Probing CPT symmetry with entangled neutral kaons

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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)

R. Jost (1957)

G. Lüders (1954)

W. Pauli (1952)

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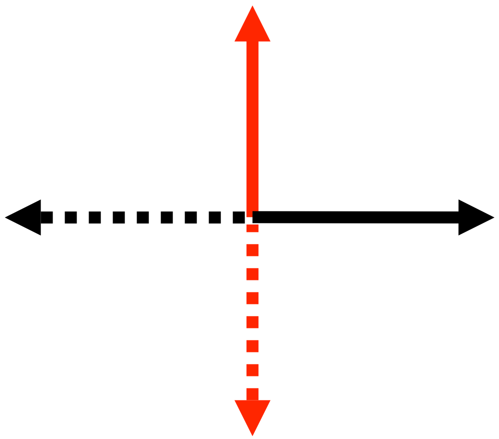
Intuitive justification of CPT symmetry [1]:
For an even-dimensional space => reflection of all axes is equivalent to a rotation e.g. in 2-dim. space: reflection of 2 axes = rotation of π around the origin



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

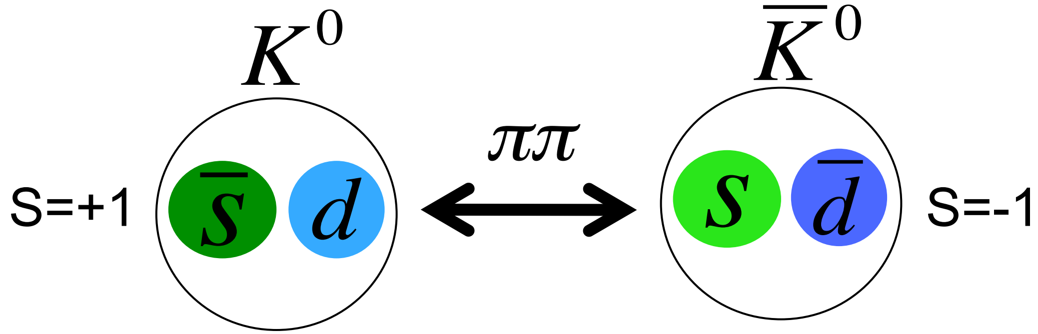
proton- anti-proton $\left|m_p - m_{\overline{p}}\right| / m_p < 10^{-8}$

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.

....

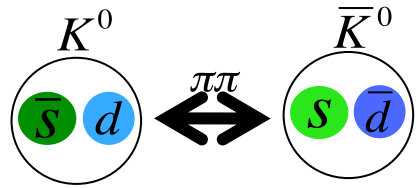
If the K mesons did not exist, they should have been invented "on purpose" in order to teach students the principles of quantum mechanics.

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 $\quad\tau_L$ ~ 51 ns

$K_L \to \pi\pi$ violates CP

eigenstates

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

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

$|K_{1,2}\rangle$ are CP=±1 states

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

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 $\Im\Gamma_{12} = 0$)

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

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

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

CPT violation: standard picture

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

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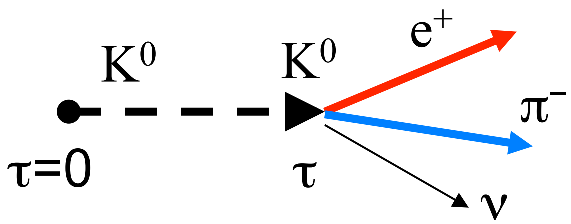
neutral kaons vs other oscillating meson systems

	<m> (GeV)	Δm (GeV)	<Γ> (GeV)	ΔΓ/2 (GeV)
K^0	0.5	$3x10^{-15}$	$3x10^{-15}$	$3x10^{-15}$
D^0	1.9	$6x10^{-15}$	$2x10^{-12}$	$1x10^{-14}$
B^0_d	5.3	$3x10^{-13}$	$4x10^{-13}$	$O(10^{-15})$ (SM prediction)
B^0_s	5.4	$1x10^{-11}$	$4x10^{-13}$	$3x10^{-14}$

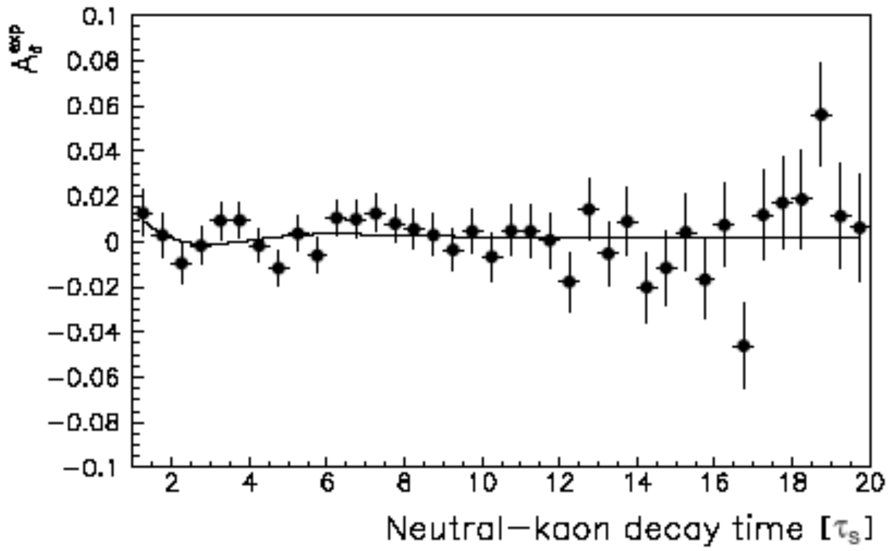
“Standard” CPT tests

CPT test at CPLEAR

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



survival probabilities



$$A_{CPT}(\tau) = \frac{P[\overline{K}^0(0) \to \overline{K}^0(\tau)] - P[K^0(0) \to K^0(\tau)]}{P[\overline{K}^0(0) \to \overline{K}^0(\tau)] + P[K^0(0) \to K^0(\tau)]}$$

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

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

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:

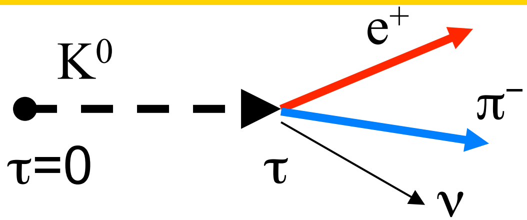
$$\langle K_L|K_S\rangle = 2(\Re\varepsilon + i\Im\delta) = \frac{\sum_f \langle f|T|K_S\rangle\langle f|T|K_L\rangle^*}{i(\lambda_S - \lambda_L^*)}$$

All observables quantities

"Standard" CPT test

measuring the time evolution of a neutral kaon beam into semileptonic decays:

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



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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)

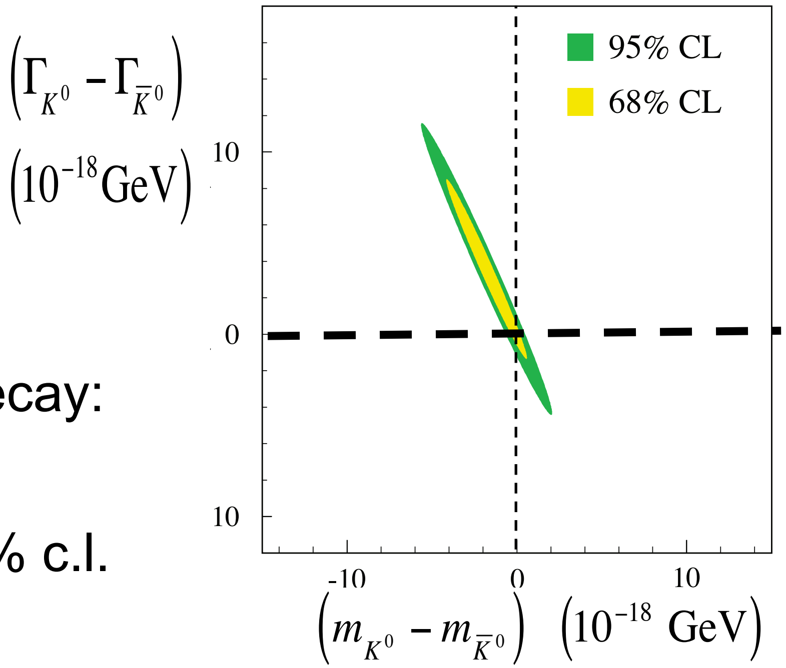
$$\delta = \frac{1}{2}\frac{\left(m_{\bar{K}^0} - m_{K^0}\right) - (i/2)\left(\Gamma_{\bar{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

Combining Reδ and Imδ results

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

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

at 95% c.l.

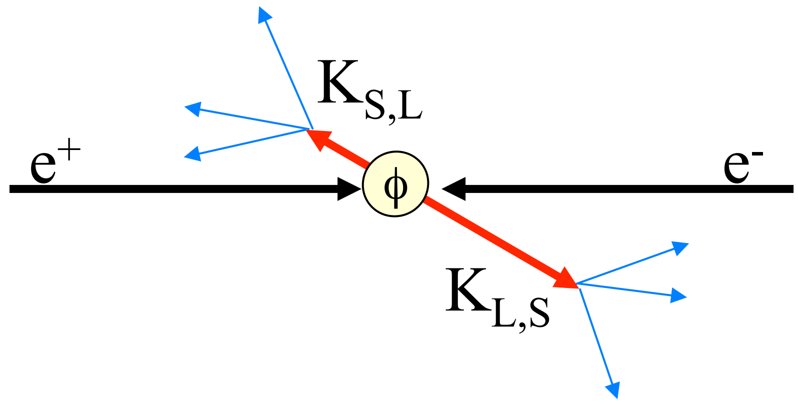


Entangled neutral kaon pairs

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 $J^{PC} = 1^{--}$:



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

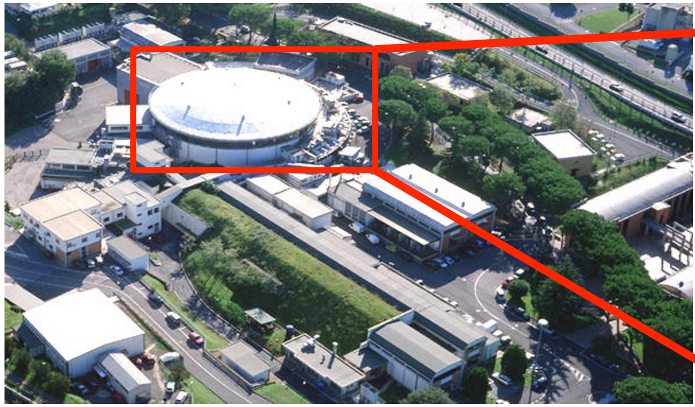
$$= \frac{N}{\sqrt{2}}\left[\left|K_S(\vec{p})\right\rangle\left|K_L(-\vec{p})\right\rangle - \left|K_L(\vec{p})\right\rangle\left|K_S(-\vec{p})\right\rangle\right]$$

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

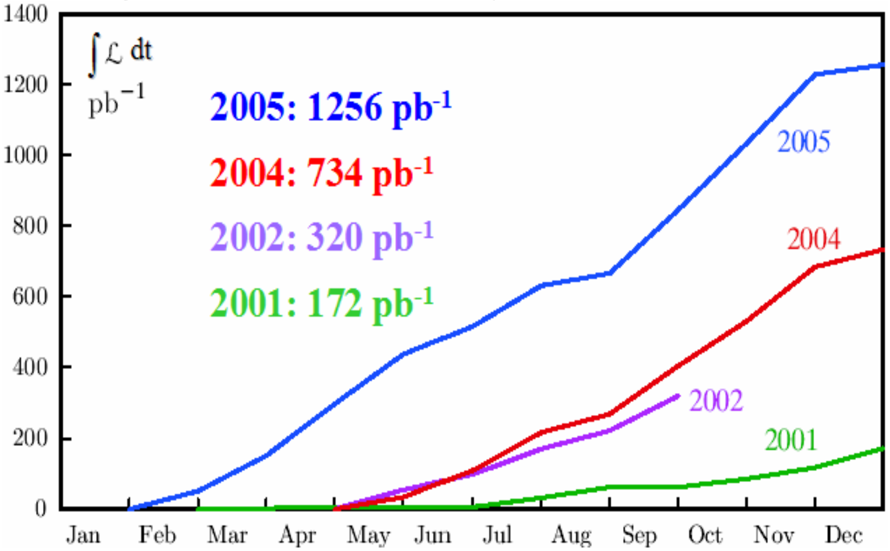
$p_K = 110$ MeV/c
$\lambda_S = 6$ mm $\quad \lambda_L = 3.5$ m

The KLOE detector at the Frascati φ-factory DAΦNE

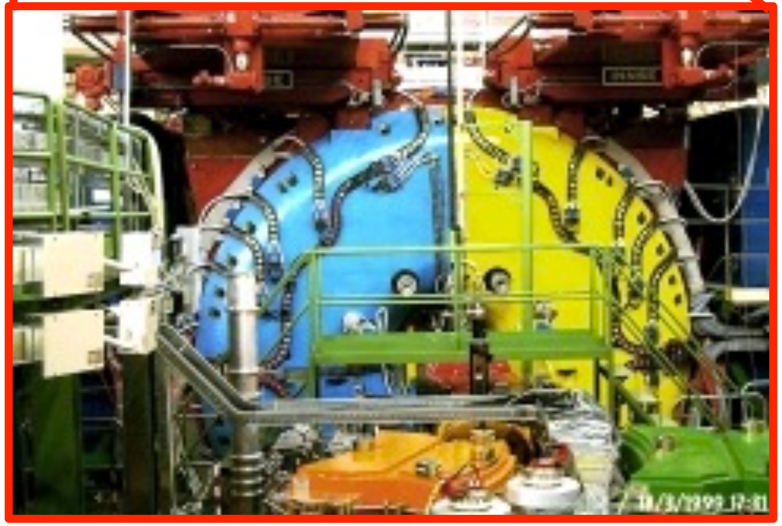
DAFNE collider



Integrated luminosity (KLOE)



KLOE detector



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

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

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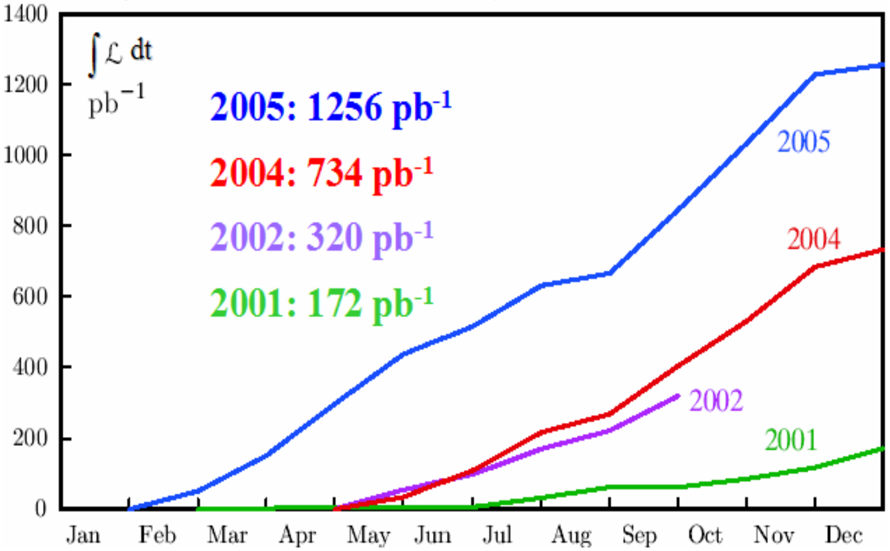

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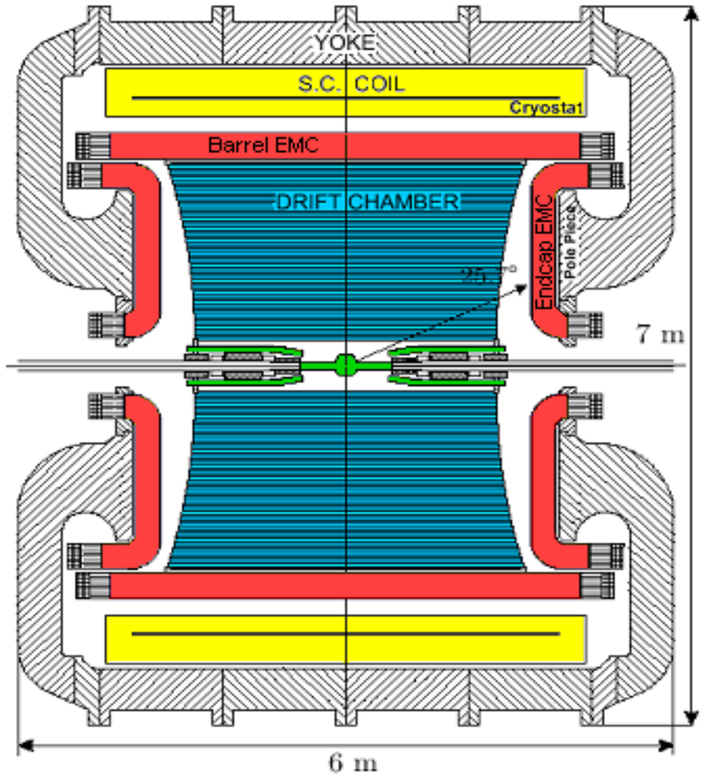


Lead/scintillating fiber calorimeter

drift chamber

4 m diameter × 3.3 m length

helium based gas mixture

Direct CPT symmetry test in transitions

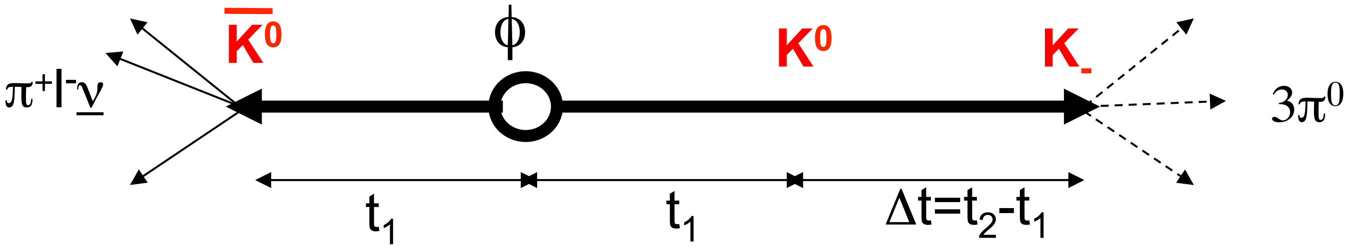
Direct test of CPT symmetry in neutral kaon transitions

- 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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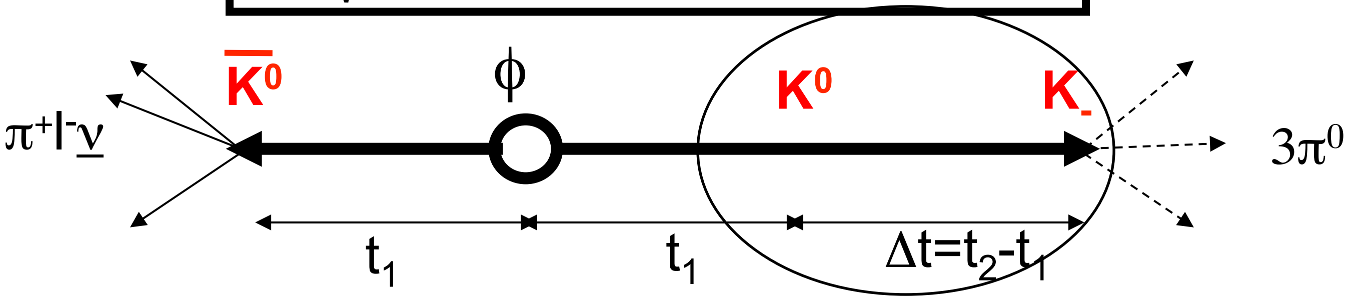

$$K^0 \rightarrow K_-$$ reference process

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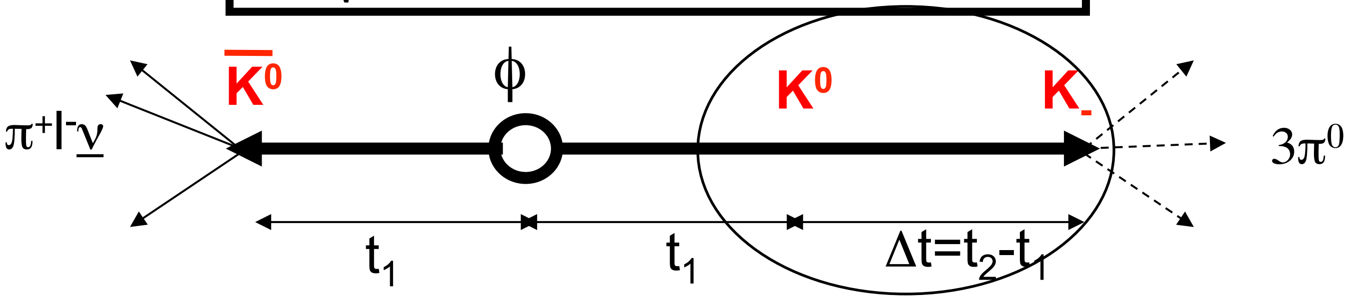
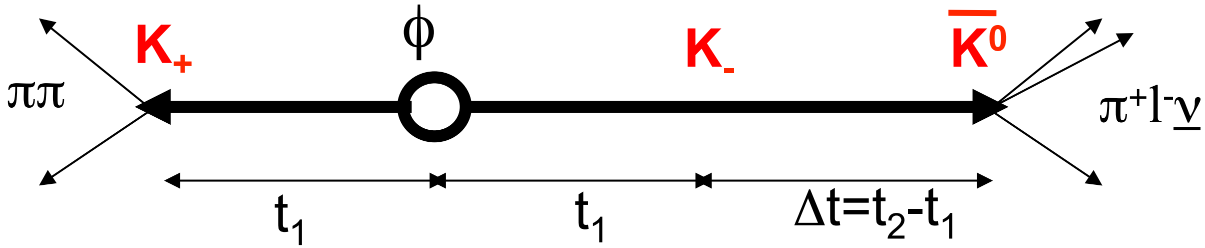


$K^0 \rightarrow K_-$ reference process



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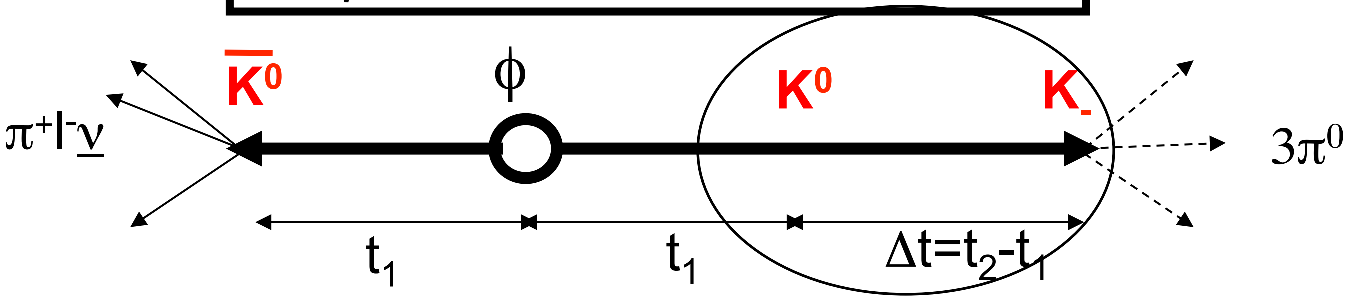
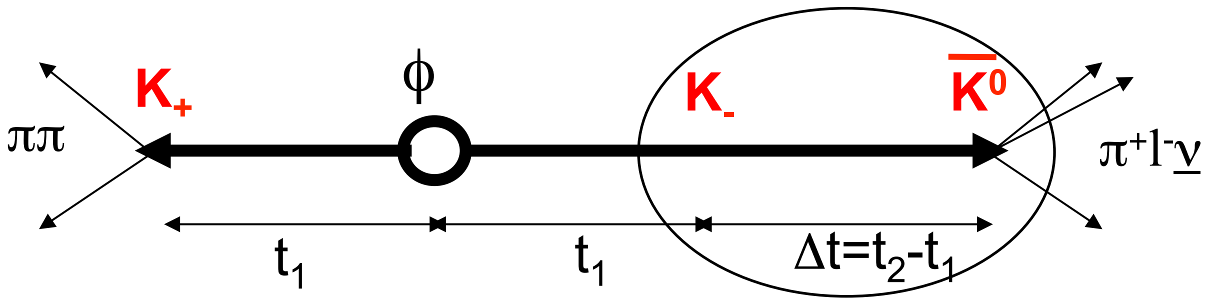


$K^0 \to K_-$ reference process

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



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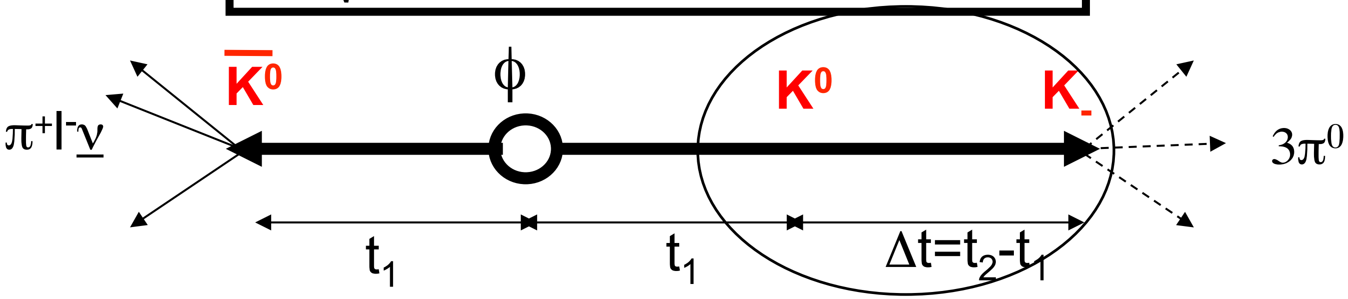
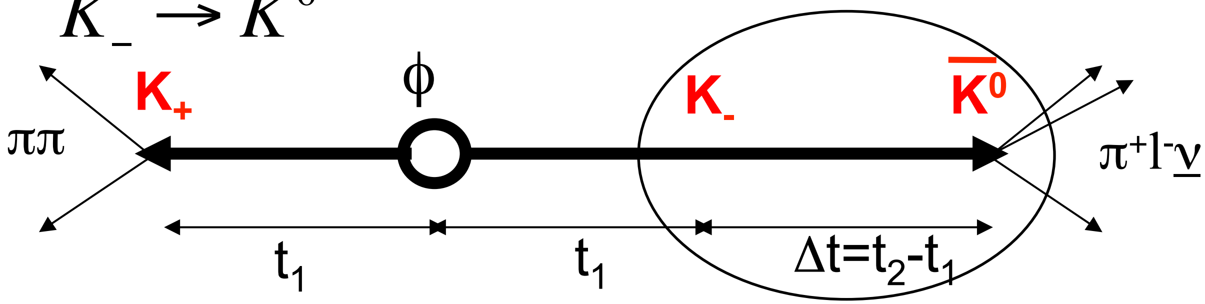


$K^0 \rightarrow K_-$ reference process

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

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

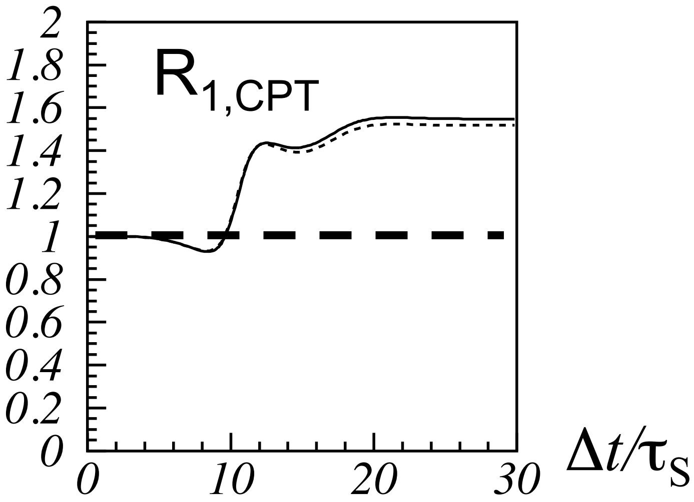
One can define the following ratios of probabilities:

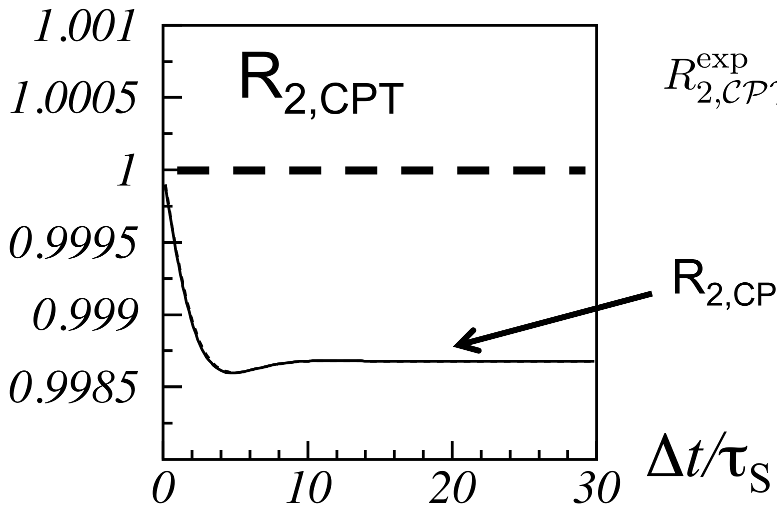
$$R_{1,\mathcal{CPT}}(\Delta t) = P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] / P\left[K^0(0) \to K_+(\Delta t)\right]$$
$$R_{2,\mathcal{CPT}}(\Delta t) = P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right]$$
$$R_{3,\mathcal{CPT}}(\Delta t) = P\left[K_+(0) \to K^0(\Delta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

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

Direct test of CPT symmetry in neutral kaon transitions

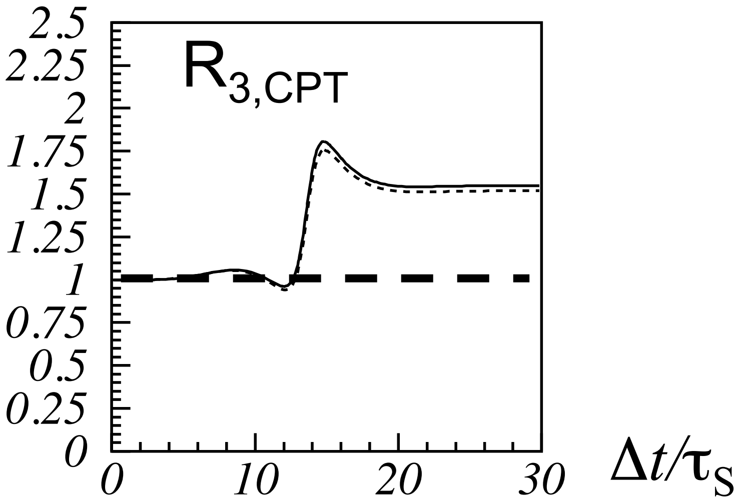
for visualization purposes, plots with Re(δ)=3.3 10^{-4} Im(δ)=1.6 10^{-5} (---- Im(δ)=0)

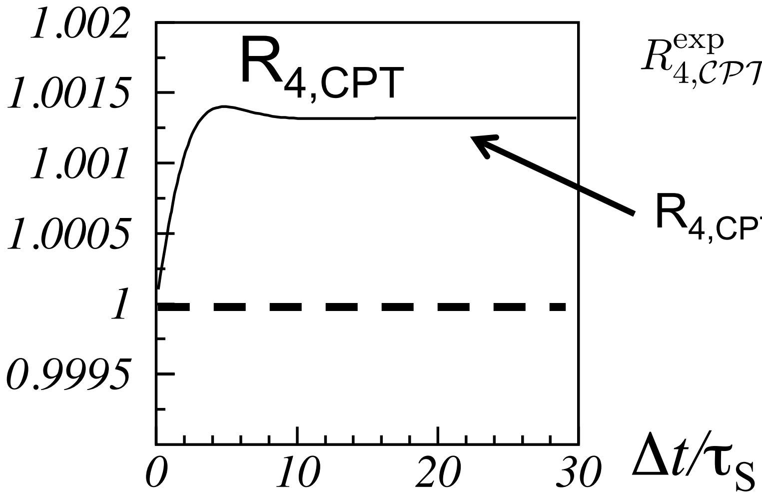




$$R^{exp}_{2,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}$$

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



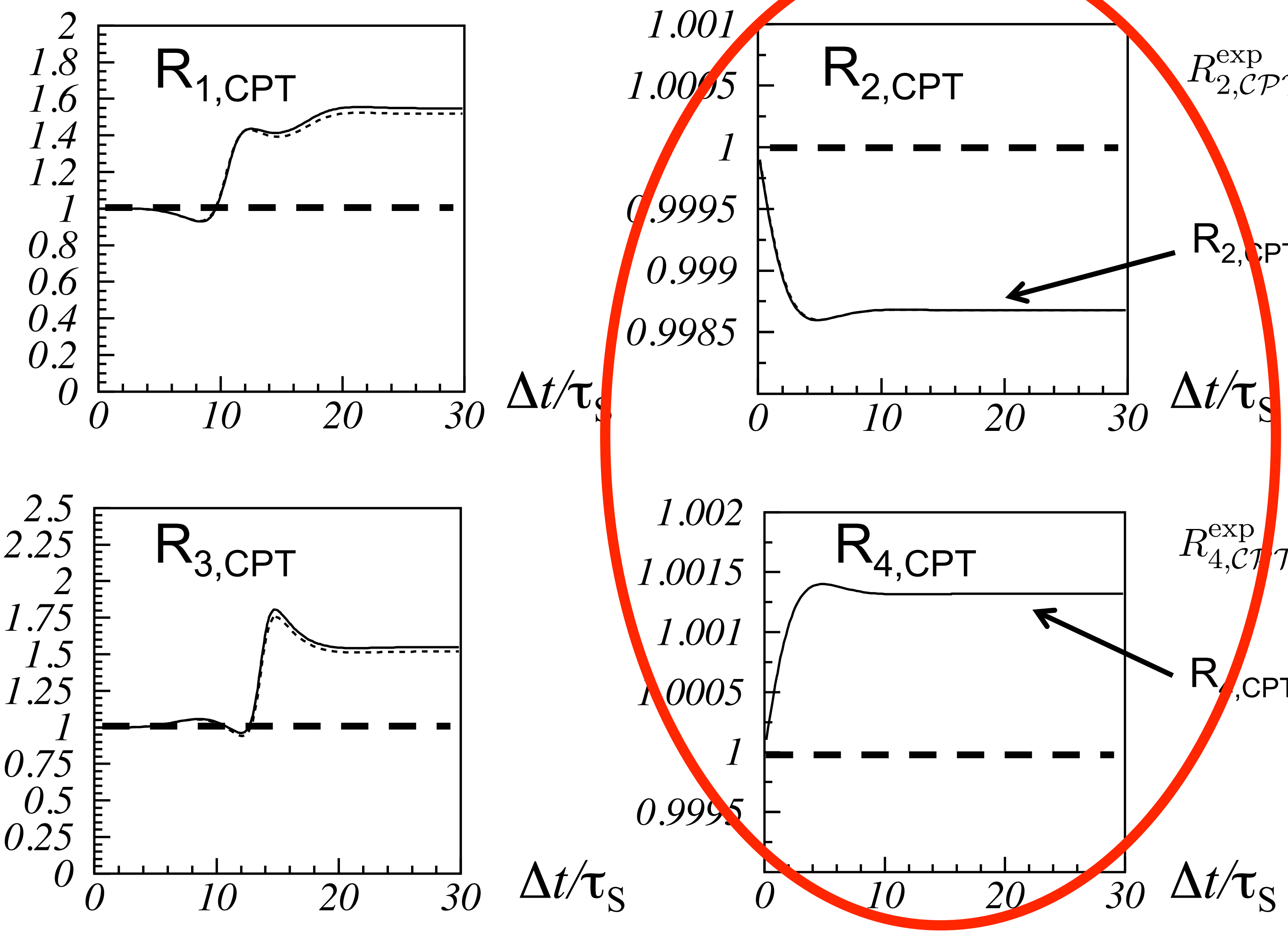


$$R^{exp}_{4,\mathcal{CPT}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)}$$

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

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)



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

measurable at KLOE

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

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

Direct test of CPT symmetry in neutral kaon transitions

- It would be possible for the first time 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.

- 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.

- The proposed CPT test is model independent and fully robust. It might shed light on possible new CPT violating mechanisms.

- KLOE-2 could reach a statistical sensitivity of $O(10^{-3})$ on the newly proposed observable quantities.

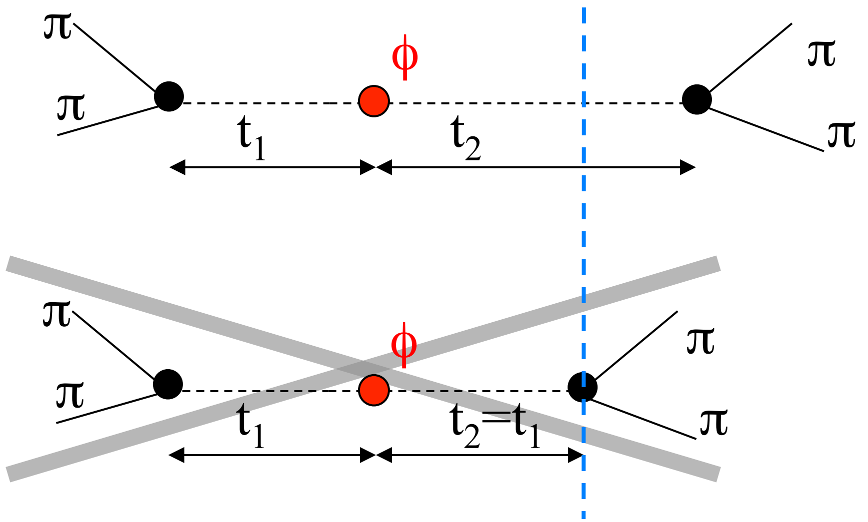
J. Bernabeu, A.D.D., P. Villanueva: arXiv:1509.02000 [hep-ph] accepted on JHEP

Test of Quantum Coherence

EPR correlations in entangled neutral kaon pairs from ϕ

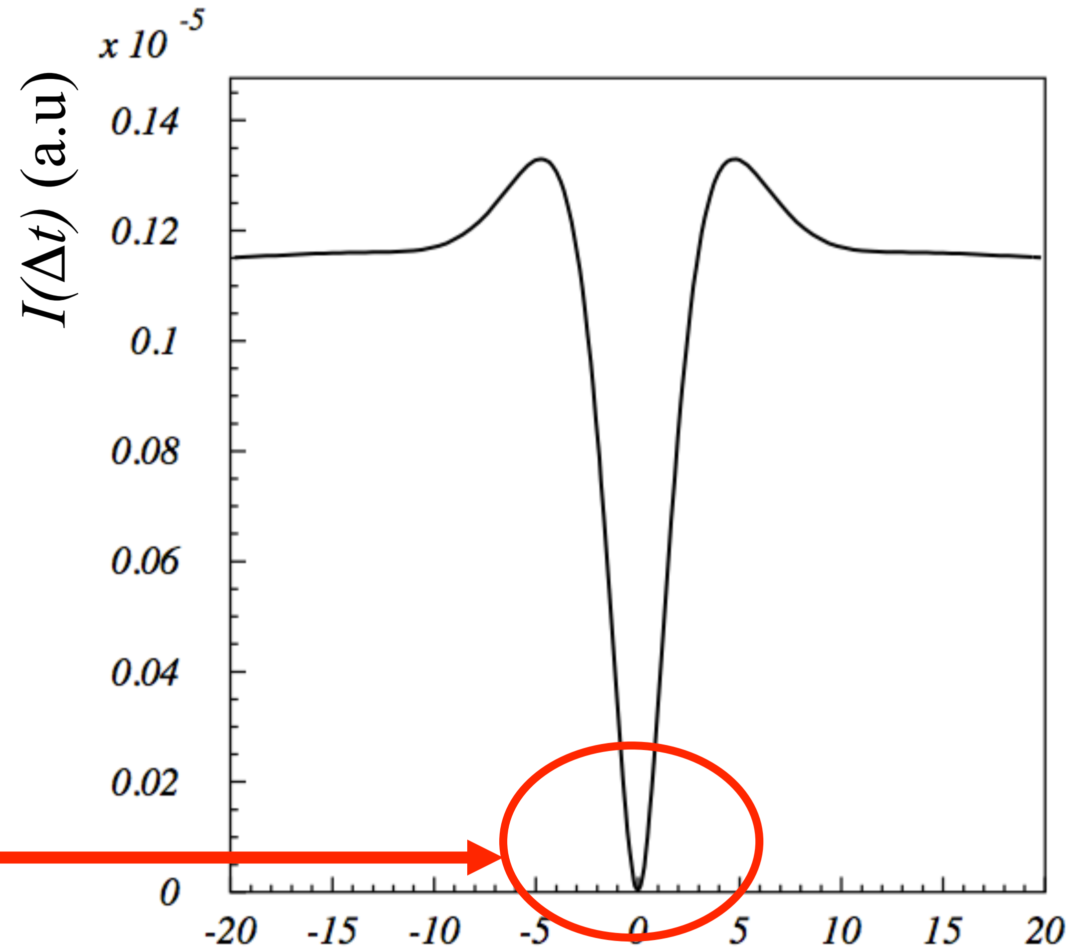
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$

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



$\Delta t = t_1 - t_2$

$\Delta t/\tau_S$

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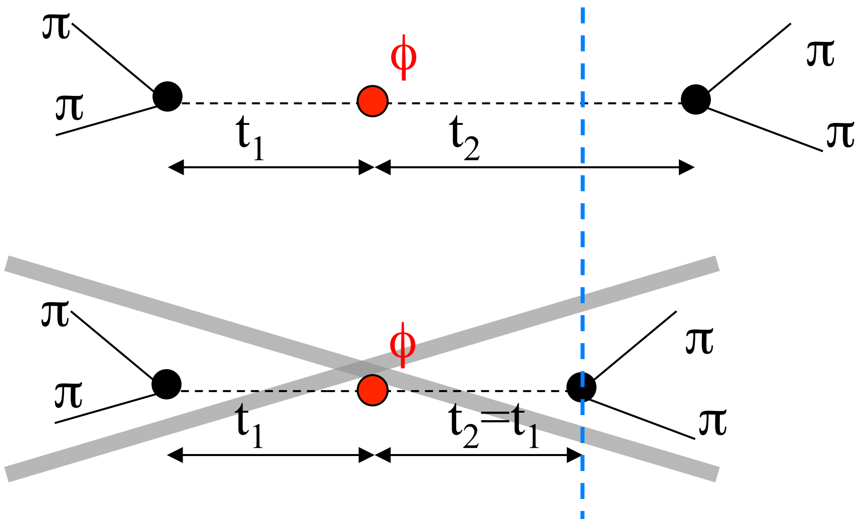

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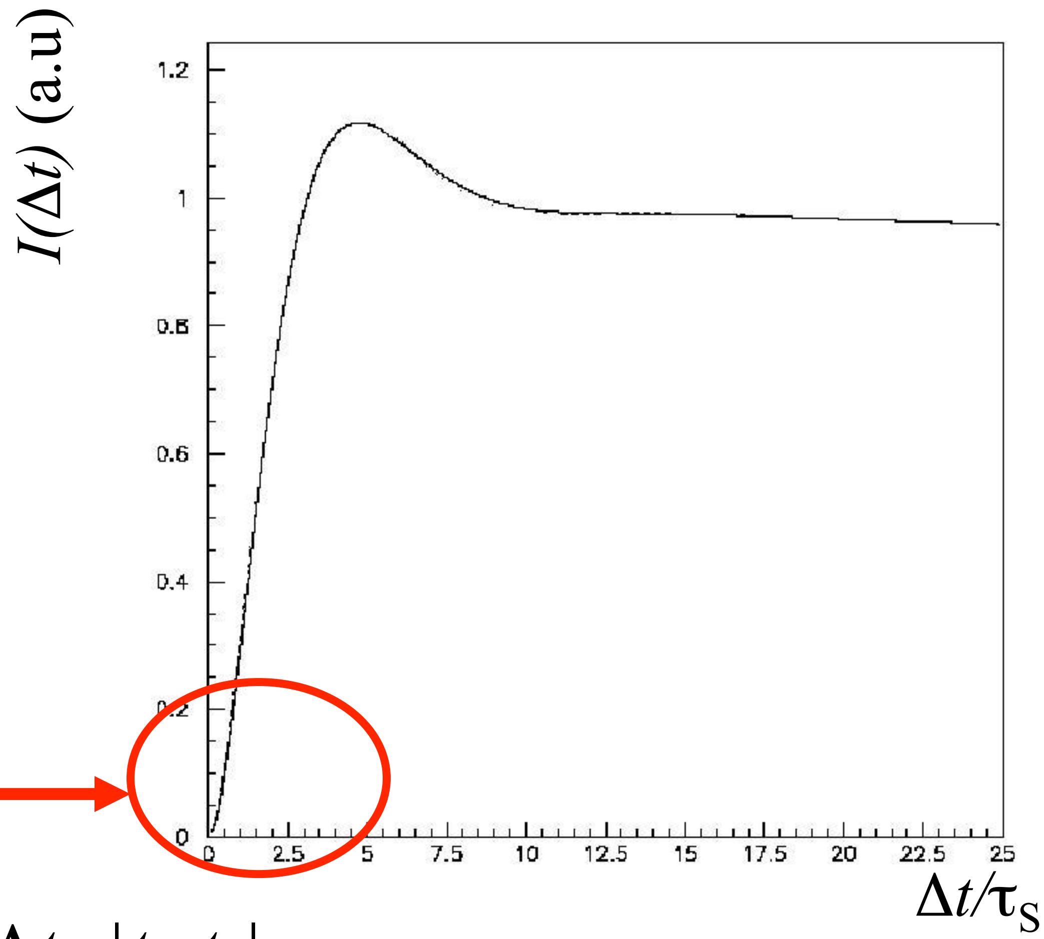

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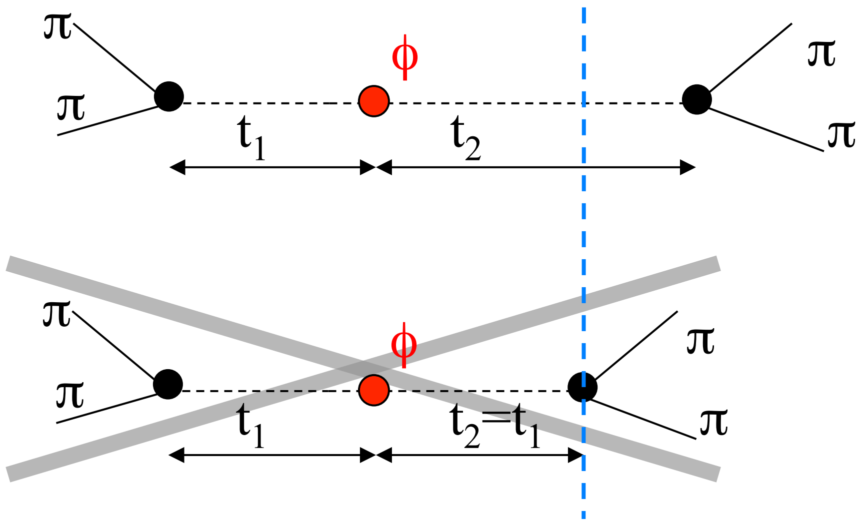

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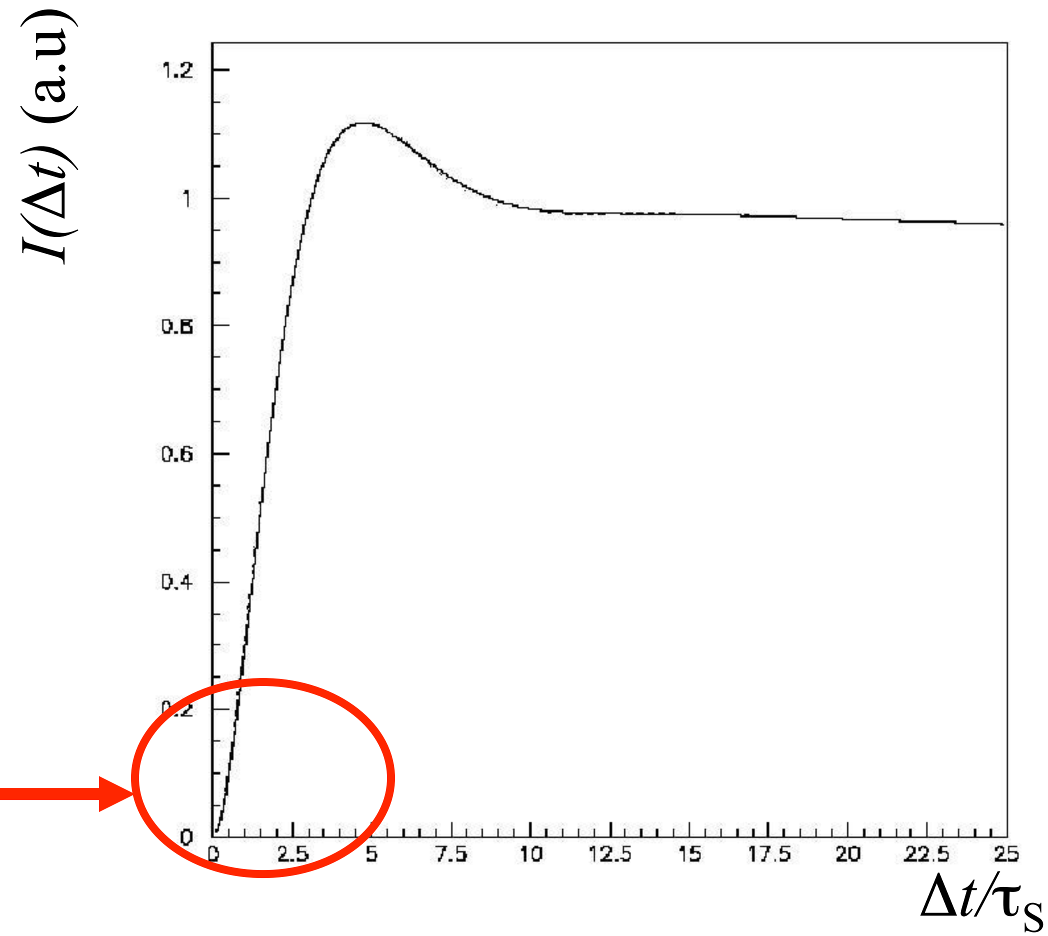

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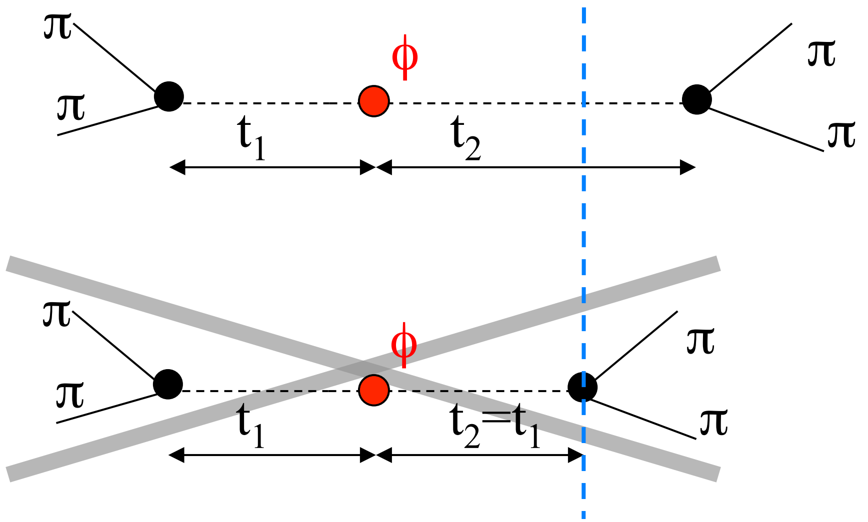

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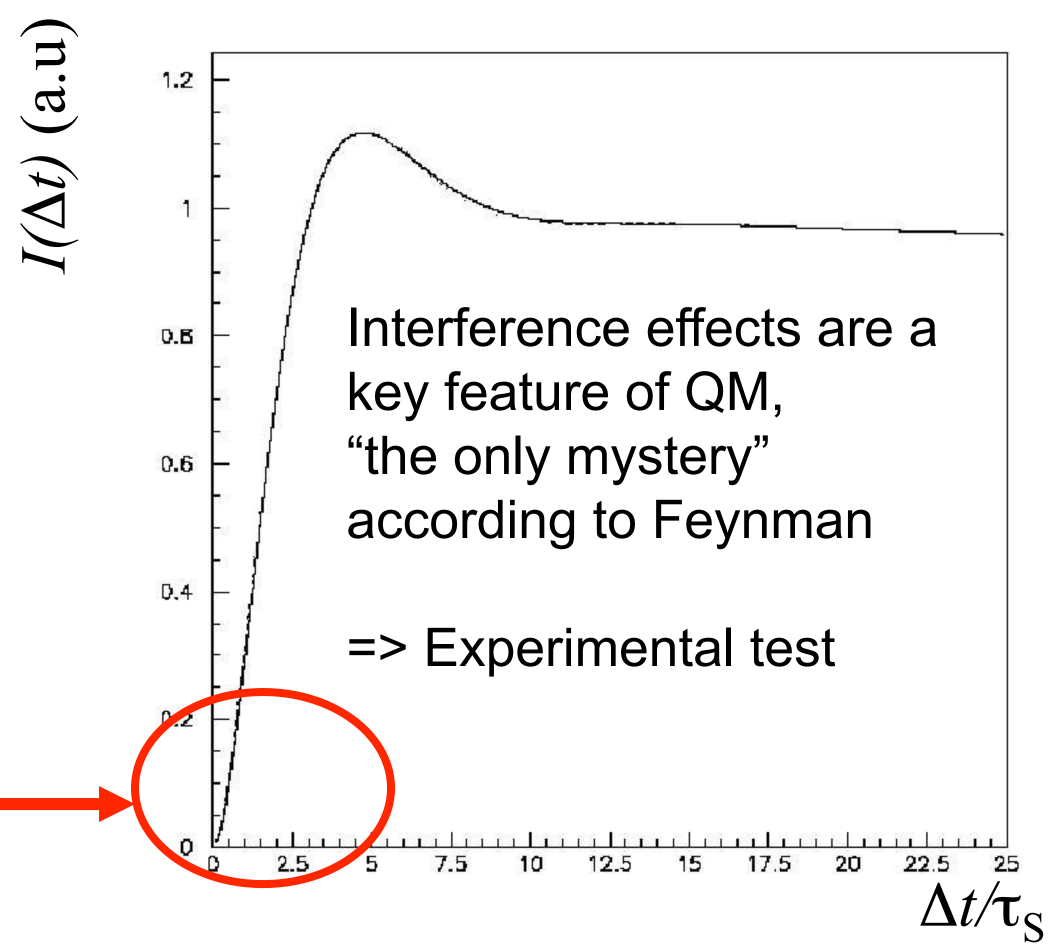

Interference effects are a key feature of QM, "the only mystery" according to Feynman

=> Experimental test

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

EPR correlations in entangled neutral kaon pairs from ϕ

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

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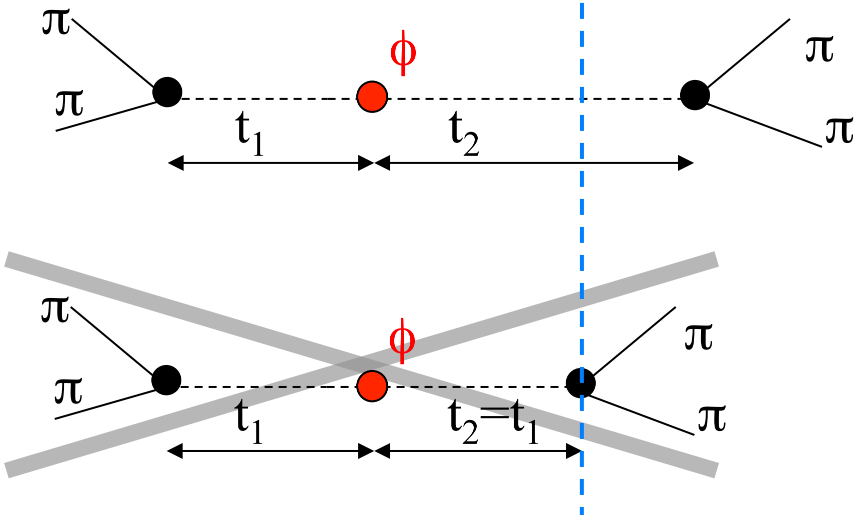

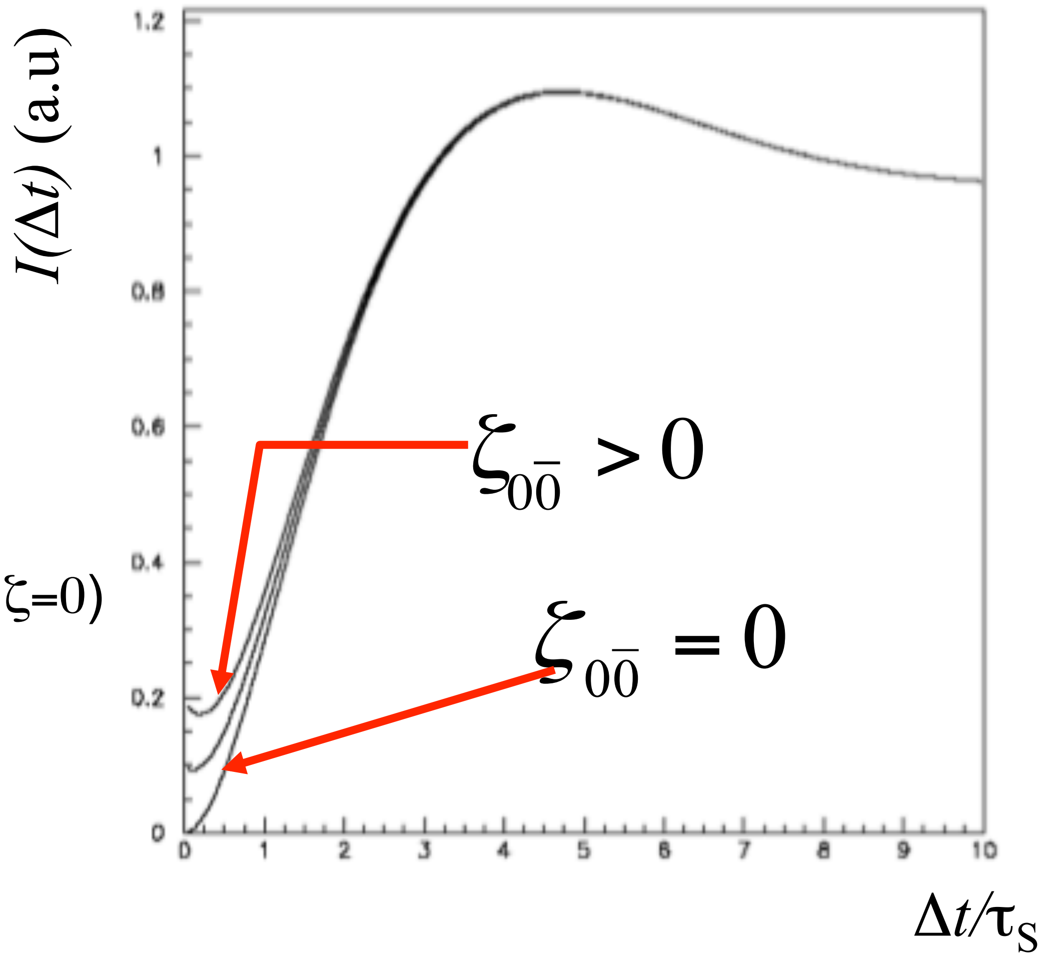

ζ decoherence parameter (QM predicts ζ=0)

$\Delta t = |t_1 - t_2|$

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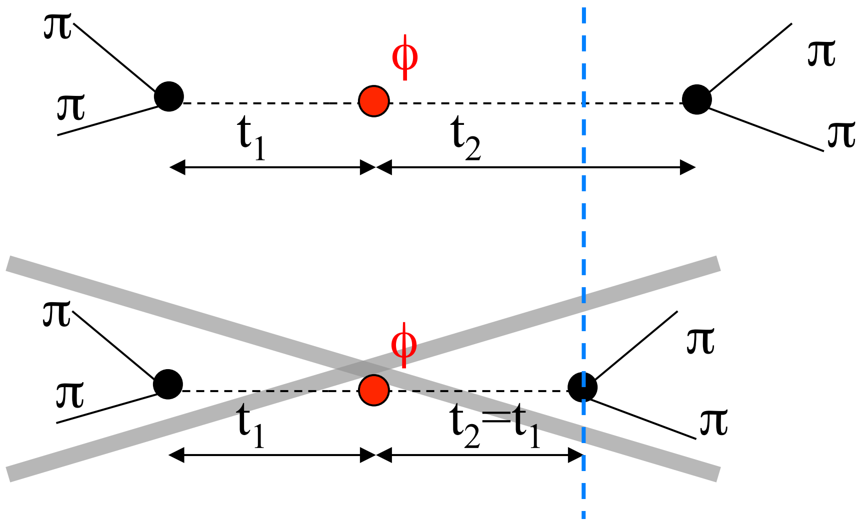

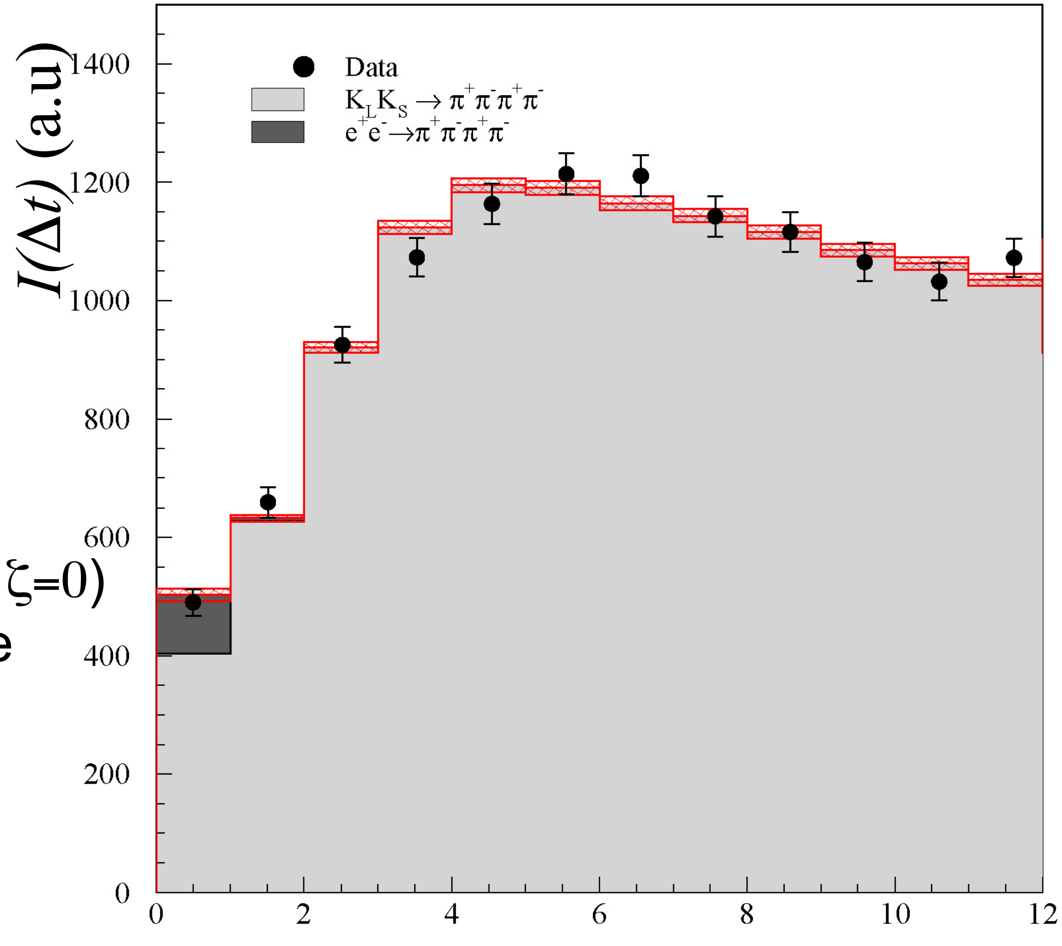

ζ decoherence parameter (QM predicts ζ=0)
Most precise test of quantum coherence in an entangled system

KLOE result:

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

PLB 642(2006) 315   L=1.5 fb^{-1} : FP40 (2010) 852

terms $\zeta_{00}/|\varepsilon|^2$ with CPV $|\varepsilon|^2 \sim 10^{-6}$ => high sensitivity to ζ_{00}

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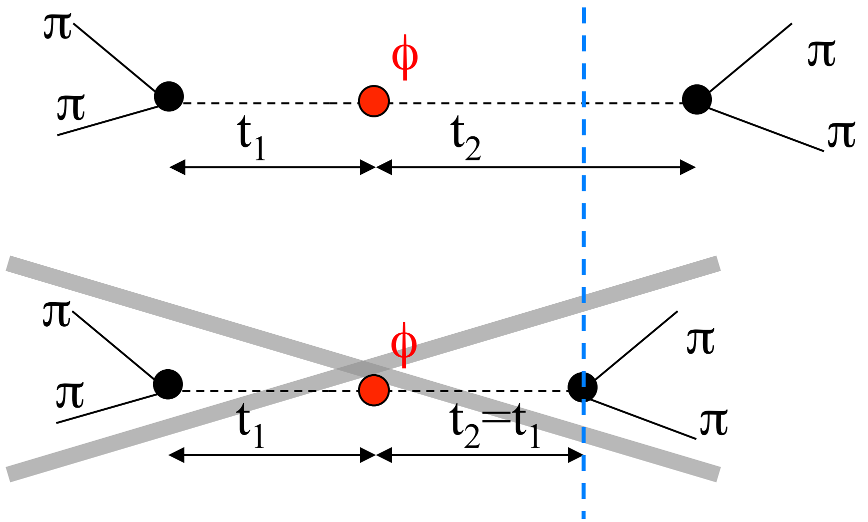

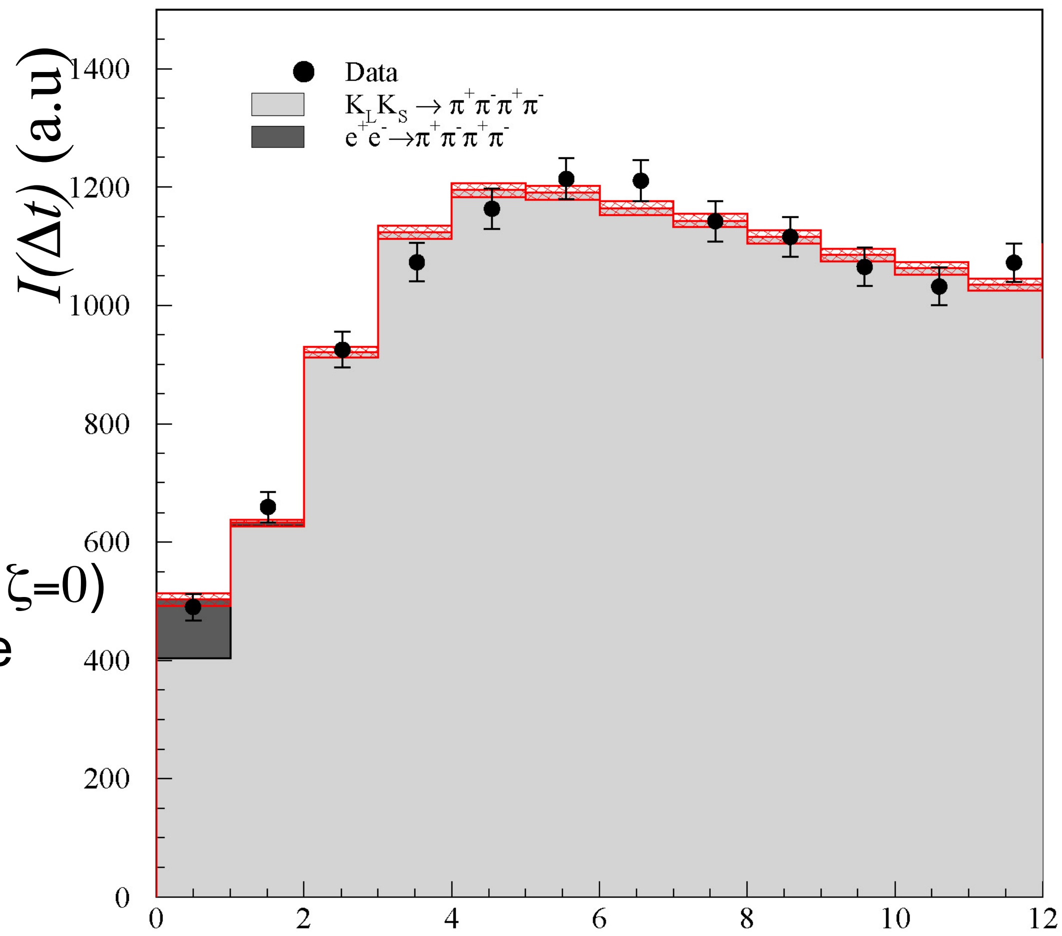

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Search for decoherence and CPT violation effects

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]:

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

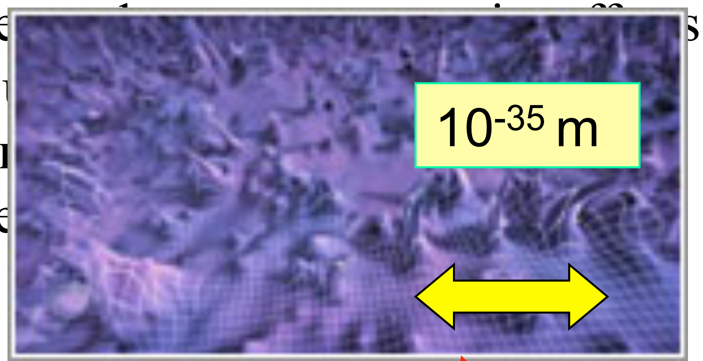
extra term inducing decoherence: pure state => mixed state

[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

Decoherence and CPT violation

S. Hawking (1975)

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



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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], M. Arzano PRD90 (2014) 024016

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

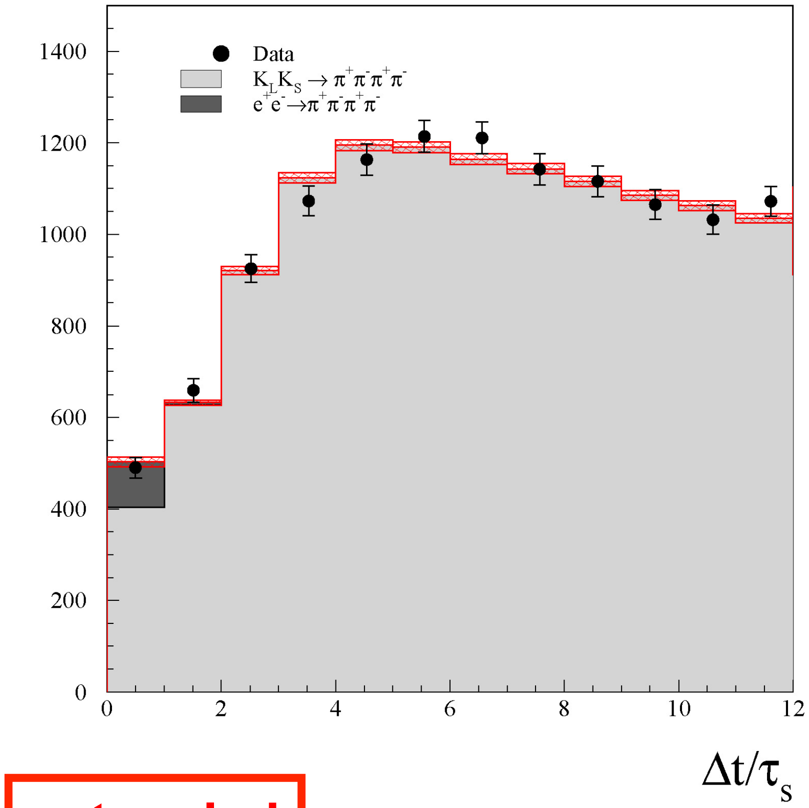
In the complete positivity hypothesis
$\alpha = \gamma$, $\beta = 0$
=> only one independent parameter: γ

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

high sensitivity due to $\Delta\lambda$ and CPV

Future perspectives

KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:

- a new scheme of the interaction region has been implemented (crabbed waist scheme)

KLOE-2 experiment:

- extend the KLOE physics program at DAΦNE upgraded in luminosity
- goal: to collect $L > 5\ fb^{-1}$ of integrated luminosity in the next 2-3 years
- Data taking (started on Nov. 2014) and commissioning in progress
  $\sim 1\ fb^{-1}$ delivered up to now

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, …)

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. (G. Amelino-Camelia et al. EPJC 68 (2010) 619-681)

- The precision of several tests could be improved by about one order of magnitude

- KLOE-2 could also test CPT symmetry in transition processes for the first time