Test of CPT in transitions with entangled neutral kaons

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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..

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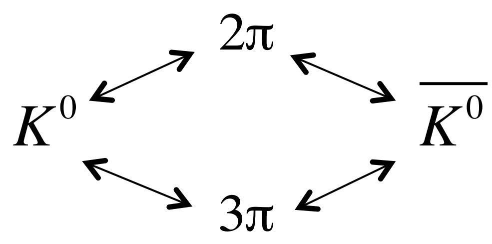
The neutral kaon two-level oscillating system in a nutshell

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

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

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

τ_S ~ 90 ps τ_L ~ 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

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

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:

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

huge amplification factor!!

- $\delta \neq 0$ implies CPT violation
- $\varepsilon \neq 0$ implies T violation
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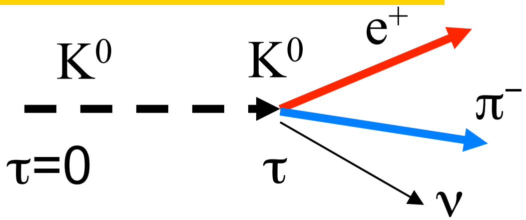
neutral kaons vs other oscillating meson systems

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

"Standard" CPT 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
PLB444 (1998) 52

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

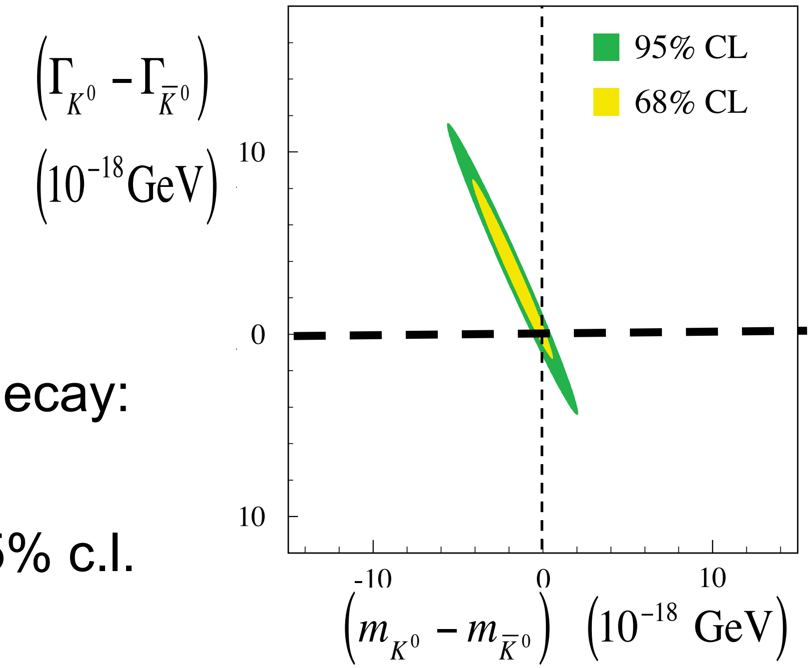
$$2\Im\delta = \Im\left[\langle K_L | K_S \rangle\right] = \Im\left[\frac{\sum_f \langle f|T|K_S\rangle \langle f|T|K_L\rangle^*}{i\left(\lambda_S - \lambda_L^*\right)}\right]$$

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

PDG fit (2014)

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

Combining Reδ and Imδ results →



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

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

at 95% c.l.

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

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

Let us also consider the states $|\mathrm{K}_+\rangle$, $|\mathrm{K}_-\rangle$ defined as follows: $|\mathrm{K}_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP $=+1$ state; analogously $|\mathrm{K}_-\rangle$ 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

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

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

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

Even though the decay products are orthogonal, the filtered $|\mathrm{K}_+\rangle$ and $|\mathrm{K}_-\rangle$ 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' →

$$|\mathrm{K}_+\rangle \equiv |\widetilde{\mathrm{K}}_+\rangle$$
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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
$K^0 \to K^0$	~~$K^0 \to K^0$~~	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	~~$K^0 \to \bar{K}^0$~~
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$	$K^0 \to \bar{K}^0$	~~$\bar{K}^0 \to K^0$~~
$\bar{K}^0 \to \bar{K}^0$	~~$\bar{K}^0 \to \bar{K}^0$~~	$K^0 \to K^0$	$K^0 \to K^0$
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	$K^0 \to K_+$	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	$K^0 \to K_-$	$K_- \to K^0$
$K_+ \to K^0$	$K^0 \to K_+$	$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_+ \to K_+$	~~$K_+ \to K_+$~~	~~$K_+ \to K_+$~~	~~$K_+ \to K_+$~~
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$K_- \to K_+$	$K_+ \to K_-$	~~$K_- \to K_+$~~	$K_+ \to K_-$
$K_- \to K_-$	~~$K_- \to K_-$~~	~~$K_- \to K_-$~~	~~$K_- \to K_-$~~

Direct test of symmetries with neutral kaons

Conjugate= reference (red bar)

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

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

Direct test of symmetries with neutral kaons

Conjugate= reference (red)

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
$K^0 \to K^0$	$K^0 \to K^0$	$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$
$K^0 \to \bar{K}^0$	$\bar{K}^0 \to K^0$	$\bar{K}^0 \to K^0$	$K^0 \to \bar{K}^0$
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$\bar{K}^0 \to K^0$	[redacted]	[redacted]	$\bar{K}^0 \to K^0$
$\bar{K}^0 \to \bar{K}^0$	$\bar{K}^0 \to \bar{K}^0$	[redacted]	[redacted]
$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$	[redacted]	$K_+ \to K^0$
$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$	[redacted]	$K_- \to K^0$
$K_+ \to K^0$	[redacted]	$K_+ \to \bar{K}^0$	[redacted]
$K_+ \to \bar{K}^0$	[redacted]	[redacted]	[redacted]
$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$	$K_+ \to K_+$
$K_+ \to K_-$	$K_- \to K_+$	$K_+ \to K_-$	$K_- \to K_+$
$K_- \to K^0$	[redacted]	$K_- \to \bar{K}^0$	[redacted]
$K_- \to \bar{K}^0$	[redacted]	[redacted]	[redacted]
$K_- \to K_+$	[redacted]	$K_- \to K_+$	[redacted]
$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$	$K_- \to K_-$

already in the table with conjugate as reference

Two identical conjugates for one reference

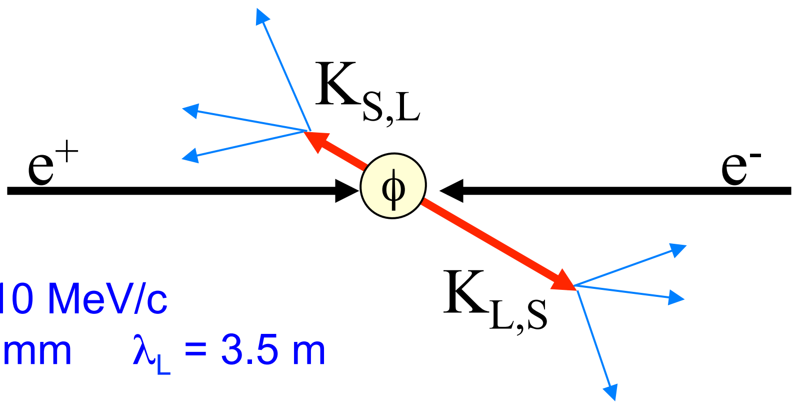
4 distinct tests of T symmetry

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
- At a ϕ-factory: $\sigma(e^+e^- \to \phi) \sim 3$ mb; $W = m_\phi = 1019.4$ MeV BR($\phi \to K^0\overline{K}^0$) ~34% ~$10^6$/pb^{-1} KK pairs produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:



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

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

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

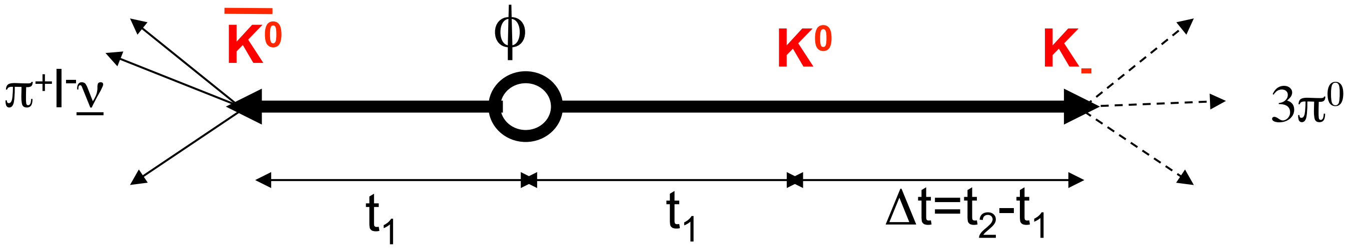
$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)} \Big/ \left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

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



Entanglement in neutral kaon pairs

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

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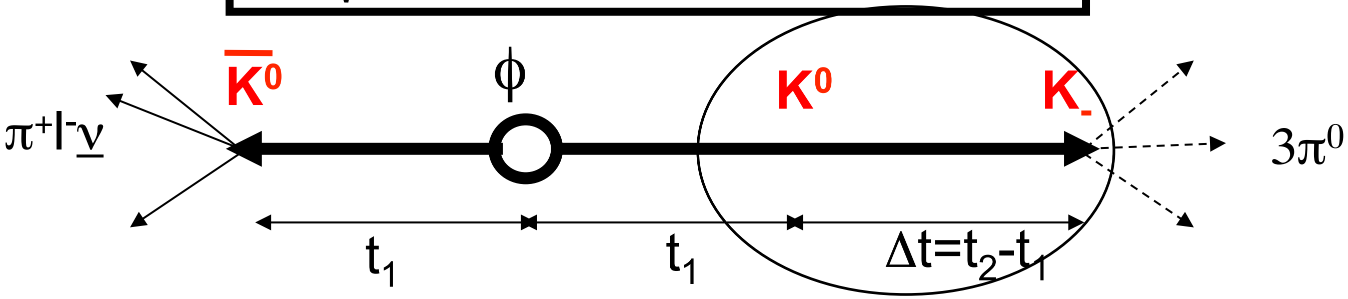


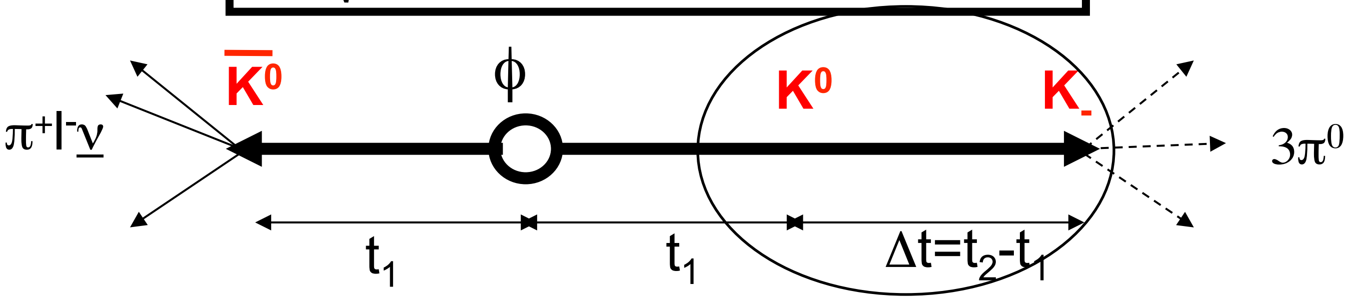
$K^0 \rightarrow K_-$ reference process

Entanglement in neutral kaon pairs

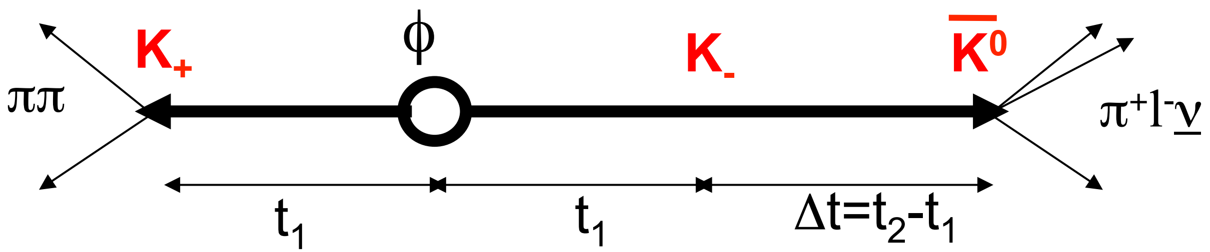
- EPR correlations at a ϕ-factory can be exploited to study transitions involving orthogonal "CP states" K_+ and K_-

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

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



$K^0 \to K_-$ reference process

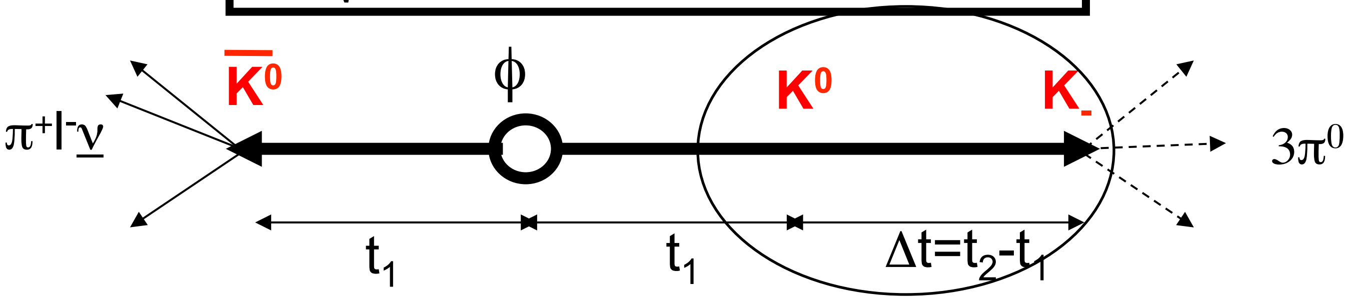


Entanglement in neutral kaon pairs

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

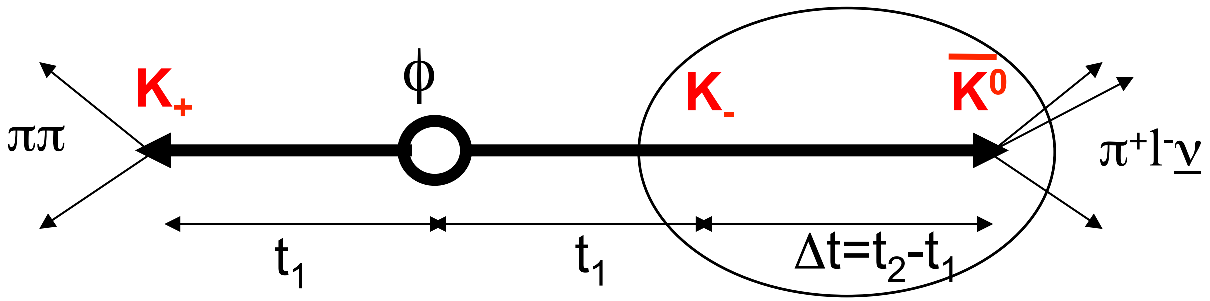
$$
\begin{aligned}
|i\rangle &= \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\overline{K}^0(-\vec{p})\rangle - |\overline{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right] \\
&= \frac{1}{\sqrt{2}}\left[|K_+(\vec{p})\rangle|K_-(-\vec{p})\rangle - |K_-(\vec{p})\rangle|K_+(-\vec{p})\rangle\right]
\end{aligned}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

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



$K^0 \rightarrow K_-$ reference process

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

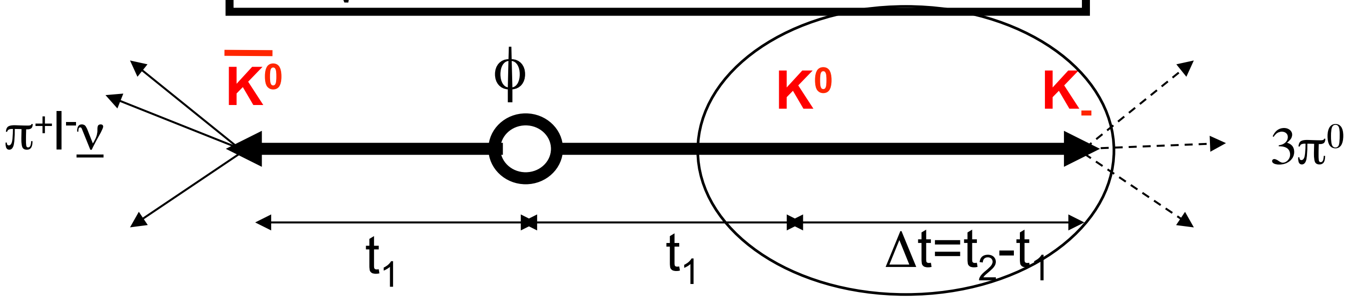


Entanglement in neutral kaon pairs

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

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

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

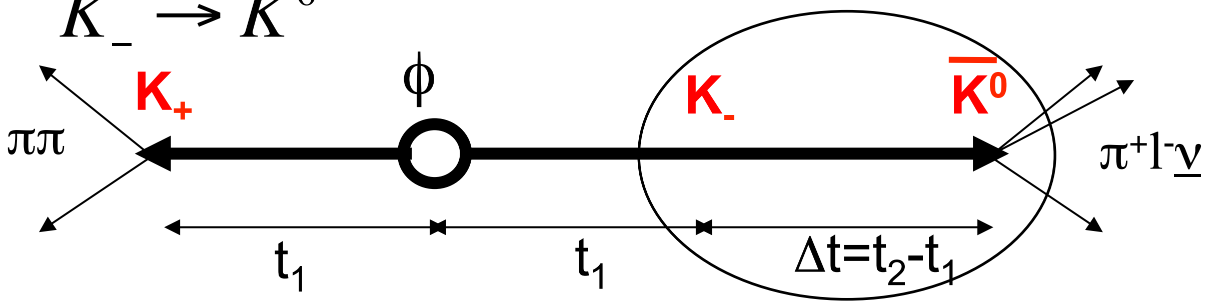


$K^0 \rightarrow K_-$ reference process

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

Note: CP and T conjugated process

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



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 $\Delta S = \Delta Q$ rule violation.

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

CLEANEST CPT OBSERVABLE !

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

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

Impact of the approximations

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

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

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 $\Delta S=\Delta Q$ rule violation.

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CLEANEST CPT OBSERVABLE !

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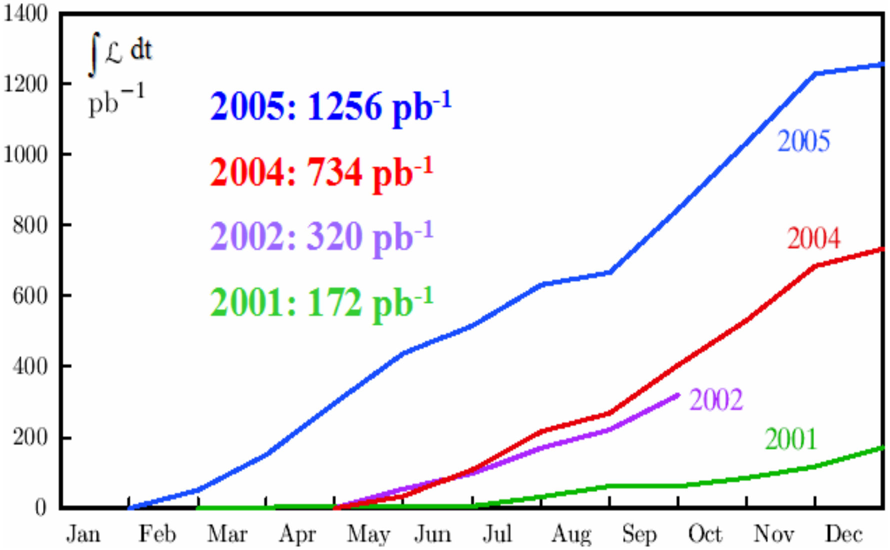
$$DR_{CPT} = \frac{R^{\rm exp}_{2,{\rm CPT}}(\Delta t \gg \tau_S)}{R^{\rm exp}_{4,{\rm CPT}}(\Delta t \gg \tau_S)} = \frac{1+A_L}{1-A_L} \times \frac{1-A_S}{1+A_S} \simeq 1 + 2(A_L - A_S)$$

The KLOE detector at the Frascati φ-factory DAΦNE

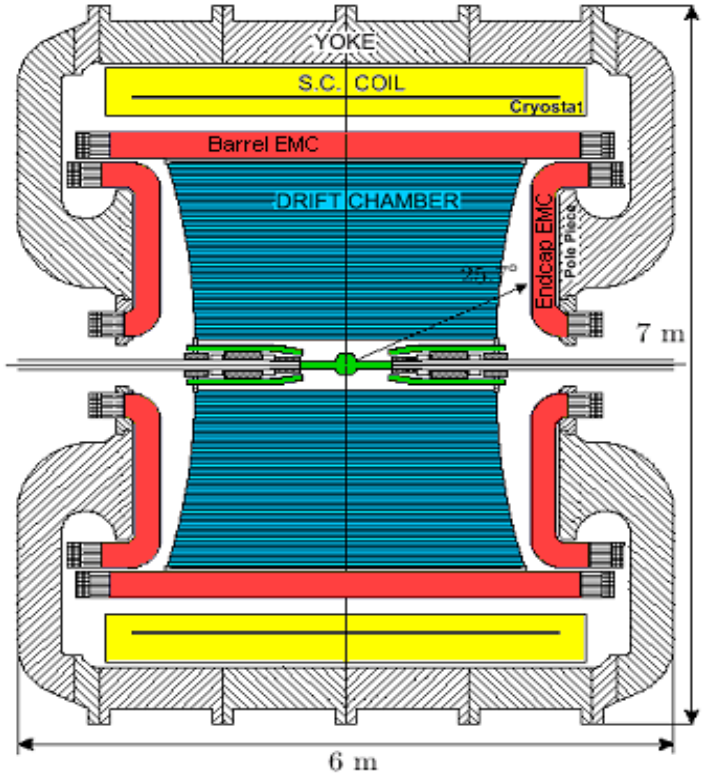
DAFNE collider

Integrated luminosity (KLOE)



Total KLOE $\int\mathcal{L}\,dt$ ~ 2.5 fb^{-1}
(2001 - 05) → ~2.5×10^9 K_SK_L pairs

KLOE detector



Lead/scintillating fiber calorimeter

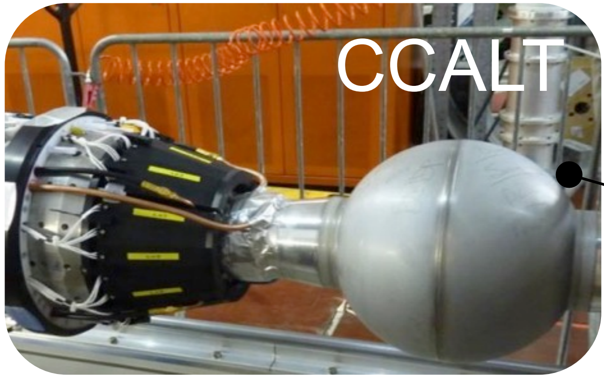
drift chamber

4 m diameter × 3.3 m length

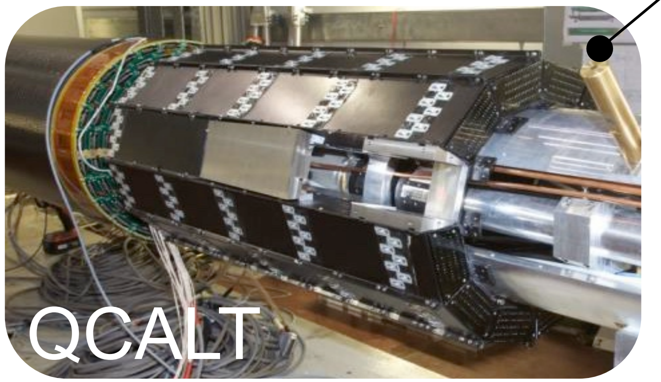
helium based gas mixture

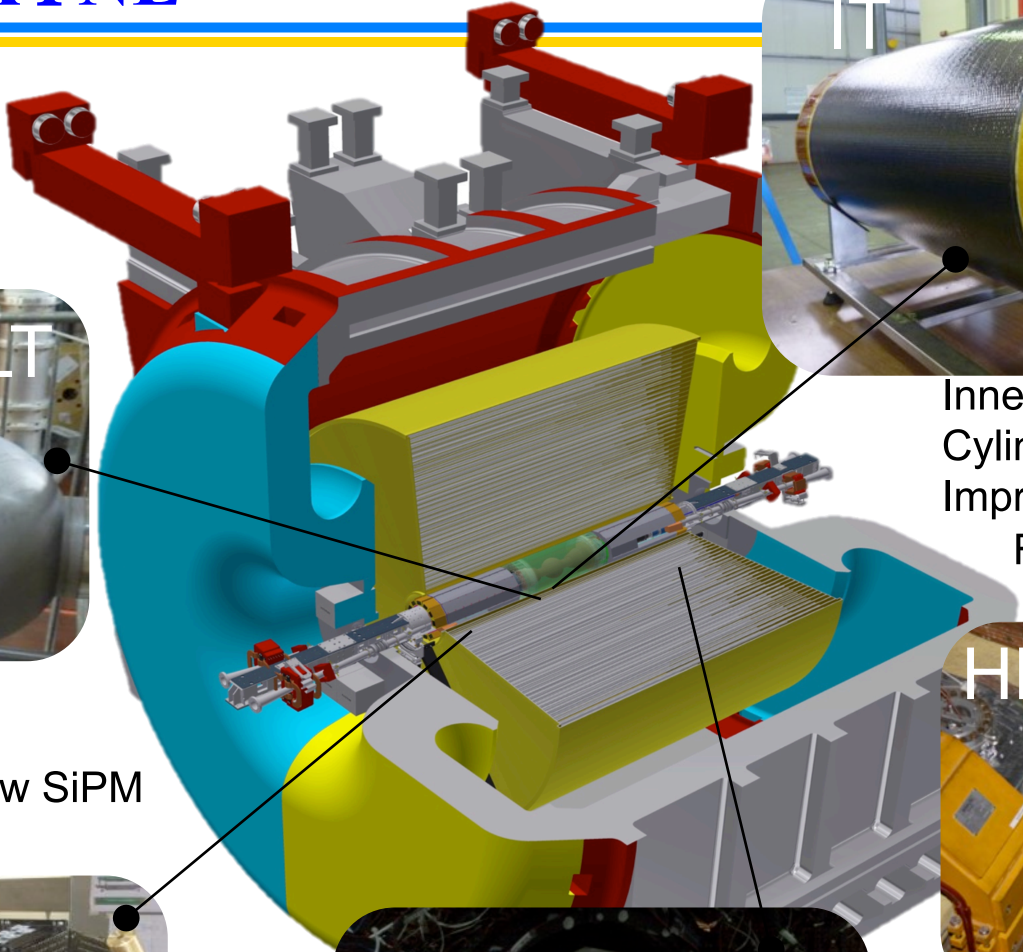
KLOE-2 at DAΦNE

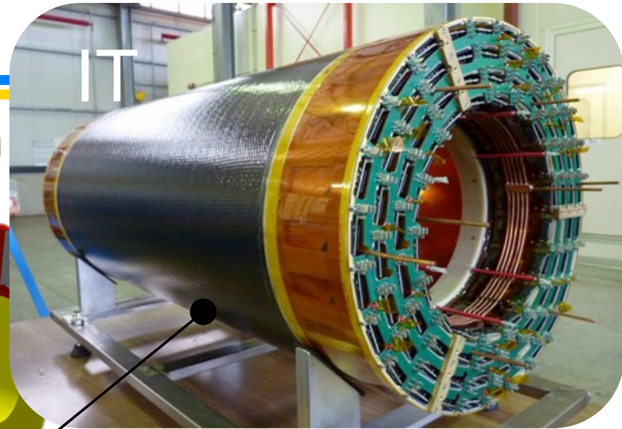
LYSO Crystal w SiPM
Low polar angle



Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation





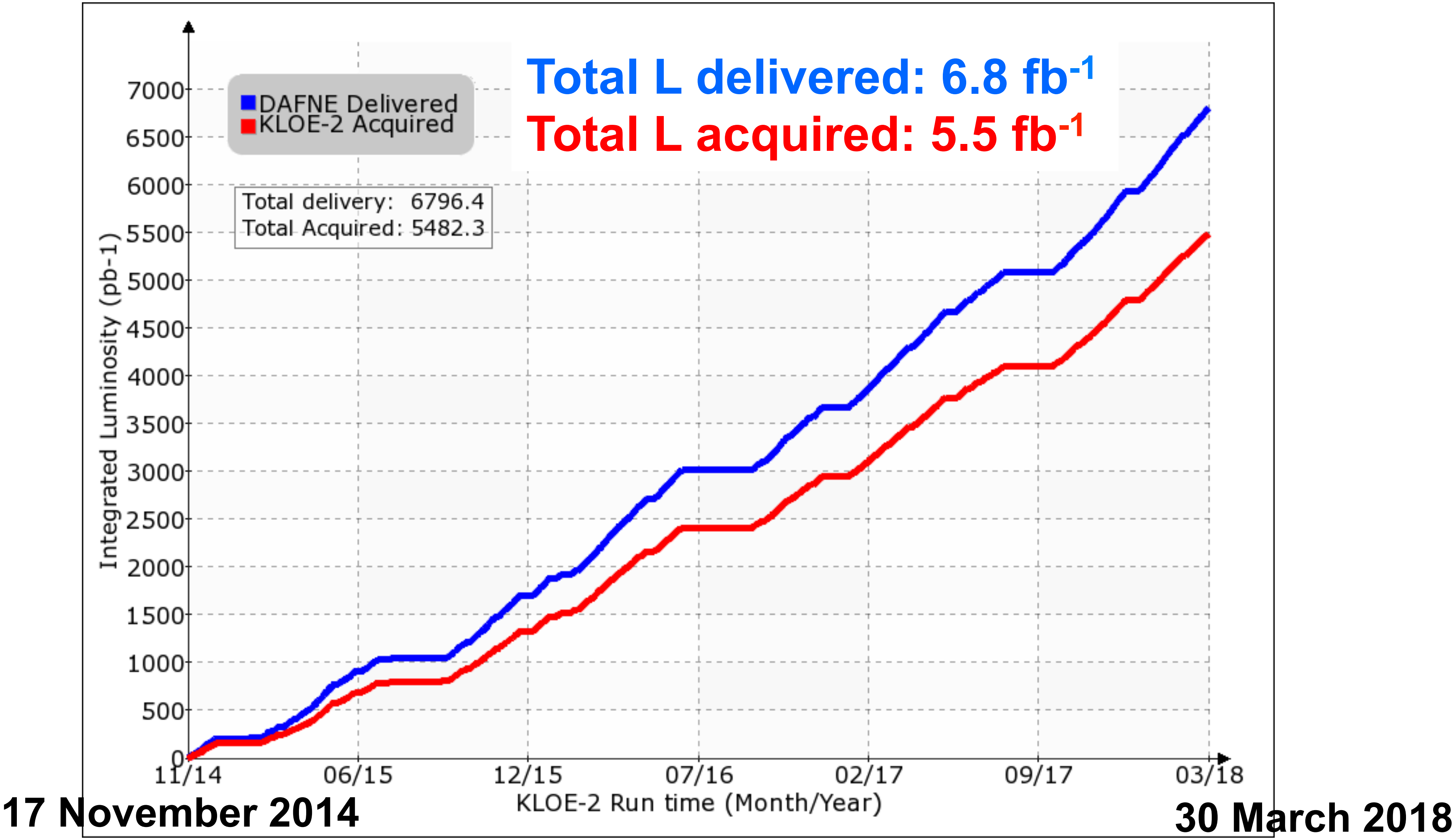


Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vtx reconstr.
First CGEM in HEP expt.

Scintillator hodoscope +PMTs

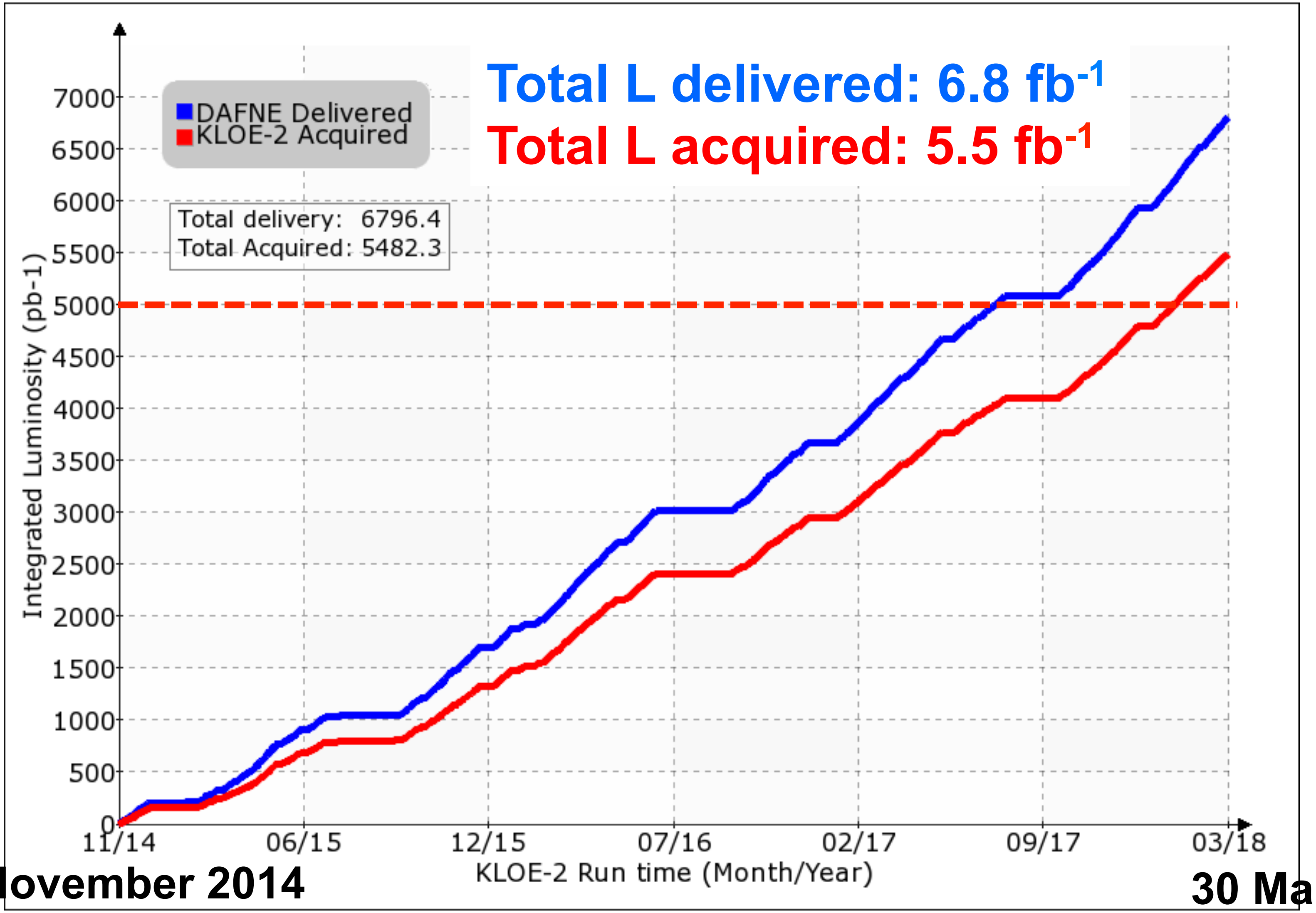
calorimeters LYSO+SiPMs
at ~ 1 m from IP

KLOE-2 run



KLOE-2 goal accomplished: L acquired > 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}

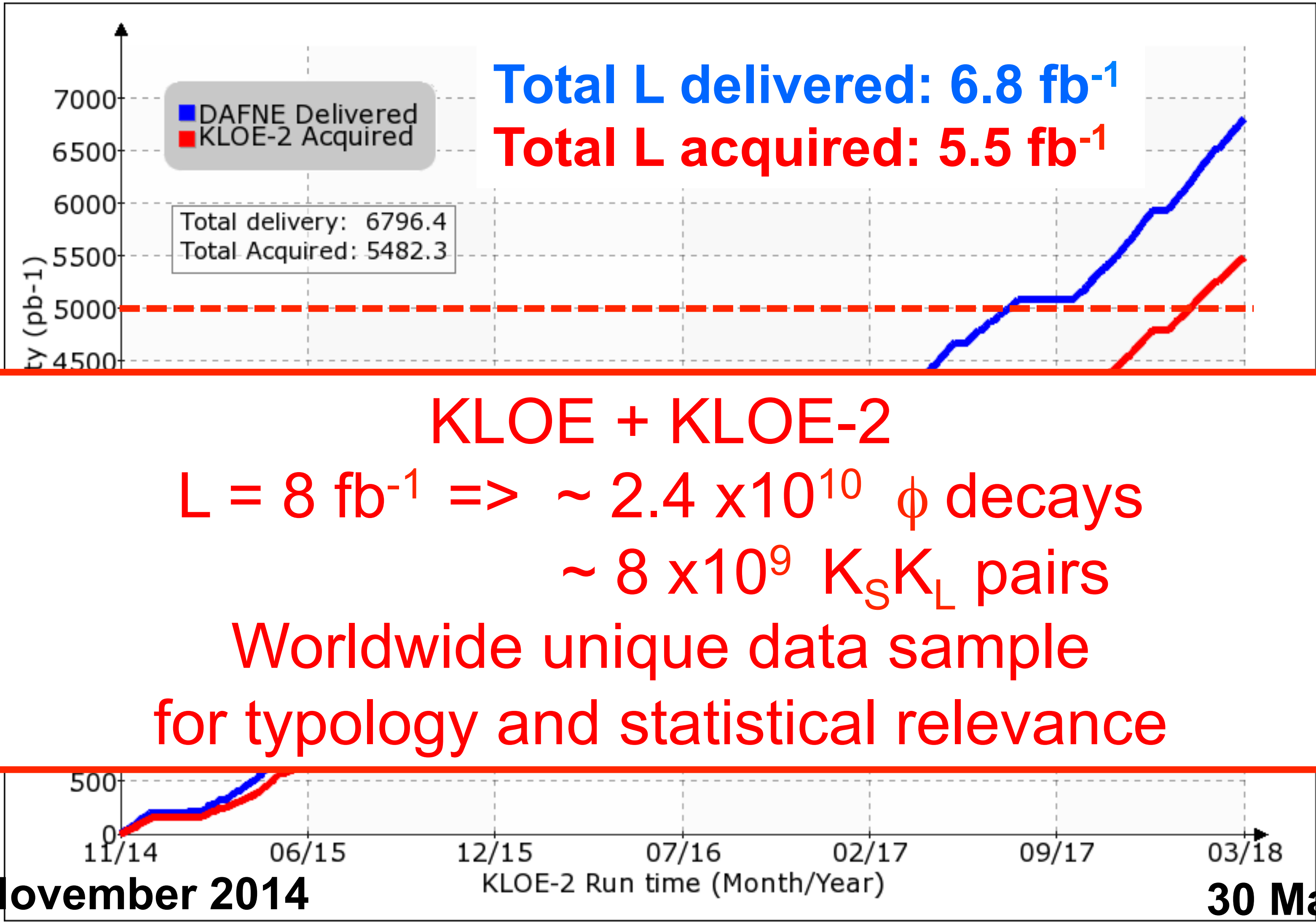
KLOE-2 run

KLOE-2 data-taking closing ceremony

30 March 2018 *INFN - Laboratori Nazionali di Frascati*

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

KLOE-2 run



Total L delivered: 6.8 fb^{-1}

Total L acquired: 5.5 fb^{-1}

KLOE + KLOE-2

L = 8 fb^{-1} => ~ 2.4 $\times 10^{10}$ ϕ decays

~ 8 $\times 10^{9}$ $K_S K_L$ pairs

Worldwide unique data sample

for typology and statistical relevance

17 November 2014 **30 March 2018**

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

List of KLOE CP/CPT 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	$Re(\varepsilon)$ $Im(\delta)$	$(159.6 \pm 1.3) \times 10^{-5}$ $(0.4 \pm 2.1) \times 10^{-5}$
$K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$	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

K_S semileptonic charge asymmetry

K_S and K_L semileptonic charge asymmetry

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

T ($2\Re\varepsilon$), CPT viol. in mixing ($2\Re\delta$)

CPTV in $\Delta S=\Delta Q$ ($2\Re y$), $\Delta S\neq\Delta Q$ decays ($2\Re x_-$)

$A_{S,L}\neq 0$ signals CP violation

$A_S \neq A_L$ signals CPT violation

$A_L = (\,3.322 \pm 0.058 \pm 0.047\,) \times 10^{-3}$

KTEV PRL88,181601(2002)

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

KLOE PLB 636(2006) 173

Data sample: L=410 pb^{-1}

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = (\,-0.8 \pm 2.5) \times 10^{-3}$$

CPT & $\Delta S=\Delta Q$ viol.

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = (\,0.4 \pm 2.5) \times 10^{-3}$$

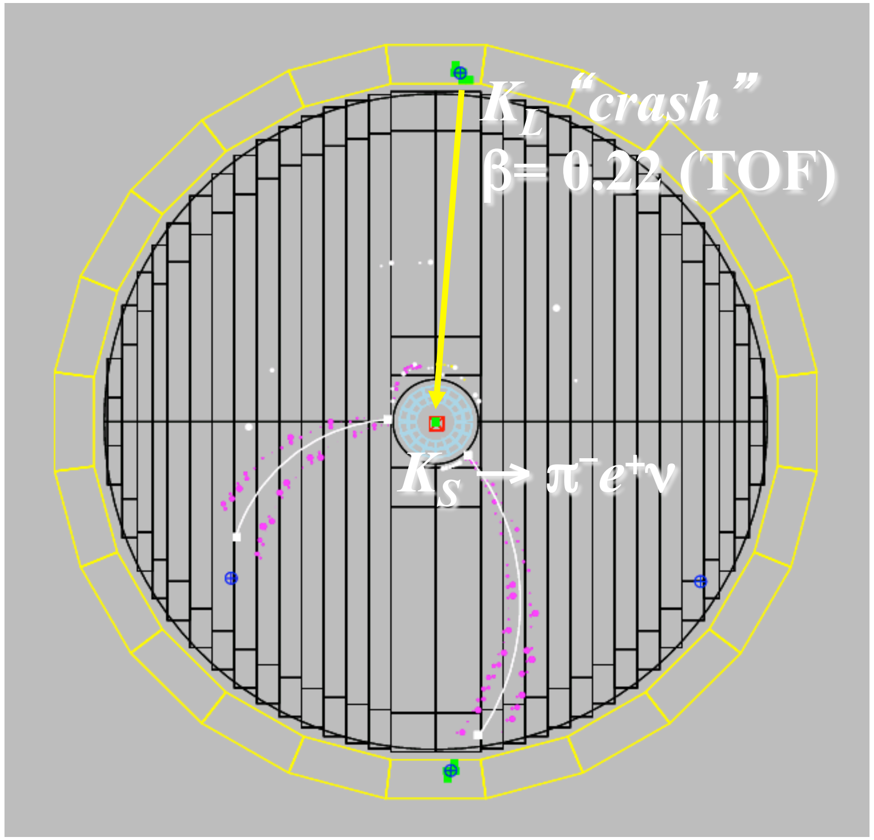
CPT viol.

input from other experiments ($\Re\delta$, $\Re\varepsilon$)

KLOE PLB 636(2006) 173

K_S semileptonic charge asymmetry

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

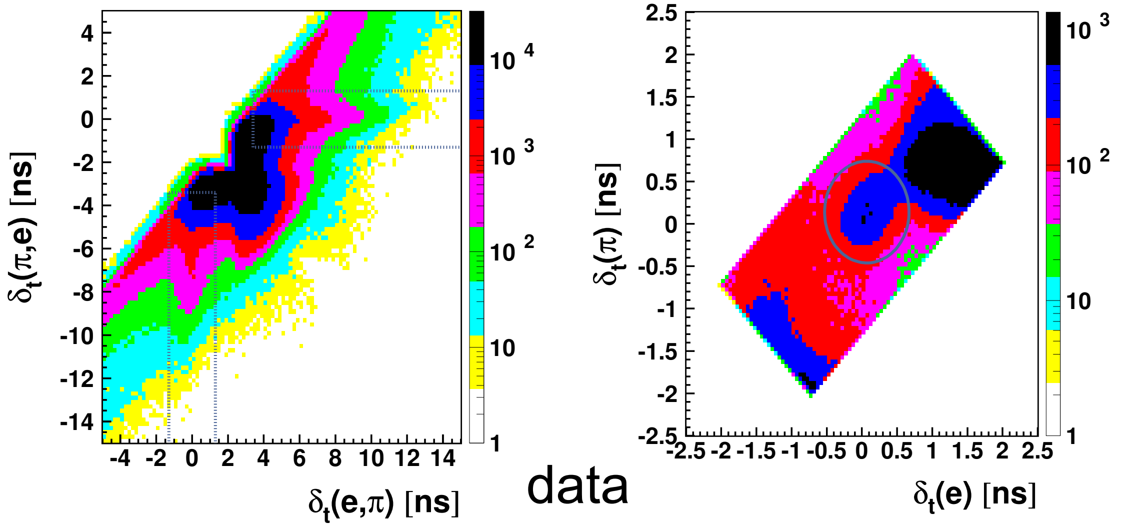


***K_S* tagged by *K_L* interaction in EmC**
Efficiency ~ 30% (largely geometrical)

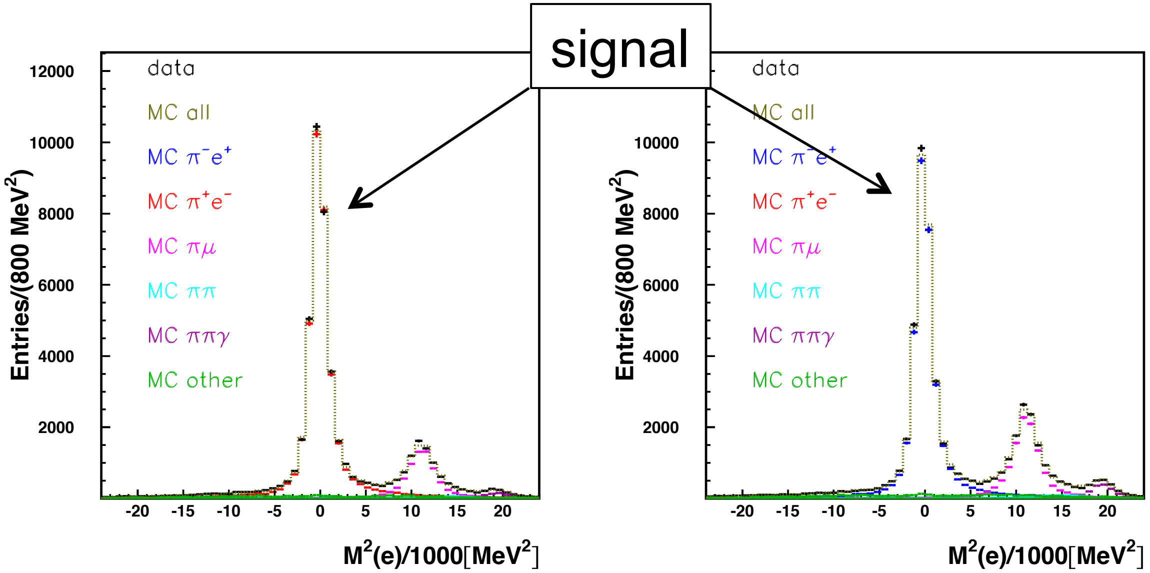
- Pure K_S sample selected exploiting entanglement
- L=1.6 fb^{-1}; ~ 4 × statistics w.r.t. previous measurement
- Pre-selection: 1 vtx close to IP with $M_{inv}(\pi,\pi)<M_K$ + K_L crash
- PID with time of flight technique

$$\delta_t(X) = (t_{cl} - T_0) - \frac{L}{c\beta(X)} \quad ; \quad X = e,\pi$$

$$\delta_t(X,Y) = \delta_t(X)_1 - \delta_t(Y)_2$$

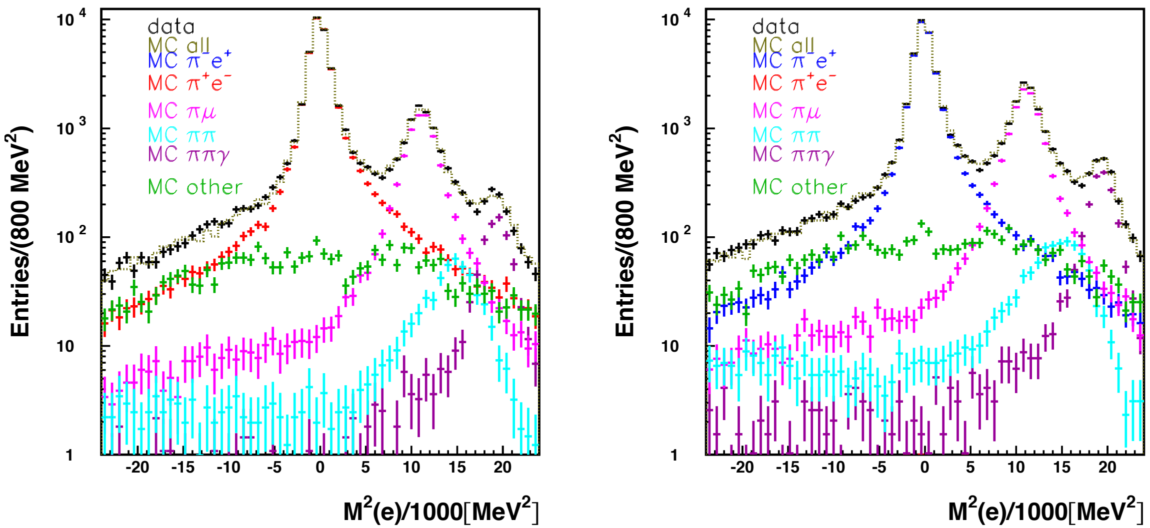


K_S semileptonic charge asymmetry

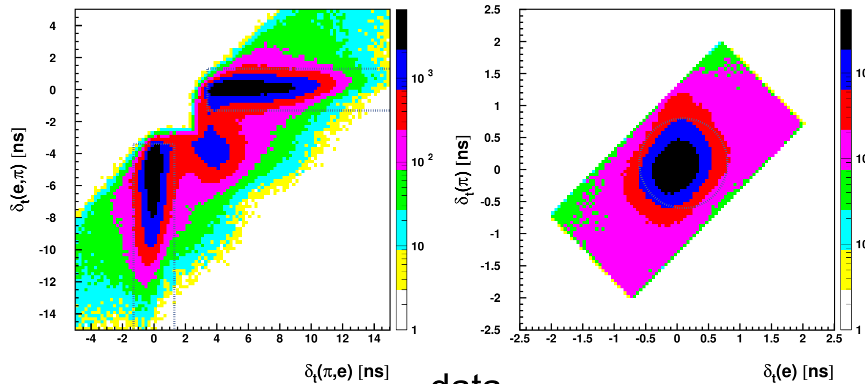


- Fit of M^2(e) distribution varying MC normalizations of signal and bkg contributions

- Control sample: $K_L \rightarrow \pi e \nu$ close to IP tagged by $K_S \rightarrow \pi^0\pi^0$
- track to EMC cluster and TOF efficiency correction from data c.s.

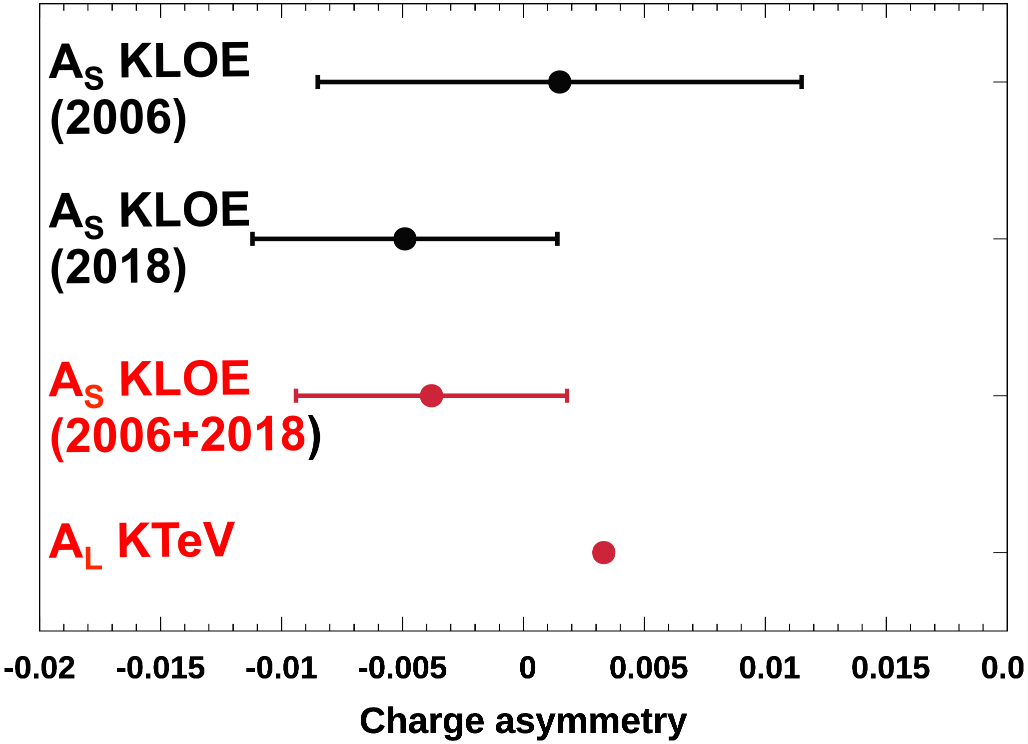


$K_L \rightarrow \pi e \nu$



data

K_S semileptonic charge asymmetry



Data sample: L=1.7 fb^{-1}

KLOE (2018)

$$A_S = (-4.8 \pm 5.6 \pm 2.6) \times 10^{-3}$$

Combination KLOE(2006)+KLOE (2018)

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

arXiv:1806.08654 [hep-ex] accepted on JHEP

It will improve the CPT test (Imδ) using Bell-Steinberger relationship

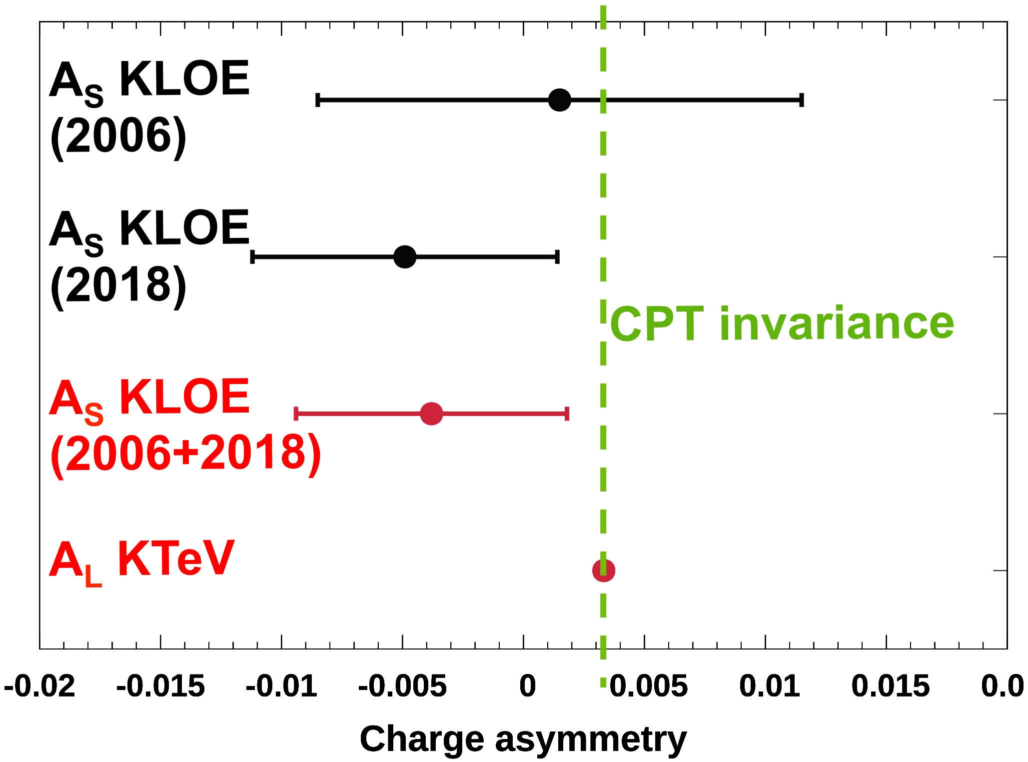
with KLOE-2 data: $\delta A_S(\text{stat}) \rightarrow \sim 3\times10^{-3}$

$$A_S - A_L = 4(\Re\delta + \Re x_-) \longrightarrow \Re x_- = (-2.0 \pm 1.4) \times 10^{-3}$$ CPT & $\Delta S = \Delta Q$ viol.

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \longrightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$ CPT viol.

input from other experiments

K_S semileptonic charge asymmetry



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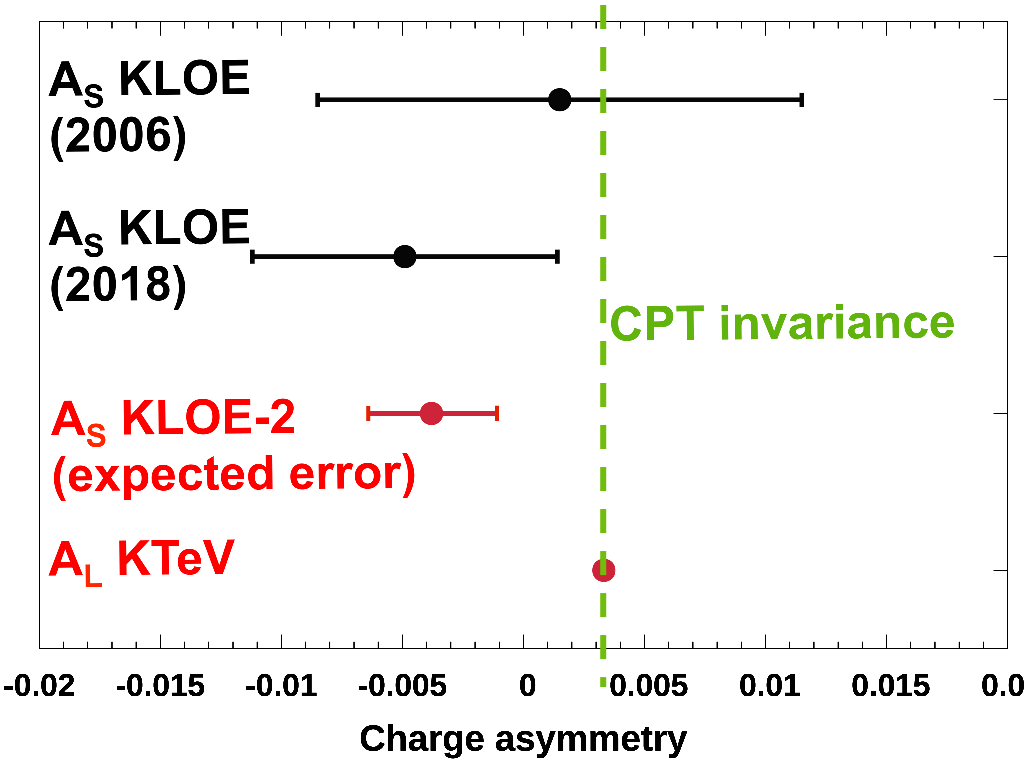
K_S semileptonic charge asymmetry



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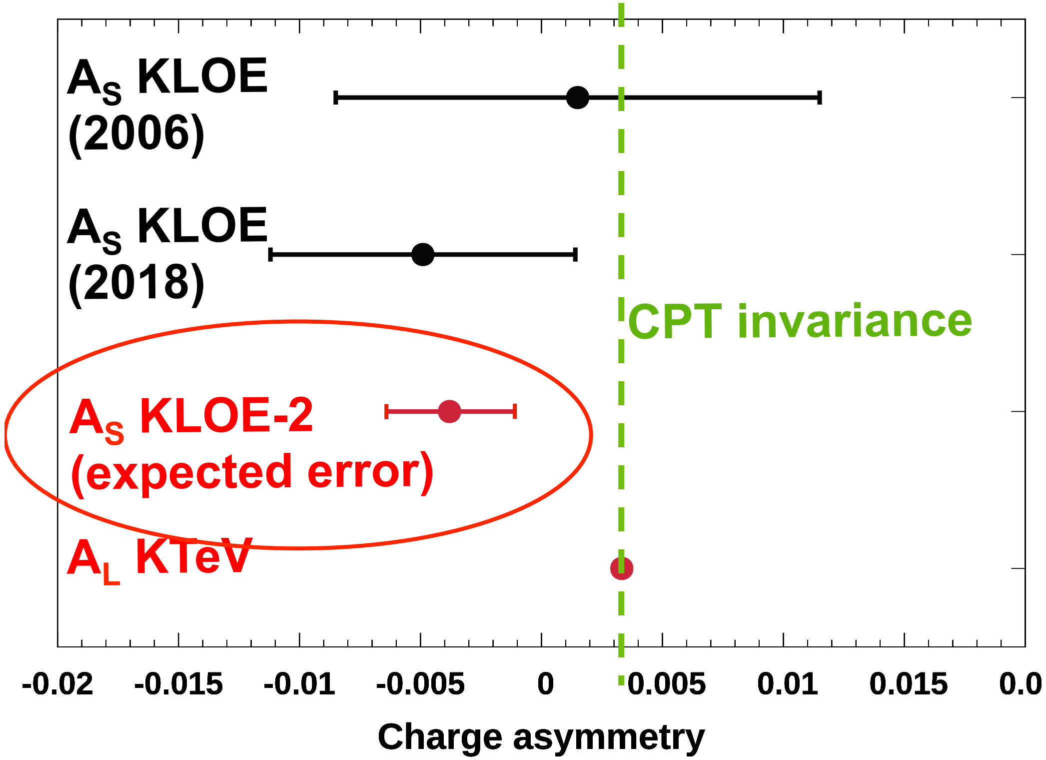
with KLOE-2 data: δA_S(stat) → ~ 3×10^{-3}

$$A_S - A_L = 4(\Re\delta + \Re x_-) \rightarrow \Re x_- = (\,-2.0 \pm 1.4) \times 10^{-3}$$ **CPT & ΔS=ΔQ viol.**

$$A_S + A_L = 4(\Re\varepsilon - \Re y) \rightarrow \Re y = (\,1.7 \pm 1.4) \times 10^{-3}$$ **CPT viol.**

input from other experiments

K_S semileptonic charge asymmetry



Data sample: L=1.7 fb^{-1}

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Combination KLOE(2006)+KLOE (2018)

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$$A_S + A_L = 4(\Re\varepsilon - \Re y) \rightarrow \Re y = (1.7 \pm 1.4) \times 10^{-3}$$ CPT viol.

input from other experiments

Direct test of T and CPT in neutral kaon transitions

- First test of T and CPT in transitions with neutral kaons (L=1.7 fb^{-1})
- $\phi \to K_S K_L \to \pi e^{\pm}\nu\ 3\pi^0$ and $\pi^+\pi^-\ \pi e^{\pm}\nu$
- Selection efficiencies estimated from data with 4 independent control samples

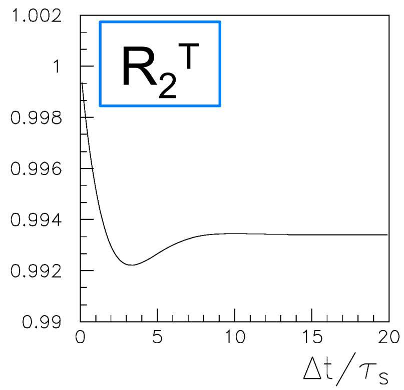
$K_S K_L \to \pi e^{\pm}\nu\ 3\pi^0$ → $K_S \to \pi e \nu$ Klcrash ; $K_S K_L \to \pi^+\pi^-\ 3\pi^0$

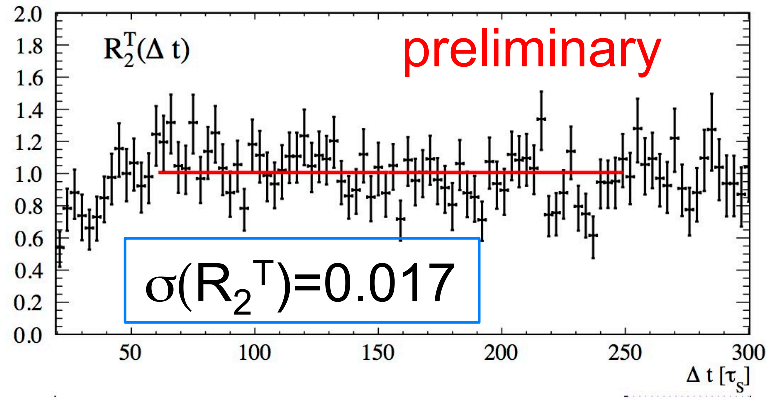
$K_S K_L \to \pi^+\pi^-\ \pi e^{\pm}\nu$ → $K_S \to \pi^+\pi^-$-Klcrash ; $K_S K_L \to \pi^0\pi^0\ \pi e \nu$

T test

$$R_{2,T}(\Delta t) = \frac{P\left[K^0(0) \to K_-(\Delta t)\right]}{P\left[K_-(0) \to K^0(\Delta t)\right]}$$

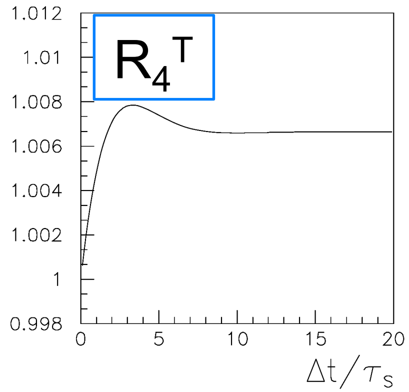
$$R_{2,T}(\Delta t >> \tau_S) = 1 - 4\Re\varepsilon$$

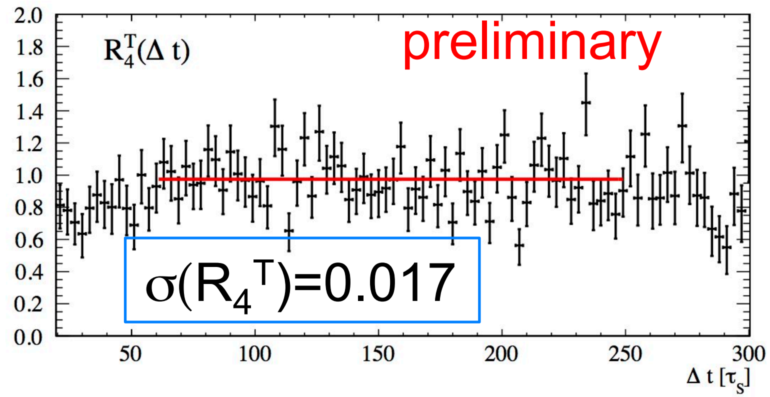




$$R_{4,T}(\Delta t) = \frac{P\left[\overline{K}^0(0) \to K_-(\Delta t)\right]}{P\left[K_-(0) \to \overline{K}^0(\Delta t)\right]}$$

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





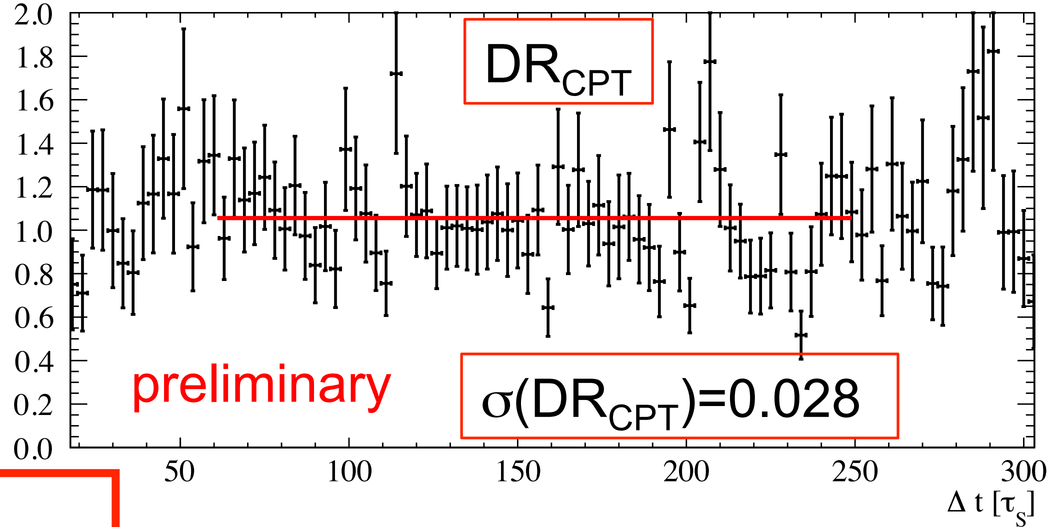
Direct test of T and CPT in neutral kaon transitions

CPT test

(L=1.7 fb^{-1})

$$R_{2,CPT}(\Delta t) = \frac{P\left[K^0(0) \rightarrow K_-(\Delta t)\right]}{P\left[K_-(0) \rightarrow \overline{K}^0(\Delta t)\right]}$$

$$R_{4,CPT}(\Delta t) = \frac{P\left[\overline{K}^0(0) \rightarrow K_-(\Delta t)\right]}{P\left[K_-(0) \rightarrow K^0(\Delta t)\right]}$$



$$DR_{CPT} = \frac{R_{2,CPT}(\Delta t >> \tau_S)}{R_{4,CPT}(\Delta t >> \tau_S)} = 1 - 8\Re\delta - 8\Re x_-$$

DR_{CPT} is the cleanest CPT observable; $DR_{CPT} \neq 1$ implies CPT violation.

KLOE-2 can reach a precision <1%.

There exists a connection between DR_{CPT} and the $A_{S,L}$ charge asymmetries :

$$DR_{CPT} = 1 + 2(A_L - A_S)$$

Using KTeV result on A_L and KLOE on A_S: **DR_{CPT}= 1.016 ± 0.011** (preliminary)

Conclusions

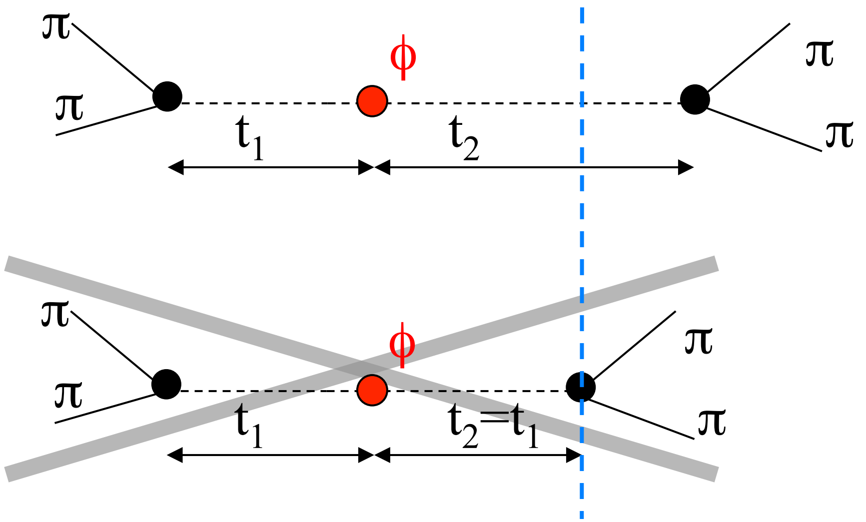
- The entangled neutral kaon system at a ϕ-factory is an excellent laboratory for the study of discrete symmetries and fundamental principles of QM.
- It is the ideal place to directly test discrete symmetries, and in particular CPT, in transition processes for the first time between neutral kaon states.
- 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}.
- The KLOE+KLOE-2 data sample (~ 8 fb^{-1}) is worldwide unique for typology and statistical relevance.
- New measurement of the K_S semileptonic charge asymmetry (accepted on JHEP)
- First test of T and CPT in neutral kaon transitions: analysis in advanced phase; the connection of the CPT test with $A_{S,L}$ opens new interesting possibilities.
- At KLOE-2 the test can reach a statistical sensitivity of $O(10^{-3})$ on the new observables.

Spare slides

Entanglement in neutral kaon pairs from ϕ

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

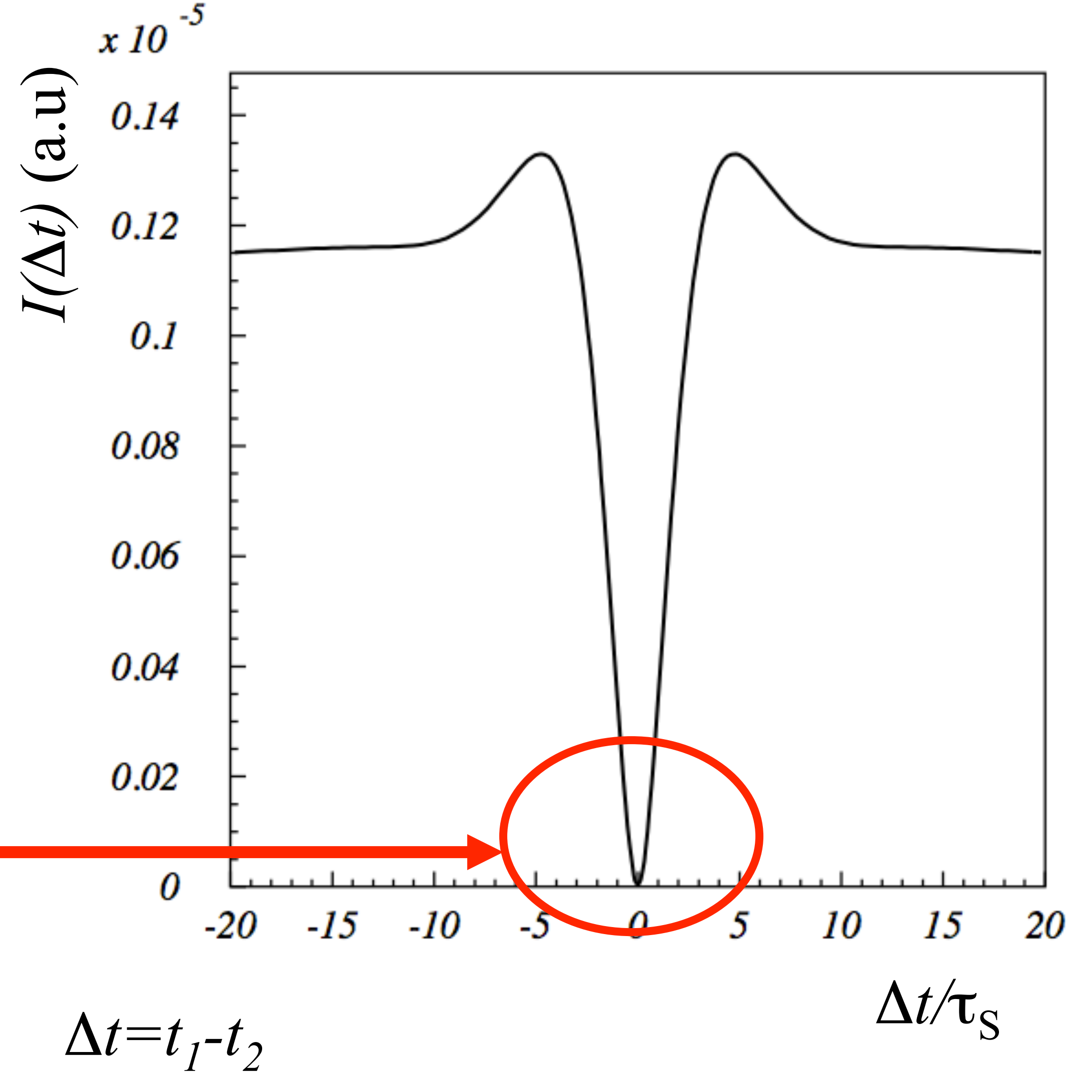


EPR correlation:

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

Both kaons decay in the same final state:

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



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

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

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

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

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

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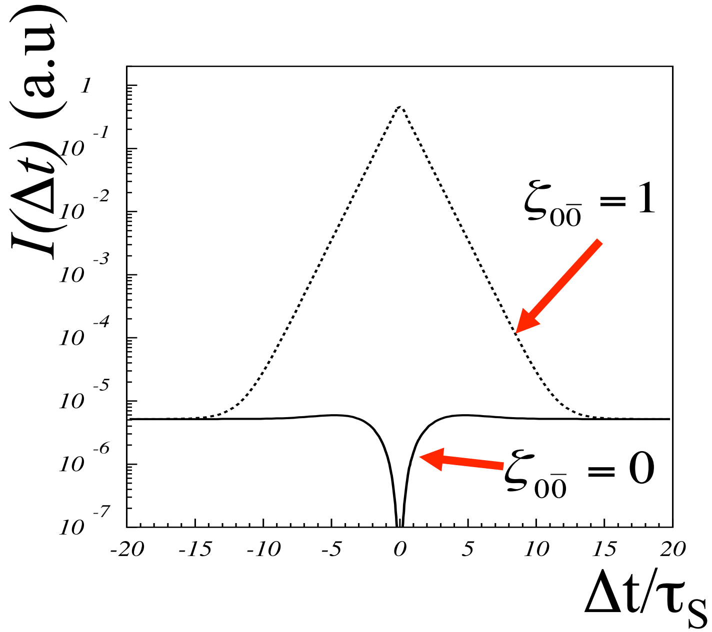
$$\left. -\left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\left\langle\pi^+\pi^-,\pi^+\pi^-\left|K^0\overline{K}^0(\Delta t)\right.\right\rangle\left\langle\pi^+\pi^-,\pi^+\pi^-\left|\overline{K}^0K^0(\Delta t)\right.\right\rangle^*\right)\right]$$

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

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

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

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



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)

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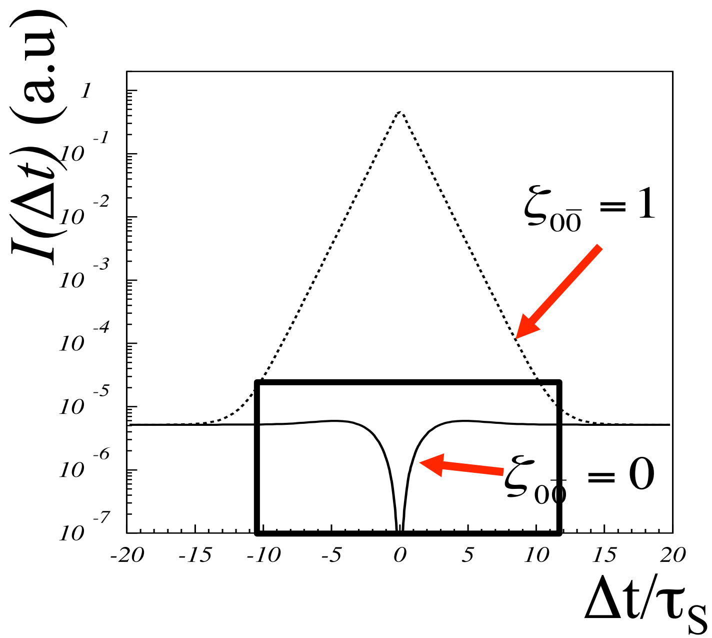
$$I(\pi^+\pi^-,\pi^+\pi^-;\Delta t) = \frac{N}{2}\Big[\left|\langle\pi^+\pi^-,\pi^+\pi^-|K^0\overline{K}^0(\Delta t)\rangle\right|^2 + \left|\langle\pi^+\pi^-,\pi^+\pi^-|\overline{K}^0K^0(\Delta t)\rangle\right|^2$$

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



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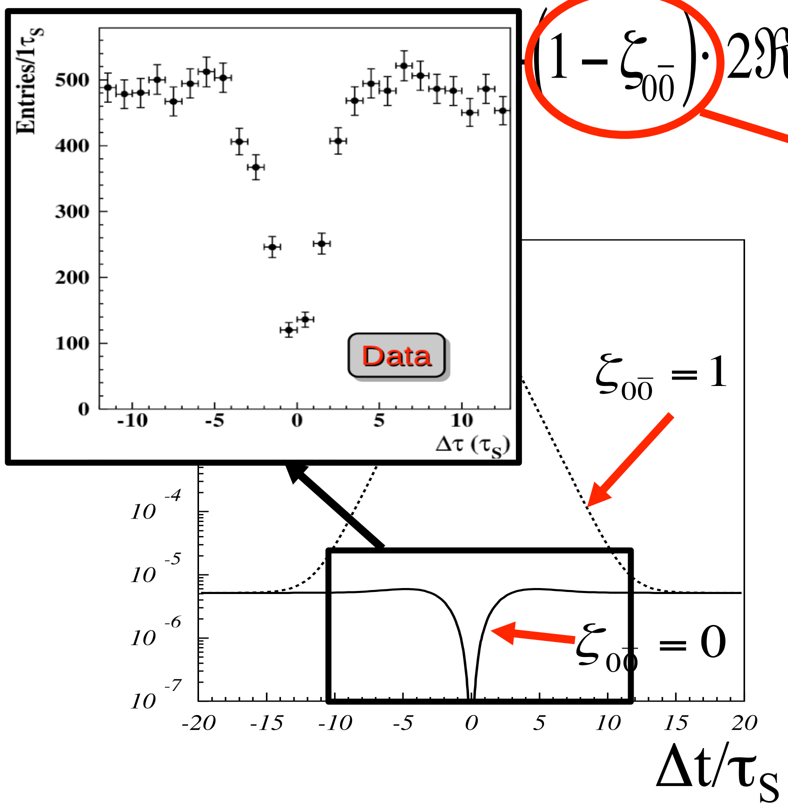
$$\left. - \left(1-\zeta_{0\bar{0}}\right)\cdot 2\Re\left(\left\langle\pi^+\pi^-,\pi^+\pi^-\middle|K^0\overline{K}^0(\Delta t)\right\rangle\left\langle\pi^+\pi^-,\pi^+\pi^-\middle|\overline{K}^0K^0(\Delta t)\right\rangle^*\right)\right]$$



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

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

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

The most precise test in an entangled system