Testing fundamental physical principles with entangled neutral K mesons

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Fundamental tests possible with entangled neutral kaons

a) **Test of Quantum coherence**
Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
KLOE coll. PLB 642(2006) 315, FP40 (2010) 852
CPLEAR PLB 422 (1999) 339

b) **Test of CPT symmetry + Quantum coherence**
Bernabeu, Mavromatos et al. PRL 92 (2004) 131601, NPB744 (2006) 180 [J.Ellis et al. NPB241, 381; PRD 53, 3846]
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c) **Test of Lorentz and CPT symmetry**
Kostelecky PRD61 (1999) 016002, PRD64 (2001) 076001
KLOE coll. PLB 730 (2014) 89

d) **Direct Test of T (time-reversal), CPT symmetries**
Bernabeu, A.D.D. et al. NPB 868 (2013) 102

e) **Bell's inequality test**
Hiesmayr, A.D.D. et al. EPJC (2012) 72:1856

f) **Kaonic quantum eraser (Bohr's complementarity)**
Bramon, Garbarino, Hiesmayr PRL (2004) 020405

g) **Test of collapse models**
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Found Phys 43 (2013) 813, Sci. Rep. 3 (2013) 1952

h) **.......**

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see Bloise’s talk

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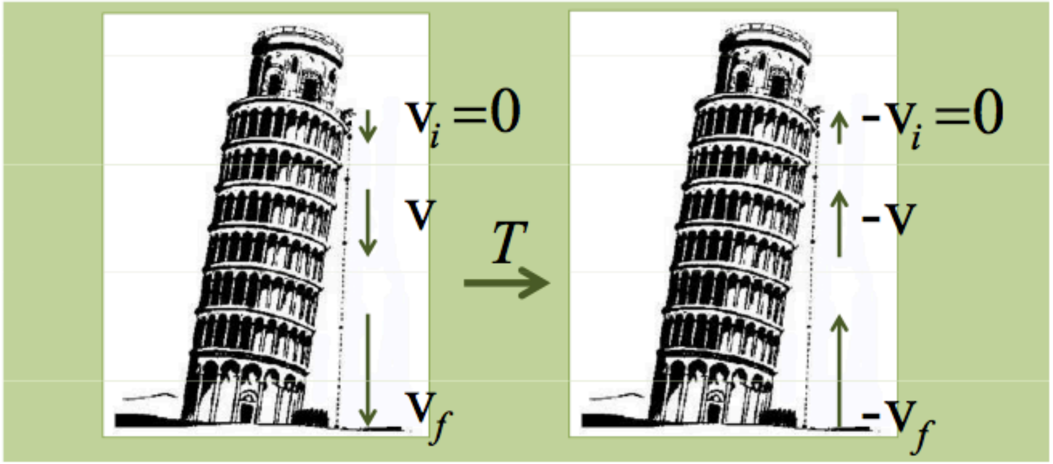
Time Reversal: introduction

•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

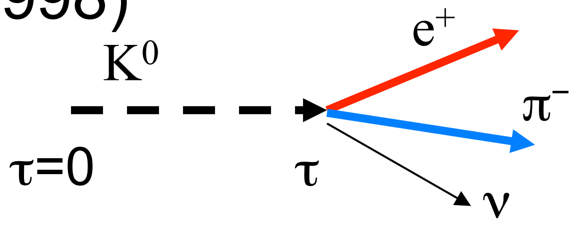
- T-Violation exists in the Standard Model of electro-weak interactions
- CPT theorem => All local unitary field theories with Lorentz invariance have CPT symmetry
- Automatic connection between CP-violation and T-violation
- T and CPT described by ANTIUNITARY rather than unitary operators, introducing 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

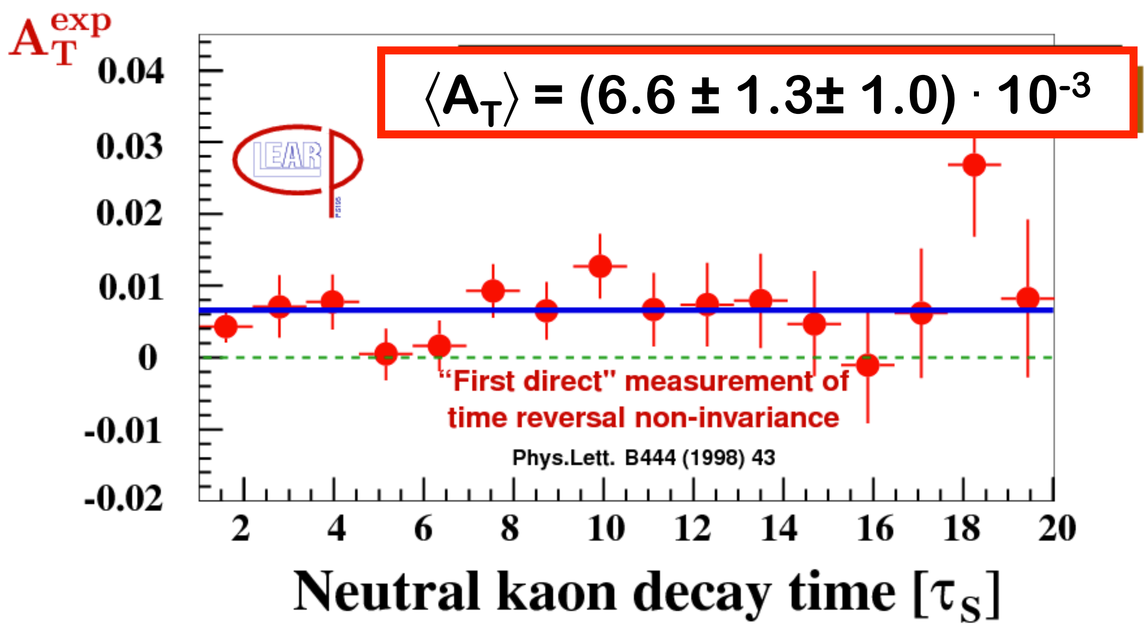
(i) T-odd observable for a non degenerate stationary state: e.g. electric dipole moment of neutron;
(ii) transition between stable particles: e.g. neutrino oscillations
(iii) transition between unstable particles: e.g. K^0 oscillations

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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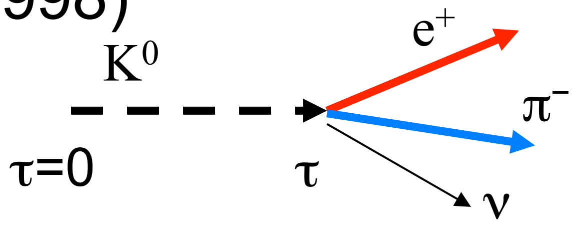


$$A_T = \frac{P(\bar{K}^0 \to K^0) - P(K^0 \to \bar{K}^0)}{P(\bar{K}^0 \to K^0) + P(K^0 \to \bar{K}^0)} = 4\Re\varepsilon$$

assumption: no CPT violation in semileptonic decay:

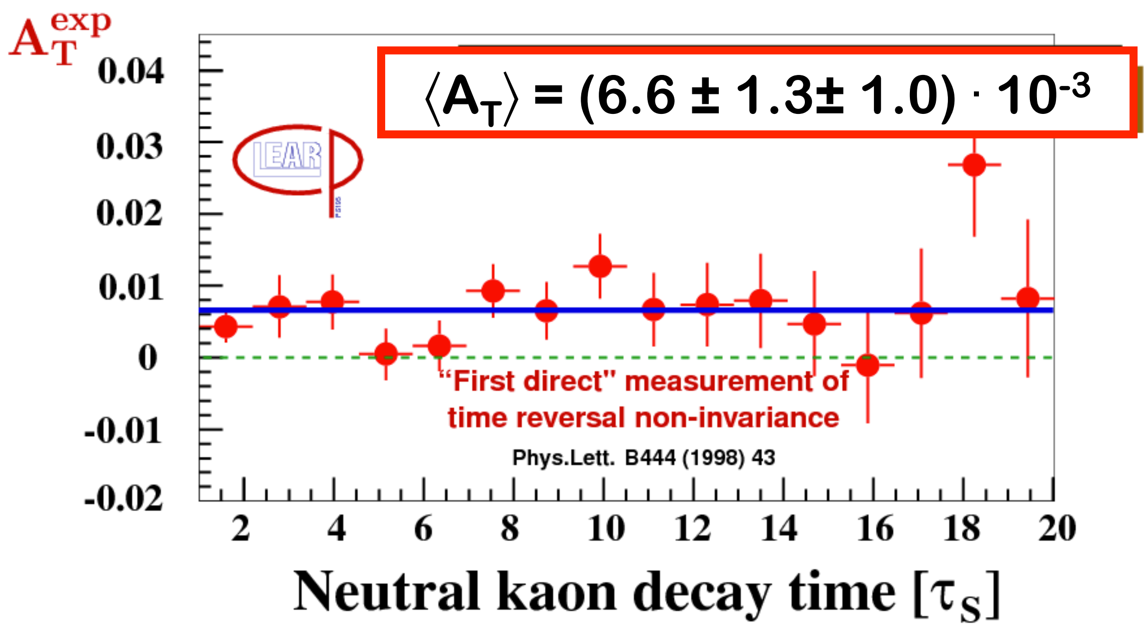
$$\Re(y - x_-) = 0$$

T viol

$$\varepsilon = \frac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)}$$

CPT viol

$$\delta = \frac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)}$$



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Test of Time Reversal symmetry using Kabir's asymmetry

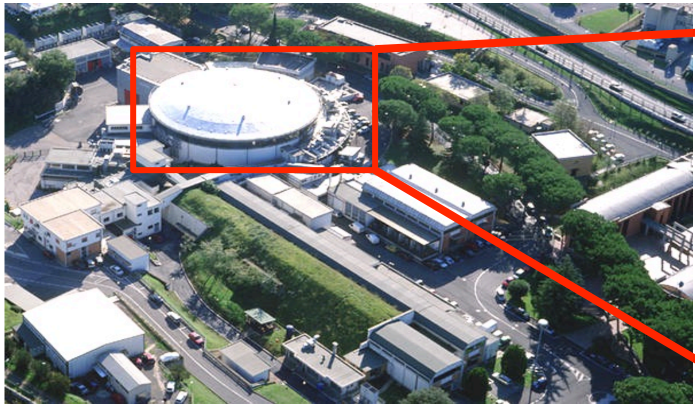
- A direct evidence for T violation would mean an experiment that, considered by itself, clearly shows T violation INDEPENDENT and unconnected to the results for CP violation and CPT invariance
- Controversial interpretation of the CPLEAR result as "direct" test: L. Wolfenstein "It is known from the 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"

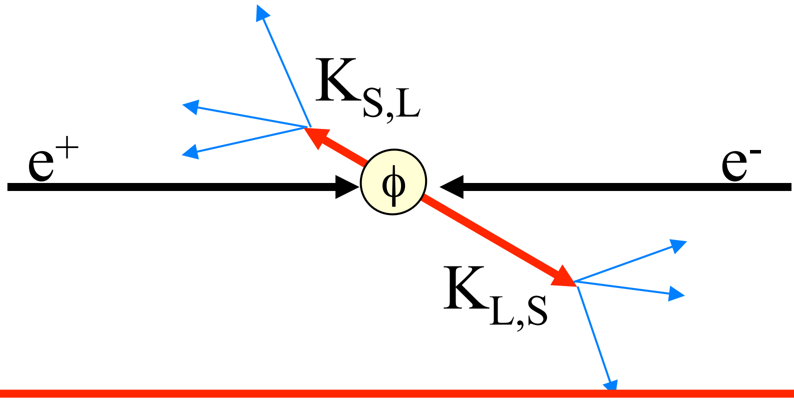
- 1) Remark: $K^0 \to \bar{K}^0$ is a CPT-even transition, so $CP \equiv T$ in this case !
  CP and T cannot be distinguished (not independent)
  T test: $K^0 \to \bar{K}^0$ vs $\bar{K}^0 \to K^0$
  CP test: $K^0 \to \bar{K}^0$ vs $\bar{K}^0 \to K^0$

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

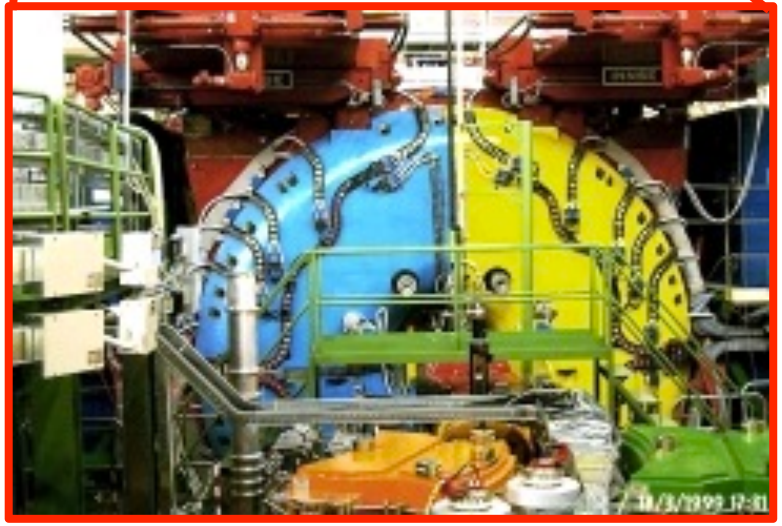
KLOE/KLOE-2 experiment at the Frascati ϕ-factory DAΦNE

DAFNE collider





KLOE detector



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

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

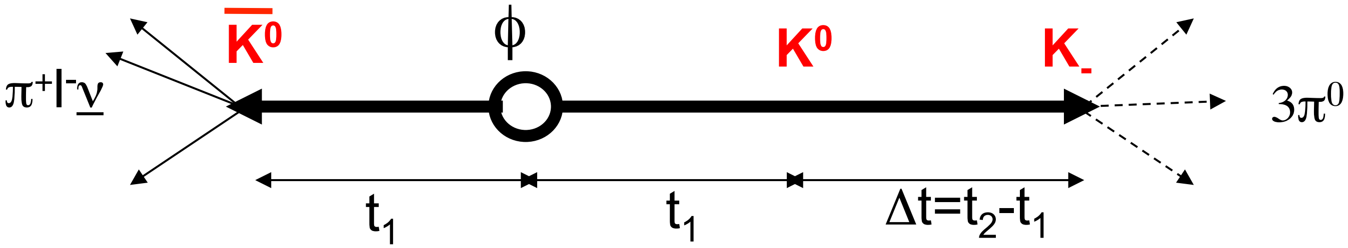
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

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)

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

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



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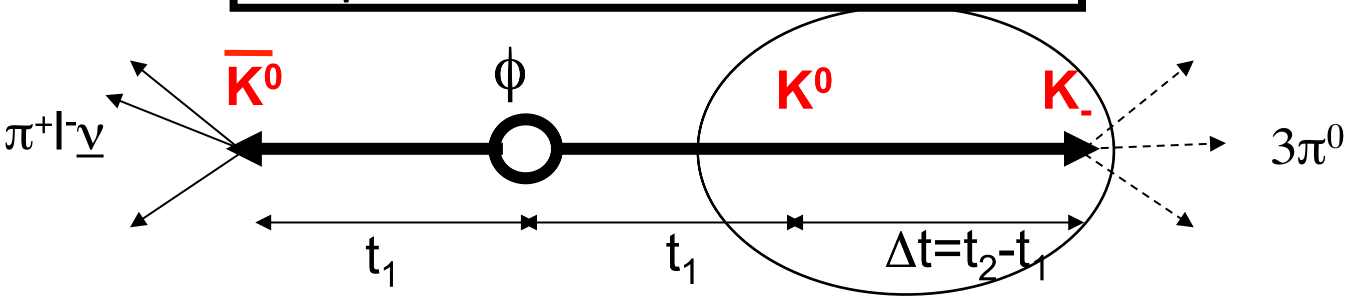

$K^0 \rightarrow K_-$ reference process

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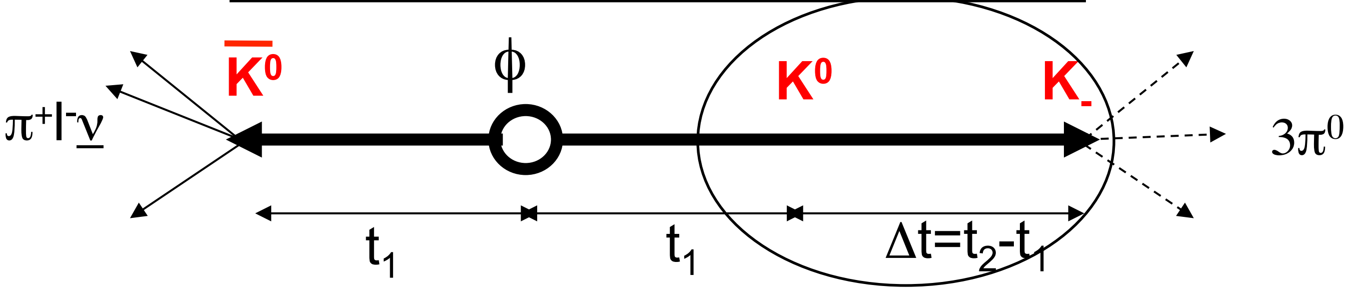

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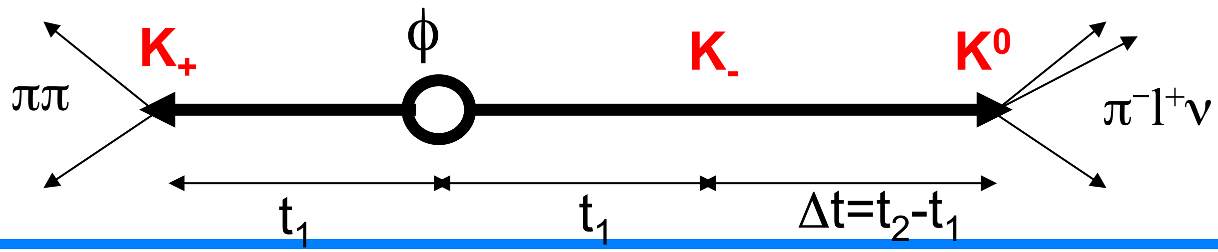

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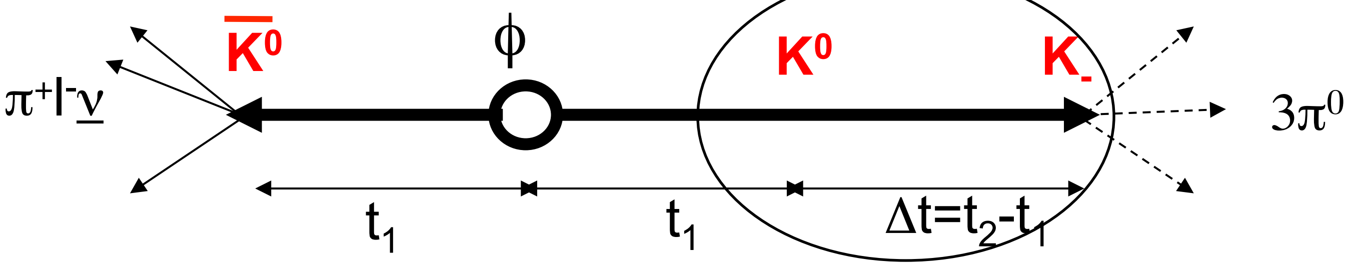
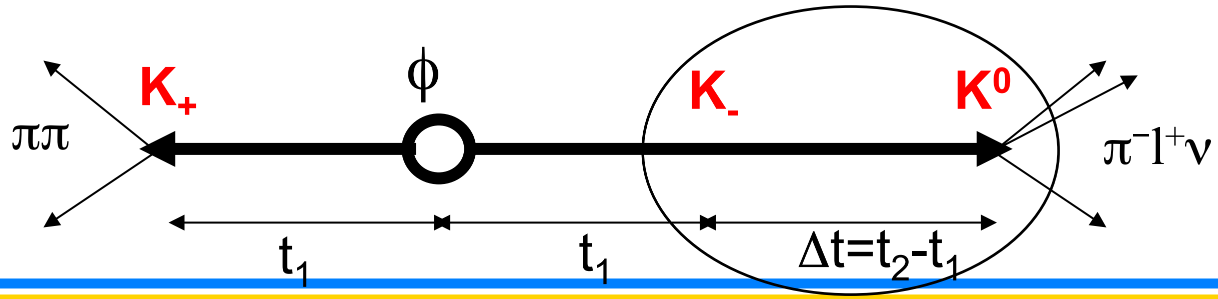


$K^0 \to K_-$ reference process

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



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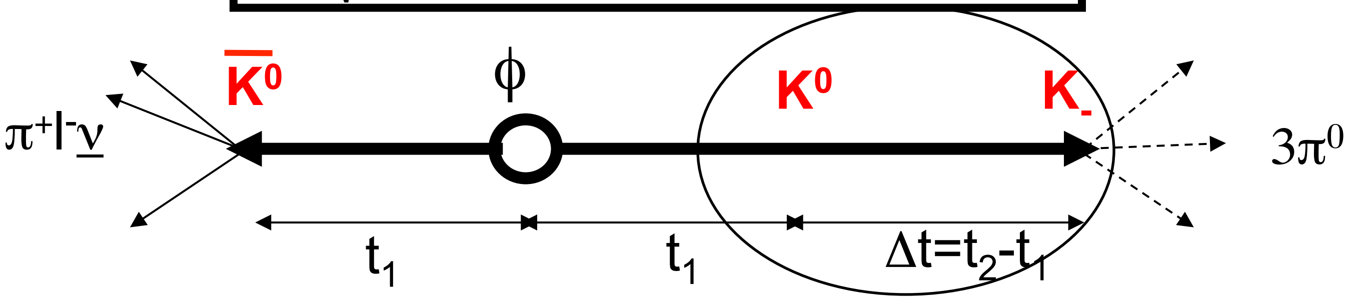
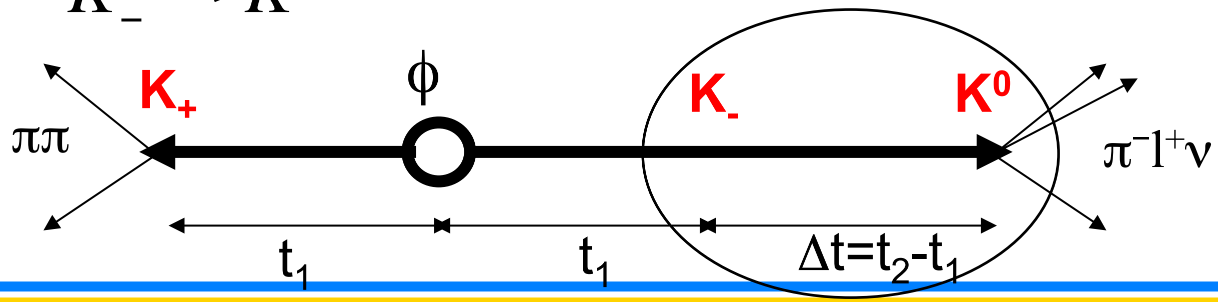


$K^0 \rightarrow K_-$ reference process

Note: CP and CPT conjugated process

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

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



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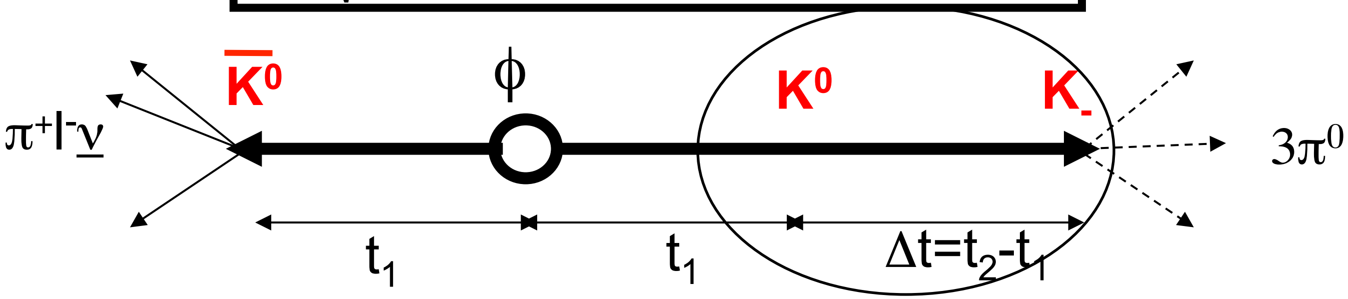

$K^0 \to K_-$ reference process

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

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

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

with $C(f_{\bar{X}}, f_Y) = \dfrac{1}{2(\Gamma_S + \Gamma_L)} \left|\langle f_{\bar{X}}|T|\bar{K}_X\rangle\langle f_Y|T|K_Y\rangle\right|^2$

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

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

Direct test of symmetries with neutral kaons

Conjugate= reference (red bar)

already in the table with conjugate as reference (black bar)

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

already in the table with conjugate as reference

Two identical conjugates for one reference

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

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

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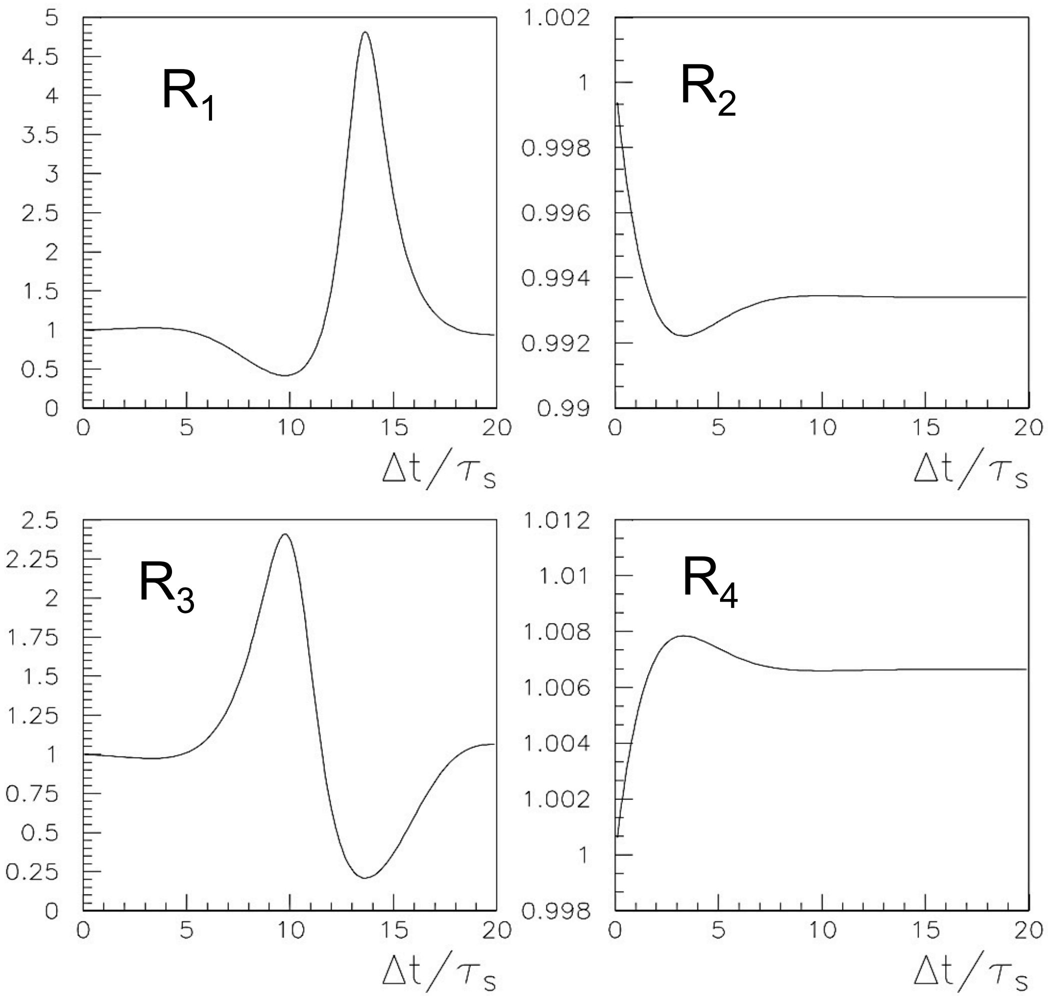
Direct test of Time Reversal symmetry with neutral kaons

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



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

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

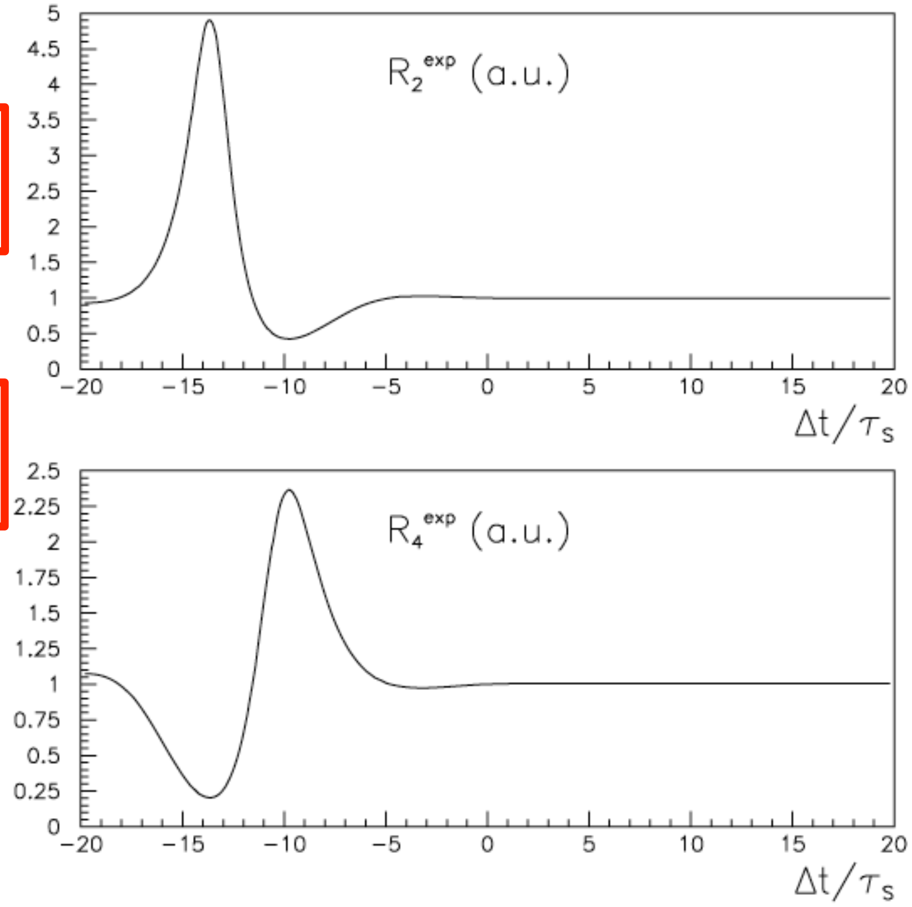
Direct test of Time Reversal symmetry with neutral kaons

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

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

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

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



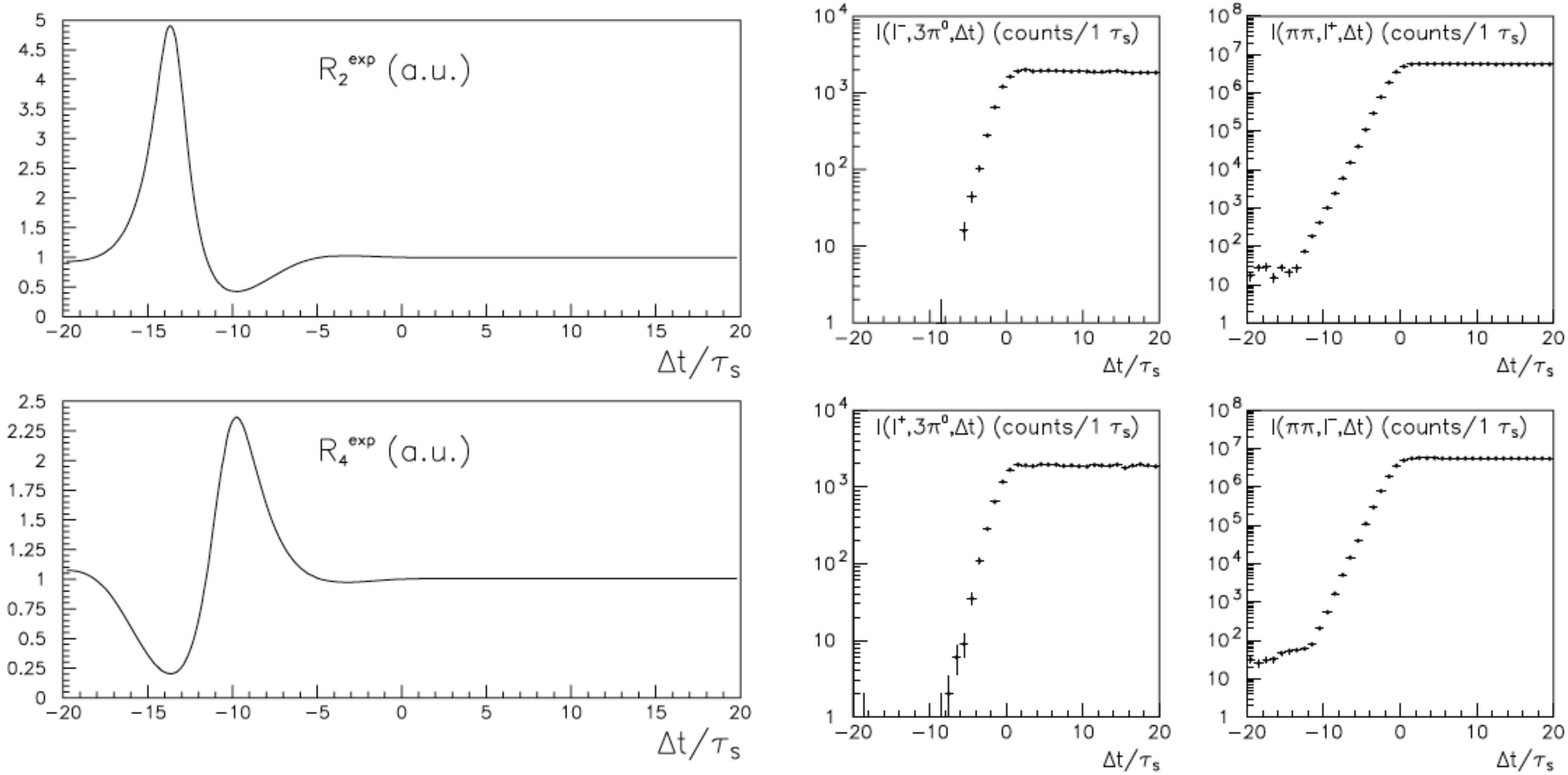
In practice two measurable ratios with $\Delta t < 0$ or > 0

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

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

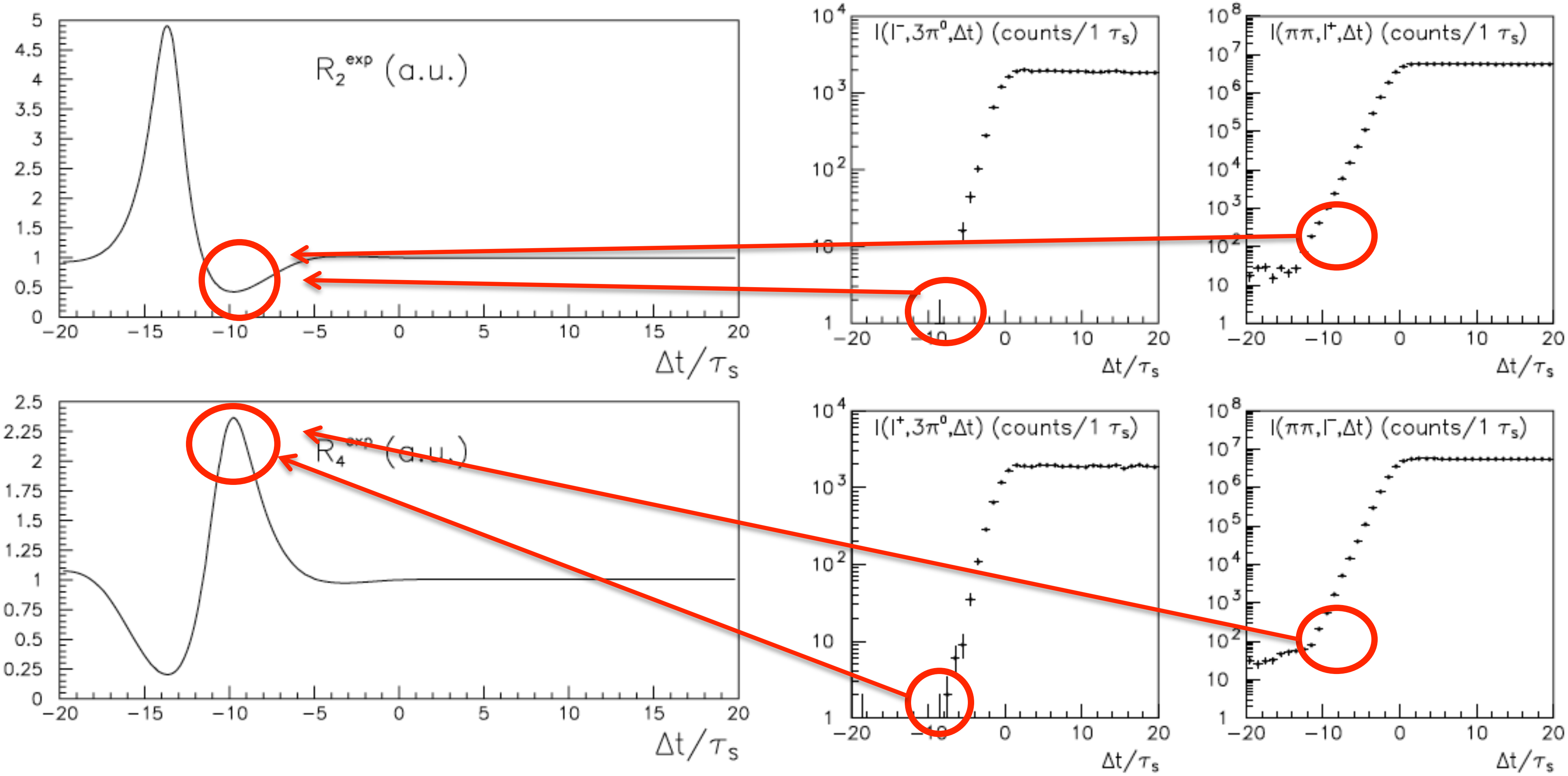
Direct test of Time Reversal symmetry with neutral kaons

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



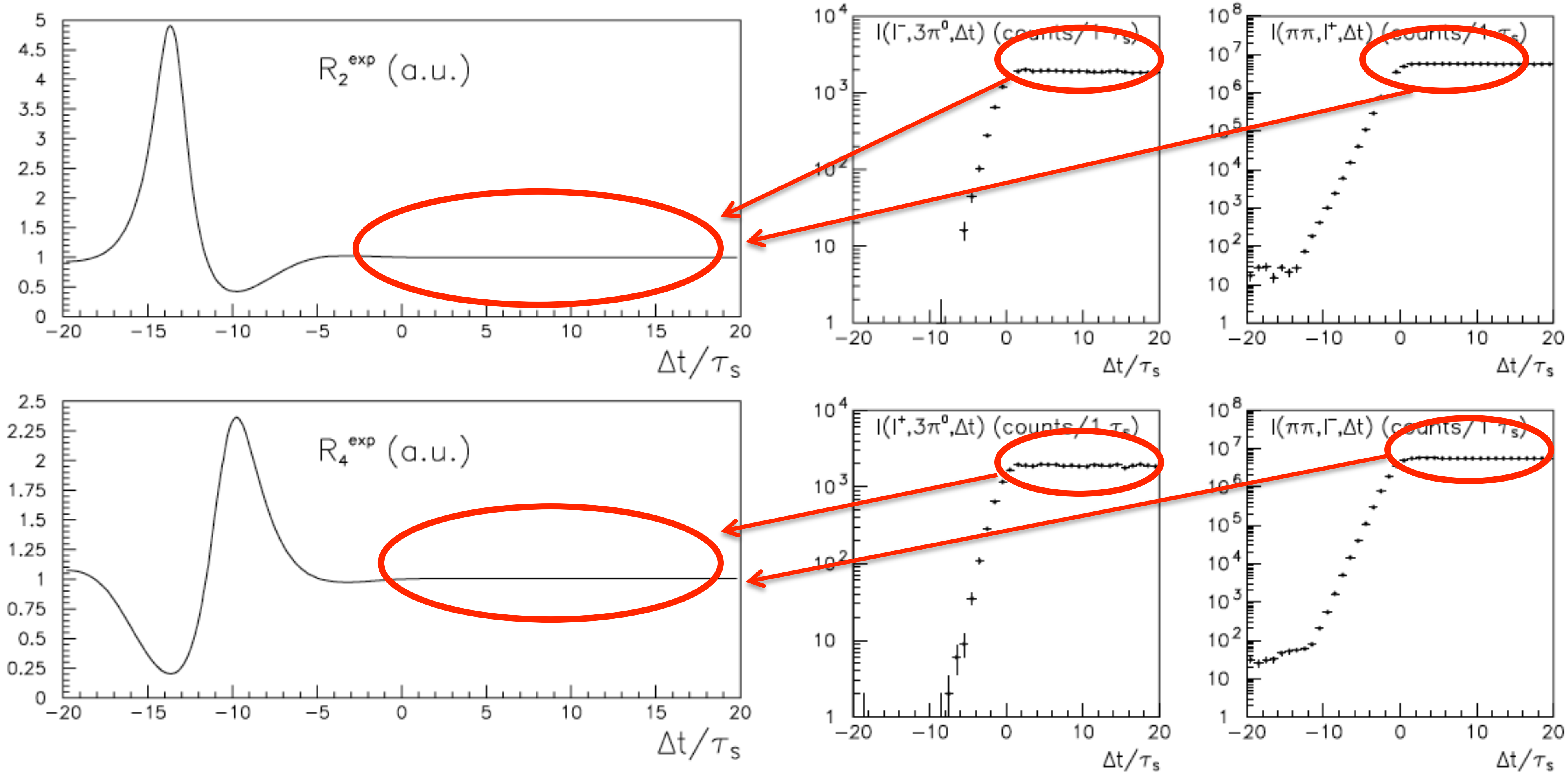
Direct test of Time Reversal symmetry with neutral kaons

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



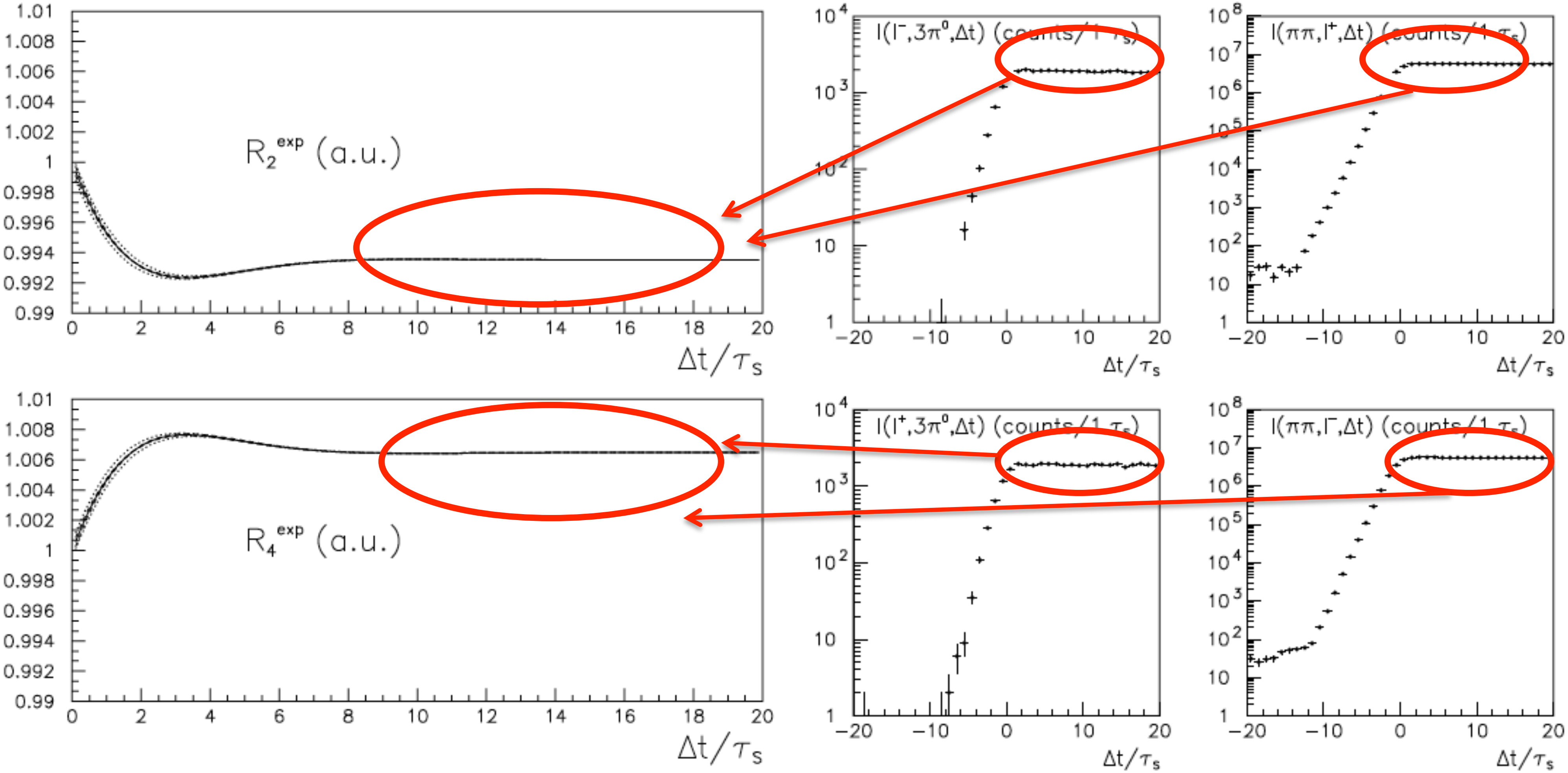
Direct test of Time Reversal symmetry with neutral kaons

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



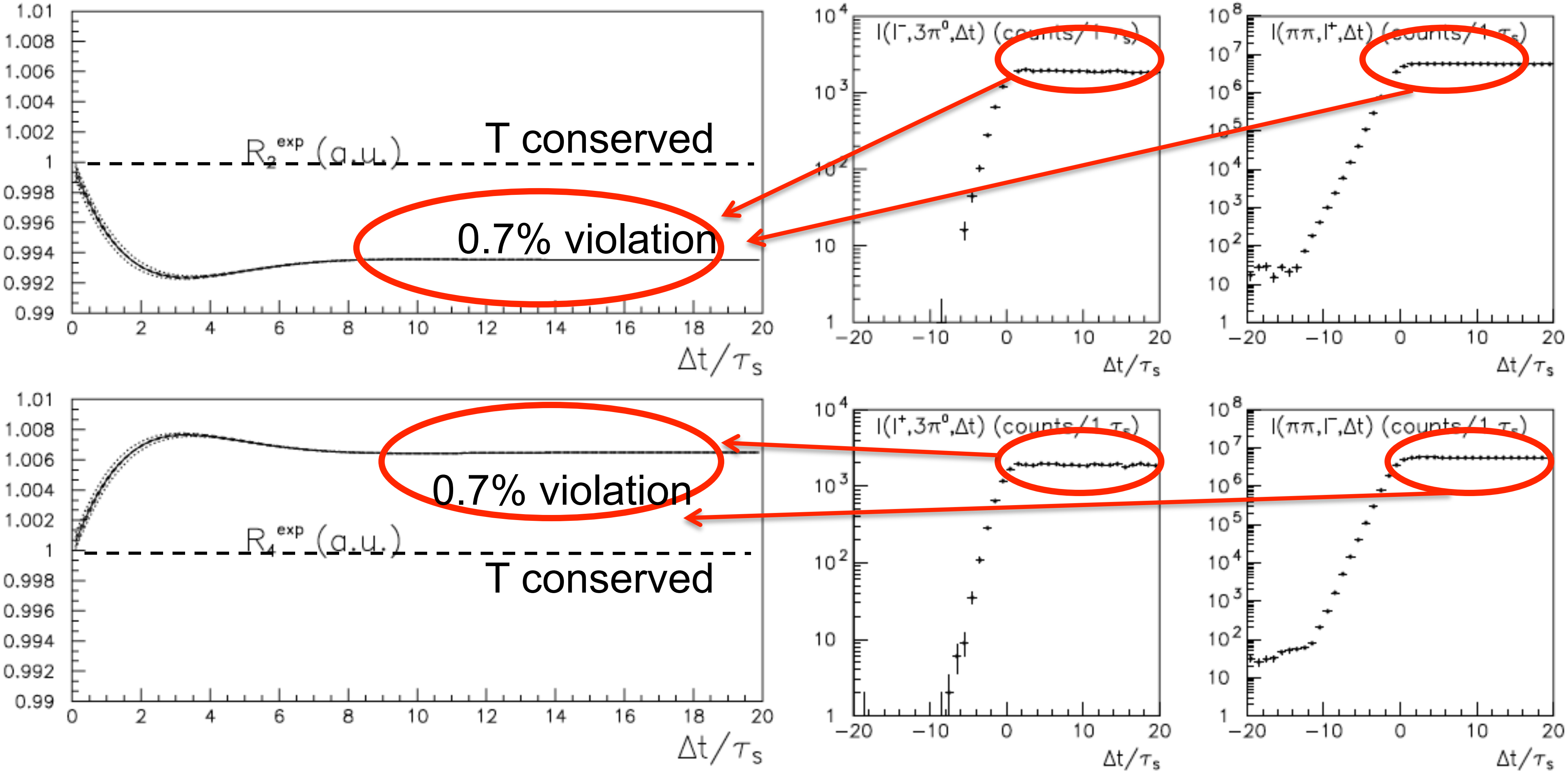
Direct test of Time Reversal symmetry with neutral kaons

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)

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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:

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

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

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

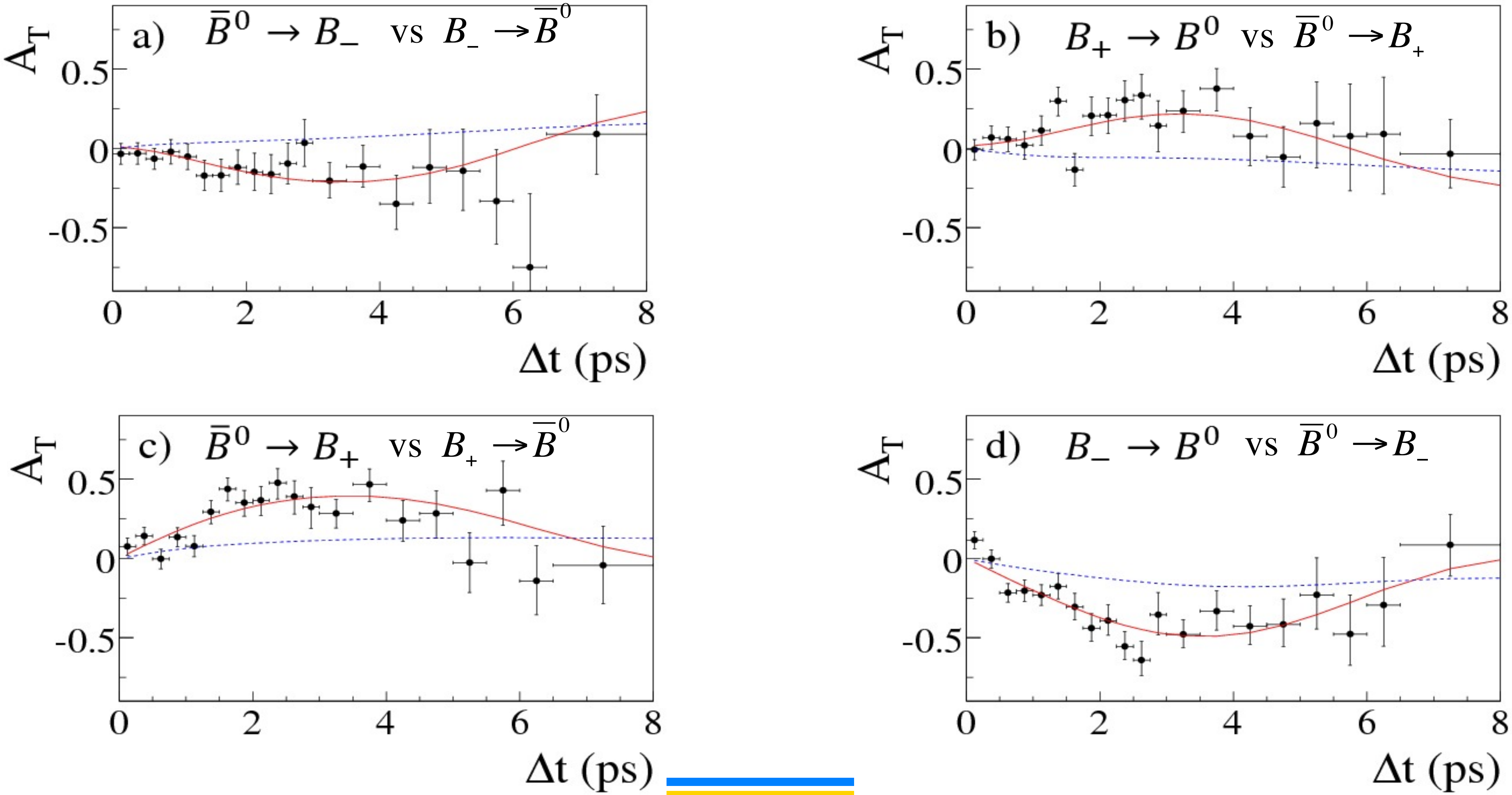
- It is needed to measure the constant D with ~ 0.1% precision, i.e. BRs and K_S, K_L lifetimes
-in the "plateau" region effect proportional to Re(ε)

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

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

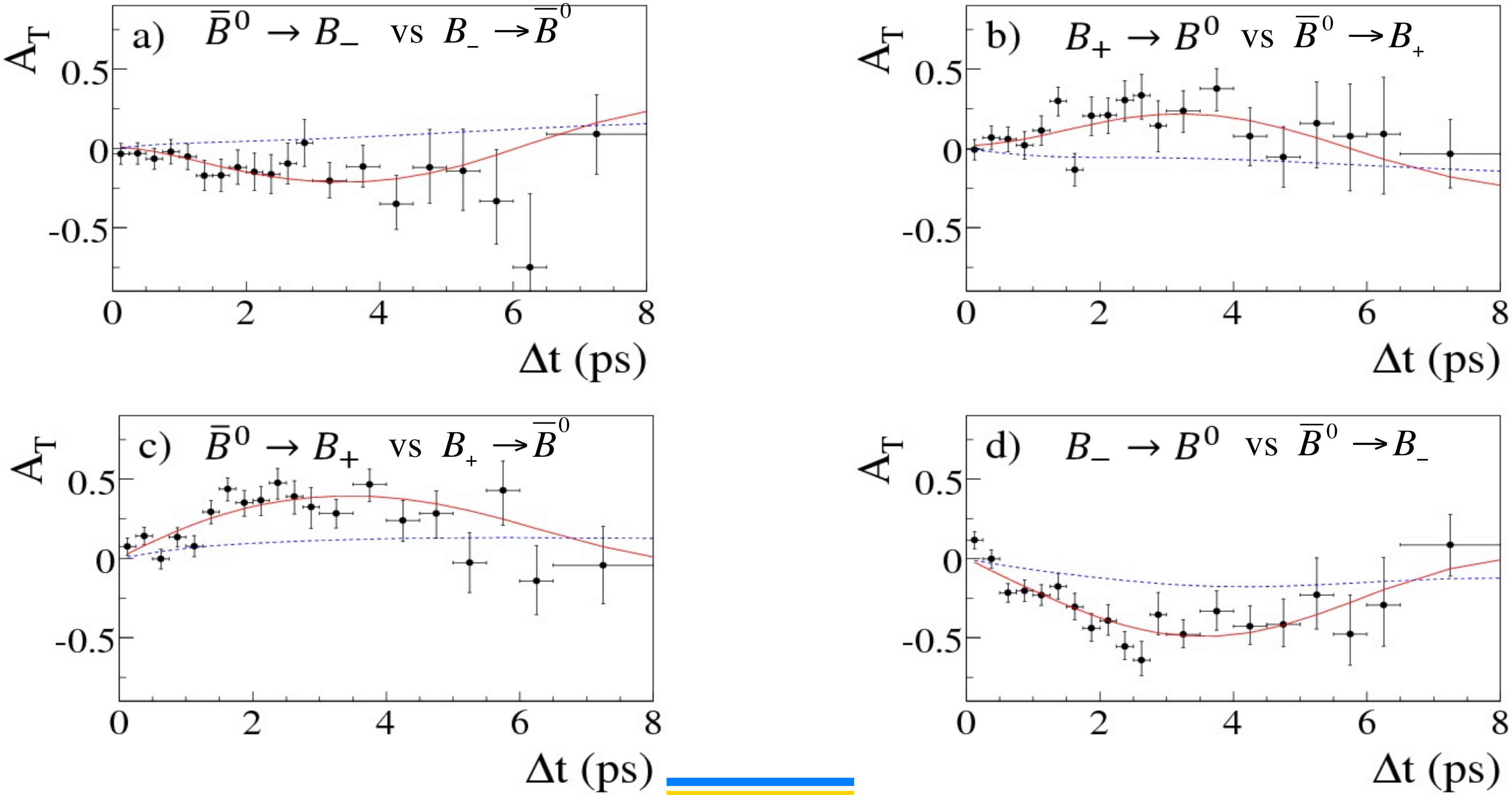


Direct test of Time Reversal symmetry in neutral **B mesons**

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 Time Reversal 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:

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

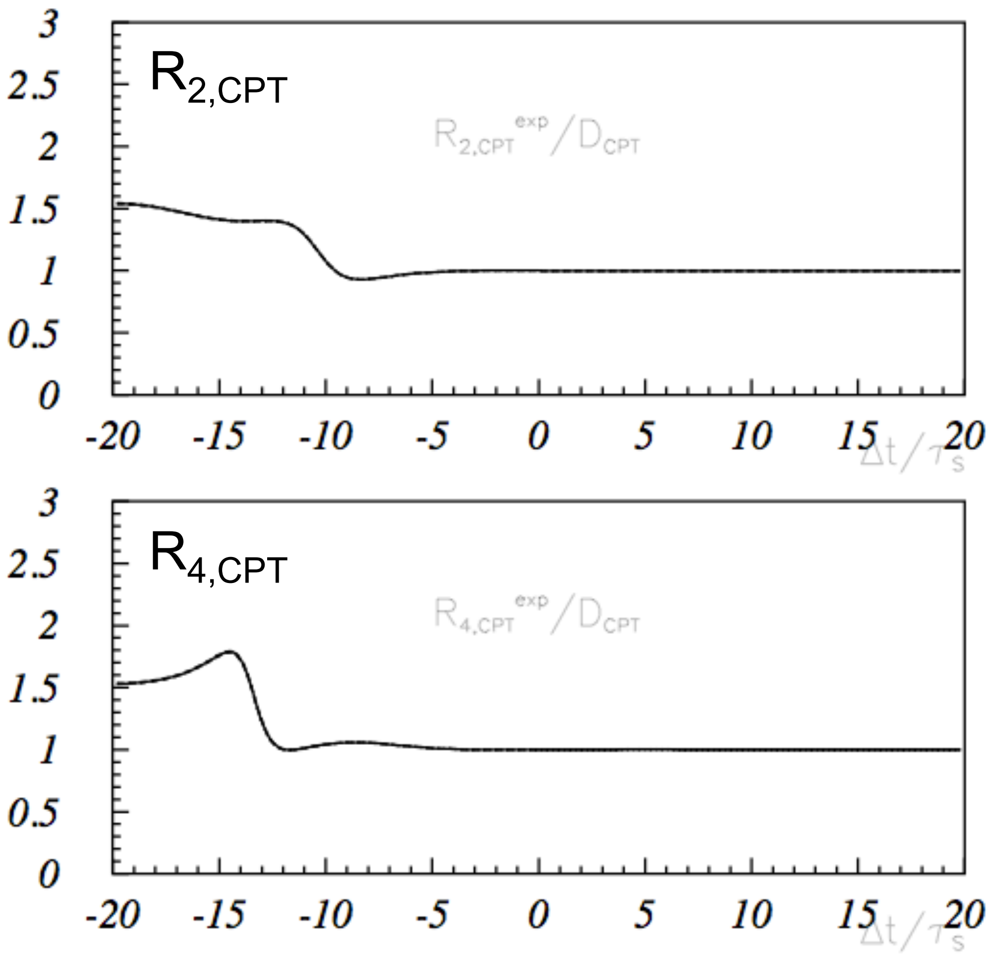
Any deviation from $R_{i,CPT}$=1 constitutes a violation of T-symmetry

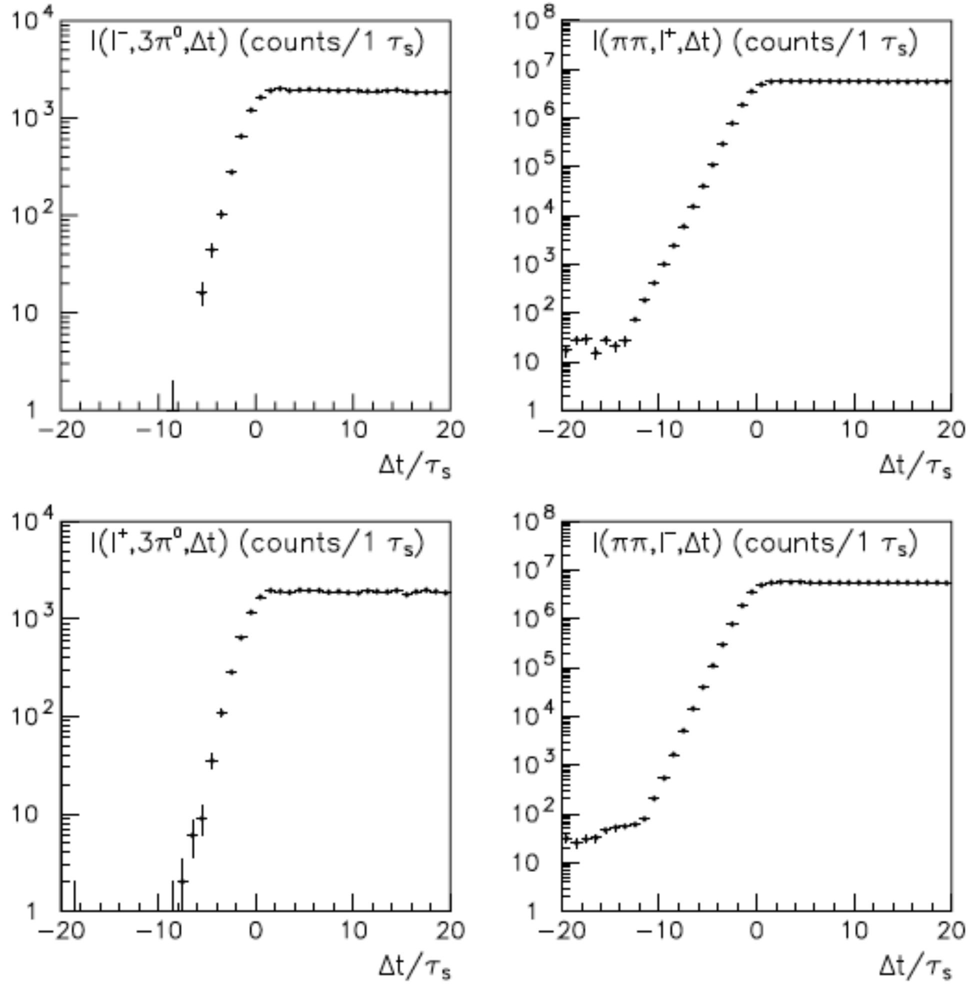
J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102 **A.D.D. PoS KAON13 (2013) 009**

Direct test of CPT symmetry with neutral kaons

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

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

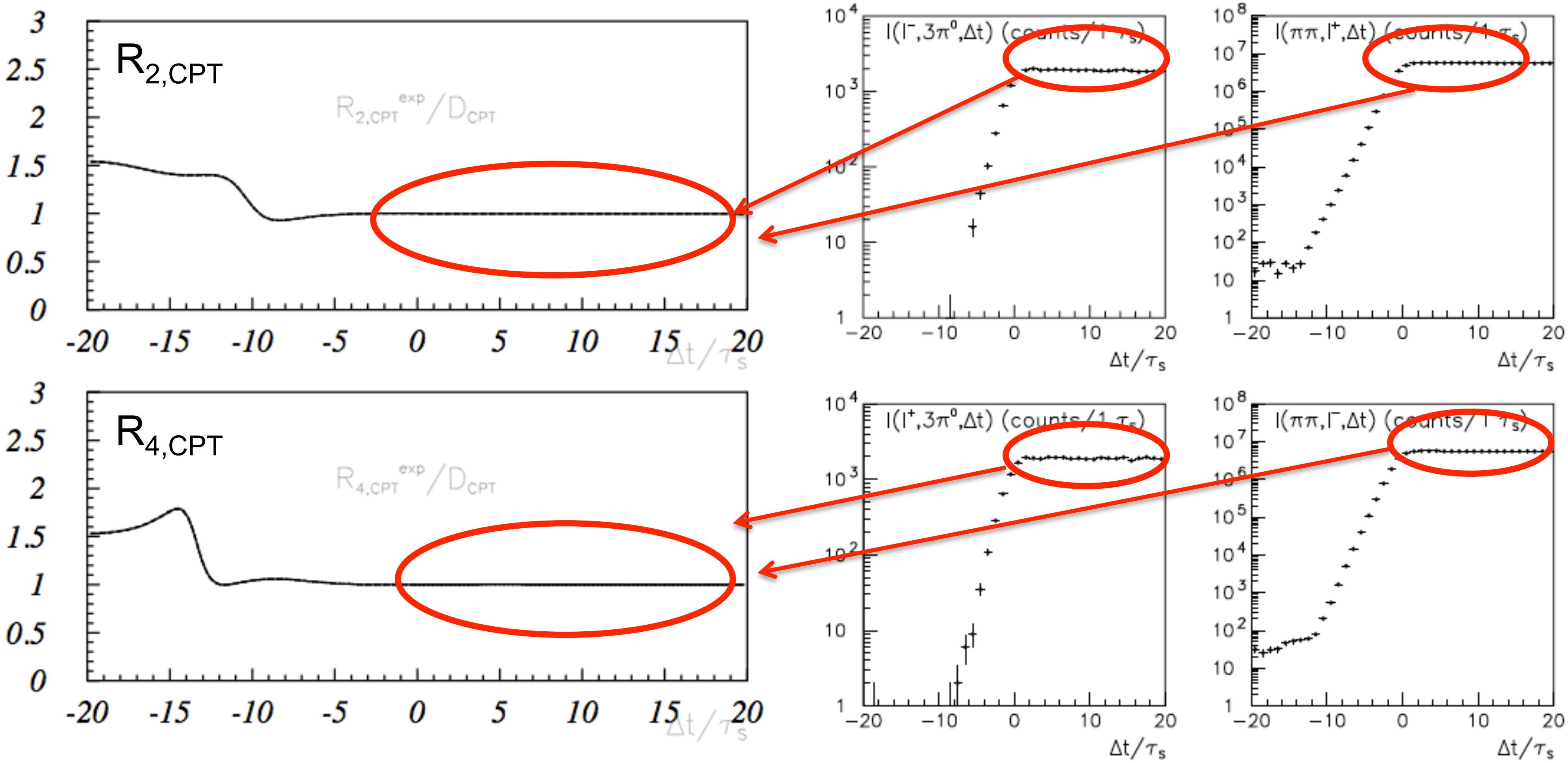




Direct test of CPT symmetry with neutral kaons

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

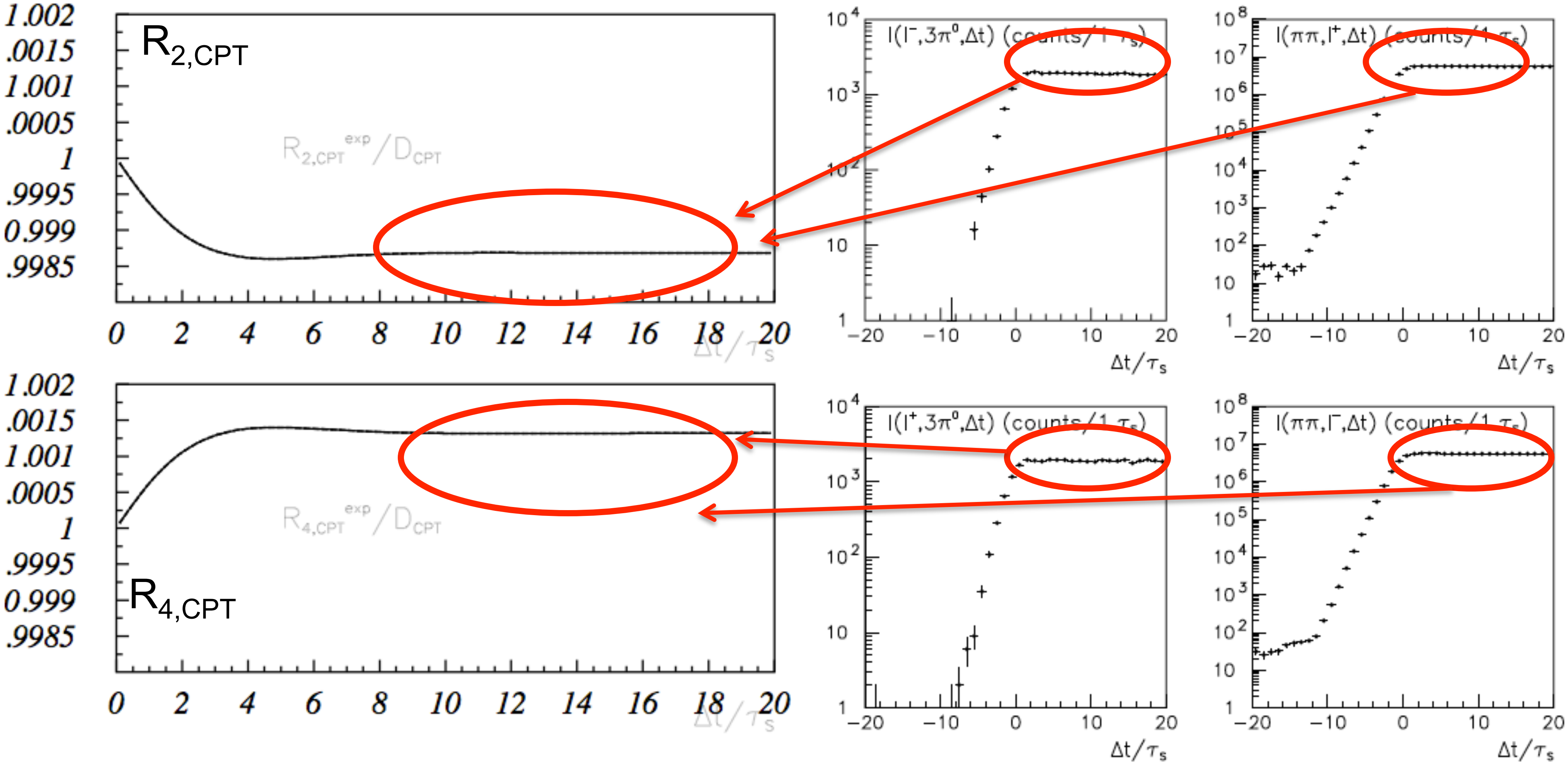
toy MC with $L=10\ fb^{-1}$



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}

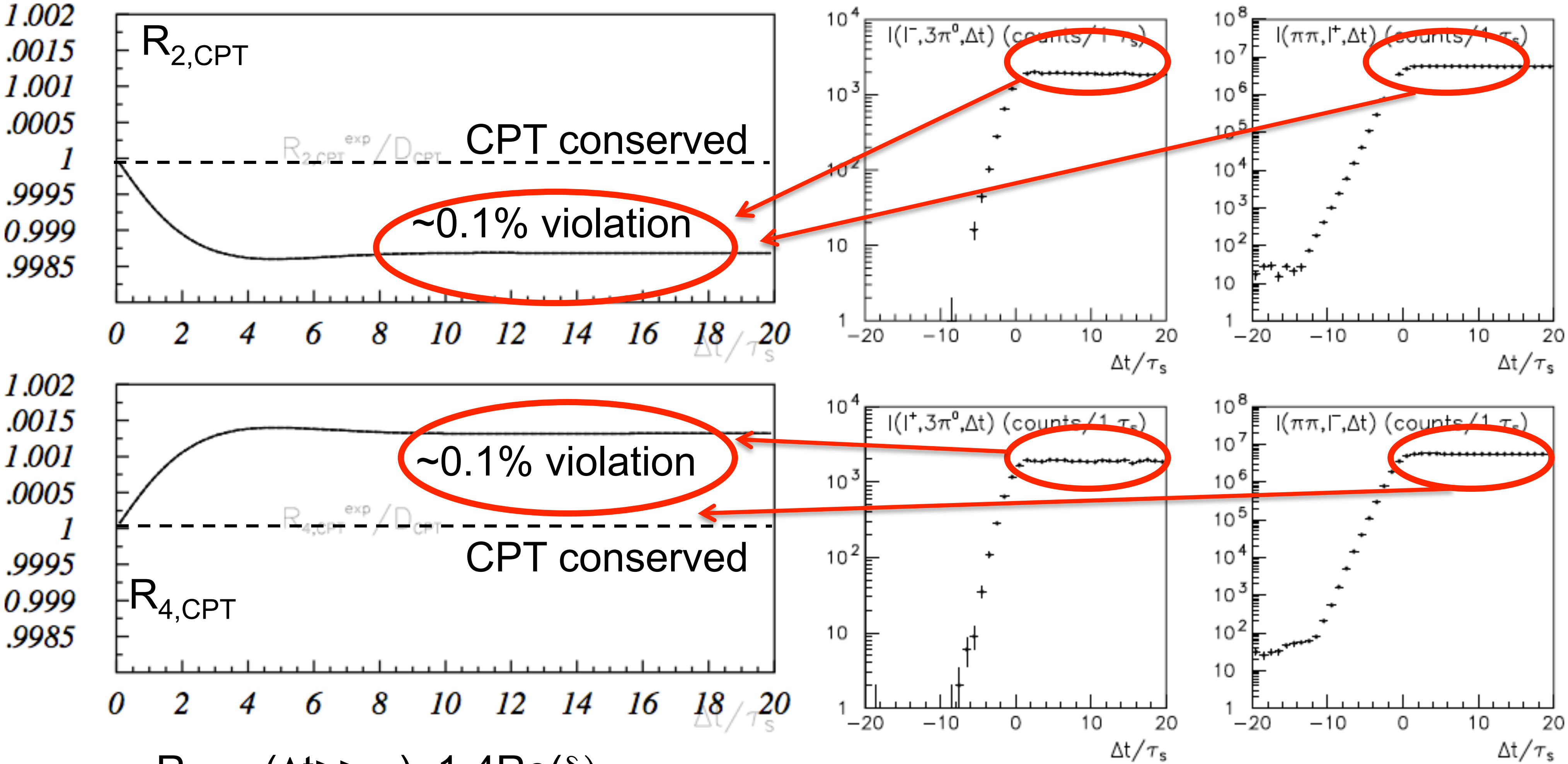
toy MC with L=10 fb^{-1}



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}

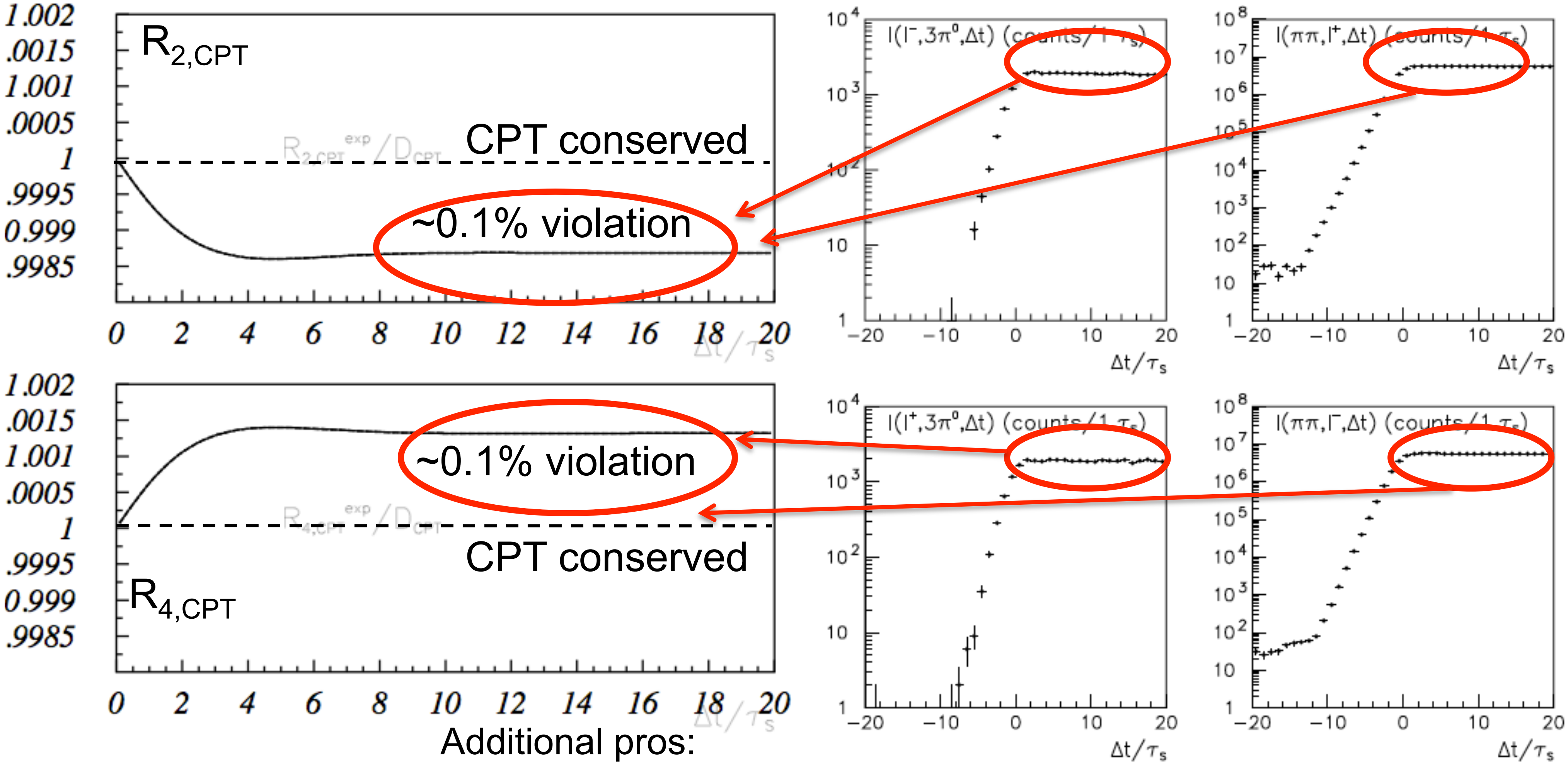


$R_{2,CPT}(\Delta t >> \tau_S) = 1 - 4Re(\delta)$
$R_{4,CPT}(\Delta t >> \tau_S) = 1 + 4Re(\delta)$

Direct test of CPT symmetry with neutral kaons

for visualization purposes, plots with
Re(δ)=3.3 10^{-4} Im(δ)=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 kaon 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 also new kind of CPT tests in transitions could be performed.

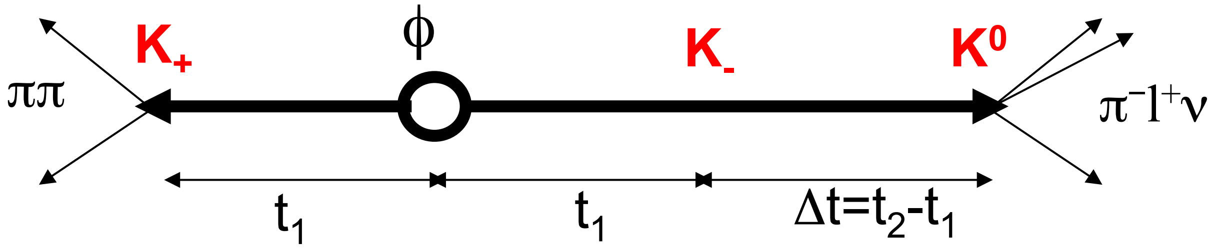
- The KLOE-2 experiment at the DAFNE could make a statistically significant T, CPT symmetry test with an integrated luminosity of $O(10\ fb^{-1})$.

backup slides

The kaon states

$|K_{+(-)}\rangle \equiv$ state filtered by the decay in $\pi\pi(3\pi^0)$ (pure CP = +1(-1) state)

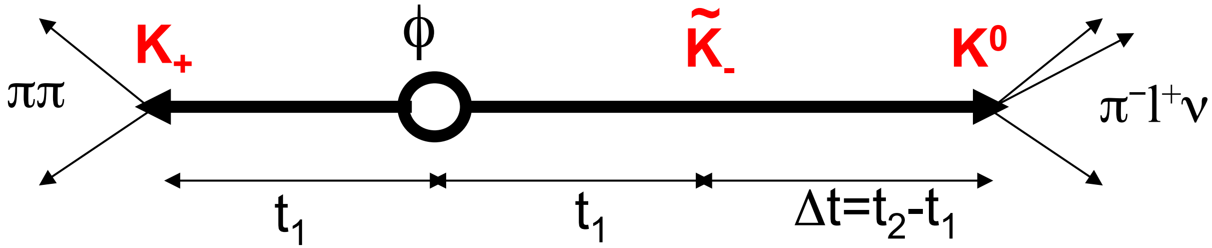
$|K_{-(+)}\rangle \equiv$ state ortogonal to $|K_{+(-)}\rangle$ which cannot decay in $\pi\pi(3\pi^0)$



The kaon states

$|K_{+(-)}\rangle \equiv$ state filtered by the decay in $\pi\pi(3\pi^0)$ (pure CP = +1(-1) state)

$|\tilde{K}_{-(+)}\rangle \equiv$ state ortogonal to $|K_{+(-)}\rangle$ which cannot decay in $\pi\pi(3\pi^0)$



state orthogonal to K_+ cannot decay in $\pi\pi$

$$|\tilde{K}_-\rangle \equiv \tilde{N}_-\left[|K_L\rangle - \eta_{\pi\pi}|K_S\rangle\right]$$

$$|K_+\rangle = N_+\left[|K_S\rangle + \alpha|K_L\rangle\right]$$

where

$$\alpha = \frac{\eta^\star_{\pi\pi} - \langle K_L|K_S\rangle}{1 - \eta^\star_{\pi\pi}\langle K_S|K_L\rangle},$$

state orthogonal to K_- cannot decay in $3\pi^0$

$$|\tilde{K}_+\rangle \equiv \tilde{N}_+\left[|K_S\rangle - (\eta^{-1}_{3\pi^0})|K_L\rangle\right]$$

$$|K_-\rangle = N_-\left[|K_L\rangle + \beta|K_S\rangle\right]$$

where

$$\beta = \frac{(\eta^{-1}_{3\pi^0})^\star - \langle K_S|K_L\rangle}{1 - (\eta^{-1}_{3\pi^0})^\star\langle K_L|K_S\rangle},$$

need to assume $|K_+\rangle \equiv |\tilde{K}_+\rangle$, $|K_-\rangle \equiv |\tilde{K}_-\rangle$ => $\eta_{\pi\pi} + (\eta^{-1}_{3\pi^0})^\star \simeq \langle K_S|K_L\rangle \simeq \epsilon_L + \epsilon^\star_S.$

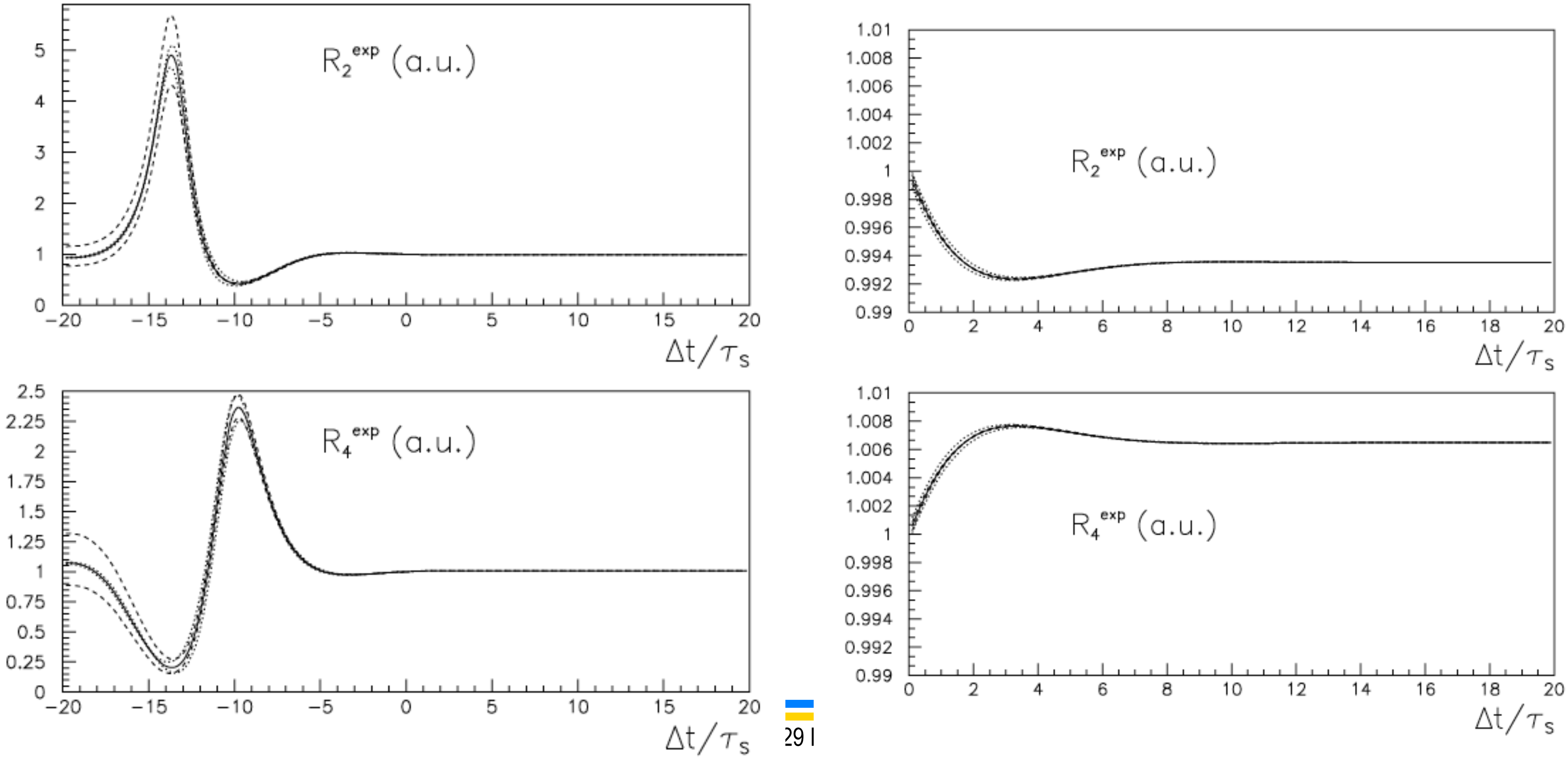
not valid if direct CP violation is present

assumption: direct CPV negligible

Direct test of Time Reversal symmetry with neutral kaons

Direct CP violation effects have to be evaluated, they could spoil the significance of the T test.

For 2π decay, ε' can be neglected. For $3\pi^0$, bound on ε'_{000} from KLOE still too crude! ($|\eta_{000}| < \mathbf{0.0088}$ **@ 90% CL**). Assuming as max. variation $|\eta_{3\pi 0}| = |\eta_{2\pi}| \pm 10\%$, $\phi(\eta_{3\pi 0}) = \phi(\eta_{2\pi}) \pm 10°$, ε'_{000} effects can be neglected



Direct test of CPT symmetry with neutral kaons

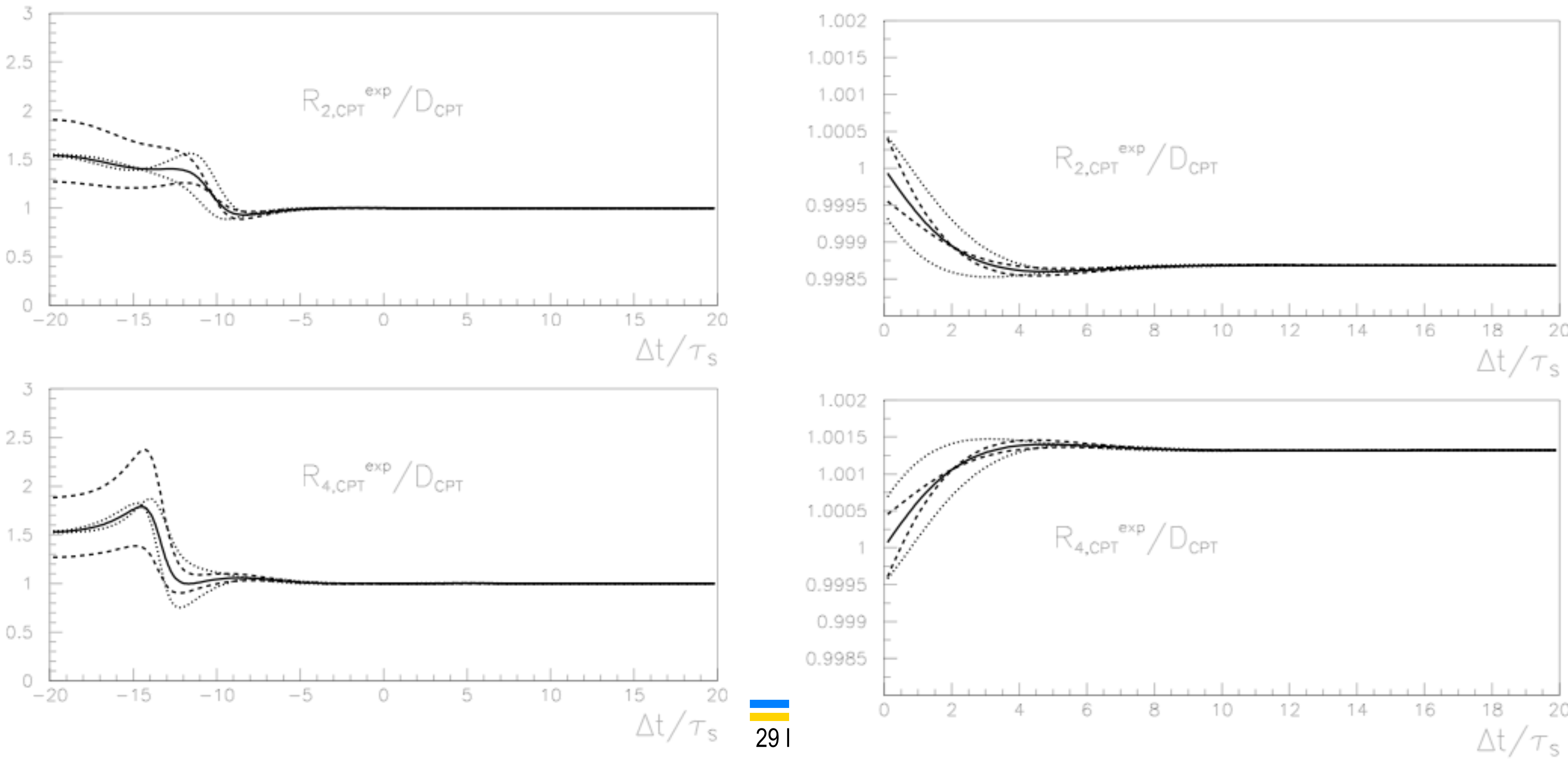
Direct CP violation effects have to be evaluated, they could spoil the significance of the T test.

For 2π decay, ε' can be neglected. For $3\pi^0$, bound on ε'_{000} from KLOE still too crude! ($|\eta_{000}| < \mathbf{0.0088}$ **@ 90% CL**). Assuming as max. variation

$|\eta_{3\pi 0}| = |\eta_{2\pi}| \pm 10\%$

$\phi(\eta_{3\pi 0}) = \phi(\eta_{2\pi}) \pm 10°$

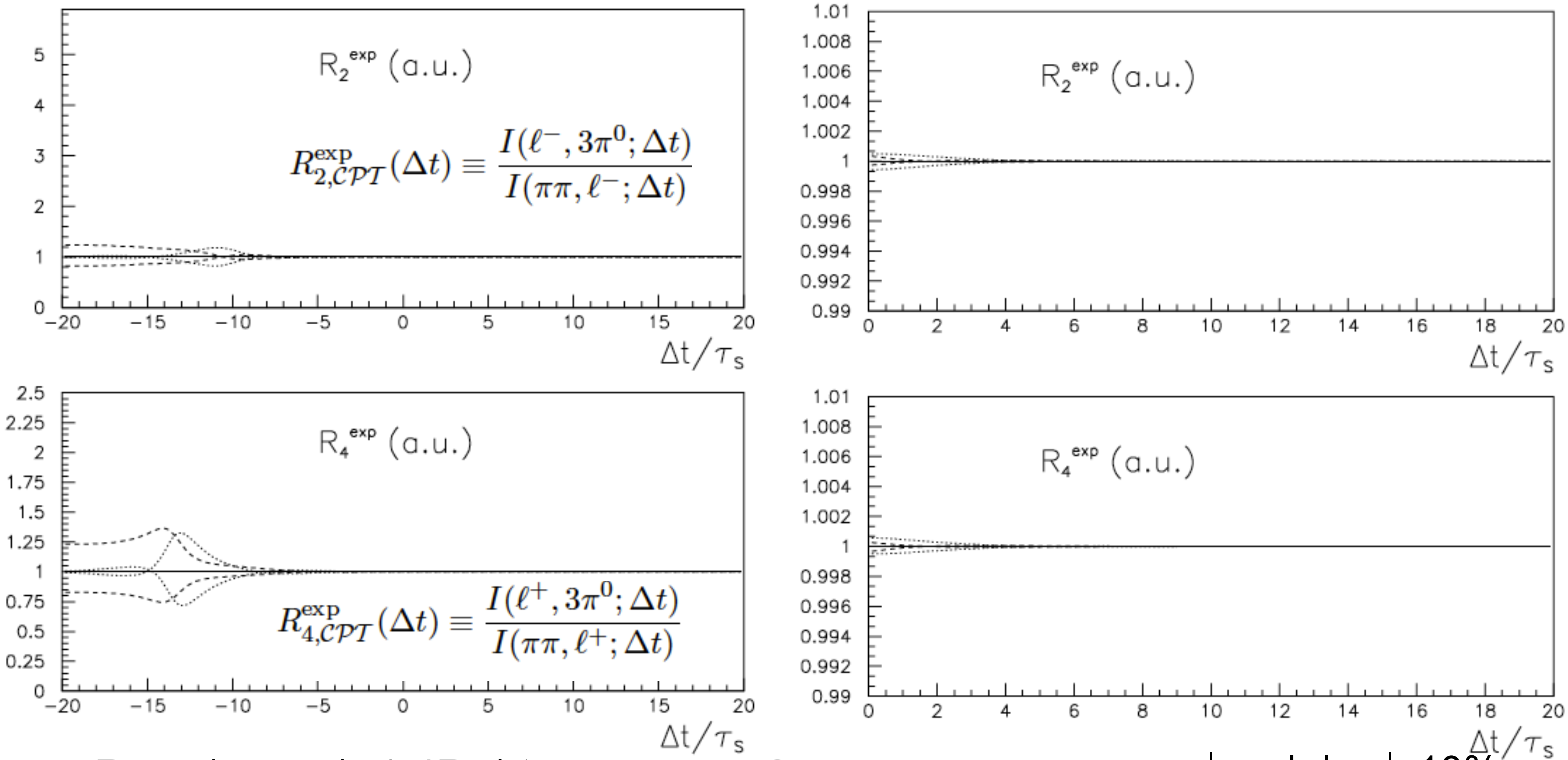
ε'_{000} effects can be neglected



direct CPT test

plots with Re(δ)=0 Im(δ)=0

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

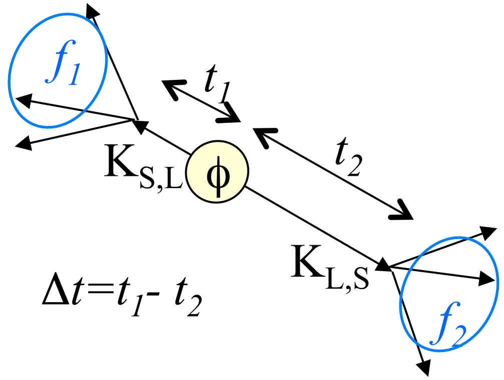


$R_{2,CPT}(\Delta t >> \tau_S) = 1 - 4Re(\delta)$
$R_{4,CPT}(\Delta t >> \tau_S) = 1 + 4Re(\delta)$

Direct CP violation effects negligible for $\Delta t >> \tau_S$

$|\eta_{3\pi 0}| = |\eta_{2\pi}| \pm 10\%$
$\phi(\eta_{3\pi 0}) = \phi(\eta_{2\pi}) \pm 10°$

Neutral kaon interferometry



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

Double differential time distribution:

$$I(f_1,t_1;f_2,t_2) = C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2}\right.$$

$$\left. -2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2}\cos\left[\Delta m(t_2 - t_1) + \phi_1 - \phi_2\right]\right\}$$

characteristic interference term at a ϕ-factory => interferometry

where $t_1(t_2)$ is the proper time of one (the other) kaon decay into f_1 (f_2) final state and:

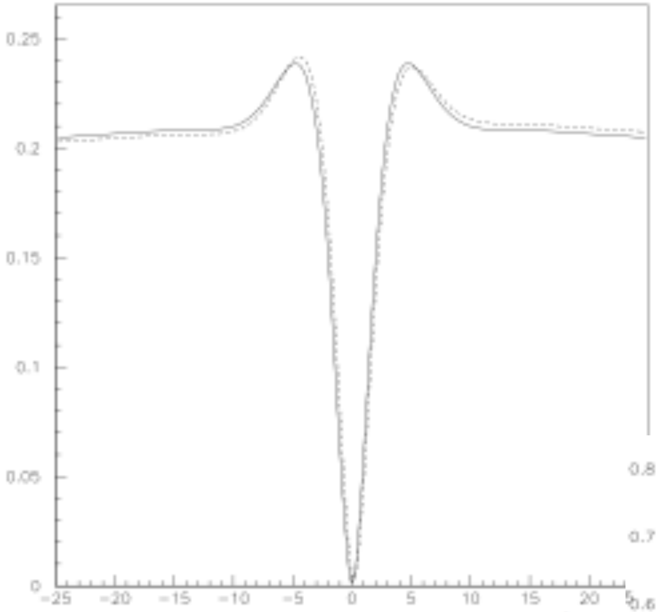
$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

$$C_{12} = \frac{|N|^2}{2}\left|\langle f_1|T|K_S\rangle\langle f_2|T|K_S\rangle\right|^2$$

From these distributions for various final states f_i one can measure the following quantities: Γ_S , Γ_L , Δm , $|\eta_i|$, $\phi_i \equiv \arg(\eta_i)$

Neutral kaon interferometry: main observables

$I(\Delta t)$ (a.u)



$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^0\pi^0$

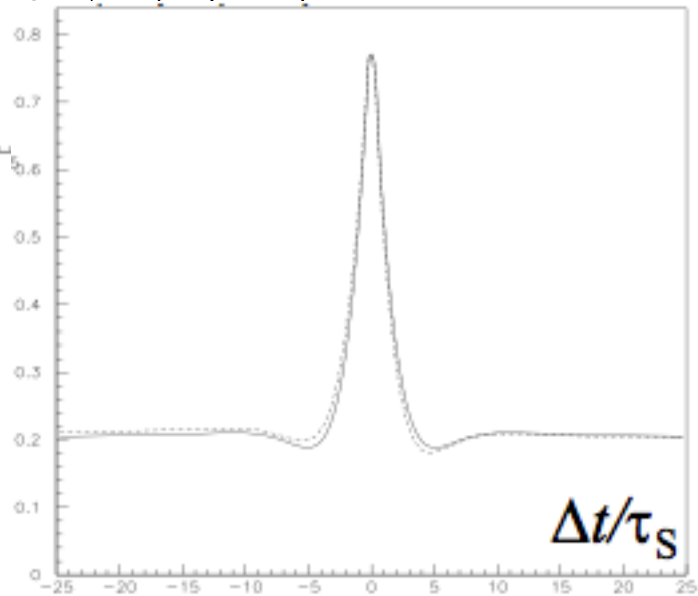
$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$

$\Re\delta + \Re x_-$

$\Im\delta + \Im x_+$

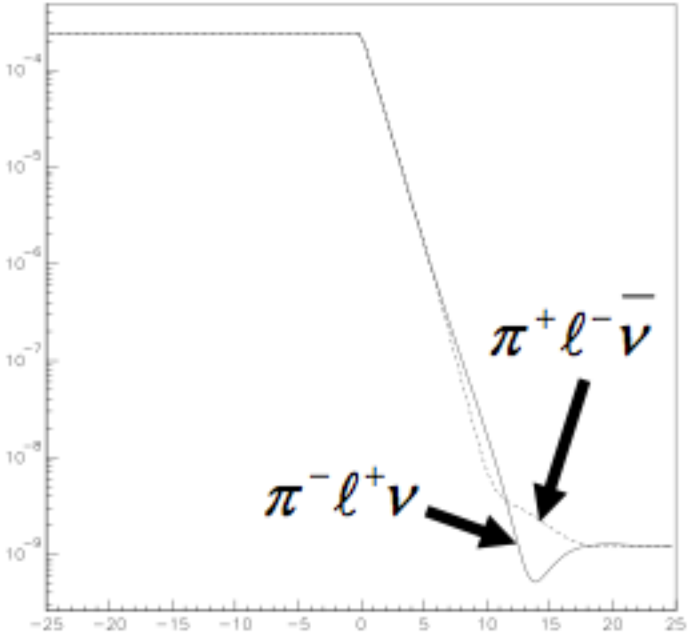
$\phi \to K_S K_L \to \pi^+\ell^-\bar{\nu} \; \pi^-\ell^+\nu$

$I(\Delta t)$ (a.u)



$\Delta t/\tau_S$

$I(\Delta t)$ (a.u)



$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi\pi \; \pi\ell\nu$

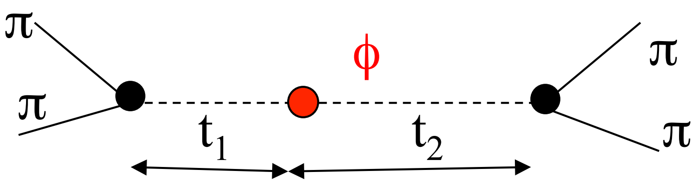
$$A_L = 2\Re\varepsilon - \Re\delta - \Re y - \Re x_-$$

$\phi_{\pi\pi}$

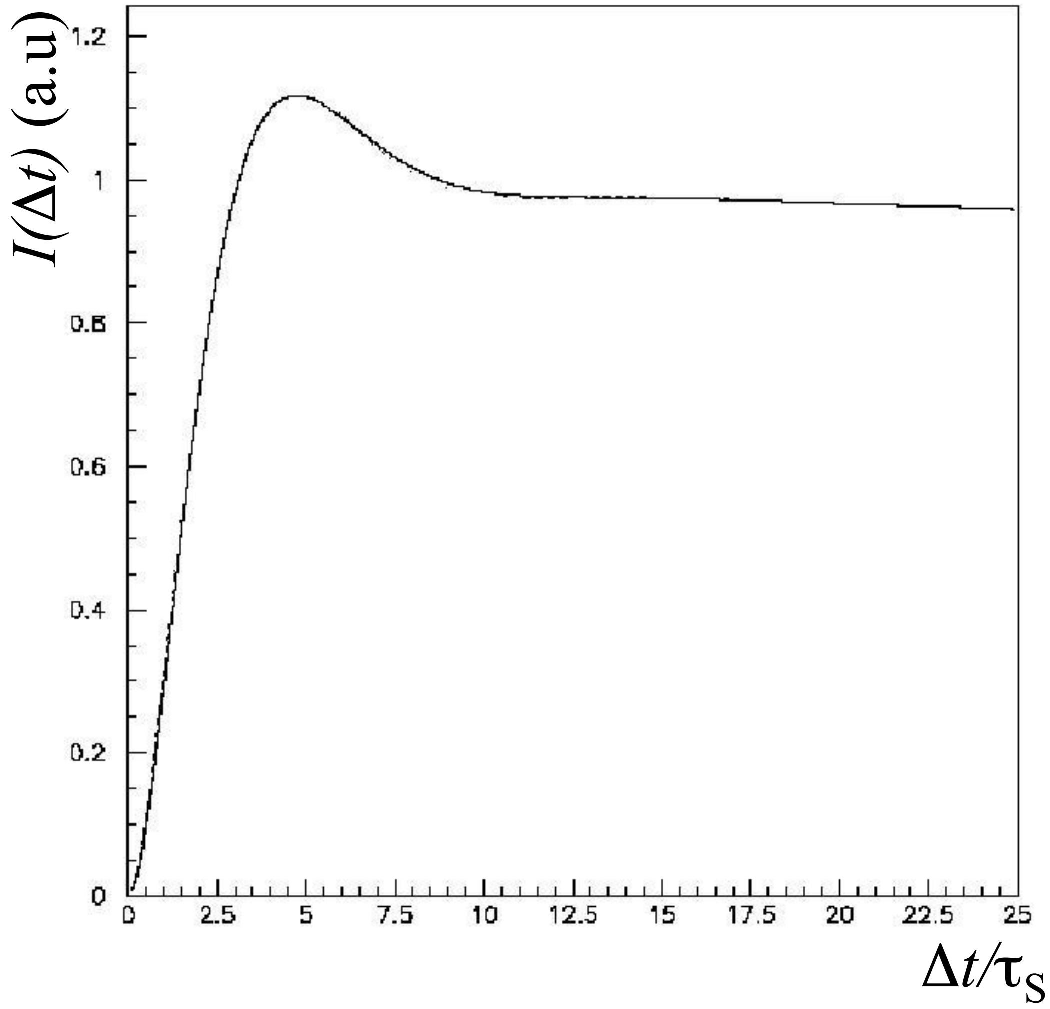
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

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

$$\Delta t = |t_1 - t_2|$$



Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$



$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \ \pi^+\pi^-$

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle \right]$$

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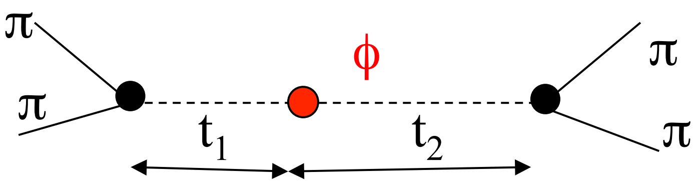
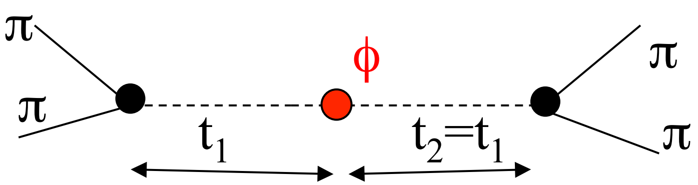
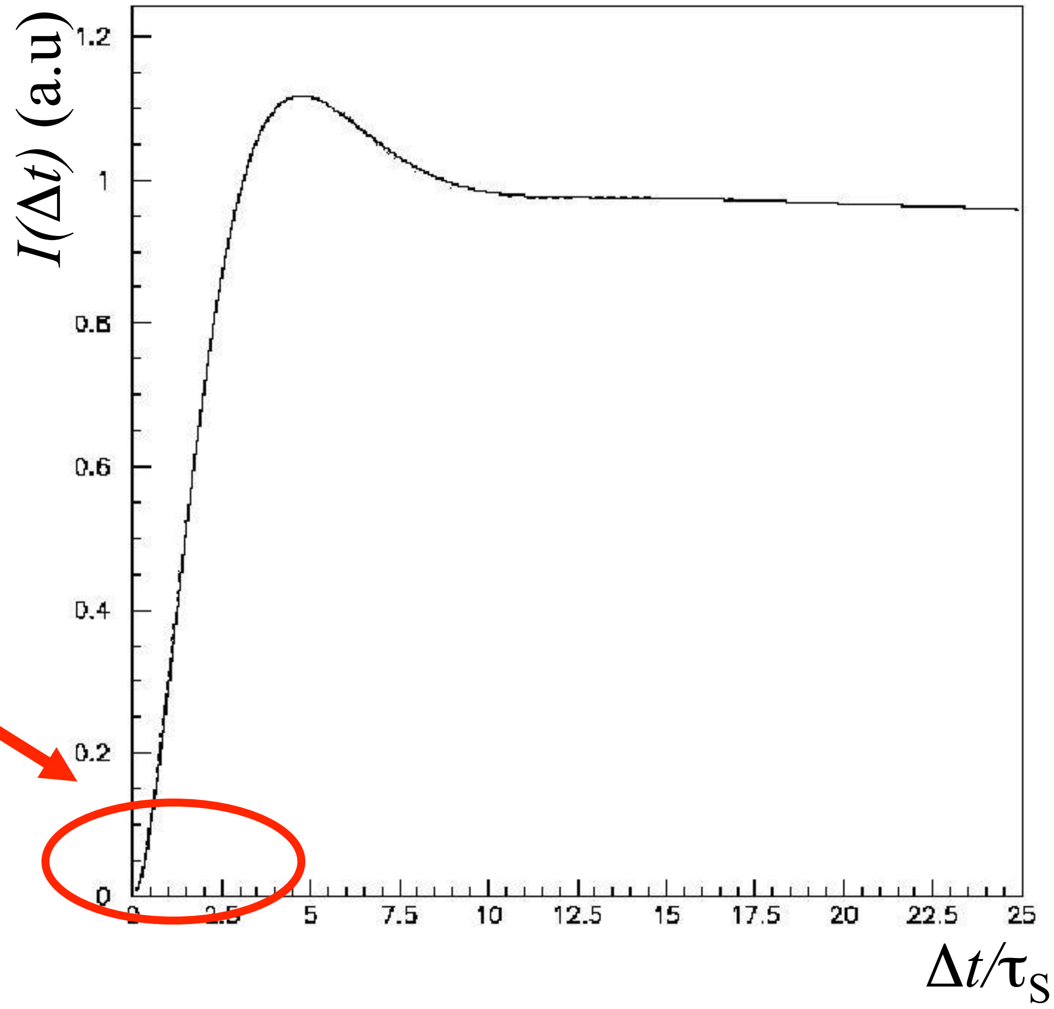


EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the destructive quantum interference

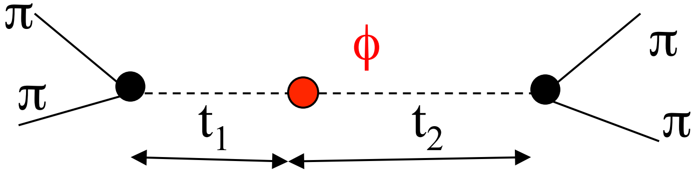




$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \, \pi^+\pi^-$

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

$$\Delta t = |t_1 - t_2|$$



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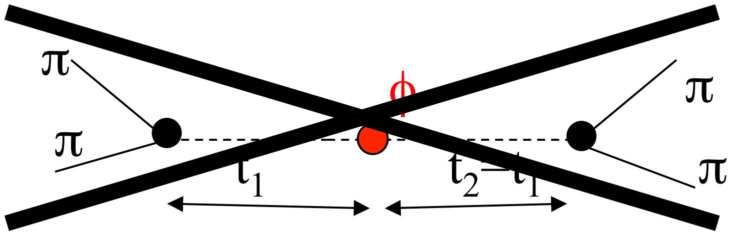

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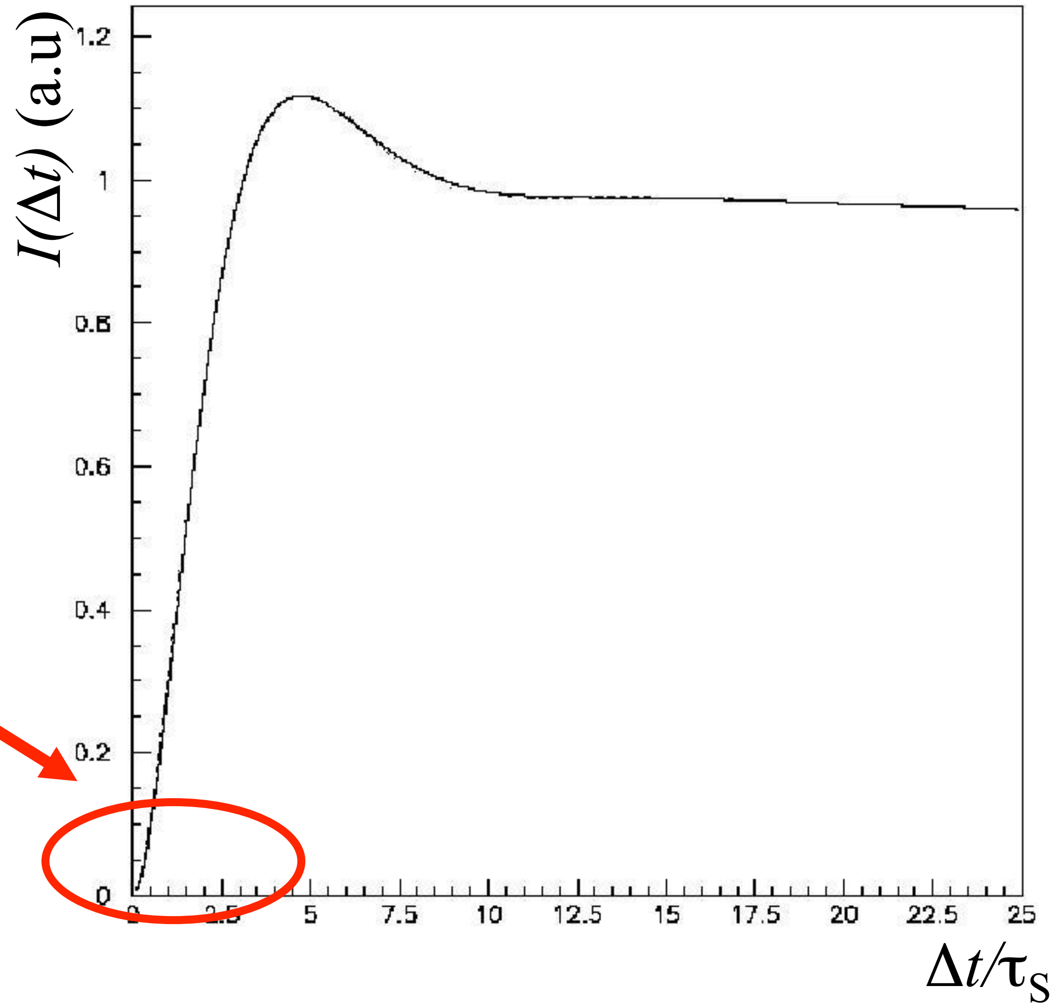

T, CP and CPT violation parameters for neutral kaons

$$|\Psi\rangle = a(t)|K^0\rangle + b(t)|\bar{K}^0\rangle \qquad i\frac{\partial}{\partial t}|\Psi\rangle = \mathbf{H}|\Psi\rangle \qquad \mathbf{H} = \mathbf{M} - \frac{i}{2}\Gamma = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

$$|K_{S,L}\rangle = \frac{1}{\sqrt{2\left(1+|\varepsilon_{S,L}|^2\right)}}\left[(1+\varepsilon_{S,L})|K^0\rangle \pm (1-\varepsilon_{S,L})|\bar{K}^0\rangle\right]$$

$$\lambda_S = m_S - \frac{i}{2}\Gamma_S \quad , \quad \lambda_L = m_L - \frac{i}{2}\Gamma_L$$

$$|K_{S,L}(t)\rangle = e^{-i\lambda_{S,L}t}|K_{S,L}(0)\rangle$$

T, CP and CPT violation parameters:

T viol. $\varepsilon = \dfrac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)} = \dfrac{-i\Im m_{12} - \Im\Gamma_{12}/2}{\Delta m + i\Delta\Gamma/2}$

CP viol. $\varepsilon_{S,L} = \varepsilon \pm \delta$

CPT viol. $\delta = \dfrac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)} = \dfrac{1}{2}\dfrac{(m_{22} - m_{11}) - (i/2)(\Gamma_{22} - \Gamma_{11})}{\Delta m + i\Delta\Gamma/2}$

$|\varepsilon| \cong 2.232 \times 10^{-3}$

CPT violation: $|\delta| <\sim 10^{-4}$ $\quad \Rightarrow \left|m_{K^0} - m_{\bar{K}^0}\right| / m_K < 10^{-18}$