CPT and QM tests using kaon Interferometry

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Heavy Quarks and Leptons
June 5-9, 2008 - School of Physics, University of Melbourne, Melbourne, Australia

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 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.

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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.

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

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

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

CPT test: the Bell-Steinberger relation

CPT violation in the mixing

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

$$\varepsilon_{S,L} = \varepsilon \pm \delta \qquad \delta = \frac{1}{2}\frac{\left(m_{\overline{K}^0} - m_{K^0}\right) - \left(i/2\right)\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

$$\Delta m = m_L - m_S$$

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

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

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

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

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

K_S K_L observables

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}	$((-2 \pm 7) + i(-2 \pm 9)) \times 10^{-3}$	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

$$\mathbf{Re}\,\varepsilon = (159.6 \pm 1.3) \times 10^{-5}$$
$$\mathbf{Im}\,\delta = (0.4 \pm 2.1) \times 10^{-5}$$

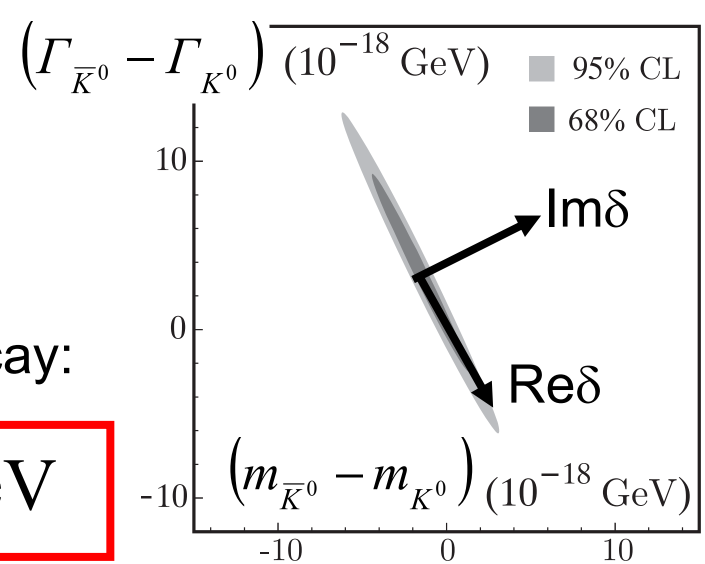
CPLEAR: study of the time evolution of neutral kaons in semileptonic decays

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

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:

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

at 95% c.l.

CPT test: the Bell-Steinberger relation

PDG 2007 fit:

Re ε = $(161.2 \pm 0.6) \times 10^{-5}$
Im δ = $(-0.6 \pm 1.9) \times 10^{-5}$

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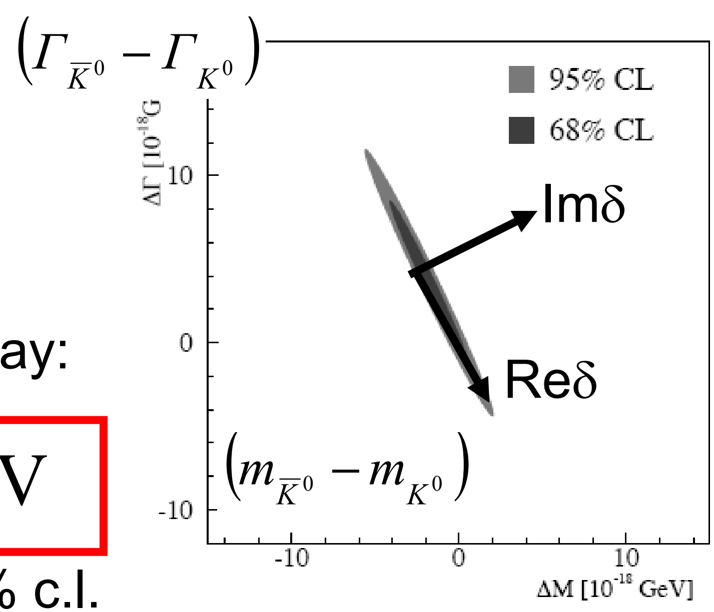

Assuming $\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right) = 0$, i.e. no CPT viol. in decay:

$$-5.1 \times 10^{-19} < m_{\overline{K}^0} - m_{K^0} < 5.1 \times 10^{-19} \text{ GeV}$$

at 95% c.l.

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Re ε = (161.2 ± 0.6) ×10^{-5}
Im δ =(–0.6 ± 1.9) × 10^{-5}

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Now main limitation comes from uncertainty on ϕ_{+-}
(expected improvement using new KTeV results)

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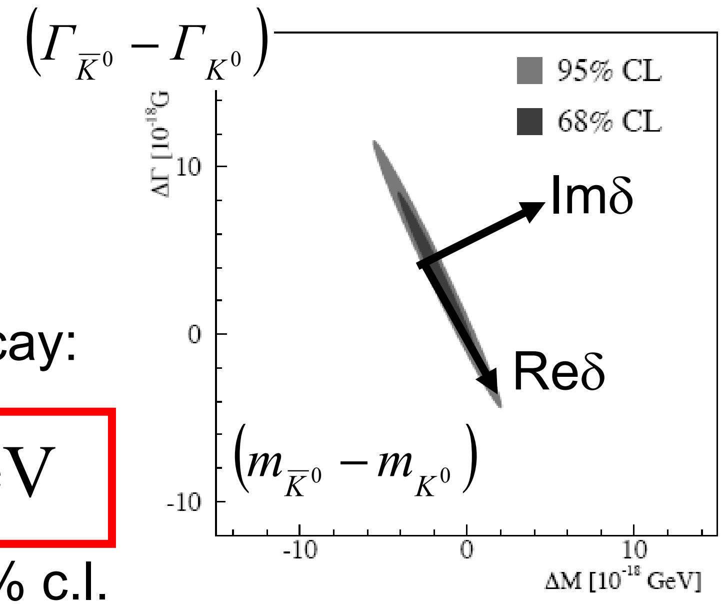

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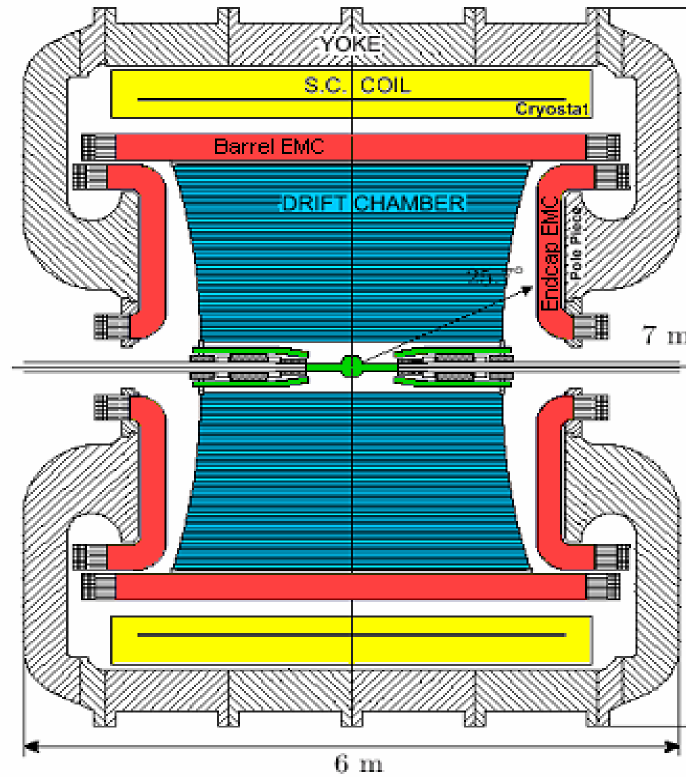
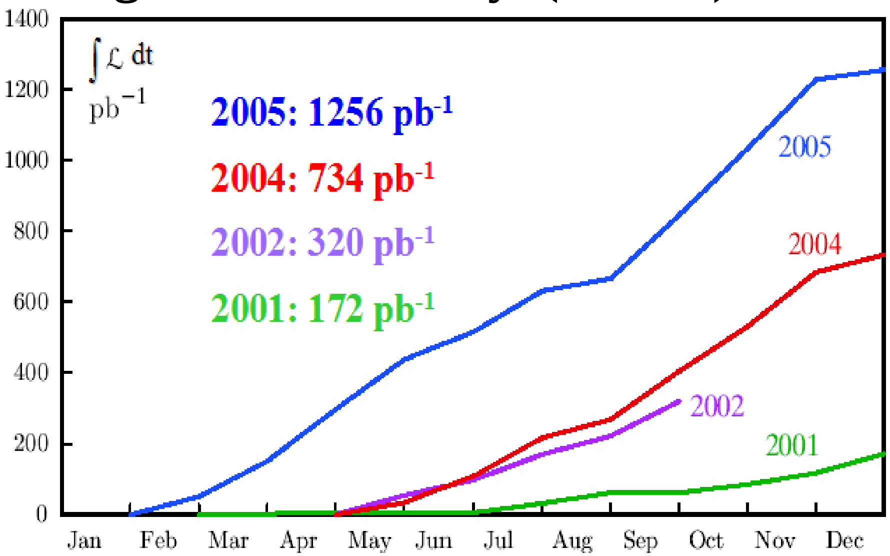
2) Tests of QM and CPT symmetry in the neutral kaon system

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

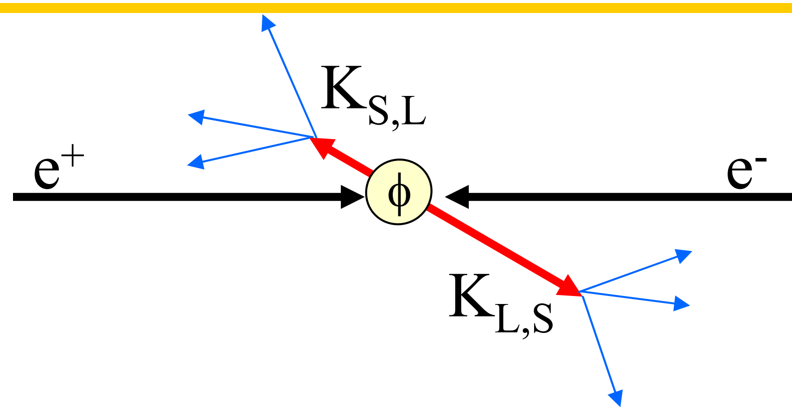
helium based gas mixture

Total KLOE $\int \mathcal{L}\, dt \sim 2.5\ \mathrm{fb}^{-1}$

(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:



- $e^+e^- \to \phi \qquad \sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ 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 $J^{PC} = 1^{--}$:

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

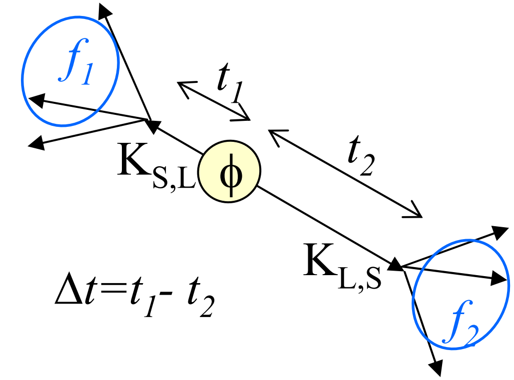
$p_K = 110$ MeV/c

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

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

The detection of a kaon at large (small) times tags a K_S (K_L)
$\Rightarrow$ possibility to select a pure K_S beam (**unique** 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:

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

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

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

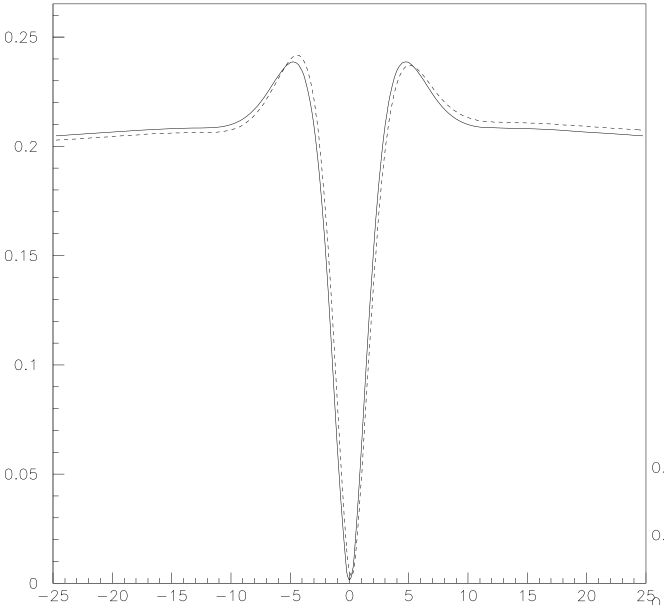
$$C_{12} = \frac{|N|^2}{2}\left|\langle f_1|T|K_S\rangle\langle f_2|T|K_S\rangle\right|^2$$

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

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



$\Delta t/\tau_S$

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

$$\phi \to K_S K_L \to \pi^+\ell^-\overline{\nu} \;\; \pi^-\ell^+\nu$$

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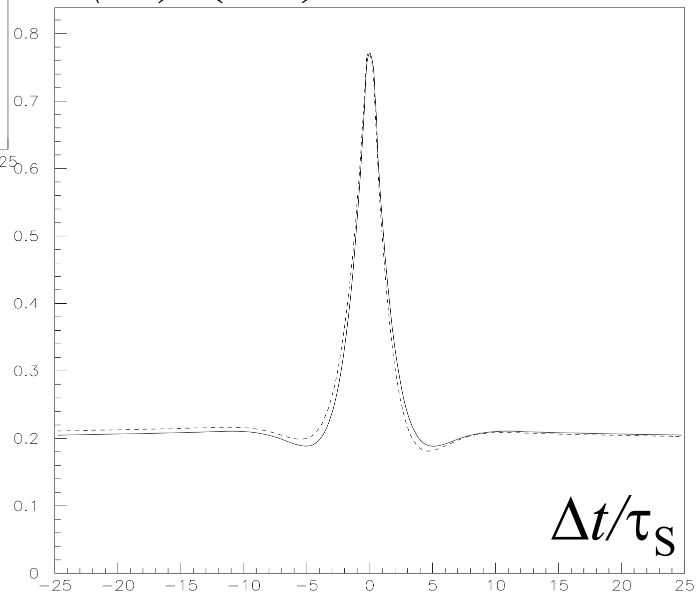

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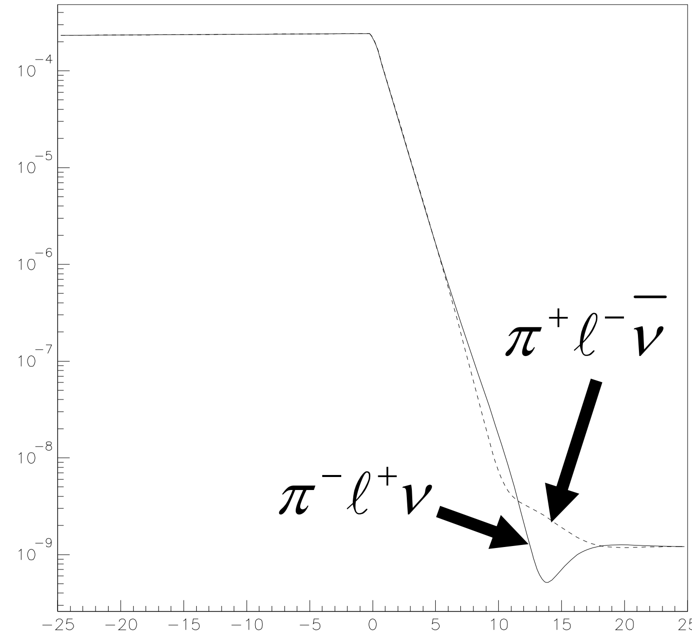

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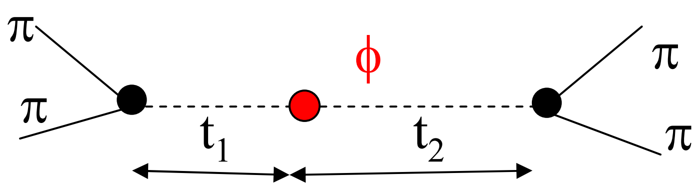
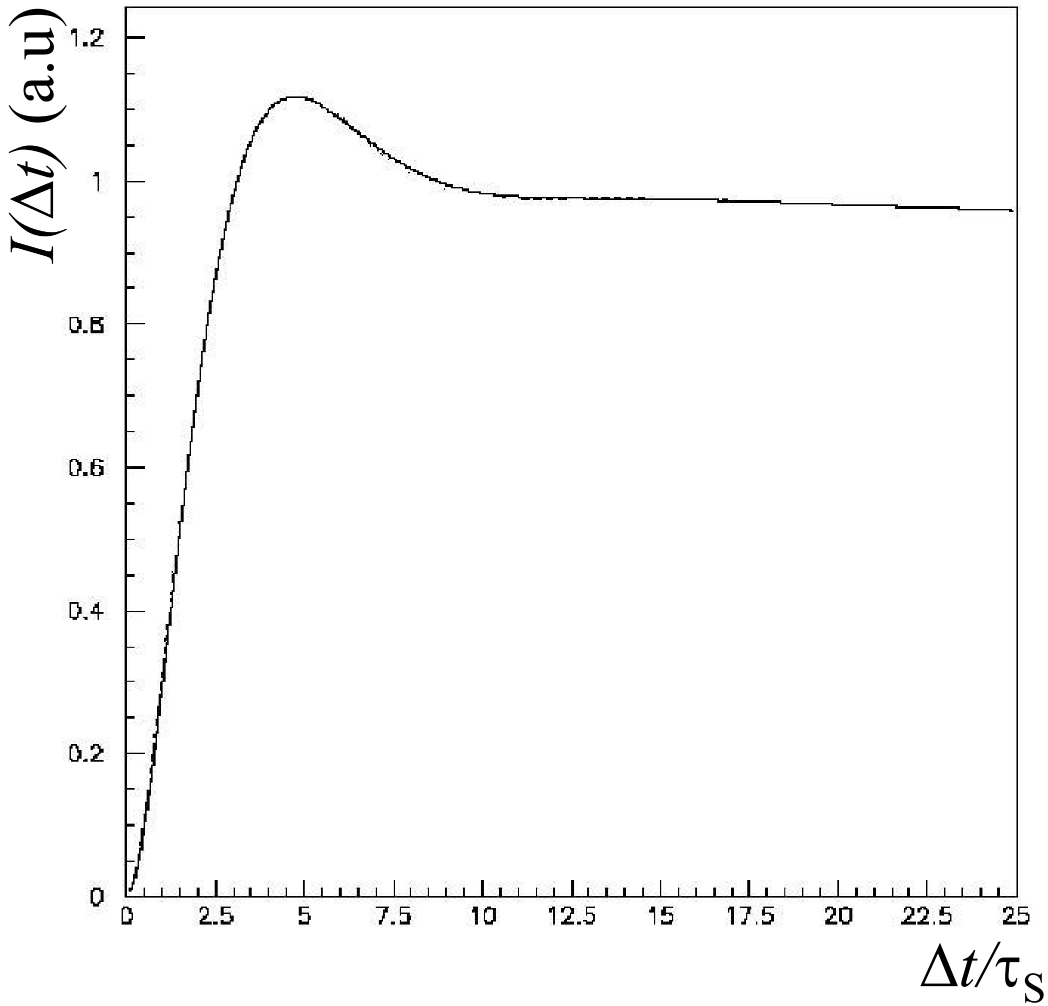
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \quad \pi^+\pi^-$

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

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

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





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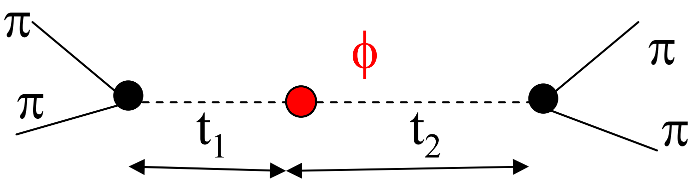
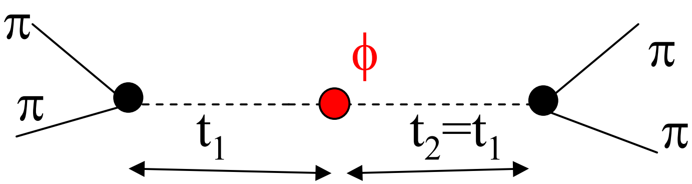
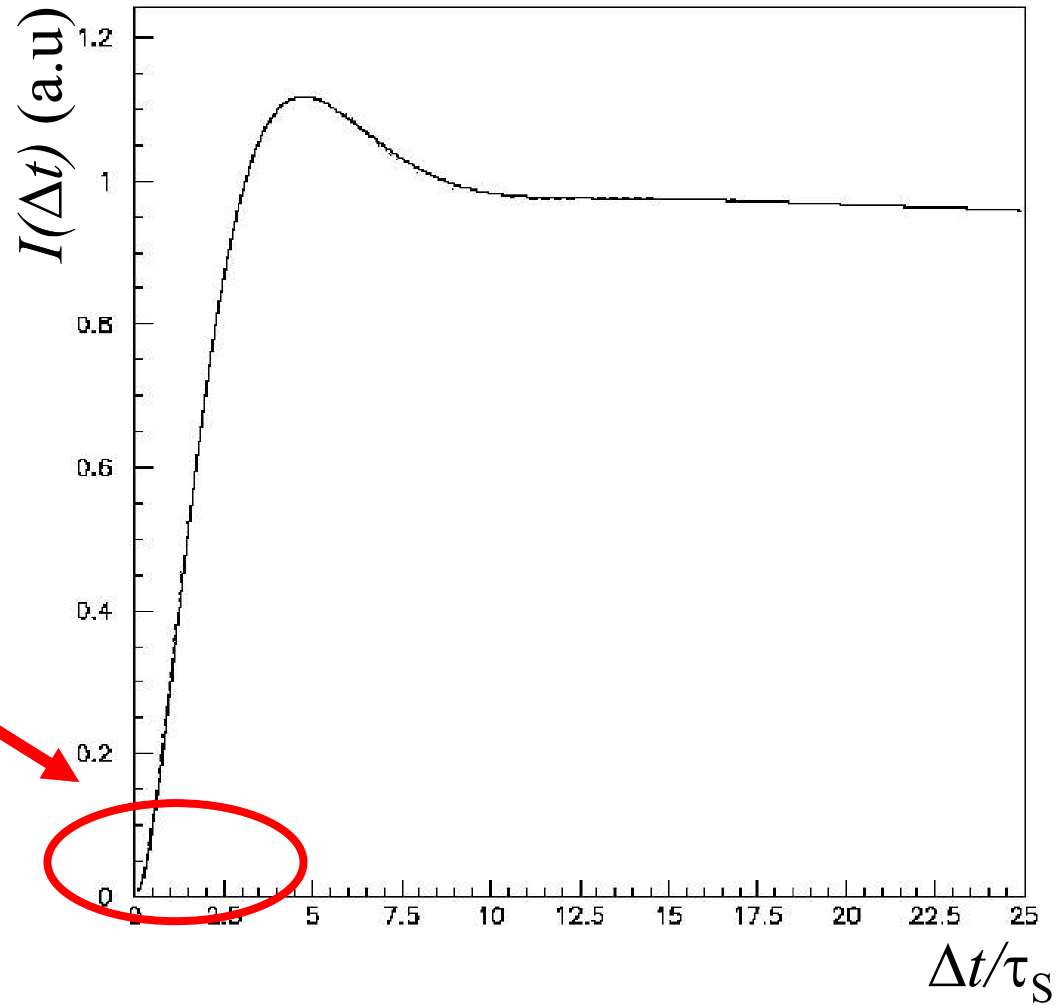


EPR correlation:

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





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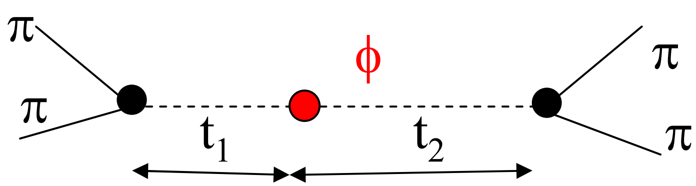

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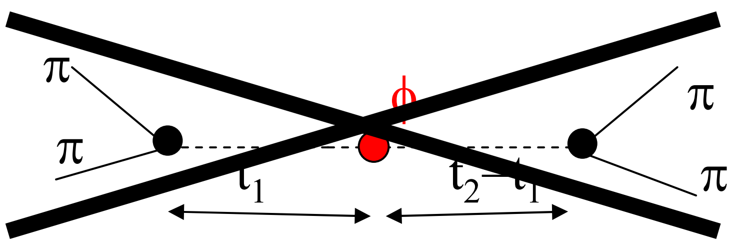

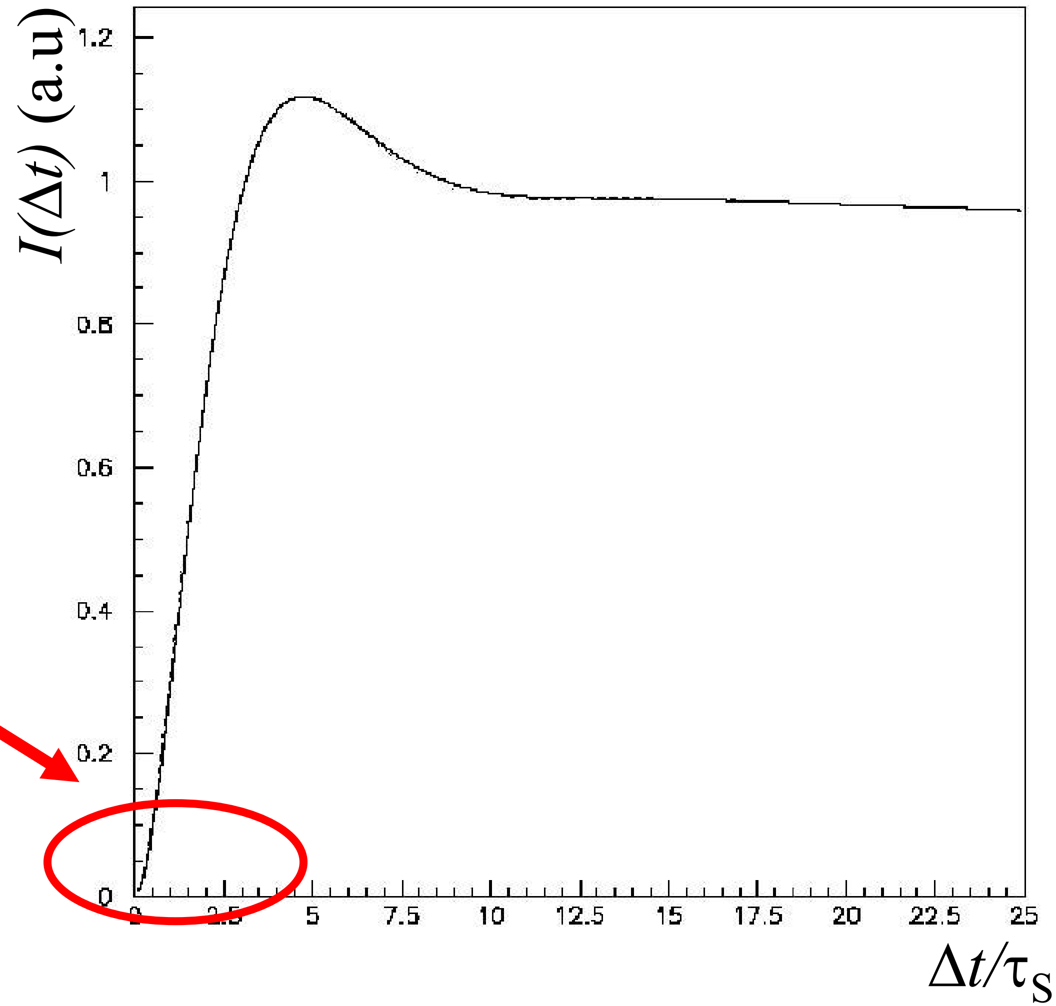

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

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

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

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

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

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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]

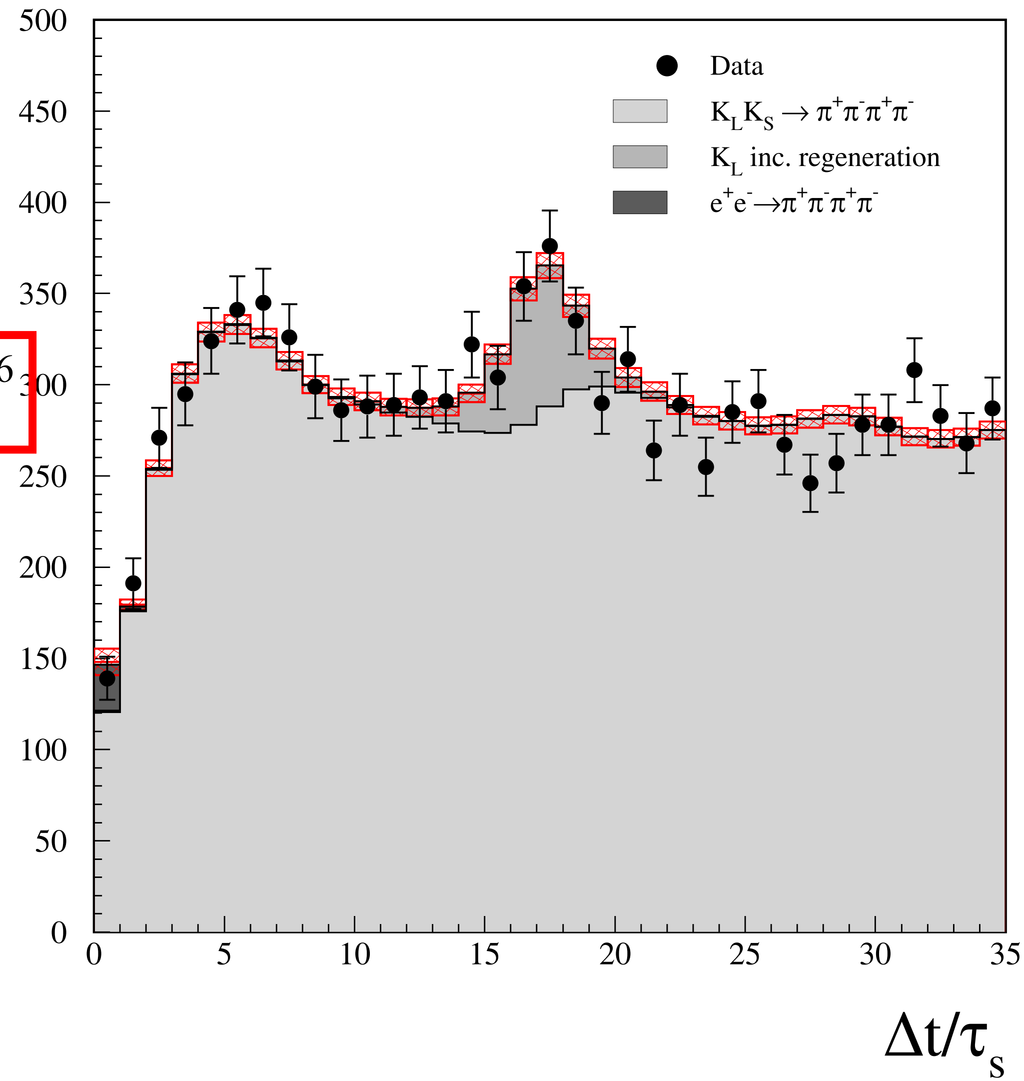
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data: L=380 pb^{-1}
- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L, Δm fixed from PDG

KLOE result: PLB 642(2006) 315

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

as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
=> 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. (PRL 99 (2007) 131802) obtains:

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

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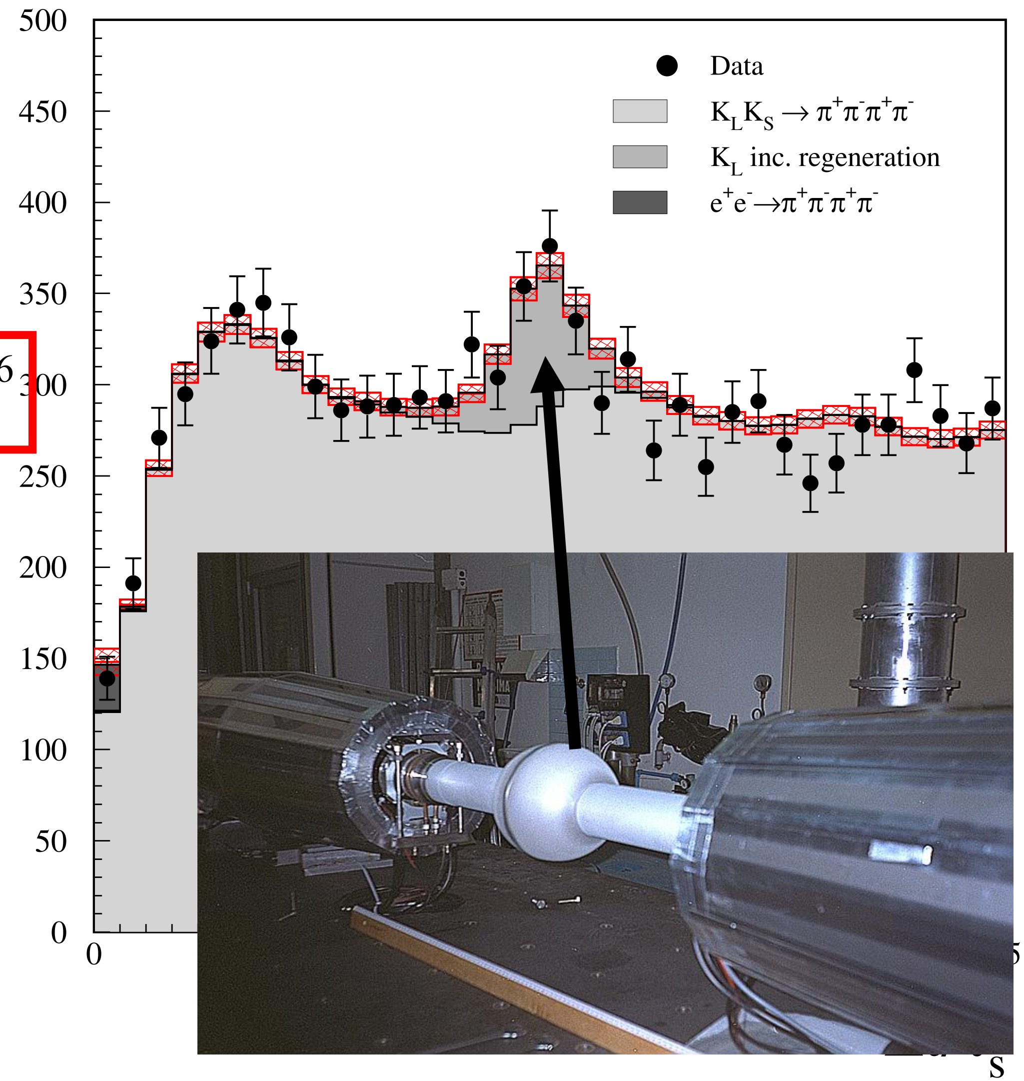

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$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$

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

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

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

- Analysed data: L=380 pb^{-1}
- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L, Δm fixed from PDG

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

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

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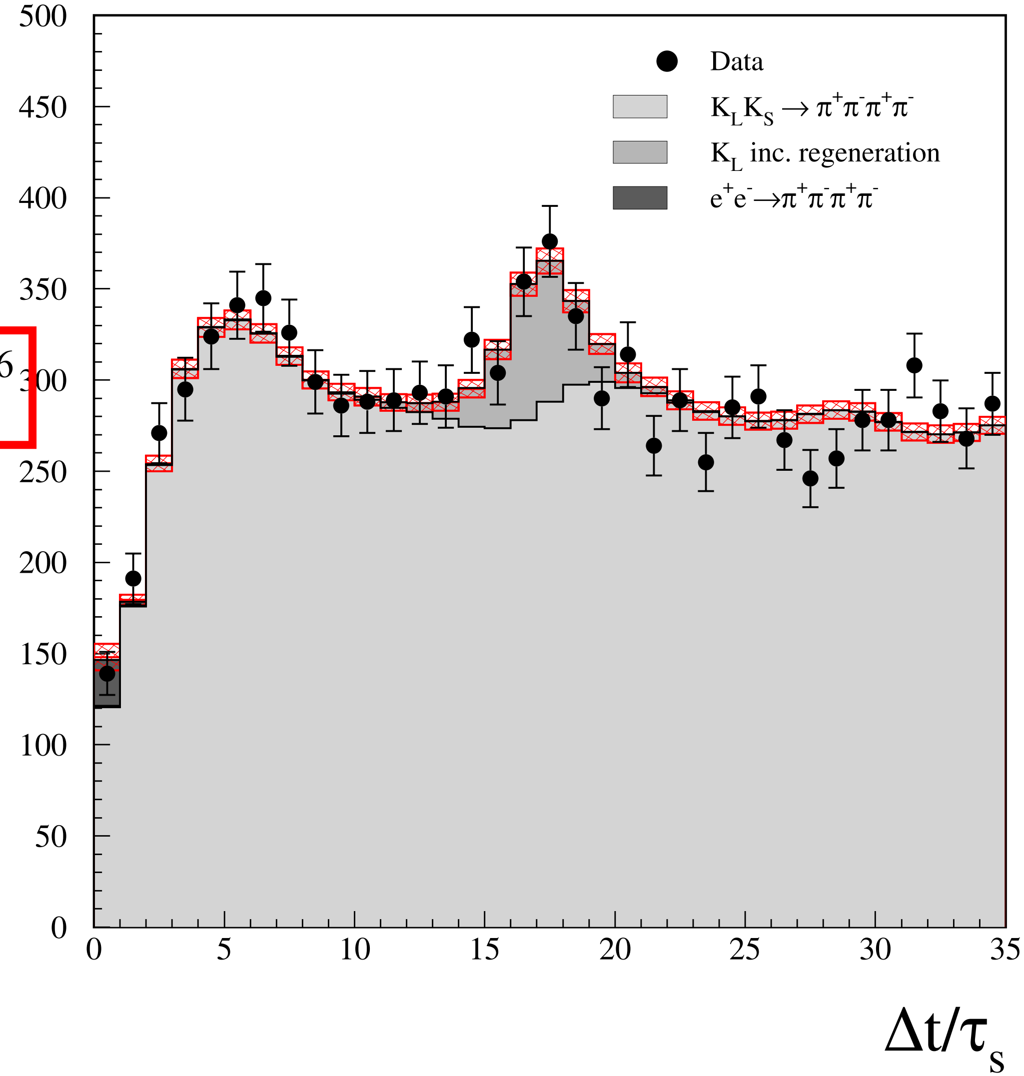


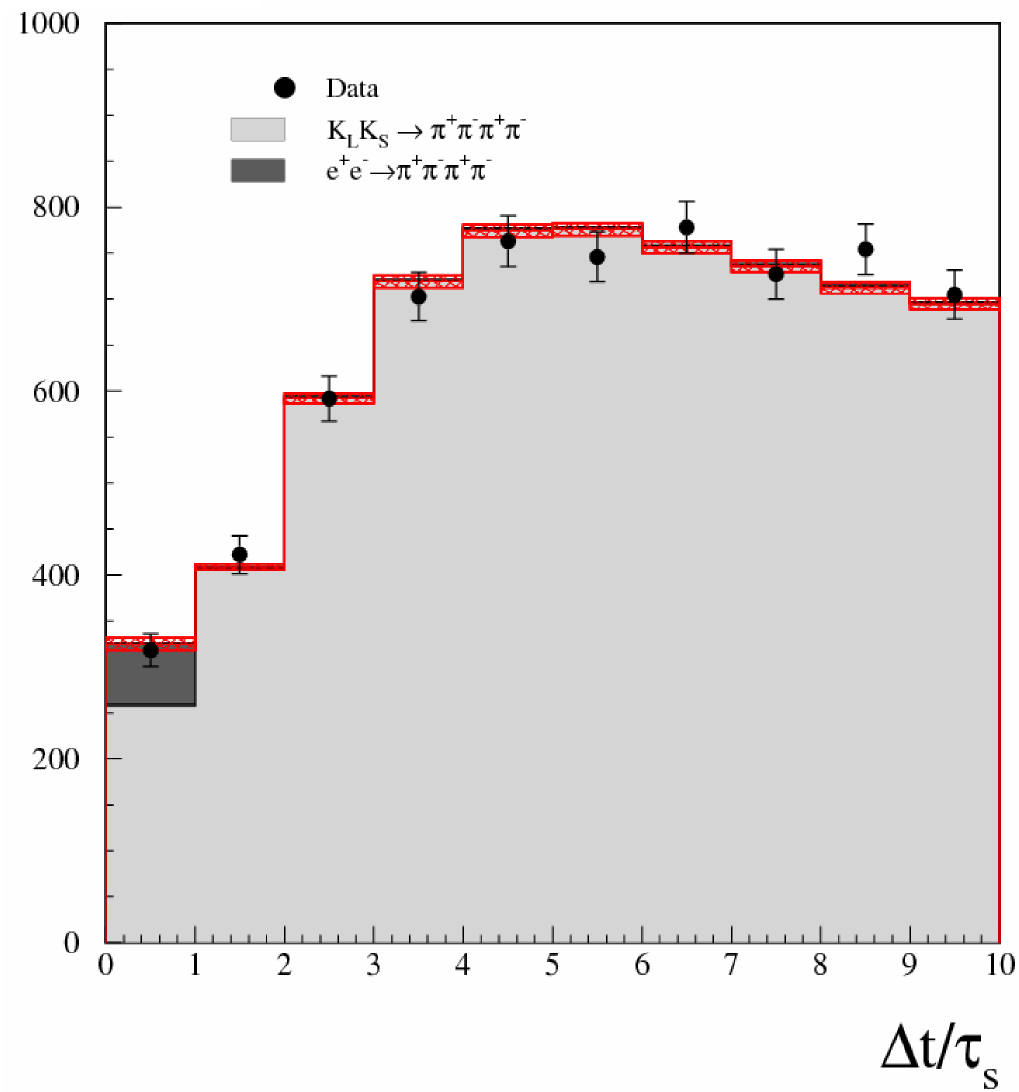
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data: L=1 fb^{-1} (2005 data)
- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L, Δm fixed from PDG

KLOE preliminary:

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

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



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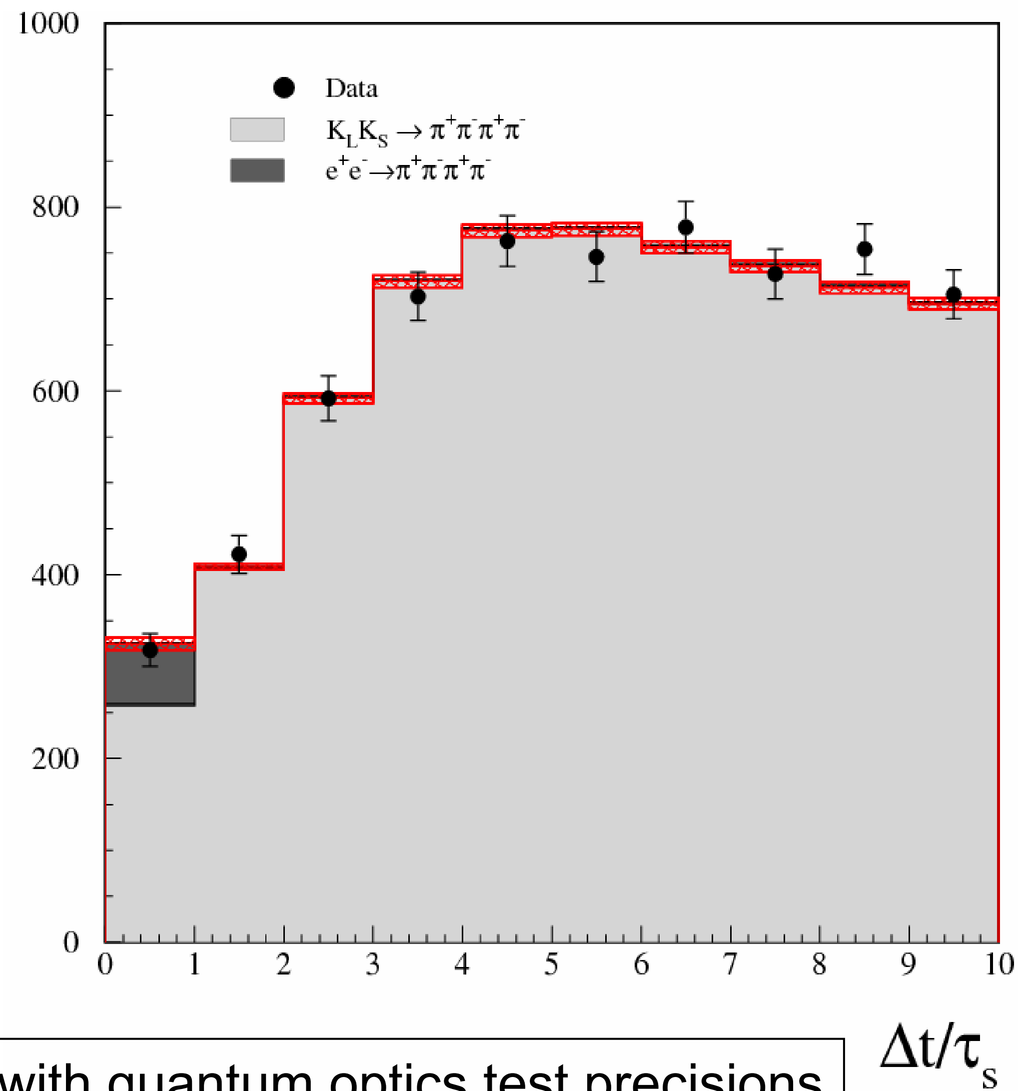

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Comparison with quantum optics test precisions

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

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extra term inducing decoherence: 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 π+π− and semileptonic final state

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

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

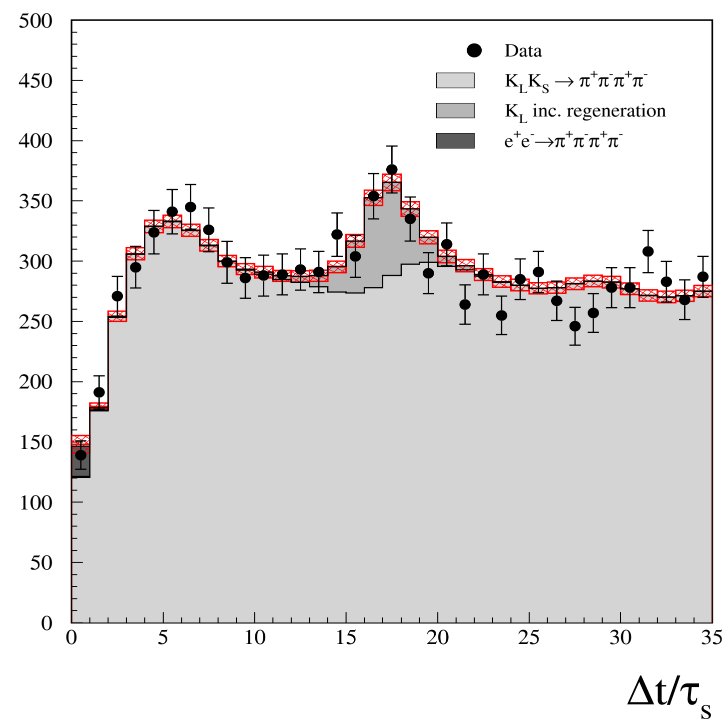
Complete positivity guarantees the positivity of the eigenvalues of density matrices describing states of correlated kaons.

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

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



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=> only one independent parameter: γ

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

KLOE preliminary L=1 fb^{-1}

$$\gamma = \left(0.8^{+1.5}_{-1.3\,STAT}\right) \times 10^{-21}\ \text{GeV}$$

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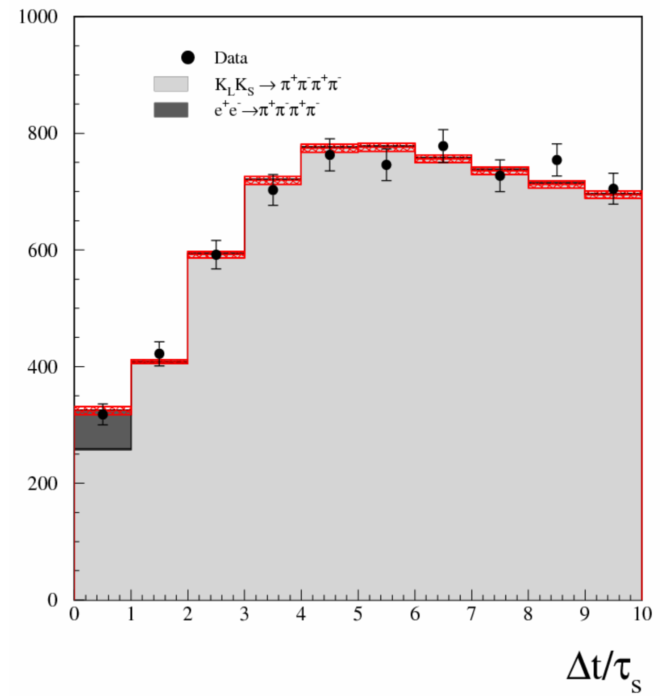


$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \, \pi^+\pi^-$: CPT violation in correlated K states

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]:

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

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

KLOE result
(ω measured for the first time)

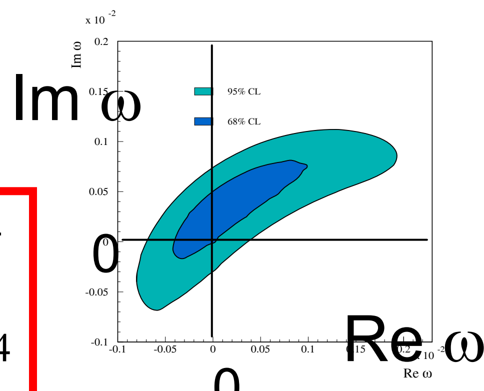
Fit of $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$:

- Analysed data: 380 pb^{-1}

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

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

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



KLOE result :
PLB 642(2006) 315

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

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KLOE result

(ω measured for the first time)

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

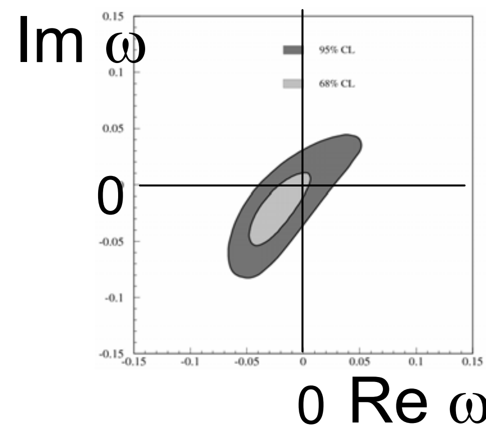
- Analysed data:
  1 fb^{-1} (2005 data)

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

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

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

KLOE preliminary :



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 SME manifests to lowest order only in δ => **No CPT viol. in decays**
and exhibits a kaon momentum dependence:

<u>δ cannot be a constant</u>

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

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

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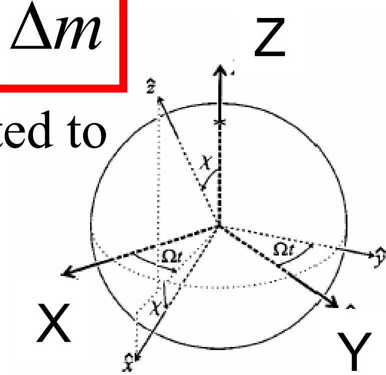


δ depends on sidereal time t since laboratory frame rotates with Earth:

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

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**):

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

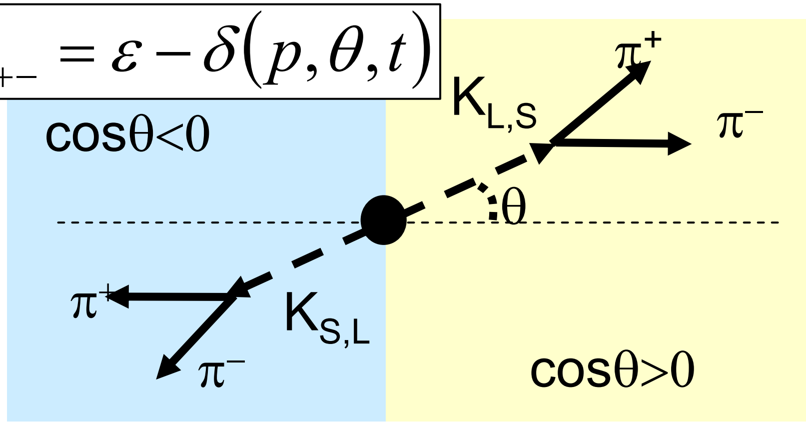
with L=2.5 fb^{-1} : $\sigma(\Delta a_0)$ ~ 7×10^{-18} GeV (Δa_0 evaluated for the first time)

$\Delta a_{X,Y,Z}$ 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, $\Delta a_Y < 9.2 \times 10^{-22}$ 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]

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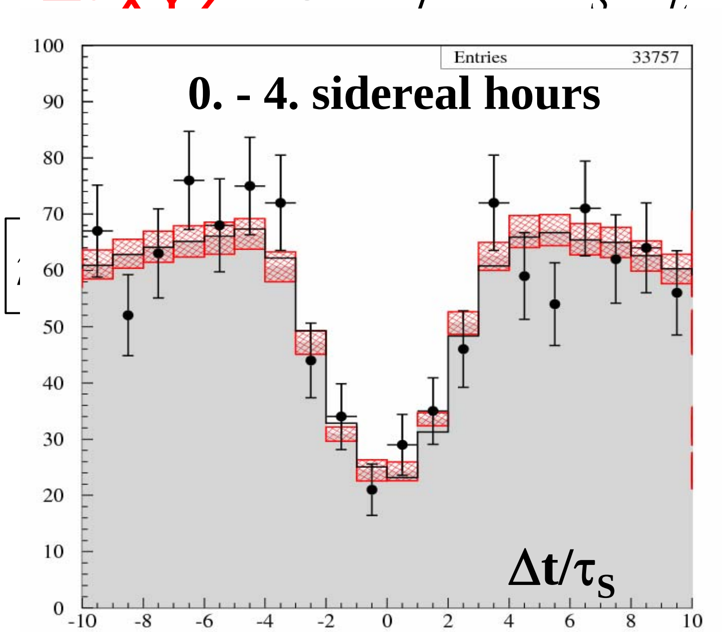
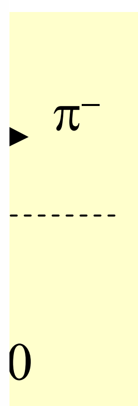
d sidereal time t)

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





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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

see talk of M. Moulson

KLOE-2 Proposal:

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, $e^+e^- \to pp$, 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 $L=50\ fb^{-1}$
$K_S \to \pi e \nu$	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	$Re(\varepsilon'/\varepsilon)$	$(1.47 \pm 0.22) \times 10^{-3}$	$\pm 0.2 \times 10^{-3}$
$\pi^+\pi^-$ $\pi^0\pi^0$	CP, CPT	$Im(\varepsilon'/\varepsilon)$	$(2.3 \pm 2.9) \times 10^{-3}$	$\pm 3 \times 10^{-3}$
$\pi e \nu$ $\pi e \nu$	CPT	$Re(\delta)+Re(x_-)$	$Re(\delta) = (0.30 \pm 0.33) \times 10^{-3}$ $Re(x_-) = (-0.8 \pm 2.5) \times 10^{-3}$	$\pm 0.2 \times 10^{-3}$
$\pi e \nu$ $\pi e \nu$	CPT	$Im(\delta)+Im(x_+)$	$Im(\delta) = (0.4 \pm 2.1) \times 10^{-5}$ $Im(x_+) = (0.8 \pm 0.7) \times 10^{-2}$	$\pm 3 \times 10^{-3}$
$\pi^+\pi^-$ $\pi^+\pi^-$		Δm	$(5.288 \pm 0.043) \times 10^9\ s^{-1}$	$\pm 0.03 \times 10^9\ s^{-1}$

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]	$O(10^{-19})$GeV

[….] = preliminary

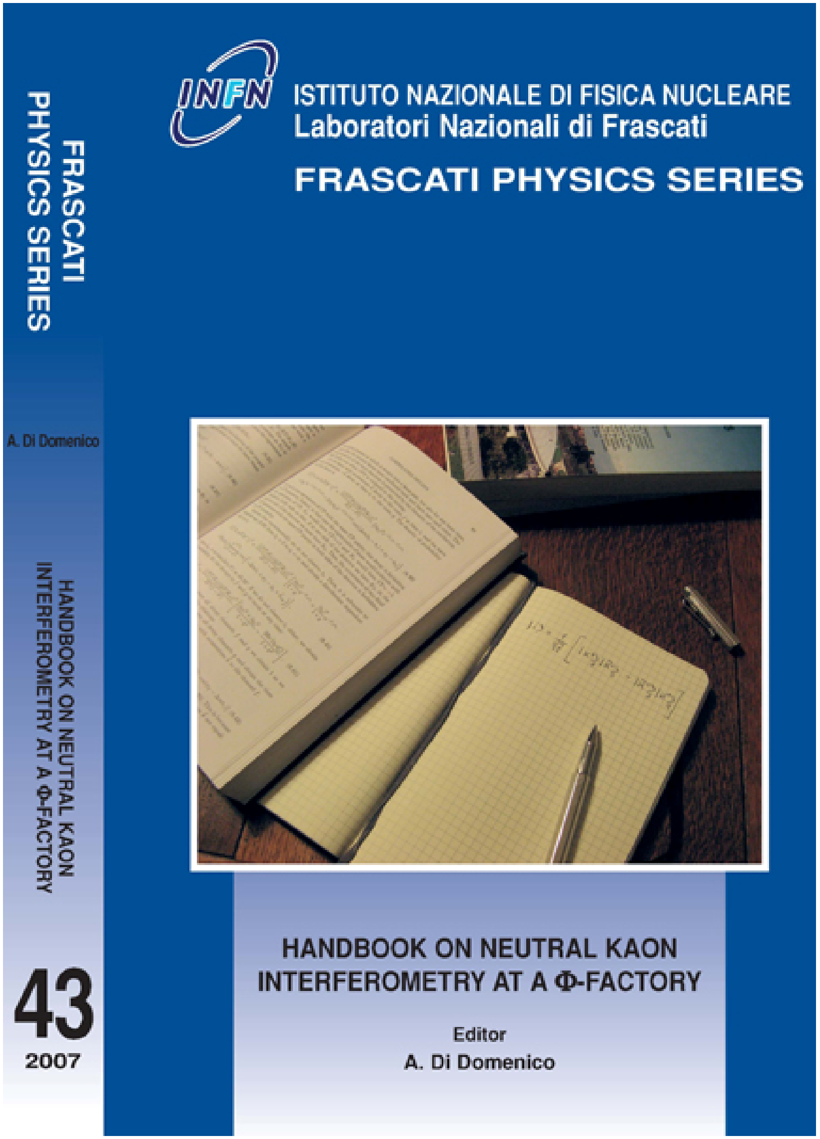
Conclusions

- 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 measured, in same cases with a precision reaching the interesting Planck's scale region;
- <u>All results are consistent with no CPT violation</u>

- The analysis of the full KLOE data sample (2.5 fb^{-1}) is in progress;
- 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



More detailed information can be found in:

Handbook on neutral kaon interferometry at a ϕ-factory

G. Amelino-Camelia, M. Arzano, F. Benatti, J. Bernabeu, R. Bertlmann, A. Bramon, A. Di Domenico, R. Floreanini, A. Go, B. Hiesmayr, G. Isidori, R. Lehnert, N. Mavromatos J. Ellis, G. Garbarino, A. Marcianò, D. Nanopoulos, J. Papavassiliou, S. Sarkar

(editor A. D. D.)

published in
Frascati Physics Series, Vol. 43, 2007
also available at:

http://www.roma1.infn.it/people/didomenico/roadmap/handbook.html

Spare

A. Di Domenico
Neutral kaon interferometry at a phi-factory

J. Bernabeu, J. Ellis, N. Mavromatos, D. Nanopoulos, J. Papavassiliou
CPT and quantum mechanics tests with kaons

S. Sarkar
Methods and models for the study of decoherence

F. Benatti, R. Floreanini
Open quantum dynamics: complete positivity and correlated kaons

R. Lehnert
CPT and Lorentz symmetry breaking: a review

G. Amelino-Camelia, M. Arzano, A. Marciano'
On the quantum gravity phenomenology of multiparticle states

G. Isidori
Testing CPT in the neutral kaon system by means of the Bell-Steinberger relation

R. Bertlmann, B. Hiesmayr
Strangeness measurements of kaon pairs, CP violation and Bell inequalities

A. Bramon, R. Escribano, G. Garbarino
A review of Bell inequality tests with neutral kaons

A. Bramon, G. Garbarino, B. Hiesmayr
Kaonic quantum erasers at a phi-factory: "erasing the present, changing the past"

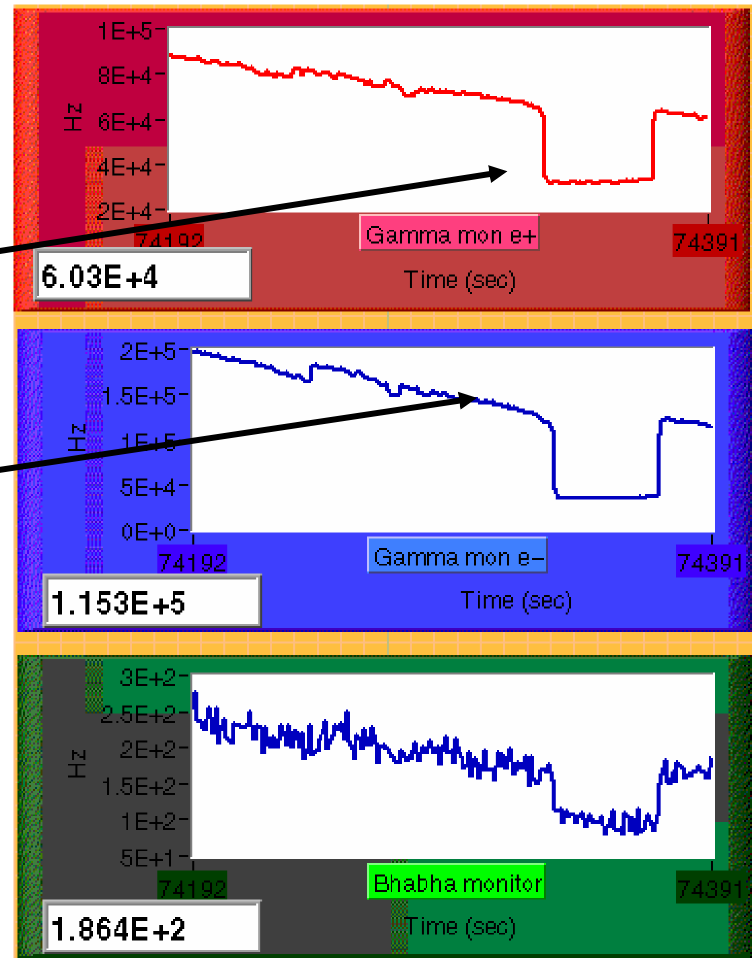
A. Go
Kaon interferometry at CPLEAR

http://www.roma1.infn.it/people/didomenico/roadmap/handbook.html

EFFECTS OF CRAB SEXTUPOLES ON LUMINOSITY

A huge work on machine optimization has been done and is still in progress in term of feedbacks systems tuning, background minimization and tuning of the machine luminosity…

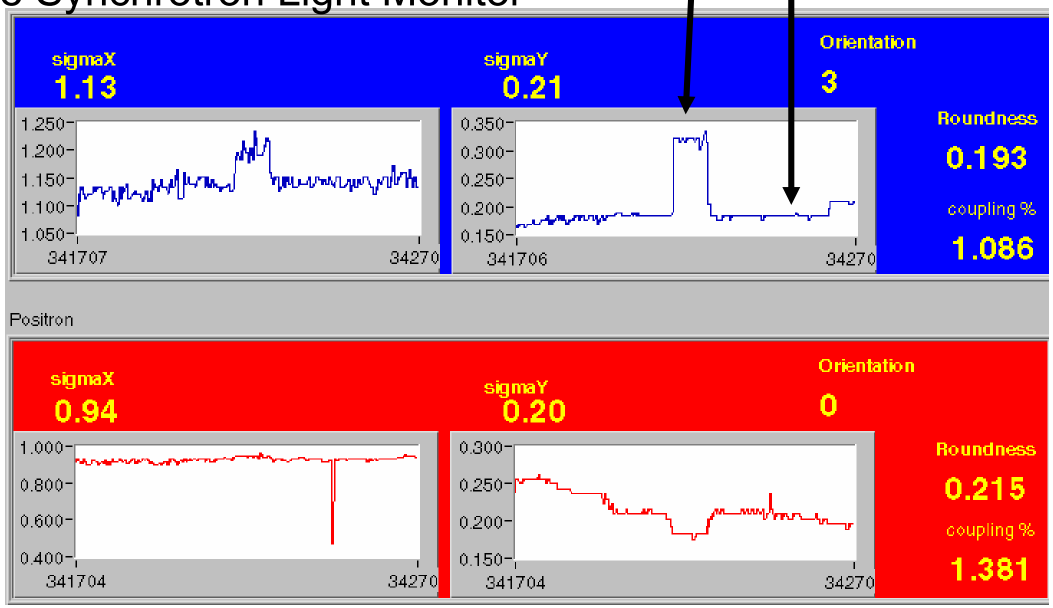
LUMINOMETERS



Crab off

Crab on

Transverse beam dimensions at the Synchrotron Light Monitor

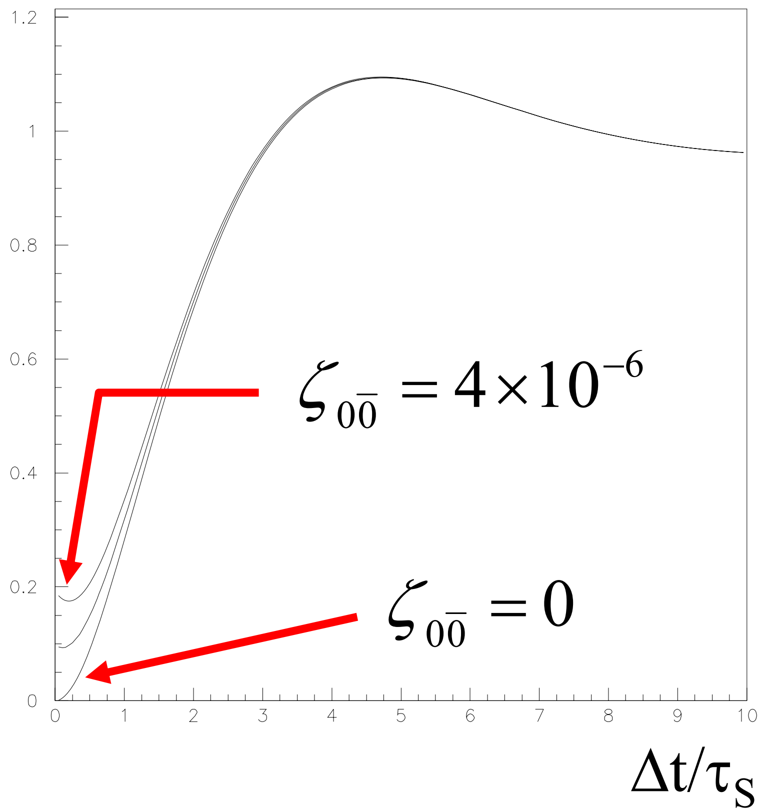


P. Raimondi May 6, 2008

Example of interferometry at KLOE-2: $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$

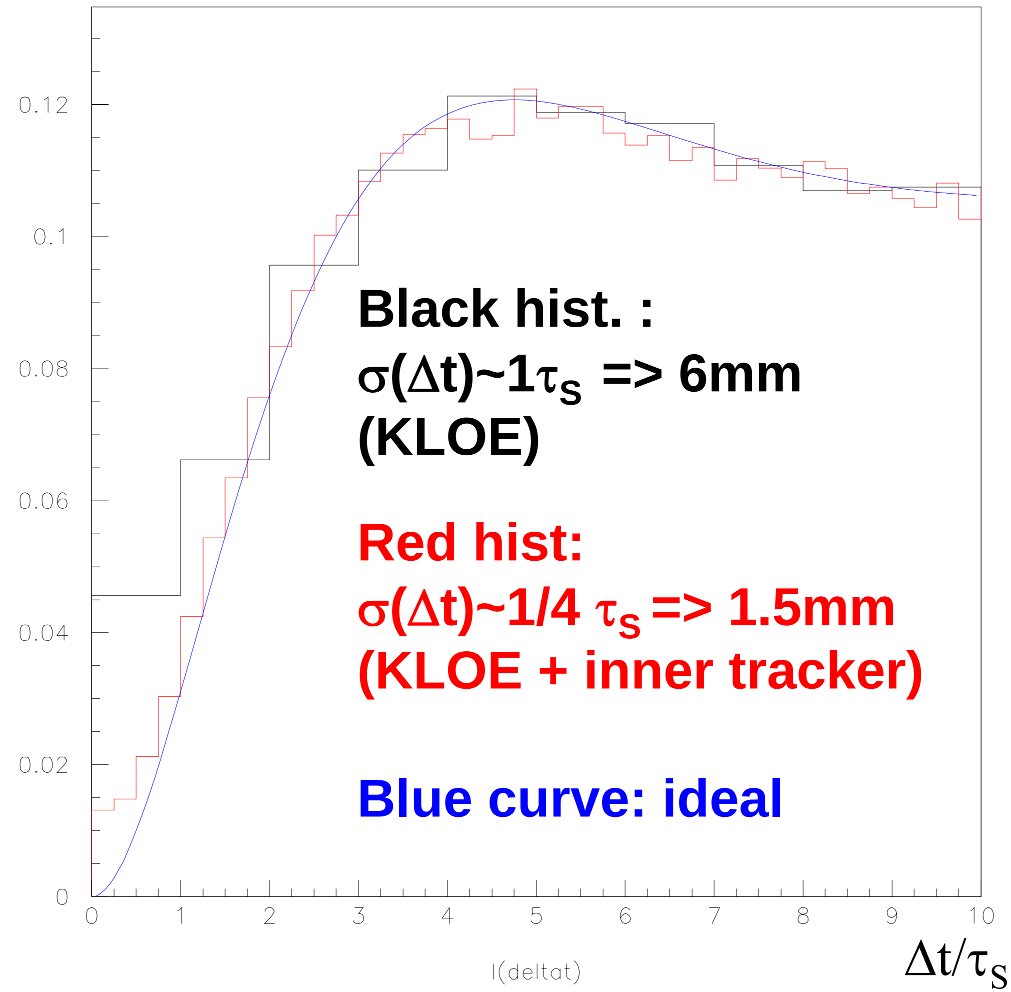
Possible signal of decoherence concentrated at very small Δt

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



Theoretical distribution

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

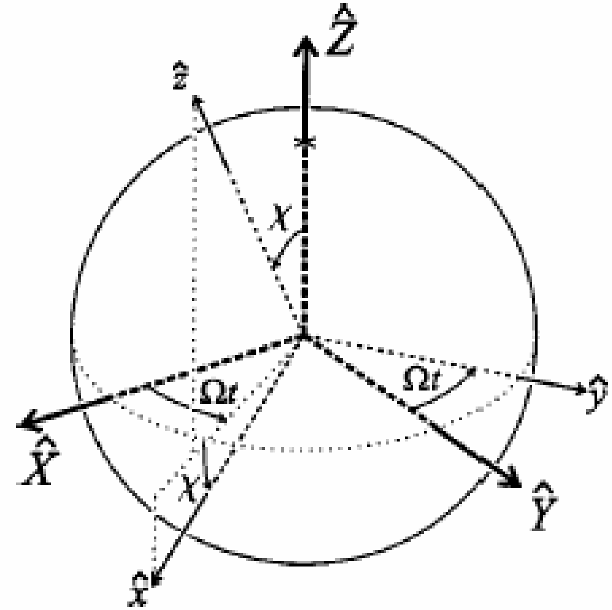


Reconstructed distribution (MC)

CPT and Lorentz invariance violation (SME)

For a fixed target experiment (fixed momentum direction) 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:



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

$$\bar{\delta}\left(|\vec{p}|,\theta,t\right)=\frac{1}{2\pi}\int_0^{2\pi}\delta(\vec{p},t)\,d\phi$$

$$=\frac{i\sin\phi_{SW}e^{i\phi_{SW}}}{\Delta m}\gamma_K\left[\underline{\Delta a_0}+\beta_K\underline{\Delta a_Z}\cos\chi\cos\theta\right.$$

$$+\beta_K\underline{\Delta a_Y}\sin\chi\cos\theta\sin\Omega t$$

$$\left.+\beta_K\underline{\Delta a_X}\sin\chi\cos\theta\cos\Omega t\right]$$

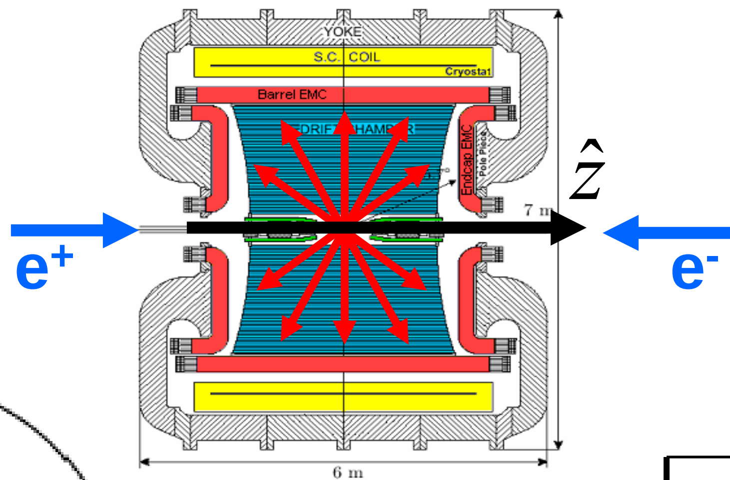
Ω: Earth's sidereal frequency

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

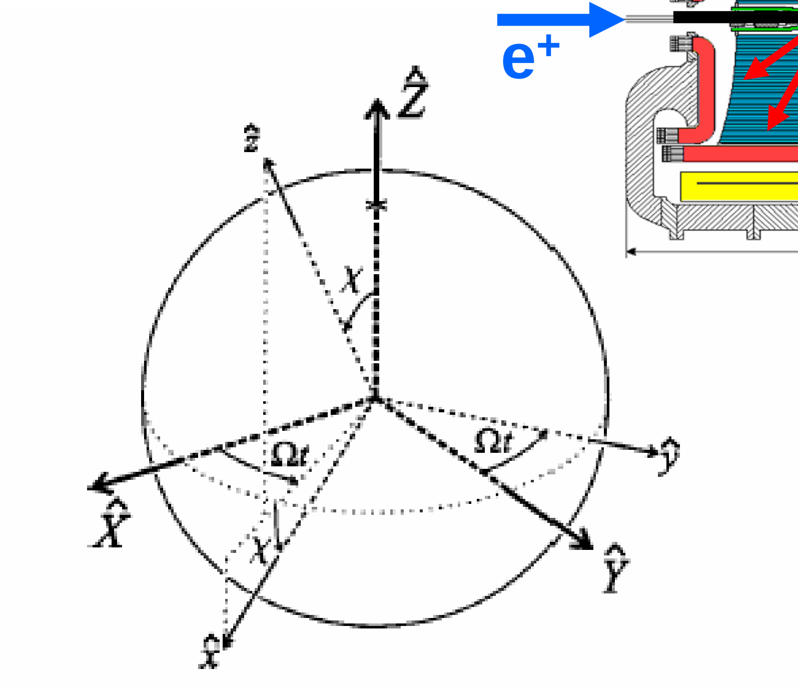
CPT and Lorentz invariance violation (SME)

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

KLOE is a kind of telescope, able to explore with a kaon beam almost any direction in space



KLOE latitude	~41.8°
KLOE longitude	~12.7°
e^+ beam axis	~S57.8°W
$\gamma_K\beta_K$	~0.22



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

term	coefficient	value
Δa_0	γ_K	1.02
Δa_Z	$\gamma_K\beta_K\cos\chi$	-0.09
Δa_X	$\gamma_K\beta_K\sin\chi$	0.20
Δa_Y	$\gamma_K\beta_K\sin\chi$	0.20

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

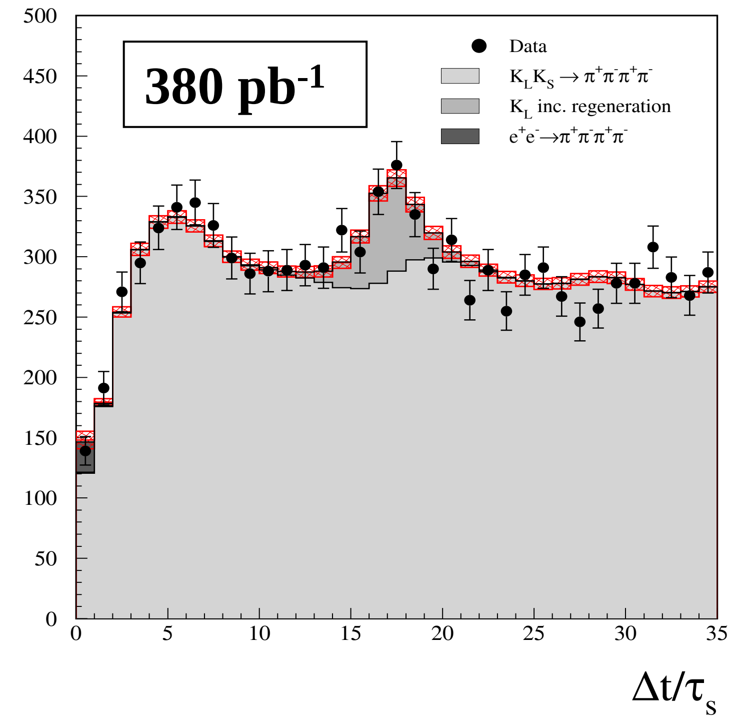
The fit with $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\alpha,\beta,\gamma)$ gives:

KLOE preliminary

$$\alpha = \left(-10^{+41}_{-31\,STAT} \pm 9_{SYST}\right)\times 10^{-17}\ \text{GeV}$$

$$\beta = \left(3.7^{+6.9}_{-9.2\,STAT} \pm 1.8_{SYST}\right)\times 10^{-19}\ \text{GeV}$$

$$\gamma = \left(-0.4^{+5.8}_{-5.1\,STAT} \pm 1.2_{SYST}\right)\times 10^{-21}\ \text{GeV}$$



In the complete positivity hypothesis

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

=> only one independent parameter: γ

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

KLOE result PLB 642(2006) 315

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

$$\gamma < 6.4\times 10^{-21}\ \text{GeV} \quad \text{at } 95\%\ \text{C.L.}$$

with L=2.5 fb^{-1}:

→ $\pm 1.1_{STAT} \times 10^{-21}$ GeV

CPT violation in the neutral kaon system: "standard" picture

CPT violation in the mixing

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

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

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

$$\Delta m = m_L - m_S$$

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

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

CPT violation in semileptonic decays

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

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

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

Semileptonic charge asymmetry:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \overline{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \overline{\nu})}$$

$$= 2\Re\varepsilon \pm 2\Re\delta - 2\Re y \pm 2\Re x_-$$

Standard Model prediction of ΔS=ΔQ rule violation is x ~ $O(10^{-7})$

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

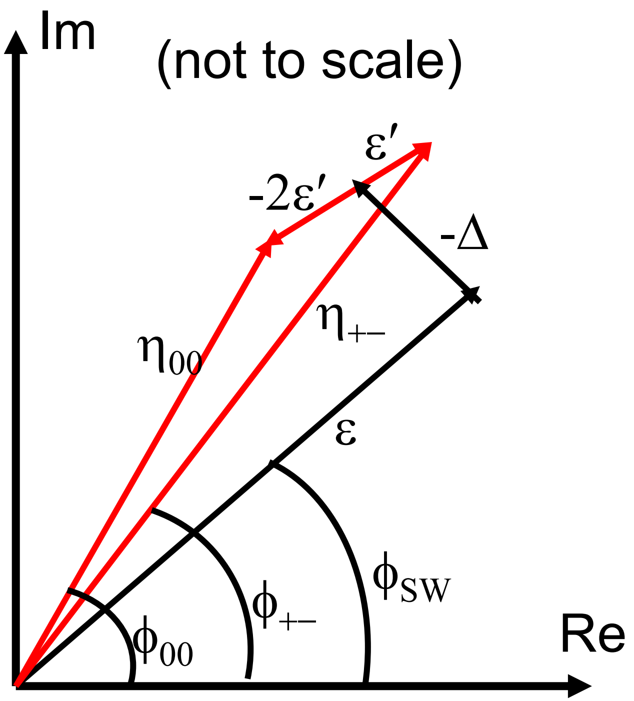
CPT violation in the neutral kaon system: "standard" picture

CPT violation in ππ decays

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

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

A_I(B_I) CPT conserving (violating)
K→ ππ amplitudes for I=0,2
(δ_I strong phase shift for I=0,2)



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

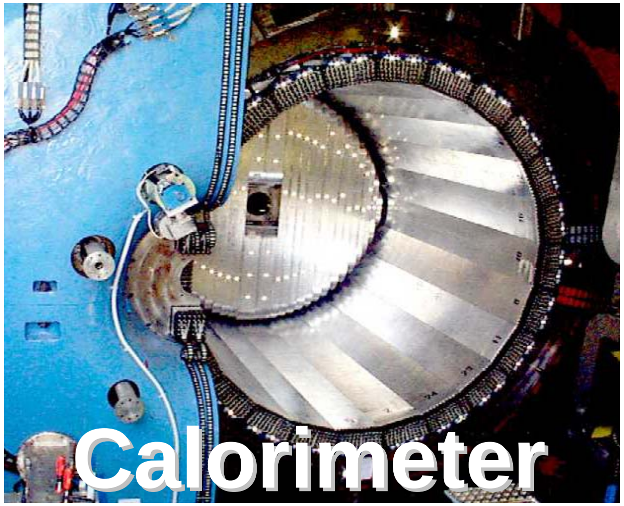
$$\eta_{00} = |\eta_{00}| e^{i\phi_{00}} = \frac{\langle \pi^0\pi^0 | T | K_L \rangle}{\langle \pi^0\pi^0 | T | K_S \rangle} = \varepsilon - \Delta - 2\varepsilon'$$

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

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

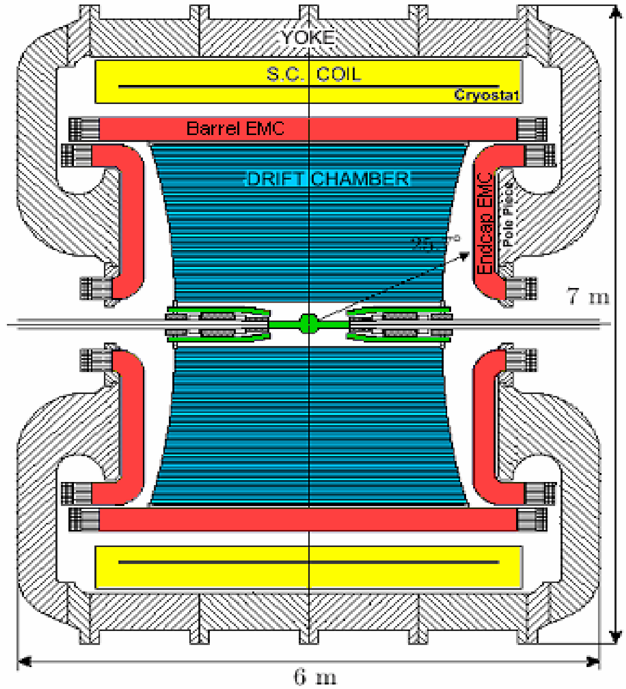
$$\phi_{+-} - \phi_{SW} \approx \frac{-1}{\sqrt{2}|\eta_{+-}|} \left[\frac{m_{11} - m_{22}}{2\Delta m} + \frac{\Re B_0}{\Re A_0} \right]$$

The KLOE detector



Superconducting coil

B = 0.52 T



Lead/scintillating fiber

4880 PMTs

98% coverage of solid angle

4 m diameter × 3.3 m length

90% helium, 10% isobutane

12582/52140 sense/total wires

All-stereo geometry

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

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

(relative time between clusters)

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

$\sigma_p/p \cong 0.4$ % (tracks with $\theta > 45°$)

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

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

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.

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CPT theorem (Luders, Jost, Pauli, Bell 1955 -1957):
Exact CPT invariance holds for any quantum field theory which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

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(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).

Measurement of $\Delta a_{X,Y,Z}$ at KLOE

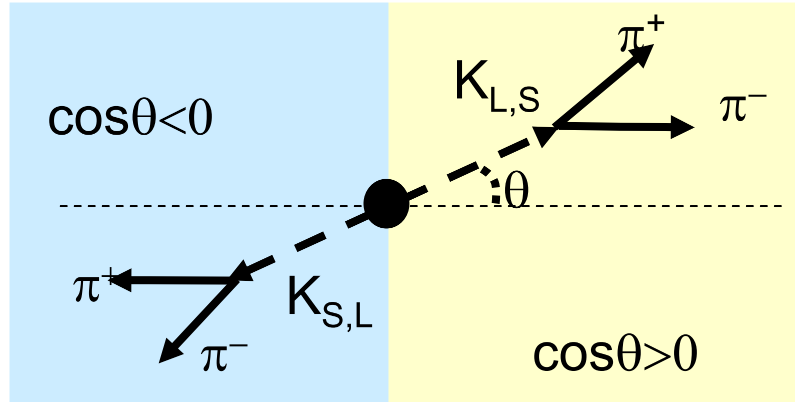
$\Delta a_{X,Y,Z}$ **from** $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$

(analysis vs polar angle θ and sidereal time t)

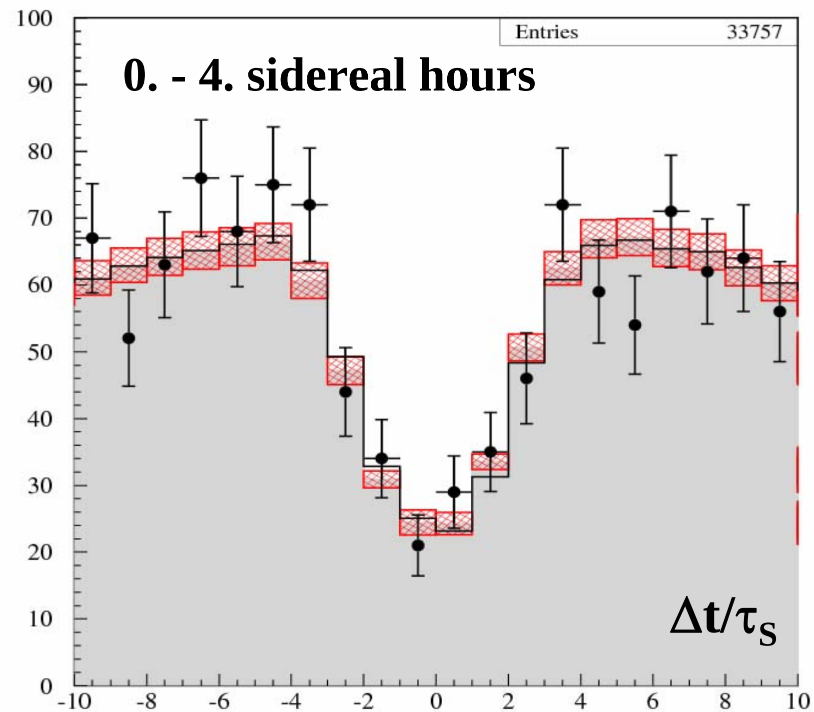
$$\eta_{+-} = \varepsilon - \delta(p, \theta, t)$$

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

- at $\Delta t >> \tau_s$ sensitive to $Re(\delta/\varepsilon)=0$
- at $\Delta t \sim \tau_s$ sensitive to $Im(\delta/\varepsilon)$



With L=1 fb^{-1} (**preliminary**): $\chi^2/dof=131/117$



$$\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18} \text{ GeV}$$
$$\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18} \text{ GeV}$$

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

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

CPT violation in the neutral kaon system: "standard" picture

CPT violation in the mixing

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

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

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$$\left\langle \pi^- \ell^+ \nu \left| T \right| K^0 \right\rangle = a + b \qquad \left\langle \pi^+ \ell^- \overline{\nu} \left| T \right| K^0 \right\rangle = c + d$$

$$\left\langle \pi^+ \ell^- \overline{\nu} \left| T \right| \overline{K}^0 \right\rangle = a^* - b^* \qquad \left\langle \pi^- \ell^+ \nu \left| T \right| \overline{K}^0 \right\rangle = c^* - d^*$$

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

$$\eta_{\pi\pi} = |\eta_{\pi\pi}|e^{i\phi_{\pi\pi}} = \frac{\langle \pi\pi|T|K_L\rangle}{\langle \pi\pi|T|K_S\rangle}$$

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

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

Some results of CPT tests

CPLEAR

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

PLB444 (1998) 52

KTeV

$$\phi_{+-} - \phi_{SW} = 0.61^o \pm 0.62^o \pm 1.01^o$$
$$\phi_{00} - \phi_{+-} = 0.39^o \pm 0.22^o \pm 0.45^o$$

PRL88, 181601 (2002)

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

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

PRD67, 012005 (2003)

KLOE

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

PLB 636(2006) 173

input from other experiments

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = (-0.8 \pm 2.4 \pm 0.7) \times 10^{-3}$$

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

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = (0.4 \pm 2.4 \pm 0.7) \times 10^{-3}$$

CPT viol.

Some results of CPT tests

CPLEAR

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

PLB444 (1998) 52

KTeV

$\phi(\varepsilon) - \phi_{SW} = [0.40 \pm 0.56]°$

$\phi_{00}-\phi_{+-} = [0.30 \pm 0.35]°$

UPDATE 2008

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

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PLB 636(2006) 173

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$A_S + A_L = 4(\Re\varepsilon - \Re y)$ → $\Re y = (0.4 \pm 2.4 \pm 0.7) \times 10^{-3}$ **CPT viol.**

CPT test: the Bell-Steinberger relation

Unitarity constraint:

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

K_S K_L observables

Experimental inputs:

	Value	Source
τ_{K_S}	0.08958 ± 0.00005 ns	PDG [14]
τ_{K_L}	50.84 ± 0.23 ns	KLOE average
$m_L - m_S$	$(5.290 \pm 0.016) \times 10^9\ \mathrm{s}^{-1}$	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}	$((-2 \pm 7) + i(-2 \pm 9)) \times 10^{-3}$	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 of K_S semileptonic and $3\pi^0$ decays

Perspectives with KLOE-2 at upgraded DAΦNE

Param.	Present best published measurement	KLOE-2 $L=50\ fb^{-1}$
A_S	$(1.5 \pm 11) \times 10^{-3}$	$\pm 1 \times 10^{-3}$
A_L	$(3322 \pm 58 \pm 47) \times 10^{-6}$	$\pm 25 \times 10^{-6}$
$Re(\varepsilon'/\varepsilon)$	$(1.47 \pm 0.22) \times 10^{-3}$	$\pm 0.2 \times 10^{-3}$
$Im(\varepsilon'/\varepsilon)$	$(2.3 \pm 2.9) \times 10^{-3}$	$\pm 3 \times 10^{-3}$
$Re(\delta)$ $+Re(x_-)$	$Re(\delta) = (0.30 \pm 0.33) \times 10^{-3}$ $Re(x_-) = (-0.8 \pm 2.5) \times 10^{-3}$	$\pm 0.2 \times 10^{-3}$
$Im(\delta)$ $+Im(x_+)$	$Im(\delta) = (0.4 \pm 2.1) \times 10^{-5}$ $Im(x_+) = (0.8 \pm 0.7) \times 10^{-2}$	$\pm 3 \times 10^{-3}$
Δm	$(5.288 \pm 0.043) \times 10^{9}\ s^{-1}$	$\pm 0.03 \times 10^{9}\ s^{-1}$

Param.	Present best published measurement	KLOE-2 $L=50\ fb^{-1}$
ζ_{00}	$(1.0 \pm 2.1) \times 10^{-6}$	$\pm 0.1 \times 10^{-6}$
ζ_{SL}	$(1.8 \pm 4.1) \times 10^{-2}$	$\pm 0.2 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 2 \times 10^{-17}$ GeV
β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.1 \times 10^{-19}$ GeV
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
$Re(\omega)$	$(1.1 \pm 7.0) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
$Im(\omega)$	$(3.4 \pm 4.9) \times 10^{-4}$	$\pm 2 \times 10^{-5}$
Δa_0	$[(0.4 \pm 1.8) \times 10^{-17}$ GeV]	$\pm 2 \times 10^{-18}$ GeV
Δa_Z	$[(2.4 \pm 9.7) \times 10^{-18}$ GeV]	$\pm 7 \times 10^{-19}$ GeV
$\Delta a_{X,Y}$	$[<10^{-21}$ GeV]	$O(10^{-19})$GeV