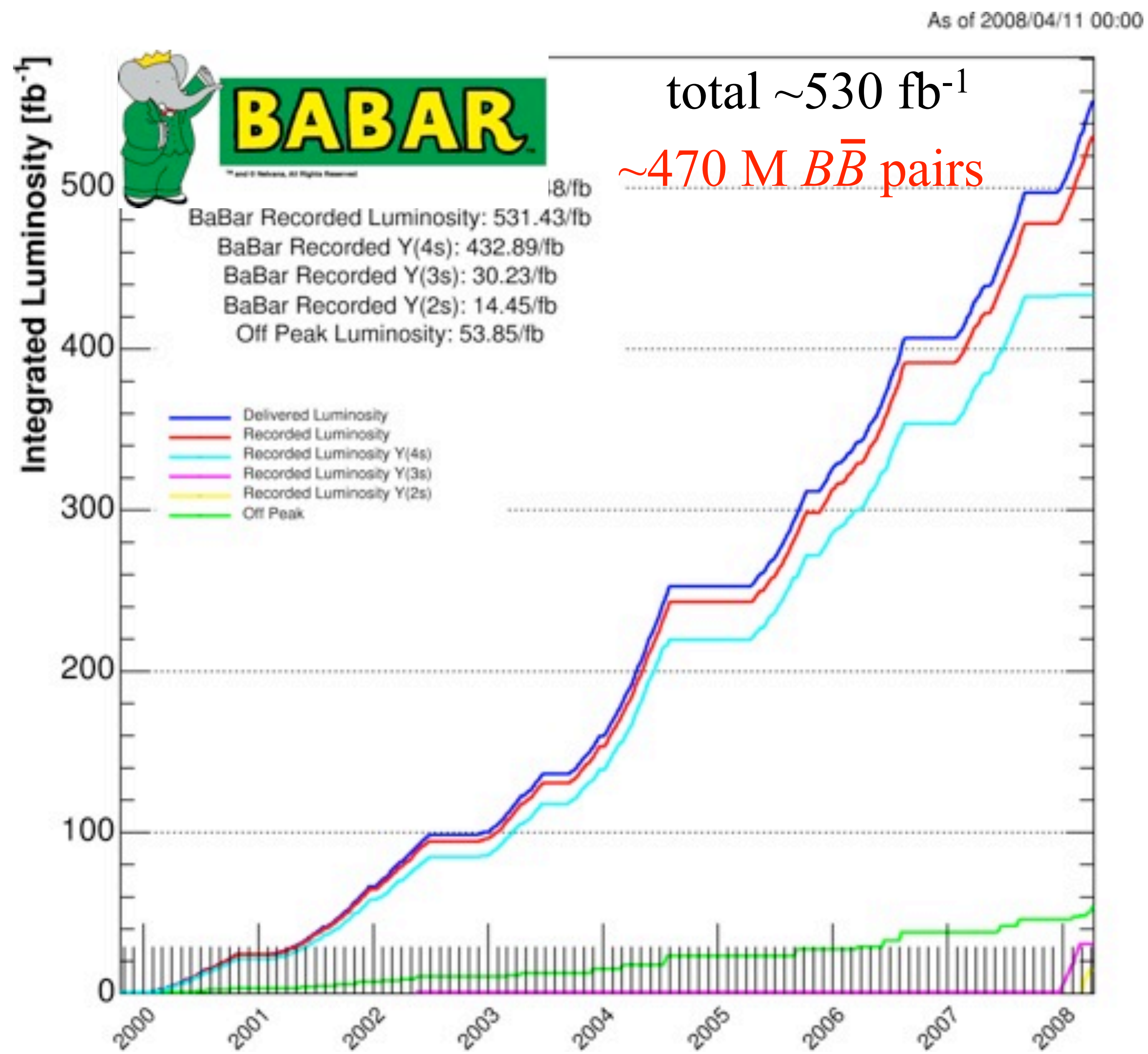
BABAR detector at PEP-II



NIM A479, 1 (2002)

Dataset





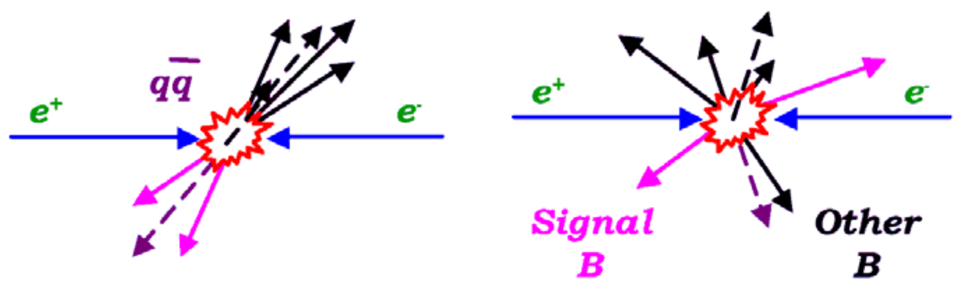
Reconstructed modes

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

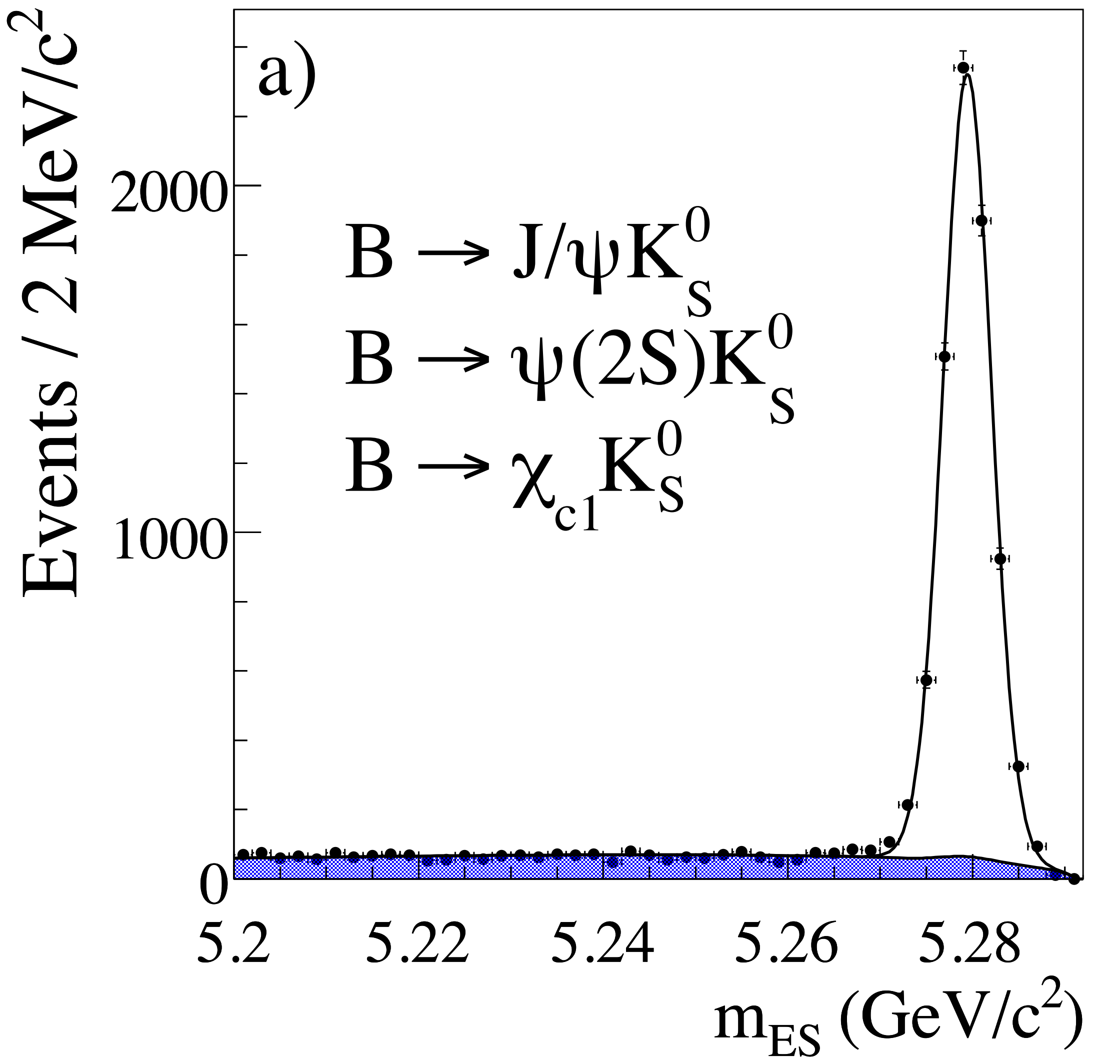
Signal selection

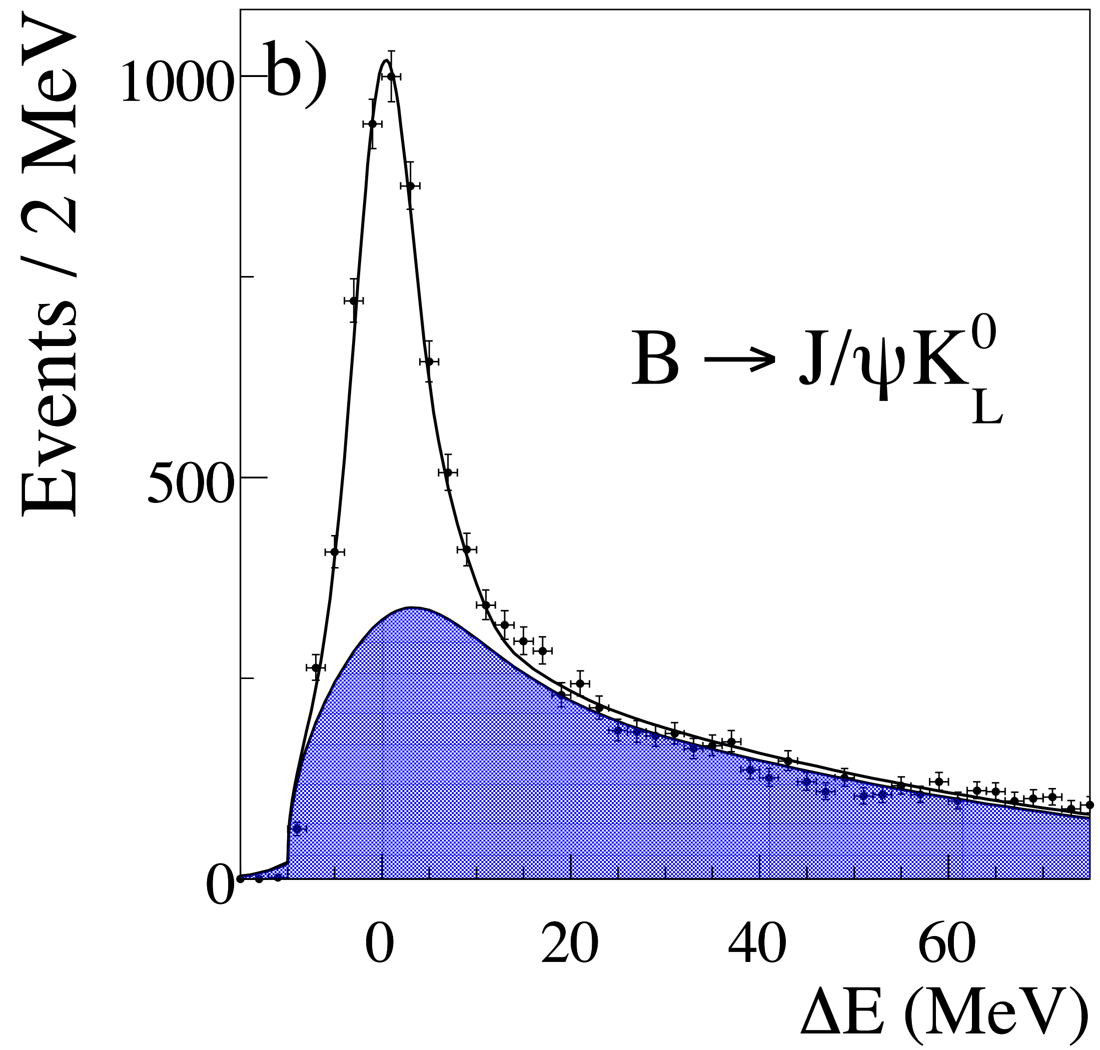
- *CP* final states are fully reconstructed, and selected using
  - Beam-energy substituted mass $m_{\mathrm{ES}} = \sqrt{E^{*}_{\mathrm{beam}} - |\vec{p}^{*}_{B}|^2}$
    where $E^{*}_{B} \rightarrow E^{*}_{\mathrm{beam}}$ $\vec{p}^{*}_{B} \simeq 300\,\mathrm{MeV}/c$
    - Beam energy spread determines resolution ~ 3 MeV.
  - Energy difference $\Delta E = E^{*}_{B} - E^{*}_{\mathrm{beam}}$
    - Resolution 10–50 MeV, depending on final-state neutrals.
  - K_L energy cannot be fully reconstructed; *B* candidate is constrained at *B* mass and use ΔE as the discriminator.
- Continuum u,d,s,c backgrounds are suppressed using angular distributions and event shape variables



- Flavor tagging is inclusive:
  - For each fully reconstructed B_{CP}, search for features from the other *B* such as high momentum leptons, kaons, soft-pion from *D**, etc. These features are fed into a neural net to determine the *B* flavor.

Event samples





7796 events, purity 87%–96% (5.27–5.29 GeV)
(depending on mode)

5813 events, purity 56% (<10 MeV)

Signal model

- PDF for the 8 signal processes

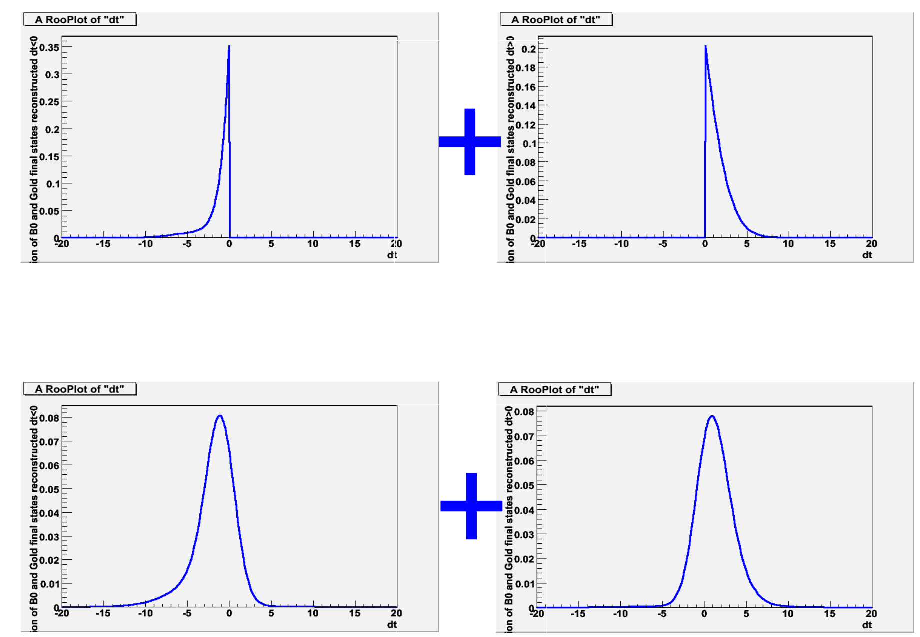
$$g^{\pm}_{\alpha,\beta}(\tau) \propto e^{-\Gamma|\tau|}\left\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \tau)\right\}$$

$$\alpha \in \{B^0,\ \overline{B}^0\};\quad \beta \in \{K^0_S,\ K^0_L\} \qquad \tau = \pm\Delta t > 0$$

Mistag dilutes the S, C parameters by a factor of (1-2w)

- Fit model is the signal PDF combined with a step function *H* in Δt and convolved with a resolution function

$$\mathcal{H}_{\alpha,\beta}(\Delta t) \ \propto\ g^{+}_{\alpha,\beta}(\Delta t_{\rm true})H(\Delta t_{\rm true}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t}) + g^{-}_{\alpha,\beta}(-\Delta t_{\rm true})H(-\Delta t_{\rm true}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t})$$



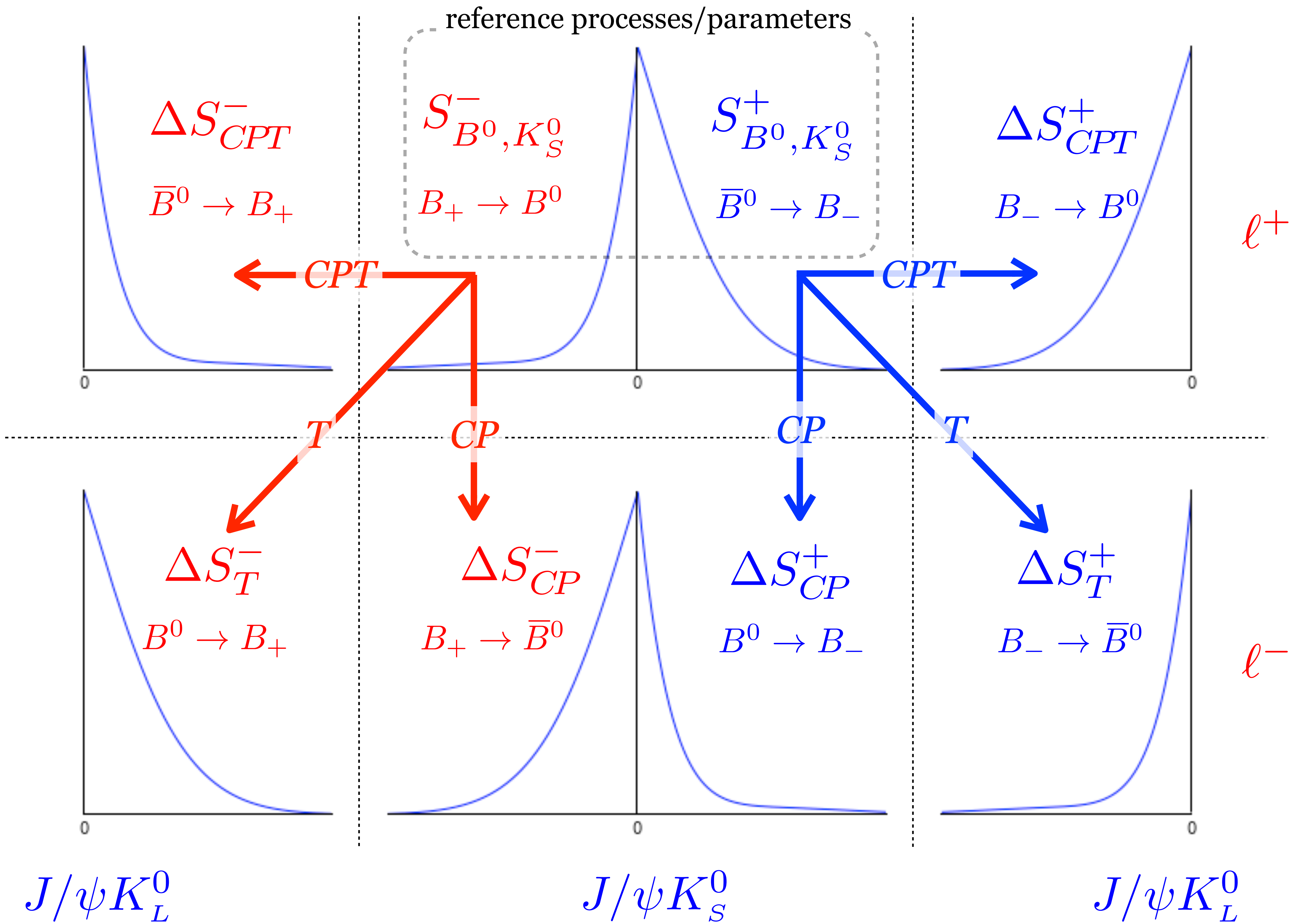
- The signal model has 8 different sets of (S, C) parameters

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

- The canonical *CP* violation study* has one set of (S, C) parameters.

*e.g., PRD 79 (2009) 072009

Fit parameters ΔS± and ΔC±

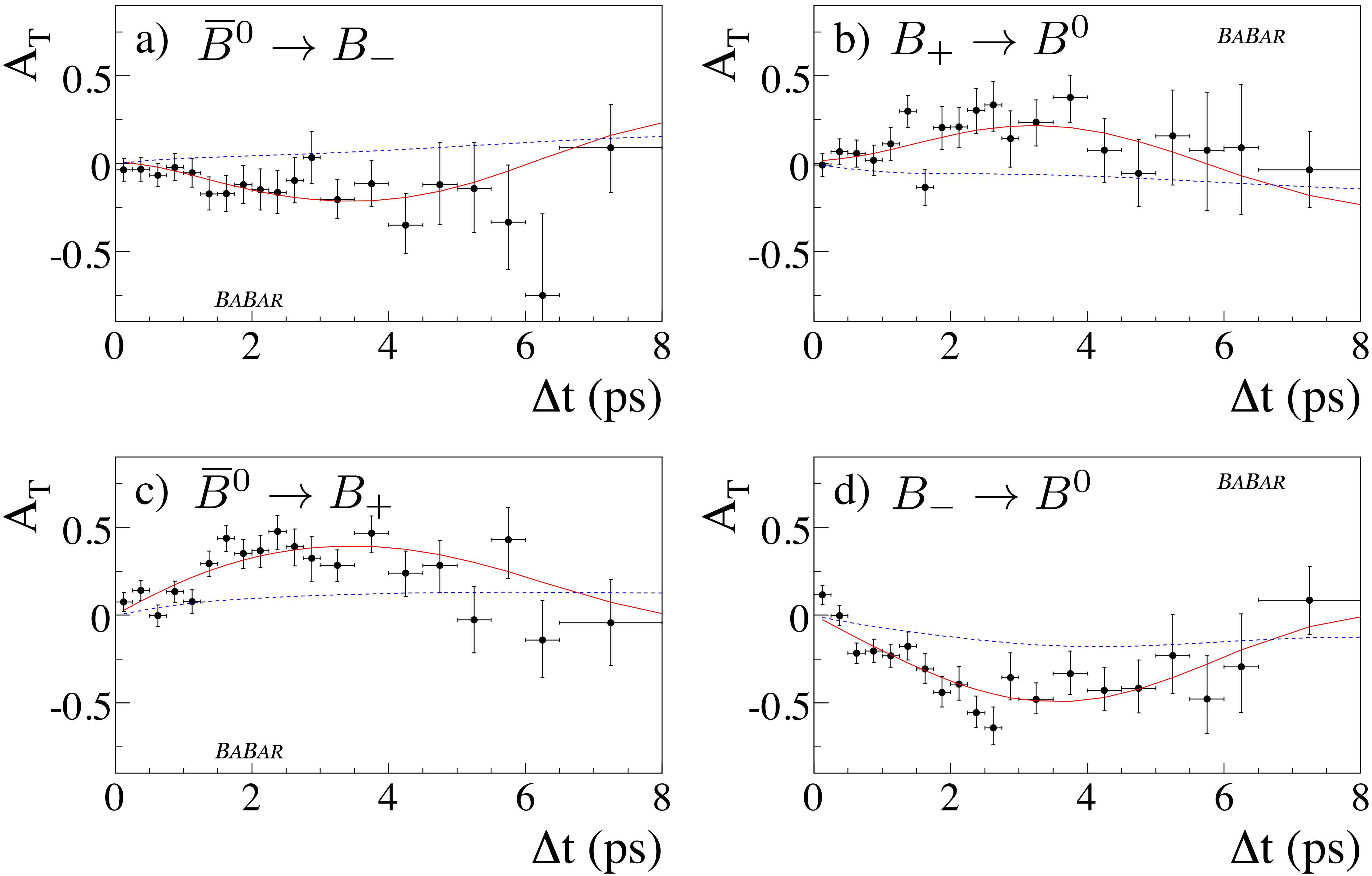


Results

	Parameter	Result	expectation from canonical *CP*
Reference parameters	$S^+_{\ell^+X,c\bar{c}K^0_S}$	$0.55 \pm 0.08 \pm 0.06$	+sin2β
	$S^-_{\ell^+X,c\bar{c}K^0_S}$	$-0.66 \pm 0.06 \pm 0.04$	–sin2β
	$C^+_{\ell^+X,c\bar{c}K^0_S}$	$0.11 \pm 0.06 \pm 0.05$	0
	$C^-_{\ell^+X,c\bar{c}K^0_S}$	$-0.05 \pm 0.06 \pm 0.03$	0
T	$\Delta S^+_{\mathrm{T}} = S^-_{\ell^-X,J/\psi K^0_L} - S^+_{\ell^+X,c\bar{c}K^0_S}$	$-1.37 \pm 0.14 \pm 0.06$	–2sin2β
	$\Delta S^-_{\mathrm{T}} = S^+_{\ell^-X,J/\psi K^0_L} - S^-_{\ell^+X,c\bar{c}K^0_S}$	$1.17 \pm 0.18 \pm 0.11$	+2sin2β
	$\Delta C^+_{\mathrm{T}} = C^-_{\ell^-X,J/\psi K^0_L} - C^+_{\ell^+X,c\bar{c}K^0_S}$	$0.10 \pm 0.16 \pm 0.08$	0
	$\Delta C^-_{\mathrm{T}} = C^+_{\ell^-X,J/\psi K^0_L} - C^-_{\ell^+X,c\bar{c}K^0_S}$	$0.04 \pm 0.16 \pm 0.08$	0
CP	$\Delta S^+_{\mathrm{CP}} = S^+_{\ell^-X,c\bar{c}K^0_S} - S^+_{\ell^+X,c\bar{c}K^0_S}$	$-1.30 \pm 0.10 \pm 0.07$	–2sin2β
	$\Delta S^-_{\mathrm{CP}} = S^-_{\ell^-X,c\bar{c}K^0_S} - S^-_{\ell^+X,c\bar{c}K^0_S}$	$1.33 \pm 0.12 \pm 0.06$	+2sin2β
	$\Delta C^+_{\mathrm{CP}} = C^+_{\ell^-X,c\bar{c}K^0_S} - C^+_{\ell^+X,c\bar{c}K^0_S}$	$0.07 \pm 0.09 \pm 0.03$	0
	$\Delta C^-_{\mathrm{CP}} = C^-_{\ell^-X,c\bar{c}K^0_S} - C^-_{\ell^+X,c\bar{c}K^0_S}$	$0.08 \pm 0.10 \pm 0.04$	0
CPT	$\Delta S^+_{\mathrm{CPT}} = S^-_{\ell^+X,J/\psi K^0_L} - S^+_{\ell^+X,c\bar{c}K^0_S}$	$0.16 \pm 0.20 \pm 0.09$	0
	$\Delta S^-_{\mathrm{CPT}} = S^+_{\ell^+X,J/\psi K^0_L} - S^-_{\ell^+X,c\bar{c}K^0_S}$	$-0.03 \pm 0.13 \pm 0.06$	0
	$\Delta C^+_{\mathrm{CPT}} = C^-_{\ell^+X,J/\psi K^0_L} - C^+_{\ell^+X,c\bar{c}K^0_S}$	$0.15 \pm 0.17 \pm 0.07$	0
	$\Delta C^-_{\mathrm{CPT}} = C^+_{\ell^+X,J/\psi K^0_L} - C^-_{\ell^+X,c\bar{c}K^0_S}$	$0.03 \pm 0.14 \pm 0.08$	0

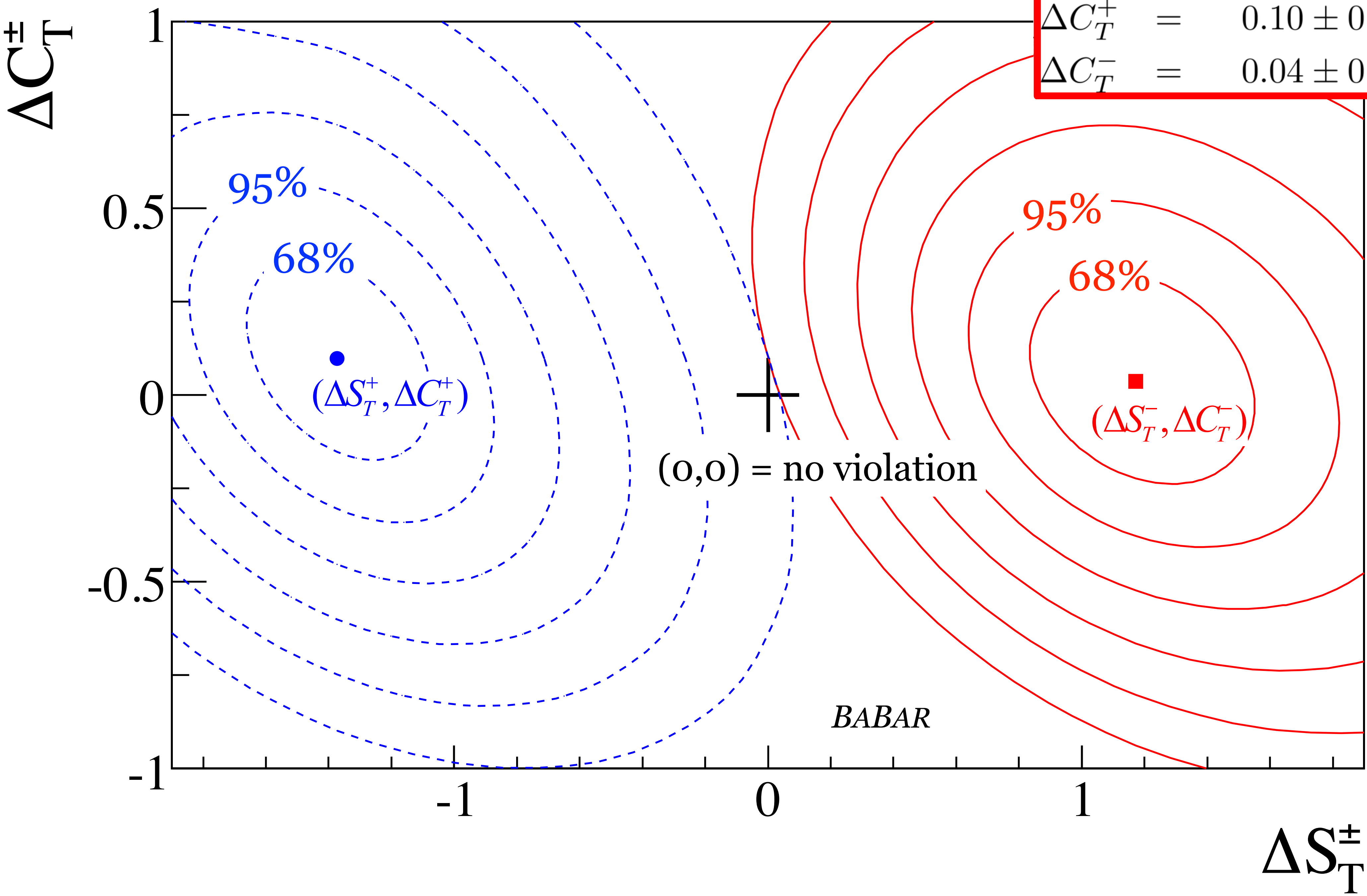
sin2β= 0.679±0.020 (HFAG winter'12)

Independent T asymmetries



Points: data; red (blue) curves: projections of fits with (without) T violation

Interpretation of T violation result

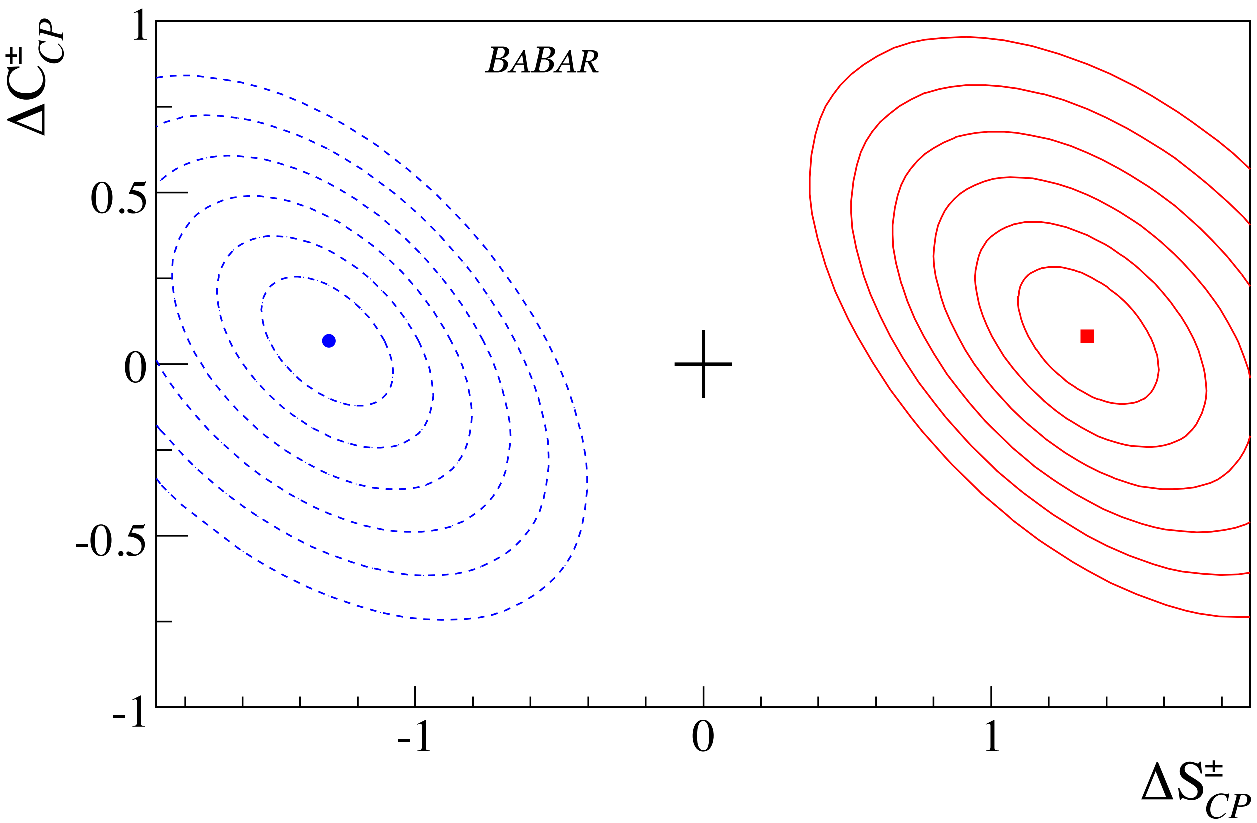


$$
\begin{aligned}
\Delta S_T^+ &= -1.37 \pm 0.14 \pm 0.06 \\
\Delta S_T^- &= 1.17 \pm 0.18 \pm 0.11 \\
\Delta C_T^+ &= 0.10 \pm 0.16 \pm 0.08 \\
\Delta C_T^- &= 0.04 \pm 0.16 \pm 0.08
\end{aligned}
$$

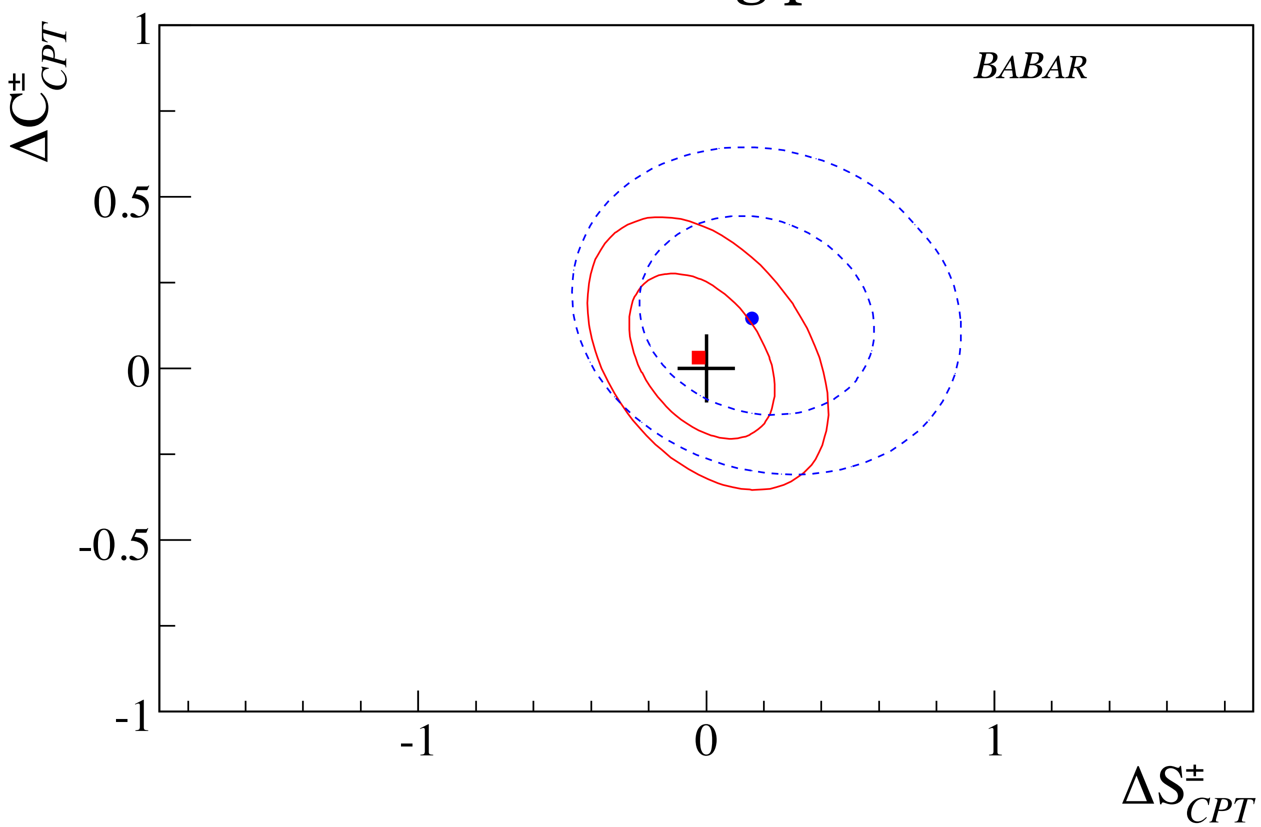
CP and *CPT* results

$$\begin{aligned}
\Delta S^+_{CP} &= -1.30 \pm 0.10 \pm 0.07 \\
\Delta S^-_{CP} &= 1.33 \pm 0.12 \pm 0.06 \\
\Delta C^+_{CP} &= 0.07 \pm 0.10 \pm 0.03 \\
\Delta C^-_{CP} &= 0.08 \pm 0.09 \pm 0.04
\end{aligned}$$

CP violating parameters



CPT violating parameters



$$\begin{aligned}
\Delta S^+_{CPT} &= 0.16 \pm 0.20 \pm 0.09 \\
\Delta S^-_{CPT} &= -0.03 \pm 0.13 \pm 0.06 \\
\Delta C^+_{CPT} &= 0.15 \pm 0.17 \pm 0.07 \\
\Delta C^-_{CPT} &= 0.03 \pm 0.14 \pm 0.08
\end{aligned}$$

(0,0) = no violation

Conclusion

- *BABAR* has measured *T*-violating parameters in neutral *B* meson decays by comparing conjugate processes that can only be achieved by *T* reversal, not *CP*.
  - ✦ The first time this kind of process is utilized to demonstrate *T* violation.
- This novel approach does not need *CPT* invariance to link *T* with *CP*.
- *T* violation is observed at >10 σ level.
- *CP* and *CPT* violations are also tested.
- Result is consistent with measurements of *CP* violation assuming *CPT* invariance.

Back up

Systematics (for $\Delta S_T^{\pm}$)

Systematic source	ΔS_T^+	ΔS_T^-
misID flavour	0.019	0.019
Δt resolution function	0.02	0.05
Outlier's scale factor	0.012	-0.013
m_{ES} parameters	0.012	0.0018
ΔE parameters	0.017	0.017
K_L systematics	0.03	0.03
Differences between B_{CP} and B_{flav}	0.02	0.02
Background effects	0.03	0.04
Uncertainty on fit bias from MC	0.010	0.08
Detector and vertexing effects.	0.011	0.04
$\Delta\Gamma \neq 0$ effects	0.004	0.003
External physics parameters	0.005	0.006
Normalization effects	0.012	0.009
Total Systematics	0.06	0.11

Significance of *T* violation

- Standard fit yields a likelihood value of the fit to S, C using the 8 independent samples.
- Repeat the fit, applying constraints to the parameters for T-conjugate processes
- Difference in likelihood values yields the significance of T violation.

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

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

- CP and CPT significance can be determined the same way with proper constraints.
- Systematic uncertainties are included by calculating $2\Delta\ln L$ ($=m^2_j$) varying each parameter by $\pm 1\ \sigma_{\mathrm{syst.}}$ and reduce the overall statistical $-2\Delta\ln L$ by $1+\max(m^2_j)$.

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