Test of CPT in transitions with entangled neutral kaons

Antonio Di Domenico
Dipartimento di Fisica, Sapienza Università di Roma
and INFN sezione di Roma, Italy

Is Quantum Theory exact?
The quest for spin-statistics connection violation and related items
LNF, Italy, 2-5 July 2018

CPT: introduction

Essays Dedicated to Niels Bohr on the Occasion of his Seventieth Birthday

Edited by W. Pauli

EXCLUSION PRINCIPLE, LORENTZ GROUP AND REFLECTION OF SPACE-TIME AND CHARGE

W. Pauli

DEDICATION

The 70th anniversary of Niels Bohr's birthday reminds me of a long and still continuing common pilgrimage since the year 1922, in which so many stations are involved. Without pretension of completeness I mention here only some of them in their relation to the particular subject of this paper which, I hope, he will permit me to dedicate to him on the occasion of this celebration.

. . .

I believe that this paper also illustrates the fact that a rigorous mathematical formalism and epistemological analysis are both indispensable in physics in a complementary way in the sense of Niels Bohr. While I try to use the former to connect all mentioned features of the theory with help of a richer "fulness" of plus and minus signs in an increasing "clarity," the latter makes me aware that the final "truth" on the subject is still "dwelling in the abyss"*.

* I refer here to Bohr's favourite verses of Schiller:

CPT: introduction

The three discrete symmetries of QM, C (charge conjugation: $q \rightarrow -q$), P (parity: $x \rightarrow -x$), and T (time reversal: $t \rightarrow -t$) 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.

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..

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

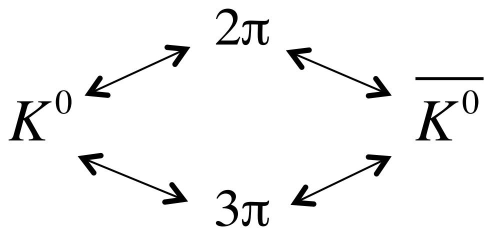
neutral B system $\left|m_{B^0} - m_{\overline{B}^0}\right| / m_B < 10^{-14}$

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 two-level oscillating system in a nutshell

K^0 and $\overline{K^0}$ can decay to common final states due to weak interactions: strangeness oscillations



$$|\Psi\rangle = a|K^0\rangle + b|\overline{K}^0\rangle$$

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

H is the effective hamiltonian (non-hermitian), decomposed into a Hermitian part (mass matrix **M**) and an anti-Hermitian part (i/2 decay matrix $\mathbf{\Gamma}$) :

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

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: physical states

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

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

$|K_{1,2}\rangle$ are CP=±1 states

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

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

The neutral kaon two-level oscillating system in a nutshell

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

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:

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

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

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

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

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

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

The neutral kaon two-level oscillating system in a nutshell

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

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:

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

huge amplification factor!!

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

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

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

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

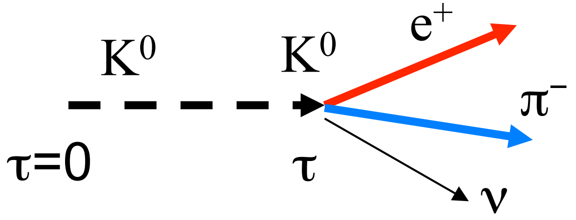
$$\Delta\Gamma \approx \Gamma_S \approx 2\Delta m = 7 \times 10^{-15}\ \text{GeV}$$

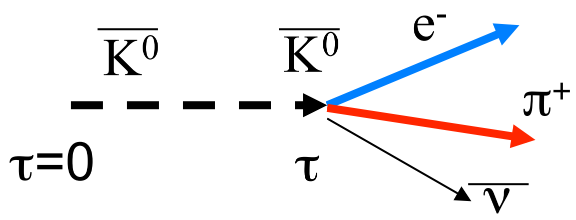
neutral kaons vs other oscillating meson systems

	<m> (GeV)	Δm (GeV)	<Γ> (GeV)	ΔΓ/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	$1\text{x}10^{-11}$	$4\text{x}10^{-13}$	$3\text{x}10^{-14}$

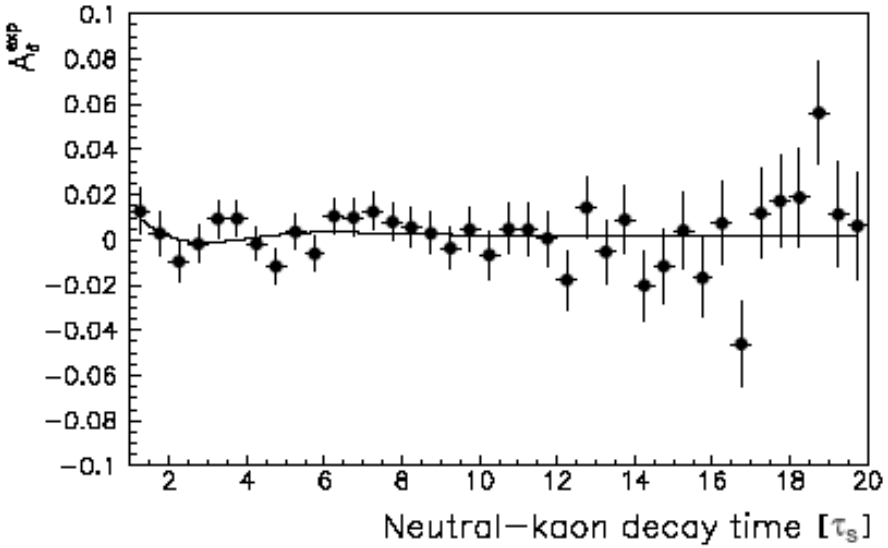
CPT test at CPLEAR

Test of **CPT** in the time evolution of neutral kaons using the semileptonic Asymmetry, i.e. comparing **"survival" probabilities**: $K^0 \to K^0$ vs $\bar{K}^0 \to \bar{K}^0$





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



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

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

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,
inputs from KLOE, NA48, KTEV, CPLEAR, etc.

PDG fit (2016)

Re ε = (161.1 ± 0.5) ×10^{-5}
Im δ =(−0.7 ± 1.4) × 10^{-5}

"Standard" CPT test

CPLEAR
PLB444 (1998) 52

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

PDG fit (2016)

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

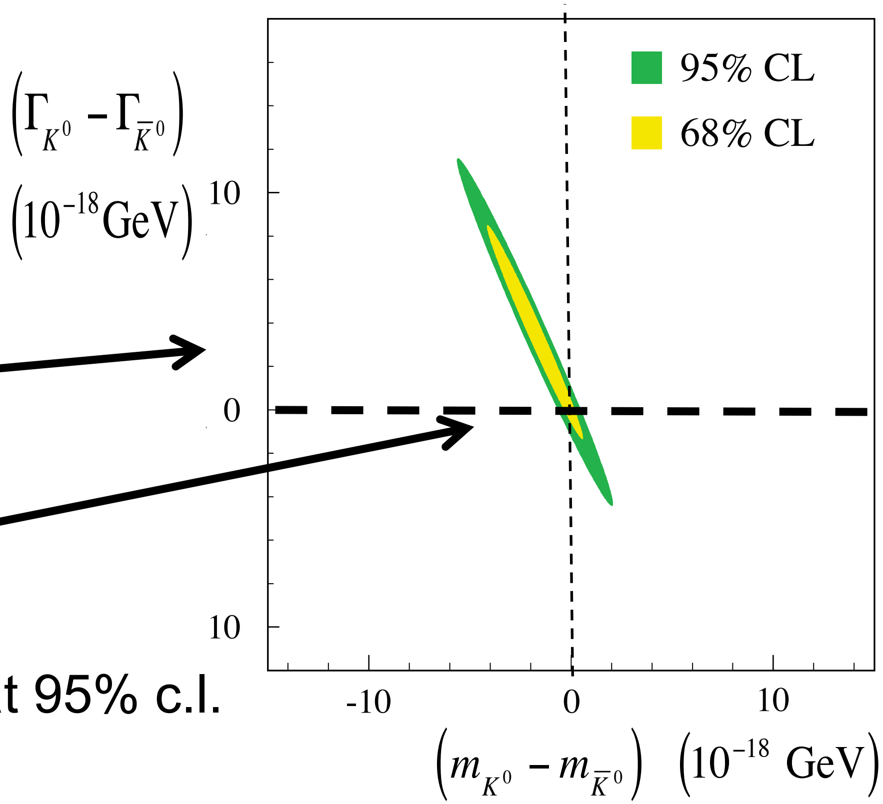
$$\delta = \frac{1}{2}\frac{\left(m_{\bar{K}^0} - m_{K^0}\right) - (i/2)\left(\Gamma_{\bar{K}^0} - \Gamma_{K^0}\right)}{\Delta m + i\Delta\Gamma/2}$$

- Combining Reδ and Imδ results
- Assuming no CPT viol. in decay:

$$\left(\Gamma_{\bar{K}^0} - \Gamma_{K^0}\right) = 0$$

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

at 95% c.l.



Direct CPT test in transitions

- Is it possible to test the CPT symmetry directly in transition processes between kaon states, rather than comparing masses, lifetimes, or other intrinsic properties of particle and anti-particle states?

- 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).

- Clean formulation required. Possible spurious effects induced by CP violation in the decay and/or a violation of the $\Delta S = \Delta Q$ rule have to be well under control.

- In standard WWA the test is related to Reδ, a genuine CPT violating effect independent of $\Delta\Gamma$, i.e. not requiring the decay as an essential ingredient.

Probing CPT: J. Bernabeu, A.D.D., P. Villanueva, JHEP 10 (2015) 139
Time-reversal violation: J. Bernabeu, A.D.D., P. Villanueva, NPB 868 (2013) 102

Definition of states

We need two orthogonal bases:

1) $|K^0\rangle$ and $|\bar{K}^0\rangle$ assuming ΔS=ΔQ rule identified by their πlν decay (l^+ or l^-)

2) $|K_+\rangle$ and $|K_-\rangle$ (* not to be confused with charged kaons K^+ and K^-)

Let us also consider the states $|K_+\rangle$, $|K_-\rangle$ defined as follows: $|K_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP $= +1$ state; analogously $|K_-\rangle$ is the state filtered by the decay into $3\pi^0$, a pure CP $= -1$ state. Their orthogonal states correspond to the states which cannot decay into $\pi\pi$ or $3\pi^0$, defined, respectively, as

$$|\widetilde{K}_-\rangle \equiv \widetilde{N}_- \left[|K_L\rangle - \eta_{\pi\pi}|K_S\rangle\right]$$
$$|\widetilde{K}_+\rangle \equiv \widetilde{N}_+ \left[|K_S\rangle - \eta_{3\pi^0}|K_L\rangle\right]$$

$$\eta_{\pi\pi} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle}$$
$$\eta_{3\pi^0} = \frac{\langle 3\pi^0|T|K_S\rangle}{\langle 3\pi^0|T|K_L\rangle}$$

Orthogonal bases: $\{K_+, \widetilde{K}_-\}$ $\{\widetilde{K}_+, K_-\}$

Even though the decay products are orthogonal, the filtered $|K_+\rangle$ and $|K_-\rangle$ states can still be non-orthoghonal.

Condition of orthoghonality:

$$\eta_{\pi\pi} + \eta^{\star}_{3\pi^0} = \epsilon_L + \epsilon^{\star}_S$$

Neglecting direct CP violation ε' ⟶

$$|K_+\rangle \equiv |\widetilde{K}_+\rangle$$
$$|K_-\rangle \equiv |\widetilde{K}_-\rangle$$

Definition of states

We need two orthogonal bases:

1) $|K^0\rangle$ and $|\bar{K}^0\rangle$ assuming ΔS=ΔQ rule identified by their πlν decay (l^+ or l^-)

2) $|K_+\rangle$ and $|K_-\rangle$ (* not to be confused with charged kaons K^+ and K^-)

Let us also consider the states $|K_+\rangle$, $|K_-\rangle$ defined as follows: $|K_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP = +1 state; analogously $|K_-\rangle$ is the state filtered by the decay into $3\pi^0$, a pure CP = −1 state. Their orthogonal states correspond to the states which cannot decay into $\pi\pi$ or $3\pi^0$, defined, respectively, as

$$|\widetilde{K}_-\rangle \equiv \widetilde{N}_- \left[|K_L\rangle - \eta_{\pi\pi}|K_S\rangle\right]$$
$$|\widetilde{K}_+\rangle \equiv \widetilde{N}_+ \left[|K_S\rangle - \eta_{3\pi^0}|K_L\rangle\right]$$

$$\eta_{\pi\pi} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle}$$

$$\eta_{3\pi^0} = \frac{\langle 3\pi^0|T|K_S\rangle}{\langle 3\pi^0|T|K_L\rangle}$$

Orthogonal bases: $\{K_+, \widetilde{K}_-\}$ $\{\widetilde{K}_+, K_-\}$

Even though the decay products are orthogonal, the filtered $|K_+\rangle$ and $|K_-\rangle$ states can still be non-orthoghonal.
Condition of orthoghonality:

$$\eta_{\pi\pi} + \eta^{\star}_{3\pi^0} = \epsilon_L + \epsilon^{\star}_S$$

Neglecting direct CP violation ε' ⟶

$$|K_+\rangle \equiv |\widetilde{K}_+\rangle$$
$$|K_-\rangle \equiv |\widetilde{K}_-\rangle$$

Definition of states

We need two orthogonal bases:

1) $|K^0\rangle$ and $|\bar{K}^0\rangle$ assuming $\Delta S=\Delta Q$ rule identified by their $\pi l \nu$ decay (l^+ or l^-)

2) $|K_+\rangle$ and $|K_-\rangle$ (* not to be confused with charged kaons K^+ and K^-)

Let us also consider the states $|K_+\rangle$, $|K_-\rangle$ defined as follows: $|K_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP $= +1$ state; analogously $|K_-\rangle$ is the state filtered by the decay into $3\pi^0$, a pure CP $= -1$ state. Their orthogonal states correspond to the states which cannot decay into $\pi\pi$ or $3\pi^0$, defined, respectively, as

$$|\widetilde{K}_-\rangle \equiv \widetilde{N}_- \left[|K_L\rangle - \eta_{\pi\pi}|K_S\rangle\right]$$
$$|\widetilde{K}_+\rangle \equiv \widetilde{N}_+ \left[|K_S\rangle - \eta_{3\pi^0}|K_L\rangle\right]$$

$$\eta_{\pi\pi} = \frac{\langle\pi\pi|T|K_L\rangle}{\langle\pi\pi|T|K_S\rangle}$$
$$\eta_{3\pi^0} = \frac{\langle 3\pi^0|T|K_S\rangle}{\langle 3\pi^0|T|K_L\rangle}$$

Orthogonal bases: $\{K_+, \widetilde{K}_-\}$ $\{\widetilde{K}_+, K_-\}$

Even though the decay products are orthogonal, the filtered $|K_+\rangle$ and $|K_-\rangle$ states can still be non-orthoghonal.

Condition of orthoghonality:

$$\eta_{\pi\pi} + \eta^\star_{3\pi^0} = \epsilon_L + \epsilon^\star_S$$

Neglecting direct CP violation ε' ⟶

$$|K_+\rangle \equiv |\widetilde{K}_+\rangle$$
$$|K_-\rangle \equiv |\widetilde{K}_-\rangle$$

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, JHEP 10 (2015) 139

Direct test of symmetries with neutral kaons

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

Direct test of symmetries with neutral kaons

Conjugate= reference

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$\mathrm{K}^0 \to \mathrm{K}^0$	~~$\mathrm{K}^0 \to \mathrm{K}^0$~~	$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$
$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$	~~$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$~~
$\mathrm{K}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \mathrm{K}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$
$\mathrm{K}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \mathrm{K}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$
$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$	$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$	$\mathrm{K}^0 \to \bar{\mathrm{K}}^0$	~~$\bar{\mathrm{K}}^0 \to \mathrm{K}^0$~~
$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$	~~$\bar{\mathrm{K}}^0 \to \bar{\mathrm{K}}^0$~~	$\mathrm{K}^0 \to \mathrm{K}^0$	$\mathrm{K}^0 \to \mathrm{K}^0$
$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	$\mathrm{K}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \mathrm{K}^0$
$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	$\mathrm{K}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \mathrm{K}^0$
$\mathrm{K}_+ \to \mathrm{K}^0$	$\mathrm{K}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$
$\mathrm{K}_+ \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_+$	$\mathrm{K}_+ \to \mathrm{K}^0$	$\mathrm{K}^0 \to \mathrm{K}_+$
$\mathrm{K}_+ \to \mathrm{K}_+$	~~$\mathrm{K}_+ \to \mathrm{K}_+$~~	~~$\mathrm{K}_+ \to \mathrm{K}_+$~~	~~$\mathrm{K}_+ \to \mathrm{K}_+$~~
$\mathrm{K}_+ \to \mathrm{K}_-$	$\mathrm{K}_- \to \mathrm{K}_+$	~~$\mathrm{K}_+ \to \mathrm{K}_-$~~	$\mathrm{K}_- \to \mathrm{K}_+$
$\mathrm{K}_- \to \mathrm{K}^0$	$\mathrm{K}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$
$\mathrm{K}_- \to \bar{\mathrm{K}}^0$	$\bar{\mathrm{K}}^0 \to \mathrm{K}_-$	$\mathrm{K}_- \to \mathrm{K}^0$	$\mathrm{K}^0 \to \mathrm{K}_-$
$\mathrm{K}_- \to \mathrm{K}_+$	$\mathrm{K}_+ \to \mathrm{K}_-$	~~$\mathrm{K}_- \to \mathrm{K}_+$~~	$\mathrm{K}_+ \to \mathrm{K}_-$
$\mathrm{K}_- \to \mathrm{K}_-$	~~$\mathrm{K}_- \to \mathrm{K}_-$~~	~~$\mathrm{K}_- \to \mathrm{K}_-$~~	~~$\mathrm{K}_- \to \mathrm{K}_-$~~

Direct test of symmetries with neutral kaons

Conjugate= reference (red bar)

already in the table with conjugate as reference (black bar)

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	~~$K^0 \to K^0$~~	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	~~$K^0 \to \bar{K}^0$~~
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	~~$K^0 \to \bar{K}^0$~~	~~$K^0 \to \bar{K}^0$~~	~~$\bar{K}^0 \to K^0$~~
$\bar{K}^0 \to \bar{K}^0$	~~$\bar{K}^0 \to \bar{K}^0$~~	~~$K^0 \to K^0$~~	~~$K^0 \to K^0$~~
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	~~$K^0 \to K_+$~~	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	~~$K^0 \to K_-$~~	$K_- \to K^0$
$K_+ \to K^0$	~~$K^0 \to K_+$~~	$K_+ \to \bar{K}^0$	~~$\bar{K}^0 \to K_+$~~
$K_+ \to \bar{K}^0$	~~$\bar{K}^0 \to K_+$~~	~~$K_+ \to K^0$~~	~~$K^0 \to K_+$~~
$K_+ \to K_+$	~~$K_+ \to K_+$~~	~~$K_+ \to K_+$~~	~~$K_+ \to K_+$~~
$K_+ \to K_-$	$K_- \to K_+$	~~$K_+ \to K_-$~~	$K_- \to K_+$
$K_- \to K^0$	~~$K^0 \to K_-$~~	$K_- \to \bar{K}^0$	~~$\bar{K}^0 \to K_-$~~
$K_- \to \bar{K}^0$	~~$\bar{K}^0 \to K_-$~~	~~$K_- \to K^0$~~	~~$K^0 \to K_-$~~
$K_- \to K_+$	~~$K_+ \to K_-$~~	~~$K_- \to K_+$~~	~~$K_+ \to K_-$~~
$K_- \to K_-$	~~$K_- \to K_-$~~	~~$K_- \to K_-$~~	~~$K_- \to K_-$~~

Direct test of symmetries with neutral kaons

Conjugate= reference (red)

already in the table with conjugate as reference (black)

Two identical conjugates for one reference (blue)

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	~~$K^0 \to \bar{K}^0$~~	~~$K^0 \to \bar{K}^0$~~	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	~~$K^0 \to K^0$~~	~~$K^0 \to K^0$~~
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	~~$K^0 \to K_+$~~	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	~~$K^0 \to K_-$~~	$K_- \to K^0$
$K_+ \to K^0$	~~$K^0 \to K_+$~~	$K_+ \to \bar{K}^0$	~~$\bar{K}^0 \to K_+$~~
$K_+ \to \bar{K}^0$	~~$\bar{K}^0 \to K_+$~~	~~$K_+ \to K^0$~~	~~$K^0 \to K_+$~~
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	~~$K^0 \to K_-$~~	$K_- \to \bar{K}^0$	~~$\bar{K}^0 \to K_-$~~
$K_- \to \bar{K}^0$	~~$\bar{K}^0 \to K_-$~~	~~$K_- \to K^0$~~	~~$K^0 \to K_-$~~
$K_- \to K_+$	~~$K_+ \to K_-$~~	$K_- \to K_+$	~~$K_+ \to K_-$~~
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

Direct test of symmetries with neutral kaons

Conjugate= reference

Reference	T-conjugate	CP-conjugate	CPT-conjugate
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	$K^0 \to K_-$	$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$
$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

already in the table with conjugate as reference

Two identical conjugates for one reference

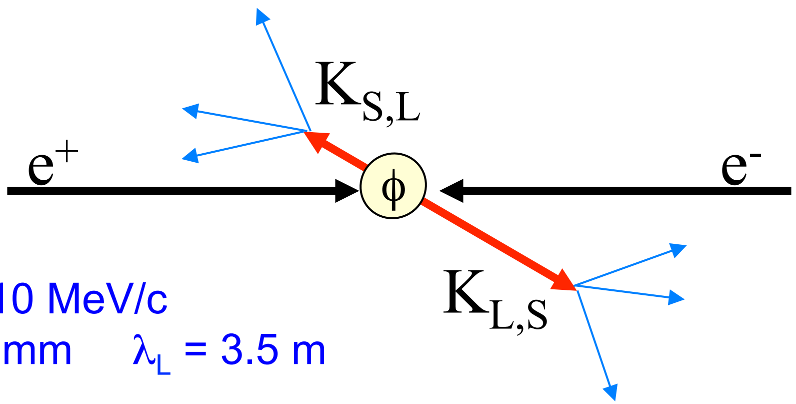
4 distinct tests of T symmetry

4 distinct tests of CP symmetry

4 distinct tests of CPT symmetry

Quantum entanglement as a tool

- The in<->out states inversion required in a DIRECT test of CPT (or T) can be performed exploiting the properties of the quantum entanglement.
- In maximally entangled systems the complete knowledge of the system as a whole is encoded in the state, no information on single subsystems is available.
- Once a measurement is performed on one subsystem, then the information is immediately transferred to its partner, which is prepared in the orthogonal state
- $\sigma(e^+e^- \to \phi)$ ~3 mb;   W = m_ϕ = 1019.4 MeV BR($\phi \to K^0\bar{K}^0$) ~ 34%
  ~10^6/pb^{-1} KK pairs produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:



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

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

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

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

(

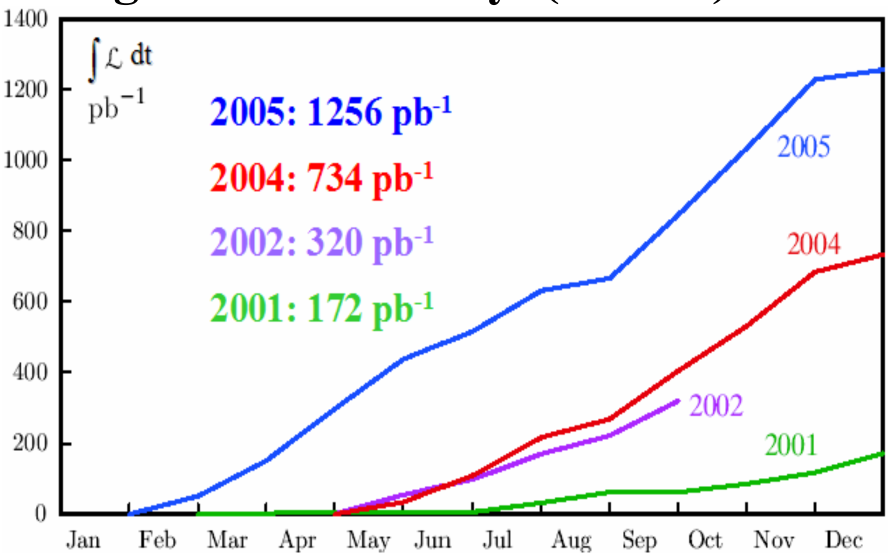
(

- Where to produce entangled kaons?
- How perfect is anticorrelation of the initial entangled state?

The KLOE detector at the Frascati ϕ-factory DAΦNE

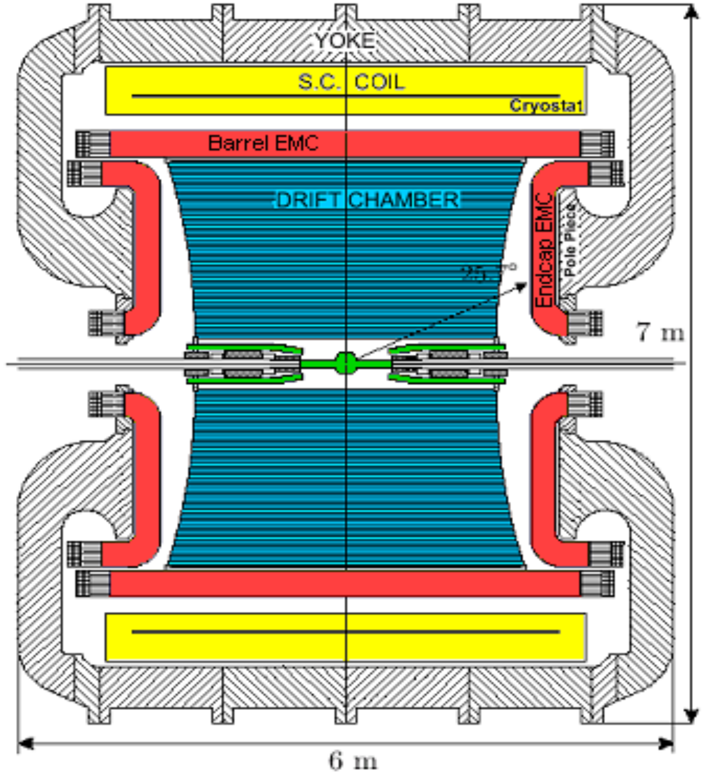
DAFNE collider

Integrated luminosity (KLOE)



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

KLOE detector



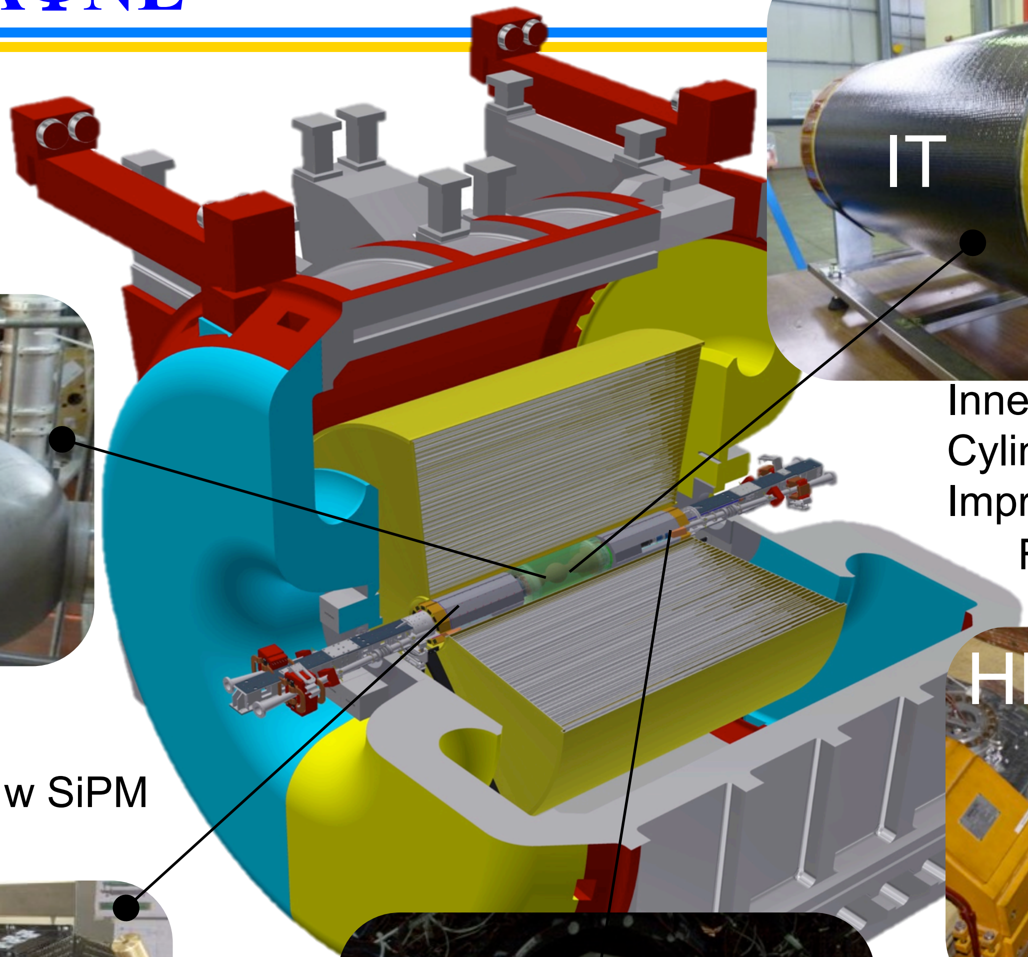
Lead/scintillating fiber calorimeter

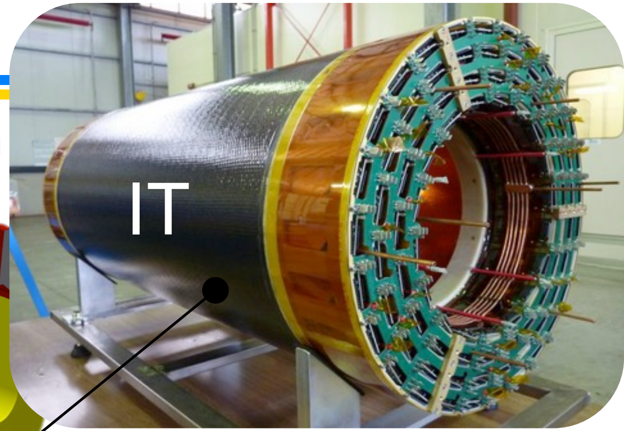
drift chamber

4 m diameter × 3.3 m length

helium based gas mixture

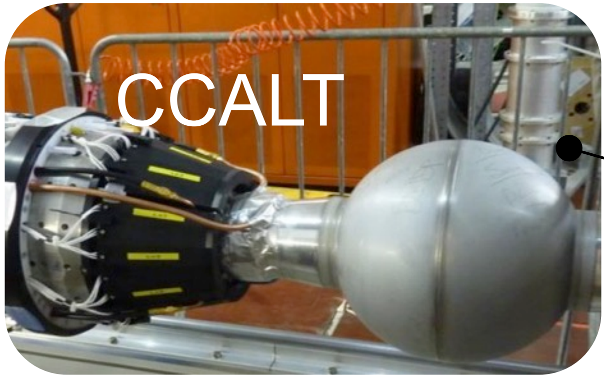
KLOE-2 at DAΦNE





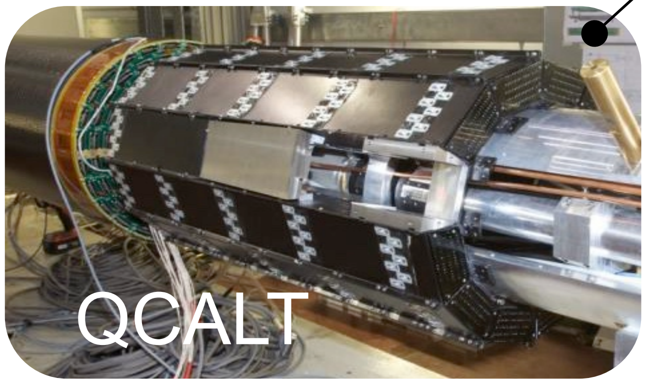
Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vtx reconstr.
First CGEM in HEP expt.

LYSO Crystal w SiPM
Low polar angle



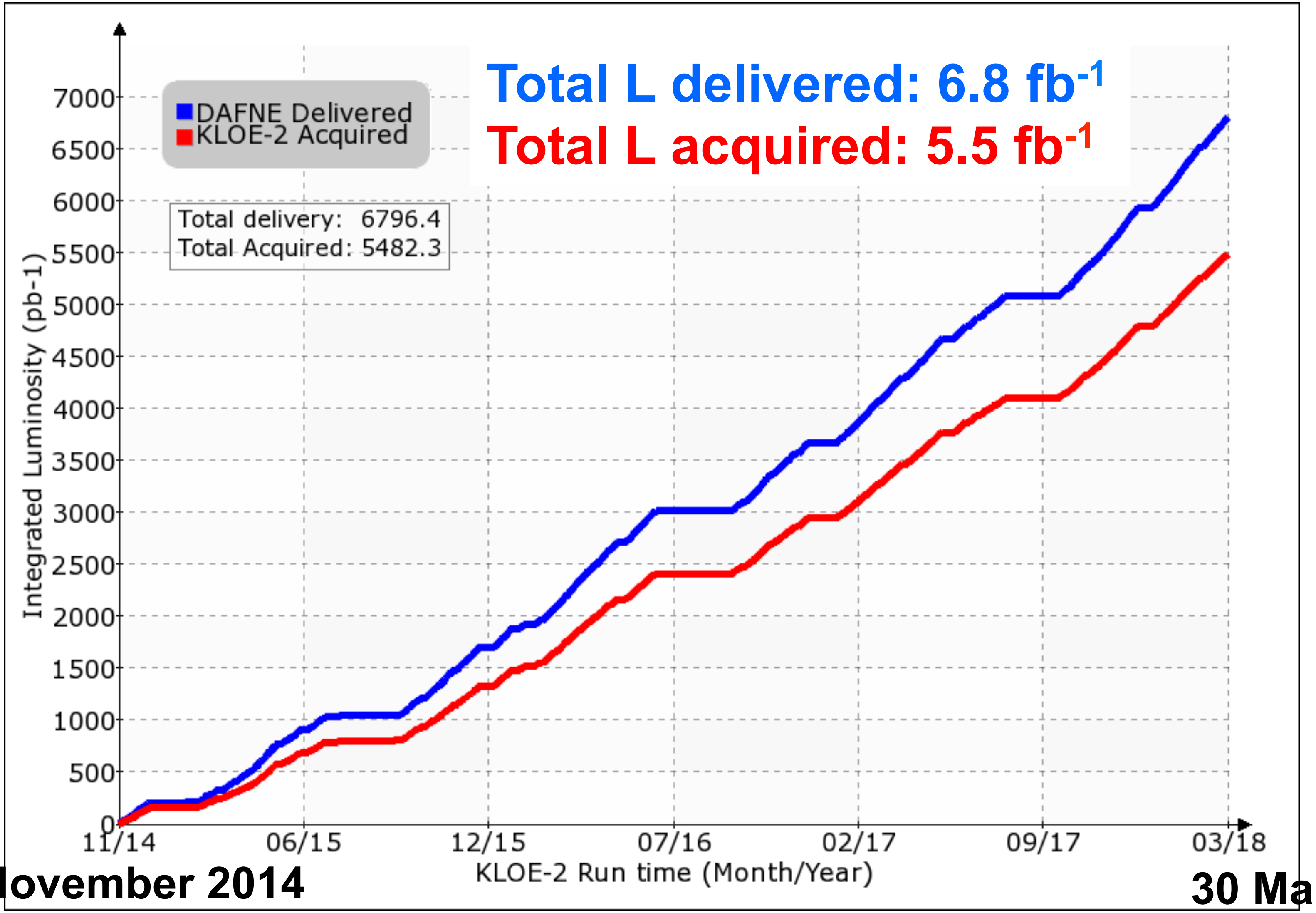
Scintillator hodoscope +PMTs

Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation



calorimeters LYSO+SiPMs
at ~ 1 m from IP

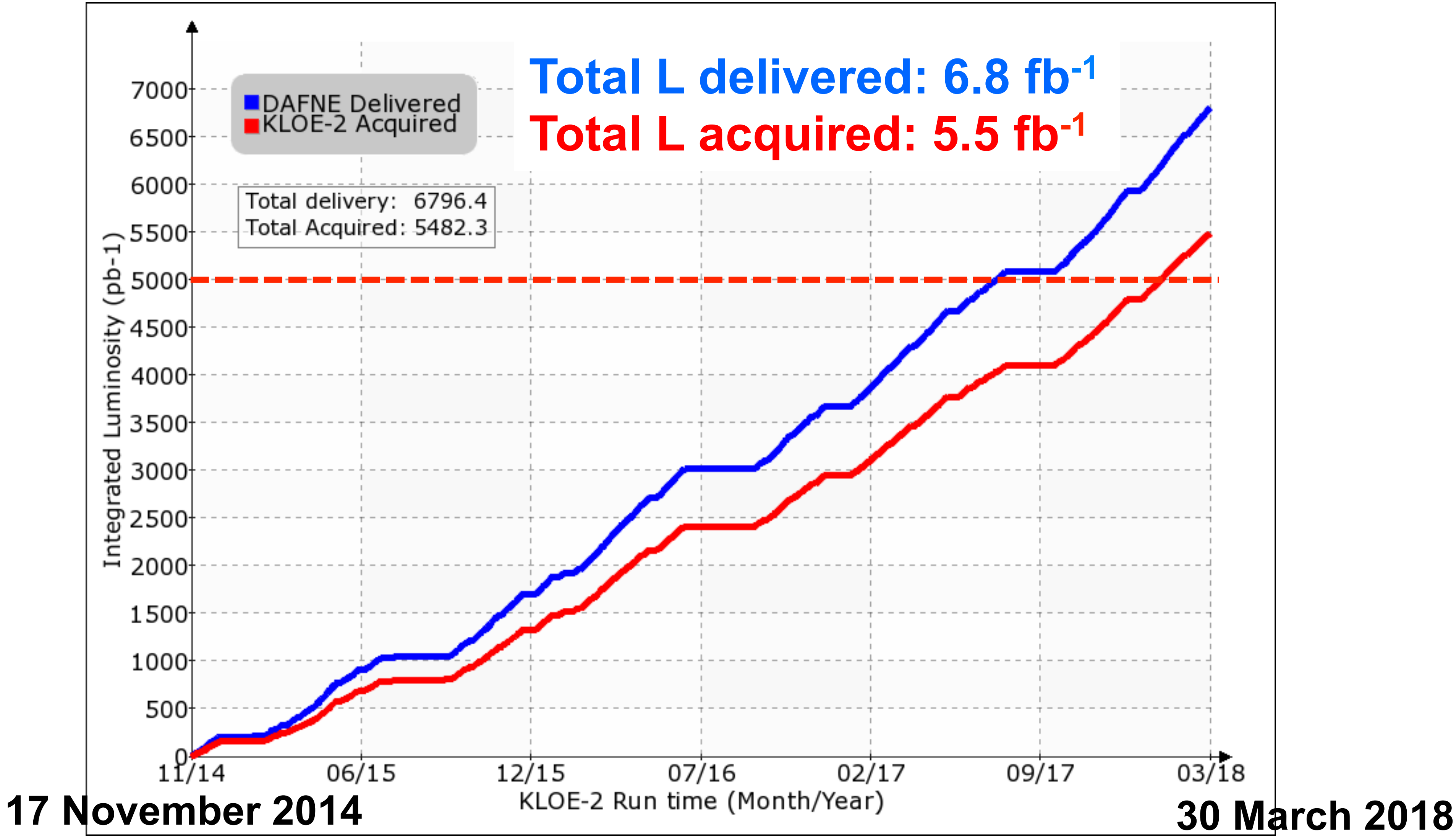
KLOE-2 run



17 November 2014 **30 March 2018**

KLOE-2 goal accomplished: L acquired > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

KLOE-2 run



KLOE-2 goal accomplished: L acquired > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

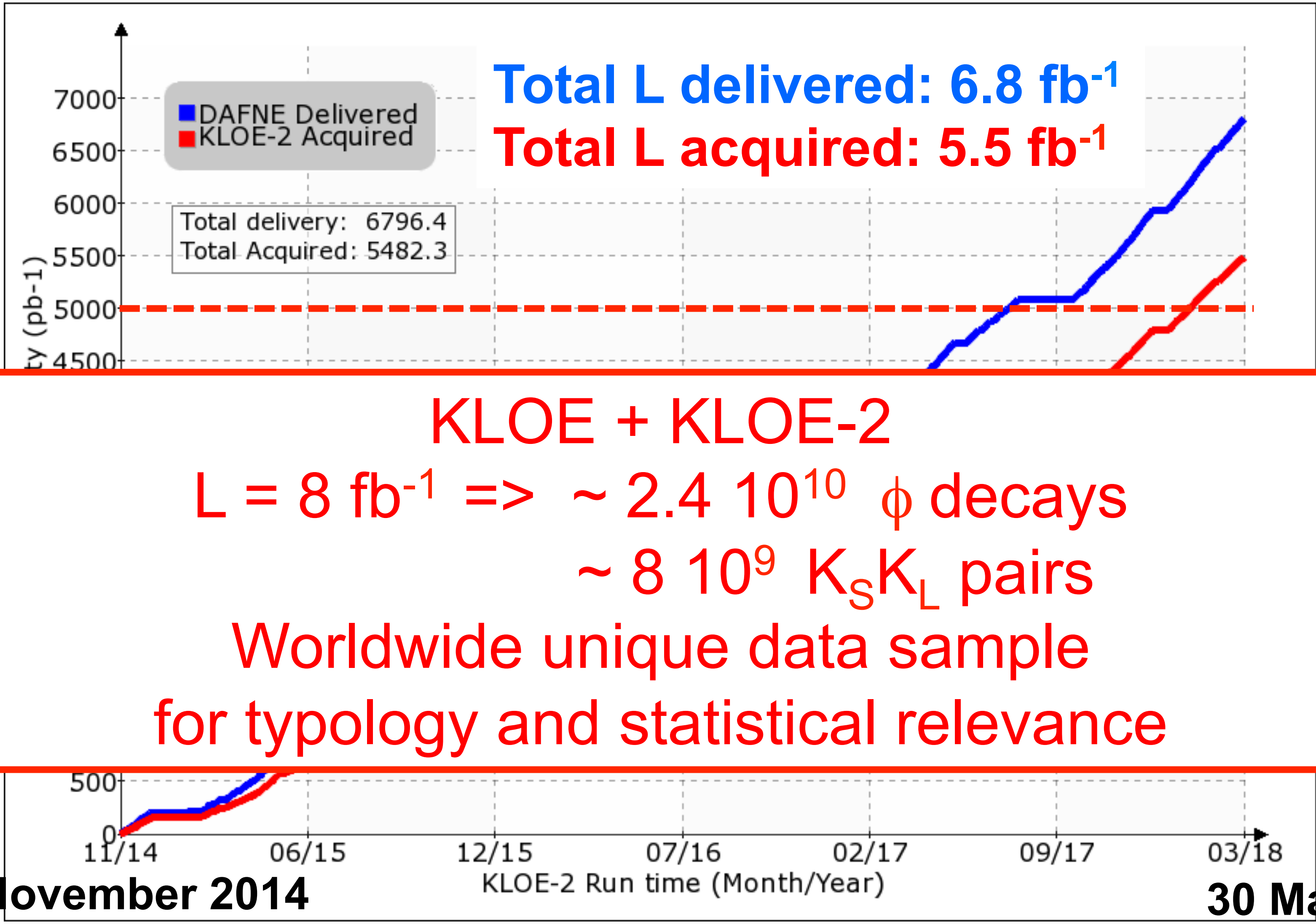
KLOE-2 run

KLOE-2 data-taking closing ceremony

30 March 2018 *INFN - Laboratori Nazionali di Frascati*

KLOE-2 goal accomplish... ...d > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

KLOE-2 run



17 November 2014 **30 March 2018**

KLOE-2 goal accomplished: L acquired > 5 fb^{-1} => L delivered > ~ 6.2 fb^{-1}

KLOE-2 Physics

KAON Physics:

- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \to 3\pi^0$
  direct measurement of Im(ε'/ε) (lattice calc. improved)
- CKM Vus:
  K_S semileptonic decays and A_S (also CP and CPT test)
  $K\mu3$ form factors, Kl3 radiative corrections
- χpT : $K_S \to \gamma\gamma$
- Search for rare K_S decays

Hadronic cross section

- Measurement of a_μ^{HLO} in the space-like region using Bhabha process
- ISR studies with 3π, 4π final states
- F_π with increased statistics

EPJC (2010) 68, 619, EPJ WoC 166 (2018)

Dark forces:

- Improve limits on:
  $U\gamma$ associate production
  $e^+e^- \to U\gamma \to \pi\pi\gamma, \mu\mu\gamma$
- Higgstrahlung
  $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy
- Leptophobic B boson search
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

Light meson Physics:

- η decays, ω decays, TFF $\phi \to \eta e^+e^-$
- C,P,CP violation:
  improve limits on $\eta \to \gamma\gamma\gamma, \pi^+\pi^-, \pi^0\pi^0, \pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^- e^+e^-$
- χpT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $\phi \to K_S K_S \gamma$
- $\gamma\gamma$ Physics: $\gamma\gamma \to \pi^0$ and π^0 TFF
- light-by-light scattering
- axion-like particles

List of KLOE CP/CPT/QM tests with neutral kaons

Mode	Test	Param.	KLOE measurement
$K_L \to \pi^+\pi^-$	CP	BR	$(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$
$K_S \to 3\pi^0$	CP	BR	$< 2.6 \times 10^{-8}$
$K_S \to \pi e \nu$	CP	A_S	$(1.5 \pm 10) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(x_-)$	[illegible]
$K_S \to \pi e \nu$	CPT	$Re(y)$	[illegible]
All $K_{S,L}$ BRs, η's etc... (unitarity)	CP CPT	$Re(\varepsilon)$ $Im(\delta)$	[illegible] [illegible]
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	α	$(-10 \pm 37) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	β	$(1.8 \pm 3.6) \times 10^{-19}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	γ	$(0.4 \pm 4.6) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_0	$(-6.2 \pm 8.8) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$(-0.7 \pm 1.0) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV

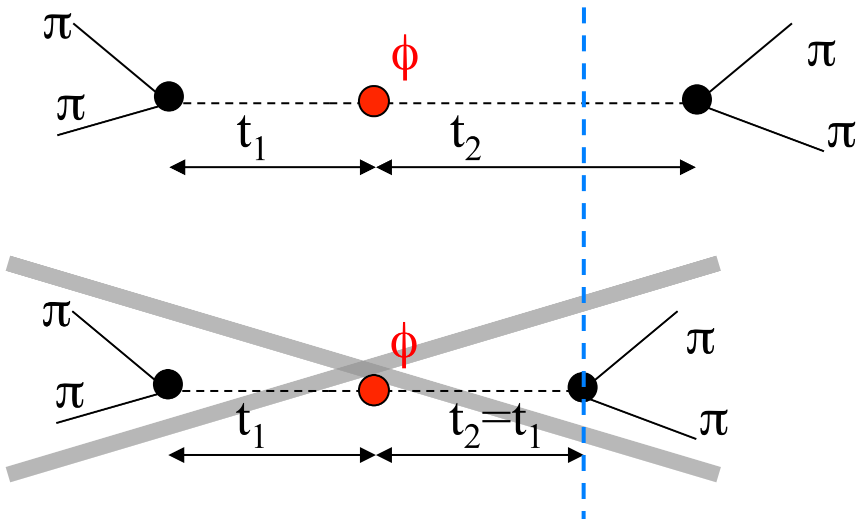
Most stringent limits on decoherence effects in an entangled system

List of KLOE CP/CPT/QM tests with neutral kaons

Mode	Test	Param.	KLOE measurement
$K_L \to \pi^+\pi^-$	CP	BR	$(1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$
$K_S \to 3\pi^0$	CP	BR	$< 2.6 \times 10^{-8}$
$K_S \to \pi e \nu$	CP	A_S	$(1.5 \pm 10) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(x_-)$	$(-0.8 \pm 2.5) \times 10^{-3}$
$K_S \to \pi e \nu$	CPT	$Re(y)$	$(0.4 \pm 2.5) \times 10^{-3}$
All $K_{S,L}$ BRs, η's etc... (unitarity)	CP CPT	$Re(\varepsilon)$ $Im(\delta)$	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{00}	$(0.1 \pm 1.0) \times 10^{-6}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	QM	ζ_{SL}	$(0.3 \pm 1.9) \times 10^{-2}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	α	$(-10 \pm 37) \times 10^{-17}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	β	$(1.8 \pm 3.6) \times 10^{-19}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	γ	$(0.4 \pm 4.6) \times 10^{-21}$ GeV compl. pos. hyp. $(0.7 \pm 1.2) \times 10^{-21}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Re(\omega)$	$(-1.6 \pm 2.6) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & QM	$Im(\omega)$	$(-1.7 \pm 3.4) \times 10^{-4}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_0	$(-6.2 \pm 8.8) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Z	$(-0.7 \pm 1.0) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_X	$(3.3 \pm 2.2) \times 10^{-18}$ GeV
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	CPT & Lorentz	Δa_Y	$(-0.7 \pm 2.0) \times 10^{-18}$ GeV

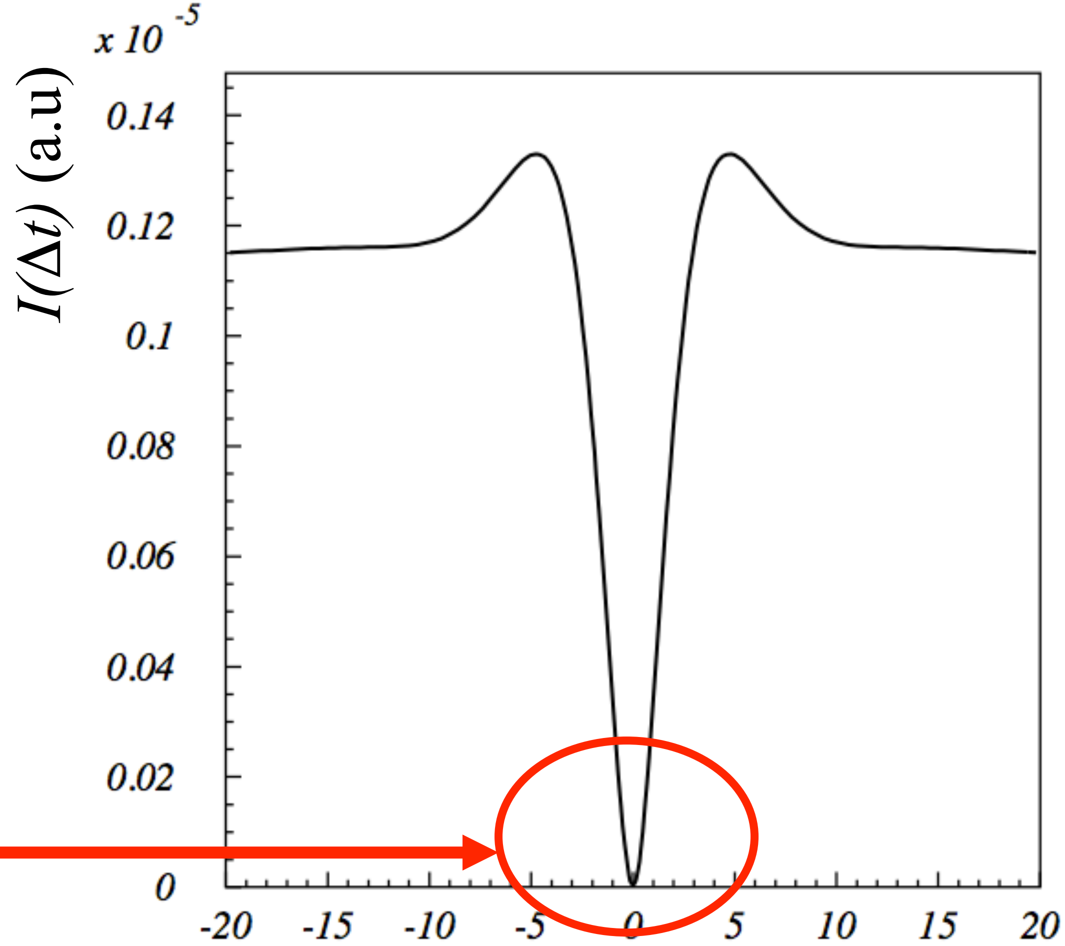
Entanglement in neutral kaon pairs from ϕ

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



Both kaons decay in the same final state:

$f_1 = f_2 = \pi^+\pi^-$



$\Delta t = t_1 - t_2$

EPR correlation:

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

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

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

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

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

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

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

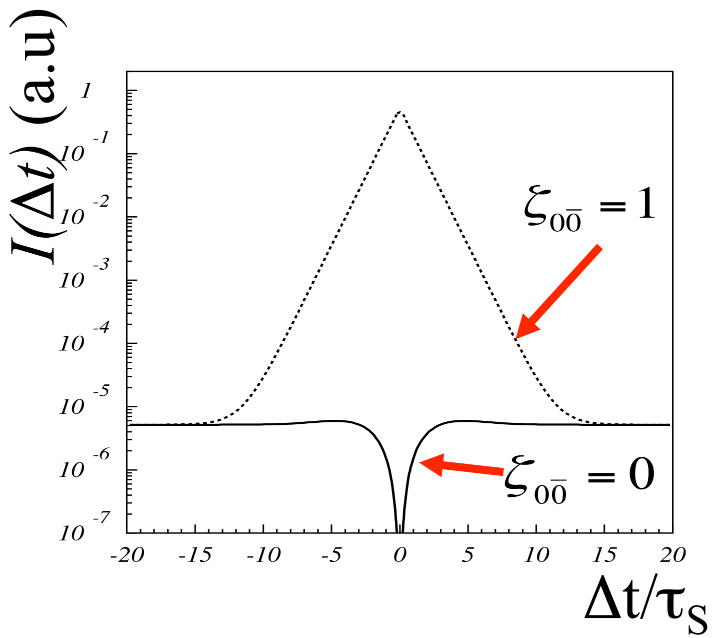
$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\Big[\left|\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle\right|^2$$

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

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

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

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



Decoherence parameter:

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

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

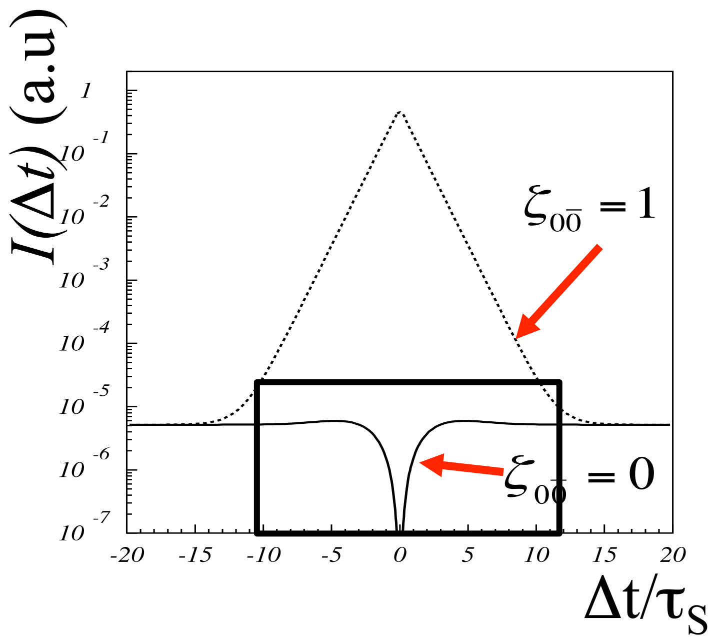
Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

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

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

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

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



Decoherence parameter:

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

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

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

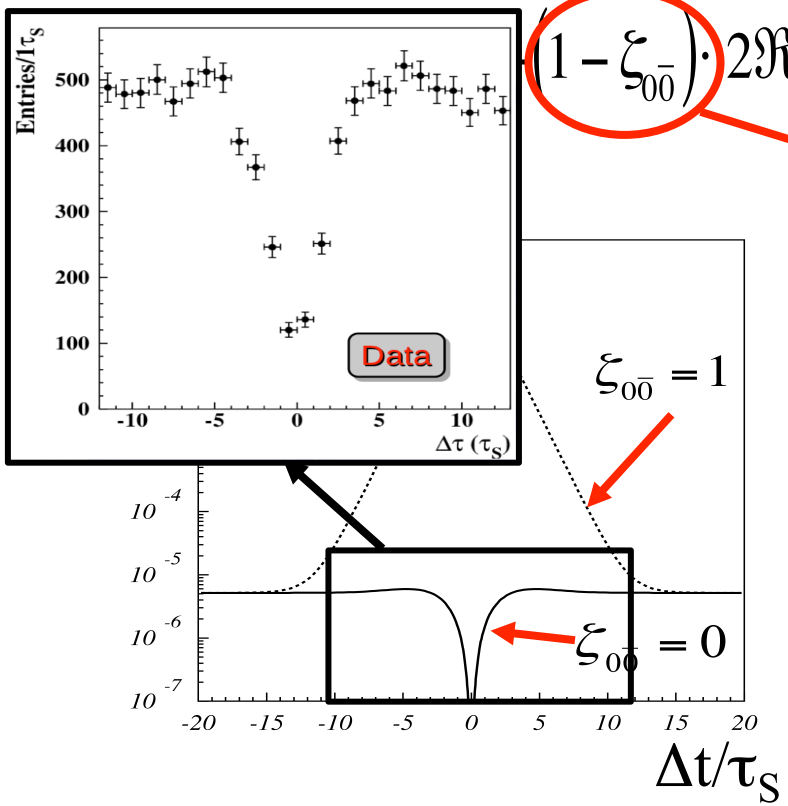
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

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

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

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

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



Decoherence parameter:

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

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

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)

KLOE result: **PLB 642(2006) 315, FP 40 (2010) 852**

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

The most precise test in an entangled system

(

- Where to produce entangled kaons?
- How perfect is anticorrelation of the initial entangled state?

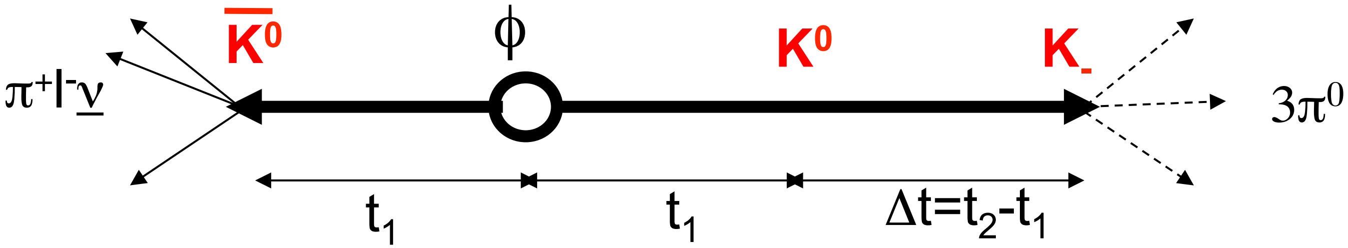
- Where to produce entangled kaons?
- How perfect is anticorrelation of the initial entangled state?

Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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

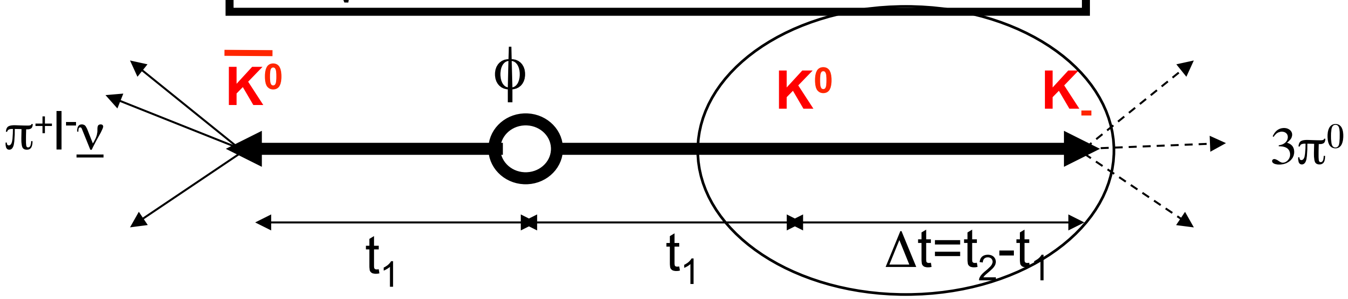


Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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



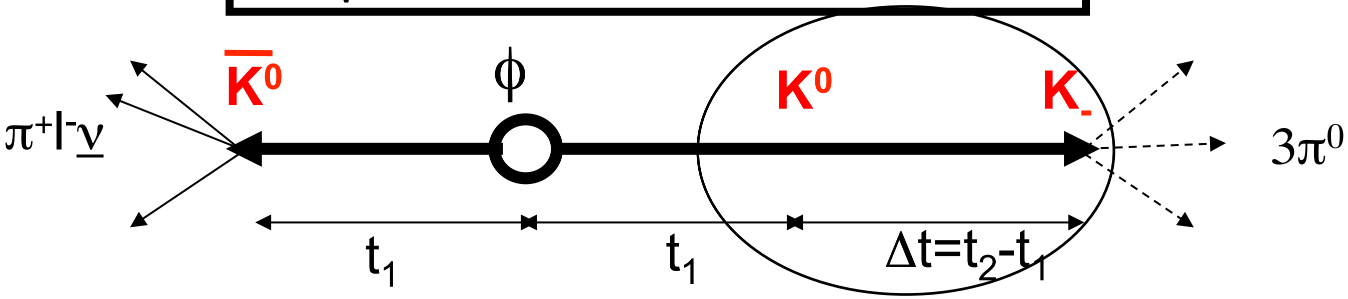
$$K^0 \to K_-$$ reference process

Entanglement in neutral kaon pairs

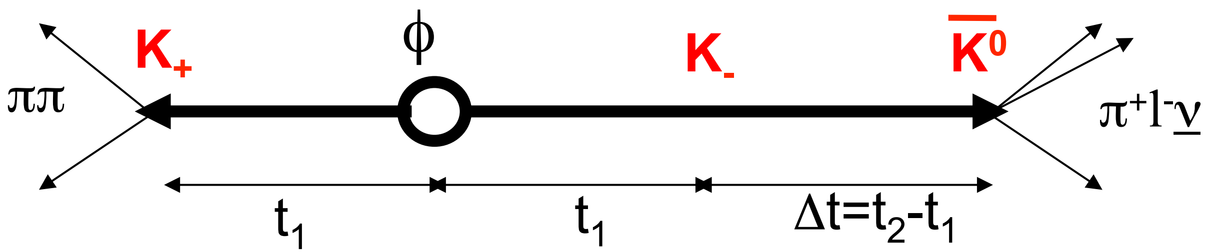
- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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



$K^0 \rightarrow K_-$ reference process

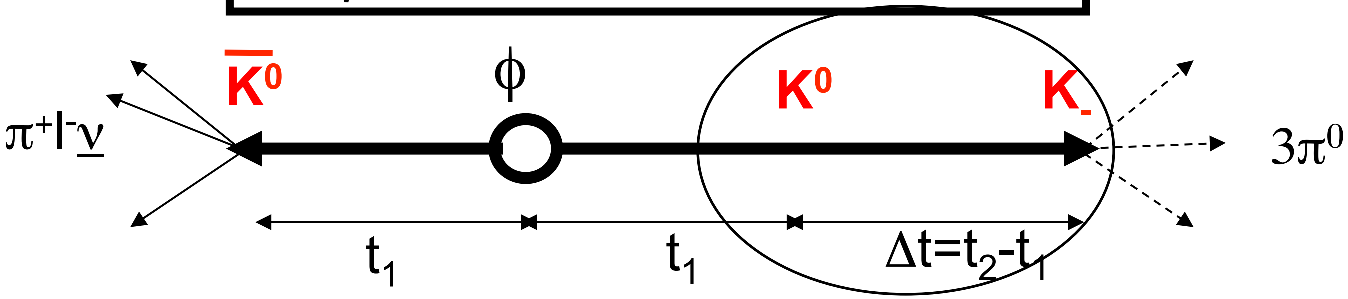


Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

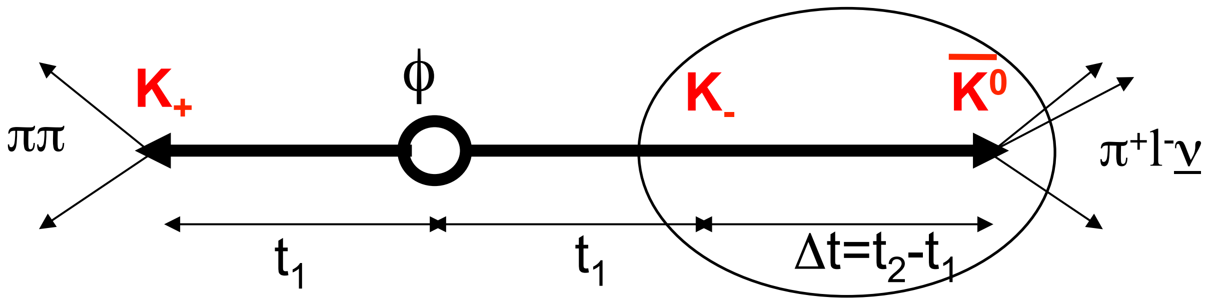
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\overline{K}^0(-\vec{p})\rangle - |\overline{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$
$$= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]$$

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



$K^0 \rightarrow K_-$ reference process

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

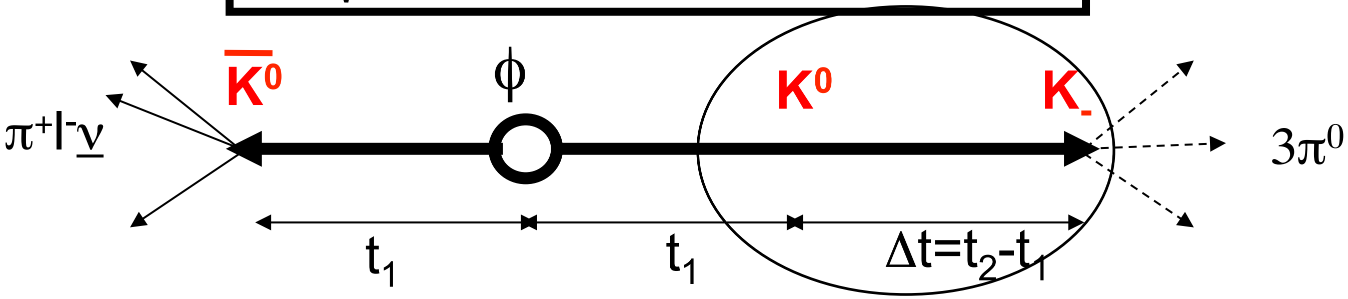


Entanglement in neutral kaon pairs

- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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

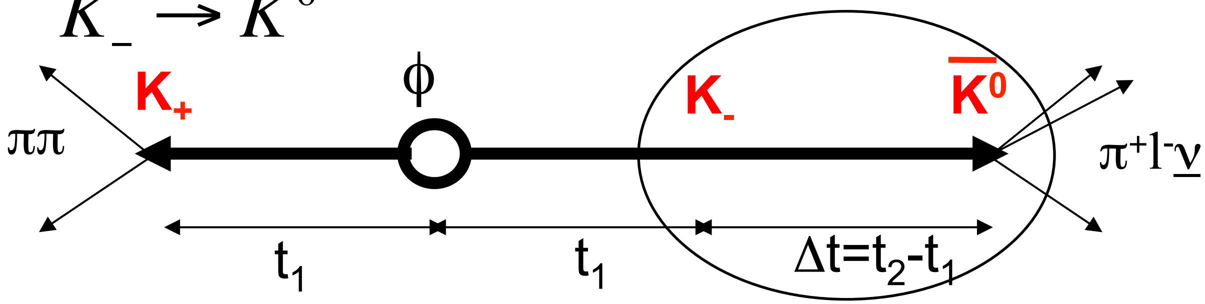


$K^0 \to K_-$ reference process

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

Note: CP and T conjugated process

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



Direct test of CPT symmetry in neutral kaon transitions

Two observable ratios of double decay intensities

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

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

with $D_{\rm CPT}$ constant

Explicitly in standard Wigner Weisskopf approach for Δt>0:

$$R^{\rm exp}_{2,{\rm CPT}}(\Delta t) = \frac{P[{\rm K}^0(0) \to {\rm K}_-(\Delta t)]}{P[{\rm K}_-(0) \to \bar{\rm K}^0(\Delta t)]} \times D_{\rm CPT}$$
$$\simeq |1-2\delta|^2 \left|1+2\delta e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2 \times D_{\rm CPT}$$

$$R^{\rm exp}_{4,{\rm CPT}}(\Delta t) = \frac{P[\bar{\rm K}^0(0) \to {\rm K}_-(\Delta t)]}{P[{\rm K}_-(0) \to {\rm K}^0(\Delta t)]} \times D_{\rm CPT}$$
$$\simeq |1+2\delta|^2 \left|1-2\delta e^{-i(\lambda_S-\lambda_L)\Delta t}\right|^2 \times D_{\rm CPT}$$

For comparison the ratio of survival probabilities:

$$\frac{I(\ell^-, \ell^+; \Delta t)}{I(\ell^+, \ell^-; \Delta t)} = \frac{P[{\rm K}^0(0) \to {\rm K}^0(\Delta t)]}{P[\bar{\rm K}^0(0) \to \bar{\rm K}^0(\Delta t)]}$$
$$\simeq |1-4\delta|^2 \left|1+\frac{8\delta}{1+e^{+i(\lambda_S-\lambda_L)\Delta t}}\right|^2$$

Vanishes for ΔΓ->0

As an illustration of the different sensitivity: it vanishes up to second order in CPTV and decoherence parameters α,β,γ (Ellis, Mavromatos et al. PRD1996)

Impact of the approximations

In general K_+ and K_-
(and K0 and $\overline{\text{K0}}$)
can be non-orthogonal

Direct CP (CPT) violation

$$\eta_{\pi\pi} = \epsilon_L + \epsilon'_{\pi\pi}$$

$$\eta_{3\pi^0} = \epsilon_S + \epsilon'_{3\pi^0}$$

CPT cons. and CPT viol.
ΔS=ΔQ violation

$$x_+,\ x_-$$

Orthoghonal
bases

$$\{\mathrm{K}_+, \widetilde{\mathrm{K}}_-\} \quad \{\widetilde{\mathrm{K}}_+, \mathrm{K}_-\} \qquad \{\widetilde{\mathrm{K}}_0, \mathrm{K}_{\bar{0}}\} \text{ and } \{\widetilde{\mathrm{K}}_{\bar{0}}, \mathrm{K}_0\}$$

Explicitly for Δt>0:

$$R^{\exp}_{2,\mathrm{CPT}}(\Delta t) = \frac{P[\widetilde{\mathrm{K}}_0(0) \to \mathrm{K}_-(\Delta t)]}{P[\widetilde{\mathrm{K}}_-(0) \to \mathrm{K}_{\bar{0}}(\Delta t)]} \times D_{\mathrm{CPT}}$$

$$= |1 - 2\delta + 2x_+^\star - 2x_-^\star|^2 \left|1 + \left(2\delta + \epsilon'_{3\pi^0} - \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\mathrm{CPT}}$$

$$R^{\exp}_{4,\mathrm{CPT}}(\Delta t) = \frac{P[\widetilde{\mathrm{K}}_{\bar{0}}(0) \to \mathrm{K}_-(\Delta t)]}{P[\widetilde{\mathrm{K}}_-(0) \to \mathrm{K}_0(\Delta t)]} \times D_{\mathrm{CPT}}$$

$$= |1 + 2\delta + 2x_+ + 2x_-|^2 \left|1 - \left(2\delta + \epsilon'_{3\pi^0} - \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2 \times D_{\mathrm{CPT}}$$

Impact of the approximations

$$\frac{R^{\rm exp}_{2,{\rm CPT}}(\Delta t)}{R^{\rm exp}_{4,{\rm CPT}}(\Delta t)} \simeq (1 - 8\Re\delta - 8\Re x_-) \left|1 + 2\left(\eta_{3\pi^0} - \eta_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2$$

$$= (1 - 8\Re\delta - 8\Re x_-) \left|1 + 2\left(2\delta + \epsilon'_{3\pi^0} - \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2$$

The double ratio constitutes one of the most robust observables for the proposed CPT test. In the limit $\Delta t \gg \tau_S$ it exhibits a pure and genuine CPT violating effect, even without assuming negligible contaminations from direct CP violation and/or ΔS=ΔQ rule violation.

$$\mathrm{DR}_{\mathrm{CPT}} = \frac{R^{\rm exp}_{2,{\rm CPT}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,{\rm CPT}}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

CLEANEST CPT OBSERVABLE !

There exists a connection with charge semileptonic asymmetries of K_S and K_L

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

Impact of the approximations

$$\frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t)}{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t)} \simeq (1 - 8\Re\delta - 8\Re x_-) \left|1 + 2\left(\eta_{3\pi^0} - \eta_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2$$

$$= (1 - 8\Re\delta - 8\Re x_-) \left|1 + 2\left(2\delta + \epsilon'_{3\pi^0} - \epsilon'_{\pi\pi}\right) e^{-i(\lambda_S - \lambda_L)\Delta t}\right|^2$$

The double ratio constitutes one of the most robust observables for the proposed CPT test. In the limit $\Delta t \gg \tau_S$ it exhibits a pure and genuine CPT violating effect, even without assuming negligible contaminations from direct CP violation and/or ΔS=ΔQ rule violation.

$$DR_{CPT} = \frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t \gg \tau_S)}{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

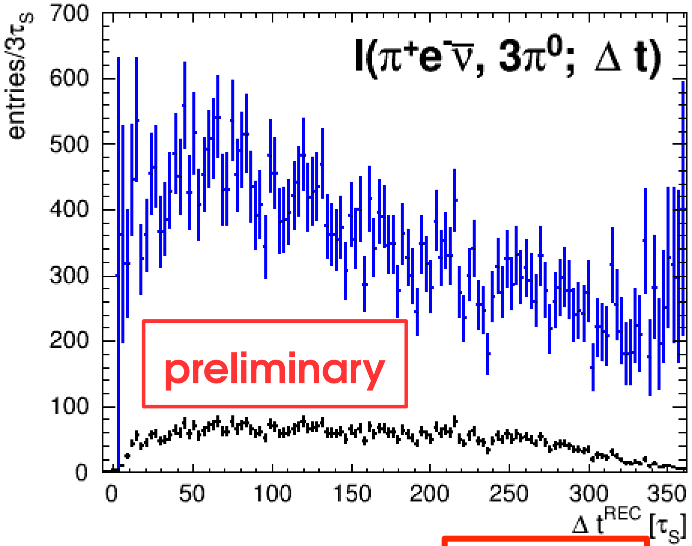
CLEANEST CPT OBSERVABLE !

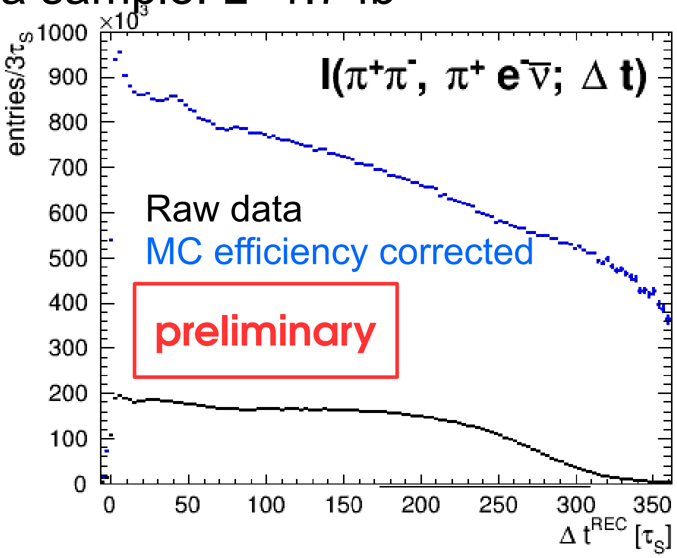
There exists a connection with charge semileptonic asymmetries of K_S and K_L

$$DR_{CPT} = \frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t \gg \tau_S)}{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t \gg \tau_S)} = \frac{1 + A_L}{1 - A_L} \times \frac{1 - A_S}{1 + A_S} \simeq 1 + 2(A_L - A_S)$$

Direct test of CPT in transitions with neutral kaons at KLOE

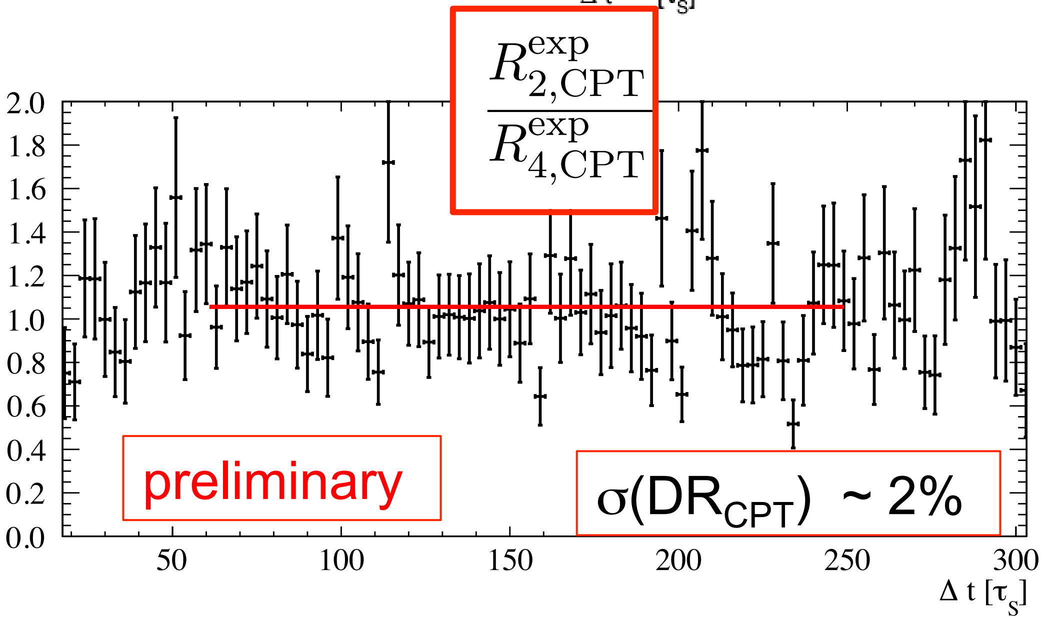
KLOE data sample: L=1.7 fb^{-1}





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

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



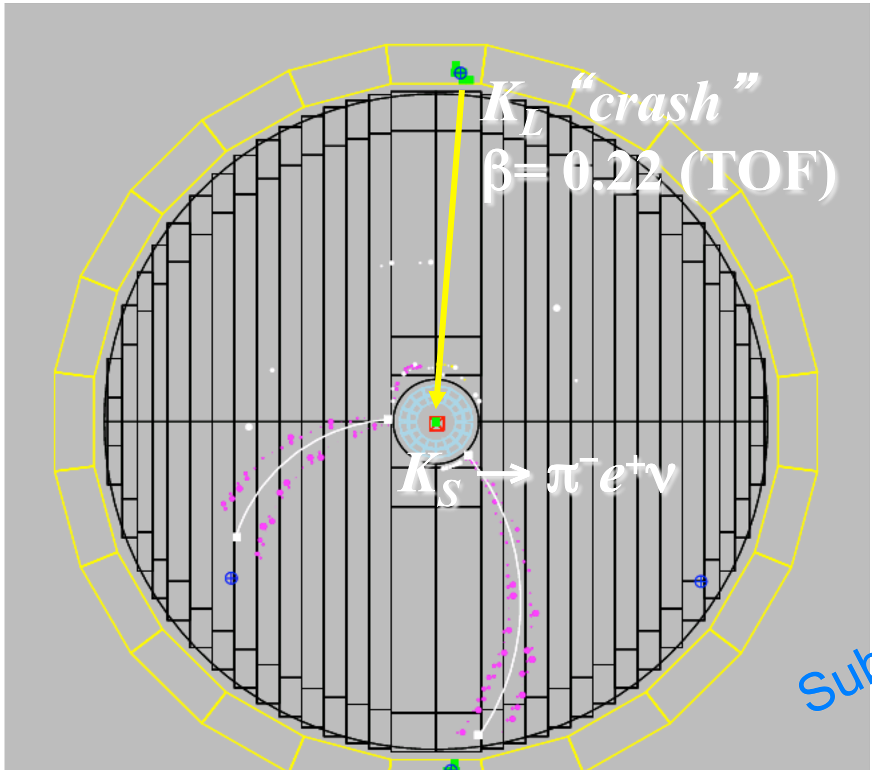
CPT test with the double ratio DR_{CPT}:

$$DR_{CPT} = \frac{R^{exp}_{2,CPT}(\Delta t \gg \tau_S)}{R^{exp}_{4,CPT}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

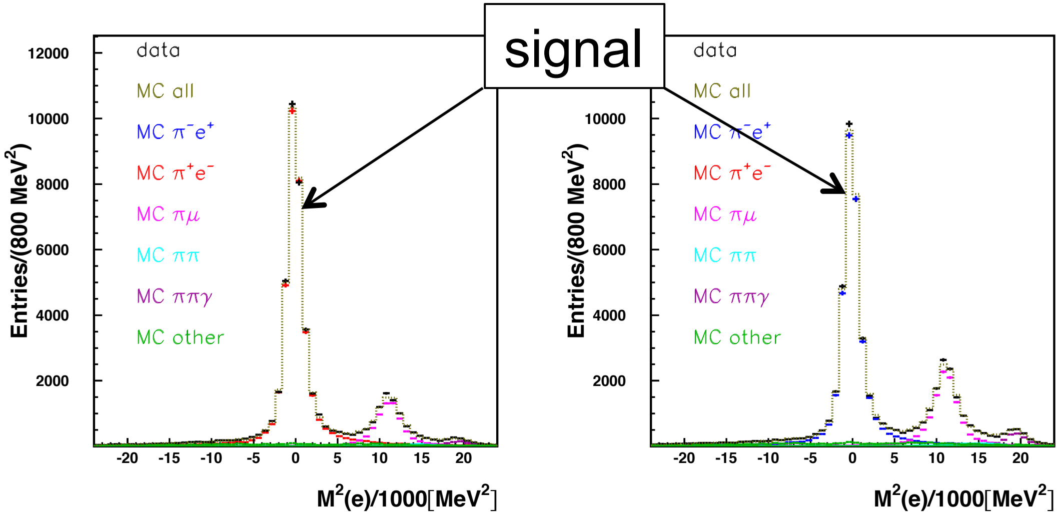
- $K_L \to 3\pi^0$ vtx reconstr. with GPS-like technique
- Analysis in progress:
  efficiency correction from data control samples
- KLOE-2 can reach a precision <1% on DR_{CPT}

K_S semileptonic charge asymmetry at KLOE

$$|i\rangle \propto \left[|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right]$$



***K_S* tagged by *K_L* interaction in EmC**



L=1.7 fb^{-1}

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

Submitted to JHEP

arXiv:1806.08654 [hep-ex]

$$A_S = (-3.8 \pm 5.0 \pm 2.6) \times 10^{-3}$$

with KLOE-2 data: $\delta A_S(\text{stat}) \to \sim 3\times10^{-3}$

Using KTeV result on A_L : CPT test in transitions with kaons (preliminary)

$$DR_{CPT} = 1 + 2\,(A_L - A_S) = 1.016 \pm 0.011$$

Conclusions

- The entangled neutral kaon system at a ϕ-factory is an excellent laboratory for the study of discrete symmetries and fundamental principles of QM.
- It is the ideal place to directly test discrete symmetries, and in particular CPT, in transition processes for the first time between neutral kaon states.
- The proposed CPT test is model independent, fully robust, and very clean. Possible spurious effects are well under control, e.g. direct CP violation, $\Delta S=\Delta Q$ rule violation, decoherence effects.

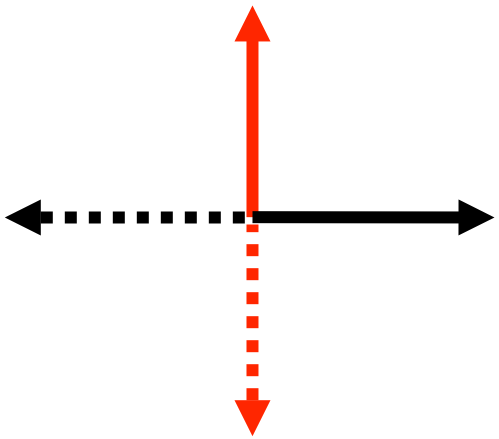
- The KLOE-2 experiment at the upgraded DAFNE completed its data-taking at the end of March 2018 collecting L = 5.5 fb^{-1}.
- KLOE data analysis for testing CPT in transitions is in progress.
  The connection of the "double ratio" observable with KS and KL semileptonic charge asymmetries can be fully exploited to increase the sensitivity of the test.
- At KLOE-2 the test can reach a statistical sensitivity of $O(10^{-3})$ on these new observables.
- The study of the other discrete symmetries, T and CP, in transitions is in progress.

Spare slides

CPT: introduction

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

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

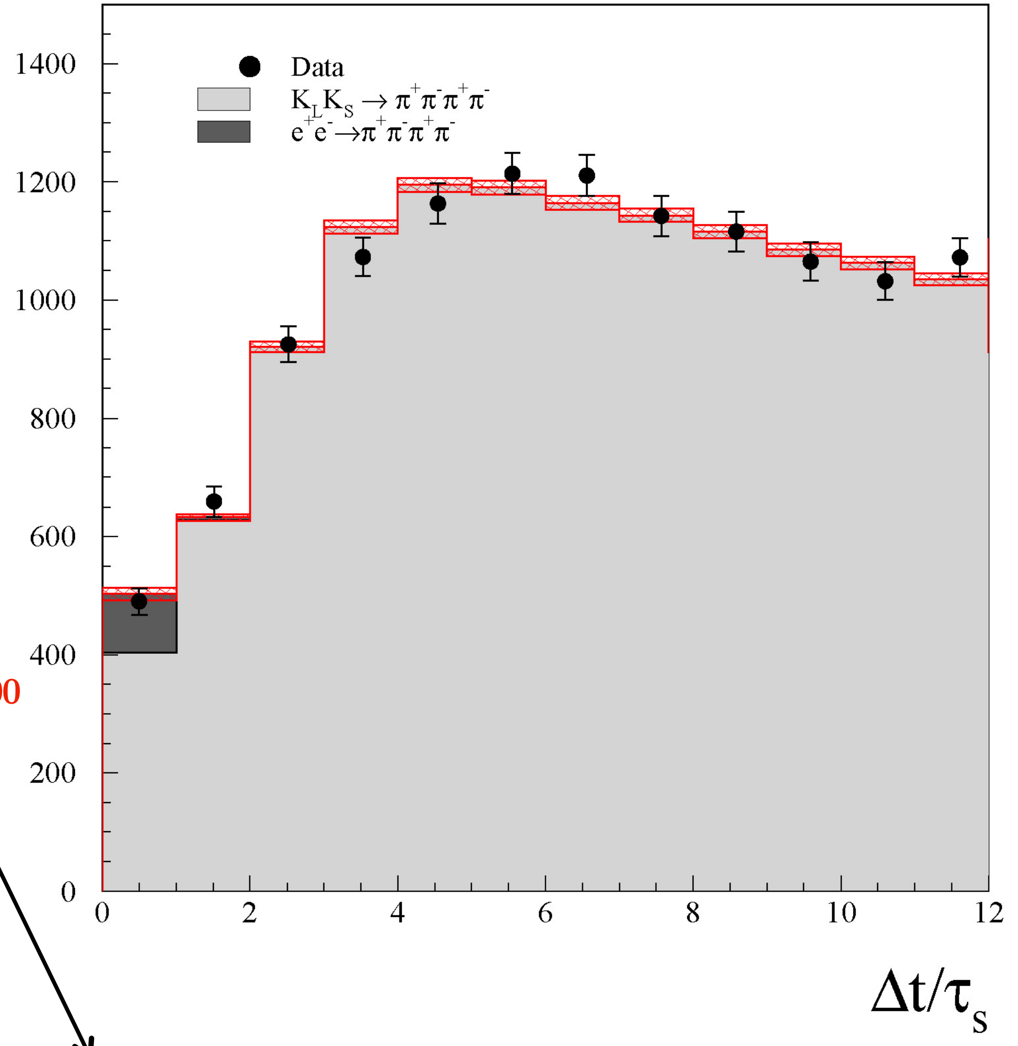


In 4-dimensional pseudo-euclidean space-time PT reflection is NOT equivalent to a rotation. Time coordinate is not exactly equivalent to space coordinate. Charge conjugation is also needed to change sign to e.g. 4-vector current j_{μ}. (or axial 4-v).
CPT (and not PT) is equivalent to a rotation in the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

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

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

- 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:

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

Best precision achievable in an entangled system

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.
This beautiful argument was defined a "sweet candy" 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]:

At most:

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

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

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]

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.
This beautiful argument was defined a "sweet candy" 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]:

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

At most:

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

$$\gamma = \left(0.7 \pm 1.2_{STAT} \pm 0.3_{SYST}\right)\times10^{-21}\ \text{GeV}$$

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

[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]

Loss of EPR correlations due to Quantum Gravity effects

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, Mavromatos, Papavassiliou PRL 92 (2004) 131601, NPB744 (2006) 180].

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

at most one expects:

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

In some microscopic models of space-time foam arising from non-critical string theory:
$\omega \sim 10^{-4} \div 10^{-5}$
[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]

KLOE result

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

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

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

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