# CPT, entanglement and neutral kaons

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# 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 :**

J. Schwinger (1951)

W. Pauli (1952)

G. Lüders (1954)

R. Jost (1957)

J. Bell (1955)

Exact CPT invariance holds for any quantum field theory (like the Standard Model) formulated on flat space-time which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

Testing the validity of the CPT symmetry probes the most fundamental assumptions of our present understanding of particles and their interactions.

# CPT: introduction

Extension of CPT theorem to a theory of quantum gravity far from obvious.
(e.g. CPT violation appears in several QG models)
No predictive theory incorporating CPT violation => only phenomenological models 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 $$\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}$$

neutral B system $$\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$$

proton- anti-proton $$\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$$

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

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# Neutral kaons

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

$$\boxed{i\frac{\partial}{\partial t}\Psi(t) = \mathbf{H}\Psi(t)} \qquad \mathbf{H} = \mathbf{M} - \frac{i}{2}\Gamma$$

**CP violation:**

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

**T violation:**

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

**CPT violation:**

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

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

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

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

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

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

# Neutral kaons

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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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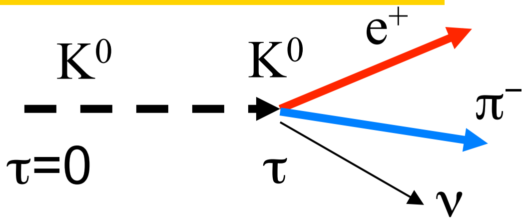
# neutral kaons vs other oscillating meson systems

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

# "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) →

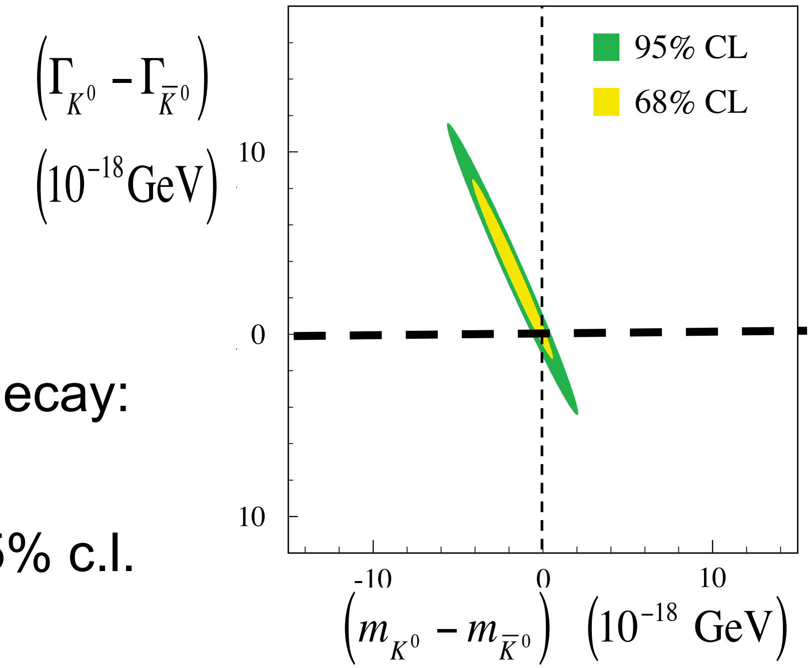
$$2\Im\delta = \Im\left[\langle K_L | K_S \rangle\right] = \Im\left[\frac{\sum_f \langle f|T|K_S\rangle \langle f|T|K_L\rangle^*}{i\left(\lambda_S - \lambda_L^*\right)}\right]$$

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

**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 Re$\delta$ and Im$\delta$ 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.

# 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 (survival probabilities) while they can manifest at first order in transitions (non-diagonal terms).
- In standard WWA the test is related to 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 |
| $\mathrm{K}^0 \to \mathrm{K}_+$ | $(\ell^-, \pi\pi)$ | $\mathrm{K}_+ \to \bar{\mathrm{K}}^0$ | $(3\pi^0, \ell^-)$ |
| $\mathrm{K}^0 \to \mathrm{K}_-$ | $(\ell^-, 3\pi^0)$ | $\mathrm{K}_- \to \bar{\mathrm{K}}^0$ | $(\pi\pi, \ell^-)$ |
| $\bar{\mathrm{K}}^0 \to \mathrm{K}_+$ | $(\ell^+, \pi\pi)$ | $\mathrm{K}_+ \to \mathrm{K}^0$ | $(3\pi^0, \ell^+)$ |
| $\bar{\mathrm{K}}^0 \to \mathrm{K}_-$ | $(\ell^+, 3\pi^0)$ | $\mathrm{K}_- \to \mathrm{K}^0$ | $(\pi\pi, \ell^+)$ |

One can define the following ratios of probabilities:

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

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 |
|---|---|---|---|
| $K^0 \to K^0$ | $K^0 \to K^0$ | $\bar{K}^0 \to \bar{K}^0$ | $\bar{K}^0 \to \bar{K}^0$ |
| $K^0 \to \bar{K}^0$ | $\bar{K}^0 \to K^0$ | $\bar{K}^0 \to K^0$ | $K^0 \to \bar{K}^0$ |
| $K^0 \to K_+$ | $K_+ \to K^0$ | $\bar{K}^0 \to K_+$ | $K_+ \to \bar{K}^0$ |
| $K^0 \to K_-$ | $K_- \to K^0$ | $\bar{K}^0 \to K_-$ | $K_- \to \bar{K}^0$ |
| $\bar{K}^0 \to K^0$ | $K^0 \to \bar{K}^0$ | $K^0 \to \bar{K}^0$ | $\bar{K}^0 \to K^0$ |
| $\bar{K}^0 \to \bar{K}^0$ | $\bar{K}^0 \to \bar{K}^0$ | $K^0 \to K^0$ | $K^0 \to K^0$ |
| $\bar{K}^0 \to K_+$ | $K_+ \to \bar{K}^0$ | $K^0 \to K_+$ | $K_+ \to K^0$ |
| $\bar{K}^0 \to K_-$ | $K_- \to \bar{K}^0$ | $K^0 \to K_-$ | $K_- \to K^0$ |
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| $K_- \to \bar{K}^0$ | $\bar{K}^0 \to K_-$ | $K_- \to K^0$ | $K^0 \to K_-$ |
| $K_- \to K_+$ | $K_+ \to K_-$ | $K_- \to K_+$ | $K_+ \to K_-$ |
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# Direct test of symmetries with neutral kaons

Conjugate= reference

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

already in the table with conjugate as reference

Two identical conjugates for one reference

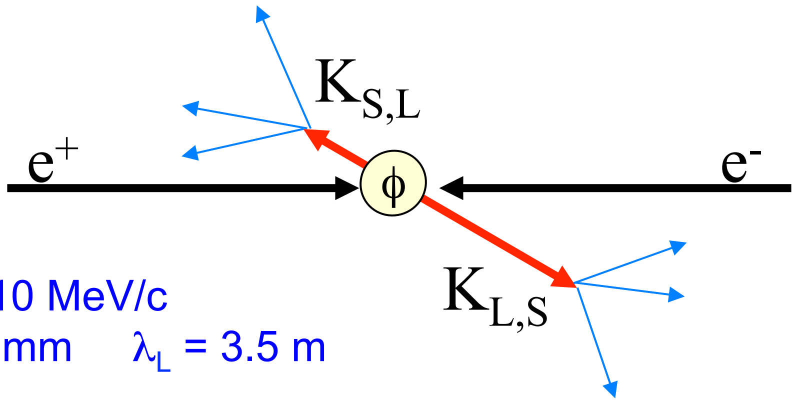
4 distinct tests of T symmetry

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
$\lambda_S$ = 6 mm $\lambda_L$ = 3.5 m

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

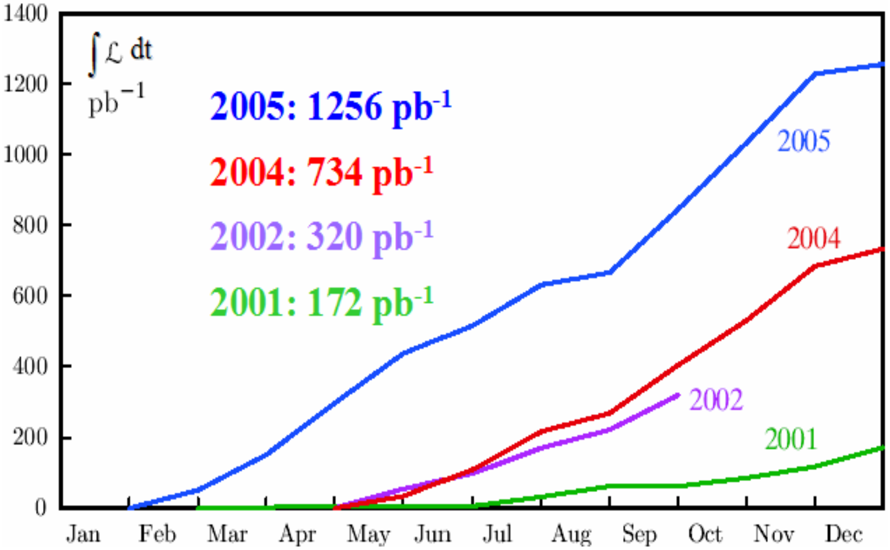
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

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

# The KLOE detector at the Frascati φ-factory DAΦNE

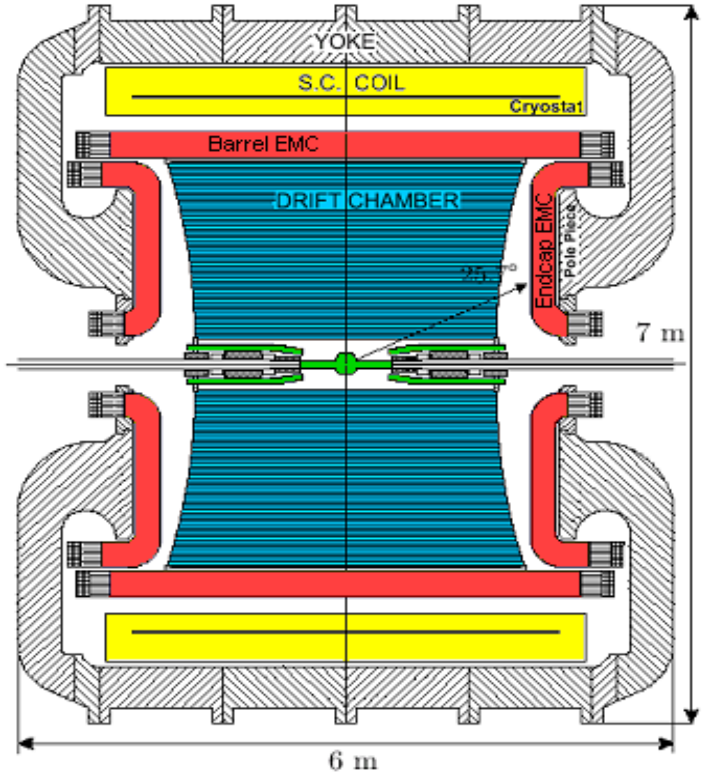
DAFNE collider

Integrated luminosity (KLOE)




Total KLOE $\int\mathcal{L}\,dt$ ~ 2.5 $fb^{-1}$
(2001 - 05) → ~$2.5\times10^9$ $K_SK_L$ pairs

KLOE detector



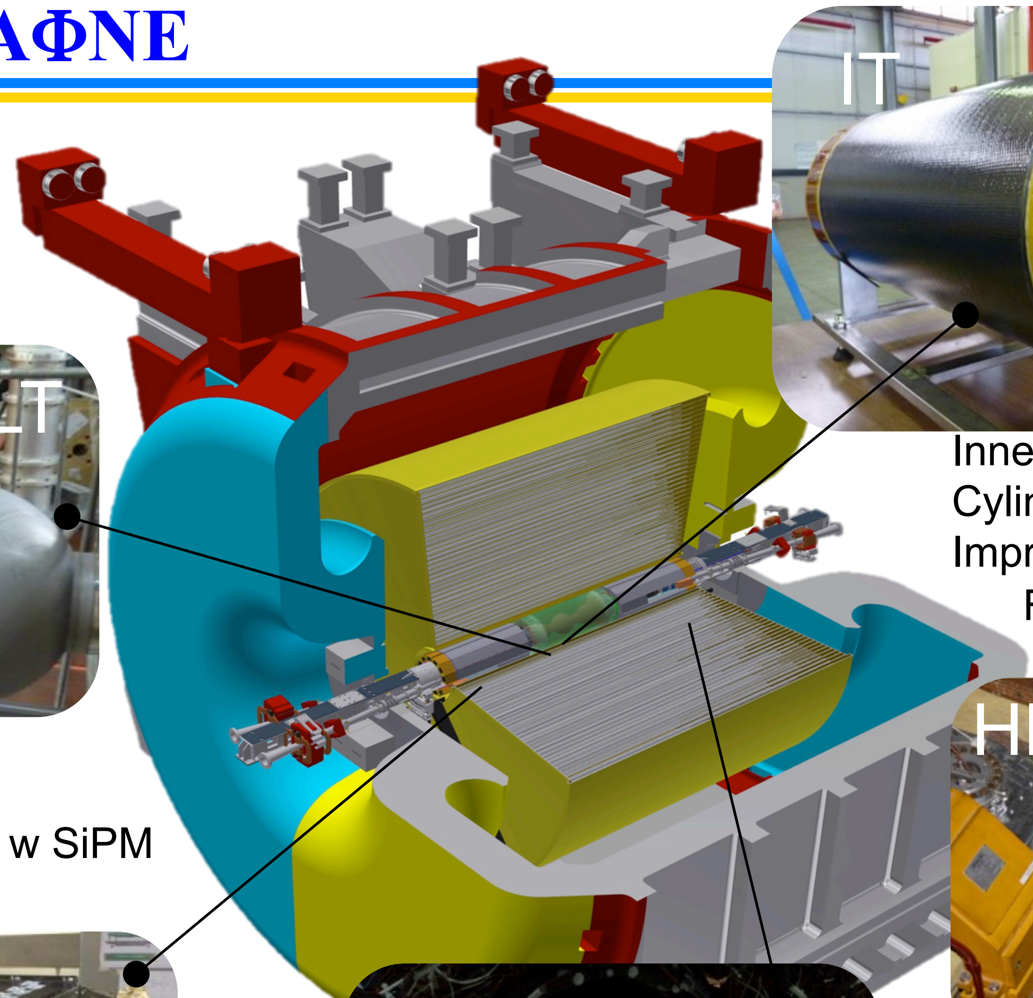

Lead/scintillating fiber calorimeter

drift chamber

4 m diameter × 3.3 m length

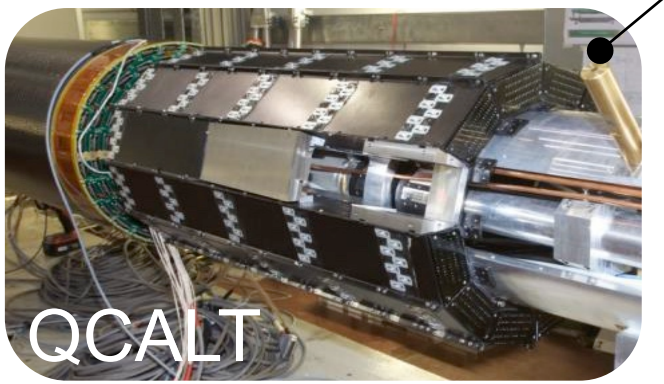
helium based gas mixture

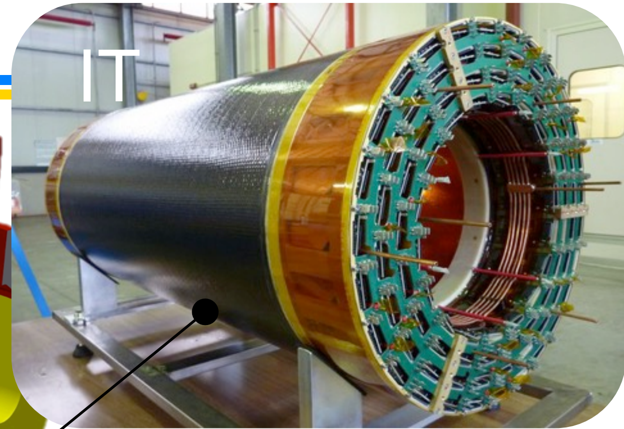
# KLOE-2 at DAΦNE



LYSO Crystal w SiPM
Low polar angle


Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation



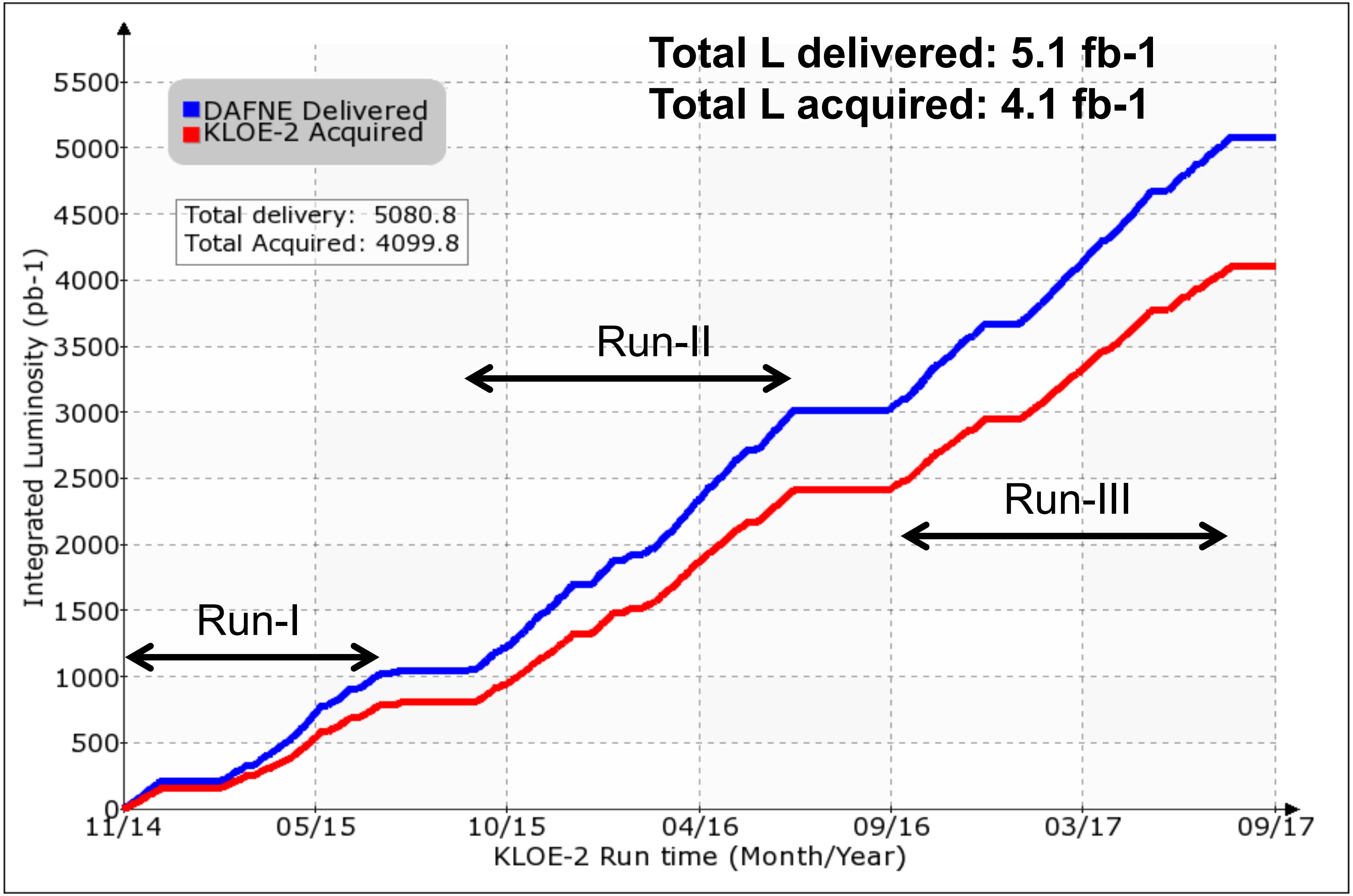




Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vtx reconstr.
First CGEM in HEP expt.


Scintillator hodoscope +PMTs


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**

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

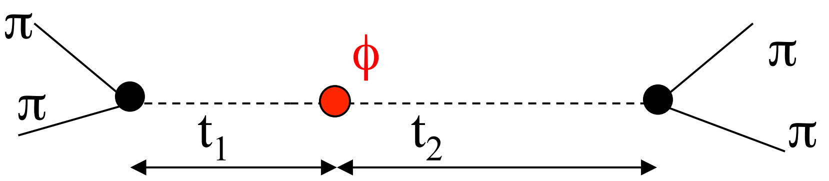
| Mode | Test | Param. | KLOE measurement |
|---|---|---|---|
| $K_L \to \pi^+\pi^-$ | CP | BR | $(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$ |
| $K_S \to 3\pi^0$ | CP | BR | $< 2.6 \times 10^{-8}$ |
| $K_S \to \pi e \nu$ | CP | $A_S$ | $(1.5 \pm 10) \times 10^{-3}$ |
| $K_S \to \pi e \nu$ | CPT | $Re(x_-)$ | $(-0.8 \pm 2.5) \times 10^{-3}$ |
| $K_S \to \pi e \nu$ | CPT | $Re(y)$ | $(0.4 \pm 2.5) \times 10^{-3}$ |
| All $K_{S,L}$ BRs, η's etc... (unitarity) | CP<br>CPT | $Re(\varepsilon)$<br>$Im(\delta)$ | $(159.6 \pm 1.3) \times 10^{-5}$<br>$(0.4 \pm 2.1) \times 10^{-5}$ |
| $K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ | QM | $\zeta_{00}$ | $(0.1 \pm 1.0) \times 10^{-6}$ |
| $K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ | QM | $\zeta_{SL}$ | $(0.3 \pm 1.9) \times 10^{-2}$ |
| $K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ | 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<br>compl. pos. hyp.<br>$(0.7 \pm 1.2) \times 10^{-21}$ 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 | $\Delta a_0$ | $(-6.2 \pm 8.8) \times 10^{-18}$ GeV |
| $K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ | CPT & Lorentz | $\Delta a_Z$ | $(-0.7 \pm 1.0) \times 10^{-18}$ GeV |
| $K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ | CPT & Lorentz | $\Delta a_X$ | $(3.3 \pm 2.2) \times 10^{-18}$ GeV |
| $K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ | CPT & Lorentz | $\Delta a_Y$ | $(-0.7 \pm 2.0) \times 10^{-18}$ GeV |

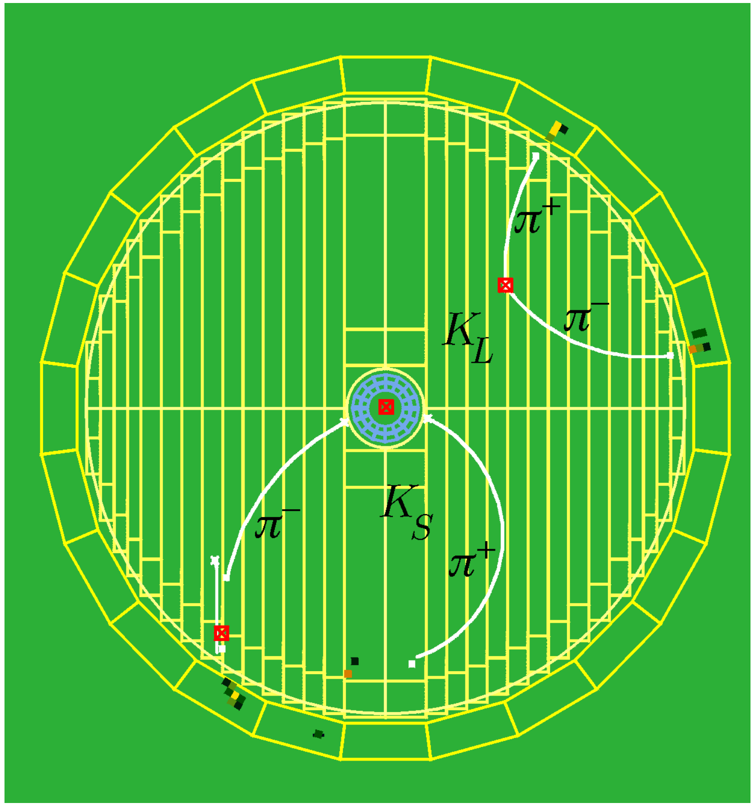
# Entanglement in neutral kaon pairs from φ

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

Both kaons decay in the same final state:

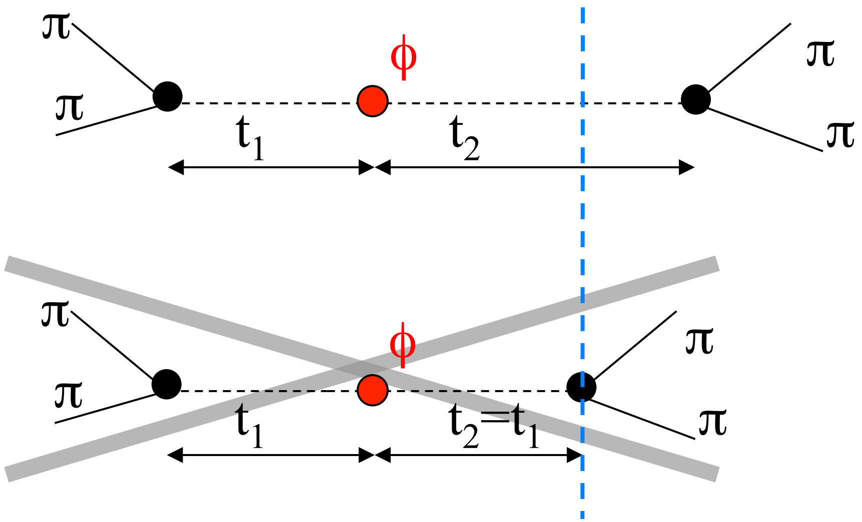
$f_1 = f_2 = \pi^+\pi^-$



# Entanglement in neutral kaon pairs from φ

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

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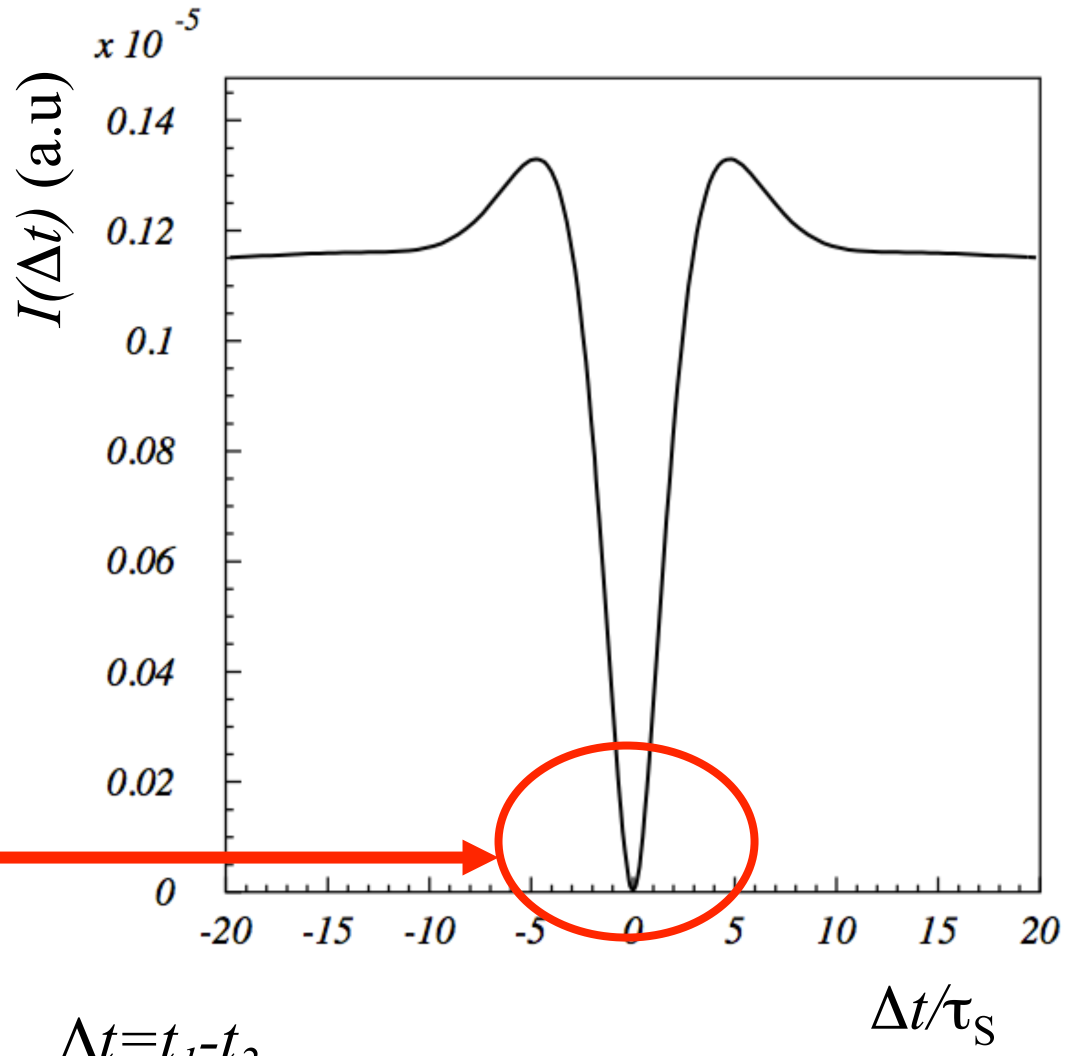
$f_1 = f_2 = \pi^+\pi^-$




EPR correlation:

no simultaneous decays ($\Delta t=0$) in the same final state due to the fully destructive quantum interference

$\Delta t = t_1 - t_2$

# $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ : test of quantum coherence

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

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\Big[\left|\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle\right|^2$$

$$-(1-\zeta_{0\bar{0}})\cdot 2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle^*\right)\Big]$$

# $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ : test of quantum coherence

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

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\Big[\left|\langle\pi^+\pi^-,\pi^+\pi^-|K^0\bar{K}^0(\Delta t)\rangle\right|^2 + \left|\langle\pi^+\pi^-,\pi^+\pi^-|\bar{K}^0K^0(\Delta t)\rangle\right|^2$$

$$-(1-\zeta_{0\bar{0}})\cdot 2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\bar{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\bar{K}^0K^0(\Delta t)\rangle^*\right)\Big]$$

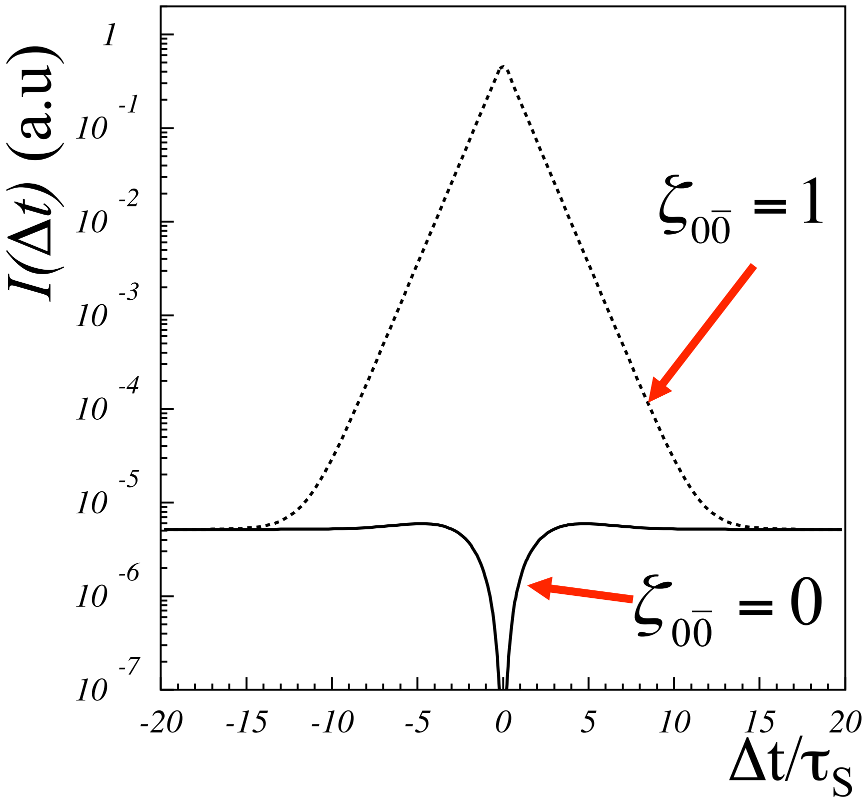
Decoherence parameter:

$\zeta_{0\bar{0}} = 0 \quad \rightarrow \quad$ QM

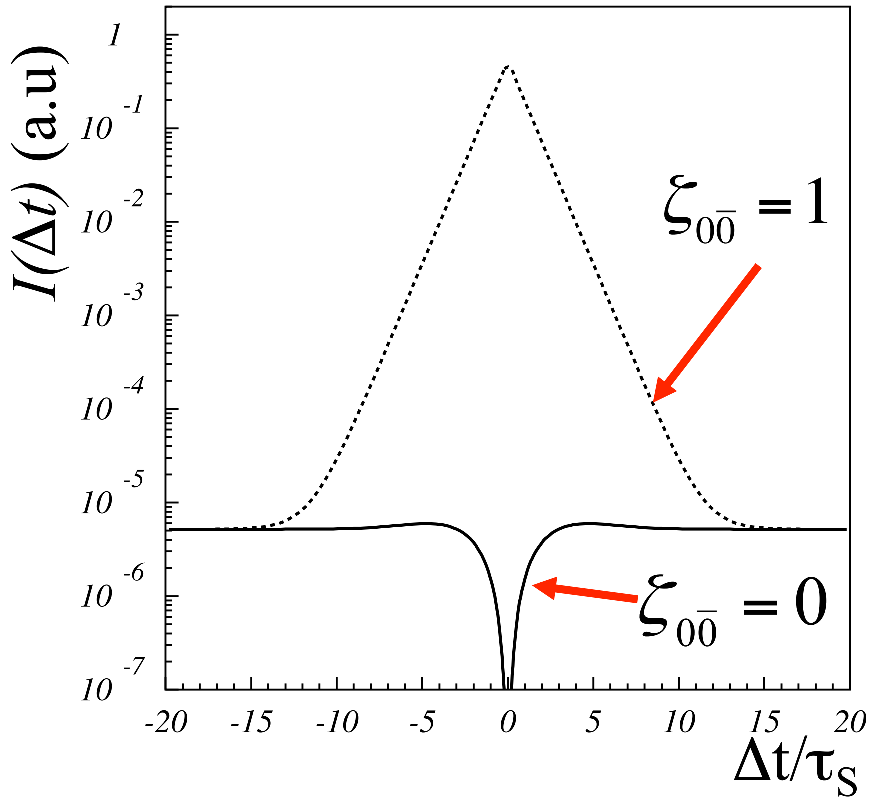
$\zeta_{0\bar{0}} = 1 \quad \rightarrow \quad$ total decoherence

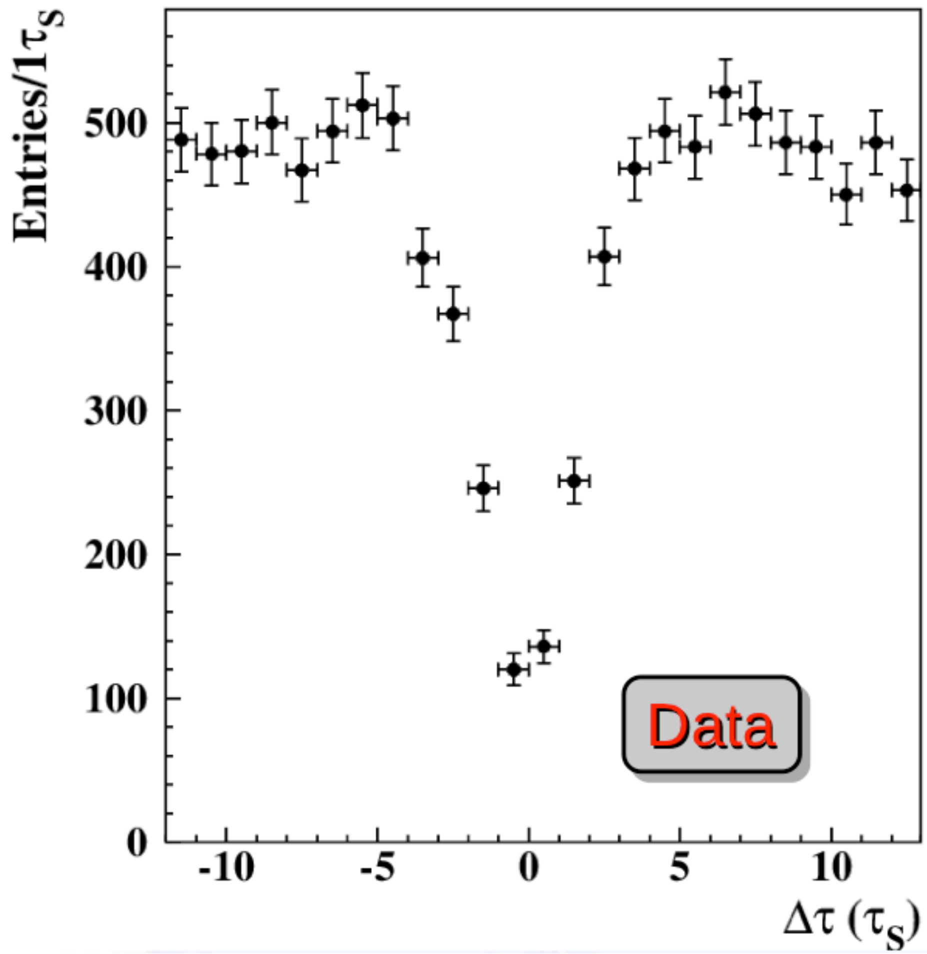
Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

# $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ : test of quantum coherence

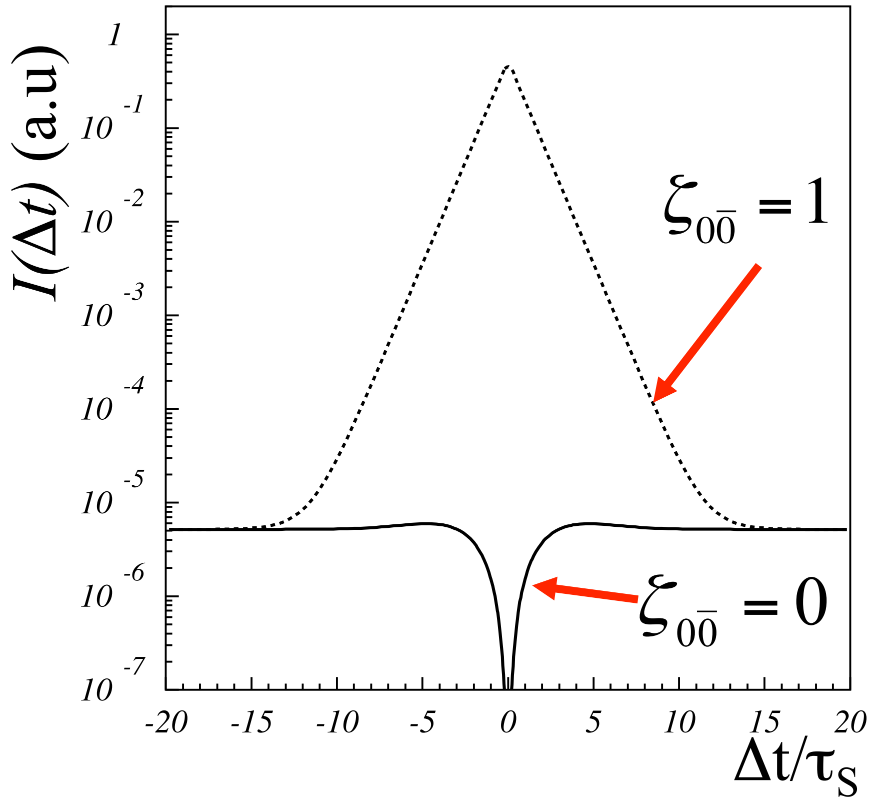


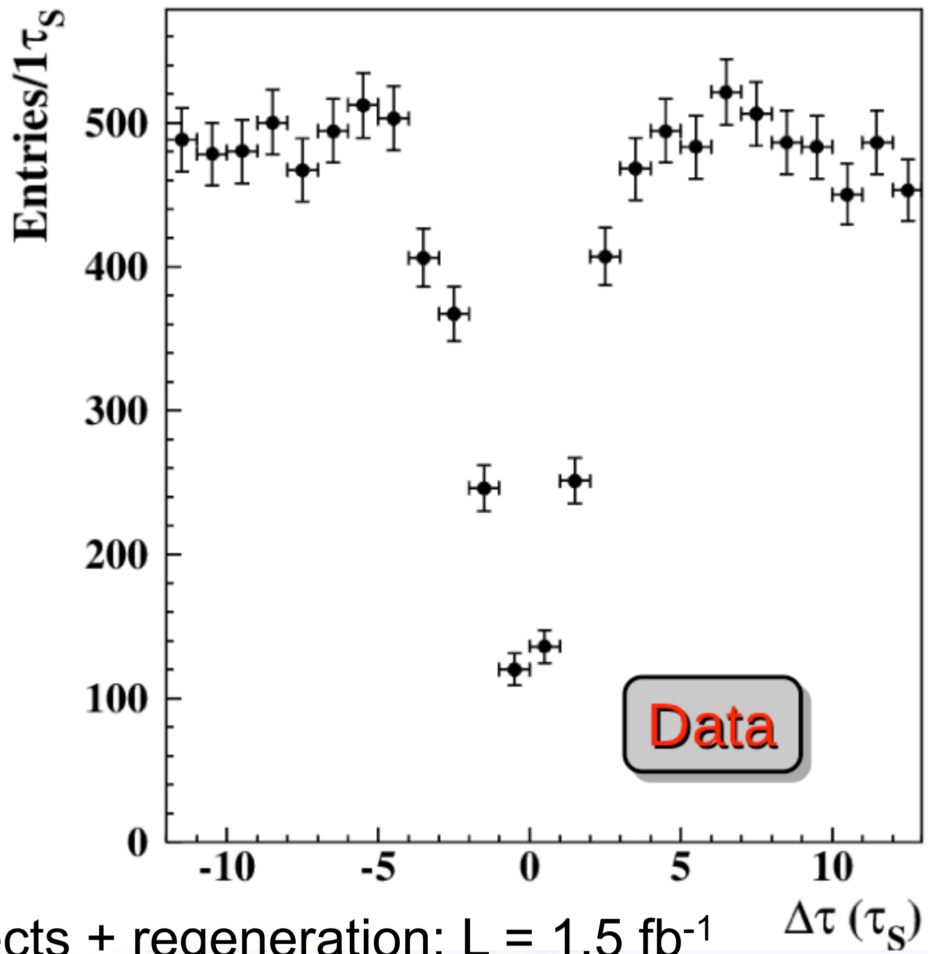
# $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$ : test of quantum coherence



# $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$ : test of quantum coherence




Fit including Δt resolution and efficiency effects + regeneration; L = 1.5 fb$^{-1}$

**KLOE result:**

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

A new refined analysis is being finalized: $\sigma(\zeta)$ improved ~15%

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

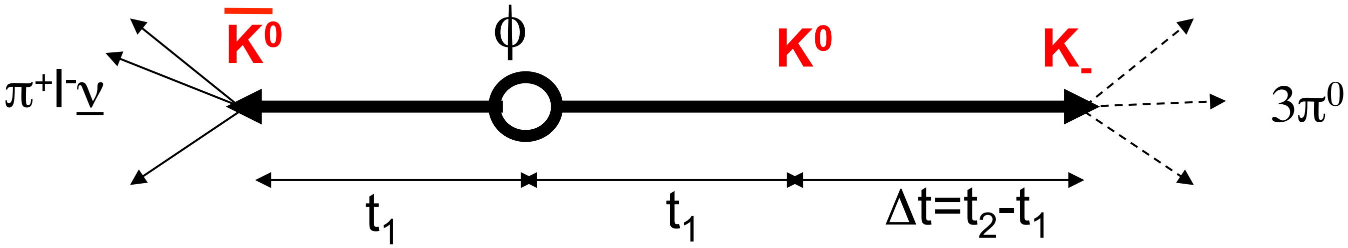
**The most precise test in an entangled system**

# Entanglement in neutral kaon pairs

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

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

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



# Entanglement in neutral kaon pairs

- EPR correlations at a $\phi$-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
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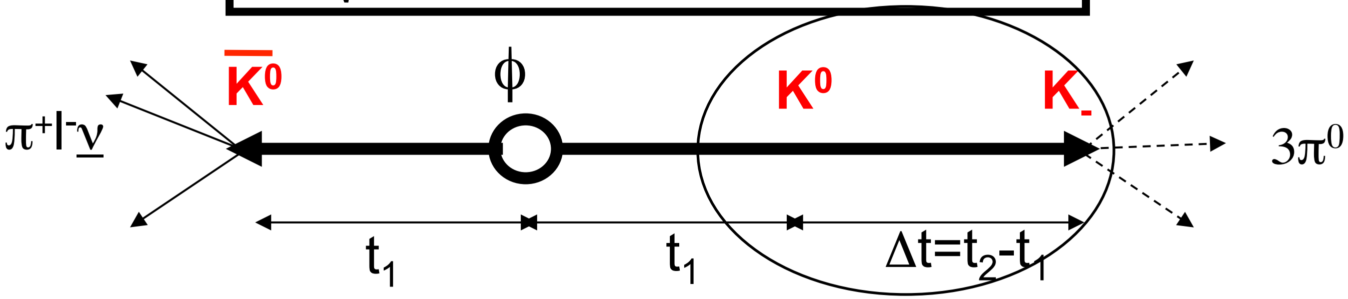


$K^0 \rightarrow K_-$ reference process

# Entanglement in neutral kaon pairs

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

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

- decay as filtering measurement
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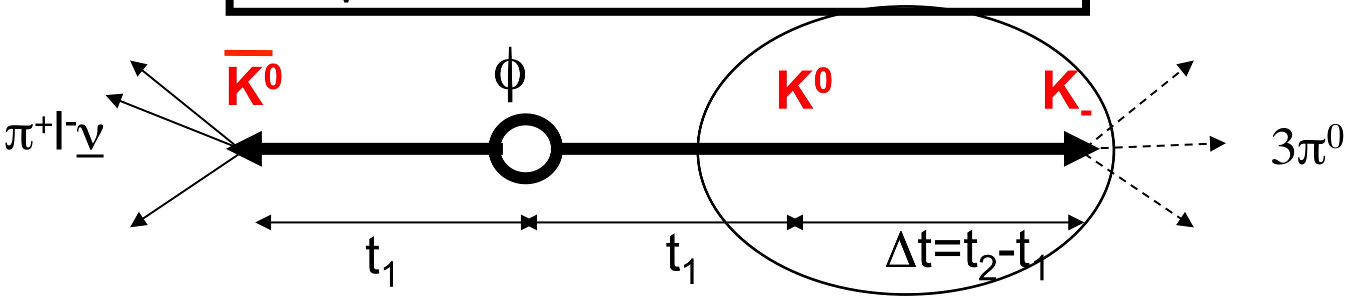
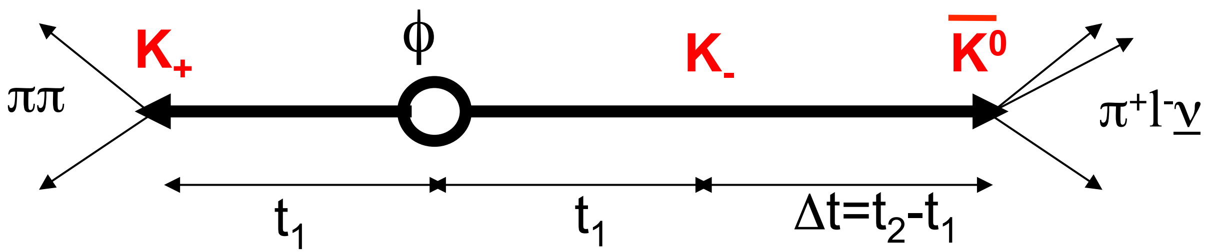



$K^0 \rightarrow K_-$ reference process

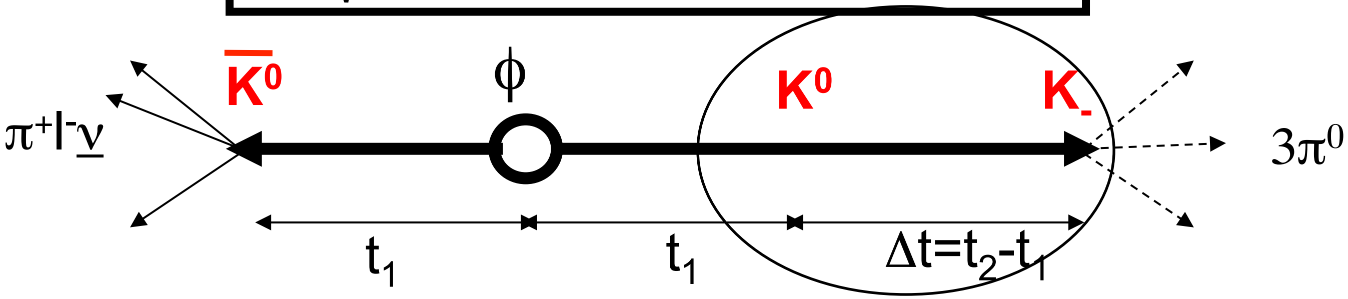


# Entanglement in neutral kaon pairs

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

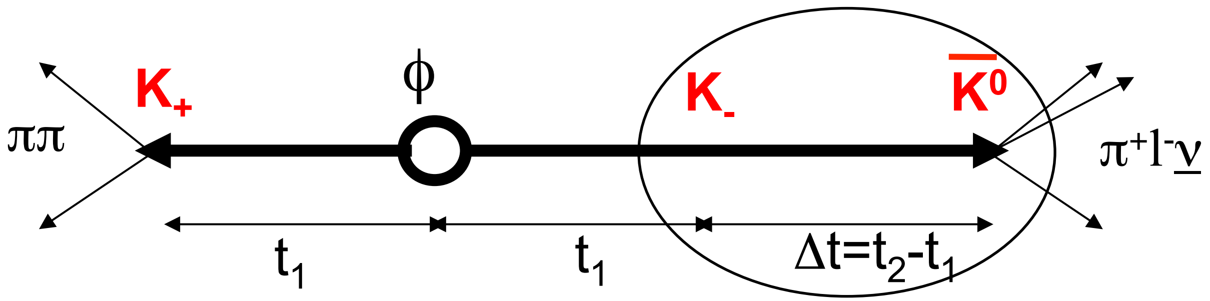
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

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




$K^0 \rightarrow K_-$ reference process

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

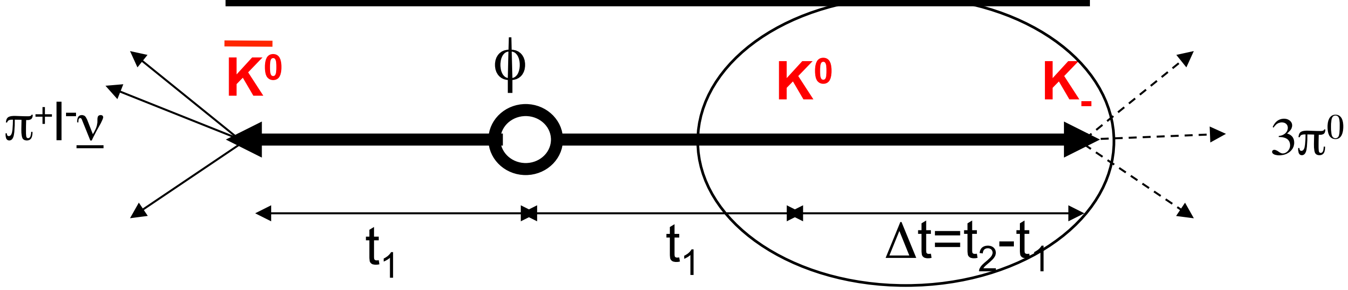


# Entanglement in neutral kaon pairs

- EPR correlations at a $\phi$-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

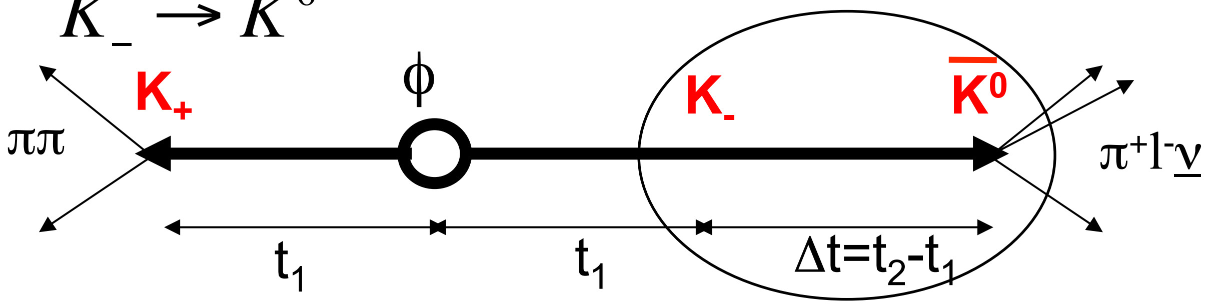



$K^0 \rightarrow K_-$ reference process

Note: CP and T conjugated process

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

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



# 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

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

# Direct test of CPT symmetry in neutral kaon transitions

Explicitly in standard Wigner Weisskopf approach for Δt>0:

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

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

For comparison the ratio of survival probabilities:

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

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

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

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

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.

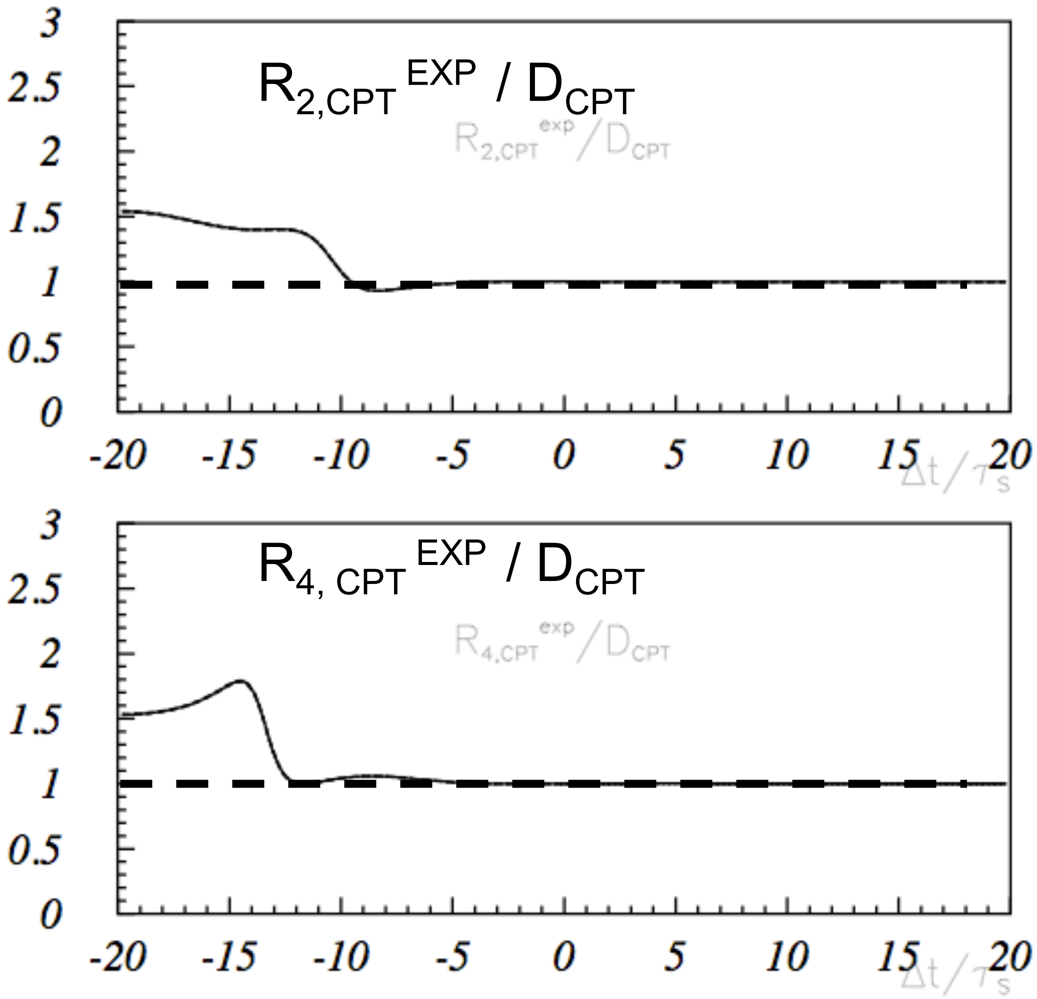
$$DR_{CPT} = \frac{R^{\exp}_{2,\mathrm{CPT}}(\Delta t \gg \tau_S)}{R^{\exp}_{4,\mathrm{CPT}}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

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

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

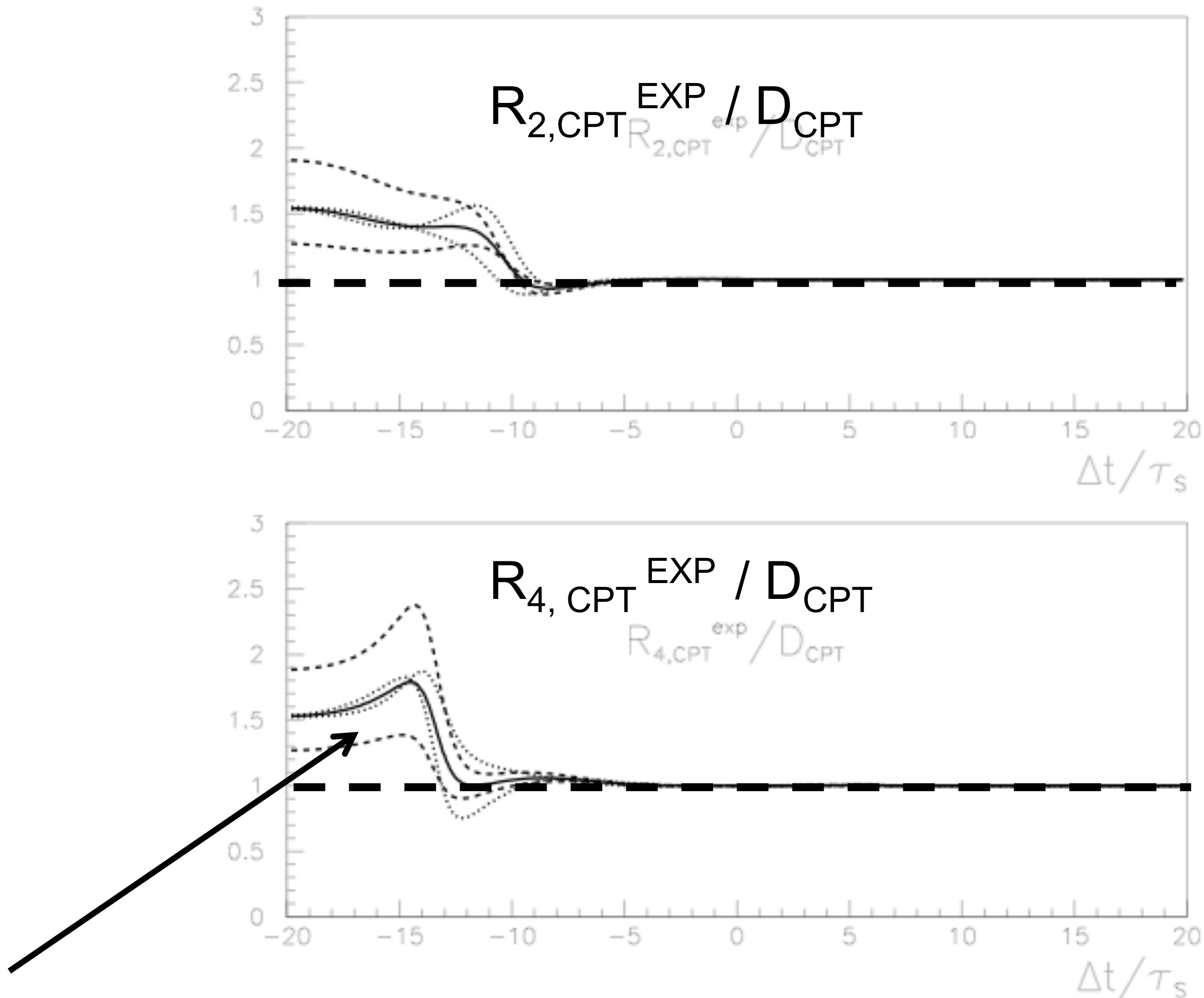
# Direct test of CPT in transitions with neutral kaons

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

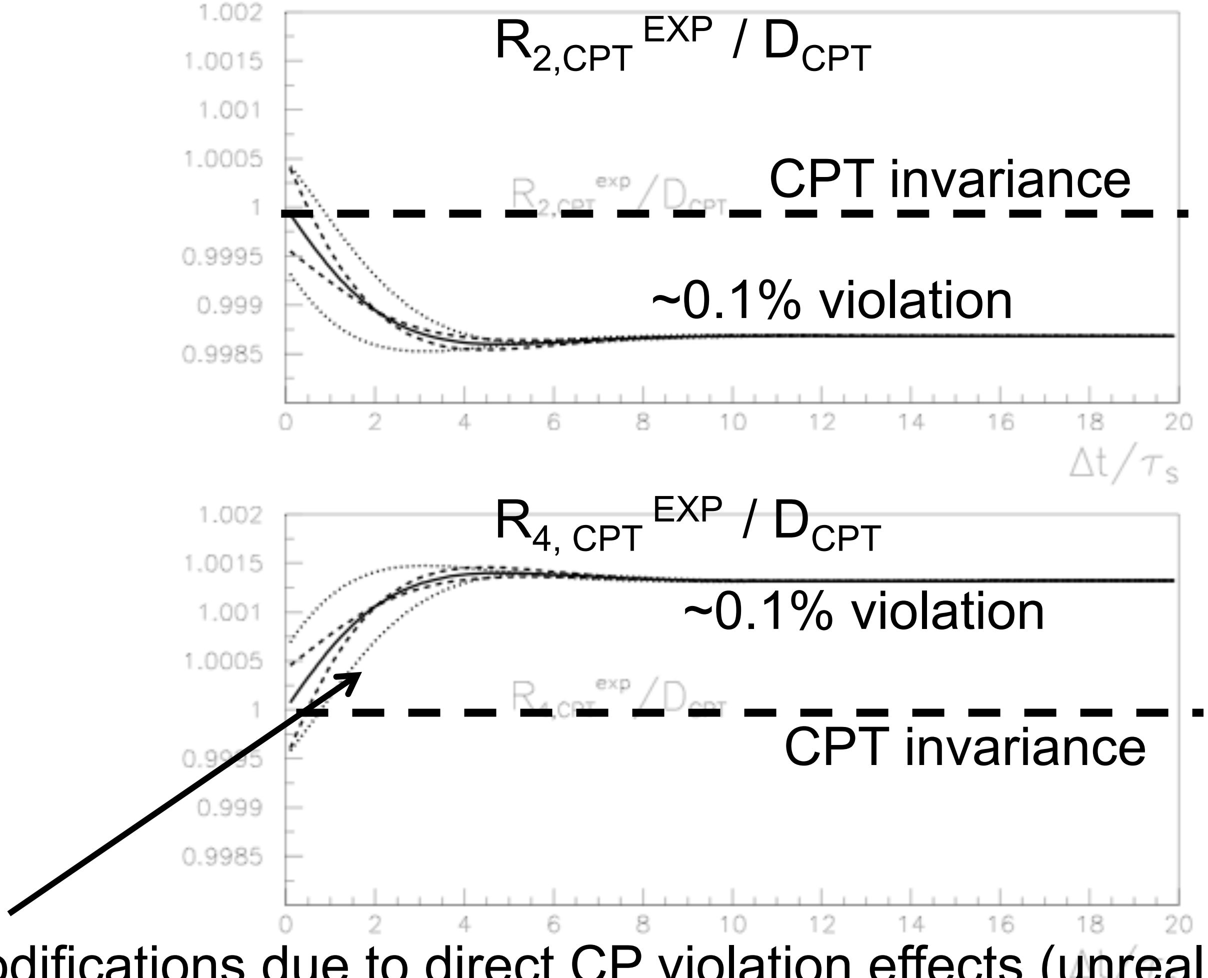
for visualization purposes, plots with
$Re(\delta)=3.3\ 10^{-4}$ $Im(\delta)=1.6\ 10^{-5}$




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

# Direct test of CPT in transitions with neutral kaons

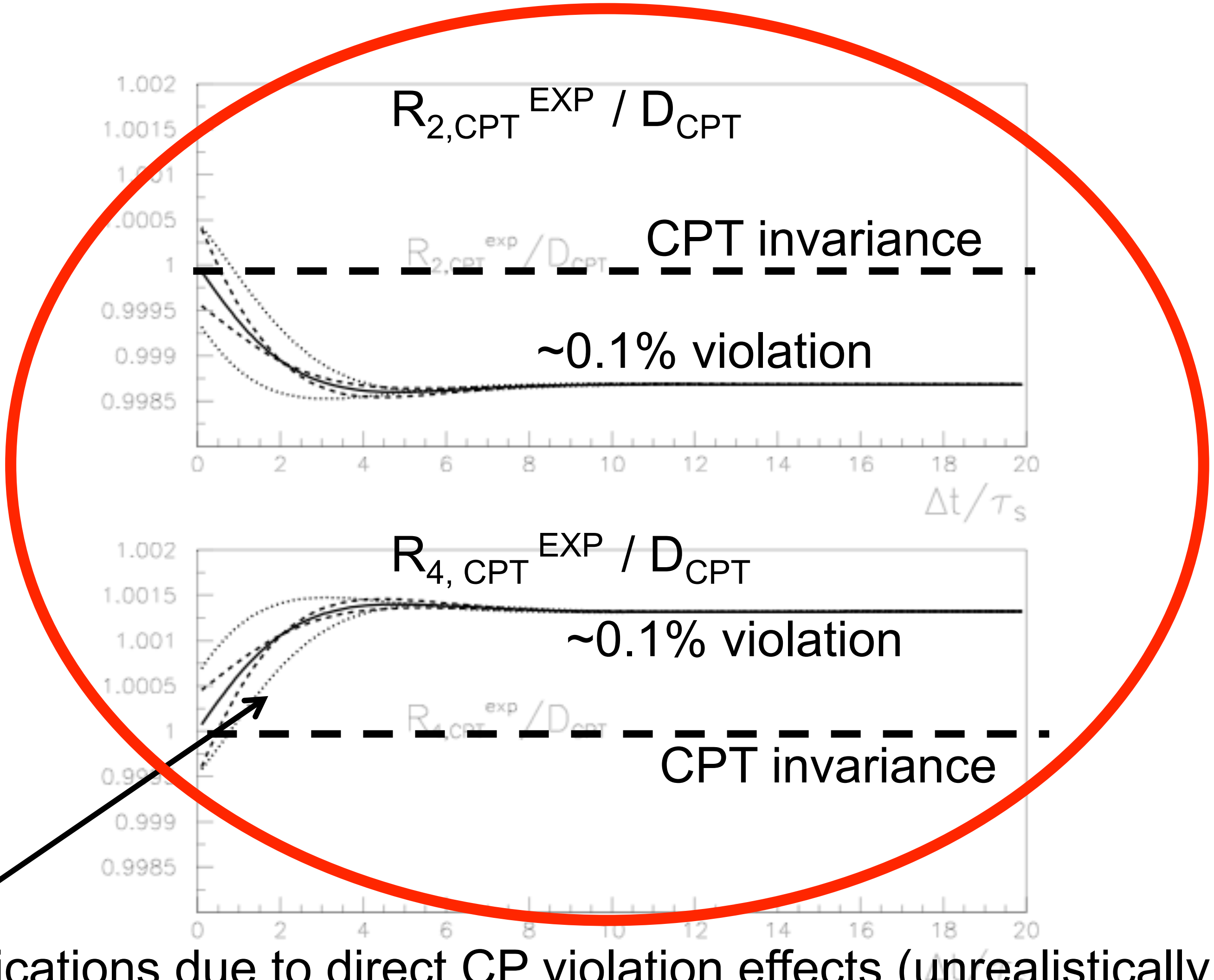
for visualization purposes, plots with
Re(δ)=3.3 $10^{-4}$ Im(δ)=1.6 $10^{-5}$




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

# Direct test of CPT symmetry with neutral kaons

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

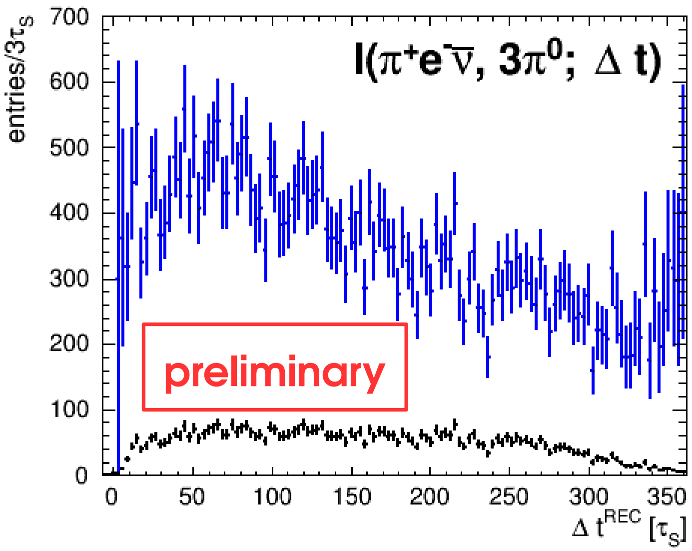


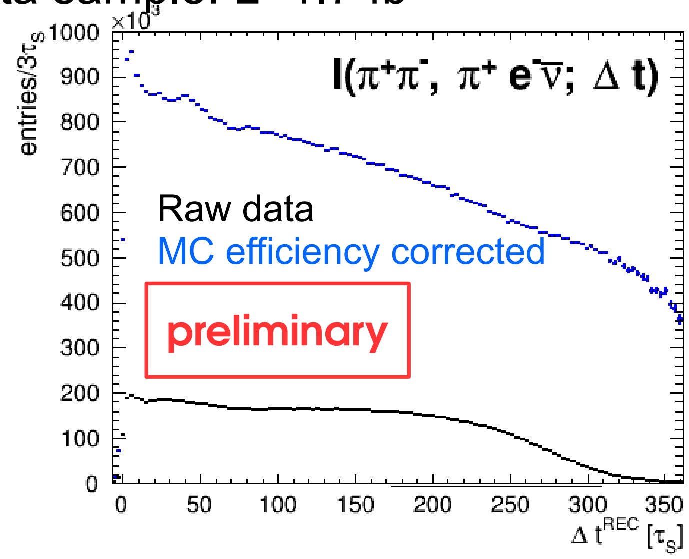

measurable
at KLOE/KLOE-2

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

# Direct test of CPT in neutral kaon transitions

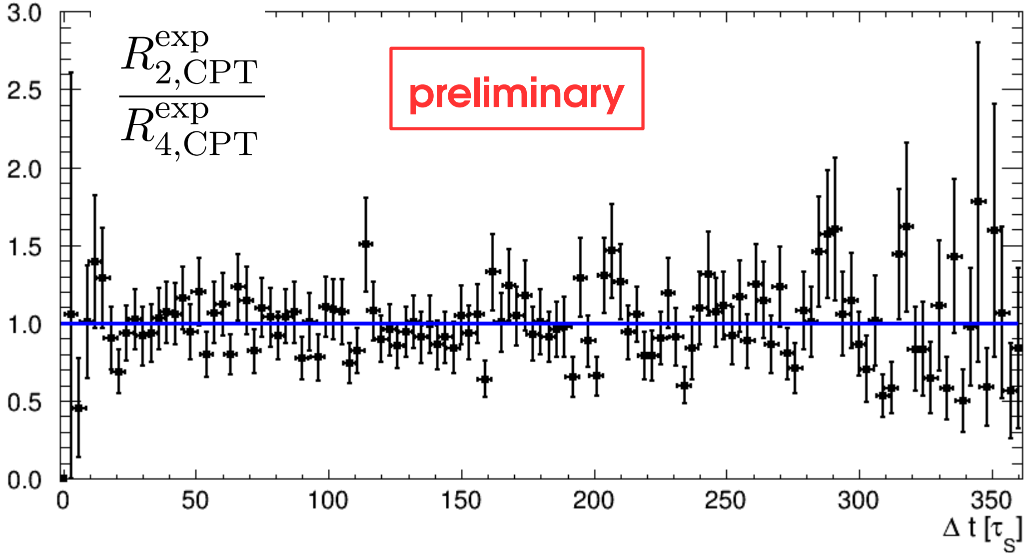
KLOE data sample: L=1.7 fb$^{-1}$




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

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




⬅ $R_2/R_4=1$

CPT test with the double ratio $DR_{CPT}$:

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

- $K_L \to 3\pi^0$ 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 $R_2/R_4$

# $K_S$ semileptonic charge asymmetry

$K_S$ and $K_L$ semileptonic charge asymmetry

T CPT viol. in mixing

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

CPTV in $\Delta S=\Delta Q$ $\Delta S\neq\Delta Q$ decays

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

$A_S\neq A_L$ signals CPT violation

$$\mathbf{A_L = (\,3.322 \pm 0.058 \pm 0.047\,) \times 10^{-3}}$$

KTEV PRL88,181601(2002)

$$\mathbf{A_S = (\,1.5 \pm 9.6 \pm 2.9\,) \times 10^{-3}}$$

KLOE PLB 636(2006) 173

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

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

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

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

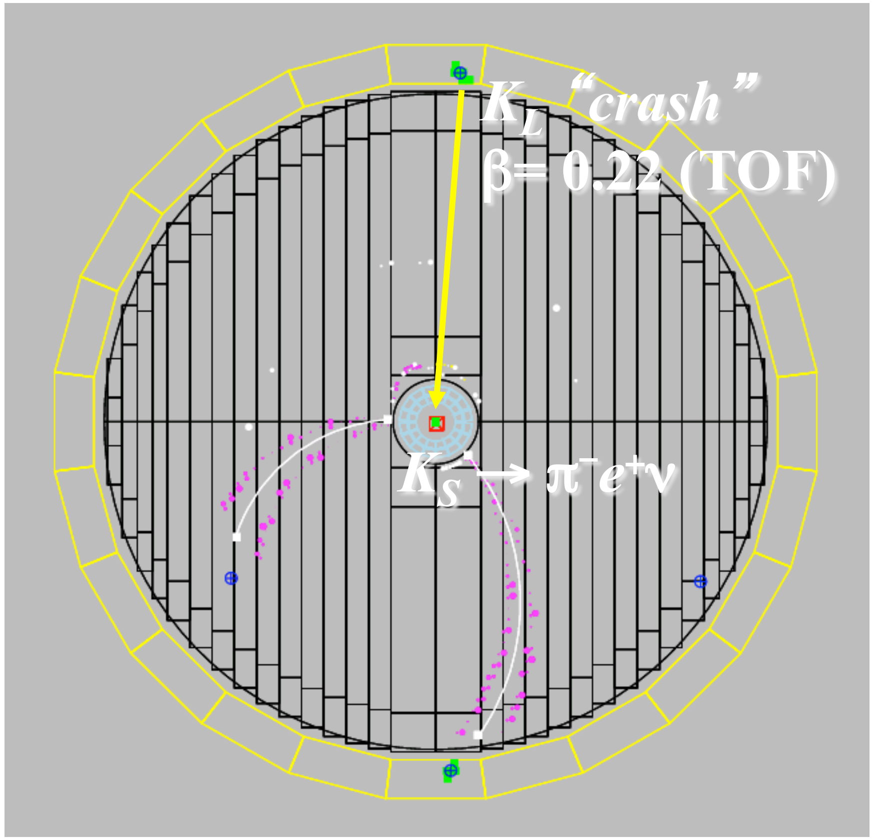
**CPT viol.**

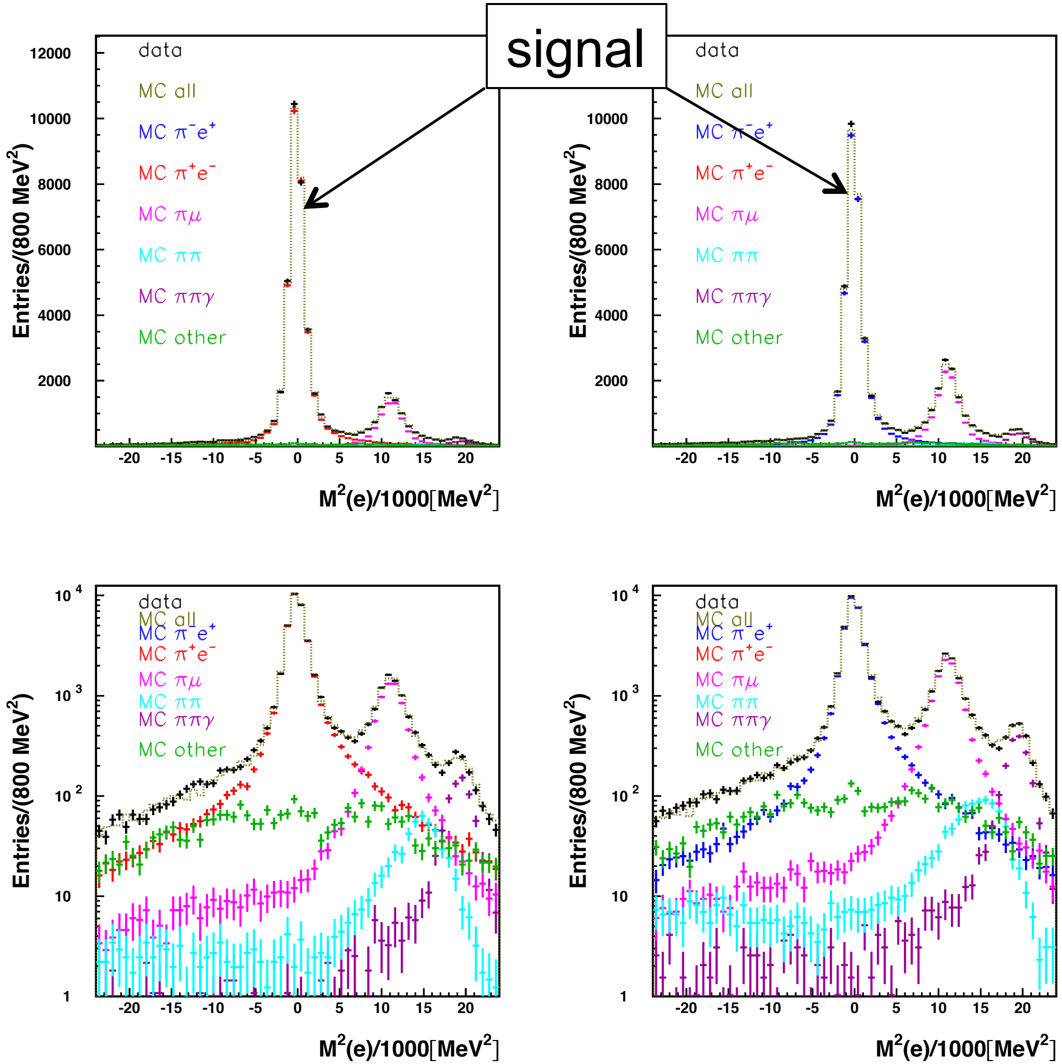
**input from other experiments**

KLOE PLB 636(2006) 173

# $K_S$ semileptonic charge asymmetry at KLOE

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



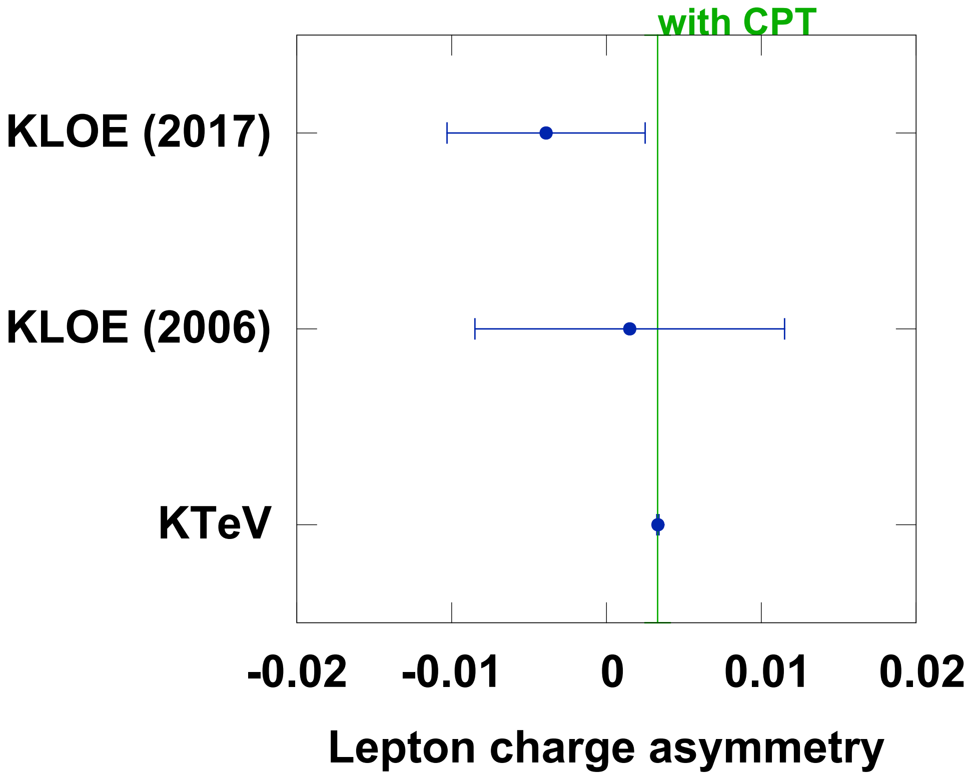




***$K_S$* tagged by *$K_L$* interaction in EmC (fapp)**

Efficiency ~ 30% (largely geometrical)

Fit of $M^2(e)$ distribution

# $K_S$ semileptonic charge asymmetry at KLOE




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

preliminary

**KLOE (2017)**

Presented at EPS 2017, Venice

$$A_S = ( -3.9 \pm 5.7 \,^{+3.3}_{-2.4} ) \times 10^{-3}$$

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

with KLOE-2 data: $\delta A_S$(stat) → ~ $3\times10^{-3}$

preliminary

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = ( -2.1 \pm 1.6) \times 10^{-3}$$ **CPT & ΔS=ΔQ viol.**

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = ( 1.8 \pm 1.6) \times 10^{-3}$$ **CPT viol.**

**input from other experiments**

# Conclusions

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

- It is possible to directly test CPT in transition processes for the first time between neutral kaon states. The proposed CPT test is model independent and fully robust.
- VERY CLEAN TEST. Possible spurious effects are well under control.
- Genuine test not depends on $\Delta\Gamma$ (the decay is not as an essential ingredient).
- Maximal entanglement of the initial state is assumed (impact of possible loss of coherence under evaluation; however marginal for precision of $DR_{CPT}$ of $O(10^{-3})$ ).

- KLOE data analysis ongoing; KLOE-2 could reach a statistical sensitivity of $O(10^{-3})$ on these new observables.
- New preliminary measurement of the KS semileptonic charge asymmetry
- 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 tests of discrete symmetries and QM are expected to be improved at KLOE-2.

Spare slides

# 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($\varepsilon'/\varepsilon$) (lattice calc. improved)
- CKM Vus:
  $K_S$ semileptonic decays and $A_S$ (also CP and CPT test)
  $K\mu 3$ form factors, Kl3 radiative corrections
- $\chi$pT : $K_S \to \gamma\gamma$
- Search for rare $K_S$ decays

**Hadronic cross section**

- Measurement of $a_\mu^{HLO}$ in the space-like region using Bhabha process
- ISR studies with $3\pi$, $4\pi$ final states
- $F_\pi$ 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:**

- $\eta$ decays, $\omega$ 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 $\eta \to \pi^+\pi^- e^+e^-$
- $\chi$pT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $\phi \to K_S K_S \gamma$
- $\gamma\gamma$ Physics: $\gamma\gamma \to \pi^0$ and $\pi^0$ TFF
- light-by-light scattering
- axion-like particles

# Direct test of Time Reversal symmetry with neutral kaons

## T symmetry test

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

One can define the following ratios of probabilities:

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

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

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

# Direct test of Time Reversal symmetry with neutral kaons

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:

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

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

# Impact of the approximations

In general $K_+$ and $K_-$ (and K0 and <u>K0)</u> 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:

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

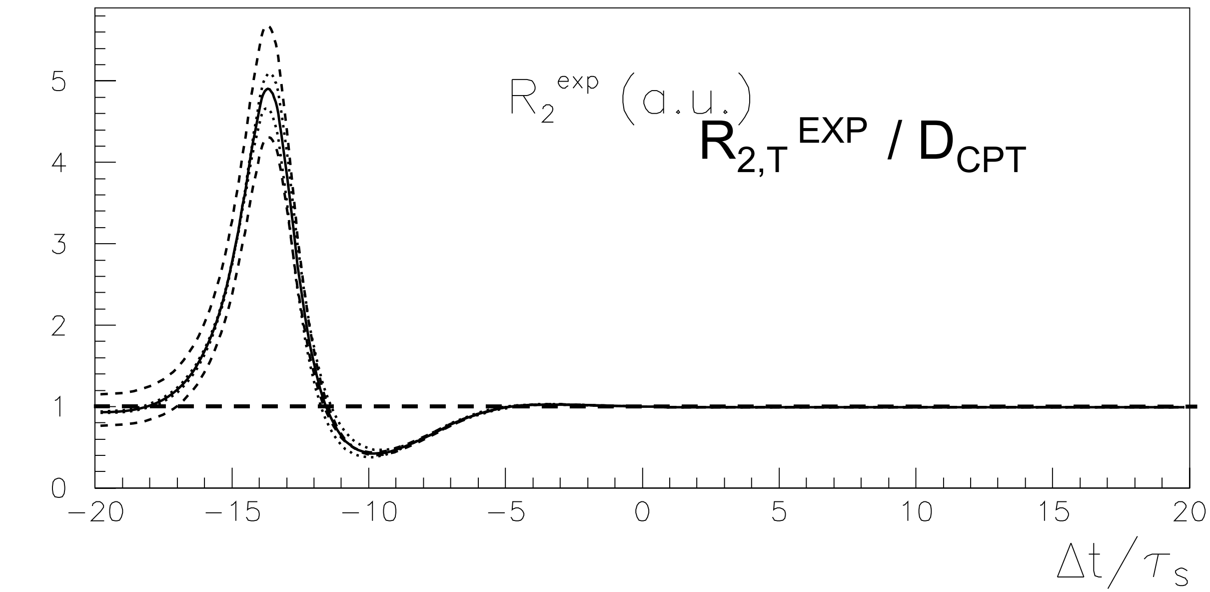
$$= (1 - 4\Re\epsilon + 4\Re x_+ + 4\Re y) \left|1 + \left(2\epsilon + \epsilon'_{3\pi^0} + \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\mathcal{CPT}}$$

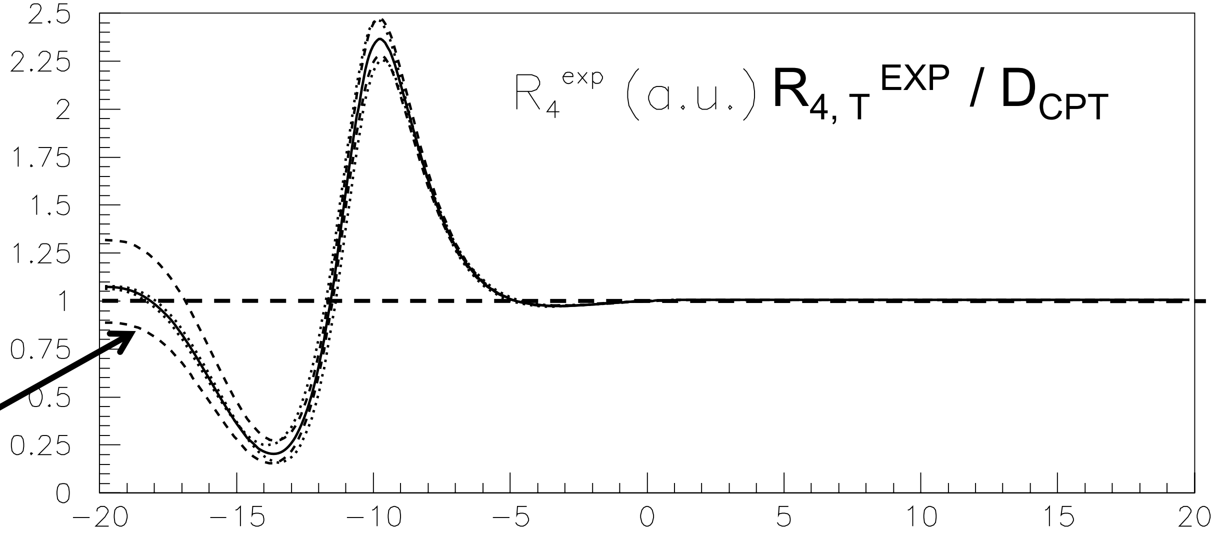
$$R^{\rm exp}_{4,\mathcal{T}}(\Delta t) = \frac{P[\widetilde{\mathrm{K}}_{\bar{0}}(0) \to \mathrm{K}_-(\Delta t)]}{P[\widetilde{\mathrm{K}}_-(0) \to \mathrm{K}_{\bar{0}}(\Delta t)]} \times D_{\mathcal{T},4}$$

$$= (1 + 4\Re\epsilon + 4\Re x_+ - 4\Re y) \left|1 - \left(2\epsilon + \epsilon'_{3\pi^0} + \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\mathcal{CPT}}$$

# Direct test of Time Reversal symmetry with neutral kaons

plots with CPV
Reε and Imε
values




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

# Direct test of Time Reversal symmetry with neutral kaons

plots with CPV
Reε and Imε
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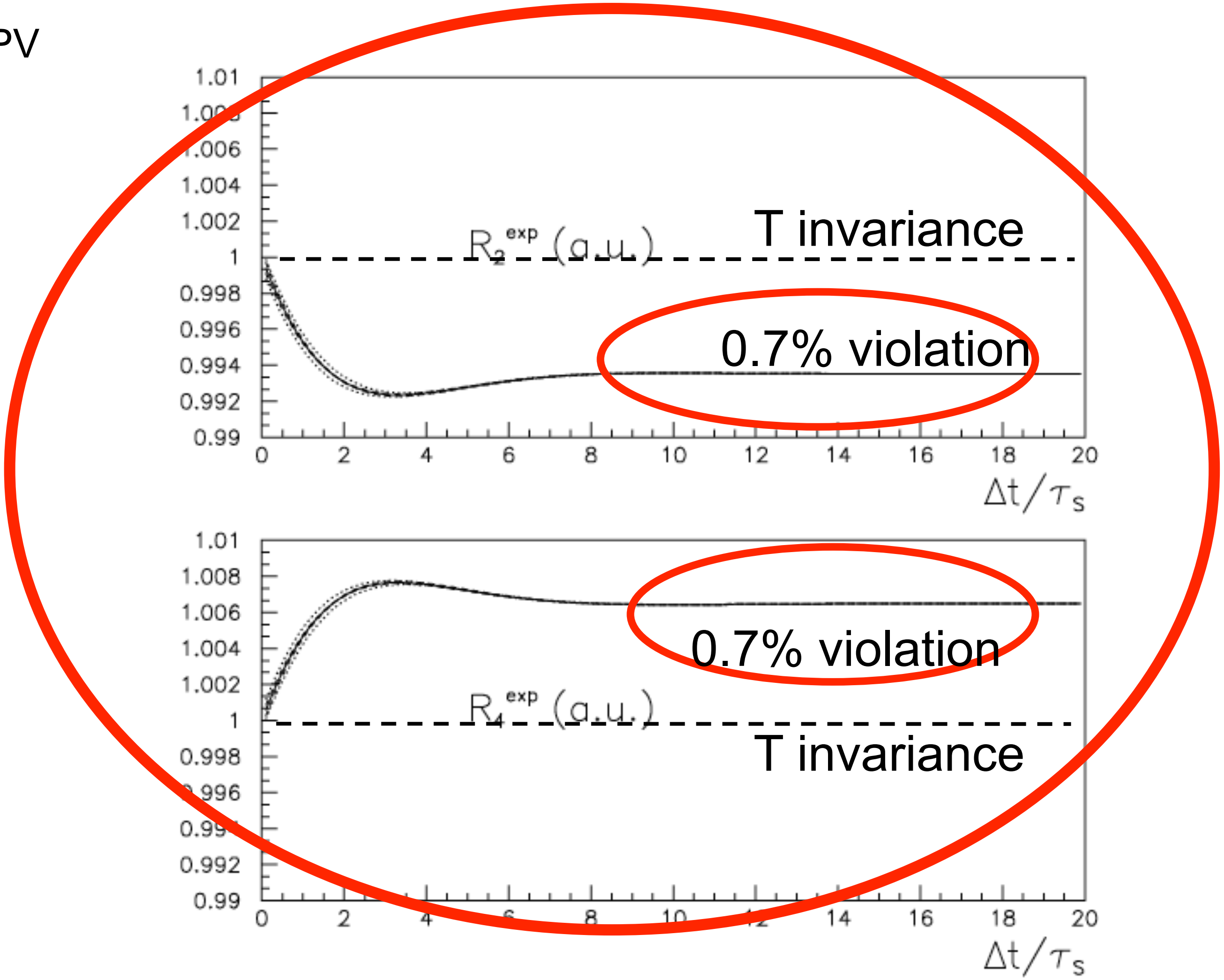


measurable
at KLOE-2

$R_2(\Delta t >> \tau_S) = 1 - 4Re(\varepsilon) \sim 0.993$
$R_4(\Delta t >> \tau_S) = 1 + 4Re(\varepsilon) \sim 1.007$