
Search for CPT Violation and Decoherence Effects in the Neutral Kaon System



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CPT: introduction

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

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

Exact CPT invariance holds for any quantum field theory (flat space-time) which assumes:

(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

Testing the validity of the CPT symmetry probes the most fundamental assumptions of our present understanding of particles and their interactions.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

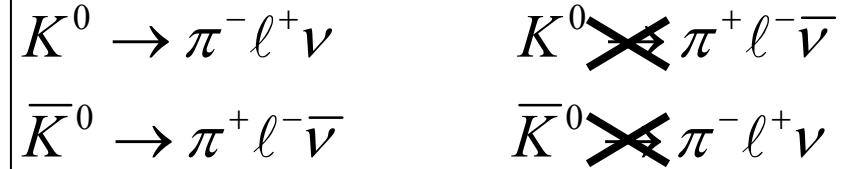
CPT violation in the neutral kaon system: “standard” picture

CPT violation in semileptonic decays

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

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

$\Delta S = \Delta Q$ rule



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

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

Semileptonic charge asymmetry:

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

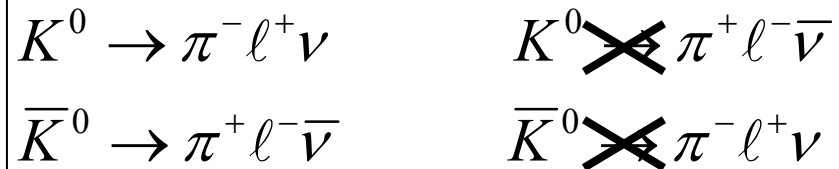
$$A_S - A_L = 4(\Re \delta + \Re x_{-})$$

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

CPT violation in semileptonic decays

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

$\Delta S = \Delta Q$ rule



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

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

Semileptonic charge asymmetry:

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

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

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

CPT violation in $\pi\pi$ decays

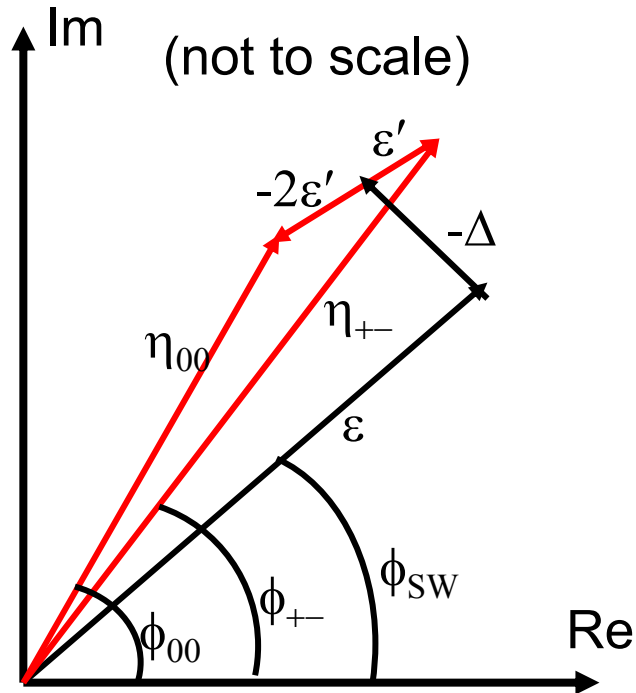
$$\langle \pi\pi; I | T | K^0 \rangle = (A_I + B_I) e^{i\delta_I}$$

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

$A_I(B_I)$ CPT conserving (violating)

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

(δ_I strong phase shift for $I=0,2$)



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

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

$$\Delta = \delta - \frac{\Re B_0}{\Re A_0}$$

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

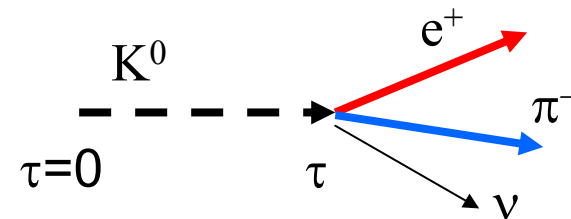
$$\phi_{00} - \phi_{+-} \approx \frac{3}{\sqrt{2}} \frac{1}{|\eta_{+-}|} \frac{\Re A_2}{\Re A_0} \left(\frac{\Re B_2}{\Re A_2} - \frac{\Re B_0}{\Re A_0} \right) \approx -3 \Im \left(\frac{\varepsilon'}{\varepsilon} \right)$$

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

Some results of CPT tests

Study of the time evolution of neutral kaons in semileptonic decays

CLEAR



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

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KTeV

Study of regenerator beam two pion decay distribution

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

PRL88,
181601(2002)

K_L semileptonic charge asymmetry:

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

KTeV

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

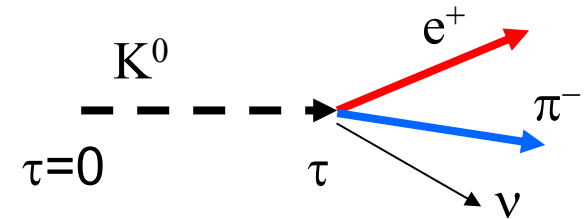
$$\Re \left(\frac{2}{3} \eta_{+-} + \frac{1}{3} \eta_{00} \right) - \frac{A_L}{2} = \Re \left(y + x_- + \frac{\Re B_0}{\Re A_0} \right) = (-3 \pm 35) \times 10^{-6}$$

PRD67,012005 (2003)

Some results of CPT tests

Study of the time evolution of neutral kaons in semileptonic decays

CLEAR



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

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KTeV

Study of regenerator beam two pion decay distribution

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

Presented at Moriond08, HQL08

K_L semileptonic charge asymmetry:

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KTeV

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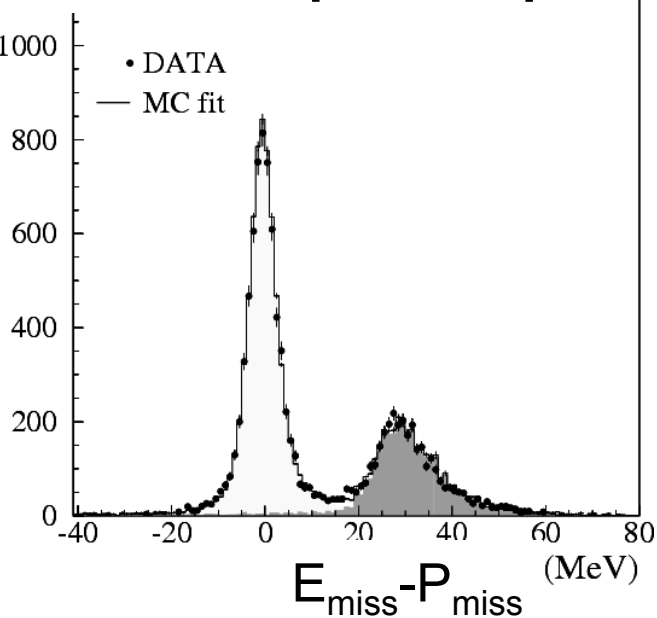
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PRD67,012005 (2003)

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

PLB 636(2006) 173

Data sample: 410 pb⁻¹



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

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

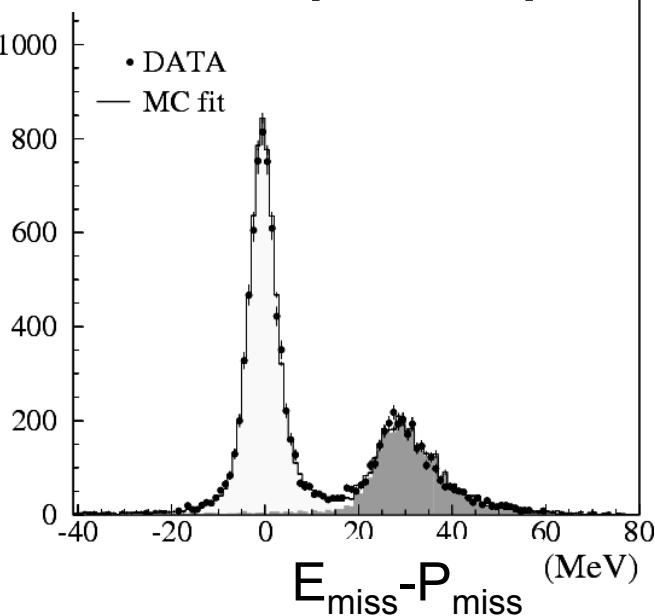
$$\text{BR}(K_S \rightarrow \pi e \nu) = (7.046 \pm 0.076 \pm 0.050) \times 10^{-4}$$

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

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

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

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

with 2.5 fb⁻¹:

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

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

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

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

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

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

CPT viol.

input from other experiments

CPT test: the Bell-Steinberger relation

Unitarity constraint:

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

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

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

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

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

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

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

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

$$\alpha_{kl3} = 2\tau_S / \tau_L \text{BR}(K_L 13) [(A_S + A_L) / 4 - i \text{Im } x_+]$$

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

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

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

Experimental inputs to the Bell-Steinberger relation

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

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

CPT test: the Bell-Steinberger relation

KLOE result: JHEP12(2006) 011

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

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

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

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

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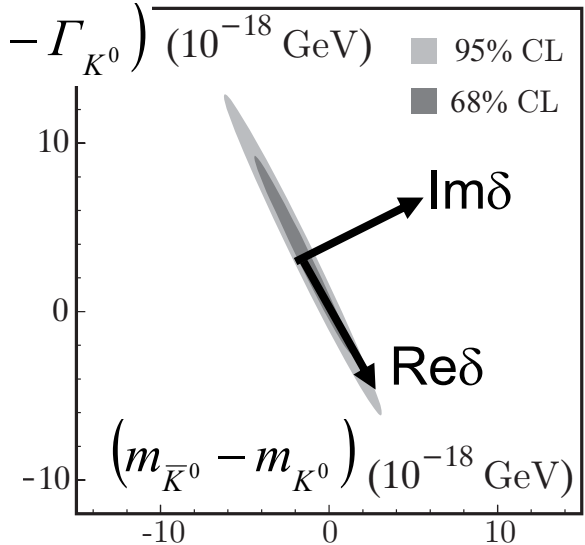
Combining $\text{Re } \delta$ and $\text{Im } \delta$ results:

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

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

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

at 95% c.l.



CPT test: the Bell-Steinberger relation

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

$$\begin{aligned} \text{Re } \varepsilon &= (161.2 \pm 0.6) \times 10^{-5} \\ \text{Im } \delta &= (-0.1 \pm 1.4) \times 10^{-5} \end{aligned}$$

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

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

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

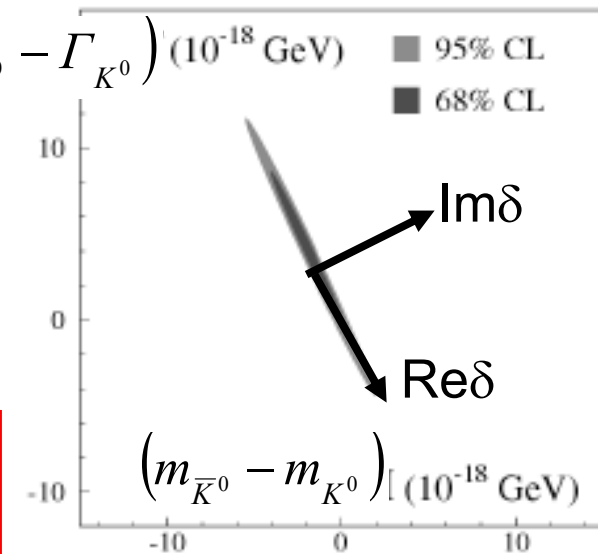
Assuming $(\Gamma_{\bar{K}^0} - \Gamma_{K^0}) = 0$, i.e. no CPT viol. in decay:

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

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

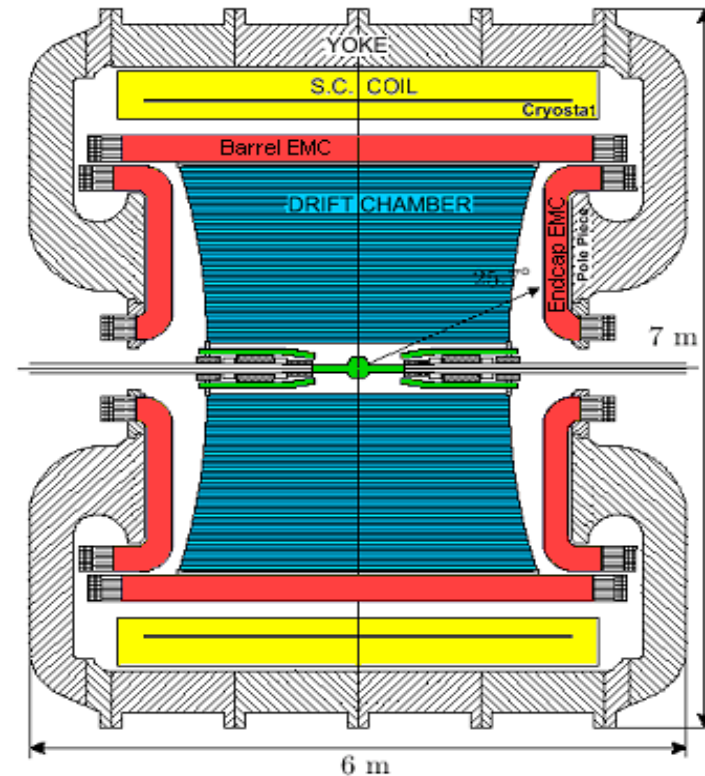
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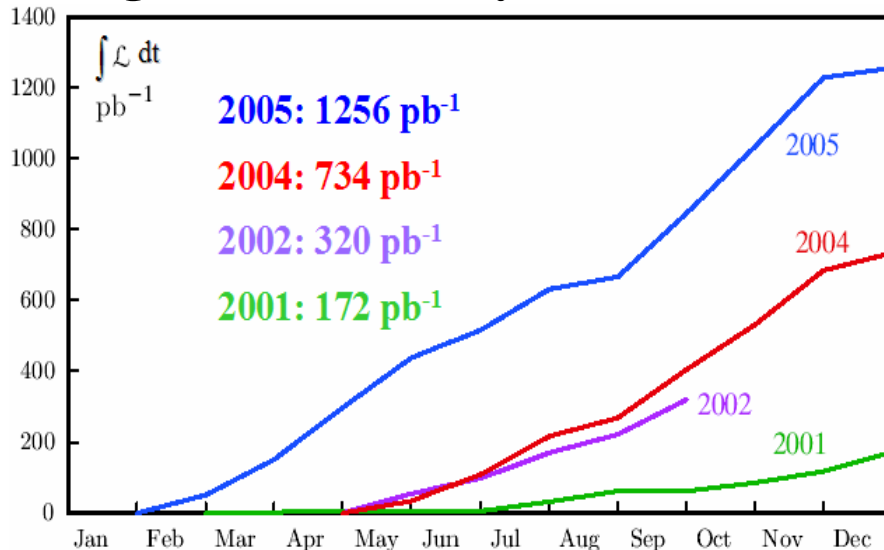


2) Search for decoherence and CPT violation in the neutral kaon system

The KLOE detector at the Frascati ϕ -factory DAΦNE



Integrated luminosity (KLOE)



Lead/scintillating fiber calorimeter
 drift chamber
 4 m diameter \times 3.3 m length
 helium based gas mixture

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

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

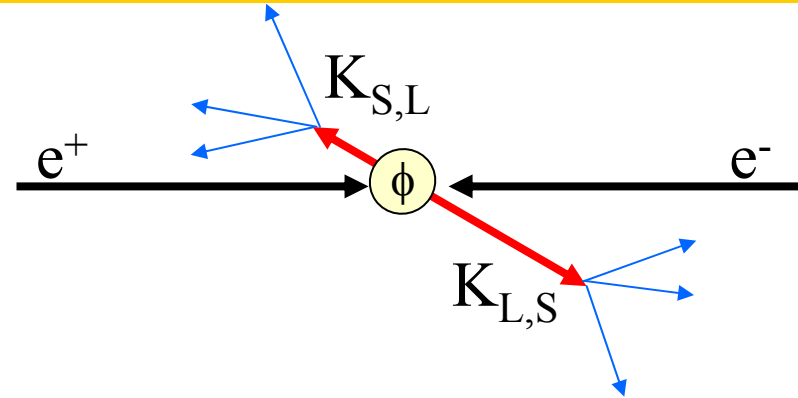
Neutral kaons at a ϕ -factory

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

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

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

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



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

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

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

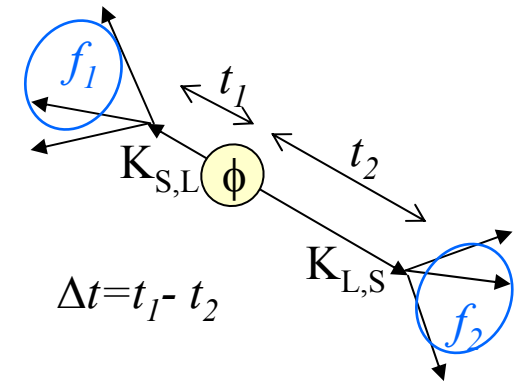
The detection of a kaon at large (small) times tags a K_S (K_L)
 \Rightarrow possibility to select a pure K_S beam (**unique** at a ϕ -factory, not possible at fixed target experiments)

Neutral kaon interferometry

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

Double differential time distribution:

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



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

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

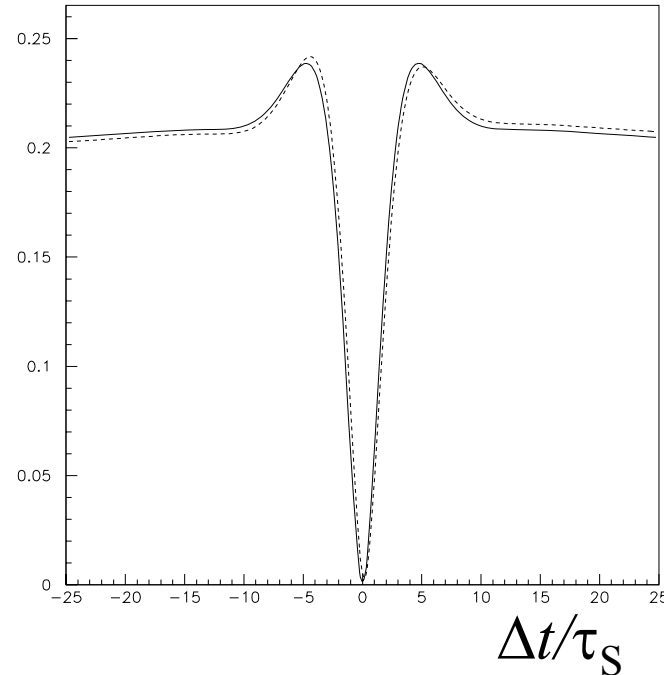
$$C_{12} = \frac{|N|^2}{2} \left| \langle f_1 | T | K_S \rangle \langle f_2 | T | K_S \rangle \right|^2$$

**characteristic interference term
at a ϕ -factory \Rightarrow interferometry**

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

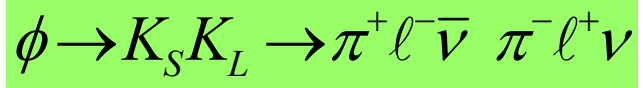
Neutral kaon interferometry: main observables

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

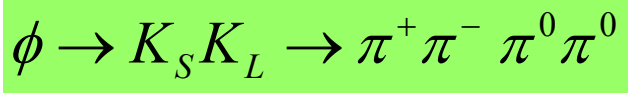
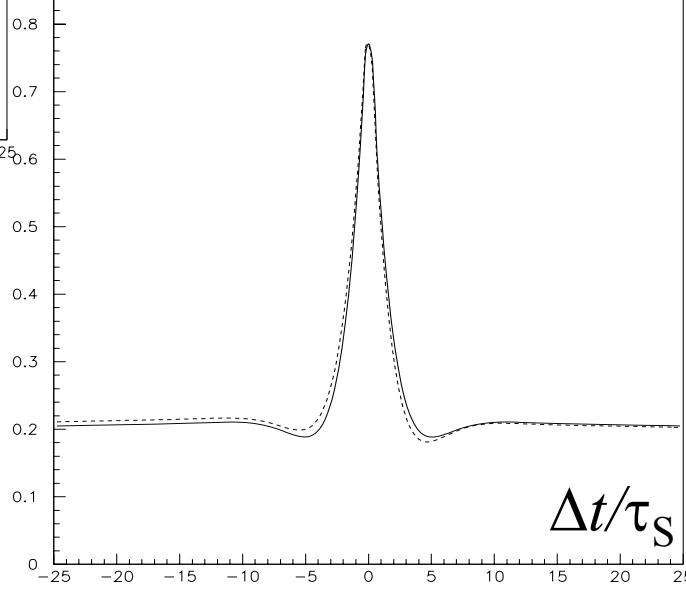


$$\Re \delta + \Re x_-$$

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

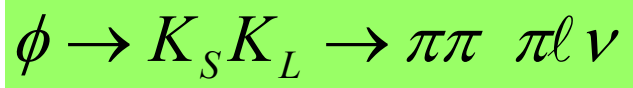
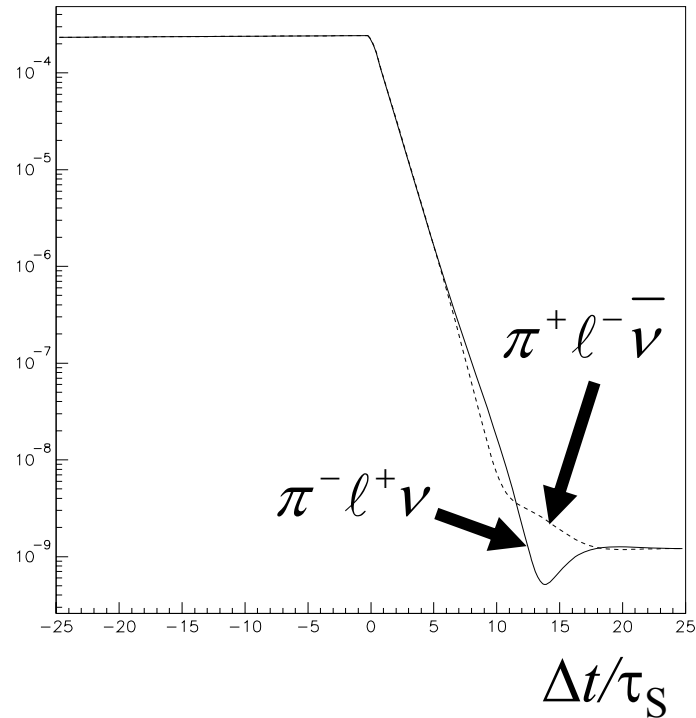


$I(\Delta t)$ (a.u)



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

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



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

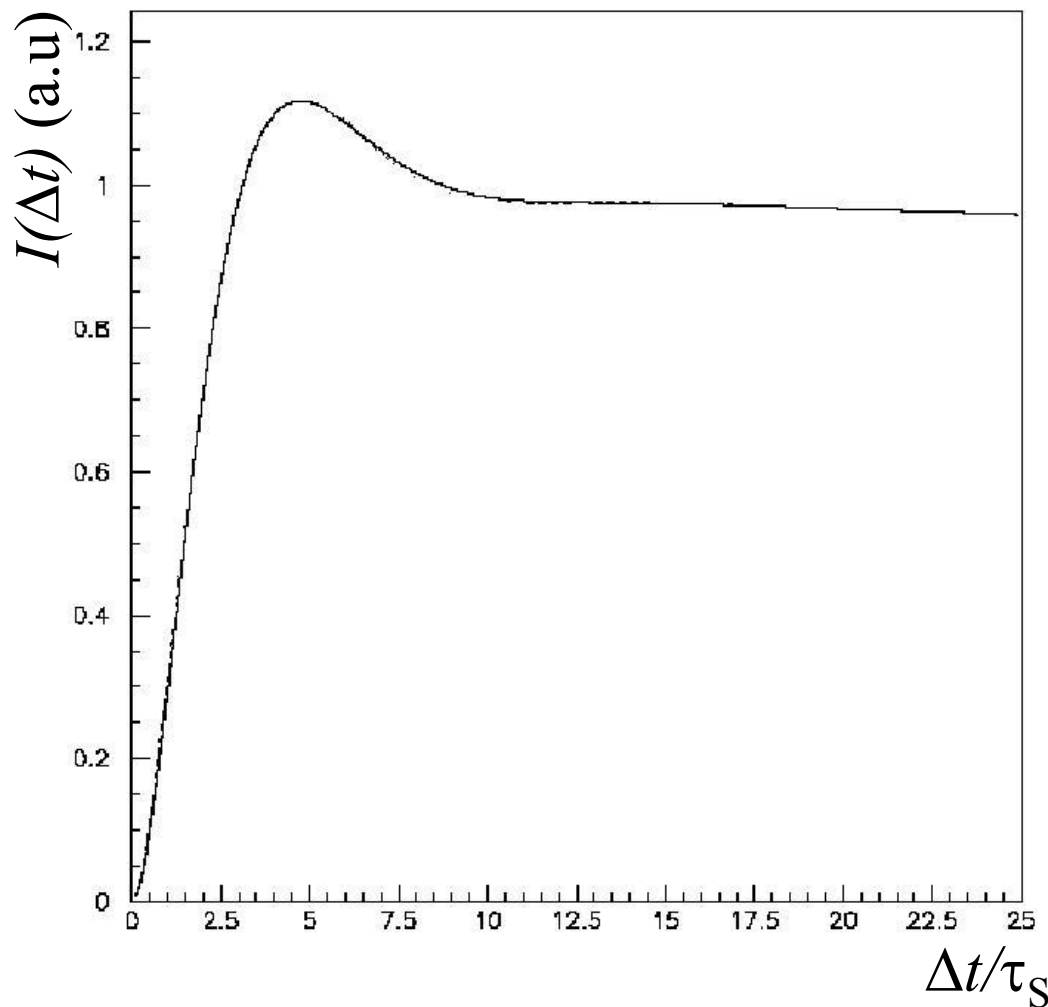
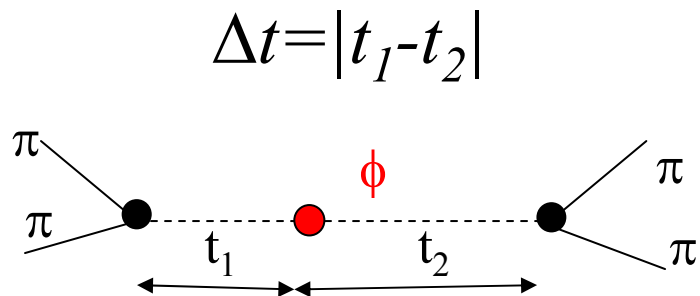
$$- \Re y - \Re x_-$$

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

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

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

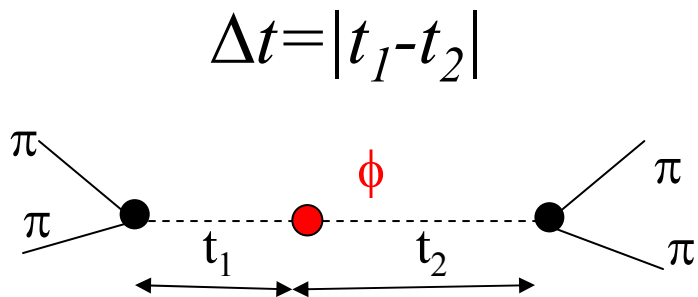
Same final state for both kaons: $f_1 = f_2 = \pi^+ \pi^-$



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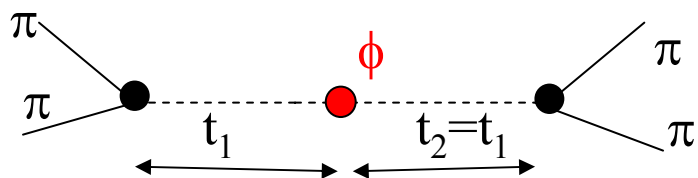
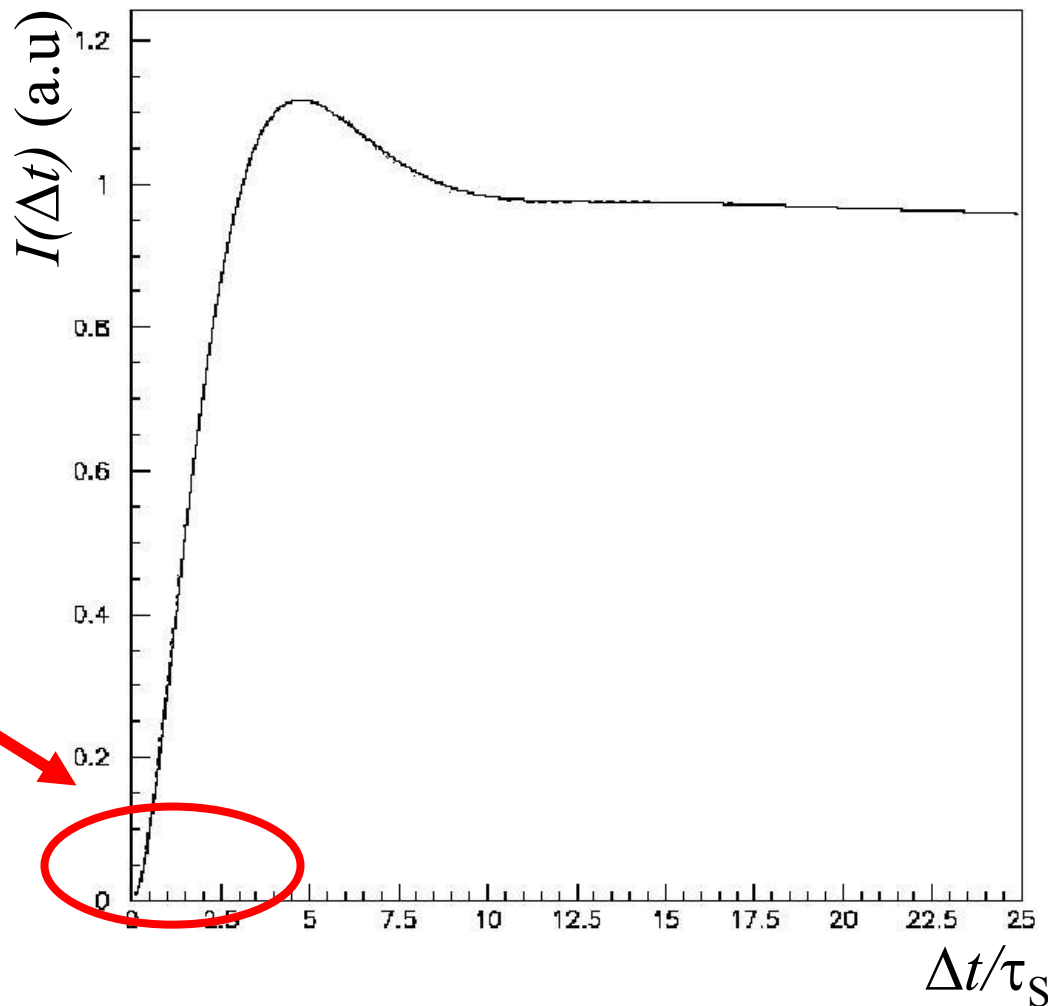
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EPR correlation:

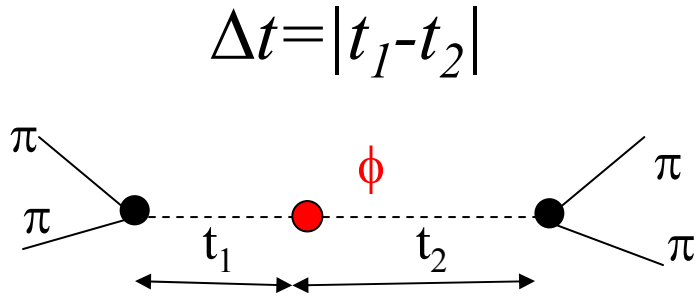
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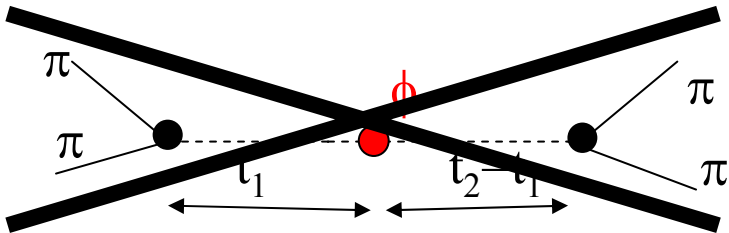
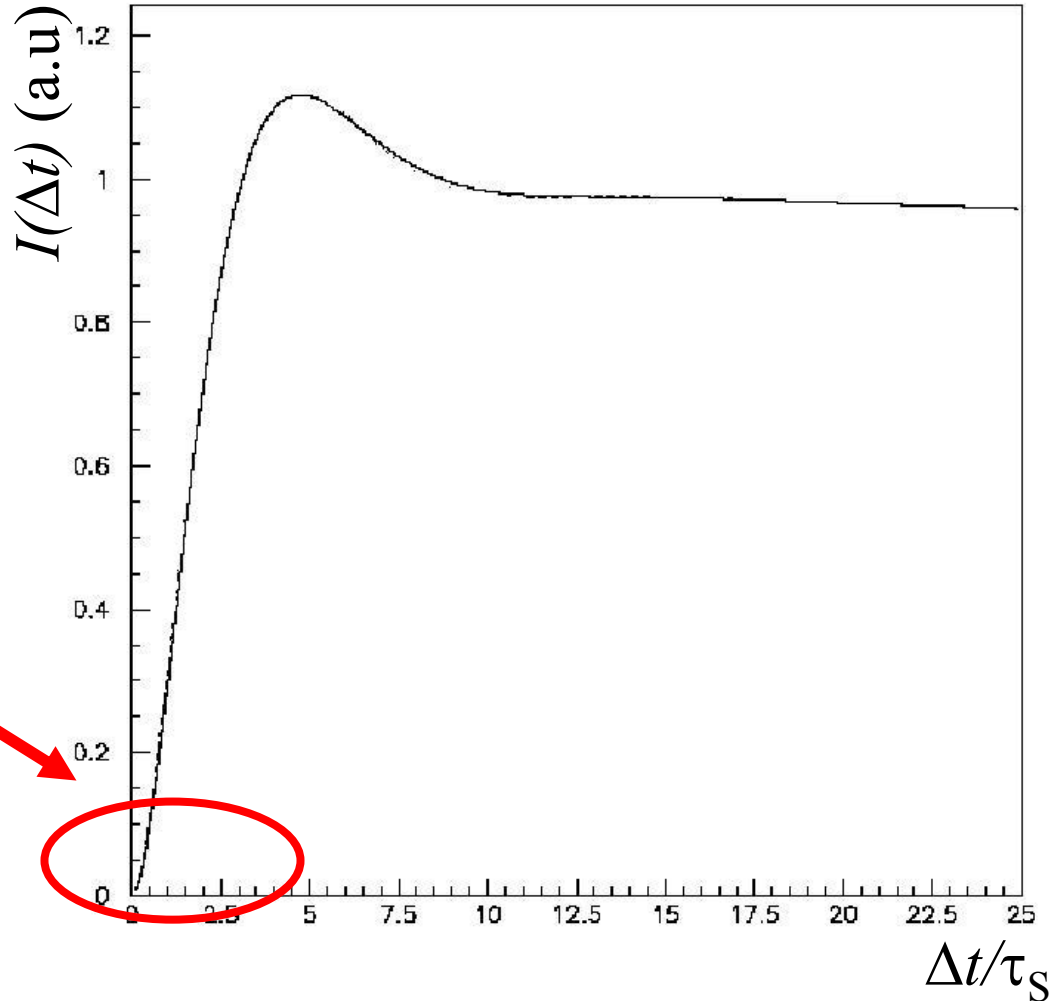
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$\phi \rightarrow \mathbf{K}_S \mathbf{K}_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

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

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

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

Decoherence parameter:

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

$$\zeta_{0\bar{0}} = 1 \rightarrow \text{total decoherence}$$

(also known as Furry's hypothesis or spontaneous factorization)
[W.Furry, PR 49 (1936) 393]

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

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

KLOE result: [PLB 642\(2006\) 315](#)

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

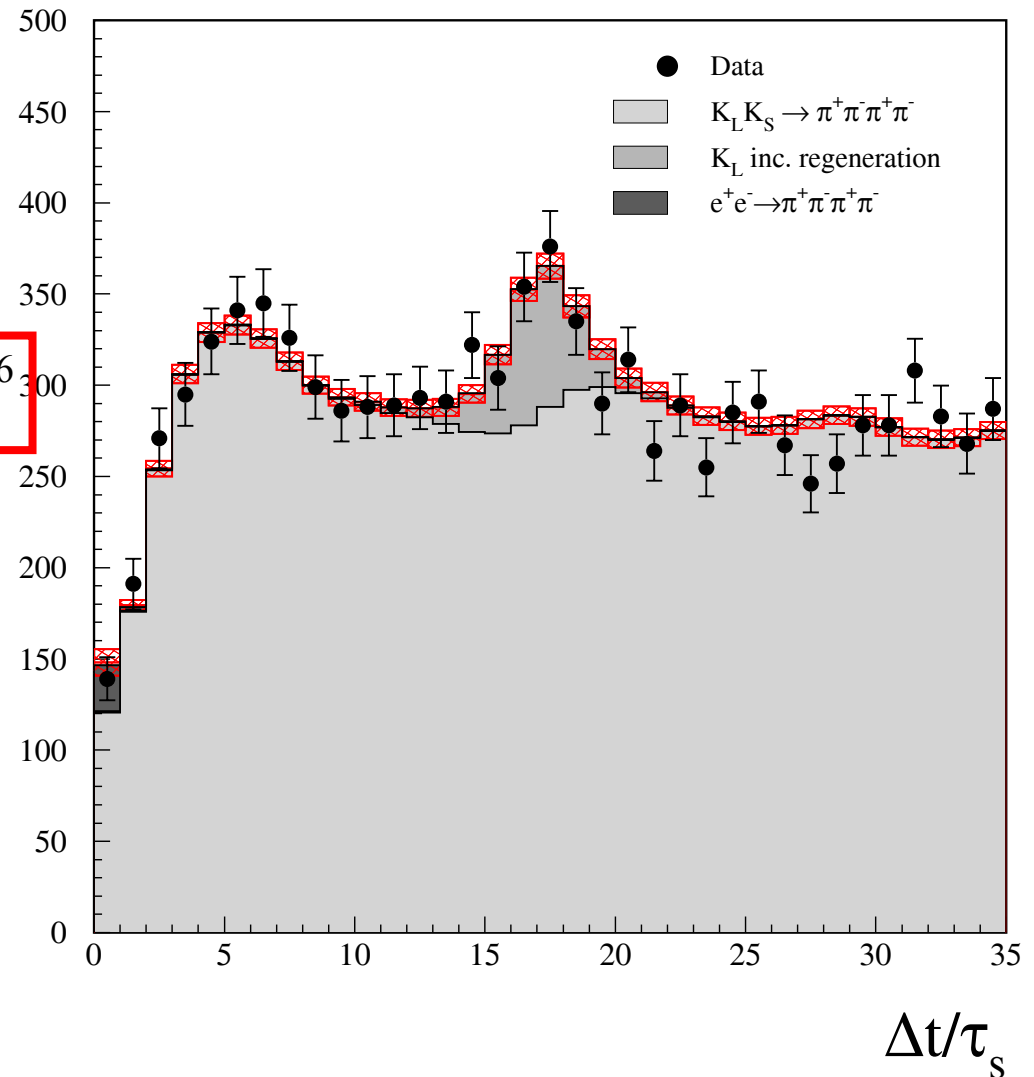
as CP viol. $O(|\eta_{+-}|^2) \sim 10^{-6}$
=> high sensitivity to $\zeta_{0\bar{0}}$

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:

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



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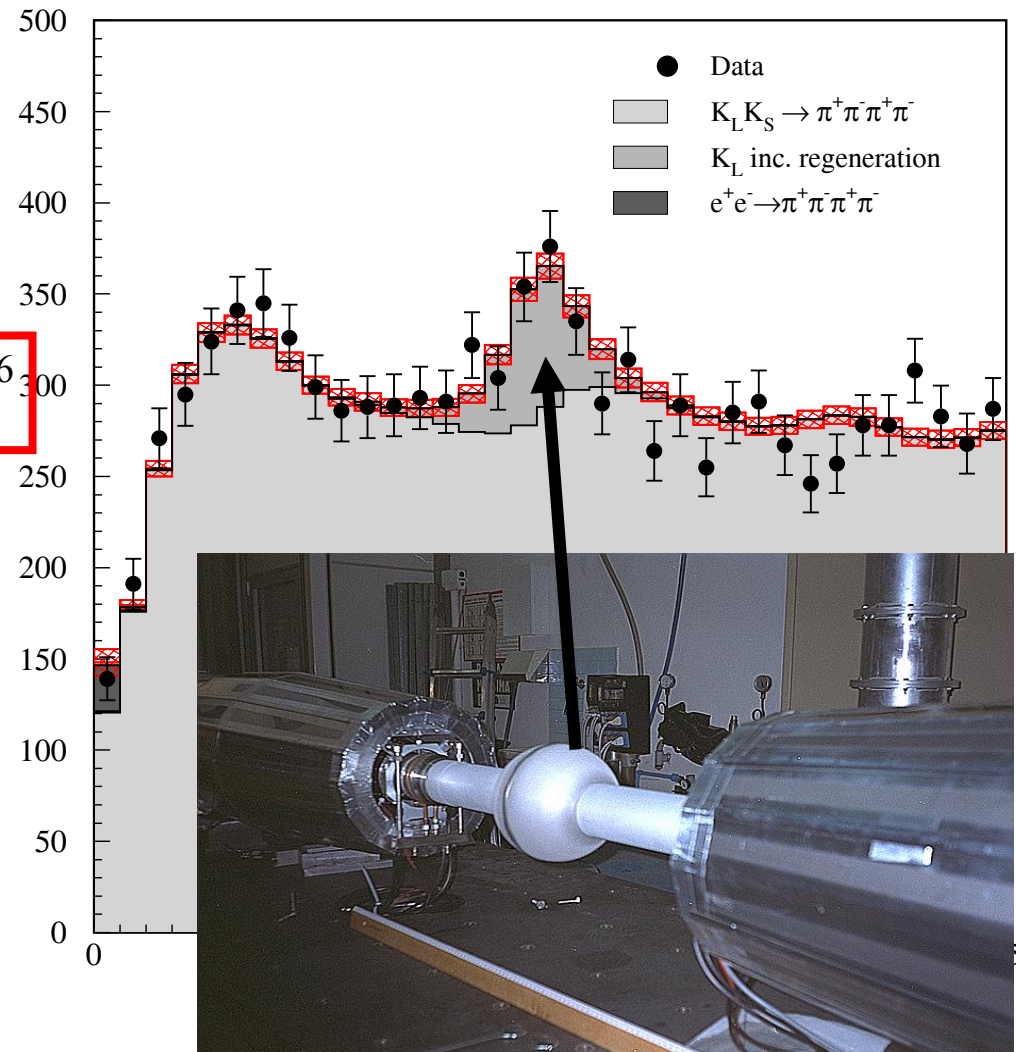
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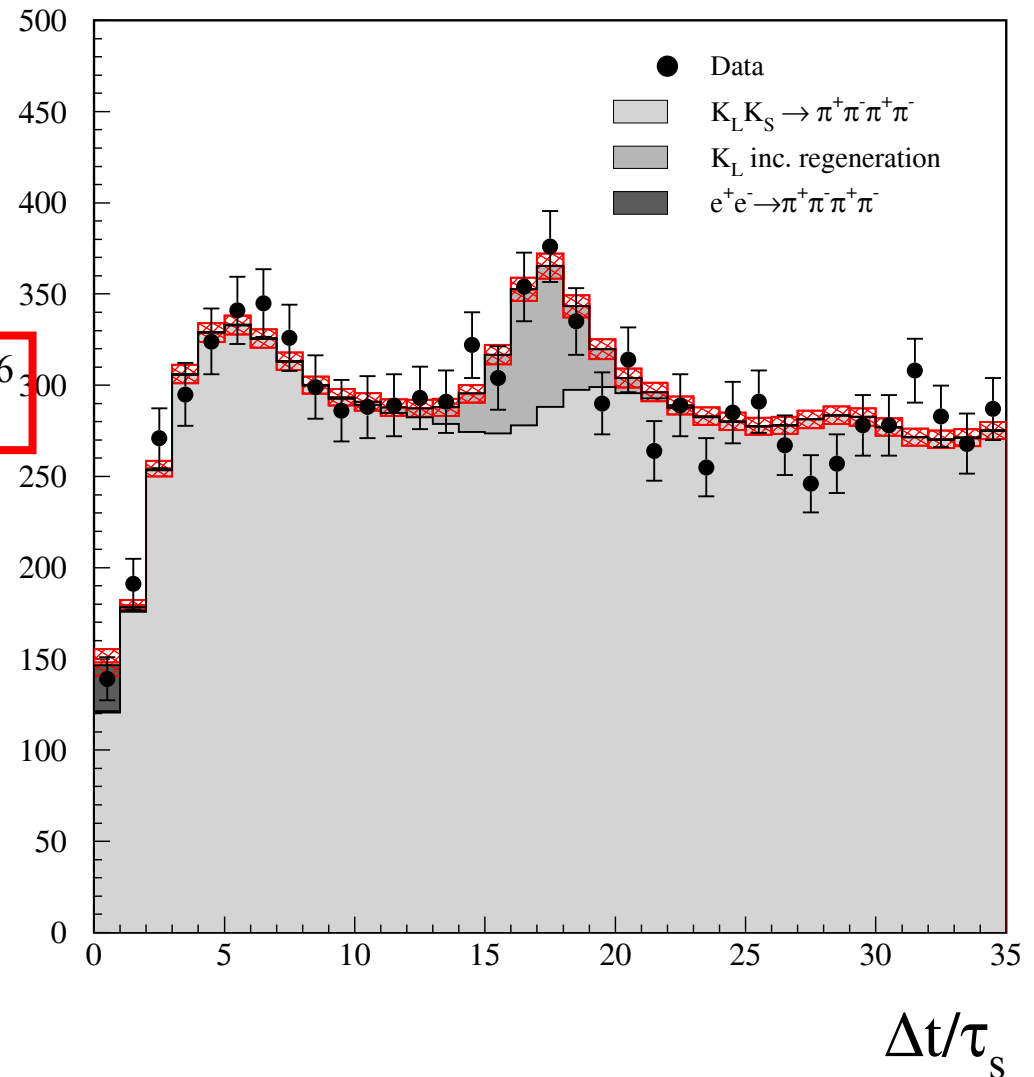
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$\phi \rightarrow \mathbf{K}_S \mathbf{K}_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$: test of quantum coherence

- Analysed data: $L=1 \text{ fb}^{-1}$ (2005 data)
- Fit including Δt resolution and efficiency effects + regeneration
- $\Gamma_S, \Gamma_L, \Delta m$ fixed from PDG

KLOE preliminary:

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

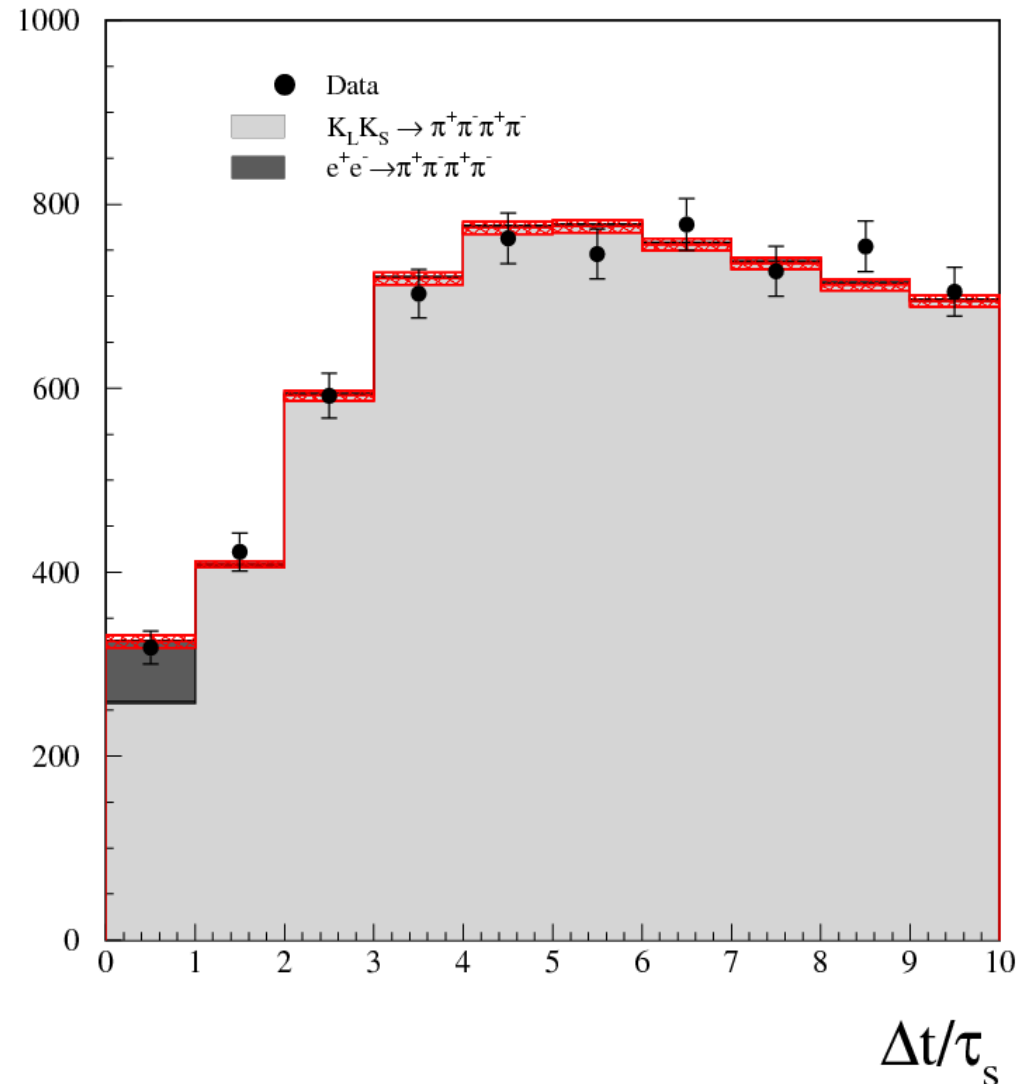
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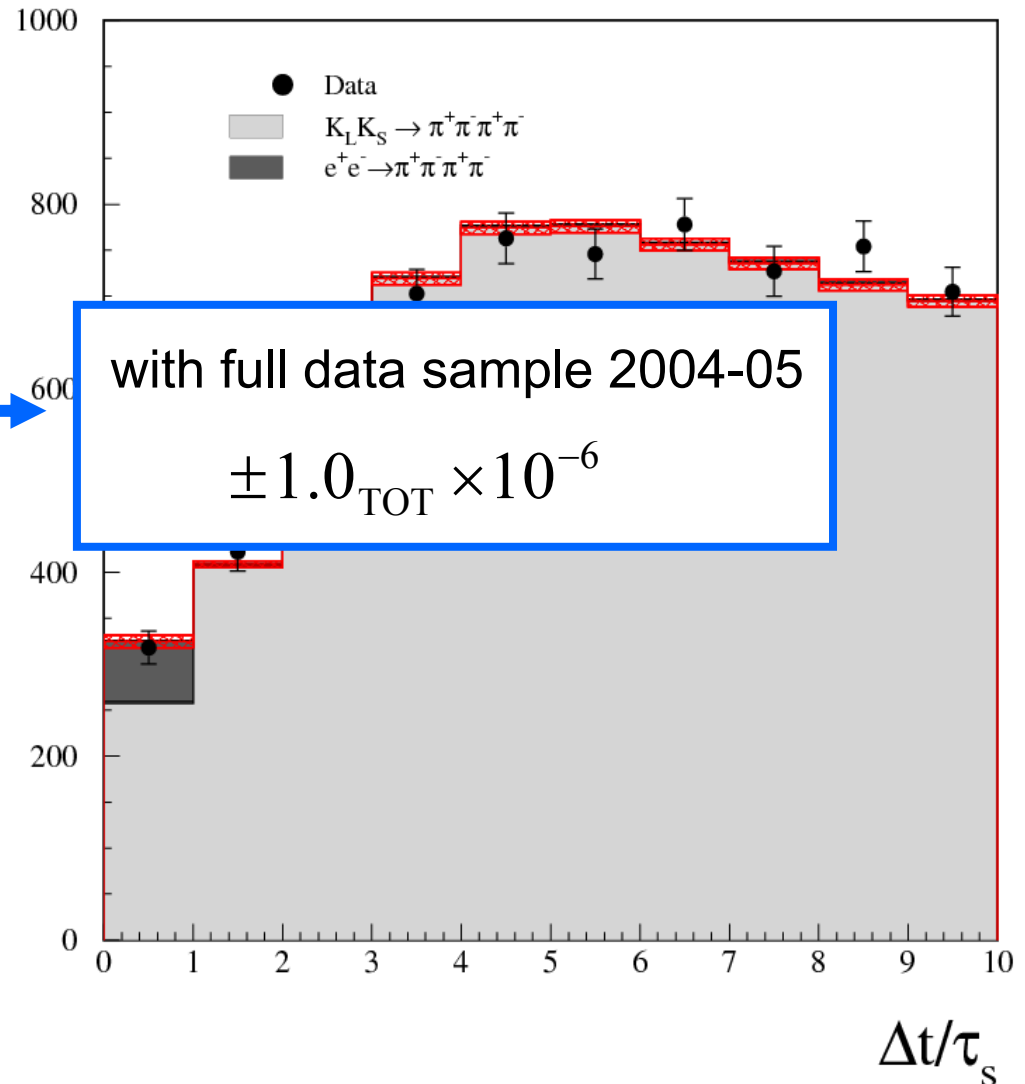
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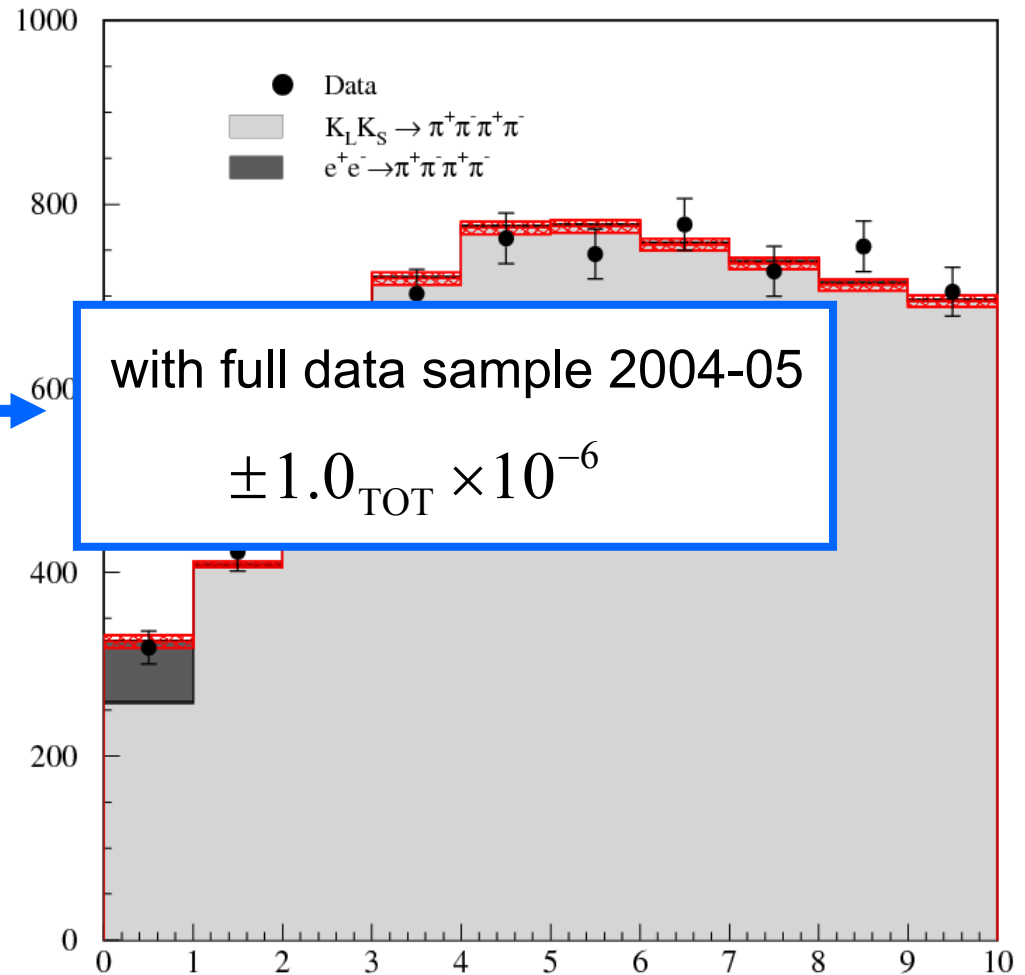
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Comparison with quantum optics test precisions



$\Delta t / \tau_S$

Decoherence and CPT violation

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

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

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

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Possible decoherence due quantum gravity effects:

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

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

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

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

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

see Mavromatos' talk

[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]

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

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

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

$$\alpha = (-0.5 \pm 2.8) \times 10^{-17} \text{ GeV}$$

$$\beta = (2.5 \pm 2.3) \times 10^{-19} \text{ GeV}$$

$$\gamma = (1.1 \pm 2.5) \times 10^{-21} \text{ GeV}$$

In the complete positivity hypothesis

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

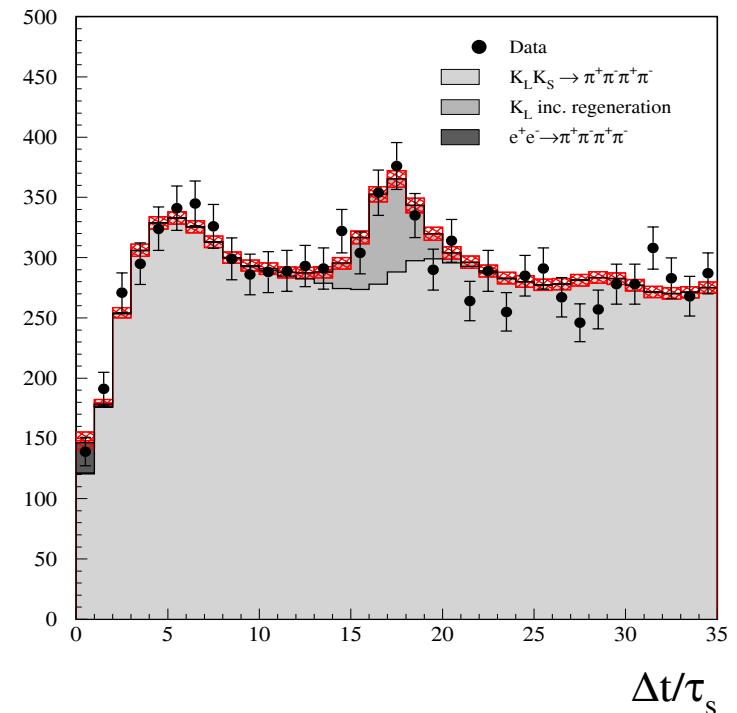
=> only one independent parameter: γ

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

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

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

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



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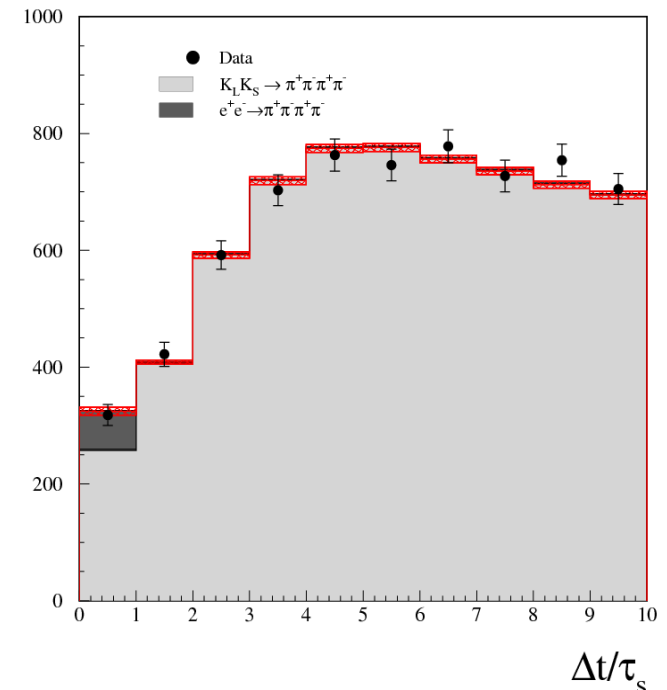
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The fit with $I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \gamma)$ gives:

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

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

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



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

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

see Mavromatos' and Sarkar's talks

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

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

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

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

[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]

$$|\omega| \sim 10^{-4} \div 10^{-5}$$

The maximum sensitivity to ω is expected for $f_1=f_2=\pi^+\pi^-$

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

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

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

- Analysed data: 380 pb⁻¹

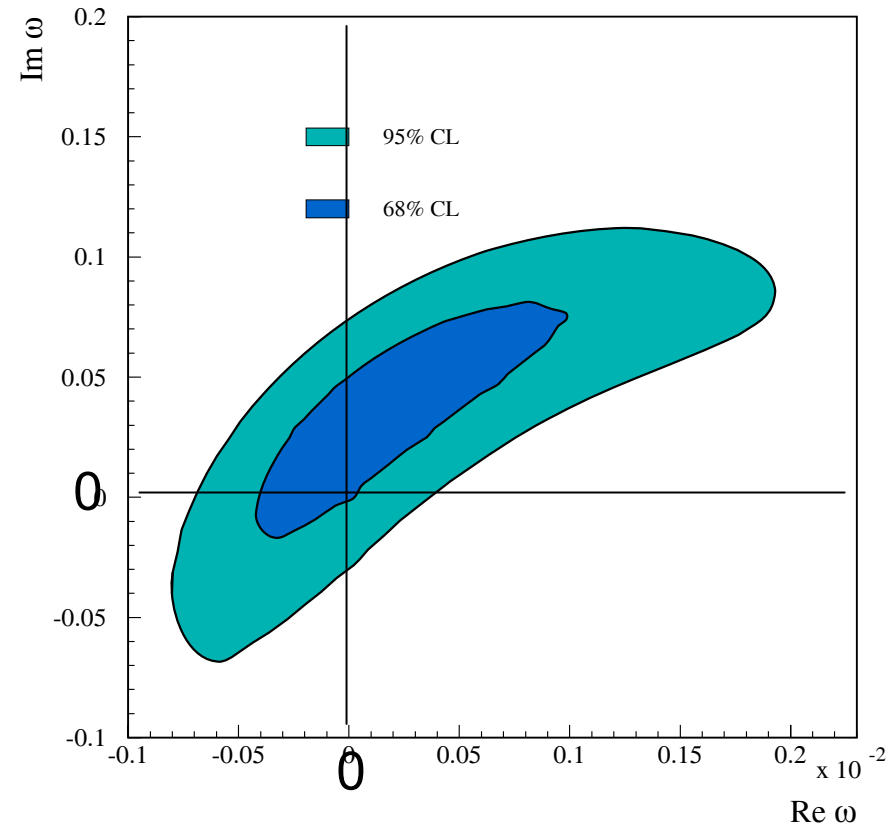
KLOE result : **PLB 642(2006) 315**

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

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

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

Im ω x10⁻²



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

Re ω x10⁻²

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

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

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

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

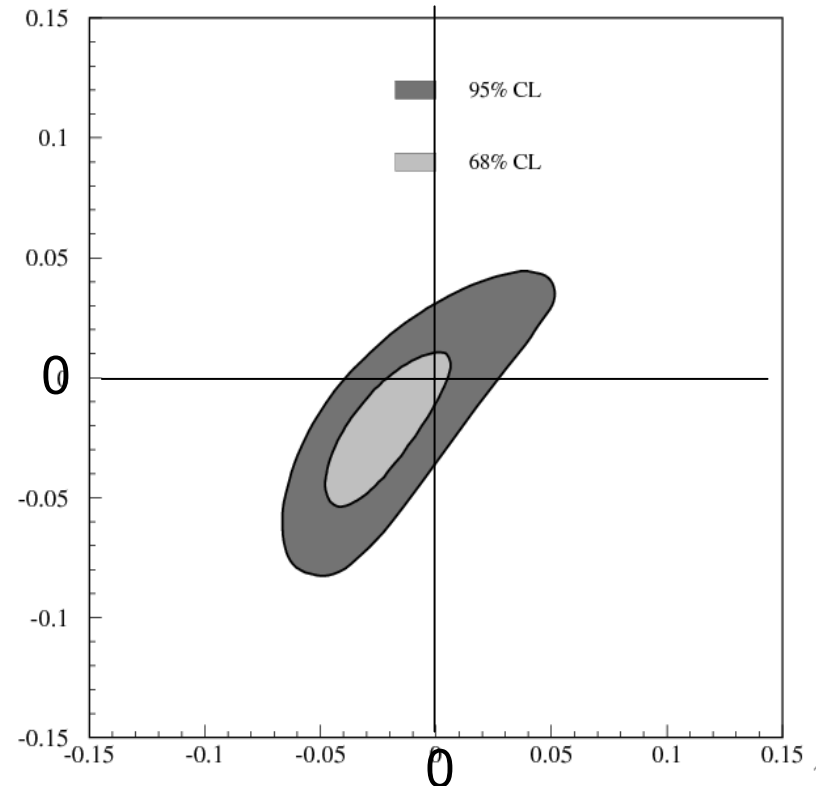
- Analysed data: 1 fb^{-1} (2005 data)

KLOE preliminary :

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

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

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



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

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

CPT and Lorentz invariance violation (SME)

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

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

see Lehnert's talk

CPT violation in neutral kaons according to SME:

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

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

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

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

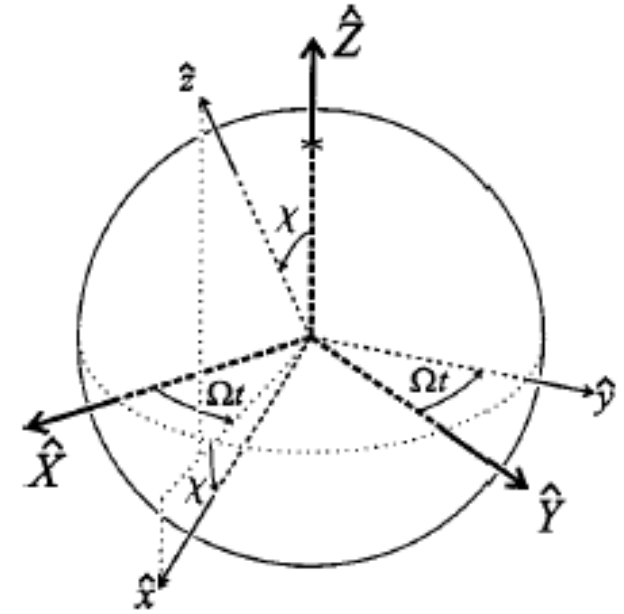
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δ depends on sidereal time t since laboratory frame rotates with Earth.

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

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



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

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

CPT and Lorentz invariance violation (SME)

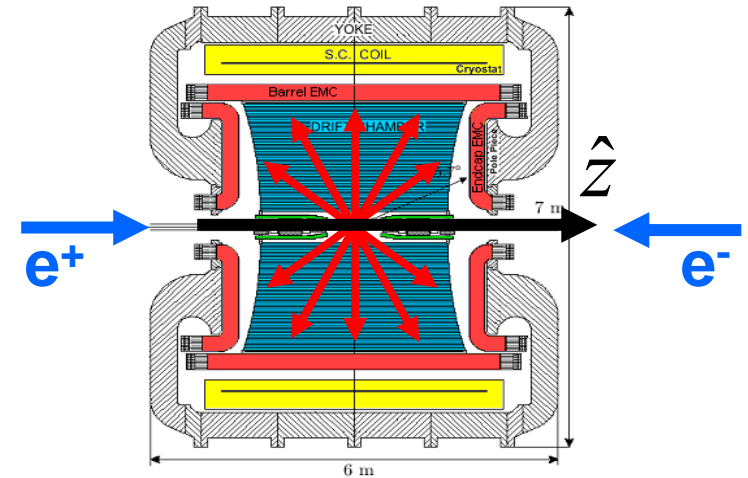
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For a ϕ -factory there is an additional dependence on the polar and azimuthal angle θ, ϕ of the kaon momentum in the laboratory frame:

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

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



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

Measurement of Δa_μ at KLOE

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

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

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

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

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

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

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

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

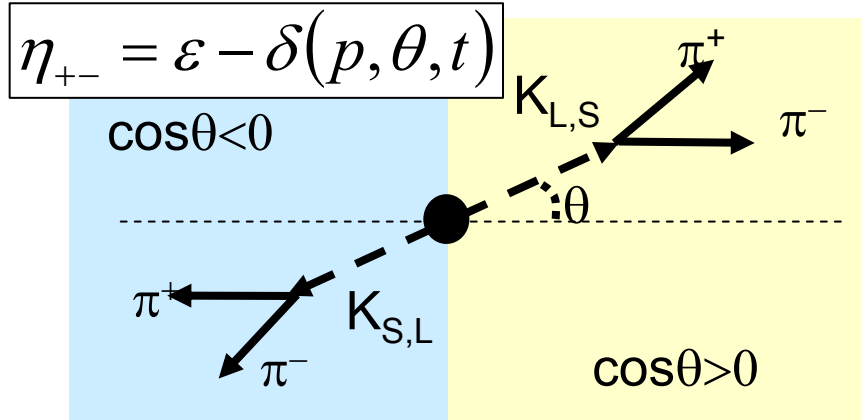
• at $\Delta t \sim \tau_s$ sensitive to $\text{Im}(\delta/\varepsilon)$

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

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

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

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



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

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

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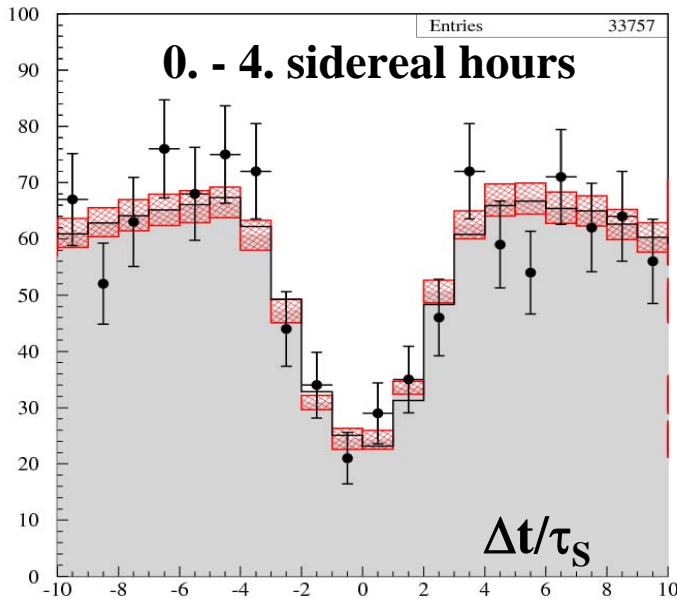
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 [PRL 100 (2008) 131802]

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 Bossi's talk

KLOE-2 Plan:

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

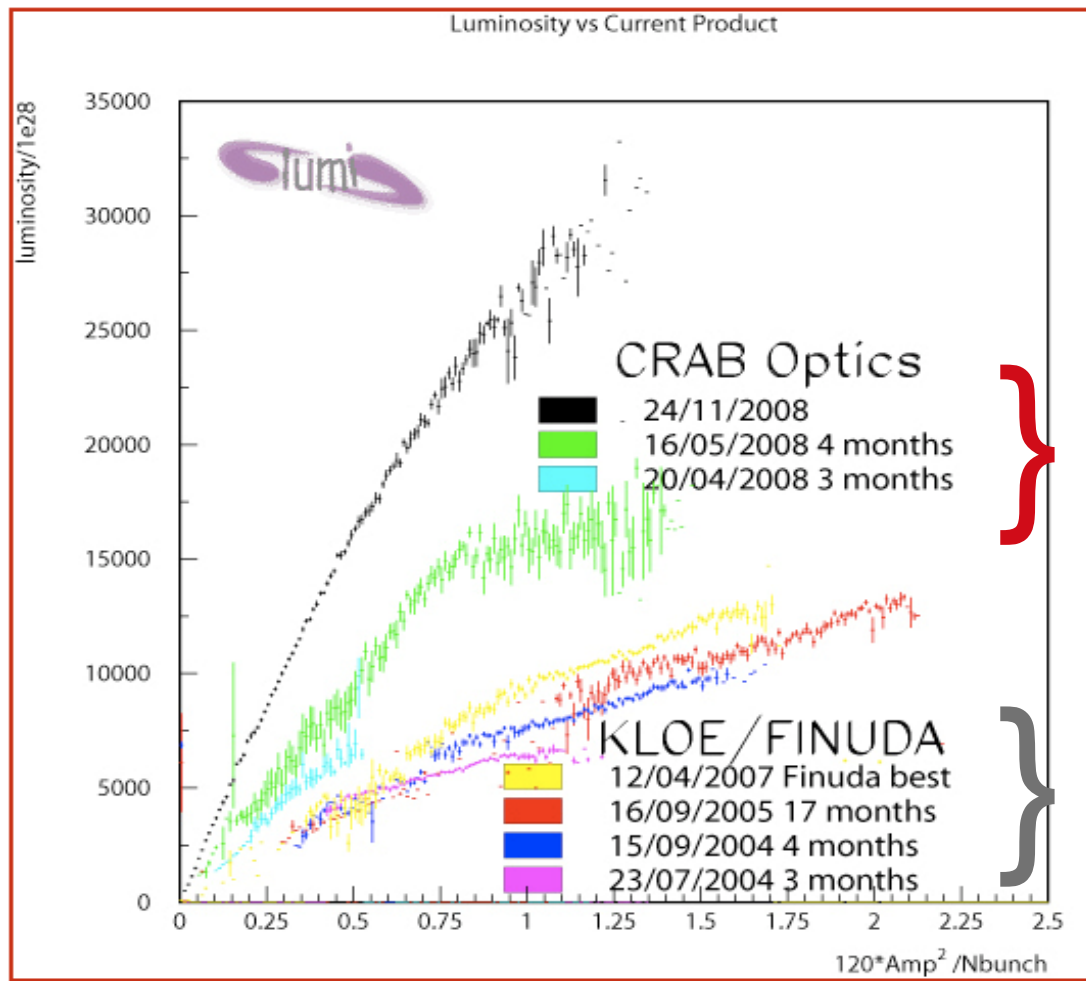
Physics issues:

- 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

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, ...)

DAΦNE Luminosity versus colliding currents



NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

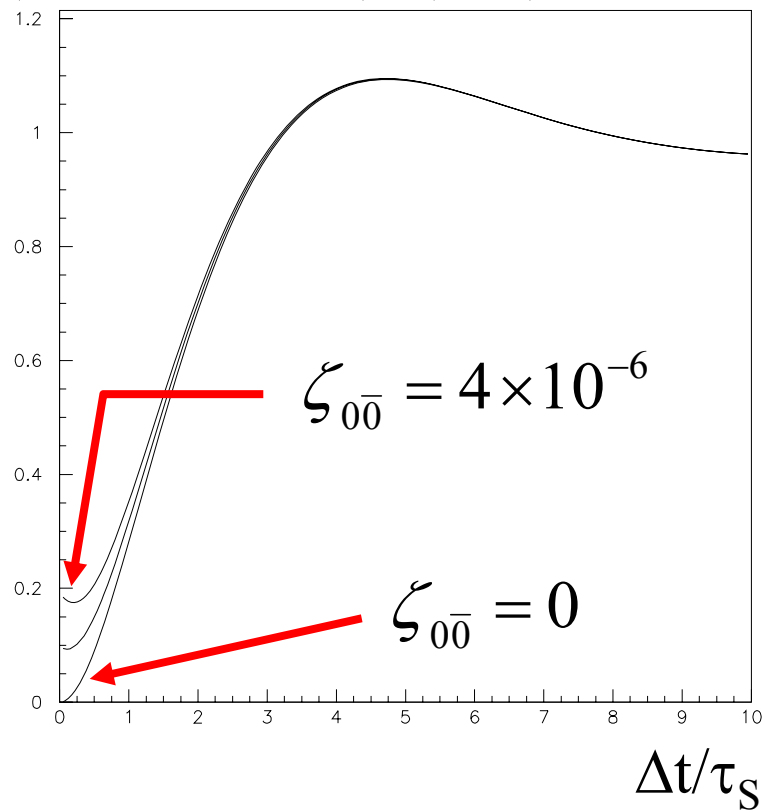
original collision scheme

from P. Raimondi's talk

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

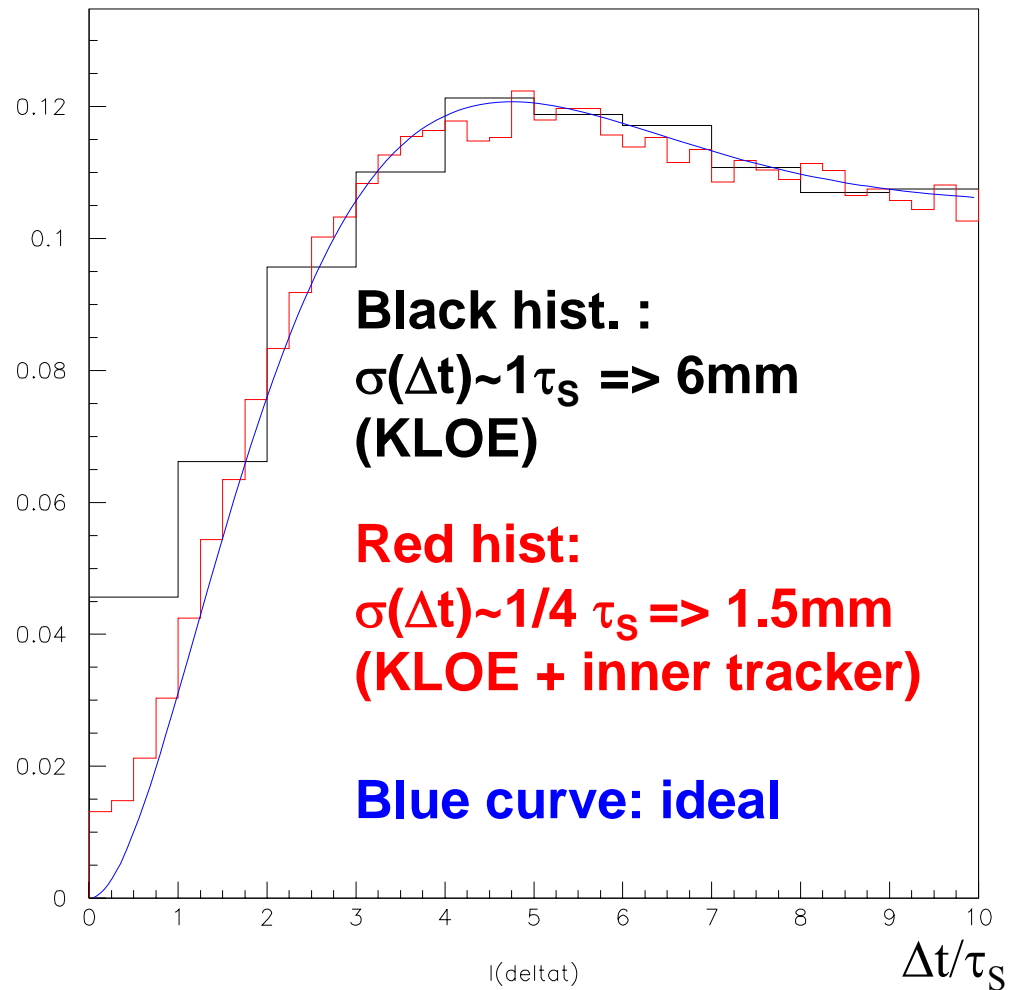
Possible signal of decoherence concentrated at very small Δt

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



Theoretical distribution

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

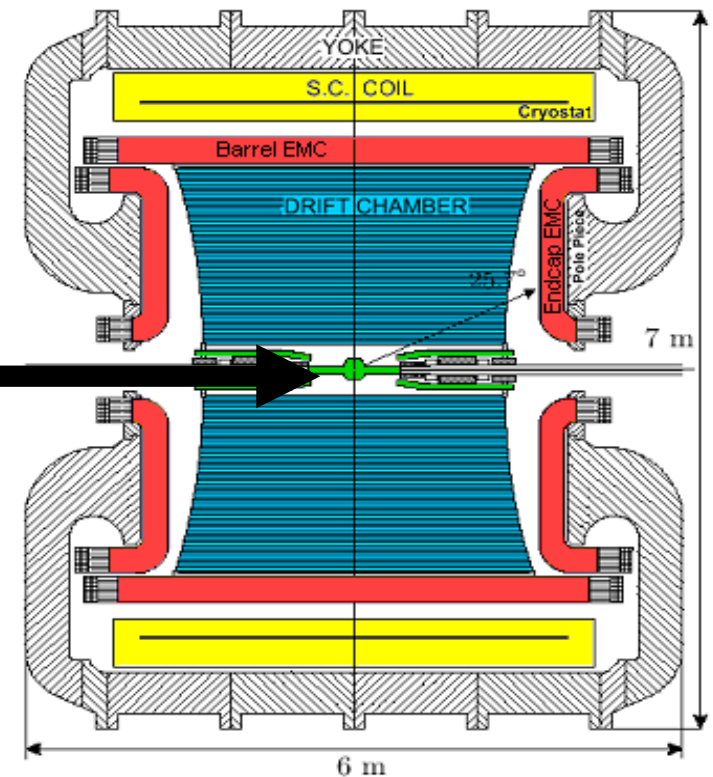
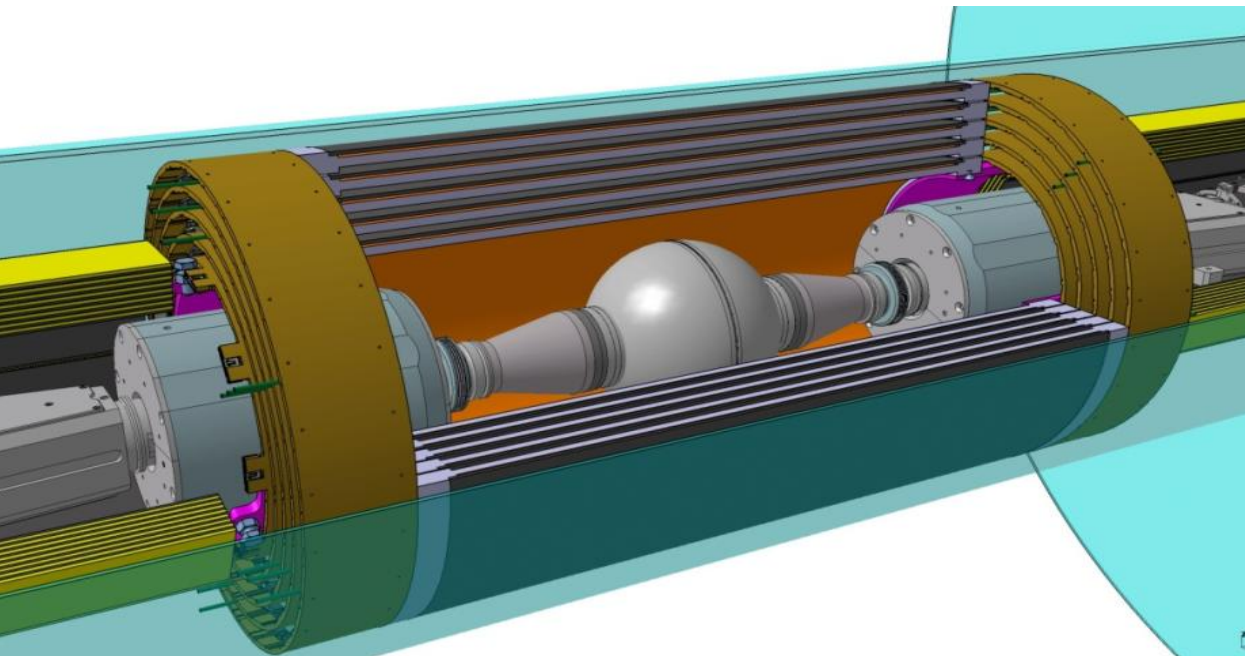


Reconstructed distribution (MC)

Inner tracker at KLOE

- 5 independent tracking layers for a fine vertex reconstruction of K_S and η
- $200 \mu\text{m}$ $\sigma_{r\phi}$ and $500 \mu\text{m}$ σ_z spatial resolutions with XV readout
- 700 mm active length
- from 150 to 250 mm radii
- 1.8% X_0 total radiation length in the active region

Realized with **Cylindrical-GEM** detectors



Perspectives with KLOE-2 at upgraded DAΦNE

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

(*) = PDG 2008 fit

Perspectives with KLOE-2 at upgraded DAΦNE

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

[...] = preliminary

Conclusions

- The neutral kaon system is an excellent laboratory for the study of CPT symmetry and the basic principles of Quantum Mechanics;
- Several parameters related to possible
 - CPT violation (within QM)
 - CPT violation and decoherence
 - CPT violation and Lorentz symmetry breakinghave been recently measured at KLOE, in some cases with a precision reaching the interesting Planck's scale region;
- All results are consistent with no CPT violation
- The analysis of the full KLOE data sample ($\sim 2.5 \text{ fb}^{-1}$) is being completed;
- KLOE and DAΦNE are going to be upgraded;
- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program
- Other interesting QM tests possible, e.g. quantum eraser.

see Hiesmayr's talk