Entangled kaons and tests of CPT symmetry and quantum mechanical correlations

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On behalf of KLOE & KLOE-2

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Entanglement - (more than) century after QM was born ..

1960: T.D. Lee and C.N. Yang, T.B. Day and D.R. Inglis
– first recognitions of how to use pairs of neutral kaons in C=-1 state for research on Einstein-Podolsky-Rosen paradox

In decays of **Φ(1019),** entangled pairs of neutral kaons produced in $J^{PC} = 1^{--}$ state

$$|\psi_I\rangle = \frac{1}{\sqrt{2}}(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle)$$

Nb. pairs of beauty mesons can also be used but are less favourable than kaons

CPT and decoherence study using interfering kaons – three main theoretical scenarios

$$\Delta t = |t_1 - t_2|, \qquad \Delta m = m_L - m_S$$

Assume same final states of decaying kaons - $\pi^+ \pi^-$ in this analysis

Hypothesis of spontaneous factorization of states (Furry, 1936)

Recalled for entangled kaons (Bertlmann, Grimus, Hiesmayr, 1999)

Straight-away parametrization of decoherence;

$$I(\Delta t) \simeq e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1 - \zeta_{SL}) e^{-\frac{1}{2}(\Gamma_L + \Gamma_S)\Delta t} \cos(\Delta m \Delta t)$$

$\zeta=1$ complete coherence breakdown

$0<\zeta<1$ partial decoherence

CPT and decoherence study using interfering kaons – three main theoretical scenarios, cont.

Density matrix approach for dissipative systems (Kossakowski, Lindbladt, Gorini, Sudarshan – 1976); applied to neutral kaons (Ellis, Hagelin, Nanonopulos, Srednicki – 1984, Huet, Peskin - 1995)

Dissipative term, linear in ρ

$$d\rho/dt = i[\rho, H] + L(\alpha, \beta, \gamma; \rho)$$

Decoherence due to interaction with environment:
induces T- and CPT violation due to dissipative arrow of time

Requirement of complete positivity (Benatti, Floreanini 1997) of evolution reduces nr of variables

$$\beta = 0, \quad \alpha = \gamma$$

CPT and decoherence study using interfering kaons – three main theoretical scenarios, cont.

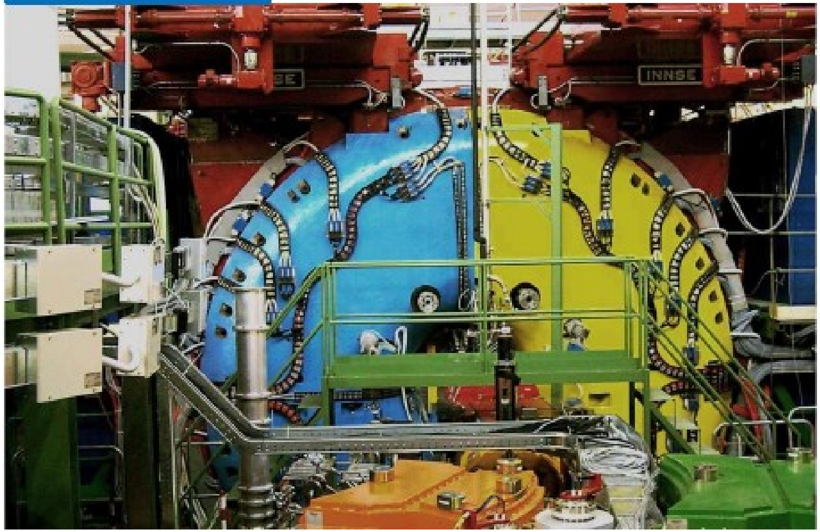
ill-defined CPT due to decoherence: admixture of wrong-parity states (Bernabeu, Mavromatos, Papavassiliou - 2003)

$$|\psi_I\rangle \sim |K_L\rangle|K_S\rangle - |K_S\rangle|K_L\rangle + \omega(|K_L\rangle|K_L\rangle - |K_S\rangle|K_S\rangle)$$

Complex parameter quantifying explicit CPT violation

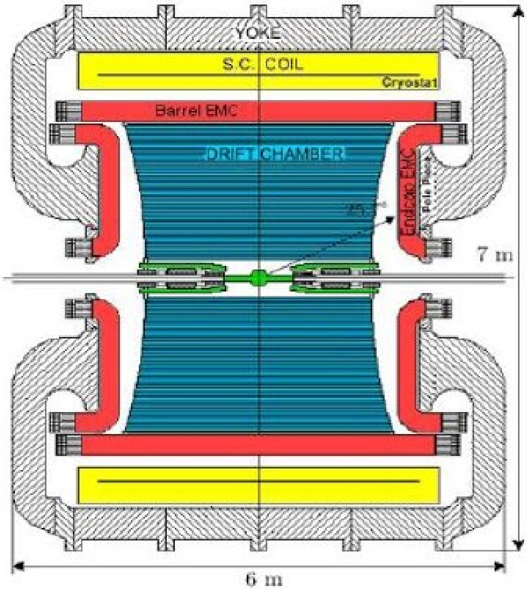
Leads to ω-modified K_S decay term and interference term in final expression for time-dependent intensity

KLOE does it



DAΦNE – the European Phi Factory
at INFN's Frascati

$$\sigma(p_T)/p_T = 0.4\%$$
$$\sigma_{m(\pi^+\pi^-)} = 1\ \mathrm{MeV}$$
$$\sigma_t \simeq 1\tau_S$$



e^+ e^- collider at 1019 MeV (or off peak)

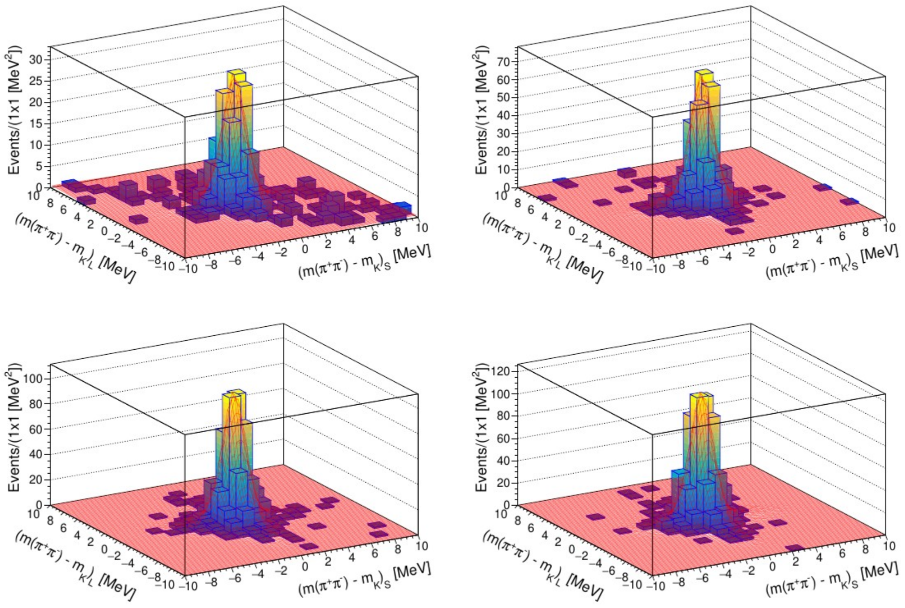
Data sample in this analysis 1.7 fb^{-1} or 1.7×10^9 $\Phi \rightarrow K_L\ K_S$

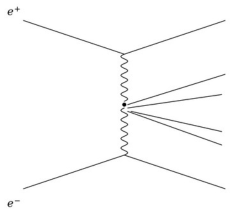
Recent results published KLOE-2, JHEP 04(2022)059

Background

At $\Delta t \approx 0$
- sensitive to (hypothetic) decoherence
- non-resonant $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ is there

$0 \leq \Delta t < \tau_S$



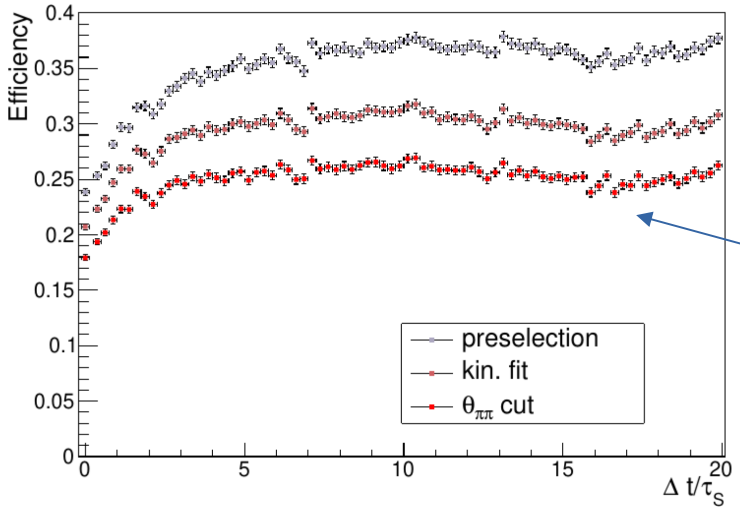


Estimated by max.- likelihood fit
Sizable only for small Δt

Regeneration on spherical beam pipe, contributes at large $\Delta t > 17\ \tau_S$
Analysis fits done for $\Delta t < 12\ \tau_S$;

Still small incoherent regeneration background on Be cyllinder, smeared over $5 – 12\ \tau_S$;
MC estimated using measured cross sections

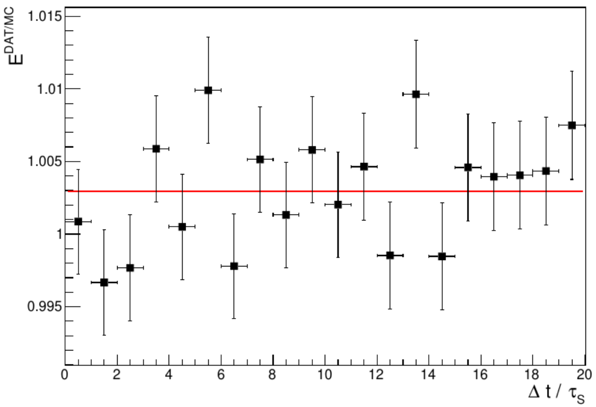
Efficiencies and corrections for them



$$\varepsilon_{tot} = \varepsilon_{trig} \cdot \varepsilon_{rec} \cdot \varepsilon_{cut}$$

Determined by MC

Used in analysis; drop for small Δt due to longer track extrapolation and possible swap of tracks from different kaon vertices



Data/MC efficiency correction; data from pure sample with semileptonic K_L decays

Account of systematic effects and errors

	$\delta\zeta_{SL}$ $\cdot 10^2$	$\delta\zeta_{0\bar{0}}$ $\cdot 10^7$	$\delta\gamma$ $\cdot 10^{21}$ GeV	$\delta\Re\omega$ $\cdot 10^4$	$\delta\Im\omega$ $\cdot 10^4$	$\delta\|\omega\|$ $\cdot 10^4$	$\delta\phi_\omega$ (rad)
Cut stability	0.56	2.9	0.33	0.53	0.65	0.78	0.07
4π background	0.37	1.9	0.22	0.32	0.19	0.32	0.04
Regeneration	0.17	0.9	0.10	0.06	0.63	0.58	0.05
Δt resolution	0.18	0.9	0.10	0.15	0.09	0.15	0.02
Input phys. const.	0.04	0.2	0.02	0.03	0.09	0.07	0.01
Total	0.71	3.7	0.42	0.64	0.93	1.04	0.10

Systematic errors dominated by cut stability and 4π background

Testing decoherence hypotheses – method of estimation

$$N^{theo}(q)_i = \mathcal{N}\, E_i^{\frac{DAT}{MC}} \sum_j S_{ij}\, \varepsilon_j\, R_j\, I(q)_j$$

Expected nr of events in i-th reconstructed bin of Δt

Overall normalization

DATA/MC eff correction

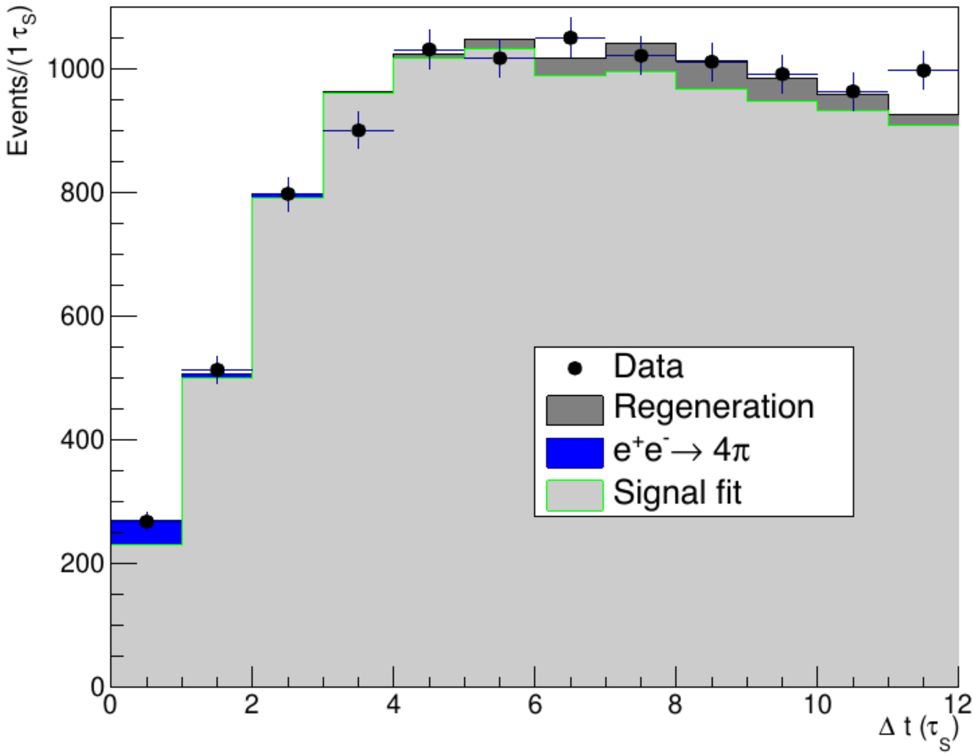
Resolution smearing matrix

Efficiency

Regeneration

Analytic model

Testing decoherence hypotheses, fit results



$$\zeta_{SL} = (0.1 \pm 1.6_{stat} \pm 0.7_{syst}) \times 10^{-2}$$

$$\zeta_{0\bar{0}} = (-0.05 \pm 0.80_{stat} \pm 0.37_{syst}) \times 10^{-6}$$

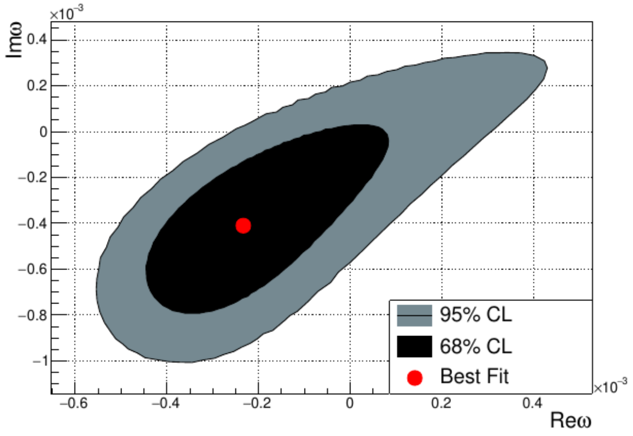
$$\gamma = (0.13 \pm 0.94_{stat} \pm 0.42_{syst}) \times 10^{-21}\ \mathrm{GeV}$$

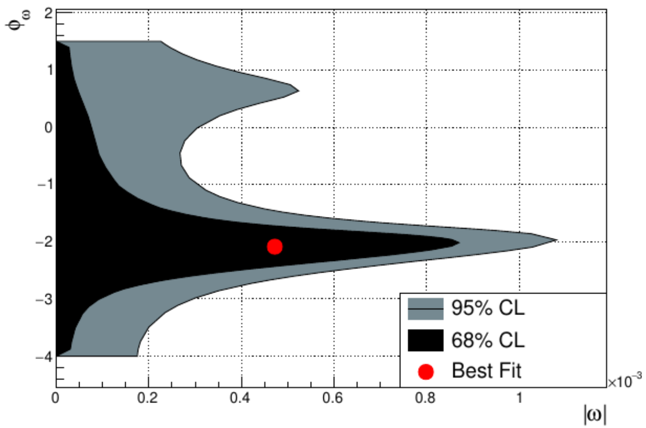
ζ_{00} is less CP-suppressed than ζ_{SL} hence higher precission

γ reaches Planck scale

$$\mathcal{O}(m_K^2/m_P) = 2 \times 10^{-20}\ \mathrm{GeV}$$

Testing wrong-parity hypothesis, fit results





$$\Re\omega = (-2.3^{+1.9}_{-1.5}\,\mathrm{stat} \pm 0.6_{\mathrm{syst}}) \times 10^{-4}$$
$$\Im\omega = (-4.1^{+2.8}_{-2.6}\,\mathrm{stat} \pm 0.9_{\mathrm{syst}}) \times 10^{-4}$$

$$|\omega| = (4.7 \pm 2.9_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}) \times 10^{-4}$$
$$\Phi_\omega = (-2.1 \pm 0.2 \pm 0.1)\ \mathrm{rad}$$

|ω| reaches Planck scale

$$\mathcal{O}[m_K^2/(m_P \Delta\Gamma)]^{1/2} \simeq 10^{-3}$$

$$\Delta\Gamma = \Gamma_S - \Gamma_L$$

Limit on $\Phi \rightarrow K_S K_S$ branching fraction

ω parametrizes mixture of C=+1 and C=-1 in initial state

$$I(\Delta t) \sim |\langle f|\Delta t, C=-1\rangle + \omega \langle f|\Delta t, C=+1\rangle|^2$$

$$\langle f| = \langle \pi^+\pi^-, \pi^+\pi^-|$$

$$|\omega|^2 = \frac{\mathcal{B}(\Phi \rightarrow K_S K_S)}{\mathcal{B}(\Phi \rightarrow K_S K_L)}$$

$$I(\Delta t) \sim e^{-\Gamma_S \Delta t}(1 + R_{SS}) + e^{-\Gamma_L \Delta t} - 2e^{-(\Gamma_L+\Gamma_S)/2\Delta t}\cos(\Delta m \Delta t)$$

$$R_{SS} = \frac{1}{|\eta_{+-}|^2} \frac{\Gamma_S + \Gamma_L}{2\Gamma_S} \frac{\mathcal{B}(\Phi \rightarrow K_S K_S)}{\mathcal{B}(\Phi \rightarrow K_L K_S)}$$

$\mathcal{B}(\Phi \rightarrow K_S K_S) < 2.4 \times 10^{-7}$ 90% c.l. From fit to data

Meaning of results and conclusions

- No signal of decoherence nor CPT violation in the most stringent experimental test in non-electromagnetic system so far

- Accuracy improvment of factor 2 with respect to KLOE 2006; improvements in analysis

- Sensitivity of dissipative and ω models at verge of Planck scale where quantum gravity effects are believed to switch on ($\gamma = 10^{-22} - 10^{-21}$) GeV

- Study of CPT symmetry complementary to
  - charge asymmetry in semi-leptonic decays
  - Standard Model extensions

- Additional information on upper limit for C-forbidden decays of $\Phi^0 \rightarrow K_L K_L$ and $\Phi^0 \rightarrow K_S K_S$ on 2.4×10^{-7} at 90% confidence level