Precision tests of CPT symmetry and Quantum coherence with entangled neutral K mesons

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CPT: introduction

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

CPT theorem :

J. Schwinger (1951)

W. Pauli (1952)

G. Lüders (1954)

R. Jost (1957)

J. Bell (1955)

Exact CPT invariance holds for any quantum field theory (like the Standard Model) formulated on 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.

CPT: introduction

Extension of CPT theorem to a theory of quantum gravity far from obvious.
(e.g. CPT violation appears in several QG models)
huge effort in the last decades to study and shed light on QG phenomenology
$\Rightarrow$ Phenomenological CPTV parameters to be constrained by experiments

Consequences of CPT symmetry: equality of masses, lifetimes, |q| and |μ| of a particle and its anti-particle.

Neutral meson systems offer unique possibilities to test CPT invariance; e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system $\left|m_{K^0} - m_{\overline{K}^0}\right| / m_K < 10^{-18}$

neutral B system $\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$

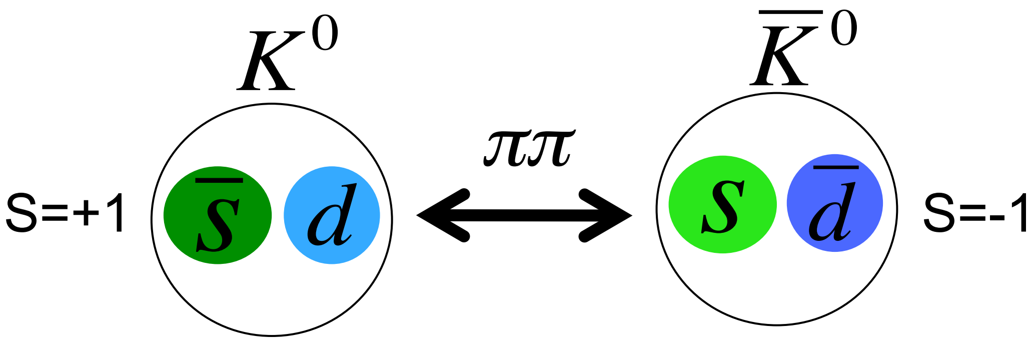
proton- anti-proton $\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$

Other interesting CPT tests: e.g. the study of anti-hydrogen atoms, etc..

The neutral kaon: a two-level quantum system

Since the first observation of a K^0 (V-particle) in 1947, several phenomena observed and several tests performed:

- strangeness oscillations
- regeneration
- CP violation
- Direct CP violation
- precise CPT tests
- …



One of the most intriguing physical systems in Nature. T. D. Lee

Neutral K mesons are a unique physical system which appears to be created by nature to demonstrate, in the most impressive manner, a number of spectacular phenomena.

....

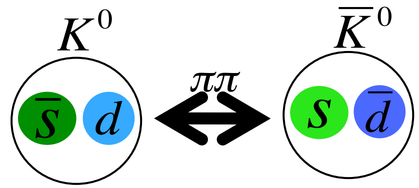
If the K mesons did not exist, they should have been invented "on purpose" in order to teach students the principles of quantum mechanics.

Lev B. Okun

The neutral kaon system: introduction

The time evolution of a two-component state vector $|\Psi\rangle = a|K^0\rangle + b|\overline{K}^0\rangle$ 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 $\mathbf{\Gamma}$) :

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

Diagonalizing the effective Hamiltonian:

eigenvalues

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

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

τ_S ~ 90 ps $\quad$ τ_L ~ 51 ns

$K_L \to \pi\pi$ violates CP

eigenstates

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

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

$|K_{1,2}\rangle$ are CP=±1 states

$$\langle K_S|K_L\rangle \cong \varepsilon_S^* + \varepsilon_L \neq 0$$

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

CPT violation: standard picture

CP violation:

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

T violation:

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

CPT violation:

$$\delta = \frac{H_{11} - H_{22}}{2\left(\lambda_S - \lambda_L\right)} = \frac{1}{2}\frac{\left(m_{\overline{K}^0} - m_{K^0}\right) - (i/2)\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

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

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

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

$$\Delta m = 3.5 \times 10^{-15} \text{ GeV}$$

$$\Delta\Gamma \approx \Gamma_S \approx 2\Delta m = 7 \times 10^{-15} \text{ GeV}$$

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neutral kaons vs other oscillating meson systems

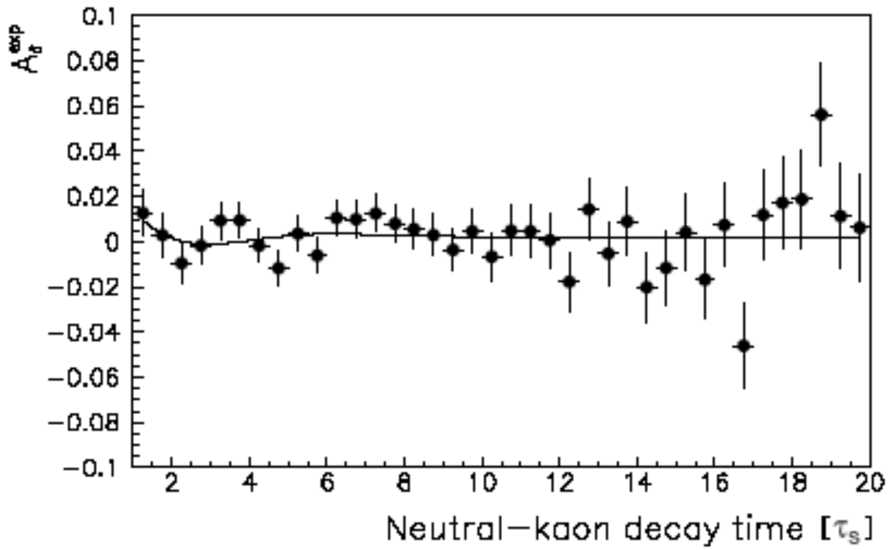
	$\langle m\rangle$ (GeV)	Δm (GeV)	$\langle\Gamma\rangle$ (GeV)	$\Delta\Gamma/2$ (GeV)
K^0	0.5	3×10^{-15}	3×10^{-15}	3×10^{-15}
D^0	1.9	6×10^{-15}	2×10^{-12}	1×10^{-14}
B^0_d	5.3	3×10^{-13}	4×10^{-13}	$O(10^{-15})$ (SM prediction)
B^0_s	5.4	1×10^{-11}	4×10^{-13}	3×10^{-14}

“Standard” CPT tests

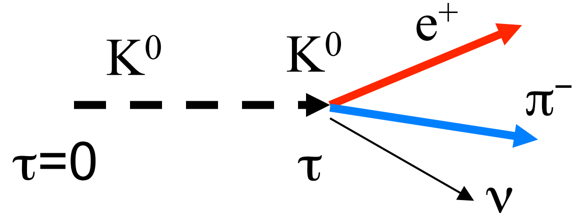
CPT test at CPLEAR

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

Comparing "survival" probabilities: $K^0 \to K^0$ $\quad \bar{K}^0 \to \bar{K}^0$



e.g.



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

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

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

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The Bell-Steinberger relationship

J. Bell

(1965)

J. Steinberger

Unitarity constraint:

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

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

Sum over all possible decay products
(sum over few decay products for kaons;
many for B and D mesons => not easy to evaluate)

yields two trivial relations:

$$\Gamma_{S,L} = \sum_f \left|\langle f|T|K_{S,L}\rangle\right|^2$$

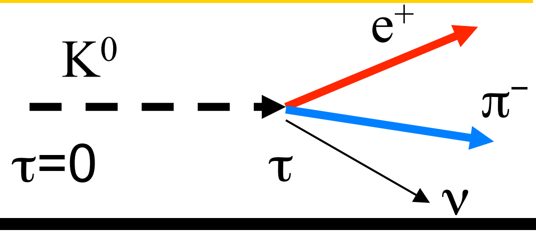
and a not trivial one, i.e. the B-S relationship:

$$\langle K_L|K_S\rangle = 2(\Re\varepsilon + i\Im\delta) = \frac{\sum_f \langle f|T|K_S\rangle\langle f|T|K_L\rangle^*}{i(\lambda_S - \lambda_L^*)}$$

All observables quantities

"Standard" CPT test

measuring the time evolution of a neutral kaon beam into semileptonic decays: $\Re\delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3}$



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using the unitarity constraint (**Bell-Steinberger** relation) →

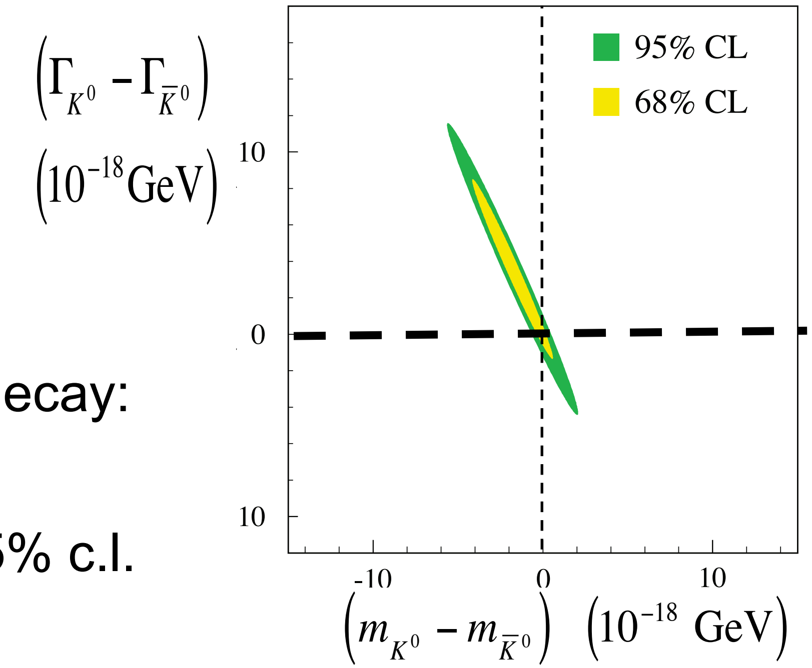
$$2\Im\delta = \Im\left[\langle K_L|K_S\rangle\right] = \Im\left[\frac{\sum_f \langle f|T|K_S\rangle\langle f|T|K_L\rangle^*}{i(\lambda_S - \lambda_L^*)}\right]$$

$\text{Im}\,\delta = (-0.7 \pm 1.4) \times 10^{-5}$

PDG fit (2014)

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

Combining Reδ and Imδ results →



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

$$\left|m_{\bar{K}^0} - m_{K^0}\right| < 4.0 \times 10^{-19} \text{ GeV}$$

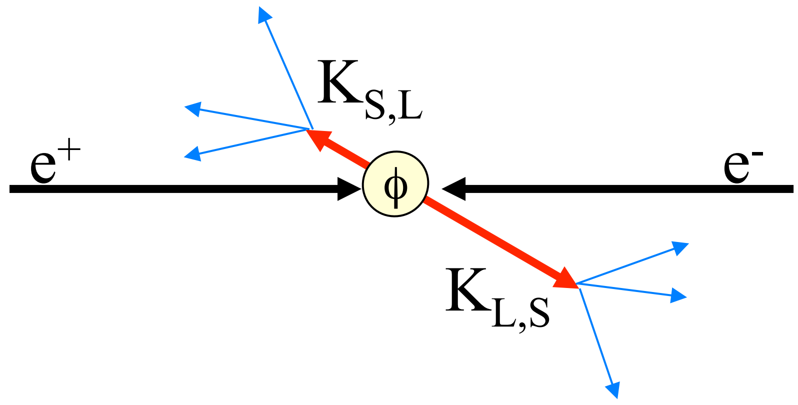
at 95% c.l.

Entangled neutral kaon pairs

Neutral kaons at a ϕ-factory

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

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



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

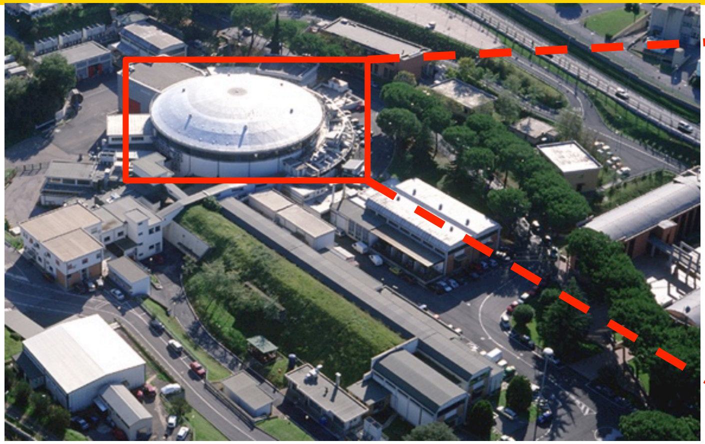
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

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

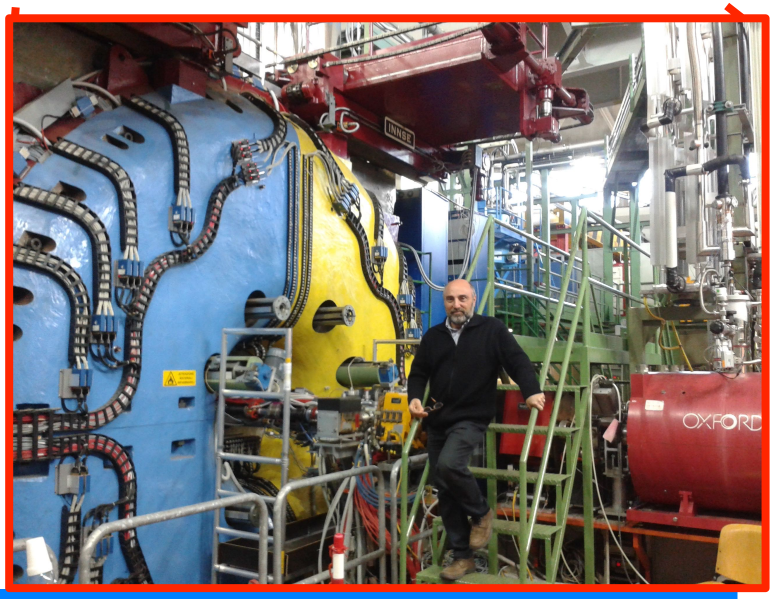
p_K = 110 MeV/c
λ_S = 6 mm λ_L = 3.5 m

The KLOE detector at the Frascati ϕ-factory DAΦNE

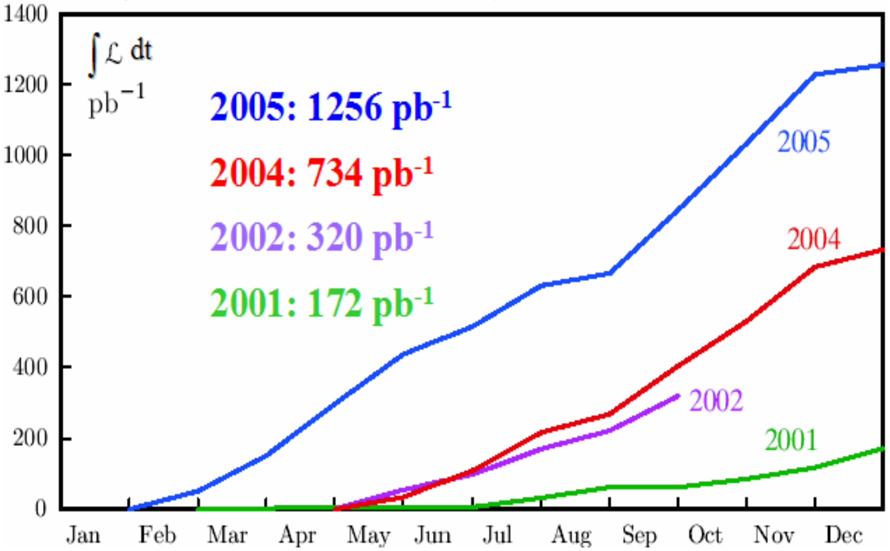
DAFNE collider



KLOE detector



Integrated luminosity (KLOE)



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

(2001 - 05) $\rightarrow \sim 2.5\times10^9\ K_S K_L$ pairs

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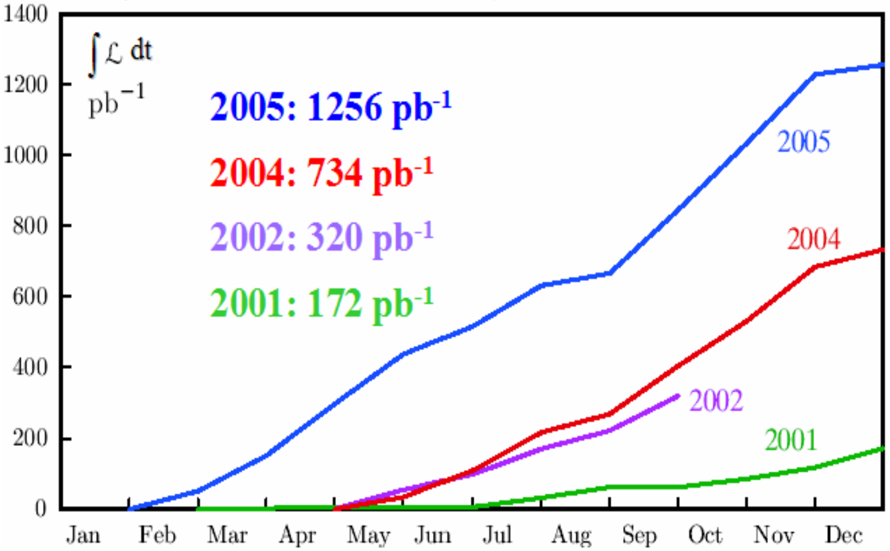

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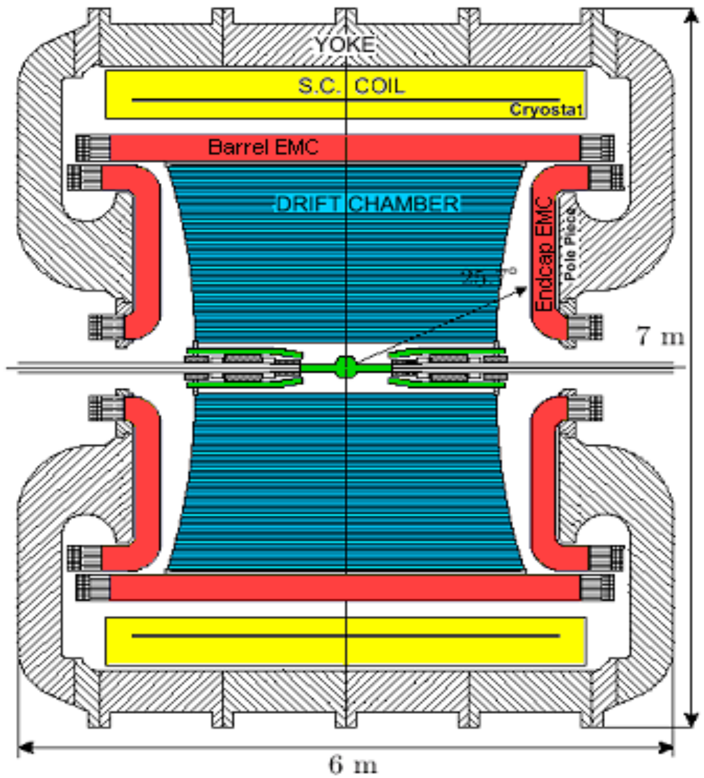


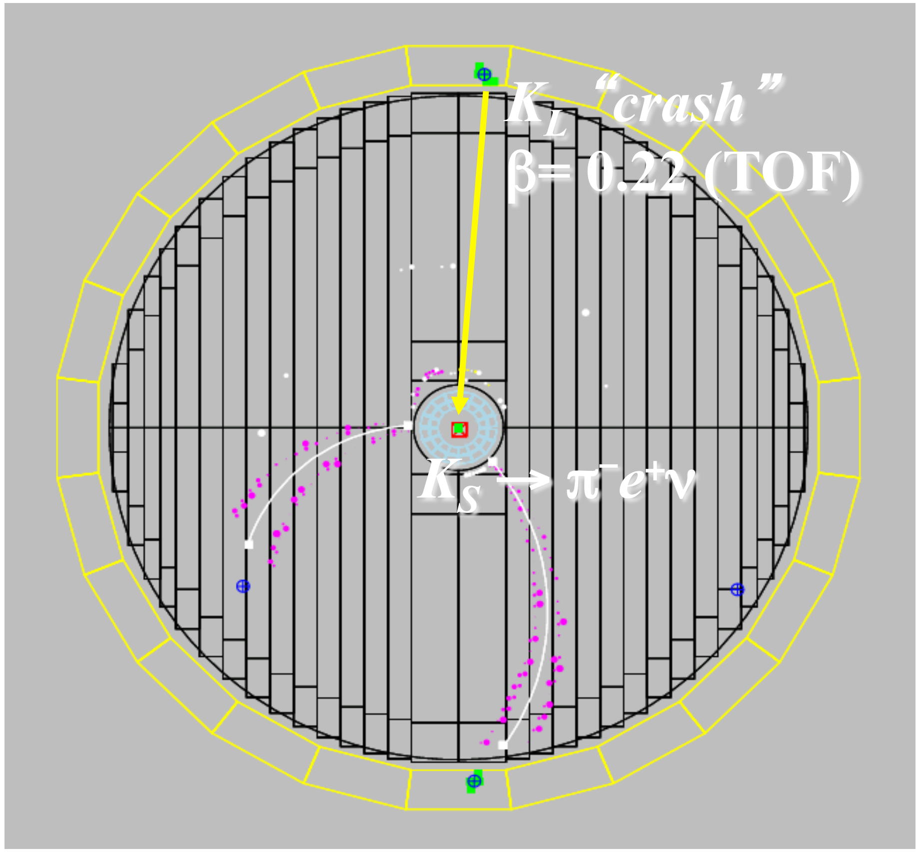
Lead/scintillating fiber calorimeter

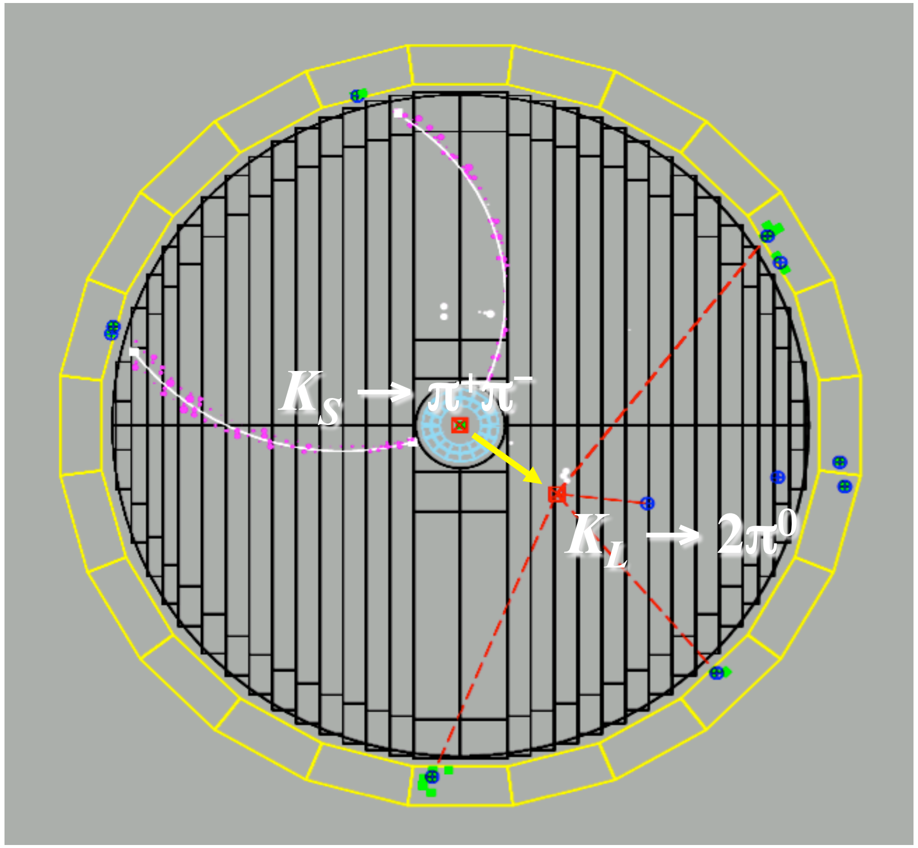
drift chamber

4 m diameter × 3.3 m length

helium based gas mixture

K_S and K_L tagging techniques 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

"Standard" CPT test with $K_{S,L} \to \pi e \nu$

Semileptonic charge asymmetry:

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

CPT viol. In decay

$\Delta S = \Delta Q$ $\Delta S \neq \Delta Q$

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

$A_S \neq A_L$ signals *CPT* violation in mixing and/or decay with $\Delta S \neq \Delta Q$

K_L semileptonic charge asymmetry:

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

KTEV, PRL88,181601(2002)

K_S semileptonic charge asymmetry:

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

KLOE, PLB 636(2006) 173 (with L~ 400 pb^{-1})

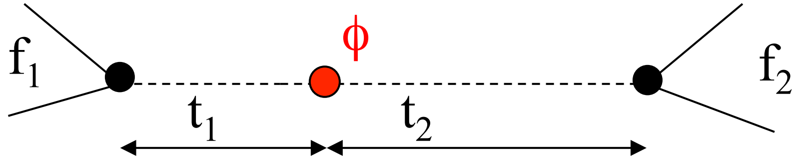
update with 2 fb^{-1}: δA_S (stat) ~ 5×10^{-3} ~ O(2Re ε)

further improvement with KLOE-2

Test of Quantum Coherence

EPR correlations in entangled neutral kaon pairs from ϕ

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



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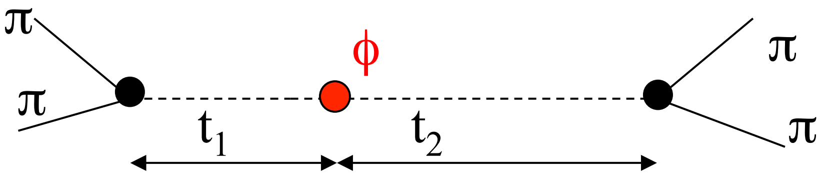

Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$
(this specific channel is suppressed by CP viol. $|\eta_{+-}|^2 = |A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-)|^2 \sim |\varepsilon|^2 \sim 10^{-6}$)

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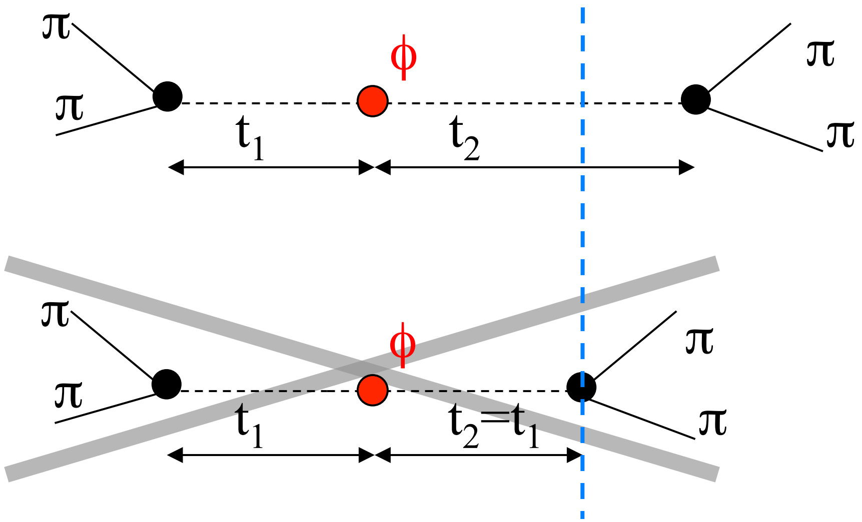

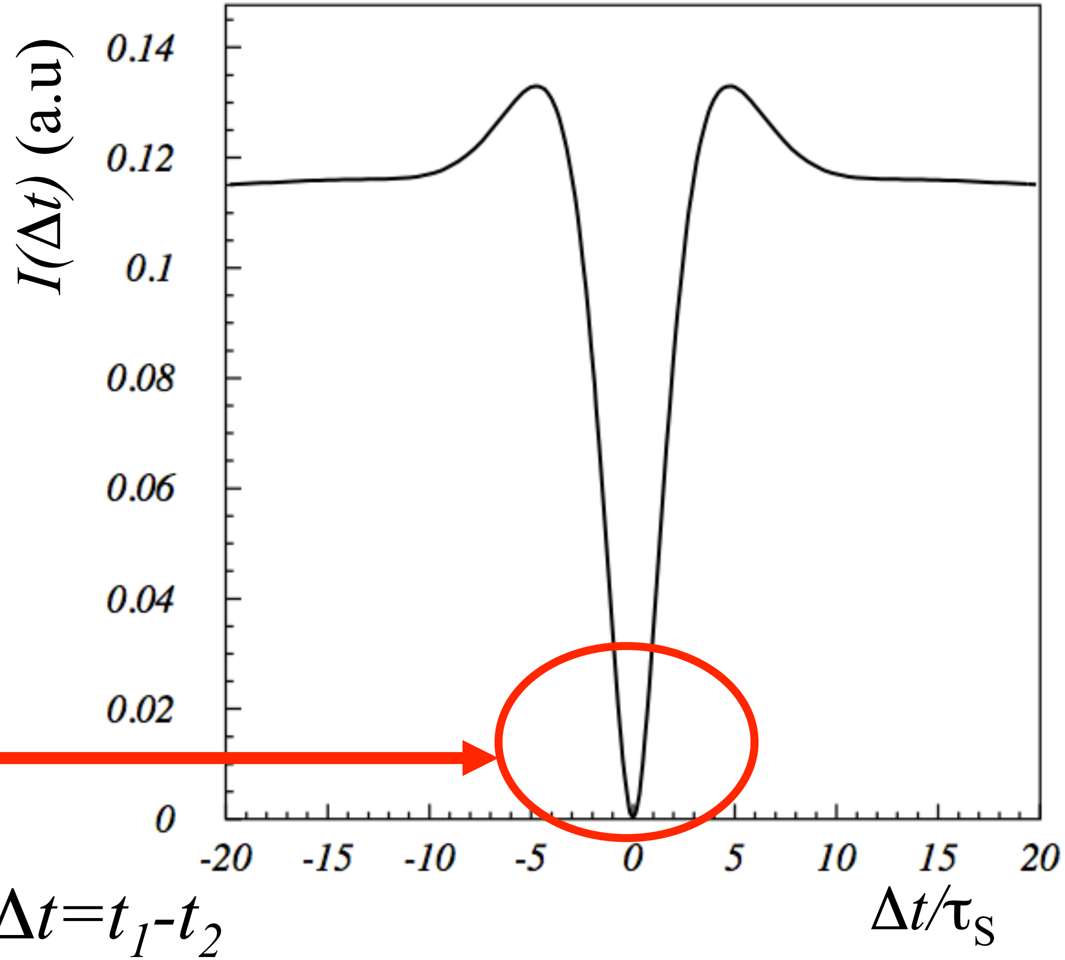

$\Delta t = t_1 - t_2$

EPR correlation:

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

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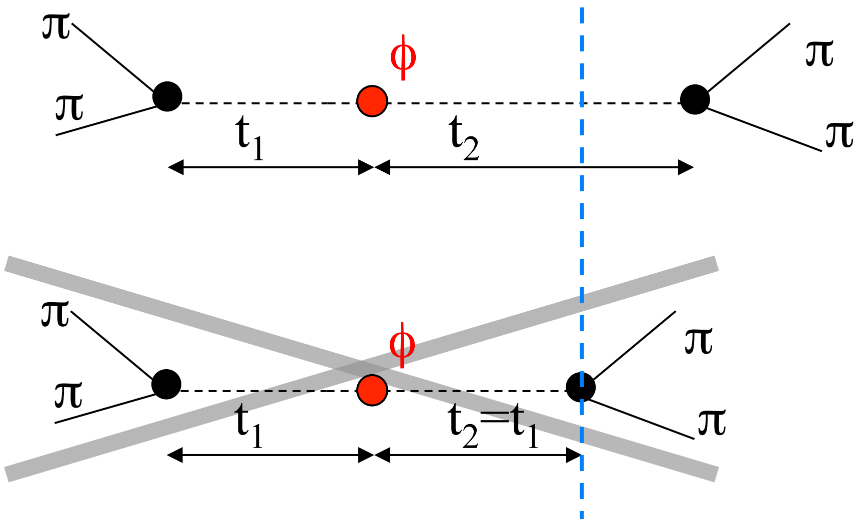

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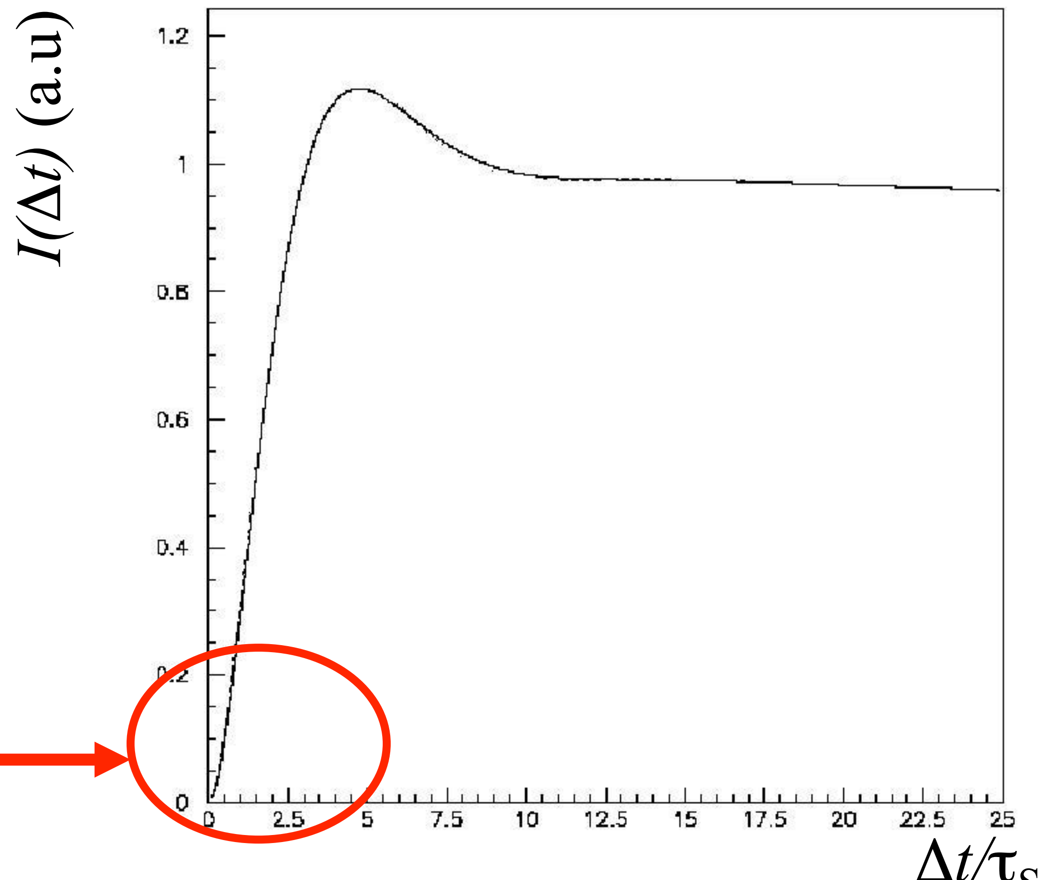

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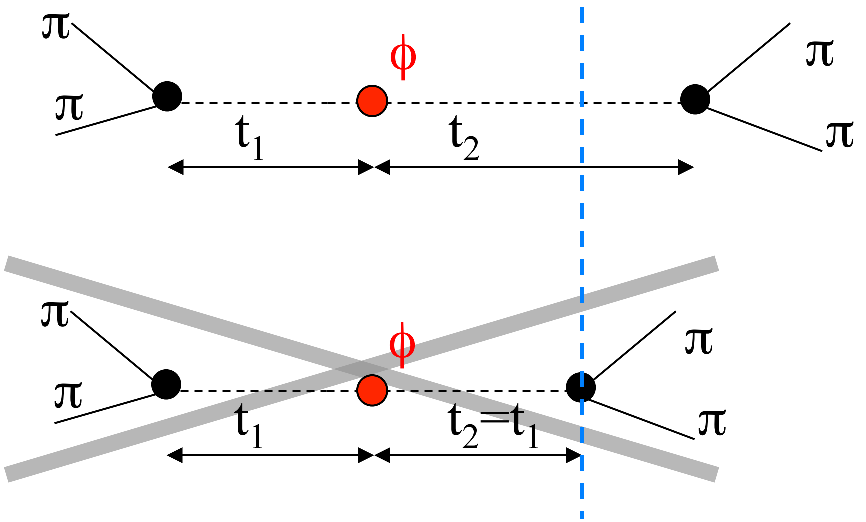

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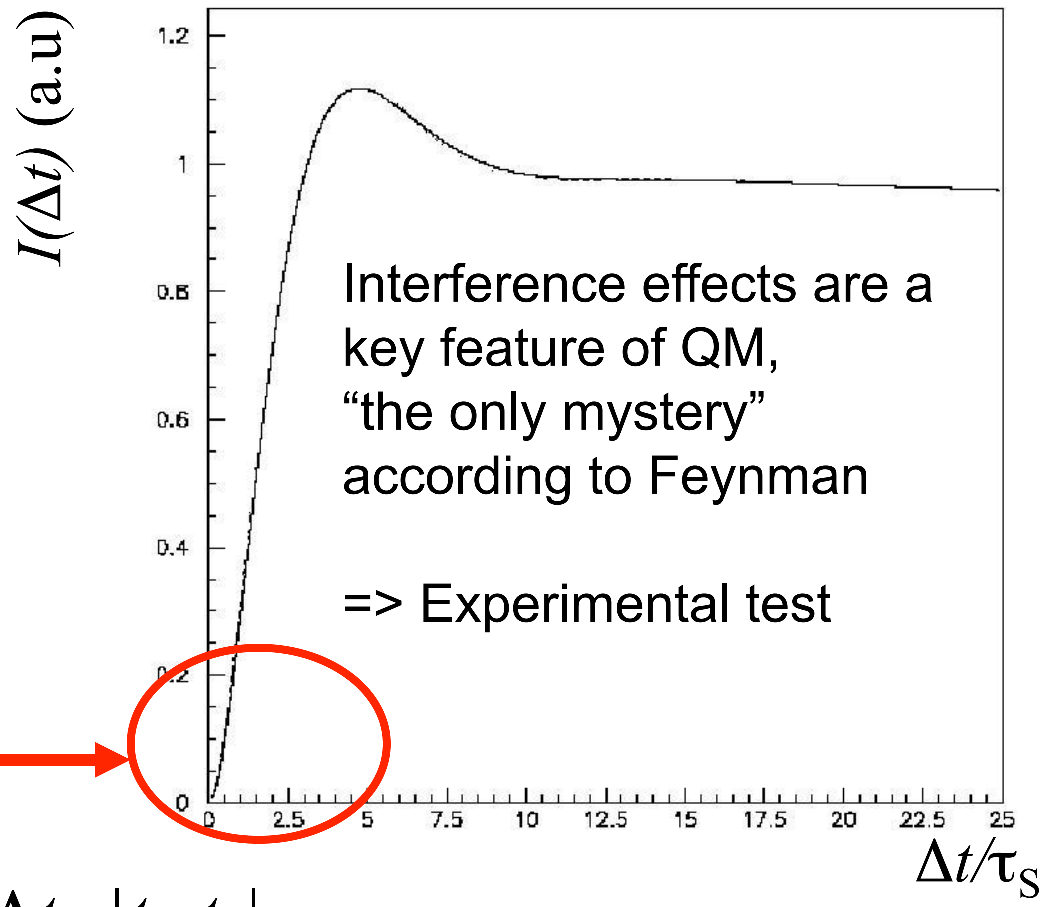

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$\Delta t = |t_1 - t_2|$

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

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

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

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

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

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

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]

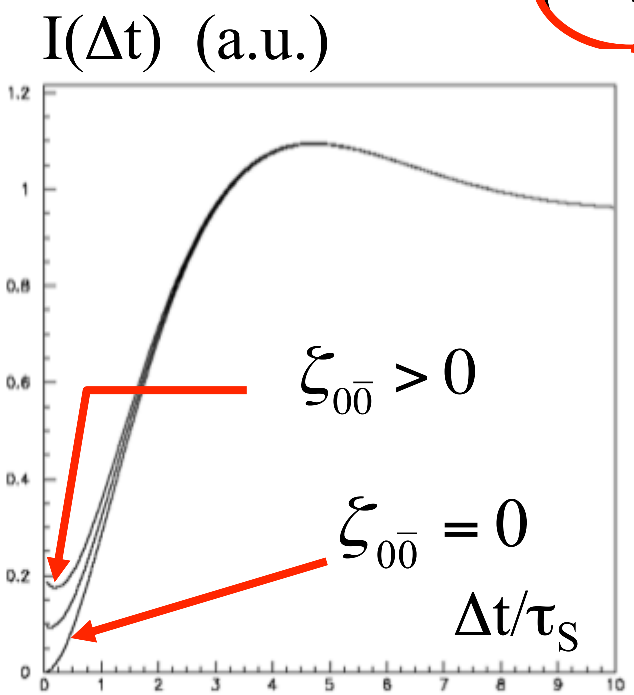
Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

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

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

$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \tfrac{N}{2}\left[\left|\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle\right|^2\right.$$
$$\left. -(1-\zeta_{0\bar{0}})\cdot 2\Re\left(\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle^*\right)\right]$$



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- Analysed data: L=1.5 fb^{-1}
- Fit including Δt resolution and efficiency effects + regeneration

KLOE result: PLB 642(2006) 315 Found. Phys. 40 (2010) 852

$$\zeta_{0\bar{0}} = \left(1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}\right) \times 10^{-7}$$

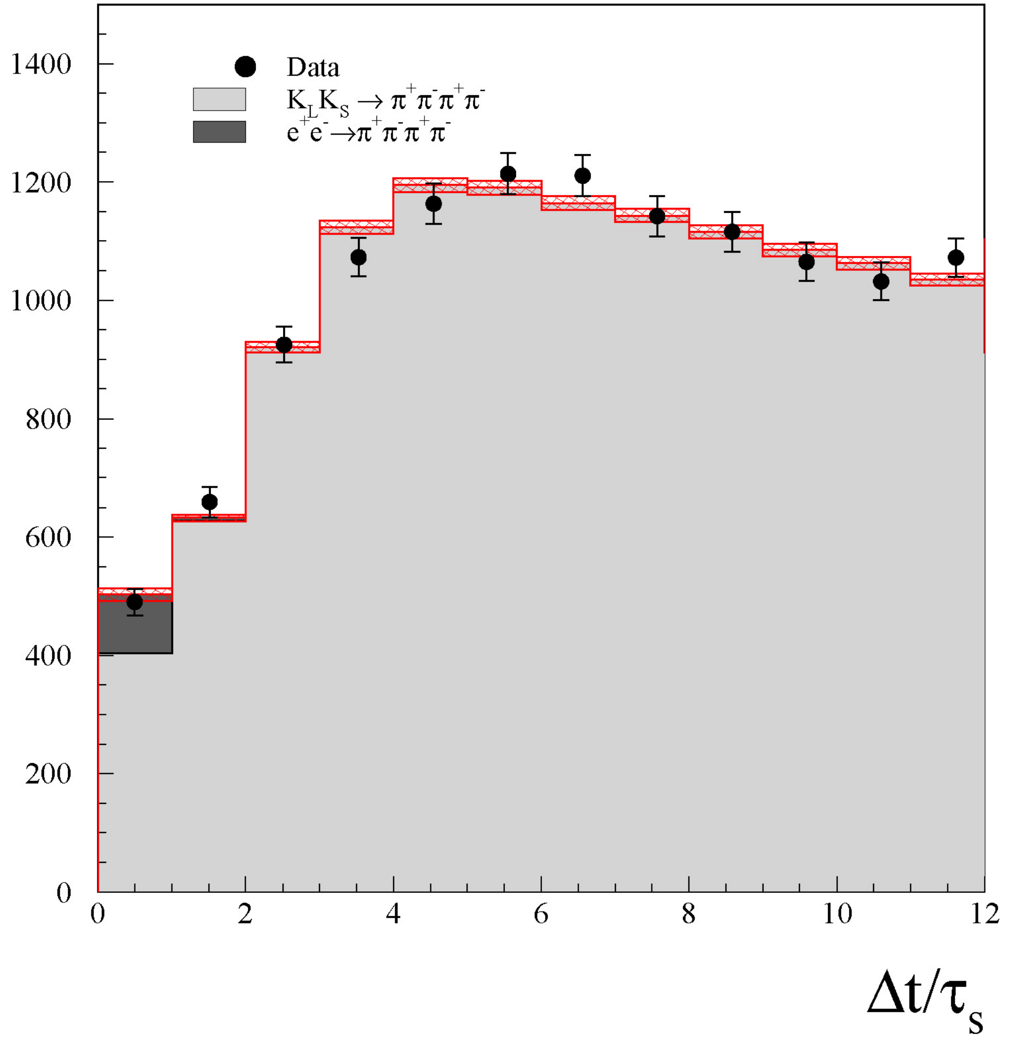
Observable suppressed by CP violation: $|\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6}$
=> terms $\zeta_{00}/|\eta_{+-}|^2$ => high sensitivity to ζ_{00}

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

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

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

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



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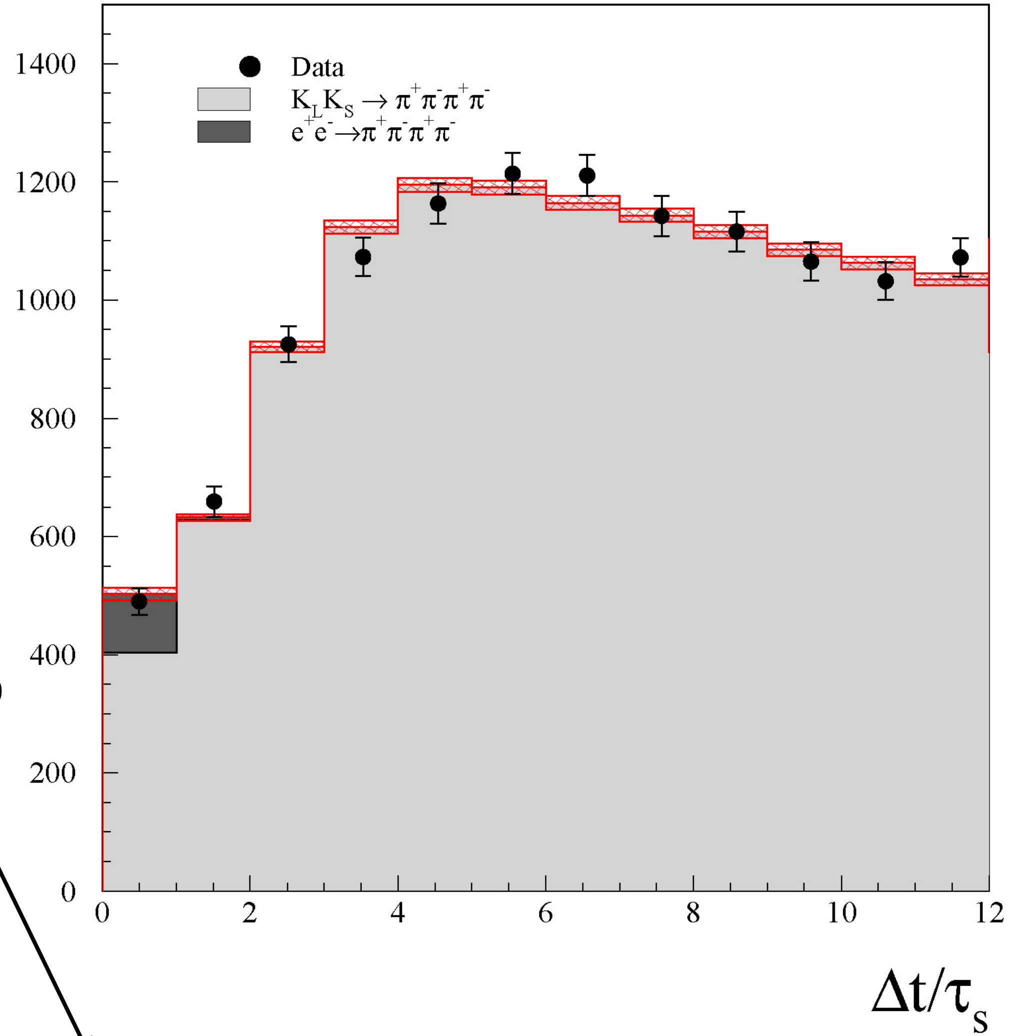

Best precision achievable in an entangled system

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Cinelli et al. PHYSICAL REVIEW A **70**, 022321 (2004)

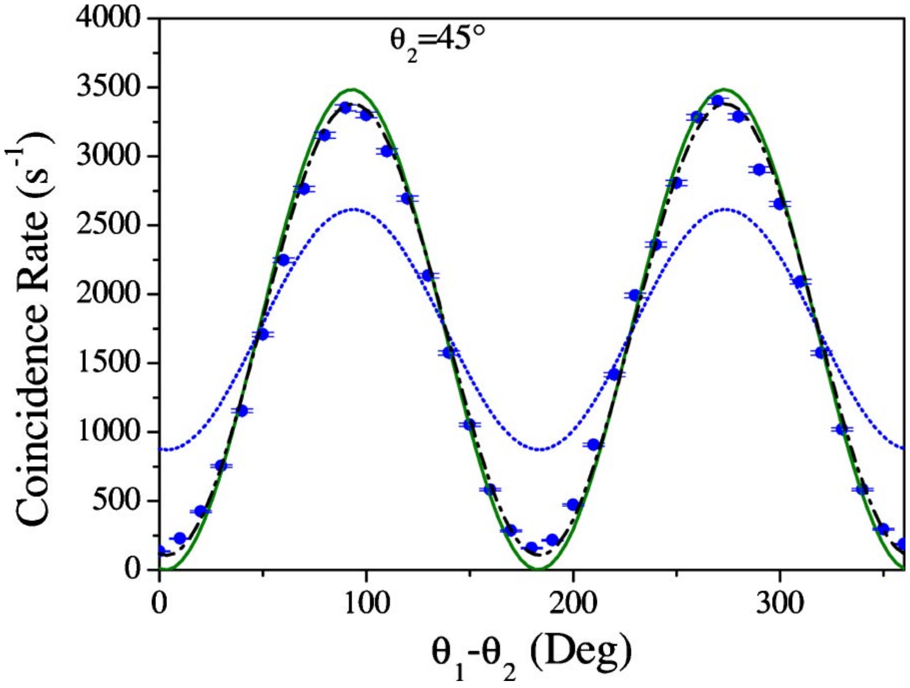

FIG. 2. Bell inequalities test. The selected state is $|\Phi^-\rangle = (1/\sqrt{2})(|H_1,H_2\rangle - |V_1,V_2\rangle)$.

$\Delta t/\tau_S$

Best precision achievable in an entangled system

Search for decoherence and CPT violation effects

Decoherence and CPT violation

S. Hawking (1975)

Possible decoherence due quantum gravity effects (BH evaporation) (apparent loss of unitarity):
Black hole information loss paradox =>
Possible decoherence near a black hole.

("like candy rolling on the tongue" by J. Wheeler)

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].

Modified Liouville – von Neumann equation for the density matrix of the kaon system with 3 new CPTV parameters α,β,γ [3]:

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

extra term inducing decoherence: pure state => mixed state

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742;[3] Ellis et. al, NP B241 (1984) 381; Ellis, Mavromatos et al. PRD53 (1996)3846; Handbook on kaon interferometry [hep-ph/0607322],
M. Arzano PRD90 **(2014)** 024016 => Theories with Planck scale deformed symmetries can induce decoherence

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at most:

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

[1] Hawking, Comm.Math.Phys.87 (1982) 395; [2] Wald, PR D21 (1980) 2742;[3] Ellis et. al, NP B241 (1984) 381; Ellis, Mavromatos et al. PRD53 (1996)3846; Handbook on kaon interferometry [hep-ph/0607322],
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$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: decoherence and CPT violation

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

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

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

single kaons

In the complete positivity hypothesis

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

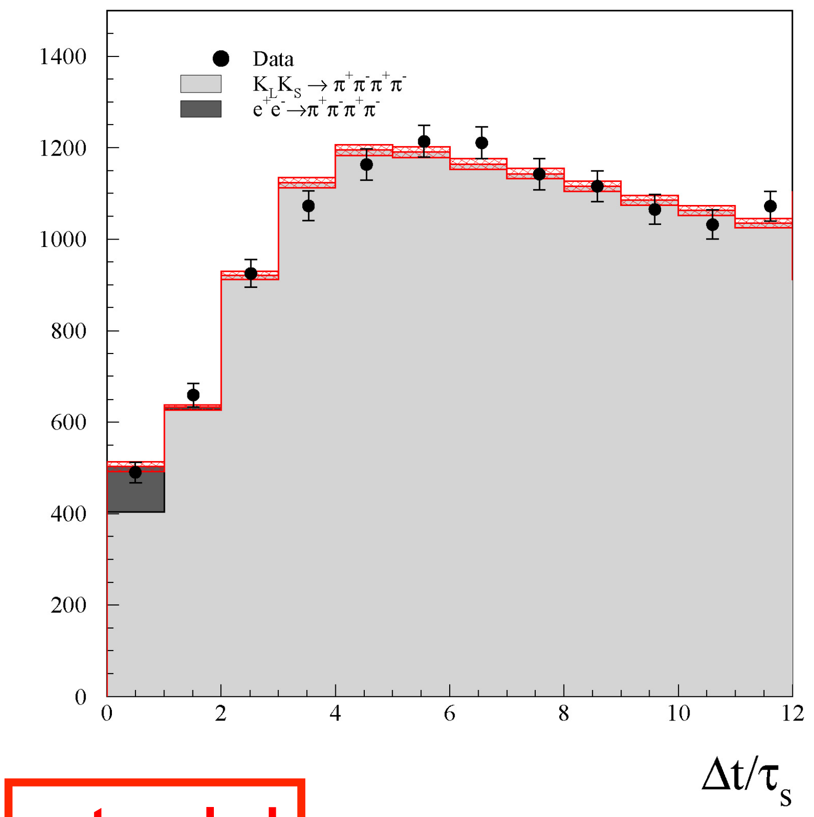
=> only one independent parameter: γ

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

KLOE result L=1.5 fb^{-1}

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

PLB 642(2006) 315
Found. Phys. 40 (2010) 852



entangled kaons

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: CPT violation in entangled 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].

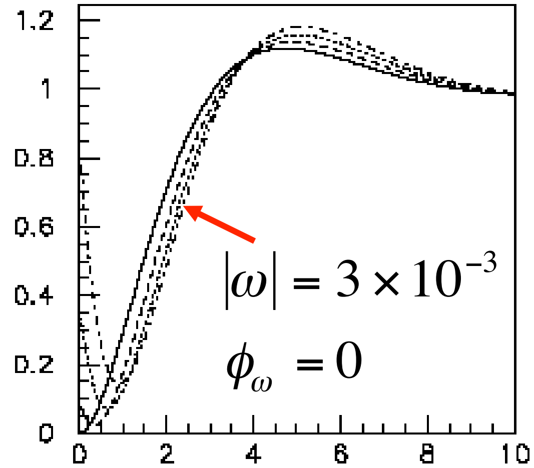
$$|i\rangle \propto \left(|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right) + \omega\left(|K^0\rangle|\overline{K}^0\rangle + |\overline{K}^0\rangle|K^0\rangle\right)$$

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

at most one expects:

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

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



$\Delta t/\tau_S$

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.

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

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

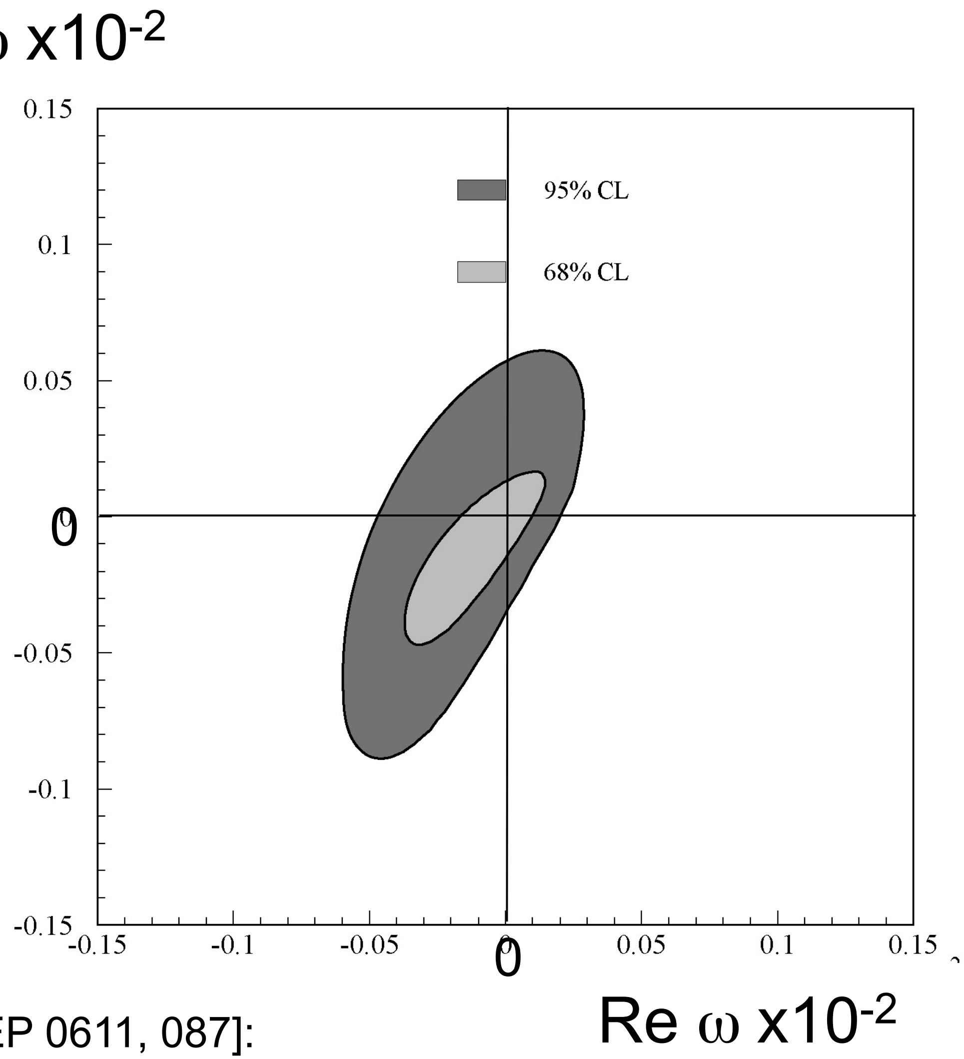
- Analysed data: 1.5 fb^{-1}

KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

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

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

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



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

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

CPT symmetry and Lorentz invariance test

CPT and Lorentz invariance violation (SME)

- CPT theorem :

Exact CPT invariance holds for any quantum field theory which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).

- "Anti-CPT theorem" (Greenberger 2002):

Any unitary, local, point-particle quantum field theory that violates CPT invariance necessarily violates Lorentz invariance.

- 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:

- At first order CPTV appears only in mixing parameter δ (no direct CPTV in decay)
- 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 $\Delta a_\mu = a_\mu^{q2} - a_\mu^{q1}$ are four parameters associated to SME lagrangian terms $-a_\mu \bar{q}\gamma^\mu q$ for the valence quarks and related to CPT and Lorentz violation.

The Earth as a moving laboratory

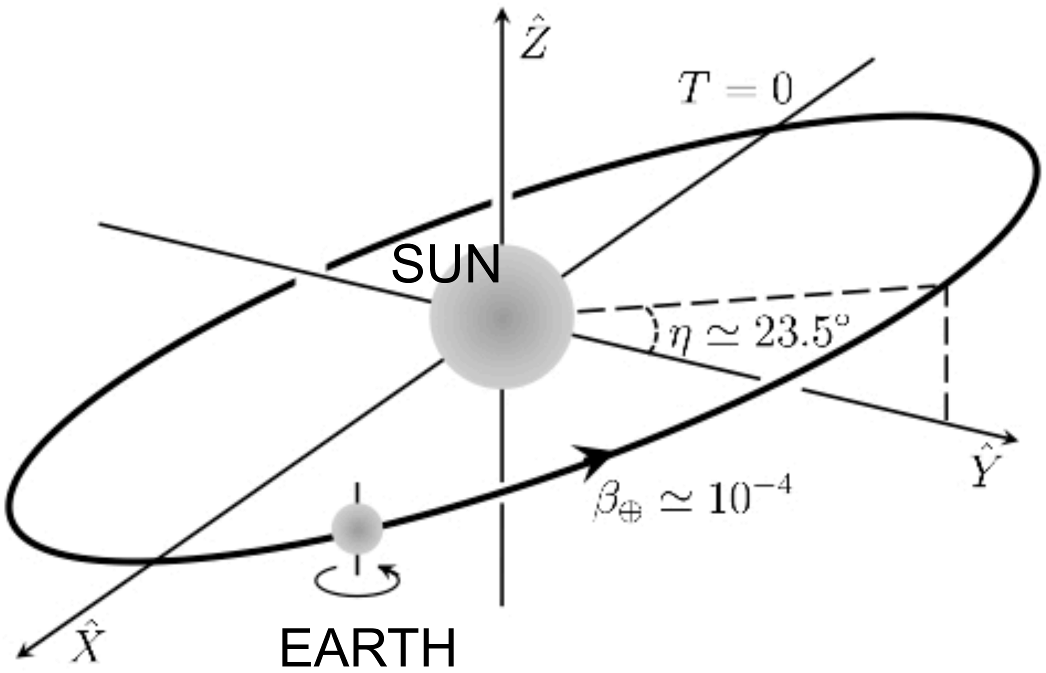
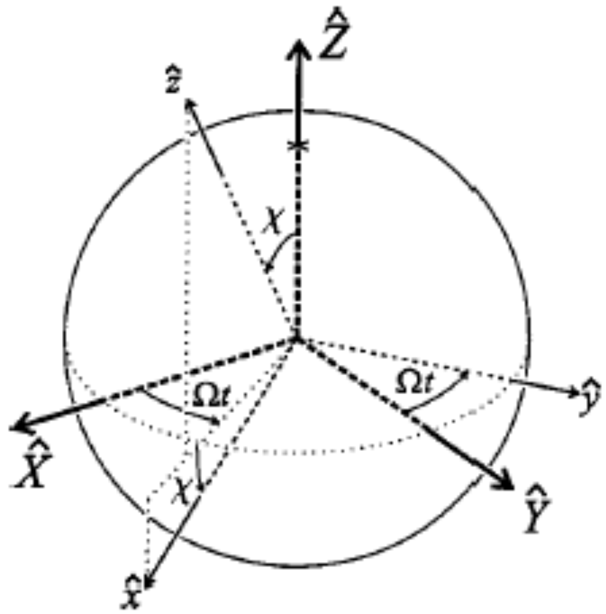


FIG. 1: Standard Sun-centered inertial reference frame [9].

Search for 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.
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)

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

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

Search for CPT and Lorentz invariance violation (SME)

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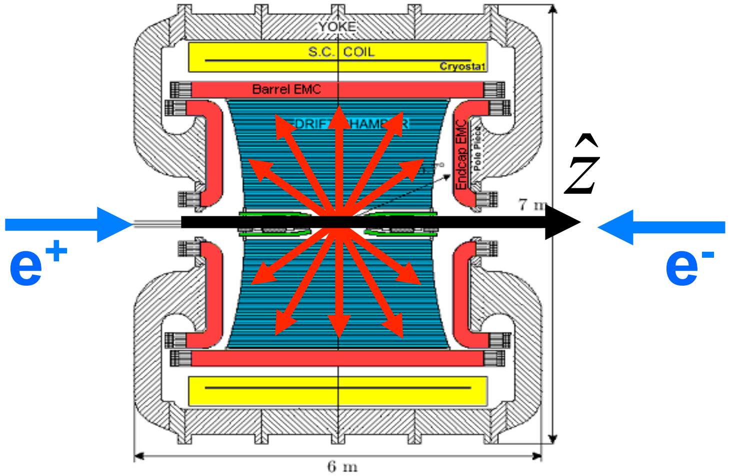
At DAΦNE K mesons are produced with angular distribution $dN/d\Omega \propto \sin^2\theta$



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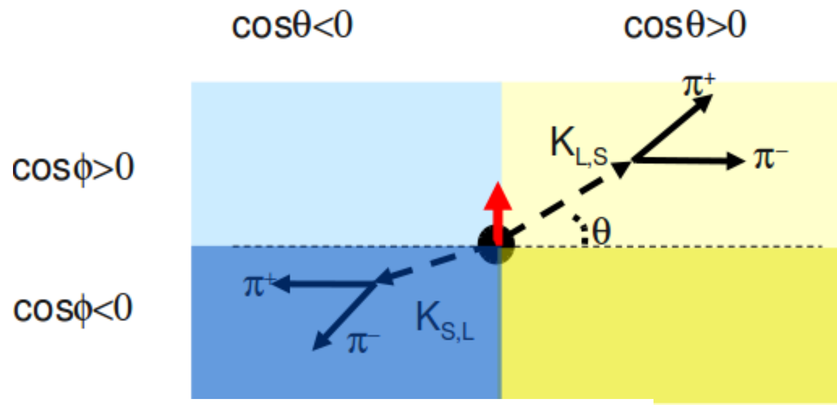
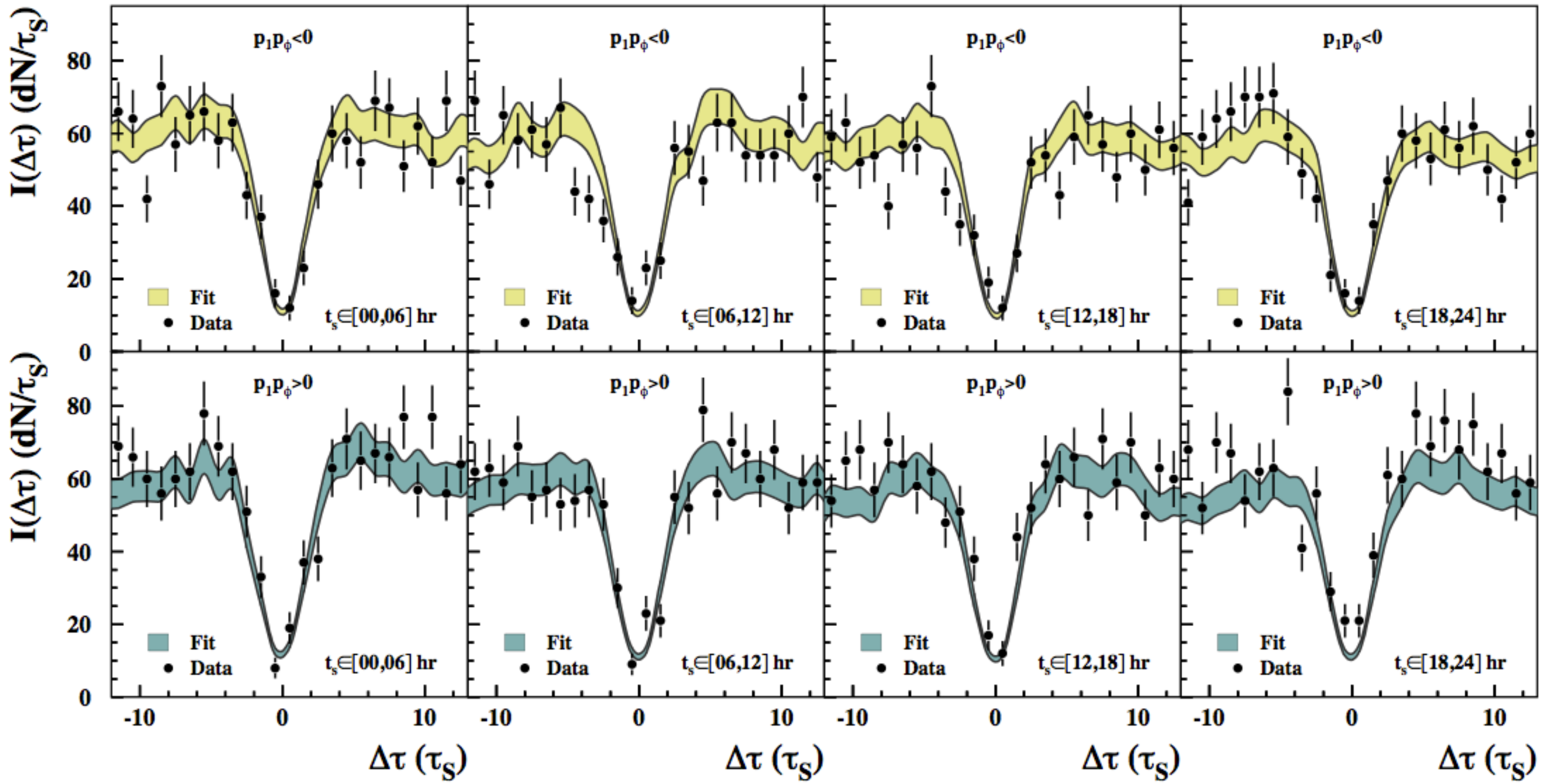
Ω: Earth's sidereal frequency   χ : angle between the z lab. axis and the Earth's rotation axis

Search for CPTV and LV: results

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

Data divided in
4 sidereal time bins x 2 angular bins
Simultaneous fit of the Δt distributions
to extract Δa_μ parameters





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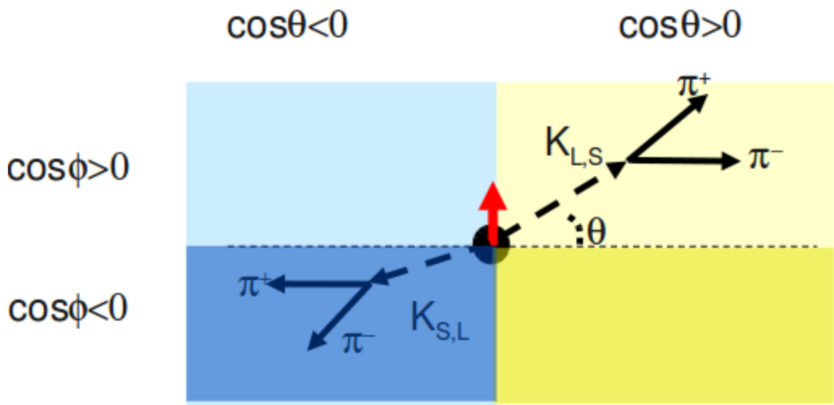


with L=1.7 fb^{-1} KLOE final result
PLB 730 (2014) 89–94

Par	Cut stability	Fit Range	Bkg. subtr	KLOE ref. frame	Total
Δa_0	1.1	2.4	1.3	1.0	**3.1**
Δa_X	0.3	0.3	0.4	0.2	**0.6**
Δa_Y	0.2	0.3	0.2	0.2	**0.5**
Δa_Z	0.2	0.2	0.4	0.4	**0.6**

$$\Delta a_0 = \left(-6.0 \pm 7.7_{STAT} \pm 3.1_{SYST}\right) \times 10^{-18} \text{ GeV}$$

$$\Delta a_X = \left(0.9 \pm 1.5_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Y = \left(-2.0 \pm 1.5_{STAT} \pm 0.5_{SYST}\right) \times 10^{-18} \text{ GeV}$$

$$\Delta a_Z = \left(-3.1 \pm 1.7_{STAT} \pm 0.6_{SYST}\right) \times 10^{-18} \text{ GeV}$$

presently the most precise measurements in the quark sector of the SME

B meson system:
$\Delta a^B_\mu \sim O(10^{-15}\,\text{GeV})$
[LHCb PRL116 (2016) 241601]

D meson system:
$\Delta a^D_{x,y}$, $(\Delta a^D_0 - 0.6\, \Delta a^D_Z) \sim O(10^{-13}\,\text{GeV})$
[Focus PLB 556 (2003) 7]

Direct CPT symmetry test in neutral kaon transitions

(or a very general and model independent test)

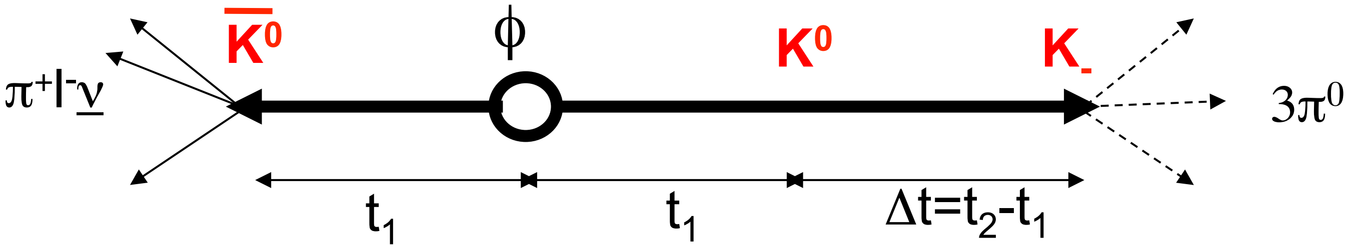
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also orthogonal "CP states" K_+ and K_-

$$|K_+\rangle = |K_1\rangle \quad (CP = +1)$$
$$|K_-\rangle = |K_2\rangle \quad (CP = -1)$$

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

- decay as filtering measurement
- entanglement -> preparation of state



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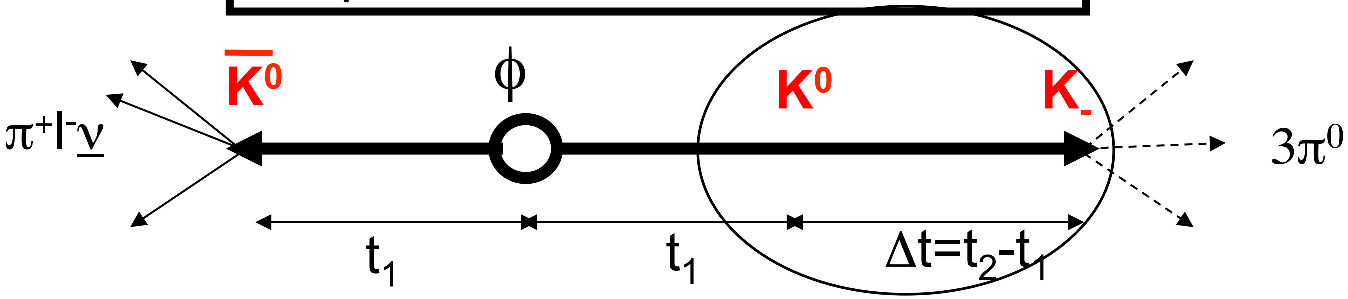

$K^0 \rightarrow K_-$ reference process

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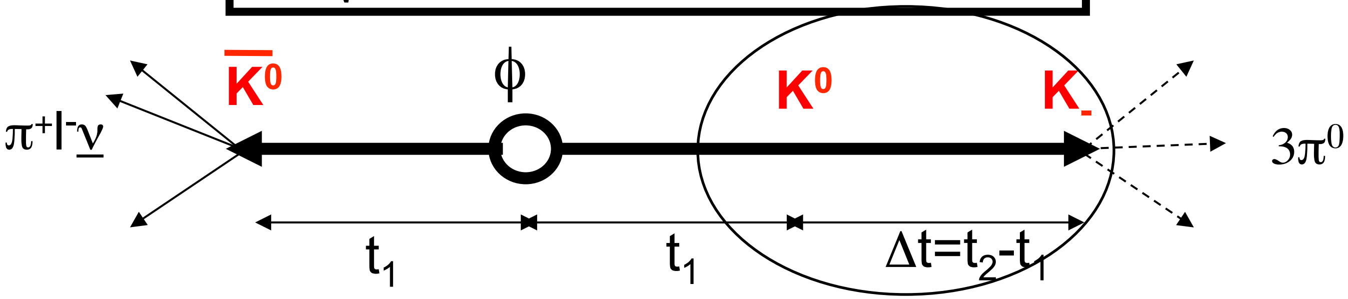
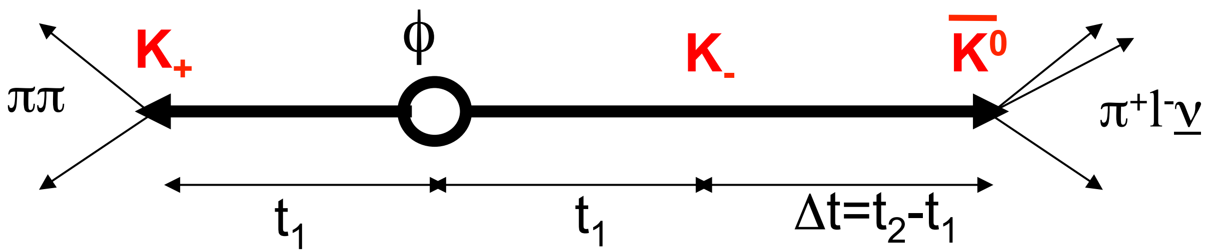


$K^0 \to K_-$ reference process



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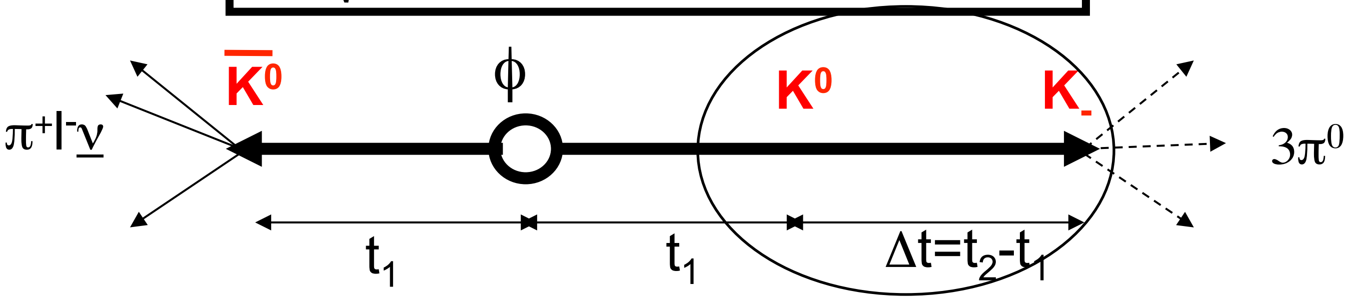
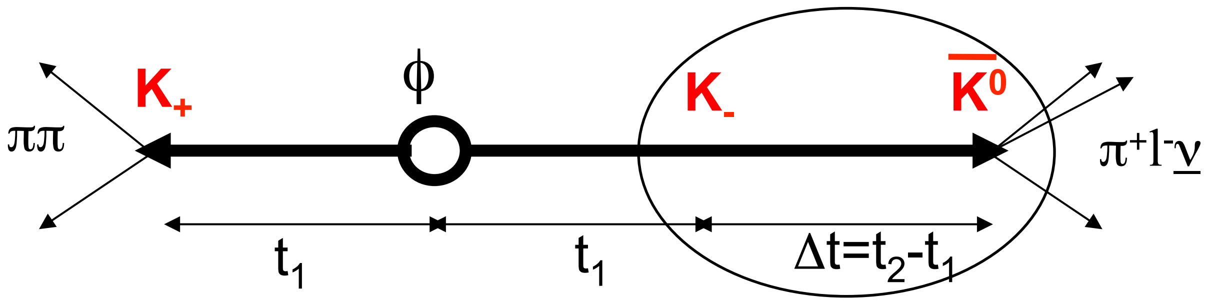
- decay as filtering measurement
- entanglement -> preparation of state



$$K^0 \rightarrow K_-$$ reference process

$$K_- \rightarrow \overline{K}^0$$ CPT-conjugated process



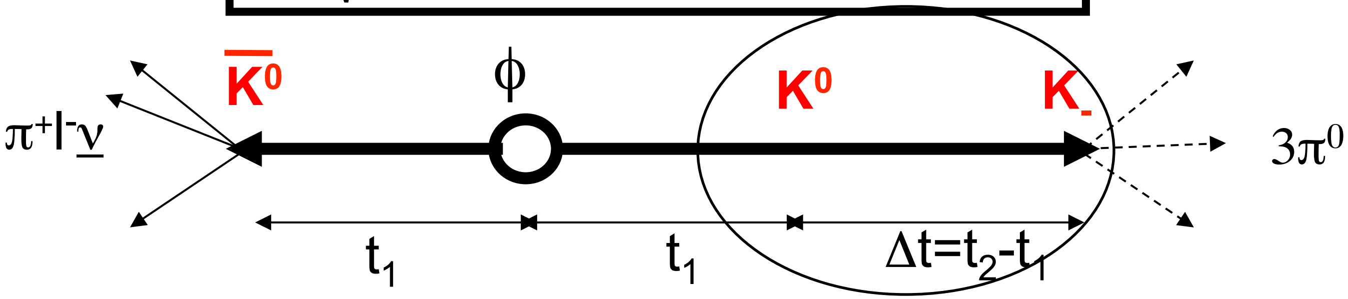
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a ϕ-factory (or B-factory) can be exploited to study other transitions involving also orthogonal "CP states" K_+ and K_-

$$|K_+\rangle = |K_1\rangle \quad (CP=+1)$$
$$|K_-\rangle = |K_2\rangle \quad (CP=-1)$$

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

- decay as filtering measurement
- entanglement -> preparation of state

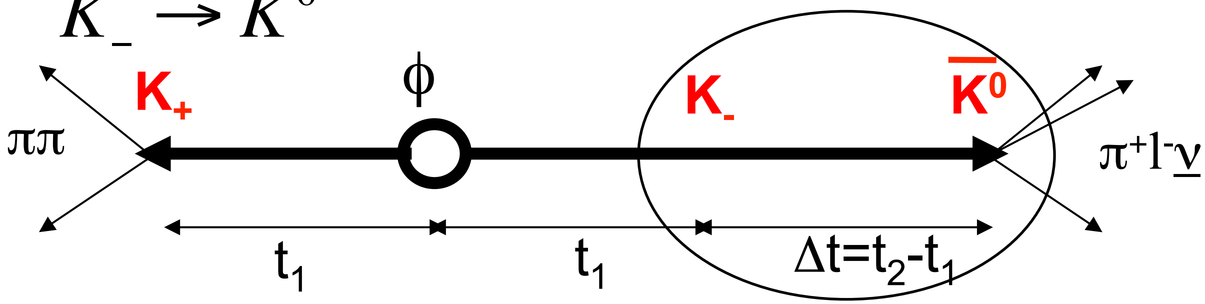


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \overline{K}^0$ CPT-conjugated process

Note: CP and T conjugated process

$\overline{K}^0 \rightarrow K_- \qquad K_- \rightarrow K^0$



Direct test of CPT symmetry in neutral kaon transitions

CPT symmetry test

J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139

Reference		$\mathcal{CPT}$-conjugate	
Transition	Decay products	Transition	Decay products
$\mathrm{K}^0 \to \mathrm{K}_+$	$(\ell^-, \pi\pi)$	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	$(3\pi^0, \ell^-)$
$\mathrm{K}^0 \to \mathrm{K}_-$	$(\ell^-, 3\pi^0)$	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	$(\pi\pi, \ell^-)$
$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$	$(\ell^+, \pi\pi)$	$\mathrm{K}_+ \to \mathrm{K}^0$	$(3\pi^0, \ell^+)$
$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$	$(\ell^+, 3\pi^0)$	$\mathrm{K}_- \to \mathrm{K}^0$	$(\pi\pi, \ell^+)$

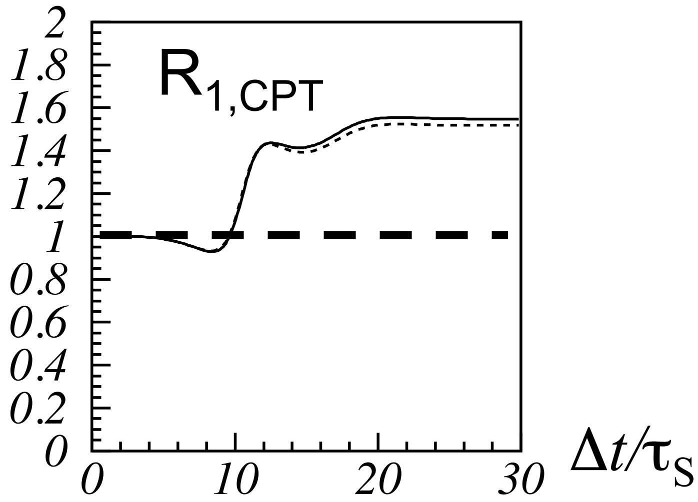
One can define the following ratios of probabilities:

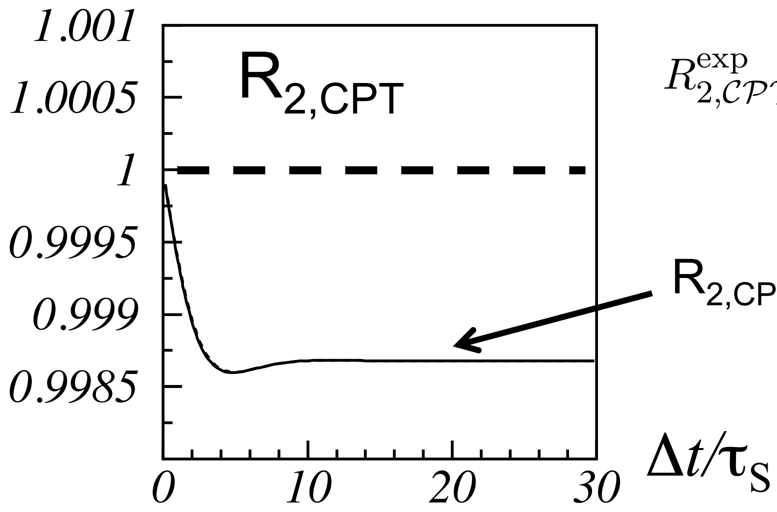
$$R_{1,\mathcal{CPT}}(\Delta t) = P\left[\mathrm{K}_+(0) \to \bar{\mathrm{K}}^0(\Delta t)\right] / P\left[\mathrm{K}^0(0) \to \mathrm{K}_+(\Delta t)\right]$$
$$R_{2,\mathcal{CPT}}(\Delta t) = P\left[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)\right] / P\left[\mathrm{K}_-(0) \to \bar{\mathrm{K}}^0(\Delta t)\right]$$
$$R_{3,\mathcal{CPT}}(\Delta t) = P\left[\mathrm{K}_+(0) \to \mathrm{K}^0(\Delta t)\right] / P\left[\bar{\mathrm{K}}^0(0) \to \mathrm{K}_+(\Delta t)\right]$$
$$R_{4,\mathcal{CPT}}(\Delta t) = P\left[\bar{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)\right] / P\left[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)\right]$$

Any deviation from $R_{i,CPT}$=1 constitutes a violation of CPT-symmetry

Direct test of CPT symmetry in neutral kaon transitions

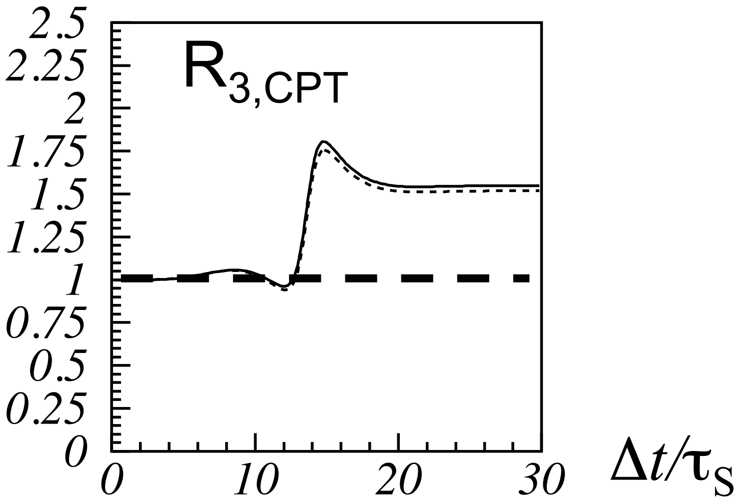
for visualization purposes, plots with Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5} (- - - - Im(δ)=0)

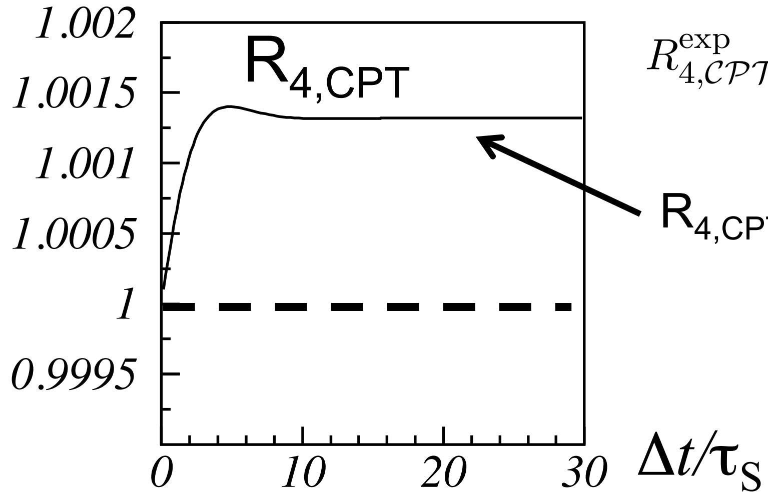




$$R^{\exp}_{2,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

$R_{2,CPT}(\Delta t >> \tau_S)=1-4Re(\delta)$



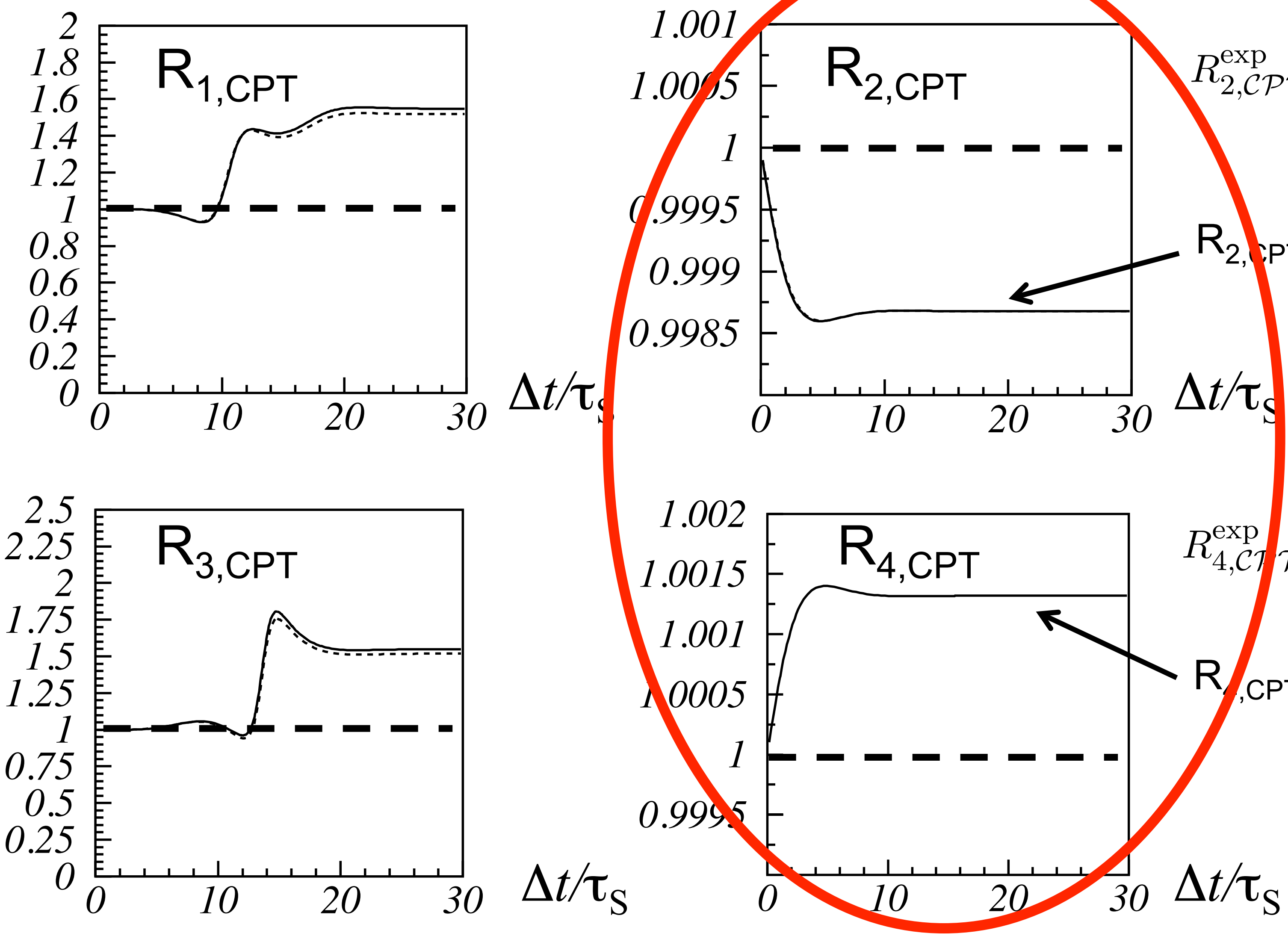


$$R^{\exp}_{4,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

$R_{4,CPT}(\Delta t >> \tau_S)=1+4Re(\delta)$

Direct test of CPT symmetry in neutral kaon transitions

for visualization purposes, plots with Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5} (- - - - Im(δ)=0)



$$R^{\rm exp}_{2,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

$R_{2,CPT}(\Delta t >> \tau_S) = 1 - 4\mathrm{Re}(\delta)$

measurable at KLOE-2

$$R^{\rm exp}_{4,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

$R_{4,CPT}(\Delta t >> \tau_S) = 1 + 4\mathrm{Re}(\delta)$

Direct test of CPT symmetry in neutral kaon transitions

- It would be possible to directly test the CPT symmetry in transition processes between meson states, rather than comparing masses, lifetimes, or other intrinsic properties of particle and anti-particle states.
- The proposed CPT test for neutral kaons is model independent and fully robust. (It can then be translated in terms of δ, α, β, γ, Δa_μ etc..).
- Possible spurious effects induced by CP violation in the decay and/or a violation of the $\Delta S = \Delta Q$ rule have been shown to be well under control.
- CPT violating effects may not appear at first order in diagonal mass terms (survival probabilities) while they can manifest at first order in transitions (non-diagonal terms).

- Connection with charge semileptonic asymmetries of K_S and K_L .
  From KLOE preliminary results [A.D.D. in Handbook on kaon interf. Fras. Phys. Ser. 43 (2007)]:

$$\frac{R^{\rm exp}_{2,{\rm CPT}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,{\rm CPT}}(\Delta t \gg \tau_S)} \simeq 1 + 2(A_L - A_S) = 1.004 \pm 0.020 \ (\Delta S{=}\Delta Q) \Rightarrow \ \mathrm{Re}(\delta) \sim \pm 2.5 \times 10^{-3}$$

- KLOE-2 can reach a statistical sensitivity of $O(10^{-4})$
  J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139

B mesons: Babar re-analysis of T viol. results :Re(z), Im(z)~±0.03 [PRD94 (2016) 011101]

Next Future perspectives

KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:

- For the very first time the "crab-waist" concept – an interaction scheme, developed in Frascati, where the transverse dimensions of the beams and their crossing angle are tuned to maximize the machine luminosity – has been applied in presence of a high-field detector solenoid.

KLOE-2 experiment:

- extend the KLOE physics program at DAΦNE upgraded in luminosity
- Collect L>5 fb^{-1} of integrated luminosity in the next couple of years

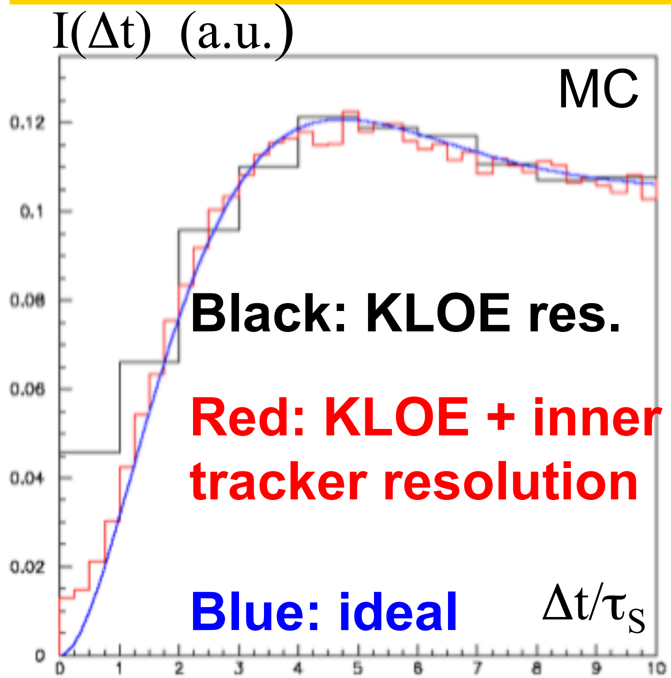
Physics program (see EPJC 68 (2010) 619-681)

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, a_μ
- Dark forces: search for light U boson

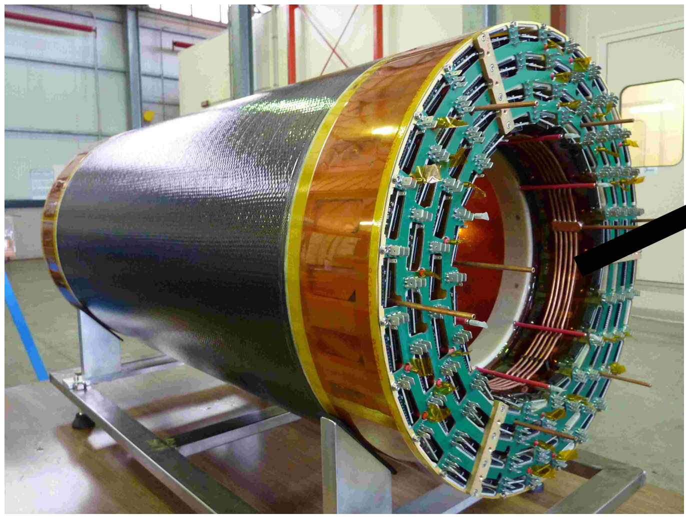
Detector upgrade:

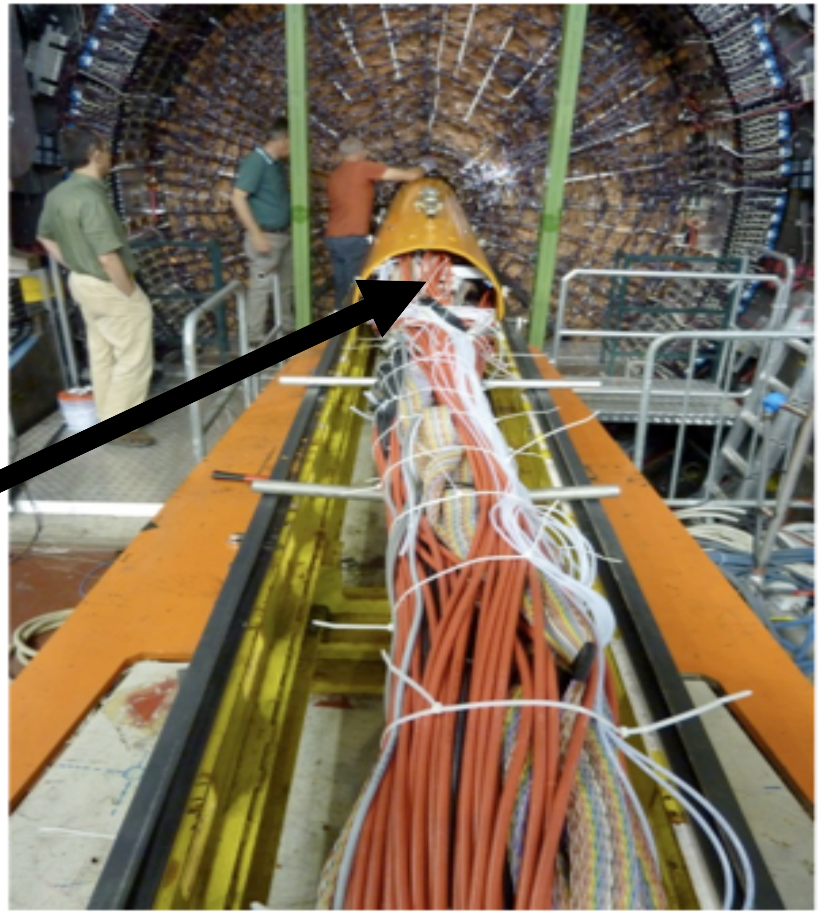
- $\gamma\gamma$ tagging system
- inner tracker
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)

Inner tracker at KLOE-2

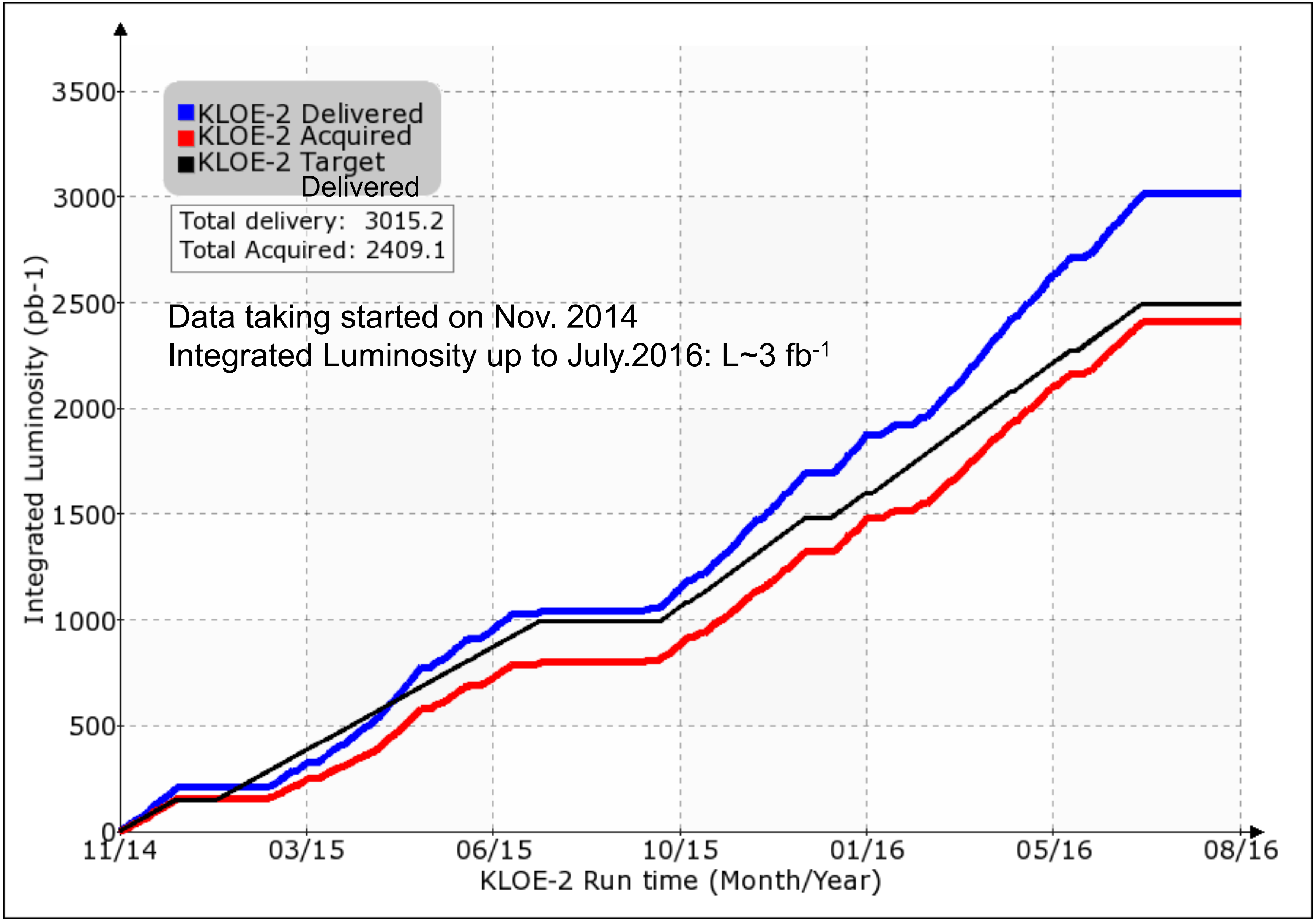


The KLOE detector has been improved with an inner tracker based on an innovative cylindrical GEM technology to improve vertex resolution close to the interaction region, and sensitivity around Δt~0.





KLOE-2 data taking in progress



Prospects for KLOE-2

Param.	Present best published measurement	KLOE-2 (IT) L=5 fb^{-1} (stat.)	KLOE-2 (IT) L=10 fb^{-1} (stat.)
A_S	$(1.5 \pm 11) \times 10^{-3}$	$\pm 2.7 \times 10^{-3}$	$\pm 1.9 \times 10^{-3}$
ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$
ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$	$\pm 0.49 \times 10^{-2}$	$\pm 0.35 \times 10^{-2}$
α	$(-0.5 \pm 2.8) \times 10^{-17}$ GeV	$\pm 5.0 \times 10^{-17}$ GeV	$\pm 3.5 \times 10^{-17}$ GeV
β	$(2.5 \pm 2.3) \times 10^{-19}$ GeV	$\pm 0.50 \times 10^{-19}$ GeV	$\pm 0.35 \times 10^{-19}$ GeV
γ	$(1.1 \pm 2.5) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV	$\pm 0.75 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.33 \times 10^{-21}$ GeV	$\pm 0.53 \times 10^{-21}$ GeV compl. pos. hyp. $\pm 0.23 \times 10^{-21}$ GeV
$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$	$\pm 0.70 \times 10^{-4}$	$\pm 0.49 \times 10^{-4}$
$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$	$\pm 0.86 \times 10^{-4}$	$\pm 0.61 \times 10^{-4}$
Δa_0	$(-6.0 \pm 8.3) \times 10^{-18}$ GeV	$\pm 2.2 \times 10^{-18}$ GeV	$\pm 1.6 \times 10^{-18}$ GeV
Δa_Z	$(3.1 \pm 1.8) \times 10^{-18}$ GeV	$\pm 0.50 \times 10^{-18}$ GeV	$\pm 0.35 \times 10^{-18}$ GeV
Δa_X	$(0.9 \pm 1.6) \times 10^{-18}$ GeV	$\pm 0.44 \times 10^{-18}$ GeV	$\pm 0.31 \times 10^{-18}$ GeV
Δa_Y	$(-2.0 \pm 1.6) \times 10^{-18}$ GeV	$\pm 0.44 \times 10^{-18}$ GeV	$\pm 0.31 \times 10^{-18}$ GeV

Conclusions

- The entangled neutral kaon system at a ϕ-factory is an excellent laboratory for the study of CPT symmetry, discrete symmetries in general, and the basic principles of Quantum Mechanics;
- Several parameters related to possible
  - CPT violation
  - Decoherence
  - Decoherence and CPT violation
  - CPT violation and Lorentz symmetry breaking

  have been measured at KLOE, in same cases with a precision reaching the interesting Planck's scale region;
- <u>All results are consistent with no CPT symmetry violation and no decoherence</u>

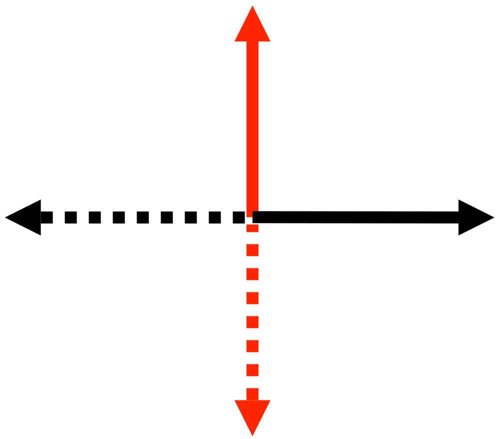
- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program.
- The precision of several tests could be improved by about one order of magnitude, possibly revealing such kind of effects or further pushing their experimental limits.

Spare slides

CPT: introduction

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

Intuitive justification of CPT symmetry [1]:
For an even-dimensional space => reflection of all axes is equivalent to a rotation
e.g. in 2-dim. space: reflection of 2 axes = rotation of π around the origin



In 4-dimensional pseudo-euclidean space-time PT reflection is NOT equivalent to a rotation. Time coordinate is not exactly equivalent to space coordinate. Charge conjugation is also needed to change sign to e.g. 4-vector current j_{μ}. (or axial 4-v). CPT (and not PT) is equivalent to a rotation in the 4-dimensional space-time

[1] Khriplovich, I.B., Lamoreaux, S.K.: CP Violation Without Strangeness.

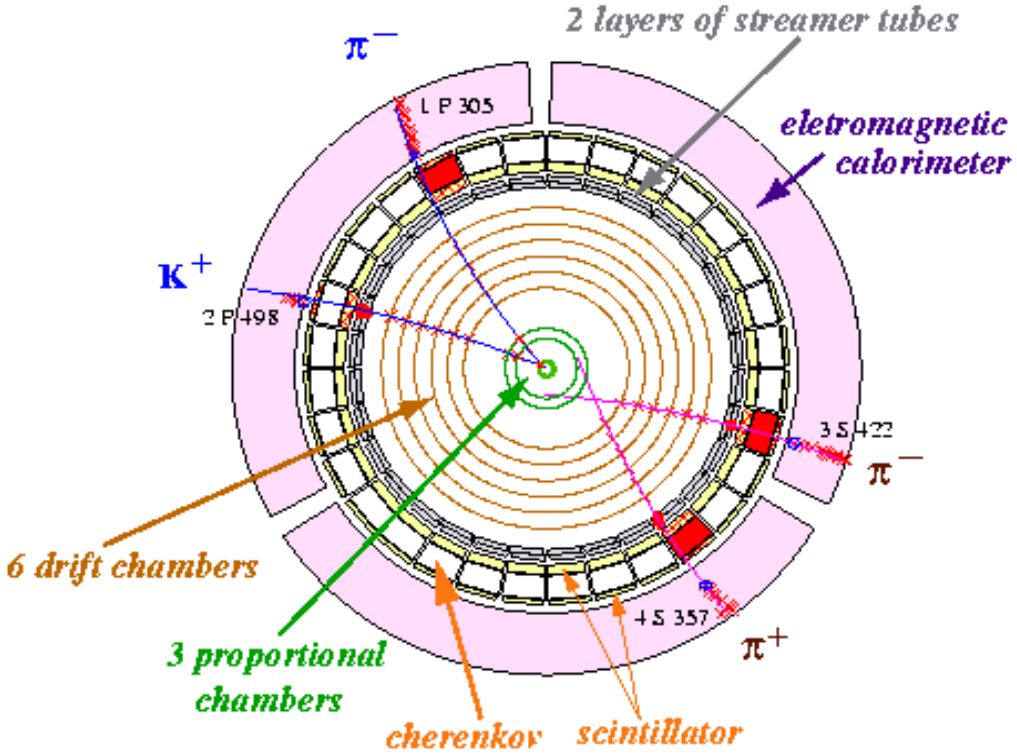
Neutral kaons at CPLEAR (CERN)

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

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

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

$$\left(p+\overline{p}\right)_{REST} \to K^0 + \overline{K}^0$$



P_K ~500 MeV

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