Search for CPT and Lorentz symmetry violation effects in entangled neutral K mesons

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Testing CPT: introduction

CPT theorem holds for any QFT formulated on flat space-time which assumes:
(1) Lorentz invariance (2) Locality (3) Unitarity (i.e. conservation of probability).
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
⇒ 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 $\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$

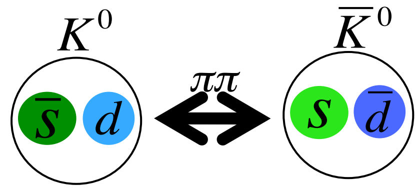
proton- anti-proton $\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$

Many other interesting CPT tests: see other presentations to this workshop

The neutral kaon system: introduction

The time evolution of a two-component state vector $|\Psi\rangle = a|K^0\rangle + b|\bar{K}^0\rangle$ in the $\{K^0, \bar{K}^0\}$ 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 $\tau_L \sim 51$ ns

$K_L \to \pi\pi$ violates CP

eigenstates

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

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

$|K_{1,2}\rangle$ are CP=±1 states

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

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

CPT violation: standard picture

CP violation:

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

T violation:

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

CPT violation:

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

- $\delta \neq 0$ 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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CP violation:

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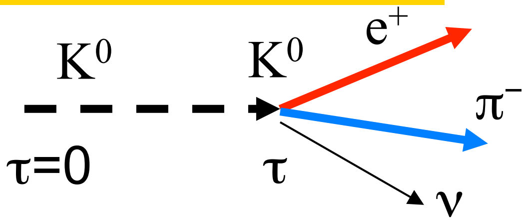
neutral kaons vs other oscillating meson systems

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

"Standard" CPT test

Comparing "survival" probabilities of K^0 and $\bar{K}^0$ measuring semileptonic decays vs time: $\Re\delta = (3.0 \pm 3.3 \pm 0.6) \times 10^{-4}$



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

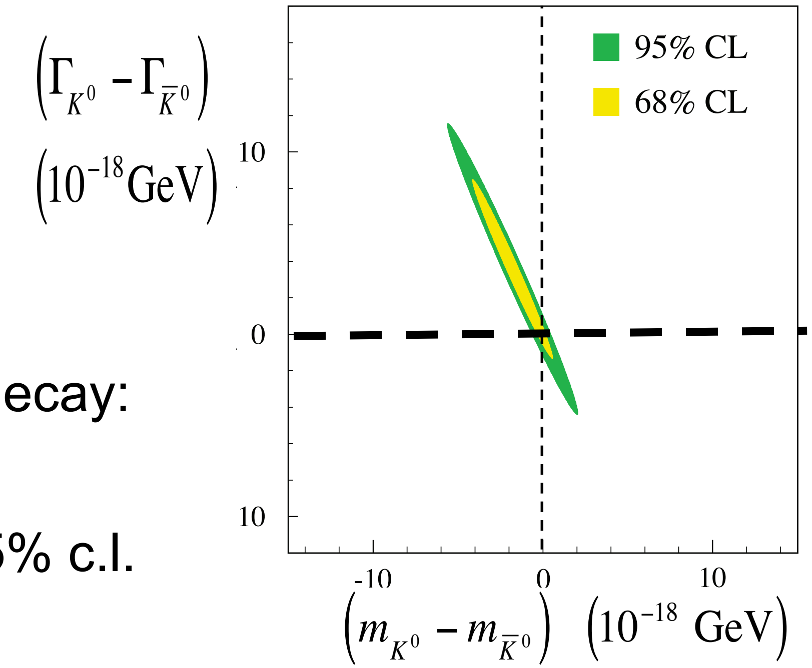
$$2\Im\delta = \Im\left[\langle K_L | K_S \rangle\right] = \Im\left[\frac{\sum_f \langle f|T|K_S\rangle \langle f|T|K_L\rangle^*}{i\left(\lambda_S - \lambda_L^*\right)}\right]$$

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

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:

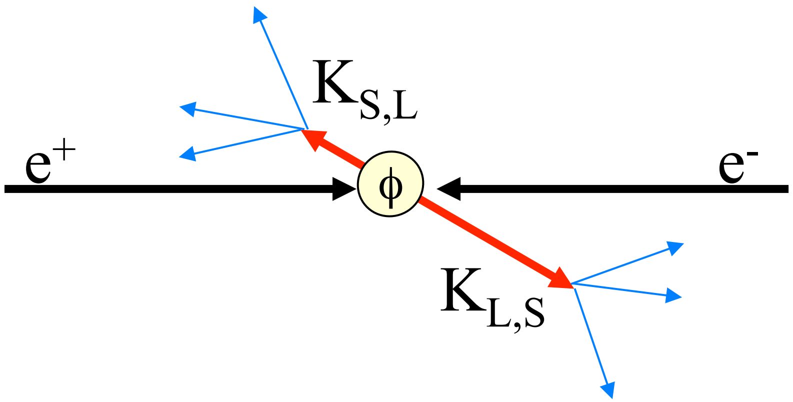
$$\left|m_{\bar{K}^0} - m_{K^0}\right| < 4.0 \times 10^{-19}\ \ \mathrm{GeV}$$ at 95% c.l.

Entangled neutral kaon pairs

Neutral kaons at a ϕ-factory

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

- $e^+e^- \to \phi$ $\sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ 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 $J^{PC} = 1^{--}$:



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

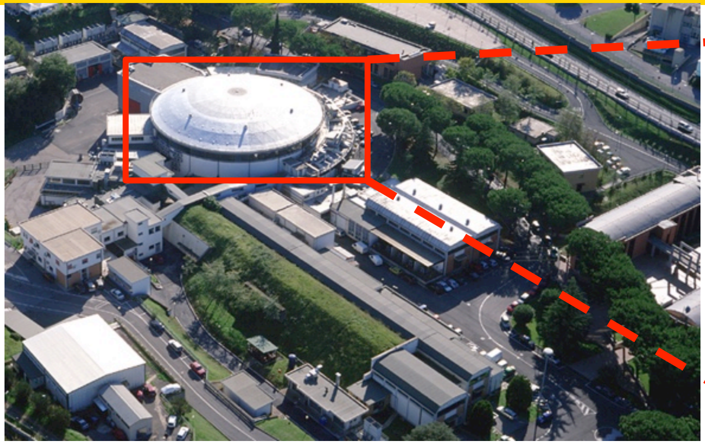
$$= \frac{N}{\sqrt{2}}\left[\left|K_S(\vec{p})\right\rangle\left|K_L(-\vec{p})\right\rangle - \left|K_L(\vec{p})\right\rangle\left|K_S(-\vec{p})\right\rangle\right]$$

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

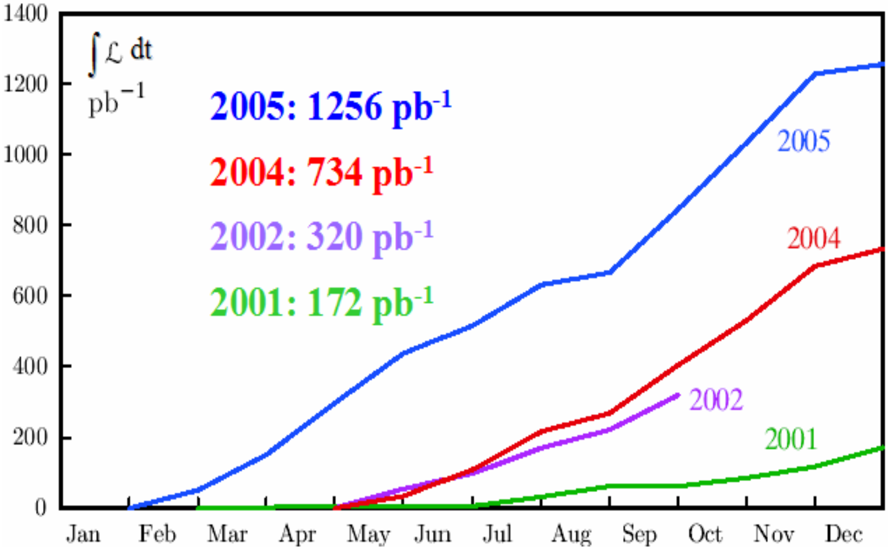
$p_K = 110$ MeV/c
$\lambda_S = 6$ mm $\quad \lambda_L = 3.5$ m

The KLOE detector at the Frascati ϕ-factory DAΦNE

DAFNE collider



Integrated luminosity (KLOE)



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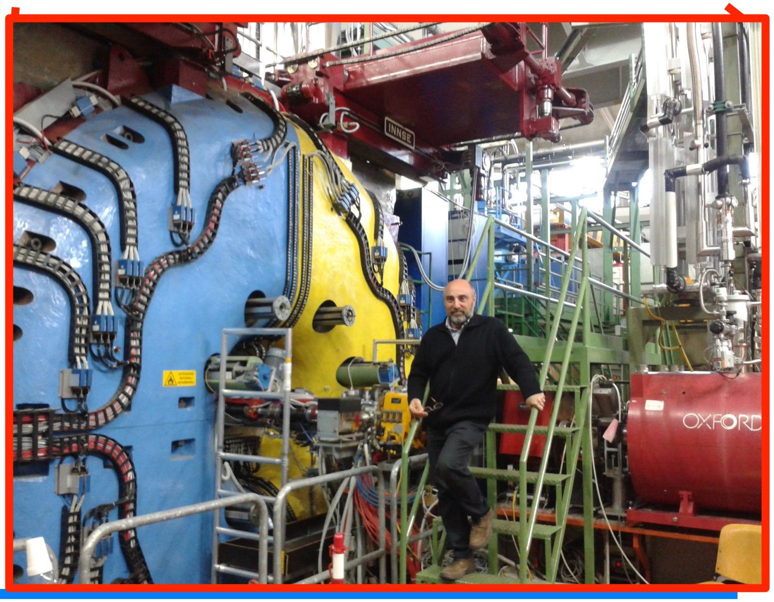

Total KLOE $\int \mathcal{L}\, dt \sim 2.5$ fb^{-1}
(2001 - 05) $\rightarrow$ $\sim 2.5\times10^9$ $K_S K_L$ pairs

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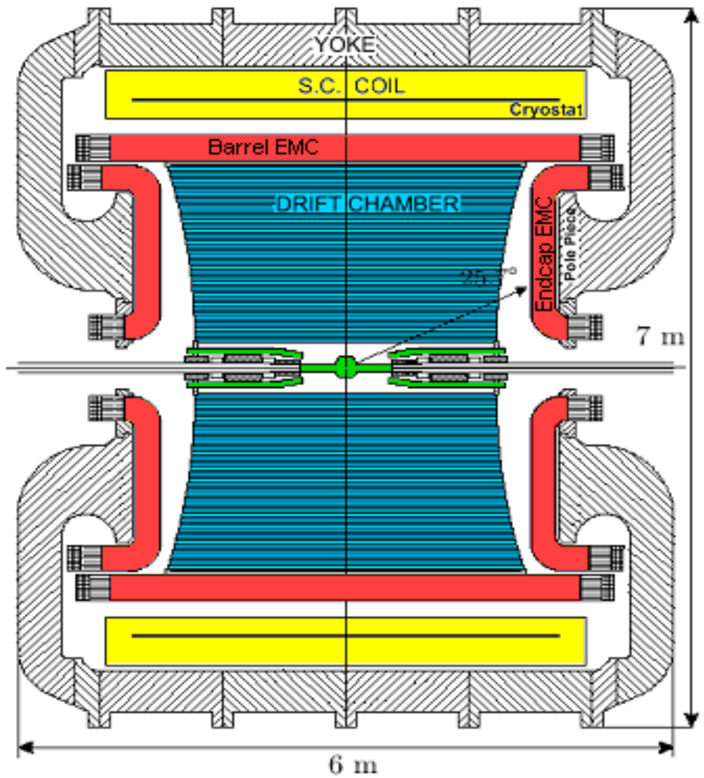

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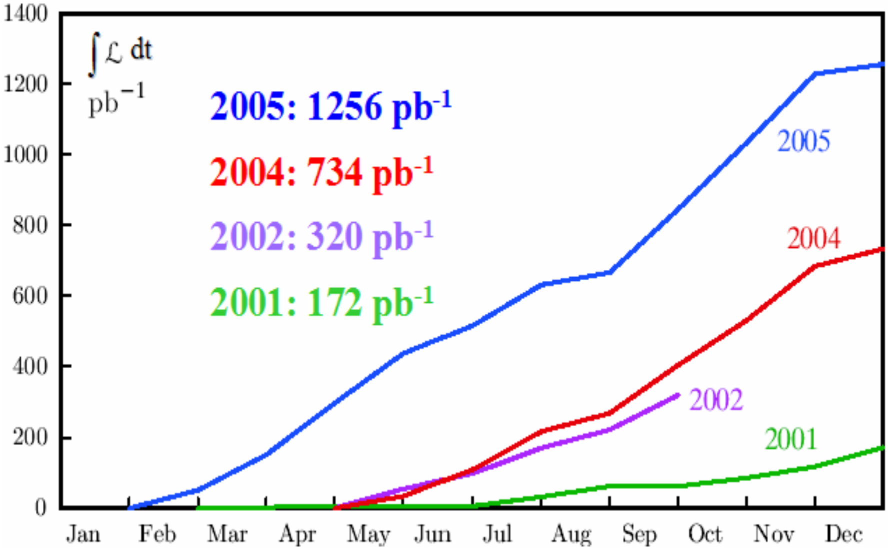

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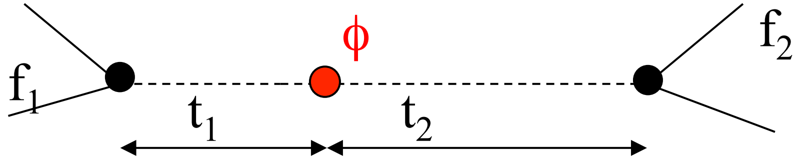
Lead/scintillating fiber calorimeter
drift chamber
4 m diameter × 3.3 m length
helium based gas mixture

Test of Quantum Coherence

EPR correlations in entangled neutral kaon pairs from ϕ

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



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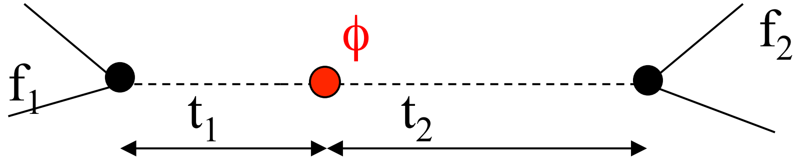

Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

(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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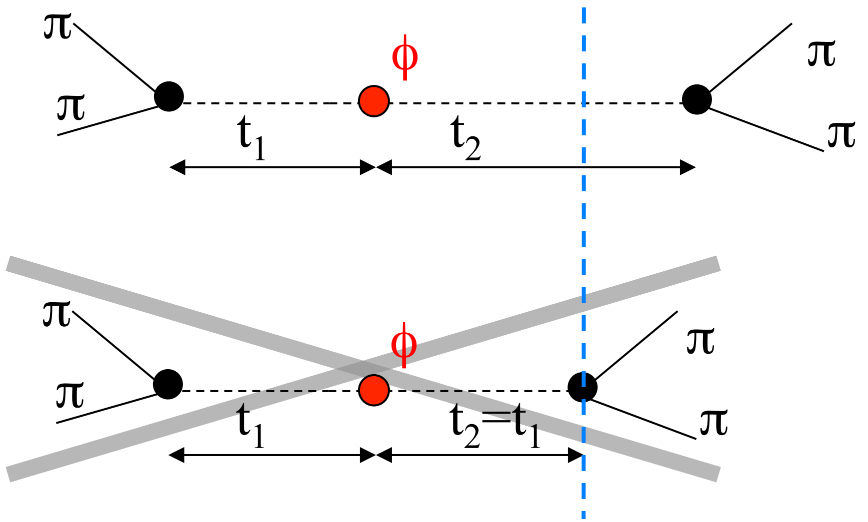

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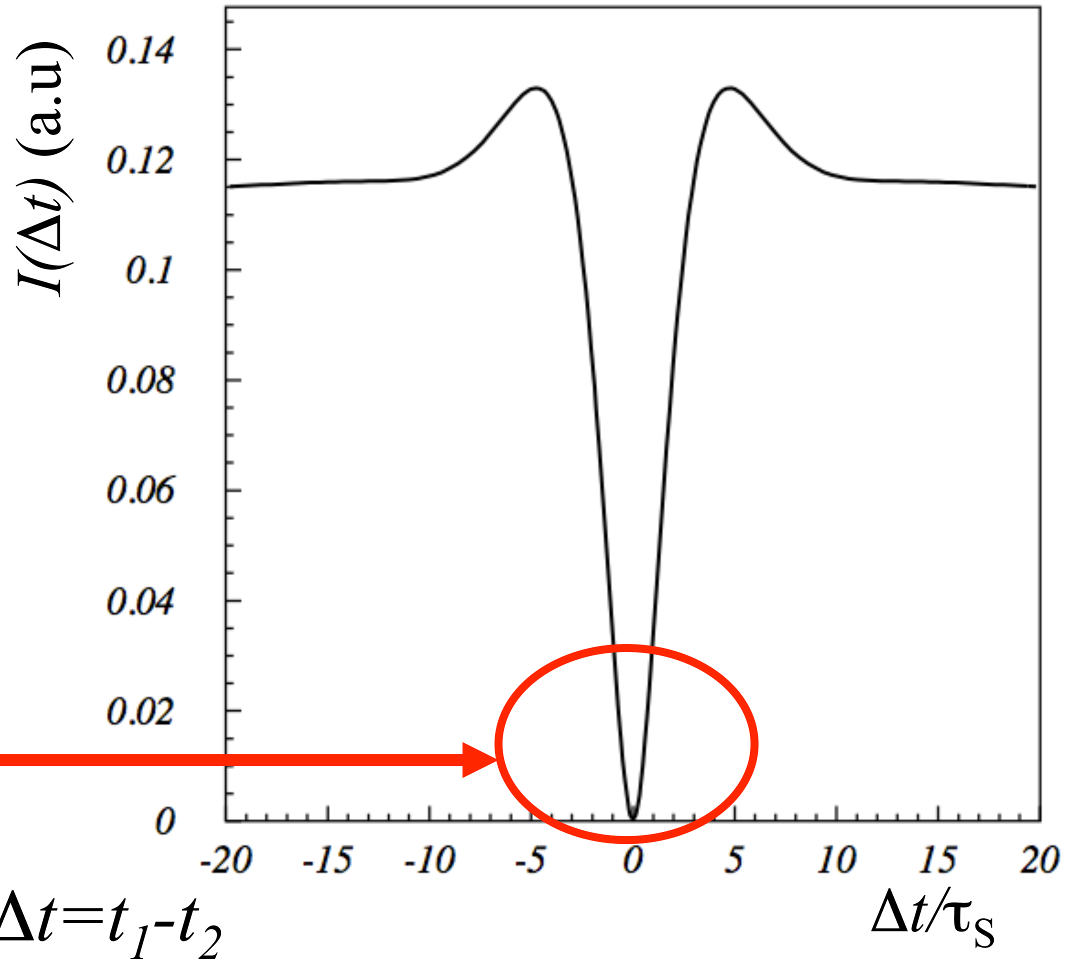

$\Delta t = t_1 - t_2$

EPR correlation:

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

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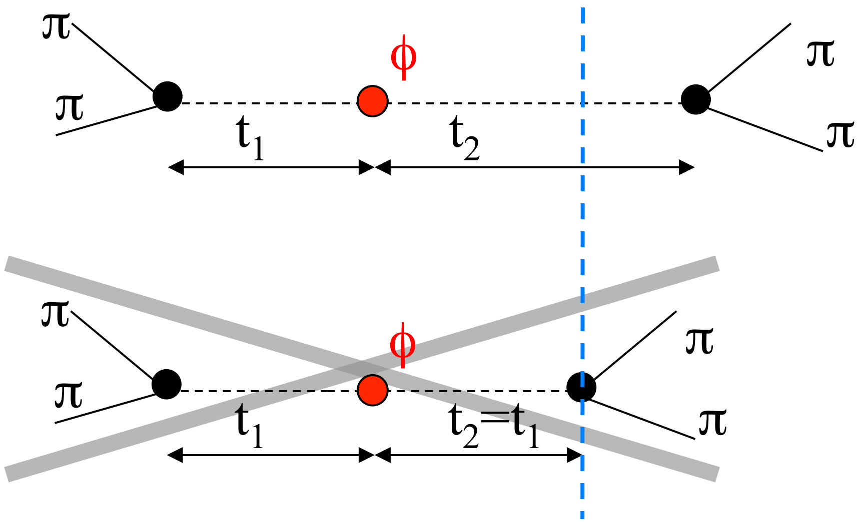

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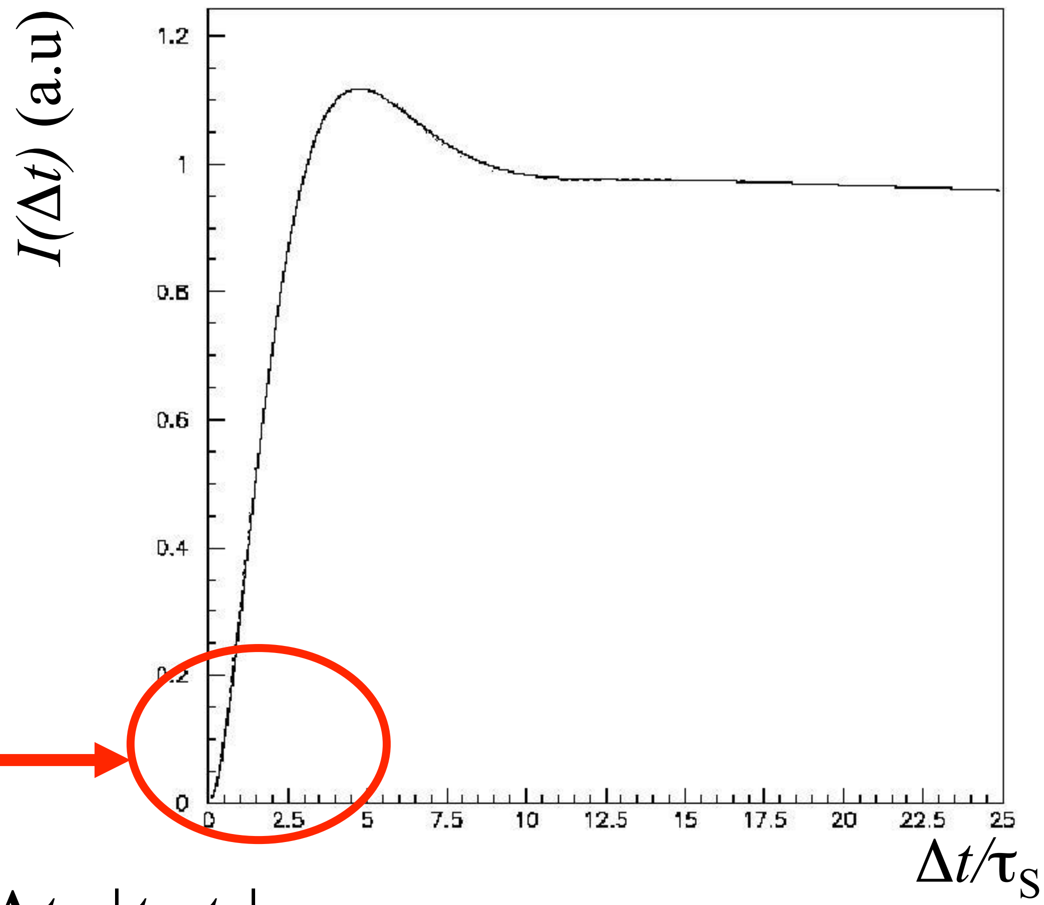

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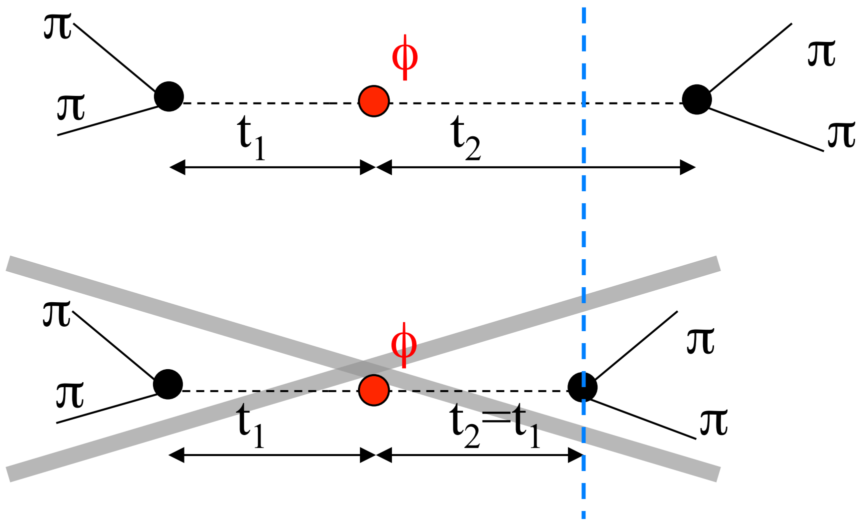

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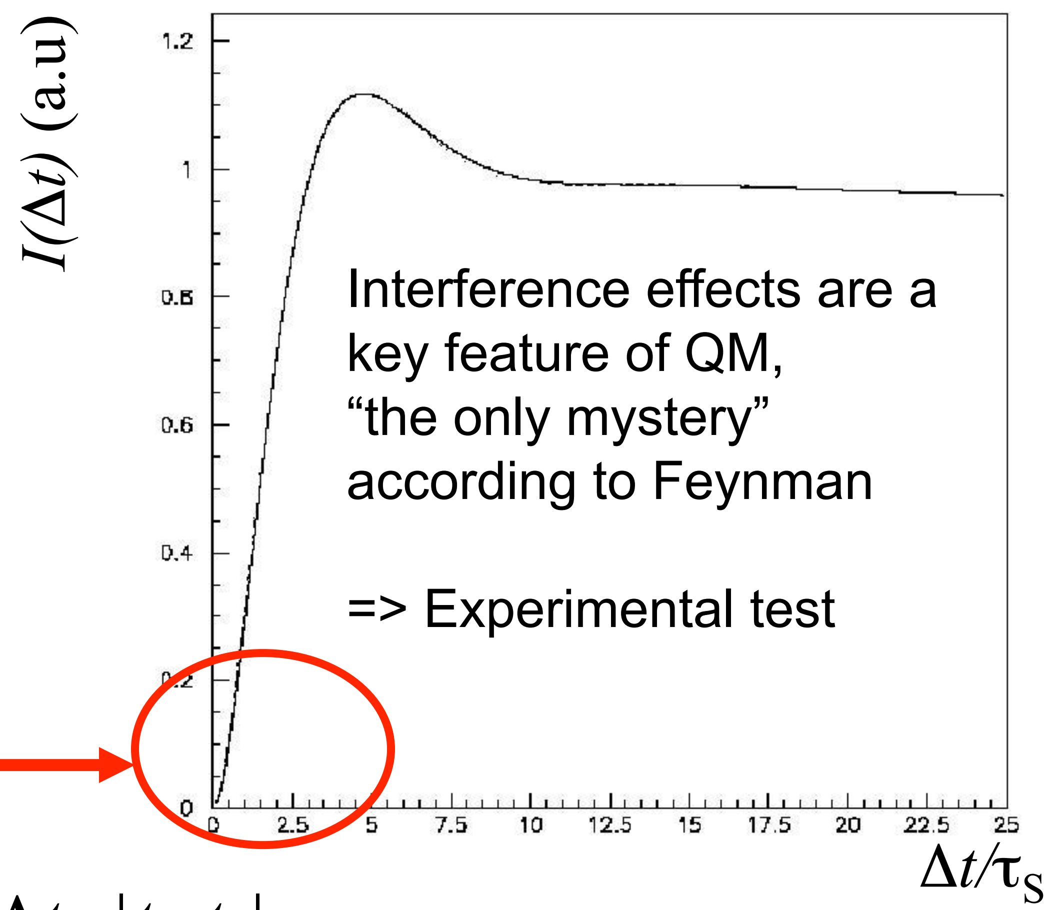

Interference effects are a key feature of QM, "the only mystery" according to Feynman

=> Experimental test

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

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

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

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

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

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Decoherence parameter:

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

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

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

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

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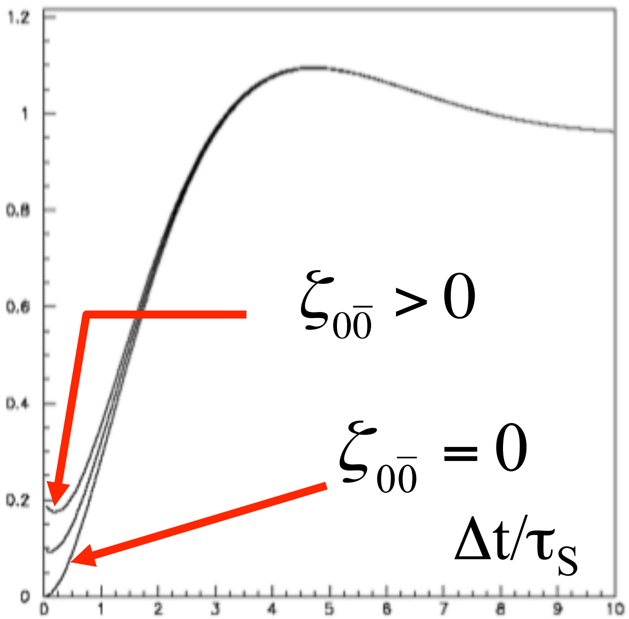
I(Δt) (a.u.)



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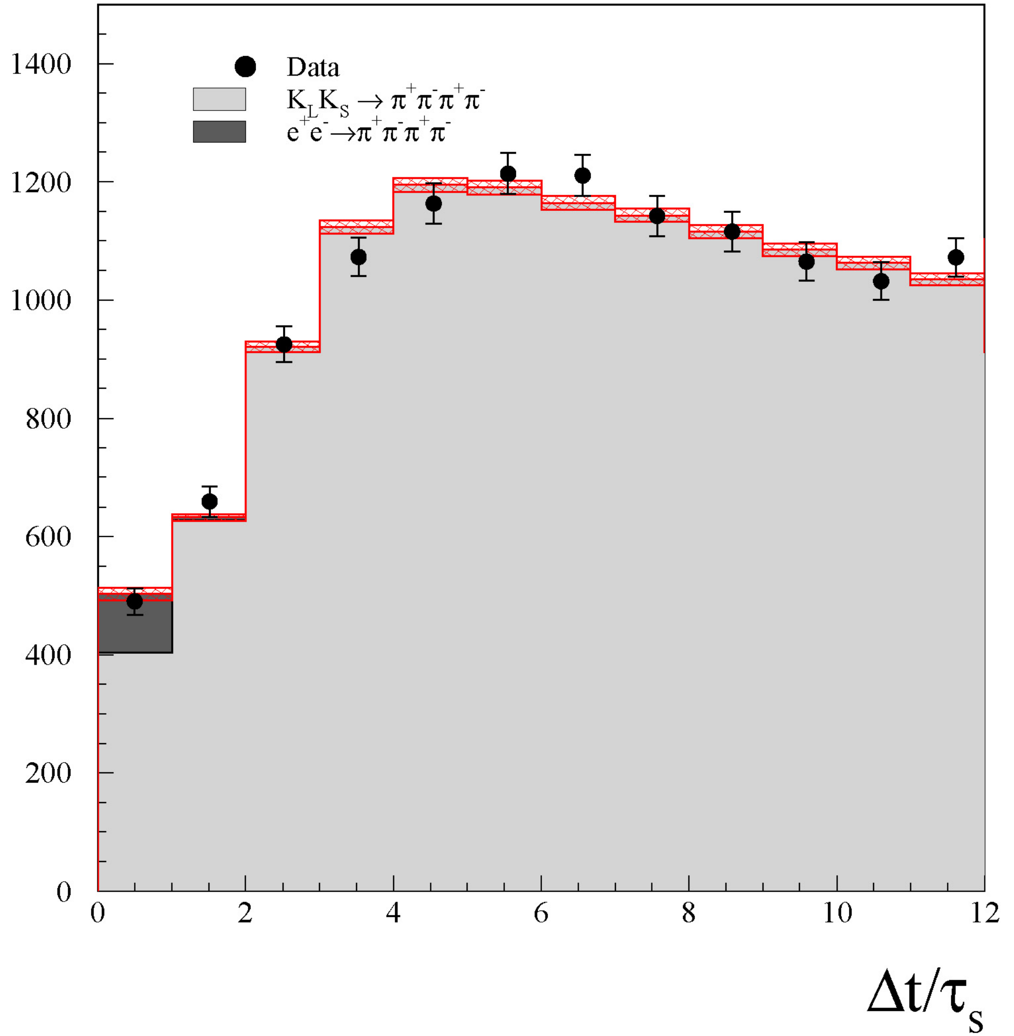
- Fit including Δt resolution and efficiency effects + regeneration



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_{00}

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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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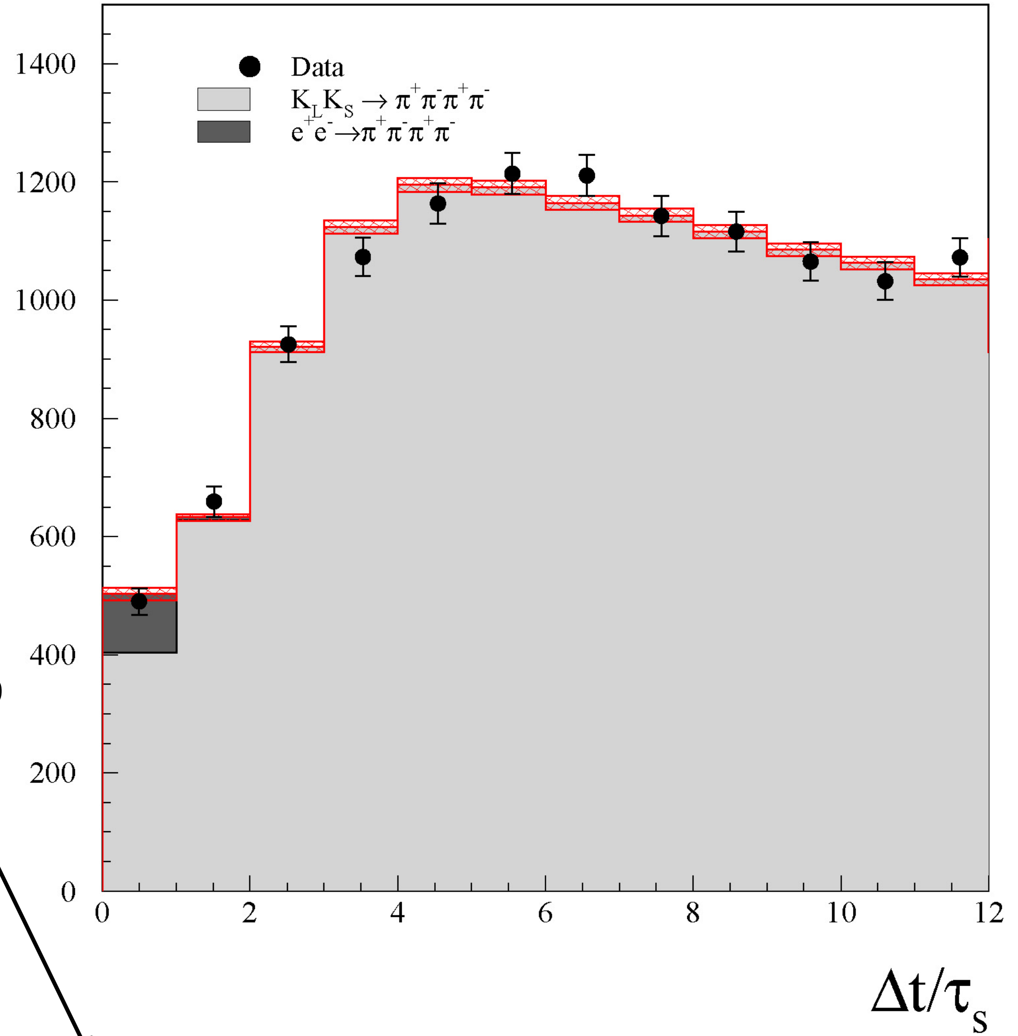

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Cinelli et al. PHYSICAL REVIEW A **70**, 022321 (2004)

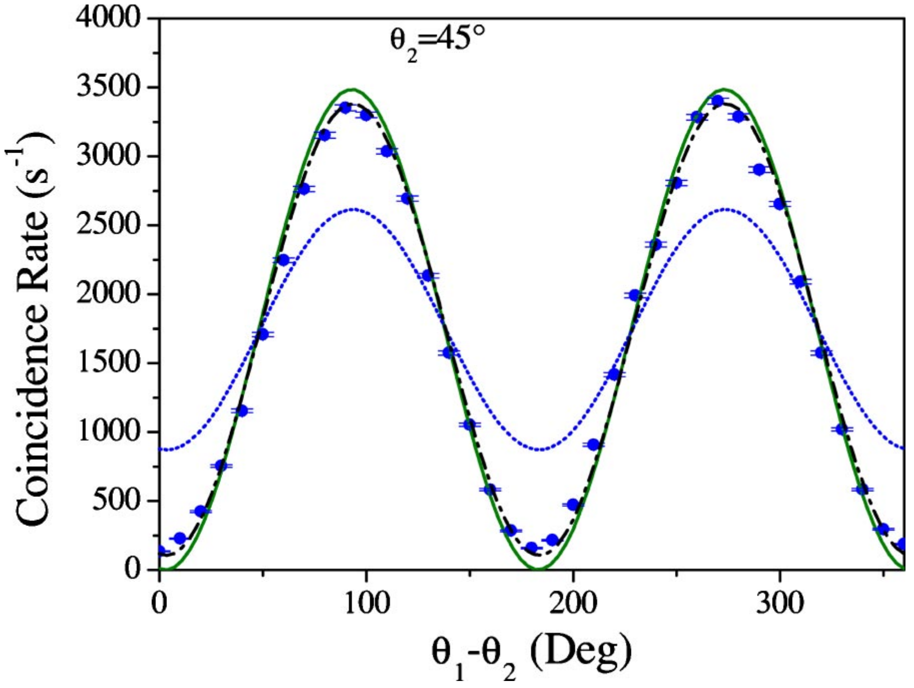

FIG. 2. Bell inequalities test. The selected state is $|\Phi^-\rangle = (1/\sqrt{2})(|H_1, H_2\rangle - |V_1, V_2\rangle)$.

$\Delta t/\tau_S$

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

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].

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

at most:

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

[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],
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$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: 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

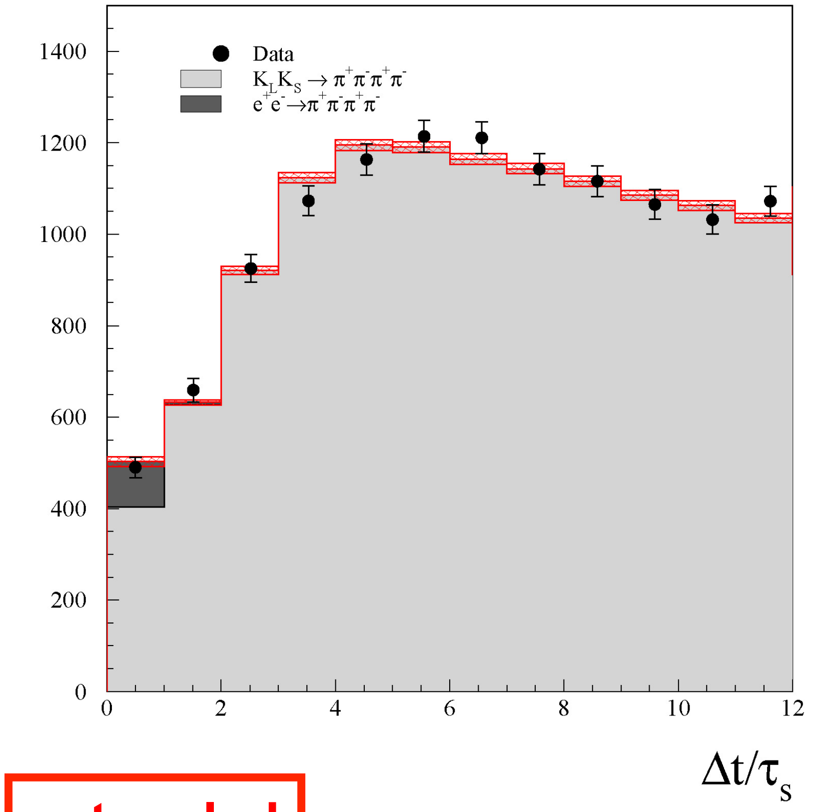
In the complete positivity hypothesis
$\alpha = \gamma$, $\beta = 0$
=> only one independent parameter: γ

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

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

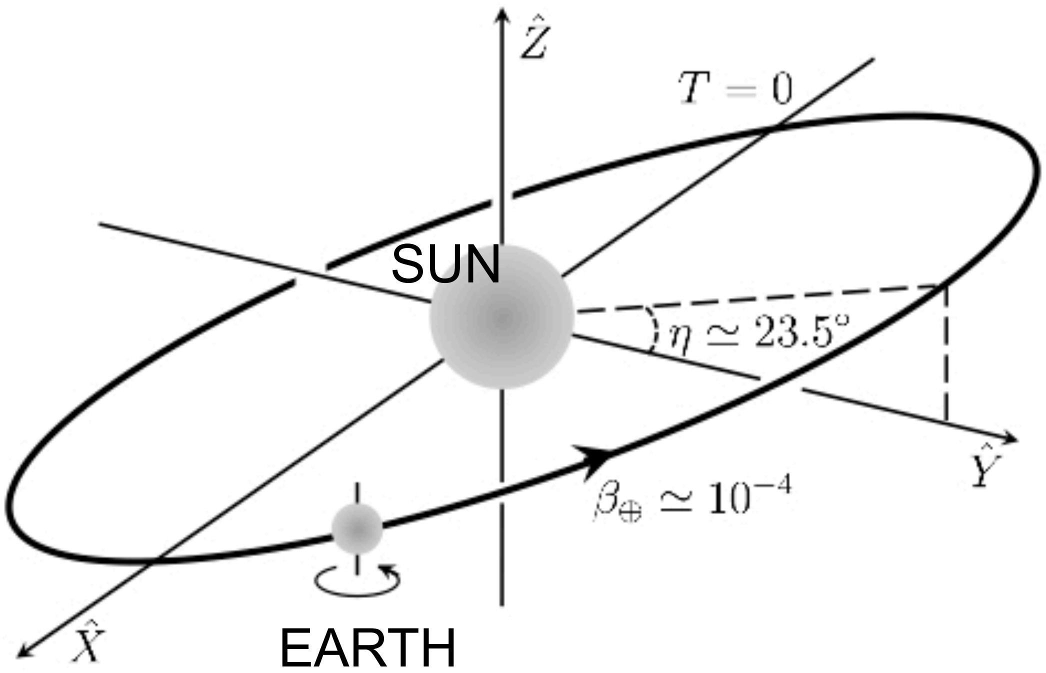
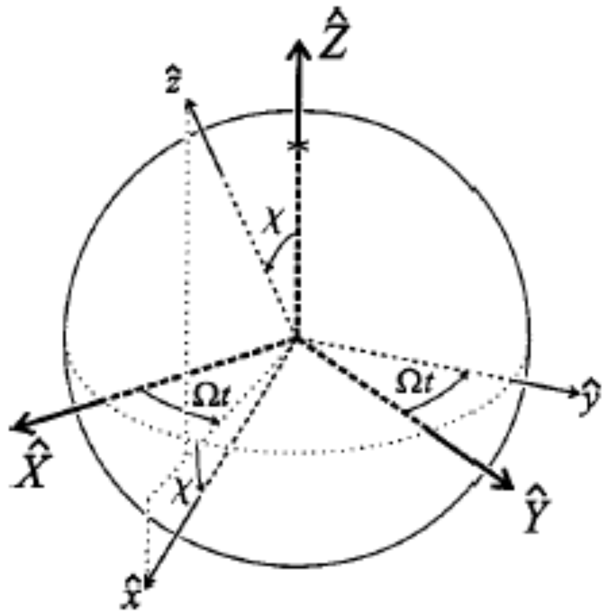


FIG. 1: Standard Sun-centered inertial reference frame [9].

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)

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

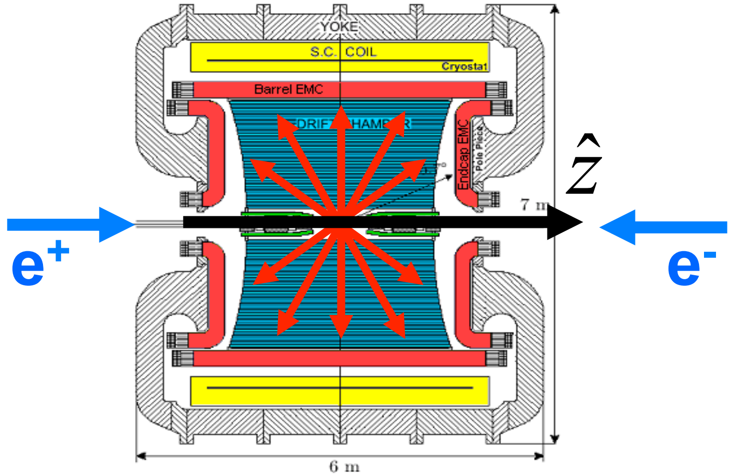
Ω: Earth's sidereal frequency χ : angle between the z lab. axis and the Earth's rotation axis

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 $dN/d\Omega \propto \sin^2\theta$



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

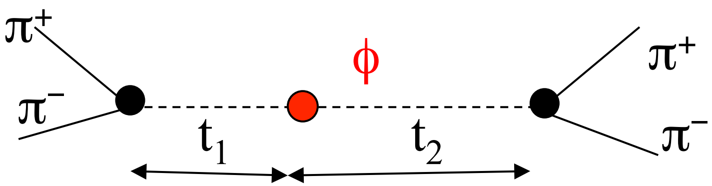
Ω: Earth's sidereal frequency χ : angle between the z lab. axis and the Earth's rotation axis

Search for CPTV and LV: exploiting EPR correlations

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

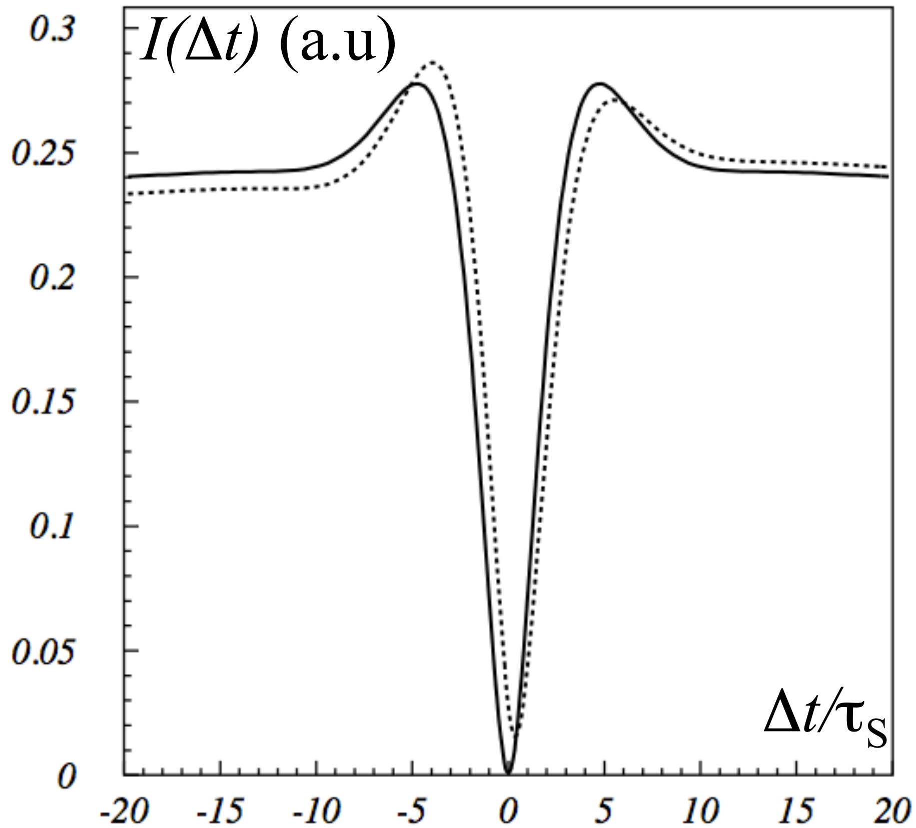
$$\eta_i = |\eta_i| e^{i\phi_i} = \langle f_i|T|K_L\rangle / \langle f_i|T|K_S\rangle$$

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



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

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



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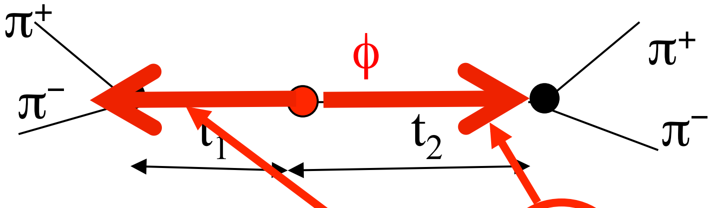
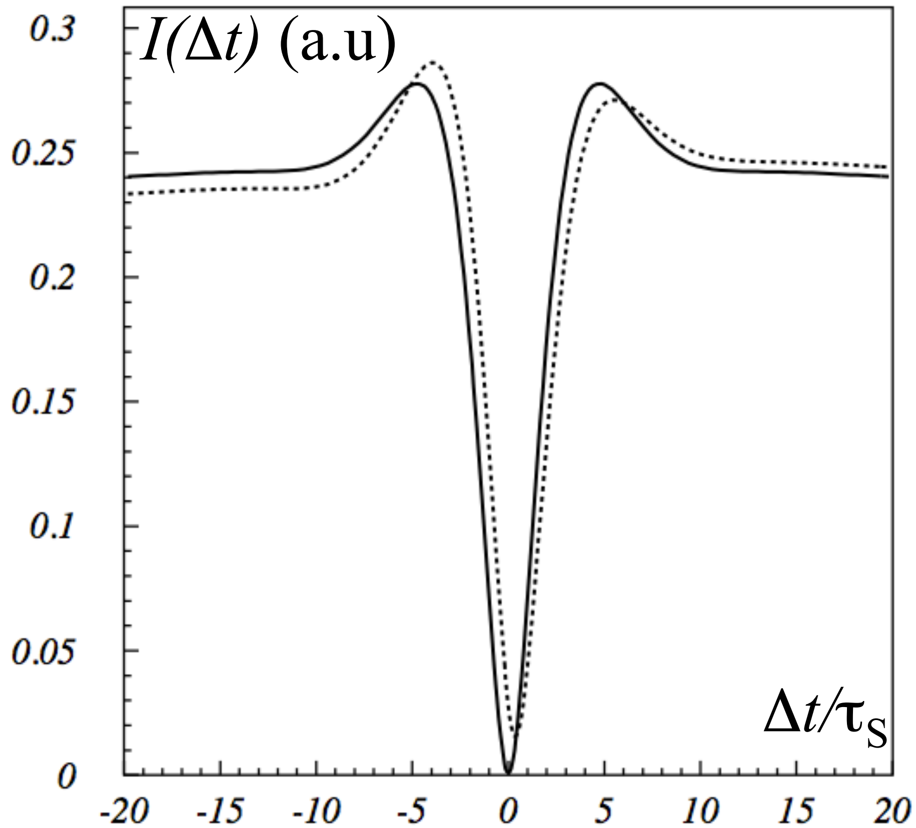


$$\eta_{+-}^{(1)} = \varepsilon\left(1 - \delta\left(+\vec{p},t\right)/\varepsilon\right)$$

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



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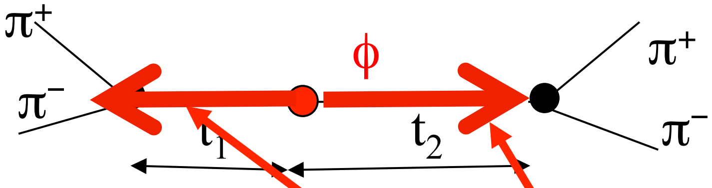
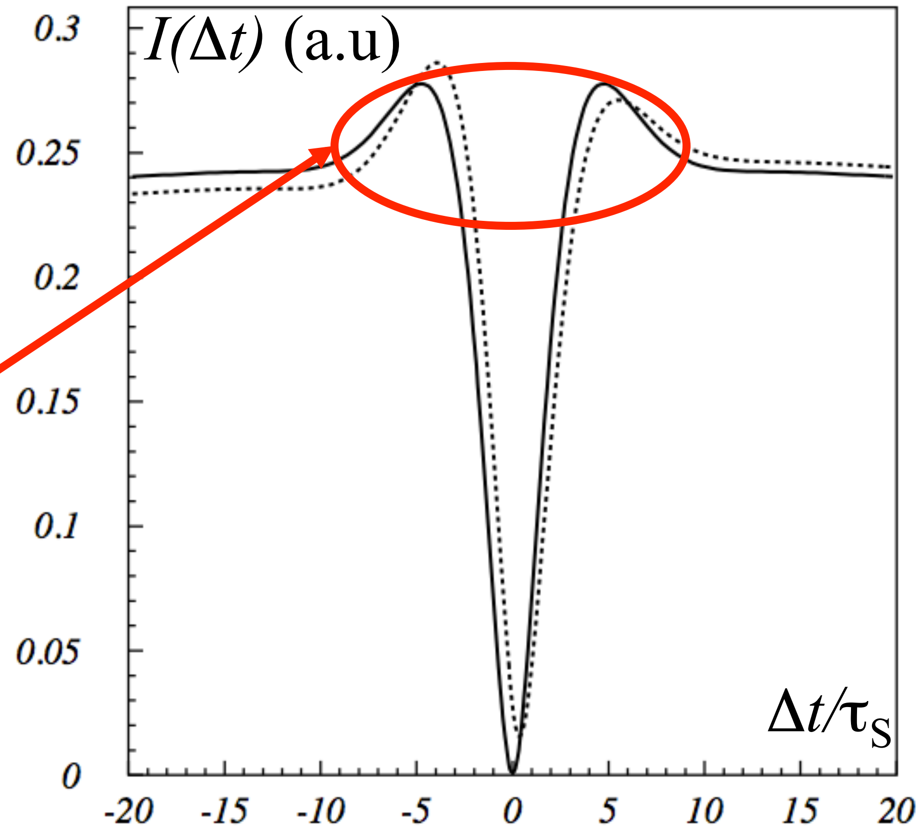


$$\eta^{(1)}_{+-} = \varepsilon\left(1 - \delta(+\vec{p}, t)/\varepsilon\right)$$

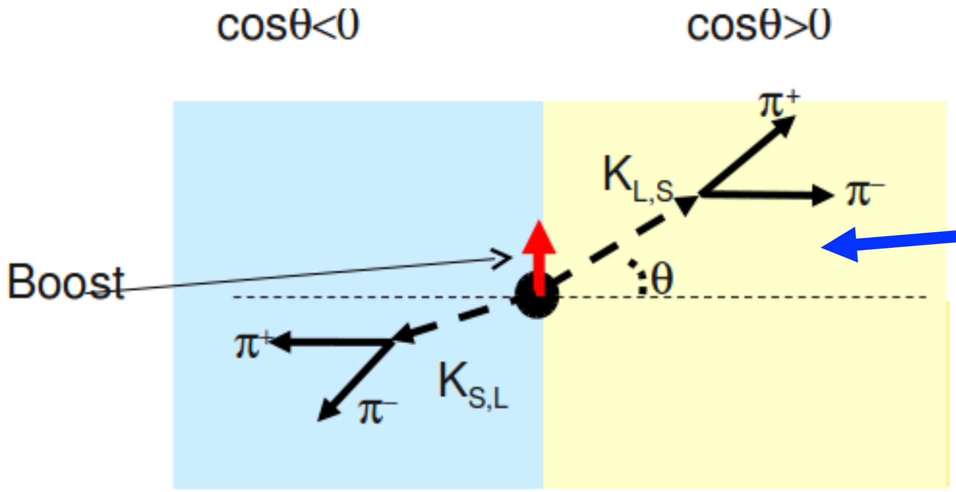
$$\eta^{(2)}_{+-} = \varepsilon\left(1 - \delta(-\vec{p}, t)/\varepsilon\right)$$

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

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



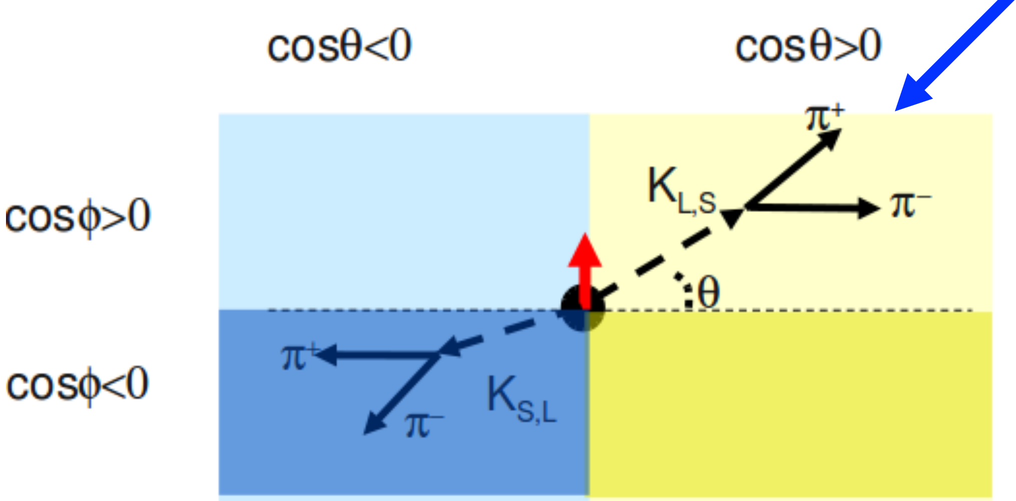
Search for CPTV and LV: exploiting EPR correlations

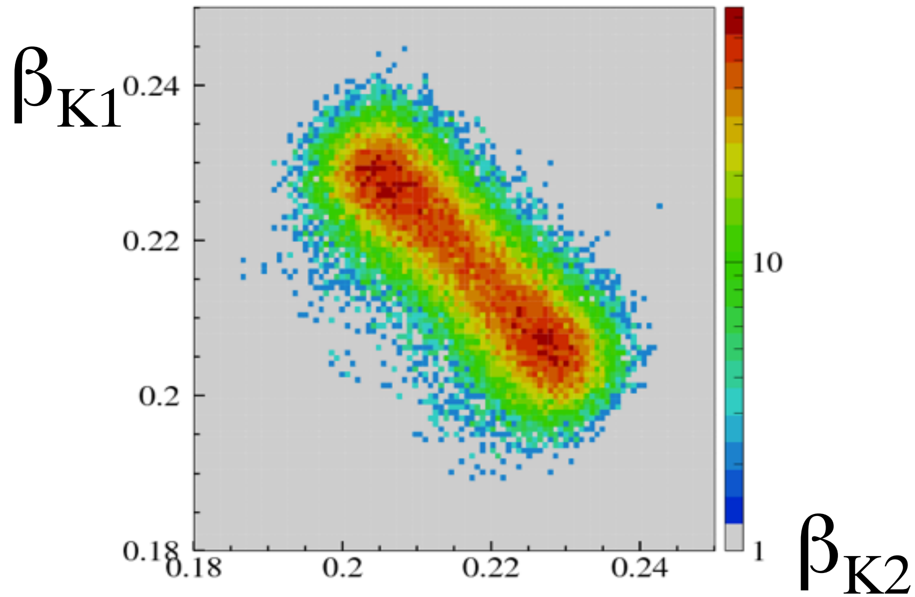


$$\delta = i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right) / \Delta m$$

Possible effects due to Δa_0 are washed out in the simple forward – backward analysis (integration in ϕ).

The quadrant analysis (kaons with $\gamma_{K1} \neq \gamma_{K2}$) recovers sensitivity to Δa_0

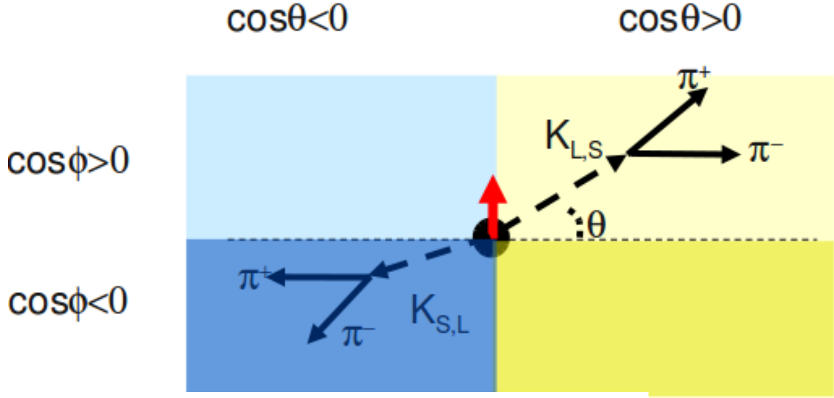


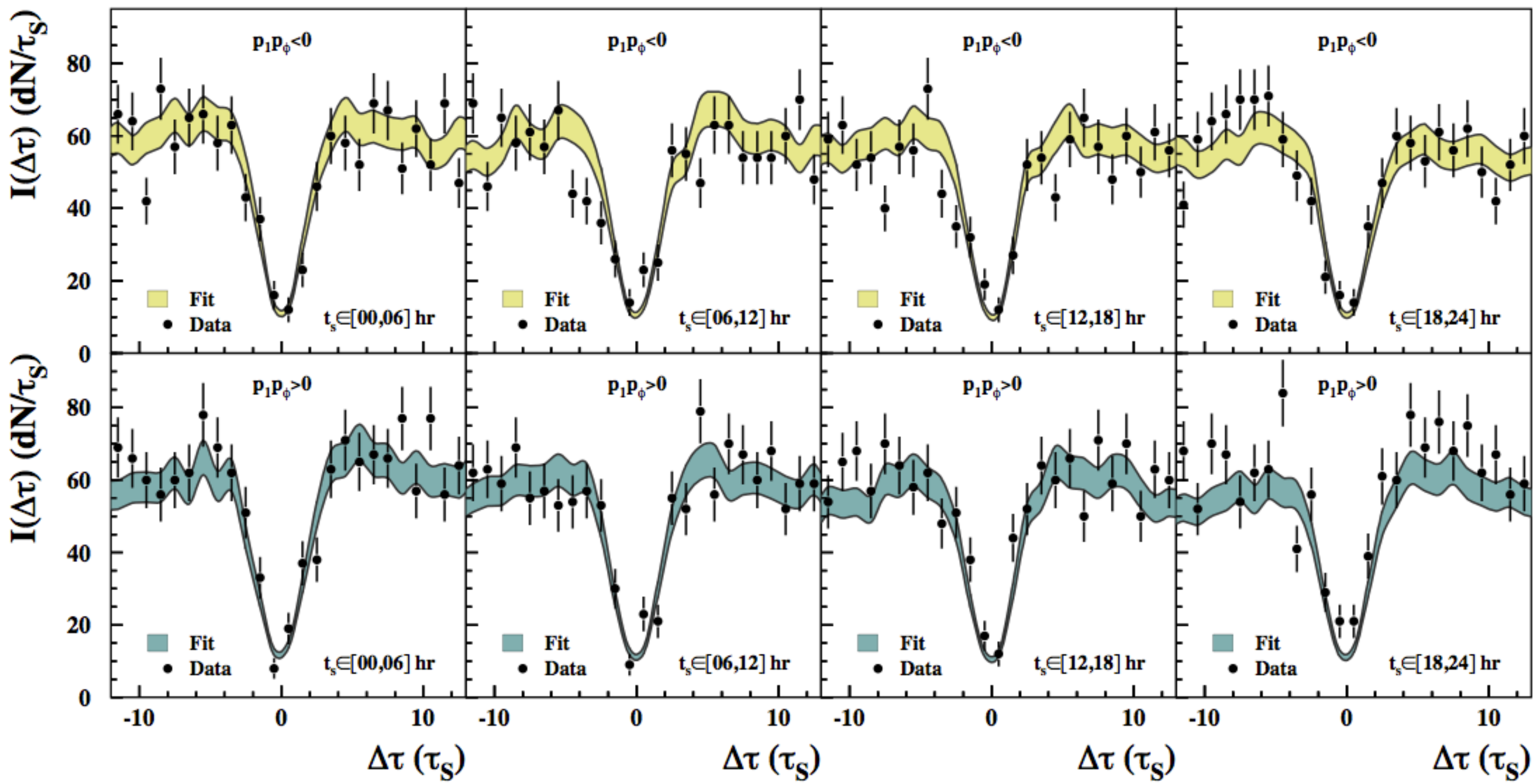


Search for CPTV and LV: results

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

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





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

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 first complete and most precise measurement in the quark sector of the SME

B meson system:
$\Delta a^B_{x,y}$, $(\Delta a^B_0 - 0.30\ \Delta a^B_Z)$ ~$O(10^{-13}$ GeV)
[Babar PRL 100 (2008) 131802]
$\Delta a^{B0}_{x,y,z,0}$ ~ $O(10^{-15}$ GeV)
$\Delta a^{BS}_{x,y,z,0}$ ~ $O(10^{-14}$ GeV)
[LHCb PRL 116, 241601 (2016)]

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

Other K meson results
KTeV : Δa_X , $\Delta a_Y < 9.2 \times 10^{-22}$ GeV @ 90% CL
$|\Delta a_0 - 0.60\ \Delta a_Z| < 5\ 10^{-21}$ GeV
[Kostelecky PRL 80 (1998) 1818]

Direct CPT symmetry test in neutral kaon transitions

(or a very general and model independent test)

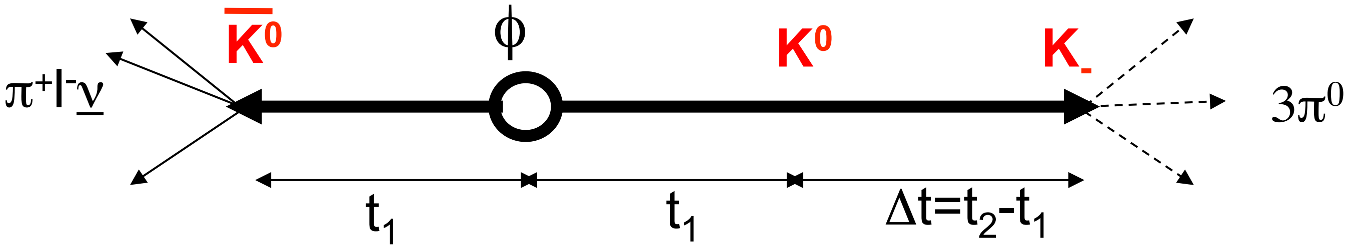
Direct test of CPT symmetry in neutral kaon transitions

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

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

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

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



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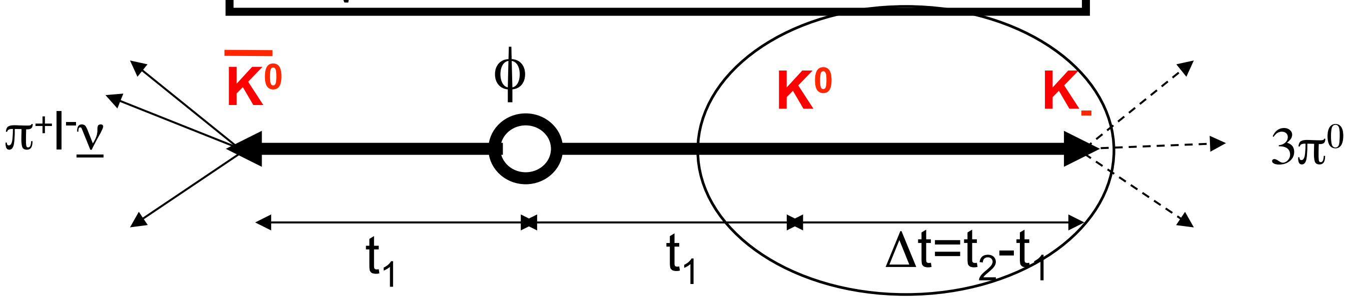

$$K^0 \rightarrow K_-$$ reference process

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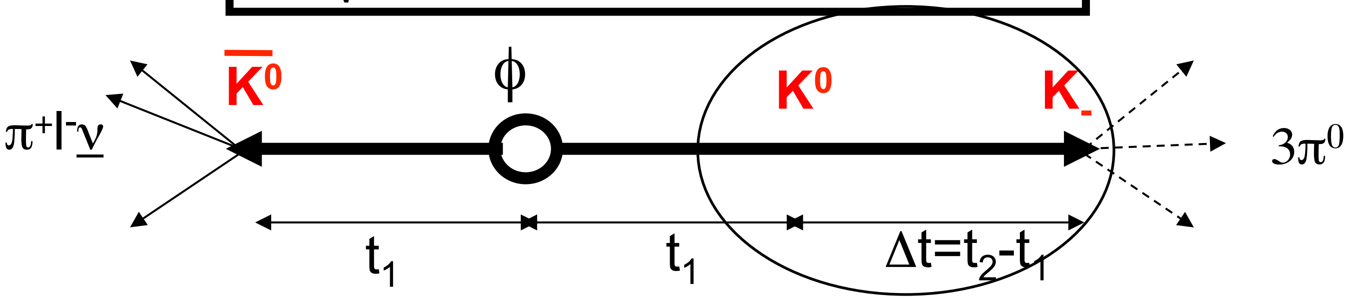

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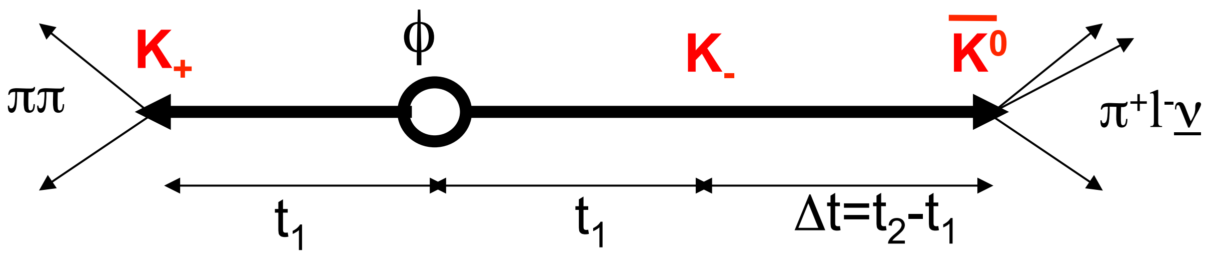

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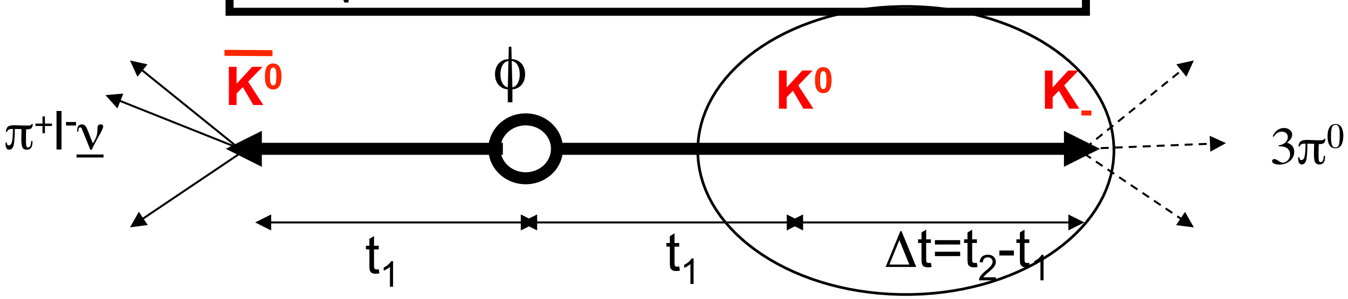
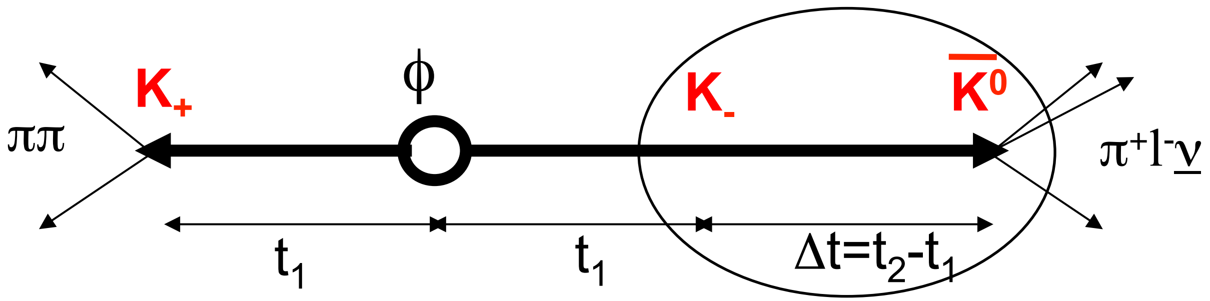


$K^0 \to K_-$ reference process

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



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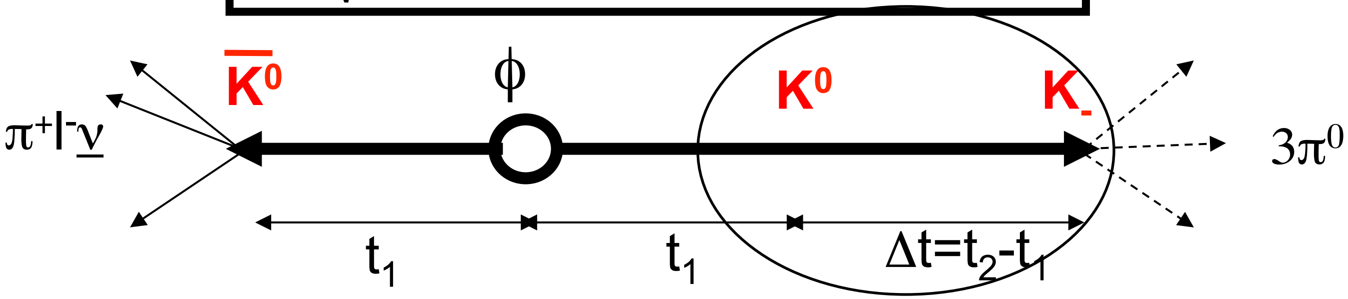
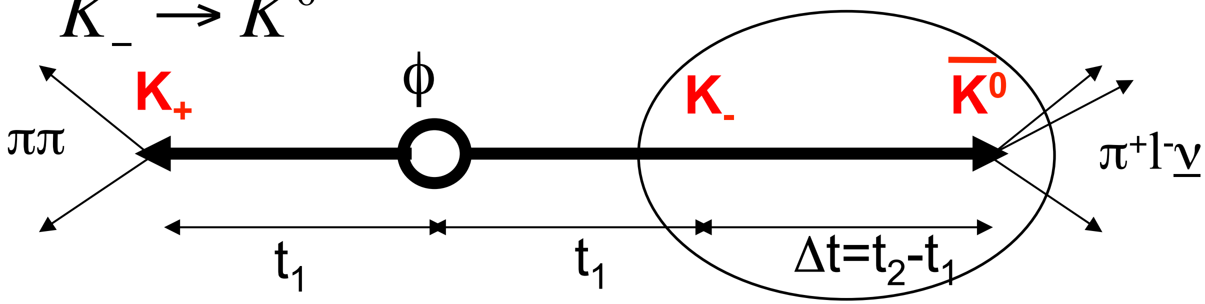


$K^0 \rightarrow K_-$ reference process

$K_- \rightarrow \overline{K}^0$ 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
$\mathrm{K}^0 \to \mathrm{K}_+$	$(\ell^-, \pi\pi)$	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	$(3\pi^0, \ell^-)$
$\mathrm{K}^0 \to \mathrm{K}_-$	$(\ell^-, 3\pi^0)$	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	$(\pi\pi, \ell^-)$
$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$	$(\ell^+, \pi\pi)$	$\mathrm{K}_+ \to \mathrm{K}^0$	$(3\pi^0, \ell^+)$
$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$	$(\ell^+, 3\pi^0)$	$\mathrm{K}_- \to \mathrm{K}^0$	$(\pi\pi, \ell^+)$

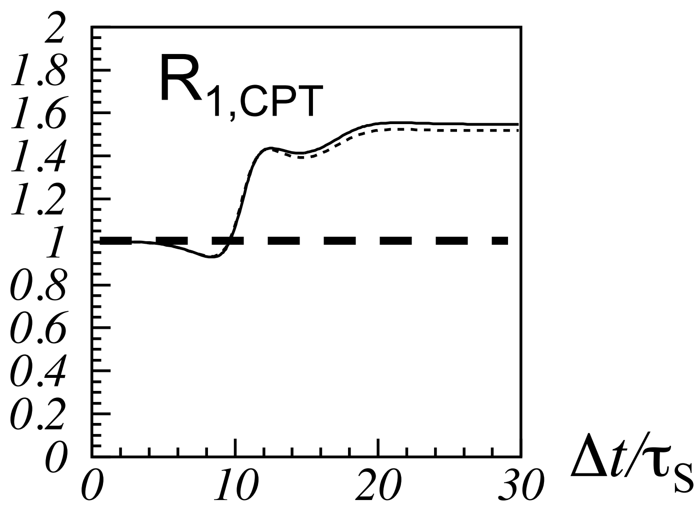
One can define the following ratios of probabilities:

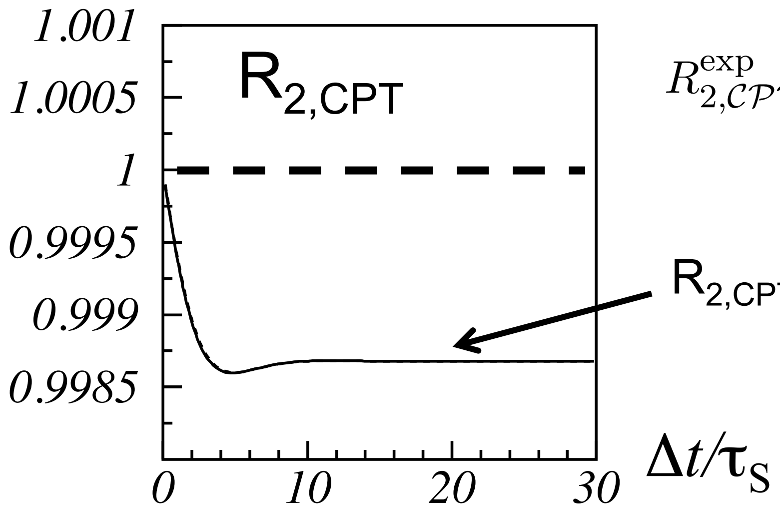
$$
\begin{aligned}
R_{1,\mathcal{CPT}}(\Delta t) &= P\left[\mathrm{K}_+(0) \to \bar{\mathrm{K}}^0(\Delta t)\right] / P\left[\mathrm{K}^0(0) \to \mathrm{K}_+(\Delta t)\right] \\
R_{2,\mathcal{CPT}}(\Delta t) &= P\left[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)\right] / P\left[\mathrm{K}_-(0) \to \bar{\mathrm{K}}^0(\Delta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

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

Direct test of CPT symmetry in neutral kaon transitions

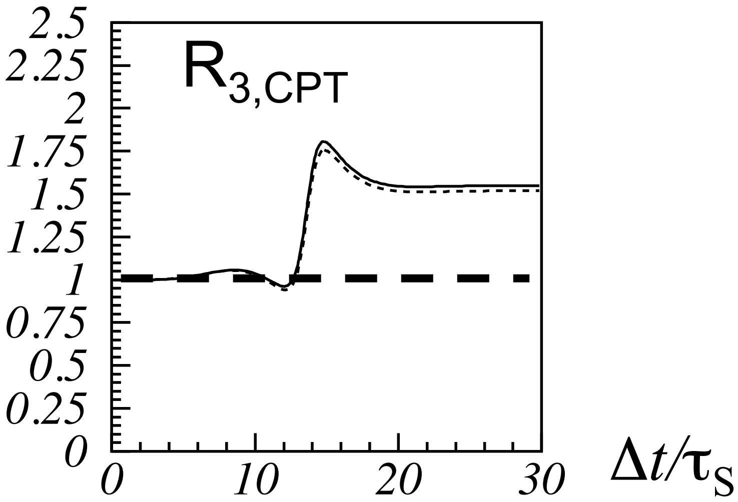
for visualization purposes, plots with Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5} (---- Im(δ)=0)

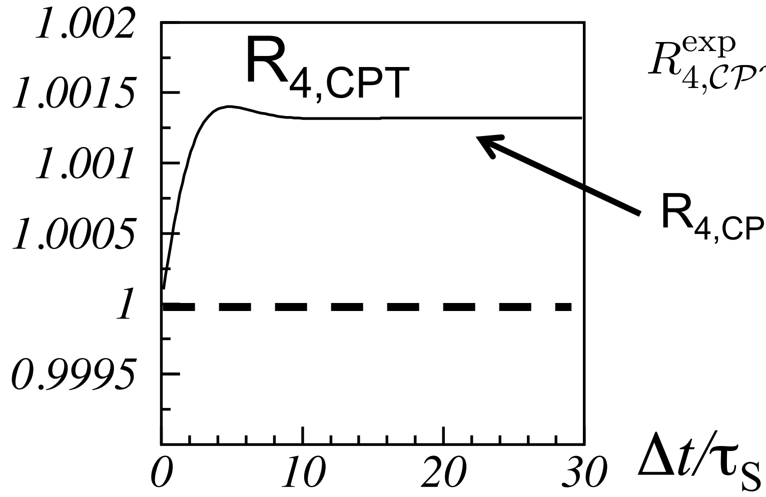




$$R^{\rm exp}_{2,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

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



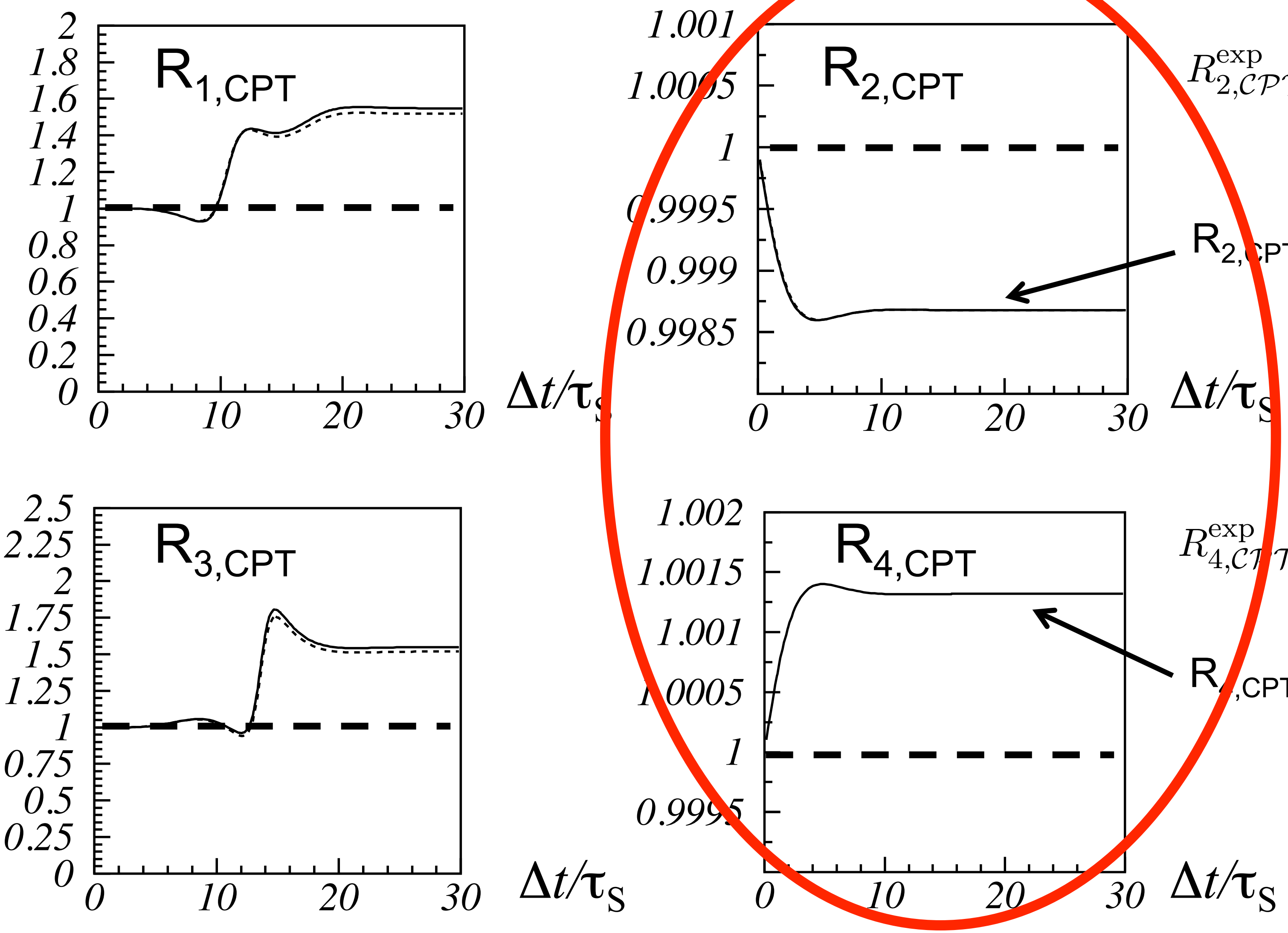


$$R^{\rm exp}_{4,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

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

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)



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

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

measurable at KLOE-2

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

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

Direct test of CPT symmetry in neutral kaon transitions

- It would be possible to directly test the CPT symmetry <u>in transition processes</u> 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)]:

$$\frac{R^{\rm exp}_{2,\rm CPT}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,\rm CPT}(\Delta t \gg \tau_S)} \simeq 1 + 2(A_L - A_S) = 1.004 \pm 0.020$$

- KLOE-2 can reach a statistical sensitivity of $O(10^{-3})$

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

See Schubert's talk for B mesons

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

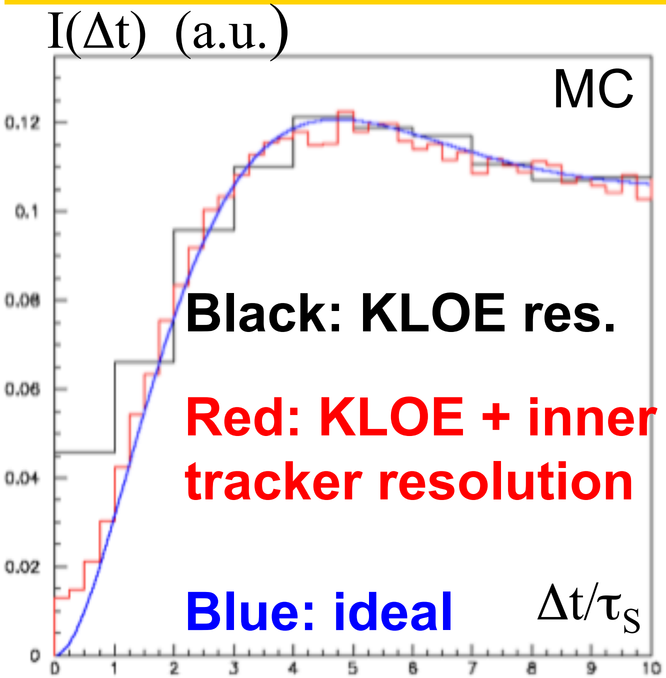
Physics program (see EPJC 68 (2010) 619-681)

- 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

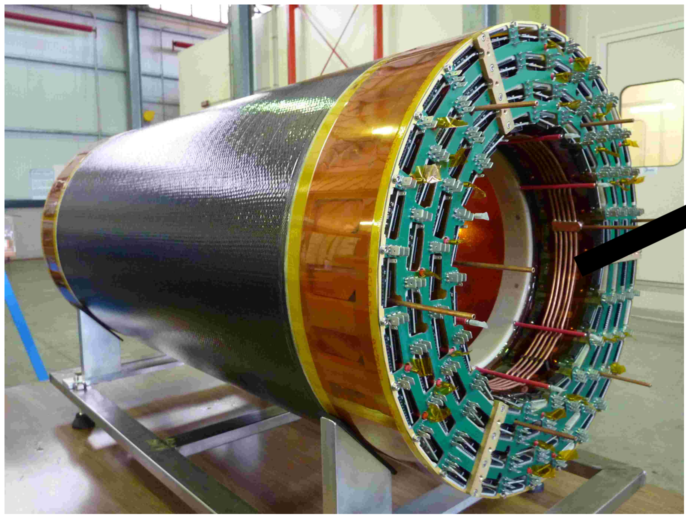
Detector upgrade:

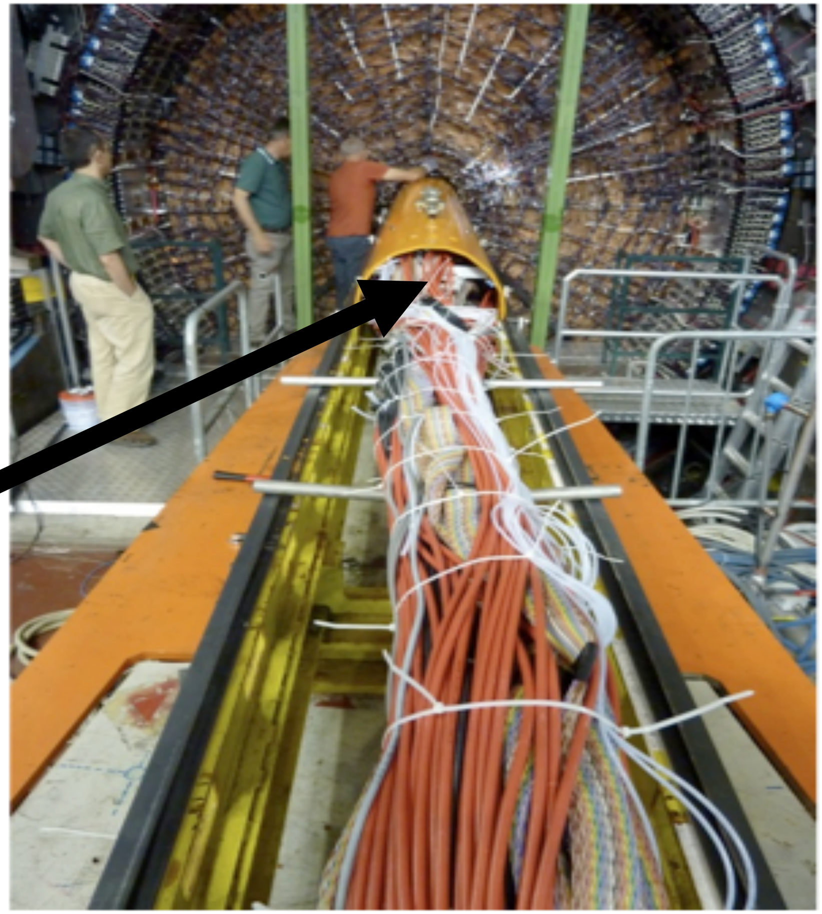
- $\gamma\gamma$ tagging system
- inner tracker
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)

Inner tracker at KLOE-2

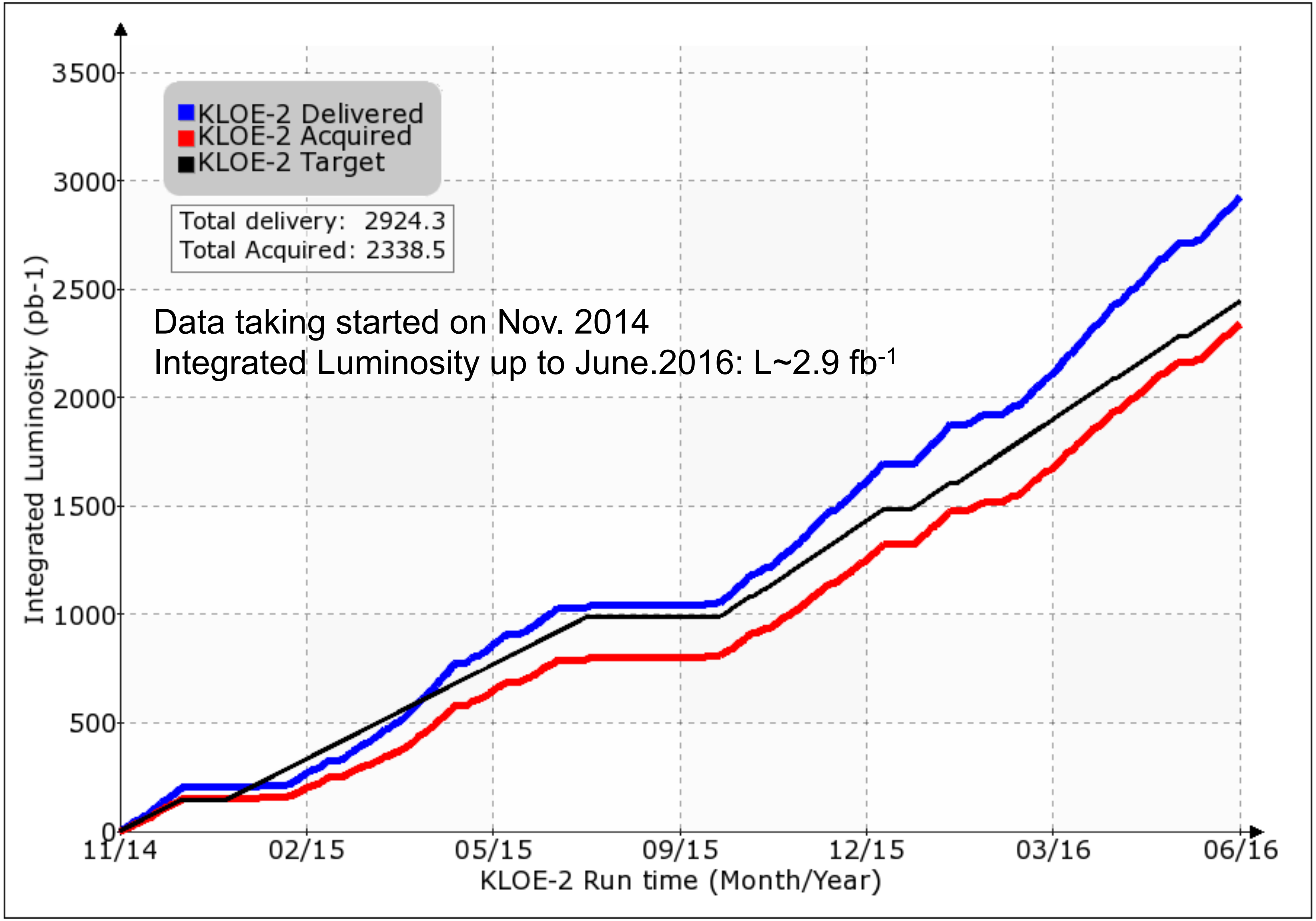


The KLOE detector has been improved with an inner tracker based on an innovative cylindrical GEM technology to improve vertex resolution close to the interaction region, and sensitivity around $\Delta t \sim 0$.





KLOE-2 data taking in progress



Data taking started on Nov. 2014
Integrated Luminosity up to June.2016: L~2.9 fb^{-1}

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.)
$\zeta_{0\bar{0}}$	$(0.1 \pm 1.0) \times 10^{-6}$	$\pm 0.26 \times 10^{-6}$	$\pm 0.18 \times 10^{-6}$
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

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

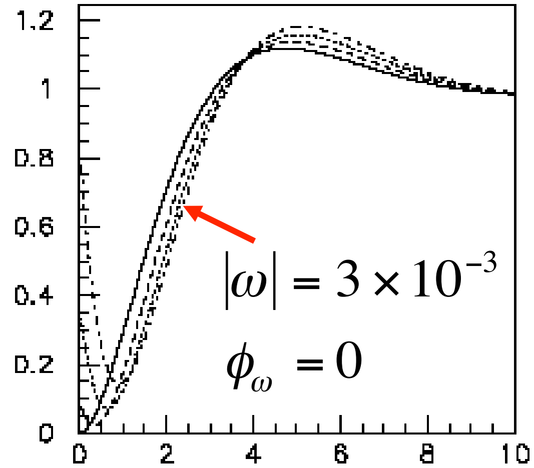
$$|i\rangle \propto \left(|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right) + \omega\left(|K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle\right)$$

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

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

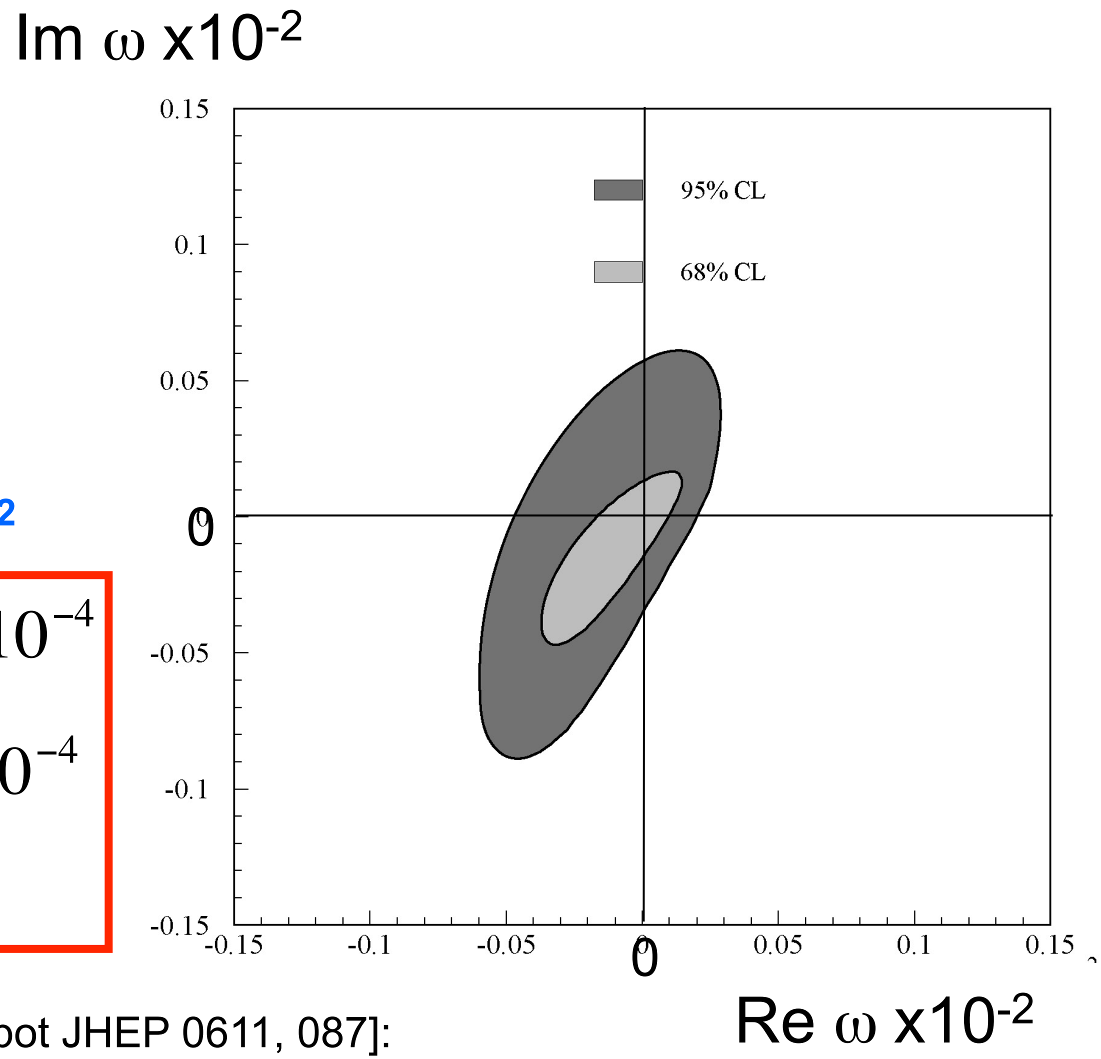
- Analysed data: 1.5 fb^{-1}

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]:

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