Precision tests of CPT symmetry with entangled neutral K mesons in the search for quantum gravity effects

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CPT: introduction

The three discrete symmetries of QM, C (charge conjugation: \( q \to -q \)), P (parity: \( x \to -x \)), and T (time reversal: \( t \to -t \)) 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)
- G. Lüders (1954)
- W. Pauli (1952)
- 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

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Intuitive justification of CPT symmetry [1]:
For an even-dimensional space => reflection of all axes is equivalent to a rotation e.g. in 2-dim. space: reflection of 2 axes = rotation of π around the origin

In 4-dimensional pseudo-euclidean space-time PT reflection is NOT equivalent to a rotation. Time coordinate is not exactly equivalent to space coordinate. Charge conjugation is also needed to change sign to e.g. 4-vector current j_µ. (or axial 4-v).

CPT (and not PT) is equivalent to a rotation in the 4-dimensional space-time

CPT: introduction

Extension of CPT theorem to a theory of quantum gravity far from obvious. (e.g. CPT violation appears in several QG models)

huge effort in the last decades to study and shed light on QG phenomenology

⇒ Phenomenological CPTV parameters to be constrained by experiments

Consequences of CPT symmetry: equality of masses, lifetimes, $|q|$ and $|\mu|$ 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

$$\frac{|m_{K^0} - m_{\bar{K}^0}|}{m_K} < 10^{-18}$$

neutral B system

$$\frac{|m_{B^0} - m_{\bar{B}^0}|}{m_B} < 10^{-14}$$

proton- anti-proton

$$\frac{|m_p - m_{\bar{p}}|}{m_p} < 10^{-8}$$

Other interesting CPT tests: e.g. the study of anti-hydrogen atoms, etc..
The neutral kaon: a two-level quantum system

Since the first observation of a $K^0$ ($\nu$-particle) in 1947, several phenomena observed and several tests performed:

- strangeness oscillations
- regeneration
- CP violation
- Direct CP violation
- precise CPT tests
- ...

One of the most intriguing physical systems in Nature.

T. D. Lee

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.

Lev B. Okun
The neutral kaon system: introduction

The time evolution of a two-component state vector \( |\Psi\rangle = a |K^0\rangle + b |\bar{K}^0\rangle \) in the \( \{ K^0, \bar{K}^0 \} \) space is given by (Wigner-Weisskopf approximation):

\[
i \frac{\partial}{\partial t} \Psi(t) = H \Psi(t)
\]

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

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

Diagonalizing the effective Hamiltonian:

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

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

\( \tau_S \sim 90 \text{ ps} \quad \tau_L \sim 51 \text{ ns} \)

\( K_L \rightarrow \pi\pi \) violates CP

\[
\langle K_S | K_L \rangle \approx \epsilon_S^* + \epsilon_L \neq 0 \quad \text{small CP impurity} \sim 2 \times 10^{-3}
\]

|\( K_{1,2} \rangle \) are CP=\pm1 states
CPT violation: standard picture

**CP violation:**

\[ \varepsilon_{S,L} = \varepsilon \pm \delta \]

**T violation:**

\[ \varepsilon = \frac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)} = \frac{-i\Im M_{12} - \Im \Gamma_{12}}{2} / 2 \]

**CPT violation:**

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

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

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

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

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

\[ \Delta \Gamma \approx \Gamma_S \approx 2\Delta m = 7 \times 10^{-15} \text{ GeV} \]
CPT violation: standard picture

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

CPT violation:
\[ \delta = \frac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)} = \frac{1}{2} \left( \frac{m_{K^0} - m_{K^0}}{m_{\bar{K}}^0 - m_K^0} \right) - \frac{(i/2)}{} \left( \frac{\Gamma_{K^0} - \Gamma_{K^0}}{\Gamma_{\bar{K}}^0 - \Gamma_K^0} \right) \]
\[ \Delta m + i \Delta \Gamma / 2 \]

- \( \delta \neq 0 \) implies CPT violation
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\( \Delta m = m_L - m_S \), \( \Delta \Gamma = \Gamma_S - \Gamma_L \)

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(with a phase convention \( \Im \Gamma_{12} = 0 \))
## neutral kaons vs other oscillating meson systems

<table>
<thead>
<tr>
<th></th>
<th>$\langle m \rangle$ (GeV)</th>
<th>$\Delta m$ (GeV)</th>
<th>$\langle \Gamma \rangle$ (GeV)</th>
<th>$\Delta \Gamma/2$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0$</td>
<td>0.5</td>
<td>$3 \times 10^{-15}$</td>
<td>$3 \times 10^{-15}$</td>
<td>$3 \times 10^{-15}$</td>
</tr>
<tr>
<td>$D^0$</td>
<td>1.9</td>
<td>$6 \times 10^{-15}$</td>
<td>$2 \times 10^{-12}$</td>
<td>$1 \times 10^{-14}$</td>
</tr>
<tr>
<td>$B^0_d$</td>
<td>5.3</td>
<td>$3 \times 10^{-13}$</td>
<td>$4 \times 10^{-13}$</td>
<td>$O(10^{-15})$ (SM prediction)</td>
</tr>
<tr>
<td>$B^0_s$</td>
<td>5.4</td>
<td>$1 \times 10^{-11}$</td>
<td>$4 \times 10^{-13}$</td>
<td>$3 \times 10^{-14}$</td>
</tr>
</tbody>
</table>
“Standard” CPT tests
Neutral kaons at CPLEAR (CERN)

Pure initial $K^0, \bar{K}^0$ are produced from antiproton annihilation at rest with a hydrogen target

$$\left(p + \bar{p}\right)_{\text{REST}} \rightarrow K^0 + K^- + \pi^+$$

$$\left(p + \bar{p}\right)_{\text{REST}} \rightarrow \bar{K}^0 + K^+ + \pi^-$$

$$\left(p + \bar{p}\right)_{\text{REST}} \rightarrow K^0 + \bar{K}^0$$

$P_K \sim 500$ MeV

The detection of a charged kaon tags the strangeness of the accompanying neutral kaon
CPT test at CPLEAR

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

\[
\mathcal{A}_e\exp = \begin{cases} 
0.1 \\
0.08 \\
0.06 \\
0.04 \\
0.02 \\
0.0 \\
-0.02 \\
-0.04 \\
-0.06 \\
-0.1 
\end{cases}
\]

Neutral–kaon decay time \([\tau_b]\)

\[\mathcal{R}\delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3}\]

\[
A_\delta(\tau >> \tau_S) = 8\mathcal{R}\delta
\]

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The Bell-Steinberger relationship

J. Bell (1965)  J. Steinberger

Unitarity constraint:

\[ |K\rangle = a_S |K_S\rangle + a_L |K_L\rangle \]

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

yields two trivial relations:

\[ \Gamma_{S,L} = \sum_f \langle f | T | K_{S,L} \rangle^2 \]

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

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

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

All observables quantities
"Standard" CPT test

measuring the time evolution of a neutral kaon beam into semileptonic decays:

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

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using the unitarity constraint (Bell-Steinberger relation)

\[ \Im \delta = (-0.7 \pm 1.4) \times 10^{-5} \]

PDG fit (2014)

\[ \delta = \frac{1}{2} \left( \frac{m_{\bar{K}^0} - m_{K^0}}{\Delta m + i \Delta \Gamma/2} \right) \left( \frac{\Gamma_{K^0} - \Gamma_{\bar{K}^0}}{10^{-18} \text{GeV}} \right)^{10} \]

Combining Re\(\delta\) and Im\(\delta\) results

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

\[ \left| m_{\bar{K}^0} - m_{K^0} \right| < 4.0 \times 10^{-19} \text{ GeV} \]

at 95% c.l.
Entangled neutral kaon pairs
Neutral kaons at a $\phi$-factory

Production of the vector meson $\phi$ in $e^+e^-$ annihilations:

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

\[
p_K = 110 \text{ MeV/c} \\
\lambda_S = 6 \text{ mm} \quad \lambda_L = 3.5 \text{ m}
\]
The KLOE detector at the Frascati φ-factory DAFNE

Integrated luminosity (KLOE)

\[ \int L \, dt \sim 2.5 \text{ fb}^{-1} \]

Total KLOE \( \int L \, dt \sim 2.5 \times 10^9 K_S K_L \) pairs
The KLOE detector at the Frascati $\phi$-factory DAFNE

**DAFNE collider**

**Integrated luminosity (KLOE)**

Integrated luminosity $\int \mathcal{L} \, dt$ for KLOE:
- 2005: 1256 pb$^{-1}$
- 2004: 734 pb$^{-1}$
- 2002: 320 pb$^{-1}$
- 2001: 172 pb$^{-1}$

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**

- DAFNE collider
- KLOE detector
- Lead/scintillating fiber calorimeter
- Drift chamber
- 4 m diameter \times 3.3 m length
- Helium based gas mixture
Test of Quantum Coherence
EPR correlations in entangled neutral kaon pairs from $\phi$

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

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

EPR correlation:
no simultaneous decays ($\Delta t=0$) in the same final state due to the fully destructive quantum interference
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$\Delta t = |t_1 - t_2|$
$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- :$ test of quantum coherence

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

$$I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[ \left| \langle \pi^+ \pi^- , \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^- , \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 + 2\Re \left( \langle \pi^+ \pi^- , \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^- , \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right) \right]$$
\[ \phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^- : \text{test of quantum coherence} \]

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\left. - (1 - \xi_{00}) \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) \right] \]
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Decoherence parameter:

\( \xi_{00} = 0 \quad \rightarrow \quad \text{QM} \)

\( \xi_{00} = 1 \quad \rightarrow \quad \text{total decoherence} \)

(also known as Furry's hypothesis or spontaneous factorization)

[W.Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)
\( \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{test of quantum coherence} \)

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\]

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

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

Decoherence parameter:

\( \xi_{0\bar{0}} = 0 \quad \rightarrow \quad \text{QM} \)

\( \xi_{0\bar{0}} > 0 \quad \rightarrow \quad \text{total decoherence} \)

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Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

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\[ \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{test of quantum coherence} \]

- Analysed data: \( L = 1.5 \text{ fb}^{-1} \)
- Fit including \( \Delta t \) resolution and efficiency effects + regeneration

**KLOE result:**

\[ \xi_{00} = \left( 1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}} \right) \times 10^{-7} \]

Observable suppressed by CP violation: \( \left| \eta_{+-} \right|^2 \sim \left| \varepsilon \right|^2 \sim 10^{-6} \)

\[ \Rightarrow \text{terms } \xi_{00}/\left| \eta_{+-} \right|^2 \Rightarrow \text{high sensitivity to } \xi_{00} \]

From CPLEAR data, Bertlmann et al. (PR D60 (1999) 114032) obtain:

\[ \xi_{00} = 0.4 \pm 0.7 \]

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

\[ \xi_{00}^B = 0.029 \pm 0.057 \]
\( \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \) test of quantum coherence

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Best precision achievable in an entangled system
\( \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{test of quantum coherence} \)

- Analysed data: \( L = 1.5 \text{ fb}^{-1} \)
- Fit including \( \Delta t \) resolution and efficiency effects + regeneration

**KLOE result:**

\[
\xi_{00}^- = \left( 1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}} \right) \times 10^{-7}
\]

Observable suppressed by CP violation: \( |\eta_+|^2 \sim |\xi|^2 \sim 10^{-6} \)
=> terms \( \xi_{00}^- |\eta_+|^2 \) => high sensitivity to \( \xi \)

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**Best precision achievable in an entangled system**

---

**FIG. 2. Bell inequalities test.** The selected state is \( |\Phi^-\rangle = (1/\sqrt{2})(|H_1,H_2\rangle - |V_1,V_2\rangle) \)
Search for decoherence and CPT violation effects
Decoherence and CPT violation

Possible decoherence due quantum gravity effects (BH evaporation) (apparent loss of unitarity):

**Black hole information loss paradox** =>
Possible decoherence near a black hole.

(“like candy rolling on the tongue” by J. Wheeler)

Hawking [1] suggested that at a microscopic level, in a quantum gravity picture, non-trivial space-time fluctuations (generically space-time foam) could give rise to decoherence effects, **which would necessarily entail a violation of CPT** [2].

Modified Liouville – von Neumann equation for the density matrix of the kaon system with 3 new CPTV parameters $\alpha, \beta, \gamma$ [3]:

$$\dot{\rho}(t) = -iH\rho + i\rho H^+ + \text{QM} L(\rho; \alpha, \beta, \gamma)$$

extra term inducing decoherence:
pure state => mixed state

Decoherence and CPT violation

Possible decoherence due to quantum gravity effects (BH evaporation) (apparent loss of unitarity):

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Modified Liouville – von Neumann equation for the density matrix of the kaon system with 3 new CPTV parameters \( \alpha, \beta, \gamma \) [3]:

\[ \alpha, \beta, \gamma = O\left(\frac{M_K^2}{M_{PLANCK}}\right) \approx 2 \times 10^{-20} \text{ GeV} \]

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- :$ decoherence and CPT violation

Study of time evolution of **single kaons**
decaying in $\pi^+\pi^-$ and semileptonic final state

**CPLEAR PLB 364, 239 (1999)**

\[ \alpha = (-0.5 \pm 2.8) \times 10^{-17} \text{ GeV} \]
\[ \beta = (2.5 \pm 2.3) \times 10^{-19} \text{ GeV} \]
\[ \gamma = (1.1 \pm 2.5) \times 10^{-21} \text{ GeV} \]

In the complete positivity hypothesis
\[ \alpha = \gamma , \quad \beta = 0 \]
=> only one independent parameter: $\gamma$

The fit with $I(\pi^+\pi^-; \pi^+\pi^-; \Delta t, \gamma)$ gives:
**KLOE result** \[ L = 1.5 \text{ fb}^{-1} \]

\[ \gamma = (0.7 \pm 1.2_{\text{STAT}} \pm 0.3_{\text{Syst}}) \times 10^{-21} \text{ GeV} \]

**PLB 642(2006) 315**

**Found. Phys. 40 (2010) 852**
\[ \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{CPT violation in entangled K states} \]

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator “ill-defined”) the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:


\[
|i\rangle \propto \left( |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right) + \omega \left( |K^0\rangle |\bar{K}^0\rangle + |\bar{K}^0\rangle |K^0\rangle \right) \\
\propto \left( |K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle \right) + \omega \left( |K_S\rangle |K_S\rangle - |K_L\rangle |K_L\rangle \right)
\]

at most one expects:

\[ |\omega|^2 = O \left( \frac{E^2 / M_{\text{PLANCK}}}{\Delta \Gamma} \right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3} \]

In some microscopic models of space-time foam arising from non-critical string theory:

[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]  \[ |\omega| \sim 10^{-4} \div 10^{-5} \]

The maximum sensitivity to \( \omega \) is expected for \( f_1 = f_2 = \pi^+ \pi^- \)

All CPTV effects induced by QG (\( \alpha, \beta, \gamma, \omega \)) could be simultaneously disentangled.
\[ \phi \to K_S K_L \to \pi^+ \pi^- \pi^+ \pi^- : \text{CPT violation in entangled K states} \]

Fit of \( I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \omega) \): 

- Analysed data: 1.5 fb\(^{-1}\)

**KLOE result:**

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

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

\[|\omega| < 1.0 \times 10^{-3} \text{ at 95\% C.L.} \]

In the B system [Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

\[ -0.0084 \leq \Re \omega \leq 0.0100 \text{ at 95\% C.L.} \]
CPT symmetry and Lorentz invariance test
CPT and Lorentz invariance violation (SME)

- CPT theorem:
  Exact CPT invariance holds for any quantum field theory which assumes:
  1. Lorentz invariance
  2. Locality
  3. Unitarity (i.e. conservation of probability).
- “Anti-CPT theorem” (Greenberger 2002):
  Any unitary, local, point-particle quantum field theory that violates CPT invariance necessarily violates Lorentz invariance.

- Kostelecky et al. developed a phenomenological effective model providing a framework for CPT and Lorentz violations, based on spontaneous breaking of CPT and Lorentz symmetry, which might happen in quantum gravity (e.g. in some models of string theory).

**Standard Model Extension (SME)** [Kostelecky PRD61, 016002, PRD64, 076001]

**CPT violation in neutral kaons according to SME:**
- At first order CPTV appears only in mixing parameter $\delta$ (no direct CPTV in decay).
- $\delta$ cannot be a constant (momentum dependence).

$$\epsilon_{S,L} = \epsilon \pm \delta$$

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

where $\Delta a_\mu = a_\mu q_2 - a_\mu q_1$ are four parameters associated to SME lagrangian terms $-a_\mu \bar{q} \gamma^\mu q$ for the valence quarks and related to CPT and Lorentz violation.
The Earth as a moving laboratory

FIG. 1: Standard Sun-centered inertial reference frame [9].
Search for CPT and Lorentz invariance violation (SME)

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

\(\delta\) depends on sidereal time \(t\) since laboratory frame rotates with Earth.
For a \(\phi\)-factory there is an additional dependence on the polar and azimuthal angle \(\theta, \phi\) of the kaon momentum in the laboratory frame:

\[
\delta(\vec{p}, t) = \frac{i \sin \phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \left\{ \Delta a_0 + \beta_K \Delta a_z (\cos \theta \cos \chi - \sin \theta \sin \phi \sin \chi) \\
+ \beta_K \left[ -\Delta a_x \sin \theta \sin \phi + \Delta a_y (\cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi) \right] \sin \Omega t \\
+ \beta_K \left[ +\Delta a_y \sin \theta \sin \phi + \Delta a_x (\cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi) \right] \cos \Omega t \right\}
\]

\(\Omega\): Earth’s sidereal frequency \(\chi\): angle between the z lab. axis and the Earth’s rotation axis

\(\sin \Omega t\), \(\cos \Omega t\): oscillating terms related to Earth’s rotation.
Search for CPT and Lorentz invariance violation (SME)

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

\(\delta\) depends on sidereal time \(t\) since laboratory frame rotates with Earth.
For a \(\phi\)-factory there is an additional dependence on the polar and azimuthal angle \(\theta, \phi\) of the kaon momentum in the laboratory frame:

\[
\delta(\vec{p},t) = \frac{i \sin \phi_{SW} e^{i \phi_{SW}}}{\Delta m} \gamma_K \left\{ \Delta a_0 + \beta_K \Delta a_Z \left( \cos \theta \cos \chi - \sin \theta \sin \phi \sin \chi \right) \\
+ \beta_K \left[ -\Delta a_X \sin \theta \sin \phi + \Delta a_Y \left( \cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi \right) \right] \sin \Omega t \\
+ \beta_K \left[ +\Delta a_Y \sin \theta \sin \phi + \Delta a_X \left( \cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi \right) \right] \cos \Omega t \right\}
\]

\(\Omega\): Earth’s sidereal frequency \(\chi\): angle between the \(z\) lab. axis and the Earth’s rotation axis

At DAΦNE K mesons are produced with angular distribution \(dN/d\Omega \propto \sin^2 \theta\)
Search for CPTV and LV: exploiting EPR correlations

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

\[ \eta_i = |\eta_i| e^{i\phi_i} = \frac{\langle f_i | T | K_L \rangle}{\langle f_i | T | K_S \rangle} \]

\[ I(f_1, f_2; \Delta t) \propto \left\{ \eta_1^2 e^{-\Gamma_L \Delta t} + \eta_2^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\} \]

\[ \eta_{++}^{(1)} = \epsilon \left( 1 - \delta \left( +\vec{p}, t \right) / \epsilon \right) \]

\[ \eta_{+-}^{(2)} = \epsilon \left( 1 - \delta \left( -\vec{p}, t \right) / \epsilon \right) \]
Search for CPTV and LV: exploiting EPR correlations

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

\[ \eta_i = |\eta_i|e^{i\phi_i} = \frac{\langle f_i|T|K_L\rangle}{\langle f_i|T|K_S\rangle} \]

\[ I(f_1, f_2; \Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2|e^{-(\Gamma_S + \Gamma_L) \Delta t / 2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\} \]

\[ \eta_{+^-}^{(1)} = \varepsilon (1 - \delta (\vec{p}_2 t)/\varepsilon) \]

\[ \eta_{+^-}^{(2)} = \varepsilon (1 - \delta (\vec{p}_2 t)/\varepsilon) \]
Search for CPTV and LV: exploiting EPR correlations

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

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

$$I(f_1, f_2; \Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1|\eta_2| e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\}$$

$$\eta_{+^-}^{(1)} = \varepsilon \left( 1 - \delta \frac{\vec{p} \cdot \hat{t}}{\varepsilon} \right)$$

$$\eta_{+^-}^{(2)} = \varepsilon \left( 1 - \delta \frac{-\vec{p} \cdot \hat{t}}{\varepsilon} \right)$$

$$\Im (\delta/\varepsilon)$$ from the asymmetry at small $\Delta t$

$$\Re (\delta/\varepsilon) \approx 0$$ because $\delta \perp \varepsilon$

from the asymmetry at large $\Delta t$
Search for CPTV and LV: results

\[ \delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \beta_K \cdot \Delta \tilde{a} \right) / \Delta m \]

Data divided in
4 sidereal time bins x 2 angular bins
Simultaneous fit of the \( \Delta t \) distributions to extract \( \Delta a_{\mu} \) parameters
Search for CPTV and LV: results

\[ \delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_{K} (\Delta a_{0} - \beta_{K} \cdot \Delta \tilde{a}) / \Delta m \]

Data divided in 4 sidereal time bins x 2 angular bins
Simultaneous fit of the \( \Delta t \) distributions to extract \( \Delta a_{\mu} \) parameters

with \( L=1.7 \text{ fb}^{-1} \) KLOE final result

**PLB 730 (2014) 89–94**

\[ \Delta a_{0} = ( -6.0 \pm 7.7_{\text{STAT}} \pm 3.1_{\text{Syst}} ) \times 10^{-18} \text{ GeV} \]
\[ \Delta a_{x} = (0.9 \pm 1.5_{\text{STAT}} \pm 0.6_{\text{Syst}} ) \times 10^{-18} \text{ GeV} \]
\[ \Delta a_{y} = (-2.0 \pm 1.5_{\text{STAT}} \pm 0.5_{\text{Syst}} ) \times 10^{-18} \text{ GeV} \]
\[ \Delta a_{z} = (-3.1 \pm 1.7_{\text{STAT}} \pm 0.6_{\text{Syst}} ) \times 10^{-18} \text{ GeV} \]

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

<table>
<thead>
<tr>
<th>Par</th>
<th>Cut stability</th>
<th>Fit Range</th>
<th>Bkg. subtr</th>
<th>KLOE ref. frame</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta a_{0} )</td>
<td>1.1</td>
<td>2.4</td>
<td>1.3</td>
<td>1.0</td>
<td>3.1</td>
</tr>
<tr>
<td>( \Delta a_{x} )</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>( \Delta a_{y} )</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>( \Delta a_{z} )</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

B meson system:
\( \Delta a_{B,x,y}^{B}, (\Delta a_{B}^{B,0} - 0.30 \Delta a_{B}^{Z} ) \sim O(10^{-13} \text{ GeV}) \)
[Babar PRL 100 (2008) 131802]

D meson system:
\( \Delta a_{D,x,y}^{D}, (\Delta a_{D}^{D,0} - 0.6 \Delta a_{D}^{Z} ) \sim O(10^{-13} \text{ GeV}) \)
[Focus PLB 556 (2003) 7]
Direct CPT symmetry test in neutral kaon transitions
(or a very general and model independent test)
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$

\[
|K_+\rangle = |K_1\rangle \quad (CP = +1) \\
|K_-\rangle = |K_2\rangle \quad (CP = -1)
\]

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

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

- $K^-$ sembra $K$ carico... cambiare o Sottolineare che non e’
Direct test of CPT symmetry in neutral kaon transitions

EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$.

\[ |K_+\rangle = |K_1\rangle \quad (CP = +1) \]
\[ |K_-\rangle = |K_2\rangle \quad (CP = -1) \]

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

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

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

$\pi^+\nu \rightarrow K^0 \phi \rightarrow K^0 K_-$

reference process
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$.

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|K_+\rangle = |K_1\rangle \quad (CP = +1) \\
|K_-\rangle = |K_2\rangle \quad (CP = -1)
\]

\[
|i\rangle = \frac{1}{\sqrt{2}} \left[ |K_0(\bar{p})\rangle |K_0(-\bar{p})\rangle - |\bar{K}_0(\bar{p})\rangle |K_0(-\bar{p})\rangle \right]
\]

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

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

\[
\pi^+\pi^- \rightarrow K_+ \quad K_0 \rightarrow K_- 
\]

\[
\Delta t = t_2 - t_1 
\]

Reference process
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal "CP states" $K_+\!$ and $K_-\!$

$$\left| K_+ \right\rangle = \left| K_1 \right\rangle \quad (CP = +1)$$

$$\left| K_- \right\rangle = \left| K_2 \right\rangle \quad (CP = -1)$$

$$\left| \psi \right\rangle = \frac{1}{\sqrt{2}} \left[ \left| K_+ (\bar{p}) \right\rangle \left| K_0 (\bar{p}) \right\rangle - \left| K_0 (\bar{p}) \right\rangle \left| K_+ (\bar{p}) \right\rangle \right]$$

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

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

Reference process

$$K^0 \rightarrow K_-$$

CPT-conjugated process

$$K_- \rightarrow \bar{K}^0$$
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$

$$|K_+\rangle = |K_1\rangle \quad (CP = +1)$$
$$|K_-\rangle = |K_2\rangle \quad (CP = -1)$$

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

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

- Decay as filtering measurement
- Entanglement -> preparation of state

Note: CP and T conjugated process

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

Reference process

$$K^0 \rightarrow K_-$$

CPT-conjugated process

$$K_- \rightarrow \bar{K}^0$$
## Direct test of CPT symmetry in neutral kaon transitions

### CPT symmetry test

<table>
<thead>
<tr>
<th>Reference</th>
<th>Transition</th>
<th>Decay products</th>
<th>CPT-conjugate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K^0 \to K_+$</td>
<td>$(\ell^-, \pi\pi)$</td>
<td>$K_+ \to \bar{K}^0$</td>
</tr>
<tr>
<td></td>
<td>$K^0 \to K_-$</td>
<td>$(\ell^-, 3\pi^0)$</td>
<td>$K_+ \to \bar{K}^0$</td>
</tr>
<tr>
<td></td>
<td>$\bar{K}^0 \to K_+$</td>
<td>$(\ell^+, \pi\pi)$</td>
<td>$K_+ \to K^0$</td>
</tr>
<tr>
<td></td>
<td>$\bar{K}^0 \to K_-$</td>
<td>$(\ell^+, 3\pi^0)$</td>
<td>$K_+ \to K^0$</td>
</tr>
</tbody>
</table>

One can define the following ratios of probabilities:

\[
R_{1,\text{CPT}}(\Delta t) = \frac{P[\bar{K}^0(0) \to K^0(\Delta t)]}{P[K^0(0) \to \bar{K}^0(\Delta t)]}
\]

\[
R_{2,\text{CPT}}(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \bar{K}^0(\Delta t)]}
\]

\[
R_{3,\text{CPT}}(\Delta t) = \frac{P[K_+(0) \to K^0(\Delta t)]}{P[\bar{K}^0(0) \to K_+(\Delta t)]}
\]

\[
R_{4,\text{CPT}}(\Delta t) = \frac{P[\bar{K}^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K^0(\Delta t)]}
\]

Any deviation from $R_{i,\text{CPT}}=1$ constitutes a violation of CPT-symmetry.
for visualization purposes, plots with Re(δ)=3.3 10^{-4} \; \text{Im}(δ)=1.6 10^{-5} (\ldots \text{Im}(δ)=0 )

\begin{align*}
R_{1,\text{CPT}} & = R_{1,\text{CPT}}(\Delta t) = \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} \\
R_{2,\text{CPT}} & = R_{2,\text{CPT}}(\Delta t) = 1 - 4\text{Re}(δ) \\
R_{3,\text{CPT}} & = R_{3,\text{CPT}}(\Delta t) = 1 + 4\text{Re}(δ) \\
R_{4,\text{CPT}} & = R_{4,\text{CPT}}(\Delta t) = 1 + 4\text{Re}(δ)
\end{align*}
Direct test of CPT symmetry in neutral kaon transitions

For visualization purposes, plots with Re(δ) = 3.3 \times 10^{-4}, Im(δ) = 1.6 \times 10^{-5} (\ldots Im(δ) = 0)

\[ R_1^{CPT} \]

\[ R_2^{CPT} \]

\[ R_3^{CPT} \]

\[ R_4^{CPT} \]

\[ R_{2,CPT}(\Delta t \gg \tau_S) = 1 - 4\text{Re}(\delta) \]

\[ R_{4,CPT}(\Delta t \gg \tau_S) = 1 + 4\text{Re}(\delta) \]

\[ R_{exp}^{CPT}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} \]

\[ R_{exp}^{CPT}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} \]

Measurable at KLOE
Direct test of CPT symmetry in neutral kaon transitions

- It would be possible for the first time to directly test the CPT symmetry in transition processes between meson states, rather than comparing masses, lifetimes, or other intrinsic properties of particle and anti-particle states.

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

- The proposed CPT test is model independent and fully robust. It might shed light on possible new CPT violating mechanisms.

- A preliminary indirect extrapolation based on the KLOE measurements of charge semileptonic asymmetries of $K_S$ and $K_L$ with $L \sim 400$ pb$^{-1}$ yields (deviation from unity is a signal of CPT violation) [A.D.D. in Handbook on kaon interf. Fras. Phys. Ser. 43 (2007)]:

$$\frac{R_{2,CPT}^{\exp}(\Delta t \geq \tau_S)}{R_{4,CPT}^{\exp}(\Delta t \geq \tau_S)} \approx 1 + 2(A_L - A_S) = 1.004 \pm 0.020$$

- KLOE-2 can reach a statistical sensitivity of $O(10^{-3})$

J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139
Future perspectives
KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:
- For the very first time the “crab-waist” concept – an interaction scheme, developed in Frascati, where the transverse dimensions of the beams and their crossing angle are tuned to maximize the machine luminosity – has been applied in presence of a high-field detector solenoid.

KLOE-2 experiment:
- extend the KLOE physics program at DAΦNE upgraded in luminosity
- collect O(10) fb\(^{-1}\) of integrated luminosity in the next 2-3 years

Physics program (see EPJC 68 (2010) 619-681)
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare \(K_S\) decays
- \(\eta,\eta'\) physics
- Light scalars, \(\gamma\gamma\) physics
- Hadron cross section at low energy, \(a_\mu\)
- Dark forces: search for light U boson

Detector upgrade:
- \(\gamma\gamma\) tagging system
- inner tracker
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)
The KLOE detector has been improved with an inner tracker based on an innovative cylindrical GEM technology to improve vertex resolution close to the interaction region, and sensitivity around $\Delta t \sim 0$. 

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

MC

Black: KLOE res.

Red: KLOE + inner tracker resolution

Blue: ideal $\Delta t/\tau_S$
KLOE-2 data taking in progress

Data taking started on Nov. 2014
Integrated Luminosity up to Feb. 2016: \( L \sim 1.9 \text{ fb}^{-1} \)
## Prospects for KLOE-2

<table>
<thead>
<tr>
<th>Param.</th>
<th>Present best published measurement</th>
<th>KLOE-2 (IT) (L=5) fb(^{-1}) (stat.)</th>
<th>KLOE-2 (IT) (L=10) fb(^{-1}) (stat.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\xi_{00})</td>
<td>((0.1 \pm 1.0) \times 10^{-6})</td>
<td>(\pm 0.26 \times 10^{-6})</td>
<td>(\pm 0.18 \times 10^{-6})</td>
</tr>
<tr>
<td>(\xi_{sL})</td>
<td>((0.3 \pm 1.9) \times 10^{-2})</td>
<td>(\pm 0.49 \times 10^{-2})</td>
<td>(\pm 0.35 \times 10^{-2})</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>((-0.5 \pm 2.8) \times 10^{-17}) GeV</td>
<td>(\pm 5.0 \times 10^{-17}) GeV</td>
<td>(\pm 3.5 \times 10^{-17}) GeV</td>
</tr>
<tr>
<td>(\beta)</td>
<td>((2.5 \pm 2.3) \times 10^{-19}) GeV</td>
<td>(\pm 0.50 \times 10^{-19}) GeV</td>
<td>(\pm 0.35 \times 10^{-19}) GeV</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>((1.1 \pm 2.5) \times 10^{-21}) GeV</td>
<td>(\pm 0.75 \times 10^{-21}) GeV</td>
<td>(\pm 0.53 \times 10^{-21}) GeV</td>
</tr>
<tr>
<td></td>
<td>compl. pos. hyp. ((0.7 \pm 1.2) \times 10^{-21}) GeV</td>
<td>compl. pos. hyp. (\pm 0.33 \times 10^{-21}) GeV</td>
<td>compl. pos. hyp. (\pm 0.23 \times 10^{-21}) GeV</td>
</tr>
<tr>
<td>(\text{Re}(\omega))</td>
<td>((-1.6 \pm 2.6) \times 10^{-4})</td>
<td>(\pm 0.70 \times 10^{-4})</td>
<td>(\pm 0.49 \times 10^{-4})</td>
</tr>
<tr>
<td>(\text{Im}(\omega))</td>
<td>((-1.7 \pm 3.4) \times 10^{-4})</td>
<td>(\pm 0.86 \times 10^{-4})</td>
<td>(\pm 0.61 \times 10^{-4})</td>
</tr>
<tr>
<td>(\Delta a_0)</td>
<td>((-6.0 \pm 8.3) \times 10^{-18}) GeV</td>
<td>(\pm 2.2 \times 10^{-18}) GeV</td>
<td>(\pm 1.6 \times 10^{-18}) GeV</td>
</tr>
<tr>
<td>(\Delta a_Z)</td>
<td>((3.1 \pm 1.8) \times 10^{-18}) GeV</td>
<td>(\pm 0.50 \times 10^{-18}) GeV</td>
<td>(\pm 0.35 \times 10^{-18}) GeV</td>
</tr>
<tr>
<td>(\Delta a_X)</td>
<td>((0.9 \pm 1.6) \times 10^{-18}) GeV</td>
<td>(\pm 0.44 \times 10^{-18}) GeV</td>
<td>(\pm 0.31 \times 10^{-18}) GeV</td>
</tr>
<tr>
<td>(\Delta a_Y)</td>
<td>((-2.0 \pm 1.6) \times 10^{-18}) GeV</td>
<td>(\pm 0.44 \times 10^{-18}) GeV</td>
<td>(\pm 0.31 \times 10^{-18}) GeV</td>
</tr>
</tbody>
</table>
Conclusions

• The entangled neutral kaon system at a \( \phi \)-factory is an excellent laboratory for the study of CPT symmetry, discrete symmetries in general, and the basic principles of Quantum Mechanics;

• Several parameters related to possible CPT violation, Decoherence, Decoherence and CPT violation, CPT violation and Lorentz symmetry breaking have been measured at KLOE, in some cases with a precision reaching the interesting Planck’s scale region;

• All results are consistent with no CPT symmetry violation and no decoherence.

• Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program.

• The precision of several tests could be improved by about one order of magnitude, possibly revealing such kind of effects or further pushing their experimental limits.