Quantum coherence and CPT symmetry tests in the neutral kaon system at KLOE

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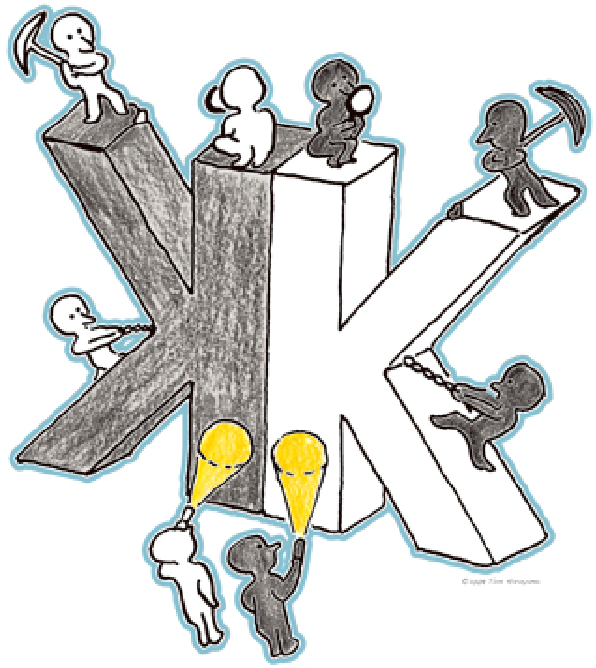
on behalf of **KLOE collaboration**



2009 Kaon International Conference, June 9th – 12th, 2009, Tsukuba, Japan

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 together with decoherence 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. :

$$\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}, \quad \left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}, \quad \left|m_p - m_{\overline{p}}\right| / m_p < 10^{-9}$$

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

CPT test: the Bell-Steinberger relation

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

CPT violation in the mixing:

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

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

$$\Delta m = m_L - m_S$$

$$\Delta\Gamma = \Gamma_S - \Gamma_L$$

$$\phi_{SW} = \arctan\left(2\Delta m/\Delta\Gamma\right)$$

Unitarity constraint: $\left|K\right\rangle = a_S\left|K_S\right\rangle + a_L\left|K_L\right\rangle$

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

Bell-Steinberger relation:

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

K_S K_L observables: they can be expressed in terms of BR's, decay amplitude ratios, Δm, lifetimes of K_S and K_L

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

Re ε = (159.6 ± 1.3) ×10^{-5}
Im δ =(0.4 ± 2.1) × 10^{-5}

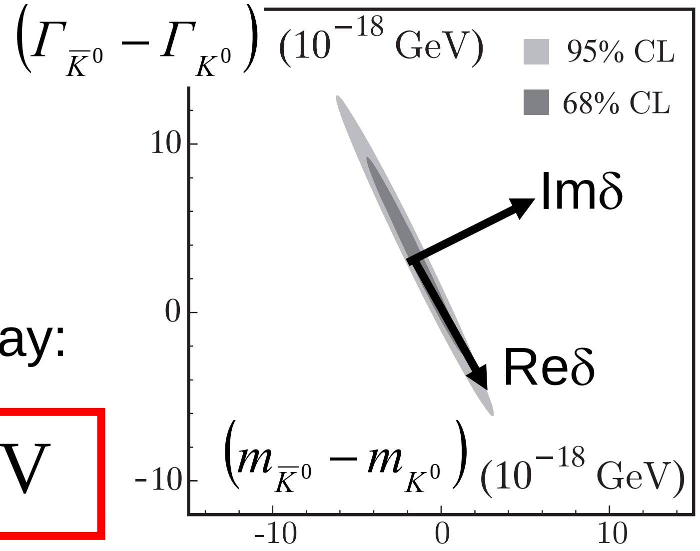
CPLEAR: study of the time evolution of neutral kaons in semileptonic decays

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

PLB444 (1998) 52

Combining Reδ and Imδ results:

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



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

$$-5.3\times10^{-19} < m_{\overline{K}^0} - m_{K^0} < 6.3\times10^{-19} \text{ GeV}$$

at 95% c.l.

CPT test: the Bell-Steinberger relation

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

$$\mathrm{Re}\,\varepsilon = (161.2 \pm 0.6) \times 10^{-5}$$
$$\mathrm{Im}\,\delta = (-0.1 \pm 1.4) \times 10^{-5}$$

(using latest KTeV results on $\phi_{\pi\pi}$)

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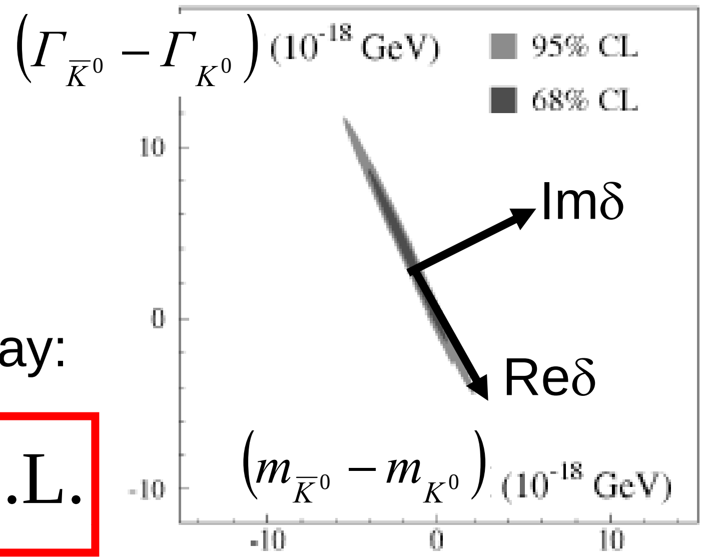


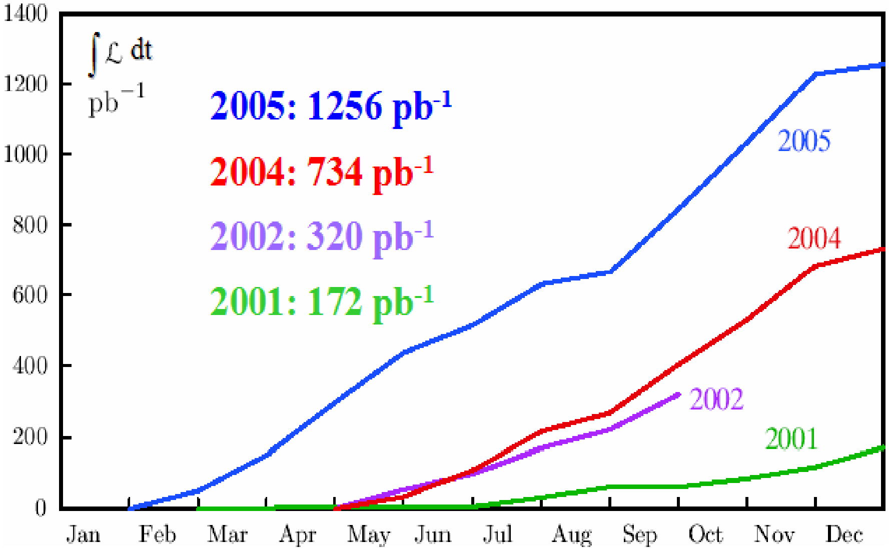
Assuming $\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right) = 0$, i.e. no CPT viol. in decay:

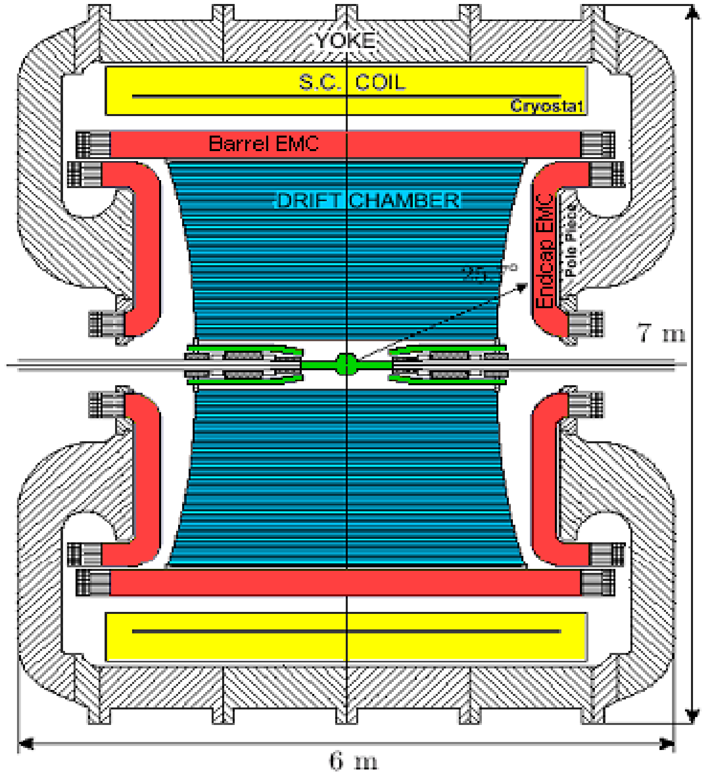
$$\left|m_{\overline{K}^0} - m_{K^0}\right| < 4.0 \times 10^{-19}\ \text{GeV at } 95\%\ \text{C.L.}$$

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

The KLOE detector at the Frascati ϕ-factory DAΦNE

Integrated luminosity (KLOE)





Lead/scintillating fiber calorimeter

drift chamber

4 m diameter × 3.3 m length

helium based gas mixture

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

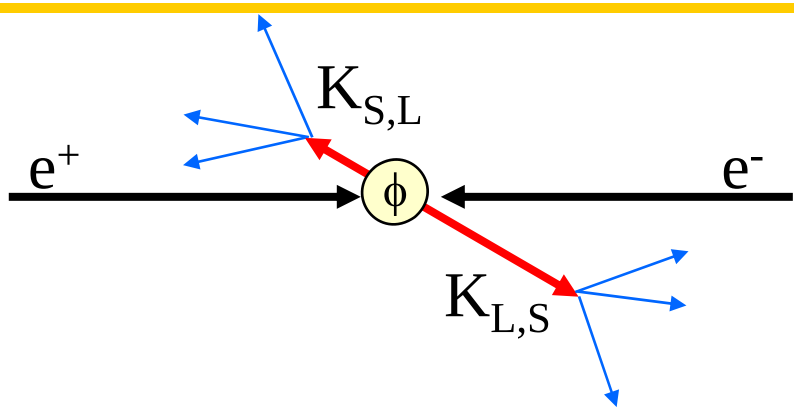
Neutral kaons at a ϕ-factory

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

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

$p_K = 110$ MeV/c

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



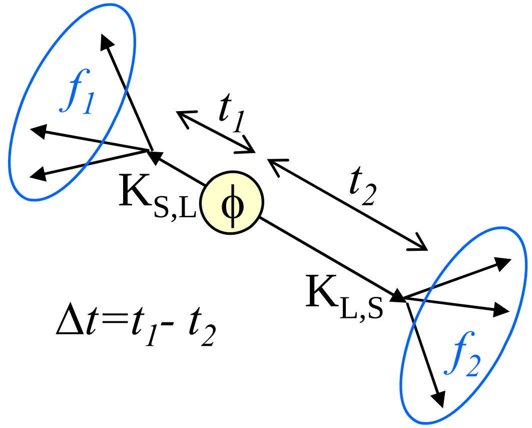
$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0(\vec{p})\right\rangle\left|\bar{K}^0(-\vec{p})\right\rangle - \left|\bar{K}^0(\vec{p})\right\rangle\left|K^0(-\vec{p})\right\rangle\right]$$

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

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

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

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:

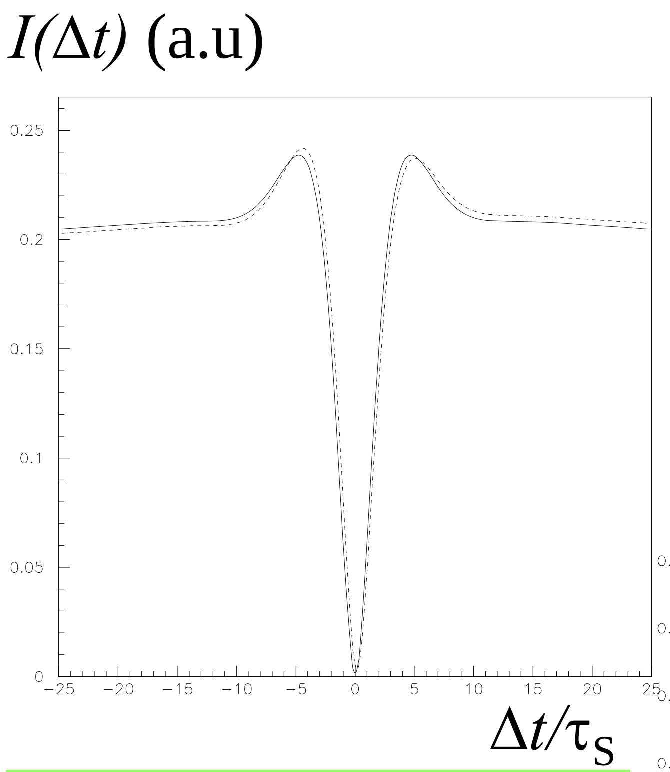
$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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

characteristic interference term at a ϕ-factory => interferometry

From these distributions for various final states f_i one can measure the following quantities: Γ_S , Γ_L , Δm , $|\eta_i|$, $\phi_i \equiv \arg(\eta_i)$

Neutral kaon interferometry: main observables



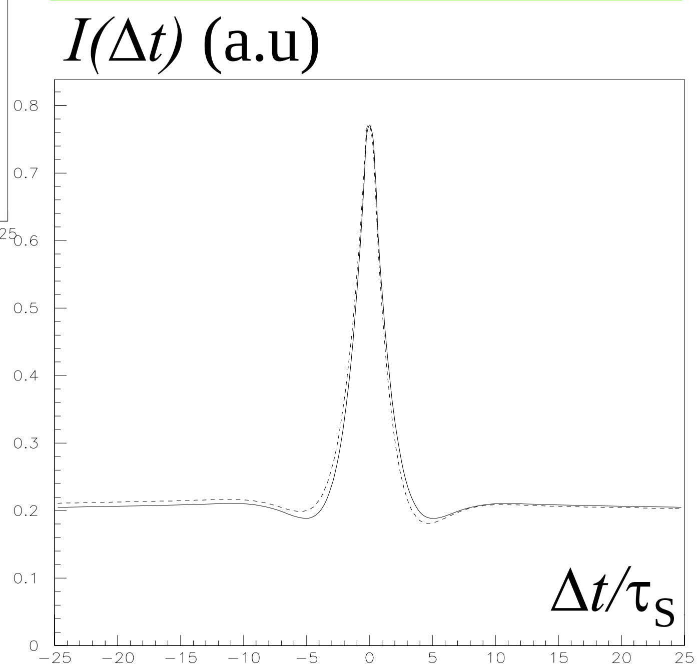
$$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \; \pi^0\pi^0$$

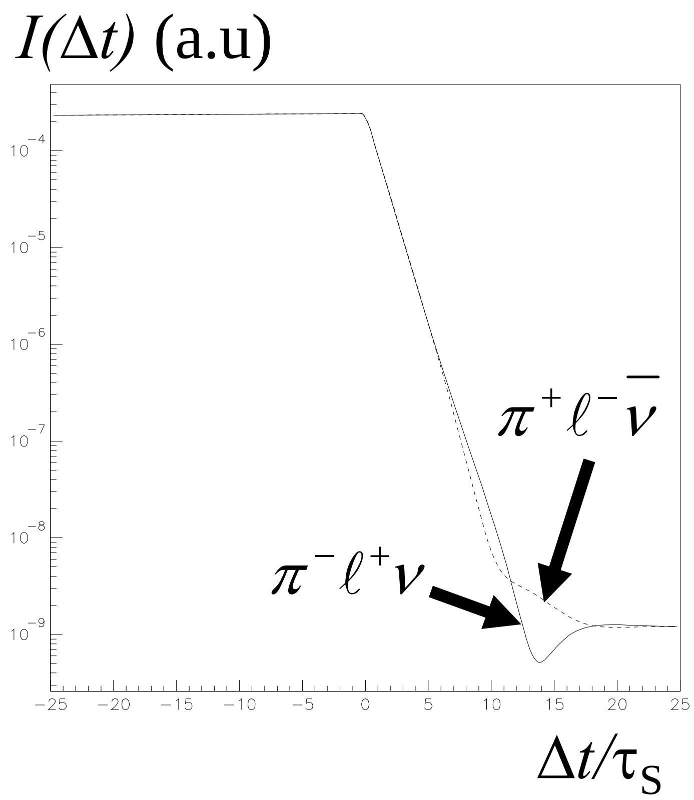
$$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

$$\Re\delta + \Re x_-$$

$$\Im\delta + \Im x_+$$

$$\phi \rightarrow K_S K_L \rightarrow \pi^+\ell^-\bar{\nu} \;\; \pi^-\ell^+\nu$$





$$\phi \rightarrow K_S K_L \rightarrow \pi\pi \;\; \pi\ell\nu$$

$$A_L = 2\Re\varepsilon - \Re\delta$$

$$- \Re y - \Re x_-$$

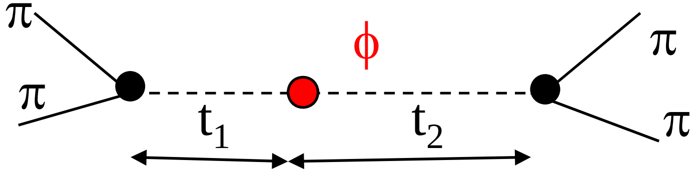
$$\phi_{\pi\pi}$$

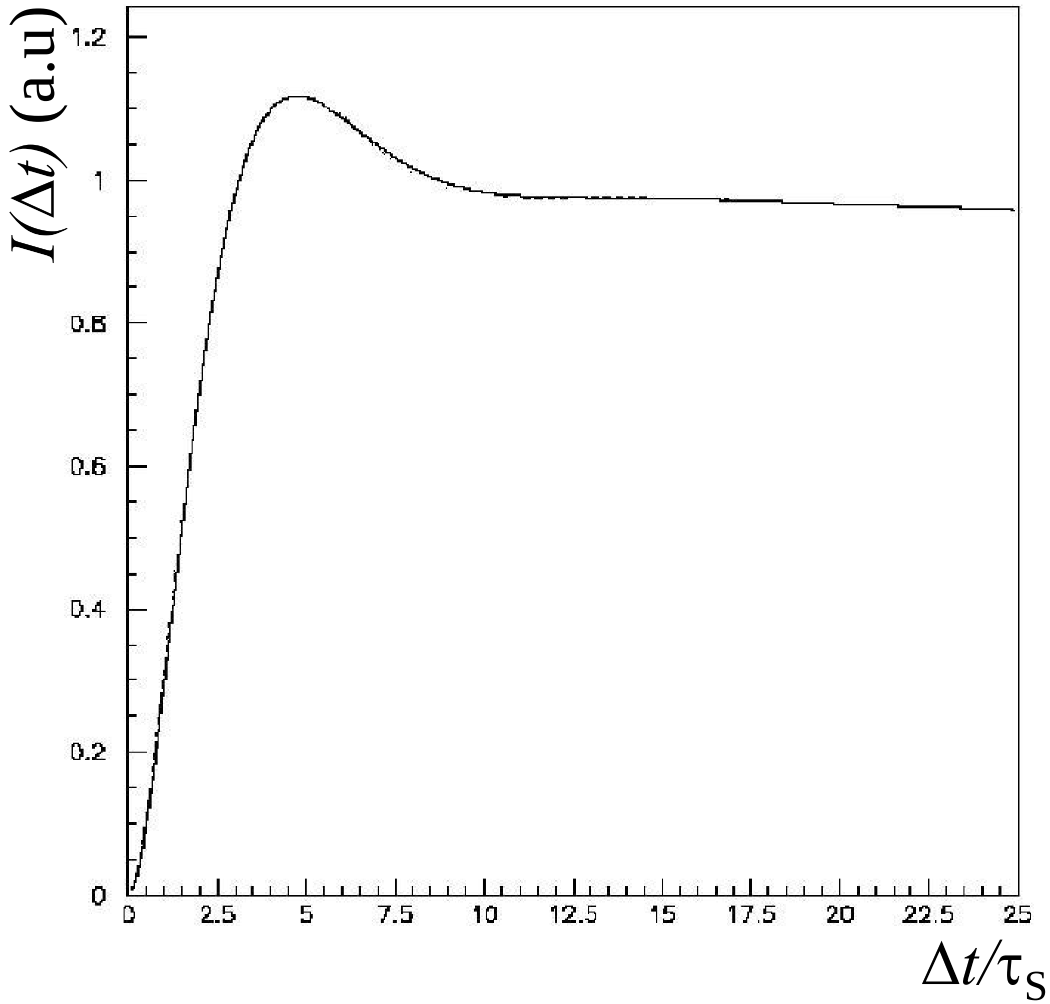
$\phi \to K_S K_L \to \pi^+\pi^- \quad \pi^+\pi^-$

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

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

$$\Delta t = |t_1 - t_2|$$





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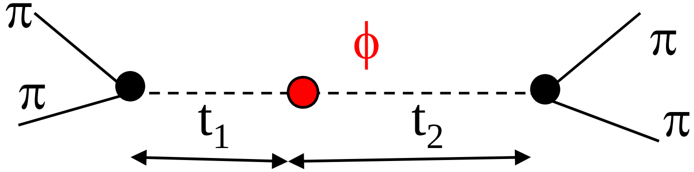
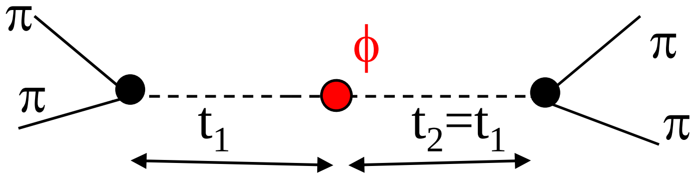
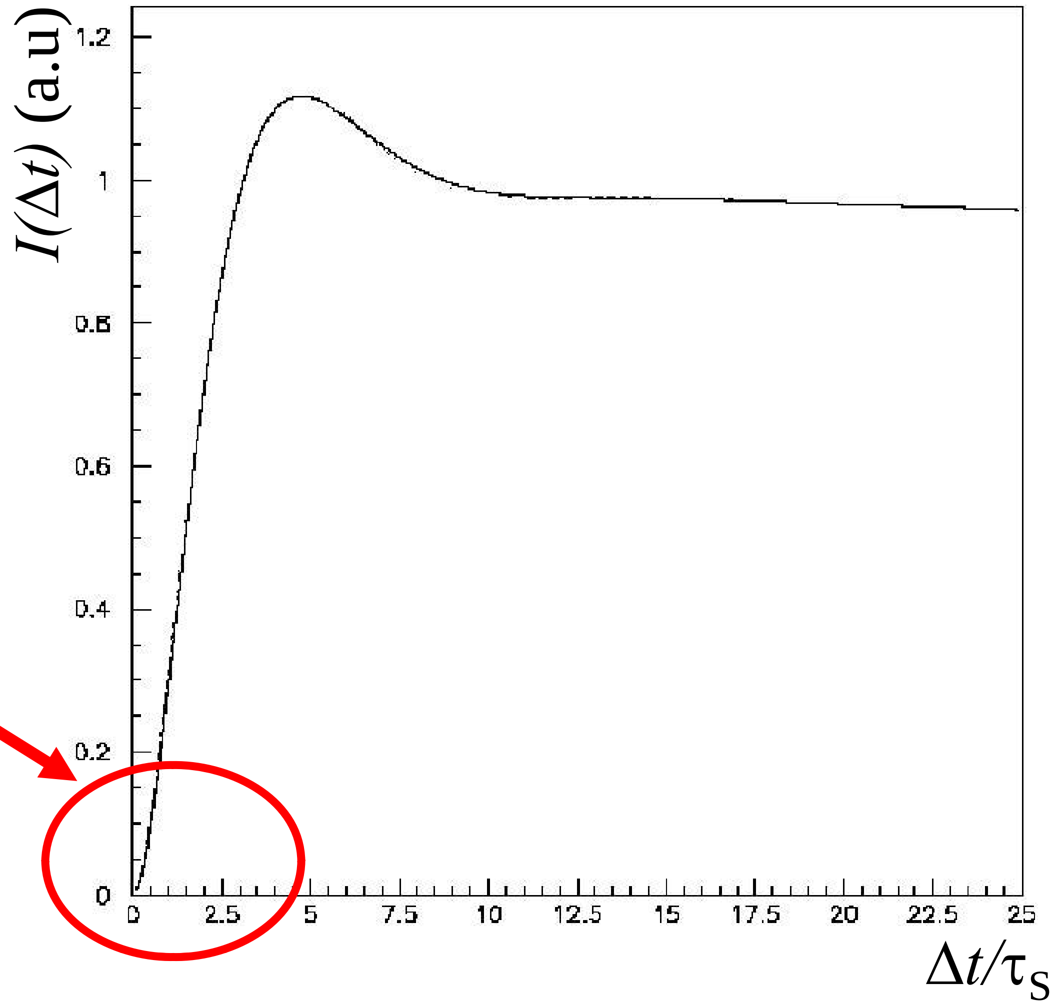


EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the destructive quantum interference





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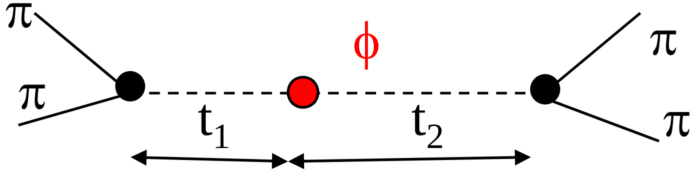

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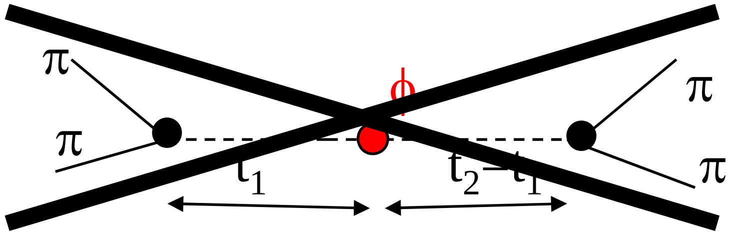
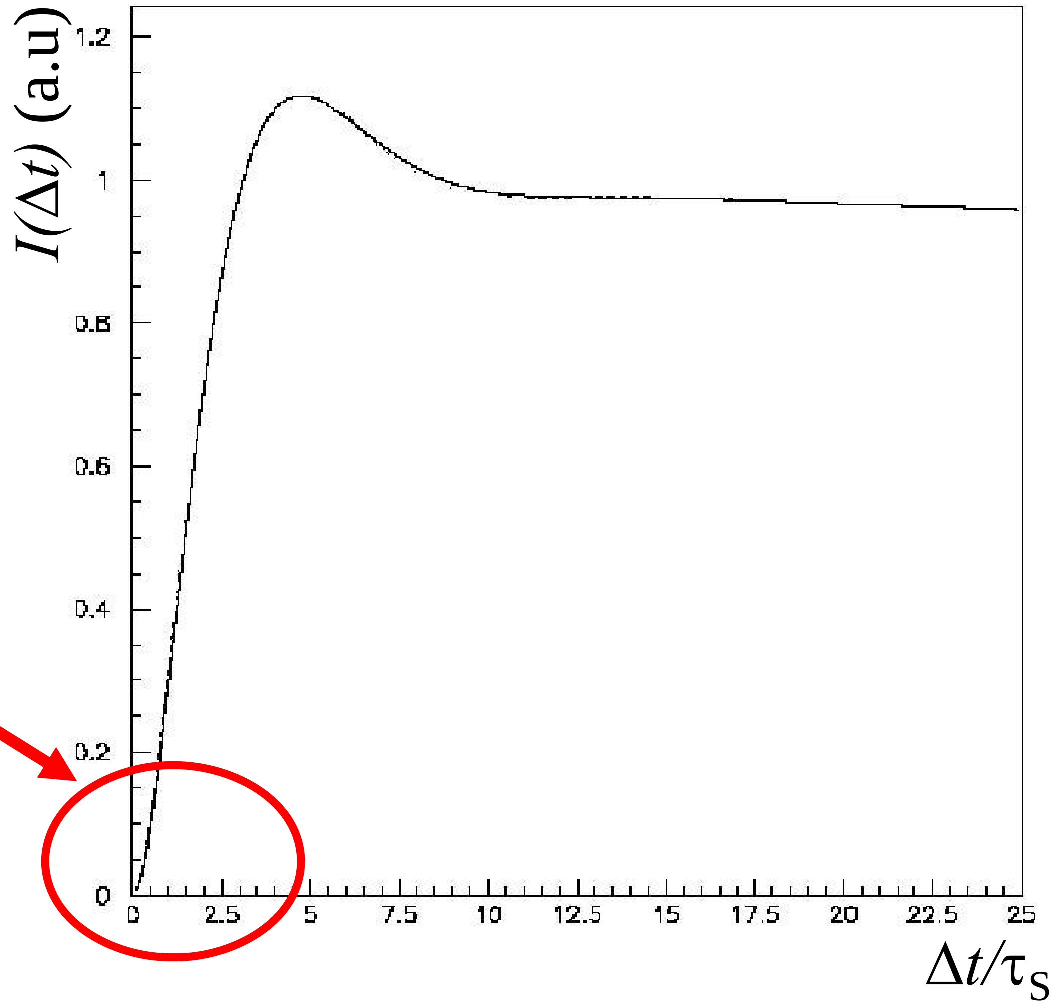


Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$



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

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

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

Feynman described the phenomenon of interference as containing "the only mistery" of quantum mechanics

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

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

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

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

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

Feynman described the phenomenon of interference as containing "the only mistery" of quantum mechanics

Decoherence parameter:

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

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

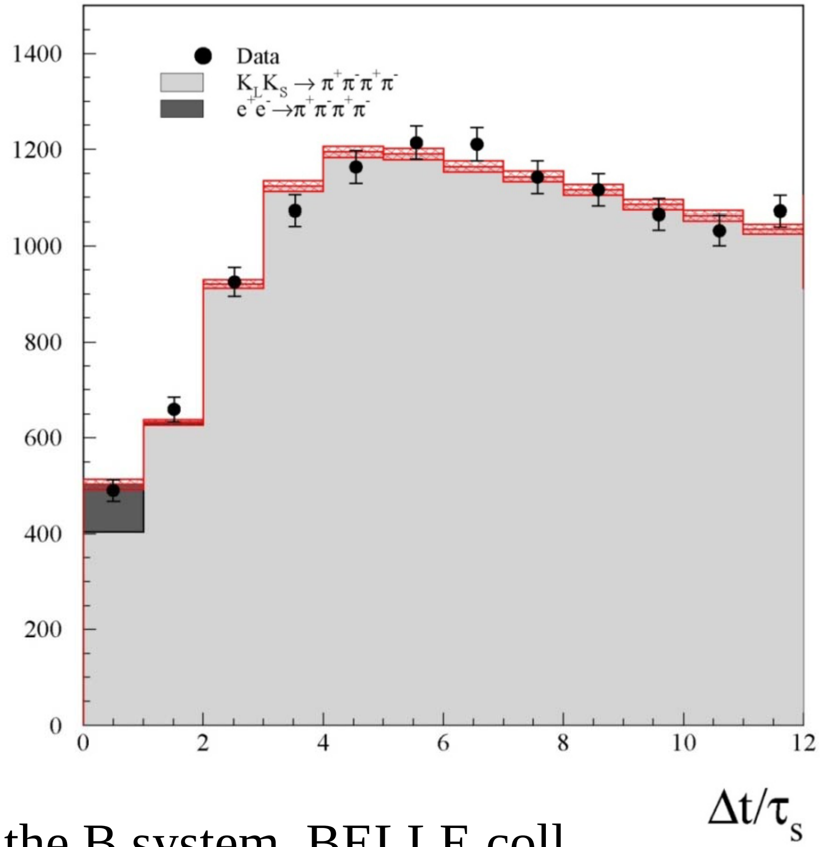
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data:
  L=1.5 fb^{-1} (2004-05 data)
- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L, Δm fixed from PDG

KLOE FINAL:

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

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



- Improvement x 2 wrt published KLOE measurement (PLB 642(2006) 315)

- From CPLEAR data $(p\bar{p})_{REST} \to K^0 \overline{K}^0$ Bertlmann et al. obtain (PR D60 (1999) 114032):

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

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

$$\zeta^B_{0\bar{0}} = 0.029 \pm 0.057$$

- Comparison with quantum optics tests: precision O(10^{-3})

Decoherence and CPT violation

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

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

extra term inducing decoherence:
pure state => mixed state

Decoherence and CPT violation

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

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pure state => mixed state

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:

$$L(\rho) = L(\rho; \alpha, \beta, \gamma)$$

$$\alpha, \gamma > 0 \quad , \quad \alpha\gamma > \beta^2$$

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

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

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

CPLEAR PLB 364, 239 (1999)

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

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

In the complete positivity hypothesis

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

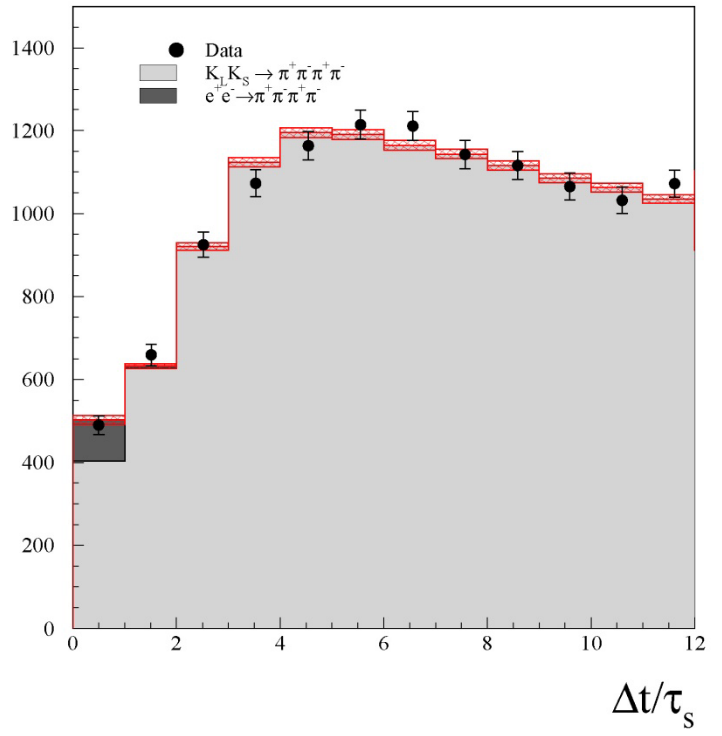
=> only one independent parameter: γ

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

KLOE FINAL L=1.5 fb^{-1}

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

- Improvement x 2 wrt published KLOE



$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: 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]:

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

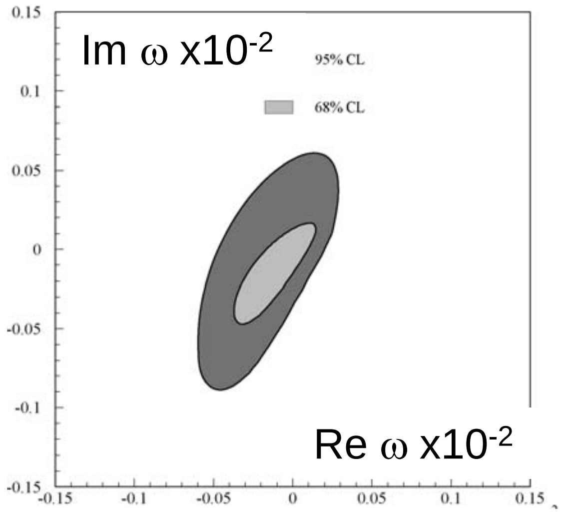
$|\omega|$ could be at most: $$|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}$$

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

L=1.5 fb^{-1}

KLOE FINAL :

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$
$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$
$$|\omega| < 1.0\times 10^{-3} \quad \text{at } 95\%\ \text{C.L.}$$



-Improvement x 2 wrt published KLOE

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

$$-0.0084 \le \Re\omega \le 0.0100 \quad \text{at } 95\%\ \text{C.L.}$$

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)

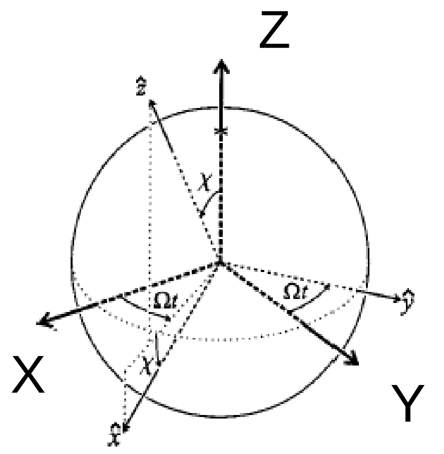
Standard Model Extension (SME)

[Kostelecky PRD61 (1999) 016002, PRD 64 (2001) 076001]

CPT violation in neutral kaons according to SME: only in mixing, not in decay.

• **δ cannot be a constant (momentum dependence)**

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



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

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

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

Ω: Earth's sidereal freq.
χ: angle bet. the z lab. axis and the Earth's rotat. axis
θ: kaon polar angle in the lab.

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)

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

with L=400 pb^{-1} (**preliminary**):

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

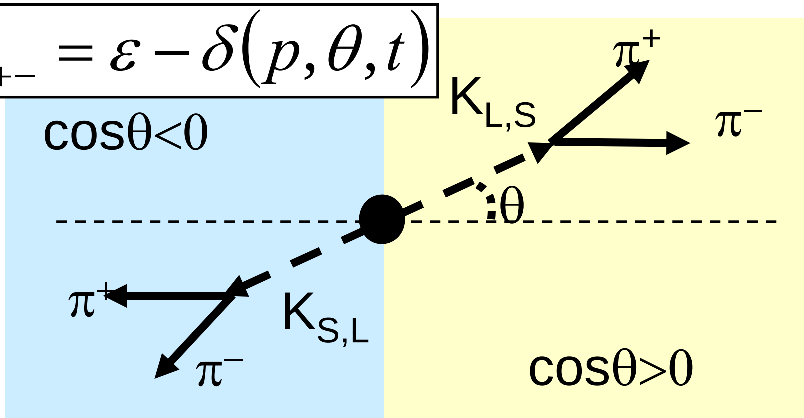
with L=2.5 fb^{-1} : $\sigma(\Delta a_0)$ ~ 7×10^{-18} GeV (Δa_0 evaluated for the first time)

$\Delta a_{X,Y,Z}$ from $\phi \to K_S K_L \to \pi^+\pi^-\ \pi^+\pi^-$
(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 Im(δ/ε)

$$\eta_{+-} = \varepsilon - \delta(p,\theta,t)$$



With L=1 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 : Δa_X, Δa_Y < 9.2×10^{-22}GeV @ 90% CL

BABAR $\Delta a^B_{x,y}$, $(\Delta a^B_0 - 0.30\ \Delta a^B_Z)$ ~O(10^{-13} GeV)
[PRL 100 (2008) 131802]

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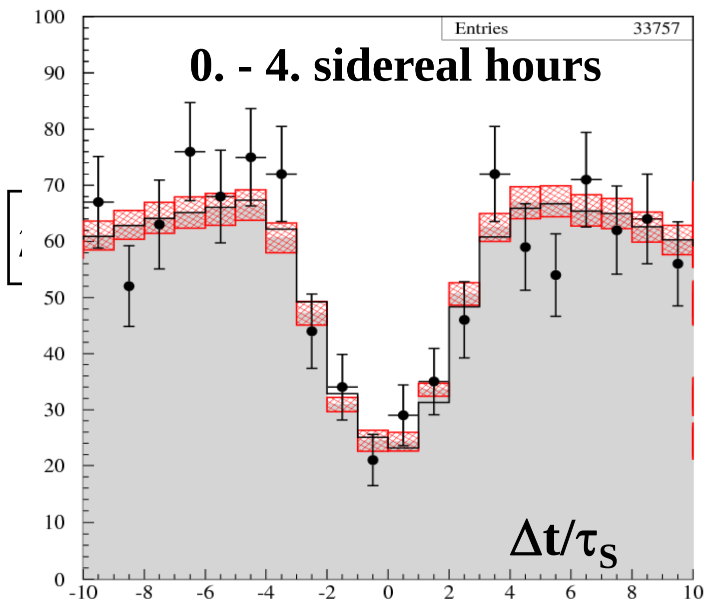
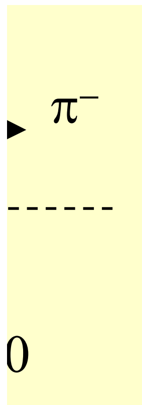
d sidereal time t)

$s\theta<0);\Delta t]$





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

BABAR $\Delta a^B_{x,y}$, $(\Delta a^B_0 - 0.30\ \Delta a^B_Z)$ ~O(10^{-13} GeV) [PRL 100 (2008) 131802]

4) Future plans

KLOE-2 at upgraded DAΦNE

Upgrade of DAΦNE in luminosity:

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

- increase L by a factor *O*(5)
- requires minor modifications
- relatively low cost

- Successful experimental test at DAΦNE

see Branchini's talk

KLOE-2 Plan:
- phase 0: KLOE restart taking data end 2009 with a minimal upgrade (L~5 fb^{-1})
- phase 1: full KLOE upgrade (KLOE-2) > 2011 (L>20 fb^{-1})

Physics issues:

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, γγ physics
- Hadron cross section at low energy, muon anomaly

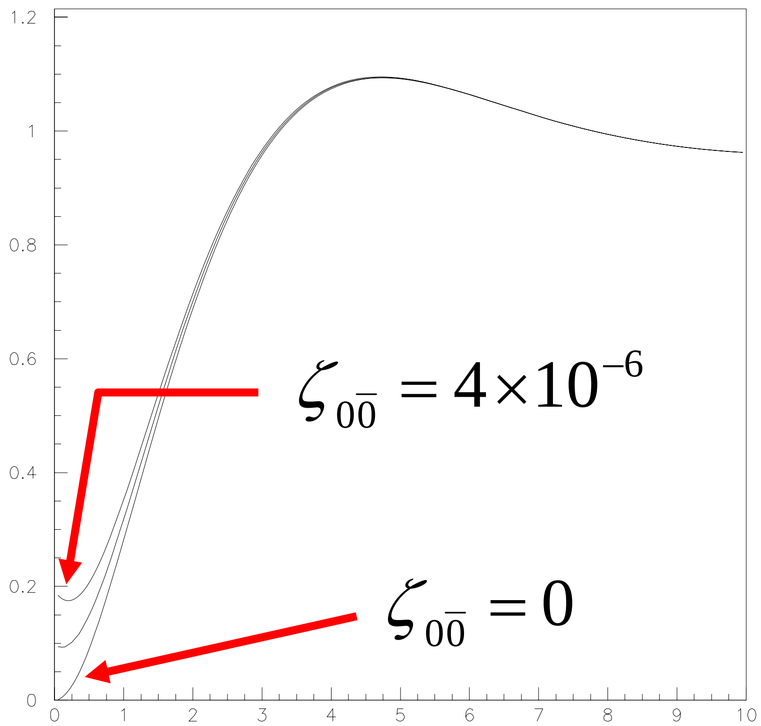
Detector upgrade issues:

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

Interferometry at KLOE-2: $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

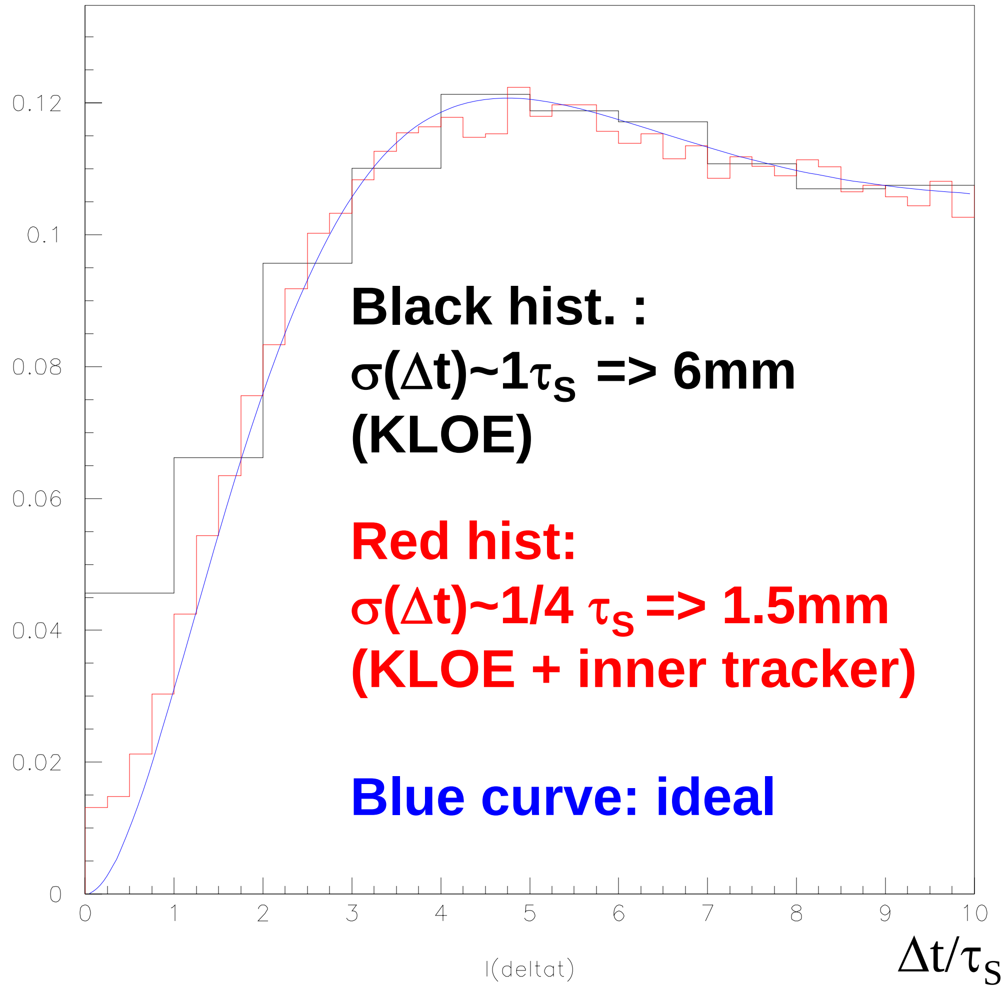
Possible signal of decoherence concentrated at very small Δt

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



Theoretical distribution

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



Black hist. :
$\sigma(\Delta t)\sim1\tau_S$ => 6mm (KLOE)

Red hist:
$\sigma(\Delta t)\sim1/4\ \tau_S$ => 1.5mm (KLOE + inner tracker)

Blue curve: ideal

Reconstructed distribution (MC)

Perspectives with KLOE-2 at upgraded DAΦNE

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

(*) = PDG 2008 fit

Perspectives with KLOE-2 at upgraded DAΦNE

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

  have been recently measured at KLOE, in same 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 is completed (apart CPTV and LV);
- KLOE and DAΦNE are going to be upgraded
- KLOE (KLOE-2) will restart taking data at the end of this year
- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program
- Other interesting QM tests possible, e.g. quantum eraser.