Fundamental Physics test with entangled neutral kaons:
testing CPT symmetry and quantum coherence in the large

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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.

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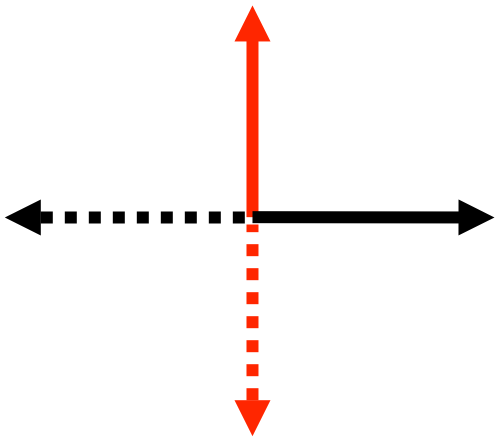
Intuitive justification of CPT symmetry [1]:
For an even-dimensional space => reflection of all axes is equivalent to a rotation
e.g. in 2-dim. space: reflection of 2 axes = rotation of π around the origin



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.

CPT: introduction

Extension of CPT theorem to a theory of quantum gravity far from obvious.
(e.g. CPT violation appears in several QG models)
No predictive theory incorporating CPT violation => only phenomenological models 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 $\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$

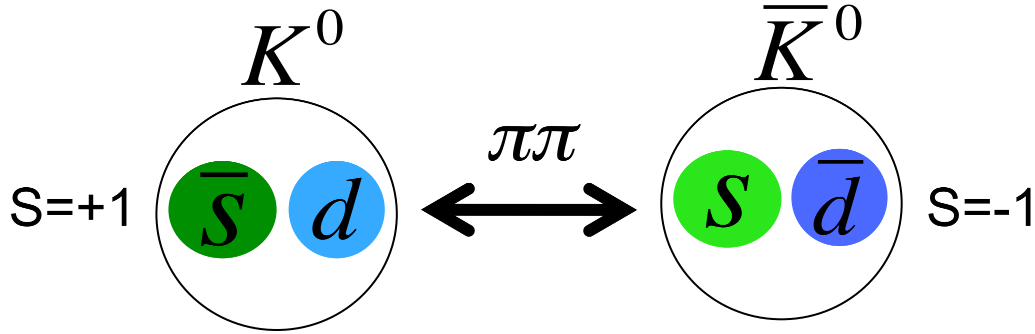
proton- anti-proton $\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$

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.

....

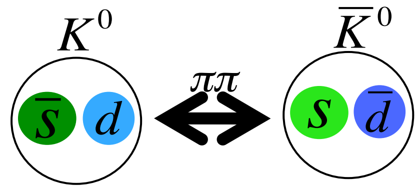
If the K mesons did not exist, they should have been invented "on purpose" in order to teach students the principles of quantum mechanics.

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

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

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

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

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

- δ ≠ 0 implies CPT violation
- ε ≠ 0 implies T violation
- ε ≠ 0 or δ ≠ 0 implies CP violation

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

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

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

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

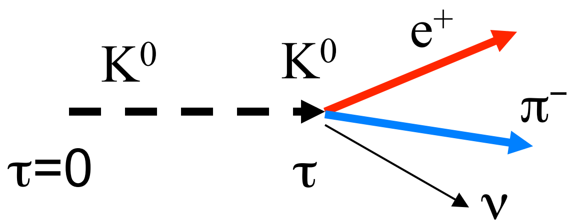
neutral kaons vs other oscillating meson systems

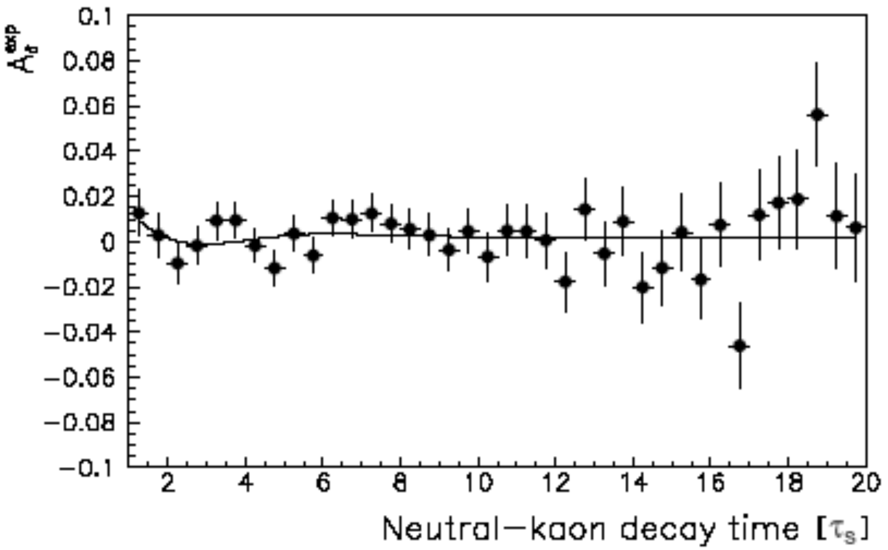
	$<m>$ (GeV)	Δm (GeV)	$<\Gamma>$ (GeV)	$\Delta\Gamma/2$ (GeV)
K^0	0.5	3×10^{-15}	3×10^{-15}	3×10^{-15}
D^0	1.9	6×10^{-15}	2×10^{-12}	1×10^{-14}
B^0_d	5.3	3×10^{-13}	4×10^{-13}	$O(10^{-15})$ (SM prediction)
B^0_s	5.4	1×10^{-11}	4×10^{-13}	3×10^{-14}

“Standard” CPT tests

CPT test at CPLEAR

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





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

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

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

CPLEAR PLB444 (1998) 52

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:

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

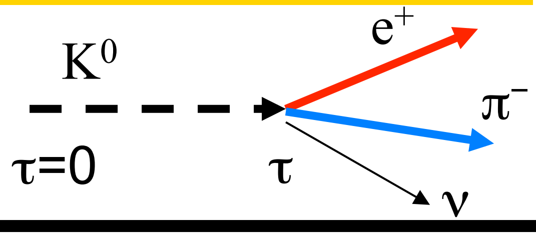
and a not trivial one, i.e. the B-S relationship:

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

All observables quantities

"Standard" CPT test

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



CPLEAR
PLB444 (1998) 52

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

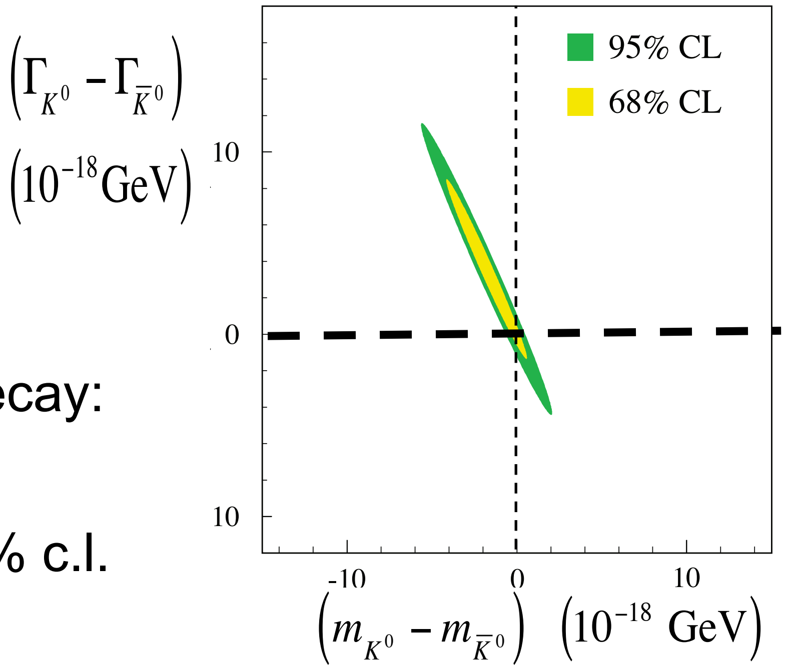
$$2\Im\delta = \Im\left[\langle K_L | K_S \rangle\right] = \Im\left[\frac{\sum_f \langle f|T|K_S\rangle \langle f|T|K_L\rangle^*}{i\left(\lambda_S - \lambda_L^*\right)}\right]$$

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

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:

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

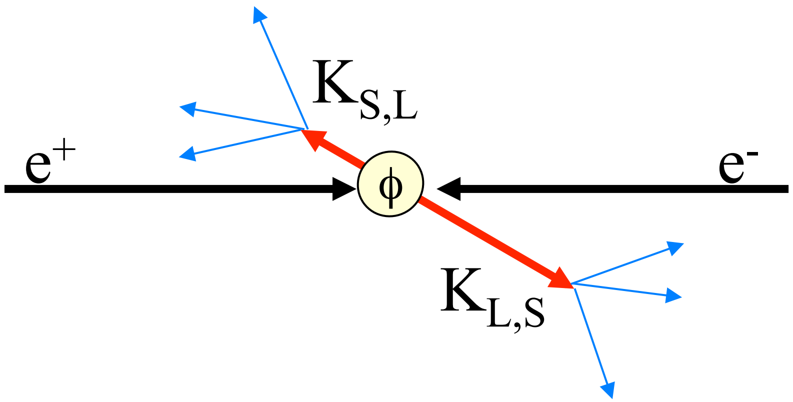
at 95% c.l.

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
- $BR(\phi \rightarrow K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:



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

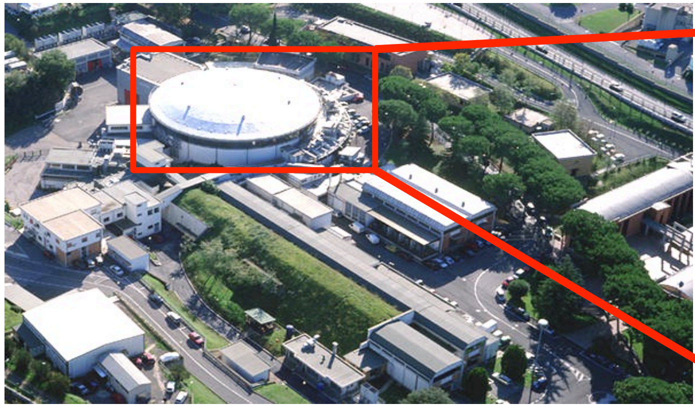
$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

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

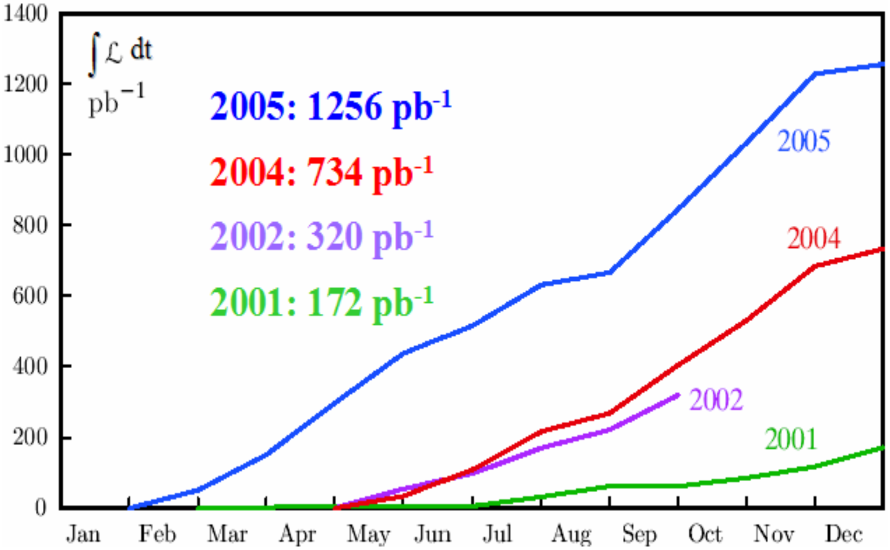
$p_K = 110$ MeV/c
$\lambda_S = 6$ mm $\lambda_L = 3.5$ m

The KLOE detector at the Frascati φ-factory DAΦNE

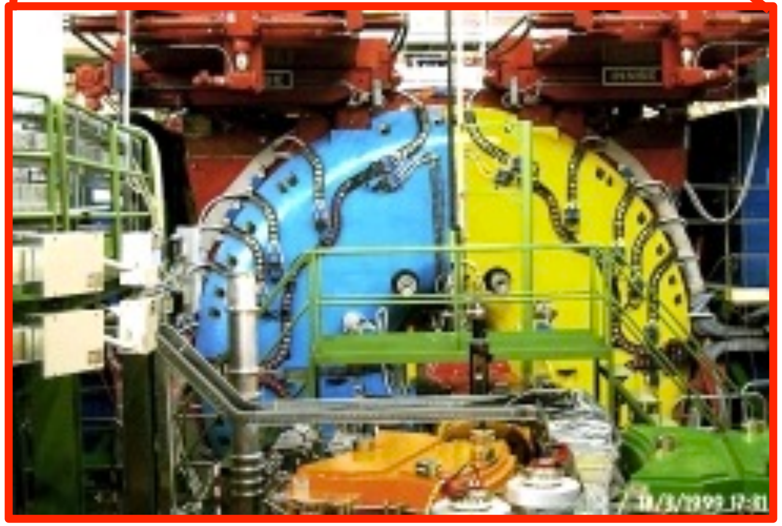
DAFNE collider



Integrated luminosity (KLOE)



KLOE detector



Total KLOE $\int \mathcal{L}\, dt \sim 2.5$ fb^{-1}
(2001 - 05) $\rightarrow$ $\sim 2.5 \times 10^9$ $K_S K_L$ pairs

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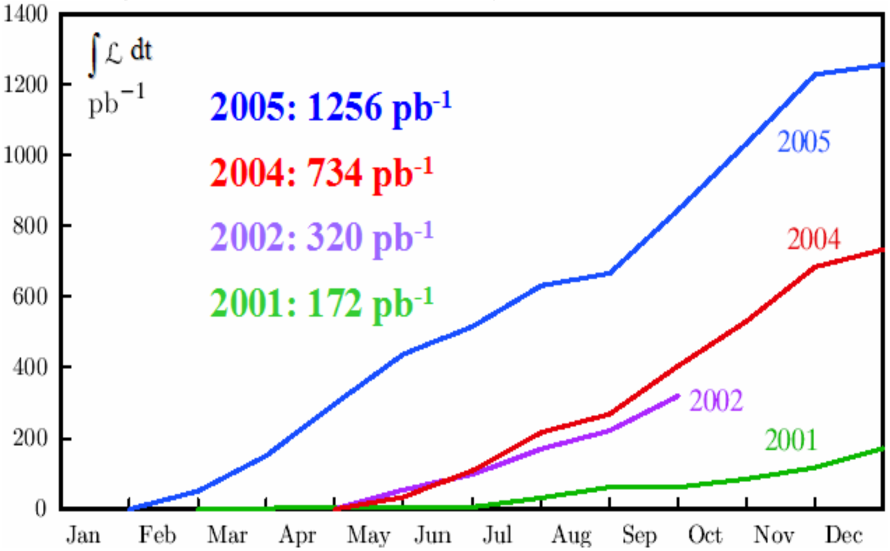

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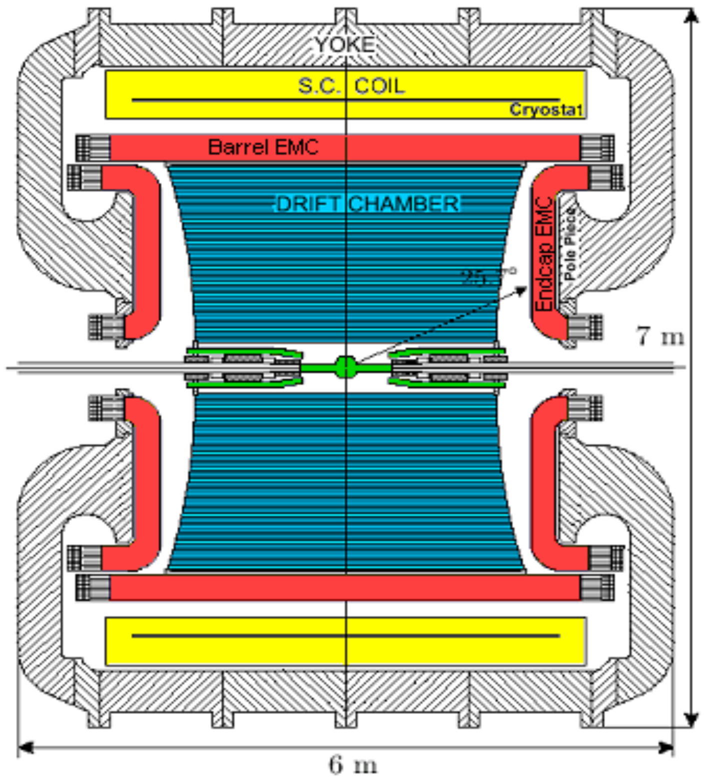


Lead/scintillating fiber calorimeter

drift chamber

4 m diameter × 3.3 m length

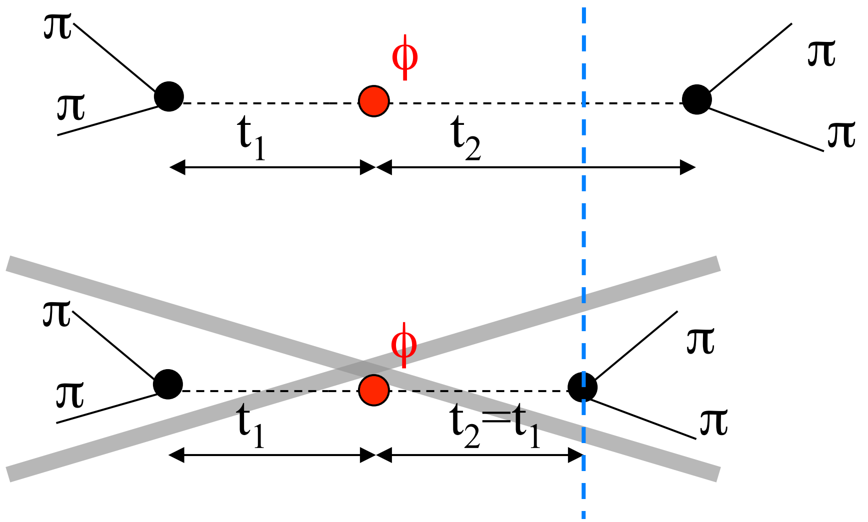
helium based gas mixture

Test of Quantum Coherence

EPR correlations in entangled neutral kaon pairs from ϕ

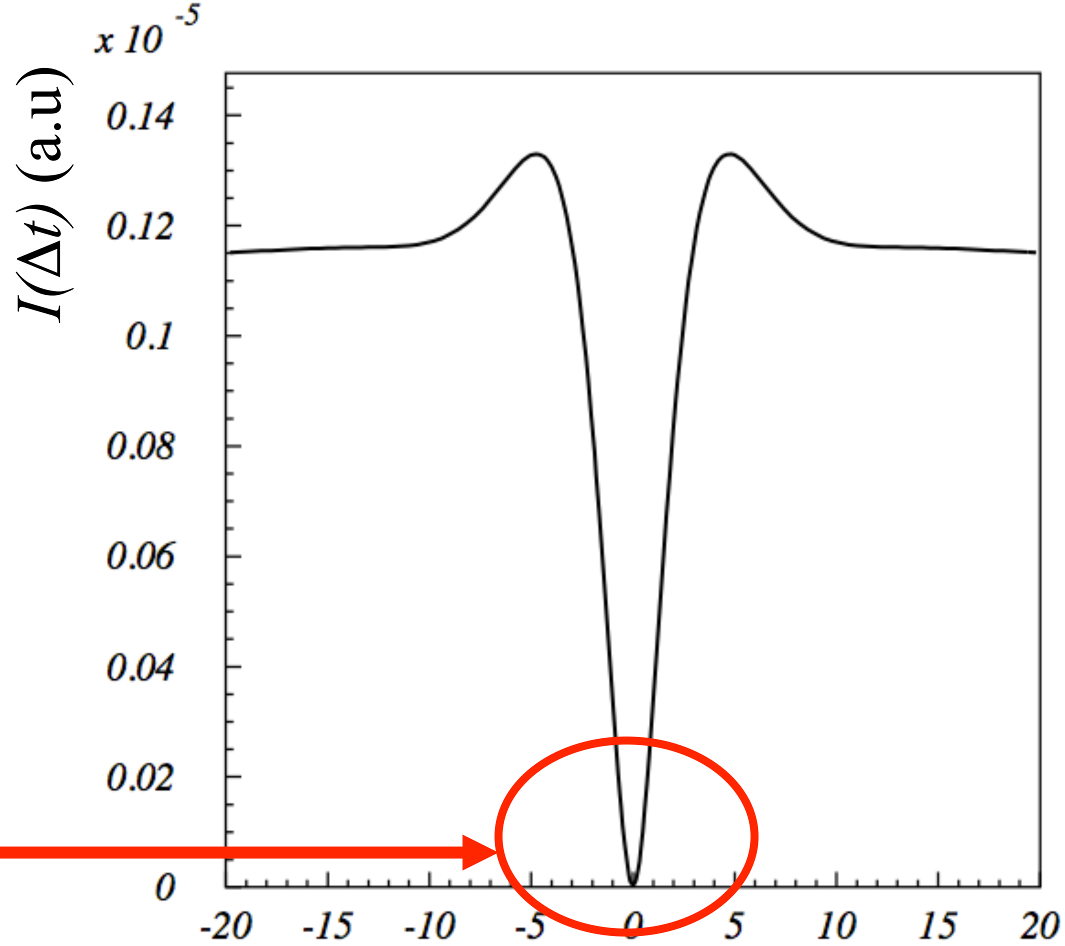
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$

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



EPR correlation:

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



$\Delta t = t_1 - t_2$

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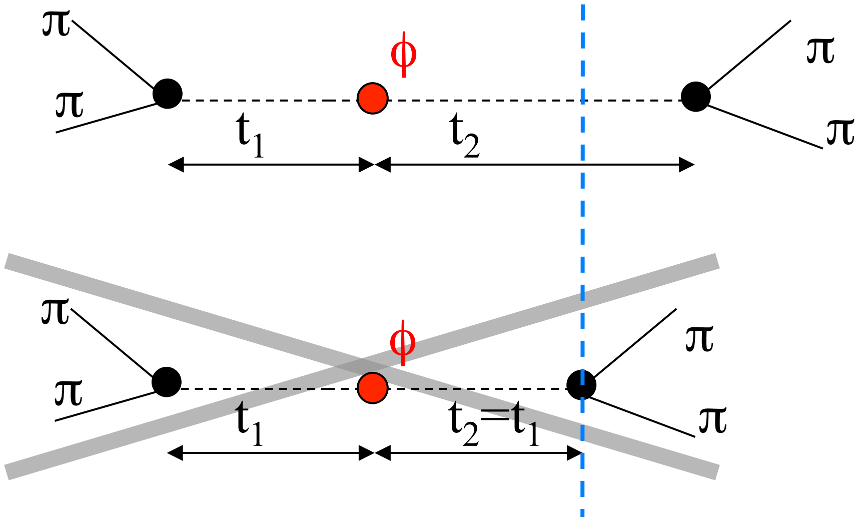

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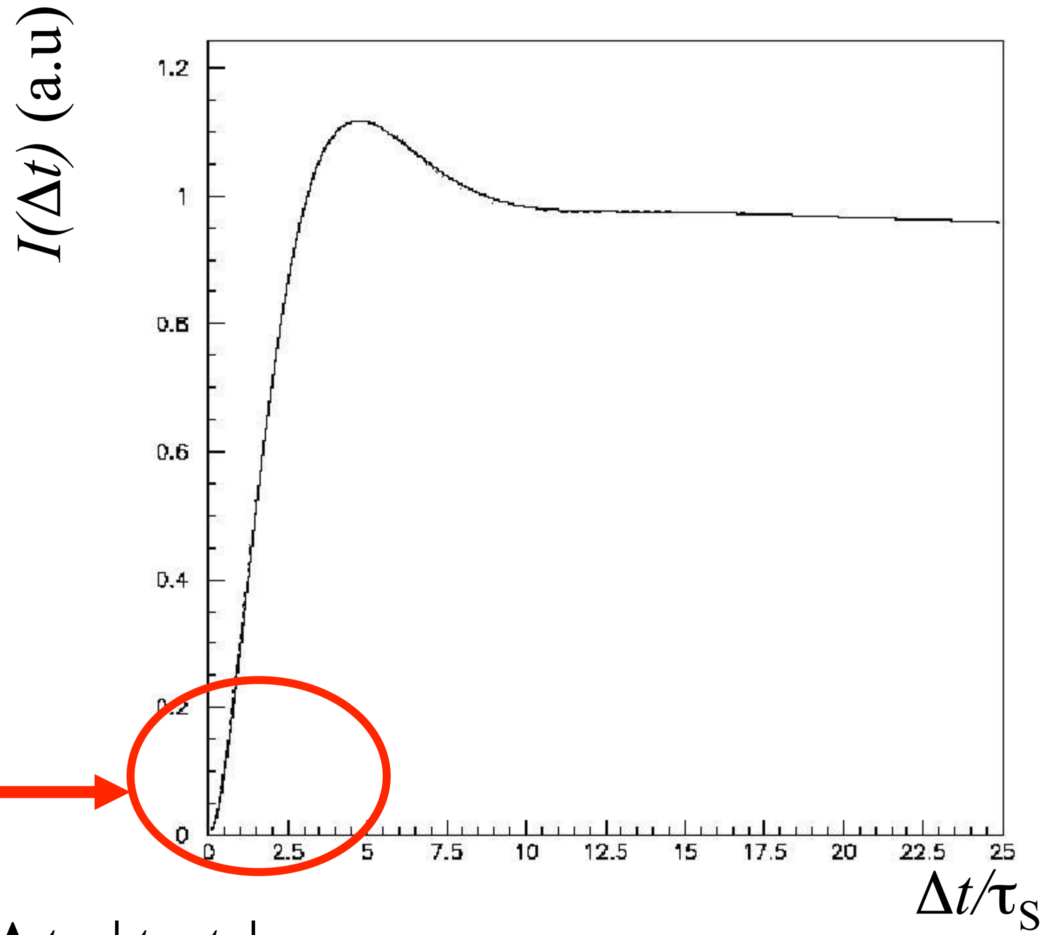

$\Delta t = |t_1 - t_2|$

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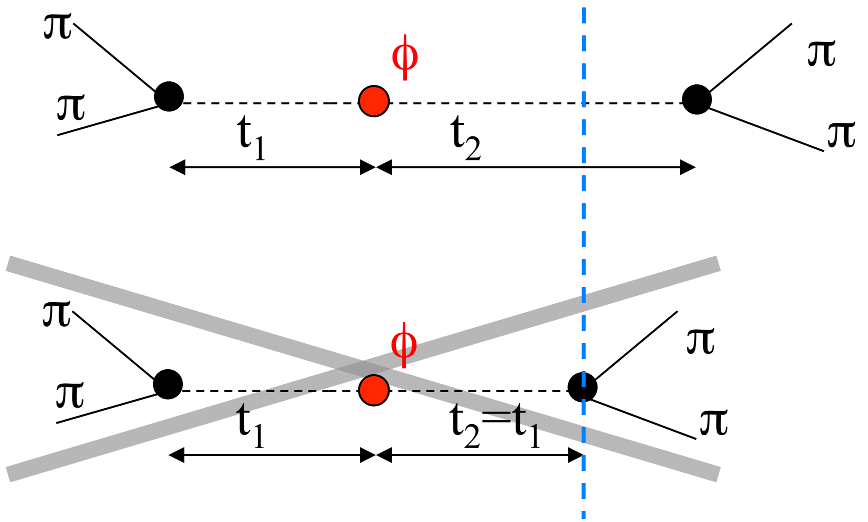

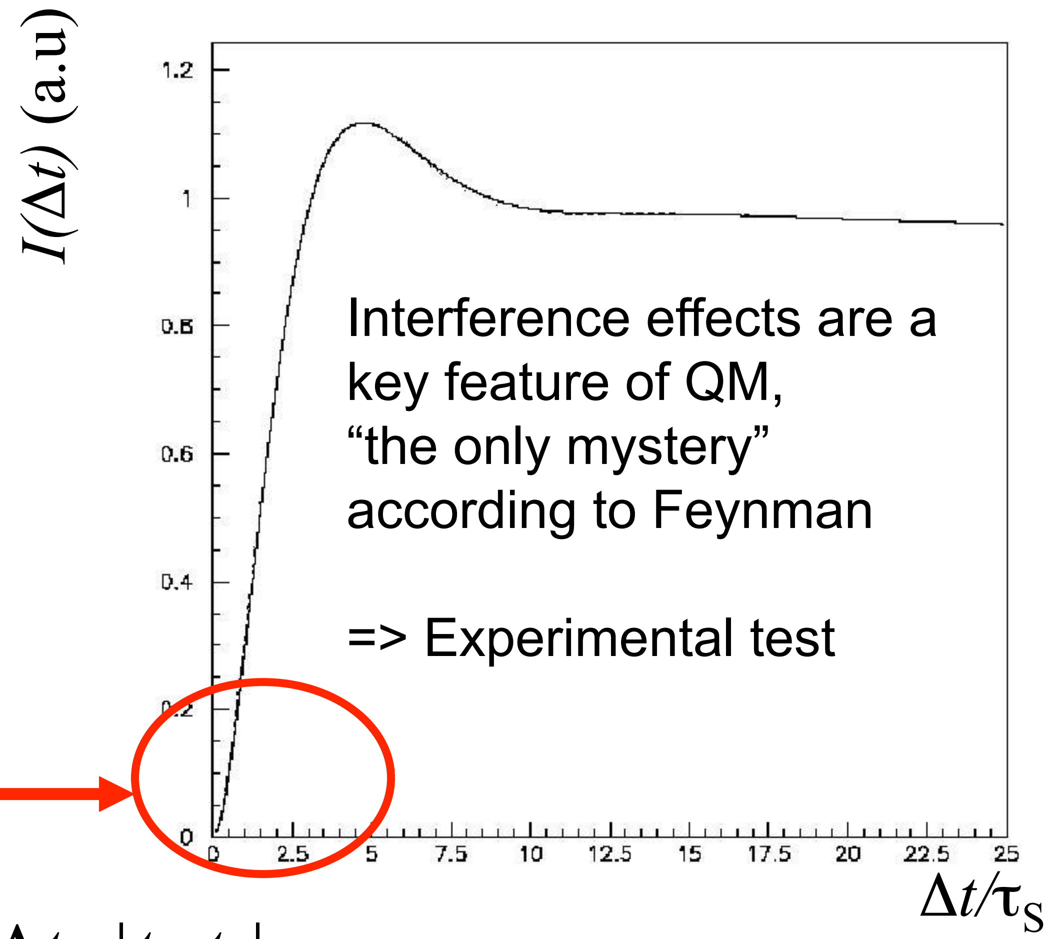

Interference effects are a key feature of QM, "the only mystery" according to Feynman

=> Experimental test

EPR correlation:

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

$\Delta t = |t_1 - t_2|$

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

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

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

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

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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]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

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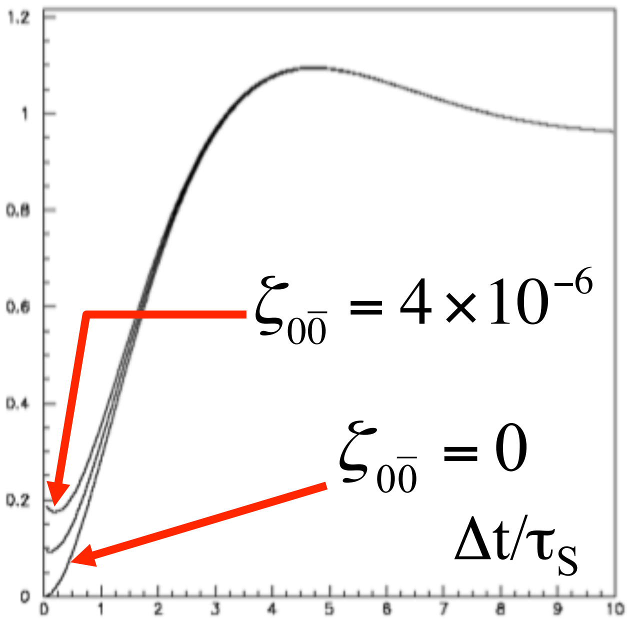
I(Δt) (a.u.)



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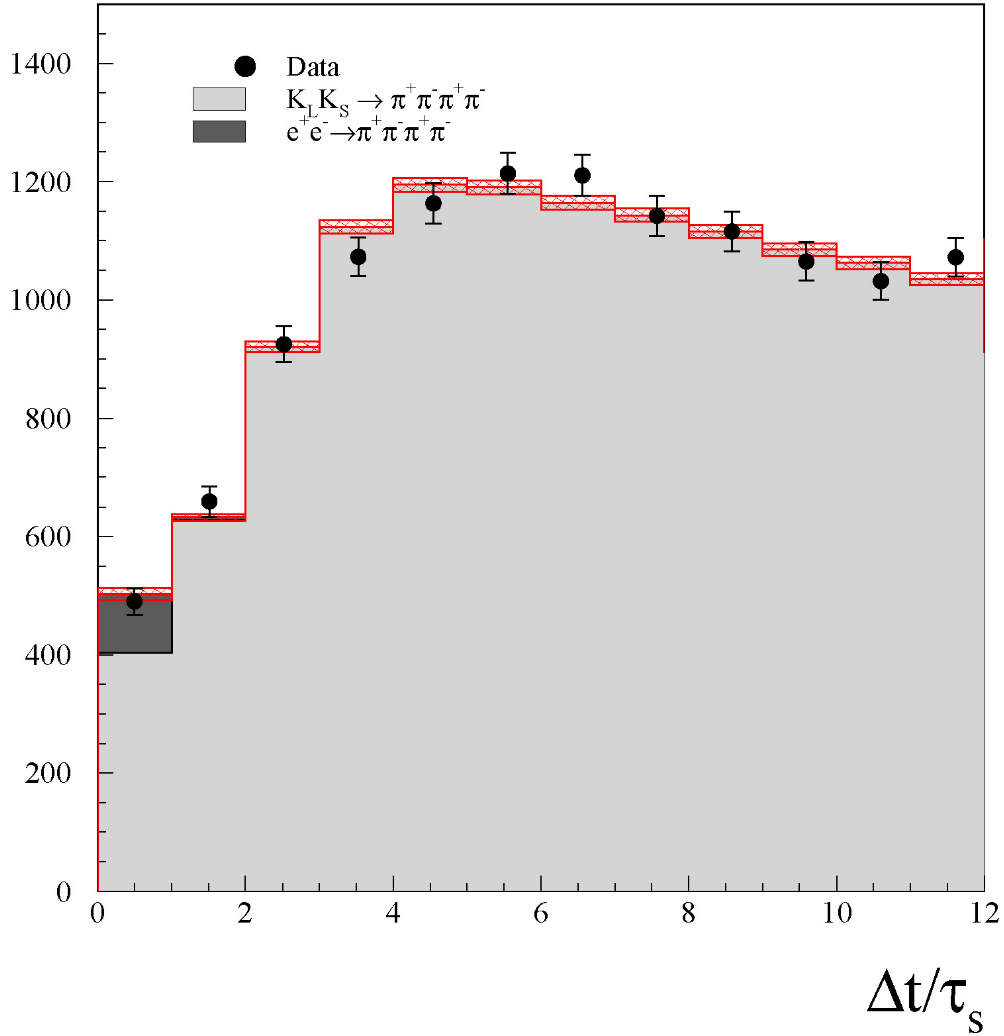
- Analysed data: L=1.5 fb^{-1}
- Fit including Δt resolution and efficiency effects + regeneration



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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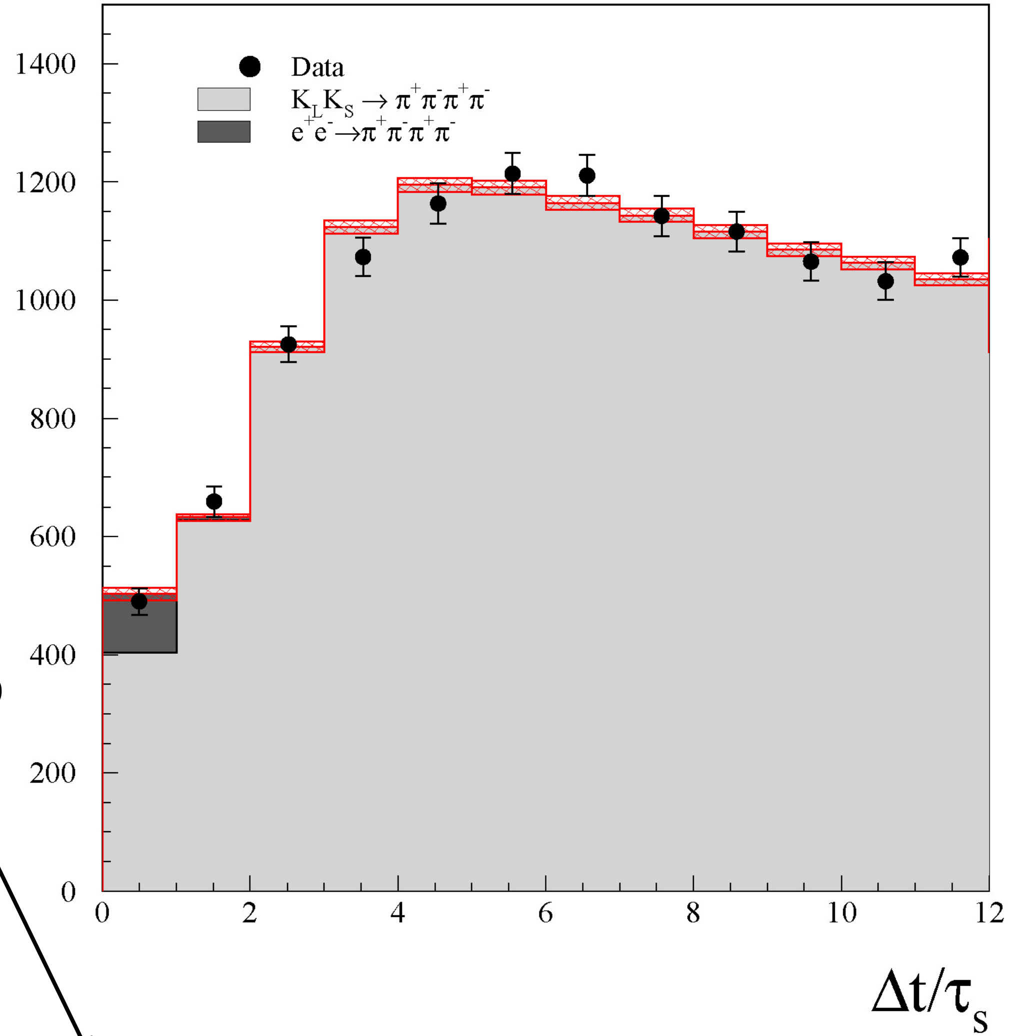

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Best precision achievable in an entangled system

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- Fit including Δt resolution and efficiency effects + regeneration

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

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

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

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:

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

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

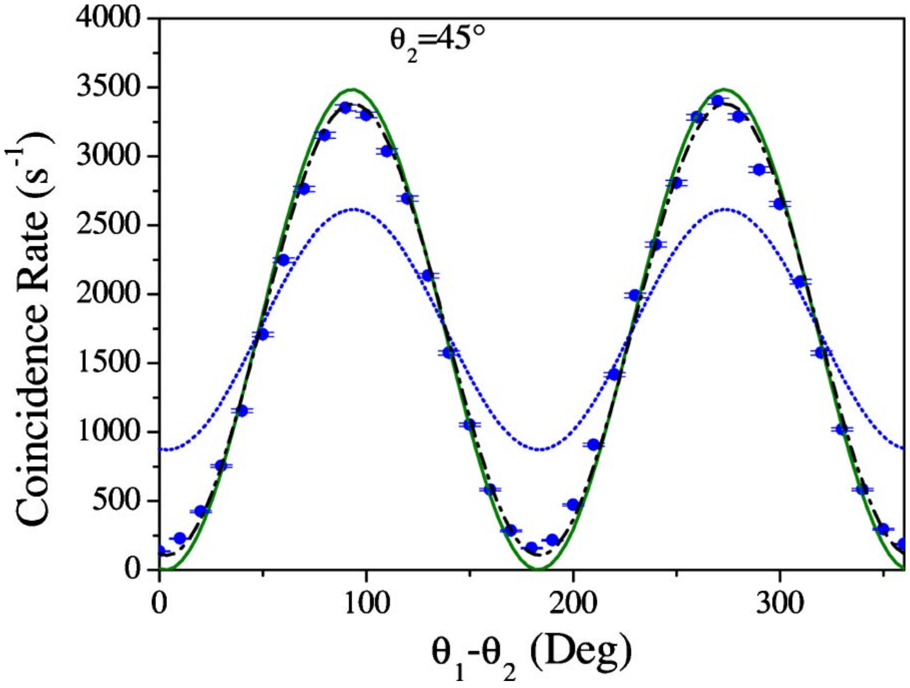

FIG. 2. Bell inequalities test. The selected state is $|\Phi^-\rangle = (1/\sqrt{2})(|H_1,H_2\rangle - |V_1,V_2\rangle)$.

$\Delta t/\tau_S$

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]

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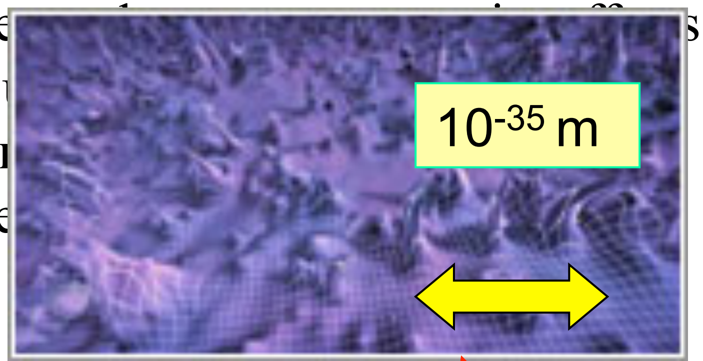
Possible decohere … s (BH evaporation)
(apparent loss of …
Black hole infor…
Possible decohere…



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

[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]

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

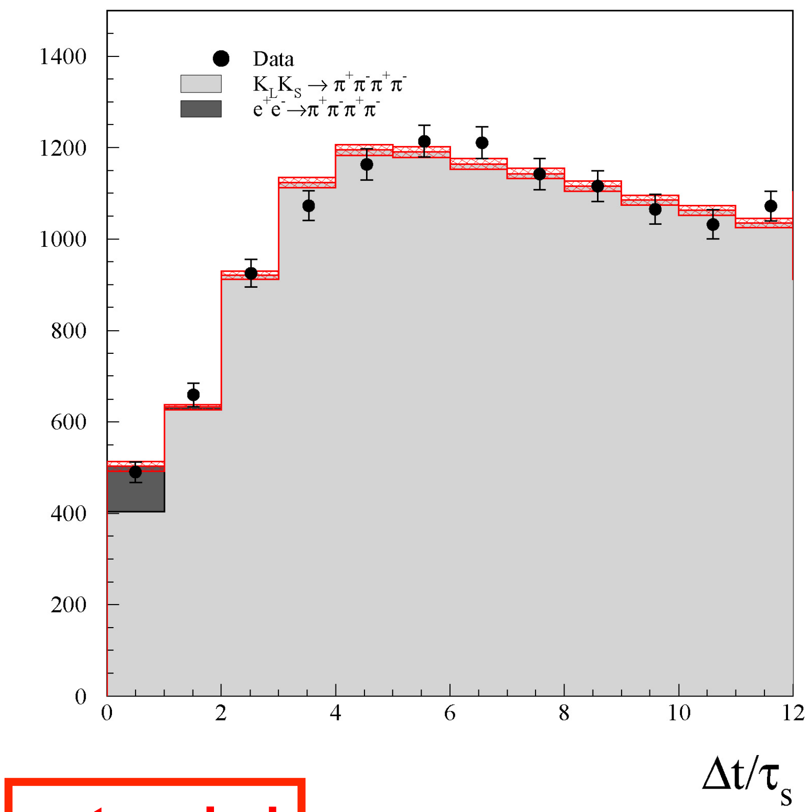
In the complete positivity hypothesis
$\alpha = \gamma$, $\beta = 0$
=> only one independent parameter: γ

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:

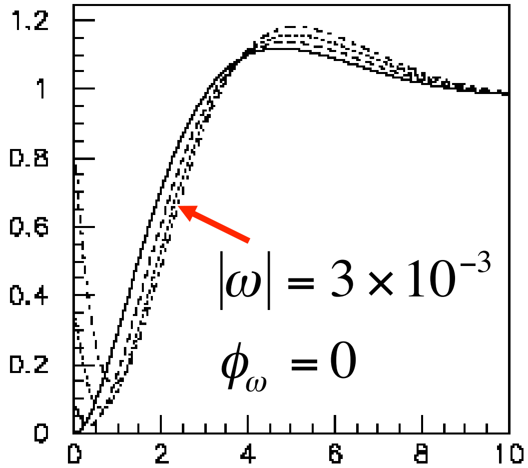
[Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

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

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.

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

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

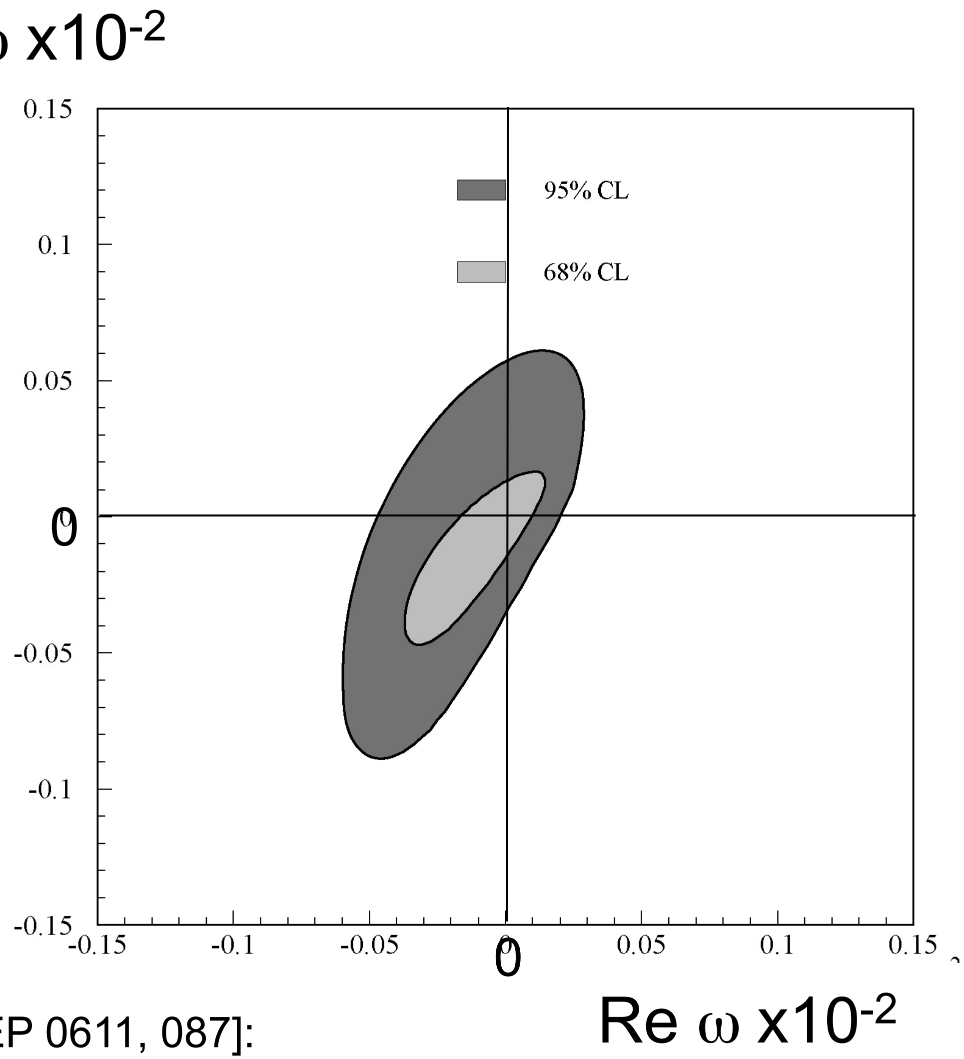
- Analysed data: 1.5 fb^{-1}

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

The Earth as a moving laboratory

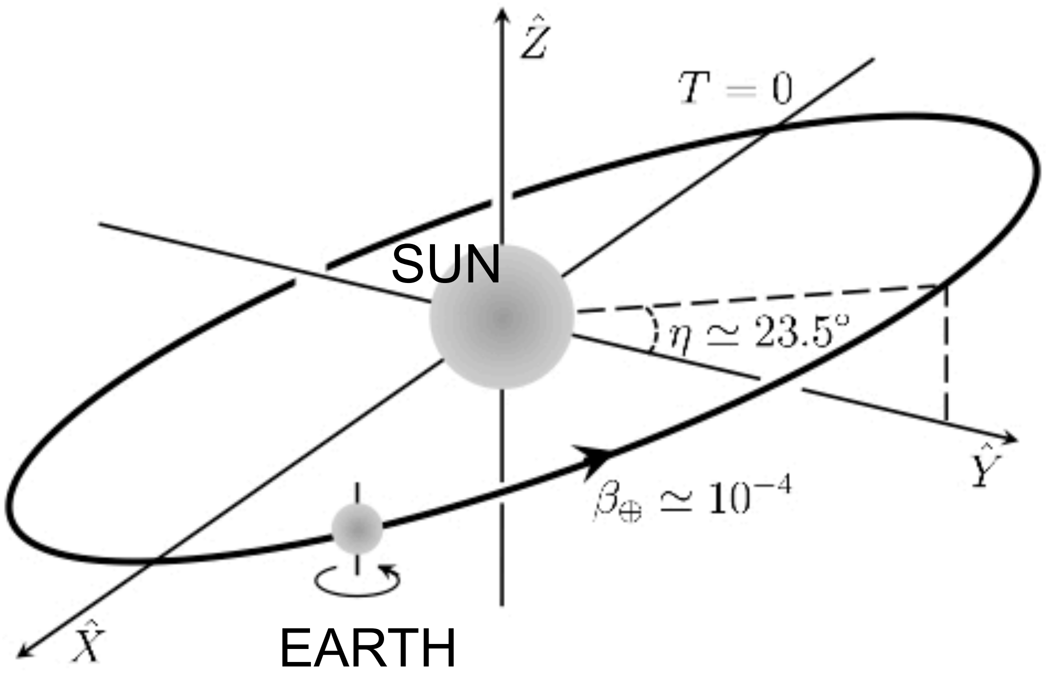
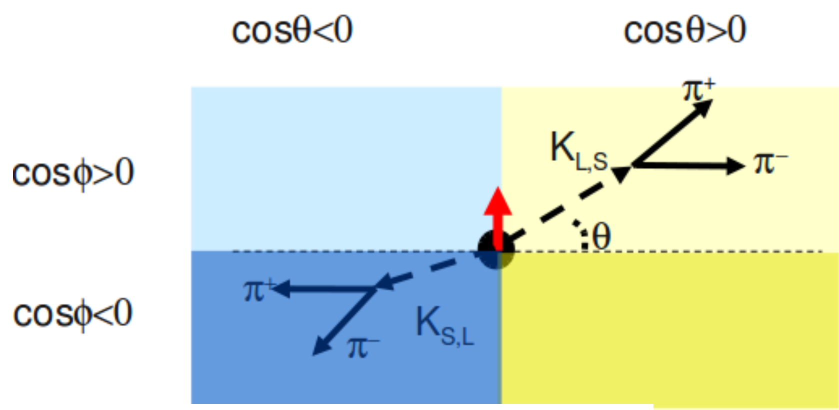


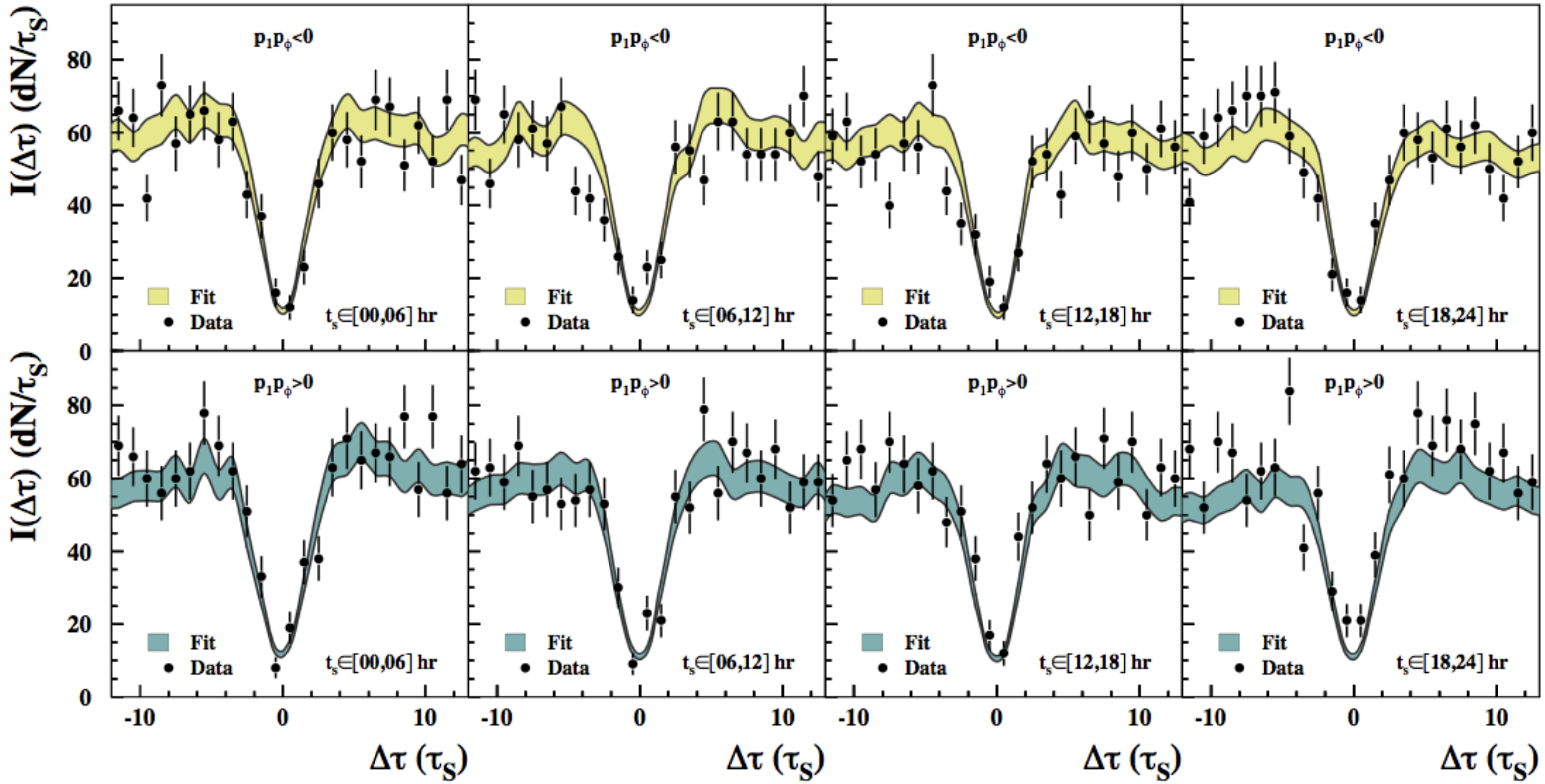
FIG. 1: Standard Sun-centered inertial reference frame [9].

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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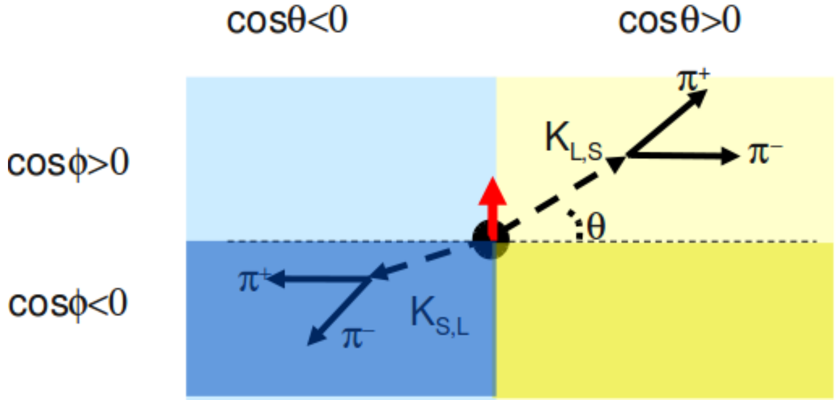


with L=1.7 fb^{-1} KLOE final result

PLB 730 (2014) 89–94

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

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

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

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

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

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**

B meson system:
$\Delta a^B_{x,y}$, $(\Delta a^B_0 - 0.30\ \Delta a^B_Z) \sim O(10^{-13}\ \text{GeV})$
[Babar PRL 100 (2008) 131802]
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

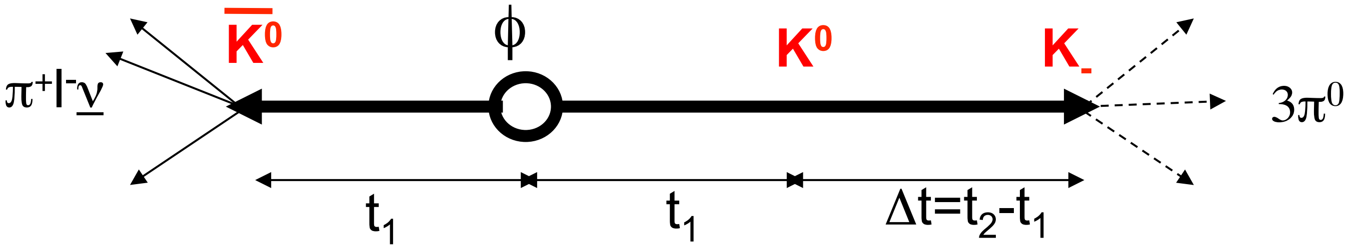
Direct test of CPT symmetry in neutral kaon transitions

- 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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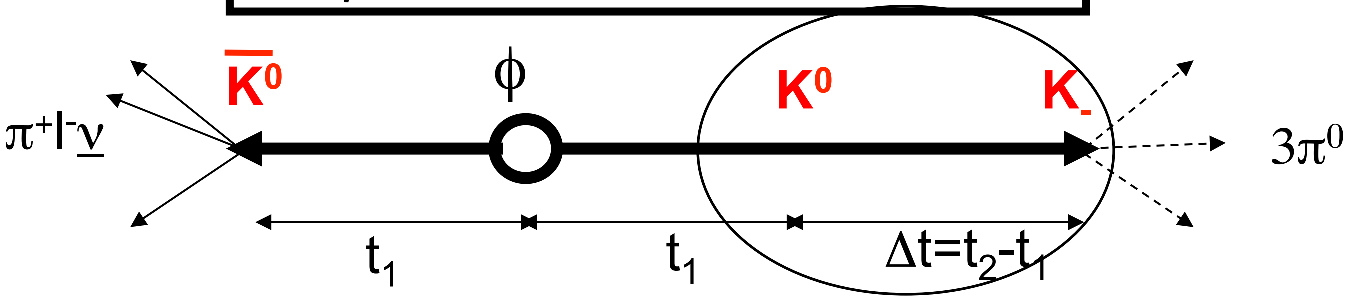

$K^0 \rightarrow K_-$ reference process

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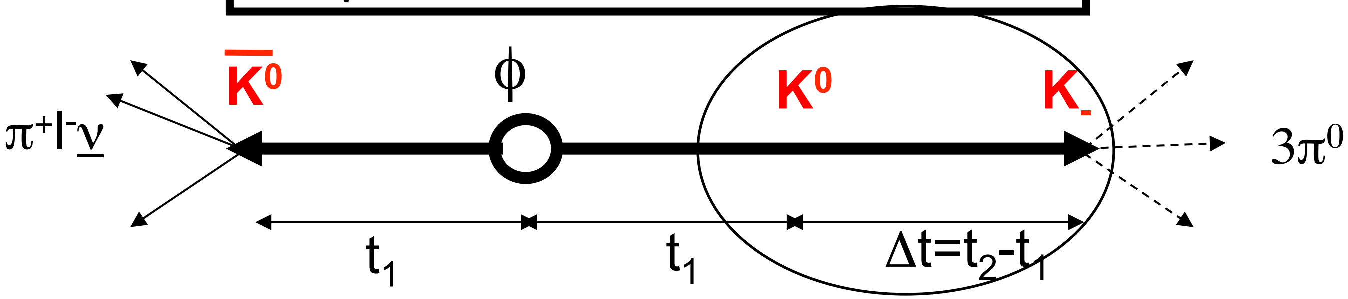
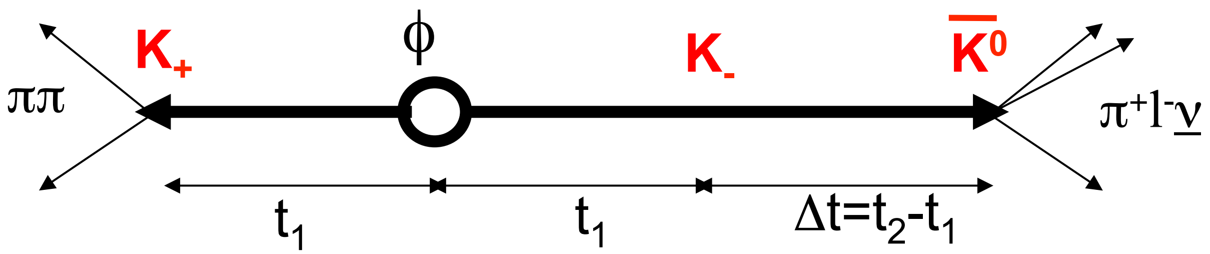


$K^0 \to K_-$ reference process



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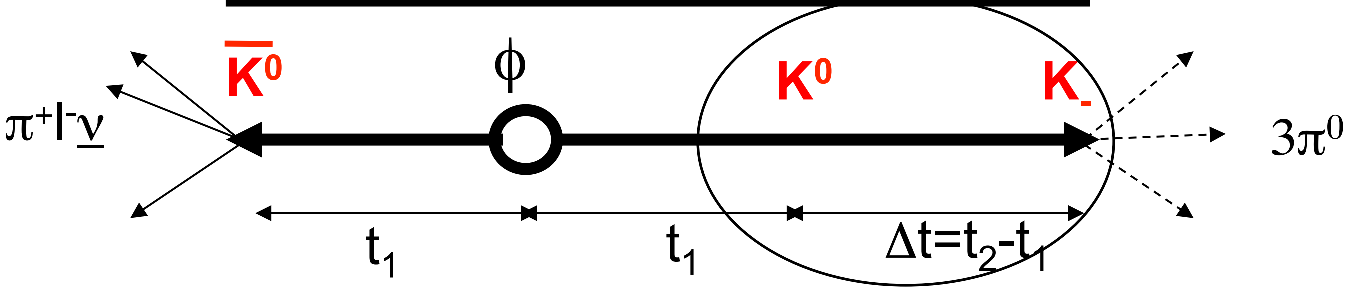
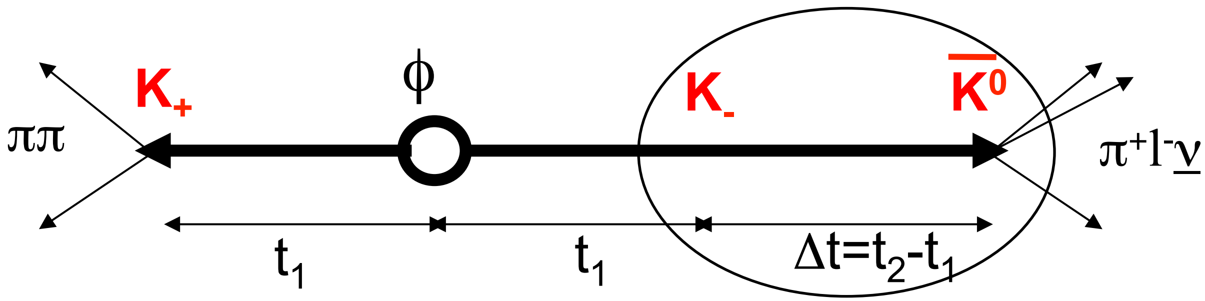
- decay as filtering measurement
- entanglement -> preparation of state



$K^0 \to K_-$ reference process

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



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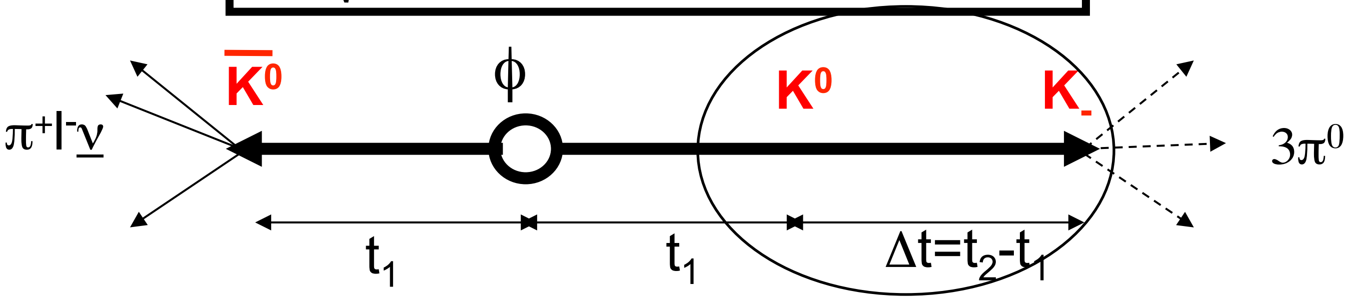
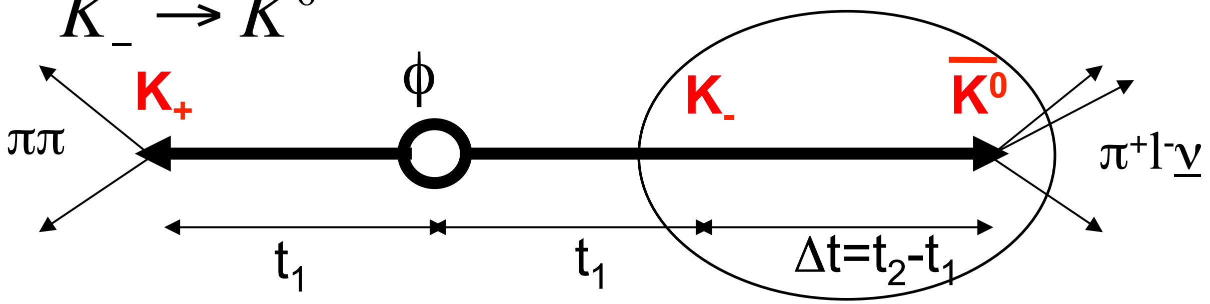


$K^0 \to K_-$ reference process

$K_- \to \bar{K}^0$ CPT-conjugated process

Note: CP and T conjugated process

$\bar{K}^0 \to K_- \qquad K_- \to K^0$



Direct test of CPT symmetry in neutral kaon transitions

CPT symmetry test

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

One can define the following ratios of probabilities:

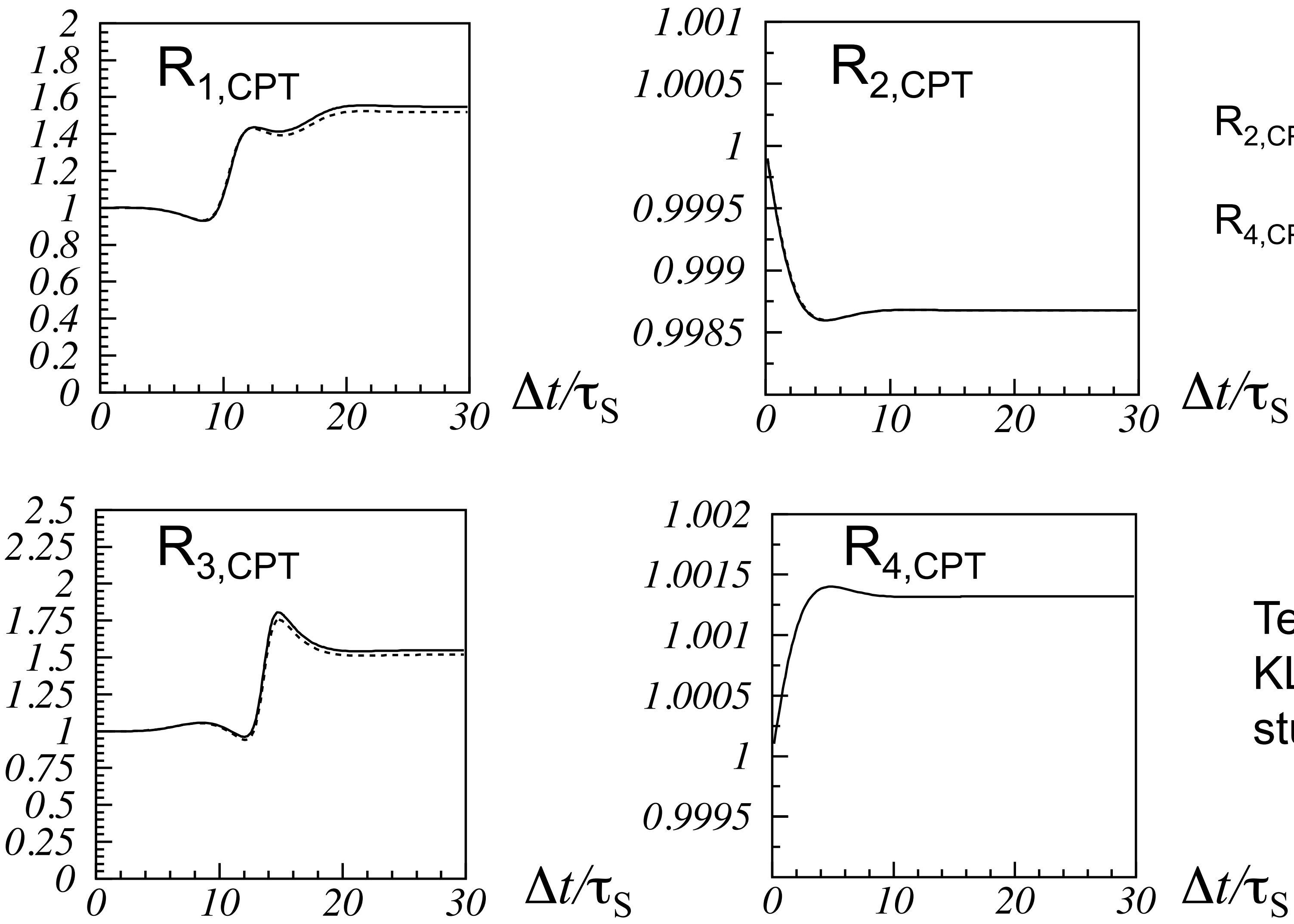
$$R_{1,\mathcal{CPT}}(\Delta t) = P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right]$$
$$R_{2,\mathcal{CPT}}(\Delta t) = P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]$$
$$R_{3,\mathcal{CPT}}(\Delta t) = P\left[K_+(0) \to K^0(\Delta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

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

J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102 **J. Bernabeu, A.D.D. in preparation**

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)



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

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

Test feasible at KLOE/KLOE-2 studies in progress !!

Future perspectives

KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:

- a new scheme of the interaction region has been implemented (crabbed waist scheme)
- increase of L by a factor ~ 3 demonstrated by an experimental test (without KLOE solenoid), PRL104, 174801, 2010.

KLOE-2 experiment:

- extend the KLOE physics program at DAΦNE upgraded in luminosity
- collect O(10) fb^{-1} of integrated luminosity in the next 2-3 years

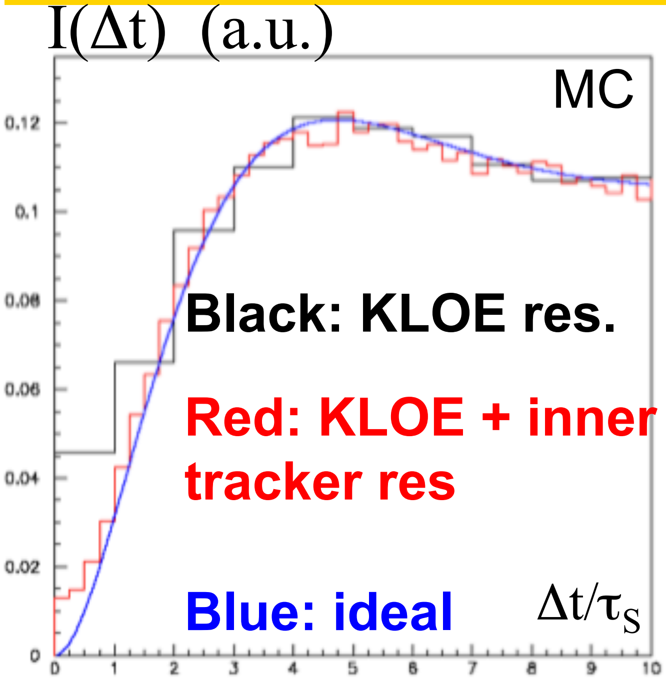
Physics program (see **EPJC 68 (2010) 619-681**)

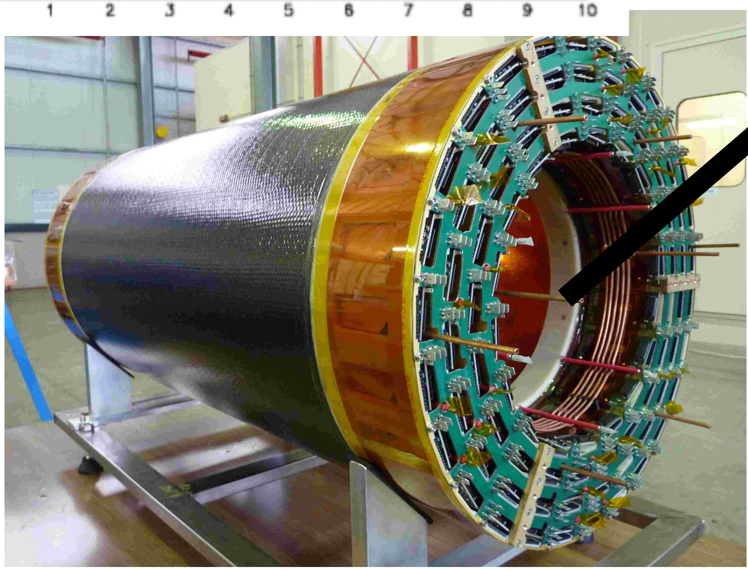
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, $\gamma\gamma$ physics
- Hadron cross section at low energy, a_μ
- Dark forces: search for light U boson

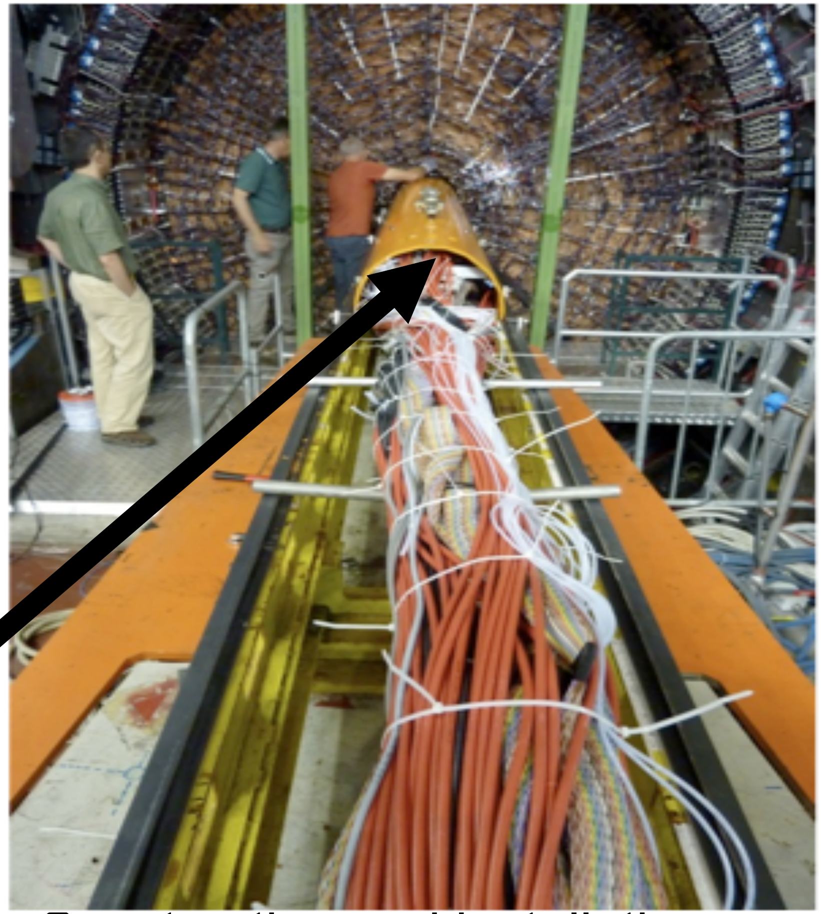
Detector upgrade:

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

Inner tracker at KLOE







-Construction and installation inside KLOE completed (July 2013)
- Data taking (started on Nov. 2014) and commissioning in progress
- ~ 1 fb^{-1} delivered up to now

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.)
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

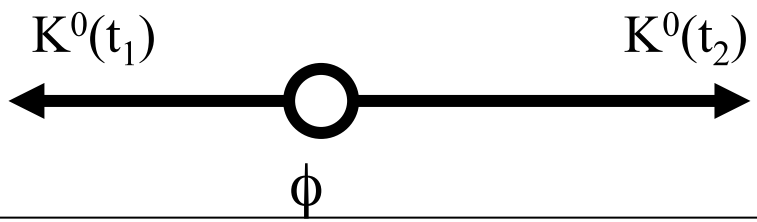
  have been measured at KLOE, in same cases with a precision reaching the interesting Planck's scale region;
- All results are consistent with no CPT symmetry violation and no decoherence

- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program. (G. Amelino-Camelia et al. EPJC 68 (2010) 619-681)
- The precision of several tests could be improved by about one order of magnitude

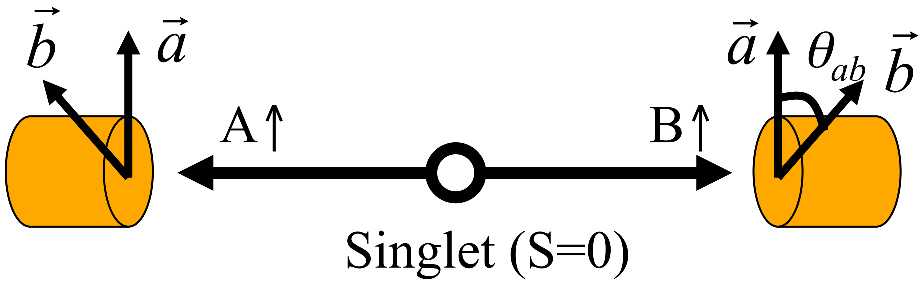
Spare slides

Analogy with spin ½ particles

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



$$|S=0\rangle = \frac{1}{\sqrt{2}}\left[|A\uparrow\rangle|A\downarrow\rangle - |A\downarrow\rangle|A\uparrow\rangle\right]$$



$$P(K^0,t_1;K^0,t_2) = \frac{1}{4}\left[1-\cos(\Delta m(t_1-t_2))\right]$$

ideal case with $\Gamma_S = \Gamma_L = 0$ (no decay!)

$$P(A\uparrow;B\uparrow) = \frac{1}{4}\left[1-\cos(\theta_{ab})\right]$$

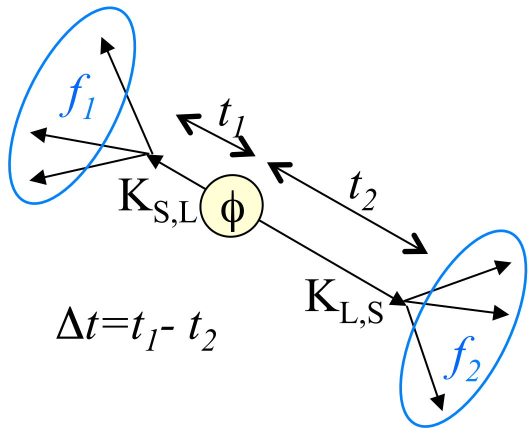
The time difference plays the same role as the angle between the spin analyzers

with the actual Γ_S and Γ_L (kaons decay!):

$$P(K^0,t_1;K^0,t_2) = \frac{1}{8}\left\{e^{-\Gamma_L t_1-\Gamma_S t_2} + e^{-\Gamma_S t_1-\Gamma_L t_2} - 2e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2}\cos\left[\Delta m(t_2-t_1)\right]\right\}$$

kaons change their identity with time, but remain correlated

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:

$$I(f_1,t_1;f_2,t_2) = C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2}\right.$$

$$\left. -2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2}\cos\left[\Delta m(t_2 - t_1) + \phi_1 - \phi_2\right]\right\}$$

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

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

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

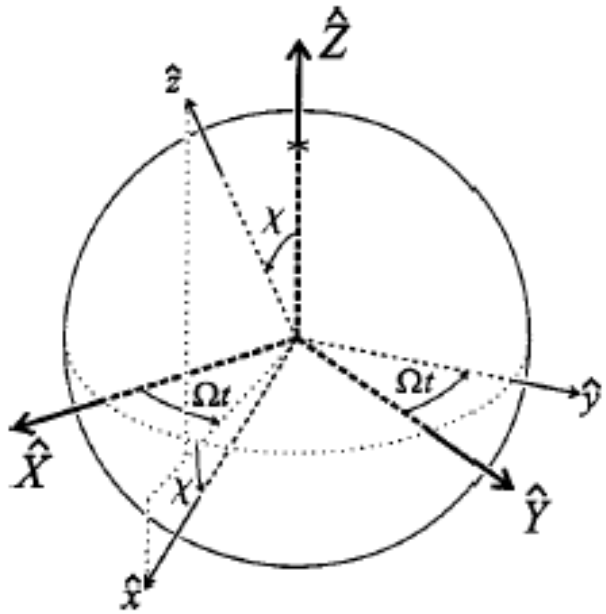
characteristic interference term at a ϕ-factory => interferometry

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

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)

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

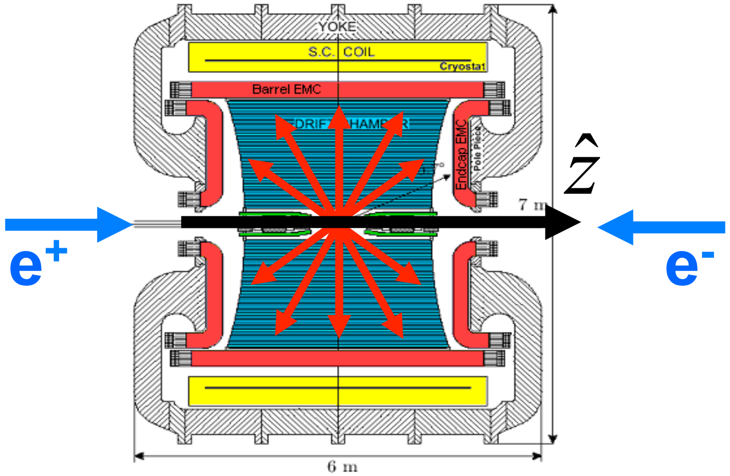
Ω: Earth's sidereal frequency   χ : angle between the z lab. axis and the Earth's rotation axis

Search for CPT and Lorentz invariance violation (SME)

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

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:

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



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

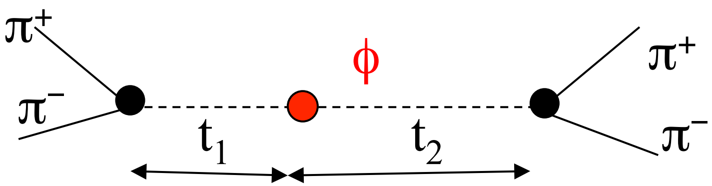
Ω: Earth's sidereal frequency   χ : angle between the z lab. axis and the Earth's rotation axis

Search for CPTV and LV: exploiting EPR correlations

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

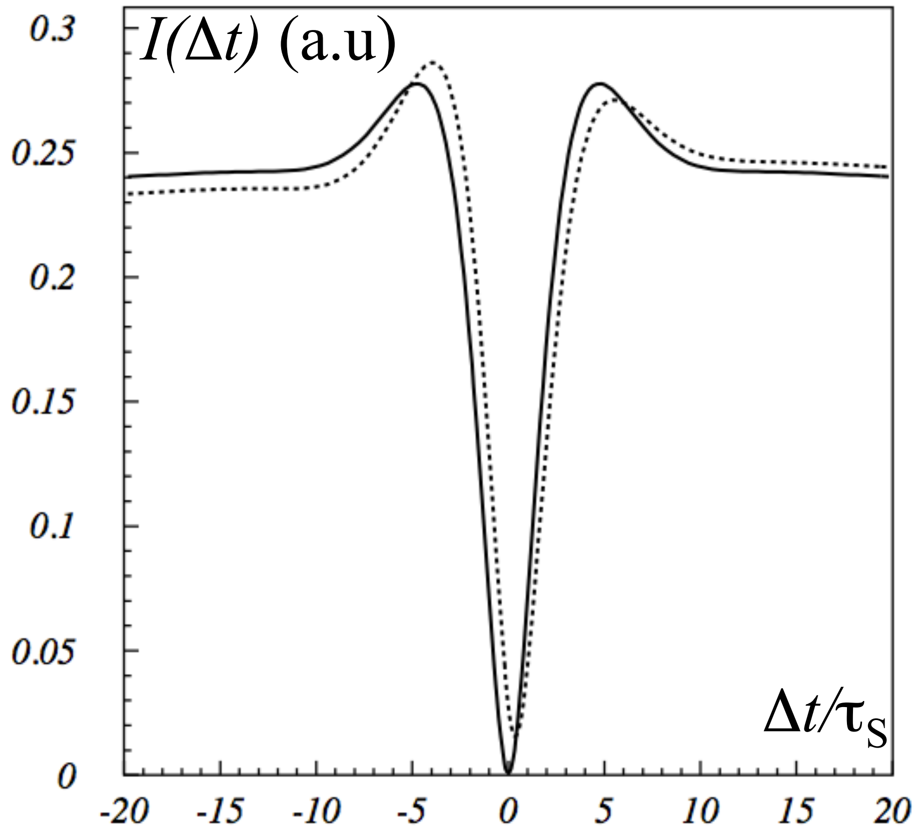
$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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



$$\eta_{+-}^{(1)} = \varepsilon\left(1 - \delta(+\vec{p}, t)/\varepsilon\right)$$

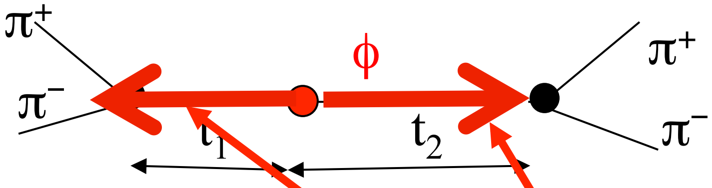
$$\eta_{+-}^{(2)} = \varepsilon\left(1 - \delta(-\vec{p}, t)/\varepsilon\right)$$



Search for CPTV and LV: exploiting EPR correlations

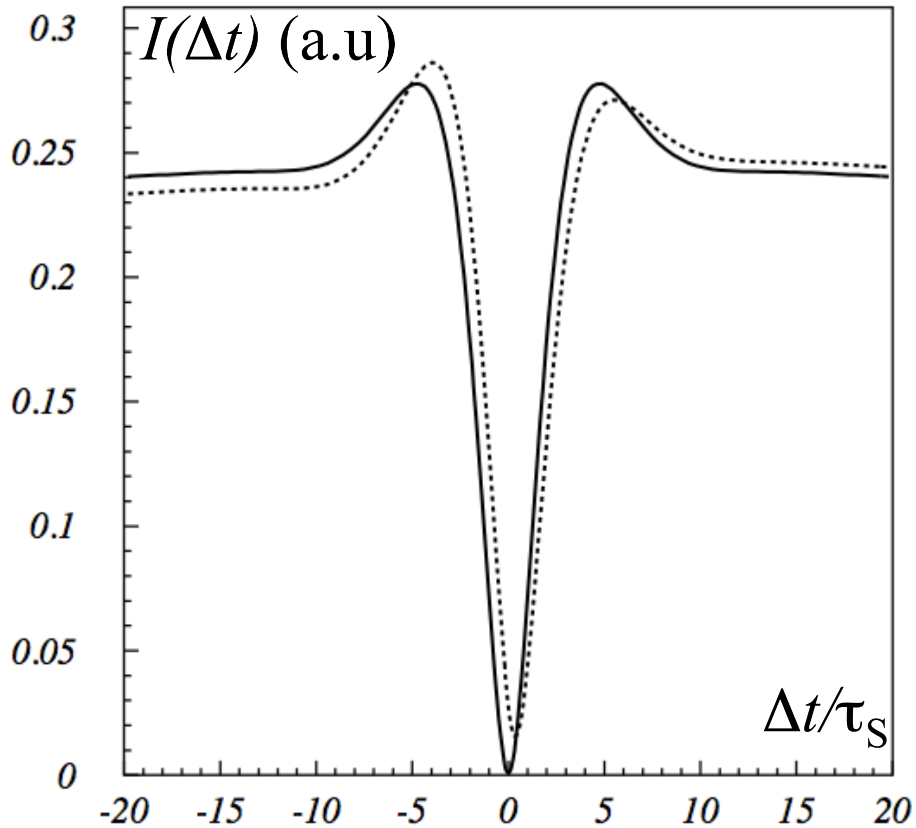
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right] \qquad \eta_i = |\eta_i|e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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



$$\eta_{+-}^{(1)} = \varepsilon\left(1 - \delta(+\vec{p},t)/\varepsilon\right)$$

$$\eta_{+-}^{(2)} = \varepsilon\left(1 - \delta(-\vec{p},t)/\varepsilon\right)$$

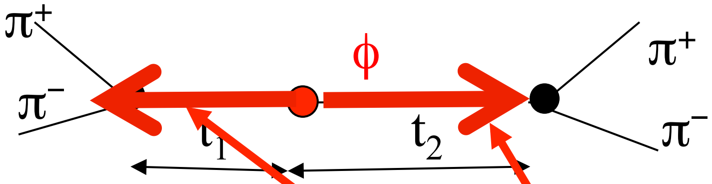


Search for CPTV and LV: exploiting EPR correlations

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

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

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

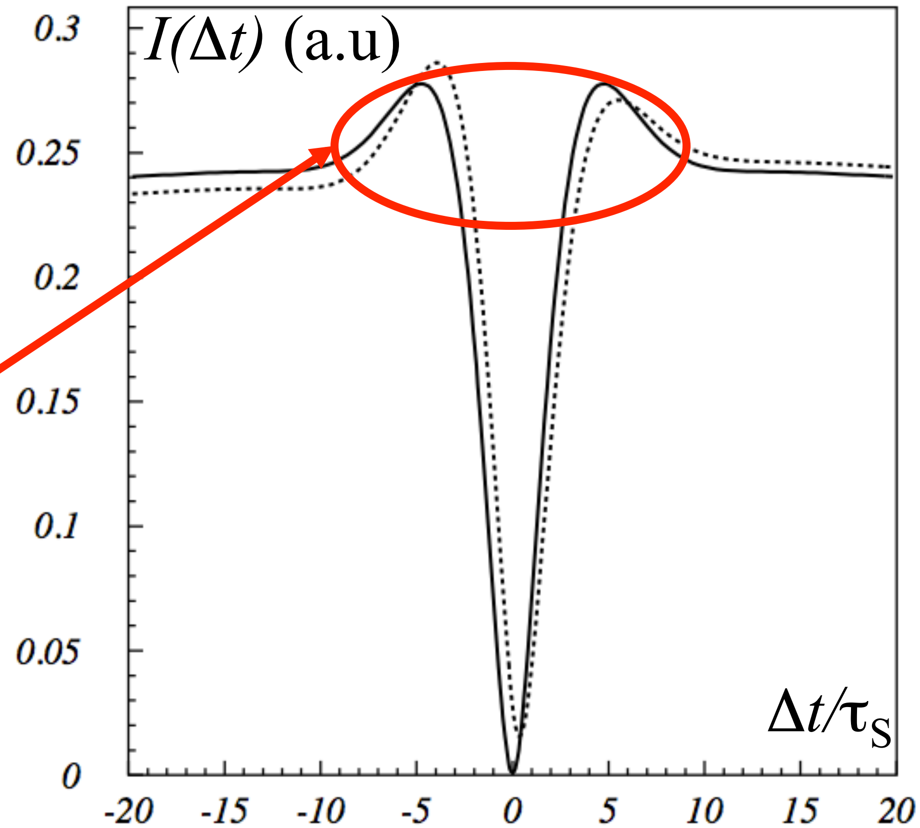


$$\eta_{+-}^{(1)} = \varepsilon\left(1 - \delta(+\vec{p}, t)/\varepsilon\right)$$

$$\eta_{+-}^{(2)} = \varepsilon\left(1 - \delta(-\vec{p}, t)/\varepsilon\right)$$

$\Im(\delta/\varepsilon)$
from the asymmetry at **small** Δt

$\Re(\delta/\varepsilon) \approx 0$ because $\delta \perp \varepsilon$
from the asymmetry at **large** Δt



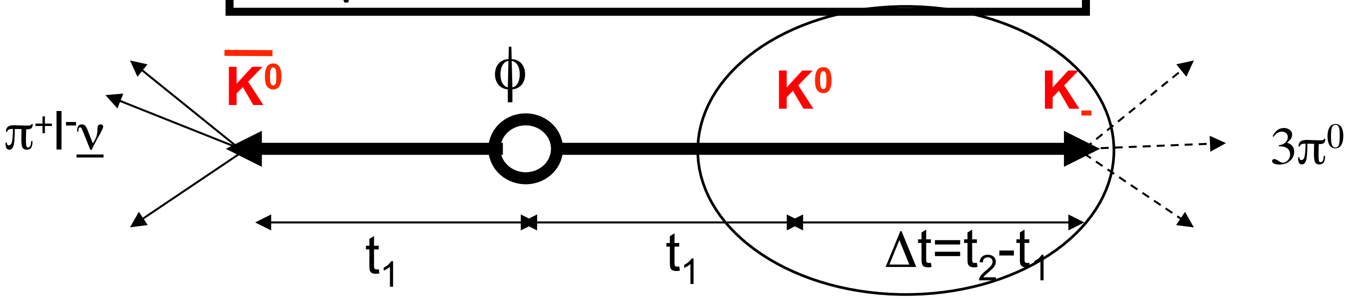
Direct test of CPT symmetry in neutral kaon transitions

- 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



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

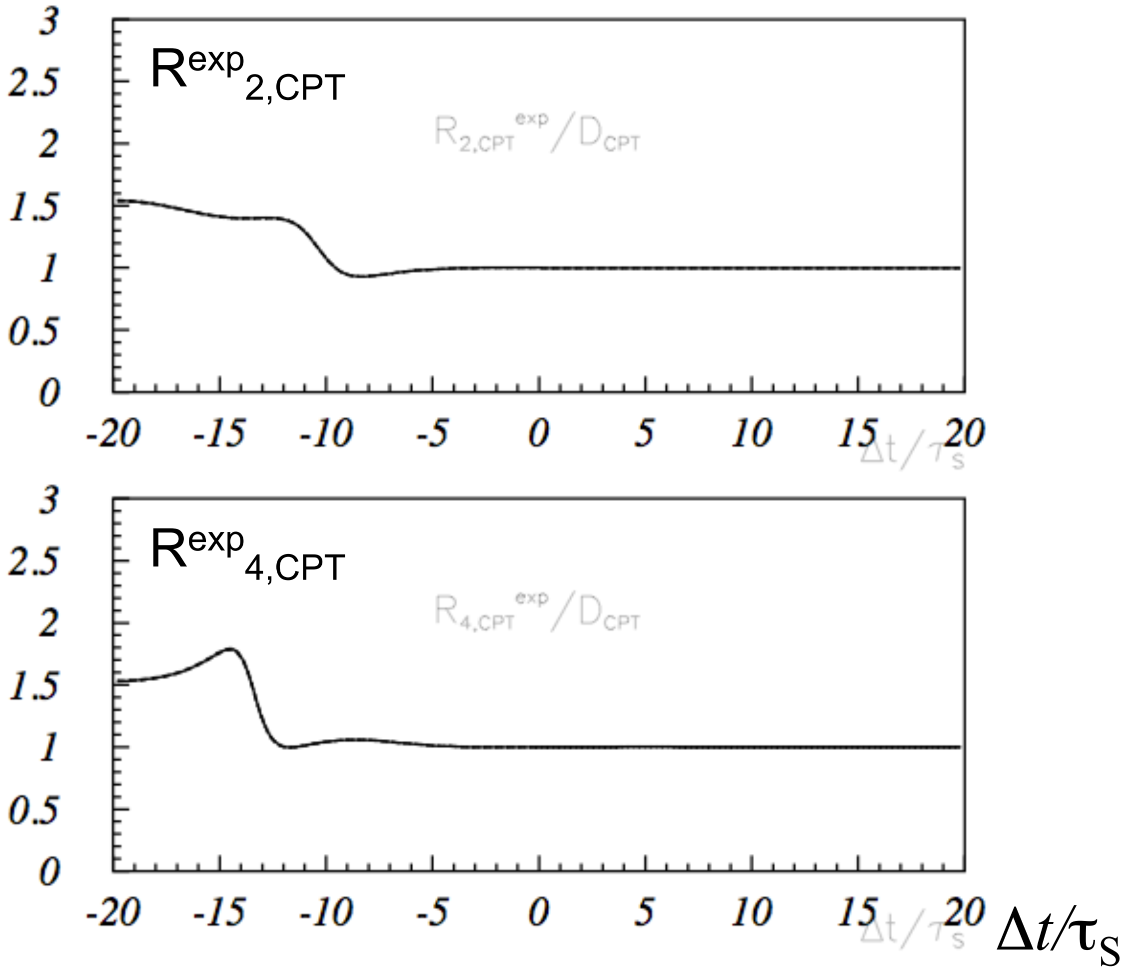
In general with $f_{\underline{X}}$ decayng before f_Y, i.e. $\Delta t>0$ $\quad$ ($K_{X,Y} = K^0$, $\underline{K}^0$, K_+ , K_-) :

$$I(f_{\bar{X}}, f_Y; \Delta t) = C(f_{\bar{X}}, f_Y) \times P\left[\mathrm{K_X}(0) \rightarrow \mathrm{K_Y}(\Delta t)\right]$$

with $C(f_{\bar{X}}, f_Y) = \frac{1}{2(\Gamma_S + \Gamma_L)} \left|\langle f_{\bar{X}}|T|\bar{\mathrm{K}}_\mathrm{X}\rangle\langle f_Y|T|\mathrm{K_Y}\rangle\right|^2$

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}



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

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

$$R^{\rm exp}_{2,\mathcal{CPT}}(\Delta t) = R_{2,\mathcal{CPT}}(\Delta t) \times D_{\mathcal{CPT}}$$

$$R^{\rm exp}_{4,\mathcal{CPT}}(\Delta t) = R_{4,\mathcal{CPT}}(\Delta t) \times D_{\mathcal{CPT}}$$

$$R^{\rm exp}_{2,\mathcal{CPT}}(-\Delta t) = R_{1,\mathcal{CPT}}(|\Delta t|) \times D_{\mathcal{CPT}}$$

$$R^{\rm exp}_{4,\mathcal{CPT}}(-\Delta t) = R_{3,\mathcal{CPT}}(|\Delta t|) \times D_{\mathcal{CPT}}$$

Test feasible at KLOE-2, studies in progress !!