Direct Test of time reversal and CPT symmetries with entangled neutral mesons

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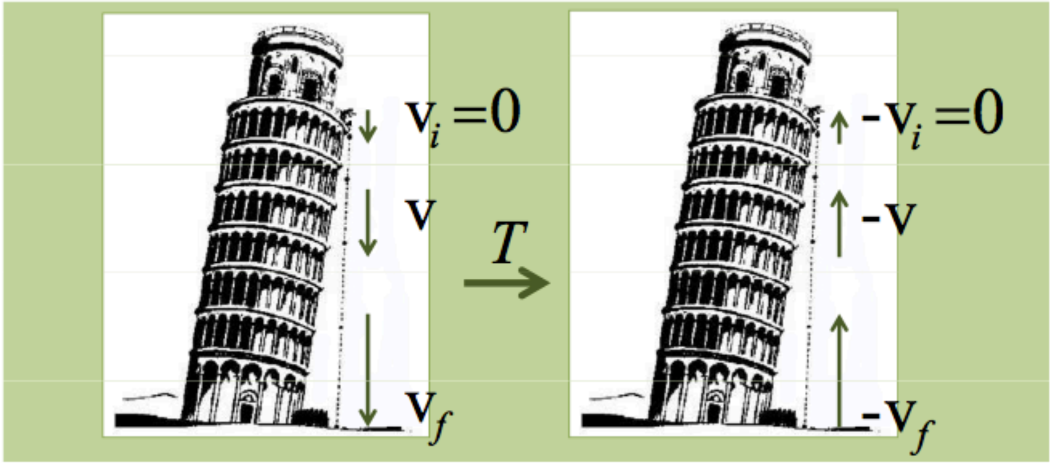
Time Reversal: introduction

•The transformation of a system corresponding to the inversion of the time coordinate, the formal substitution t → −t, is usually called '**time reversal**', but a more appropriate name would actually be **motion reversal**.



•Exchange of in <-> out states and reversal of all momenta and spins tests time reversal, i.e. the symmetry of the responsible dynamics for the observed process under time reversal t → −t (transformation implemented in QM by an antiunitary operator)

•Similarly for CPT tests: the exchange of in <-> out states etc.. is required.

Test of Time Reversal symmetry

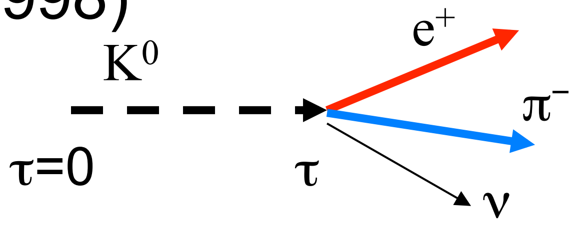
- T-Violation exists in the Standard Model of electro-weak interactions
- CPT theorem => All local unitary field theories with Lorentz invariance have CPT symmetry
- Automatic connection between CP-violation and T-violation
- T and CPT described by ANTIUNITARY rather than unitary operators, introducing many intriguing subtleties.
- Even though CPT invariance has been experimentally confirmed, particularly in the neutral kaon system with stringent limits, the theoretical connection between CP and T symmetries does not imply an experimental identity between them.

- Time reversal symmetry can be tested e.g. in the case of

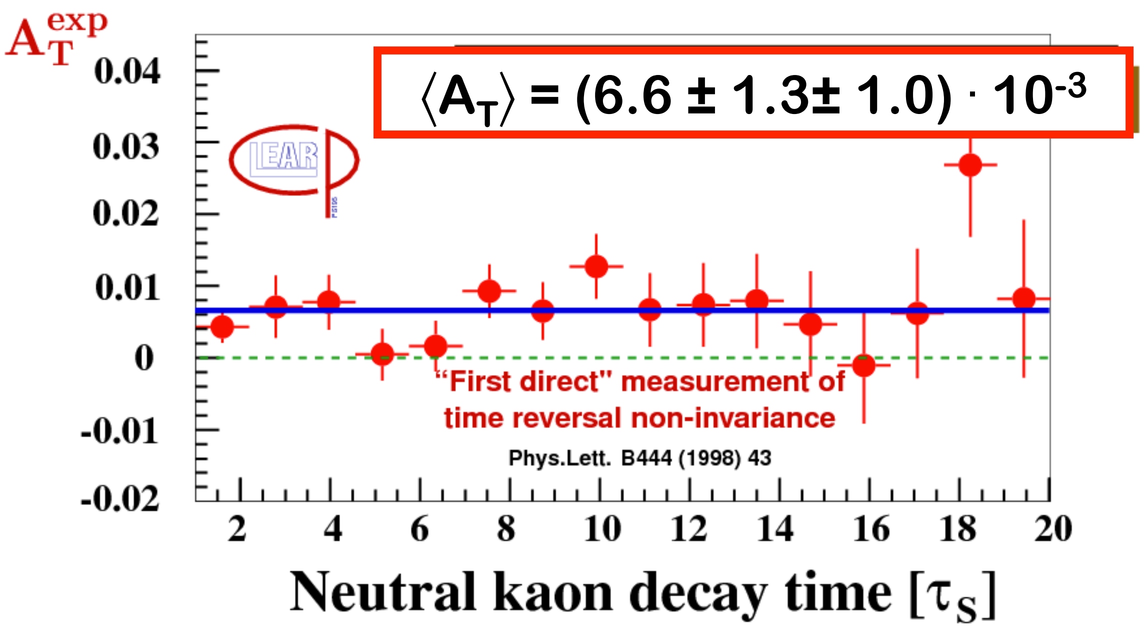
(i) T-odd observable for a non degenerate stationary state: e.g. electric dipole moment of neutron;
(ii) transition between stable particles: e.g. neutrino oscillations
(iii) transition between unstable particles: e.g. K^0 oscillations

Test of Time Reversal symmetry using Kabir's asymmetry

- Only one evidence of T violation: Kabir asymmetry ('70), comparing a process with its T-conjugated one, i.e. $K^0 \to \bar{K}^0$ vs $\bar{K}^0 \to K^0$ performed by the CPLEAR experiment (1998)



$$A_T = \frac{P(\overline{K}^0 \to K^0) - P(K^0 \to \overline{K}^0)}{P(\overline{K}^0 \to K^0) + P(K^0 \to \overline{K}^0)}$$



PLB444(1998)43

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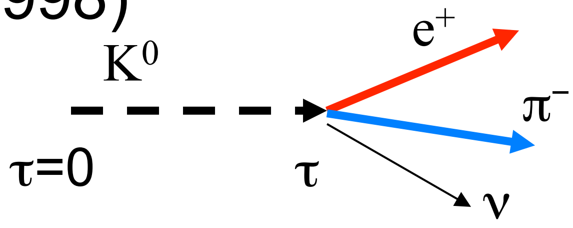


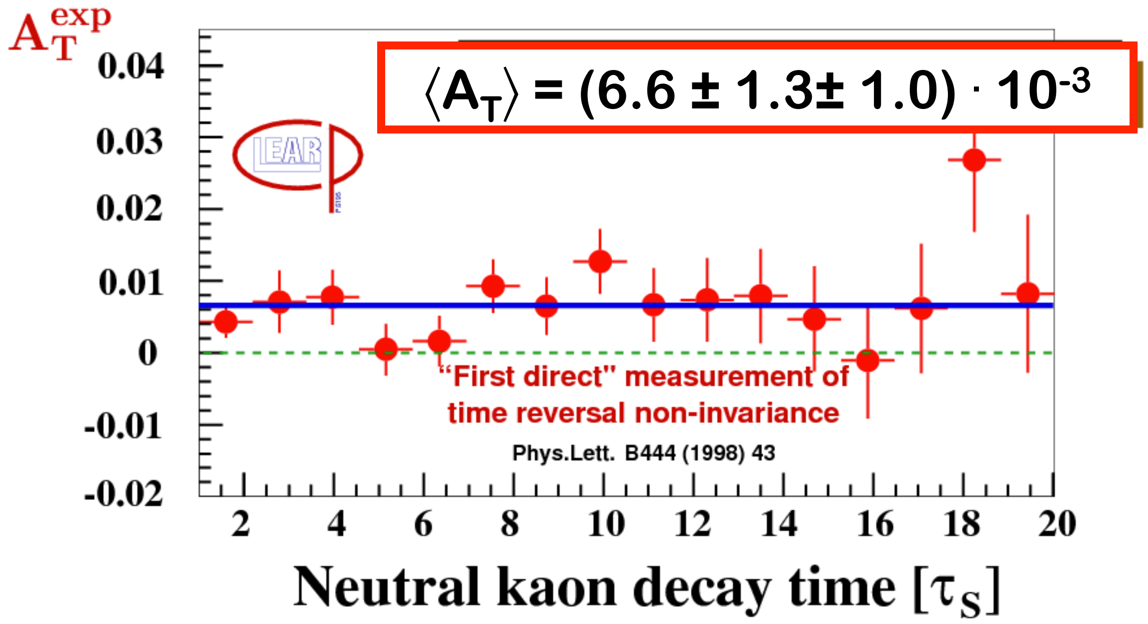
$$A_T = \frac{P(\overline{K}^0 \to K^0) - P(K^0 \to \overline{K}^0)}{P(\overline{K}^0 \to K^0) + P(K^0 \to \overline{K}^0)}$$

$$= 4\Re\varepsilon$$

assumption: no CPT violation in semileptonic decay:

$$\Re(y - x_-) = 0$$

T viol	CPT viol
$\varepsilon = \frac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)}$	$\delta = \frac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)}$



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Test of Time Reversal symmetry using Kabir's asymmetry

- A direct evidence for T violation would mean an experiment that, considered by itself, clearly shows T violation INDEPENDENT and unconnected to the results for CP violation and CPT invariance
- Controversial interpretation of the CPLEAR result as "direct" test:
  L. Wolfenstein "It is known from the detailed analysis of the CP-violating effects that this mixing indeed violates T as expected from CPT invariance. Thus the question we ask is not whether T is violated, which is known, but a didactic question as to whether we now have direct evidence." "it is not as direct a test of TRV as one might like"

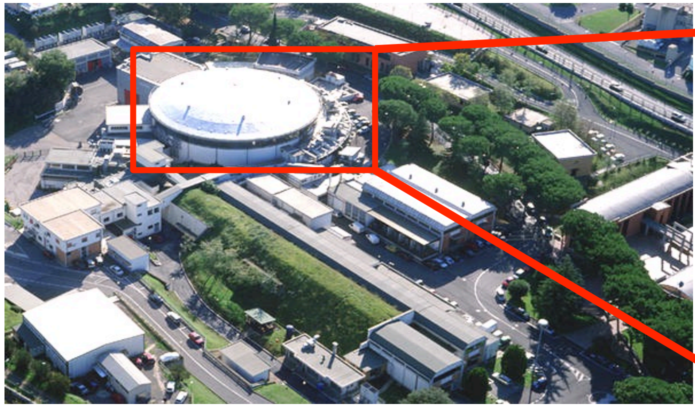
- 1) Remark: $K^0 \to \bar{K}^0$ is a CPT-even transition, so $CP \equiv T$ in this case !
  CP and T cannot be distinguished (not independent)
  T test: $K^0 \to \bar{K}^0$ vs $\bar{K}^0 \to K^0$
  CP test: $K^0 \to \bar{K}^0$ vs $\bar{K}^0 \to K^0$

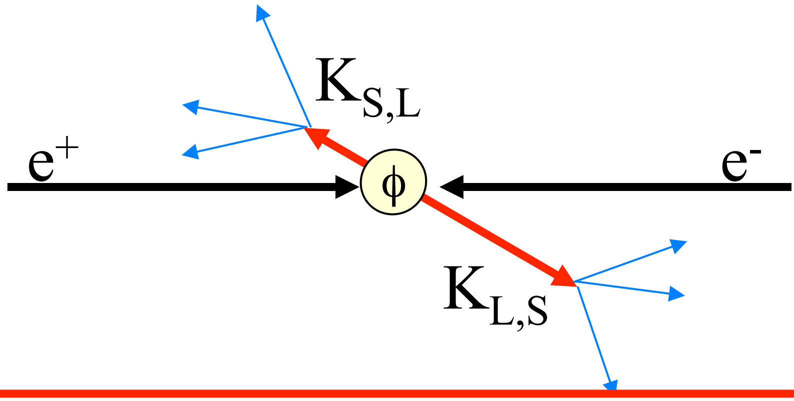
- 2) $A_T \propto \Re\varepsilon \propto \Delta\Gamma = \Gamma_S - \Gamma_L$; if $\Delta\Gamma$~ 0 the TRV effect vanishes (in B meson system $\Delta\Gamma$~0 : no TRV through $B^0 \to \overline{B}^0$ transition); decay plays an essential role => not negligible initial state interaction effects associated with $\Delta\Gamma \neq 0$

- L. Wolfenstein IJMP(1999),PRL (1999), Bernabeu PLB (1999), NPB (2000), H. Quinn (JPPS (2008); Bernabeu et al. JHEP (2012)

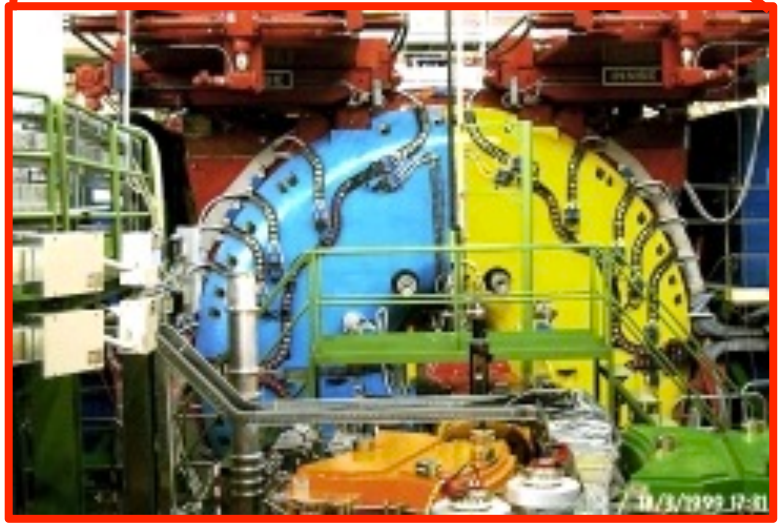
KLOE/KLOE-2 experiment at the Frascati φ-factory DAΦNE

DAFNE collider





KLOE detector



$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0(\vec{p})\right\rangle\left|\overline{K}^0(-\vec{p})\right\rangle - \left|\overline{K}^0(\vec{p})\right\rangle\left|K^0(-\vec{p})\right\rangle\right]$$

$$= \frac{N}{\sqrt{2}}\left[\left|K_S(\vec{p})\right\rangle\left|K_L(-\vec{p})\right\rangle - \left|K_L(\vec{p})\right\rangle\left|K_S(-\vec{p})\right\rangle\right]$$

$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

Entanglement in neutral meson pairs

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also orthogonal "CP states" K_+ and K_- (K_1, K_2)

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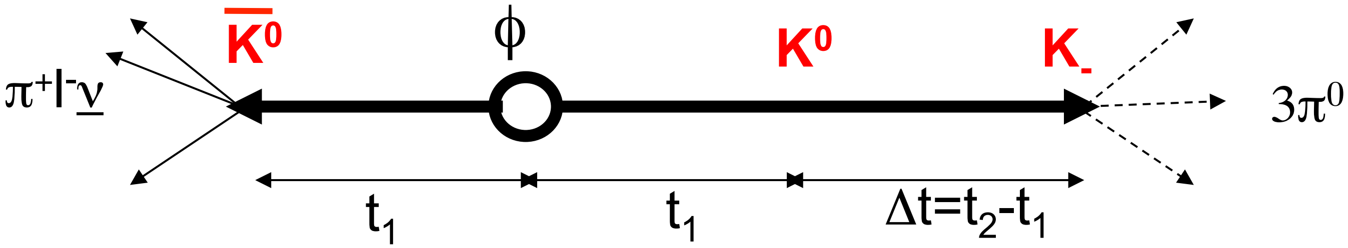
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state



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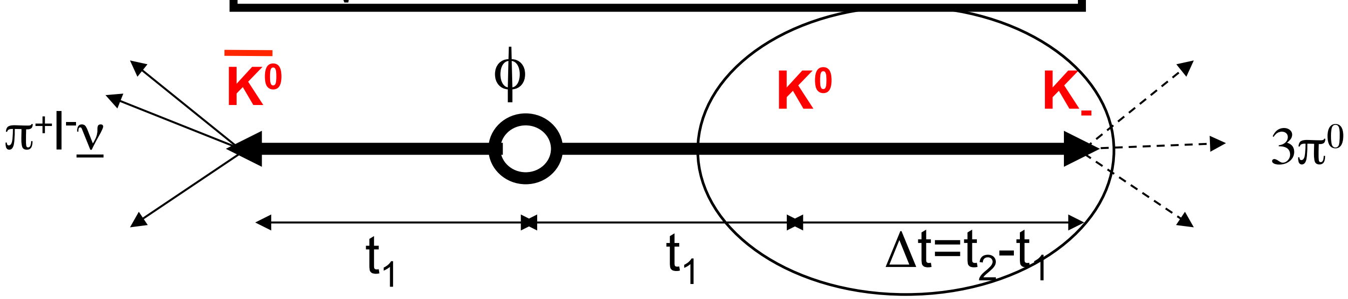

$K^0 \rightarrow K_-$ reference process

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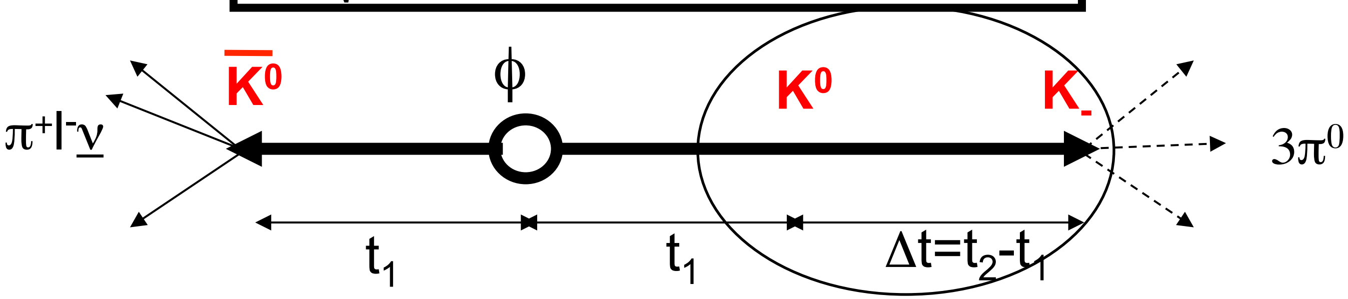

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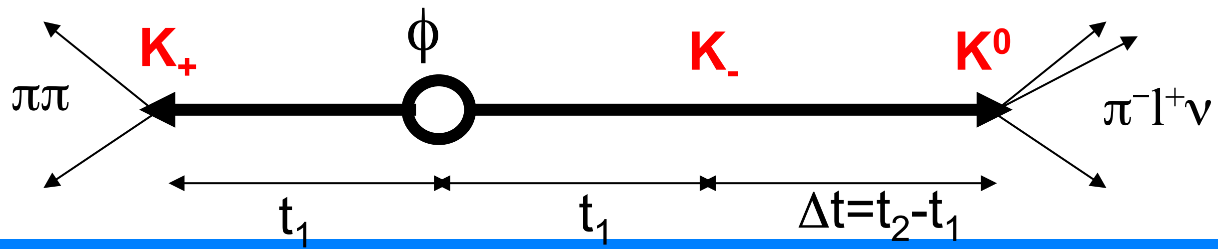

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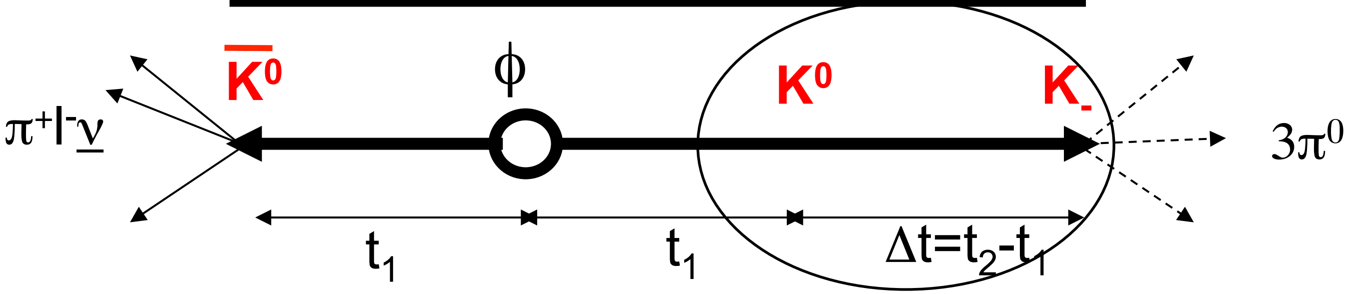
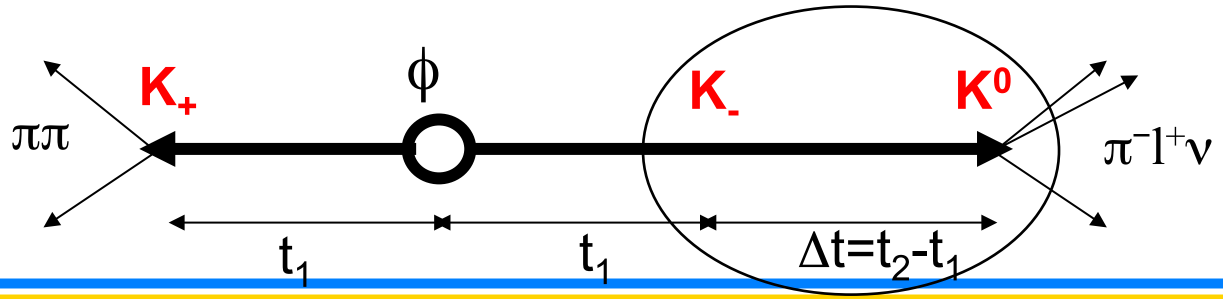


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow K^0$ T-conjugated process



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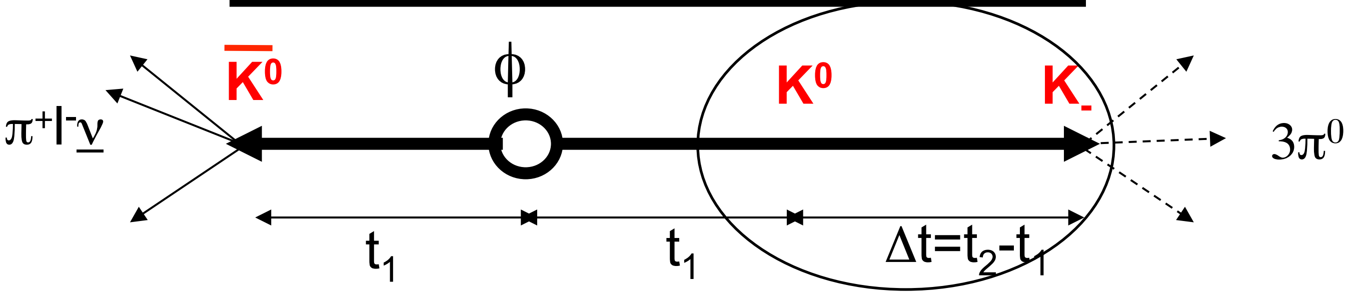

$K^0 \rightarrow K_-$ reference process

Note: CP and CPT conjugated process

$\overline{K}^0 \rightarrow K_-$ $\quad K_- \rightarrow \overline{K}^0$

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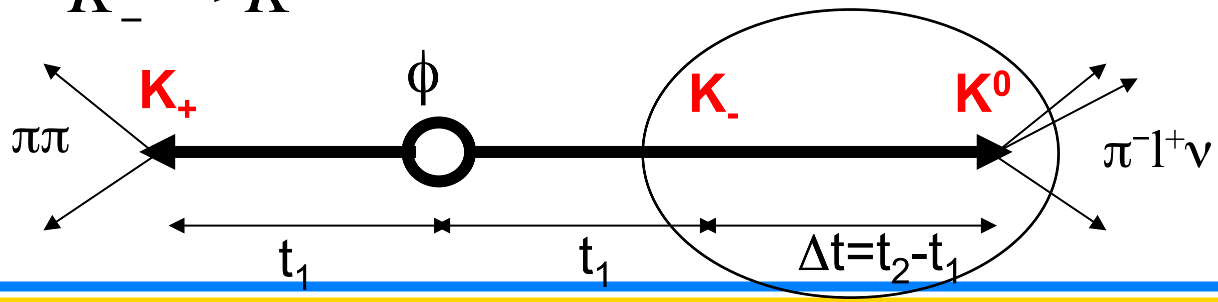

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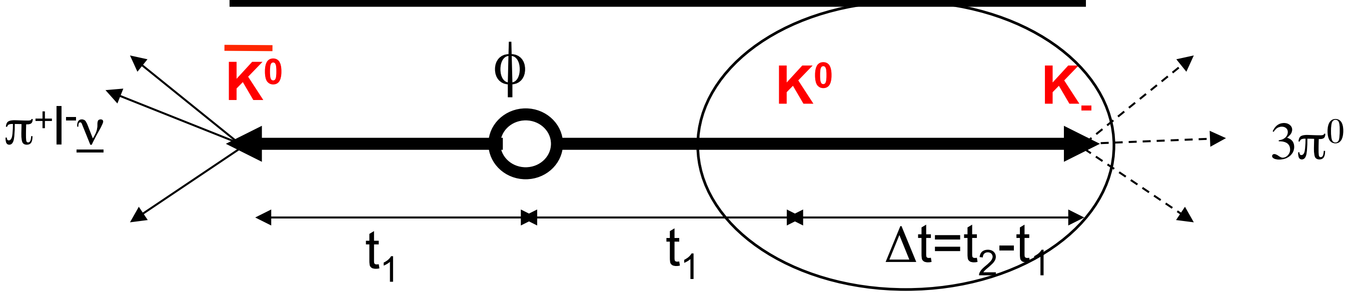

$K^0 \rightarrow K_-$ reference process

$$I(\pi\pi, l^+; \Delta t) = C(\pi\pi, l^+) \times P[K_-(0) \rightarrow K^0(\Delta t)]$$

In general with $f_{\underline{X}}$ decayng before f_Y, i.e. $\Delta t>0$:

$$I(f_{\bar{X}}, f_Y; \Delta t) = C(f_{\bar{X}}, f_Y) \times P\left[\mathrm{K_X}(0) \rightarrow \mathrm{K_Y}(\Delta t)\right]$$

with $C(f_{\bar{X}}, f_Y) = \frac{1}{2(\Gamma_S + \Gamma_L)} |\langle f_{\bar{X}}|T|\bar{\mathrm{K}}_\mathrm{X}\rangle\langle f_Y|T|\mathrm{K_Y}\rangle|^2$

Direct test of symmetries with neutral kaons

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

Direct test of symmetries with neutral kaons

Conjugate= reference (struck through in red)

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	~~$K^0 \to K^0$~~	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	~~$K^0 \to \bar{K}^0$~~
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	~~$\bar{K}^0 \to K^0$~~
$\bar{K}^0 \to \bar{K}^0$	~~$\bar{K}^0 \to \bar{K}^0$~~	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	~~$K_+ \to K_+$~~	~~$K_+ \to K_+$~~	~~$K_+ \to K_+$~~
$K_+ \to K_-$	$K_- \to K_+$	~~$K_+ \to K_-$~~	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	~~$K_- \to K_+$~~	$K_+ \to K_-$
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Direct test of symmetries with neutral kaons

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already in the table with conjugate as reference

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$\mathrm{K}^0 \to \mathrm{K}^0$	~~$\mathrm{K}^0 \to \mathrm{K}^0$~~	$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$
$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$	~~$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$~~
$\mathrm{K}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \mathrm{K}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$
$\mathrm{K}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \mathrm{K}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$
$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$	~~$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$~~	~~$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$~~	~~$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$~~
$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$	~~$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$~~	~~$\mathrm{K}^0 \to \mathrm{K}^0$~~	~~$\mathrm{K}^0 \to \mathrm{K}^0$~~
$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	~~$\mathrm{K}^0 \to \mathrm{K}_+$~~	$\mathrm{K}_+ \to \mathrm{K}^0$
$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	~~$\mathrm{K}^0 \to \mathrm{K}_-$~~	$\mathrm{K}_- \to \mathrm{K}^0$
$\mathrm{K}_+ \to \mathrm{K}^0$	~~$\mathrm{K}^0 \to \mathrm{K}_+$~~	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	~~$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$~~
$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	~~$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$~~	~~$\mathrm{K}_+ \to \mathrm{K}^0$~~	~~$\mathrm{K}^0 \to \mathrm{K}_+$~~
$\mathrm{K}_+ \to \mathrm{K}_+$	~~$\mathrm{K}_+ \to \mathrm{K}_+$~~	~~$\mathrm{K}_+ \to \mathrm{K}_+$~~	~~$\mathrm{K}_+ \to \mathrm{K}_+$~~
$\mathrm{K}_+ \to \mathrm{K}_-$	$\mathrm{K}_- \to \mathrm{K}_+$	~~$\mathrm{K}_+ \to \mathrm{K}_-$~~	$\mathrm{K}_- \to \mathrm{K}_+$
$\mathrm{K}_- \to \mathrm{K}^0$	~~$\mathrm{K}^0 \to \mathrm{K}_-$~~	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	~~$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$~~
$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	~~$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$~~	~~$\mathrm{K}_- \to \mathrm{K}^0$~~	~~$\mathrm{K}^0 \to \mathrm{K}_-$~~
$\mathrm{K}_- \to \mathrm{K}_+$	~~$\mathrm{K}_+ \to \mathrm{K}_-$~~	~~$\mathrm{K}_- \to \mathrm{K}_+$~~	~~$\mathrm{K}_+ \to \mathrm{K}_-$~~
$\mathrm{K}_- \to \mathrm{K}_-$	~~$\mathrm{K}_- \to \mathrm{K}_-$~~	~~$\mathrm{K}_- \to \mathrm{K}_-$~~	~~$\mathrm{K}_- \to \mathrm{K}_-$~~

Direct test of symmetries with neutral kaons

Conjugate= reference

already in the table with conjugate as reference

Two identical conjugates for one reference

Reference	T-conjugate	CP-conjugate	CPT-conjugate
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$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

Direct test of symmetries with neutral kaons

Conjugate= reference

already in the table with conjugate as reference

Two identical conjugates for one reference

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

4 distinct tests of T symmetry

4 distinct tests of CP symmetry

4 distinct tests of CPT symmetry

Direct test of Time Reversal symmetry with neutral kaons

T symmetry test

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\bar{K}^0 \to K_-$	$(\ell^+, \pi^0\pi^0\pi^0)$	$K_- \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_+ \to K^0$	$(\pi^0\pi^0\pi^0, \ell^+)$	$K^0 \to K_+$	$(\ell^-, \pi\pi)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_- \to K^0$	$(\pi\pi, \ell^+)$	$K^0 \to K_-$	$(\ell^-, \pi\pi)$

One can define the following ratios of probabilities:

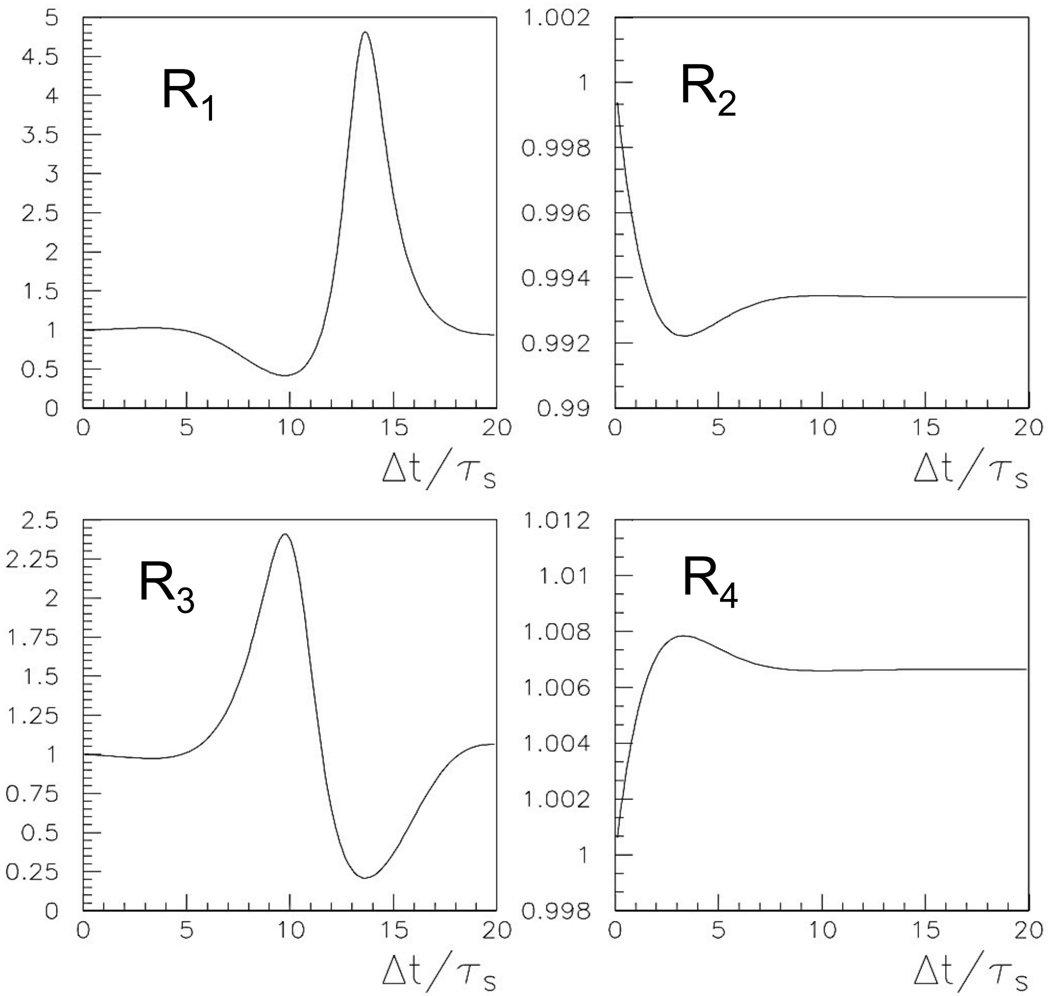
$$\begin{aligned}
R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] .
\end{aligned}$$

Any deviation from R_i=1 constitutes a violation of T-symmetry

J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102

Direct test of Time Reversal symmetry with neutral kaons

Any deviation from R_i=1 constitutes
a direct evidence of T-symmetry violation



$R_i(\Delta t=0)=1$

$R_2(\Delta t>>\tau_S)=1-4Re(\varepsilon)$
$R_4(\Delta t>>\tau_S)=1+4Re(\varepsilon)$

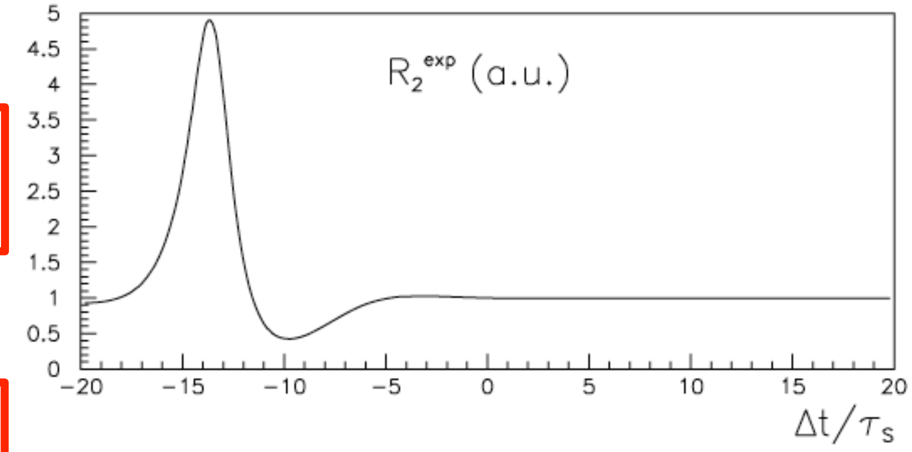
Direct test of Time Reversal symmetry with neutral kaons

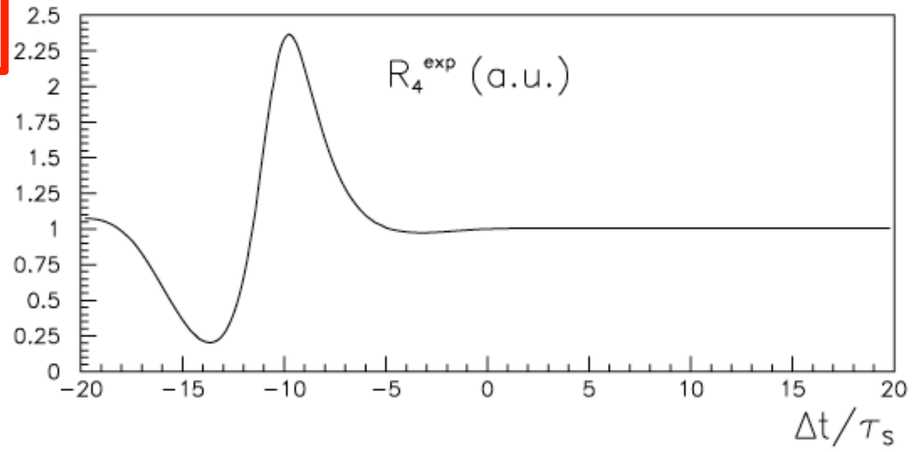
$$R_1^{\rm exp}(\Delta t) \equiv \frac{I(\ell^-,\pi\pi;\Delta t)}{I(3\pi^0,\ell^+;\Delta t)} = R_1(\Delta t)\times\frac{C(\ell^-,\pi\pi)}{C(3\pi^0,\ell^+)}$$

$$R_2^{\rm exp}(\Delta t) \equiv \frac{I(\ell^-,3\pi^0;\Delta t)}{I(\pi\pi,\ell^+;\Delta t)} = R_2(\Delta t)\times\frac{C(\ell^-,3\pi^0)}{C(\pi\pi,\ell^+)}$$

$$R_3^{\rm exp}(\Delta t) \equiv \frac{I(\ell^+,\pi\pi;\Delta t)}{I(3\pi^0,\ell^-;\Delta t)} = R_3(\Delta t)\times\frac{C(\ell^+,\pi\pi)}{C(3\pi^0,\ell^-)}$$

$$R_4^{\rm exp}(\Delta t) \equiv \frac{I(\ell^+,3\pi^0;\Delta t)}{I(\pi\pi,\ell^-;\Delta t)} = R_4(\Delta t)\times\frac{C(\ell^+,3\pi^0)}{C(\pi\pi,\ell^-)}$$





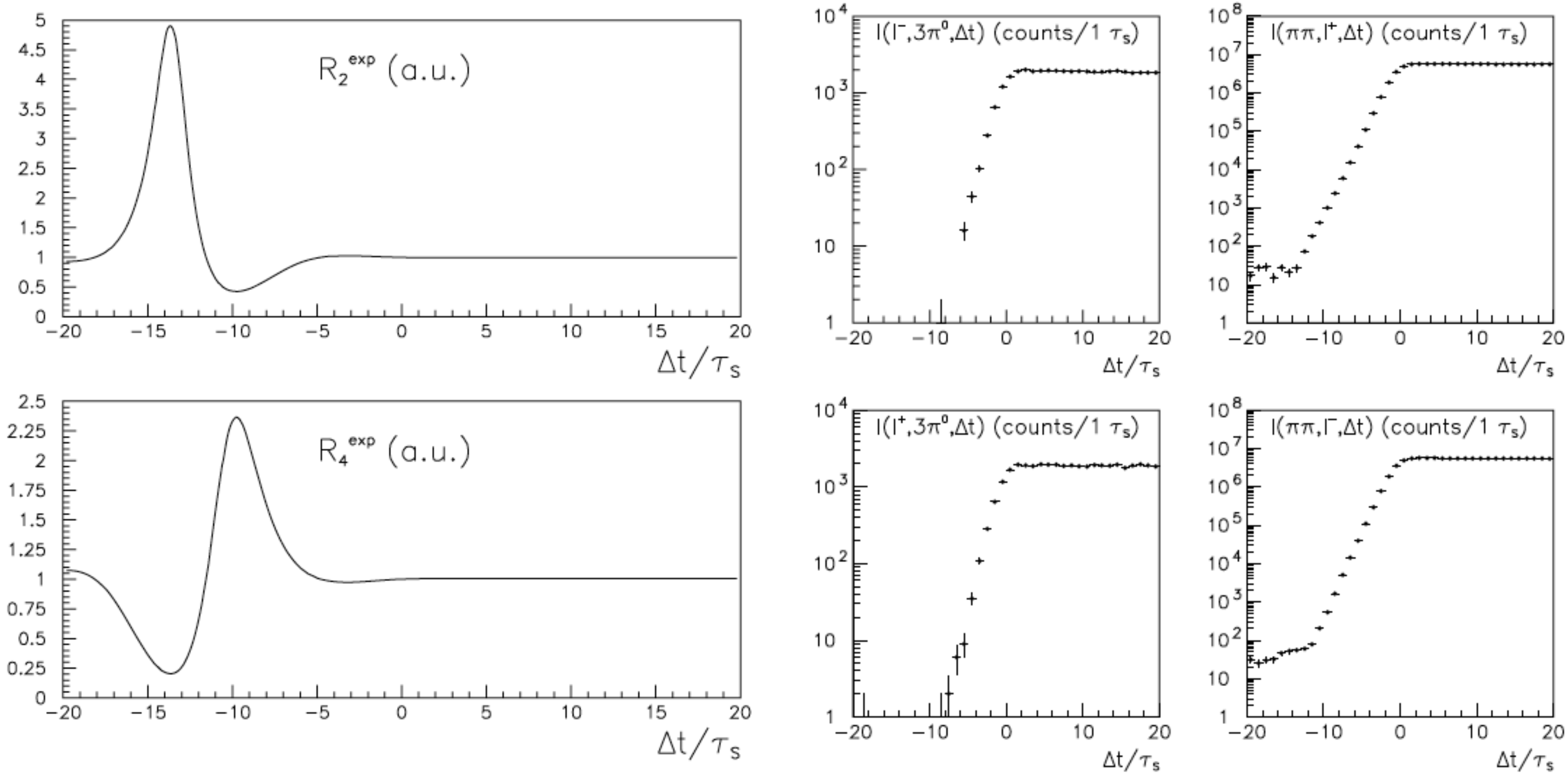
In practice two measurable ratios with
Δt <0 or >0

$$R_2^{\rm exp}(-\Delta t) = \frac{1}{R_3^{\rm exp}(\Delta t)} = \frac{1}{R_3(\Delta t)}\times\frac{C(3\pi^0,\ell^-)}{C(\ell^+,\pi\pi)},$$

$$R_4^{\rm exp}(-\Delta t) = \frac{1}{R_1^{\rm exp}(\Delta t)} = \frac{1}{R_1(\Delta t)}\times\frac{C(3\pi^0,\ell^+)}{C(\ell^-,\pi\pi)}.$$

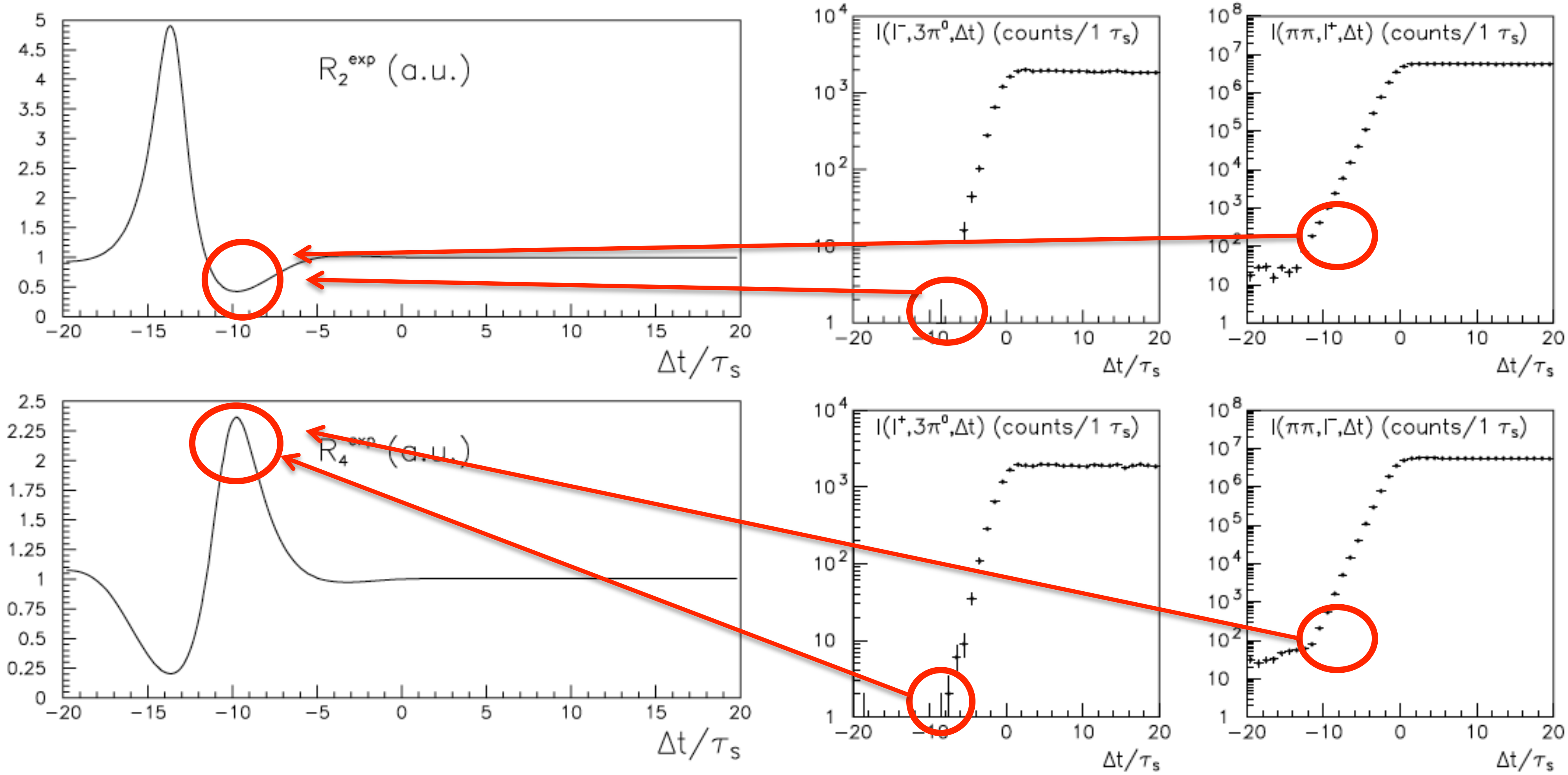
Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



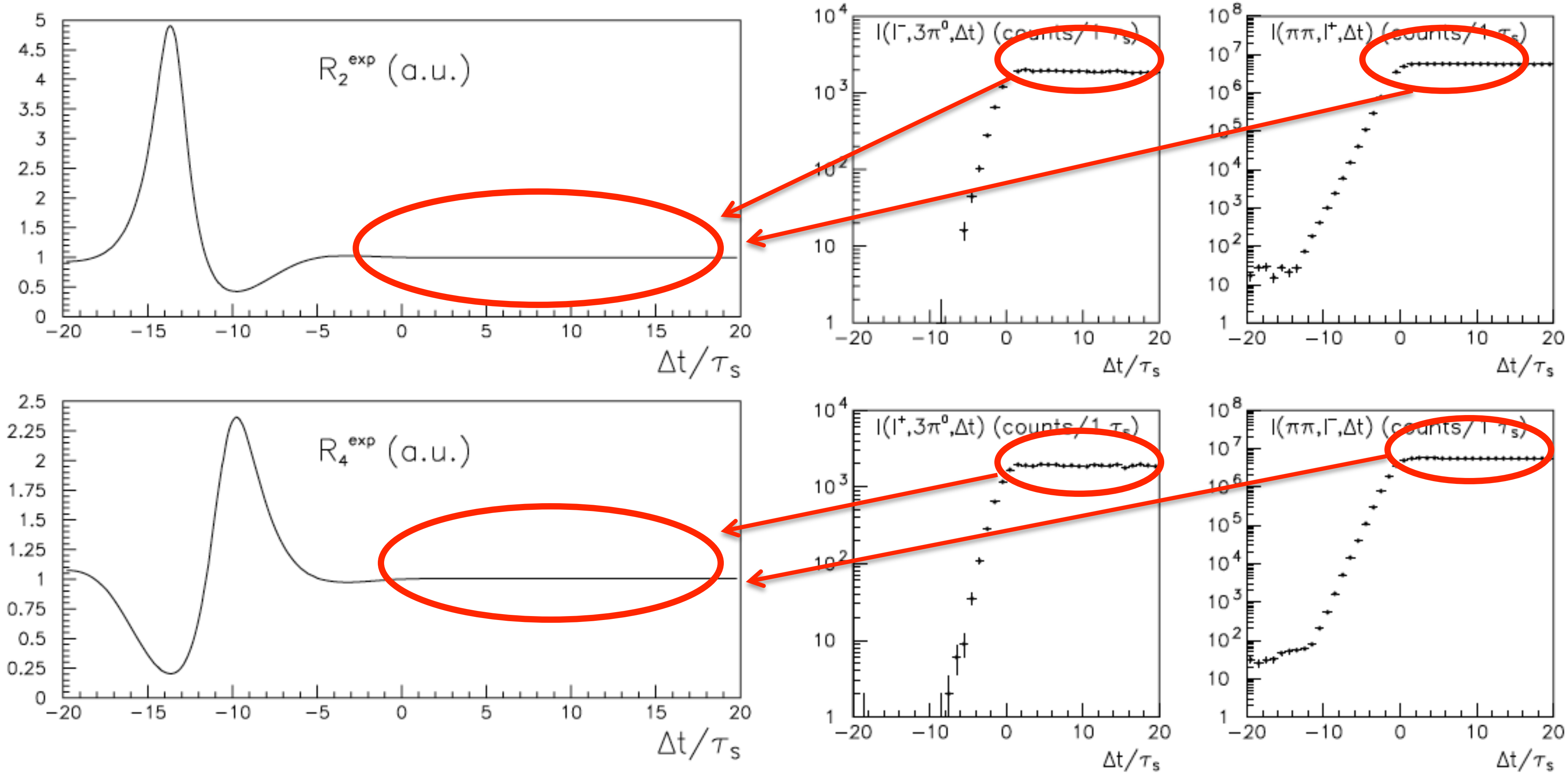
Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



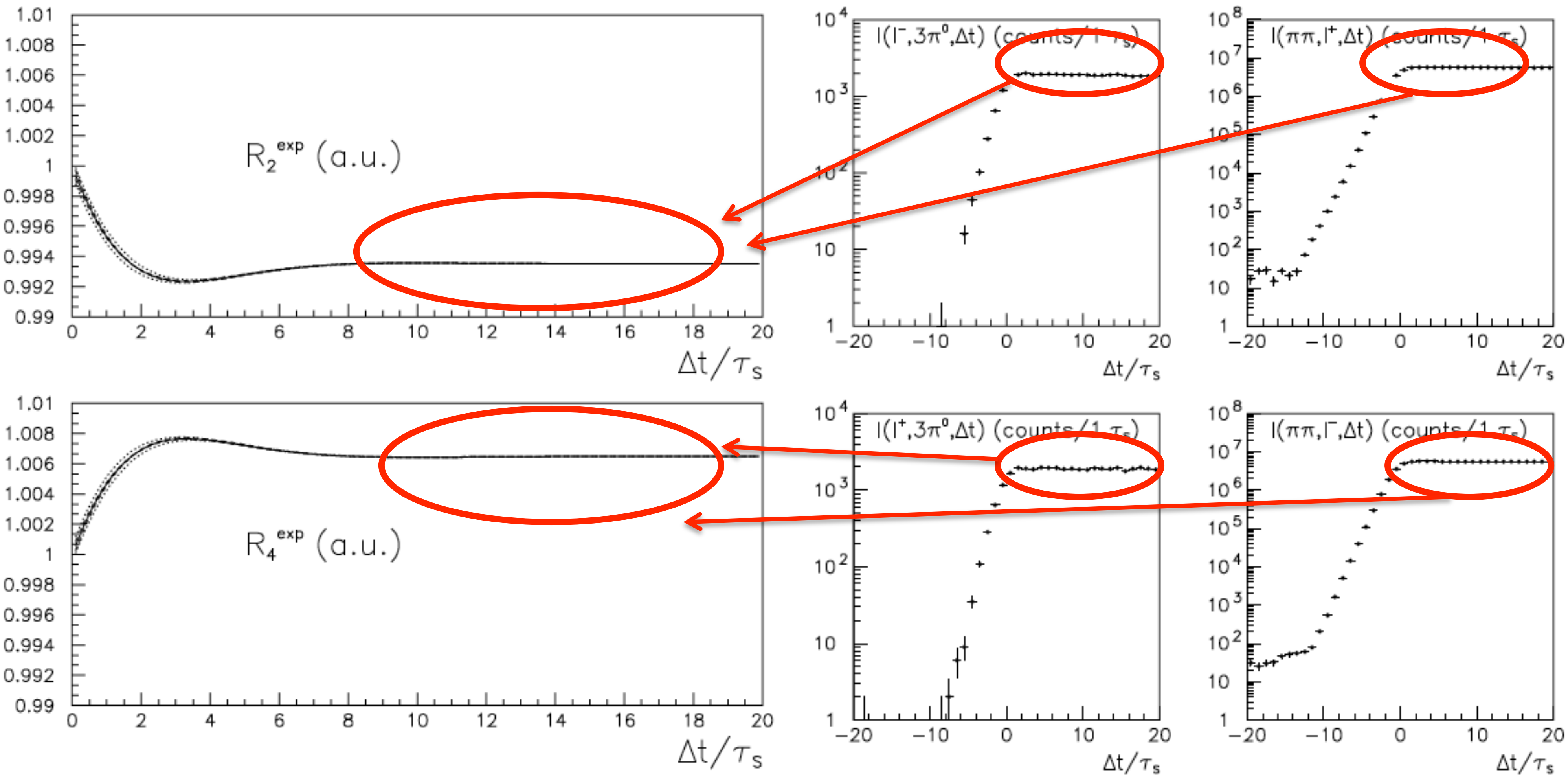
Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



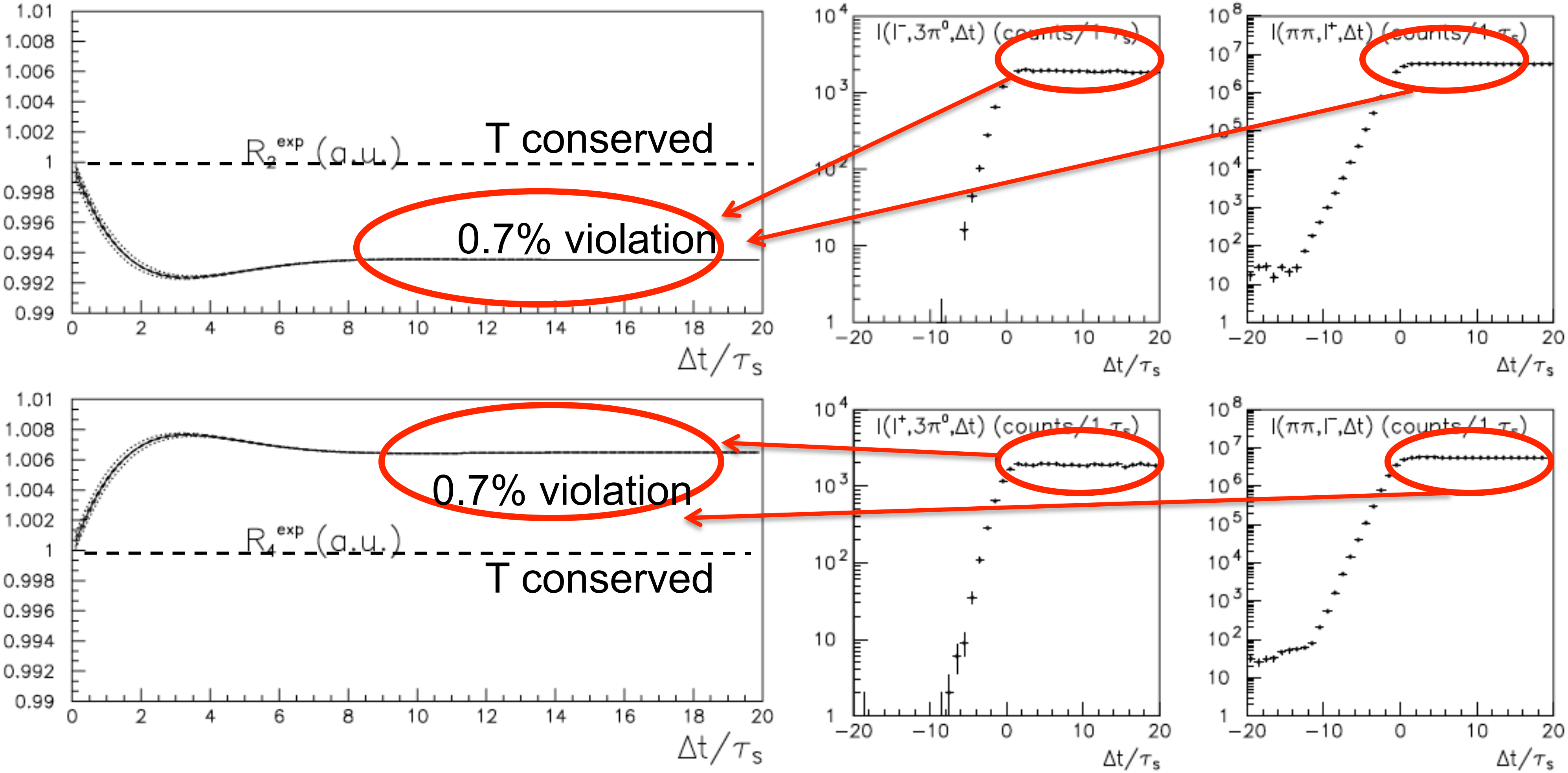
Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



Direct test of Time Reversal symmetry with neutral kaons

toy MC with L=10 fb^{-1}



$R_2(\Delta t >> \tau_S) = 1 - 4Re(\varepsilon) \sim 0.993$

$R_4(\Delta t >> \tau_S) = 1 + 4Re(\varepsilon) \sim 1.007$

Direct test of Time Reversal symmetry with neutral kaons

Integrating in a Δt region between 0 and 300 τ_S =>
stat. significance of 4.4, 6.2, 8.8 σ with L=5, 10, 20 fb^{-1} (full efficiency)

NPB 868 (2013) 102

pros:
in the "plateau" region the impact of direct CP violation effects on the assumption of orthogonality of K+ and K- states has been evaluated => negligible

cons:
-in the "plateau" region one needs to measure the absolute value of R_i.
Assuming no CPT violation in semileptonic decays:

$$\frac{C(\ell^-,3\pi^0)}{C(\pi\pi,\ell^+)} \simeq \frac{C(\ell^+,3\pi^0)}{C(\pi\pi,\ell^-)} \simeq \frac{\mathrm{BR}(\mathrm{K_L}\to 3\pi^0)}{\mathrm{BR}(\mathrm{K_S}\to\pi\pi)}\frac{\Gamma_L}{\Gamma_S} \equiv D.$$

$$R_2(\Delta t) = \frac{R_2^{\exp}(\Delta t)}{D},$$

$$R_4(\Delta t) = \frac{R_4^{\exp}(\Delta t)}{D}.$$

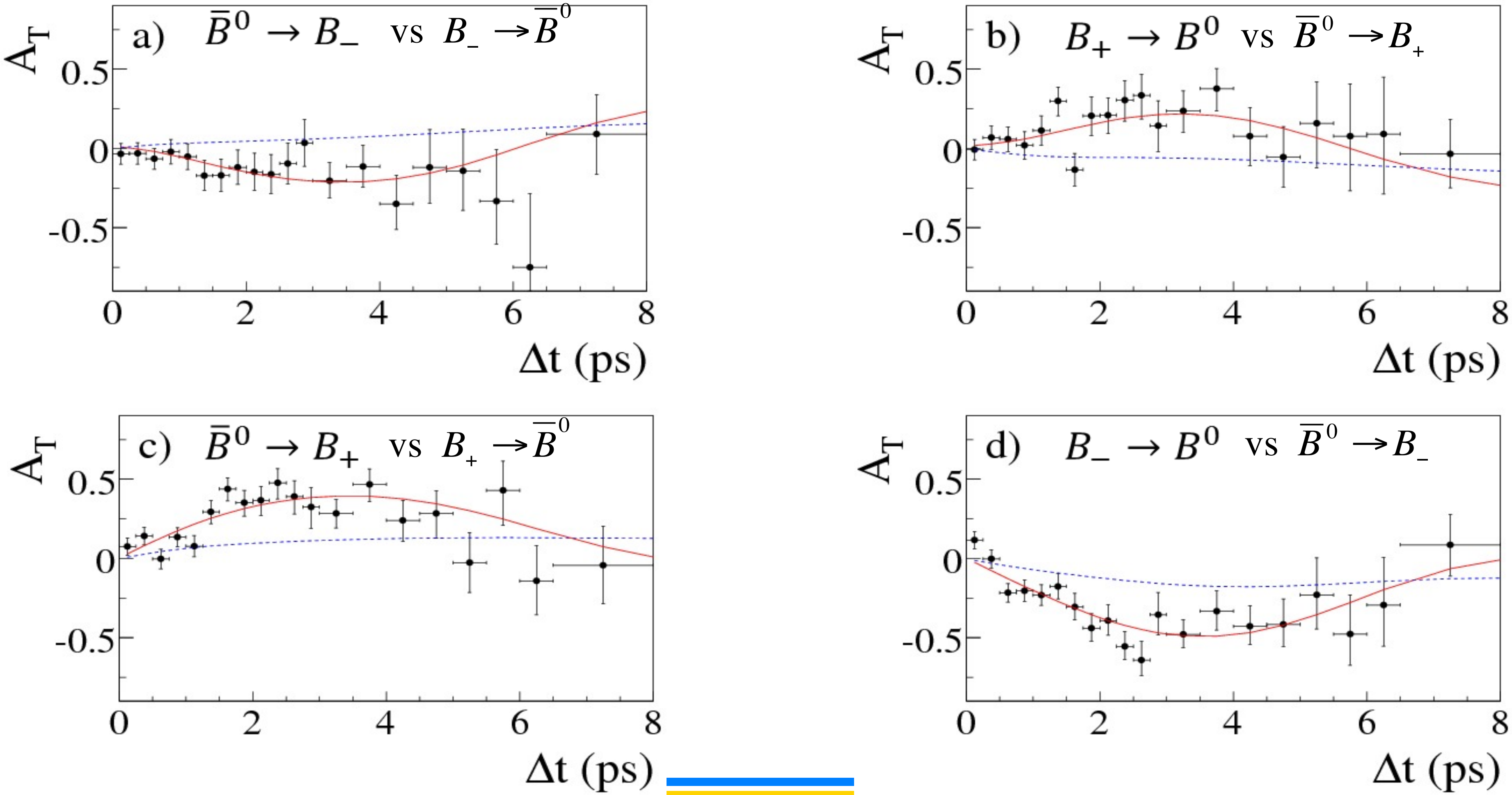
- It is needed to measure the constant D with ~ 0.1% precision,
  i.e. BRs and K_S, K_L lifetimes
-in the "plateau" region effect proportional to Re(ε)

T test could be feasible at KLOE-2 @ DAΦNE with L=O(10 fb^{-1})

Direct test of Time Reversal symmetry in neutral B mesons

Direct T violation observed at BABAR in the B's with significance of 14 σ
Babar coll. PRL 109 (2012) 211801

$$I_i(\Delta\tau) \sim e^{-\Gamma\Delta\tau}\left\{ C_i \cos(\Delta m \Delta\tau) + S_i \sin(\Delta m \Delta\tau) + C'_i \cosh(\Delta\Gamma\Delta\tau) + S'_i \sinh(\Delta\Gamma\Delta\tau) \right\}$$

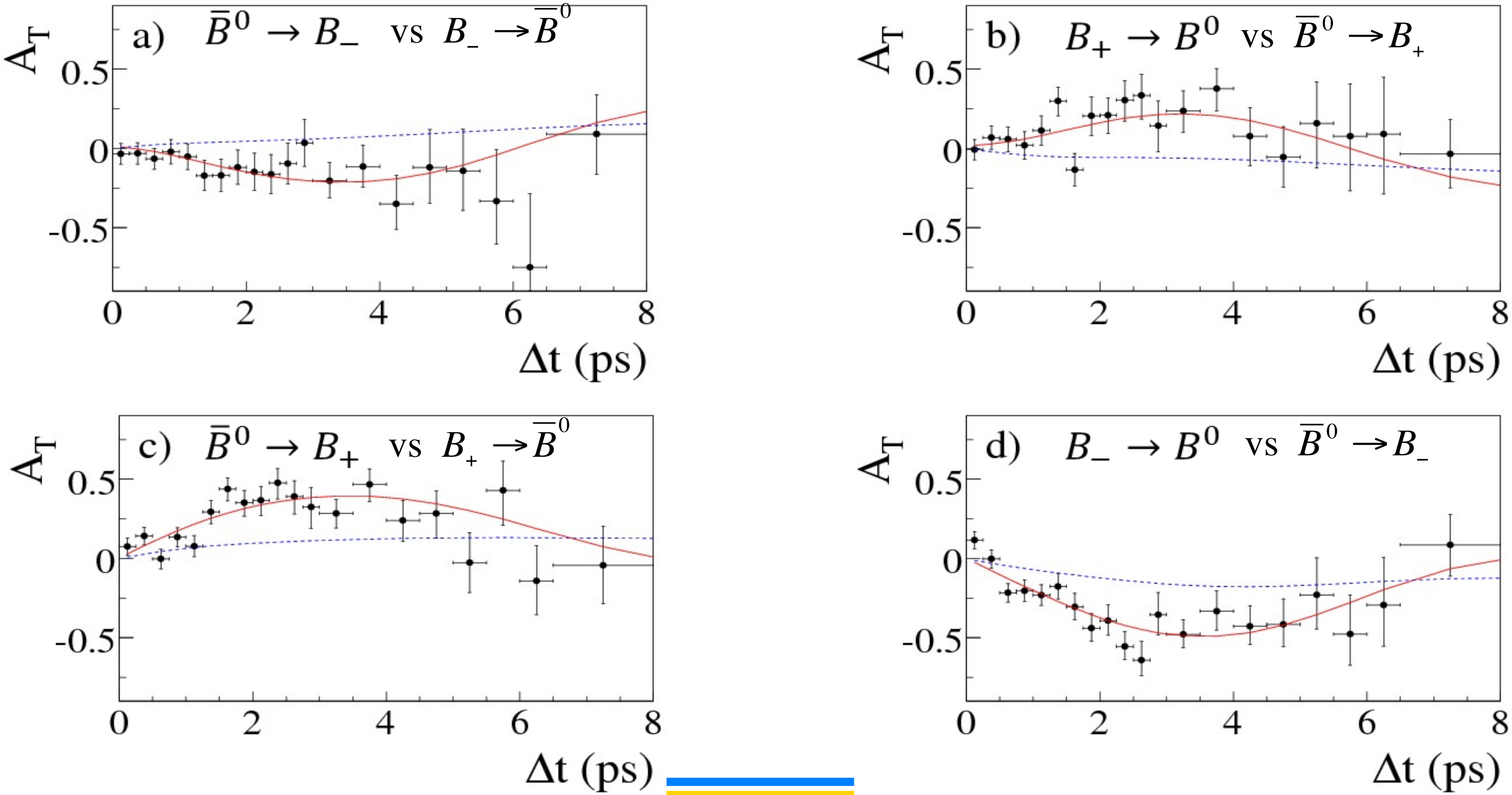


Direct test of Time Reversal symmetry in neutral B mesons

Direct T violation observed at BABAR in the B's with significance of 14 σ

Babar coll. PRL 109 (2012) 211801

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



Direct test of CPT symmetry with neutral kaons

CPT symmetry test

Reference		CPT-conjugate	
Transition	Decay products	Transition	Decay products
$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$K_- \to \bar{K}^0$	$(\pi\pi, \ell^-)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to K^0$	$(3\pi^0, \ell^+)$
$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K_- \to K^0$	$(\pi\pi, \ell^+)$

One can define the following ratios of probabilities:

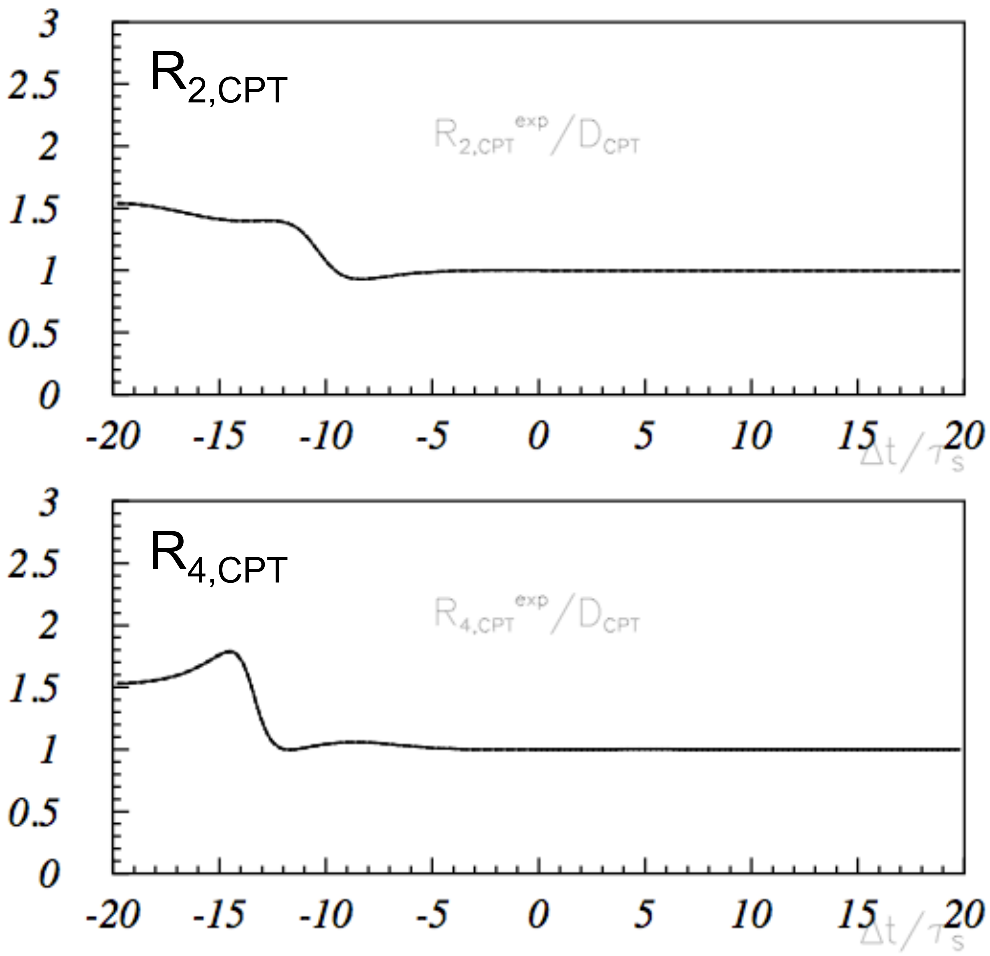
$$R_{1,\mathcal{CPT}}(\Delta t) = P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right]$$
$$R_{2,\mathcal{CPT}}(\Delta t) = P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]$$
$$R_{3,\mathcal{CPT}}(\Delta t) = P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right]$$
$$R_{4,\mathcal{CPT}}(\Delta t) = P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right]$$

Any deviation from $R_{i,CPT}$=1 constitutes a violation of T-symmetry

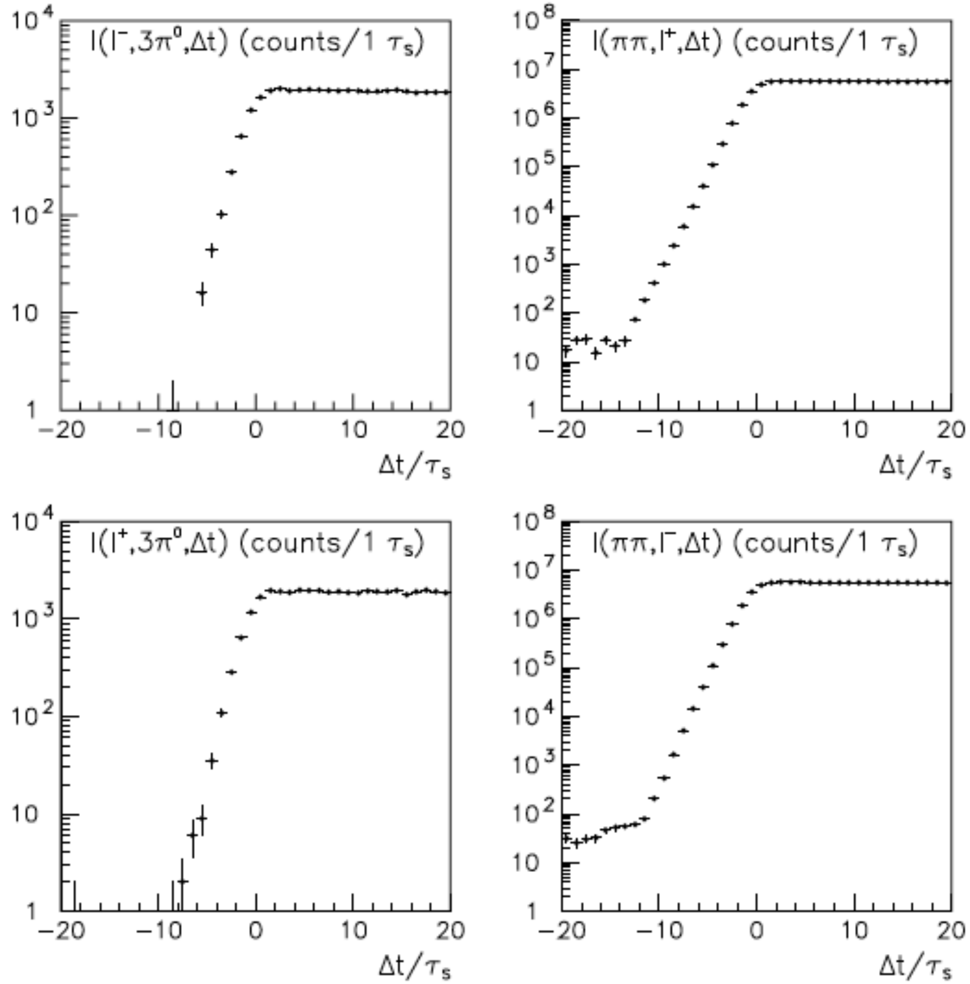
J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102 **A.D.D. PoS KAON13 (2013) 009**

Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$



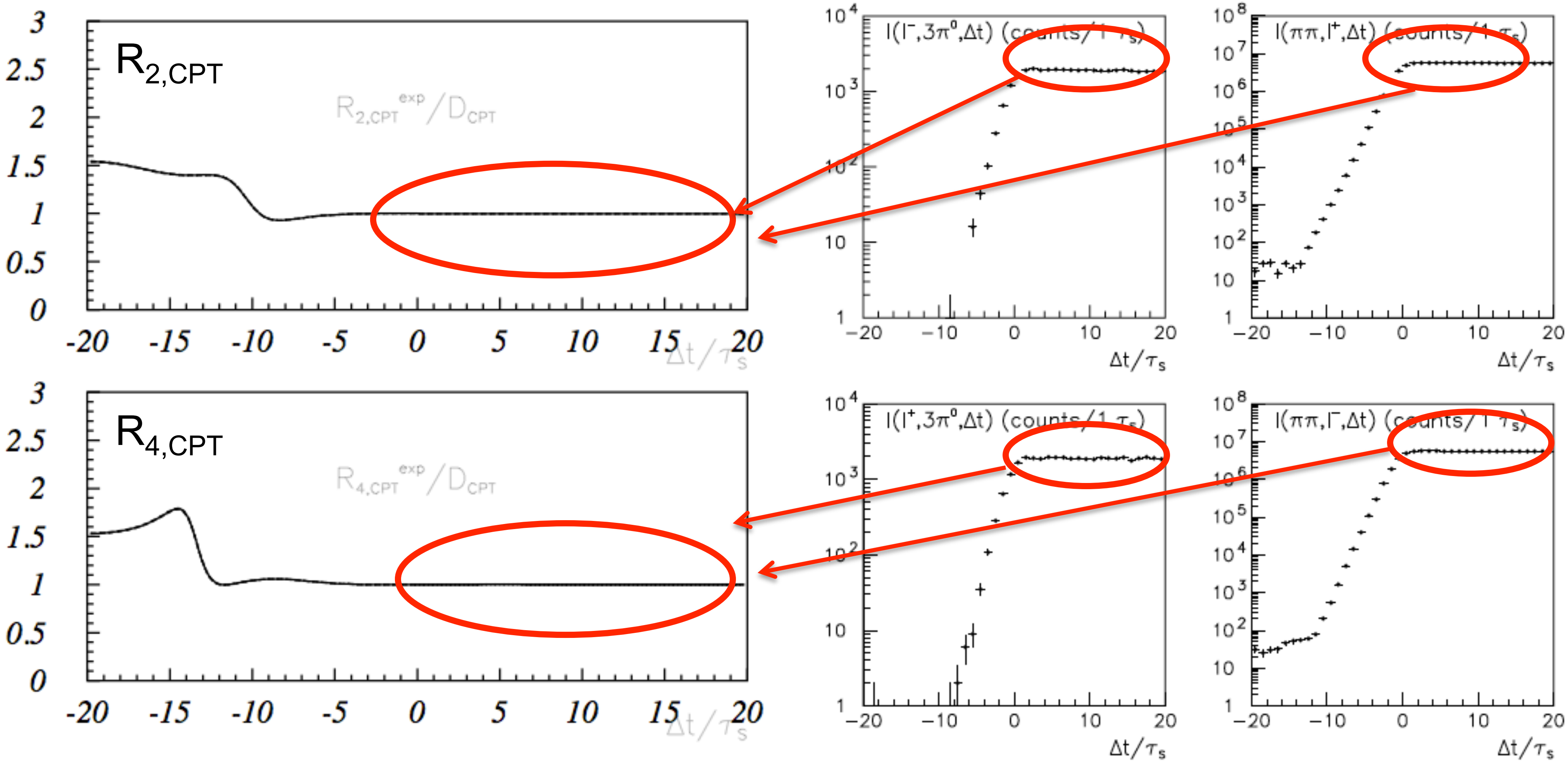
toy MC with $L=10\ fb^{-1}$



Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5}

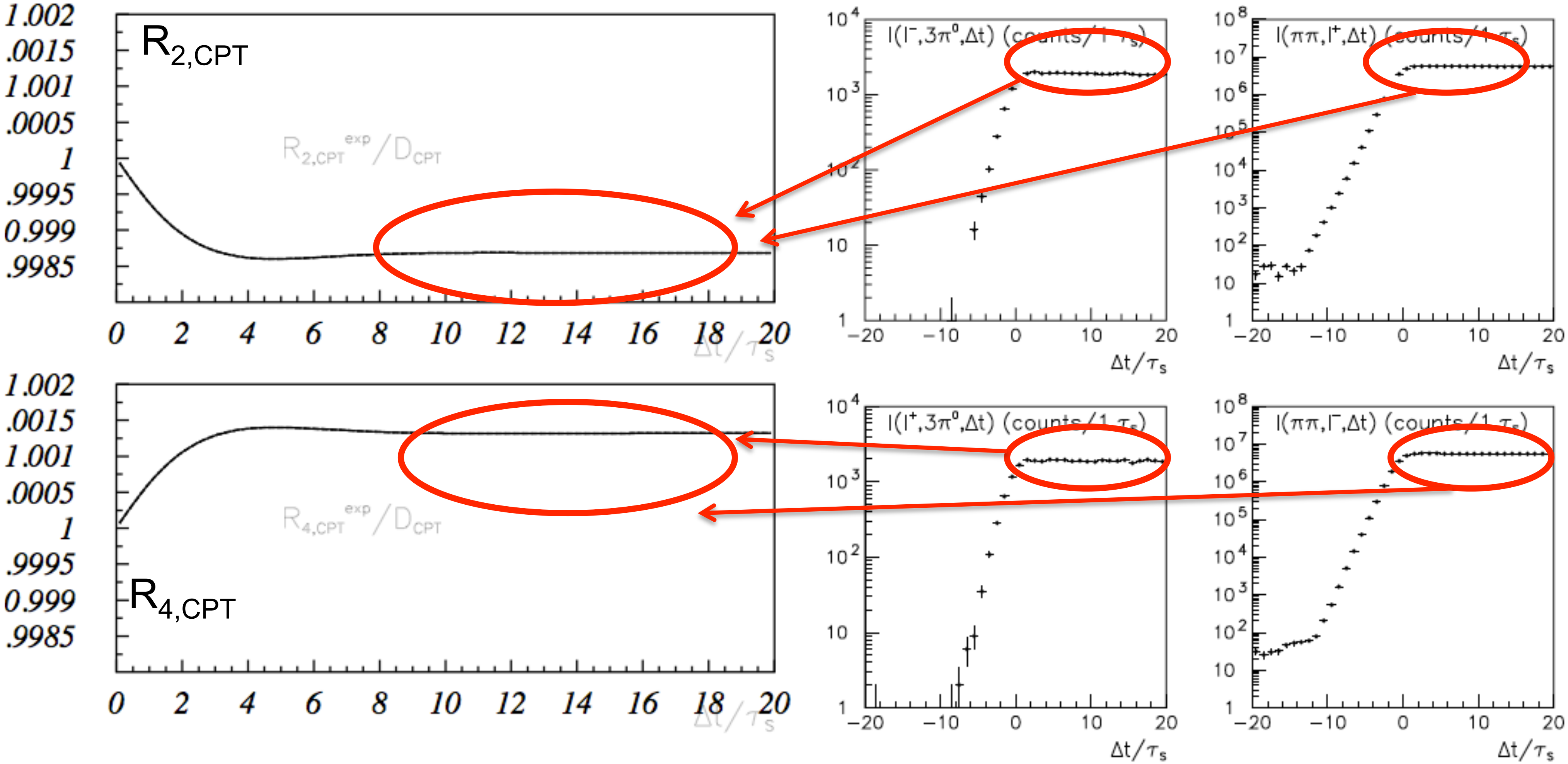
toy MC with L=10 fb^{-1}



Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5}

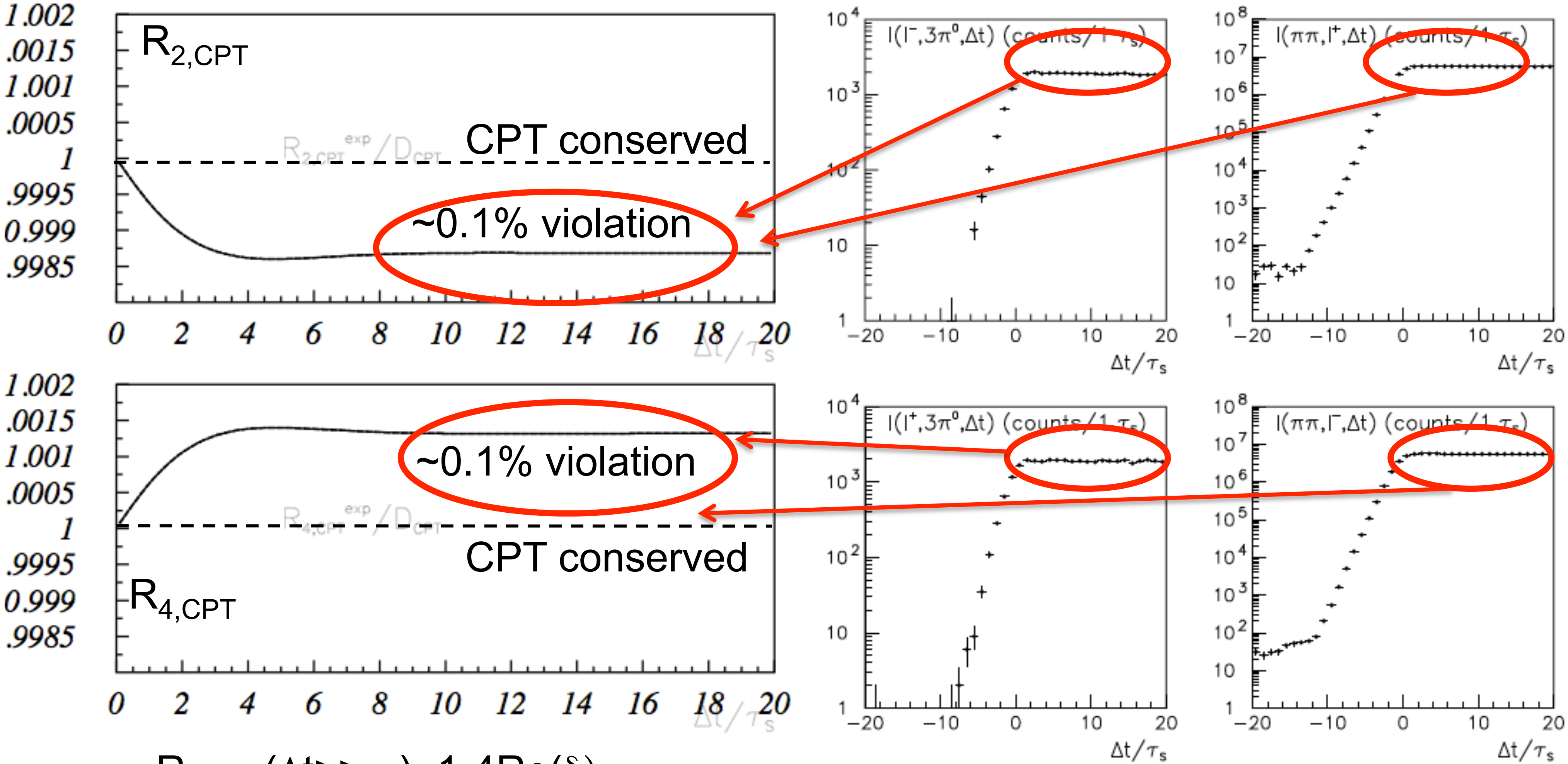
toy MC with L=10 fb^{-1}



Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$

toy MC with $L=10\ fb^{-1}$

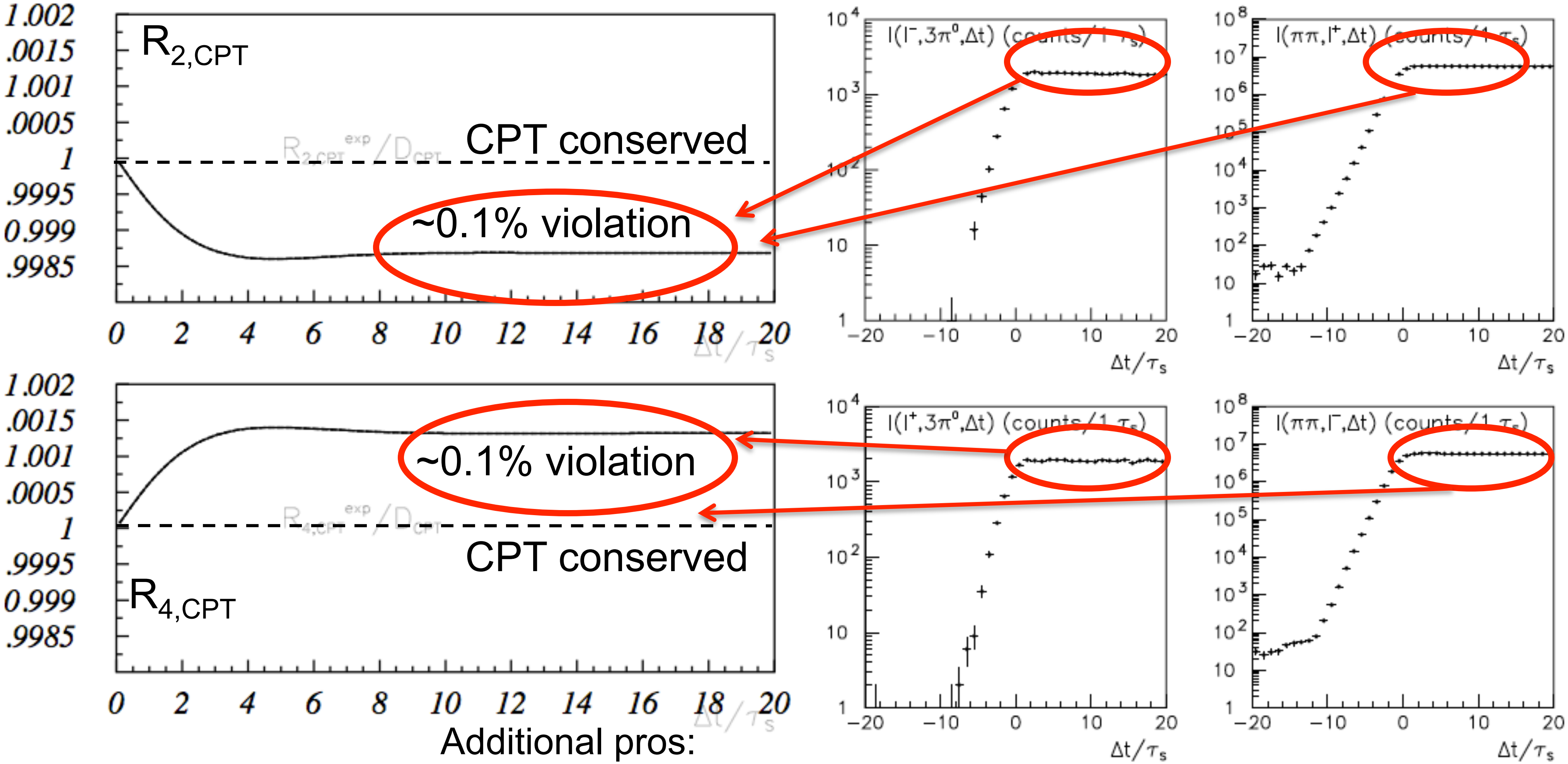


$R_{2,CPT}(\Delta t >> \tau_S)=1-4Re(\delta)$
$R_{4,CPT}(\Delta t >> \tau_S)=1+4Re(\delta)$

Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$

toy MC with $L=10\ fb^{-1}$



Additional pros:

$R_{2,CPT}(\Delta t >> \tau_S)=1-4Re(\delta)$ - contrary to T violation, the effect $\propto \Re\delta$ does not vanish with $\Delta\Gamma$-> 0

$R_{4,CPT}(\Delta t >> \tau_S)=1+4Re(\delta)$ - No assumption on CPT violation in semileptonic decays is needed

Conclusions

- The neutral meson system is an excellent laboratory for the study of discrete symmetries.
- By exploiting the EPR entanglement of neutral meson pairs produced at a φ-factory (or B-factories), it is possible to overcome some conceptual difficulties affecting previous tests of time reversal symmetry. It is possible to perform a direct test of the time reversal symmetry, independently from CP violation and CPT invariance constraints.
- In this conceptual framework theoretically very clean direct CPT tests in neutral kaon transitions could be also performed.

- The KLOE-2 experiment at the DAFNE collider could perform - with an integrated luminosity of O(10 fb^{-1}) - a statistically significant direct T symmetry test for the first time in the kaon sector, and a direct CPT symmetry test.