
Experimental tests of CPT symmetry and quantum mechanics in the neutral kaon system



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CPT: introduction

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

CPT theorem (Luders, Jost, Pauli, Bell 1955 -1957):

Exact CPT invariance holds for any quantum field theory (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.

Extension of CPT theorem to a theory of quantum gravity far from obvious (e.g. CPT violation appears in some models with space-time foam backgrounds).

No predictive theory incorporating CPT violation => only phenomenological models to be constrained by experiments.

The neutral kaon system offers unique possibilities to test CPT invariance e.g. :

$$\left| m_{K^0} - m_{\bar{K}^0} \right| / m_K < 10^{-18}, \quad \left| m_{B^0} - m_{\bar{B}^0} \right| / m_B < 10^{-14}, \quad \left| m_p - m_{\bar{p}} \right| / m_p < 10^{-8}$$

1) “Standard” tests of CPT symmetry in the neutral kaon system

The neutral kaon system

The time evolution of a two-component state vector Ψ in the $\{K^0, \bar{K}^0\}$ space is given by (Wigner-Weisskopf approximation):

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

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

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

Diagonalizing the effective Hamiltonian:

eigenvalues

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

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

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

$$m_L - m_S = 3.5 \times 10^{-15} \text{ GeV} \sim \Gamma_S / 2$$

eigenstates

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

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

$|K_{1,2}\rangle$ are
CP=±1 states

small CP impurity $\sim 2 \times 10^{-3}$

CPT violation in the neutral kaon system: “standard” picture

CPT violation in the mixing:

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

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

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

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

$$m_{11} \equiv m_{K^0} \quad , \quad m_{22} \equiv m_{\bar{K}^0}$$

$$\Gamma_{11} \equiv \Gamma_{K^0} \quad , \quad \Gamma_{22} \equiv \Gamma_{\bar{K}^0}$$

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

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

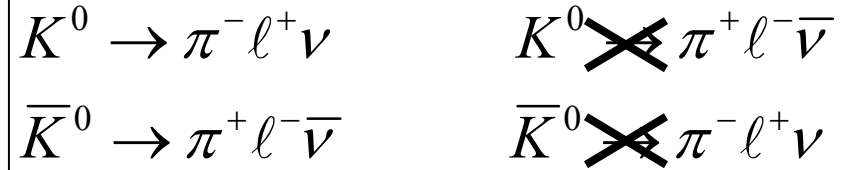
CPT violation in the neutral kaon system: “standard” picture

CPT violation in semileptonic decays

$$\langle \pi^- \ell^+ \nu | T | K^0 \rangle = a + b \quad \langle \pi^+ \ell^- \bar{\nu} | T | K^0 \rangle = c + d$$

$$\langle \pi^+ \ell^- \bar{\nu} | T | \bar{K}^0 \rangle = a^* - b^* \quad \langle \pi^- \ell^+ \nu | T | \bar{K}^0 \rangle = c^* - d^*$$

$\Delta S = \Delta Q$ rule



	CP	T	CPT	$\Delta S = \Delta Q$
a	$\Im = 0$	$\Im = 0$		
b	$\Re = 0$	$\Im = 0$	$= 0$	
c	$\Im = 0$	$\Im = 0$		$= 0$
d	$\Re = 0$	$\Im = 0$	$= 0$	$= 0$

Standard Model prediction of $\Delta S = \Delta Q$ rule violation is $x = c/a \sim O(10^{-7})$

Semileptonic charge asymmetry:

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

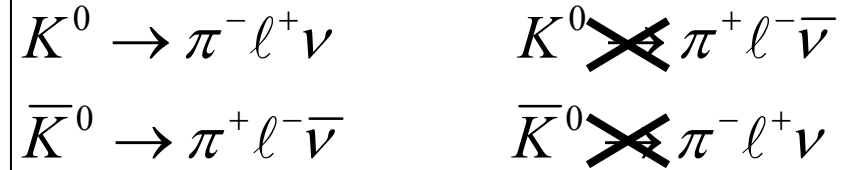
$$A_S - A_L = 4(\Re \delta + \Re x_{-})$$

CPT violation in the neutral kaon system: “standard” picture

CPT violation in semileptonic decays

$$\begin{aligned} \langle \pi^- \ell^+ \nu | T | K^0 \rangle &= a + b & \langle \pi^+ \ell^- \bar{\nu} | T | K^0 \rangle &= c + d \\ \langle \pi^+ \ell^- \bar{\nu} | T | \bar{K}^0 \rangle &= a^* - b^* & \langle \pi^- \ell^+ \nu | T | \bar{K}^0 \rangle &= c^* - d^* \end{aligned}$$

$\Delta S = \Delta Q$ rule



CPT viol.	CPT & $\Delta S = \Delta Q$ viol.	$\Delta S = \Delta Q$ Viol.
$y = -\frac{b}{a}$	$x_- = -\frac{d^*}{a}$	$x_+ = \frac{c^*}{a}$

Standard Model prediction of $\Delta S = \Delta Q$ rule violation is $x = c/a \sim O(10^{-7})$

Semileptonic charge asymmetry:

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

$$A_S - A_L = 4(\Re \delta + \Re x_-)$$

CPT violation in the neutral kaon system: “standard” picture

CPT violation in $\pi\pi$ decays

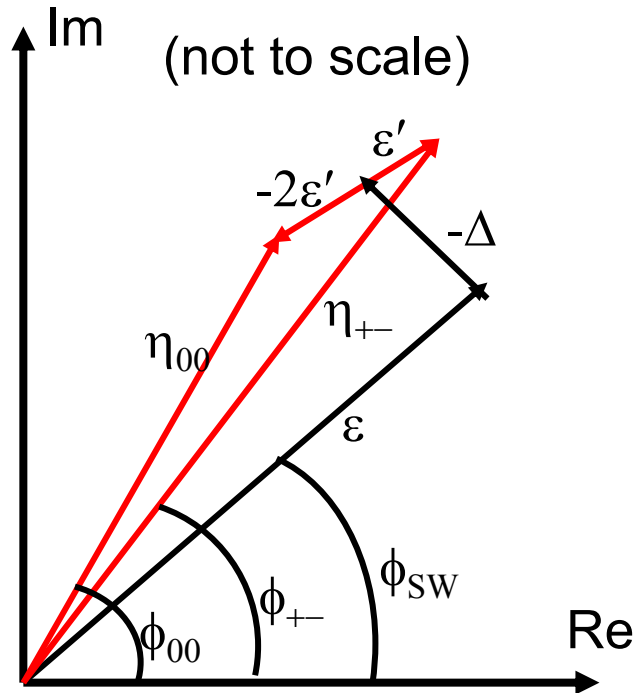
$$\langle \pi\pi; I | T | K^0 \rangle = (A_I + B_I) e^{i\delta_I}$$

$$\langle \pi\pi; I | T | \bar{K}^0 \rangle = (A_I^* - B_I^*) e^{i\delta_I}$$

$A_I(B_I)$ CPT conserving (violating)

$K \rightarrow \pi\pi$ amplitudes for $I=0,2$

(δ_I strong phase shift for $I=0,2$)



$$\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} = \frac{\langle \pi^+ \pi^- | T | K_L \rangle}{\langle \pi^+ \pi^- | T | K_S \rangle} = \varepsilon - \Delta + \varepsilon'$$

$$\eta_{00} = |\eta_{00}| e^{i\phi_{00}} = \frac{\langle \pi^0 \pi^0 | T | K_L \rangle}{\langle \pi^0 \pi^0 | T | K_S \rangle} = \varepsilon - \Delta - 2\varepsilon'$$

$$\Delta = \delta - \frac{\Re B_0}{\Re A_0} \quad \phi_{SW} = \arctan(2\Delta m / \Delta\Gamma)$$

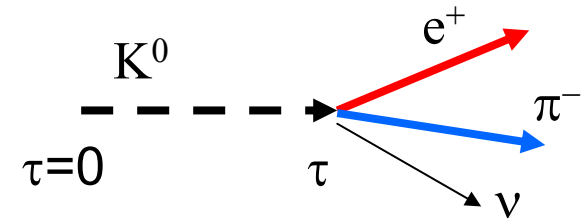
$$\phi_{00} - \phi_{+-} \approx \frac{3}{\sqrt{2}} \frac{1}{|\eta_{+-}|} \frac{\Re A_2}{\Re A_0} \left(\frac{\Re B_2}{\Re A_2} - \frac{\Re B_0}{\Re A_0} \right) \approx -3 \Im \left(\frac{\varepsilon'}{\varepsilon} \right)$$

$$\phi_{+-} - \phi_{SW} \approx \frac{-1}{\sqrt{2} |\eta_{+-}|} \left[\frac{m_{11} - m_{22}}{2\Delta m} + \frac{\Re B_0}{\Re A_0} \right]$$

Some results of CPT tests

Study of the time evolution of neutral kaons in semileptonic decays

CLEAR



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

PLB444 (1998) 52

KTeV

Study of regenerator beam two pion decay distribution

$$\begin{aligned} \phi_{+-} - \phi_{SW} &= 0.61^\circ \pm 0.62^\circ \pm 1.01^\circ \\ \phi_{00} - \phi_{+-} &= 0.39^\circ \pm 0.22^\circ \pm 0.45^\circ \end{aligned}$$

PRL88,
181601(2002)

K_L semileptonic charge asymmetry:

$$A_L = (3322 \pm 58 \pm 47) \times 10^{-6}$$

KTeV

Constraints on CPT violation in $\pi\pi$ and semileptonic decays obtained combining KTeV and PDG results:

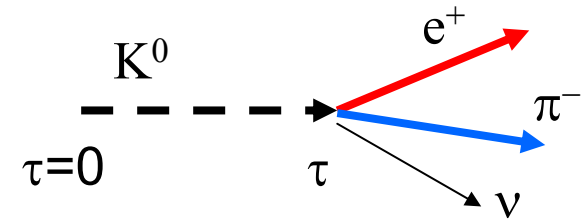
$$\Re\left(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}\right) - \frac{A_L}{2} = \Re\left(y + x_- + \frac{\Re B_0}{\Re A_0}\right) = (-3 \pm 35) \times 10^{-6}$$

PRD67,012005 (2003)

Some results of CPT tests

Study of the time evolution of neutral kaons in semileptonic decays

CLEAR



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

PLB444 (1998) 52

KTeV

Study of regenerator beam two pion decay distribution

$$\begin{aligned} \phi_\varepsilon - \phi_{SW} &= 0.40^\circ \pm 0.56^\circ \\ \phi_{00} - \phi_{+-} &= 0.30^\circ \pm 0.35^\circ \end{aligned}$$

Presented at Moriond08, HQL08

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PRD67,012005 (2003)

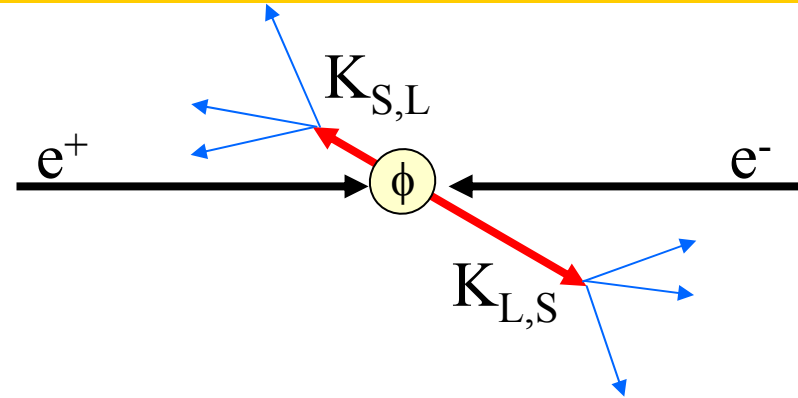
Neutral kaons at a ϕ -factory

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

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

$$\mathbf{p}_K = 110 \text{ MeV}/c$$

$$\lambda_S = 6 \text{ mm} \quad \lambda_L = 3.5 \text{ m}$$



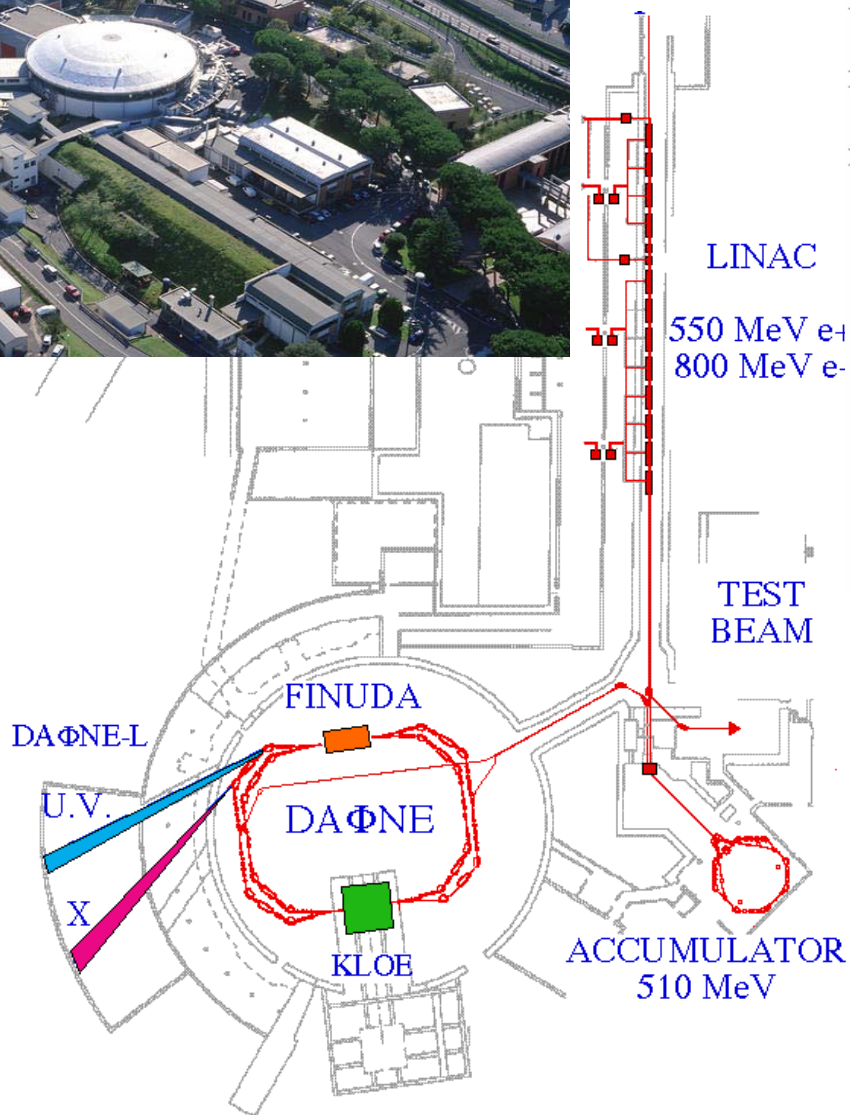
$$|i\rangle = \frac{1}{\sqrt{2}} \left[|K^0(\vec{p})\rangle |\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle |K^0(-\vec{p})\rangle \right]$$

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

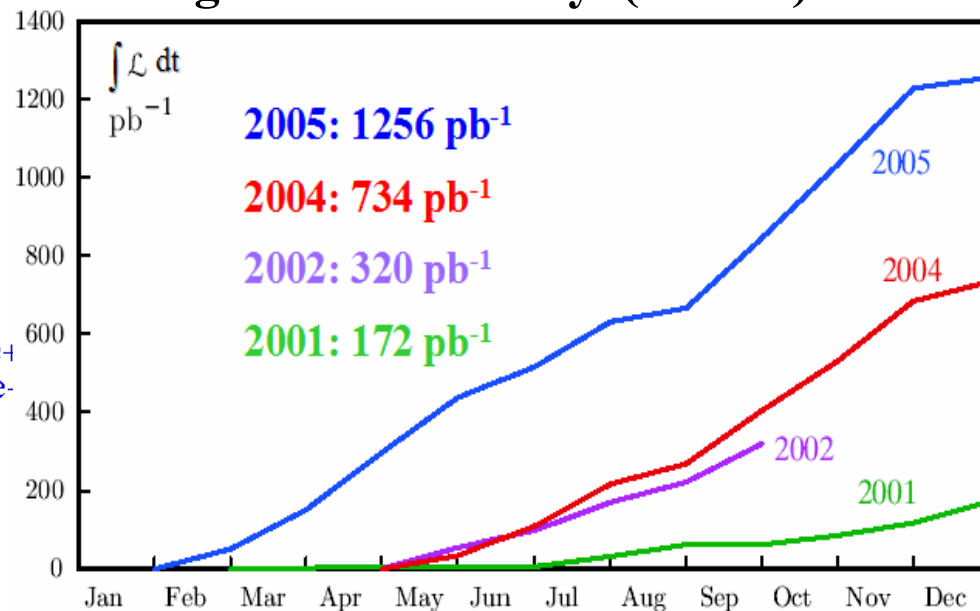
$$N = \sqrt{(1+|\varepsilon_S|^2)(1+|\varepsilon_L|^2)} / (1-\varepsilon_S\varepsilon_L) \cong 1$$

The detection of a kaon at large (small) times tags a K_S (K_L)
 \Rightarrow possibility to select a pure K_S beam (**unique** at a ϕ -factory, not possible at fixed target experiments)

DAΦNE: the Frascati ϕ -factory



Integrated luminosity (KLOE)



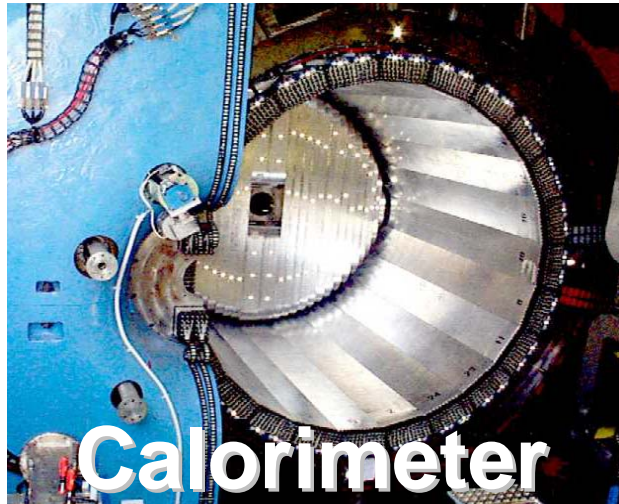
Day performance: 7-8 pb^{-1}

Best month $\int \mathcal{L} dt \sim 200 \text{ pb}^{-1}$

Total KLOE $\int \mathcal{L} dt \sim 2.5 \text{ fb}^{-1}$
(2001 - 05)

$\rightarrow \sim 2.5 \times 10^9 \text{ K}_S \text{K}_L \text{ pairs}$

The KLOE detector at DAΦNE



Lead/scintillating fiber
4880 PMTs
98% coverage of solid angle

$$\sigma_E/E \cong 5.7\% / \sqrt{E(\text{GeV})}$$

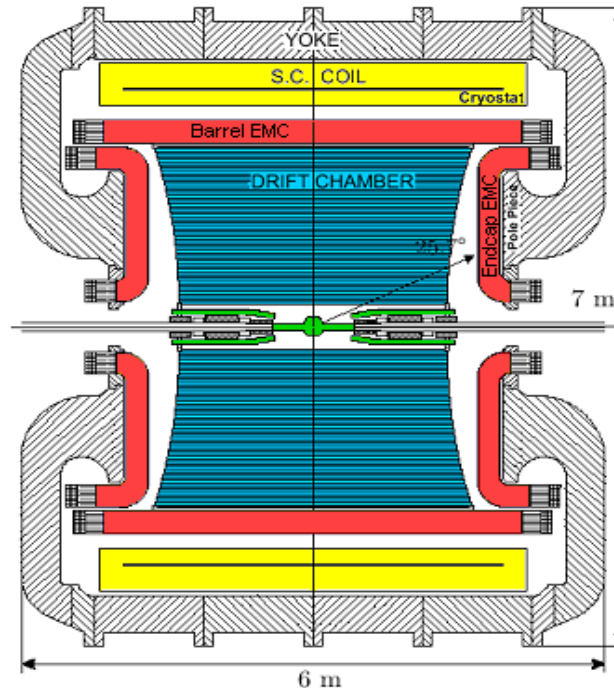
$$\sigma_t \cong 54 \text{ ps} / \sqrt{E(\text{GeV})} \oplus 50 \text{ ps}$$

(relative time between clusters)

$$\sigma_{\gamma\gamma} \sim 2 \text{ cm} (\pi^0 \text{ from } K_L \rightarrow \pi^+\pi^-\pi^0)$$

Superconducting coil

$$B = 0.52 \text{ T}$$



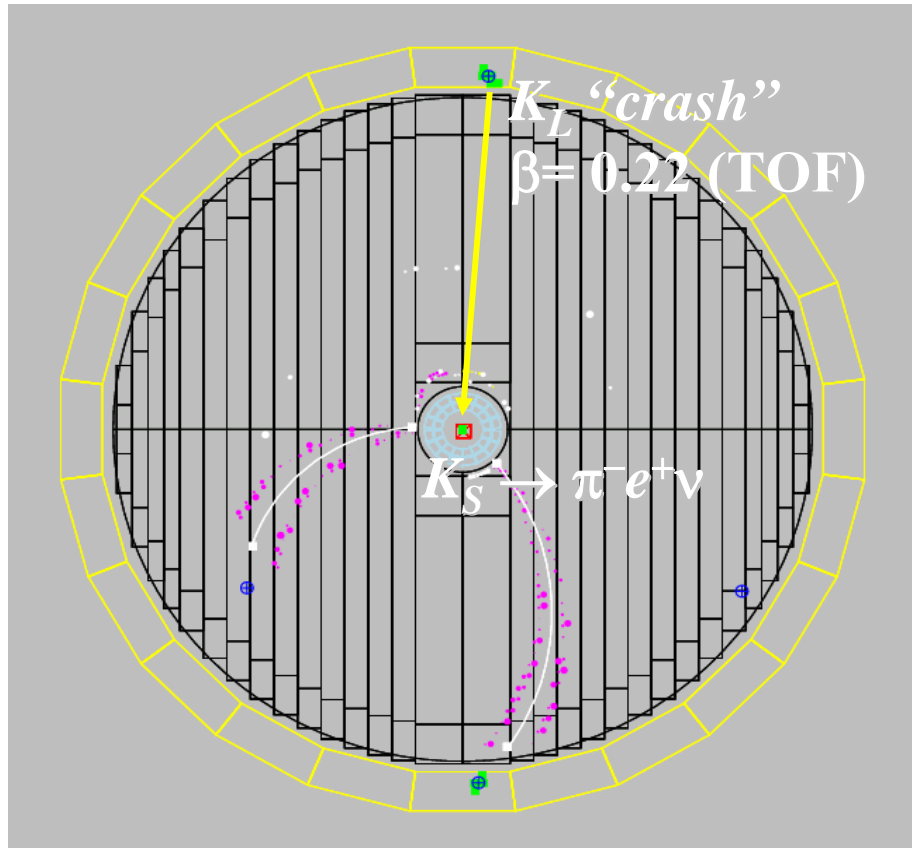
4 m diameter \times 3.3 m length
90% helium, 10% isobutane
12582/52140 sense/total wires
All-stereo geometry

$$\sigma_p/p \cong 0.4\% \text{ (tracks with } \theta > 45^\circ)$$

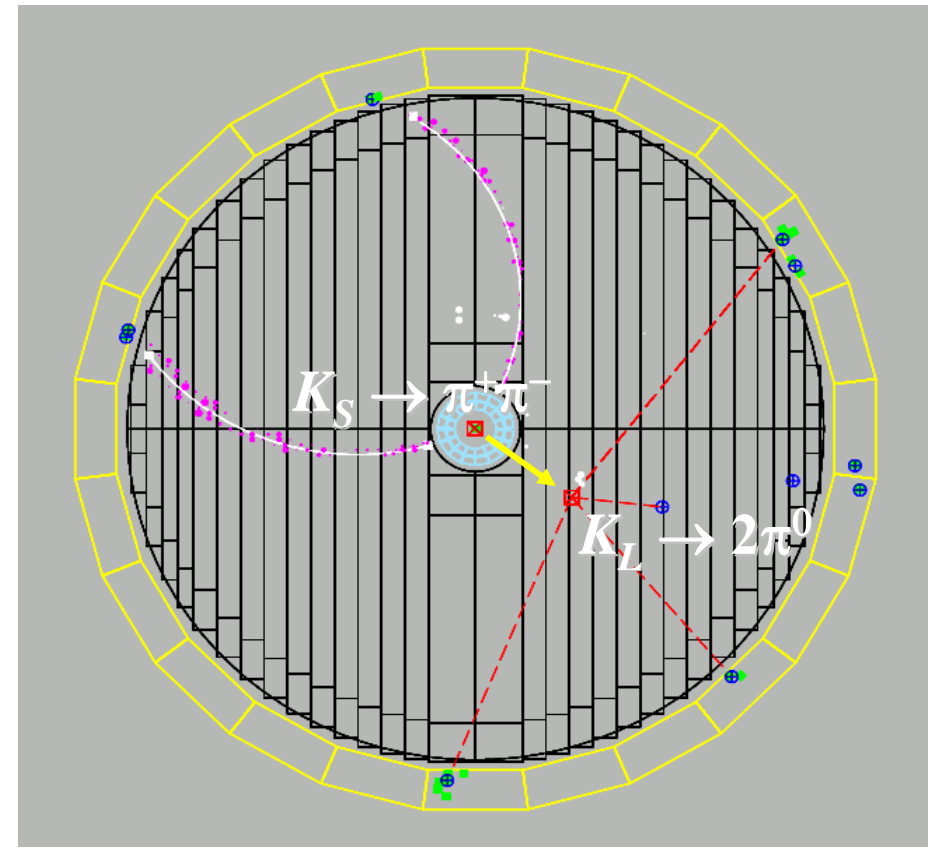
$$\sigma_x^{\text{hit}} \cong 150 \mu\text{m (xy), 2 mm (z)}$$

$$\sigma_x^{\text{vertex}} \sim 1 \text{ mm}$$

K_S and K_L Tagging at KLOE



K_S tagged by K_L interaction in EmC
Efficiency $\sim 30\%$ (largely geometrical)
 K_S angular resolution: $\sim 1^\circ$ (0.3° in ϕ)
 K_S momentum resolution: ~ 2 MeV

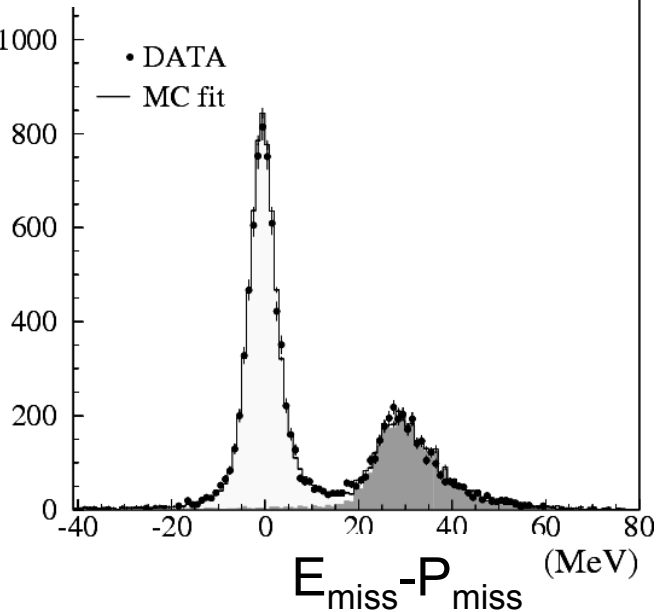


K_L tagged by $K_S \rightarrow \pi^+ \pi^-$ vertex at IP
Efficiency $\sim 70\%$ (mainly geometrical)
 K_L angular resolution: $\sim 1^\circ$
 K_L momentum resolution: ~ 2 MeV

$K_S \rightarrow \pi e \nu$: KLOE results

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Data sample: 410 pb⁻¹



$$\text{BR}(K_S \rightarrow \pi^- e^+ \nu) = (3.528 \pm 0.057 \pm 0.027) \times 10^{-4}$$

$$\text{BR}(K_S \rightarrow \pi^+ e^- \bar{\nu}) = (3.517 \pm 0.051 \pm 0.029) \times 10^{-4}$$

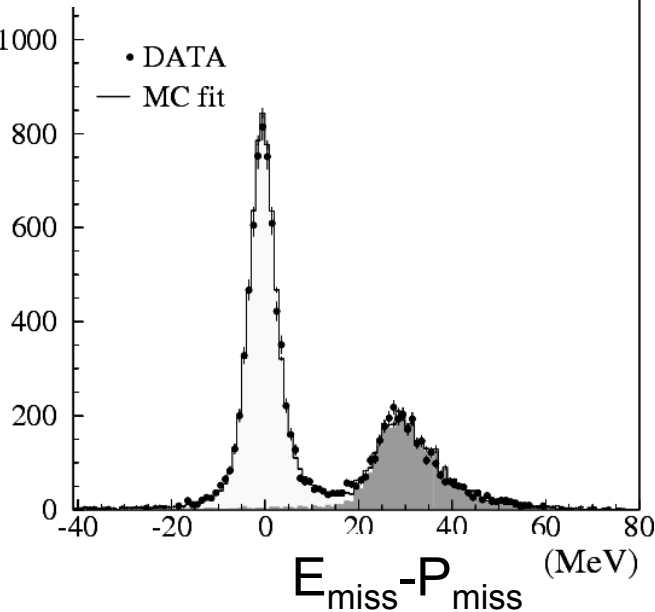
$$\text{BR}(K_S \rightarrow \pi e \nu) = (7.046 \pm 0.076 \pm 0.050) \times 10^{-4}$$

$$\text{BR}(\pi e \nu) [\text{KLOE '02, } 17 \text{ pb}^{-1}]: (6.91 \pm 0.34 \pm 0.15) \times 10^{-4}$$

$K_S \rightarrow \pi e \nu$: KLOE results

PLB 636(2006) 173

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$$A_S = \frac{\Gamma(K_S \rightarrow \pi^- e^+ \nu) - \Gamma(K_S \rightarrow \pi^+ e^- \bar{\nu})}{\Gamma(K_S \rightarrow \pi^- e^+ \nu) + \Gamma(K_S \rightarrow \pi^+ e^- \bar{\nu})}$$

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

with 2.5 fb⁻¹:

$$\delta A_S \sim 3 \times 10^{-3} \sim 2 \text{Re } \varepsilon$$

$$A_S - A_L = 4(\Re \delta + \Re x_-)$$

$$A_S + A_L = 4(\Re \varepsilon - \Re y)$$

$$\Re x_- = (-0.8 \pm 2.4 \pm 0.7) \times 10^{-3}$$

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

$$\Re y = (0.4 \pm 2.4 \pm 0.7) \times 10^{-3}$$

CPT viol.

input from other experiments

CPT test: the Bell-Steinberger relation

Unitarity constraint:

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

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

$$\left(\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW} \right) \left(\frac{\Re \varepsilon}{1 + |\varepsilon|^2} - i \Im \delta \right) = \frac{1}{\Gamma_S - \Gamma_L} \sum_f \langle f|T|K_S\rangle^* \langle f|T|K_L\rangle$$

$$\left(\begin{array}{c} \underline{\Re \varepsilon} \\ 1 + |\varepsilon|^2 \\ \underline{\Im \delta} \end{array} \right) = \frac{1}{N} \left(\begin{array}{cc} 1 + k(1 - 2b) & (1 - k) \tan \phi_{SW} \\ (1 - k) \tan \phi_{SW} & -(1 + k) \end{array} \right) \left(\begin{array}{c} \sum_i \Re \alpha_i \\ \sum_i \Im \alpha_i \end{array} \right) \rightarrow \begin{array}{l} K_S \ K_L \\ \text{observables} \end{array}$$

$$\alpha_{+-} = \eta_{+-} \text{BR}(K_S \rightarrow \pi^+ \pi^-)$$

$$\alpha_{+-0} = \tau_S / \tau_L \eta_{+-0}^* \text{BR}(K_L \rightarrow \pi^+ \pi^- \pi^0)$$

$$\alpha_{00} = \eta_{00} \text{BR}(K_S \rightarrow \pi^0 \pi^0)$$

$$\alpha_{000} = \tau_S / \tau_L \eta_{000}^* \text{BR}(K_L \rightarrow \pi^0 \pi^0 \pi^0)$$

$$\alpha_{k13} = 2\tau_S / \tau_L \text{BR}(K_L 13) [(A_S + A_L) / 4 - i \text{Im } x_+]$$

$$k = \tau_S / \tau_L, \quad b = \text{BR}(K_L \rightarrow \pi \ell \nu)$$

$$\eta_i = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$$

$$N = (1 + k)^2 + (1 - k)^2 \tan^2 \phi_{SW} - 2bk(1 + k)$$

Experimental inputs to the Bell-Steinberger relation

	Value	Source
τ_{K_S}	0.08958 ± 0.00005 ns	PDG [14]
τ_{K_L}	50.84 ± 0.23 ns	KLOE average
$m_L - m_S$	$(5.290 \pm 0.016) \times 10^9$ s ⁻¹	PDG [14]
$\text{BR}(K_S \rightarrow \pi^+ \pi^-)$	0.69186 ± 0.00051	KLOE average
$\text{BR}(K_S \rightarrow \pi^0 \pi^0)$	0.30687 ± 0.00051	KLOE average
$\text{BR}(K_S \rightarrow \pi \ell \nu)$	$(11.77 \pm 0.15) \times 10^{-4}$	KLOE [6]
$\text{BR}(K_L \rightarrow \pi^+ \pi^-)$	$(1.933 \pm 0.021) \times 10^{-3}$	KLOE average
$\text{BR}(K_L \rightarrow \pi^0 \pi^0)$	$(0.848 \pm 0.010) \times 10^{-3}$	KLOE average
ϕ_{+-}	$(43.4 \pm 0.7)^\circ$	PDG [14]
ϕ_{00}	$(43.7 \pm 0.8)^\circ$	PDG [14]
$R_{S,\gamma} (E_\gamma > 20\text{MeV})$	$(0.710 \pm 0.016) \times 10^{-2}$	E731 [18]
$R_{S,\gamma}^{\text{th-IB}} (E_\gamma > 20\text{MeV})$	$(0.700 \pm 0.001) \times 10^{-2}$	KLOE MC [19]
$ \eta_{+-\gamma} $	$(2.359 \pm 0.074) \times 10^{-3}$	E773 [17]
$\phi_{+-\gamma}$	$(43.8 \pm 4.0)^\circ$	E773 [17]
$\text{BR}(K_L \rightarrow \pi^+ \pi^- \pi^0)$	0.1262 ± 0.0011	KLOE average
η_{+-0}	$((-2 \pm 7) + i(-2 \pm 9)) \times 10^{-3}$	CPLEAR [10]
$\text{BR}(K_L \rightarrow 3\pi^0)$	0.1996 ± 0.0021	KLOE average
$\text{BR}(K_S \rightarrow 3\pi^0)$	$< 1.5 \times 10^{-7}$ at 95% CL	KLOE [5]
ϕ_{000}	uniform from 0 to 2π	
$\text{BR}(K_L \rightarrow \pi \ell \nu)$	0.6709 ± 0.0017	KLOE average
$A_L + A_S$	$(0.5 \pm 1.0) \times 10^{-2}$	$K_{\ell 3}$ average
$\text{Im}(x_+)$	$(0.8 \pm 0.7) \times 10^{-2}$	$K_{\ell 3}$ average

Main improvements done with KLOE measurements on K_S semileptonic and $3\pi^0$ decays

CPT test: the Bell-Steinberger relation

KLOE result: JHEP12(2006) 011

$$\text{Re } \varepsilon = (159.6 \pm 1.3) \times 10^{-5}$$

$$\text{Im } \delta = (0.4 \pm 2.1) \times 10^{-5}$$

CPLEAR: study of the time evolution of neutral kaons in semileptonic decays

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

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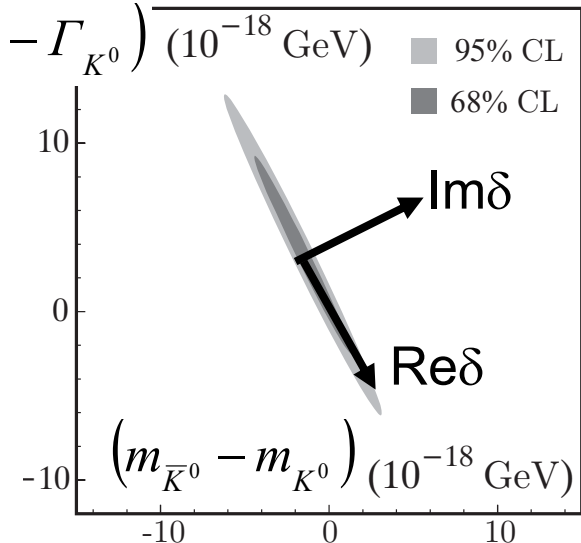
Combining $\text{Re } \delta$ and $\text{Im } \delta$ results:

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

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

$$-5.3 \times 10^{-19} < m_{\bar{K}^0} - m_{K^0} < 6.3 \times 10^{-19} \text{ GeV}$$

at 95% c.l.



CPT test: the Bell-Steinberger relation

M. Palutan, presented at
FLAVIANET Kaon ws 08 (prelim.):

$$\text{Re } \varepsilon = (161.2 \pm 0.6) \times 10^{-5}$$

$$\text{Im } \delta = (-0.1 \pm 1.4) \times 10^{-5}$$

(using new KTeV results on $\phi_{\pi\pi}$:
 Moriond EW 08, HQL08)

Combining $\text{Re}\delta$ and $\text{Im}\delta$ results:

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

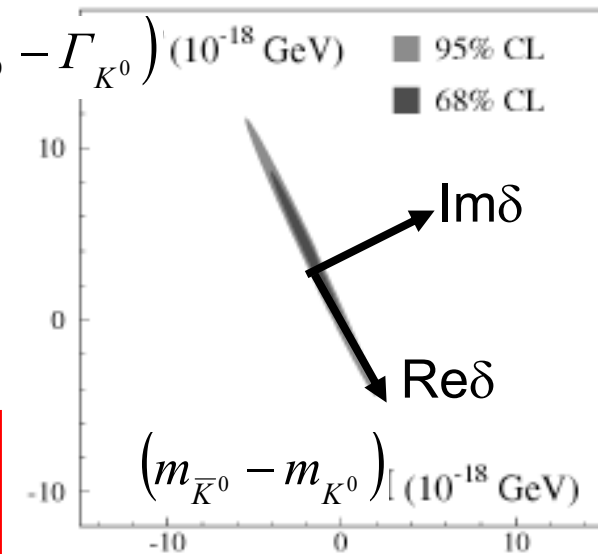
Assuming $(\Gamma_{\bar{K}^0} - \Gamma_{K^0}) = 0$, i.e. no CPT viol. in decay:

$$|m_{\bar{K}^0} - m_{K^0}| < 4.0 \times 10^{-19} \text{ GeV at 95\% C.L.}$$

CPLEAR: study of the time evolution of
 neutral kaons in semileptonic decays

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

PLB444 (1998) 52



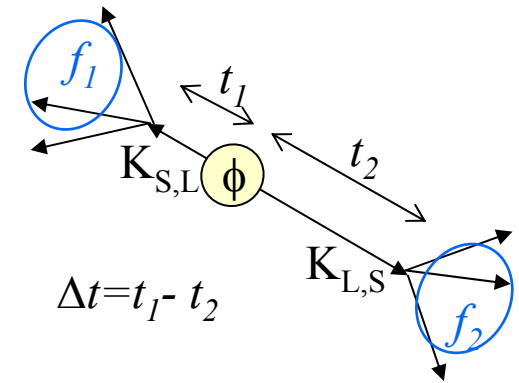
2) Search for decoherence and CPT violation in the neutral kaon system

Neutral kaon interferometry

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

Double differential time distribution:

$$I(f_1, t_1; f_2, t_2) = C_{12} \left\{ |\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)(t_1 + t_2)/2} \cos[\Delta m(t_2 - t_1) + \phi_1 - \phi_2] \right\}$$



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

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

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

characteristic interference term at a ϕ -factory \Rightarrow interferometry

$$f_i = \pi^+\pi^-, \pi^0\pi^0, \pi l\nu, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma \text{ ..etc}$$

Neutral kaon interferometry

Integrating in (t_1+t_2) we get the time difference ($\Delta t=t_1-t_2$) distribution (1-dim plot simpler to manipulate than 2-dim plot):

$$I(f_1, f_2; \Delta t \geq 0) = \frac{C_{12}}{\Gamma_S + \Gamma_L} \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2 |\eta_1| |\eta_2| e^{-(\Gamma_S + \Gamma_L) \Delta t / 2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\}$$

for $\Delta t < 0$ $\Delta t \rightarrow |\Delta t|$ and $1 \leftrightarrow 2$

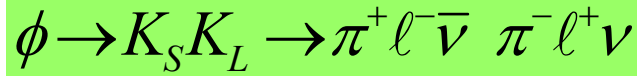
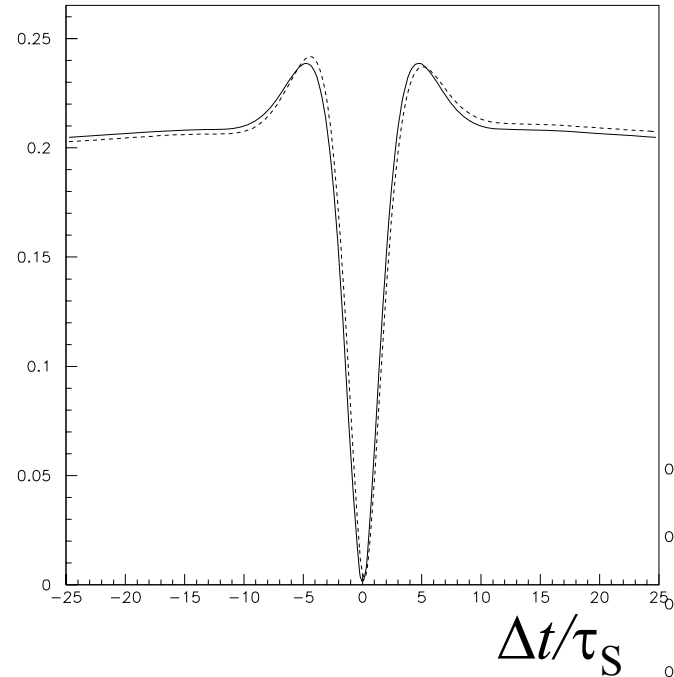
From these distributions for various final states f_i one can measure the following quantities:

$$\Gamma_S, \Gamma_L, \Delta m, |\eta_i|, \phi_i \equiv \arg(\eta_i)$$

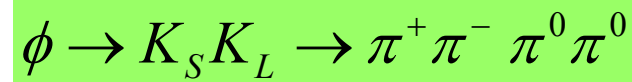
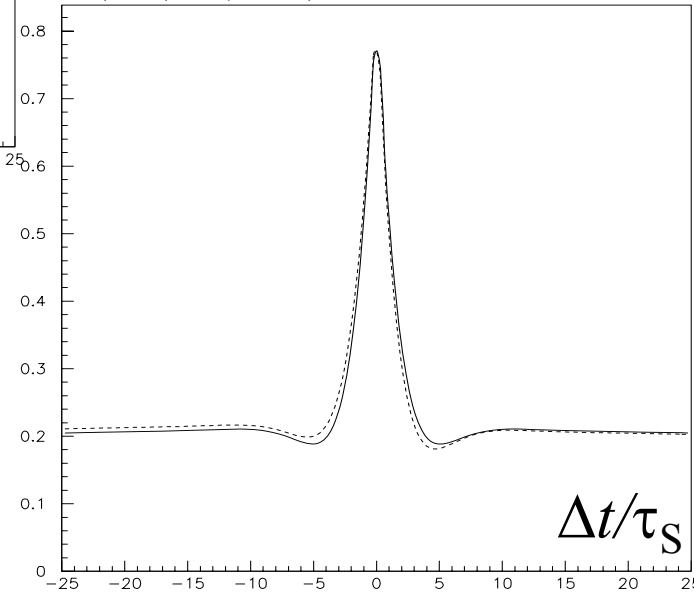
Phases (difference of) from the interference term => **interferometry**

Neutral kaon interferometry: main observables

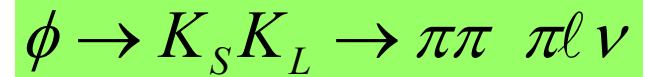
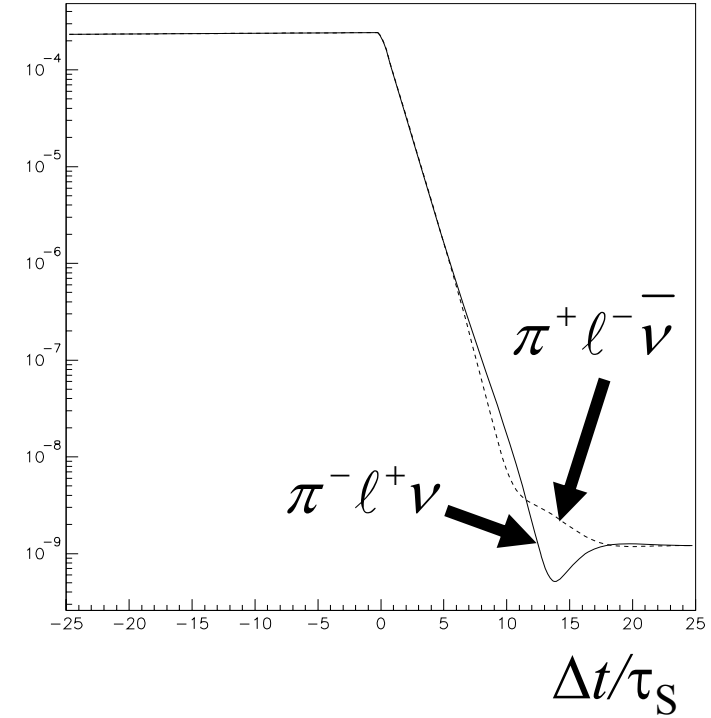
$I(\Delta t)$ (a.u)



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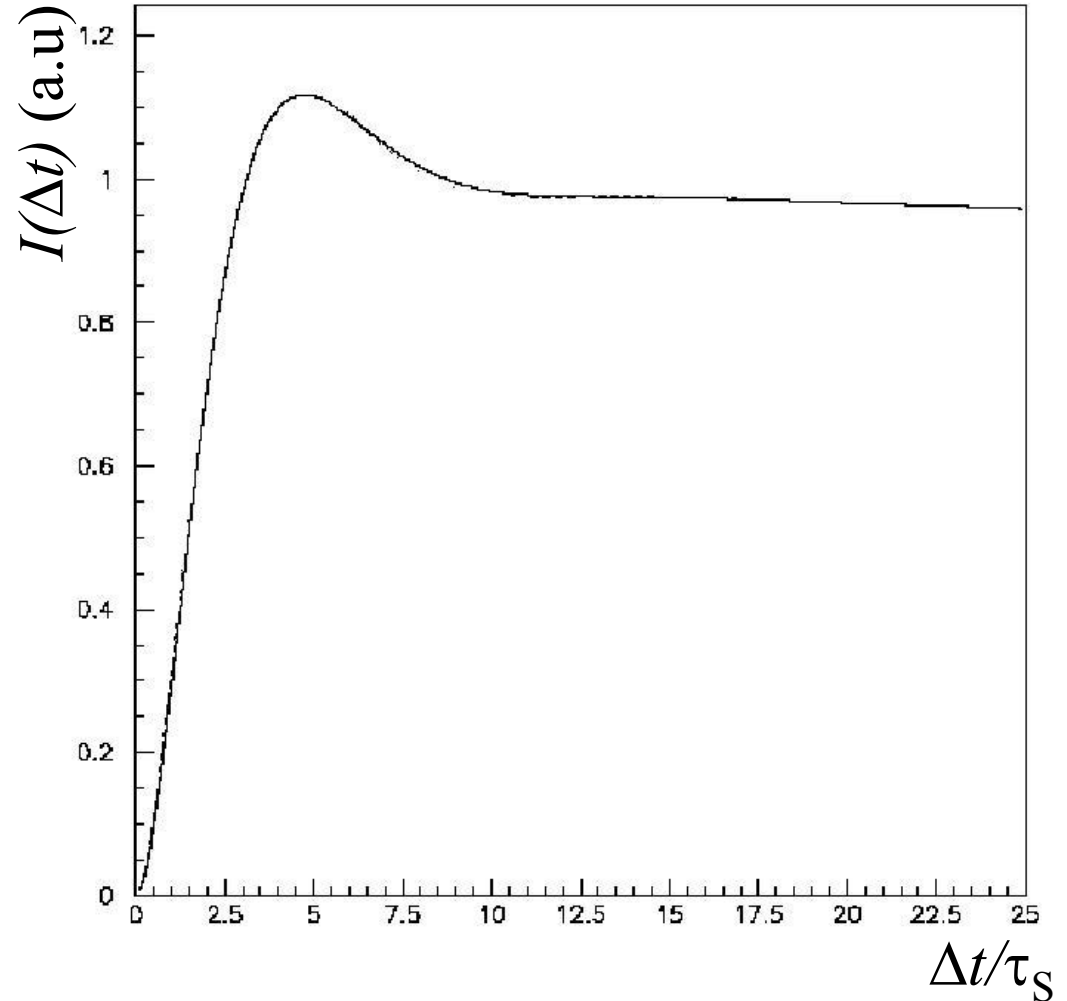
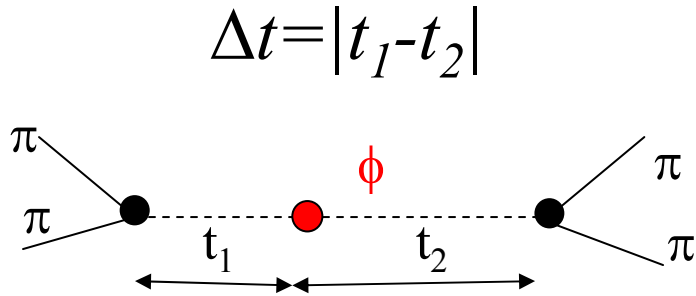
$I(\Delta t)$ (a.u)



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

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

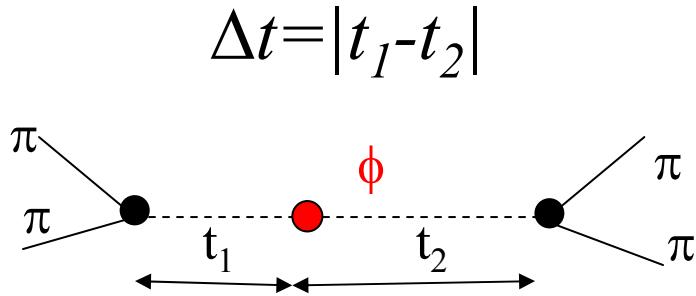
Same final state for both kaons: $f_1 = f_2 = \pi^+ \pi^-$



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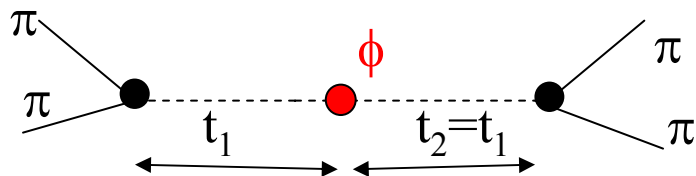
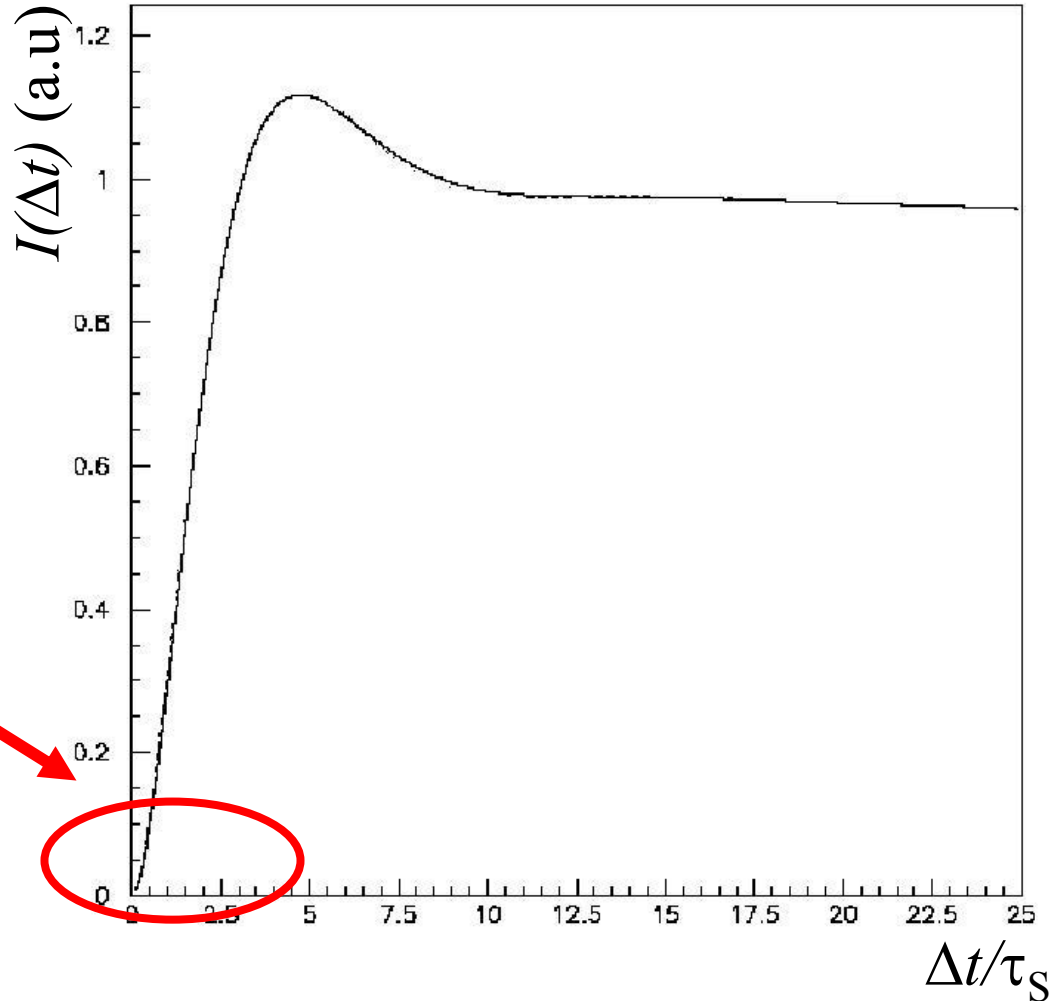
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EPR correlation:

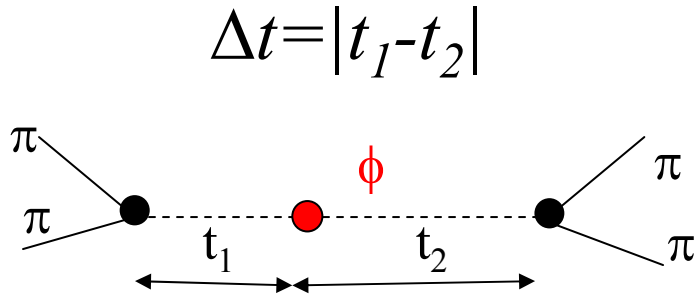
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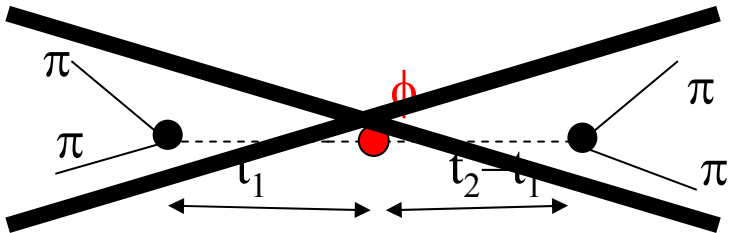
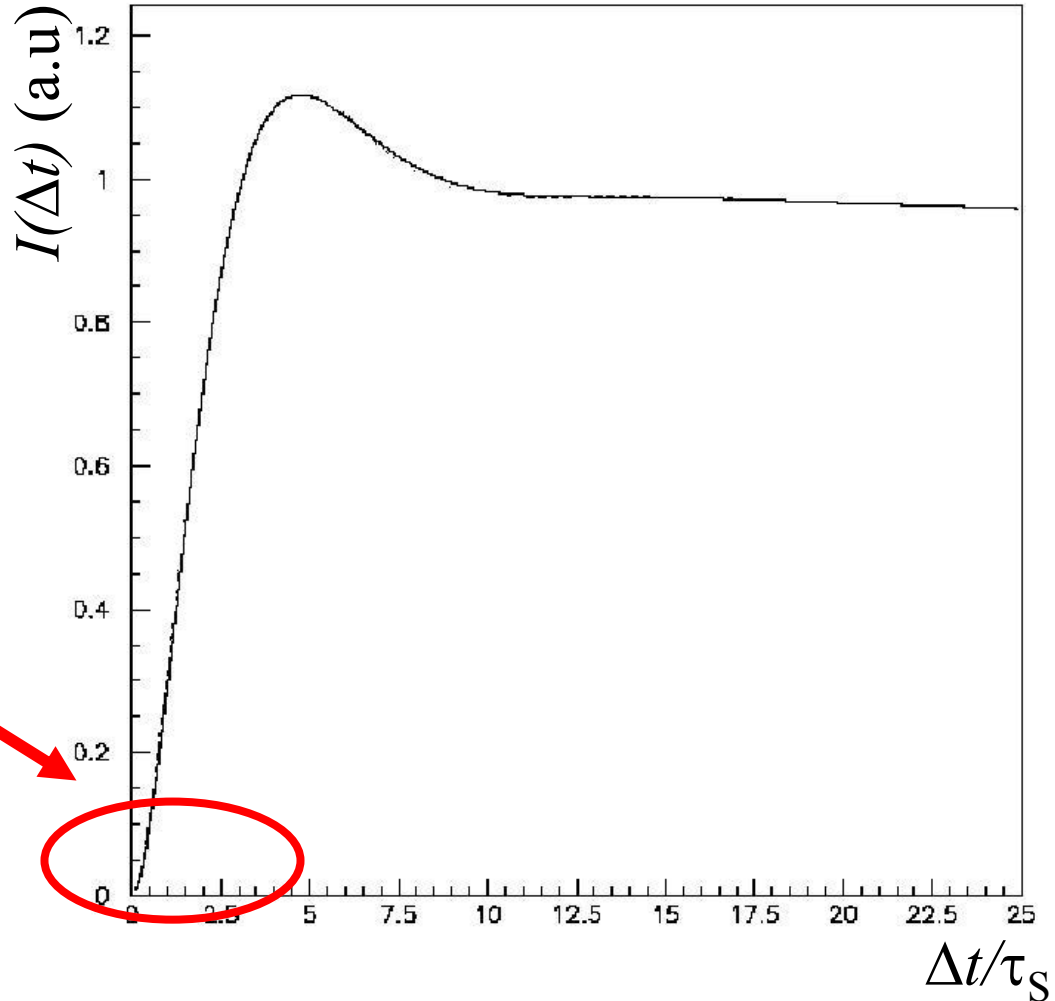
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$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

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

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

Feynman described the phenomenon of interference as containing “the only mystery” of quantum mechanics

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Feynman described the phenomenon of interference as containing “the only mystery” of quantum mechanics

Decoherence parameter:

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

$$\zeta_{0\bar{0}} = 1 \rightarrow \text{total decoherence} \\ \text{(also known as Furry's hypothesis} \\ \text{or spontaneous factorization)} \\ \text{[W.Furry, PR 49 (1936) 393]}$$

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

- Analysed data: $L=380 \text{ pb}^{-1}$
- Fit including Δt resolution and efficiency effects + regeneration
- $\Gamma_S, \Gamma_L, \Delta m$ fixed from PDG

KLOE result: PLB 642(2006) 315

$$\zeta_{0\bar{0}} = (1.0 \pm 2.1_{\text{STAT}} \pm 0.4_{\text{SYST}}) \times 10^{-6}$$

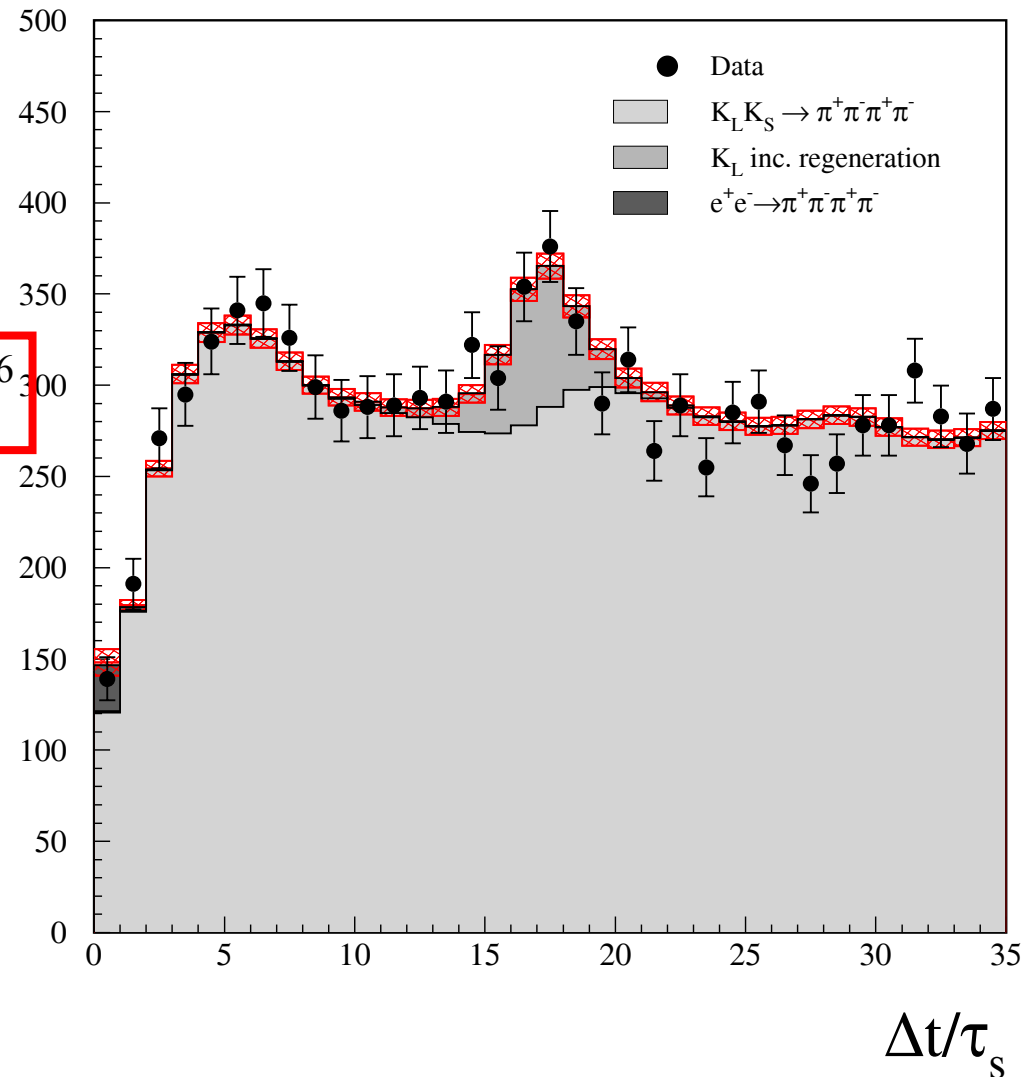
as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
 \Rightarrow high sensitivity to $\zeta_{0\bar{0}}$

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

$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$

In the B-meson system, BELLE coll.
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$$\zeta_{0\bar{0}}^B = 0.029 \pm 0.057$$



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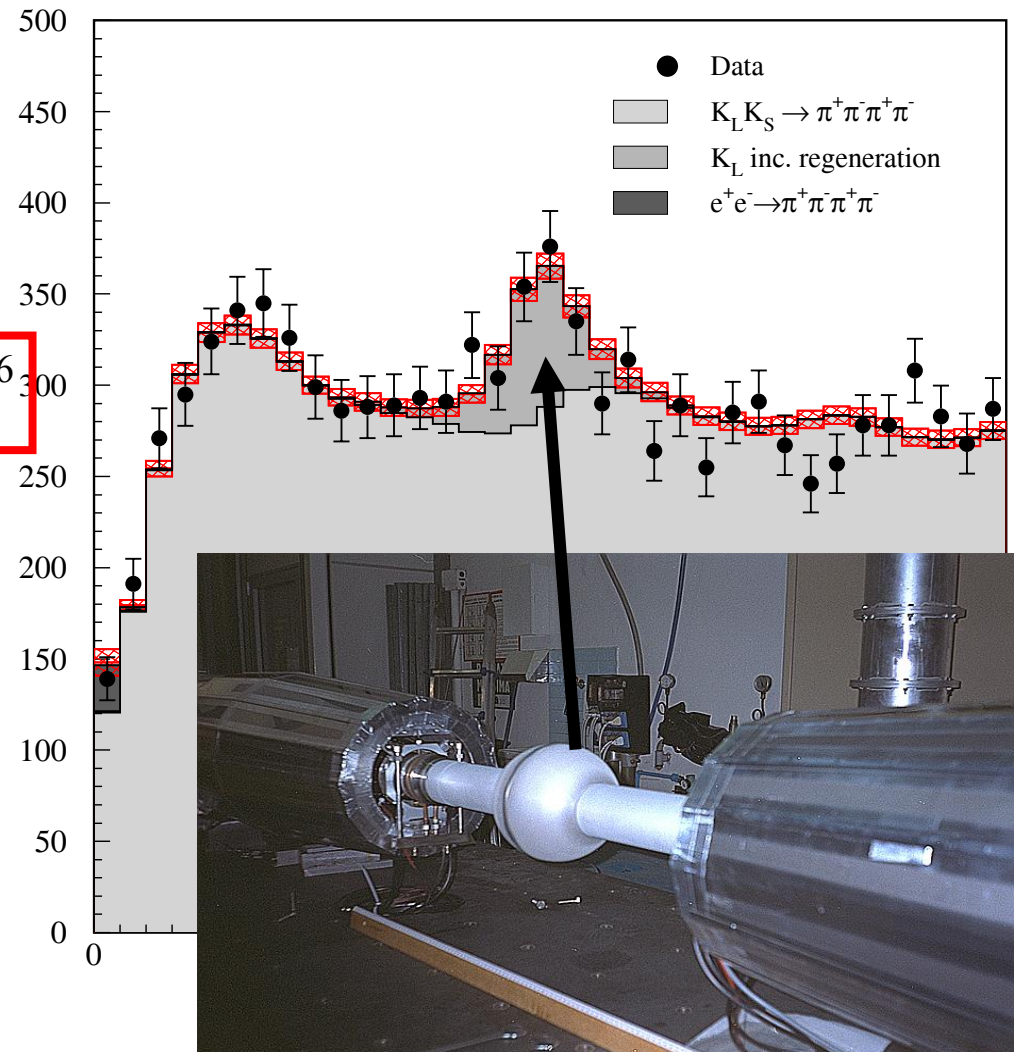
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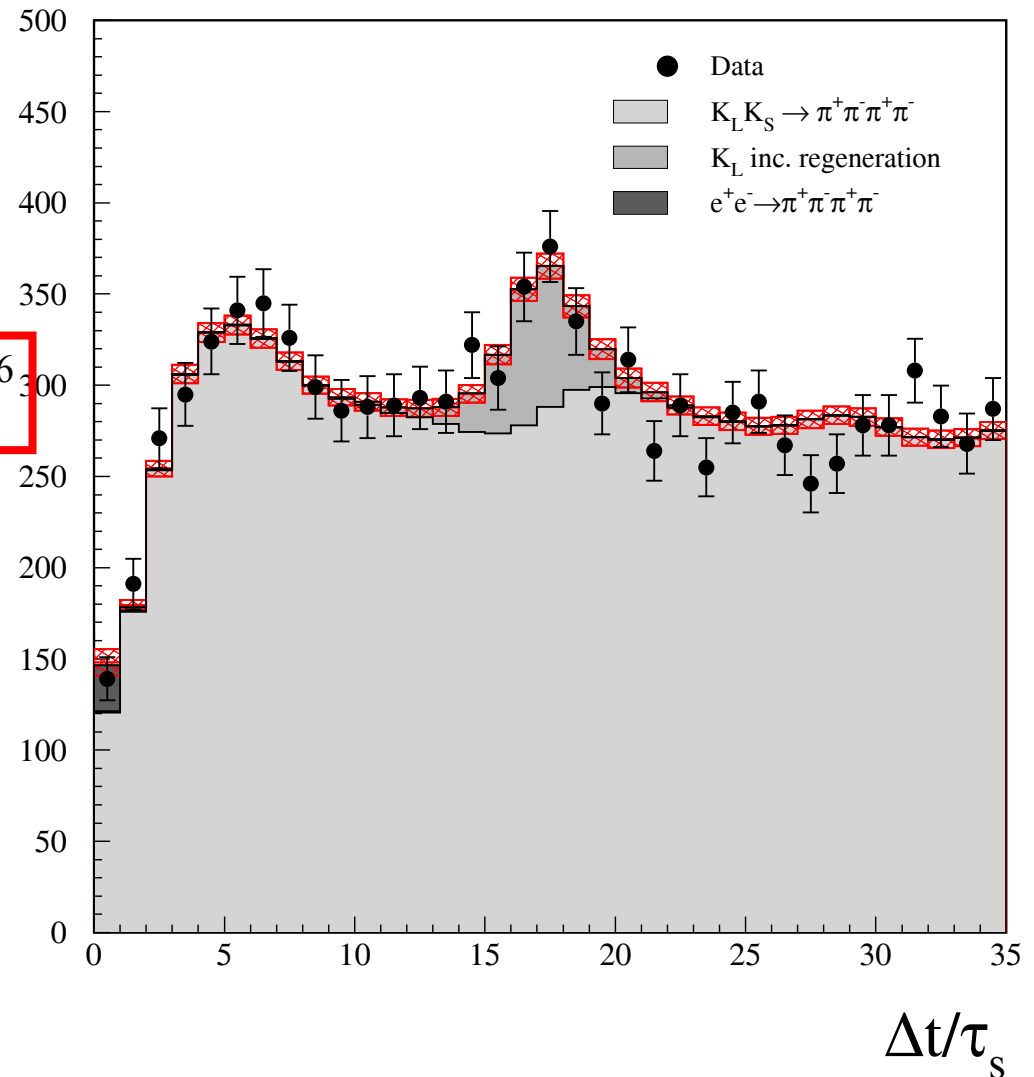
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- Analysed data: $L=1 \text{ fb}^{-1}$ (2005 data)
- Fit including Δt resolution and efficiency effects + regeneration
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KLOE preliminary:

$$\zeta_{0\bar{0}} = (0.3 \pm 1.2_{\text{STAT}}) \times 10^{-6}$$

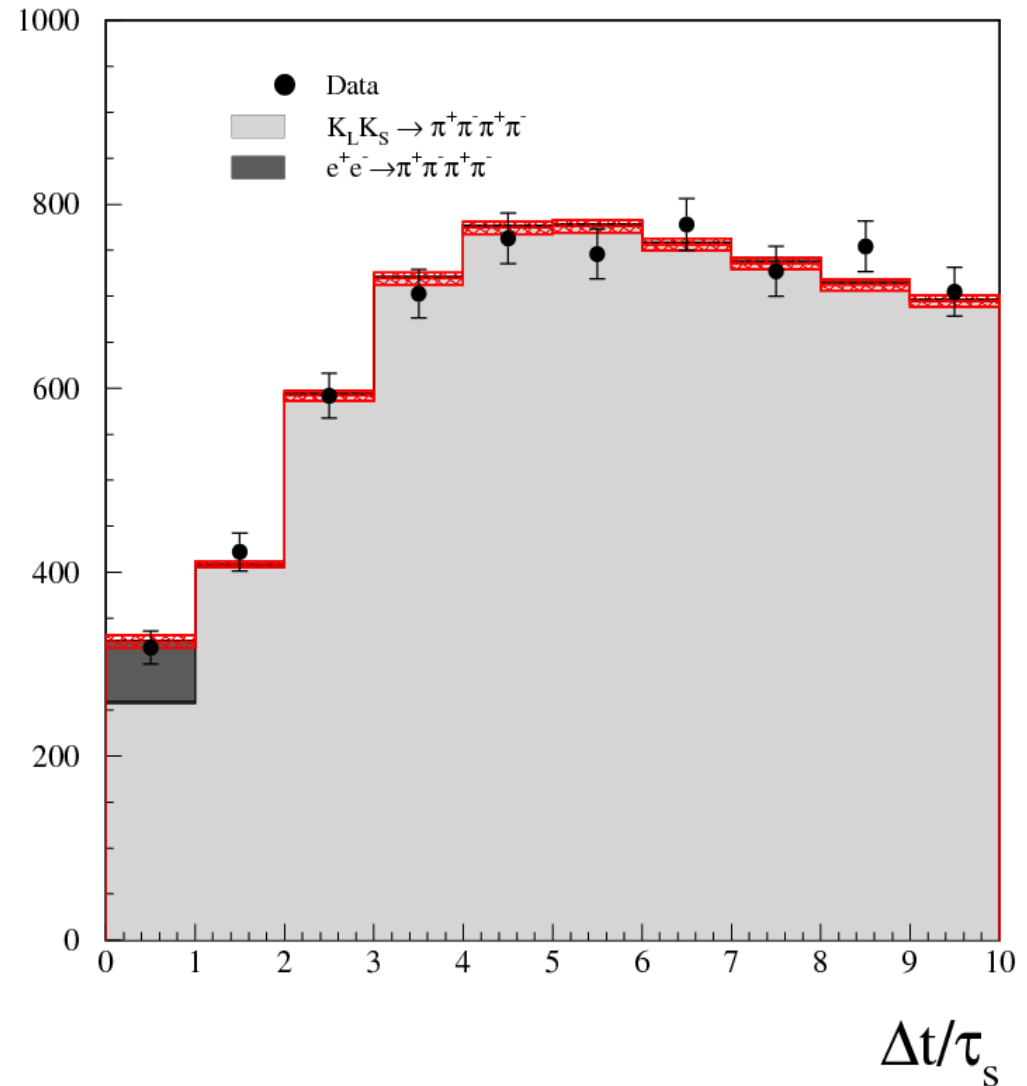
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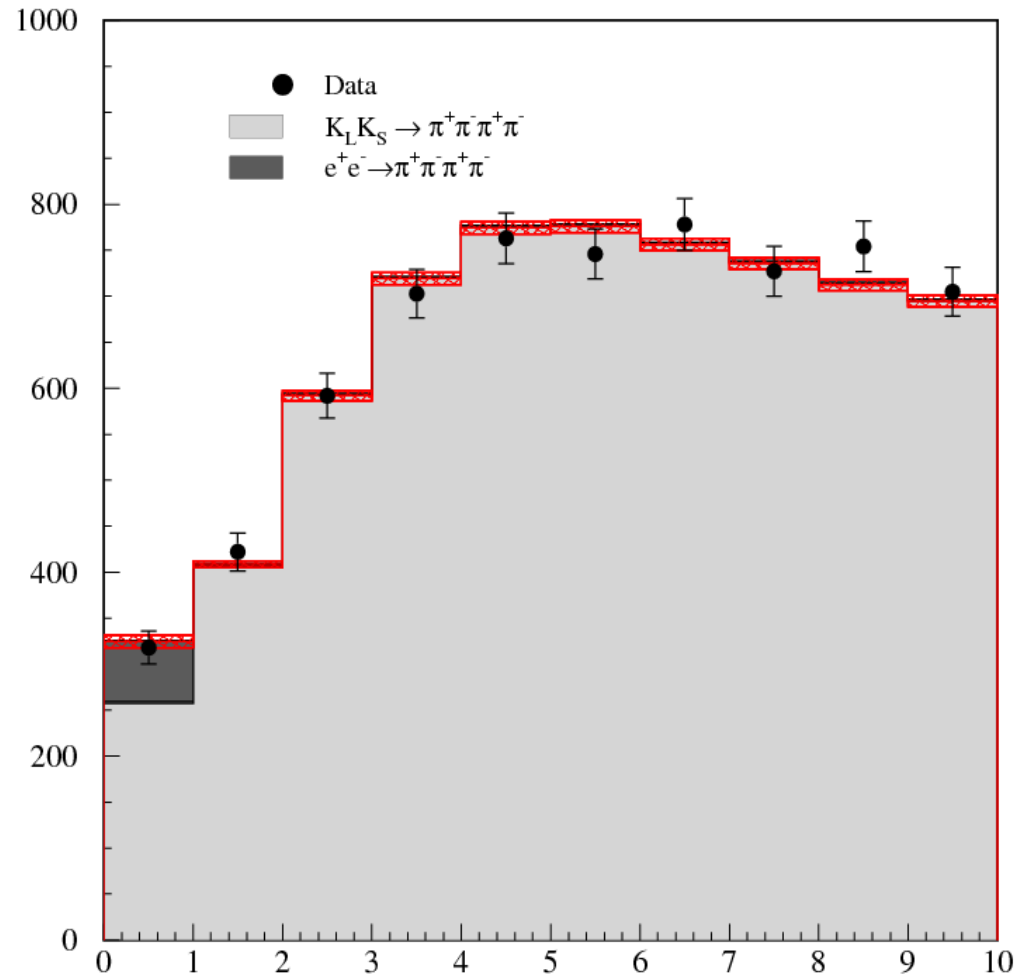
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Comparison with quantum optics test precisions

$\Delta t / \tau_S$



Decoherence and CPT violation

Modified Liouville – von Neumann equation for the density matrix of the kaon system:

$$\dot{\rho}(t) = \underbrace{-iH\rho + i\rho H^\dagger}_{\text{QM}} + L(\rho)$$

← extra term inducing decoherence:
pure state => mixed state

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Possible decoherence due quantum gravity effects:

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

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].

J. Ellis et al.[3-6] => model of decoherence for neutral kaons => 3 new CPTV param. α, β, γ :

$$L(\rho) = L(\rho; \alpha, \beta, \gamma)$$
$$\alpha, \gamma > 0, \quad \alpha\gamma > \beta^2$$

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

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742; [3] Ellis et. al, NP B241 (1984) 381; PRD53 (1996)3846 [4] Huet, Peskin, NP B434 (1995) 3; [5] Benatti, Floreanini, NPB511 (1998) 550 [6] Bernabeu, Ellis, Mavromatos, Nanopoulos, Papavassiliou: Handbook on kaon interferometry [hep-ph/0607322]

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Black h

Hawkin

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J. Ellis

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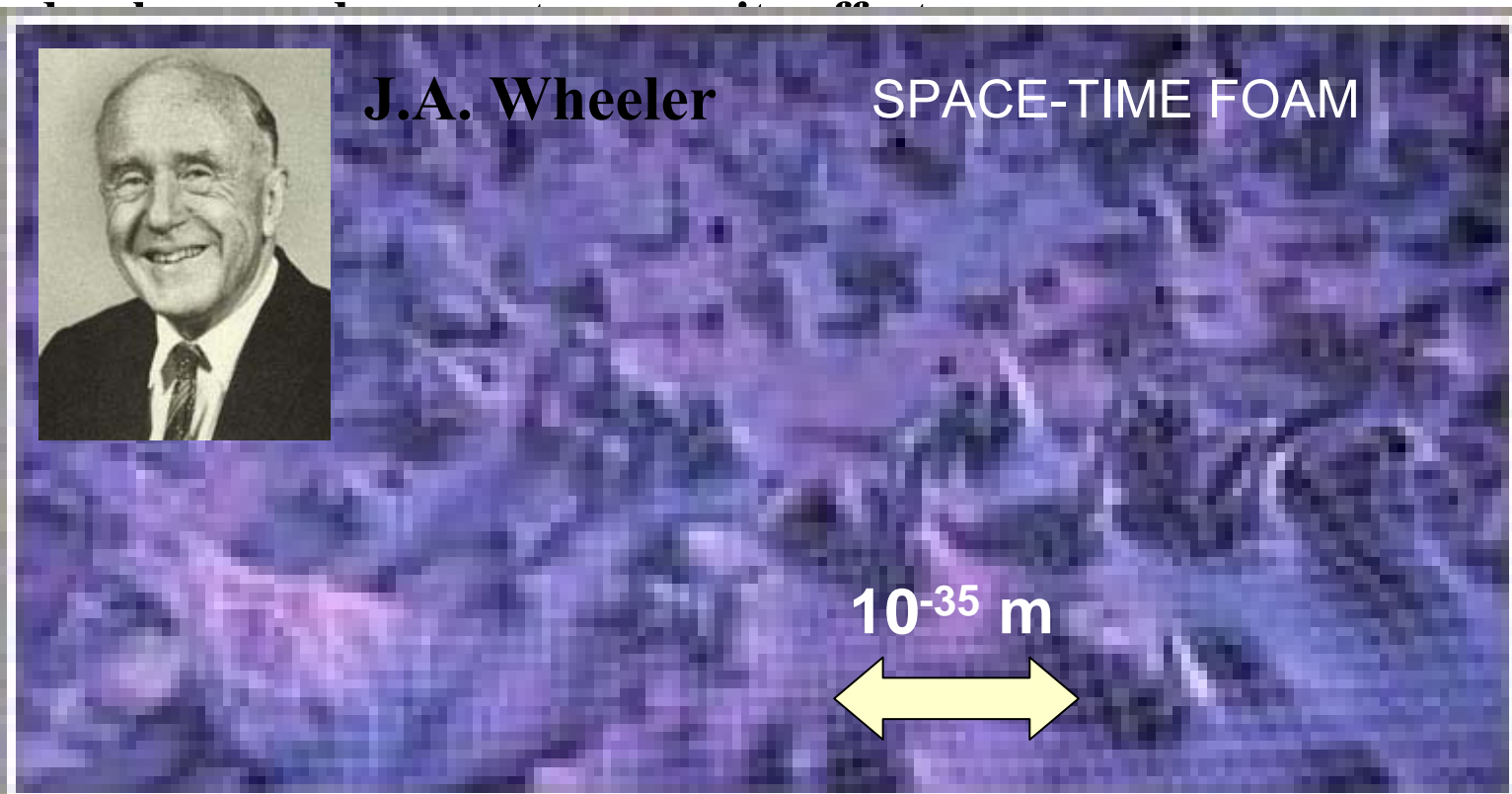
PRD53 (1

Bernabeu,



J.A. Wheeler

SPACE-TIME FOAM



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241 (1984) 381;

50 [6]

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$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: decoherence & CPTV by QG

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

$$\alpha = \gamma \quad , \quad \beta = 0$$

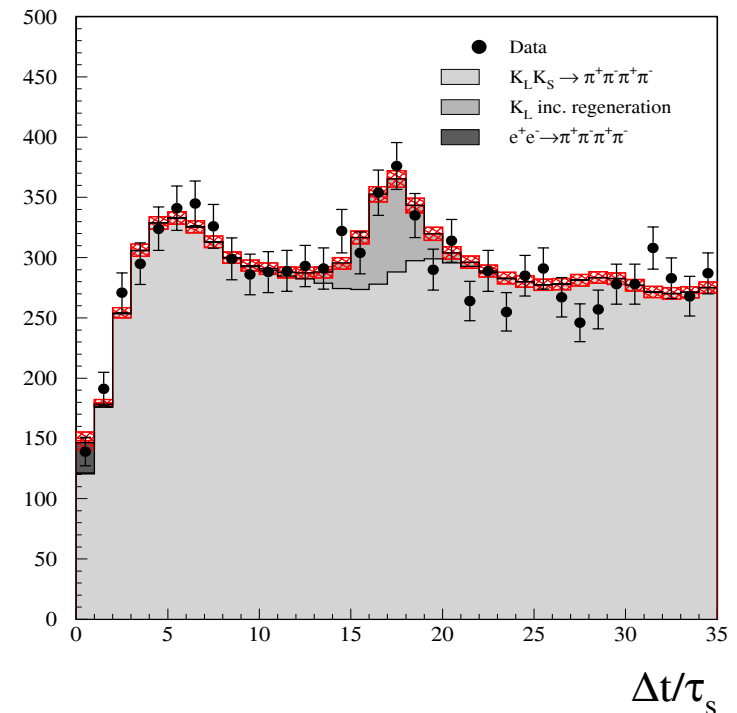
=> only one independent parameter: γ

The fit with $I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \gamma)$ gives:

KLOE result $L=380 \text{ pb}^{-1}$ **PLB 642(2006) 315**

$$\gamma = \left(1.1_{-2.4}^{+2.9} \text{STAT} \pm 0.4_{\text{SYST}} \right) \times 10^{-21} \text{ GeV}$$

Complete positivity guarantees the positivity of the eigenvalues of density matrices describing states of correlated kaons.



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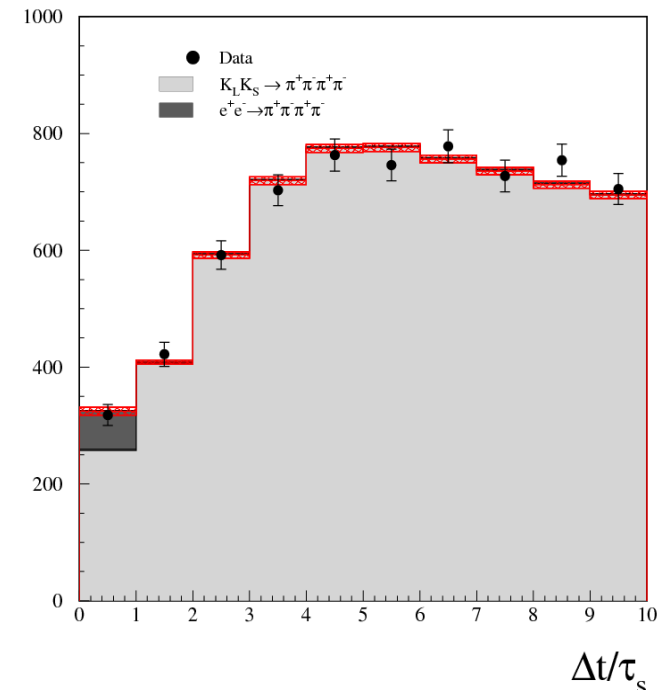
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KLOE preliminary $L=1 \text{ fb}^{-1}$

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Complete positivity guarantees the positivity of the eigenvalues of density matrices describing states of correlated kaons.



$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: CPT violation in correlated 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:

[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

$$\begin{aligned} |i\rangle &\propto (K^0 \bar{K}^0 - K^0 \bar{K}^0) + \omega (K^0 \bar{K}^0 + K^0 \bar{K}^0) \\ &\propto (K_S K_L - K_L K_S) + \omega (K_S K_S - K_L K_L) \end{aligned}$$

at most one expects: $|\omega|^2 = O\left(\frac{E^2 / M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}$

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 ω is expected for $f_1=f_2=\pi^+\pi^-$

All CPTV effects induced by QG ($\alpha, \beta, \gamma, \omega$) could be simultaneously disentangled.

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: CPT violation in correlated K states

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

- Analysed data: 380 pb^{-1}

KLOE result : **PLB 642(2006) 315**

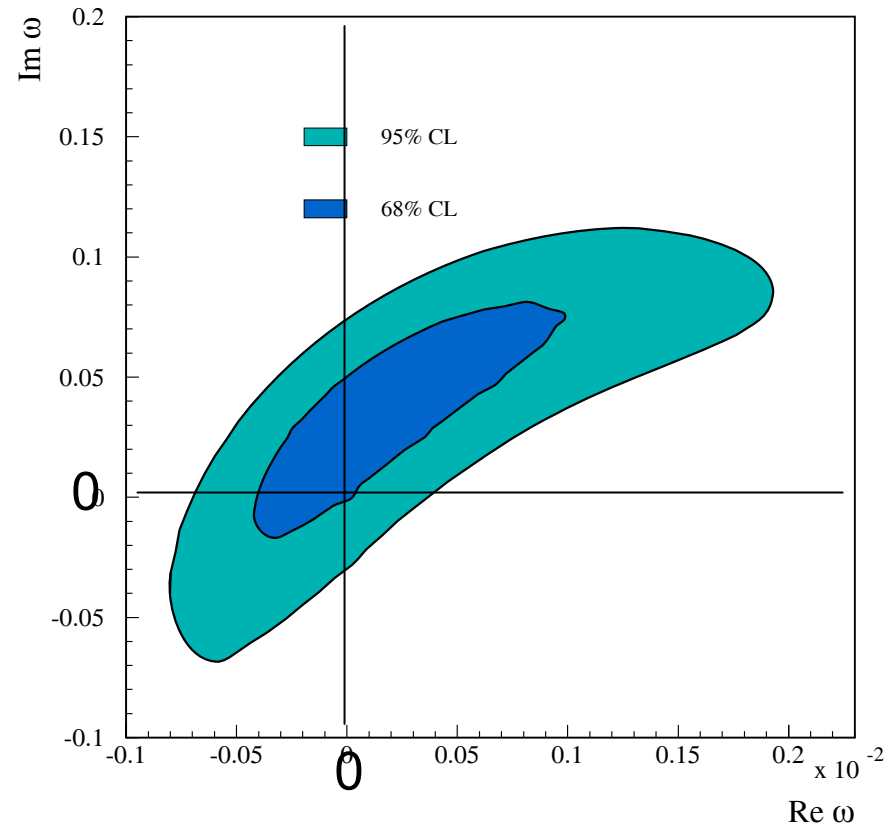
$$\Re \omega = \left(1.1_{-5.3}^{+8.7} \text{STAT} \pm 0.9_{\text{SYST}} \right) \times 10^{-4}$$

$$\Im \omega = \left(3.4_{-5.0}^{+4.8} \text{STAT} \pm 0.6_{\text{SYST}} \right) \times 10^{-4}$$

$$|\omega| < 2.1 \times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$

(ω measured for the first time)

$\text{Im } \omega \times 10^{-2}$



$\text{Re } \omega \times 10^{-2}$

$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: CPT violation in correlated K states

$\text{Im } \omega \times 10^{-2}$

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

- Analysed data: 1 fb^{-1} (2005 data)

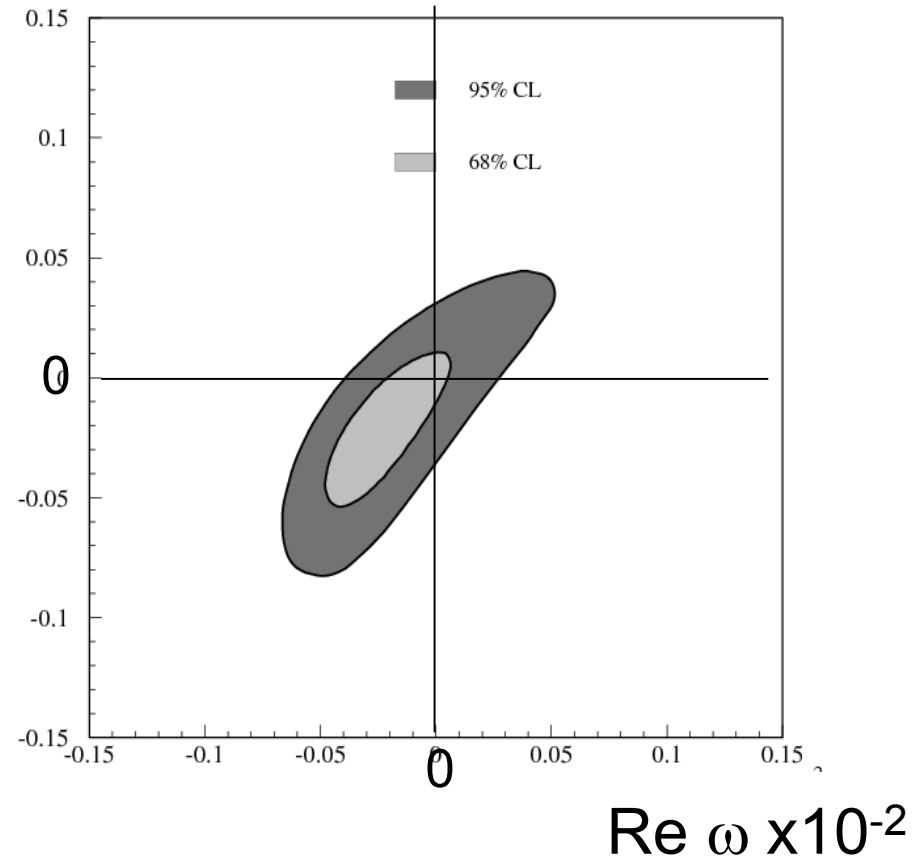
KLOE preliminary :

$$\Re \omega = \left(-2.5^{+3.1}_{-2.3 \text{ STAT}} \right) \times 10^{-4}$$

$$\Im \omega = \left(-2.2^{+3.4}_{-3.1 \text{ STAT}} \right) \times 10^{-4}$$

$$|\omega| < 0.98 \times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$

(ω measured for the first time)



3) Tests of Lorentz invariance and CPT symmetry in the neutral kaon system

CPT and Lorentz invariance violation (SME)

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:

- CPTV only in mixing, not in decay, at first order (i.e. $B_I = y = x_- = 0$)
- δ cannot be a constant (momentum dependence)

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

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

where Δa_μ are four parameters associated to SME lagrangian terms and related to CPT and Lorentz violation.

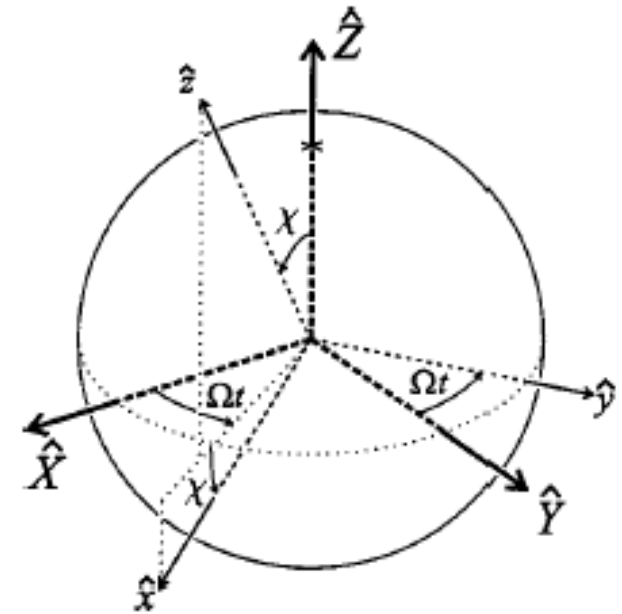
CPT and Lorentz invariance violation (SME)

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

δ depends on sidereal time t since laboratory frame rotates with Earth.

For a ϕ -factory there is an additional dependence on the polar and azimuthal angle θ, ϕ of the kaon momentum in the laboratory frame:

$$\begin{aligned} \bar{\delta}(|\vec{p}|, \theta, t) &= \frac{1}{2\pi} \int_0^{2\pi} \delta(\vec{p}, t) d\phi \\ &= \frac{i \sin \phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \left[\Delta a_0 + \beta_K \Delta a_Z \cos \chi \cos \theta \right. \\ &\quad \left. + \beta_K \Delta a_Y \sin \chi \cos \theta \sin \Omega t \right. \\ &\quad \left. + \beta_K \Delta a_X \sin \chi \cos \theta \cos \Omega t \right] \end{aligned}$$



(in general z lab. axis is non-normal to Earth's surface)

Ω : Earth's sidereal frequency
 χ : angle between the z lab. axis and the Earth's rotation axis

CPT and Lorentz invariance violation (SME)

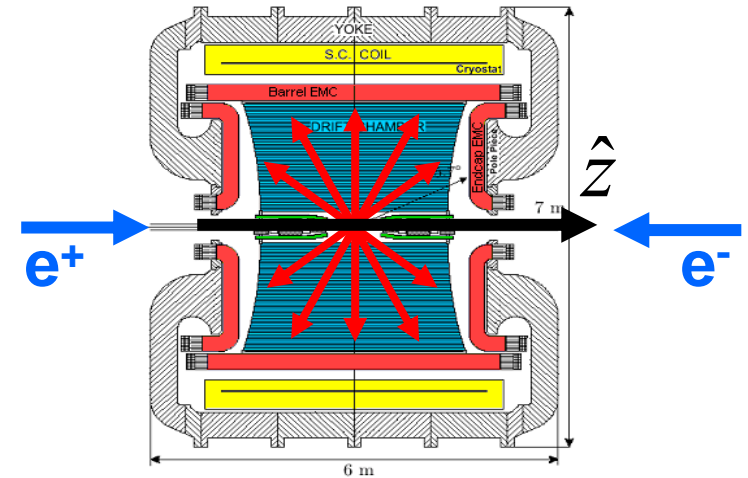
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At DAΦNE K mesons are produced with angular distribution $dN/d\Omega \propto \sin^2\theta$



Ω : Earth's sidereal frequency
 χ : angle between the z lab. axis and the Earth's rotation axis

Measurement of Δa_μ at KLOE

Δa_0 from $K_{S,L}$ semileptonic asymmetries

$A_{S,L}$ (with symmetric polar angle θ and sidereal time t integration)

$$A_S - A_L \cong \frac{4\Re(i \sin\phi_{SW} e^{i\phi_{SW}}) \gamma_K}{\Delta m} \Delta a_0$$

with $L=400 \text{ pb}^{-1}$ (preliminary):

$$\Delta a_0 = (0.4 \pm 1.8) \times 10^{-17} \text{ GeV}$$

with $L=2.5 \text{ fb}^{-1}$: $\sigma(\Delta a_0) \sim 7 \times 10^{-18} \text{ GeV}$ (Δa_0 evaluated for the first time)

$\Delta a_{x,y,z}$ from $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$
(analysis vs polar angle θ and sidereal time t)

Fit to: $I[\pi^+ \pi^- (\cos\theta > 0), \pi^+ \pi^- (\cos\theta < 0); \Delta t]$

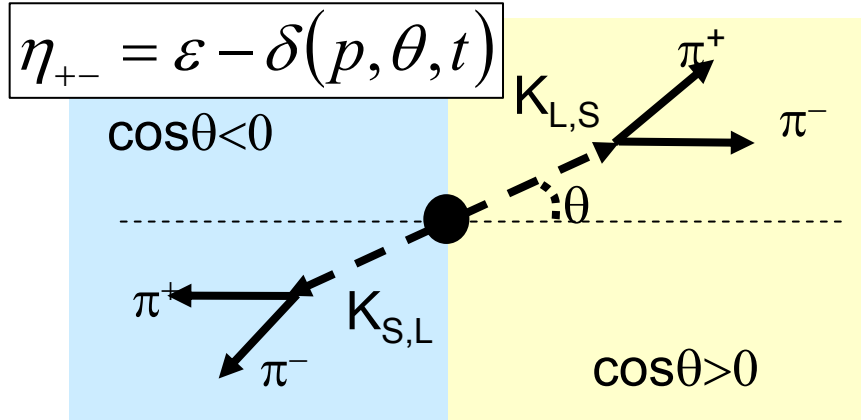
• at $\Delta t \sim \tau_s$ sensitive to $\text{Im}(\delta/\varepsilon)$

With $L=1 \text{ fb}^{-1}$ (preliminary):

$$\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18} \text{ GeV}$$



KTeV : $\Delta a_X, \Delta a_Y < 9.2 \times 10^{-22} \text{ GeV}$ @ 90% CL

BABAR $\Delta a_{x,y}^B, (\Delta a_0^B - 0.30 \Delta a_Z^B) \sim O(10^{-13} \text{ GeV})$
[PRL 100 (2008) 131802]

Measurement of Δa_μ at KLOE

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$\Delta a_{X,Y,Z}$ from $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

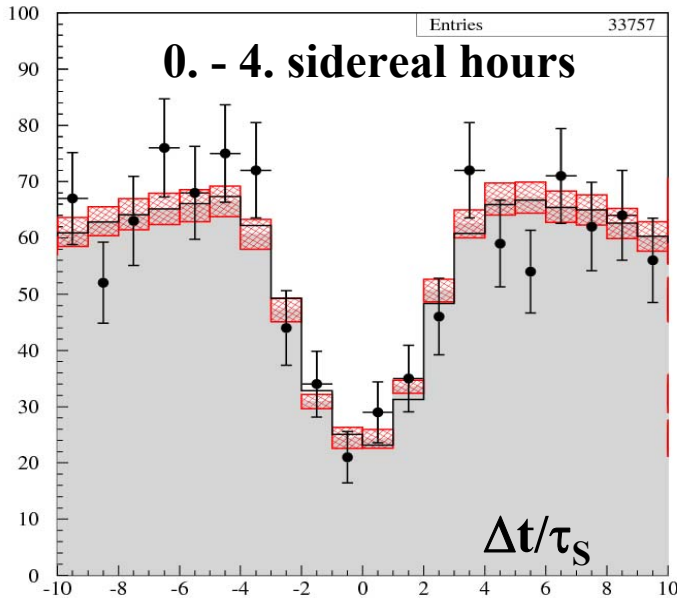
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[PRL 100 (2008) 131802]

4) Future plans

Proposals to upgrade DAΦNE in luminosity (and energy):

Crabbed waist scheme at DAΦNE (proposal by P. Raimondi)

- increase L by a factor $O(5)$
- requires minor modifications
- relatively low cost
- Experimental test at DAΦNE in progress

KLOE-2 Proposal:

- phase 0: KLOE should restart taking data mid 2009 with a minimal upgrade
- phase 1: full KLOE upgrade (KLOE-2) 2011 (?)

Physics issues:

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η, η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, muon anomaly
- (baryon electromagnetic form factors, $e^+e^- \rightarrow pp, nn, \Lambda\Lambda$)

Detector upgrade issues:

- Inner tracker R&D
- $\gamma\gamma$ tagging system
- Calorimeter, increase of granularity
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, ...)

Perspectives with KLOE-2 at upgraded DAΦNE

Mode	Test of	Param.	Present best published measurement	KLOE-2 L=50 fb ⁻¹
$K_S \rightarrow \pi e \nu$	CP, CPT	A_S	$(1.5 \pm 11) \times 10^{-3}$	$\pm 1 \times 10^{-3}$
$\pi^+ \pi^- \pi e \nu$	CP, CPT	A_L	$(3322 \pm 58 \pm 47) \times 10^{-6}$	$\pm 25 \times 10^{-6}$
$\pi^+ \pi^- \pi^0 \pi^0$	CP	$\text{Re}(\varepsilon'/\varepsilon)$	$(1.65 \pm 0.26) \times 10^{-3}$ (*)	$\pm 0.2 \times 10^{-3}$
$\pi^+ \pi^- \pi^0 \pi^0$	CP, CPT	$\text{Im}(\varepsilon'/\varepsilon)$	$(-1.2 \pm 2.3) \times 10^{-3}$ (*)	$\pm 3 \times 10^{-3}$
$\pi e \nu \pi e \nu$	CPT	$\text{Re}(\delta) + \text{Re}(x_-)$	$\text{Re}(\delta) = (0.25 \pm 0.23) \times 10^{-3}$ (*) $\text{Re}(x_-) = (-4.2 \pm 1.7) \times 10^{-3}$ (*)	$\pm 0.2 \times 10^{-3}$
$\pi e \nu \pi e \nu$	CPT	$\text{Im}(\delta) + \text{Im}(x_+)$	$\text{Im}(\delta) = (-0.6 \pm 1.9) \times 10^{-5}$ (*) $\text{Im}(x_+) = (0.2 \pm 2.2) \times 10^{-3}$ (*)	$\pm 3 \times 10^{-3}$
$\pi^+ \pi^- \pi^+ \pi^-$		Δm	$(5.288 \pm 0.043) \times 10^9 \text{ s}^{-1}$	$\pm 0.03 \times 10^9 \text{ s}^{-1}$

(*) = PDG 2008 fit

Perspectives with KLOE-2 at upgraded DAΦNE

Mode	Test of	Param.	Present best published measurement	KLOE-2 L=50 fb ⁻¹
$\pi^+\pi^- \quad \pi^+\pi^-$	QM	ζ_{00}	$(1.0 \pm 2.1) \times 10^{-6}$	$\pm 0.1 \times 10^{-6}$
$\pi^+\pi^- \quad \pi^+\pi^-$	QM	ζ_{SL}	$(1.8 \pm 4.1) \times 10^{-2}$	$\pm 0.2 \times 10^{-2}$
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & QM	α	$(-0.5 \pm 2.8) \times 10^{-17} \text{ GeV}$	$\pm 2 \times 10^{-17} \text{ GeV}$
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & QM	β	$(2.5 \pm 2.3) \times 10^{-19} \text{ GeV}$	$\pm 0.1 \times 10^{-19} \text{ GeV}$
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & QM	γ	$(1.1 \pm 2.5) \times 10^{-21} \text{ GeV}$	$\pm 0.2 \times 10^{-21} \text{ GeV}$ compl. pos. hyp. $\pm 0.1 \times 10^{-21} \text{ GeV}$
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & EPR corr.	Re(ω)	$(1.1 \pm 7.0) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & EPR corr.	Im(ω)	$(3.4 \pm 4.9) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
$K_{S,L} \rightarrow \pi e \nu$	CPT & Lorentz	Δa_0	$[(0.4 \pm 1.8) \times 10^{-17} \text{ GeV}]$	$\pm 2 \times 10^{-18} \text{ GeV}$
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$[(2.4 \pm 9.7) \times 10^{-18} \text{ GeV}]$	$\pm 7 \times 10^{-19} \text{ GeV}$
$\pi^+\pi^- \quad \pi e \nu$	CPT & Lorentz	$\Delta a_{X,Y}$	$[<10^{-21} \text{ GeV}]$	$\pm 4 \times 10^{-19} \text{ GeV}$

[....] = preliminary

Conclusions

- The neutral kaon system is an excellent laboratory for the study of CPT symmetry and the basic principles of Quantum Mechanics;
- Several parameters related to possible
 - CPT violation (within QM)
 - CPT violation and decoherence
 - CPT violation and Lorentz symmetry breakinghave been measured at KLOE, in some cases with a precision reaching the interesting Planck's scale region;
- All results are consistent with no CPT violation

- The analysis of the full KLOE data sample (2.5 fb^{-1}) is in being completed;
- KLOE and DAΦNE are going to be upgraded;
- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program