DIRECT OBSERVATION OF TIME REVERSAL VIOLATION

Pablo Villanueva Pérez
IFIC (Universitat de València-CSIC)

Outline

- Theoretical Introduction
  - Time Reversal Violation in the neutral B_d-Meson system
- Analysis
  - Monte Carlo study
  - Monte Carlo asymmetry significance

Idea based on

References

- M.C.Bañuls, J.Bernabeu,Phys. Lett. B 464,117(1999)
- M.C Bañuls, J.Bernabeu, Nucl. Phys. B 590,19(2000)
- M.C. Bañuls, J.Bernabeu, JHEP 9906:032(1999)
- T.Nakada, Discrete '08 Conference, Valencia 2008',
J.Phys.Conf.Ser.171:011001, 2009.
- L.Wolfenstein, Int. J. Mod. Phys E 8, 501 (1999)
- H.R. Quinn, Discrete '08 Conference, Valencia 2008, J.Phys.Conf.Ser. 171:011001,2009

THEORETICAL INTRODUCTION

Time Reversal Violation in the neutral B_d-meson system

- Although CPT is a good symmetry it is important the observation of T-Violation INDEPENDENTLY of CP-Violation

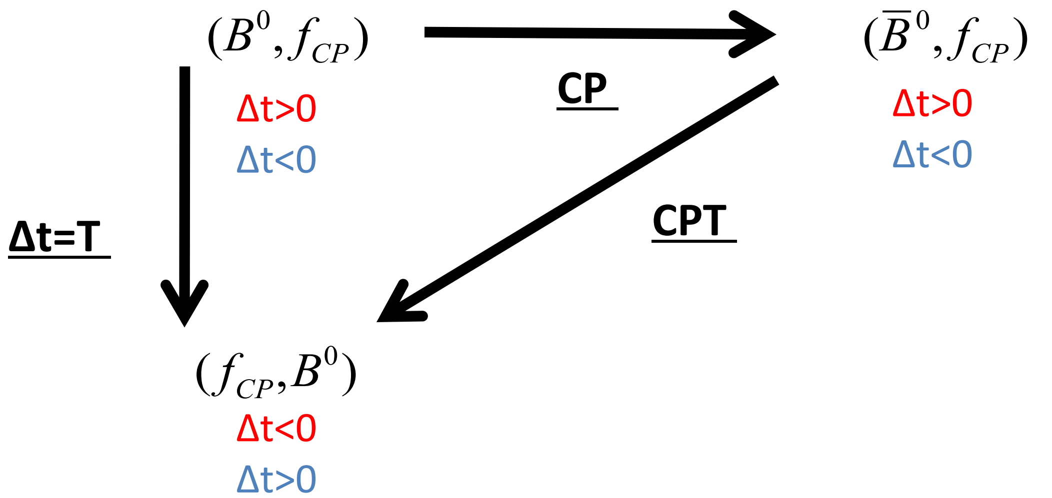
- Kabir asymmetry is not genuine of T reversal

$$\begin{tikzcd}
\begin{matrix}K^0-\overline{K}^0\\ B^0-\overline{B}^0\end{matrix} \arrow[rr, "\text{CPT EVEN!!!!}"] \arrow[d, "\text{CP}"'] \arrow[drr, "\text{T}"] & & \begin{matrix}K^0-\overline{K}^0\\ B^0-\overline{B}^0\end{matrix} \\
\begin{matrix}\overline{K}^0-K^0\\ \overline{B}^0-B^0\end{matrix} & = & \begin{matrix}\overline{K}^0-K^0\\ \overline{B}^0-B^0\end{matrix}
\end{tikzcd}$$

$$\begin{matrix}K^0-\overline{K}^0\\ B^0-\overline{B}^0\end{matrix}$$

Model independent

- The sin(2β) measurement in B^0 / $\bar{B}^0 \longrightarrow c\bar{c}$-$K^0$ at B factories (the angle of the unitary triangle) is a test of CP violation.
  - Asumes CPT invariance and ΔΓ=0 in the analysis
  - Thus, it implies an odd effect in Δt equivalent to T



Genuine

So we are aiming for an ODD and GENUINE T-Violation observable.

Discard effects that are odd under time t to -t

⇓

Non GENUINE T-Violation

⇓

Not an exchange of "in" states into "out" states

Δt=TRV $\longleftrightarrow$ Theory with CPT invariance and absence of absorptive part ($\Delta\Gamma=0$)

Method

- Main ingredient
  - EPR entanglement produced by the decay of the $\Upsilon(4S)$
    - Between neutral B-mesons
    - Between CP-tag (B_+-B_-)

$$|i>=\frac{1}{\sqrt{2}}[B^0(t_1)\overline{B}^0(t_2)-B^0(t_2)\overline{B}^0(t_1)]$$

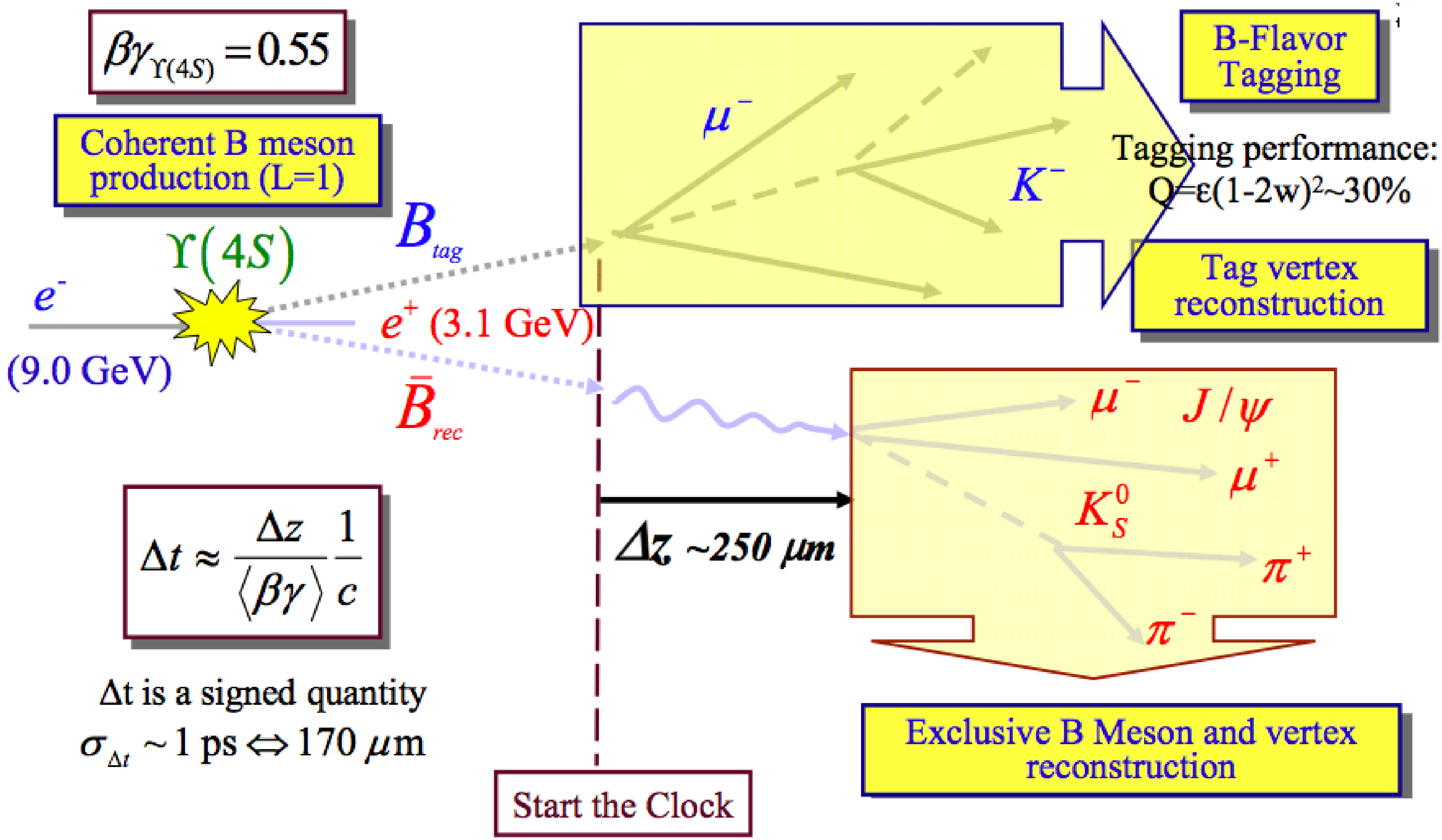
$$=\frac{1}{\sqrt{2}}[B_+(t_1)B_-(t_2)-B_+(t_2)B_-(t_1)]$$

Considering B_+ and B_-, the states where B_- is filtered for example by the decay J/ψ K_+, K_+ being the neutral K-meson decaying to π π, and B_+ is the orthogonal B_- to J/ψ K_+.

We chose the following processes as a reference to generate CP, T and CPT transformations (model independent) ⟷

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

Foundations of the study



$B^0 \longrightarrow B_- \longrightarrow (l^-,\ J/\psi\ K_S)$

Method

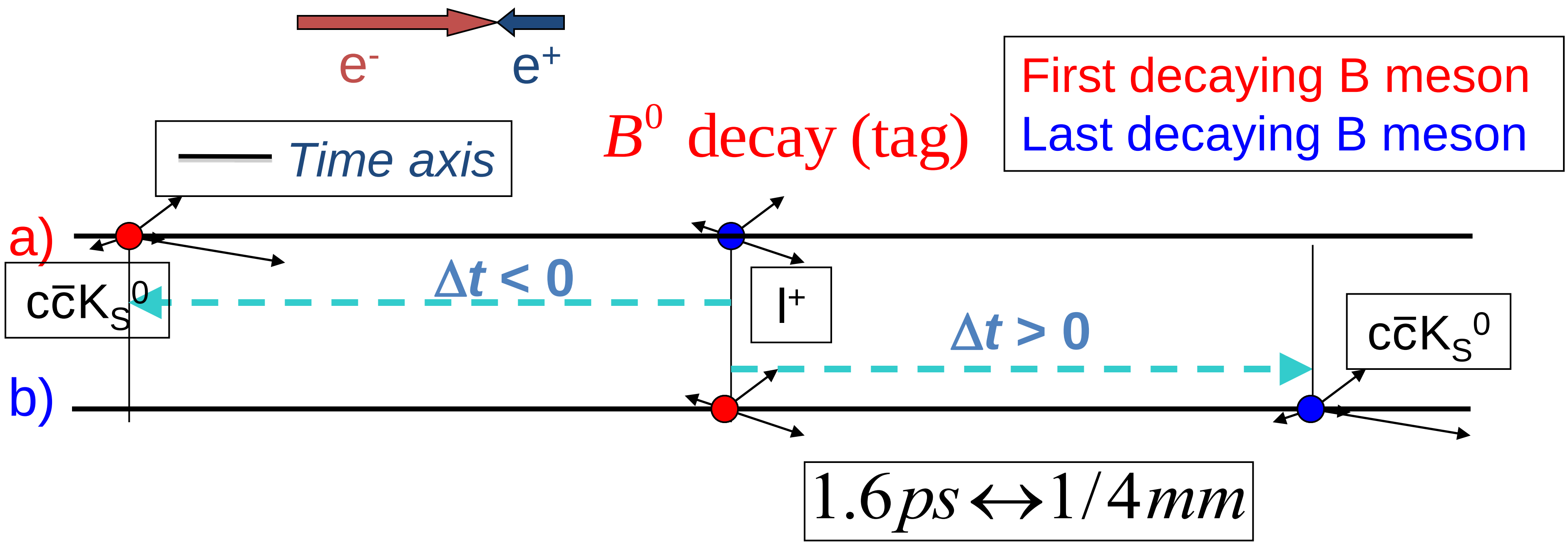
Reference: Physical Process
(X,Y): Reconstructed Final States

- T conjugated processes

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

We Impose: $\Delta t = t_Y - t_X > 0$

Foundations of the study



Process	Δt	Reconstruction	Physical Process
a)	$\Delta t < 0$	$(c\bar{c}K_S^0,\ l^+)$	$B_+ \rightarrow B^0$
b)	$\Delta t > 0$	$(l^+,\ c\bar{c}K_S^0)$	$\bar{B}^0 \rightarrow B_-$

Asymmetries

- Asymmetries for T-Violation

$$A_{T,1} = \frac{\Gamma(l^-, J/\psi K_L) - \Gamma(J/\psi K_S, l^+)}{\Gamma(l^-, J/\psi K_L) + \Gamma(J/\psi K_S, l^+)}$$

$$A_{T,2} = \frac{\Gamma(l^-, J/\psi K_S) - \Gamma(J/\psi K_L, l^+)}{\Gamma(l^-, J/\psi K_S) + \Gamma(J/\psi K_L, l^+)}$$

$$A_{T,3} = \frac{\Gamma(l^+, J/\psi K_L) - \Gamma(J/\psi K_S, l^-)}{\Gamma(l^+, J/\psi K_L) + \Gamma(J/\psi K_S, l^-)}$$

$$A_{T,4} = \frac{\Gamma(l^+, J/\psi K_S) - \Gamma(J/\psi K_L, l^-)}{\Gamma(l^+, J/\psi K_S) + \Gamma(J/\psi K_L, l^-)}$$

Asymmetries

- Asymmetries for CP-Violation:

$$A_{CP,1} = \frac{\Gamma(l^-, J/\psi K_L) - \Gamma(l^+, J/\psi K_L)}{\Gamma(l^-, J/\psi K_L) + \Gamma(l^+, J/\psi K_L)}$$

$$A_{CP,2} = \frac{\Gamma(l^-, J/\psi K_S) - \Gamma(l^+, J/\psi K_S)}{\Gamma(l^-, J/\psi K_S) + \Gamma(l^+, J/\psi K_S)}$$

$$A_{CP,3} = \frac{\Gamma(l^+, J/\psi K_L) - \Gamma(l^-, J/\psi K_L)}{\Gamma(l^+, J/\psi K_L) + \Gamma(l^-, J/\psi K_L)}$$

$$A_{CP,4} = \frac{\Gamma(l^+, J/\psi K_S) - \Gamma(l^-, J/\psi K_S)}{\Gamma(l^+, J/\psi K_S) - \Gamma(l^-, J/\psi K_S)}$$

Asymmetries

- Asymmetries for CPT-Violation:

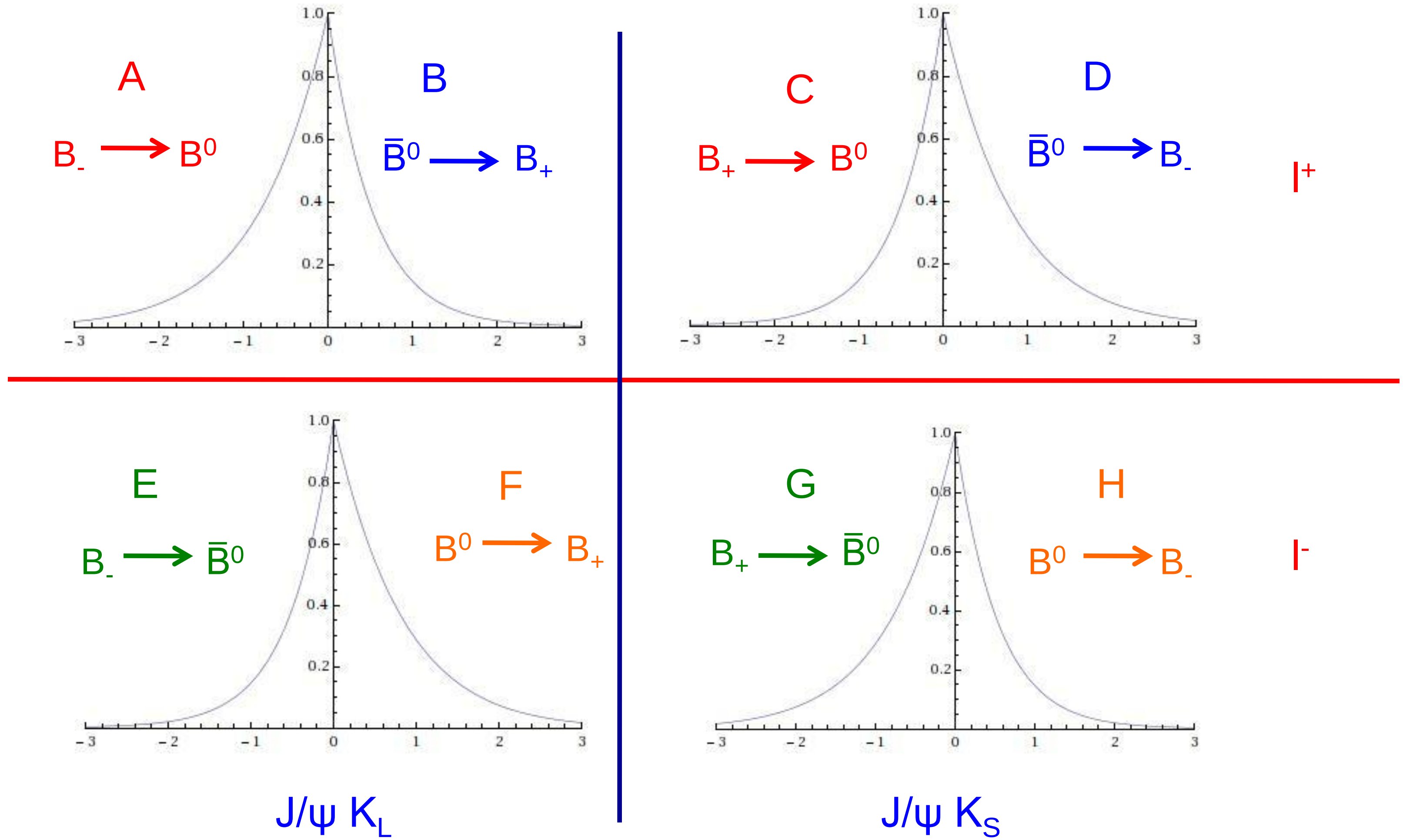
$$A_{CPT,1} = \frac{\Gamma(l^-, J/\psi K_L) - \Gamma(J/\psi K_S, l^-)}{\Gamma(l^-, J/\psi K_L) + \Gamma(J/\psi K_S, l^-)}$$

$$A_{CPT,2} = \frac{\Gamma(l^-, J/\psi K_S) - \Gamma(J/\psi K_L, l^-)}{\Gamma(l^-, J/\psi K_S) + \Gamma(J/\psi K_L, l^-)}$$

$$A_{CPT,3} = \frac{\Gamma(l^+, J/\psi K_L) - \Gamma(J/\psi K_S, l^+)}{\Gamma(l^+, J/\psi K_L) + \Gamma(J/\psi K_S, l^+)}$$

$$A_{CPT,4} = \frac{\Gamma(l^+, J/\psi K_S) - \Gamma(J/\psi K_L, l^+)}{\Gamma(l^+, J/\psi K_S) + \Gamma(J/\psi K_L, l^+)}$$

Asymmetries building

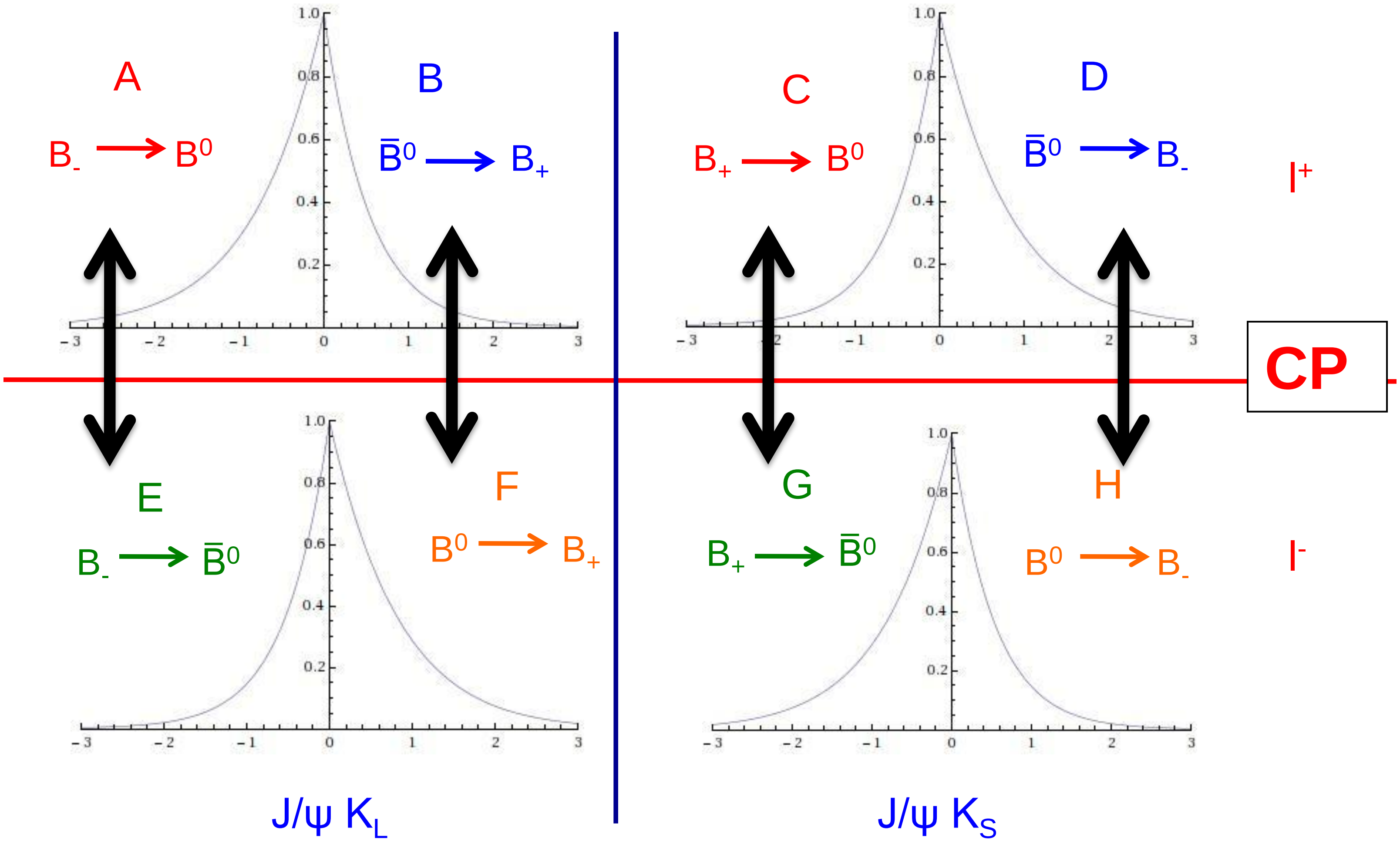


T: F vs. C, H vs. A, B vs. G , and D vs. E

CP: A vs. E, F vs. B, G vs. C, and H vs. D

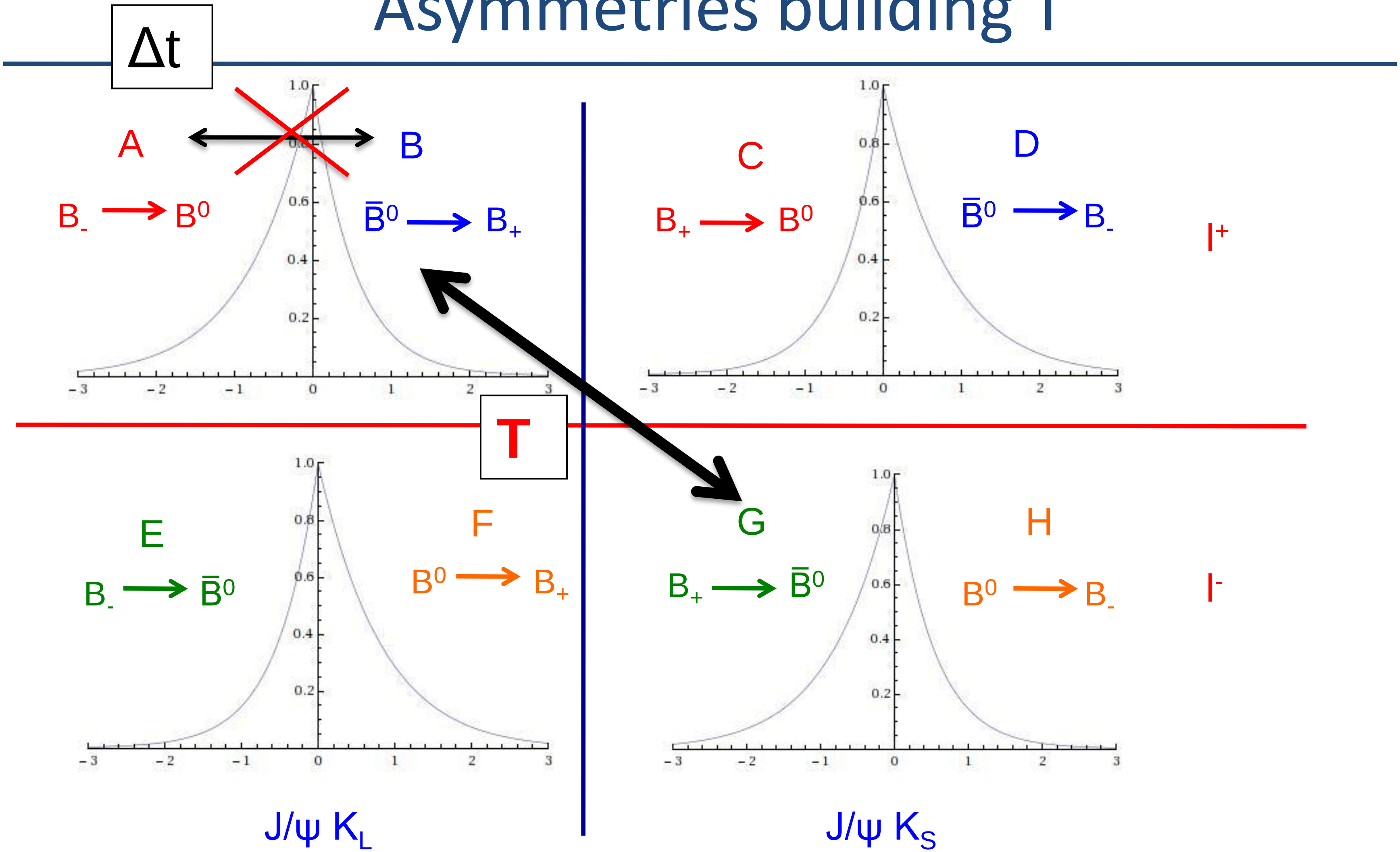
CPT: F vs. G, E vs. H, B vs. C, and A vs. D

Asymmetries building CP



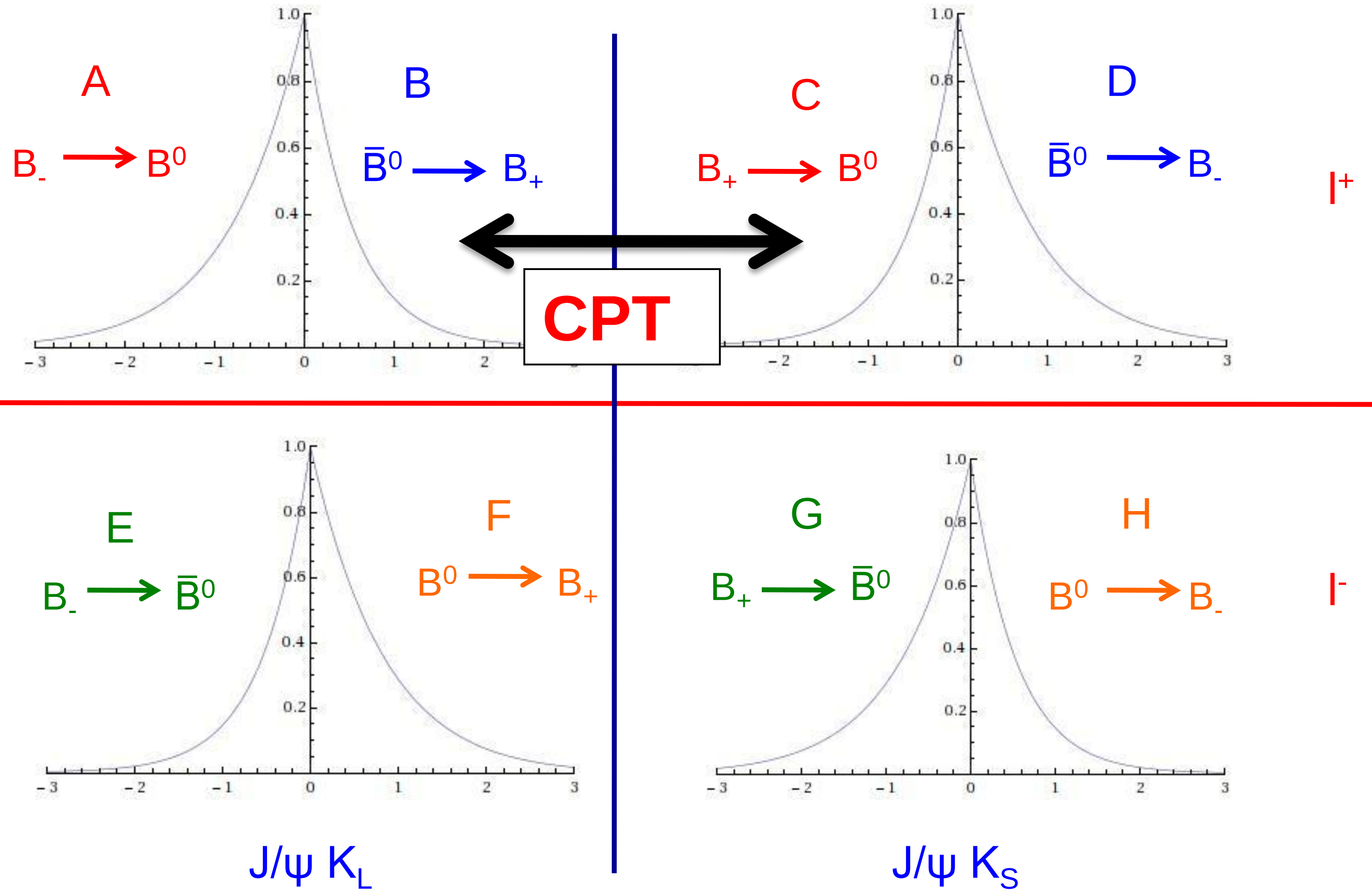
T: F vs. C, H vs. A, B vs. G , and D vs. E
CP: A vs. E, F vs. B, G vs. C, and H vs. D
CPT: F vs. G, E vs. H, B vs. C, and A vs. D

Asymmetries building T



T: F vs. C, H vs. A, B vs. G , and D vs. E
CP: A vs. E, F vs. B, G vs. C, and H vs. D
CPT: F vs. G, E vs. H, B vs. C, and A vs. D

Asymmetries building CPT



T: F vs. C, H vs. A, B vs. G , and D vs. E
CP: A vs. E, F vs. B, G vs. C, and H vs. D
CPT: F vs. G, E vs. H, B vs. C, and A vs. D

MONTE CARLO STUDY

Monte Carlo generation

– We simulate the events with a Probability Density Function (PDF) which includes T, CP and CPT violation parameters

– This PDF is based on the Wigner-Weiskopff approximation

Decay Rate for a neutral B meson to a CP eigenstate (B_+ ,B_-)

$$g_{\pm}(\Delta t) = \frac{e^{-\frac{|\Delta t|}{\tau_{B^0}}}}{4\tau_{B^0}}\{1 \pm [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}$$

$$S_f = \frac{2\,\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2}$$

($\Delta\Gamma$=0, |q/p|=1, |z|=0)

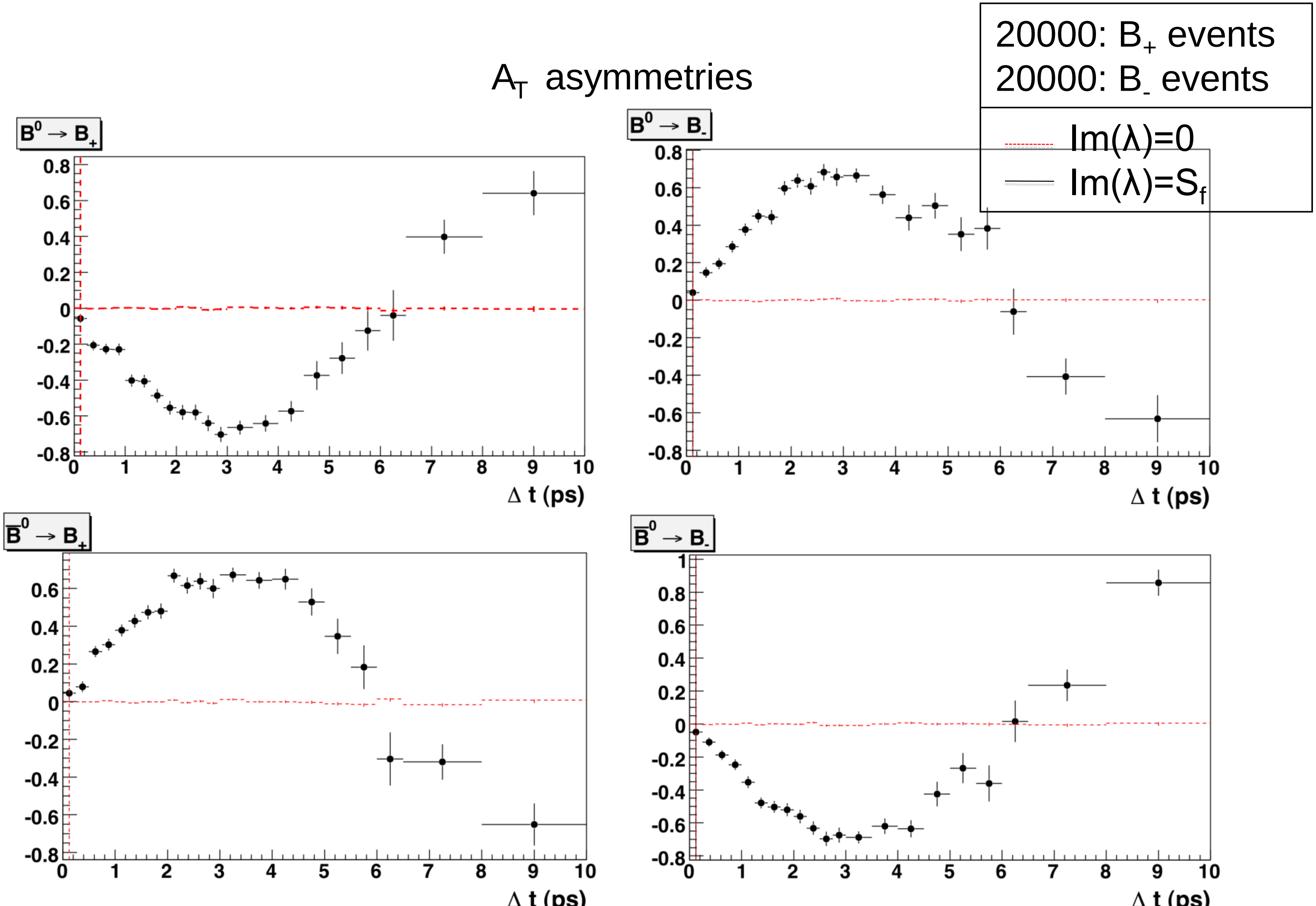
$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

$$\boxed{\begin{array}{l}\mathrm{Im}(\lambda_f) = 0.672 \\ |\lambda_f| = 1\end{array}} \Rightarrow \boxed{\begin{array}{l}S_f = 0.672 \\ C_f = 0\end{array}}$$

References
- Measurement of Time-Dependent CP Asymmetry in B^0-> ccbar$K^{(*)0}$ Decays, Phys. Rev. D. 79, 072009 (2009)
- Limits on the decay-rate difference of neutral B mesons and on CP, T and CPT violation in $B^0\overline{B}^0$, Phys. Rev. D 70, 012007 (2004)
- Measurement of CP asymmetries in B^0-> K^0 π^0 decays, Phys. Rev. D .81, 011101(2010)

Perfect reconstruction

A_T asymmetries



Perfect reconstruction

Asymmetry form

$$A_T = \frac{N_a - N_b}{N_a + N_b}$$

Asymmetry error

$$\delta A_T = \sqrt{\frac{4 N_a N_b}{(N_a + N_b)^3}}$$

This error formula has been calculated:

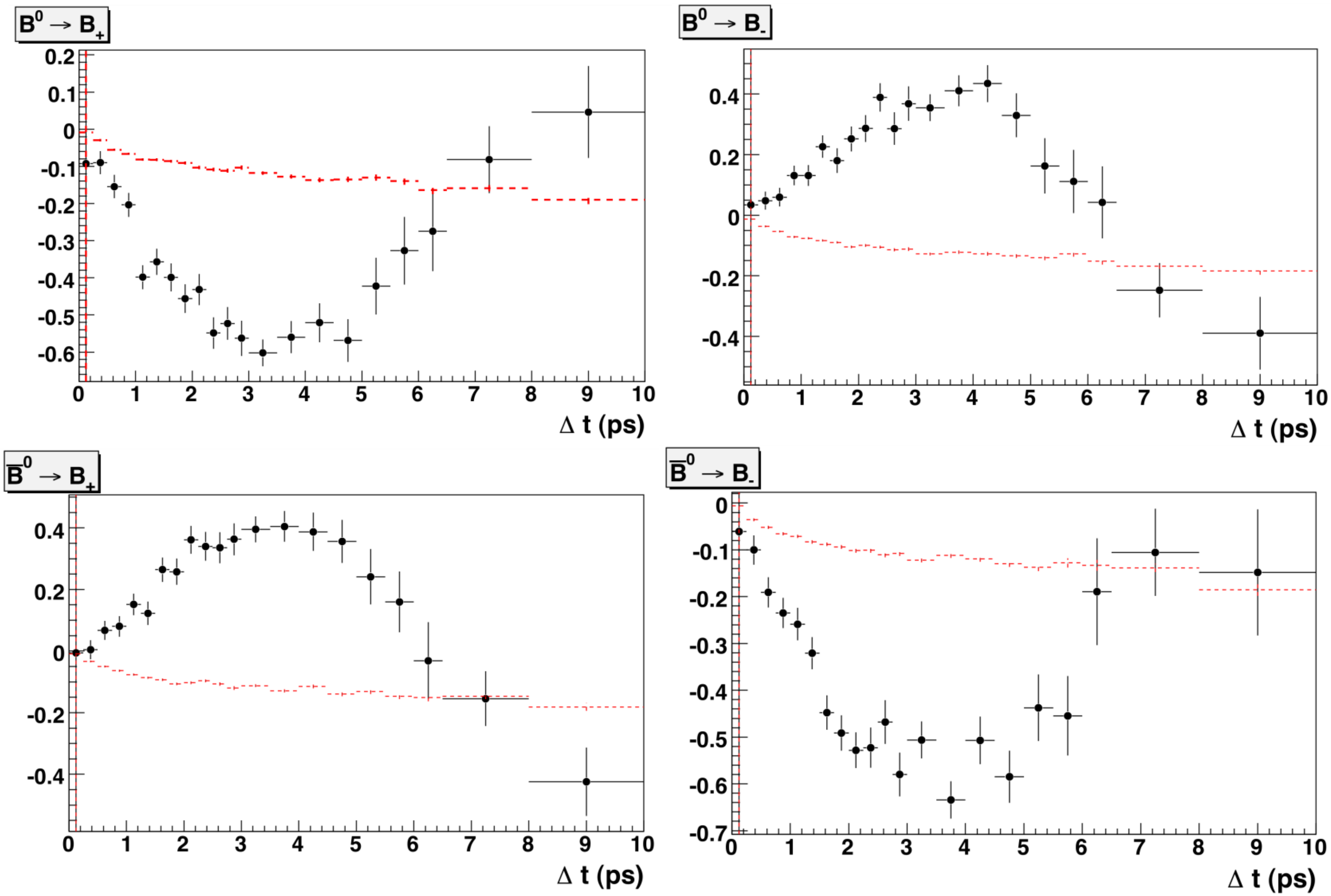
- Using error propagation
- Assumed Poissonian errors

Proper-time resolution and mistags

Im(λ)=0
Im(λ)=S_f

20000: B_+ events
20000: B_- events
ω= 5.3%   Δω=-0.1%

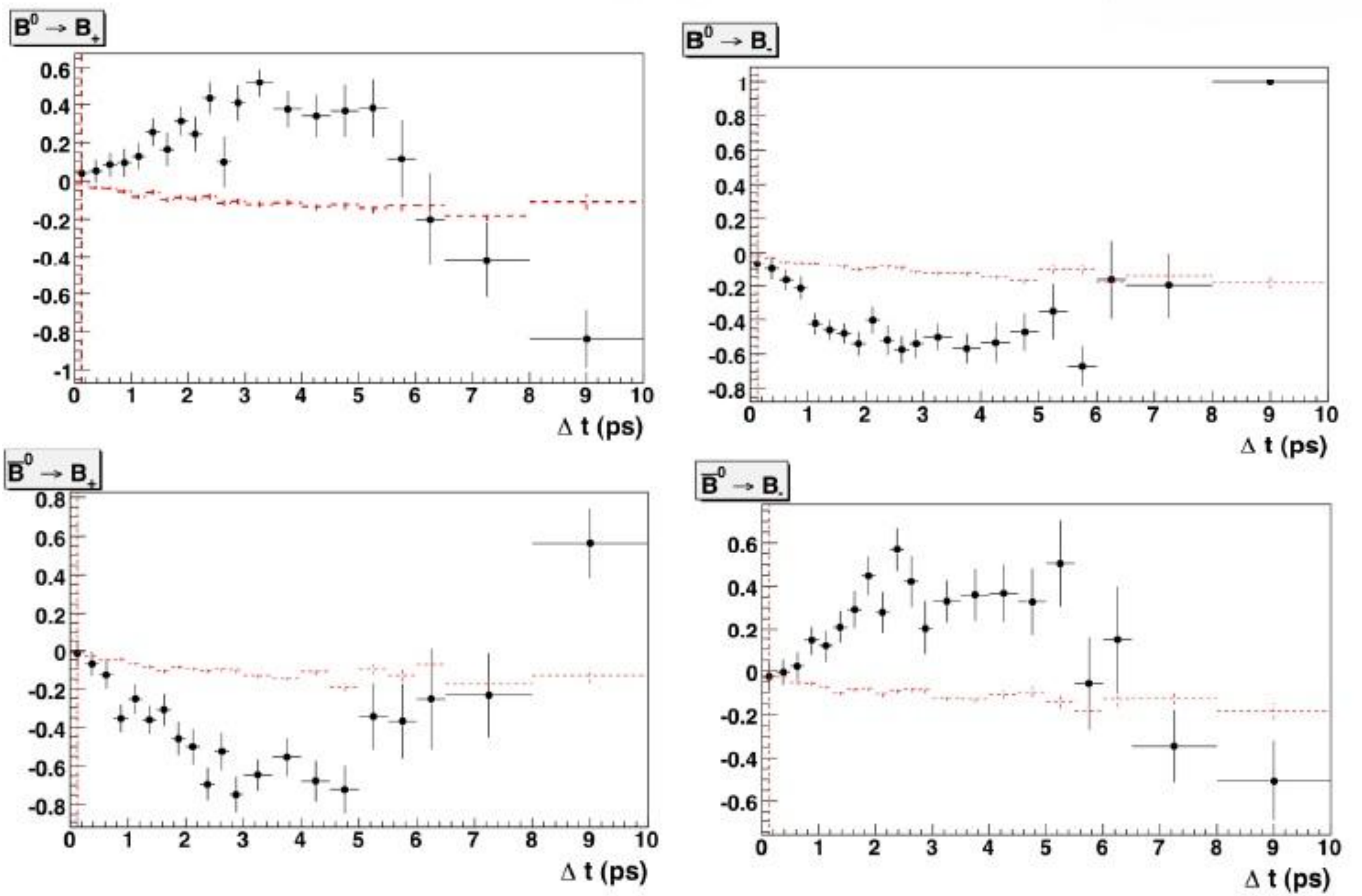
A_T asymmetries



Proper-time resolution, mistags and efficiency effects

3255: B_+ events
7750: B_- events
ω= 5.3% $\Delta\omega$=-0.1% a

A_T asymmetries



Proper-time resolution, mistags and efficiency effects

$$A_T = \frac{N_a - cN_b}{N_a + cN_b}$$

$$\boxed{c = \frac{\varepsilon_{K_S}}{\varepsilon_{K_L}} = \frac{N_{K_S}^{\exp}}{N_{K_L}^{\exp}}}$$

$$\boxed{c = \frac{\varepsilon_{K_L}}{\varepsilon_{K_S}} = \frac{N_{K_L}^{\exp}}{N_{K_S}^{\exp}}}$$

We construct the raw asymmetry:

$$A_T(\Delta t) = \frac{\Gamma_a(\Delta t) - \Gamma_b(\Delta t)}{\Gamma_a(\Delta t) + \Gamma_b(\Delta t)}, \ where\ \Gamma_i = \frac{1}{N_i}\int N_i(\Delta t)d(\Delta t) = 1$$

Error:

$$\delta A_T = \frac{2\sqrt{c^2 N_b^2 N_a + c^2 N_a^2 N_b + N_a^2 N_b^2 \delta c^2}}{(N_a + cN_b)^2}$$

Monte Carlo asymmetry and significance

- χ^2 Test:

$$\chi^2 = \sum_{\Delta t_i} \frac{\left[A_T^{exp}(\Delta t_i) - A_T^{NoT-violation}(\Delta t_i)\right]^2}{\sigma^2_{A_T^{exp}}(\Delta t_i) + \sigma^2_{A_T^{NoT-violation}}(\Delta t_i)}$$

T asymmetries Test	**$B^0 \rightarrow B_+$**	**$B^0 \rightarrow B_-$**	**$\bar{B}^0 \rightarrow B_+$**	**$\bar{B}^0 \rightarrow B_-$**
χ_0^2	99.04, 23 bins	159.47, 22 bins	150.05, 22 bins	106.36, 21 bins
Prob($\chi^2 > \chi_0^2$)	2.06×10^{-11}	7.69×10^{-23}	4.69×10^{-21}	2.13×10^{-13}
Standard Deviations	6.70	9.84	9.42	7.34

Conclusions

- An independent and genuine T Violation analysis has been built, using EPR entanglement.

- It's been tested with MC Data, giving us the chance to perform this test experimentally with more than 5σ.

BACK-UP

Method

- CP and CPT processes:

Reference	(X, Y)	$CP - Transformed$	(X, Y)
$B^0 \longrightarrow B_+$	$(l^-, J\psi K_L)$	$\bar{B}^0 \longrightarrow B_+$	$(l^+, J\psi K_L))$
$B^0 \longrightarrow B_-$	$(l^-, J\psi K_S,)$	$\bar{B}^0 \longrightarrow B_-$	$(l^+, J\psi K_S)$
$B_+ \longrightarrow B^0$	$(J\psi K_S, l^+)$	$B_+ \longrightarrow \bar{B}^0$	$(J\psi K_S, l^-)$
$B_- \longrightarrow B^0$	$(J\psi K_L, l^+)$	$B_- \longrightarrow \bar{B}^0$	$(J\psi K_L, l^-)$

TABLE 2. Transitions and CP transformed transitions

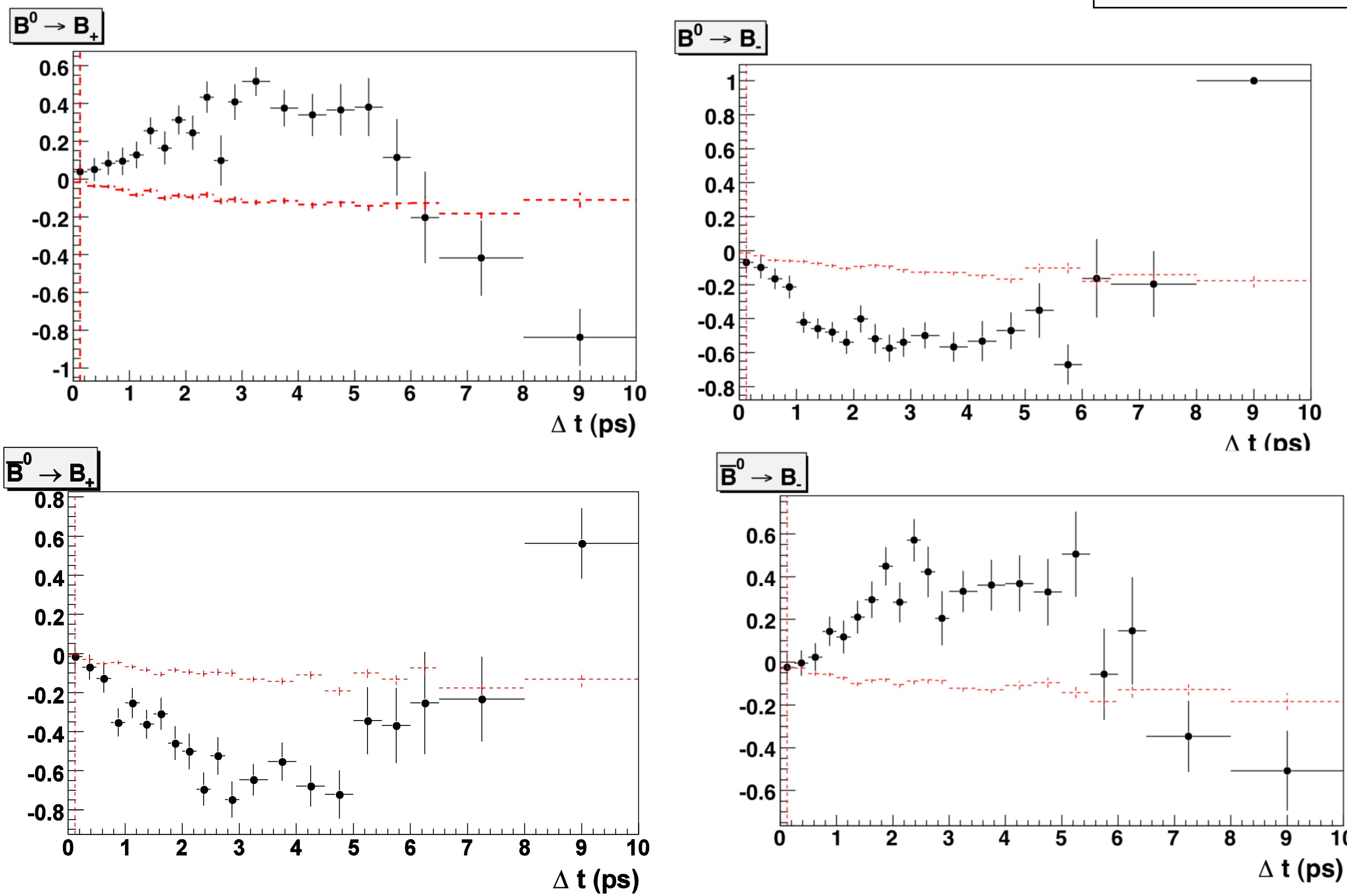
Reference	(X, Y)	$CPT - Transformed$	(X, Y)
$B^0 \longrightarrow B_+$	$(l^-, J\psi K_L)$	$B_+ \longrightarrow \bar{B}^0$	$(J\psi K_S, l^-)$
$B^0 \longrightarrow B_-$	$(l^-, J\psi K_S)$	$B_- \longrightarrow \bar{B}^0$	$(J\psi K_L, l^-)$
$\bar{B}^0 \longrightarrow B_+$	$(l^+, J\psi K_L)$	$B_+ \longrightarrow B^0$	$(J\psi K_S, l^+)$
$\bar{B}^0 \longrightarrow B_-$	$(l^+, J\psi K_S)$	$B_- \longrightarrow B^0$	$(J\psi K_L, l^+)$

TABLE 3. Transitions and CPT transformed transitions

Proper-time resolution, mistags and efficiency effects

3255: B_+ events
7750: B_- events
ω= 5.3% $\Delta\omega$=-0.1% a

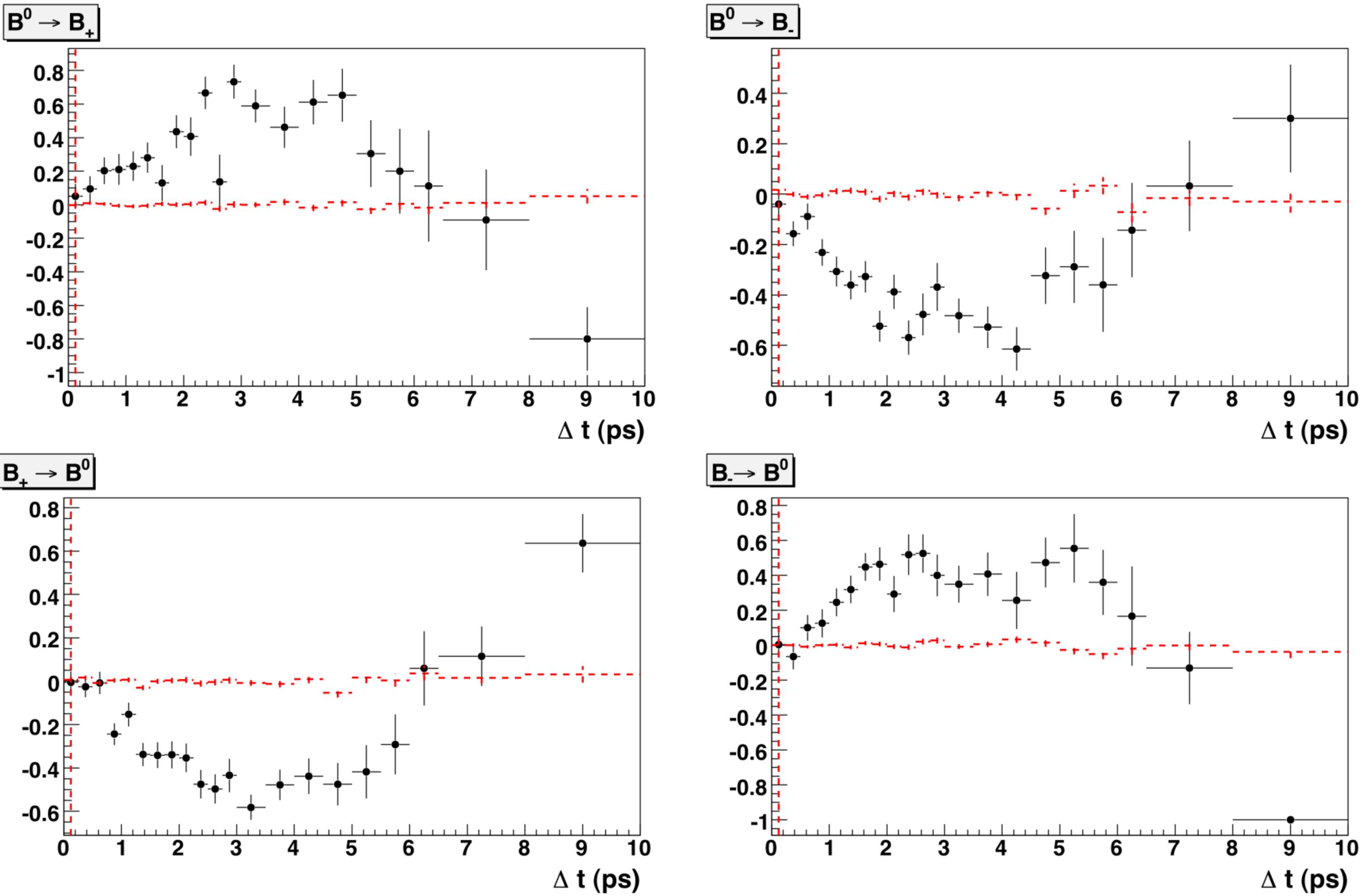
A_T asymmetries



Proper-time resolution, mistags and efficiency effects

3255: B_+ events
7750: B_- events
ω= 5.3% $\Delta\omega$=-0.1%

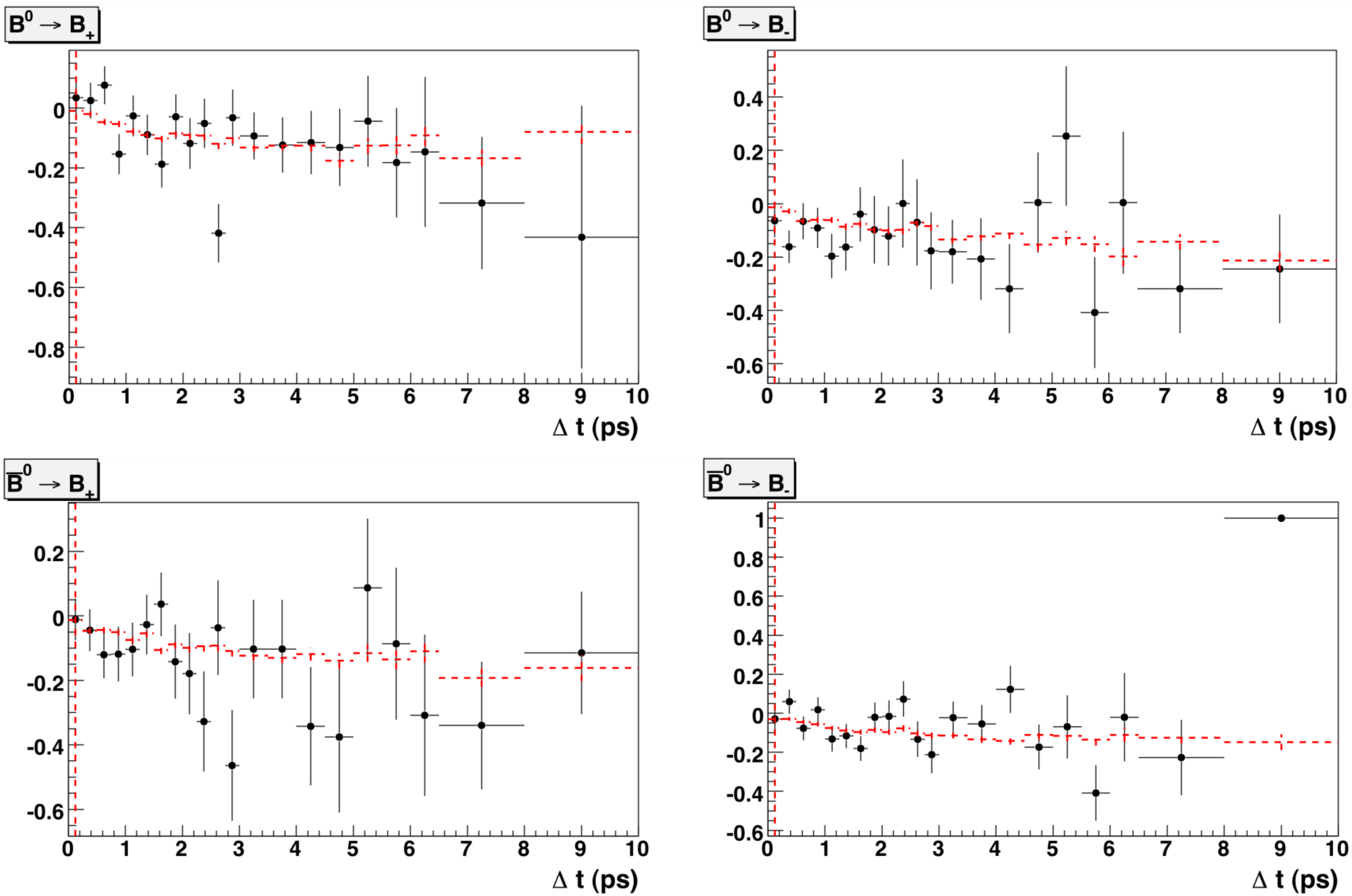
A_{CP} asymmetries



Proper-time resolution, mistags and efficiency effects

3255: B_+ events
7750: B_- events
ω= 5.3% $\Delta\omega$=-0.1%

A_{CPT} asymmetries



Monte Carlo asymmetry and significance

- χ^2 Test:

$$\chi^2 = \sum_{\Delta t_i} \frac{\left[A_{CPT}^{exp}(\Delta t_i) - A_{CPT}^{NoCPT-violation}(\Delta t_i)\right]^2}{\sigma^2_{A_{CPT}^{exp}}(\Delta t_i) + \sigma^2_{A_{CPT}^{NoCPT-violation}}(\Delta t_i)}$$

T asymmetries Test	**$B^0 \rightarrow B_+$**	**$B^0 \rightarrow B_-$**	**$\bar{B}^0 \rightarrow B_+$**	**$\bar{B}^0 \rightarrow B_-$**
χ_0^2	21.38, 21 bins	14.68, 22 bins	20.19, 21 bins	16.39, 22 bins
Prob(χ^2>χ_0^2)	4.36×10^{-1}	8.76×10^{-1}	5.09×10^{-1}	7.96×10^{-1}
Standard Deviations	0.78	0.16	0.66	0.26