Latest discrete symmetries and Quantum Mechanics studies with KLOE-2

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on behalf of the KLOE-2 Collaboration

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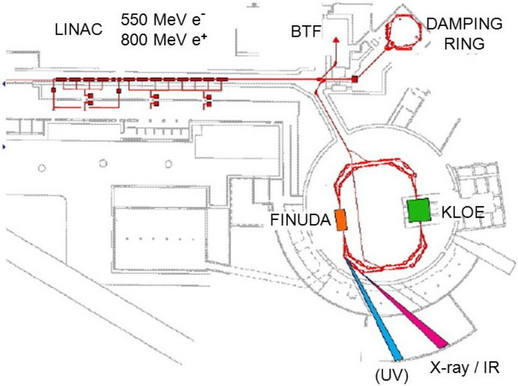
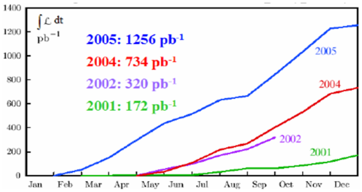
JAGIELLONIAN UNIVERSITY IN KRAKOW

Outline

- DAΦNE & KLOE
- Quantum entanglement
- Decoherence
- CPT symmetry and Lorentz invariance test
- Ongoing discrete symmetry tests
- Summary

DAΦNE





- DAΦNE e^+e^- collider located in Frascati,
- two alternate interaction regions (one for KLOE),
- $\sqrt{s} \approx m_\Phi$,
- $BR(\Phi \to K_L K_S) = 34\%$,
- KLOE has collected $\sim 2.5\text{fb}^{-1}$ of data,

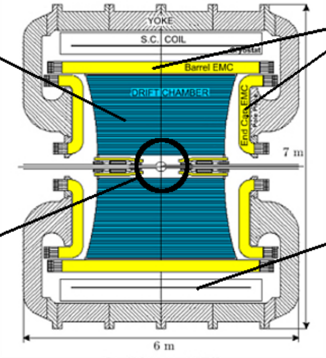
KLOE

DRIFT CHAMBER

(4 m ⌀ × 3.3 m)
σ_p/p = 0.4 %
$\sigma_{x/y}$ = 150 μm
σ_z = 2 mm
σ_{vtx} = 3 mm

INTERACTION POINT

berylium beam pipe
(⌀ 10 cm)

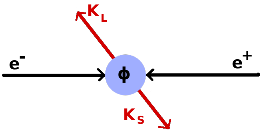


CALORIMETER

~4π solid angle coverage
barrel-endcap
$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$
$\sigma_t = 54\ ps/\sqrt{E(GeV)} \oplus 100ps$

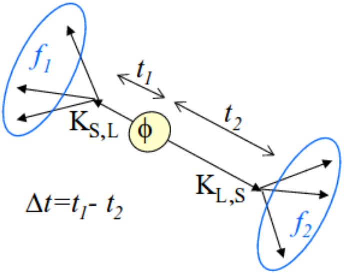
SUPERCONDUCTING MAGNET

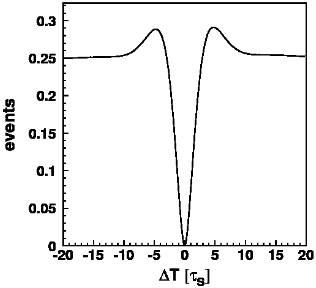
B = 0.52 T



KLOE-2 has started operation with goal to collect at least of 5 fb^{-1}
For details see a talk by A. Passeri, Saturday at 9^{40}

Quantum entanglement





$$I_{f_1,f_2}(\Delta t) = Ce^{-\Gamma|\Delta t|}(|\eta_1|^2\, e^{\frac{\Delta\Gamma}{2}\Delta t} + |\eta_2|^2\, e^{-\frac{\Delta\Gamma}{2}\Delta t} - \underbrace{2Re(\eta_1\eta_2^* e^{-i\Delta m\Delta t})}_{\text{interference term}})$$

$$\eta_i = \langle f_i|K_L\rangle / \langle f_i|K_S\rangle$$
$$\Delta\Gamma = \Gamma_S - \Gamma_L$$
$$\Gamma = (\Gamma_S + \Gamma_L)/2$$

no simultaneous decays ($\Delta t = 0$) in the same final state due to the destructive quantum interference

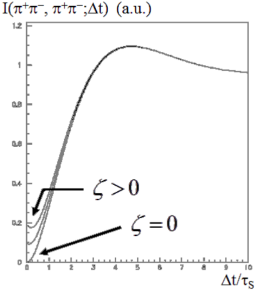
Decoherence

- Furry hypothesis [W.Furry, P.R.49 (1936) 393] of "spontaneous factorization":

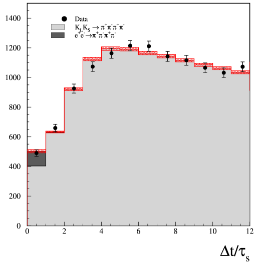
$$(|K_S\rangle\,|K_L\rangle - |K_L\rangle\,|K_S\rangle) \Rightarrow |K_S\rangle\,|K_L\rangle \text{ or } |K_L\rangle\,|K_S\rangle$$

- Decoherence parameter ζ measures the amount of deviation from the predictions of quantum mechanics:

$$I_{f_1,f_2}(\Delta t) = Ce^{-\Gamma|\Delta t|}(|\eta_1|^2\, e^{\frac{\Delta\Gamma}{2}\Delta t} + |\eta_2|^2\, e^{-\frac{\Delta\Gamma}{2}\Delta t} - (1-\zeta)\cdot 2Re(\eta_1\eta_2^* e^{-i\Delta m\Delta t}))$$



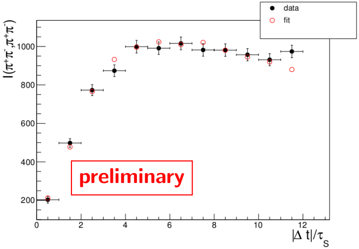
- KLOE (1.5 fb^{-1}) : $\zeta_{0\bar{0}} = (1.4 \pm 9.5 \pm 3.8)\cdot 10^{-7}$ [J.Phys.Conf.Ser. 171:012008 (2009)]
- from CPLEAR data: $\zeta_{0\bar{0}} = 0.4 \pm 0.7$ [PR D60 (1999) 114032]
- in B-meson system, Belle: $\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$ [PRL 99 (2007) 131802]



KLOE result on decoherence has a very high accuracy $\mathcal{O}(10^{-6})$

Decoherence

KLOE (1.5 fb^{-1}) : $\zeta_{0\bar{0}} = (1.4 \pm 9.5 \pm 3.8) \cdot 10^{-7}$
[J.Phys.Conf.Ser. 171:012008 (2009)]

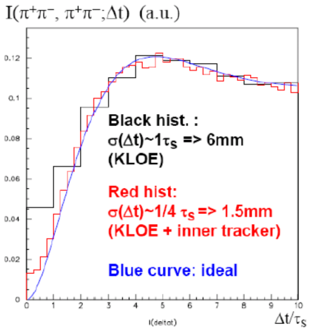


New analysis on the same statistics will improve sensitivity on decoherence parameter due to:

- refined selection of $\pi^+\pi^-$ decays,
- 15% improving on ζ statistical uncertainty.

Further improvements still possible at KLOE-2:

- expected data sample: at least 5 fb^{-1},
- due to insertion of inner tracker resolution on vertex reconstruction improves.



Testing Standard Model Extension violating CPT and Lorentz invariance

- in SME (Kostelecky) [PRD64,076001] for neutral kaons CPT violation exhibits a dependence on the 4-momentum of the kaon, hence directional dependence with respect to distant stars:

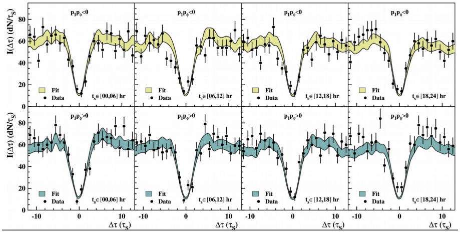
$$\delta \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta_K} \cdot \Delta\vec{a})/\Delta m$$

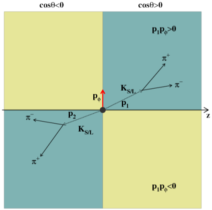
- ϕ_{SW} - superweak phase,
- γ_K and $\vec{\beta_K}$ are the kaon boost factor and velocity in the observer frame,
- a_μ - four CPT- and Lorentz-violating coefficients

- in KLOE Δa_μ parameters were measured through neutral kaon interferometry in $\phi \to K_L K_S \to \pi^+\pi^-\pi^+\pi^-$ channel

$$I(\Delta t) = Ce^{-\Gamma|\Delta t|}(|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta t} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta t} - 2Re(\eta_1\eta_2^* e^{-i\Delta m\Delta t}))$$

$$\eta_1 = \epsilon_K - \delta(\vec{p_{K1}})$$
$$\eta_2 = \epsilon_K - \delta(\vec{p_{K2}})$$





Testing Standard Model Extension violating CPT and Lorentz invariance

KLOE (1.7 **fb**$^{-1}$), PLB 730(2014)89

$$\Delta a_0 = (-6.0 \pm 7.7 \pm 3.1) \cdot 10^{-18}\ \text{GeV}$$
$$\Delta a_x = (0.9 \pm 1.5 \pm 0.6) \cdot 10^{-18}\ \text{GeV}$$
$$\Delta a_y = (-2.0 \pm 1.5 \pm 0.5) \cdot 10^{-18}\ \text{GeV}$$
$$\Delta a_z = (3.1 \pm 1.7 \pm 0.5) \cdot 10^{-18}\ \text{GeV}$$

FOCUS, PLB 556(2003)7, mixing D

$$\Delta a_{x,y,\parallel} \approx 10^{-13}\text{GeV}$$

LHCb, PRL 116(2016)241601, 2016 mixing

$B^0 \to J/\psi K_S$ $\quad \Delta a_{x,y,\parallel} \approx 10^{-15}\text{GeV}$, $\quad \Delta a_{\perp} \approx 10^{-13}\text{GeV}$

$B^0_S \to J/\psi K^+ K^-$ $\quad \Delta a_{x,y,\parallel} \approx 10^{-14}\text{GeV}$, $\quad \Delta a_{\perp} \approx 10^{-12}\text{GeV}$

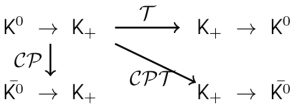
BaBar, PRL 100(2000)131802,
entangled $\Psi(4S) \to B\bar{B} \to (Xl\nu)(Xl\nu)$

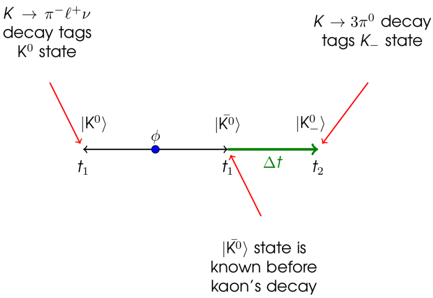
$$\Delta a_{\perp,\parallel} \approx 10^{-13}\text{GeV}$$

KLOE exhibits the best sensitivity in the quark sector

T (and CPT)-symmetry test

- the test uses transitions between states only connected by T conjugation





- $K^0, \bar{K^0}$ - starageness eigenstates
- K_+, K_- - CP eigenstates

$\bar{K^0}$	$\rightarrow \pi^+ l^- \bar{\nu}$	S	=-1
K^0	$\rightarrow \pi^- l^+ \nu$	S	=+1
K_+	$\rightarrow \pi^+ \pi^-$	CP	=+1
K_-	$\rightarrow 3\pi^0$	CP	=-1

	Transition		$\mathcal{T}$-conjugate	
1	$K^0 \rightarrow K_+$	$(\ell^-, \pi\pi)$	$K_+ \rightarrow K^0$	$(3\pi^0, \ell^+)$
2	$K^0 \rightarrow K_-$	$(\ell^-, 3\pi^0)$	$K_- \rightarrow K^0$	$(\pi\pi, \ell^+)$
3	$\bar{K^0} \rightarrow K_+$	$(\ell^+, \pi\pi)$	$K_+ \rightarrow \bar{K^0}$	$(3\pi^0, \ell^-)$
4	$\bar{K^0} \rightarrow K_-$	$(\ell^+, 3\pi^0)$	$K_- \rightarrow \bar{K^0}$	$(\pi\pi, \ell^-)$

J. Bernabeu, A. Di Domenico and P. Villanueva-Perez: Nucl.Phys. B 868 (2013) 102, JHEP 10 (2015) 139

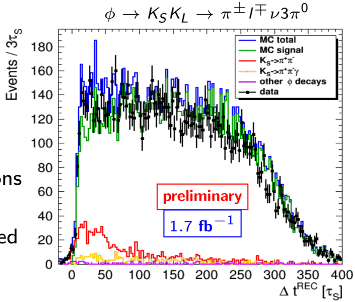
For details see a talk by A. Di Domenico, Saturday at 9^{00}

T (and CPT)-symmetry test

$$R_2^{exp}(\Delta t) = \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} = R_2(\Delta t) \times \frac{C(\ell^-, 3\pi^0)}{C(\pi\pi, \ell^+)}$$

$$R_4^{exp}(\Delta t) = \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_4(\Delta t) \times \frac{C(\ell^+, 3\pi^0)}{C(\pi\pi, \ell^-)}$$

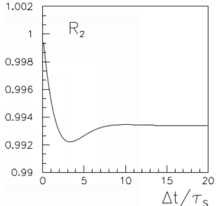
$R_{2,4} \sim 1 \pm 4Re(\delta)$ **for** $\Delta t > \tau_S$

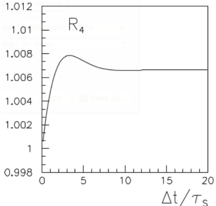


- $I(f_1, f_2, \Delta t)$ -distribution of number of events where kaons decay to final states f_1 and f_2 in times differing by Δt
- The C coefficients — time-independent, can be estimated using quantities measured by KLOE:

$$\frac{C(\ell^-, 3\pi^0)}{C(\pi\pi, \ell^+)} \simeq \frac{C(\ell^+, 3\pi^0)}{C(\pi\pi, \ell^-)} \simeq \frac{BR(K_L \to 3\pi^0)}{BR(K_S \to \pi\pi)} \frac{\Gamma_L}{\Gamma_S}$$

Asymptotic behaviour of $R_2(\Delta t > \tau_S)$ and $R_4(\Delta t > \tau_S)$ can be extracted and allows to measure of T symmetry violation





CP violation in $K_S \to \pi^+\pi^-\pi^0$ decay

$$\eta_{+-0} = \frac{\langle \pi^+\pi^-\pi^0 | K_S \rangle}{\langle \pi^+\pi^-\pi^0 | K_L \rangle} = \epsilon + \epsilon'_{+-0}$$

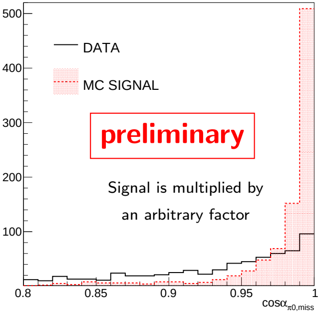
$$\eta_{000} = \frac{\langle 3\pi^0 | K_S \rangle}{\langle 3\pi^0 | K_L \rangle} = \epsilon + \epsilon'_{000}$$

- ϵ - mixture parameter ("indirect" CP violation)
- ϵ' - account for the direct CP violation

- in lowest order of χPT: $\epsilon'_{+-0} = \epsilon'_{000} = -2\epsilon'$
- $|\eta_{000}| < 0.0088$ @90% C.L. [PLB 723 (2013) 54]
- $BR(K_S \to \pi^+\pi^-\pi^0) = 3.5^{+1.1}_{-0.9} \cdot 10^{-7}$

  [Chin. Phys. C38 (2014)090001]

  - average of 3 indirect measurements
- analysis is based on 1.7 fb^{-1} of KLOE data sample (direct detection of K_S's)
- with we expect about 600 events ($\epsilon = 100\%$)



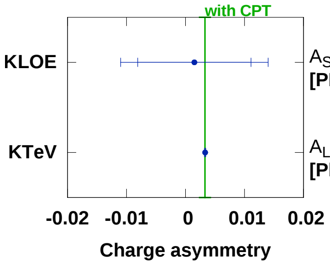
Charge asymmetry test for K_S

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

$$= 2\left[Re\left(\epsilon_K\right) \pm Re\left(\delta_K\right) - Re\left(y\right) \pm Re\left(x_-\right)\right]$$

$\mathcal{CP}$ violation
$\mathcal{CPT}$ violation in mass matrix
describes $\mathcal{CPT}$ violation in $K^0(\bar{K^0}) \to \pi e \nu$ decay
variables build on $K^0(\bar{K^0}) \to \pi e \nu$ decay amplitudes (vanish if $\Delta S = \Delta Q$ rule holds)

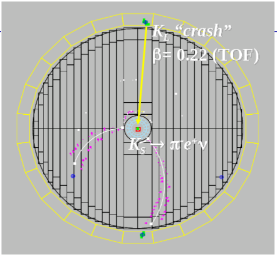
- Assuming CPT invariance: $A_S = A_L \approx 3 \cdot 10^{-3}$
- Sample used in current analysis ($1.7\ \text{fb}^{-1}$) is approx. 4 times larger in statistics than the one used in previous KLOE analysis
- further improvements of both statistical and systematical uncertainty are expected thanks to upgrade of DAΦNE and KLOE



$A_S = (1.5 \pm 9.6 \pm 2.9) \cdot 10^{-3}$
[PLB 636 (2006) 173]

$A_L = (3.322 \pm 0.058 \pm 0.047) \cdot 10^{-3}$
[Phys. Rev. Lett. 88 (2002)]

Charge asymmetry test for K_S



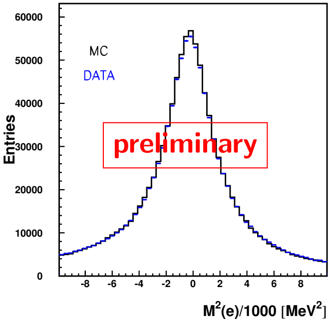
Selected channels:

signal: $\phi \to K_L K_S \to K_L(crash)\pi e \nu$

control sample: $\phi \to K_S K_L \to \pi^0\pi^0\pi e \nu$

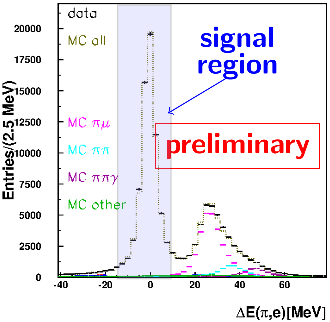
- analysis is based on 1.7 fb^{-1} of KLOE data sample
- we are presently evaluating systematic uncertainty

$\Downarrow \pi^0\pi^0\pi e \nu$



$M^2(e) = (E_{K_S} - E(\pi) - p_{miss}(\pi, e))^2 - p^2(e)$

$\Downarrow K_L(crash)\pi e \nu$



$\Delta E(\pi, e) = E_{miss} - p_{miss}$

Summary

- The neutral kaon system is an excellent laboratory for the study of CPT symmetry and the basic principles of Quantum Mechanics,
- The DAΦNE Φ-factory provides entangled $K^0\bar{K}^0$ pairs,
- KLOE has measured several parameters related to:
  - decoherence and CPT violaton
  - CPT violation and Lorentz symmetry breaking
  - charge asymetry in semileptonic decays of K_S
- KLOE-2 detector at DAΦNE is collecting data:
  - Current data-taking campaign: at least 5 fb^{-1} to be taken in next couple of years with new equipments
  - milestone (15 July '16): 2.5 fb^{-1} delivered
- Neutral kaon interferometry, discrete symmetries violation and QM tests are one of the main goals of the KLOE-2 physics program

Thank you for your attention