DIRECT OBSERVATION OF TIME REVERSAL VIOLATION

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FPCP 2012

University of Science and Technology of China, Hefei, AnHui (China)
21st-25th May

Outline

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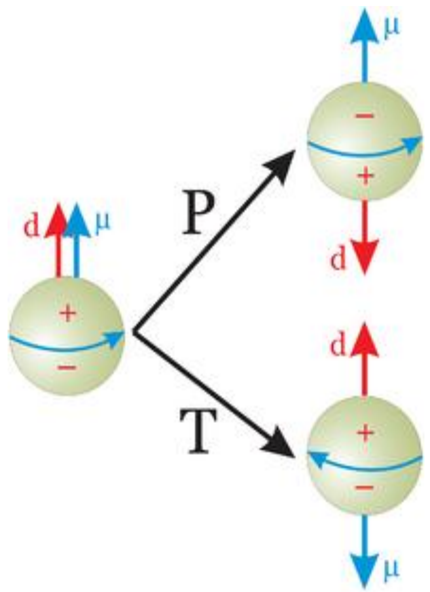
INTRODUCTION

Time Reversal Violation (TRV)

- **Time Reversal 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.

  - In an oscillation a difference in the probability of a⟶b from b⟶a at a given time, e.g., $\nu_e \to \nu_\mu$ vs. $\nu_\mu \to \nu_e$ experiment proposed for the neutrino factories with muon storage ring.



- **Time Reversal in unstable systems**

  1. Reversal of motion ($t \longrightarrow -t$).
  2. |in>↔|out> exchange.

discard ⟶ ~~Odd effects $t \longrightarrow -t$~~

⟶ Experimentally tricky!

<u>CP violation mechanisms</u>

- Decay
- Mixing
- Mixing×Decay

CPT

<u>T violation mechanisms</u>

- Decay
- Mixing
- Mixing×Decay

TRV in unstable systems

- Decay TRV searches

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

Unable to perform the T test:

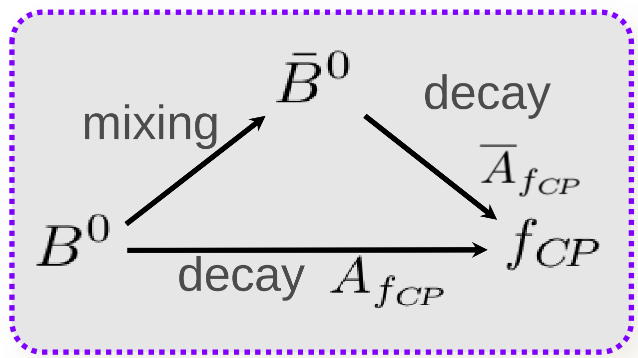
- Preparation of the initial state.
- The strong processes will swamp the feeble weak processes.

- Mixing TRV searches

$$\begin{tikzcd} \begin{array}{c} K^0 \to \bar{K}^0 \\ B^0 \to \bar{B}^0 \end{array} \arrow[r, "\mathbf{CPT}"] \arrow[d, "\mathbf{CP}"'] \arrow[dr, "\mathbf{T}"] & \begin{array}{c} K^0 \to \bar{K}^0 \\ B^0 \to \bar{B}^0 \end{array} \\ \begin{array}{c} \bar{K}^0 \to K^0 \\ \bar{B}^0 \to B^0 \end{array} & \begin{array}{c} \bar{K}^0 \to K^0 \\ \bar{B}^0 \to B^0 \end{array} \end{tikzcd}$$

We cannot distinguish CP and T.
Not a DIRECT observation of TRV

- Interference TRV searches



CPV time dependent (TD) studies:

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

Foundations of the analysis

- Ingredients:
  - EPR entanglement produced by the decay of the $\Upsilon(4S)$.

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

$$\left.\begin{matrix} B_+ \\ B_- \end{matrix}\right\} \xrightarrow{\text{projected by}} \left\{\begin{matrix} J/\psi K_L \\ J/\psi K_S \end{matrix}\right.$$

  - Quantum Mechanics.

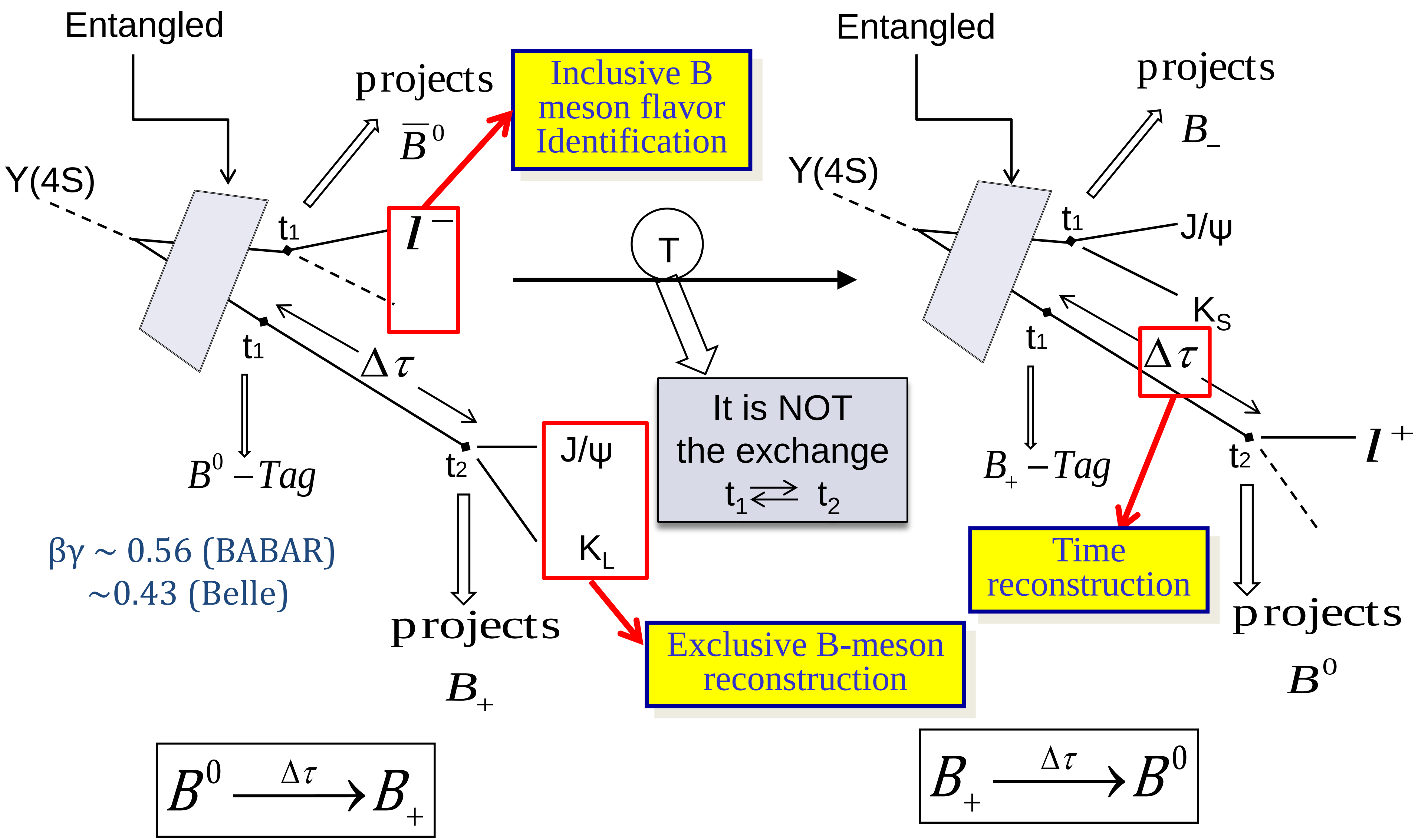
$$\Delta\tau = t_Y - t_X > 0$$

Reference: Physical Process
(X,Y): Reconstructed Final States

Reference (X, Y)	***T-Transformed (X, Y)***
$B^0 \rightarrow B_+$ $(l^-, J/\psi K_L)$	$B_+ \rightarrow B^0$ $(J/\psi K_S, l^+)$
$B^0 \rightarrow B_-$ $(l^-, J/\psi K_S)$	$B_- \rightarrow B^0$ $(J/\psi K_L, l^+)$
$\bar{B}^0 \rightarrow B_+$ $(l^+, J/\psi K_L)$	$B_+ \rightarrow \bar{B}^0$ $(J/\psi K_S, l^-)$
$\bar{B}^0 \rightarrow B_-$ $(l^+, J/\psi K_S)$	$B_- \rightarrow \bar{B}^0$ $(J/\psi K_L, l^-)$

l^+ and l^- project over the B flavor, i.e., B^0 and $\bar{B}^0$ respectively

Foundations of the analysis

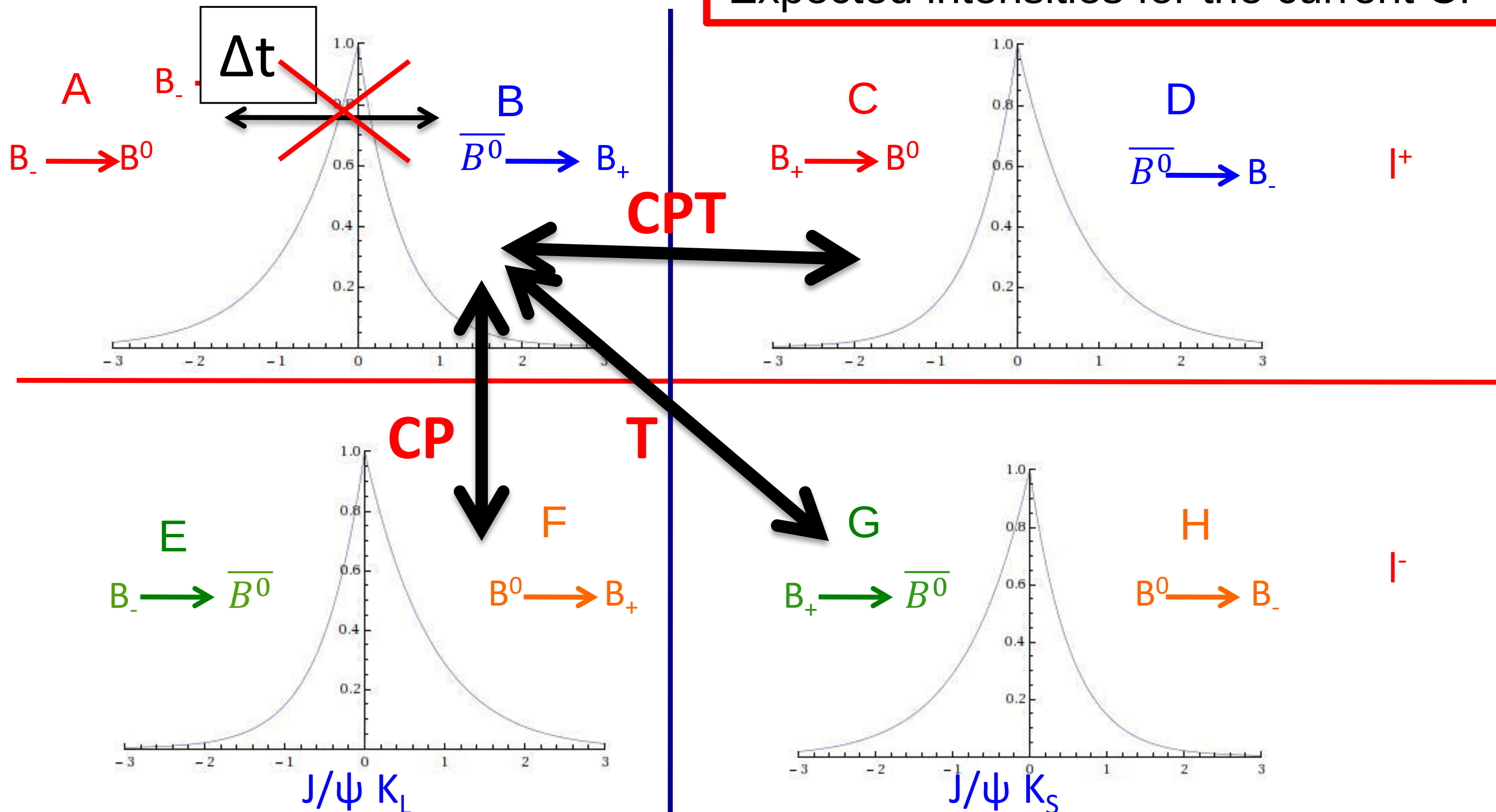


$\Delta z = \beta\gamma c \Delta\tau$

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

Foundations of the analysis

Expected intensities for the current CP studies



In total we can build:

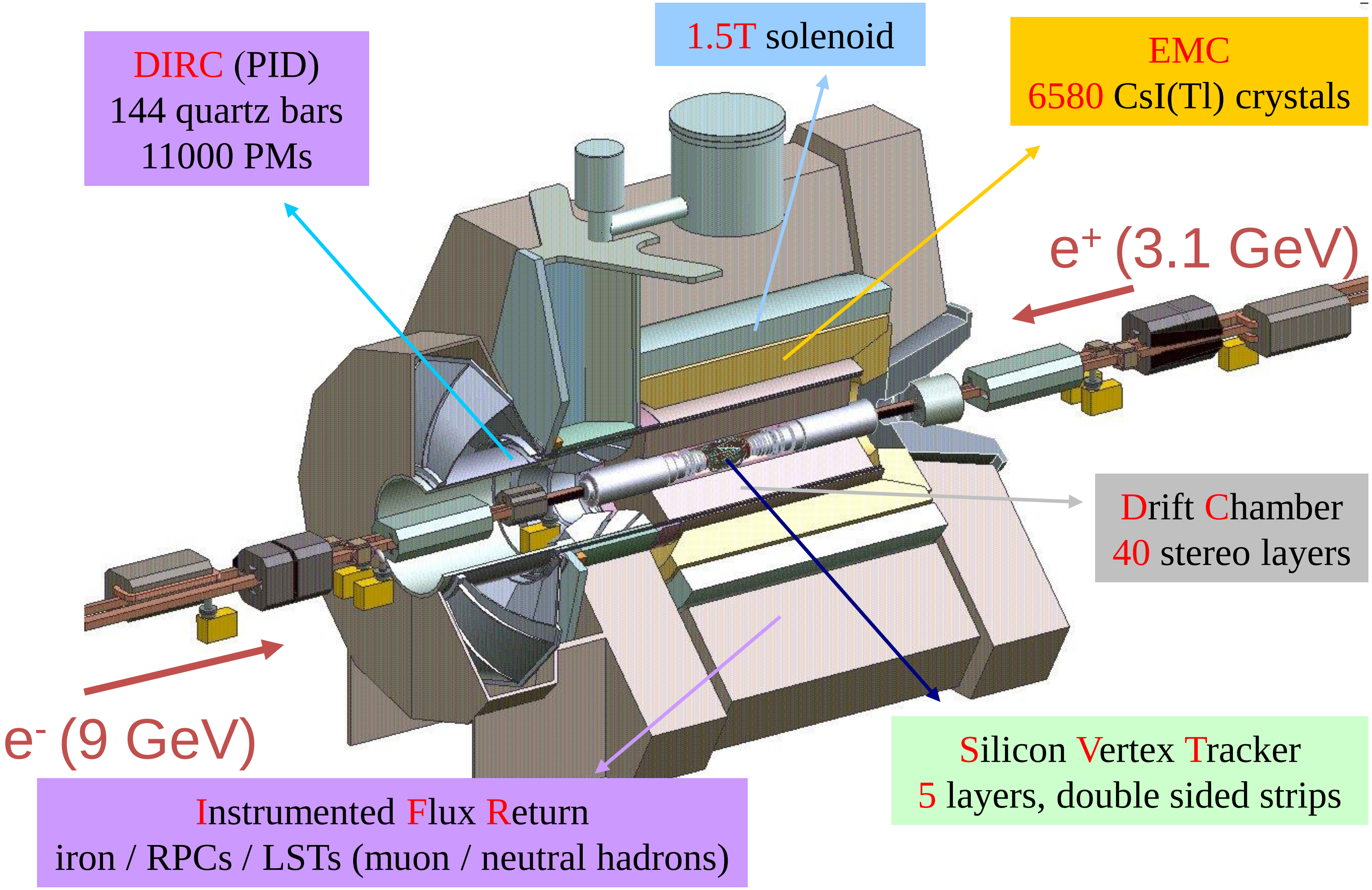
- 4 Independent T comparisons.
- 4 Independent CP comparisons.
- 4 Independent CPT comparisons.

T implies comparison of:

1) Opposite Δt sign.
2) Different reco states ($J/\Psi K_S$ vs. $J/\Psi K_L$).
3) Opposite tag states (B^0 vs $\bar{B}^0$).

ANALYSIS PROCEDURE

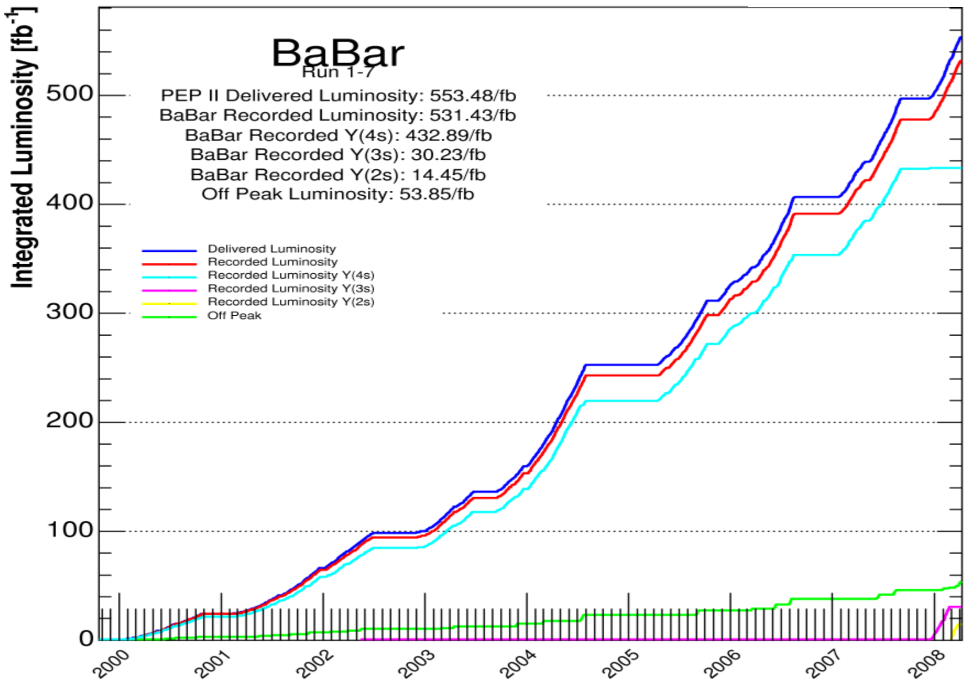
BaBar detector

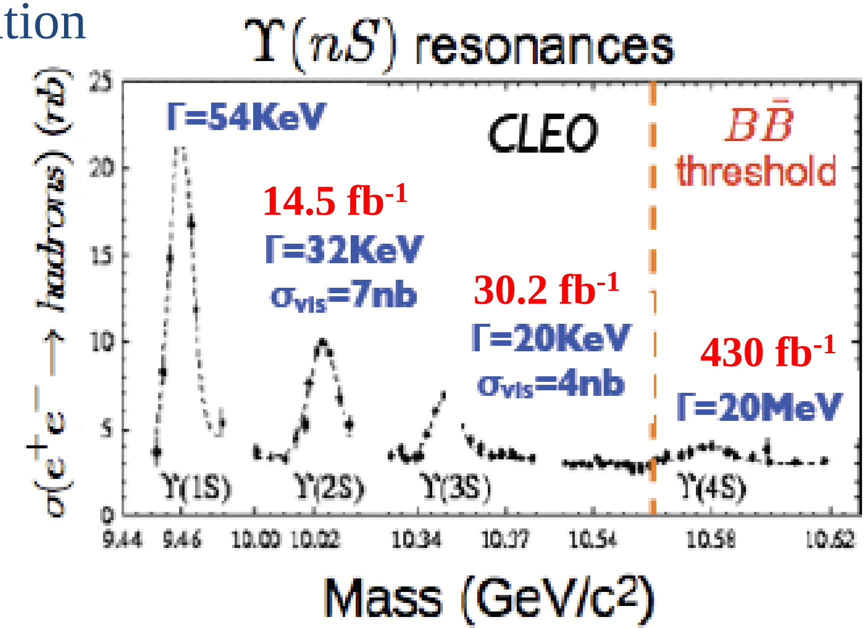


- Asymmetric B-factory: $E_{cms} = 10.58$ GeV $\quad e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Performed a wide range of flavor physics results in B, Cham and τ sectors
- General purpose detector in e^+e^- environment: precision tracking, photon/electron detection, particle ID, muon/K_L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

Data Set

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





54 fb^{-1} **Off-Υ(nS)**

4 fb^{-1} **above Υ(4S)**

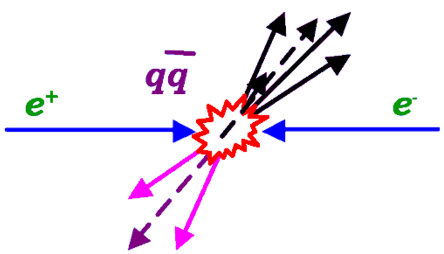
Decays used for the analysis:

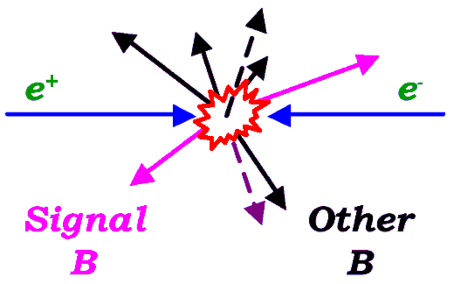
- $c\bar{c}K_S$: $B^0 \to J/\psi K_S$, $B^0 \to \psi(2S)K_S$, $B^0 \to \chi_{c1}K_S$
- $c\bar{c}K_L$: $B^0 \to J/\psi K_L$
- B_{flav}: $B^0 \to D^*\pi(\rho, a_1)$, $B^0 \to J/\psi K^{*0}$
- Control sample $c\bar{c}K^\pm$ and $J/\psi K^{*+}$, e.g.,
  $B^+ \to J/\psi K^+$, $B^+ \to \psi(2S)K^+$, $B^+ \to J/\psi K^{*+}$

- ≈ 470×10^6 BB (0.5×Belle)
- ≈ 690×10^6 cc
- ≈ 500×10^6 $\tau^+\tau^-$
- ≈ 1.2×10^8 Υ(3S) (7×Belle+Cleo)
- ≈ 1.0×10^8 Υ(2S) (0.5×Belle+Cleo)

Backgrounds and B characterization

- Veto significant/potentially dangerous B decay backgrounds
  - Depends strongly on B decay channel under study
- Suppress continuum $e^+e^- \to q\bar{q}$ (q=u,d,s,c) background using
  - Angular distribution: B flight direction
  - Event shape variables:
    - Background: "jetty"
    - Signal: almost at rest





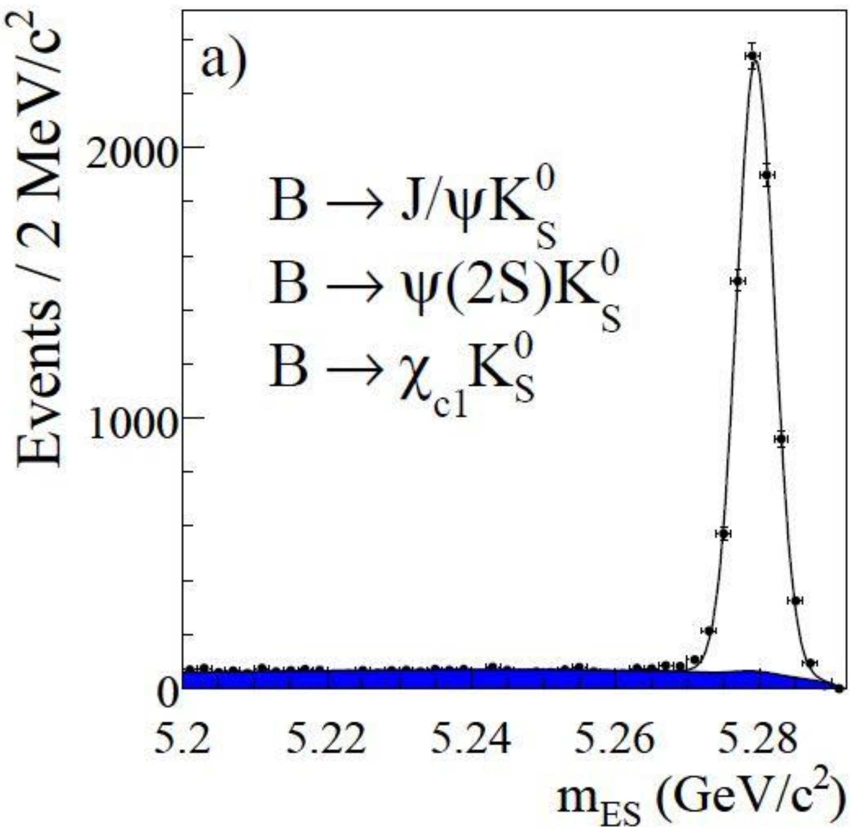
- Characterize B candidates using
  - Beam constrained mass: $m_{ES} = \sqrt{E^{*2}_{beam} - |\overrightarrow{p^*_B}|^2}$
    - B mesons produced almost at rest

$$E^*_B = E^*_{\text{beam}} \qquad p^*_B \sim 300\,\mathrm{MeV}/c$$

    - Resolution ~3 MeV dominated by beam energy spread
  - Energy difference: $\Delta E = E^*_B - E^*_{beam}$
    - Energy of B candidate almost equal to half beam energy
    - Resolution ~10-50 MeV depends on neutrals in final state
- Select best B candidates (based on invariant masses of daughter particles)

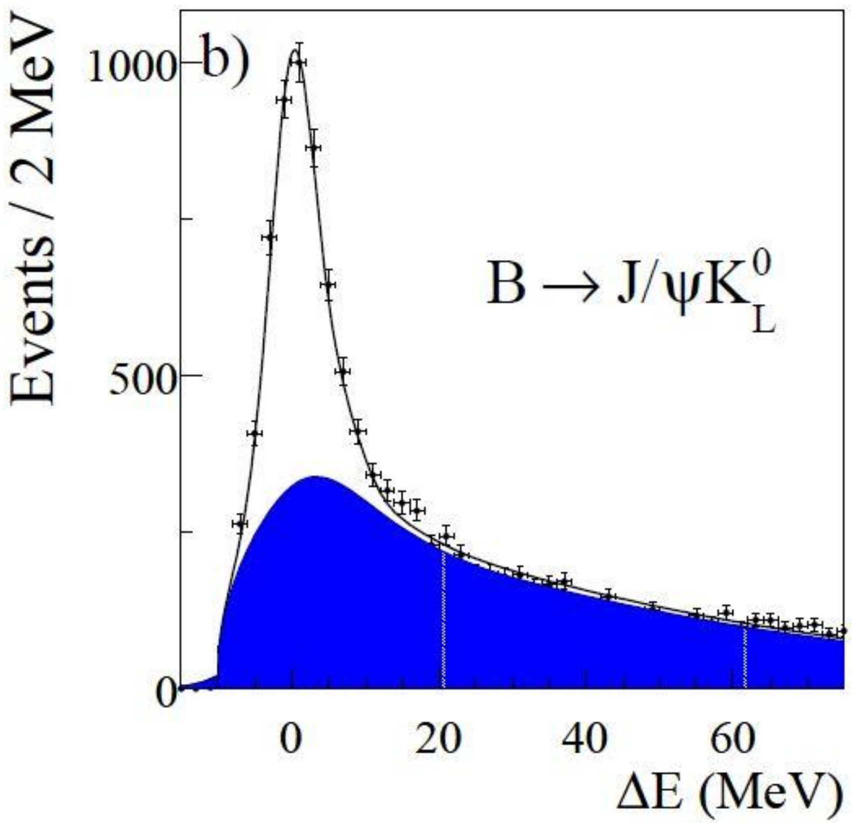
$c\bar{c}K_S$ and J/ψK_L samples composition

$c\bar{c}K_S$ sample



7796 events
Purity: 87% to 96%

$J/\psi K_S$ sample



5813 events
Purity: ~56%

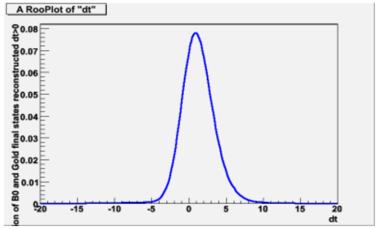
Signal model description

$\Delta t_{true} = t_{CP} - t_{flav}$

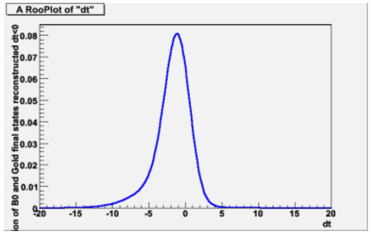
- General Signal PDF for the 8 intensities

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

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



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



where

H(Δt)≡ Heaviside function

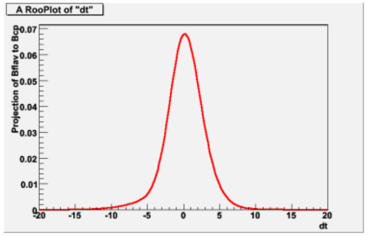
$\alpha \in \{B^0, \bar{B}^0\}$; $\beta \in \{K_S, K_L\}$ $\quad \mathcal{R}(\delta t, \sigma_{\Delta t}) \equiv$ resolution function

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

$$\boxed{2\ \Delta t\ (\Delta t > 0, \Delta t < 0)} \times \boxed{2\ flav\ (B^0, \bar{B}^0)} \times \boxed{2\ CP\ (K_S, K_L)}$$

- To be compared to the usual CPV studies: 1 single set

$$g_{\alpha,\beta}(\Delta t) \propto e^{-\Gamma|\Delta t|}\{1 \pm [\eta_f S\sin(\Delta m_d \Delta t) + C\cos(\Delta m_d \Delta t)]\}$$

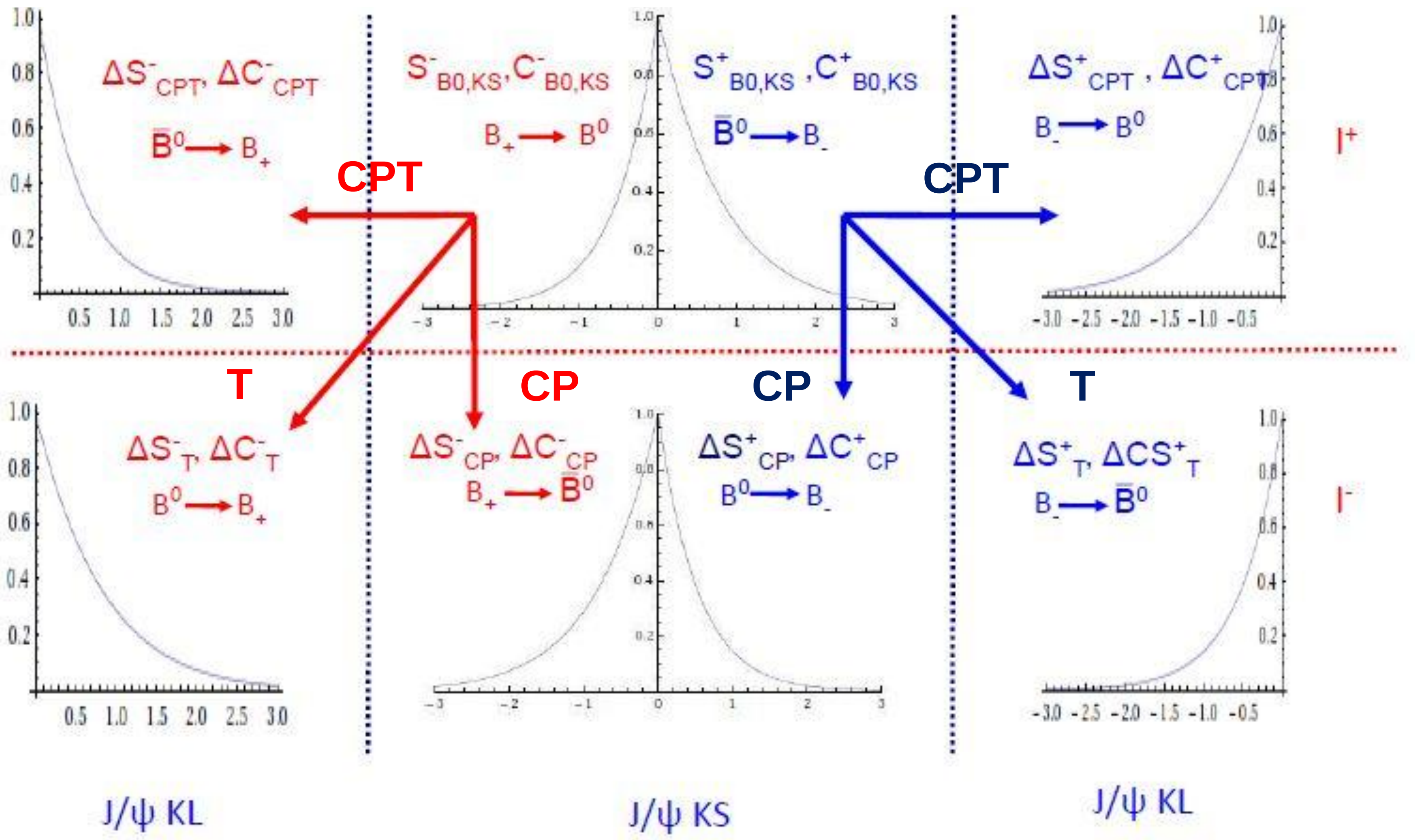


Assumes CPT and $\Delta\Gamma = 0$

Fitting strategy

- From the $\mathrm{B_{flav}}$ sample we extract the time resolution parameters and the wrong flavor ID fractions which are exported to the CP ($c\bar{c}K_S, J/\psi K_L$) sample.
- Perform simultaneous UML fit to B^0, $\bar{B}^0$, $c\bar{c}K_S$, and $J/\psi K_L$ for $\Delta t > 0$ and $\Delta t < 0$ events.
- Normalize PDF simultaneously for $B^0, \bar{B}^0$ and $\Delta t > 0$ and $\Delta t < 0$ and independently for $c\bar{c}K_S$, $J/\psi K_L$.
- Obtain the 8 sets of S, C parameters, and from these, define T, CP and CPT violating parameters ΔS, ΔC.

$(\Delta S^{\pm}, \Delta C^{\pm})$ parameters



($S^{\pm}$, $C^{\pm}$)-($\Delta S^{\pm}$, $\Delta C^{\pm}$) parameters: approx. expected values

($\Delta S^{\pm}$, $\Delta C^{\pm}$) parameters

Param.	Expected Value	Param.	Expected Value
$S^{+}_{B0,KS}$	0.7	$C^{+}_{B0,KS}$	0.
$S^{-}_{B0,KS}$	-0.7	$C^{-}_{B0,KS}$	0.
ΔS^{+}_{T}	-1.4	ΔC^{+}_{T}	0.
ΔS^{-}_{T}	1.4	ΔC^{-}_{T}	0.
ΔS^{+}_{CP}	-1.4	ΔC^{+}_{CP}	0.
ΔS^{-}_{CP}	1.4	ΔC^{-}_{CP}	0.
ΔS^{+}_{CPT}	0.	ΔC^{+}_{CPT}	0.
ΔS^{-}_{CPT}	0.	ΔC^{-}_{CPT}	0.

E.g. T is violated:

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

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

Complete results

Parameter	Final result
$\Delta S_{\mathrm{T}}^{+}$	$-1.37 \pm 0.14 \pm 0.06$
$\Delta S_{\mathrm{T}}^{-}$	$1.17 \pm 0.18 \pm 0.11$
$\Delta C_{\mathrm{T}}^{+}$	$0.10 \pm 0.16 \pm 0.08$
$\Delta C_{\mathrm{T}}^{-}$	$0.04 \pm 0.16 \pm 0.08$
$\Delta S_{\mathrm{CP}}^{+}$	$-1.30 \pm 0.10 \pm 0.07$
$\Delta S_{\mathrm{CP}}^{-}$	$1.33 \pm 0.12 \pm 0.06$
$\Delta C_{\mathrm{CP}}^{+}$	$0.07 \pm 0.09 \pm 0.03$
$\Delta C_{\mathrm{CP}}^{-}$	$0.08 \pm 0.10 \pm 0.04$
$\Delta S_{\mathrm{CPT}}^{+}$	$0.16 \pm 0.20 \pm 0.09$
$\Delta S_{\mathrm{CPT}}^{-}$	$-0.03 \pm 0.13 \pm 0.06$
$\Delta C_{\mathrm{CPT}}^{+}$	$0.15 \pm 0.17 \pm 0.07$
$\Delta C_{\mathrm{CPT}}^{-}$	$0.03 \pm 0.14 \pm 0.08$
$S_{\mathrm{B^0,K_S^0}}^{+}$	$0.545 \pm 0.084 \pm 0.06$
$S_{\mathrm{B^0,K_S^0}}^{-}$	$-0.660 \pm 0.059 \pm 0.04$
$C_{\mathrm{B^0,K_S^0}}^{+}$	$0.011 \pm 0.064 \pm 0.05$
$C_{\mathrm{B^0,K_S^0}}^{-}$	$-0.049 \pm 0.056 \pm 0.03$

T

CP

CPT

REF.

Systematic uncertainties

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

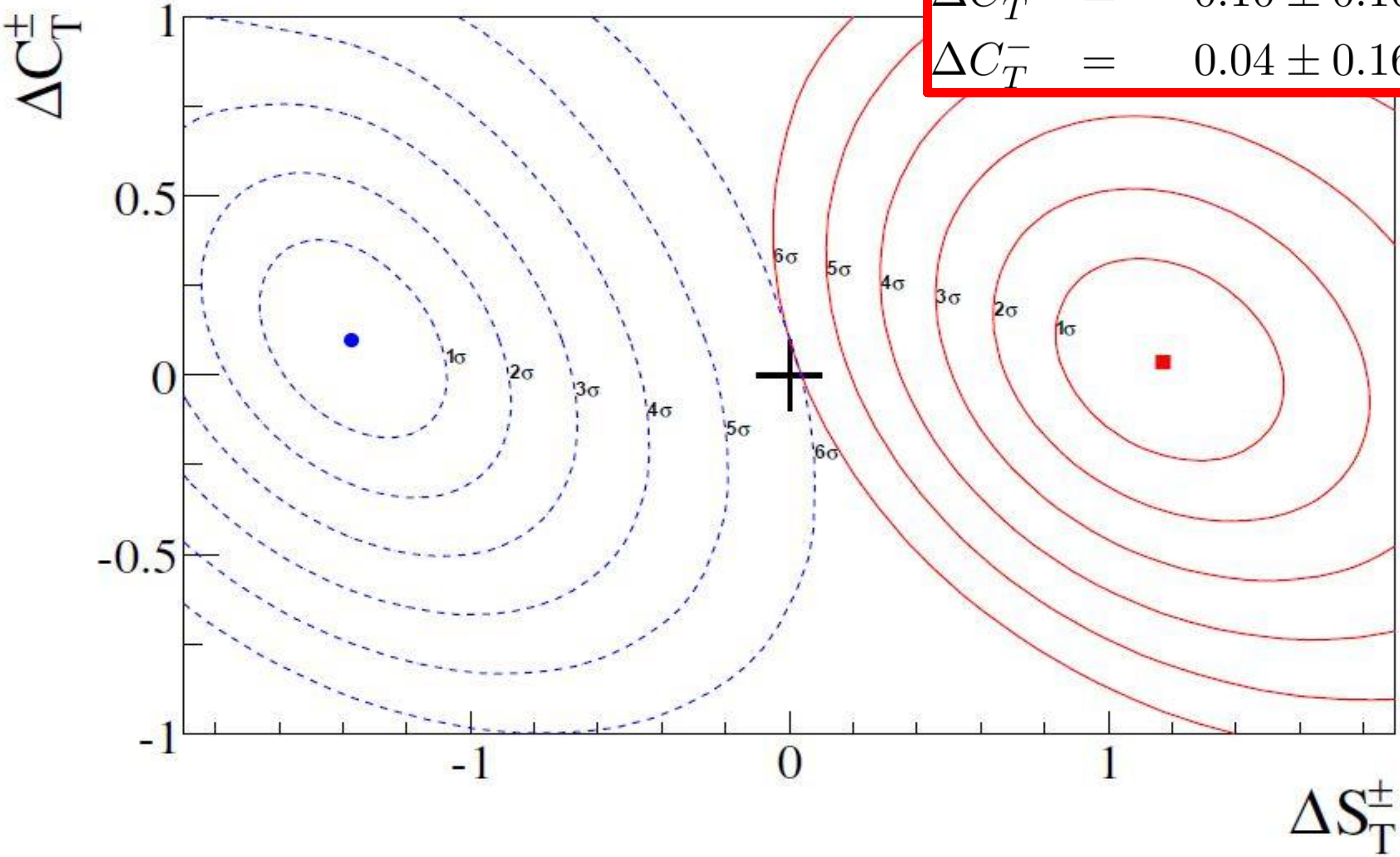
SUMMARY

AND

INTERPRETATION

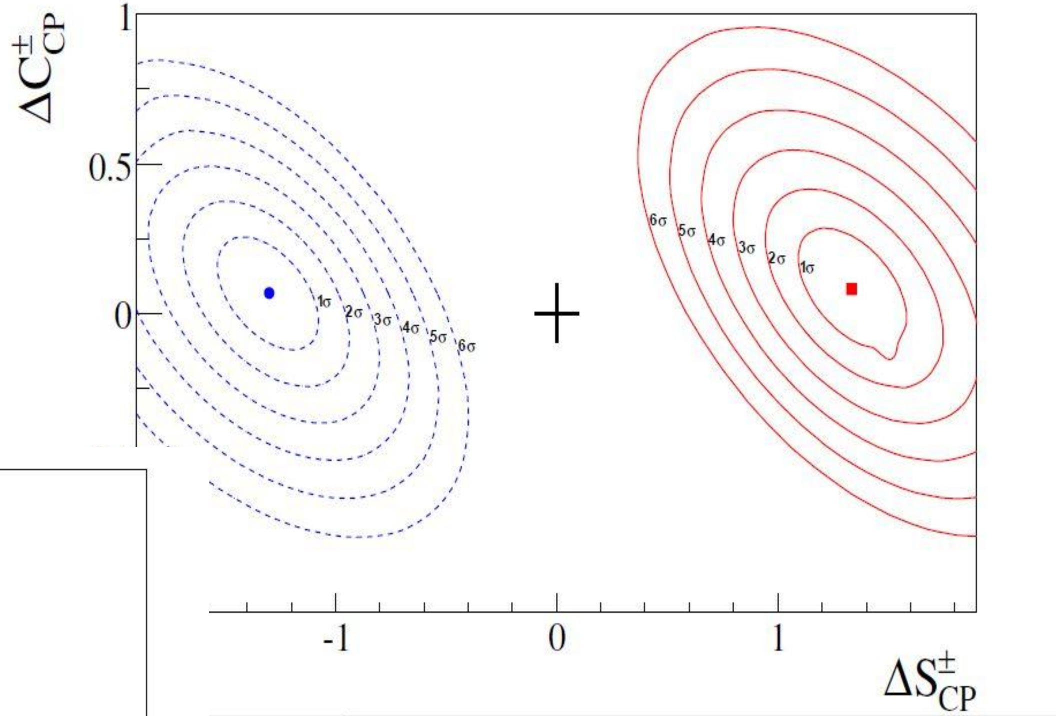
Interpretation of the results

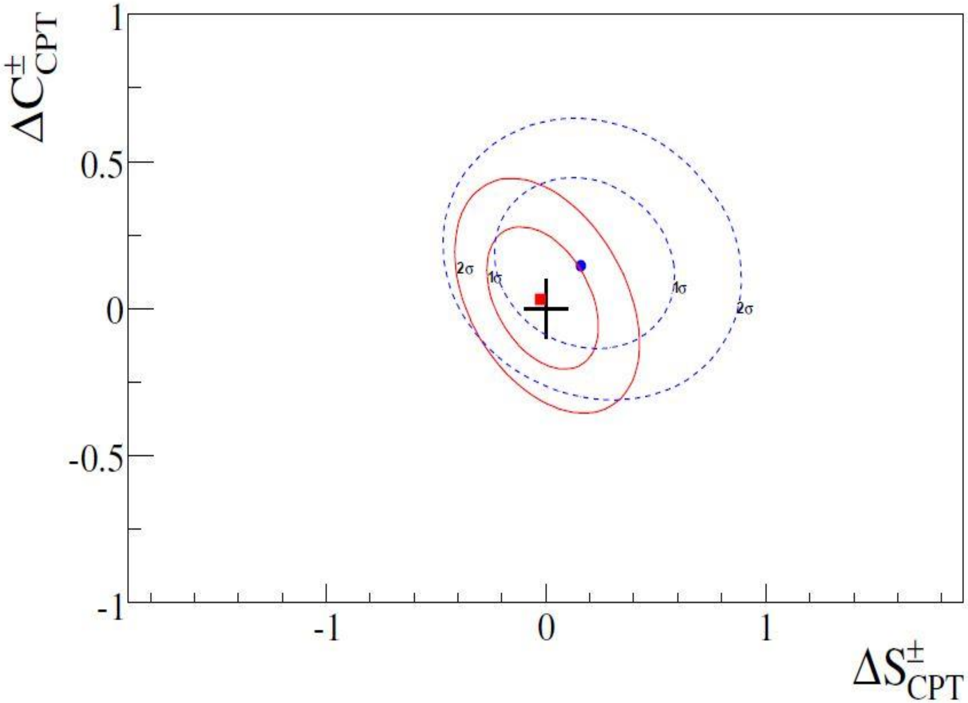
$$\begin{aligned}
\Delta S_T^+ &= -1.37 \pm 0.14 \pm 0.06 \\
\Delta S_T^- &= 1.17 \pm 0.18 \pm 0.11 \\
\Delta C_T^+ &= 0.10 \pm 0.16 \pm 0.08 \\
\Delta C_T^- &= 0.04 \pm 0.16 \pm 0.08
\end{aligned}$$



Interpretation of the results

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





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

Significance of T violation

T invariance
$\Delta S_T^+ = 0$
$\Delta S_T^- = 0$
$\Delta S_{CP}^+ = \Delta S_{CPT}^+$
$\Delta S_{CP}^- = \Delta S_{CPT}^-$
$\Delta C_T^+ = 0$
$\Delta C_T^- = 0$
$\Delta C_{CP}^+ = \Delta C_{CPT}^+$
$\Delta C_{CP}^- = \Delta C_{CPT}^-$

1. We obtain the likelihood value of the fit to S, C for the 8 independent samples (Standard Fit).
2. We repeat the fit, reassembling the parameters for T-conjugated processes, to forbid T violation.
3. Significance of T violation evaluated from the difference of the likelihood values.
4. Raw asymmetries and fit projections can be now plotted in the standard way.

$$\boxed{\begin{aligned} &\Delta\chi^2 = -2(\ln L_{No\_T\_Violation} - \ln L) \\ &\Delta\nu = 8 \end{aligned}}$$

5. CP, and CPT significance is evaluated similarly.
6. Using Gaussian approximation, we evaluate the change of likelihood in 1σ systematic variation.

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

7. We take the max{m_j^2} and we devide our significace (s^2) by (1+ max{m_j^2})

Asymmetries

- Example of asymmetry building for T-Violation:

$H^{\pm}_{\alpha,\beta}(\Delta t)$ is the intensity for each sample with Δt>0 and all experimental effects.

$$A_T(\Delta t) \equiv \frac{H^{-}_{l^-,K_L}(\Delta t) - H^{+}_{K_S,l^+}(\Delta t)}{H^{-}_{l^-,K_L}(\Delta t) + H^{+}_{K_S,l^+}(\Delta t)} \approx \boxed{\frac{\Delta C_T^{+}}{2}\cos\Delta m\Delta t + \frac{\Delta S_T^{+}}{2}\sin\Delta m\Delta t}$$

Where:

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

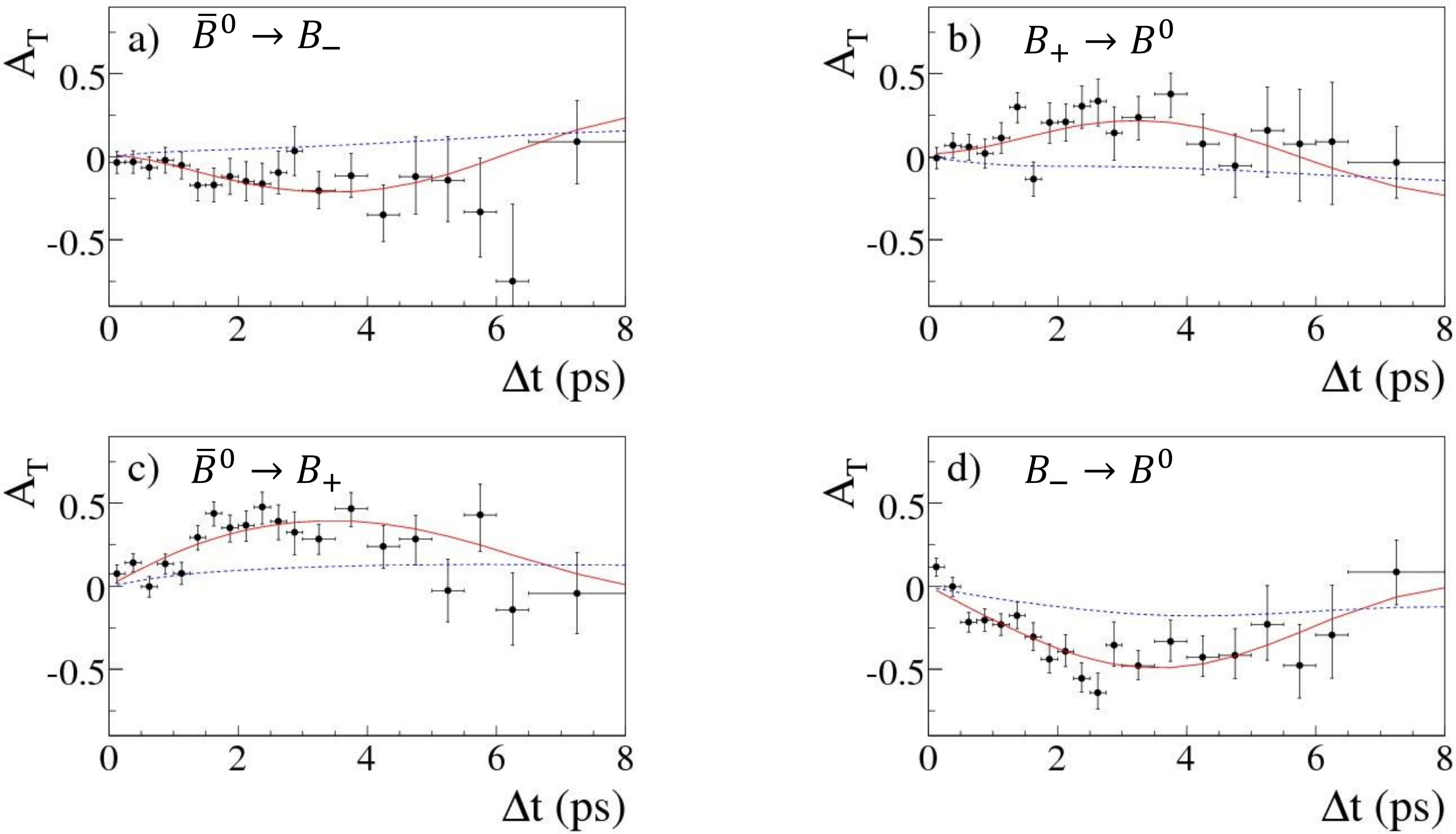
Assuming no experimental effects

T raw asymmetries + significance

Significance test

$$s^2_{NoT} = 226 \quad 14\sigma$$
$$s^2_{NoCP} = 307 \quad 16.6\sigma$$
$$s^2_{NoCPT} = 5 \quad 0.33\sigma$$

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



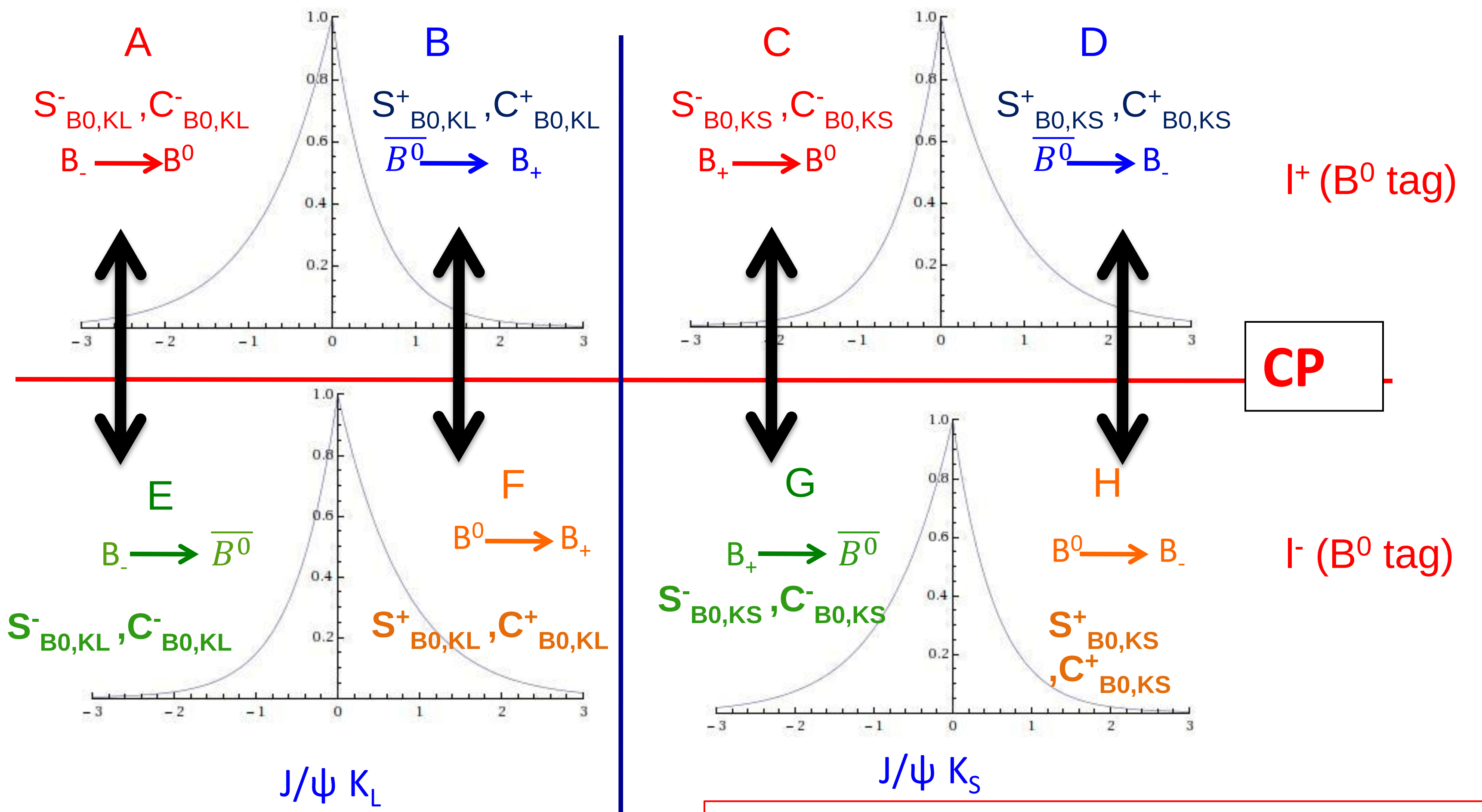
CONCLUSIONS

Conclusions

- We have measured T-violating parameters in the time evolution of neutral-B mesons.
- These parameters have been measured:
  - Directly: without exp. connection to CP and CPT.
  - Genuinely: exchanging *in-states* and *out-states*.
- We observe a large deviation of T invariance at 14σ level.
- Our result is consistent with CP-violating measurements assuming CPT invariance.
- This constitutes the first direct observation of Time Reversal Violation, in any system.

BACK-UP

($S^{\pm}$, $C^{\pm}$) parameters and CP asymmetries



A
B
C
D

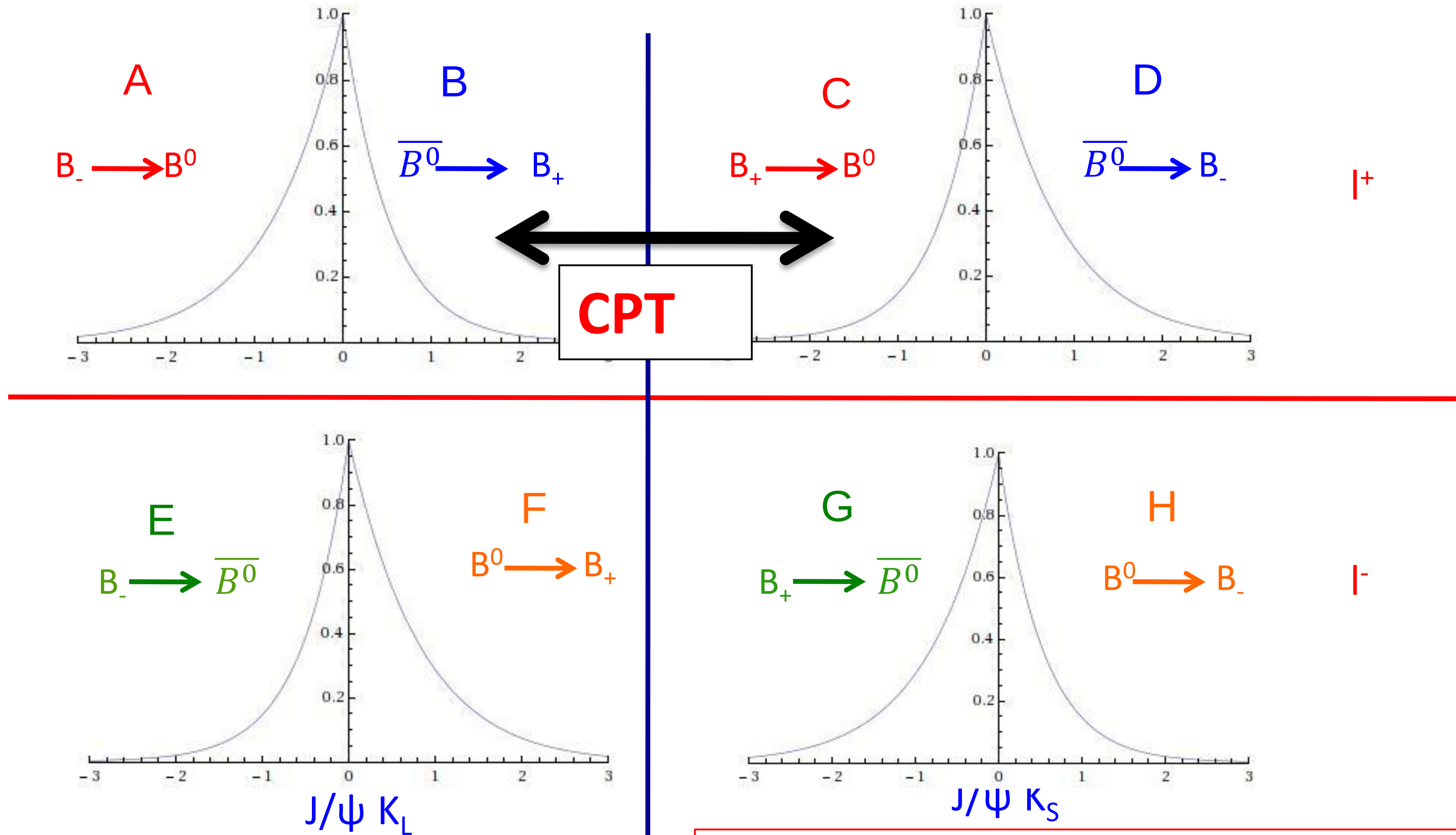
CP $\rightarrow$

E
F
G
H

CP implies comparison of:

1) Same Δt sign.
2) Same reco states (only $J/\Psi K_S$ or $J/\Psi K_L$).
3) Opposite tag states (B^0 vs $\bar{B}^0$).

($S^{\pm}$, $C^{\pm}$) parameters and CPT asymmetries



A → **D**
B → **C**
F → **G**
H → **E**

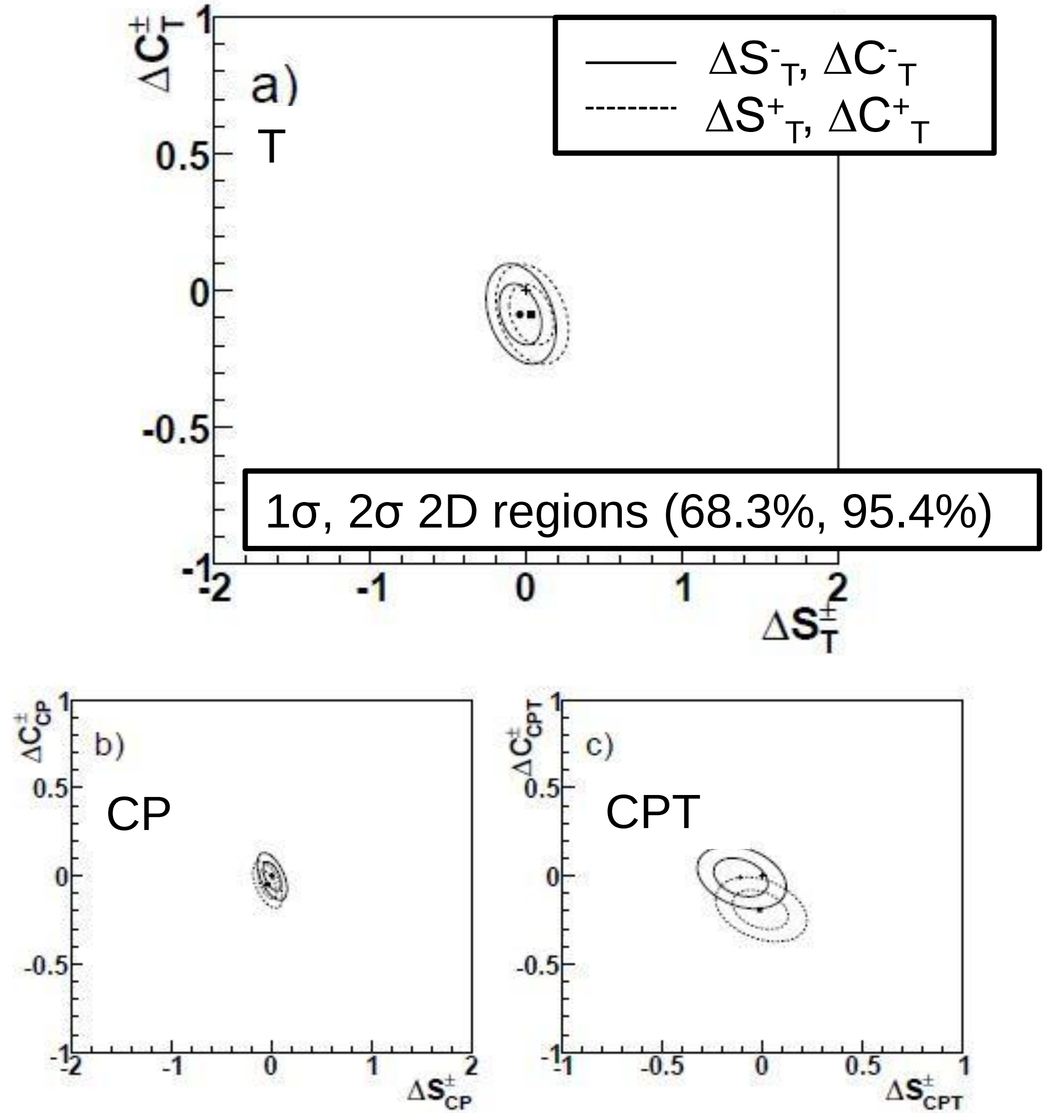
CPT

CPT implies comparison of:
1) Opposite Δt sign.
2) Different reco states ($J/\Psi K_S$ vs. $J/\Psi K_L$).
3) Same tag states (only B^0 or $\bar{B}^0$).

Fitting Fit results (Control Data Sample)

$ccK^{\pm}$ as $J/\psi K_S$
$J/\psi K^{*+}$ as $J/\psi K_L$

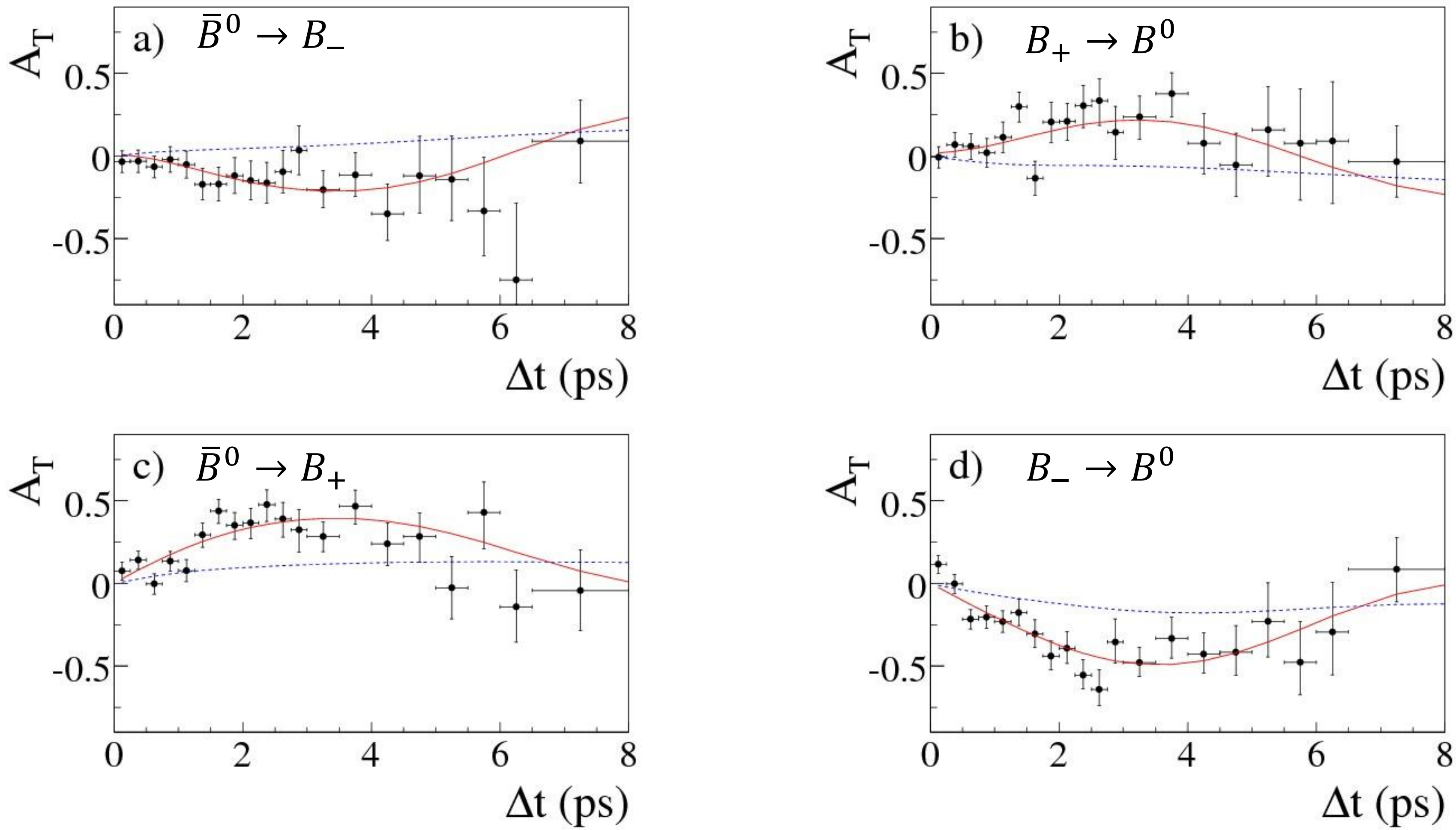
Parameter	Value
$\Delta C^{-}_{\mathrm{CP}}$	0.036 ± 0.050
$\Delta C^{-}_{\mathrm{CPT}}$	-0.0042 ± 0.068
$\Delta C^{-}_{\mathrm{T}}$	-0.0405 ± 0.073
$\Delta C^{+}_{\mathrm{CP}}$	-0.0044 ± 0.049
$\Delta C^{+}_{\mathrm{CPT}}$	-0.1586 ± 0.070
$\Delta C^{+}_{\mathrm{T}}$	-0.0237 ± 0.073
$\Delta S^{-}_{\mathrm{CP}}$	0.088 ± 0.054
$\Delta S^{-}_{\mathrm{CPT}}$	-0.1035 ± 0.083
$\Delta S^{-}_{\mathrm{T}}$	0.041 ± 0.089
$\Delta S^{+}_{\mathrm{CP}}$	0.041 ± 0.053
$\Delta S^{+}_{\mathrm{CPT}}$	0.030 ± 0.086
$\Delta S^{+}_{\mathrm{T}}$	0.155 ± 0.094
$C^{-}_{\mathrm{B^0,K^0_S}}$	0.025 ± 0.032
$C^{+}_{\mathrm{B^0,K^0_S}}$	0.038 ± 0.031
$S^{-}_{\mathrm{B^0,K^0_S}}$	-0.0072 ± 0.038
$S^{+}_{\mathrm{B^0,K^0_S}}$	-0.0002 ± 0.038



T raw asymmetries (CP Data Sample)

No T violation	
Experimental data	

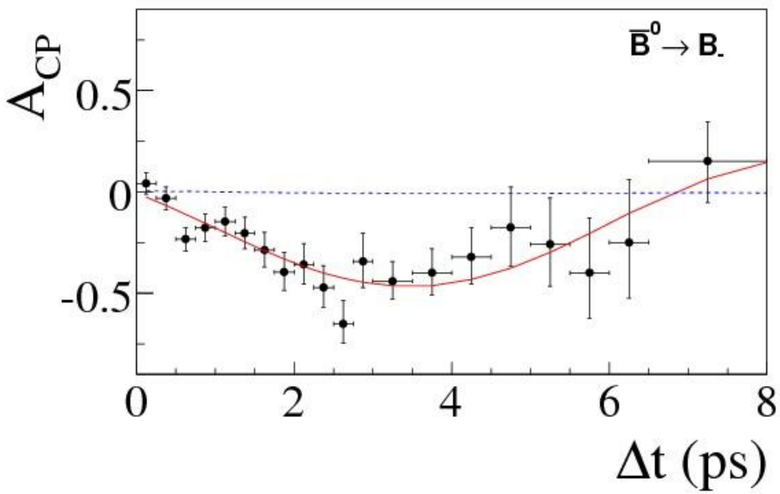
<u>Signal region:</u>
$5.27 < m_{ES} < 5.29$ GeV/c^2
$|E| < 0.010$ GeV

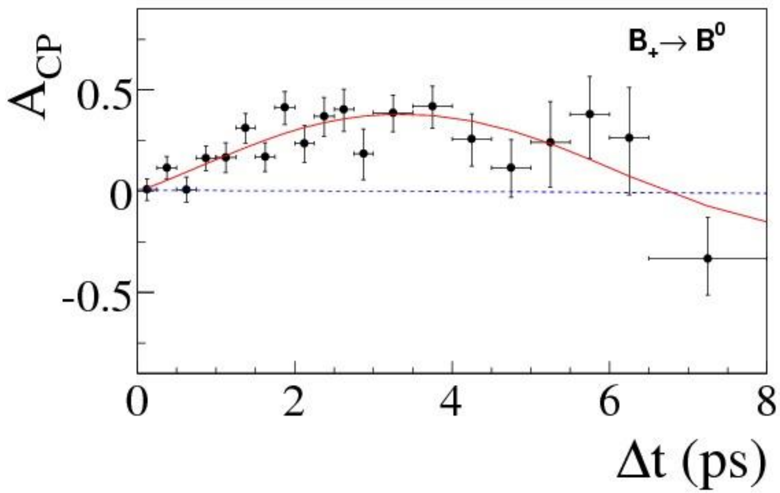


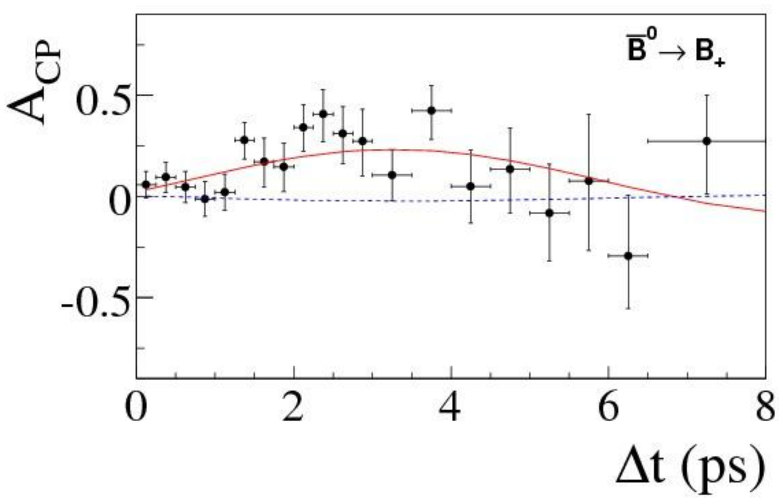
CP raw asymmetries(CP Data Sample)

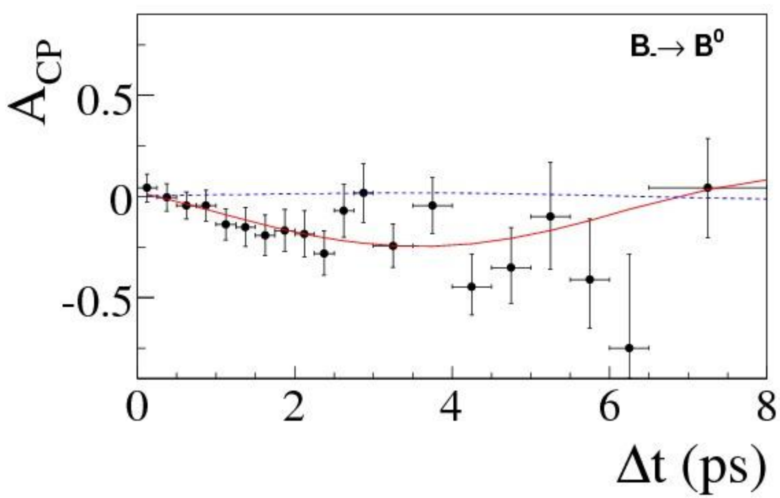
No CP violation
Experimental data

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