Tests of CPT and Quantum Mechanics: experiment

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Introduction

•The correlations between the decay modes of a system consisting of a $K\bar{K}$ pair were first considered in 1958 by Goldhaber, Lee and Yang in nucleon-antinucleon annihilation.

•In 1960 Lee and Yang and then several authors (e.g. Inglis, Day, Lipkin) emphasized the EPR-like feature of $K^0\bar{K}^0$ system in a $J^{PC}=1^{-}$ state,

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

showing correlations very similar to a pair of spin ½ particles in a singlet state (correlation between the two decays even if the two kaons are distant in space),where the quantum number strangeness S=±1 plays the same role of the spin ↑or ↓ along a chosen direction.

•Many experimental tests using Bell's inequality performed so far by using the entanglement of the polarization of two photons, all confirming QM

•It's of great interest to perform complementary test of QM using neutral kaons in a completely different physical context (different energy and time scales)

Summary

Quantum mechanics tests

Brief description of models predicting QM and decoherence in the neutral kaon system
Experimental results from CPLEAR and KLOE

CPT tests

Bell-Steinberger relation
Experimental results from CPLEAR and KLOE

Test of QM in the kaon system

Most of QM tests exploit the initial correlated state of kaons

$$|i\rangle = |K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle \quad or \quad |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle - |K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle$$

- It has been suggested that the initial state (that in orthodox QM is non-separable) spontaneously factorizes to an equal weighted mixture of states:

$$|i\rangle \quad \Rightarrow \quad |K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle \quad or \quad |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle$$

Furry's hypothesis of "spontaneous factorization"

Measurement of the amount of deviation from QM (ζ parameter)

$\zeta = 0 \rightarrow$ "orthodox" QM $\qquad \zeta = 1 \rightarrow$ Furry's hypothesis

- Decoherence can also be introduced in a more general way adding an extra term directly in the Liouville – von Neumann equation for the density matrix of the kaon system (formalism of open quantum systems coupled to an unobserved environment):

$$\dot{\rho}(t) = i[\rho, H] + L(\rho)$$

Decoherence and CPT induced by quantum gravity

- At a microscopic level, in a quantum gravity picture, non-trivial space-time fluctuations could give rise to decoherence effects, which would necessarily entail a violation of ***CPT***.

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

$$L(\rho) = \delta H(\alpha,\beta,\gamma)\rho$$

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

$$\alpha,\beta,\gamma = O\left(\frac{M_K{}^2}{M_{PLANCK}}\right) \approx 2\times10^{-20}\ \text{GeV}$$

For entangled kaon states the "complete positivity" of the density matrix of the two kaons system hypothesis imposes $\alpha = \gamma, \beta = 0$

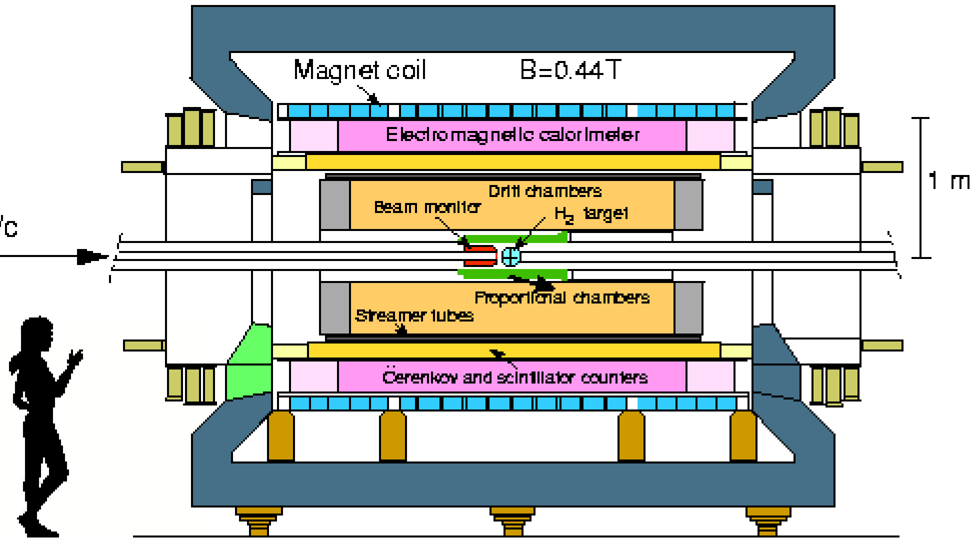
- Bernabeu, Mavromatos and Papavassiliou: in presence of decoherence induced by quantum gravity, CPT operator might be ill defined => breakdown of the correlations imposed by Bose statistics to the initial state:

$$|i\rangle \propto \left(K_S K_L - K_L K_S\right) + \omega\left(K_S K_S - K_L K_L\right) \qquad |\omega| \sim O\left(\frac{E^2/M_{PLANCK}}{\Delta\Gamma}\right)^{1/2} \sim 10^{-3}$$

Simple models of decoherence
tested at CPLEAR and KLOE

CPLEAR

Pure intial K^0 and $\overline{K}^0$ states are produced from



$$(p\bar{p})_{rest} \rightarrow K^0 K^- \pi^+$$

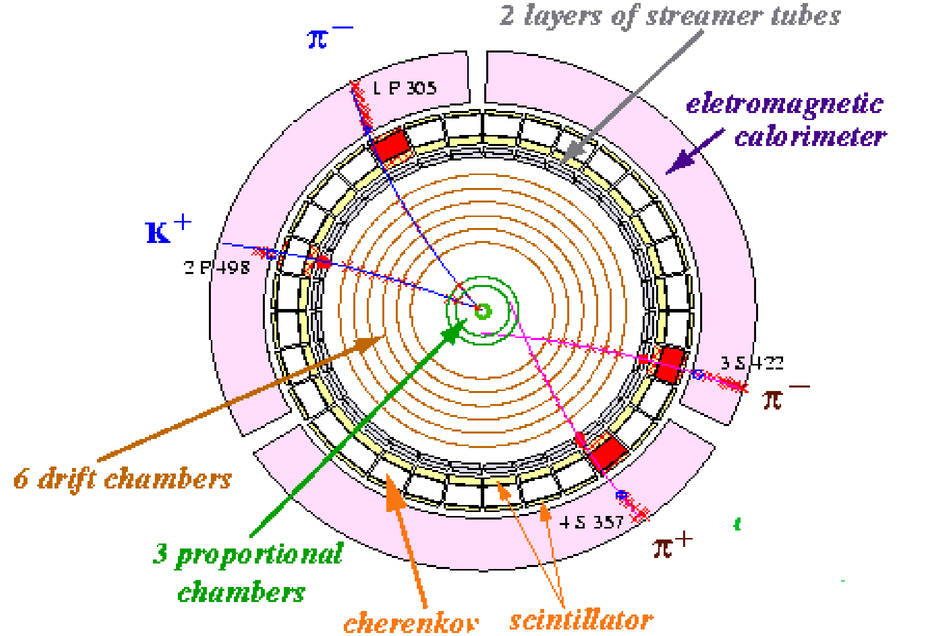
$$(p\bar{p})_{rest} \rightarrow \overline{K}^0 K^+ \pi^-$$

BR = 0.2%

$$(p\bar{p})_{rest} \rightarrow K^0 \overline{K}^0$$

BR=0.7%

Charged kaon tags the strangeness of the accompanying neutral kaon



Test of QM correlations at CPLEAR

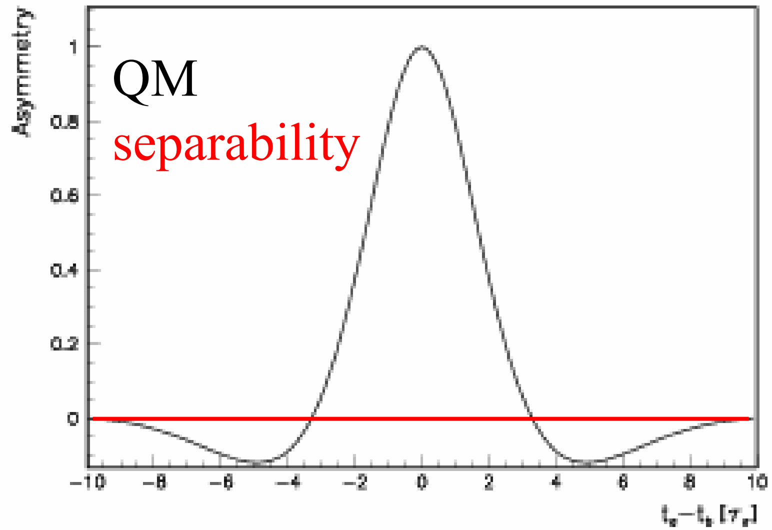
$$p\bar{p} \rightarrow |K^0, p\rangle|\bar{K}^0, -p\rangle - |K^0, -p\rangle|\bar{K}^0, p\rangle$$

- Unlike Strangeness ($K^0\bar{K}^0$)
- Like Strangeness (K^0K^0, $\bar{K}^0\bar{K}^0$)

Strangeness correlation for $J^{PC}=1^{--}$

$$A(t_1,t_2) = \frac{unlike - like}{unlike + like} = \frac{2\cos(\Delta m(\Delta t))}{e^{-\Delta\Gamma\Delta t/2} + e^{\Delta\Gamma\Delta t/2}}$$

$\Delta t = t_1 - t_2$



separability hypothesis : $A\ (t_1,t_2) = 0$ ⟺

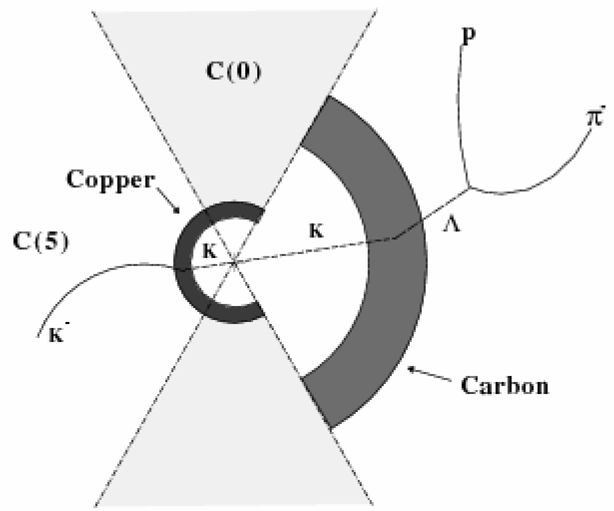
Furry's hypothesis of spontaneous factorization:
initial state = equally weighted
statistical mixture of K_SK_L and K_LK_S

test of QM versus separability hypothesis

Results

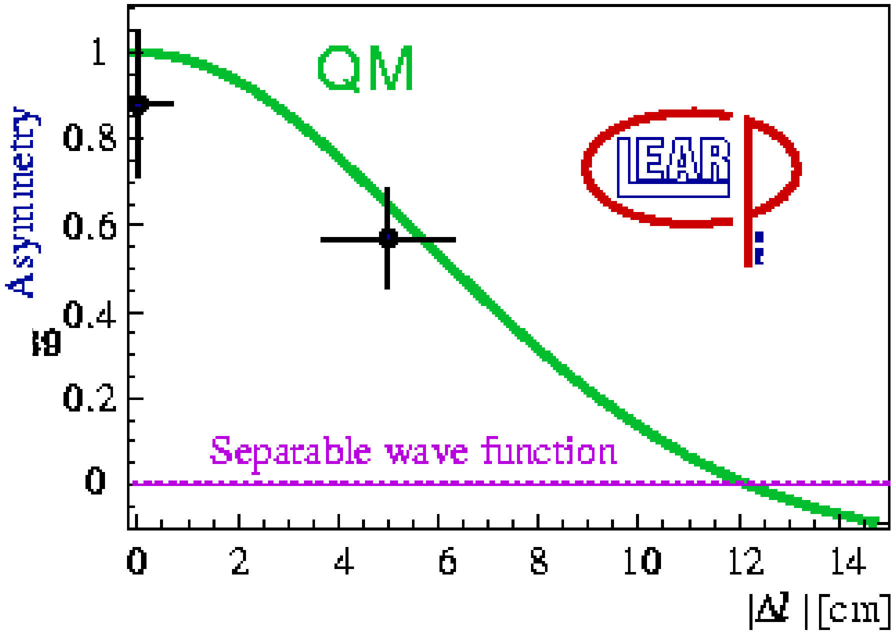
Determine the strangeness/flavor of the two K^0 by their strong interaction products with two converters ($\bar{K}^0 \rightarrow K^-, \Lambda; K^0 \rightarrow K^+$)

- Same Flavor: ***$K^- \Lambda$, $\Lambda\Lambda$***
- Opposite Flavor: ***$K^+ \Lambda$, $K^+ K^-$***



Measurements of asymmetry in both configuration consistent with QM expectations

Separability (A=0) hypothesis excluded with CL > 99.99%



Independent check: $N_{\Lambda\Lambda} \propto I_{like}$
Measured # events in C(0) and C(5) consistent with QM expectations

Decoherence parameter: fit to CPLEAR data

Interference term modified introducing a decoherence parameter ζ:
parametrizes the amount of deviation from QM predictions
Bertlmann et al, PRD 60, 114032 (1999)

The decoherence can happen either in $K_L\, K_S$ or in the $K^0\overline{K^0}$ basis:

$$A_{\zeta}^{SL}(t_r,t_l) = A^{QM}(1-\zeta)$$

$$A_{\zeta}^{OO}(t_r,t_l) = \frac{\cos(\Delta m \Delta t) + \cos(\Delta m(t_r+t_l))}{\cosh(1/2\Delta\Gamma\Delta t) - 1/2\zeta[\cosh(1/2\Delta\Gamma\Delta t)+\cosh(1/2\Delta\Gamma(t_r+t_l))]}$$

From the fit to CPLEAR data:

$$\zeta_{S,L} = 0.13^{+0.16}_{-0.15}$$
$$\zeta_{0,0} = 0.4 \pm 0.7$$

$$\dot{\rho} = i[\rho, H] - D[\rho]$$

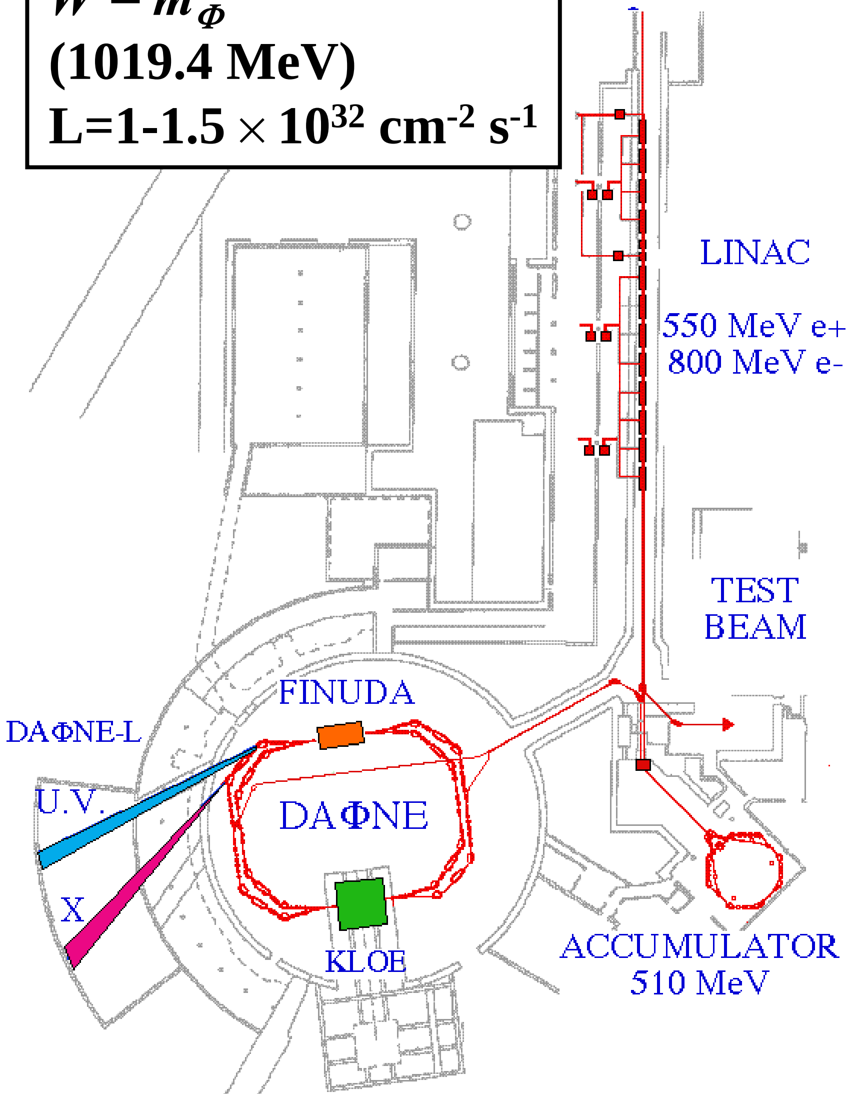
$$D[\rho] = \frac{\lambda}{2}\sum_{j=S,L}[P_j,[P_j,\rho]]$$

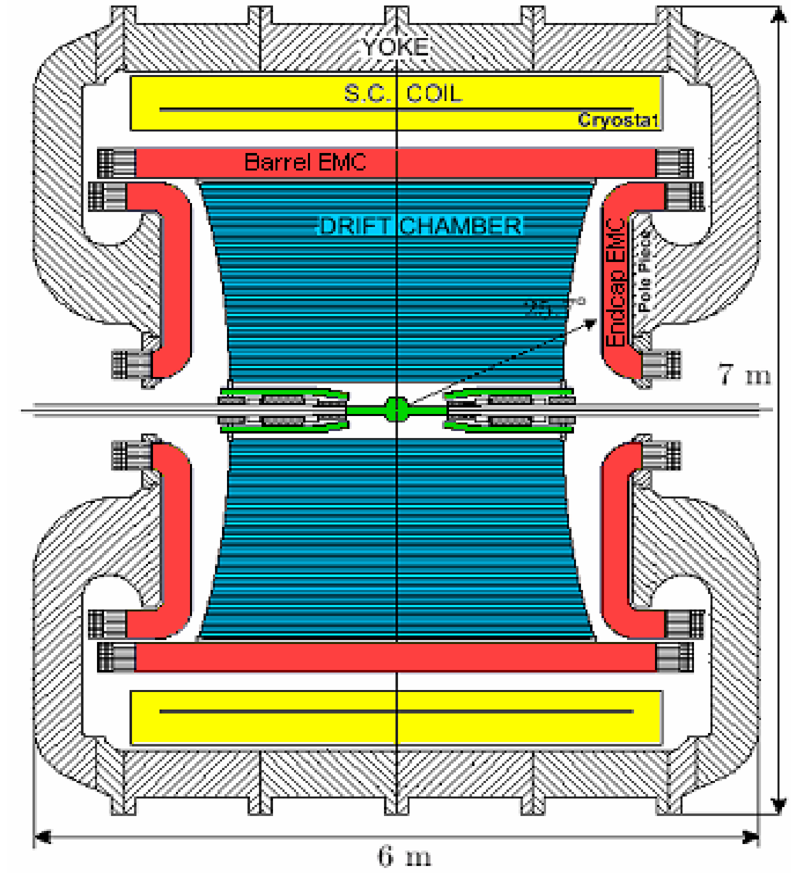
$$P_j = |K_j\rangle\langle K_j|$$

$$\lambda = (1.84^{+2.50}_{-2.17})\times 10^{-15}\ GeV$$

KLOE at DAΦNE

$W = m_{\Phi}$
(1019.4 MeV)
$L = 1\text{-}1.5 \times 10^{32}\ \mathrm{cm^{-2}\ s^{-1}}$





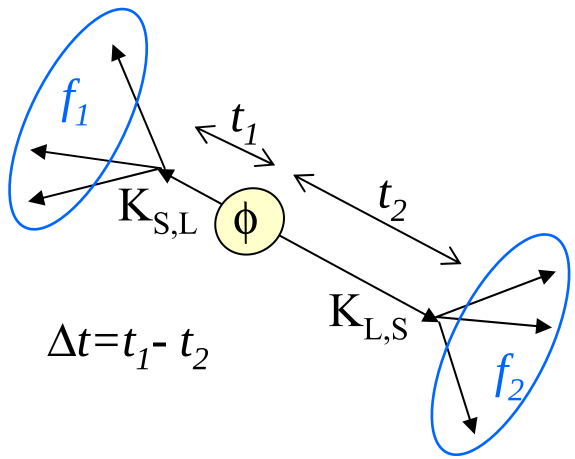
The KLOE design was driven by the measurement of direct CP through the double ratio:

$$R = \Gamma(K_L \rightarrow \pi^+\pi^-)\ \Gamma(K_S \rightarrow \pi^0\pi^0)\ /\ \Gamma(K_S \rightarrow \pi^+\pi^-)\ \Gamma(K_L \rightarrow \pi^0\pi^0)$$

Neutral kaons at a ϕ-factory

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

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



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

Decoherence parameter: fit to KLOE data

$I(\Delta t, \pi^+\pi^- \pi^+\pi^-) \propto e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2(1 - \zeta_{S,L})\, e^{-(\Gamma_S + \Gamma_L)|\Delta t|/2} \cos(\Delta m \Delta t)$

ζ decoherence parameter basis dependent: $K_S K_L$, $K^0 \bar{K}^0$

KLOE 380 pb^{-1}

$\zeta_{S,L} = 0.018 \pm 0.040 \pm 0.007$

$\zeta_{0,0} = (0.10 \pm 0.21 \pm 0.04) \times 10^{-5}$

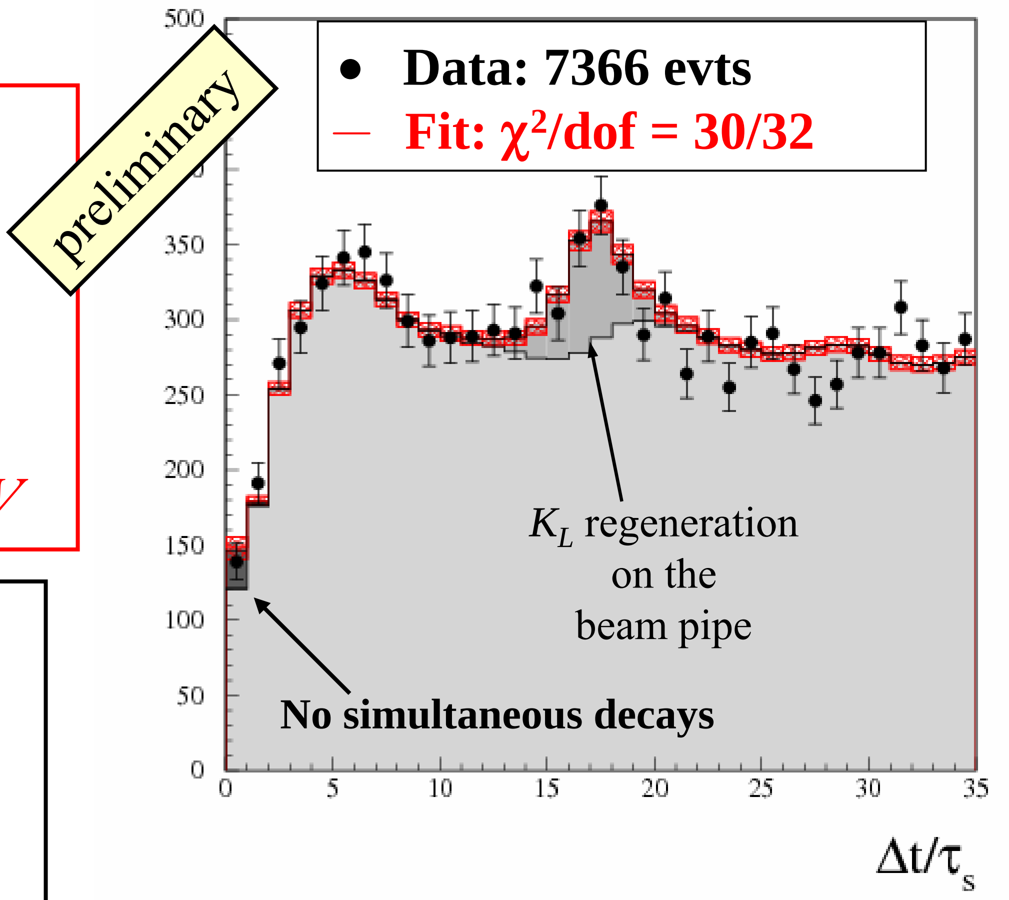
$\lambda = (0.13 \pm 0.30 \pm 0.05) \times 10^{-15}$ GeV

CPLEAR

$\zeta_{S,L} = 0.13^{+0.16}_{-0.15}$

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

$\lambda = (1.84^{+2.50}_{-2.17}) \times 10^{-15}$ GeV



Decoherence induced by space time fluctuations at the Planck scale:
Measurements of α, β, γ and ω
at CPLEAR and KLOE

Decoherence and ~~CPT~~: CPLEAR results

Space time fluctuations at the Planck scale may cause loss of quantum coherence and can be tested using QM of open systems

$$\dot{\rho} = i[\rho, H] + \delta H \rho \qquad \alpha, \beta, \gamma = O\left(\frac{M_K^{\;2}}{M_{PLANCK}}\right) \approx 2\times 10^{-20}\ \text{GeV}$$

Using **single kaons** from $\begin{cases} (p\bar{p})_{rest} \to K^0 K^- \pi^+ \\ (p\bar{p})_{rest} \to \bar{K}^0 K^+ \pi^- \end{cases}$, fit simultaneously to the model

$$A_{2\pi}(\tau;\alpha,\beta,\gamma) = \frac{N_{K^0\to\pi^+\pi^-}(\tau) - N_{\bar{K}^0\to\pi^+\pi^-}(\tau)}{N_{K^0\to\pi^+\pi^-}(\tau) + N_{\bar{K}^0\to\pi^+\pi^-}(\tau)}$$

mostly sensitive to α and β

mostly sensitive to α and Δm

$$A_{\Delta m}(\tau;\alpha,\beta,\gamma) = \frac{[N_{\bar{K}^0\to e^-\pi^+\nu}(\tau) + N_{K^0\to e^+\pi^-\nu}(\tau)] - [N_{\bar{K}^0\to e^+\pi^-\nu}(\tau) + N_{K^0\to e^-\pi^+\nu}(\tau)]}{[N_{\bar{K}^0\to e^-\pi^+\nu}(\tau) + N_{K^0\to e^+\pi^-\nu}(\tau)] + [N_{\bar{K}^0\to e^+\pi^-\nu}(\tau) + N_{K^0\to e^-\pi^+\nu}(\tau)]}$$

CPLEAR results

Performing a global fit + constraint on η_{+-} and semileptonic K_L asymmetry δ_L, both measured at long lifetimes PLB 364, 239 (1999)

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

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

$$\gamma = (1.1 \pm 2.0) \times 10^{-21}\ GeV$$

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

$$\alpha < 4.0 \times 10^{-17}\ GeV$$

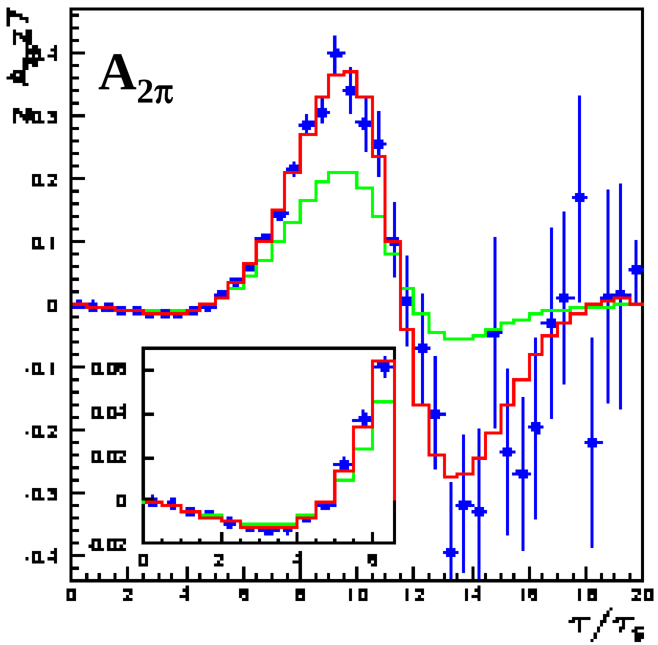
$$\beta < 2.3 \times 10^{-19}\ GeV$$

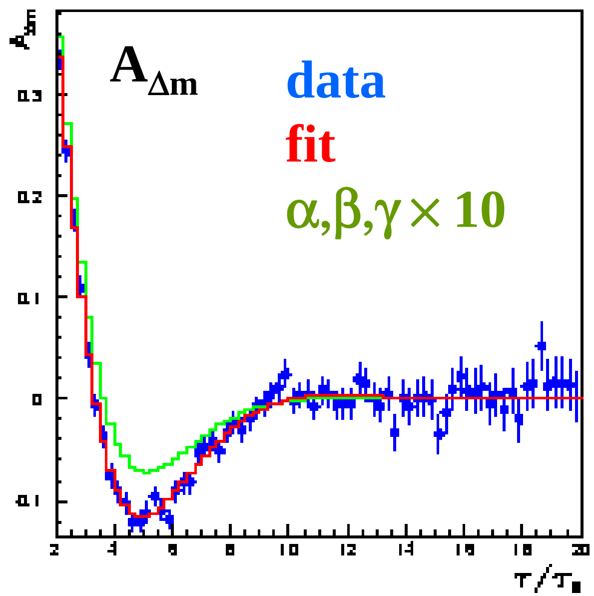
$$\gamma < 3.7 \times 10^{-21}\ GeV$$

at 90% CL

Expectations:

$$O\left(\frac{M_K^2}{M_{planck}}\right) \sim 2 \times 10^{-20}\ GeV$$





Decoherence and ~~CPT~~ at KLOE: results

Key feature at a ϕ-factory

Possible decoherence due to space-time fluctuations acting on the propagation of **one** kaon state (CPLEAR) is quite different from acting on the propagation of an entangled state of **two** kaons.

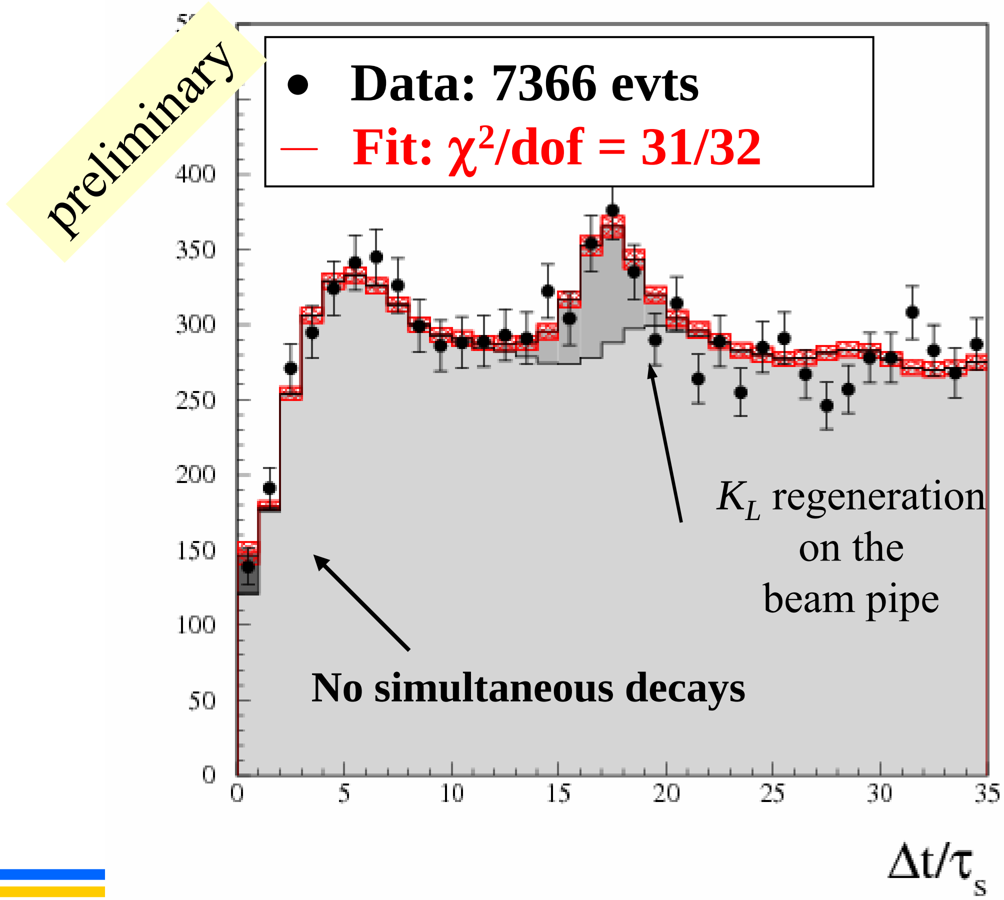
KLOE 380 pb^{-1}
Fit $I(\Delta t;\pi^+\pi^-,\pi^+\pi^-;\gamma)$
(complete positivity assumption)

$$\gamma = (1.1^{+2.9}_{-2.4} \pm 0.5) \times 10^{-21}\ GeV$$

$$\chi^2 / dof = 31/32$$

$$\gamma < 5.5 \times 10^{-21}\ GeV\ \ at\ \ 90\%\ CL$$

γ is measured for the first time in the **entangled** kaon system

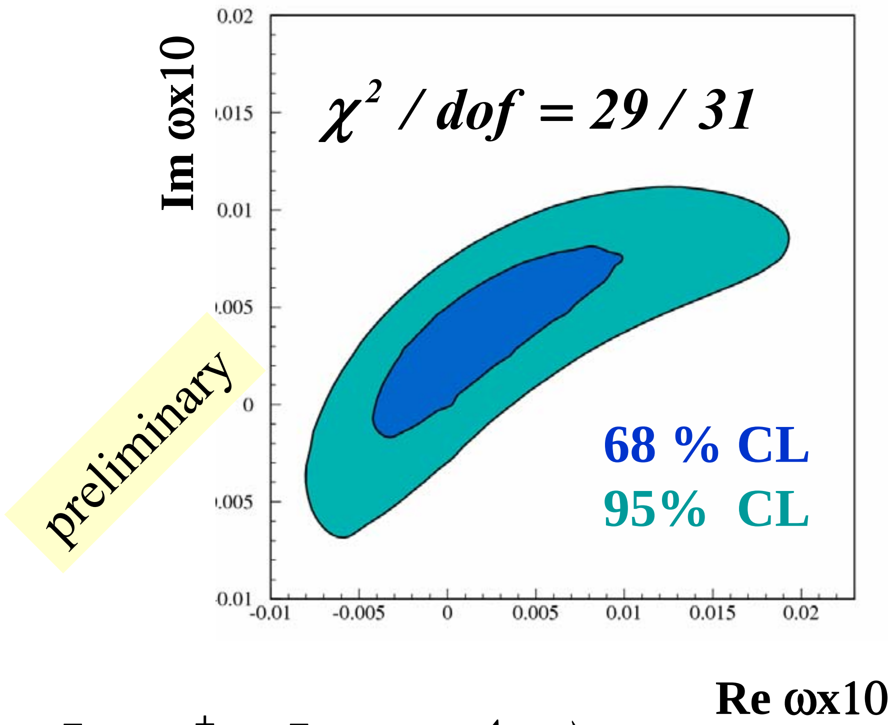


Bernabeu, Mavromatos and Papavassiliou model

"Novel type of CPT violation for EPR correlated neutral mesons", PRL92,131601 (2004)

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

$$|\omega| \sim O\left(\frac{E^2 / M_{PLANCK}}{\Delta\Gamma}\right)^{1/2} \sim 10^{-3}$$



KLOE 380 pb^{-1}

Fitting the time distribution:

$$|\langle \pi^+\pi^-, \pi^+\pi^- \mid i \rangle|^2 = I(\pi^+\pi^-, \pi^+\pi^-, \omega; \Delta t)$$

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

$$Im\,\omega = (3.4^{+4.8}_{-5.0} \pm 0.7) \times 10^{-4}$$

$$|\omega| < 2.1 \times 10^{-3} \text{ at } 95\%\, CL$$

First measurement of ω!

CPT tests

Simplest test of ***CPT:*** equality of masses and lifetimes of particles and antiparticles.
Most stringent test of ***CPT*** comes from mass difference between K^0 and $\overline{K}^0$.

Test of ***CPT*** in the neutral kaons has been performed both directly measuring the time dependent asymmetry (CPLEAR) and using the unitarity relation (CPLEAR, KLOE)

CPT test: unitarity relation

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

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

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

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

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

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

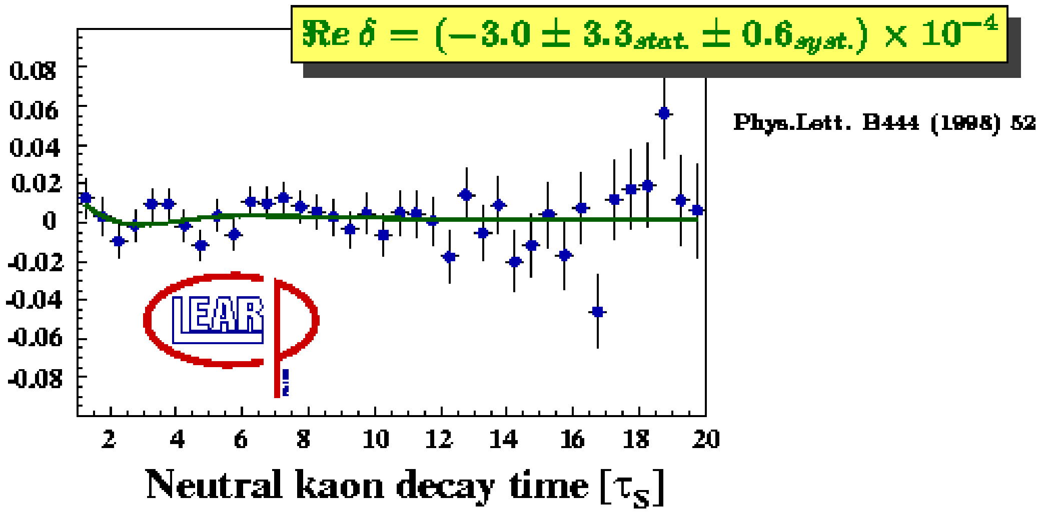
$$\alpha_{000} = \tau_S/\tau_L\, \eta_{000}^* B(K_L \to \pi^0\pi^0\pi^0)$$

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

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

CPT test at CPLEAR

Direct test of ***CPT*** through the semileptonic asymmetry $A_\delta(\tau)$



Using as constraint the unitarity relation
(+ constraint for the semileptonic K_L asymmetry δ_L)

Re ε = (164.9 ± 2.5) ×10^{-5}

Im δ =(2.4 ± 5.0) × 10^{-5}

PLB 456 297 (1999)

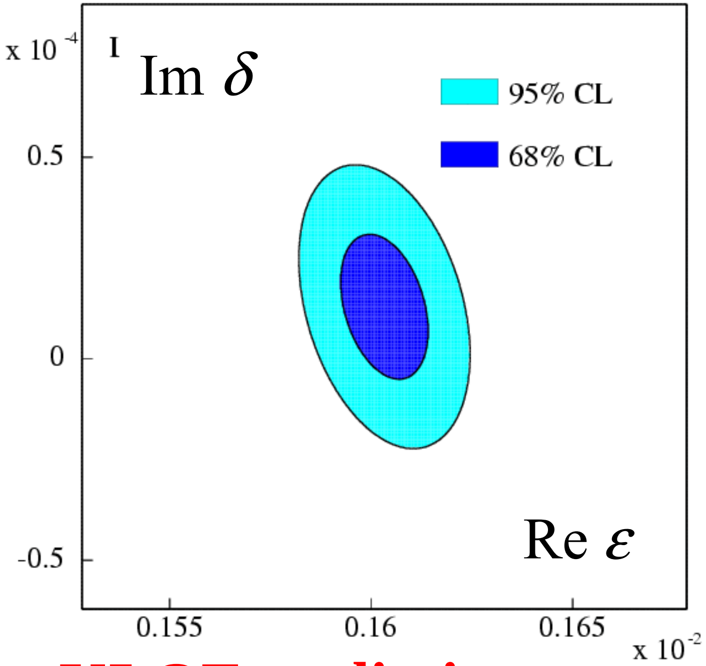
If no ~~CPT~~ in the decay

$$(\Gamma_{K^0} = \Gamma_{\overline{K}^0})$$

$$|m_{K^0} - m_{\overline{K}^0}| < 12.7 \times 10^{-19}\ GeV$$

at 90% CL

CPT test at KLOE



$$\delta = \frac{i(m_{K^0} - m_{\overline{K}^0}) + 1/2(\Gamma_{K^0} - \Gamma_{\overline{K}^0})}{\Gamma_S - \Gamma_L} \cos\phi_{SW} e^{i\phi_{SW}}$$

If no ~~CPT~~ in the decay $(\Gamma_{K^0} = \Gamma_{\overline{K}^0})$

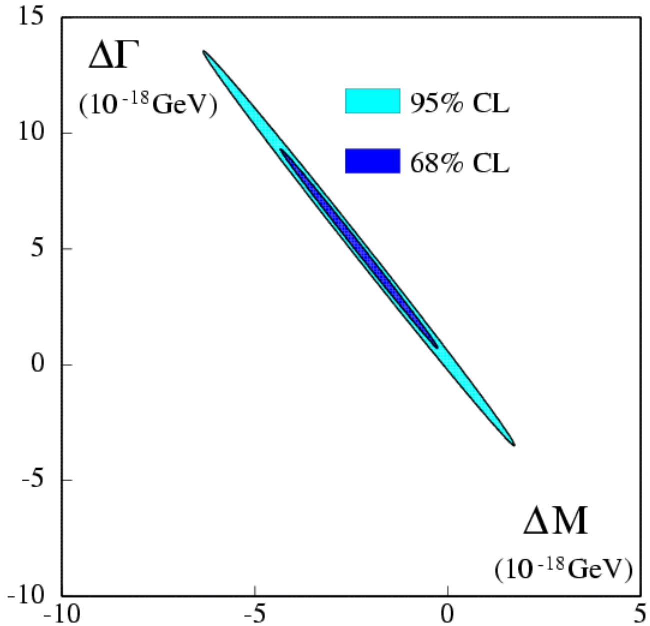
$$-4\times10^{-19} < m_{K^0} - m_{\overline{K}^0} < 7\times10^{-19}\ GeV$$

at 95% CL

KLOE preliminary:

Re $\varepsilon = (160.2 \pm 1.3) \times 10^{-5}$

Im $\delta = (1.2 \pm 1.9) \times 10^{-5}$



Main improvement:

K_S semileptonic asymmetry, UL $K_S \to \pi^0 \pi^0 \pi^0$

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

Conclusions

❖CPLEAR and KLOE have performed QM and ***CPT*** tests in the neutral kaon system both studying the time evolution of single kaons and two entangled kaons and measuring BR's (inputs for unitarity relation)

❖Results are consistent with no QM and ***CPT*** violation

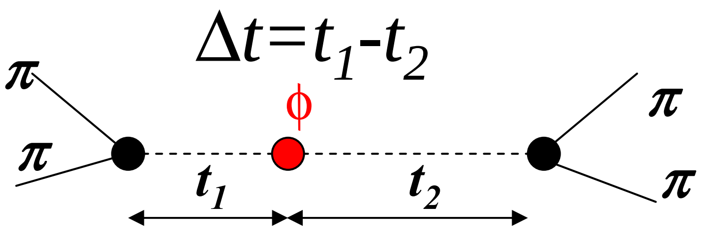
❖From these measurements we are reaching an interesting range on some ***CPT*** and QM parameters
KLOE has 5 times more data in hand: considerably improve soon these tests

Spare slides

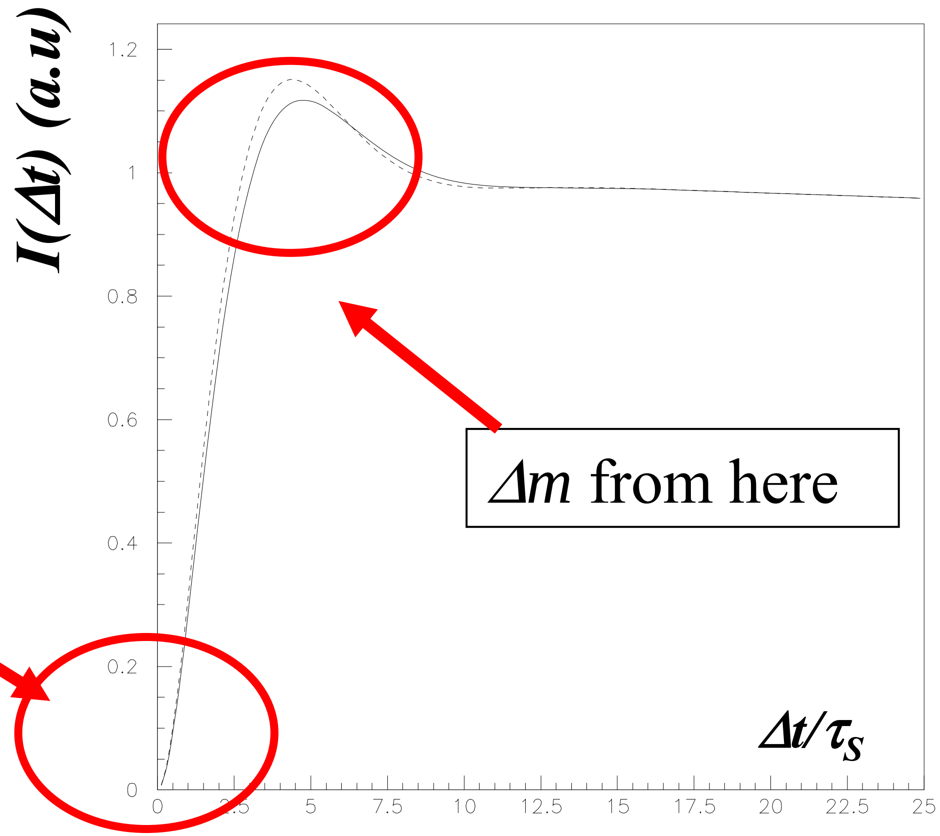
Kaon interferometry: $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$

$$|i\rangle \propto \frac{1}{\sqrt{2}}\left(|K_L, p\rangle |K_S, -p\rangle - |K_L, -p\rangle |K_S, p\rangle\right) \quad \Rightarrow$$

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



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



Kaon interferometry: main observables

mode	measured quantity	parameters
$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^0\pi^0$	$A(\Delta t) = \frac{I(\pi^+\pi^-,\pi^0\pi^0;\Delta t>0) - I(\pi^+\pi^-,\pi^0\pi^0;\Delta t<0)}{I(\pi^+\pi^-,\pi^0\pi^0;\Delta t>0) - I(\pi^+\pi^-,\pi^0\pi^0;\Delta t<0)}$	$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \; \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$
$\phi \to K_S K_L \to \pi\ell\nu \; \pi\ell\nu$	$A_{CPT}(\Delta t) = \frac{I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t>0) - I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t<0)}{I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t>0) + I(\pi^-e^+\nu,\pi^+e^-\bar{\nu};\Delta t<0)}$	$\Re\delta_K - \Re\left(\frac{d^*}{a}\right)$ $\Im\delta_K + \Im\left(\frac{c^*}{a}\right)$
$\phi \to K_S K_L \to \pi\pi \; \pi\ell\nu$	$A(\Delta t) = \frac{I(\pi^+\pi^-,\pi^-e^+\nu;\Delta t) - I(\pi^+\pi^-,\pi^+e^-\bar{\nu};\Delta t)}{I(\pi^+\pi^-,\pi^-e^+\nu;\Delta t) + I(\pi^+\pi^-,\pi^+e^-\bar{\nu};\Delta t)}$	$A_L = 2\Re\varepsilon_K - \Re\delta_K + \Re b/a + \Re d^*/a$ $\phi_{\pi\pi}$
$\phi \to K_S K_L \to \pi^+\pi^- \; \pi^+\pi^-$	$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t)$	$\Delta m \quad \Gamma_S \quad \Gamma_L$

CPT test: inputs to the Bell-Steinberger relation

$B(K_S \to \pi^+\pi^-)/B(K_S \to \pi^0\pi^0) = 2.2549 \pm 0.0059$

$B(K_S \to \pi^+\pi^-\gamma) < 9 \times 10^{-5}$

$B(K_L \to \pi^+\pi^-\gamma) = (29 \pm 1) \times 10^{-6}$

$B(K_L \to \pi l \nu) = 0.6705 \pm 0.0022$

$B(K_S \to \pi^+\pi^-\pi^0) = (3.2 \pm 1.2) \times 10^{-7}$

$B(K_L \to \pi^+\pi^-\pi^0) = 0.1263 \pm 0.0012$

$B(K_S \to \pi^0\pi^0\pi^0) < 1.2 \times 10^{-7}$

$\phi^{SW} = (0.759 \pm 0.001)$

$\phi^{000}, \phi^{+-0}, \phi^{+-\gamma} = [0, 2\pi]$

$\tau_S = 0.08958 \pm 0.00006$ ns

$\tau_L = 50.84 \pm 0.23$ns

$A_L = (3.32 \pm 0.06) \times 10^{-3}$

$A_S = (1.5 \pm 10.0) \times 10^{-3}$

$B(K_L \to \pi^+\pi^-) = (1.963 \pm 0.021) \times 10^{-3}$

$B(K_L \to \pi^0\pi^0) = (8.65 \pm 0.10) \times 10^{-4}$

$\phi^{+-} = 0.757 \pm 0.012$

$\phi^{00} = 0.763 \pm 0.014$

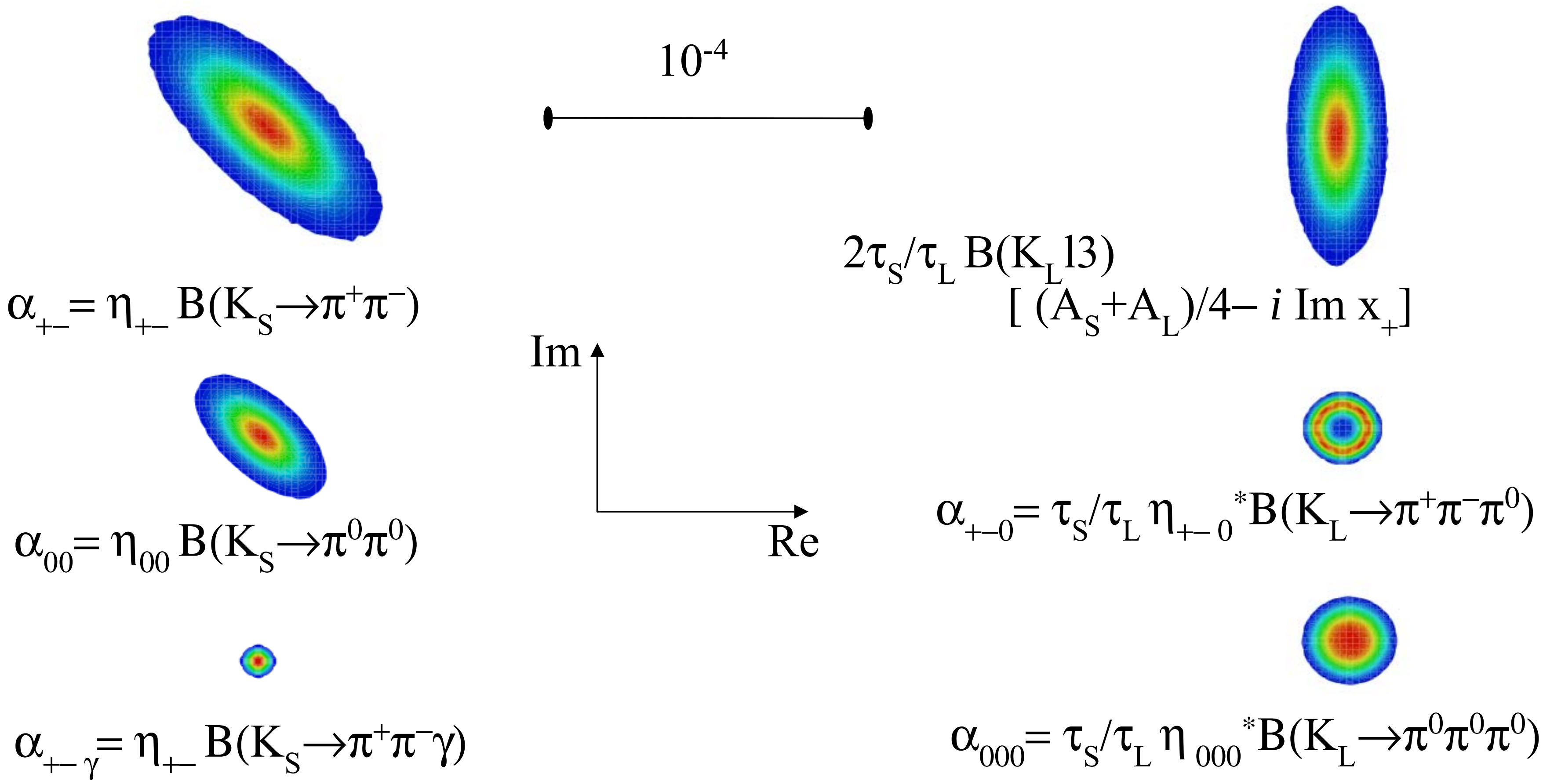
$Im\ x_+ = (0.8 \pm 0.7) \times 10^{-2}$

KLOE measurements

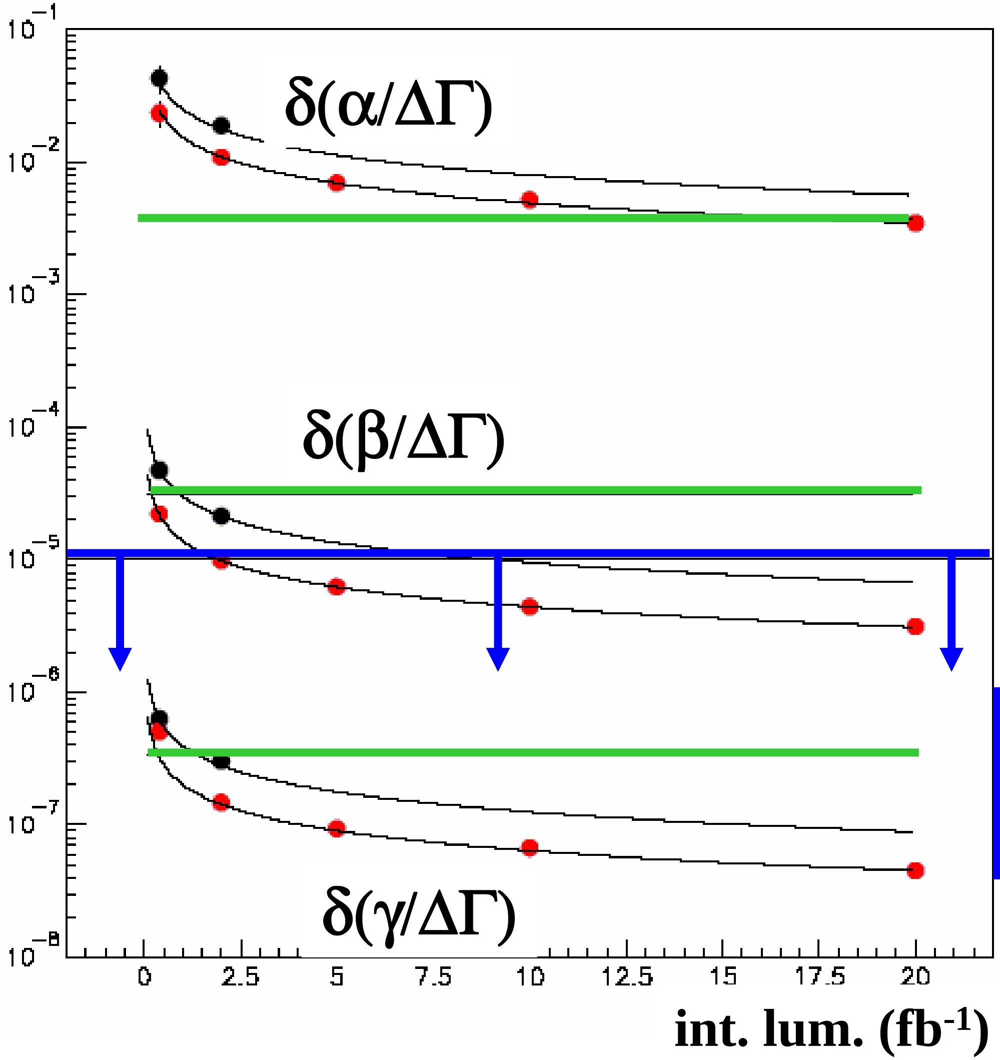
Im x_+ from a combined fit of KLOE + CPLEAR data

CPT test: accuracy on α_i

We get the following results (error contours) on each term of the sum



Prospecitves for a future ϕ factory (I)

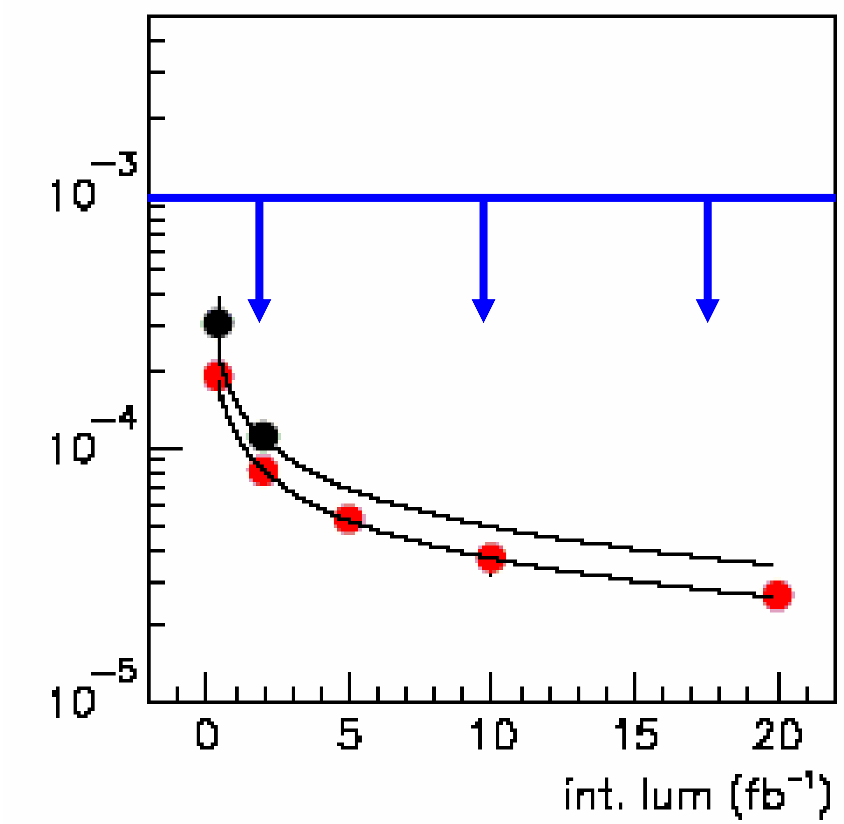


- present KLOE
- KLOE + VDET
- -- CPLEAR results
- -- Planck's scale region

$$\frac{\alpha,\beta,\gamma}{\Delta\Gamma} \approx \frac{E^2/M_{PLANCK}}{\Delta\Gamma} \sim 10^{-5} \div 10^{-6}$$

Prospecitves for a future ϕ factory (II)

δ(Re ω) (similar for Im ω)



- ● present KLOE
- ● KLOE + VDET
- -- Planck's scale region

$$|\omega|^2 \approx \frac{E^2 / M_{PLANCK}}{\Delta\Gamma} \sim 10^{-5} \div 10^{-6}$$

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

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: measurement of decoherence

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

interference term modified introducing a decoherence parameter ζ.
decoherence ζ depends on the basis in which initial state is written the (QM not!):

$$K_S K_L - K_L K_S \qquad or \qquad K^0 \overline{K}^0 - \overline{K}^0 K^0 \quad ......$$

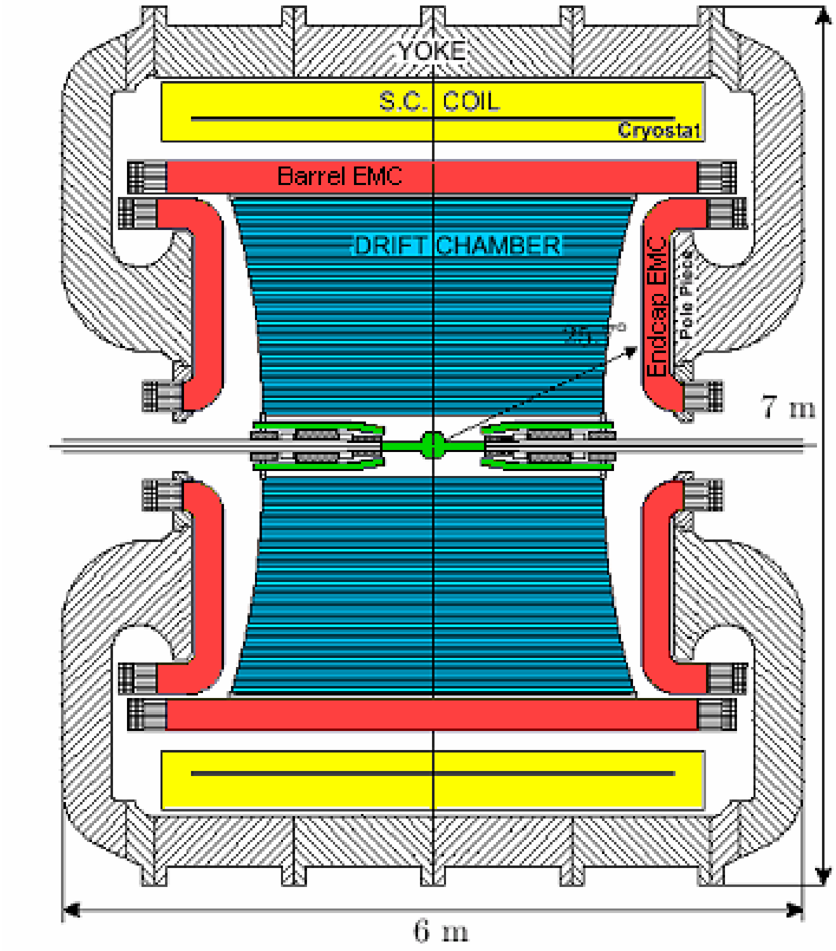
For a generic basis $\{K_\alpha, K_\beta\}$ we can write:

$$I(f_1,t_1;f_2,t_2) = \frac{N}{2}\Big[\left|\langle f_1|K_\alpha(t_1)\rangle\langle f_2|K_\beta(t_2)\rangle\right|^2 + \left|\langle f_1|K_\beta(t_1)\rangle\langle f_2|K_\alpha(t_2)\rangle\right|^2$$
$$-2\cdot\left(1-\zeta_{K_\alpha,K_\beta}\right)\cdot\Re\left(\langle f_1|K_\beta(t_1)\rangle\langle f_2|K_\alpha(t_2)\rangle\langle f_1|K_\alpha(t_1)\rangle^*\langle f_2|K_\beta(t_2)\rangle^*\right)\Big]$$

KLOE experiment

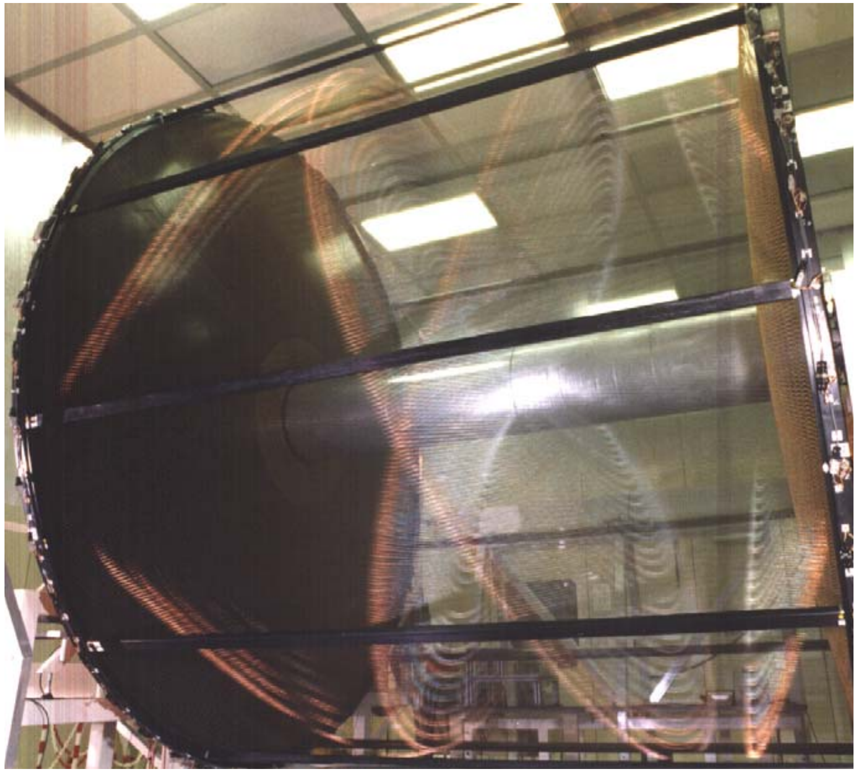
The KLOE design was driven by the measurement of direct $\not{C}$P through the double ratio:

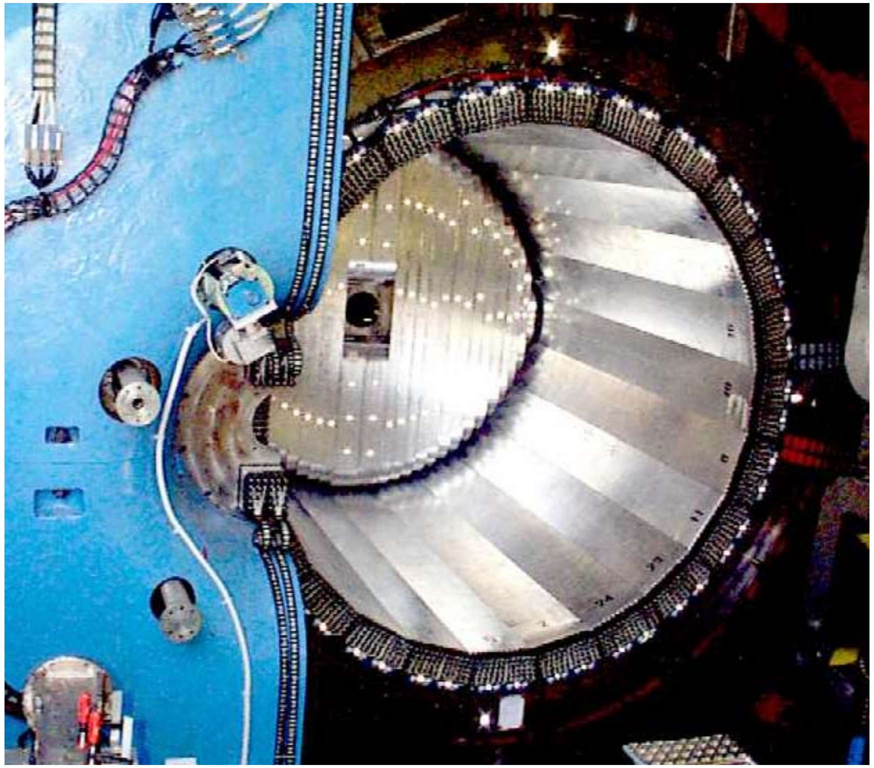
$$R = \Gamma(K_L \to \pi^+\pi^-)\ \Gamma(K_S \to \pi^0\pi^0)\ /\ \Gamma(K_S \to \pi^+\pi^-)\ \Gamma(K_L \to \pi^0\pi^0)$$



- **Be beam pipe** (spherical, 10 cm ∅, 0.5 mm thick) + **instrumented permanent magnet quadrupoles** (32 PMT's)
- **Drift chamber** (4 m ∅ × 3.75 m, CF frame)
  - Gas mixture: 90% He + 10% C_4H_{10}
  - 12582 stereo–stereo sense wires
  - almost squared cells
- **Electromagnetic calorimeter**
  - lead/scintillating fibers (1 mm ∅), 15 X_0
  - 4880 PMT's
  - 98% solid angle coverage
- **Superconducting coil** (B = 0.52 T)

KLOE detector specifications





$\sigma_p/p = 0.4\ \%$ (tracks with $\theta > 45°$)
$\sigma_x^{hit} = 150\ \mu m\ (xy),\ 2\ mm\ (z)$
$\sigma_x^{vertex} \sim 1\ mm$
$\sigma(M_{\pi\pi}) \sim 1\ MeV$

$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
$\sigma_t = 54\ ps / \sqrt{E(GeV)} \oplus 50\ ps$
$\sigma_{vtx}(\gamma\gamma) \sim 1.5\ cm$ (π^0 from $K_L \rightarrow \pi^+\pi^-\pi^0$)