Review of KLOE results on CPT, kaon interferometry and perspectives

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Mini-Workshop on Neutral Kaon Interferometry:
from Quantum Mechanics to Quantum Gravity

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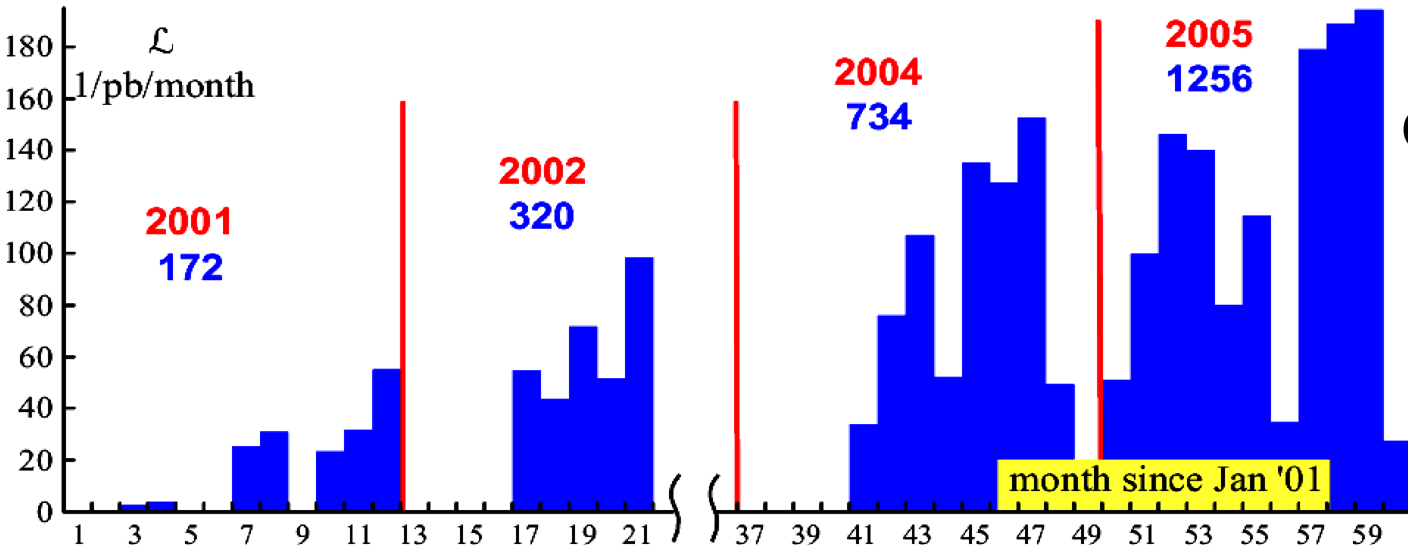
The DAΦNE e^+e^- collider

- e^+e^- collider @ $\sqrt{s}$ = 1019.4 MeV
- separate e^+, e^- rings to minimize beam-beam interactions
- crossing angle: 25 mrad
- time between collision 2.7 ns
- injection during data-taking

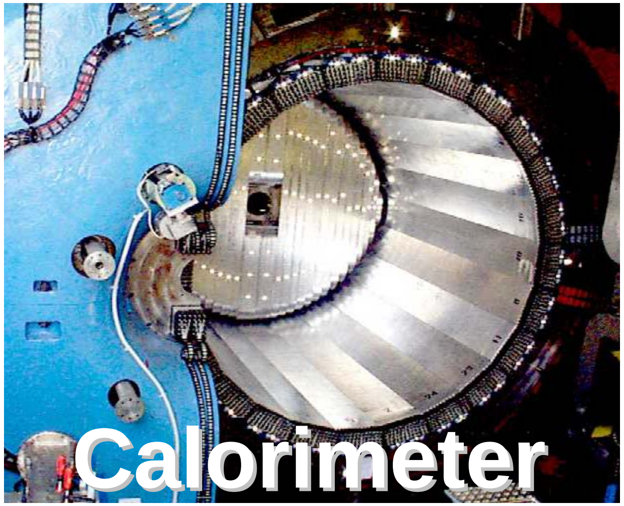


Grand total (2001/5):

$\int\mathcal{L}$ **= 2.5 fb^{-1}**

$\mathcal{L}_{peak}$**=1.3×10^{32} cm^{-2}s^{-1}**

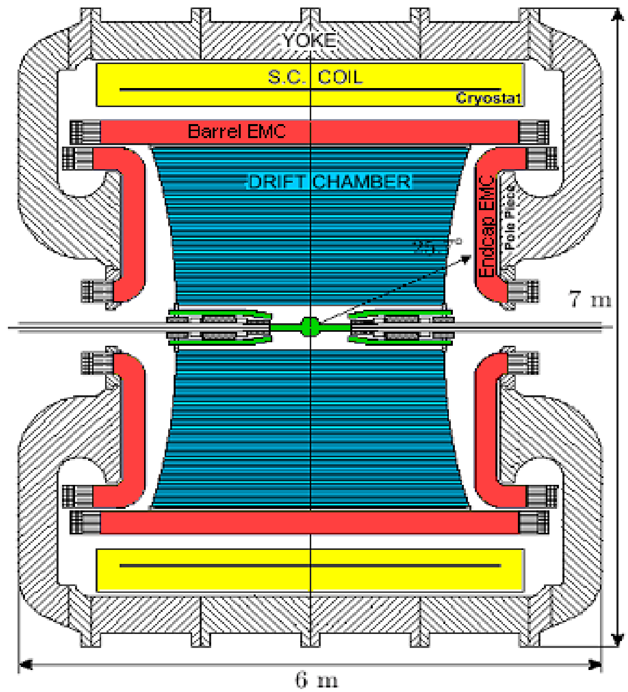
The KLOE detector



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

Superconducting coil

B = 0.52 T



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

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

$\sigma_t \cong 54$ ps $/\sqrt{E(\mathrm{GeV})} \oplus 50$ 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 $\theta > 45°$)

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

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

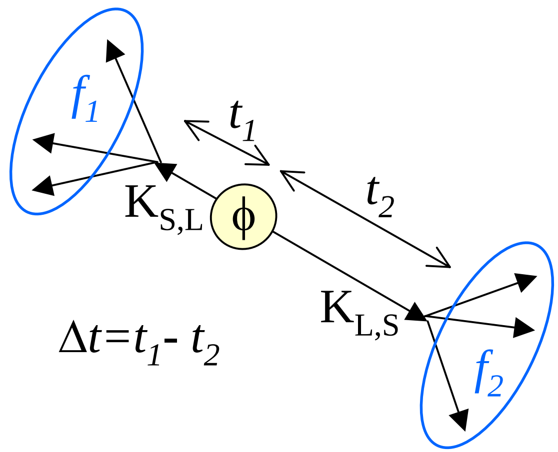
Neutral kaons at a ϕ-factory

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

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

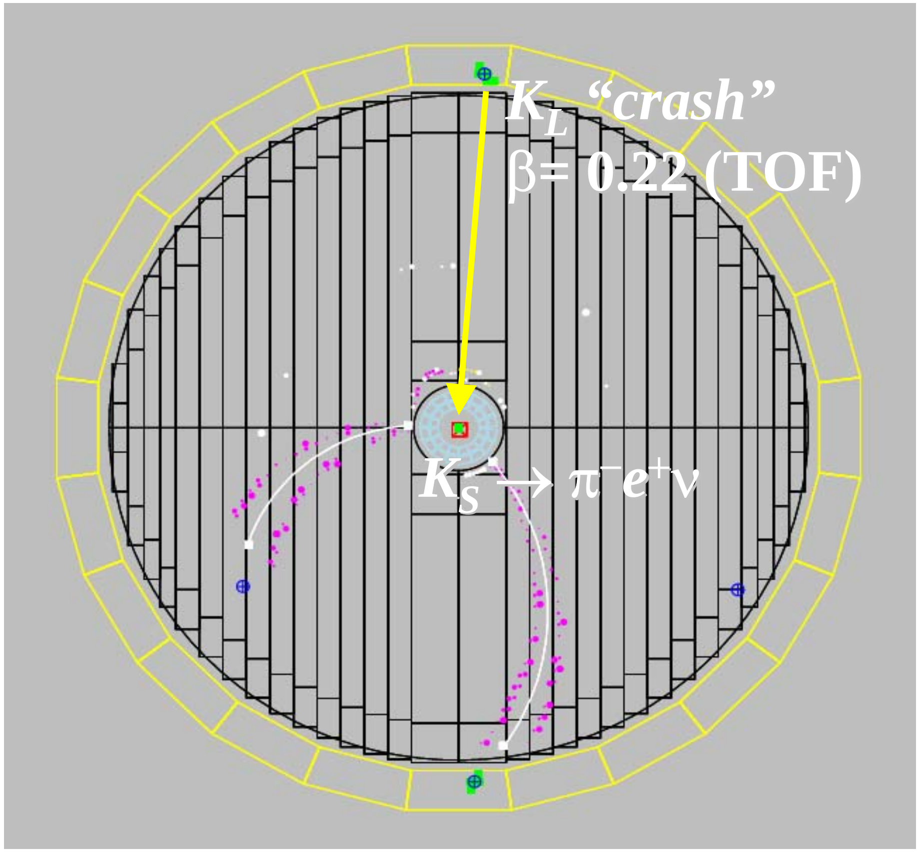
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

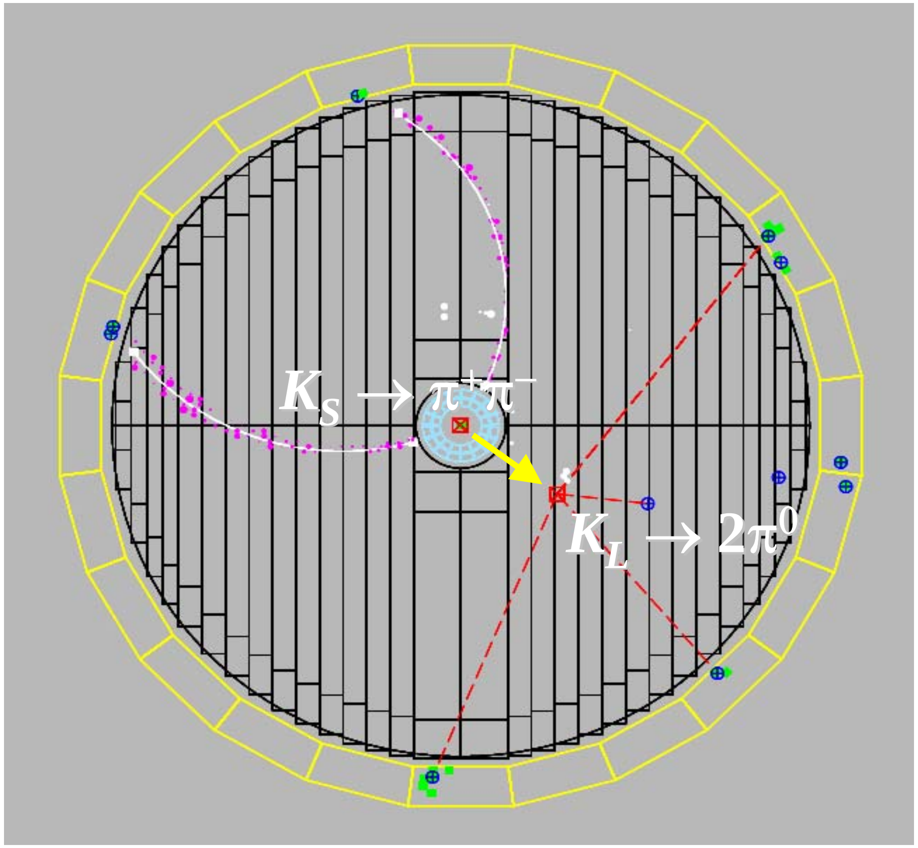
$p_K = 110$ MeV/c
$\lambda_S = 6$ mm **$\lambda_L = 3.5$ m**



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)

K_S and K_L Tagging





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

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

$K_S \rightarrow \pi^0\pi^0\pi^0$: search for a CP violating decay

Observation of $K_S \rightarrow 3\pi^0$ signals CP violation in mixing and/or in decay:

SM prediction: $\Gamma_S = \Gamma_L \, |\varepsilon + \varepsilon'_{000}|^2$, => $BR(K_S \rightarrow 3\pi^0) \sim 2\times10^{-9}$

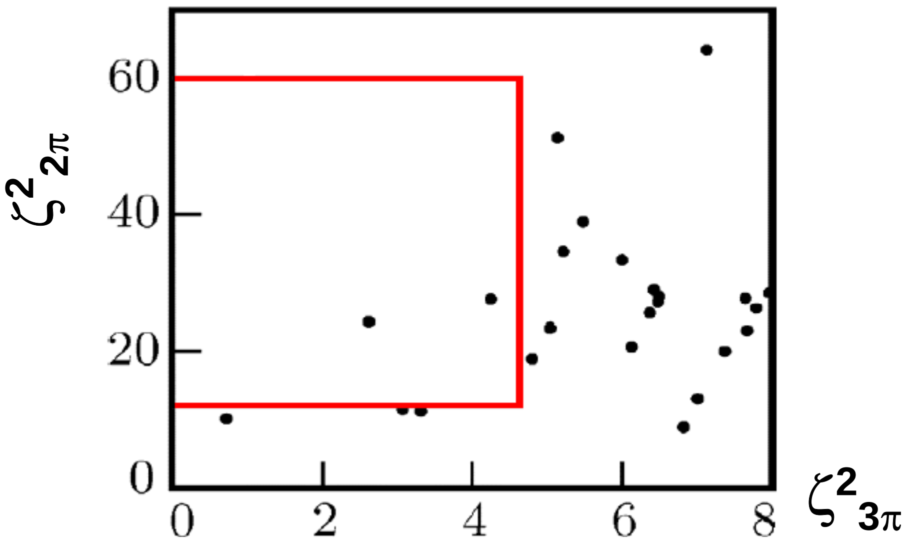
Present published results: $BR(K_S \rightarrow 3\pi^0) < 1.4\times10^{-5}$ (direct search, SND, '99)

$BR(K_S \rightarrow 3\pi^0) < 7.4\times10^{-7}$ (interferometry, NA48, '04)

$BR(K_S \rightarrow 3\pi^0) < 1.2\times10^{-7}$ (direct search, KLOE, '05)

90% C.L.

- Data sample: 450 pb^{-1}
  ~ 4 x 10^7 K_L-crash tag + $K_S \rightarrow$neutrals
- Require 6 prompt photons:
  large background ~40K events
- Analysis based on γ counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
- After all analysis cuts ($\varepsilon_{3\pi}$ = 24.4%)
  - 2 candidate events found
  - $3.13\pm0.82_{stat}\pm0.37_{syst}$ expected bckg

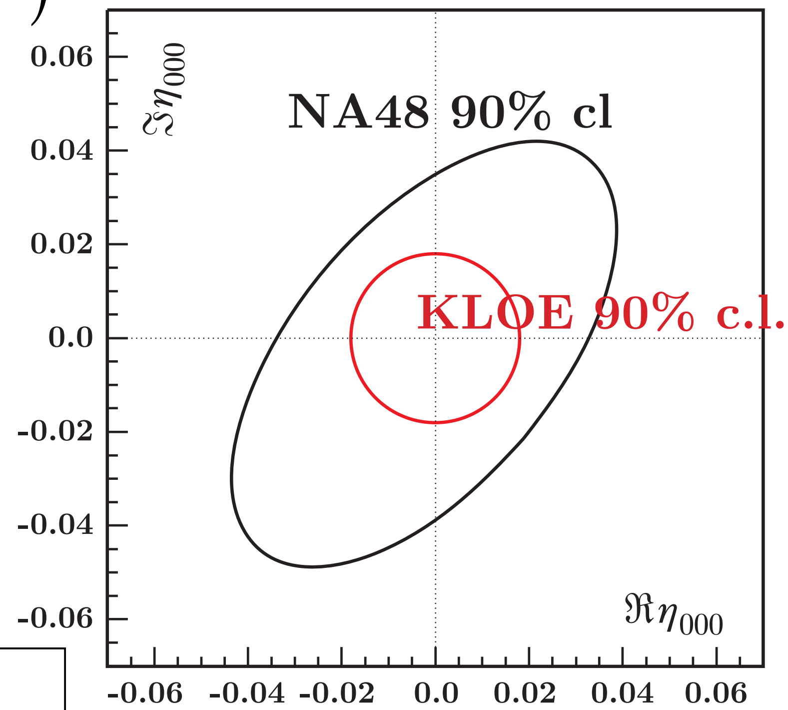


$K_S \to \pi^0\pi^0\pi^0$: test of CPT

A limit on BR($K_S \to 3\pi^0$) translates into a limit on $|\eta_{000}|$

$$|\eta_{000}| = \left|\frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)}\right| = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}} < 0.018 \quad \text{at } 90\% \text{ C.L.}$$

The CPT test from unitarity was limited by the knowledge of $|\eta_{000}|$ at the 10^{-5} level; now it is limited by uncertainties on other factors, e.g. η_{+-} etc. (see later)



with full statistics of 2.5 fb^{-1} + improved bck rejection: => BR limit improved by a factor 10

$K_S \to \pi e \nu$

Data sample: 410 pb^{-1}

Event selection:

- K_S tagged by K_L crash
- Two tracks from IP to EmC
- Kinematic cuts to reject background from $K_S \to \pi\pi$
- Track-cluster association required

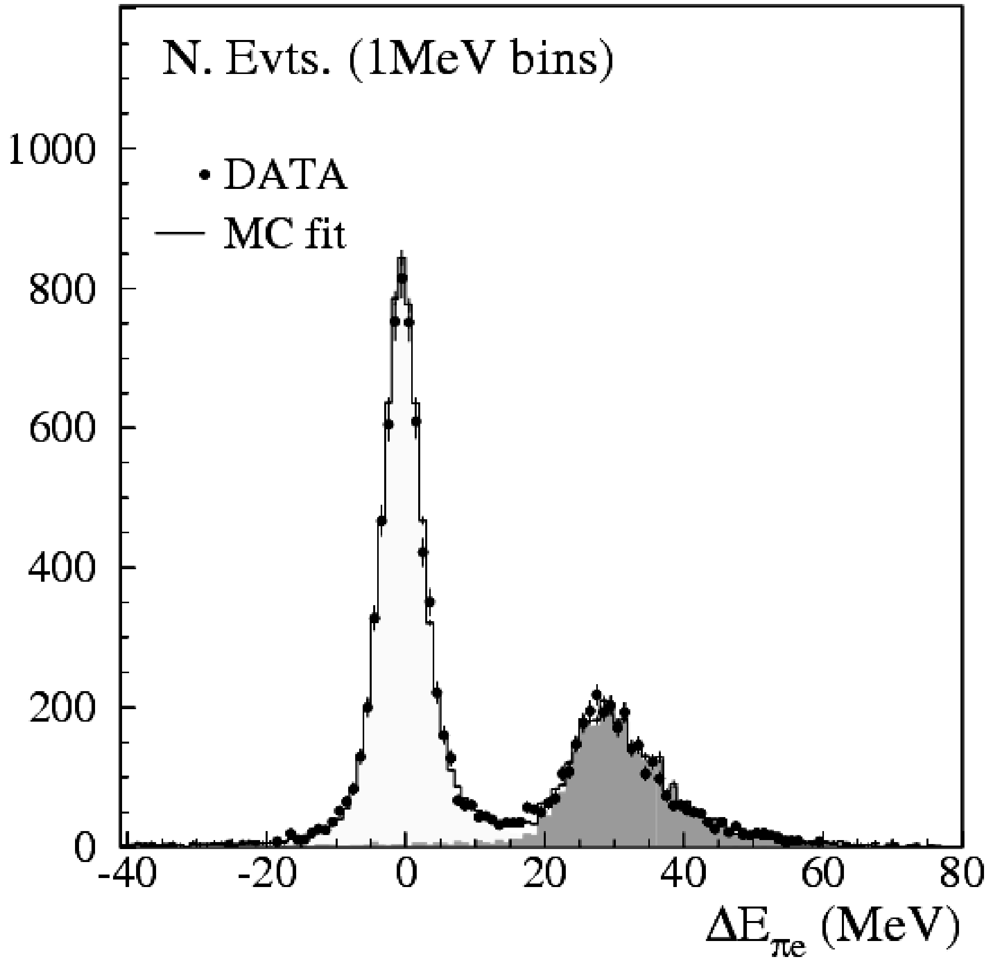
***e*/π ID from TOF**

Identifies charge of final state

Number of signal events obtained from a constrained likelihood fit of multiple data distributions

Normalization using $K_S \to \pi^+\pi^-(\gamma)$ events in same data set

pure sample of ~ 13000 signal events



$K_S \to \pi e \nu$: Results

Branching ratios:

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

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

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

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

Charge asymmetry:

$$A_S = \frac{\Gamma\left(K_S \to \pi^- e^+ \nu\right) - \Gamma\left(K_S \to \pi^+ e^- \overline{\nu}\right)}{\Gamma\left(K_S \to \pi^- e^+ \nu\right) + \Gamma\left(K_S \to \pi^+ e^- \overline{\nu}\right)}$$

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

with 2.5 fb^{-1}: $\delta A_S \sim 3 \times 10^{-3} \sim 2\,\mathrm{Re}\,\varepsilon$

Semileptonic decay amplitudes: definitions

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

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

	CP	T	CPT	ΔS=ΔQ
a	$\Im$=0	$\Im$=0		
b	$\Re$=0	$\Im$=0	=0	
c	$\Im$=0	$\Im$=0		=0
d	$\Re$=0	$\Im$=0	=0	=0

CPT violation: $y = -\frac{b}{a}$

ΔS=ΔQ violation: $x_+ = \frac{c^*}{a}$

CPT violation & ΔS=ΔQ violation : $x_- = -\frac{d^*}{a}$

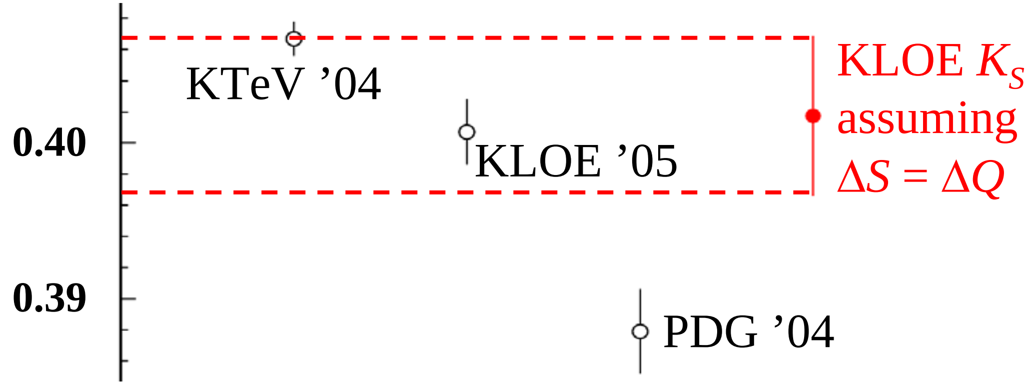
$K_S \to \pi e \nu$: test of $\Delta S = \Delta Q$ rule

Test of $\Delta S = \Delta Q$ rule:

$\tau(K_S)$ = 89.58 ± 0.06 ps
PDG fit

$\tau(K_L)$ = 50.84 ± 0.23 ns
KLOE ’05 (avg.)

BR(K_{Le3})



$$\Re x_+ = \frac{1}{4}\left(\frac{BR(K_S \to \pi e \nu)}{BR(K_L \to \pi e \nu)}\frac{\tau_L}{\tau_S} - 1\right)$$

ratio of $\Delta S = \Delta Q$ violating and conserving amplitudes (CPT cons.) SM pred. $O(10^{-7})$

$\Re x_+ = (-0.5 \pm 3.1 \pm 1.8) \times 10^{-3}$

$\tau(K_S)$	PDG
$\tau(K_L)$	KLOE ’05 (avg.)
BR($K_L \to \pi e \nu$)	KLOE

Factor 2 improvement w.r.t. current most precise measurement (CPLEAR, $\sigma = 6.1 \times 10^{-3}$)

$K_S \to \pi e \nu$: test of CPT

- **$\Re x_-$: CPT viol., $\Delta S = \Delta Q$ viol.**

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

A_L	KTeV	$\sigma = 0.75\times10^{-4}$
$\Re\delta$	CPLEAR	$\sigma = 3.4\times10^{-4}$

$$\Re x_- = (-0.8 \pm 2.4 \pm 0.7)\times10^{-3}$$

Factor 5 improvement w.r.t. current most precise measurement (CPLEAR, $\sigma = 1.3\times10^{-2}$)

- **$\Re y$: CPT viol., $\Delta S = \Delta Q$ cons.**

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

$\Re\varepsilon$ from PDG not assuming CPT

$$\Re y = (0.4 \pm 2.4 \pm 0.7)\times10^{-3}$$

Comparable with best result (CPLEAR from unitarity, $\sigma = 3.1\times10^{-3}$)

CPT test: the Bell-Steinberger relation

Measurements of K_S K_L observables can be used for the CPT test from unitarity :

$$(1 + i \tan \phi_{SW}) [\mathrm{Re}\,\varepsilon - i\,\mathrm{Im}\,\delta] = \frac{1}{\Gamma_S} \sum_f A^*(K_S \to f)\, A(K_L \to f) = \sum_f \alpha_f$$

$$\alpha_{+-} = \eta_{+-} B(K_S \to \pi^+\pi^-)$$

$$\alpha_{00} = \eta_{00} B(K_S \to \pi^0\pi^0)$$

$$\alpha_{+-\gamma} = \eta_{+-} B(K_S \to \pi^+\pi^-\gamma)$$

$$\alpha_{+-0} = \tau_S/\tau_L\, \eta_{+-0}^* B(K_L \to \pi^+\pi^-\pi^0)$$

$$\alpha_{000} = \tau_S/\tau_L\, \eta_{000}^* B(K_L \to \pi^0\pi^0\pi^0)$$

$$\alpha_{kl3} = 2\tau_S/\tau_L B(K_L l3) [\mathrm{Re}\,\varepsilon - \mathrm{Re}\,y - i(\mathrm{Im}\,\delta + \mathrm{Im}\,x_+)]$$

$$= 2\tau_S/\tau_L B(K_L l3) [(A_S + A_L)/4 - i(\mathrm{Im}\,\delta + \mathrm{Im}\,x_+)]$$

CPT test: inputs to the Bell-Steinberger relation

$B(K_S\to\pi^+\pi^-)/B(K_S\to\pi^0\pi^0)=2.2549\pm0.0059$
$B(K_S\to\pi^+\pi^-\gamma)<9\times10^{-5}$
$B(K_L\to\pi^+\pi^-\gamma)=(29\pm1)\times10^{-6}$
$B(K_L\to\pi l\nu)=0.6705\pm0.0022$
$B(K_S\to\pi^+\pi^-\pi^0)=(3.2\pm1.2)\times10^{-7}$
$B(K_L\to\pi^+\pi^-\pi^0)=0.1263\pm0.0012$
$B(K_S\to\pi^0\pi^0\pi^0)<1.2\times10^{-7}$
$\phi^{SW}=(0.759\pm0.001)$
$\phi^{000}=\phi^{+-0}=\phi^{+-\gamma}=[0,2\pi]$

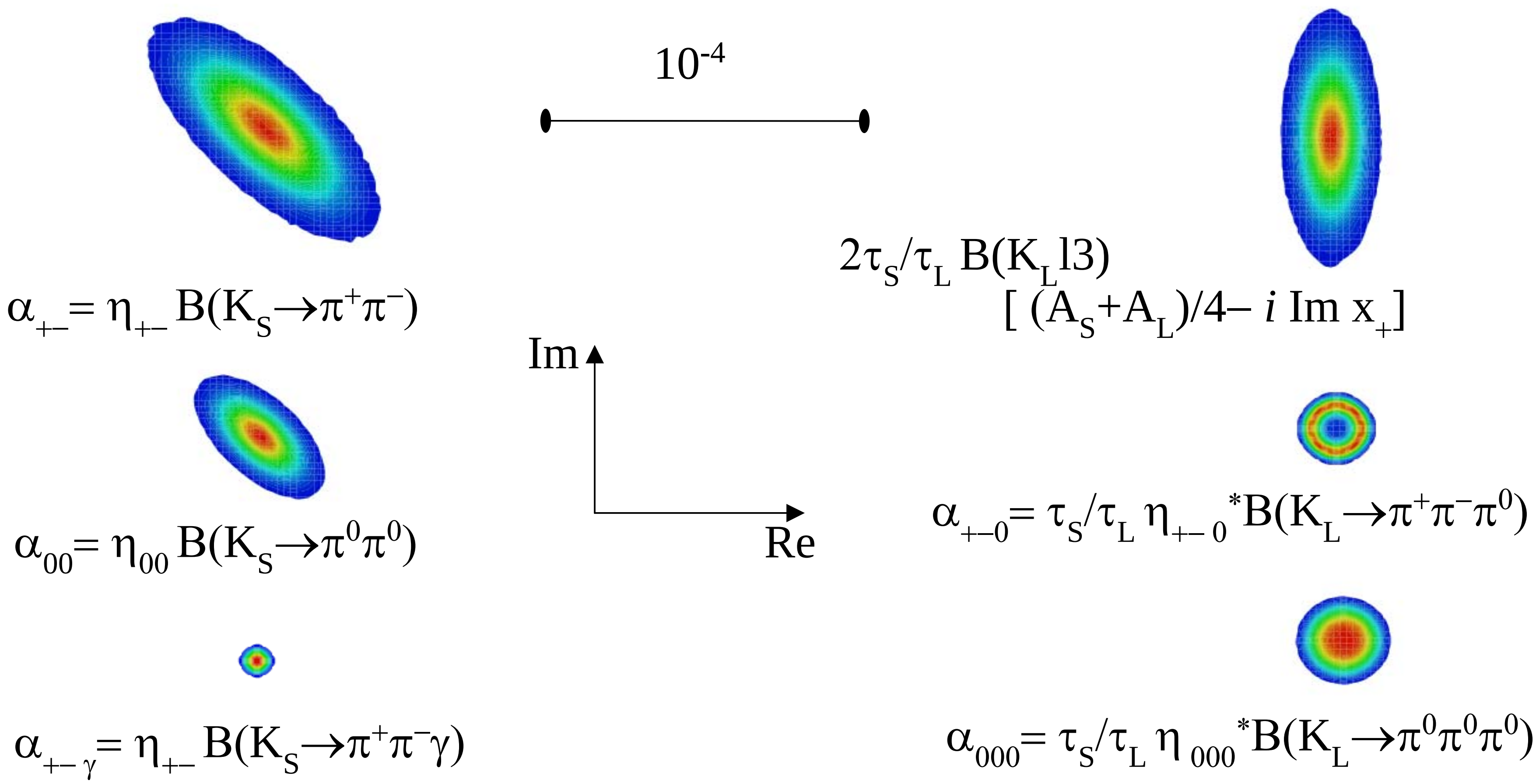
$\tau_S=0.08958\pm0.00006$ ns
$\tau_L=50.84\pm0.23$ns
$A_L=(3.32\pm0.06)\times10^{-3}$
$A_S=(1.5\pm10.0)\times10^{-3}$
$B(K_L\to\pi^+\pi^-)=(1.963\pm0.021)\times10^{-3}$
$B(K_L\to\pi^0\pi^0)=(8.65\pm0.10)\times10^{-4}$
$\phi^{+-}=0.757\pm0.012$
$\phi^{00}=0.763\pm0.014$
$\text{Im}\, x_+=(0.8\pm0.7)\times10^{-2}$

KLOE measurements

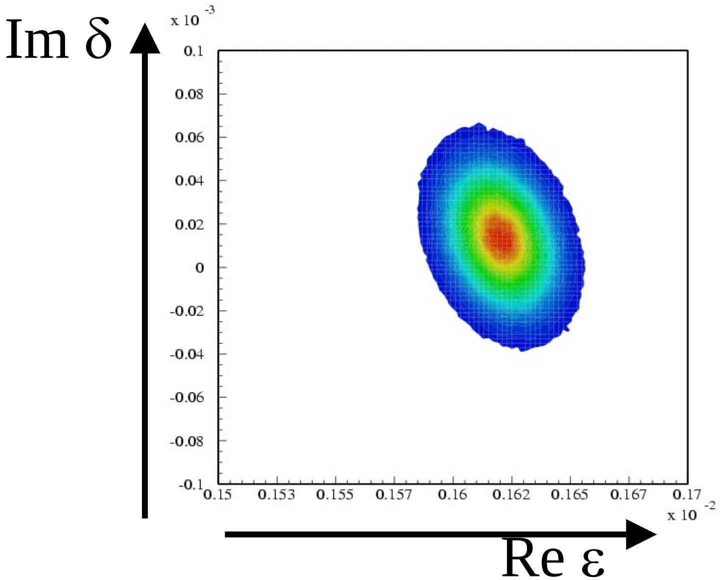
Im x_+ from a combined fit of KLOE + CPLEAR data

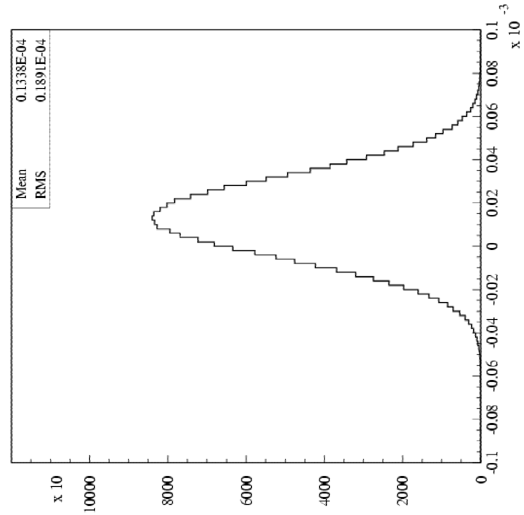
CPT test: accuracy on α_i

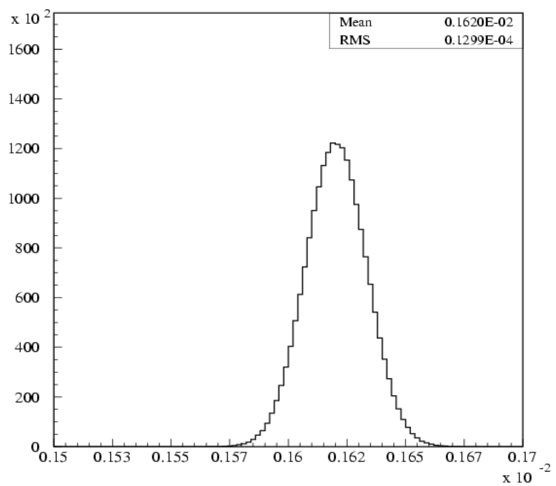
We get the following results on each term of the sum



CPT test: KLOE result







KLOE preliminary:

$$\mathrm{Re}\,\varepsilon = (160.2 \pm 1.3) \times 10^{-5}$$
$$\mathrm{Im}\,\delta = (1.2 \pm 1.9) \times 10^{-5}$$

CPLEAR:

$\mathrm{Re}\,\varepsilon = (164.9 \pm 2.5)\ 10^{-5}$

$\mathrm{Im}\,\delta = (2.4 \pm 5.0)\ 10^{-5}$

Neutral kaon interferometry

Double differential time distribution:

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

characteristic interference term at a ϕ-factory => interferometry

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

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

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

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

Neutral kaon interferometry

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

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

$$\text{for } \Delta t < 0 \qquad \Delta t \rightarrow \left|\Delta t\right| \quad \text{and } 1 \leftrightarrow 2$$

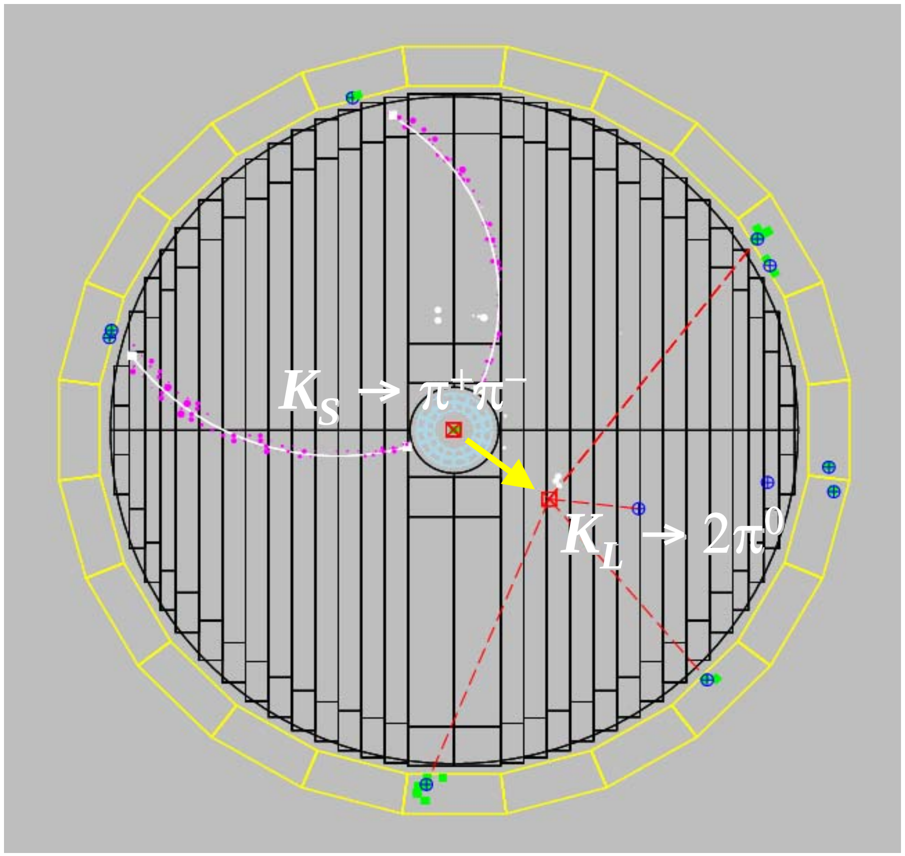
From these distributions for various final states f_i one can measure the following quantities:

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

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

Neutral kaon interferometry

p_K = 110 MeV/c
λ_S = 6 mm λ_L = 3.5 m



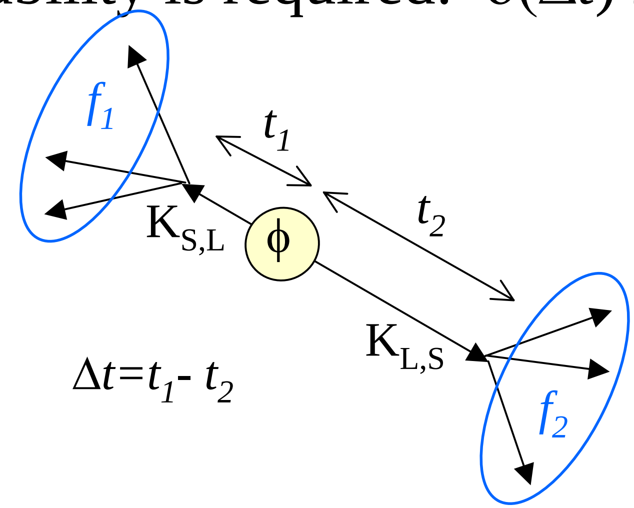
Interference term:

$$\propto e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos\left(\Delta m \Delta t + \phi_2 - \phi_1\right)$$

Oscillation period: T=h/Δm~13 τ_S

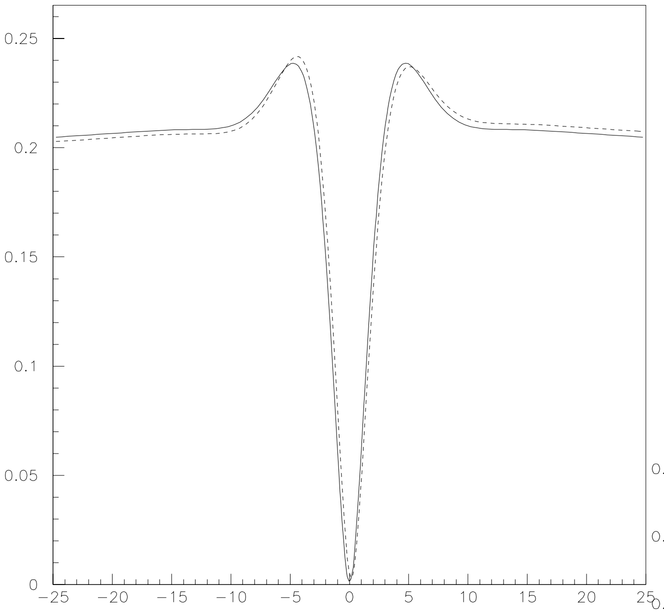
Exponential damping: ~2 τ_S

For interferometry a quite good K decay vertex reconstruction capability is required: $\delta(\Delta t) \leq 1\,\tau_S$



Neutral kaon interferometry: main observables

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

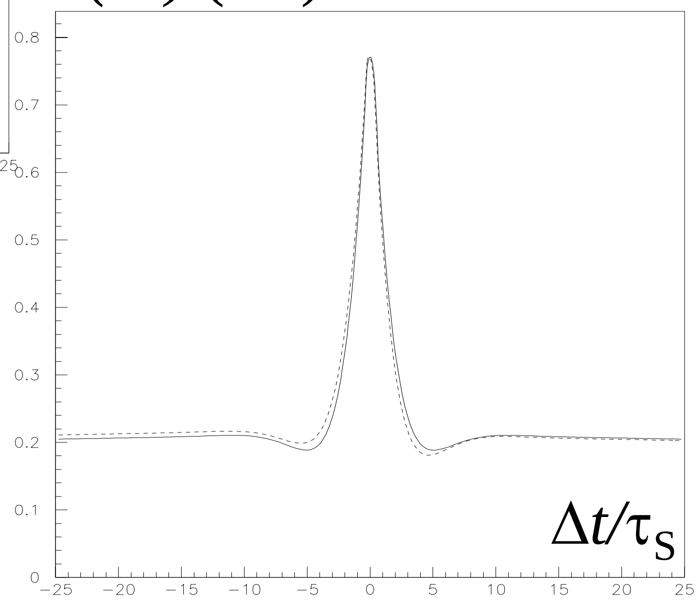


$\Delta t/\tau_S$

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

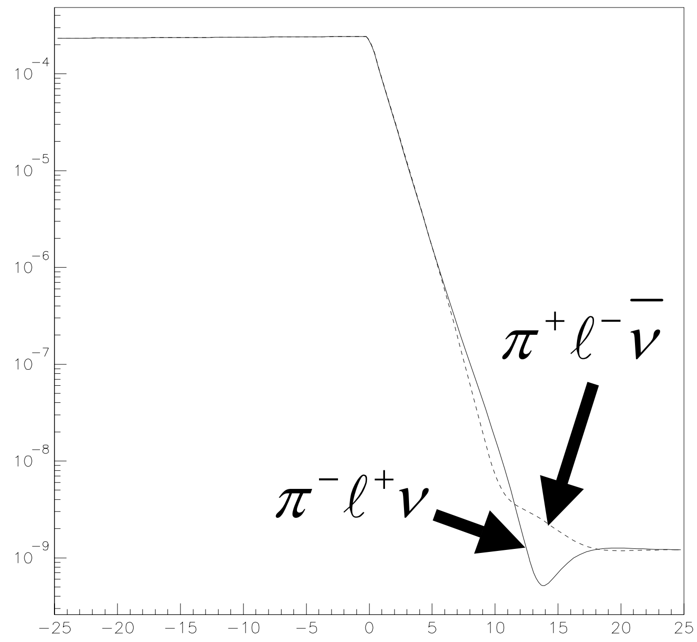
$$\phi \rightarrow K_S K_L \rightarrow \pi^+\ell^-\bar{\nu} \;\; \pi^-\ell^+\nu$$

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



$\Delta t/\tau_S$

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



$\Delta t/\tau_S$

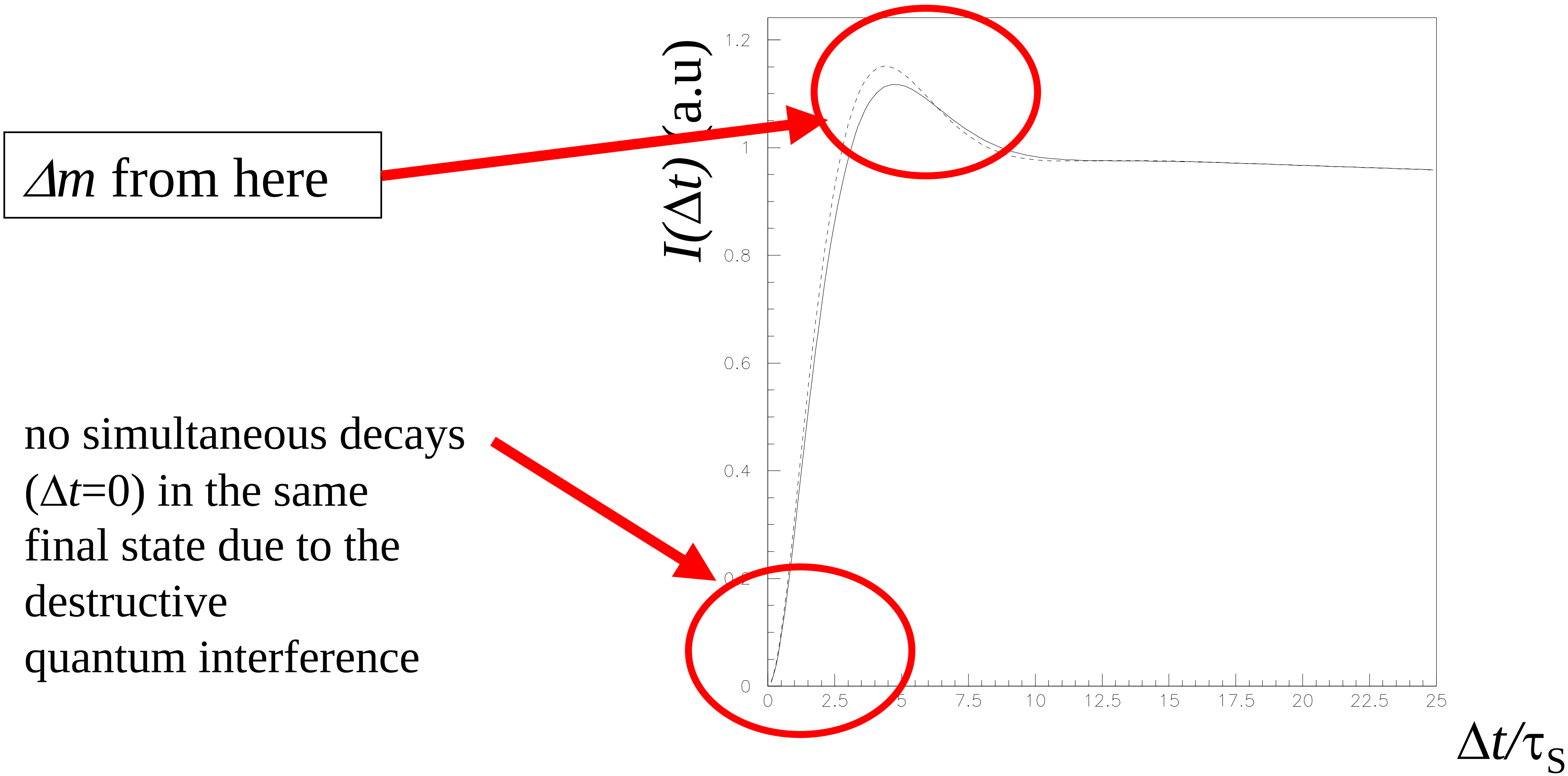
$$\phi \rightarrow K_S K_L \rightarrow \pi\pi \;\; \pi\ell\nu$$

Neutral kaon interferometry: main observables

mode	measured quantity	parameters
$\phi \to K_S K_L \to \pi^+\pi^- \ \pi^0\pi^0$	$A(\Delta t) = \frac{I(\pi^+\pi^-,\pi^0\pi^0;\Delta t>0) - I(\pi^+\pi^-,\pi^0\pi^0;\Delta t<0)}{I(\pi^+\pi^-,\pi^0\pi^0;\Delta t>0) - I(\pi^+\pi^-,\pi^0\pi^0;\Delta t<0)}$	$\Re\left(\frac{\varepsilon'}{\varepsilon}\right)$ $\Im\left(\frac{\varepsilon'}{\varepsilon}\right)$
$\phi \to K_S K_L \to \pi^+\ell^-\bar{\nu} \ \pi^-\ell^+\nu$	$A_{CPT}(\Delta t) = \frac{I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t>0) - I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t<0)}{I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t>0) + I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t<0)}$	$\Re\delta_K + \Re x_-$ $\Im\delta_K + \Im x_+$
$\phi \to K_S K_L \to \pi\pi \ \pi\ell\nu$	$A(\Delta t) = \frac{I(\pi^+\pi^-,\pi^-e^+\nu;\Delta t) - I(\pi^+\pi^-,\pi^+e^-\bar{\nu};\Delta t)}{I(\pi^+\pi^-,\pi^-e^+\nu;\Delta t) + I(\pi^+\pi^-,\pi^+e^-\bar{\nu};\Delta t)}$	$A_L = 2\Re\varepsilon_K - \Re\delta_K - \Re y - \Re x_-$ $\phi_{\pi\pi}$
$\phi \to K_S K_L \to \pi^+\pi^- \ \pi^+\pi^-$	$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t)$	Δm Γ_S Γ_L

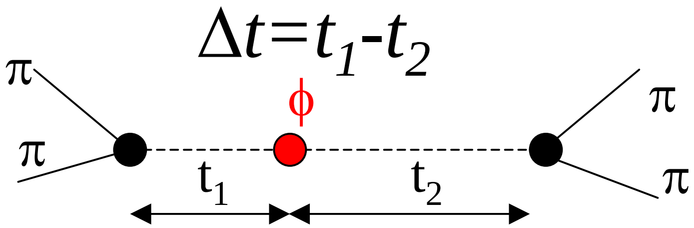
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

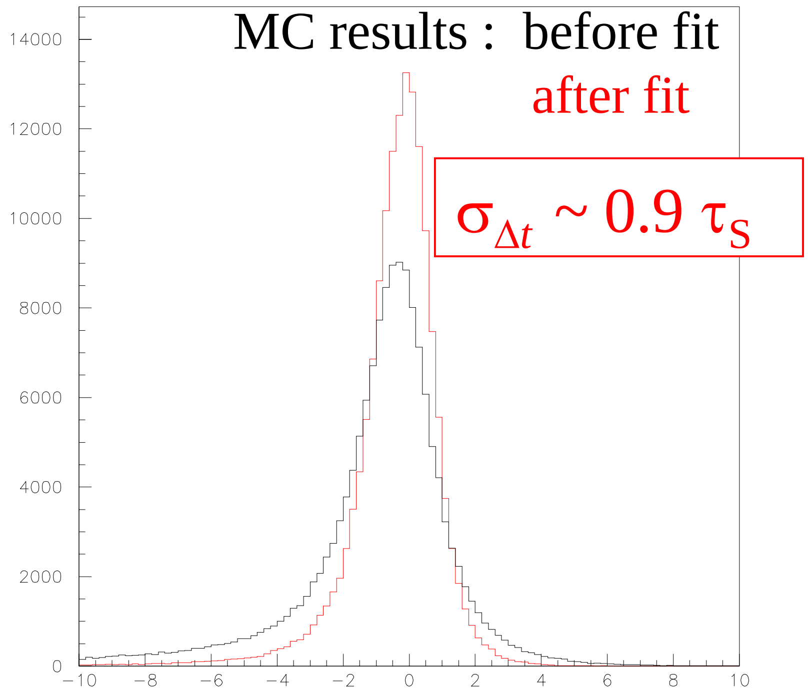
$$I\left(\pi^+\pi^-,\pi^+\pi^-;|\Delta t|\right) \propto \left\{e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2\cdot e^{-(\Gamma_S+\Gamma_L)|\Delta t|/2}\cos\left(\Delta m|\Delta t|\right)\right\}$$



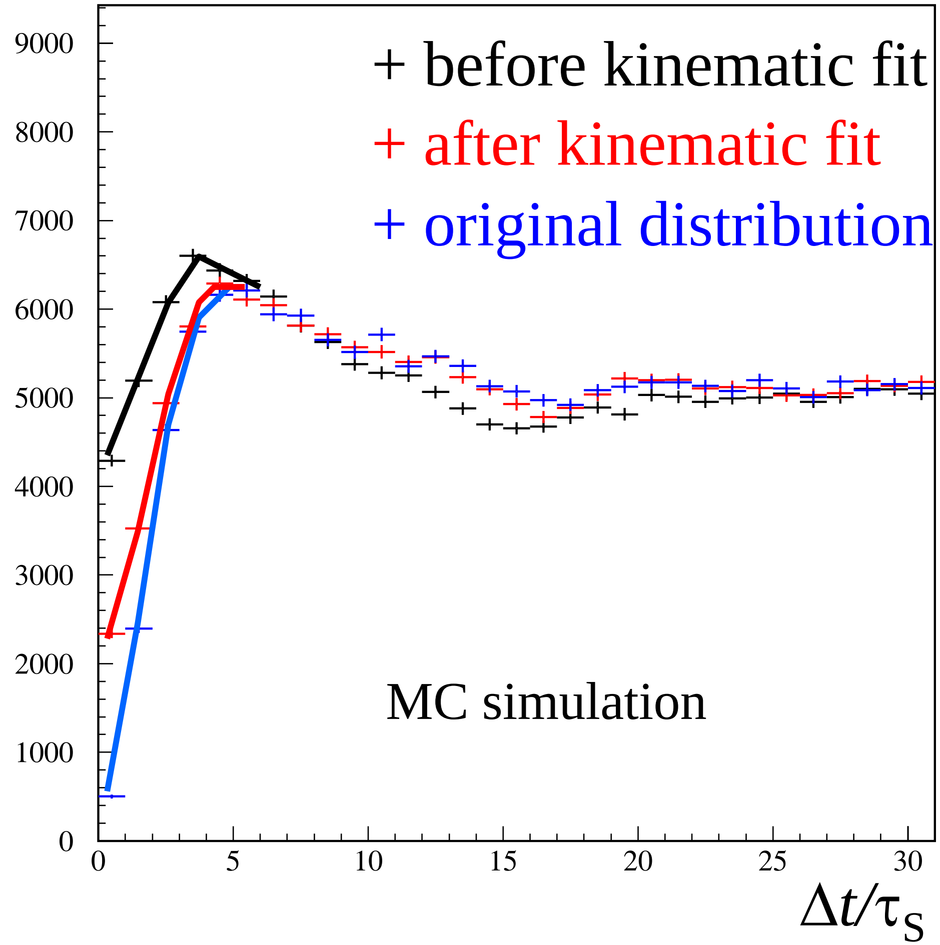
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

A kinematic fit is performed to improve the vertex and Δt resolution:





$\left|\Delta t\right|_{rec} - \left|\Delta t\right|_{true}$ in τ_S units



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

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

KLOE PRELIMINARY

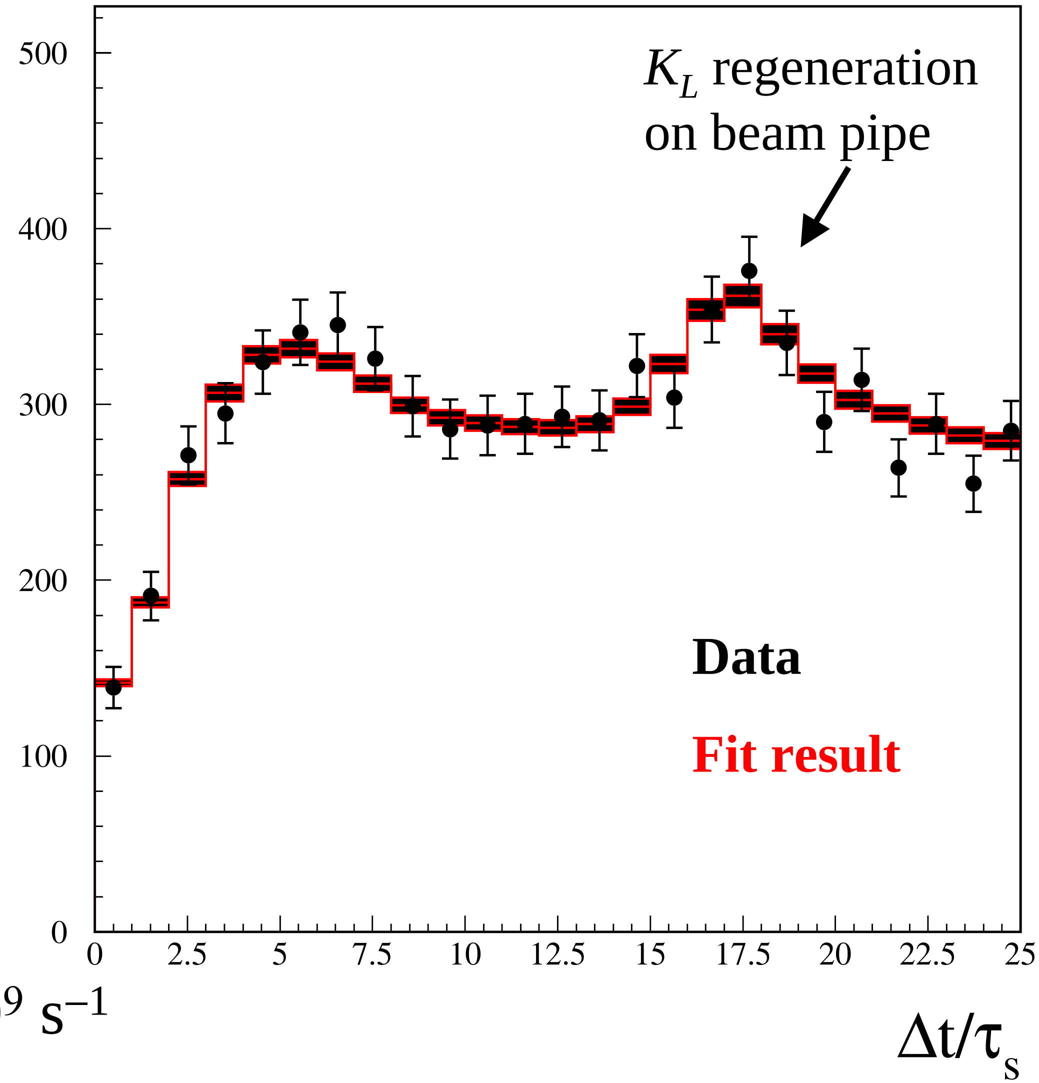
$\mathbf{\Delta m = (5.34 \pm 0.34) \times 10^9\ s^{-1}}$

At 2.5 fb^{-1} $\Delta m \pm 0.14 \times 10^9\ s^{-1}$

PDG '04:

$(5.290 \pm 0.016) \times 10^9\ s^{-1}$

Best (Ktev'03)$(5.288 \pm 0.043) \times 10^9\ s^{-1}$



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

$$I(\pi^+\pi^-,\pi^+\pi^-;|\Delta t|) \propto \left\{ e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2\cdot(1-\zeta_{SL})\cdot e^{-(\Gamma_S+\Gamma_L)|\Delta t|/2}\cos(\Delta m|\Delta t|) \right\}$$

- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L Δm fixed from PDG

Decoherence parameter:

$\zeta_{SL} = 0 \quad \rightarrow \quad$ QM

$\zeta_{SL} = 1 \quad \rightarrow \quad$ total decoherence

KLOE preliminary result:

$$\zeta_{SL} = 0.043 \pm 0.037_{\mathrm{STAT}} \pm 0.008_{\mathrm{SYST}}$$

$\longrightarrow$ with 2.5 fb^{-1} : $\pm 0.015_{\mathrm{STAT}}$

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

$$\zeta_{SL} = 0.13 \pm 0.16$$

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

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

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

- Fit including Δt resolution and efficiency effects + regeneration
- Γ_S, Γ_L Δm fixed from PDG

Decoherence parameter:

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

$\zeta_{0\bar{0}} = 1 \quad \to \quad$ total decoherence

KLOE preliminary result:

$$\zeta_{0\bar{0}} = (2.4 \pm 2.0_{\mathrm{STAT}} \pm 0.2_{\mathrm{SYST}}) \times 10^{-6}$$

→ with 2.5 fb^{-1} : $\pm 0.8_{\mathrm{STAT}} \times 10^{-6}$

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

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

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

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

Decoherence and CPT violation parameters α,β,γ due to QG

At most one expects: $\alpha,\beta,\gamma = O\left(M_K{}^2 / M_{PLANCK}\right) \approx 2\times10^{-20}$ GeV

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

KLOE preliminary

$$\alpha = \left(-10^{+41}_{-31\,STAT} \pm 9_{SYST}\right)\times10^{-17}\ \text{GeV}$$
$$\beta = \left(3.7^{+6.9}_{-9.2\,STAT} \pm 1.8_{SYST}\right)\times10^{-19}\ \text{GeV}$$
$$\gamma = \left(-0.4^{+5.8}_{-5.1\,STAT} \pm 1.2_{SYST}\right)\times10^{-21}\ \text{GeV}$$

→ with L=2.5 fb^{-1}:

$$\pm 15_{STAT} \times10^{-17}\ \text{GeV}$$
$$\pm 3.3_{STAT} \times10^{-19}\ \text{GeV}$$
$$\pm 2.2_{STAT} \times10^{-21}\ \text{GeV}$$

CPLEAR

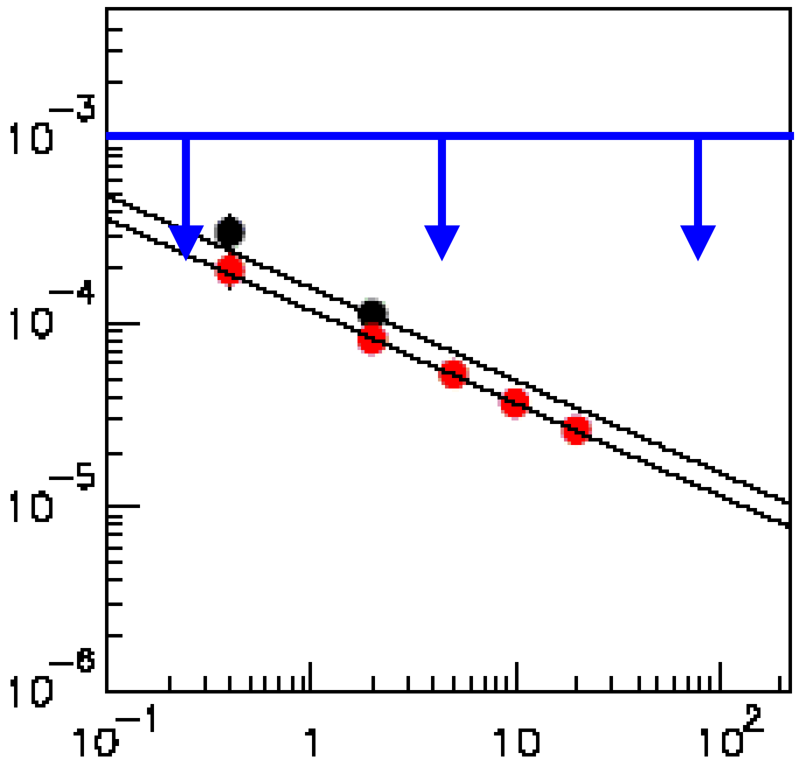
$$\alpha = \left(-0.5\pm2.8\right)\times10^{-17}\ \text{GeV}$$
$$\beta = \left(2.5\pm2.3\right)\times10^{-19}\ \text{GeV}$$
$$\gamma = \left(1.1\pm2.5\right)\times10^{-21}\ \text{GeV}$$

In the complete positivity hypothesis
$\alpha = \gamma$, $\beta = 0$ =>
only one independent parameter: γ

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

CPT violation and EPR correlation modifications might be induced by QG:

$$|i\rangle \propto \left(K_S K_L - K_L K_S\right) + \omega\left(K_S K_S - K_L K_L\right)$$



- present KLOE
- KLOE-2

-- Planck scale region

$$|\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right) \approx 10^{-5}$$

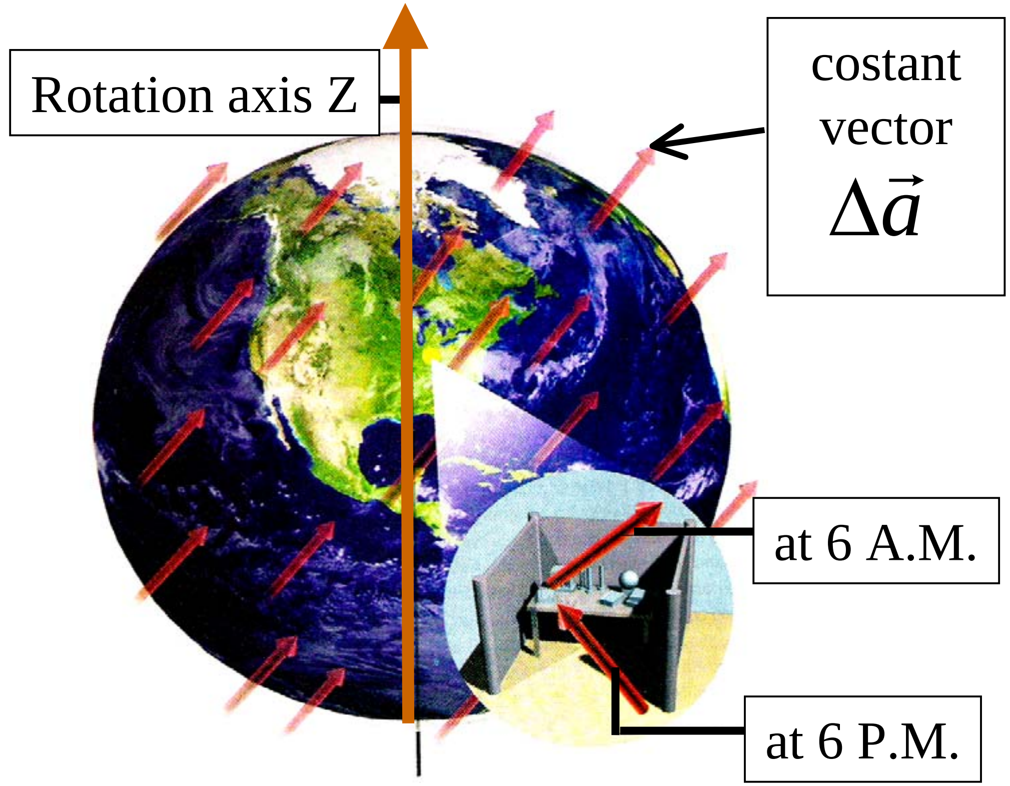
$$\Rightarrow |\omega| \sim 10^{-3}$$

CPT and Lorentz invariance violation

Spontaneous breaking of CPT and Lorentz symmetry [Kostelecky PRD61 (1999) 016002].

For a fixed target experiment δ_K 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 detector frame:



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

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

Ω: Earth's sidereal frequency

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

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi e \nu$: CPT and Lorentz violation

KLOE with 340 pb^{-1} reach
a statistical sensitivity on

$$A_L \cong 2\Re\varepsilon_K - 2\Re\delta_K$$

of $\sim 3 \div 4 \times 10^{-4}$ (very preliminary)

forward-backward asymmetry of A_L
=> limit on Δa_Z at a level:

$\delta(\Delta a_Z) = O(1 \times 10^{-17})$ GeV

KTev measured the sidereal time variation of ϕ_{+-} ;
limits at 90% C.L. on:

$\Delta a_X , \Delta a_Y < 9.2 \times 10^{-22}$ GeV

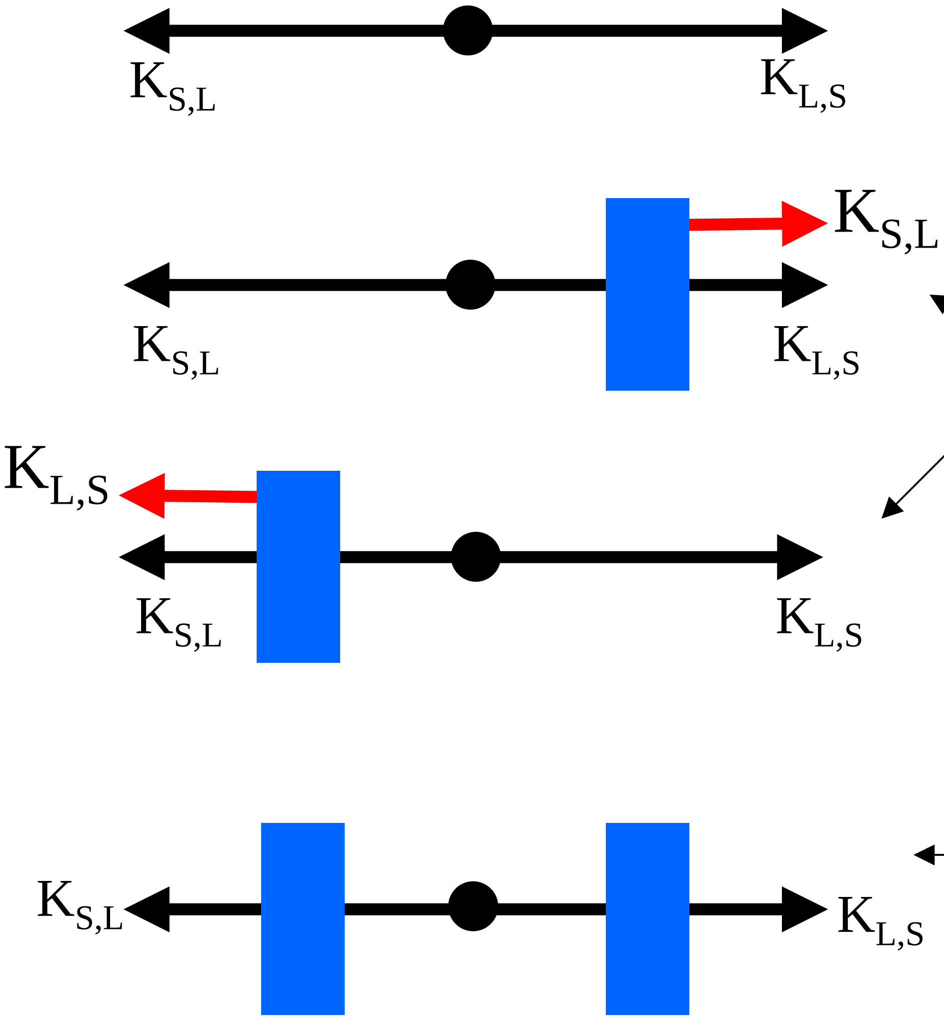
Perspectives with KLOE-2 at DAΦNE-2

Mode	Test of	Param.	Present best 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	$Re(\varepsilon'/\varepsilon)$	$(1.67 \pm 0.26) \times 10^{-3}$	$\pm 0.2 \times 10^{-3}$
$\pi^+\pi^-$ $\pi^0\pi^0$	CP, CPT	$Im(\varepsilon'/\varepsilon)$	$(1.2 \pm 2.3) \times 10^{-3}$	$\pm 3 \times 10^{-3}$
$\pi e \nu$ $\pi e \nu$	CPT	$Re(\delta_K)+Re(x_-)$	$Re(\delta_K) = (0.29 \pm 0.27) \times 10^{-3}$	$\pm 0.2 \times 10^{-3}$
$\pi e \nu$ $\pi e \nu$	CPT	$Im(\delta_K)+Im(x_+)$	$Im(\delta_K) = (2.4 \pm 5.0) \times 10^{-5}$	$\pm 3 \times 10^{-3}$
$\pi^+\pi^-$ $\pi^+\pi^-$		Δm	$(5.288 \pm 0.043) \times 10^9\ s^{-1}$	$\pm 0.03 \times 10^9\ s^{-1}$

Perspectives with KLOE-2 at DAΦNE-2

Mode	Test of	Param.	Present best measurement	KLOE-2 L=50 fb^{-1}
$\pi^+\pi^-$ $\pi^+\pi^-$	QM	ζ_{00}	$(2.4 \pm 2.0) \times 10^{-6}$	$\pm 0.1 \times 10^{-6}$
$\pi^+\pi^-$ $\pi^+\pi^-$	QM	ζ_{SL}	$(4.3 \pm 3.8) \times 10^{-2}$	$\pm 0.2 \times 10^{-2}$
$\pi^+\pi^-$ $\pi^+\pi^-$	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
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & EPR corr.	Re(ω)	-	$\pm 2 \times 10^{-5}$
$\pi^+\pi^-$ $\pi^+\pi^-$	CPT & EPR corr.	Im(ω)	-	$\pm 2 \times 10^{-5}$
$\pi^+\pi^-$ $\pi e \nu$	CPT & Lorentz	Δa_Z	-	$O(10^{-18}$ GeV)
$\pi^+\pi^-$ $\pi e \nu$	CPT & Lorentz	$\Delta a_{X,Y}$	$<10^{-21}$ GeV	$O(10^{-18}$ GeV)

Bell-type inequality test with neutral kaons



with no absorber
no regeneration

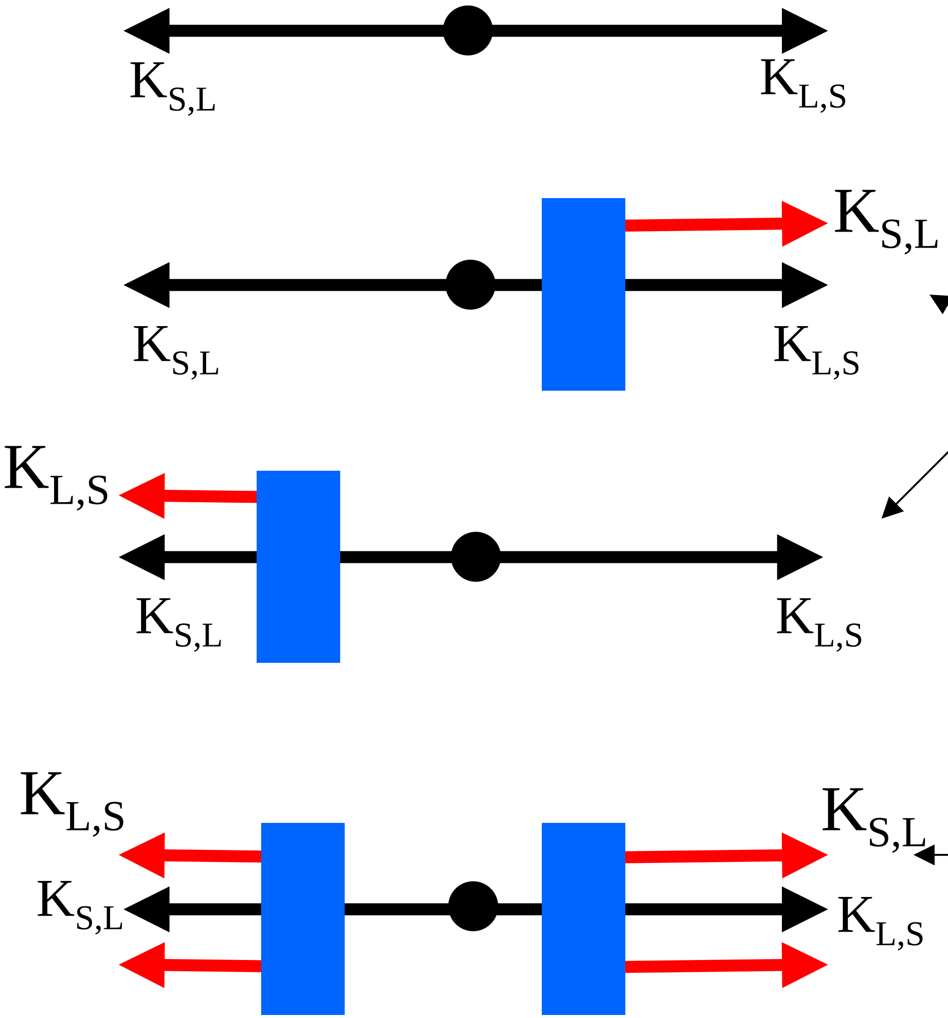
with one absorber:
appearance of coherent regeneration

$$|K_{L,S}\rangle \rightarrow |K_{L,S}\rangle + \rho_{coh}|K_{S,L}\rangle$$

the regenerator paradox

with **two symmetrical** absorbers:
disappearance of coherent regeneration
due to a totally destructive interference

Bell-type inequality test with neutral kaons



with no absorber
no regeneration

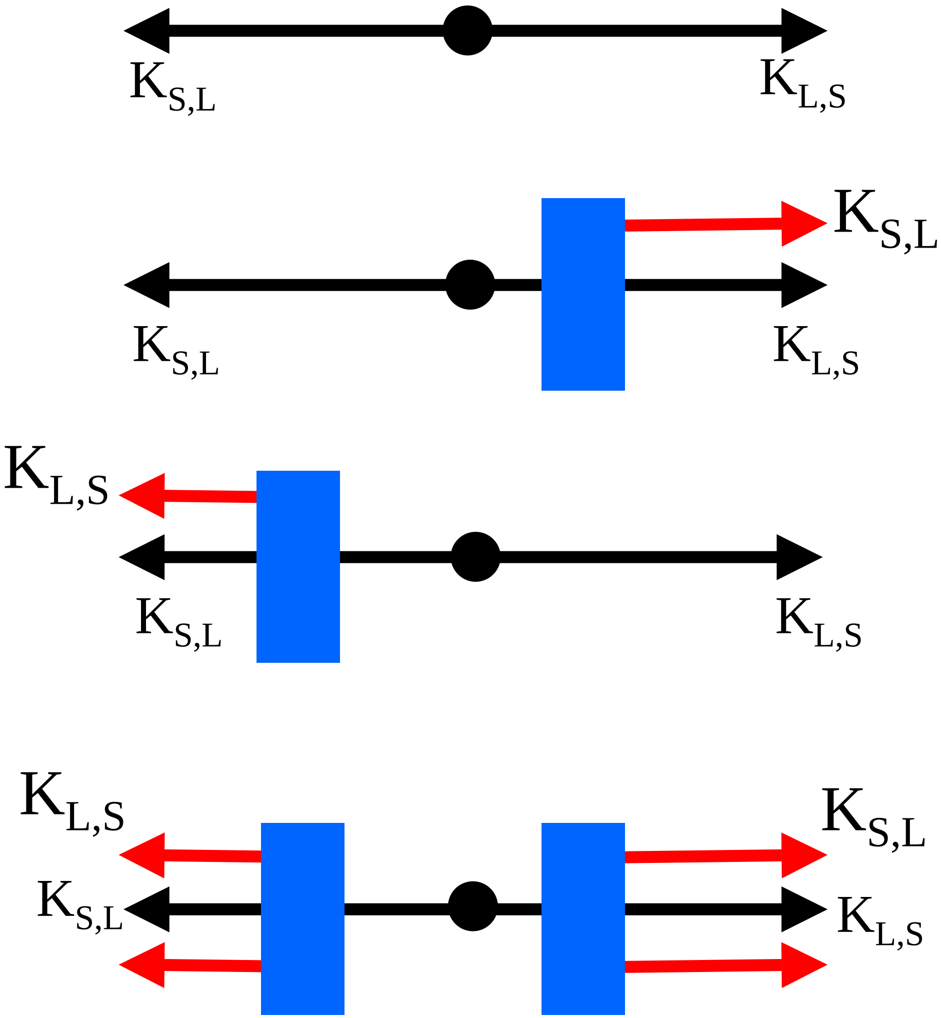
with one absorber:
appearance of coherent regeneration

$$\left|K_{L,S}\right\rangle \rightarrow \left|K_{L,S}\right\rangle + \rho_{coh}\left|K_{S,L}\right\rangle$$

the regenerator paradox

with **two non-symmetrical** absorbers:
appearance of coherent regeneration
in excess due to a constructive
interference

Bell-type inequality test with neutral kaons



Measurement of the number of $K_L K_L$ pairs in the four experimental set-ups

Detection of $K_L K_L$ pairs by K_L interaction in the calorimeter and/or decay in the DC

Bell's – type inequality

$$P_{LL}^{BOTH} \leq P_{LL}^{LEFT} + P_{LL}^{RIGHT} + P_{LL}^{0}$$

violated by QM predictions!

proposed by Eberhard (NP B398 (1993) 155)

Conclusions

- Several parameters related to CPT and QM tests are (will be) measured at KLOE, some of them for the first time.
- In the future KLOE-2 will improve the existing limits on them.
- The ω and γ parameters related to possible CPT violation induced by QG can be measured with a precision that goes inside the Planck's scale region.

- A Bell's inequality (BI) test with neutral kaons might be feasible at KLOE-2 (with some additional assumptions, i.e. loopholes)
- Also other interesting tests of QM might be possible.
- These tests require thin regenerators close to the IP =>

1) modify the beam pipe
2) dedicated run