Test of discrete symmetries with neutral kaons at KLOE-2

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on behalf of the KLOE-2 collaboration

Workshop on Quantum foundations
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K mesons – more than 70 years history

1944 : first indication of a new charged particle with mass ~0.5 GeV/c^2 in cosmic rays (Leprince-Ringuet, Lheritier)

1947 : first K^0 observation in cloud chamber - V particle (Rochester, Butler)

1955 : introduction of Strangeness (Gell-Mann, Nishijima)

K^0, $\overline{K}^0$ are two distinct particles (Gell-Mann, Pais) Strangeness oscillation

1955 prediction of regeneration of short-lived particle (Pais, Piccioni)

1956 Observation of long lived K_L (BNL Cosmotron)

1957 $\tau-\theta$ puzzle on spin-parity assignment, P violation in weak interactions

1960: $\Delta m = m_L - m_S$ measured from regeneration

1964: discovery of CP violation (Cronin, Fitch,…)

1970 : suppression of FCNC, $K_L \to \mu\mu$ - GIM mechanism/charm hypothesis

1972 : Kobayashi Maskawa six quark model: CP violation explained in SM

1992- 2000 : CPLear: K^0, $\overline{K}^0$ time evolution and decays, T, CP, CPT tests

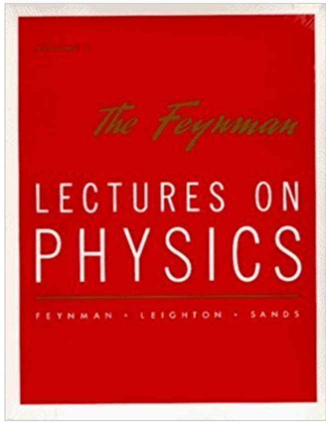
1999-2003 : KTeV and NA48 (prev. E731 and NA31): direct CP violation proven : $\varepsilon'/\varepsilon \neq 0$

2003-2008 : NA48/2: charged kaon beam, search for direct CP viol.

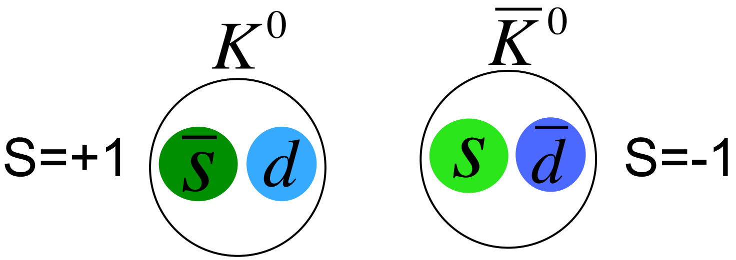
2000-2006 : KLOE at DaΦne: first Φ factory enters in operation, V_{us} and precision tests of the SM, entangled neutral K pairs and CPT and QM tests.

Neutral K meson system: a jewel donated to us by Nature

R. Feynman



"If there is any place where we have a chance to test the main principles of quantum mechanics in the purest way - does the superposition of amplitudes work or doesn't it? - this is it."



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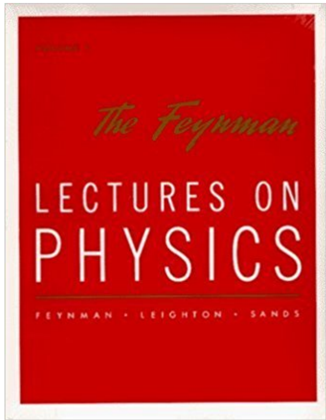

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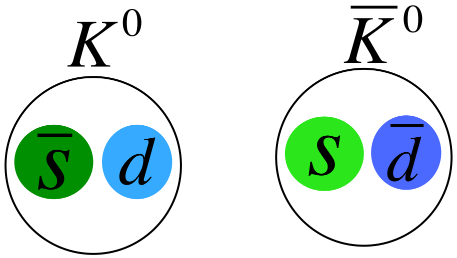
S=+1



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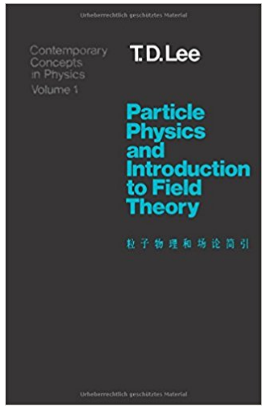
"One of the most intriguing physical systems in Nature"



T. D. Lee

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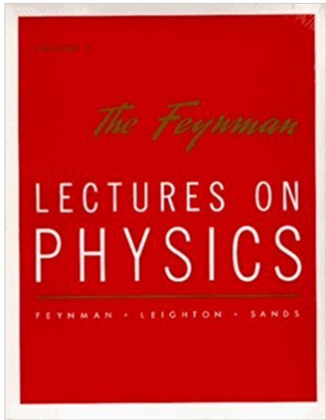

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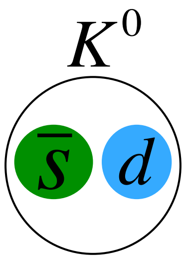

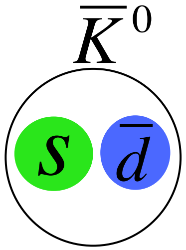

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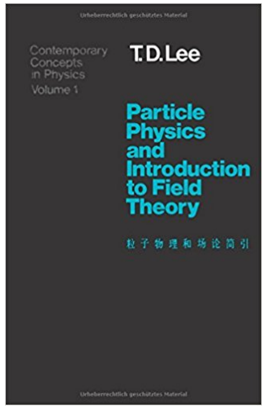
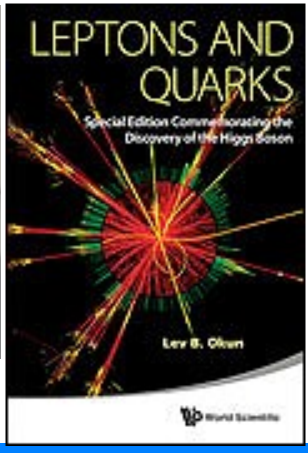


T. D. Lee

Lev B. Okun

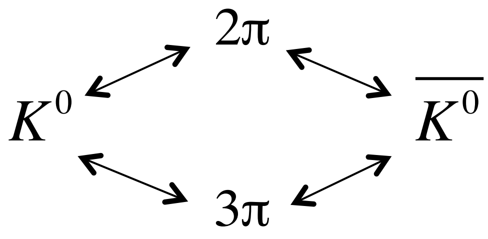


"Neutral K mesons are a unique physical system which appears to be created by nature to demonstrate, in the most impressive manner, a number of spectacular phenomena."

"If the K mesons did not exist, they should have been invented 'on purpose' in order to teach students the principles of quantum mechanics"

The neutral kaon two-level oscillating system in a nutshell

K^0 and $\overline{K^0}$ can decay to common final states due to weak interactions:
strangeness oscillations



$$|\Psi\rangle = a|K^0\rangle + b|\overline{K}^0\rangle$$

$$i\frac{\partial}{\partial t}\Psi(t) = \mathbf{H}\Psi(t)$$

H is the effective hamiltonian (non-hermitian), decomposed into a Hermitian part (mass matrix **M**) and an anti-Hermitian part (i/2 decay matrix $\boldsymbol{\Gamma}$) :

$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\Gamma = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

Diagonalizing the effective Hamiltonian:

eigenvalues

$$\lambda_{S,L} = m_{S,L} - \frac{i}{2}\Gamma_{S,L}$$

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

τ_S ~ 90 ps τ_L ~ 51 ns

$K_L \to \pi\pi$ violates CP

eigenstates: physical states

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

$$= \frac{1}{\sqrt{\left(1+|\varepsilon_{S,L}|\right)}}\left[|K_{1,2}\rangle + \varepsilon_{S,L}|K_{2,1}\rangle\right]$$

$|K_{1,2}\rangle$ are CP=±1 states

$$\langle K_S|K_L\rangle \cong \varepsilon_S^* + \varepsilon_L \neq 0$$

small CP impurity ~2 x 10^{-3}

The neutral kaon two-level oscillating system in a nutshell

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

CP violation:

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

T violation:

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

CPT violation:

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

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

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

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

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

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

The neutral kaon two-level oscillating system in a nutshell

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

CP violation:

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

T violation:

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

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!!

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

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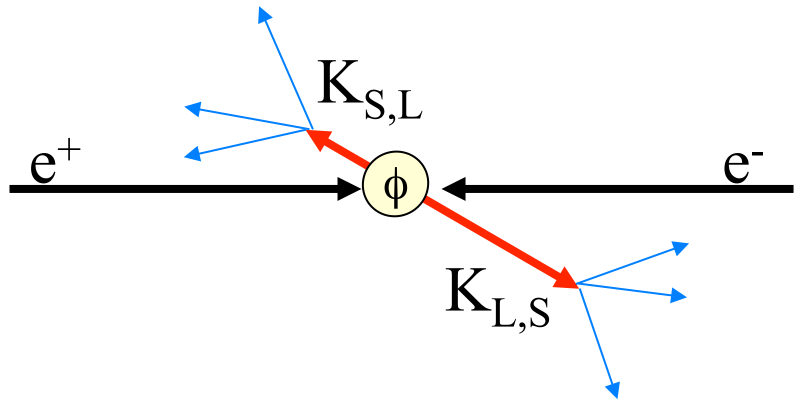
Neutral kaons at a ϕ-factory

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

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



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

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

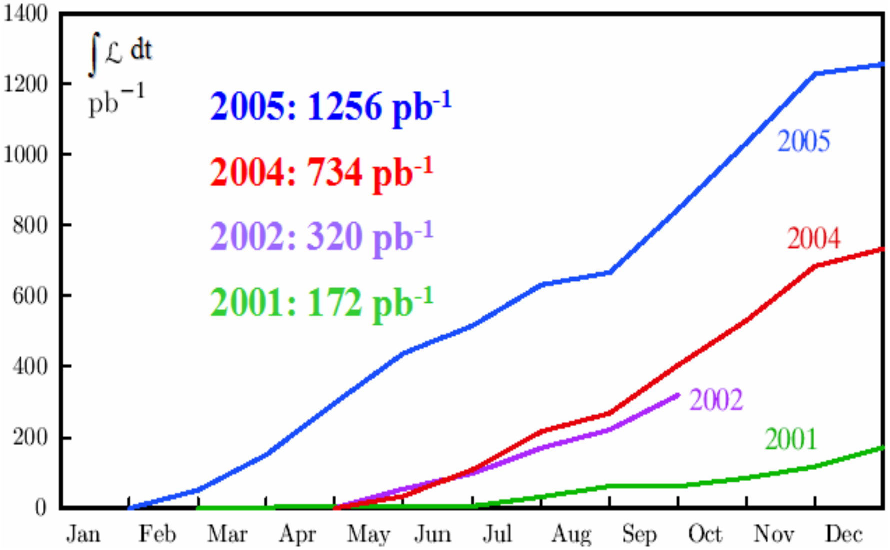
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

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

The KLOE detector at the Frascati ϕ-factory DAΦNE

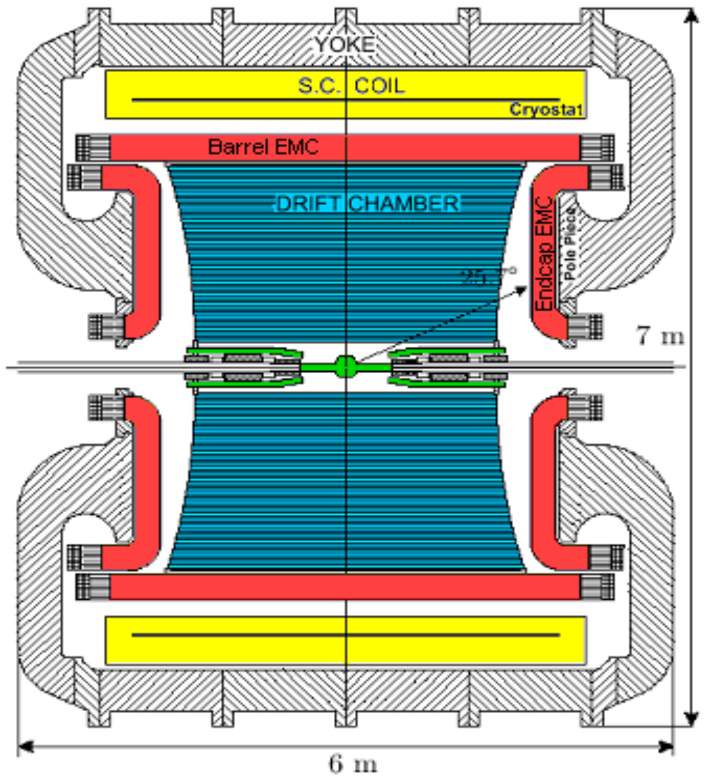
DAFNE collider

Integrated luminosity (KLOE)



Total KLOE $\int \mathcal{L}\, dt \sim 2.5$ fb^{-1}
(2001 - 05) $\rightarrow$ $\sim 2.5 \times 10^9$ $K_S K_L$ pairs

KLOE detector



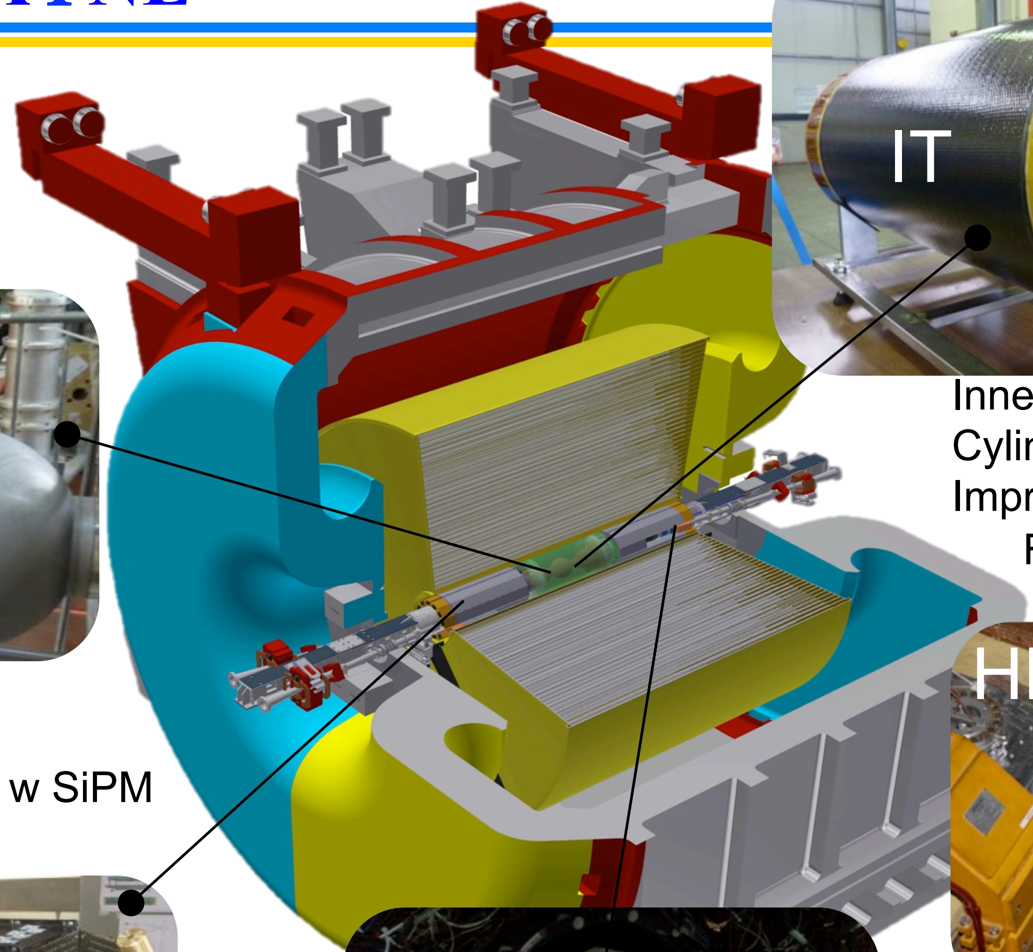
Lead/scintillating fiber calorimeter

drift chamber

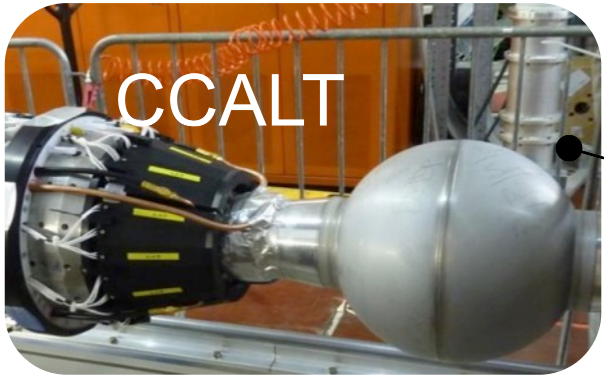
4 m diameter × 3.3 m length

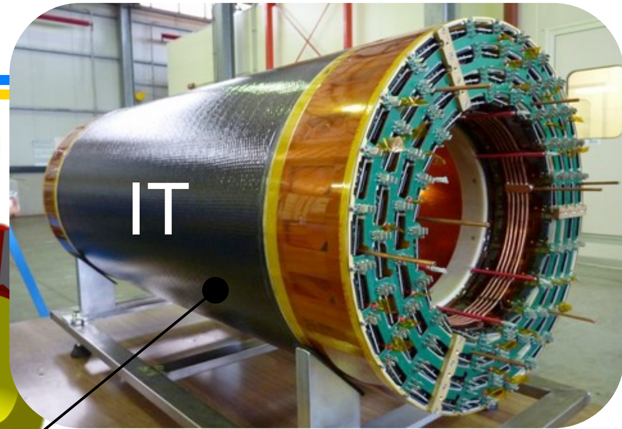
helium based gas mixture

KLOE-2 at DAΦNE



LYSO Crystal w SiPM
Low polar angle

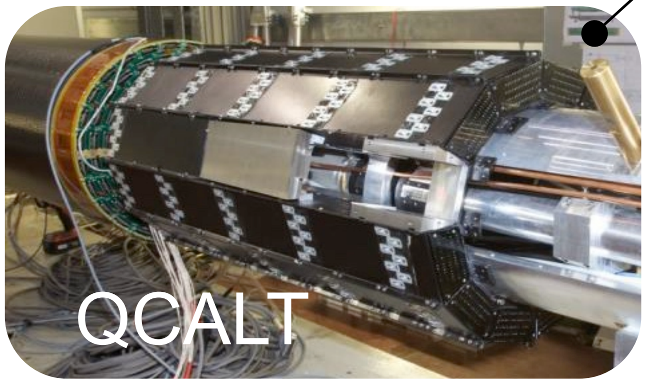




Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vtx reconstr.
First CGEM in HEP expt.

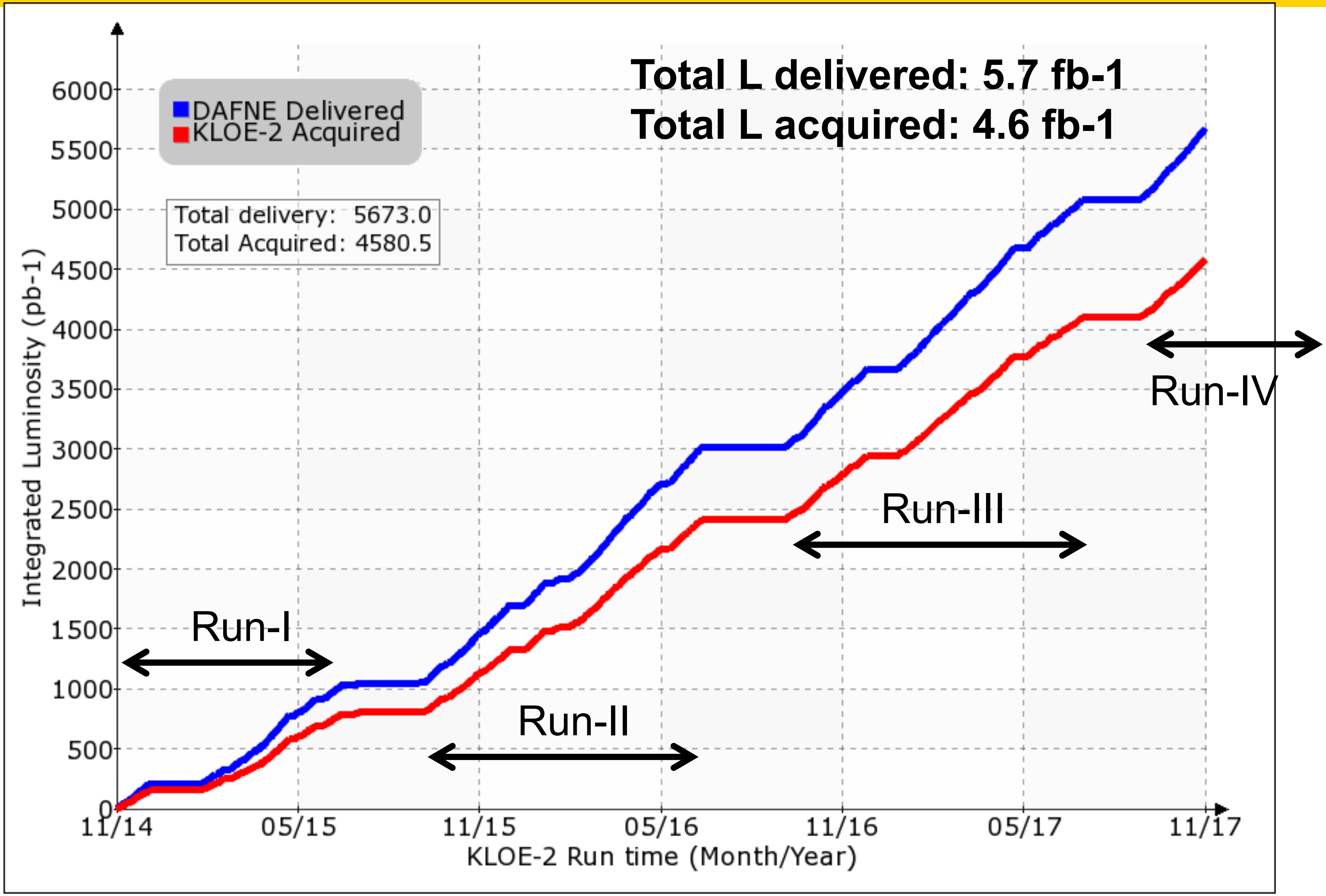
Scintillator hodoscope +PMTs

Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation



calorimeters LYSO+SiPMs
at ~ 1 m from IP

KLOE-2 Data Taking



KLOE-2 goal: L acquired > 5 fb^{-1} => L delivered > ~ 6.2 fb-1 by 31 March 2018

KLOE-2 Physics

KAON Physics:
- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \to 3\pi^0$
  direct measurement of Im(ε'/ε) (lattice calc. improved)
- CKM Vus:
  K_S semileptonic decays and A_S (also CP and CPT test)
  $K\mu3$ form factors, Kl3 radiative corrections
- χpT : $K_S \to \gamma\gamma$
- Search for rare K_S decays

Hadronic cross section
- Measurement of a_μ^{HLO} in the space-like region using Bhabha process
- ISR studies with 3π, 4π final states
- F_π with increased statistics

EPJC (2010) 68, 619 + procs LNF WS 2016 (in publication)

Dark forces:
- Improve limits on:
  $U\gamma$ associate production
  $e^+e^- \to U\gamma \to \pi\pi\gamma, \mu\mu\gamma$
- Higgstrahlung
  $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy
- Leptophobic B boson search
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

Light meson Physics:
- η decays, ω decays, TFF $\phi \to \eta e^+e^-$
- C,P,CP violation:
  improve limits on $\eta \to \gamma\gamma\gamma, \pi^+\pi^-, \pi^0\pi^0, \pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^- e^+e^-$
- χpT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $\phi \to K_S K_S \gamma$
- $\gamma\gamma$ Physics: $\gamma\gamma \to \pi^0$ and π^0 TFF
- light-by-light scattering
- axion-like particles

List of KLOE CP/CPT/QM tests with neutral kaons

Mode	Test	Param.	KLOE measurement
$K_L \to \pi^+\pi^-$	CP	BR	$(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$
$K_S \to 3\pi^0$	CP	BR	$< 2.6 \times 10^{-8}$
$K_S \to \pi e \nu$	CP	A_S	$(1.5 \pm 10) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(x_-)$	$(-0.8 \pm 2.5) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(y)$	$(0.4 \pm 2.5) \times 10^{-3}$
All $K_{S,L}$ BRs, η's etc... (unitarity)	CP CPT	$Re(\varepsilon)$ $Im(\delta)$	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	α	$(-10 \pm 37) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	β	$(1.8 \pm 3.6) \times 10^{-19}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	γ	$(0.4 \pm 4.6) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_0	$(-6.2 \pm 8.8) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$(-0.7 \pm 1.0) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV

K_S semileptonic charge asymmetry CP and CPT test

K_S semileptonic charge asymmetry

K_S and K_L semileptonic charge asymmetry

T CPT viol. in mixing

$$A_{S,L} = \frac{\Gamma\left(K_{S,L} \to \pi^- e^+ \nu\right) - \Gamma\left(K_{S,L} \to \pi^+ e^- \bar{\nu}\right)}{\Gamma\left(K_{S,L} \to \pi^- e^+ \nu\right) + \Gamma\left(K_{S,L} \to \pi^+ e^- \bar{\nu}\right)} = 2\Re\varepsilon \pm 2\Re\delta - 2\Re y \pm 2\Re x_-$$

CPTV in ΔS=ΔQ ΔS≠ΔQ decays

$A_{S,L} \neq 0$ signals CP violation

$A_S \neq A_L$ signals CPT violation

A_L=(3.322 ± 0.058 ± 0.047) × 10^{-3}

KTEV PRL88,181601(2002)

A_S = (1.5 ± 9.6 ± 2.9) × 10^{-3}

KLOE PLB 636(2006) 173

Data sample: L=410 pb^{-1}

$$A_S - A_L = 4\left(\Re\delta + \Re x_-\right) \longrightarrow \Re x_- = (-0.8 \pm 2.5) \times 10^{-3}$$

CPT & ΔS=ΔQ viol.

$$A_S + A_L = 4\left(\Re\varepsilon - \Re y\right) \longrightarrow \Re y = (0.4 \pm 2.5) \times 10^{-3}$$

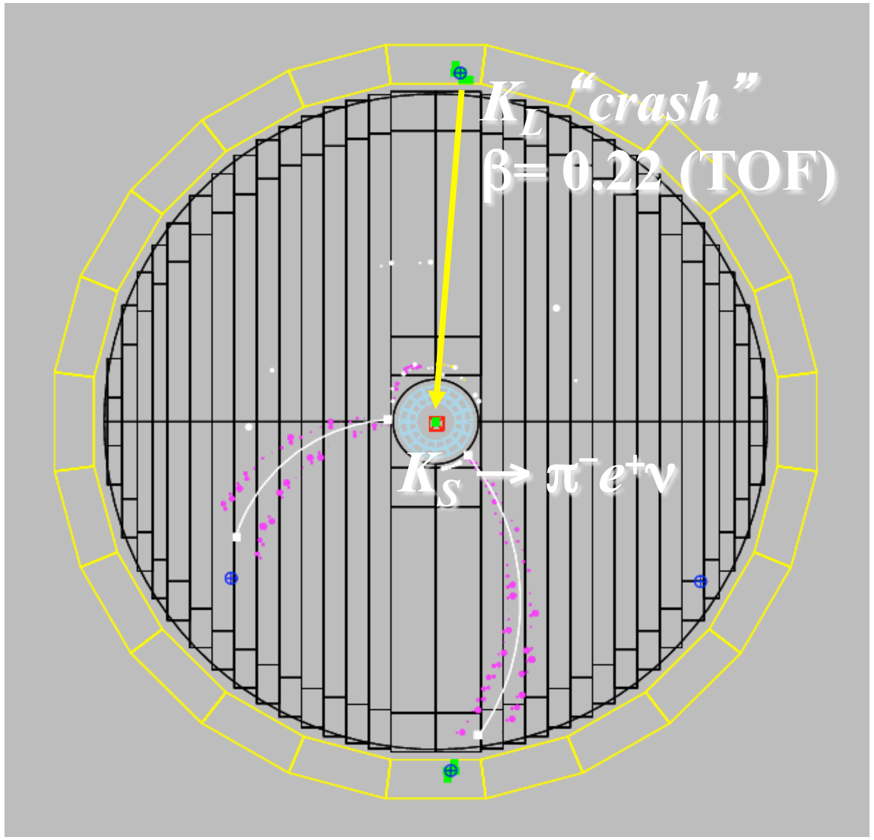
CPT viol.

input from other experiments

KLOE PLB 636(2006) 173

K_S semileptonic charge asymmetry

$$|i\rangle \propto \left[|K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle \right]$$

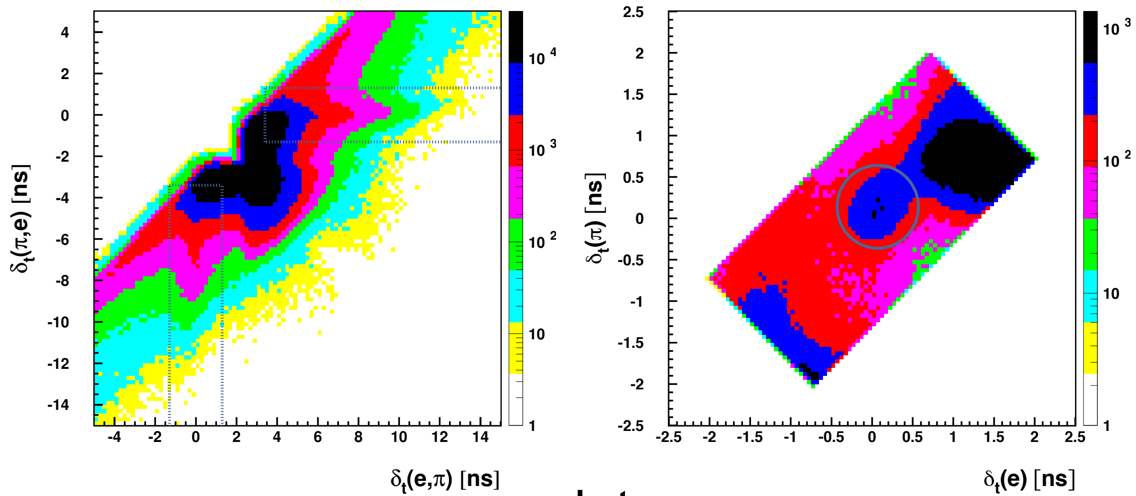


***K_S* tagged by *K_L* interaction in EmC**
Efficiency ~ 30% (largely geometrical)

- KLOE 1.7 fb^{-1}; ~ 4 × statistics w.r.t. previous measurement

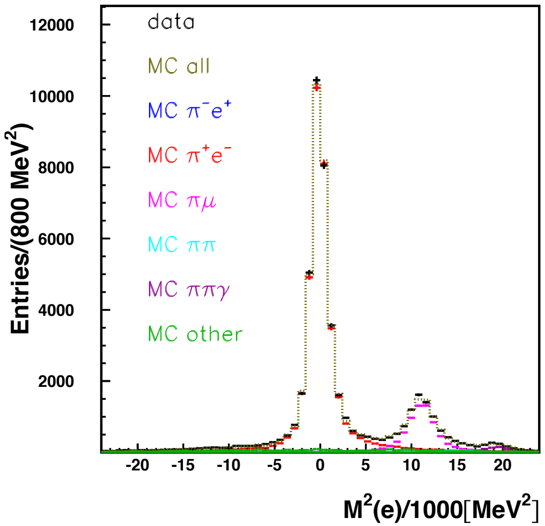
- Pre-selection
- PID with time of flight technique

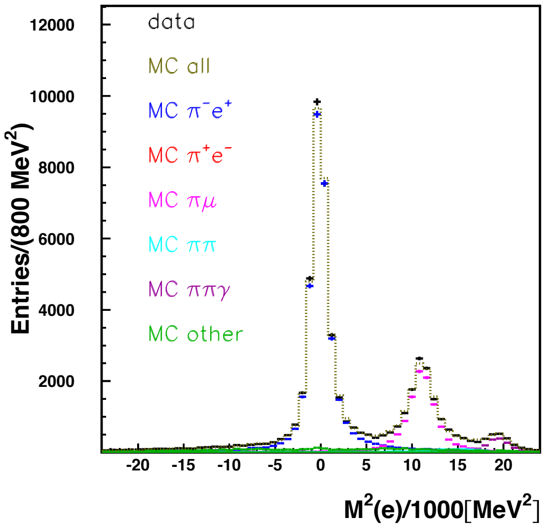
$$\delta t(m_X) = t_{cl} - \frac{L}{c\beta(m_X)} \qquad \delta_{t,ab} = \delta t(m_a) - \delta t(m_b)$$

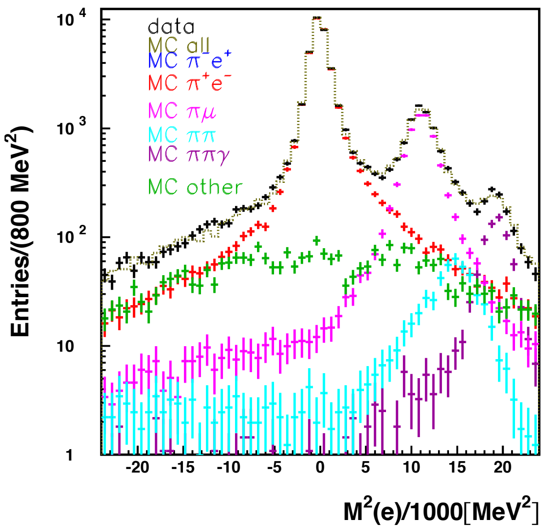


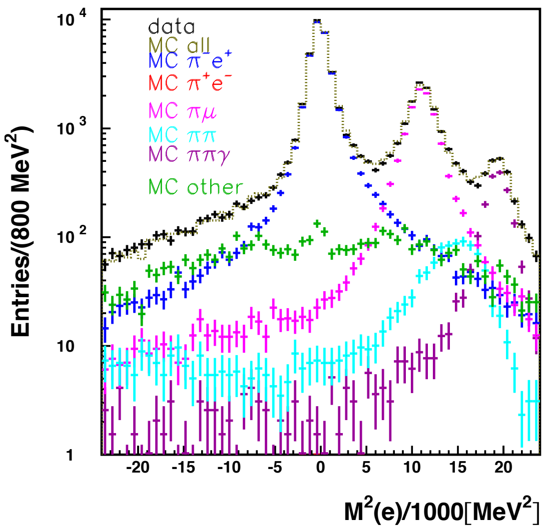
data

K_S semileptonic charge asymmetry





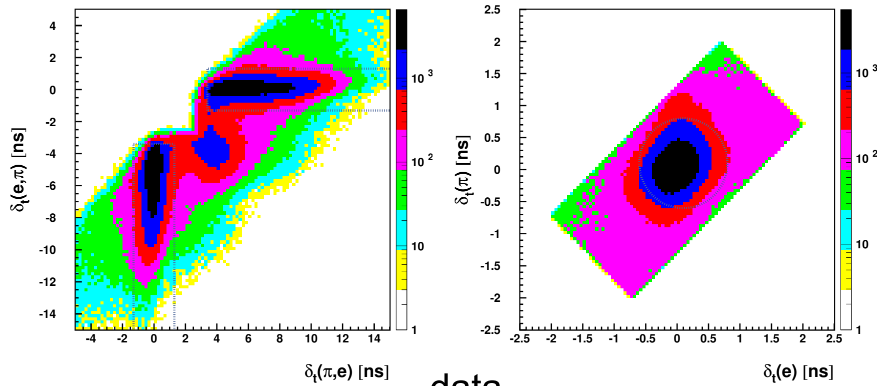




- Fit of $M^2(e)$ distribution varying MC normalizations of signal and bkg contributions

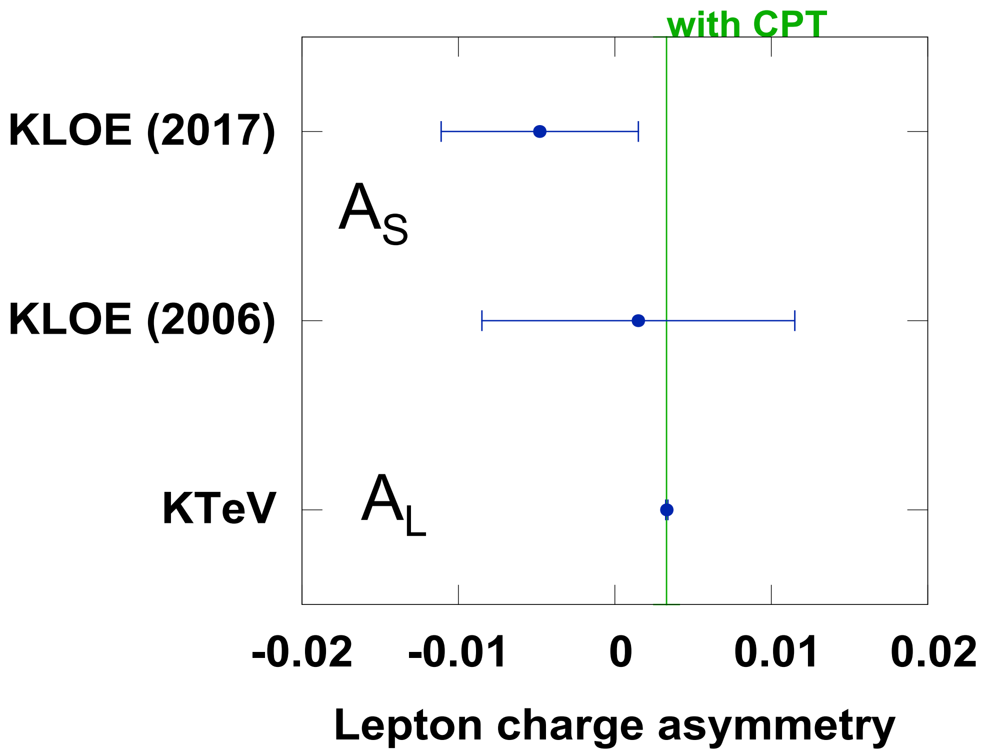
- Control sample: $K_L \to \pi e \nu$ close to IP tagged by $K_S \to \pi^0\pi^0$
- track to EMC cluster and TOF efficiency correction from data c.s.

$K_L \to \pi e \nu$



data

K_S semileptonic charge asymmetry at KLOE



Data sample: L=1.7 fb^{-1}

FINAL

KLOE (2017)

$$A_S = (-4.8 \pm 5.7 \pm 2.6) \times 10^{-3}$$

It will improve the CPT test (Imδ) using Bell-Steinberger relationship

with KLOE-2 data: δA_S(stat) → ~ 3×10^{-3}

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = (-2.3 \pm 1.6) \times 10^{-3}$$

CPT & $\Delta S = \Delta Q$ viol.

$$A_S + A_L = 4(\Re\epsilon - \Re y) \longrightarrow \Re y = (2.0 \pm 1.6) \times 10^{-3}$$

CPT viol.

input from other experiments

Direct test of CPT and T in neutral kaon transitions

Testing CPT

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)
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⇒ Phenomenological CPTV parameters to be constrained by experiments

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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..

Testing CPT

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

Direct CPT test in transitions

- Is it possible to 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 (K^0 vs $\underline{K}^0$ survival probabilities) while they can manifest at first order in transitions (non-diagonal terms).
- In standard WWA the test is related to $\mathrm{Re}\delta$, 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 $|\mathrm{K}_+\rangle$, $|\mathrm{K}_-\rangle$ defined as follows: $|\mathrm{K}_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP $= +1$ state; analogously $|\mathrm{K}_-\rangle$ 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

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

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

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

Even though the decay products are orthogonal, the filtered |K+〉 and |K−〉 states can still be non-orthoghonal.
Condition of orthoghonality:

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

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

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

J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139

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

Direct test of symmetries with neutral kaons

Conjugate= reference (red strike-through)

already in the table with conjugate as reference (black strike-through)

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 (red)

already in the table with conjugate as reference (black)

Two identical conjugates for one reference (blue)

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

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
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

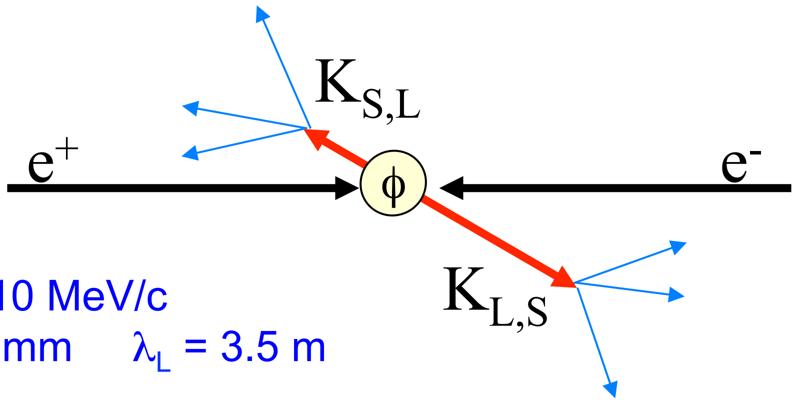
4 distinct tests of T symmetry

4 distinct tests of CP symmetry

4 distinct tests of CPT symmetry

Quantum entanglement as a tool

- The in<->out states inversion required in a DIRECT test of CPT (or T) can be performed exploiting the properties of the quantum entanglement.
- In maximally entangled systems the complete knowledge of the system as a whole is encoded in the state, no information on single subsystems is available.
- Once a measurement is performed on one subsystem, then the information is immediately transferred to its partner, which is prepared in the orthogonal state
- $\sigma(e^+e^- \to \phi)$ ~3 mb; $W = m_\phi$ = 1019.4 MeV BR($\phi \to K^0\bar{K}^0$) ~ 34% ~10^6/pb^{-1} KK pairs produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:



p_K = 110 MeV/c
λ_S = 6 mm λ_L = 3.5 m

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

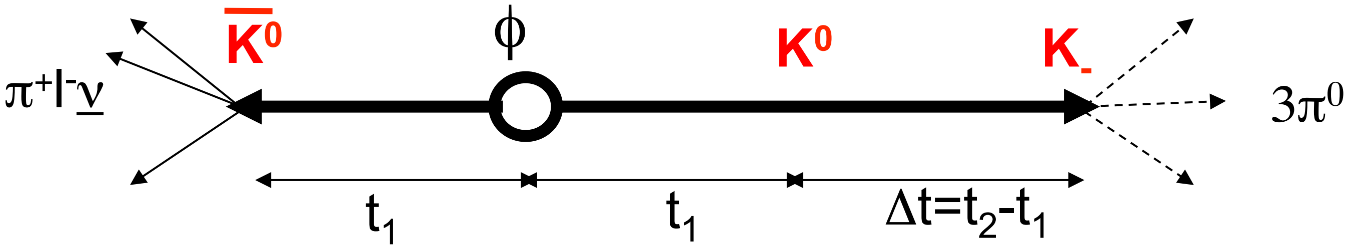
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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



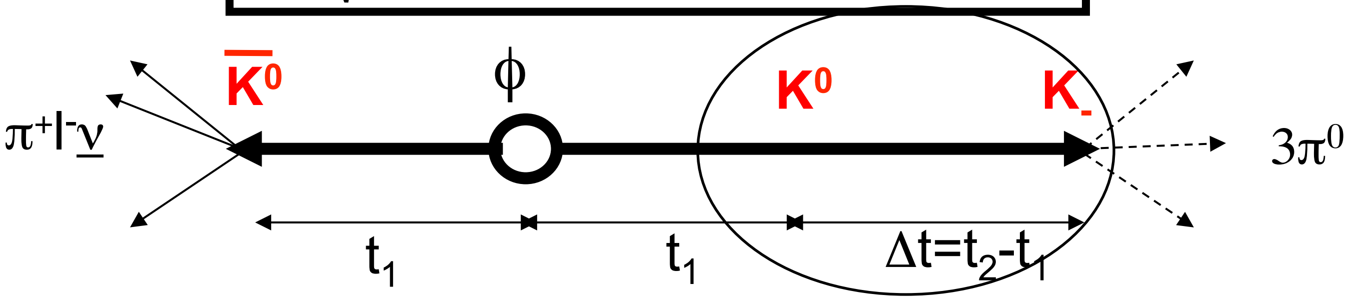
Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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

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



$K^0 \rightarrow K_-$ reference process

Entanglement in neutral kaon pairs

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

- decay as filtering measurement
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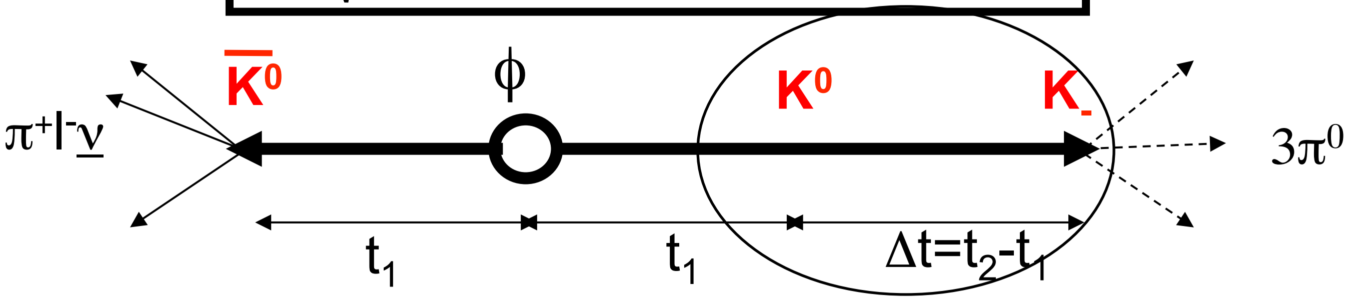
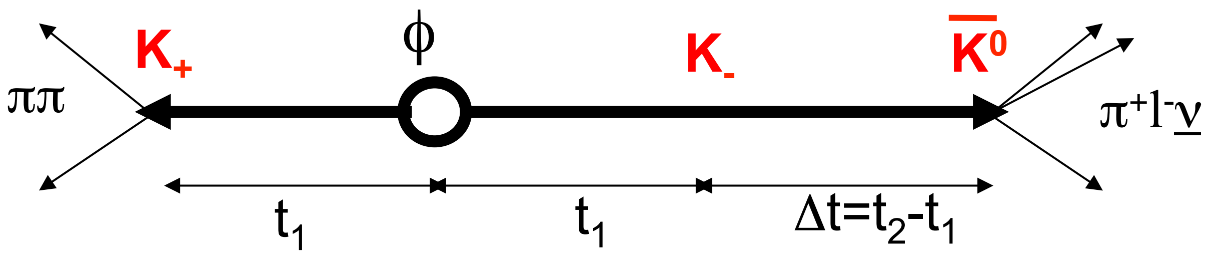


$K^0 \rightarrow K_-$ reference process

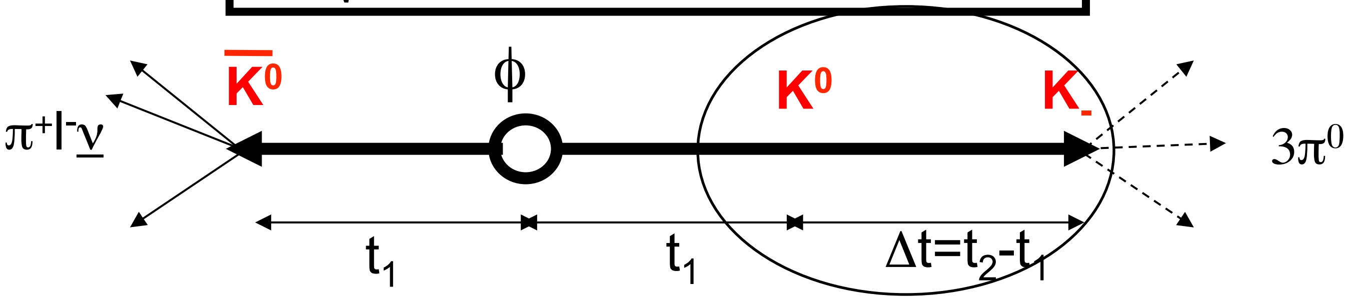


Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

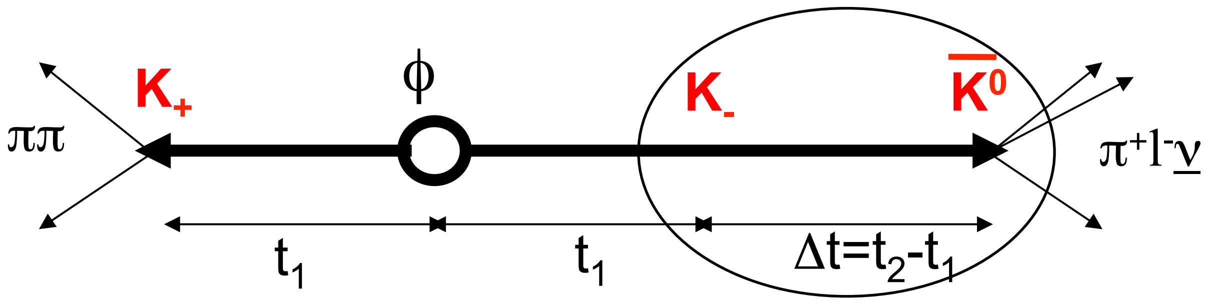
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

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



$K^0 \rightarrow K_-$ reference process

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

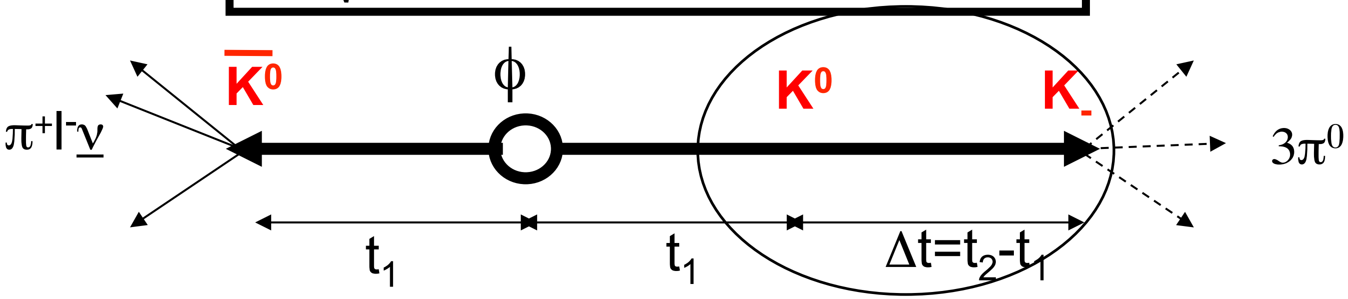


Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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

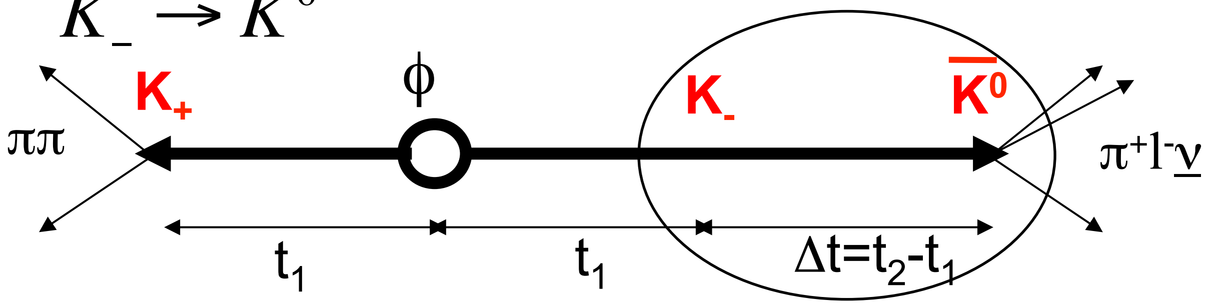


$K^0 \rightarrow K_-$ reference process

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

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 Δt>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 Δt<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

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

Direct test of CPT symmetry in neutral kaon transitions

Explicitly in standard Wigner Weisskopf approach for Δt>0:

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

$$\simeq |1 - 2\delta|^2 \left|1 + 2\delta e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\mathrm{CPT}}$$

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

$$\simeq |1 + 2\delta|^2 \left|1 - 2\delta e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\mathrm{CPT}}$$

For comparison the ratio of survival probabilities:

$$\frac{I(\ell^-, \ell^+; \Delta t)}{I(\ell^+, \ell^-; \Delta t)} = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}^0(\Delta t)]}{P[\bar{\mathrm{K}}^0(0) \to \bar{\mathrm{K}}^0(\Delta t)]}$$

$$\simeq |1 - 4\delta|^2 \left|1 + \frac{8\delta}{1 + e^{+i(\lambda_S - \lambda_L)\Delta t}}\right|^2$$

Vanishes for ΔΓ->0

As an illustration of the different sensitivity: it vanishes up to second order in CPTV and decoherence parameters α,β,γ (Ellis, Mavromatos et al. PRD1996)

Impact of the approximations

In general K_+ and K_- (and K0 and $\overline{\text{K0}}$) can be non-orthogonal

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:

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

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

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

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

Impact of the approximations

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

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

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.

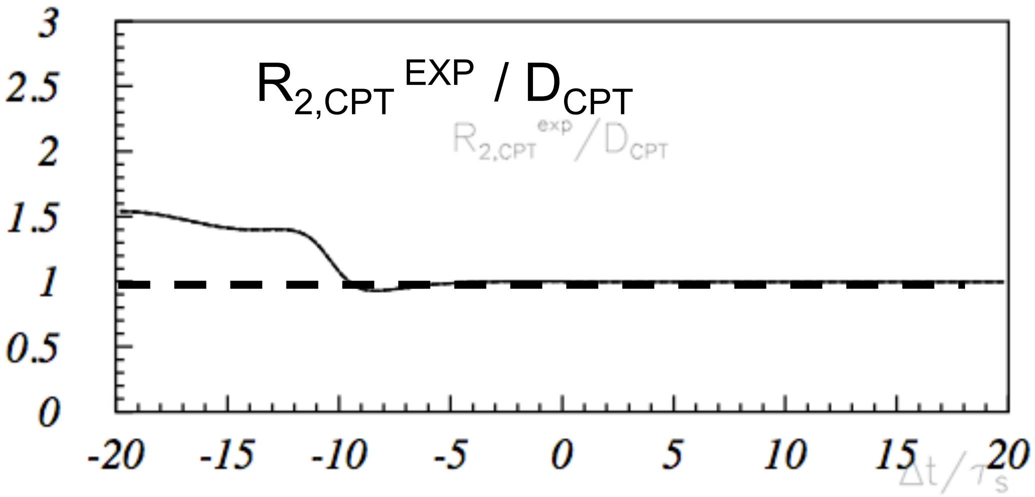
$$\mathrm{DR}_{\mathrm{CPT}} = \frac{R^{\rm exp}_{2,{\rm CPT}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,{\rm CPT}}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

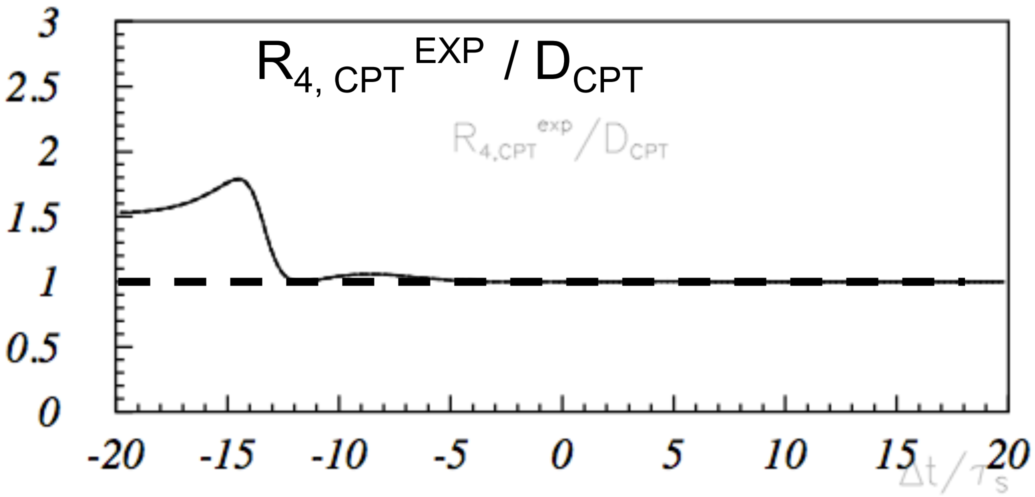
There exists a connection with charge semileptonic asymmetries of K_S and K_L

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

Direct test of CPT in transitions with neutral kaons

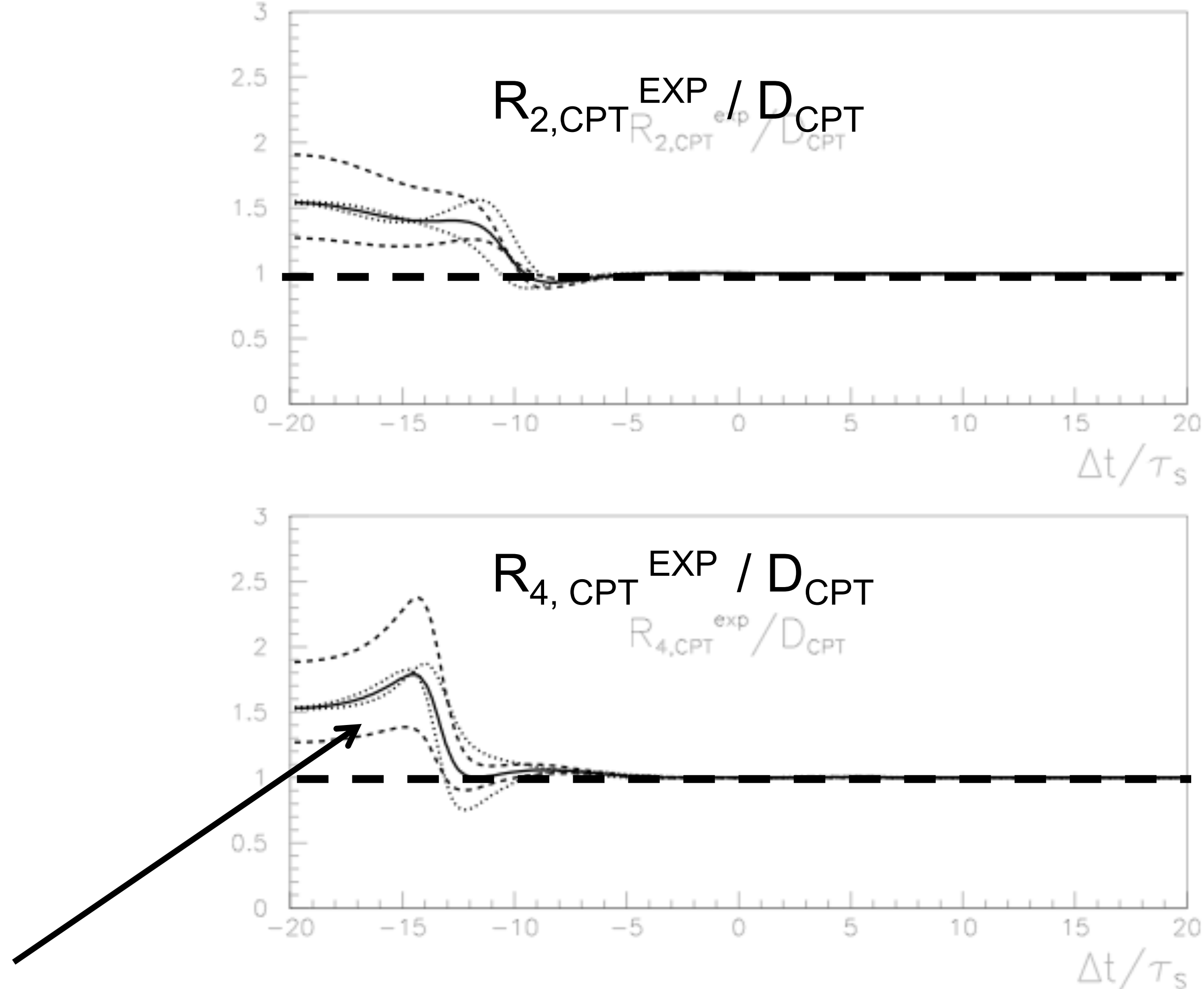
for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$





Direct test of CPT in transitions with neutral kaons

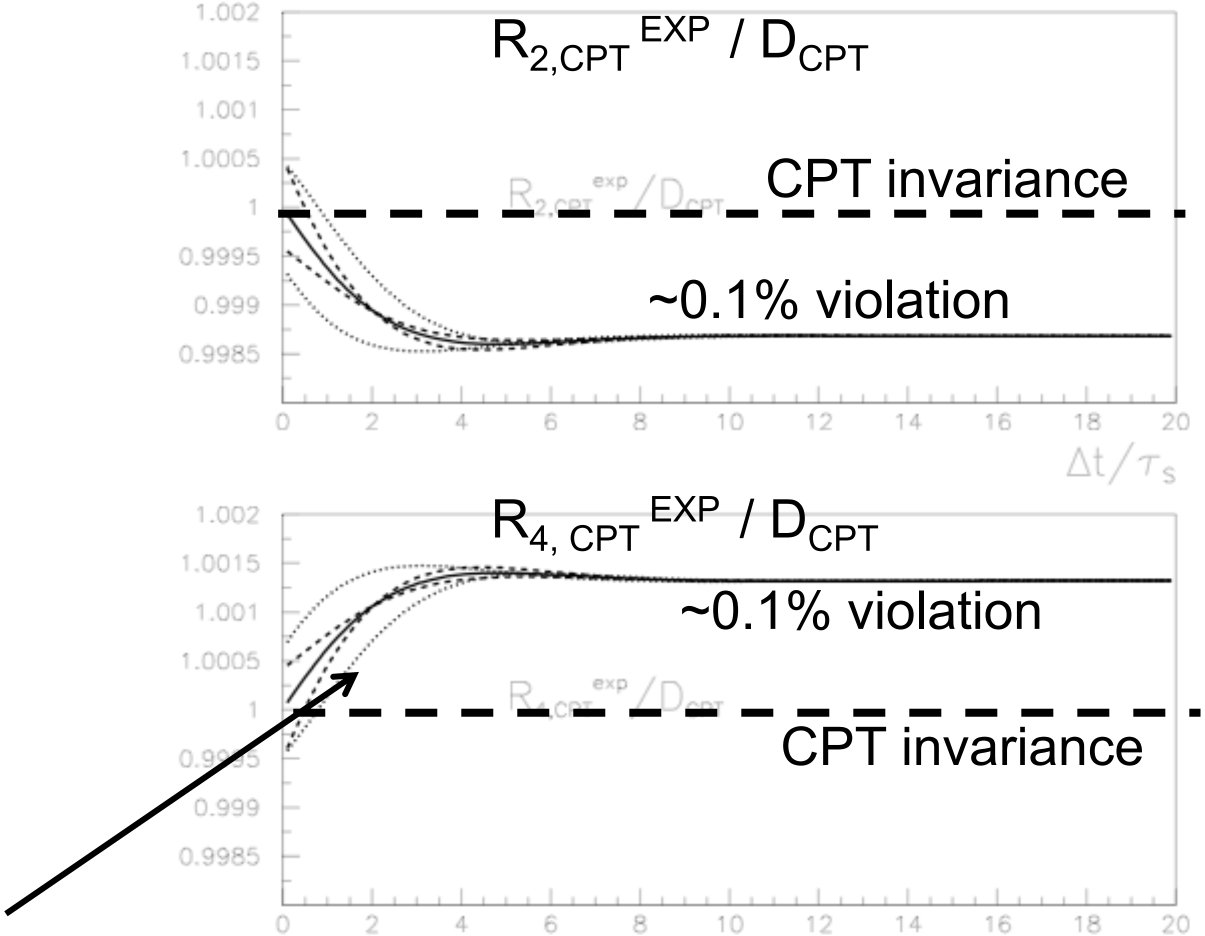
for visualization purposes, plots with
Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5}



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

Direct test of CPT in transitions with neutral kaons

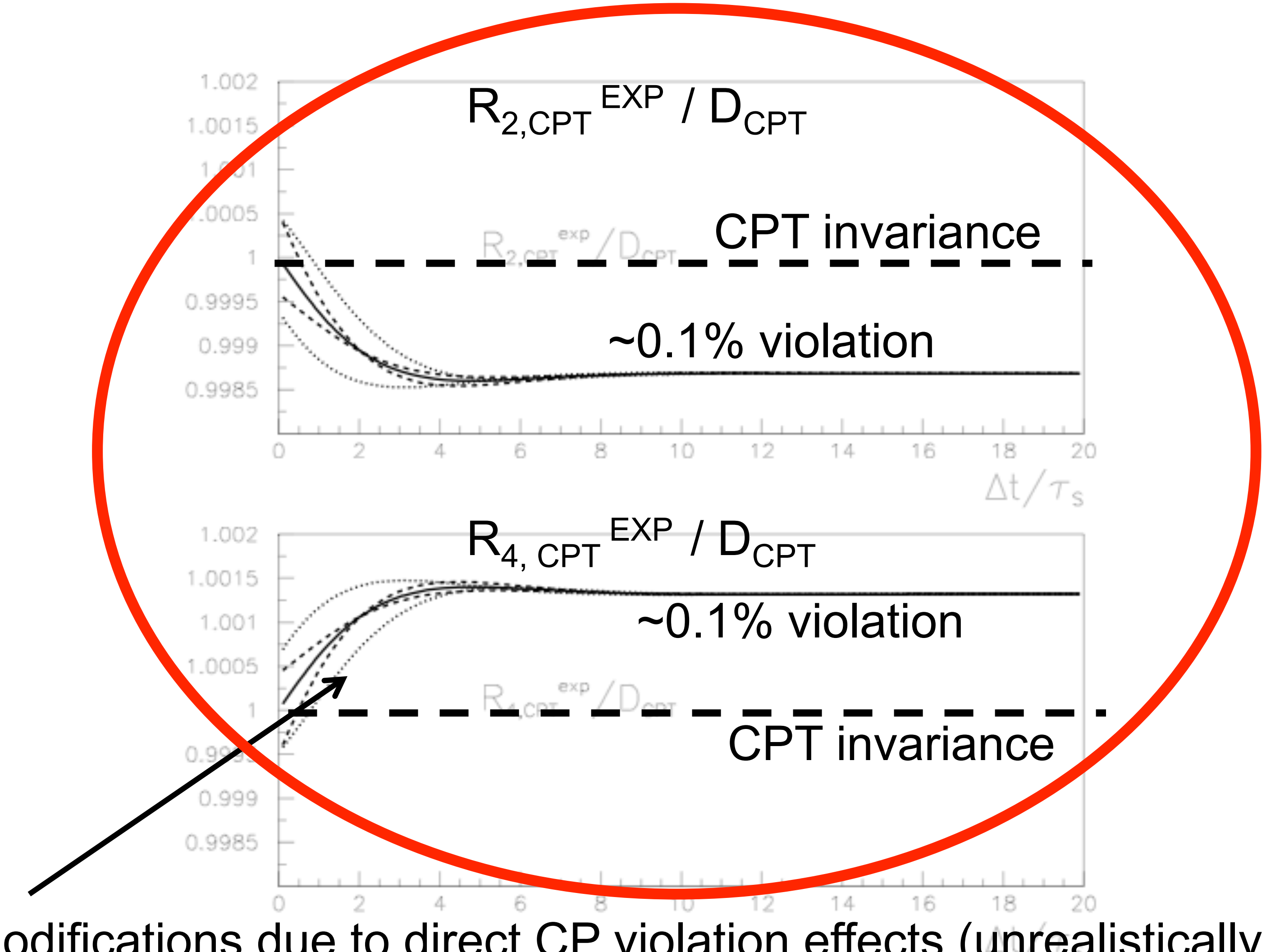
for visualization purposes, plots with
Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5}



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

Direct test of CPT in transitions with neutral kaons

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



measurable
at KLOE/KLOE-2

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

Direct test of Time Reversal symmetry with neutral kaons

Two observable ratios of double decay intensities

$$R_{2,\mathcal{T}}^{\exp}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

$$R_{4,\mathcal{T}}^{\exp}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

Direct test of Time Reversal symmetry with neutral kaons

Explicitly in standard Wigner Weisskopf approach for Δt>0:

$$R^{\rm exp}_{2,\mathcal{T}}(\Delta t) = \frac{P[{\rm K}^0(0)\to {\rm K}_-(\Delta t)]}{P[{\rm K}_-(0)\to {\rm K}^0(\Delta t)]}\times D_{\mathcal{T},2}$$

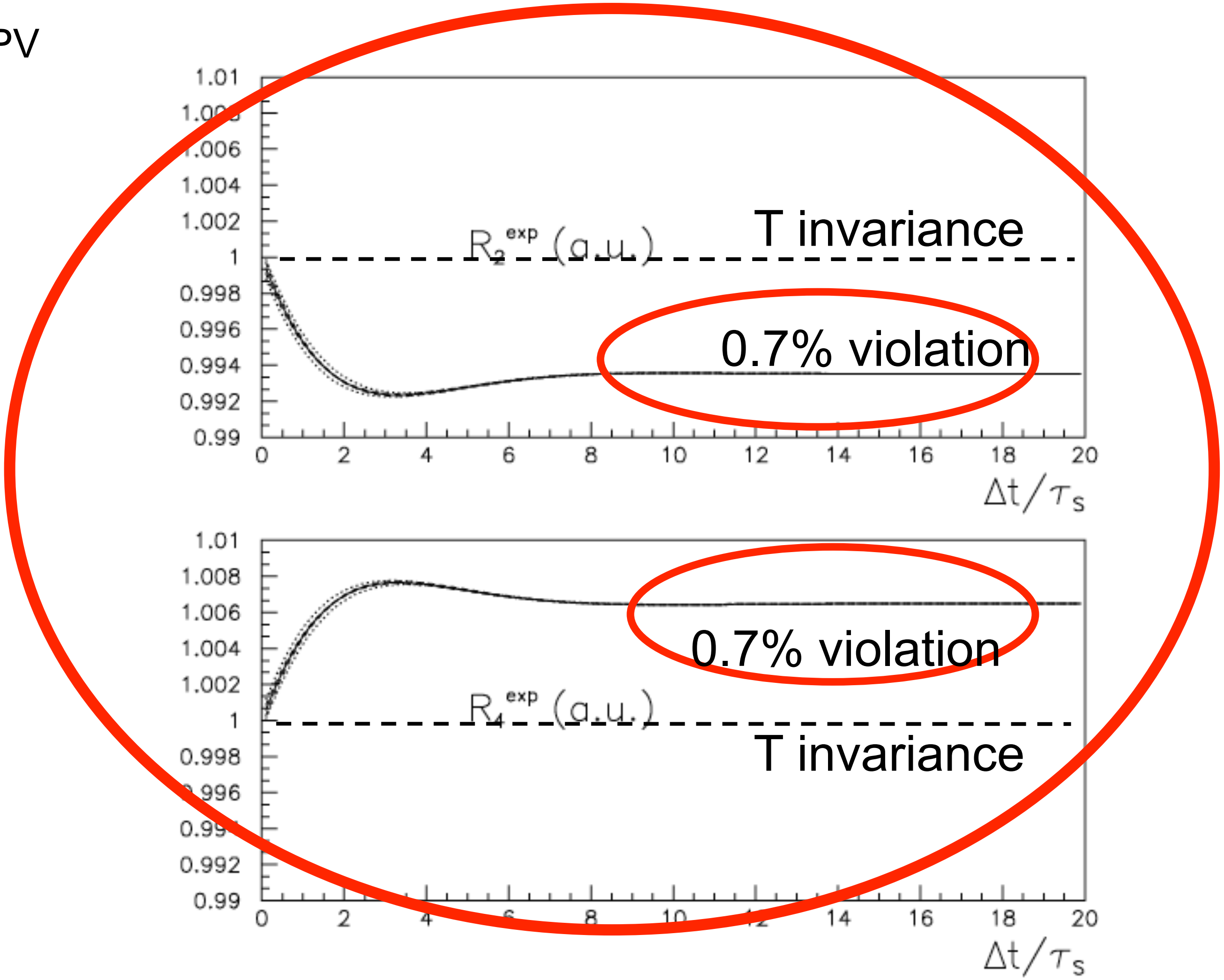
$$= (1-4\Re\epsilon)\left|1+2\epsilon e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2 \times D_{\mathcal{CPT}}$$

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

$$= (1+4\Re\epsilon)\left|1-2\epsilon e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2 \times D_{\mathcal{CPT}}$$

Direct test of Time Reversal symmetry with neutral kaons

plots with CPV
Reε and Imε
values



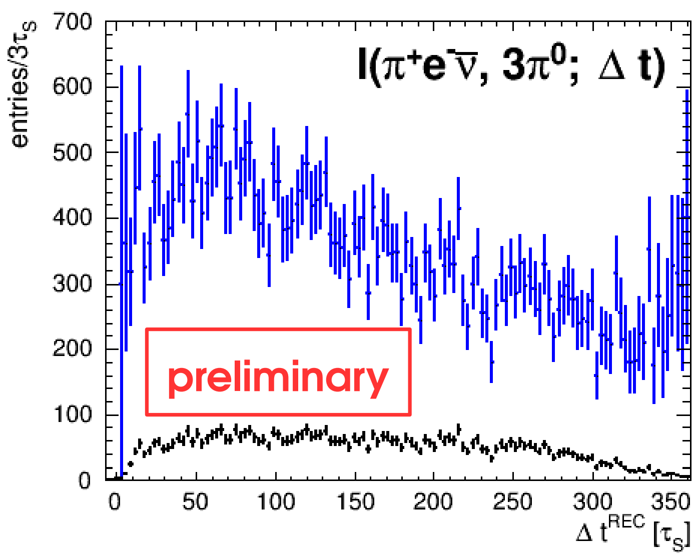
measurable
at KLOE-2

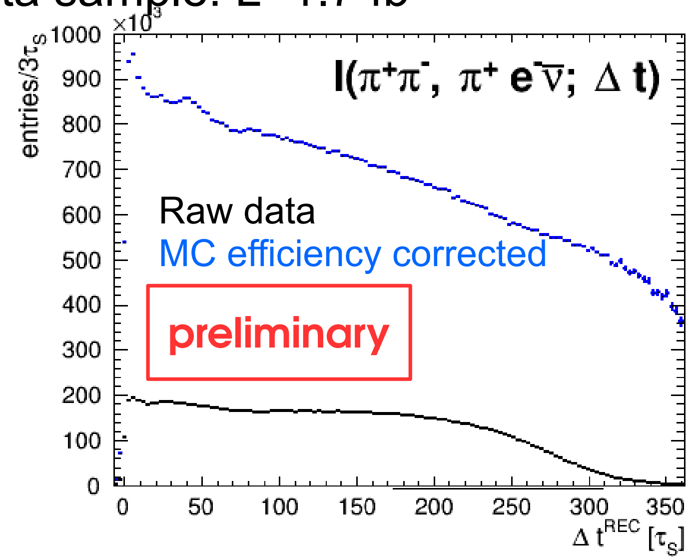
$R_2(\Delta t >> \tau_S) = 1 - 4\mathrm{Re}(\varepsilon) \sim 0.993$

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

Direct test of CPT in transitions with neutral kaons at KLOE

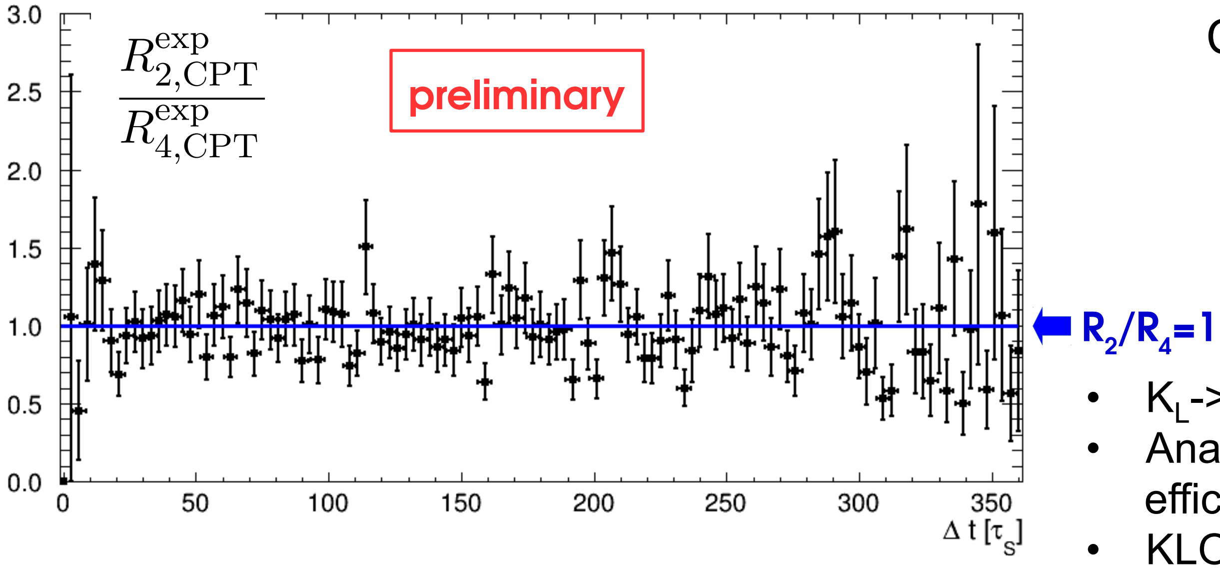
KLOE data sample: L=1.7 fb^{-1}





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

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



CPT test with the double ratio DR_{CPT}:

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

- $K_L \to 3\pi^0$ vtx reconstr. with GPS-like technique
- Analysis in progress:
  efficiency correction from data control samples
- KLOE-2 can reach a precision O(10^{-3}) on R_2/R_4

List of other KLOE CP/CPT/QM tests with neutral kaons

Mode	Test	Param.	KLOE measurement
$K_L \to \pi^+\pi^-$	CP	BR	$(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$
$K_S \to 3\pi^0$	CP	BR	$< 2.6 \times 10^{-8}$
$K_S \to \pi e \nu$	CP	A_S	$(1.5 \pm 10) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(x_-)$	$(-0.8 \pm 2.5) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(y)$	$(0.4 \pm 2.5) \times 10^{-3}$
All $K_{S,L}$ BRs, η's etc... (unitarity)	CP CPT	$Re(\varepsilon)$ $Im(\delta)$	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	α	$(-10 \pm 37) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	β	$(1.8 \pm 3.6) \times 10^{-19}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	γ	$(0.4 \pm 4.6) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_0	$(-6.2 \pm 8.8) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$(-0.7 \pm 1.0) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV

Updated results for end 2017

Expected updated results for 2018

Conclusions

- The entangled neutral kaon system at a ϕ-factory is an excellent laboratory for the study of discrete symmetries and fundamental principles of QM.

- The analysis of the full KLOE data set is being completed:
  - a new measurement of the KS semileptonic charge asymmetry
  - the analysis for first test of T and CPT in neutral kaon transitions processes is ongoing.
- It is possible to directly test CPT <u>in transition processes</u> for the first time between neutral kaon states. The proposed CPT test is model independent and fully robust.
- **VERY CLEAN CPT TEST**. Possible spurious effects are well under control, e.g. direct CP violation, $\Delta S=\Delta Q$ rule violation, decoherence effects.
- Several CPTV and/or decoherence parameters have been measured at KLOE, in same cases with a precision reaching the interesting Planck's scale region;
- All results are consistent with no CPT symmetry violation and no decoherence;

- The KLOE-2 experiment at the upgraded DAFNE is currently taking data with the plan to collect L>5 fb^{-1} by end of March 2018;
- All these tests are going to be improved at KLOE-2; a statistical sensitivity of $O(10^{-3})$ could be reached on the newly proposed observables.