CPT symmetry and quantum coherence tests in the neutral kaon system at KLOE

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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. :

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

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

The neutral kaon system

The time evolution of a two-component state vector Ψ in the $\{K^0, \overline{K}^0\}$ space is given by (Wigner-Weisskopf approximation):

$$i\frac{\partial}{\partial t}\Psi(t) = \mathbf{H}\Psi(t)$$

H is the effective hamiltonian (non-hermitian), decomposed into a Hermitian Part (mass matrix **M**) and an anti-Hermitian part (i/2 decay matrix Γ) :

$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

Diagonalizing the effective Hamiltonian:

eigenvalues

$$\lambda_{S,L} = m_{S,L} - \frac{i}{2}\Gamma_{S,L}$$

$$|K_{S,L}(t)\rangle = e^{-i\lambda_{S,L}t}|K_{S,L}(0)\rangle$$

$\tau_S \sim$ 90 ps $\quad \tau_L \sim$ 51 ns

$m_L - m_S$ = 3.5 x 10^{-15} GeV $\sim \Gamma_S / 2$

eigenstates

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

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

$|K_{1,2}\rangle$ are CP=±1 states

small CP impurity ~2 x 10^{-3}

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

CPT violation in the mixing:

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

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

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

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

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

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

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

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

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

CPT violation in semileptonic decays

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

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

ΔS=ΔQ rule

$K^0 \rightarrow \pi^- \ell^+ \nu$ $\qquad K^0 \not\rightarrow \pi^+ \ell^- \overline{\nu}$

$\overline{K}^0 \rightarrow \pi^+ \ell^- \overline{\nu}$ $\qquad \overline{K}^0 \not\rightarrow \pi^- \ell^+ \nu$

	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

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

Semileptonic charge asymmetry:

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

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

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

CPT violation in semileptonic decays

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

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

ΔS=ΔQ rule	
$K^0 \to \pi^- \ell^+ \nu$	$K^0 \not\to \pi^+ \ell^- \overline{\nu}$
$\overline{K}^0 \to \pi^+ \ell^- \overline{\nu}$	$\overline{K}^0 \not\to \pi^- \ell^+ \nu$

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

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

Semileptonic charge asymmetry:

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

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

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

CPT violation in ππ decays

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

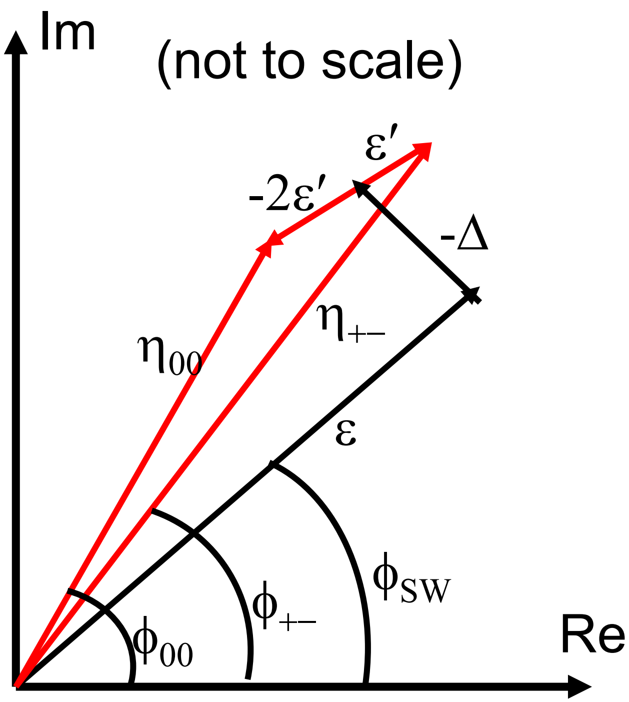
$$\langle \pi\pi; I | T | \overline{K}^0 \rangle = (A_I^* - B_I^*) e^{i\delta_I}$$

$A_I(B_I)$ CPT conserving (violating)
$K \rightarrow \pi\pi$ amplitudes for I=0,2
(δ_I strong phase shift for I=0,2)

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

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

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



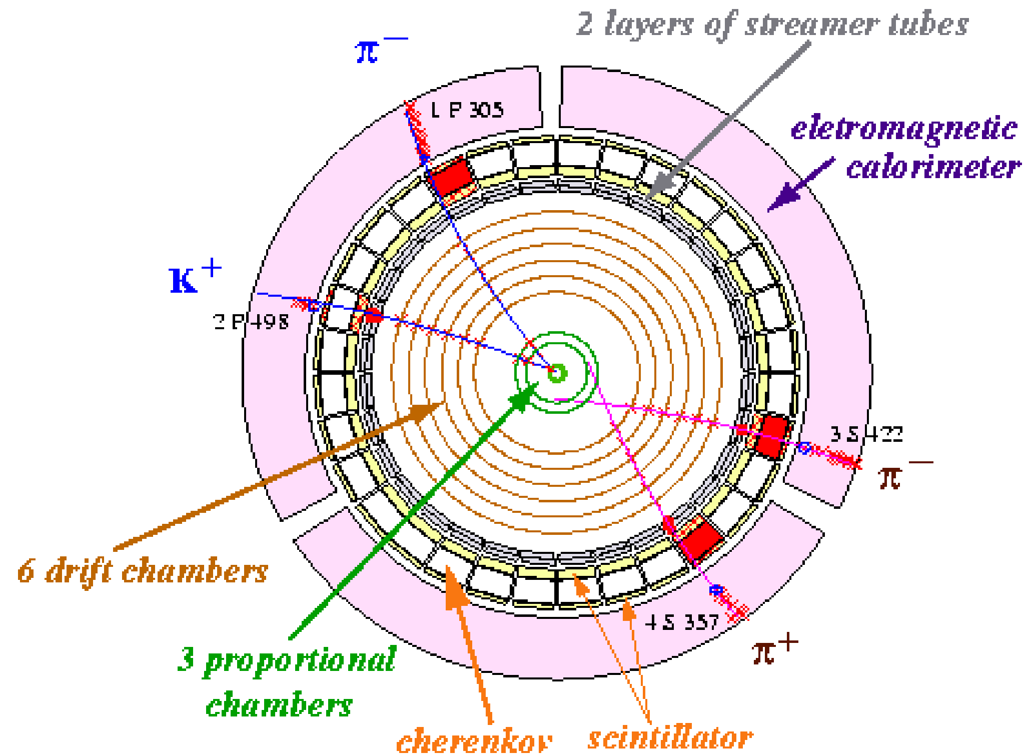
$$\phi_{00} - \phi_{+-} \approx \frac{3}{\sqrt{2}} \frac{1}{|\eta_{+-}|} \frac{\Re A_2}{\Re A_0} \left(\frac{\Re B_2}{\Re A_2} - \frac{\Re B_0}{\Re A_0} \right) \approx -3\Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

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

Neutral kaons at CPLEAR (CERN)

Pure initial $K^0, \overline{K}^0$ are produced from antiproton annihilation at rest with a hydrogen target

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

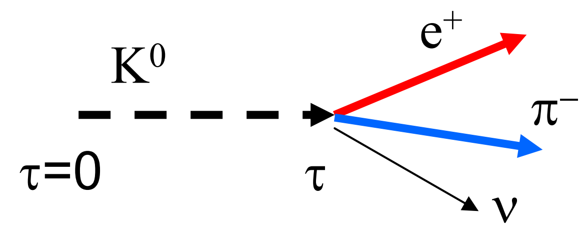


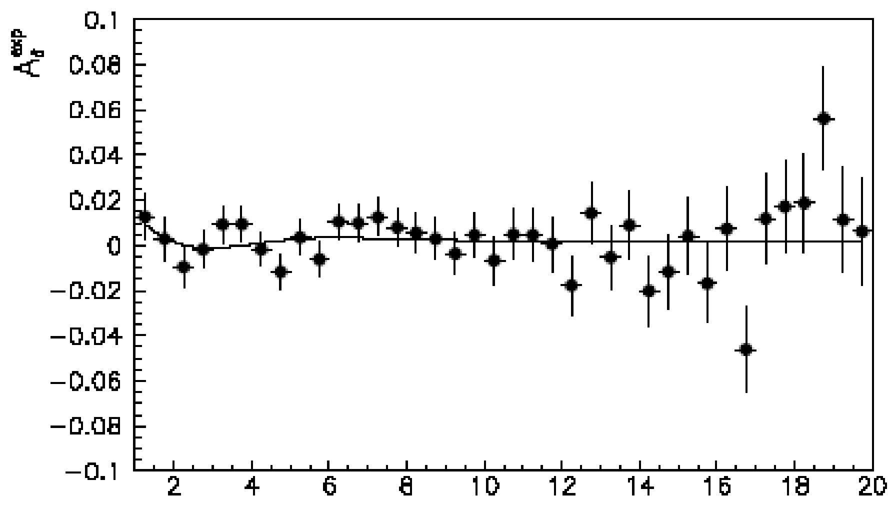
P_K ~500 MeV

The detection of a charged kaon tags the strangeness of the accompanying neutral kaon

CPLEAR results

Test of **CPT** in the time evolution of neutral kaons using the semileptonic asymmetry





$$\begin{cases} A_\delta(\tau) = \dfrac{\overline{R}_+(\tau) - \alpha R_-(\tau)}{\overline{R}_+(\tau) + \alpha R_-(\tau)} + \dfrac{\overline{R}_-(\tau) - \alpha R_+(\tau)}{\overline{R}_-(\tau) + \alpha R_+(\tau)} \\ R_{+(-)}(\tau) = R\left(K^0{}_{t=0} \to (e^{+(-)}\pi^{-(+)}\nu)_{t=\tau}\right) \\ \overline{R}_{-(+)}(\tau) = R\left(\overline{K}^0{}_{t=0} \to (e^{-(+)}\pi^{+(-)}\nu)_{t=\tau}\right) \\ \alpha = 1 + 4\Re\varepsilon_L \end{cases}$$

$$A_\delta(\tau >> \tau_S) = 8\Re\delta$$

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

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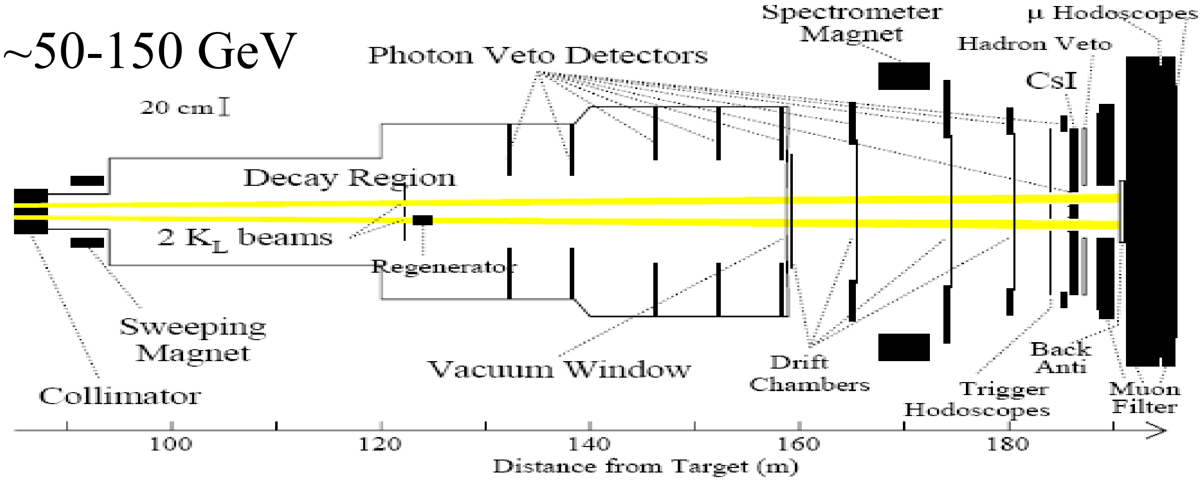
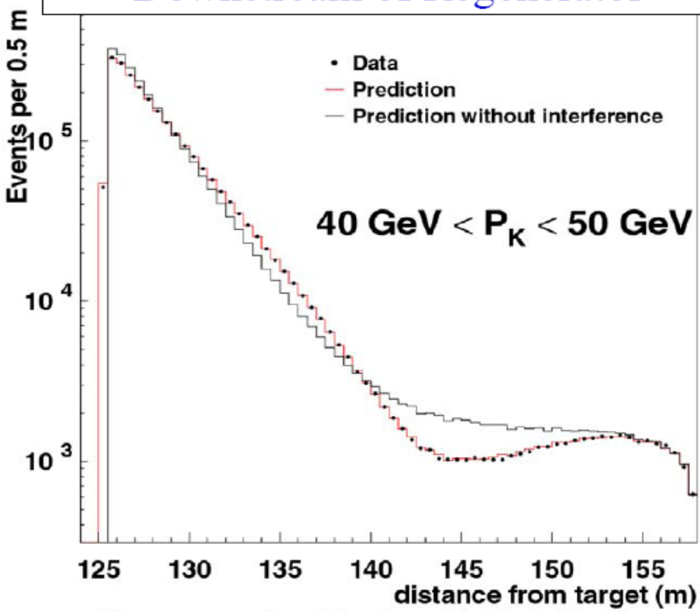
KTeV (Fermilab) results

Regenerator beam decay distribution allows *CPT* tests based on ϕ_{+-}, ϕ_{00}-ϕ_{+-}

P_K ~50-150 GeV





Regenerator Vertex Z distribution

$$|K_L\rangle \rightarrow |K_L\rangle + \rho |K_S\rangle$$

$$R(\pi^+\pi^-;t) \propto |\rho|^2 e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t}$$
$$+ 2|\rho||\eta_{+-}|e^{-(\Gamma_S+\Gamma_L)t} \cos(\Delta m t + \phi_\rho - \phi_{+-})$$

$\phi_{+-} - \phi_{SW} = 0.61^o \pm 0.62^o \pm 1.01^o$

$\phi_{00} - \phi_{+-} = 0.39^o \pm 0.22^o \pm 0.45^o$

PRD67,012005 (2003)

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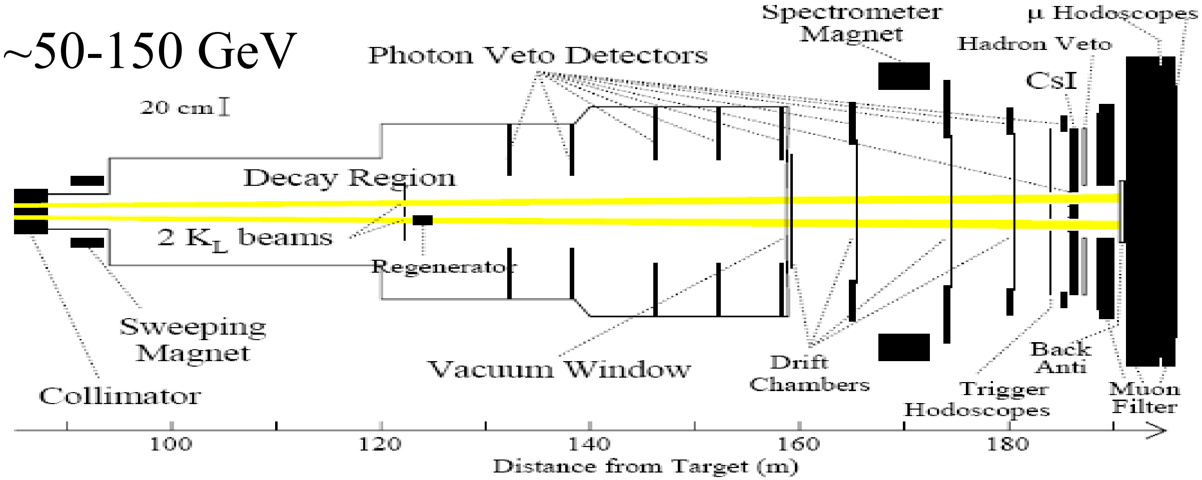

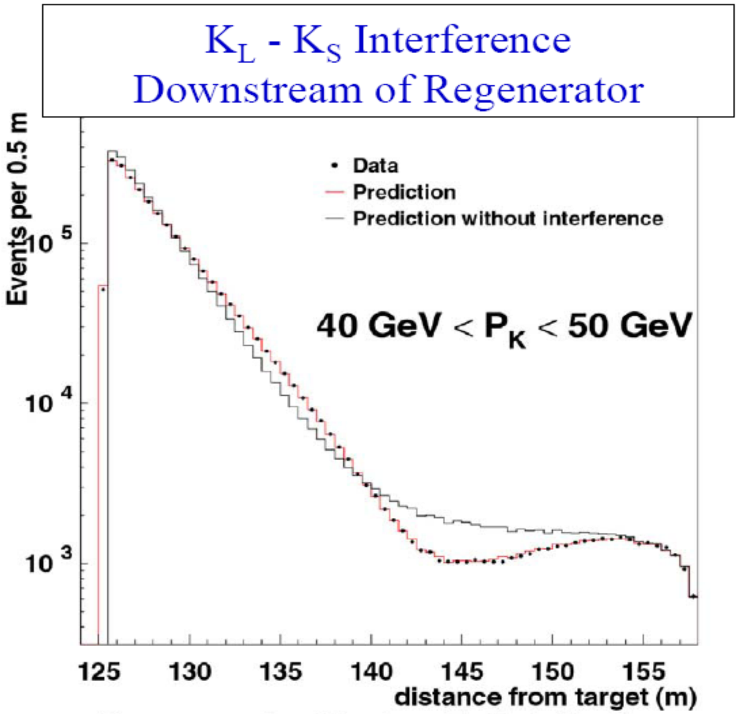

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$$+ 2|\rho||\eta_{+-}|e^{-(\Gamma_S+\Gamma_L)t}\cos(\Delta m t + \phi_\rho - \phi_{+-})$$

$\phi_\varepsilon - \phi_{SW} = 0.40^o \pm 0.56^o$

$\phi_{00} - \phi_{+-} = 0.30^o \pm 0.35^o$

Presented at Moriond08, HQL08

KTeV (Fermilab) results

K_L semileptonic charge asymmetry:

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

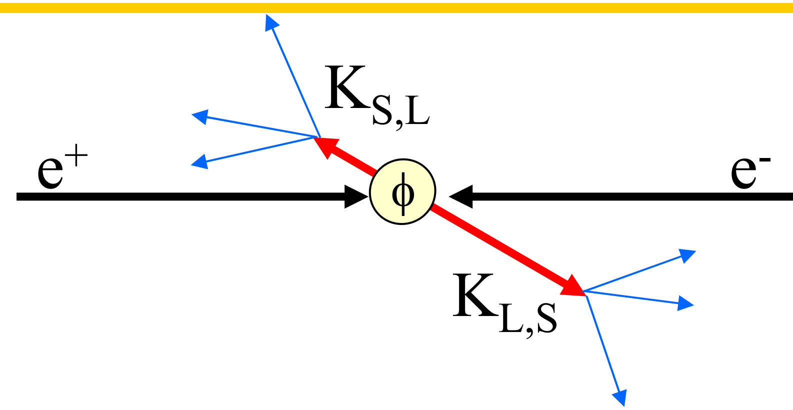
PRL88,181601(2002)

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

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

Neutral kaons at a ϕ-factory

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



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

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

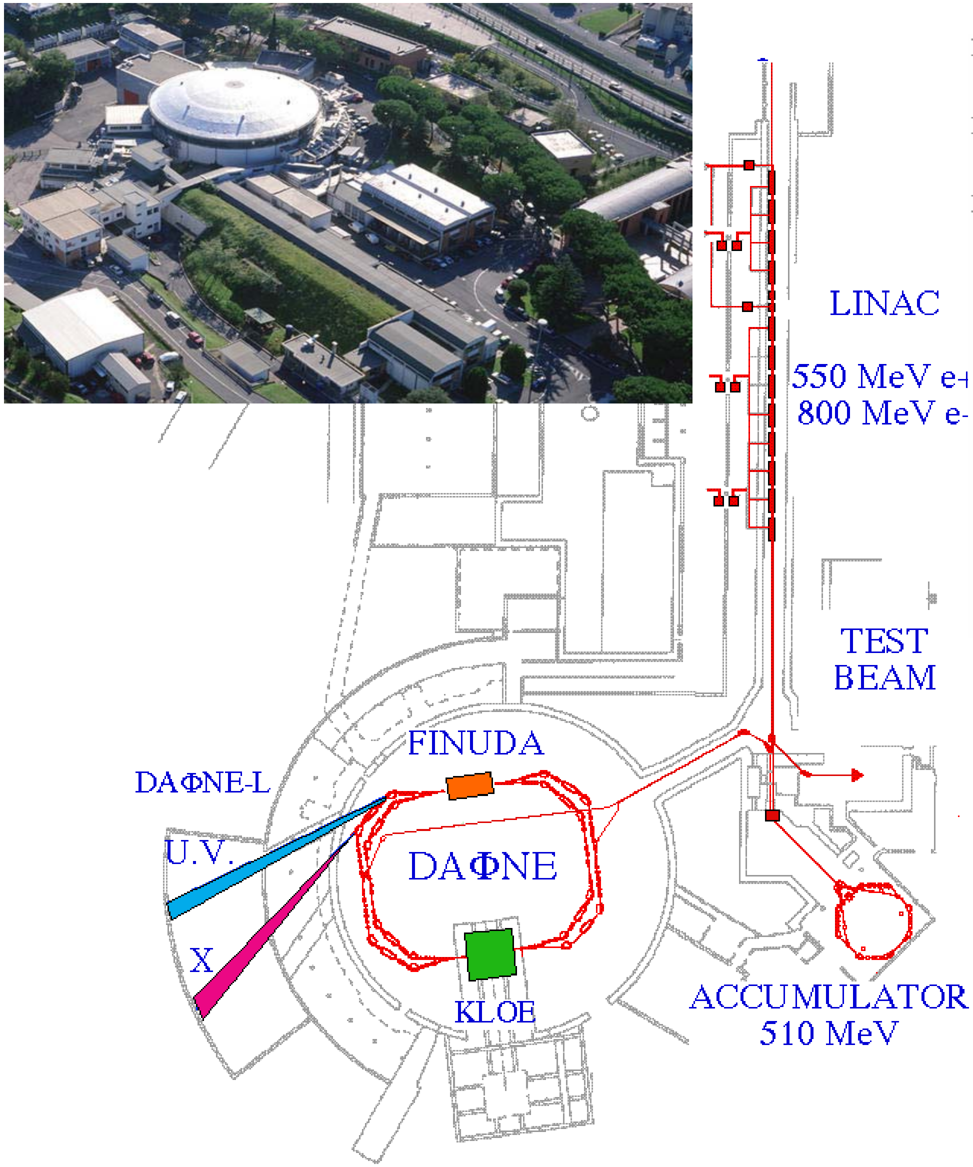
$p_K = 110$ MeV/c

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

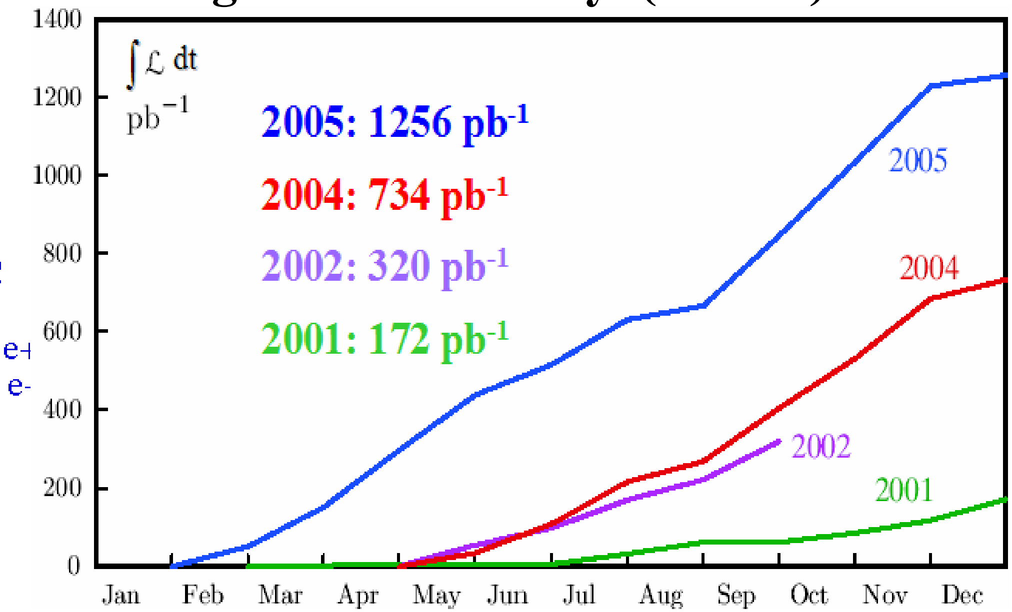
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

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

DAΦNE: the Frascati φ-factory



Integrated luminosity (KLOE)



Max $\mathcal{L} \sim$ 1.4 cm^{-2}s^{-1}

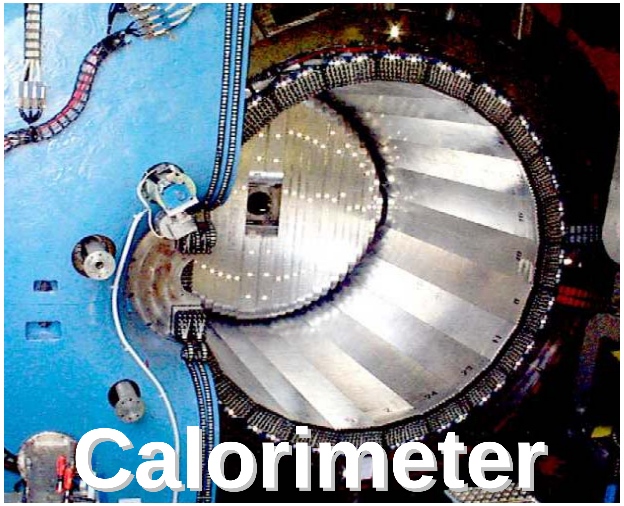
Day performance: 7-8 pb^{-1}

Best month $\int \mathcal{L}\, dt \sim$ 200 pb^{-1}

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

$\rightarrow$ ~2.5×10^9 $K_S K_L$ pairs

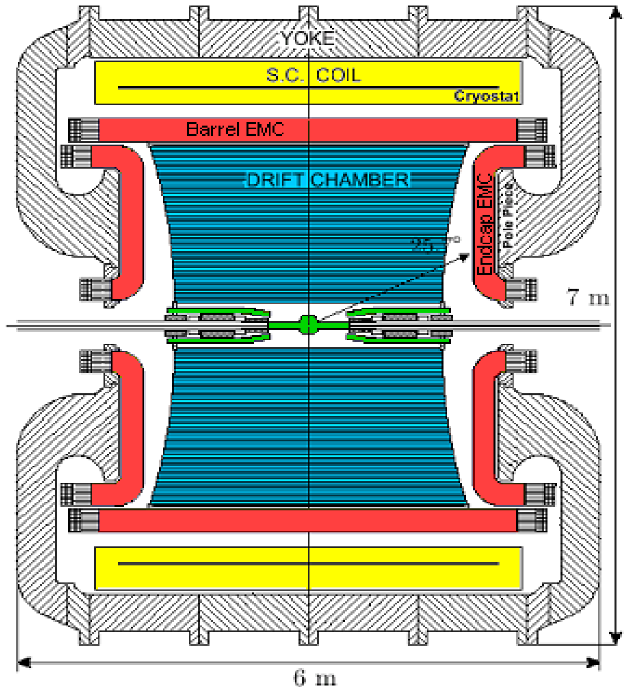
The KLOE detector at DAΦNE



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

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

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

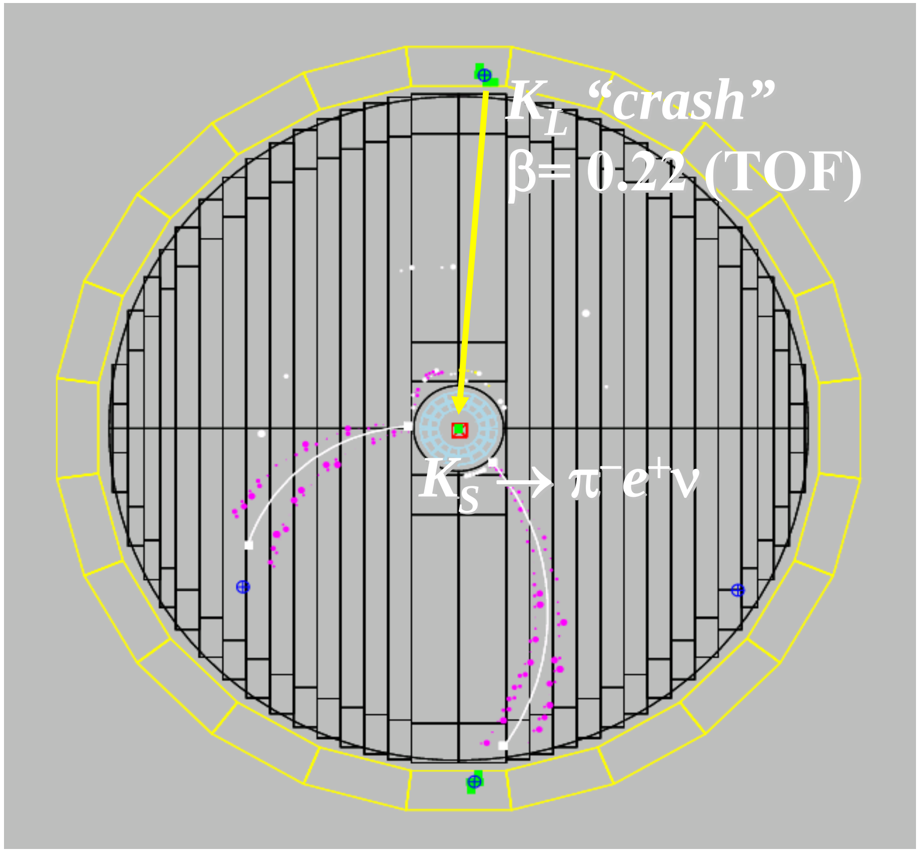
$\sigma_{\gamma\gamma} \sim 2$ cm (π^0 from $K_L \to \pi^+\pi^-\pi^0$)

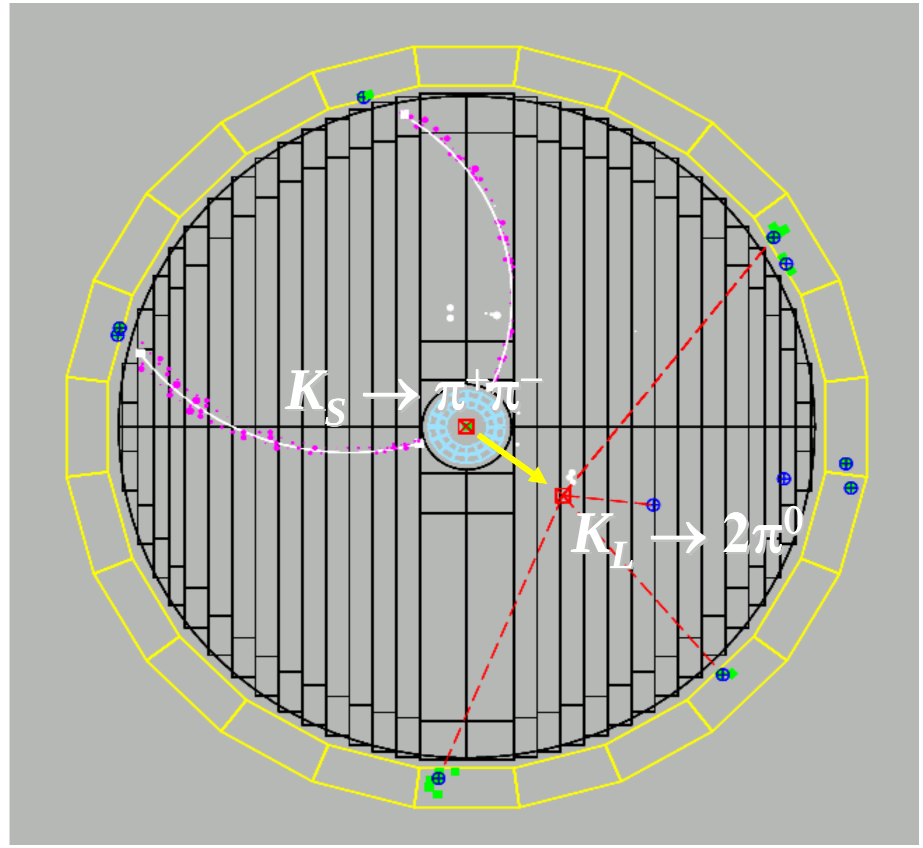
$\sigma_p/p \cong 0.4\,\%$ (tracks with $\theta > 45°$)

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

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

K_S and K_L Tagging at KLOE



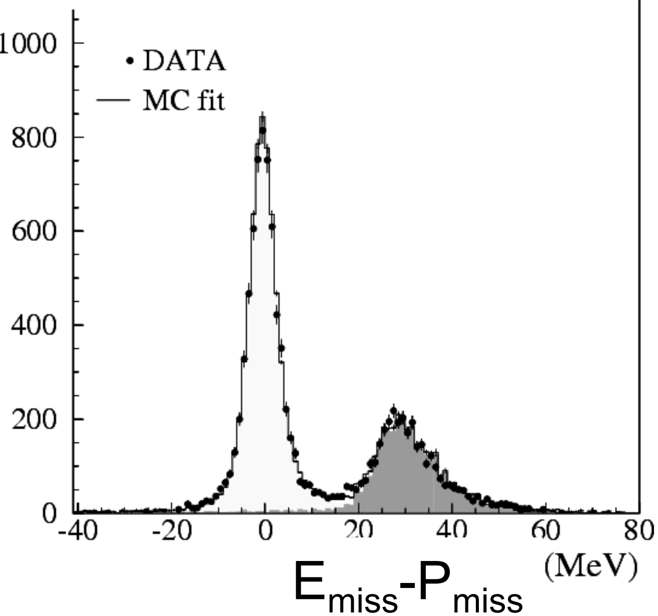


K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)
K_S angular resolution: ~ 1° (0.3° in ϕ)
K_S momentum resolution: ~ 2 MeV

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

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

Data sample: 410 pb^{-1}



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

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

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

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

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

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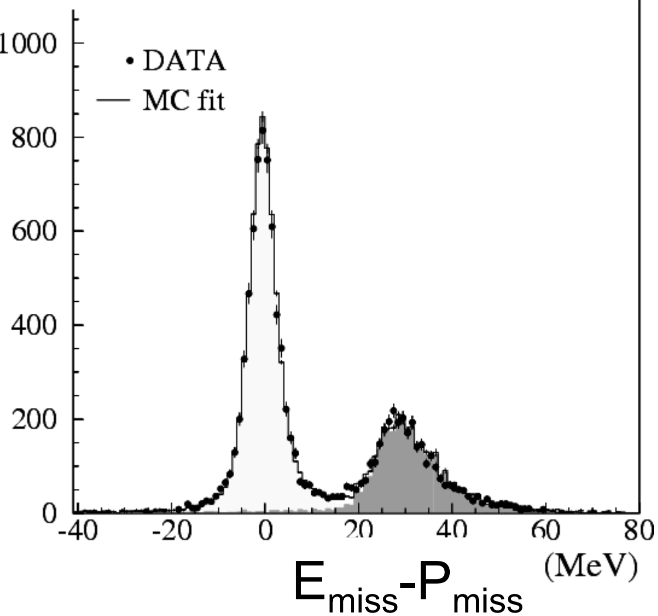
Data sample: 410 pb^{-1}



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

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

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

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = (-0.8 \pm 2.4 \pm 0.7) \times 10^{-3}$$ **CPT & $\Delta S=\Delta Q$ viol.**

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

input from other experiments

CPT test: the Bell-Steinberger relation

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

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

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

$$\begin{pmatrix} \dfrac{\Re\varepsilon}{1+|\varepsilon|^2} \\ \Im\delta \end{pmatrix} = \frac{1}{N}\begin{pmatrix} 1+k(1-2b) & (1-k)\tan\phi_{SW} \\ (1-k)\tan\phi_{SW} & -(1+k) \end{pmatrix}\begin{pmatrix} \sum_i \Re\alpha_i \\ \sum_i \Im\alpha_i \end{pmatrix}$$

→ $K_S\,K_L$ observables

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

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

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

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

$\alpha_{kl3} = 2\tau_S/\tau_L\,BR(K_L l3)\,[(A_S+A_L)/4 - i\,\mathrm{Im}\,x_+]$

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

$k = \tau_S/\tau_L$, $b = BR(K_L \to \pi\ell\nu)$

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

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

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

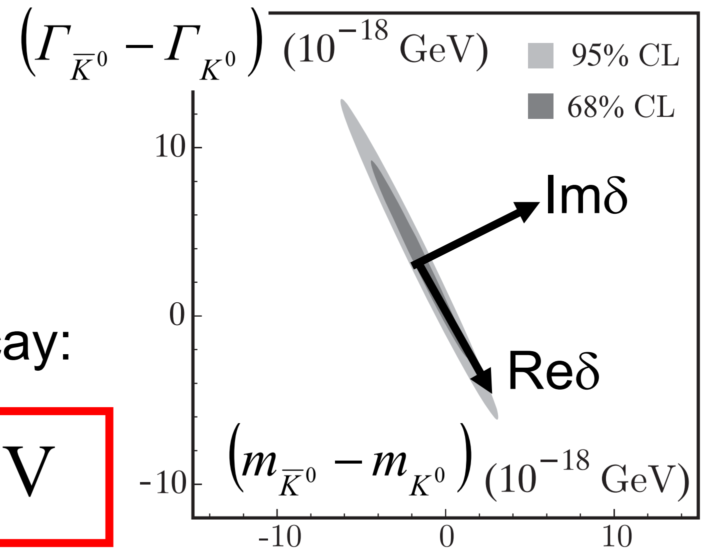
CPLEAR: study of the time evolution of neutral kaons in semileptonic decays

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

PLB444 (1998) 52

Combining Reδ and Imδ results:

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



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

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

at 95% c.l.

CPT test: the Bell-Steinberger relation

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

$$\mathrm{Re}\,\varepsilon = (161.2 \pm 0.6) \times 10^{-5}$$
$$\mathrm{Im}\,\delta = (-0.1 \pm 1.4) \times 10^{-5}$$

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

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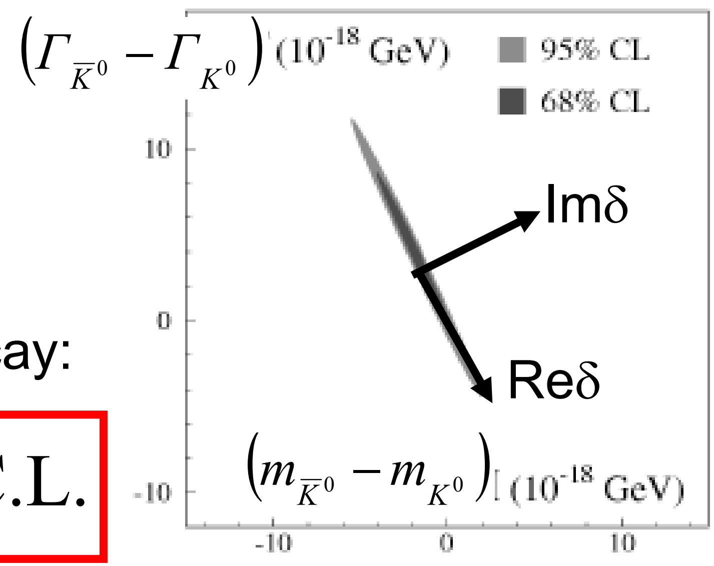
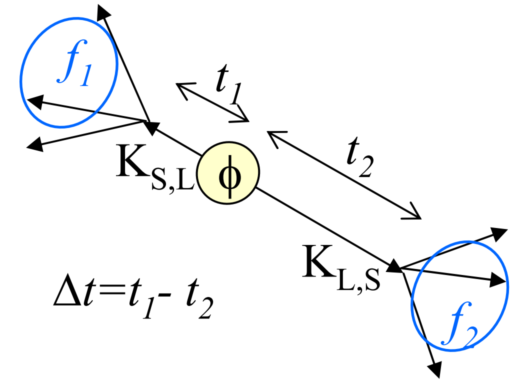


Assuming $\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right) = 0$, i.e. no CPT viol. in decay:

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

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

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:

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

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

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

characteristic interference term at a ϕ-factory => interferometry

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):

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

$$\text{for } \Delta t < 0 \quad \Delta t \to |\Delta t| \text{ and } 1 \leftrightarrow 2$$

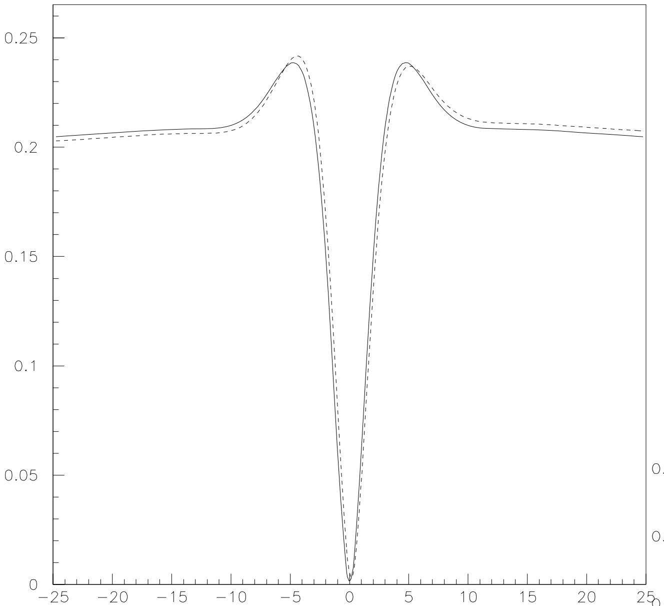
From these distributions for various final states f_i one can measure the following quantities:

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

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

Neutral kaon interferometry: main observables

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



$\Delta t/\tau_S$

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

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

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

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

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

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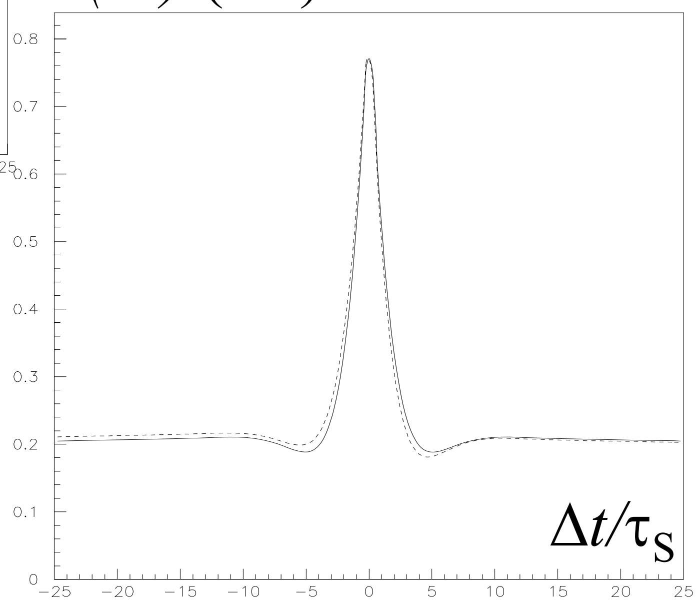

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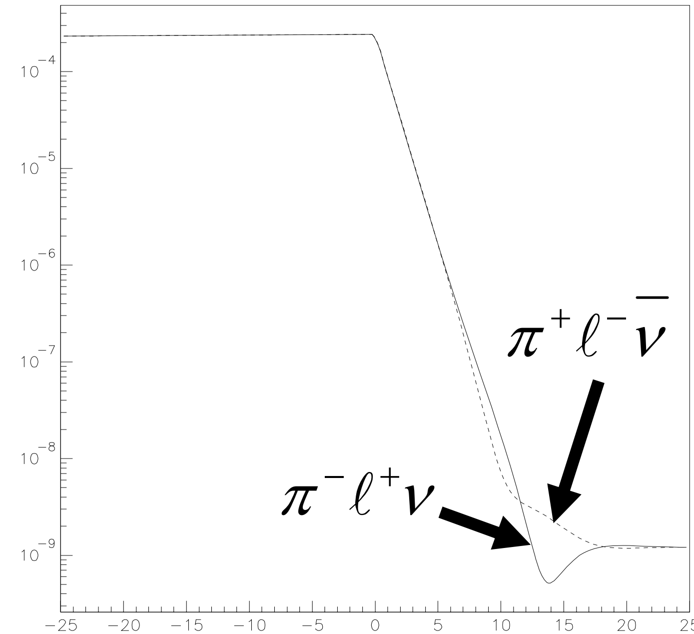


$\Delta t/\tau_S$

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

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

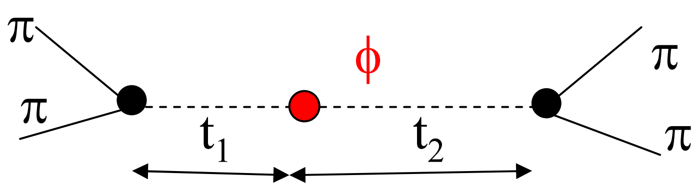
$$\phi_{\pi\pi}$$

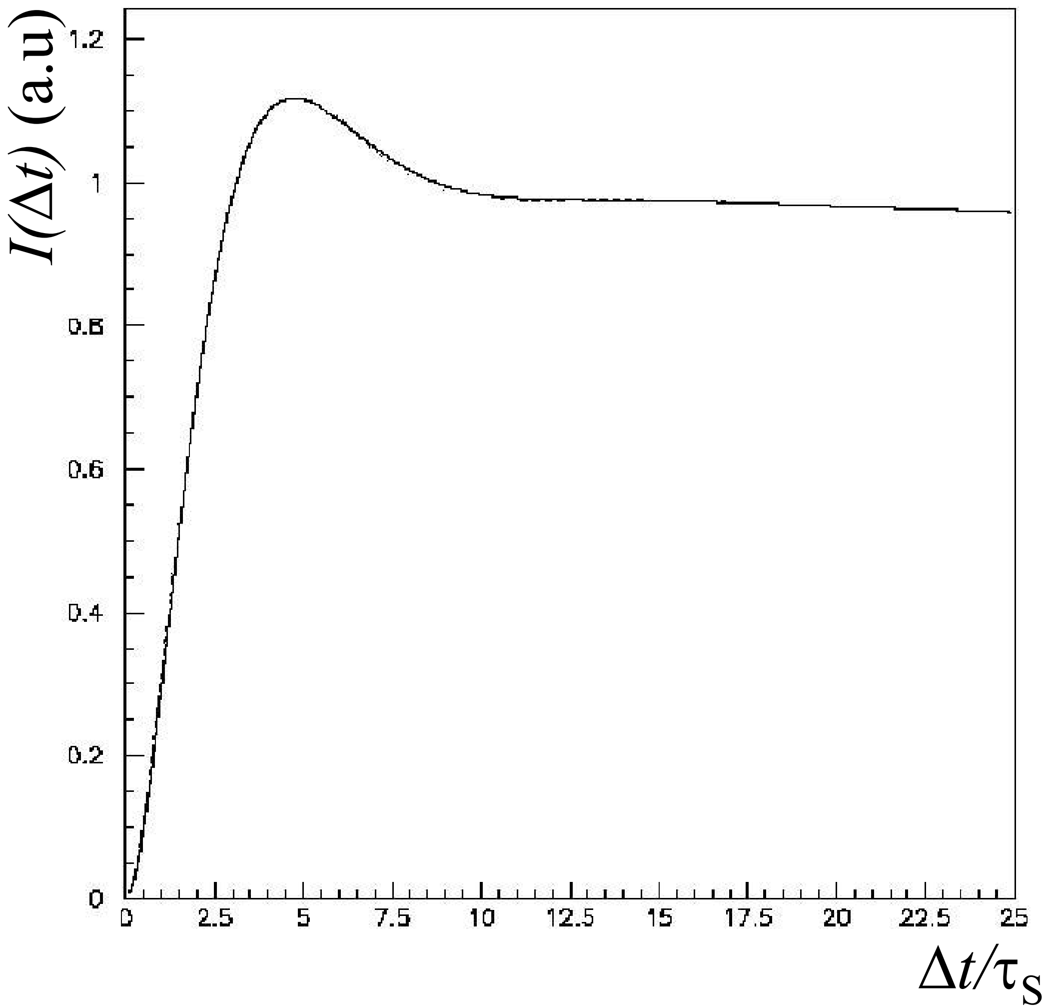
$\phi \to K_S K_L \to \pi^+\pi^- \quad \pi^+\pi^-$

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

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

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





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

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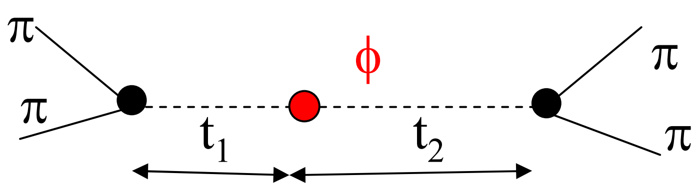
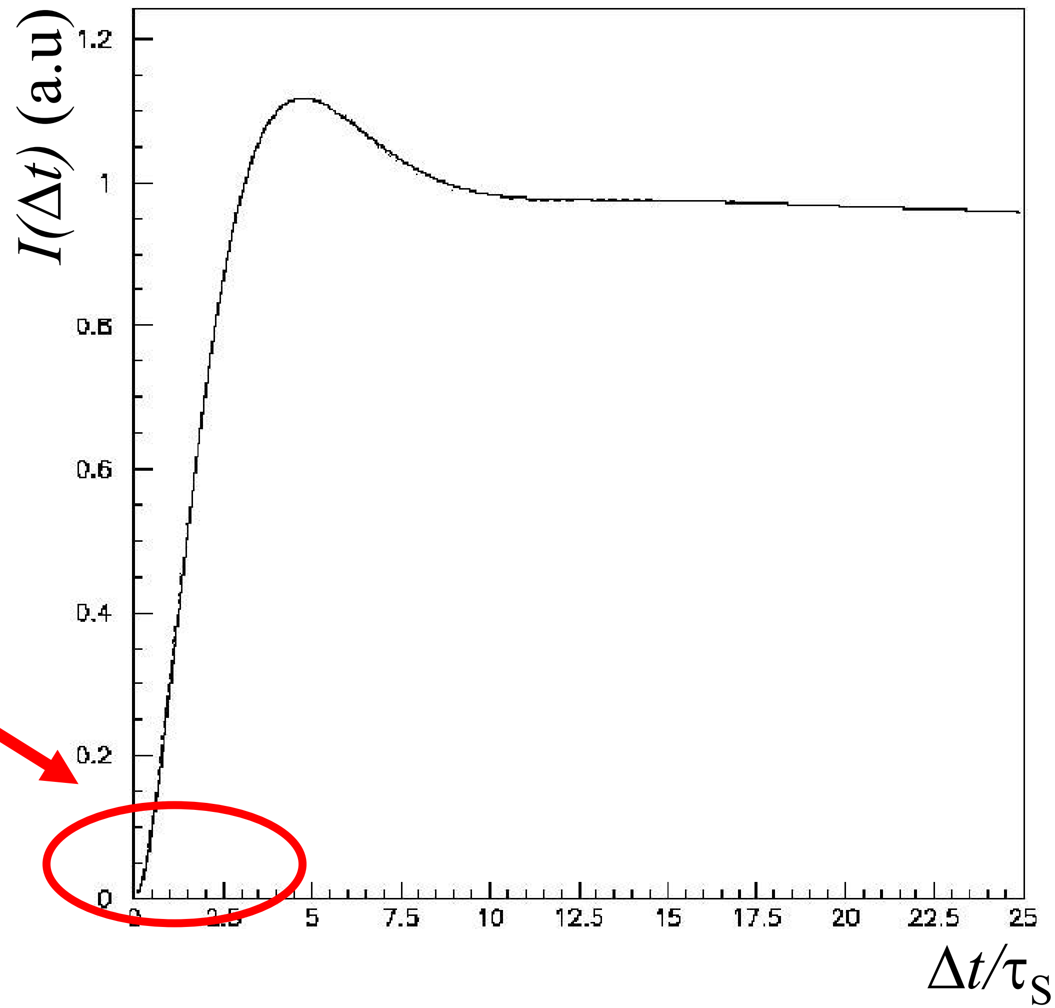
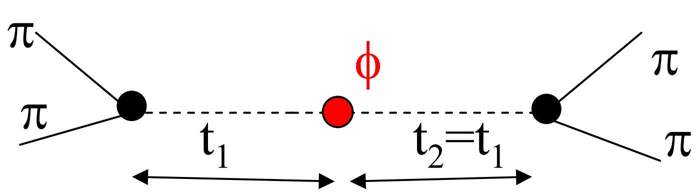




EPR correlation:

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



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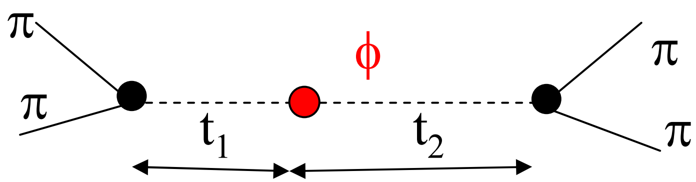

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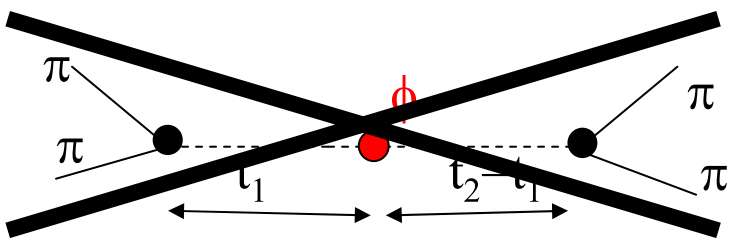

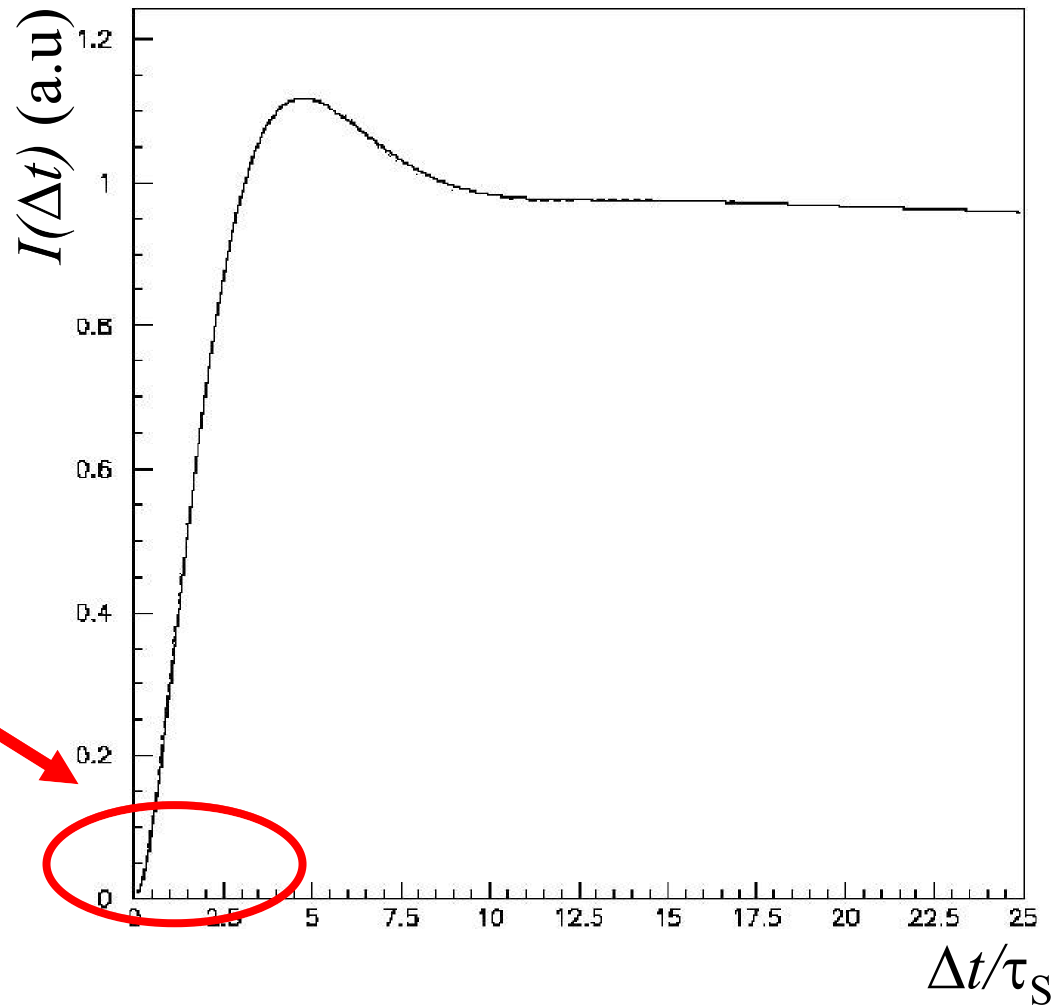

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

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

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

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

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

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Decoherence parameter:

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

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

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

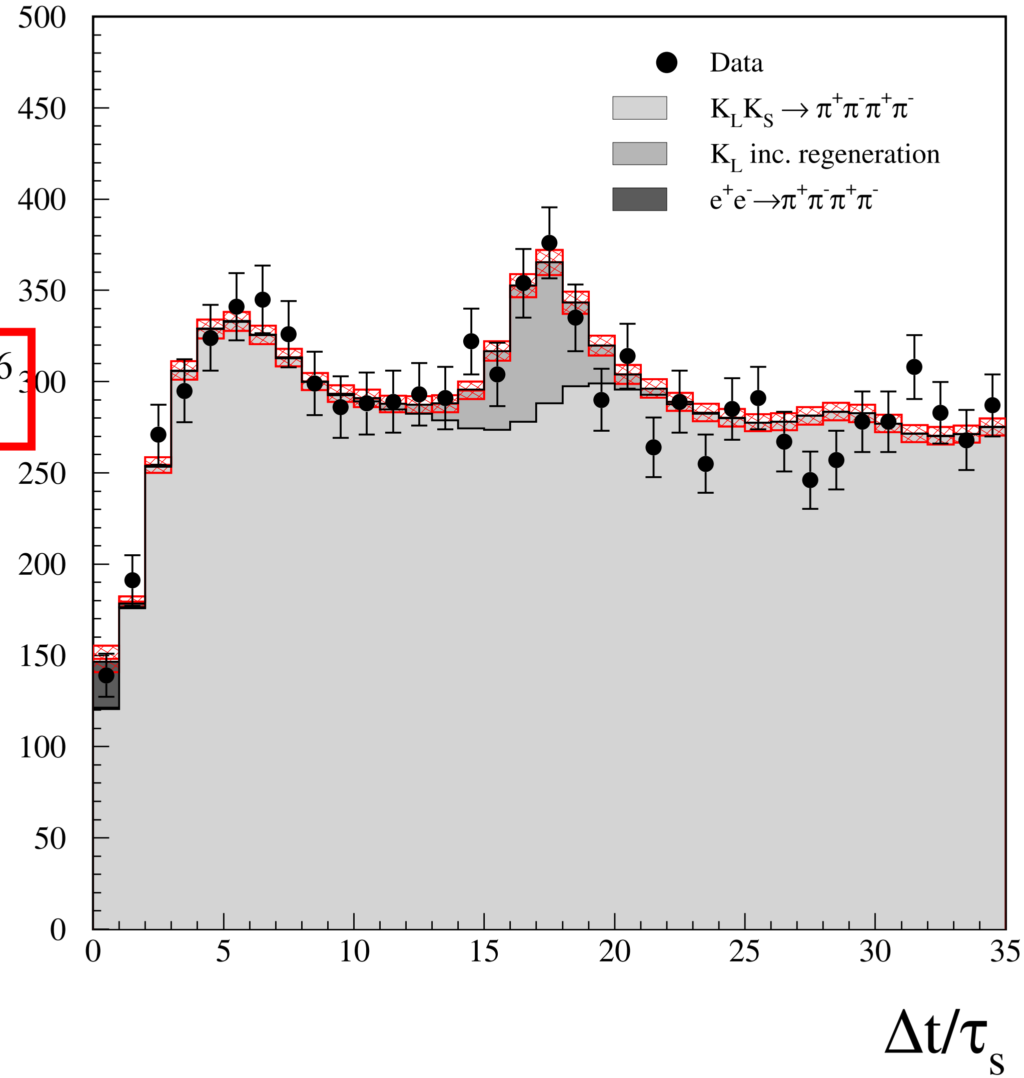
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

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

KLOE result: PLB 642(2006) 315

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

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



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

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

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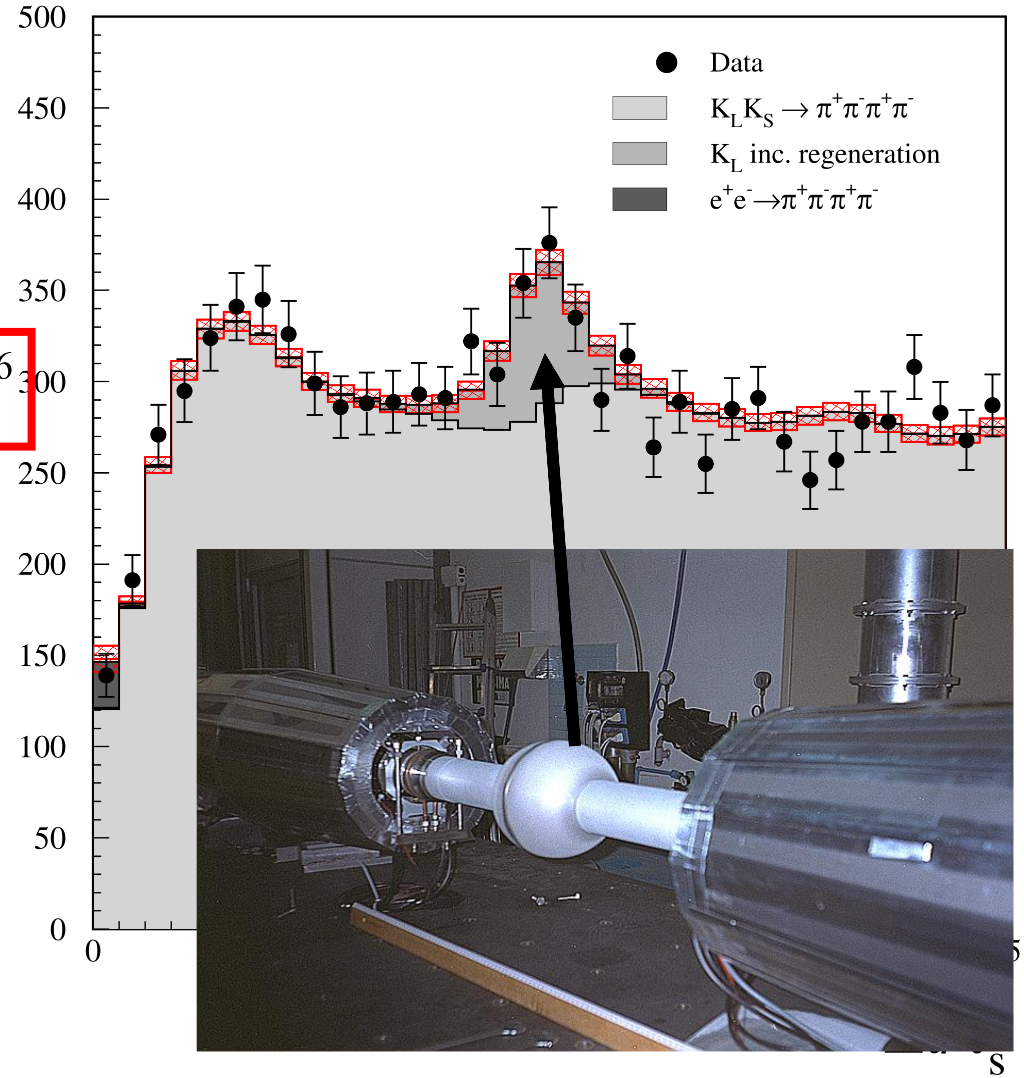

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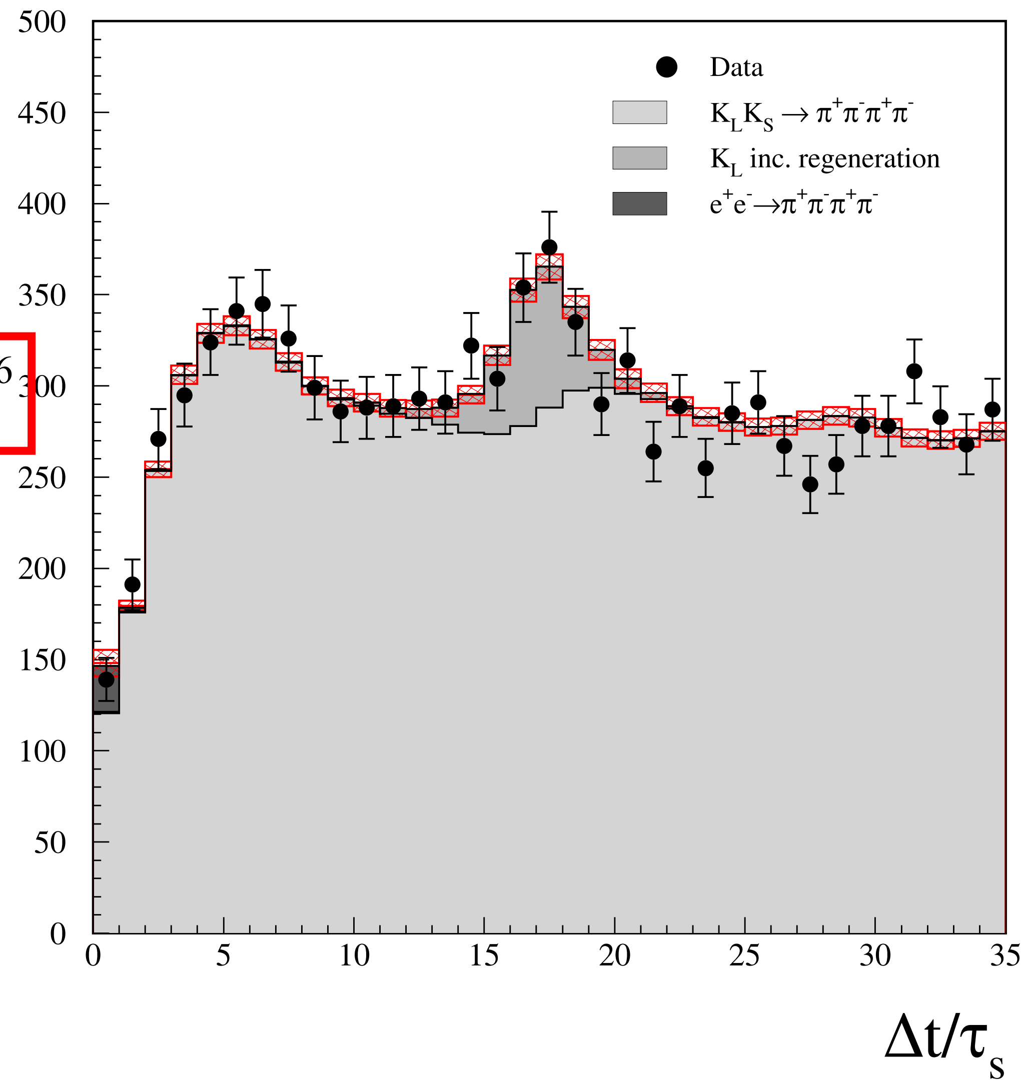

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data: L=1.5 fb^{-1} (2004-05 data)
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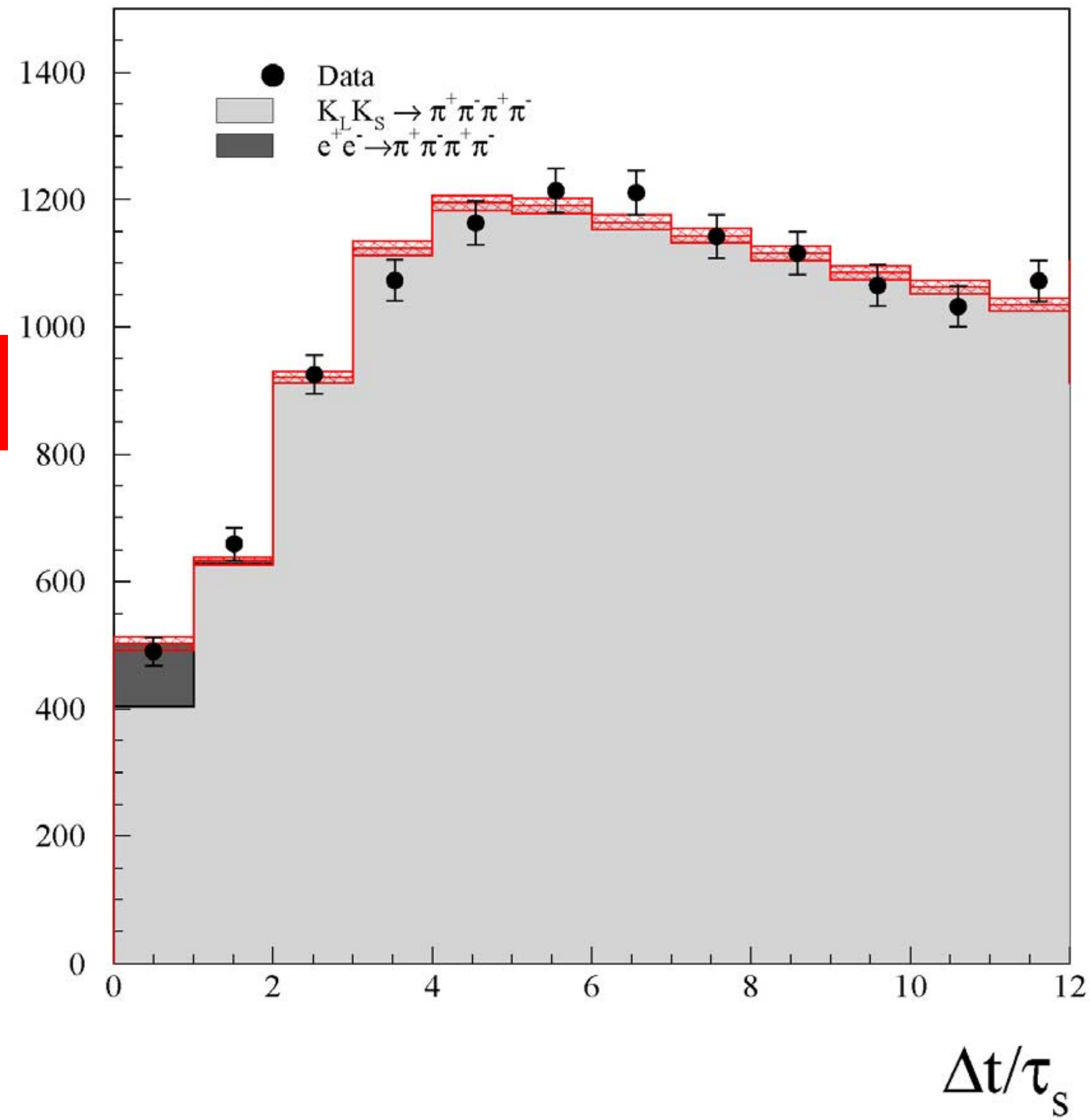

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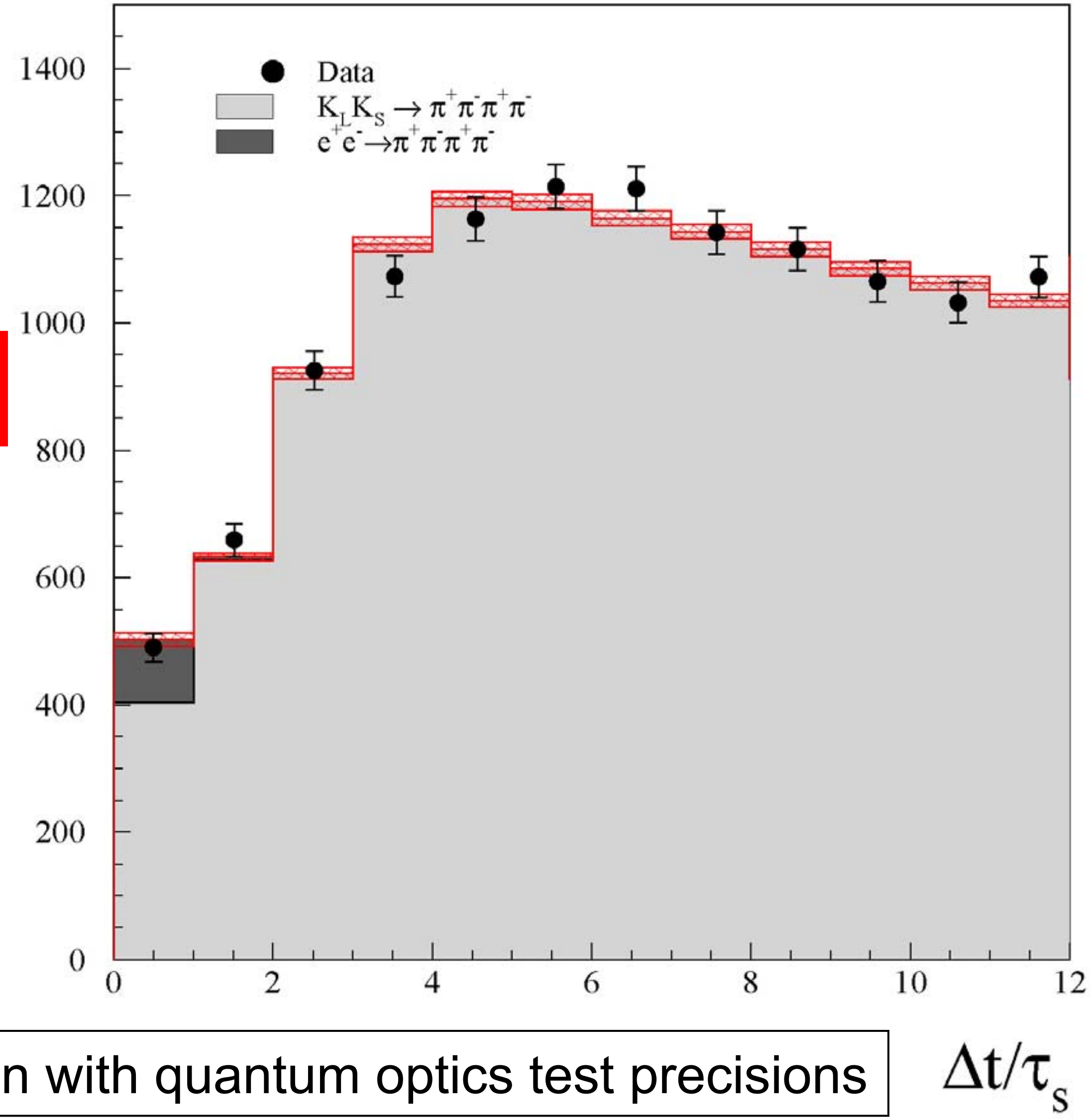

Comparison with quantum optics test precisions

Decoherence and CPT violation

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

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

extra term inducing decoherence:
pure state => mixed state

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Possible decoherence due quantum gravity effects:

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

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

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

$$L(\rho) = L(\rho; \alpha, \beta, \gamma)$$

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

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

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742;[3] Ellis et. al, NP B241 (1984) 381; PRD53 (1996)3846 [4] Huet, Peskin, NP B434 (1995) 3; [5] Benatti, Floreanini, NPB511 (1998) 550 [6] Bernabeu, Ellis, Mavromatos, Nanopoulos, Papavassiliou: Handbook on kaon interferometry [hep-ph/0607322]

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J.A. Wheeler

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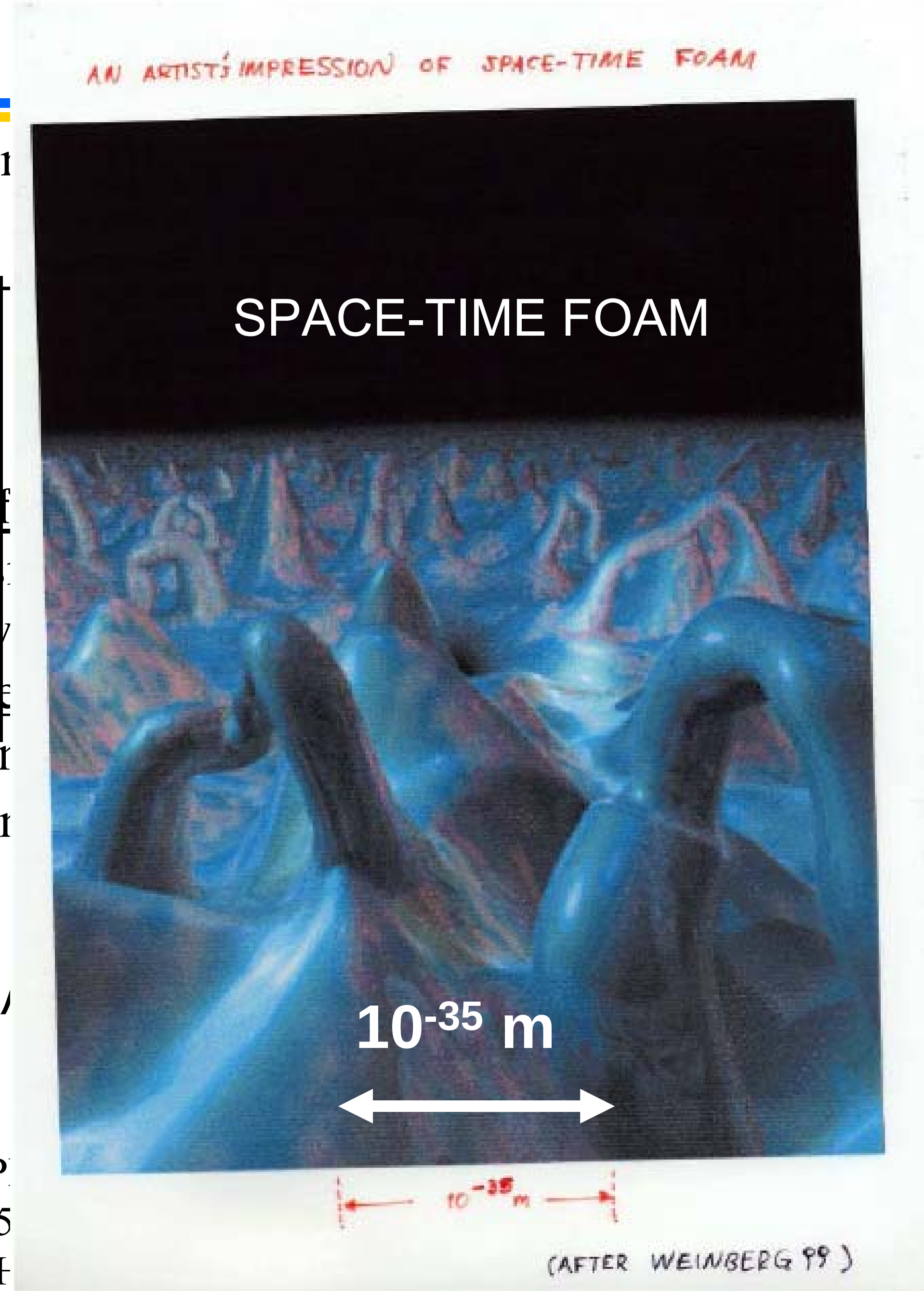

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$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: decoherence & CPTV by QG

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

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

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

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

In the complete positivity hypothesis

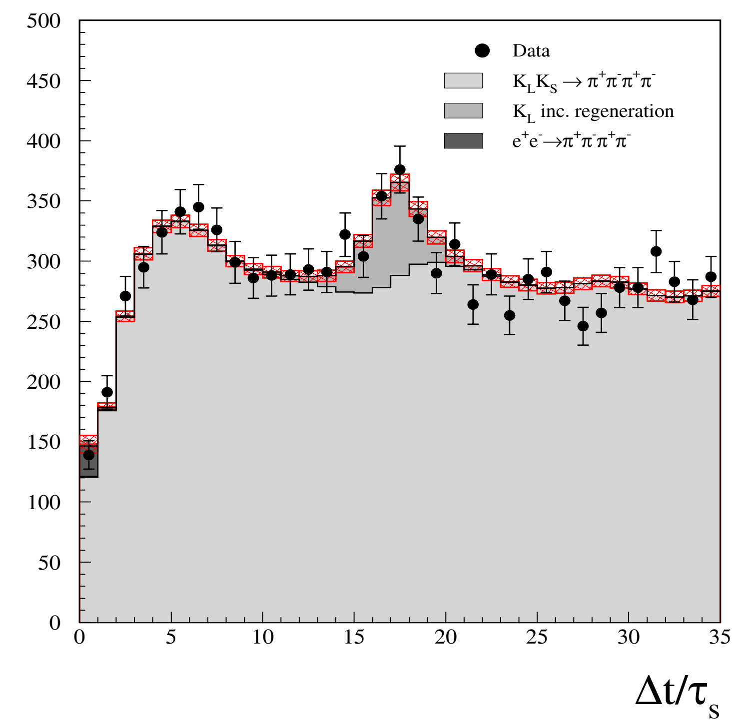
$\alpha = \gamma$, $\beta = 0$

=> only one independent parameter: γ

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

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

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



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

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

CPLEAR PLB 364, 239 (1999)

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

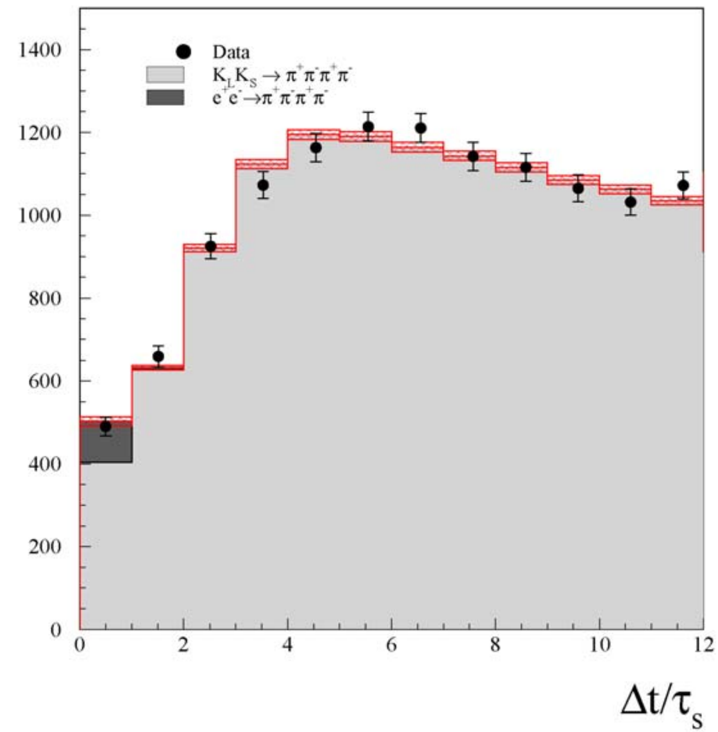
Complete positivity guarantees the positivity of the eigenvalues of density matrices describing states of correlated kaons.

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

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

KLOE FINAL $L=1.5\ fb^{-1}$

$$\gamma = (0.7 \pm 1.2_{STAT} \pm 0.3_{SYST}) \times 10^{-21}\ \text{GeV}$$



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

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

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

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

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

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 (α,β,γ,ω) could be simultaneously disentangled.

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

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

- Analysed data: 380 pb^{-1}

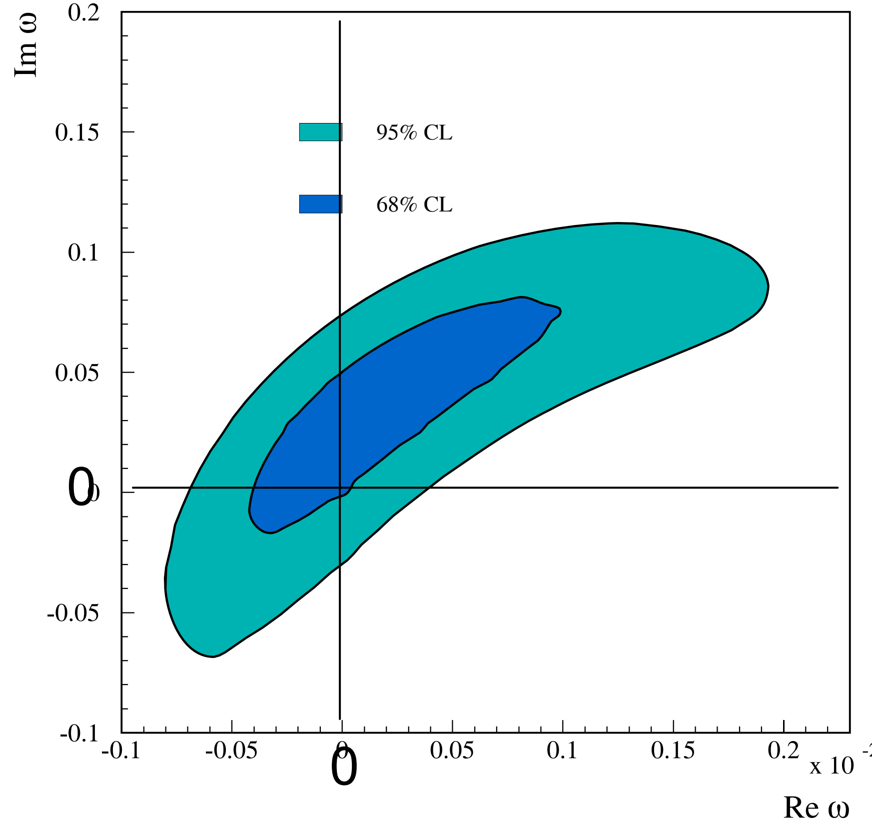
KLOE result : PLB 642(2006) 315

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

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

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

Im ω x10^{-2}



Re ω x10^{-2}

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

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

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

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

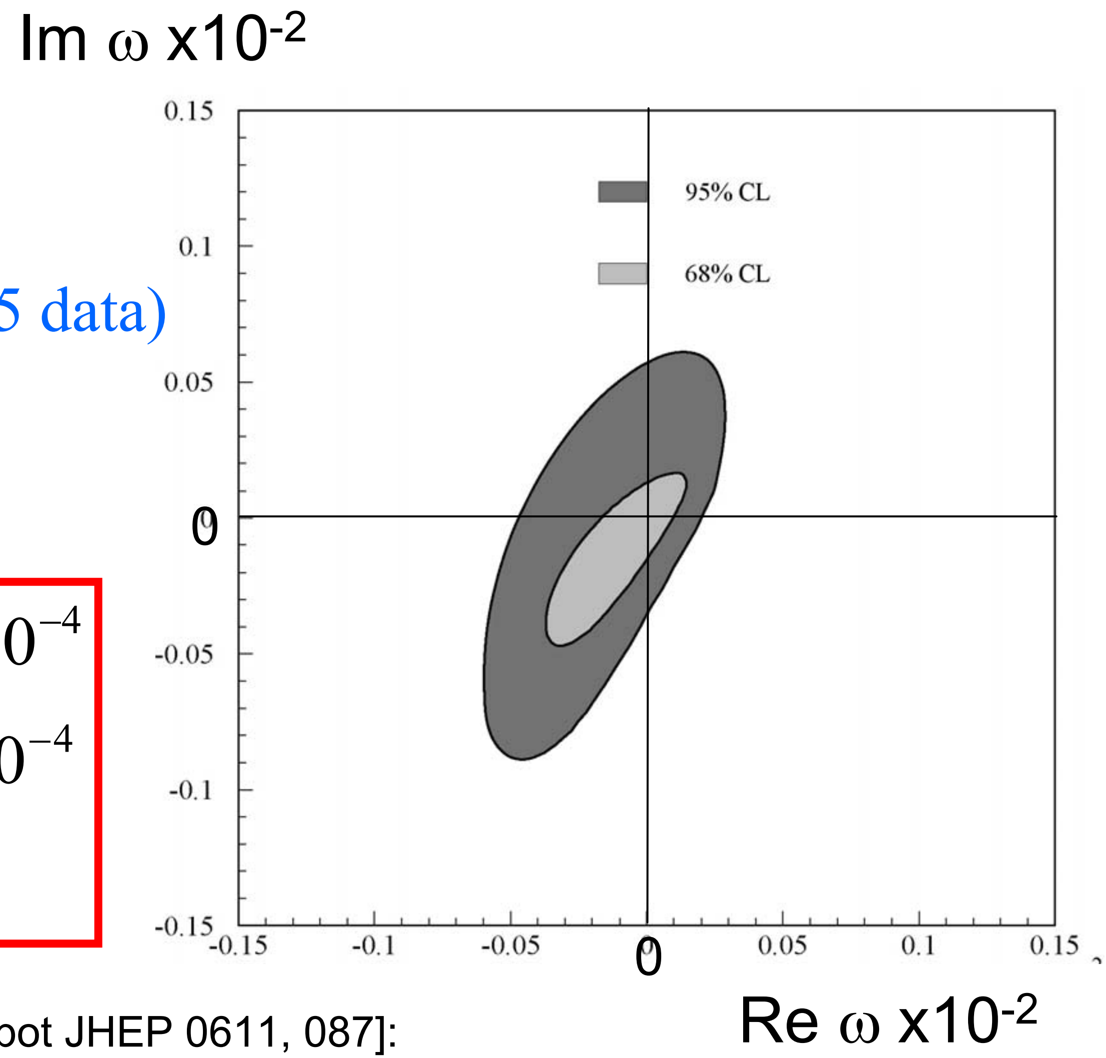
- Analysed data: 1.5 fb^{-1} (2004-05 data)

KLOE FINAL :

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

$$|\omega| < 1.0\times 10^{-3} \quad \text{at } 95\%\ \text{C.L.}$$



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

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

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]

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)

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

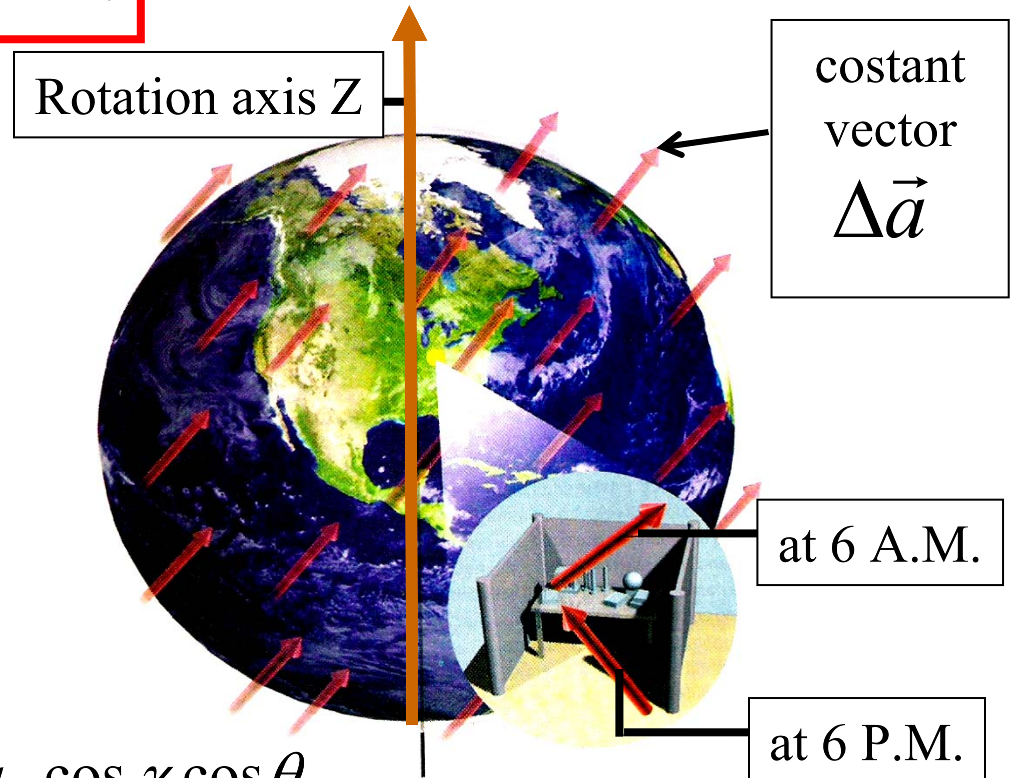
$$\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right) / \Delta m$$

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

CPT and Lorentz invariance violation (SME)

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

δ depends on sidereal time t since laboratory frame rotates with Earth (fixed beam).
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:



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

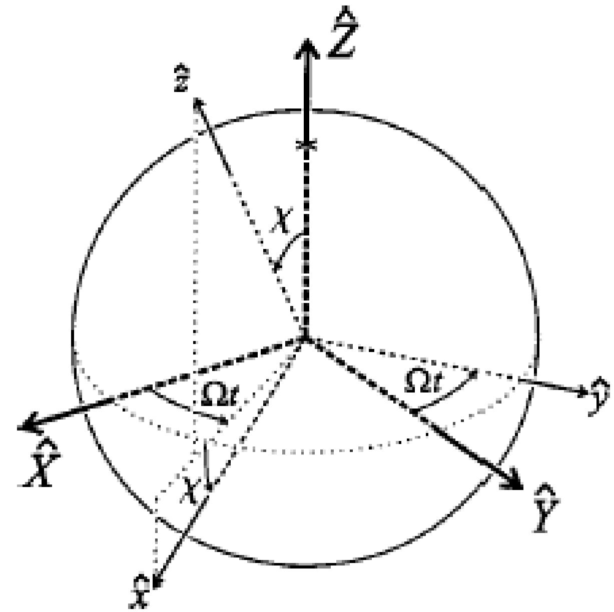
$$= \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m} \gamma_K \left[\underline{\Delta a_0} + \beta_K \underline{\Delta a_Z} \cos\chi \cos\theta + \beta_K \underline{\Delta a_Y} \sin\chi \cos\theta \sin\Omega t + \beta_K \underline{\Delta a_X} \sin\chi \cos\theta \cos\Omega t\right]$$

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

CPT and Lorentz invariance violation (SME)

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

δ depends on sidereal time t since laboratory frame rotates with Earth (fixed beam).
For a ϕ-factory there is an additional dependence on the polar and azimuthal angle θ, ϕ of the kaon momentum in the laboratory frame:



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

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

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

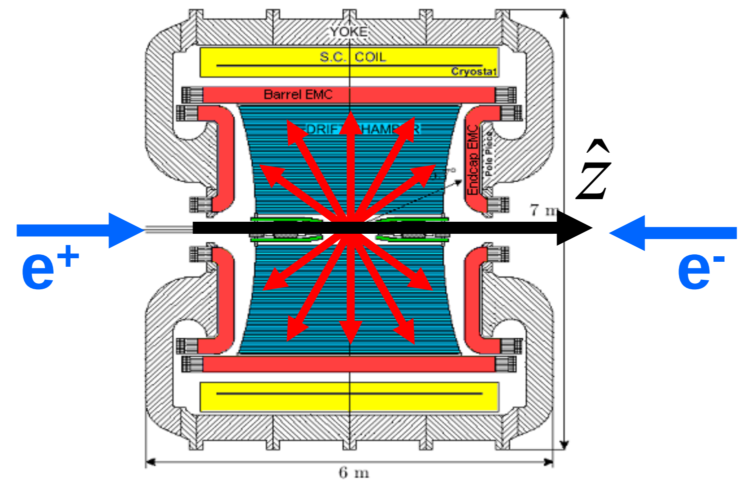
Ω: Earth's sidereal frequency
χ : angle between the z lab. axis and the Earth's rotation axis

CPT and Lorentz invariance violation (SME)

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

δ depends on sidereal time t since laboratory frame rotates with Earth (fixed beam). 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:

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



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

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

Ω: Earth's sidereal frequency

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

Measurement of Δa_0 at KLOE

Δa_0 from K_S and K_L semileptonic charge asymmetries

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

tagged K_S and K_L
(symmetric polar angle θ and
sidereal time t integration)

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

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

with L=400 pb^{-1} (**preliminary**):

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

(Δa_0 evaluated for the first time)

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

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

$\Delta a_{X,Y,Z}$ **from** $\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$
(analysis vs polar angle θ and sidereal time t)

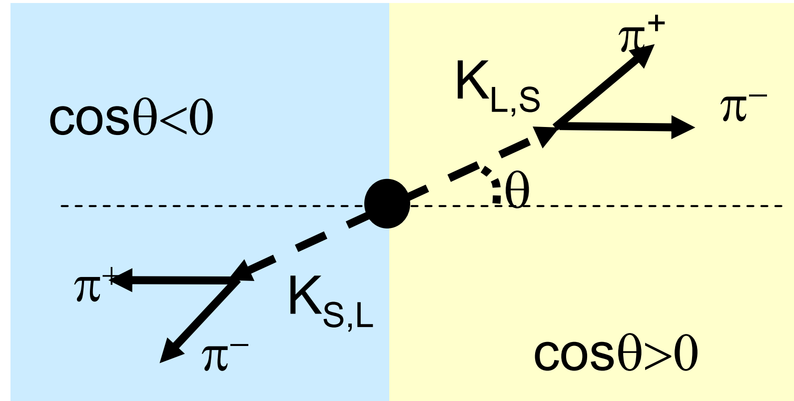
$$\eta_{+-} = \varepsilon - \delta(p,\theta,t)$$

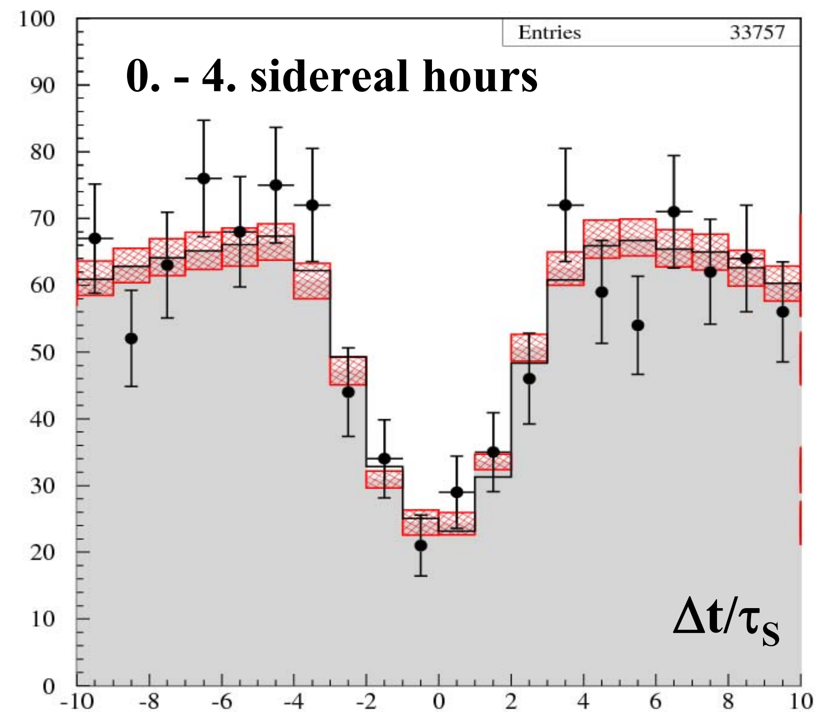
$I[\pi^+\pi^-(\cos\theta>0), \pi^+\pi^-(\cos\theta<0); \Delta t]$

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

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

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





KTeV : Δa_X, $\Delta a_Y < 9.2 \times 10^{-22}$ GeV @ 90% CL
BABAR $\Delta a^B_{x,y}$, $(\Delta a^B_0 - 0.30\ \Delta a^B_Z) \sim O(10^{-13}$ GeV)
[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

KLOE-2 Plan:

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

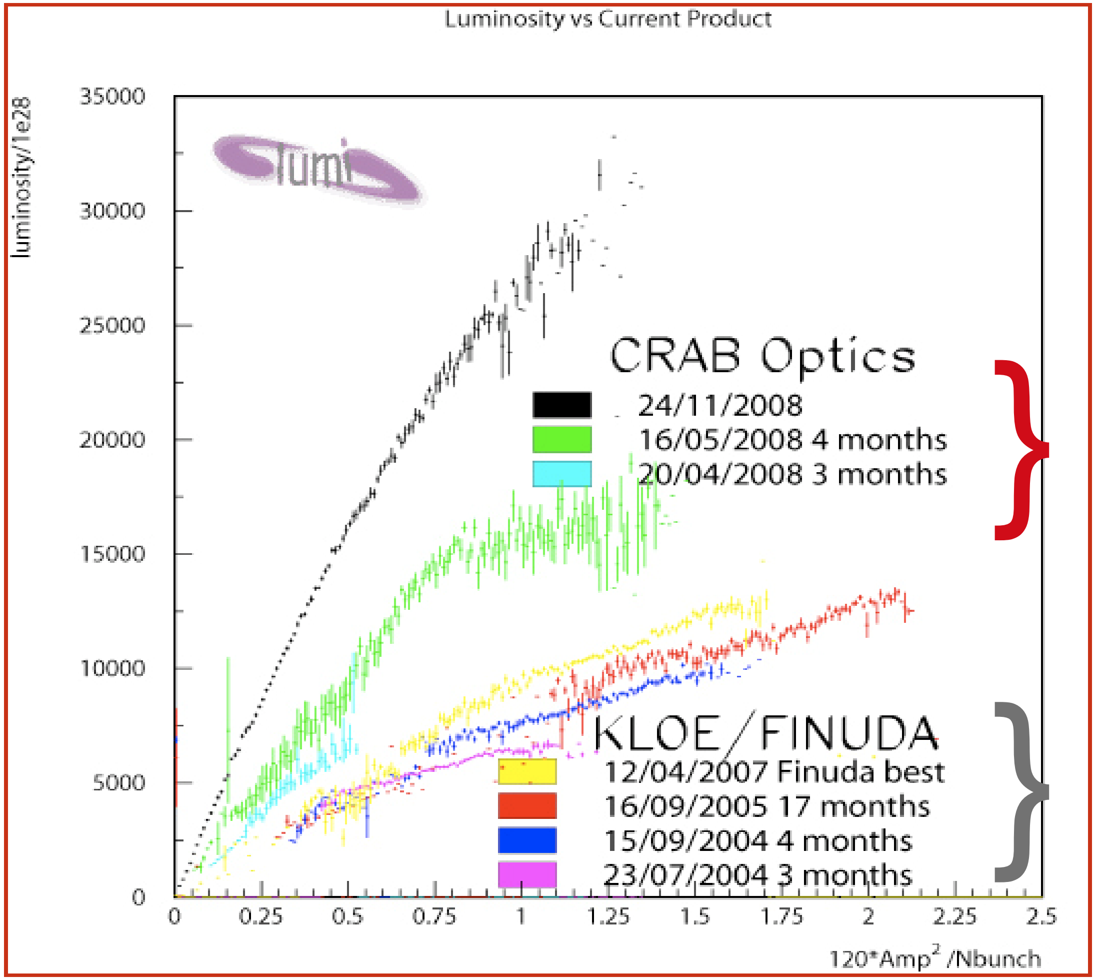
Physics issues:

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, γγ physics
- Hadron cross section at low energy, muon anomaly

Detector upgrade issues:

- Inner tracker R&D
- γγ tagging system
- Calorimeter, increase of granularity
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)

DAΦNE Luminosity versus colliding currents

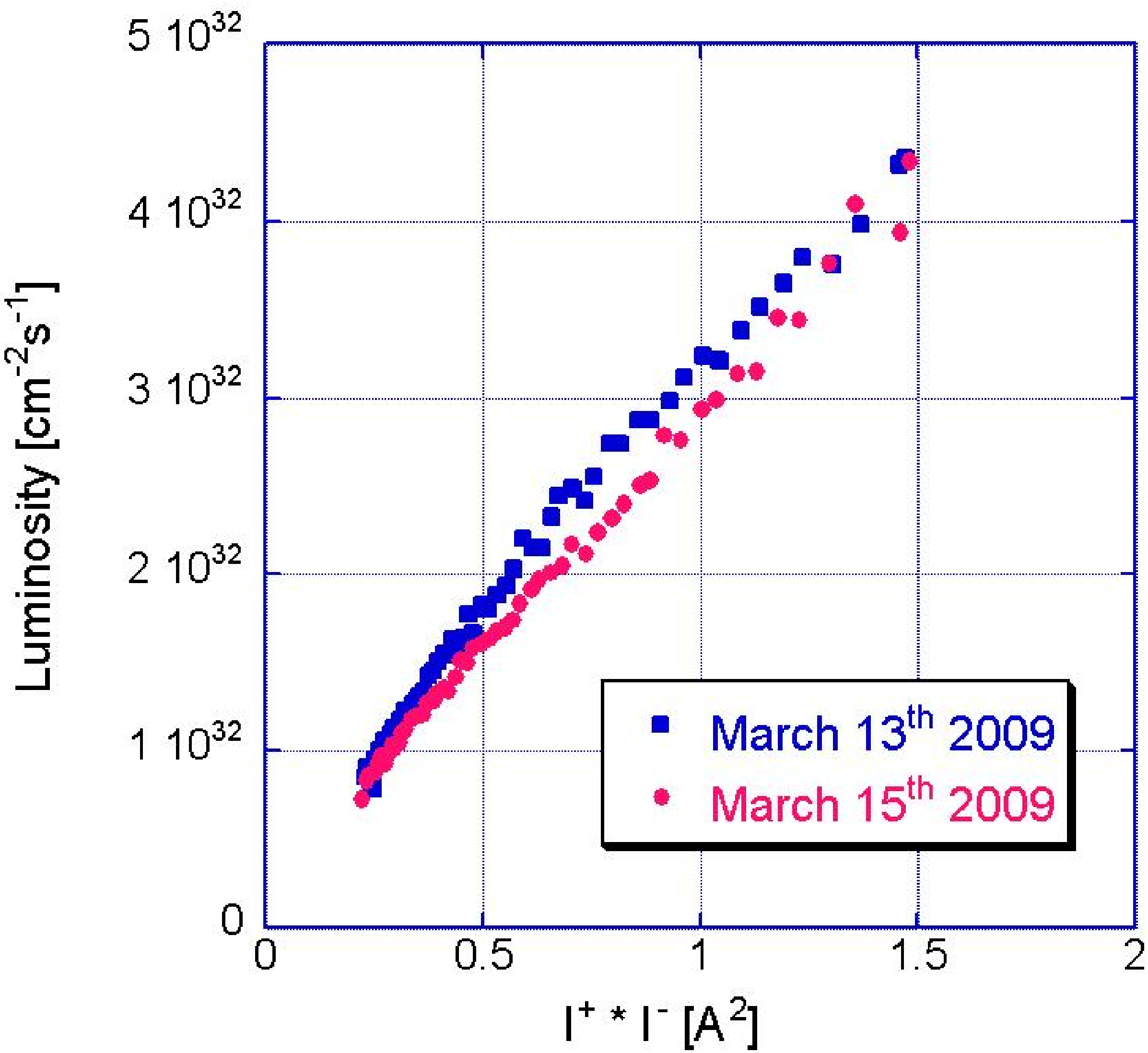


NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

original collision scheme

from P. Raimondi's talk

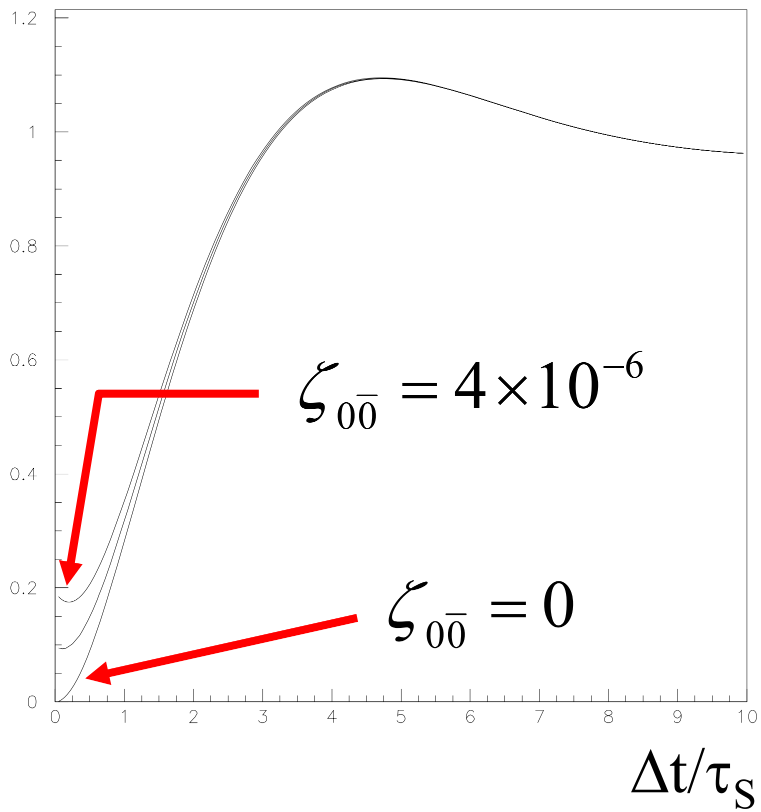
DAΦNE Luminosity versus colliding currents



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

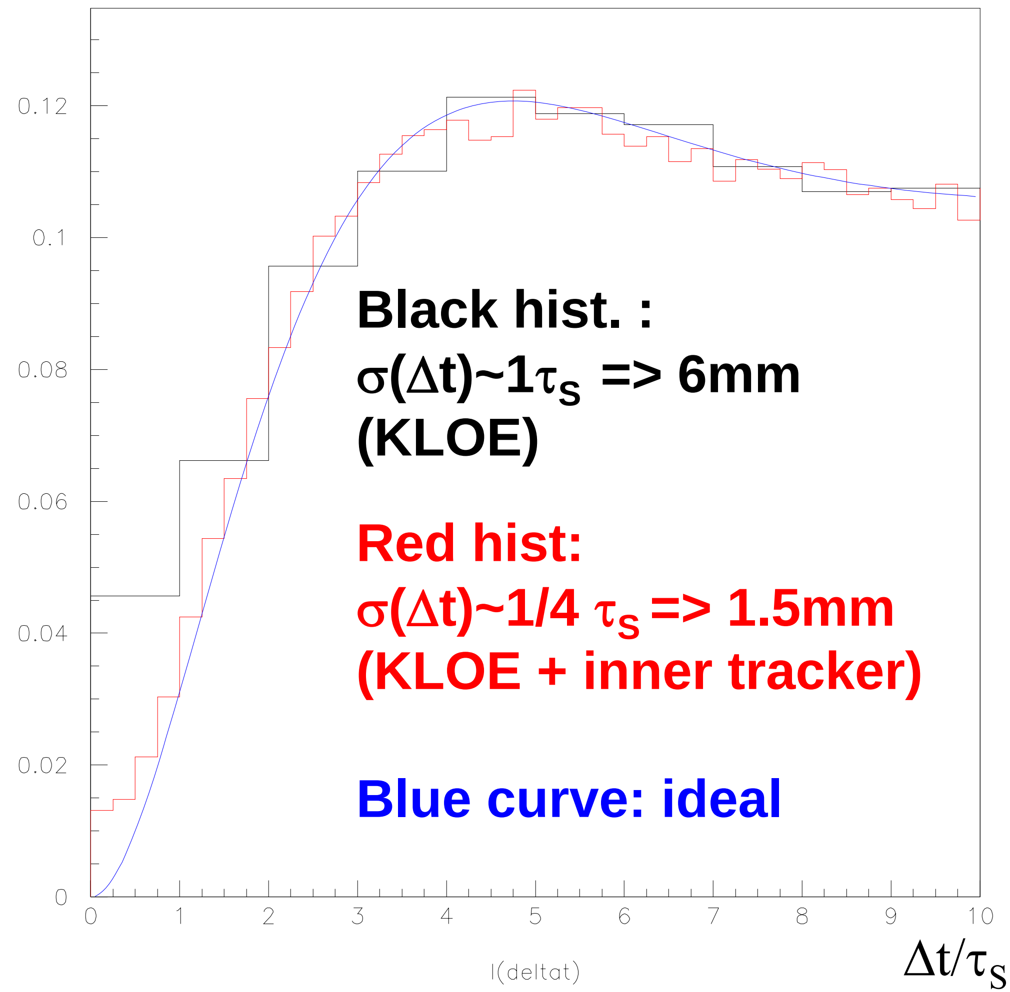
Possible signal of decoherence concentrated at very small Δt

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



Theoretical distribution

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

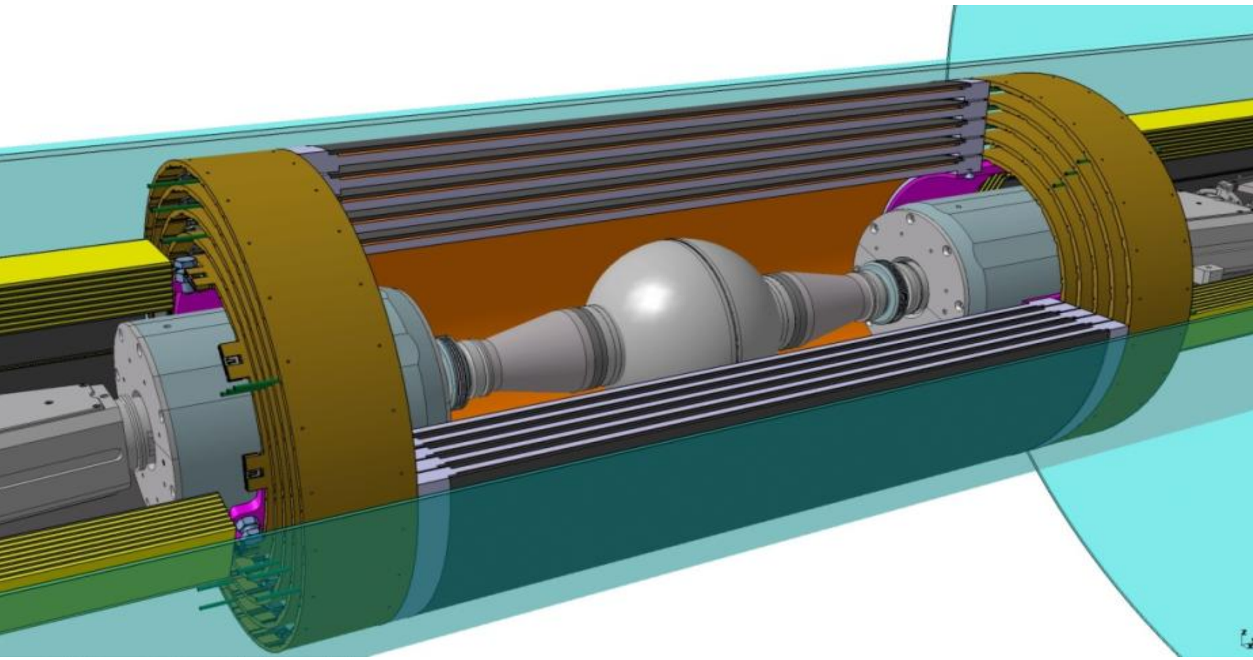


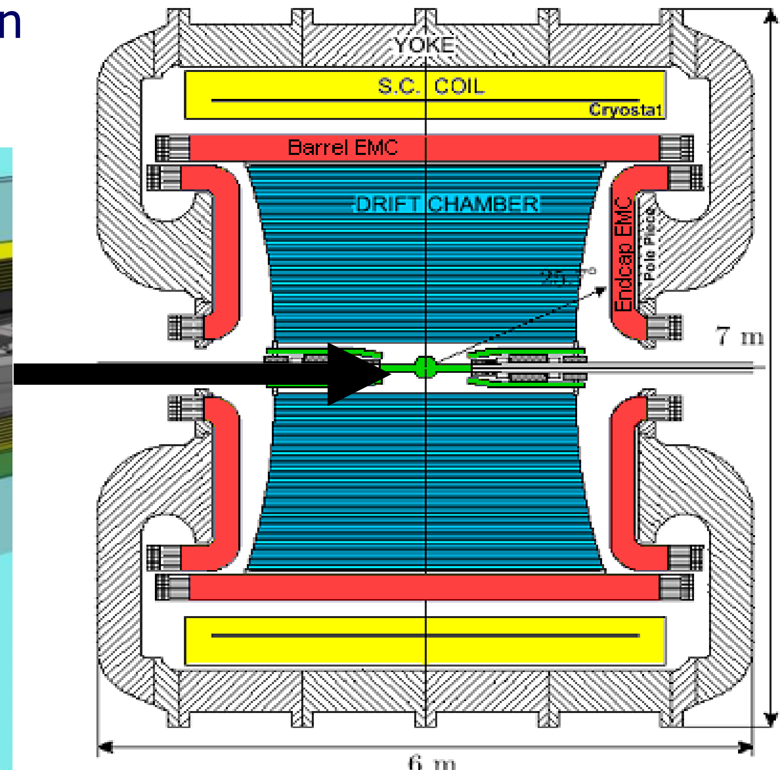
Reconstructed distribution (MC)

Inner tracker at KLOE

- 5 independent tracking layers for a fine vertex reconstruction of K_S and η
- 200 μm $\sigma_{r\varphi}$ and 500 μm 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 $L=50\ fb^{-1}$
$K_S \to \pi e \nu$	CP, CPT	A_S	$(1.5 \pm 11) \times 10^{-3}$	$\pm 1 \times 10^{-3}$
$\pi^+\pi^- \quad \pi e \nu$	CP, CPT	A_L	$(3322 \pm 58 \pm 47) \times 10^{-6}$	$\pm 25 \times 10^{-6}$
$\pi^+\pi^- \quad \pi^0\pi^0$	CP	$Re(\varepsilon'/\varepsilon)$	$(1.65 \pm 0.26) \times 10^{-3}$ (*)	$\pm 0.2 \times 10^{-3}$
$\pi^+\pi^- \quad \pi^0\pi^0$	CP, CPT	$Im(\varepsilon'/\varepsilon)$	$(-1.2 \pm 2.3) \times 10^{-3}$ (*)	$\pm 3 \times 10^{-3}$
$\pi e \nu \quad \pi e \nu$	CPT	$Re(\delta)+Re(x_-)$	$Re(\delta) = (0.25 \pm 0.23) \times 10^{-3}$ (*) $Re(x_-) = (-4.2 \pm 1.7) \times 10^{-3}$ (*)	$\pm 0.2 \times 10^{-3}$
$\pi e \nu \quad \pi e \nu$	CPT	$Im(\delta)+Im(x_+)$	$Im(\delta) = (-0.6 \pm 1.9) \times 10^{-5}$ (*) $Im(x_+) = (0.2 \pm 2.2) \times 10^{-3}$ (*)	$\pm 3 \times 10^{-3}$
$\pi^+\pi^- \quad \pi^+\pi^-$		Δm	$(5.288 \pm 0.043) \times 10^9\ s^{-1}$	$\pm 0.03 \times 10^9\ s^{-1}$

(*) = PDG 2008 fit

Perspectives with KLOE-2 at upgraded DAΦNE

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

[….] = preliminary

Conclusions

- The neutral kaon system is an excellent laboratory for the study of CPT symmetry and the basic principles of Quantum Mechanics;
- Several parameters related to possible
  - CPT violation (within QM)
  - CPT violation and decoherence
  - CPT violation and Lorentz symmetry breaking

  have been recently measured at KLOE, in same cases with a precision reaching the interesting Planck's scale region;
- <u>All results are consistent with no CPT violation</u>
- The analysis of the full KLOE data sample is completed (apart the analysis of CPTV and LV);
- KLOE and DAΦNE are going to be upgraded
- KLOE (KLOE-2) will restart taking data at the end of this year
- 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.