Probing CPT in transitions with entangled neutral kaons

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Testing CPT: introduction

The three discrete symmetries of QM, C (charge conjugation: q → -q), P (parity: x → -x), and T (time reversal: t → -t) are known to be violated in nature both singly and in pairs. Only CPT appears to be an exact symmetry of nature.

CPT theorem holds for any QFT formulated on flat space-time which assumes: (1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

Extension of CPT theorem to a theory of quantum gravity far from obvious.
(e.g. CPT violation appears in several QG models)
huge effort in the last decades to study and shed light on QG phenomenology
$\Rightarrow$ Phenomenological CPTV parameters to be constrained by experiments

Consequences of CPT symmetry: equality of masses, lifetimes, |q| and |μ| of a particle and its anti-particle.

Neutral meson systems offer unique possibilities to test CPT invariance; e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system	neutral B system	proton- anti-proton
$\left\|m_{K^0} - m_{\overline{K}^0}\right\| / m_K < 10^{-18}$	$\left\|m_{B^0} - m_{\overline{B}^0}\right\| / m_B < 10^{-14}$	$\left\|m_p - m_{\overline{p}}\right\| / m_p < 10^{-8}$

Other interesting CPT tests: e.g. the study of anti-hydrogen atoms, etc..

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CPT violation: standard picture

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

CP violation:

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

T violation:

$$\varepsilon = \frac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)} = \frac{-i\Im M_{12} - \Im\Gamma_{12}/2}{\Delta m + i\Delta\Gamma/2}$$

CPT violation:

$$\delta = \frac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)} = \frac{1}{2}\frac{(m_{\bar{K}^0} - m_{K^0}) - (i/2)(\Gamma_{\bar{K}^0} - \Gamma_{K^0})}{\Delta m + i\Delta\Gamma/2}$$

- $\delta \neq 0$ implies CPT violation
- $\varepsilon \neq 0$ implies T violation
- $\varepsilon \neq 0$ or $\delta \neq 0$ implies CP violation

(with a phase convention $\Im\Gamma_{12} = 0$)

$$\Delta m = m_L - m_S \quad , \quad \Delta\Gamma = \Gamma_S - \Gamma_L$$

$$\Delta m = 3.5 \times 10^{-15} \text{ GeV}$$

$$\Delta\Gamma \approx \Gamma_S \approx 2\Delta m = 7 \times 10^{-15} \text{ GeV}$$

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CP violation:

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CPT violation:

$$\delta = \frac{H_{11}-H_{22}}{2\left(\lambda_S-\lambda_L\right)} = \frac{1}{2}\frac{\left(m_{\bar{K}^0}-m_{K^0}\right)-(i/2)\left(\Gamma_{\bar{K}^0}-\Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

huge amplification factor!!

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- $\varepsilon \neq 0$ implies T violation
- $\varepsilon \neq 0$ or $\delta \neq 0$ implies CP violation

(with a phase convention $\Im\Gamma_{12} = 0$)

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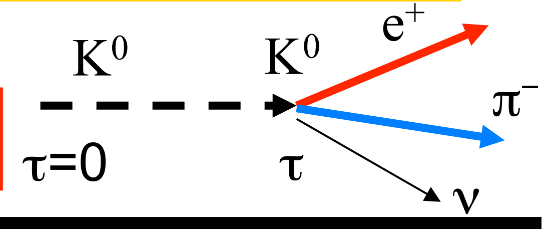
neutral kaons vs other oscillating meson systems

	$\langle m \rangle$ (GeV)	Δm (GeV)	$\langle \Gamma \rangle$ (GeV)	$\Delta\Gamma/2$ (GeV)
K^0	0.5	3×10^{-15}	3×10^{-15}	3×10^{-15}
D^0	1.9	6×10^{-15}	2×10^{-12}	1×10^{-14}
B^0_d	5.3	3×10^{-13}	4×10^{-13}	$O(10^{-15})$ (SM prediction)
B^0_s	5.4	1×10^{-11}	4×10^{-13}	3×10^{-14}

"Standard" CPT test

Comparing "survival" probabilities of K^0 and $\bar{K}^0$ measuring semileptonic decays vs time: $\Re\delta = (3.0 \pm 3.3 \pm 0.6) \times 10^{-4}$



CPLEAR
PLB444 (1998) 52

using the unitarity constraint (**Bell-Steinberger** relation) →

$$2\Im\delta = \Im\left[\langle K_L | K_S \rangle\right] = \Im\left[\frac{\sum_f \langle f|T|K_S\rangle \langle f|T|K_L\rangle^*}{i(\lambda_S - \lambda_L^*)}\right]$$

$\mathrm{Im}\,\delta = (-0.7 \pm 1.4) \times 10^{-5}$

PDG fit (2014)

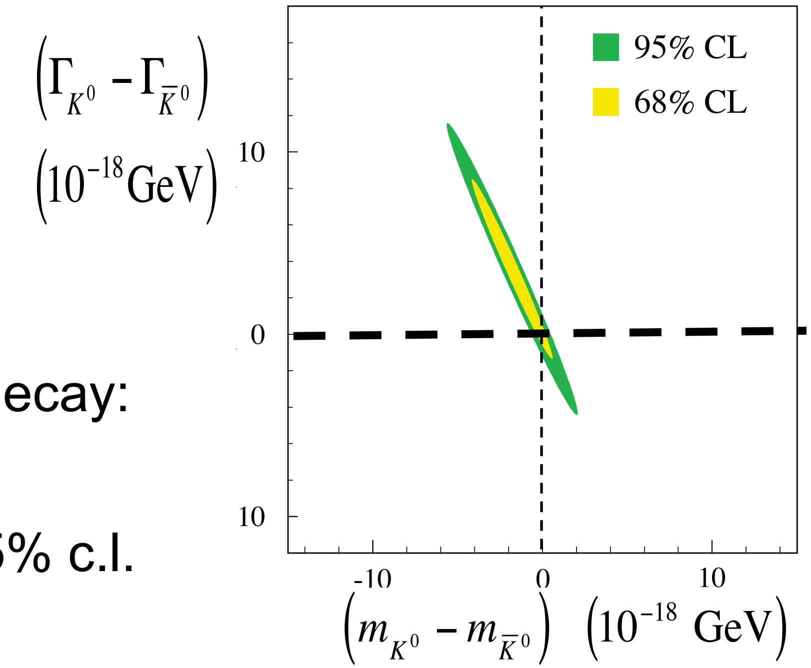
$$\delta = \frac{1}{2}\frac{\left(m_{\bar{K}^0} - m_{K^0}\right) - (i/2)\left(\Gamma_{\bar{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

Combining Reδ and Imδ results →

Assuming $\left(\Gamma_{\bar{K}^0} - \Gamma_{K^0}\right) = 0$, i.e. no CPT viol. in decay:

$$\left| m_{\bar{K}^0} - m_{K^0} \right| < 4.0 \times 10^{-19} \ \ \mathrm{GeV}$$

at 95% c.l.

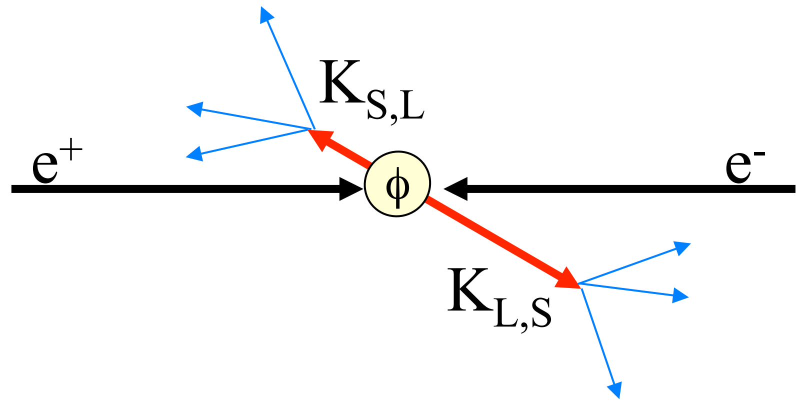


Entangled neutral kaon pairs

Neutral kaons at a ϕ-factory

Production of the vector meson ϕ in e^+e^- annihilations:

- $e^+e^- \rightarrow \phi$ $\quad \sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV
- $BR(\phi \rightarrow K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:



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

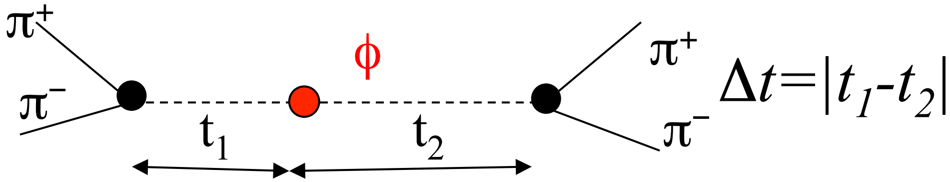
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

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

$p_K = 110$ MeV/c
$\lambda_S = 6$ mm $\quad \lambda_L = 3.5$ m

Neutral kaon interferometry: $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$

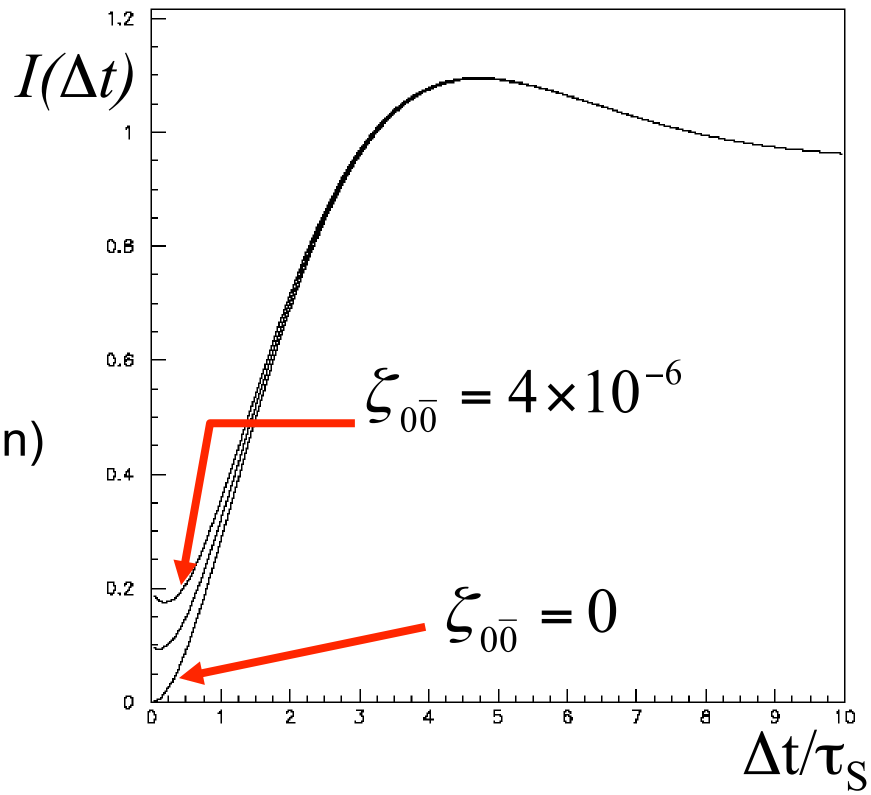
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$



Most precise test of quantum coherence in an entangled system (amplification mechanism due to CP suppression)

$$\zeta_{0\bar{0}} = \left(1.4 \pm 9.5_{\mathrm{STAT}} \pm 3.8_{\mathrm{SYST}}\right)\times 10^{-7}$$

ζ decoherence parameter (QM predicts ζ=0)



KLOE results: **PLB 642(2006) 315** **Found. Phys. 40 (2010) 852**

Quantum gravity effects might induce:

1)decoherence and CPT violation (at most γ=O(m_K^2/M_{Planck})~2x10^{-20} GeV) →

$$\gamma = \left(0.7 \pm 1.2_{STAT} \pm 0.3_{SYST}\right)\times 10^{-21}\ \mathrm{GeV}$$

Ellis et al. PRD53 (1996) 3846

2) decoherence and CPT violation induce modification of the initial correlation of the kaon pair (at most ω=O($m_K^2/M_{Planck}/\Delta\Gamma$) ~1x10^{-3}) →

$$|i\rangle \propto \left(K^0\overline{K}^0 - K^0\overline{K}^0\right) + \omega\left(K^0\overline{K}^0 + K^0\overline{K}^0\right)$$

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

Bernabeu, et al. PRL 92 (2004) 131601

Probing CPT in transitions with entangled neutral kaons

Motivations:

- test the CPT symmetry directly in transition processes between kaon states, rather than comparing masses, lifetimes, or other intrinsic properties of particle and anti-particle states.

- CPT violating effects may not appear at first order in diagonal mass terms (survival probabilities) while they can manifest at first order in transitions (non-diagonal terms).

- In standard WWA the test is related to Reδ, a genuine CPT violating effect independent of $\Delta\Gamma$, i.e. not requiring the decay as an essential ingredient.

- Clean formulation required. Possible spurious effects induced by CP violation in the decay and/or a violation of the $\Delta S = \Delta Q$ rule have to be well under control.

Probing CPT: J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139
Time-reversal violation: J. Bernabeu, A.D.D., P. Villanueva, NPB 868 (2013) 102

Definition of states

Let us also consider the states $|K_+\rangle$, $|K_-\rangle$ defined as follows: $|K_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP $= +1$ state; analogously $|K_-\rangle$ is the state filtered by the decay into $3\pi^0$, a pure CP $= -1$ state. Their orthogonal states correspond to the states which cannot decay into $\pi\pi$ or $3\pi^0$, defined, respectively, as

$$|\widetilde{K}_-\rangle \equiv \widetilde{N}_- \left[|K_L\rangle - \eta_{\pi\pi}|K_S\rangle\right]$$
$$|\widetilde{K}_+\rangle \equiv \widetilde{N}_+ \left[|K_S\rangle - \eta_{3\pi^0}|K_L\rangle\right]$$

$$\eta_{\pi\pi} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle}$$
$$\eta_{3\pi^0} = \frac{\langle 3\pi^0|T|K_S\rangle}{\langle 3\pi^0|T|K_L\rangle}$$

Orthogonal bases: $\{K_+, \widetilde{K}_-\}$ $\quad$ $\{\widetilde{K}_+, K_-\}$

Even though the decay products are orthogonal, the filtered |K+⟩ and |K−⟩ states can still be nonorthoghonal.
Condition of orthoghonality:

$$\eta_{\pi\pi} + \eta^\star_{3\pi^0} = \epsilon_L + \epsilon^\star_S \quad \longrightarrow \quad \begin{array}{l} |K_+\rangle \equiv |\widetilde{K}_+\rangle \\ |K_-\rangle \equiv |\widetilde{K}_-\rangle \end{array}$$

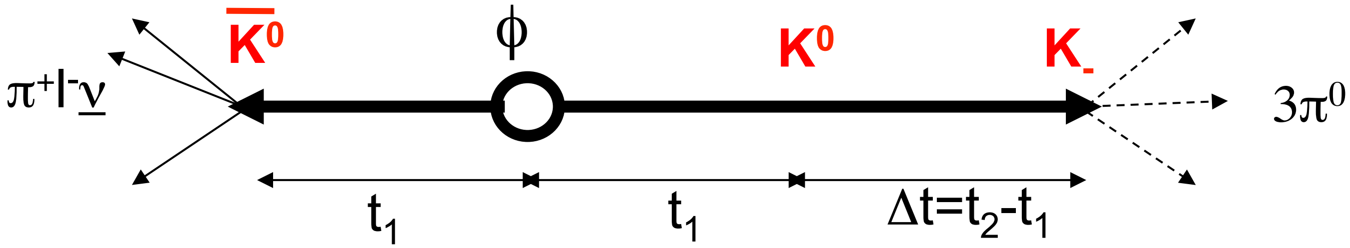
Neglect direct CP violation. Similarly any ΔS=ΔQ rule violation for $|K^0\rangle$ and $|\bar{K}^0\rangle$

Entanglement in neutral kaon 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_-

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

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



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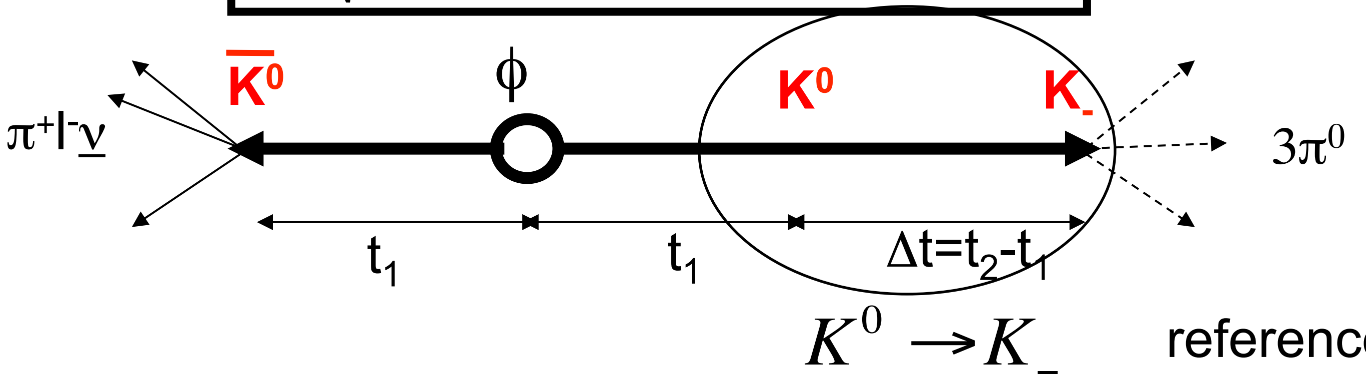

reference process

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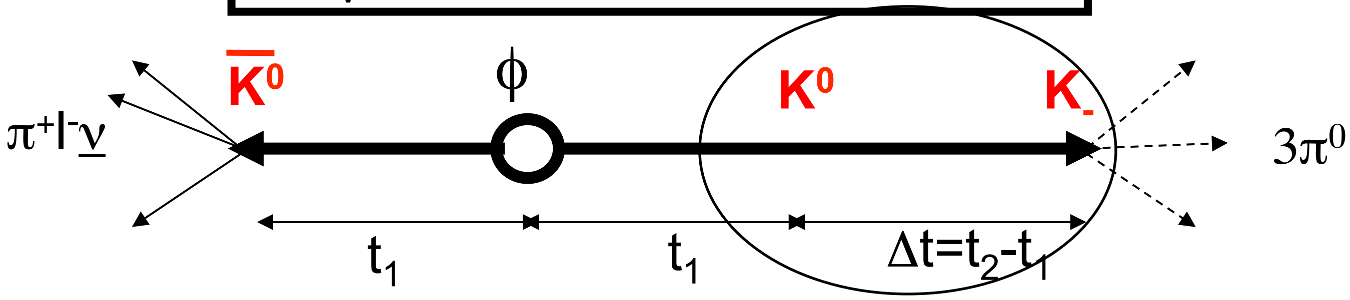
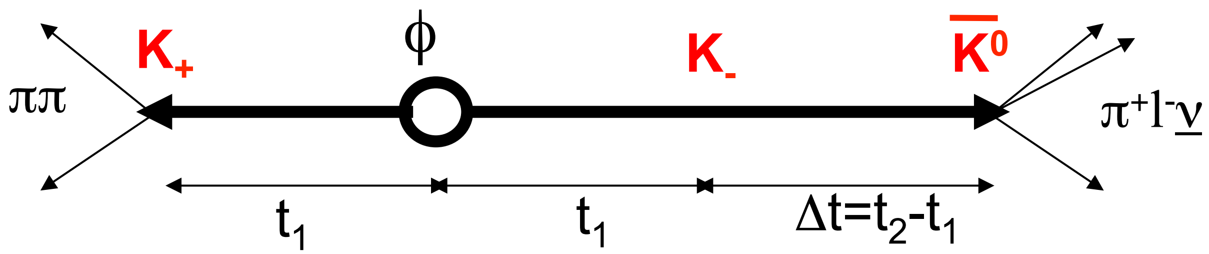


$K^0 \rightarrow K_-$ reference process



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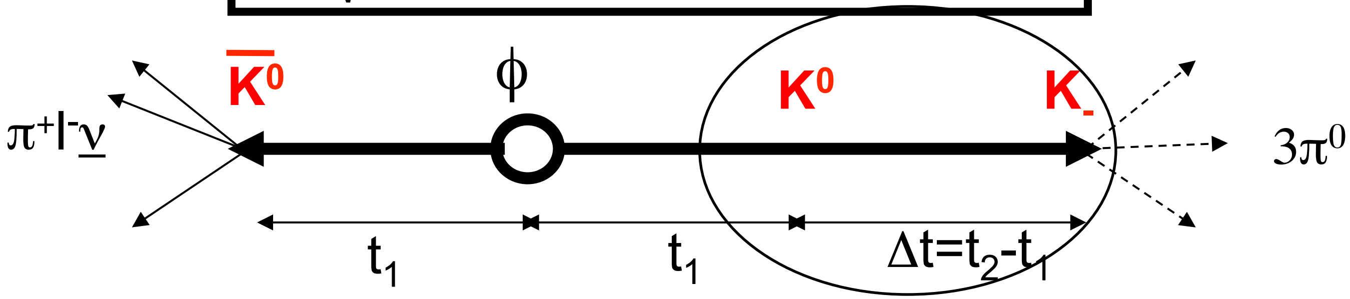
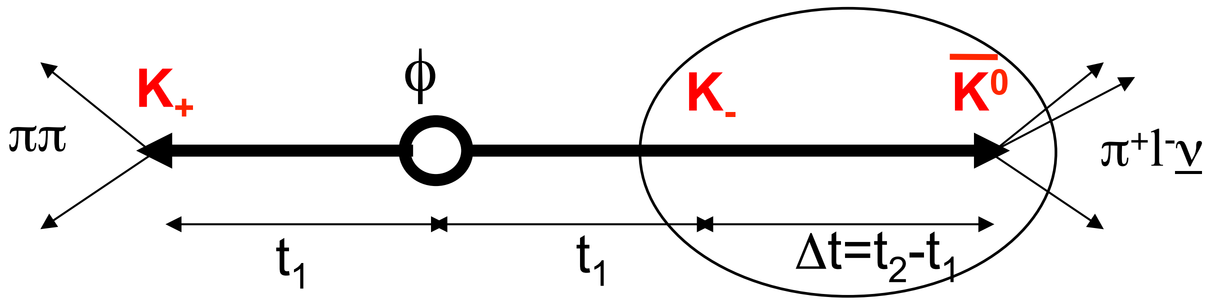


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \bar{K}^0$ CPT-conjugated process



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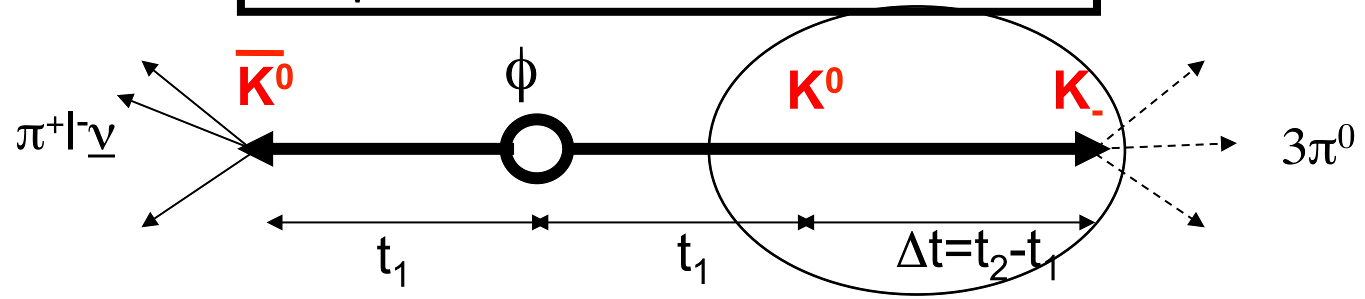
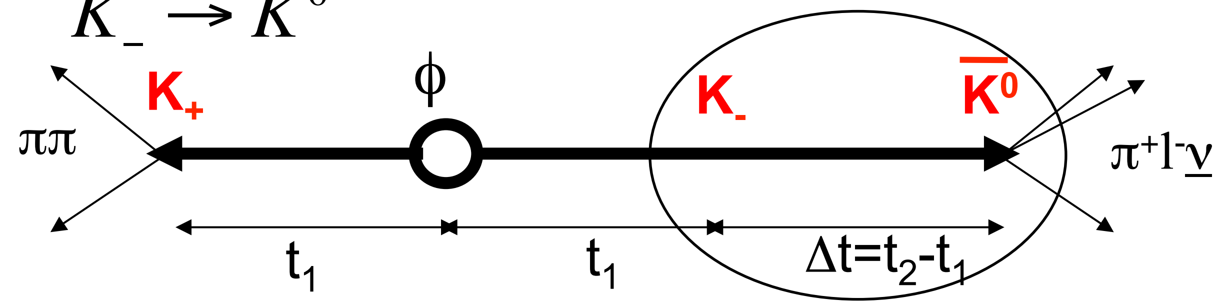


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \overline{K}^0$ CPT-conjugated process

Note: CP and T conjugated process

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



Direct test of CPT symmetry in neutral kaon transitions

CPT symmetry test

Reference		$\mathcal{CPT}$-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:

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

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

Direct test of CPT symmetry in neutral kaon transitions

Two observable ratios of double decay intensities

$$R^{\rm exp}_{2,\rm CPT}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

$$R^{\rm exp}_{4,\rm CPT}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

for $\Delta t>0$

$$R^{\rm exp}_{2,\rm CPT}(\Delta t) = R_{2,\rm CPT}(\Delta t) \times D_{\rm CPT}$$
$$R^{\rm exp}_{4,\rm CPT}(\Delta t) = R_{4,\rm CPT}(\Delta t) \times D_{\rm CPT}$$

for $\Delta t<0$

$$R^{\rm exp}_{2,\rm CPT}(\Delta t) = R_{1,\rm CPT}(|\Delta t|) \times D_{\rm CPT}$$
$$R^{\rm exp}_{4,\rm CPT}(\Delta t) = R_{3,\rm CPT}(|\Delta t|) \times D_{\rm CPT}$$

with $D_{\rm CPT}$ constant

$$D_{\rm CPT} = \frac{\rm BR\left(K_L \to 3\pi^0\right)}{\rm BR\left(K_S \to \pi\pi\right)} \frac{\Gamma_L}{\Gamma_S}$$

Direct test of CPT symmetry in neutral kaon transitions

Explicitly in standard Wigner Weisskopf approach for $\Delta t>0$:

$$R^{\rm exp}_{2,\rm CPT}(\Delta t) = \frac{P[\rm K^0(0) \to K_-(\Delta t)]}{P[\rm K_-(0) \to \bar{K}^0(\Delta t)]} \times D_{\rm CPT}$$
$$\simeq |1-2\delta|^2 \left|1+2\delta e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2 \times D_{\rm CPT}$$

$$R^{\rm exp}_{4,\rm CPT}(\Delta t) = \frac{P[\rm \bar{K}^0(0) \to K_-(\Delta t)]}{P[\rm K_-(0) \to K^0(\Delta t)]} \times D_{\rm CPT}$$
$$\simeq |1+2\delta|^2 \left|1-2\delta e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2 \times D_{\rm CPT}$$

For comparison the ratio of survival probabilities:

$$\frac{I(\ell^-,\ell^+;\Delta t)}{I(\ell^+,\ell^-;\Delta t)} = \frac{P[\rm K^0(0) \to K^0(\Delta t)]}{P[\rm \bar{K}^0(0) \to \bar{K}^0(\Delta t)]}$$
$$\simeq |1-4\delta|^2 \left|1+\frac{8\delta}{1+e^{+i(\lambda_S-\lambda_L)\Delta t}}\right|^2$$

Vanishes for $\Delta\Gamma$->0

As an illustration of the different sensitivity: it vanishes up to second order in CPTV and decoherence parameters α,β,γ

Impact of the approximations

Direct CP (CPT) violation

$$\eta_{\pi\pi} = \epsilon_L + \epsilon'_{\pi\pi}$$

$$\eta_{3\pi^0} = \epsilon_S + \epsilon'_{3\pi^0}$$

CPT cons. and CPT viol.
ΔS=ΔQ violation

$$x_+, \; x_-$$

Orthoghonal bases

$$\{\mathrm{K}_+, \widetilde{\mathrm{K}}_-\} \quad \{\widetilde{\mathrm{K}}_+, \mathrm{K}_-\} \qquad \{\widetilde{\mathrm{K}}_0, \mathrm{K}_{\bar{0}}\} \text{ and } \{\widetilde{\mathrm{K}}_{\bar{0}}, \mathrm{K}_0\}$$

Explicitly for Δt>0:

$$R^{\rm exp}_{2,\rm CPT}(\Delta t) = \frac{P[\widetilde{\mathrm{K}}_0(0) \to \mathrm{K}_-(\Delta t)]}{P[\widetilde{\mathrm{K}}_-(0) \to \mathrm{K}_{\bar{0}}(\Delta t)]} \times D_{\rm CPT}$$

$$= |1 - 2\delta + 2x_+^\star - 2x_-^\star|^2 \left|1 + \left(2\delta + \epsilon'_{3\pi^0} - \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\rm CPT}$$

$$R^{\rm exp}_{4,\rm CPT}(\Delta t) = \frac{P[\widetilde{\mathrm{K}}_{\bar{0}}(0) \to \mathrm{K}_-(\Delta t)]}{P[\widetilde{\mathrm{K}}_-(0) \to \mathrm{K}_0(\Delta t)]} \times D_{\rm CPT}$$

$$= |1 + 2\delta + 2x_+ + 2x_-|^2 \left|1 - \left(2\delta + \epsilon'_{3\pi^0} - \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\rm CPT}$$

Impact of the approximations

$$\frac{R^{\rm exp}_{2,\rm CPT}(\Delta t)}{R^{\rm exp}_{4,\rm CPT}(\Delta t)} \simeq \left(1 - 8\Re\delta - 8\Re x_-\right)\left|1 + 2\left(\eta_{3\pi^0} - \eta_{\pi\pi}\right) e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2$$

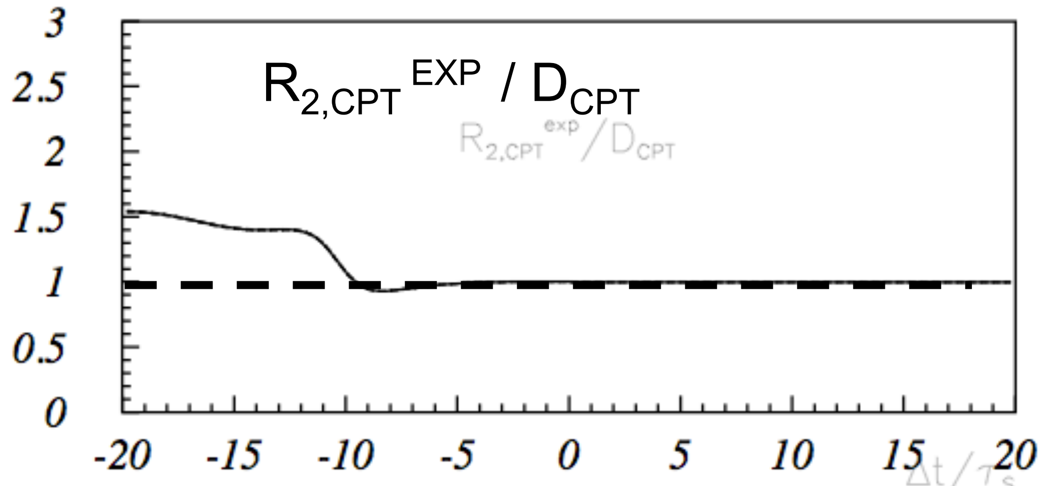
$$= \left(1 - 8\Re\delta - 8\Re x_-\right)\left|1 + 2\left(2\delta + \epsilon'_{3\pi^0} - \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2$$

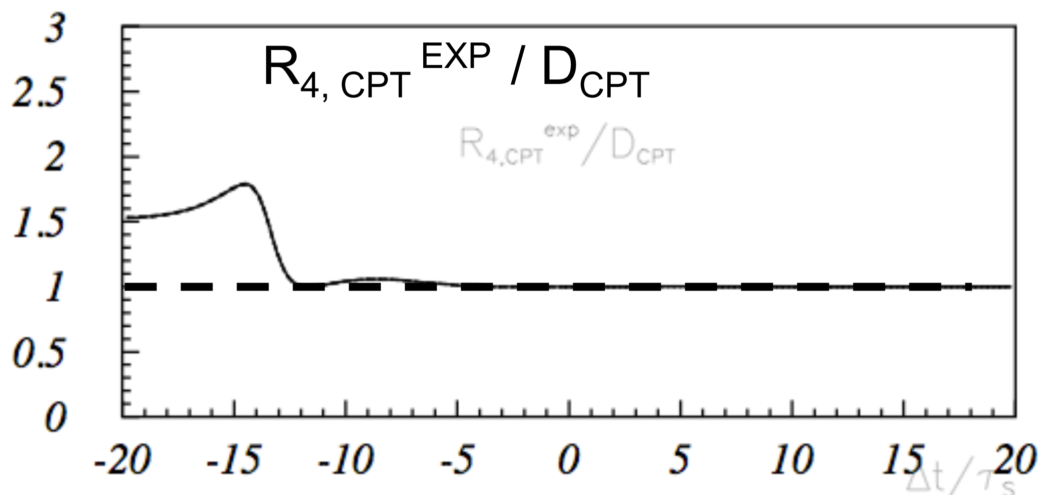
The double ratio constitutes one of the most robust observables for the proposed CPT test. In the limit $\Delta t \gg \tau_S$ it exhibits a pure and genuine CPT violating effect, even without assuming negligible contaminations from direct CP violation and/or $\Delta S=\Delta Q$ rule violation.

$$\frac{R^{\rm exp}_{2,\rm CPT}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\rm CPT}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

Direct test of CPT symmetry with neutral kaons

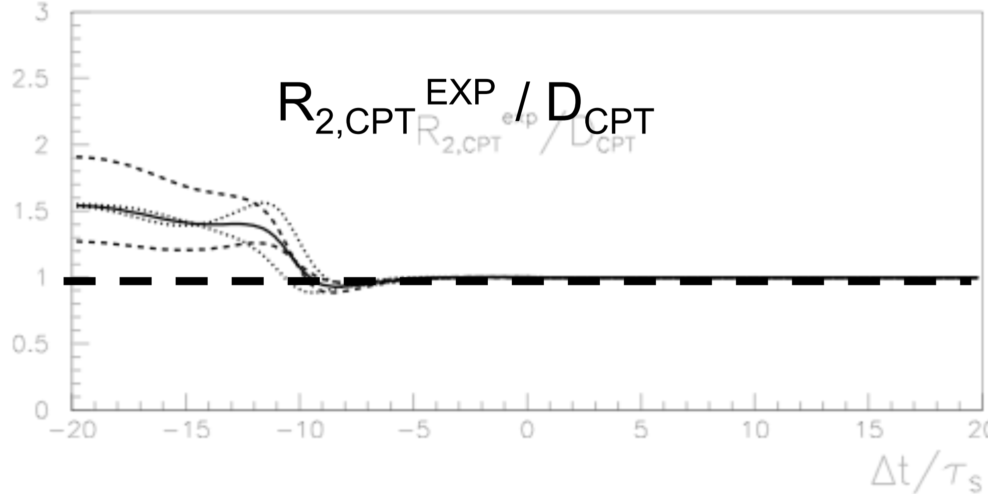
for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$

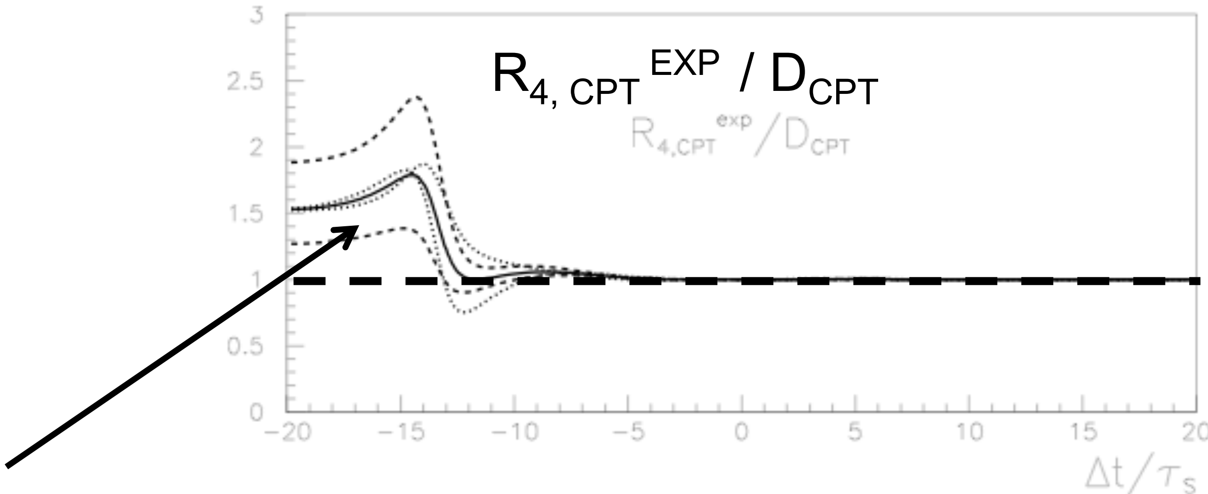




Direct test of CPT symmetry with neutral kaons

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

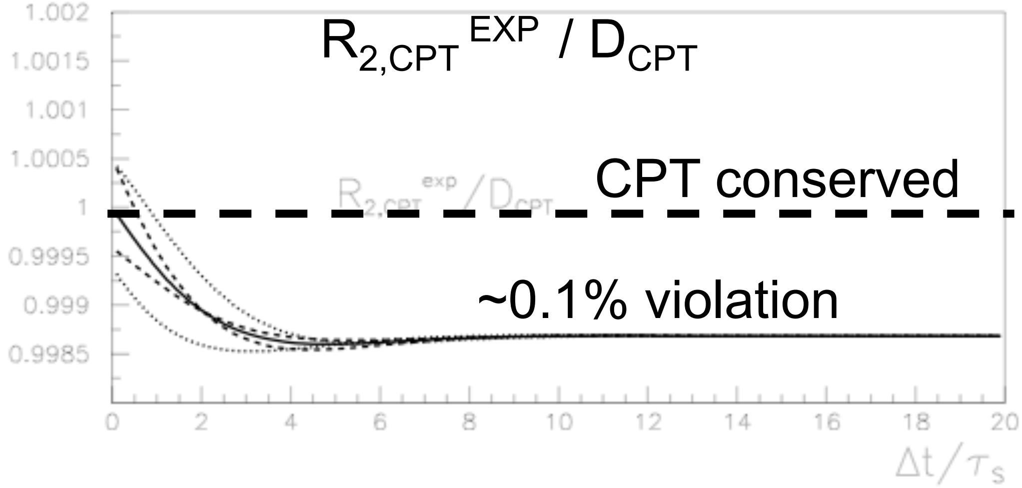


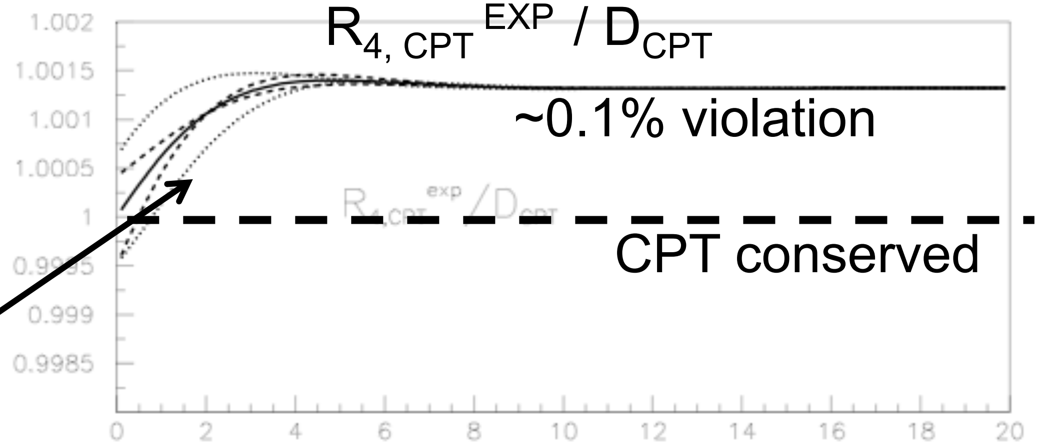


Modifications due to direct CP violation effects (unrealistically amplified ~x100)

Direct test of CPT symmetry with neutral kaons

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

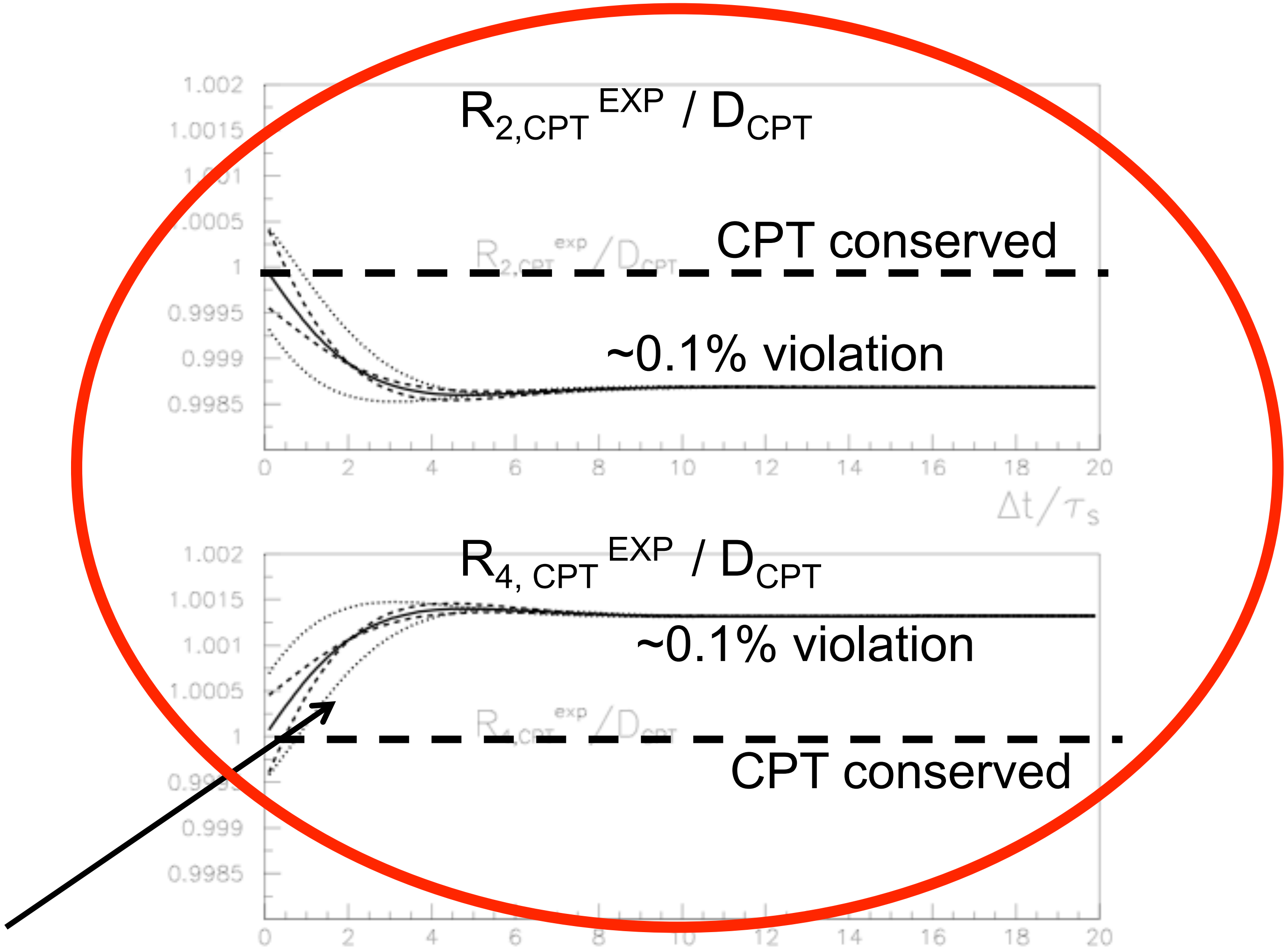




Modifications due to direct CP violation effects (unrealistically amplified ~x10)

Direct test of CPT symmetry with neutral kaons

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



measurable
at KLOE-2

Modifications due to direct CP violation effects (unrealistically amplified ~x10)

Conclusions

- It is possible to directly test the CPT symmetry in transition processes.
- The proposed CPT test for neutral kaons is model independent and fully robust. (It can then be translated in terms of δ, α, β, γ, Δa_μ etc..).
- In standard WWA the test is related to Reδ, a genuine CPT violating effect independent of $\Delta\Gamma$ and not requiring the decay as an essential ingredient.
- Possible spurious effects induced by CP violation in the decay and/or a violation of the $\Delta S = \Delta Q$ rule have been shown to be well under control.
- Perfect anti-correlation of the initial state is assumed (to be evaluated the impact of possible loss of coherence.
- There exists a connection with charge semileptonic asymmetries of K_S and K_L

$$\frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t \gg \tau_S)}{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t \gg \tau_S)} = \frac{1+A_L}{1-A_L} \times \frac{1-A_S}{1+A_S} \simeq 1 + 2(A_L - A_S)$$

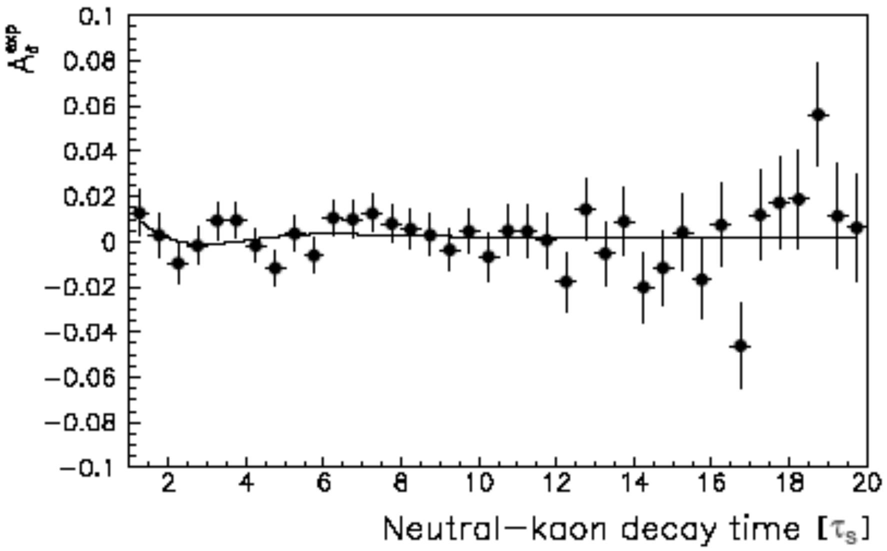
- KLOE data analysis ongoing (see Daria Kaminska's talk)
- KLOE-2 can reach a statistical sensitivity of $O(10^{-3})$ on this new observable.
- In B meson system similar test (see Miyashita's talk); less precise, more assumptions needed

Back up slides

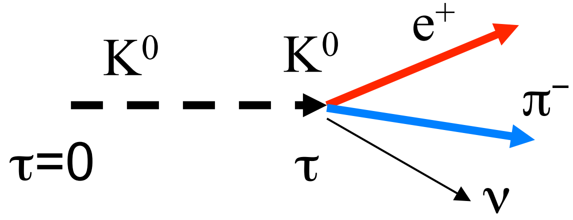
CPT test at CPLEAR

Test of **CPT** in the time evolution of neutral kaons using the semileptonic asymmetry

Comparing "survival" probabilities: $K^0 \to K^0$, $\bar{K}^0 \to \bar{K}^0$



e.g.



$$
\begin{cases}
A_\delta(\tau) = \dfrac{\bar{R}_+(\tau) - \alpha R_-(\tau)}{\bar{R}_+(\tau) + \alpha R_-(\tau)} + \dfrac{\bar{R}_-(\tau) - \alpha R_+(\tau)}{\bar{R}_-(\tau) + \alpha R_+(\tau)} \\
R_{+(-)}(\tau) = R\left(K^0{}_{t=0} \to (e^{+(-)}\pi^{-(+)}\nu)_{t=\tau}\right) \\
\bar{R}_{-(+)}(\tau) = R\left(\bar{K}^0{}_{t=0} \to (e^{-(+)}\pi^{+(-)}\nu)_{t=\tau}\right) \\
\alpha = 1 + 4\Re\varepsilon_L
\end{cases}
$$

$$\Re\delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3}$$

$$A_\delta(\tau >> \tau_S) = 8\Re\delta$$

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The Bell-Steinberger relationship

J. Bell

(1965)

J. Steinberger

Unitarity constraint:

$$|K\rangle = a_S|K_S\rangle + a_L|K_L\rangle$$

$$\left(-\frac{d}{dt}\left\||K(t)\rangle\right\|^2\right)_{t=0} = \sum_f \left|a_S\langle f|T|K_S\rangle + a_L\langle f|T|K_L\rangle\right|^2$$

Sum over all possible decay products
(sum over few decay products for kaons;
many for B and D mesons => not easy to evaluate)

yields two trivial relations:

$$\Gamma_{S,L} = \sum_f \left|\langle f|T|K_{S,L}\rangle\right|^2$$

and a not trivial one, i.e. the B-S relationship:

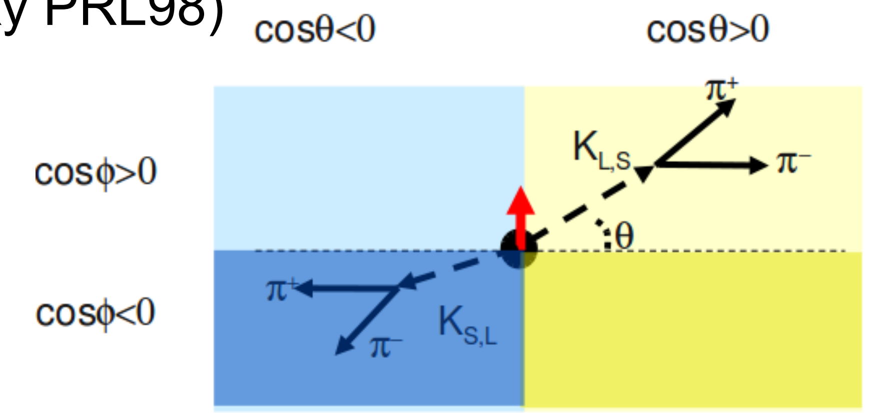
$$\langle K_L|K_S\rangle = 2(\Re\varepsilon + i\Im\delta) = \frac{\sum_f \langle f|T|K_S\rangle\langle f|T|K_L\rangle^*}{i(\lambda_S - \lambda_L^*)}$$

All observables quantities

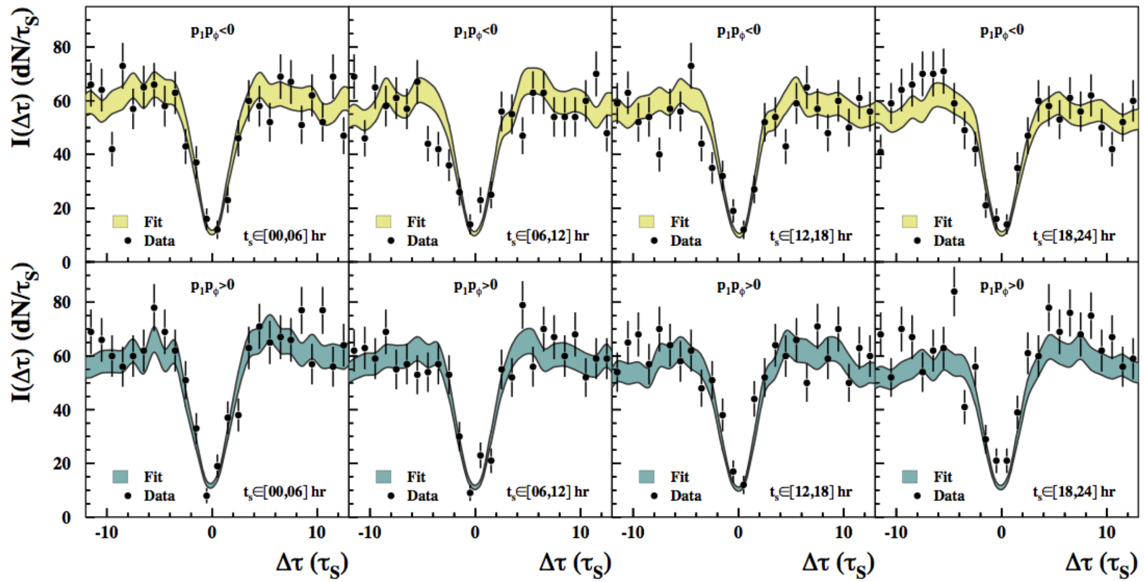
Search for CPT and Lorentz invariance violation at KLOE

$$\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right) / \Delta m$$

Standar Model extension (SME)
(Kostelecky PRL98)



Data divided in
4 sidereal time bins x 2 angular bins
Simultaneous fit of the Δt distributions
to extract Δa_μ parameters



KLOE **PLB 730 (2014) 89** with L=1.7 fb^{-1}

$$\Delta a_0 = \left(-6.0 \pm 7.7_{STAT} \pm 3.1_{SYST}\right) \times 10^{-18} \text{ GeV}$$
$$\Delta a_X = \left(0.9 \pm 1.5_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Y = \left(-2.0 \pm 1.5_{STAT} \pm 0.5_{SYST}\right) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Z = \left(-3.1 \pm 1.7_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$

presently the most precise measurements in the quark sector of the SME

B meson system: $\Delta a^B_{//,X,Y} \sim O(10^{-15}$ GeV) $\Delta a^B_{perp} \sim O(10^{-13}$ GeV) [LHCb PRL116 (2016) 241601]
D meson system: $\Delta a^D_{x,y}$, $(\Delta a^D_0 - 0.6\, \Delta a^D_Z) \sim O(10^{-13}$ GeV) [Focus PLB 556 (2003) 7]