CPT and QM tests in the neutral kaon system

Antonio Di Domenico
Dipartimento di Fisica, Università di Roma “La Sapienza”
and INFN sezione di Roma, Italy

Flavianet Kaon Workshop 2008
June 12-14, 2008, Anacapri, Italy

CPT: introduction

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.

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.

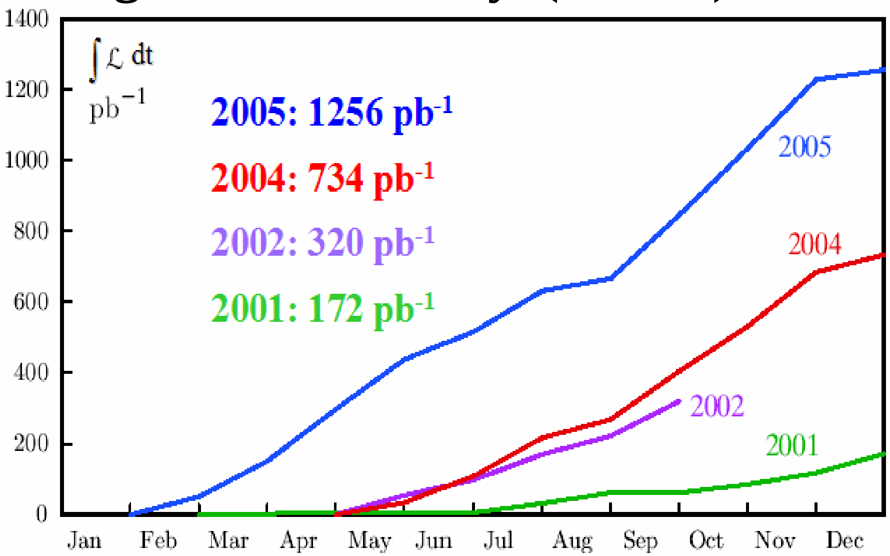
The neutral kaon system offers unique possibilities to test CPT invariance e.g. :

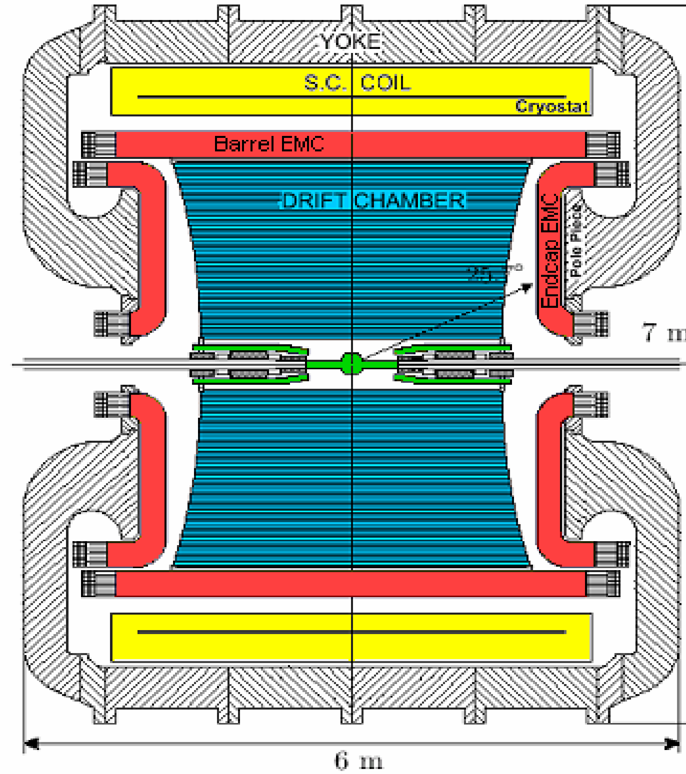
$$\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}, \quad \left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}, \quad \left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$$

1) 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

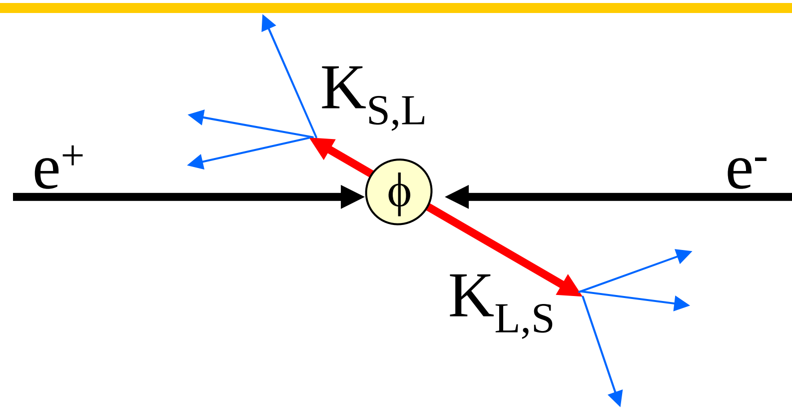
Total KLOE $\int \mathcal{L}\, dt \sim 2.5\ \mathrm{fb}^{-1}$

(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:



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

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

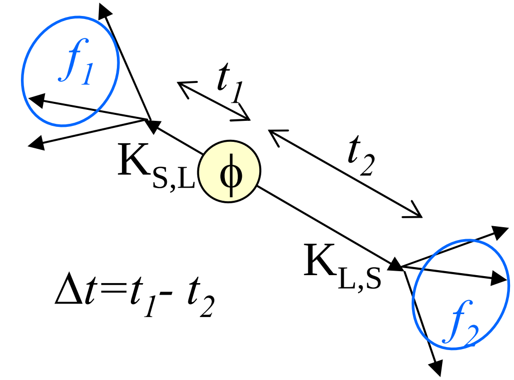
p_K = 110 MeV/c

λ_S = 6 mm λ_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:

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

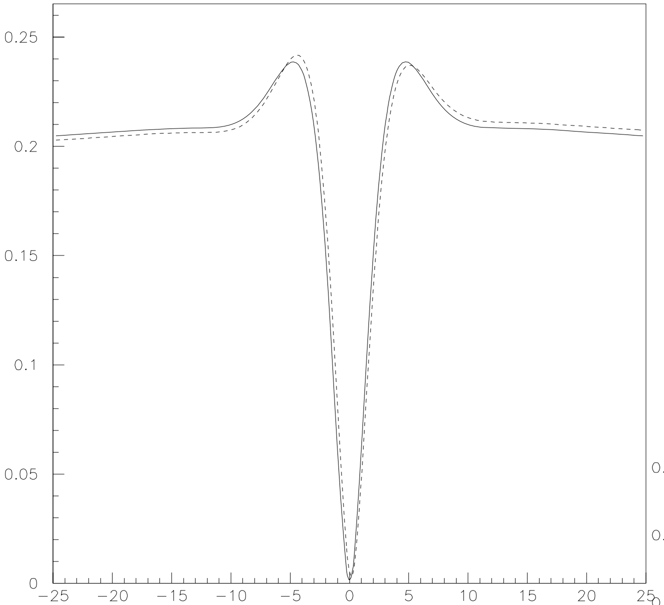
$$C_{12} = \frac{|N|^2}{2} \left| \langle f_1 | T | K_S \rangle \langle f_2 | T | K_S \rangle \right|^2$$

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)



$\Delta t/\tau_S$

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

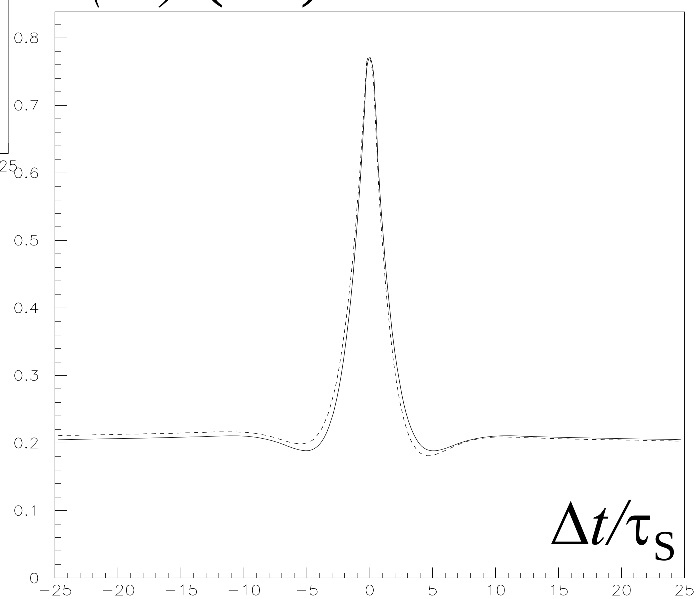
$$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

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

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

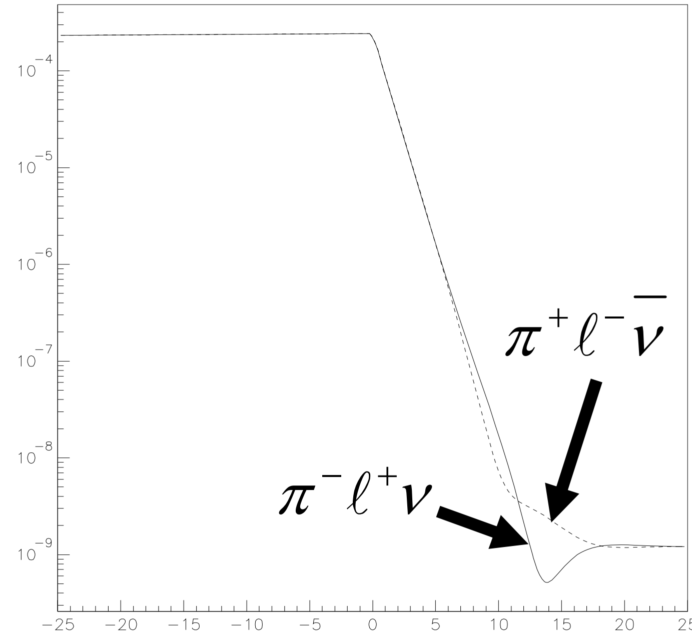
$\phi \to K_S K_L \to \pi^+\ell^-\bar{\nu} \ \ \pi^-\ell^+\nu$

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



$\Delta t/\tau_S$

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



$\Delta t/\tau_S$

$\phi \to K_S K_L \to \pi\pi \ \ \pi\ell\nu$

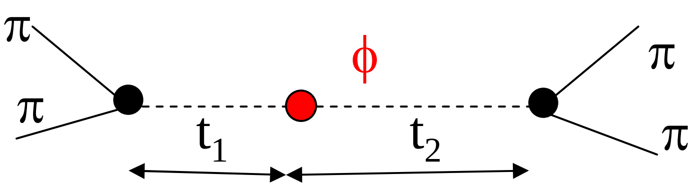
$$A_L = 2\Re\varepsilon - \Re\delta - \Re y - \Re x_-$$

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

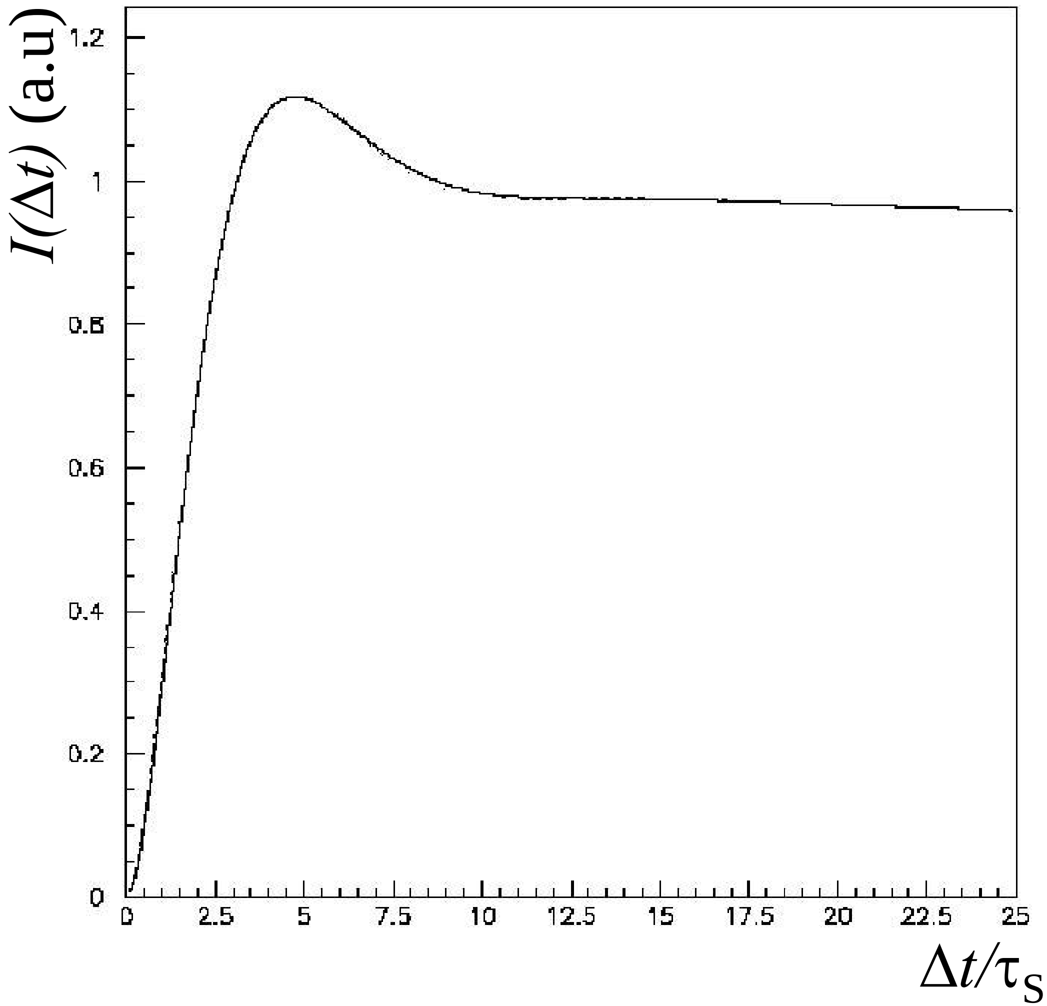
$\phi \to K_S K_L \to \pi^+\pi^- \quad \pi^+\pi^-$

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

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



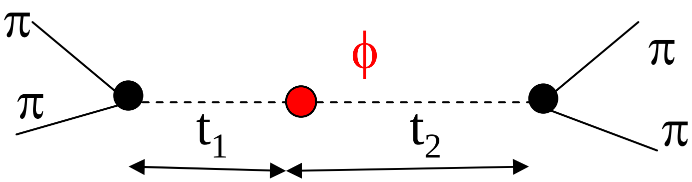
Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$



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

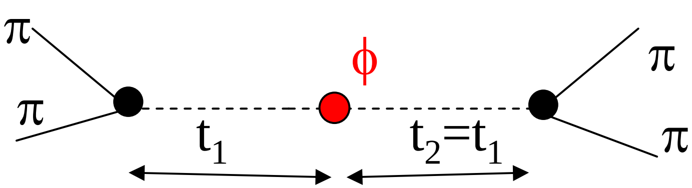
$$|i\rangle = \frac{1}{\sqrt{2}}\left[\left|K^0\right\rangle\left|\overline{K}^0\right\rangle - \left|\overline{K}^0\right\rangle\left|K^0\right\rangle\right]$$

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

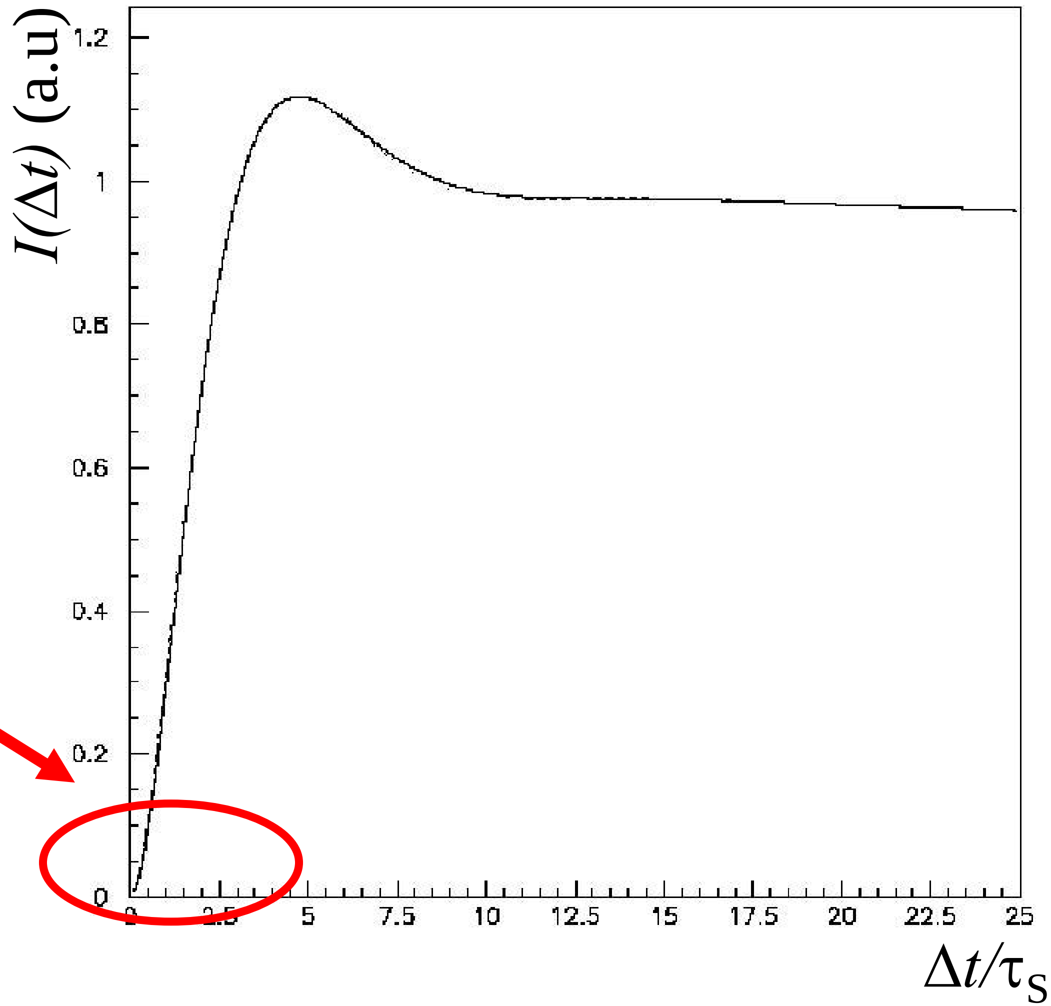


EPR correlation:

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



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

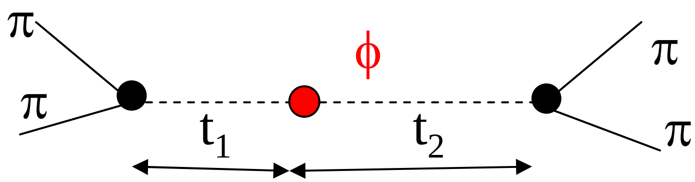


$\phi \to K_S K_L \to \pi^+\pi^- \quad \pi^+\pi^-$

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

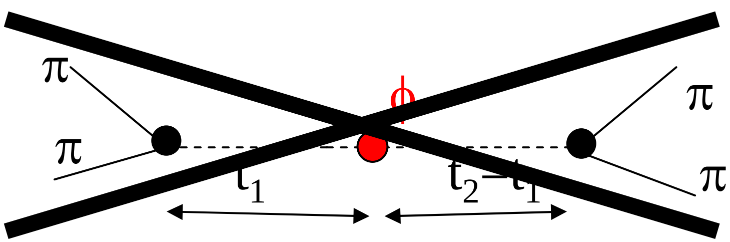
Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

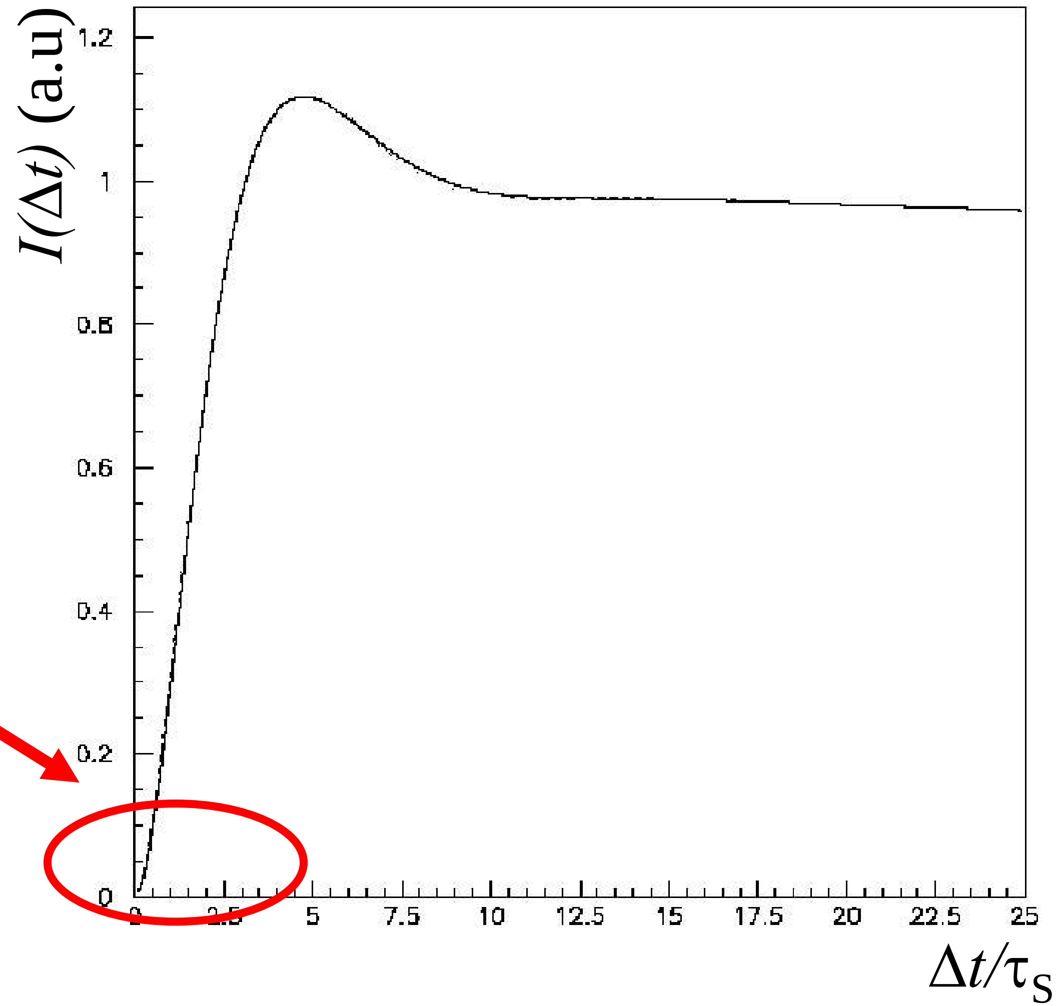
$$\Delta t = |t_1 - t_2|$$



EPR correlation:

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





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

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

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

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

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

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

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

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

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

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

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

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

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

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

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=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

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

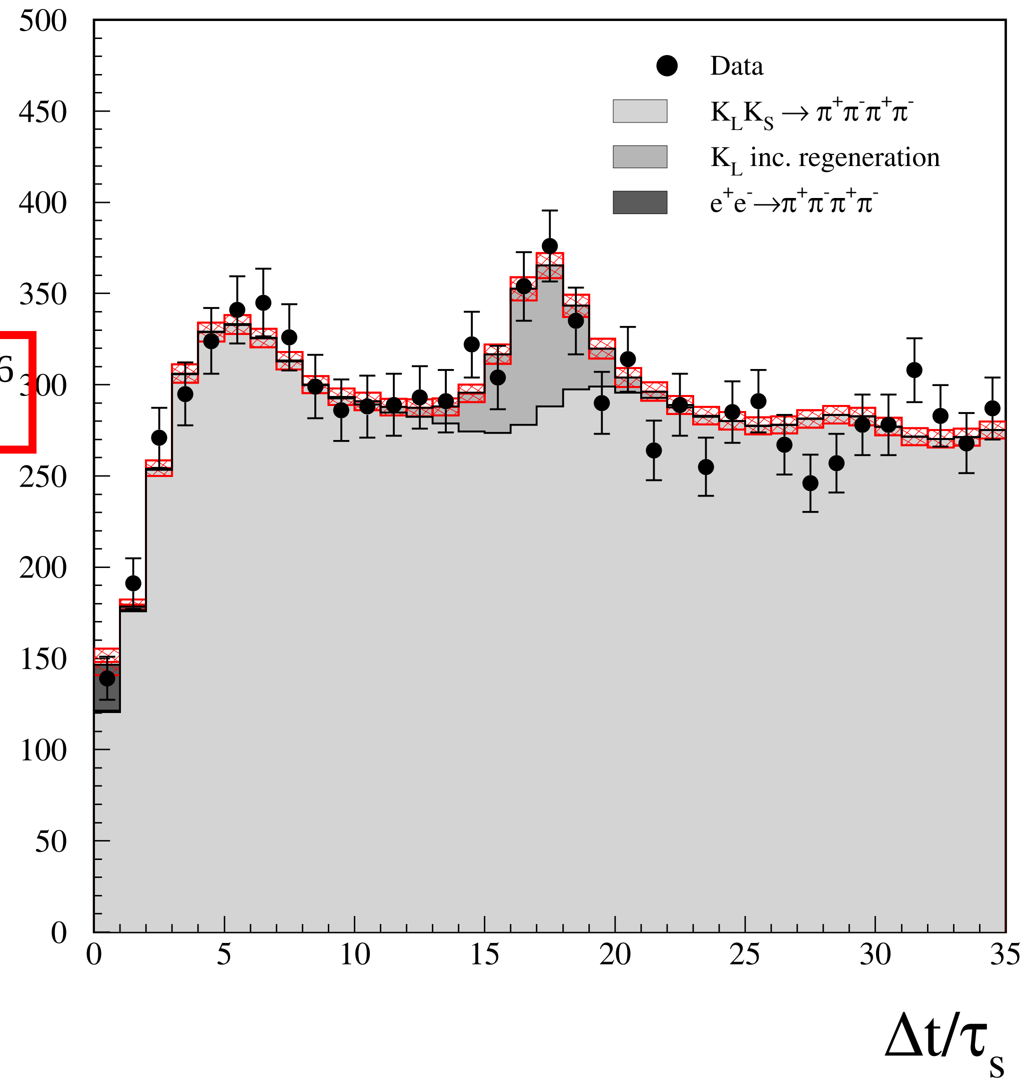
as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
=> high sensitivity to $\zeta_{0\bar{0}}$

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:

$$\zeta_{0\bar{0}}^{B} = 0.029 \pm 0.057$$



$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: 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**

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

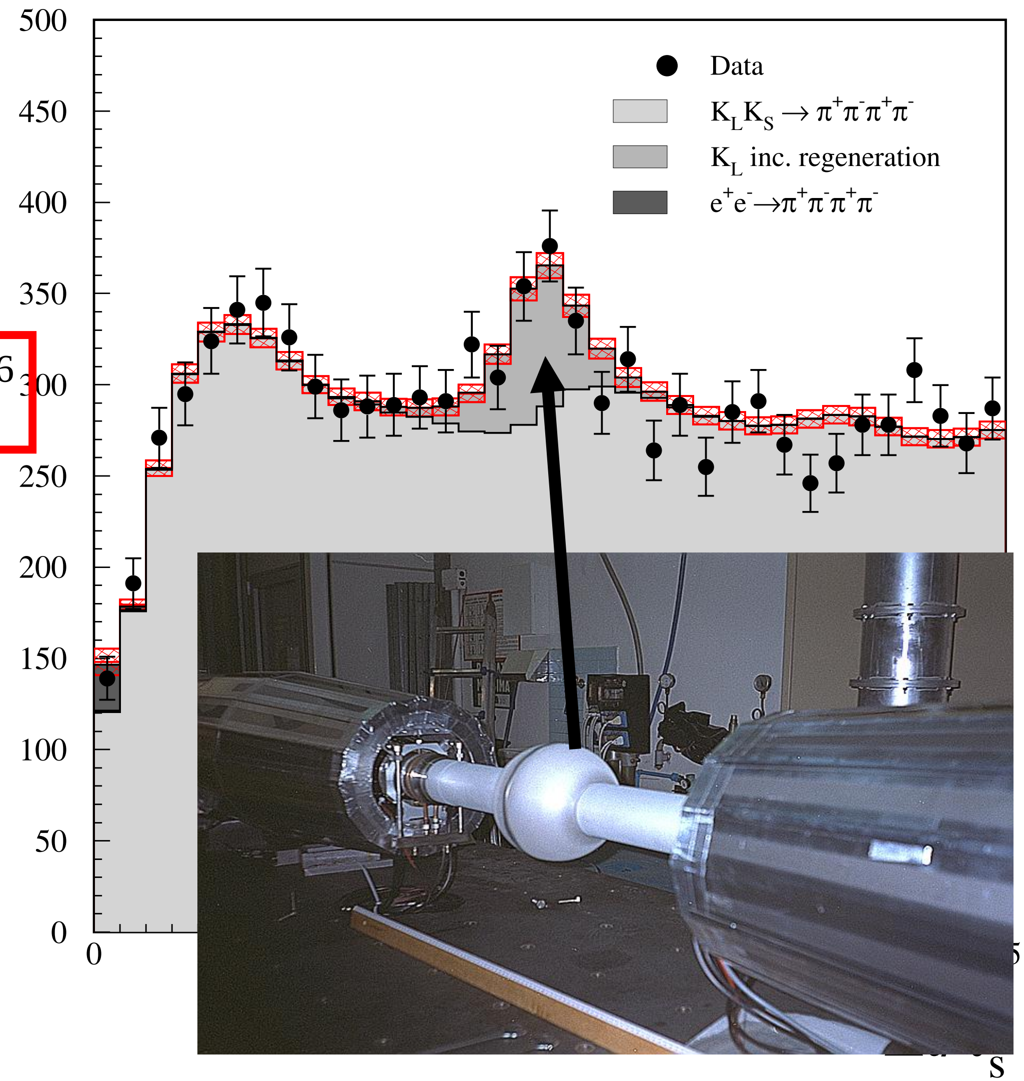
as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
=> high sensitivity to $\zeta_{0\bar{0}}$

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:

$$\zeta_{0\bar{0}}^{B} = 0.029 \pm 0.057$$



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

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

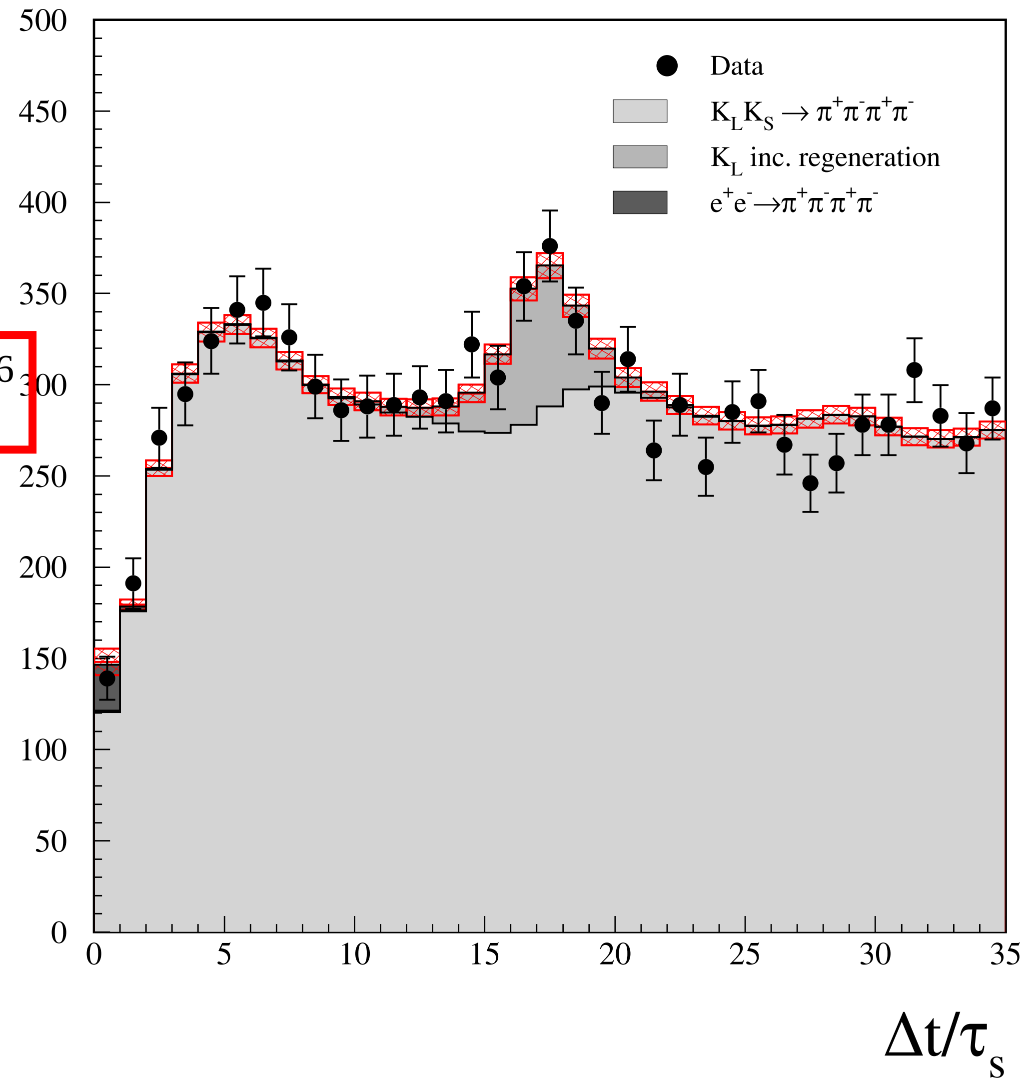
as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
=> high sensitivity to $\zeta_{0\bar{0}}$

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:

$$\zeta_{0\bar{0}}^{B} = 0.029 \pm 0.057$$



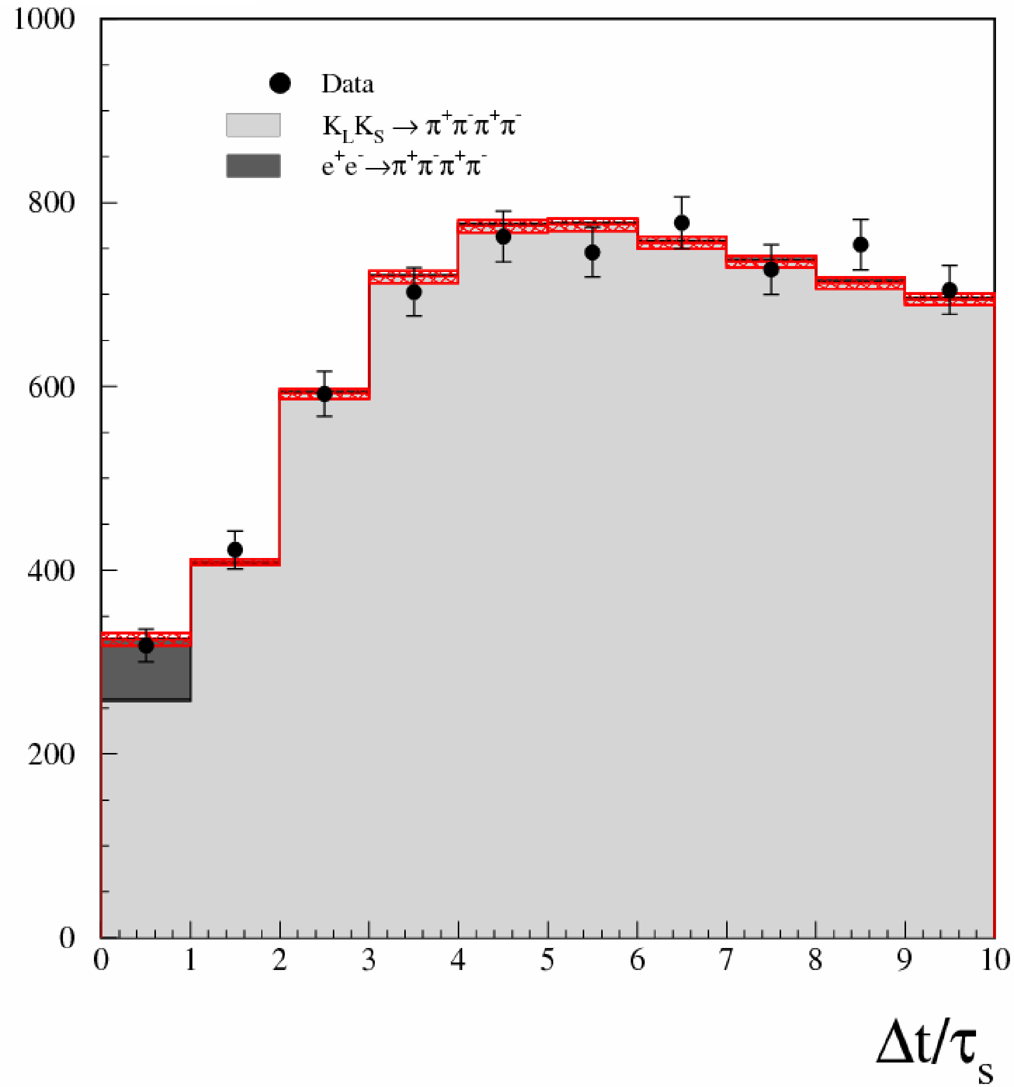
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- 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:

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

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



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:

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

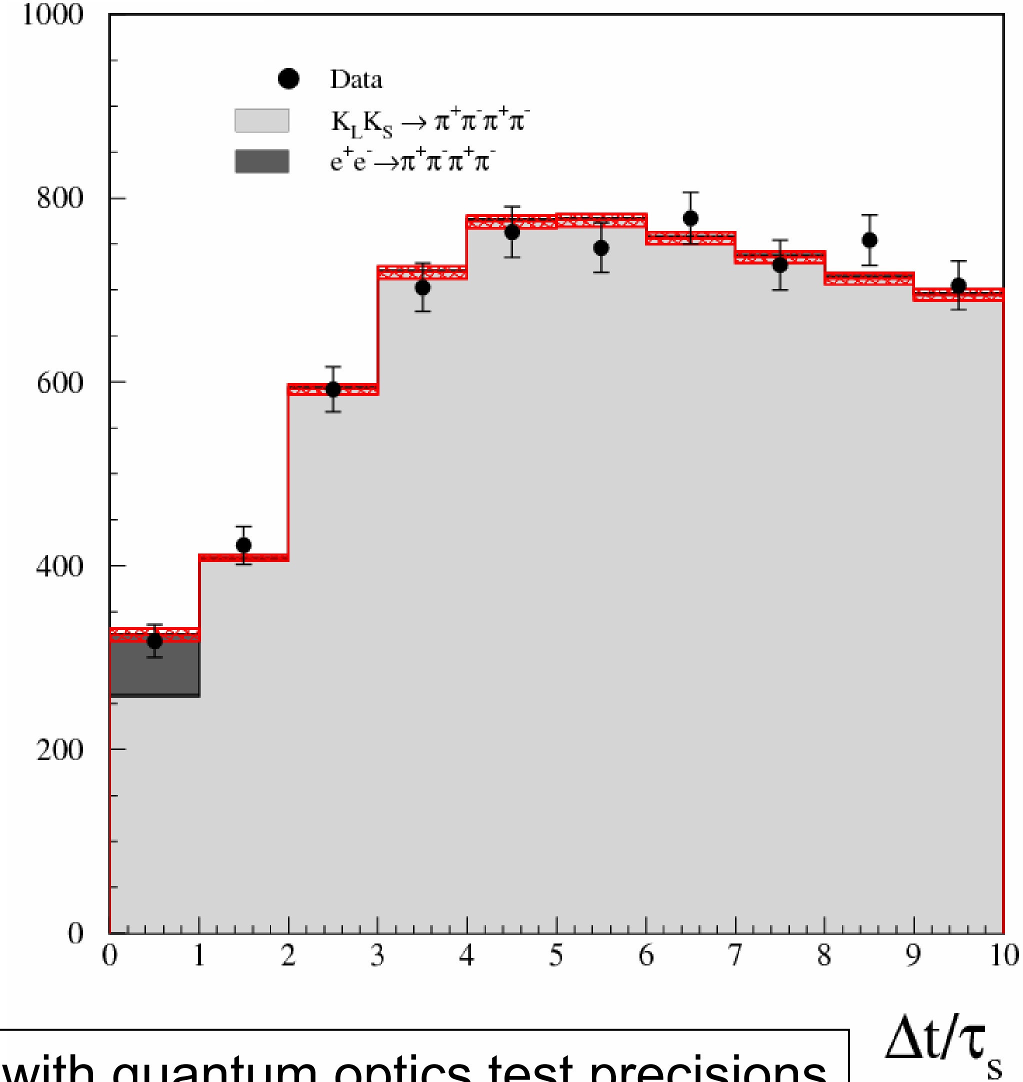
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- 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:

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

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



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:

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

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

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

<u>Possible decoherence due quantum gravity effects:</u>

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 <u>space-time foam</u>) 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)

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

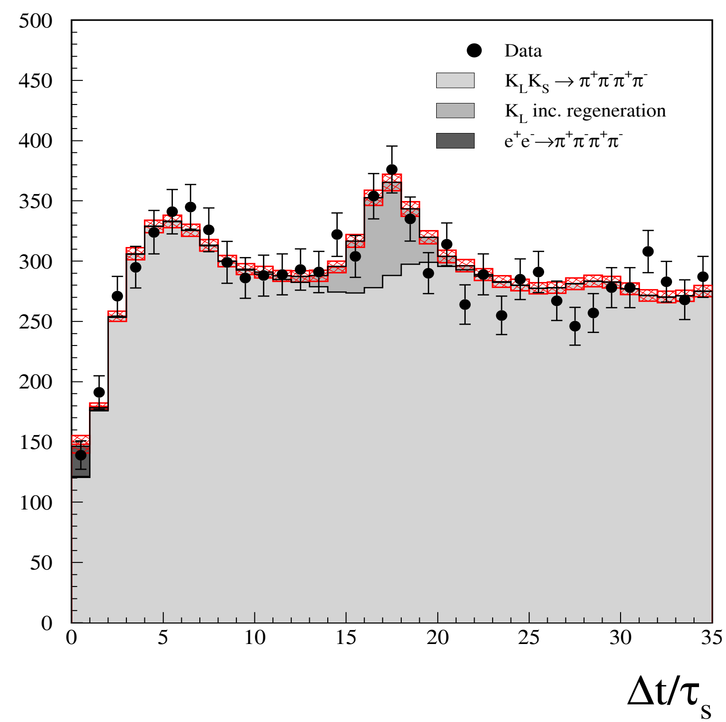
Complete positivity guarantees the positivity of the eigenvalues of density matrices describing states of correlated kaons.

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

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



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

Study of time evolution of **single kaons** decaying in π+π– and semileptonic final state

CPLEAR PLB 364, 239 (1999)

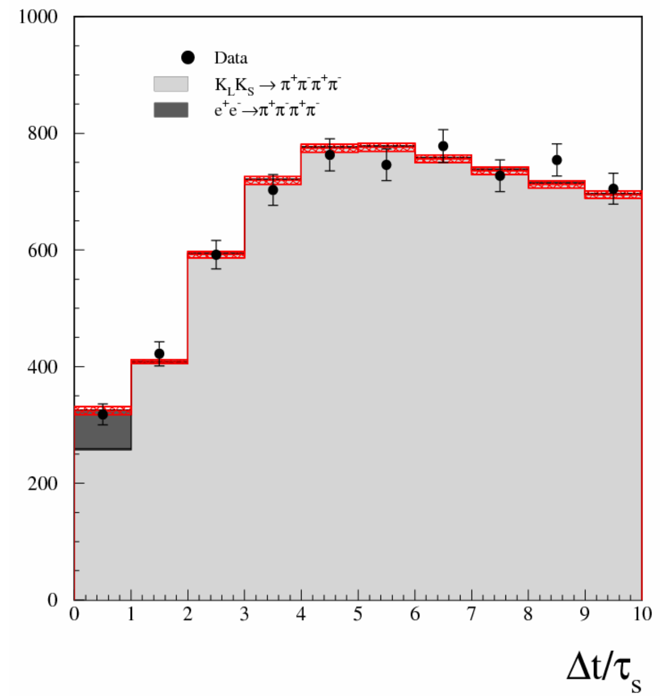
$$\alpha = (-0.5 \pm 2.8) \times 10^{-17}\ \text{GeV}$$
$$\beta = (2.5 \pm 2.3) \times 10^{-19}\ \text{GeV}$$
$$\gamma = (1.1 \pm 2.5) \times 10^{-21}\ \text{GeV}$$

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 preliminary L=1 fb^{-1}

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

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



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

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

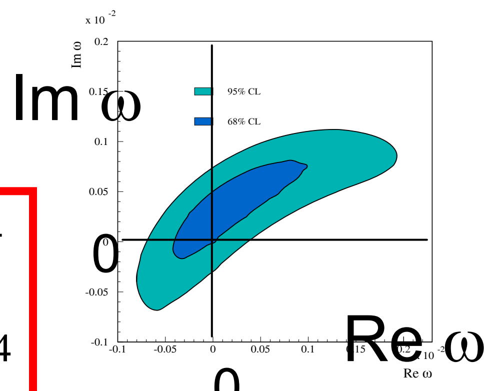
|ω| could be at most: $\boxed{|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3}}$

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

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]:

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

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

KLOE result

(ω measured for the first time)

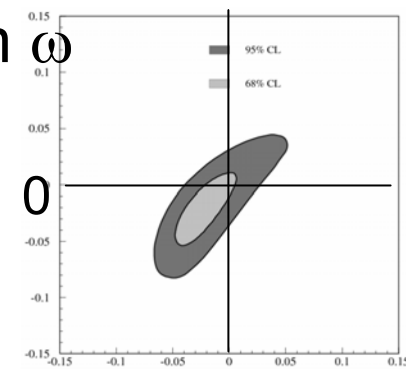
Fit of $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$:

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

KLOE preliminary :

$$\boxed{\begin{aligned} \Re\omega &= \left(-2.5^{+3.1}_{-2.3\,STAT}\right)\times 10^{-4} \\ \Im\omega &= \left(-2.2^{+3.4}_{-3.1\,STAT}\right)\times 10^{-4} \\ \left|\omega\right| &< 0.98\times 10^{-3} \quad \text{at } 95\%\ \text{C.L.} \end{aligned}}$$

Im ω



0

0 Re ω

2) 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)
- δ cannot be a constant (momentum dependence)

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

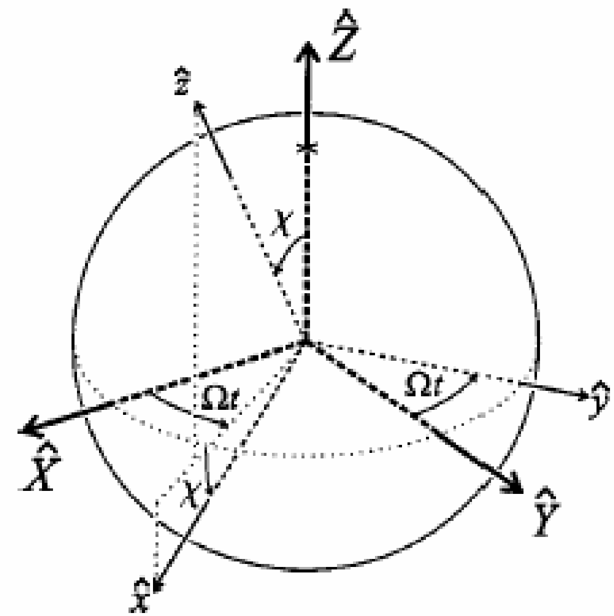
$$\boxed{\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right) / \Delta m}$$

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

CPT and Lorentz invariance violation (SME)

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

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 lab. 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

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**):

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

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

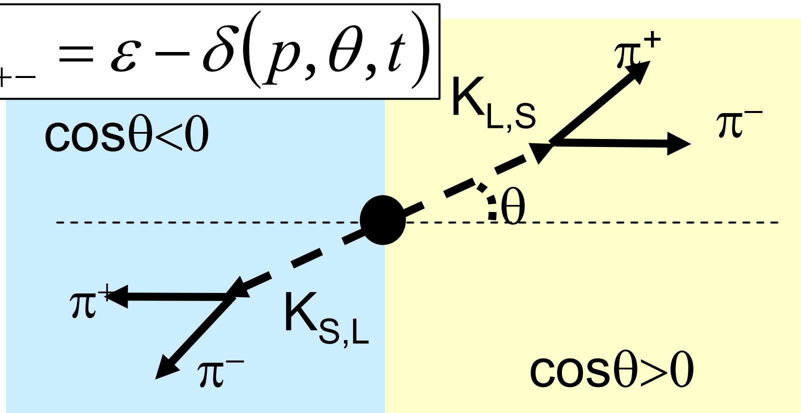
$\Delta a_{X,Y,Z}$ **from** $\phi \to K_S K_L \to \pi^+\pi^- \; \pi^+\pi^-$

(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)

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



With L=1 fb^{-1} (**preliminary**):

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

KTeV : Δa_X, Δa_Y < 9.2 × 10^{-22}GeV @ 90% CL

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

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**):

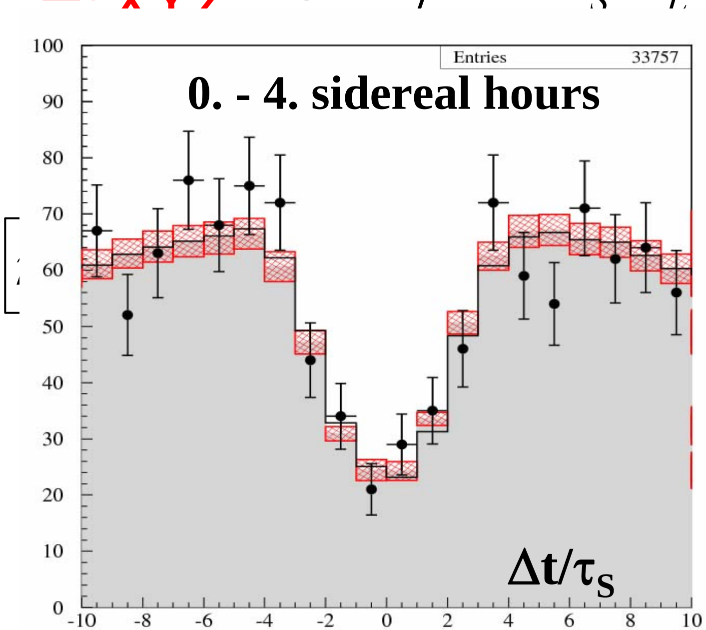
$$\boxed{\Delta a_0 = (0.4 \pm 1.8) \times 10^{-17}\ \text{GeV}}$$

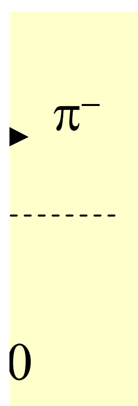
with L=2.5 fb^{-1} : $\sigma(\Delta a_0)$ ~ 7×10^{-18} GeV (Δa$_0$ evaluated for the first time)

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

d sidereal time t)

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





With L=1 fb^{-1} (**preliminary**):

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

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]

3) 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:

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, $e^+e^- \to p\bar{p}$, $n\bar{n}$, $\Lambda\bar{\Lambda}$)

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}
$\pi^+\pi^- \quad \pi^+\pi^-$	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	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm\, 2 \times 10^{-17}$ GeV
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & QM	β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm\, 0.1 \times 10^{-19}$ GeV
$\pi^+\pi^- \quad \pi^+\pi^-$	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
$\pi^+\pi^- \quad \pi^+\pi^-$	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	$[(0.4 \pm 1.8) \times 10^{-17}$ GeV$]$	$\pm\, 2 \times 10^{-18}$ GeV
$\pi^+\pi^- \quad \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$[(2.4 \pm 9.7) \times 10^{-18}$ GeV$]$	$\pm\, 7 \times 10^{-19}$ GeV
$\pi^+\pi^- \quad \pi e \nu$	CPT & Lorentz	$\Delta a_{X,Y}$	$[<10^{-21}$ GeV$]$	$O(10^{-19})$GeV

[….] = preliminary

Conclusions

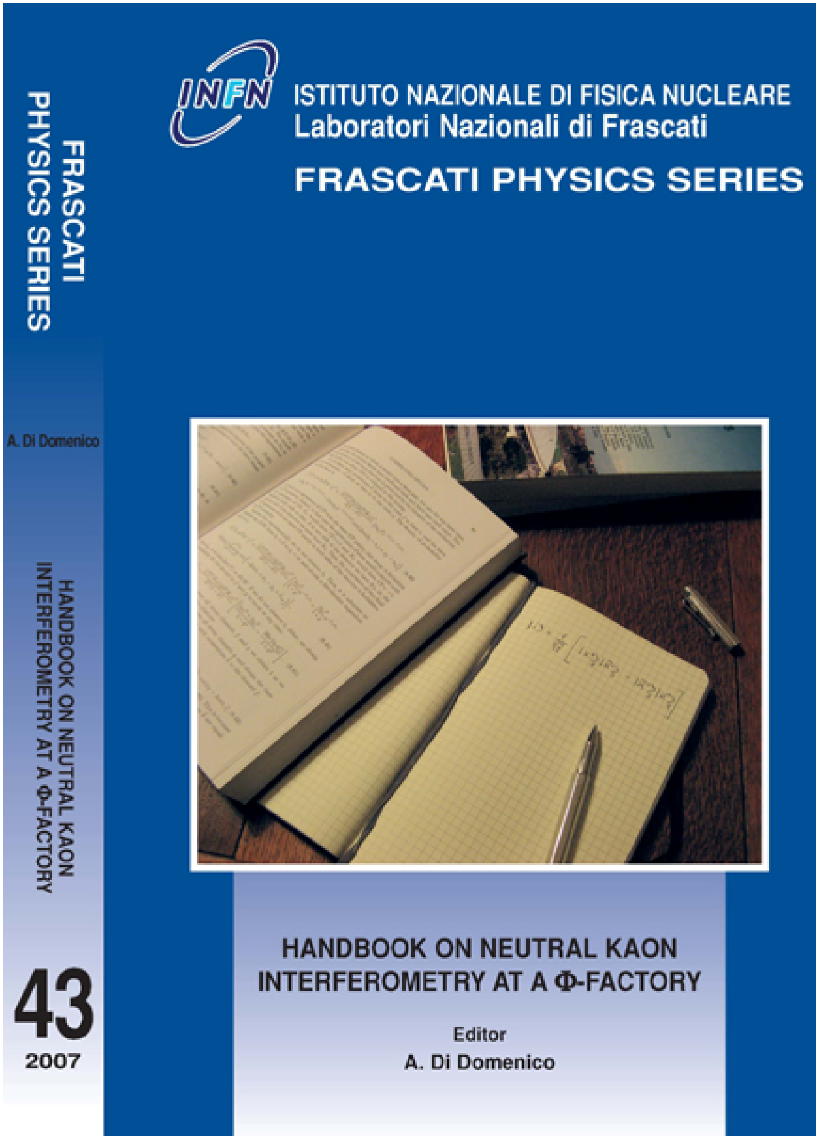
- The neutral kaon system is an excellent laboratory for the study of CPT symmetry and the basic principles of Quantum Mechanics;

- Several parameters related to possible
  - CPT violation (within QM)
  - CPT violation and decoherence
  - CPT violation and Lorentz symmetry breaking

  have been measured by KLOE, 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

Spare



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