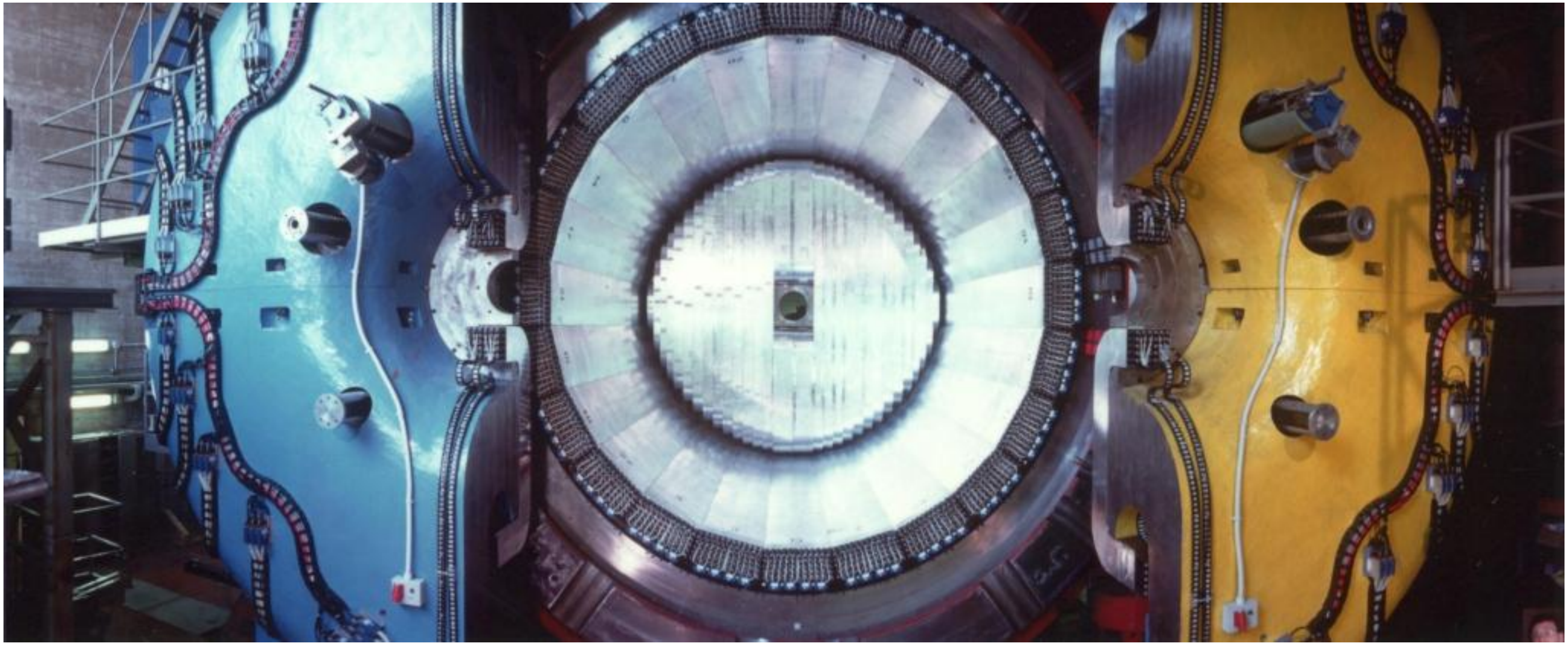
Quantum Mechanics and CPT tests with neutral kaons at the KLOE experiment



Izabela Pytko

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NARODOWA STRATEGIA SPÓJNOŚCI
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INTERNATIONAL PHD PROJECTS IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES
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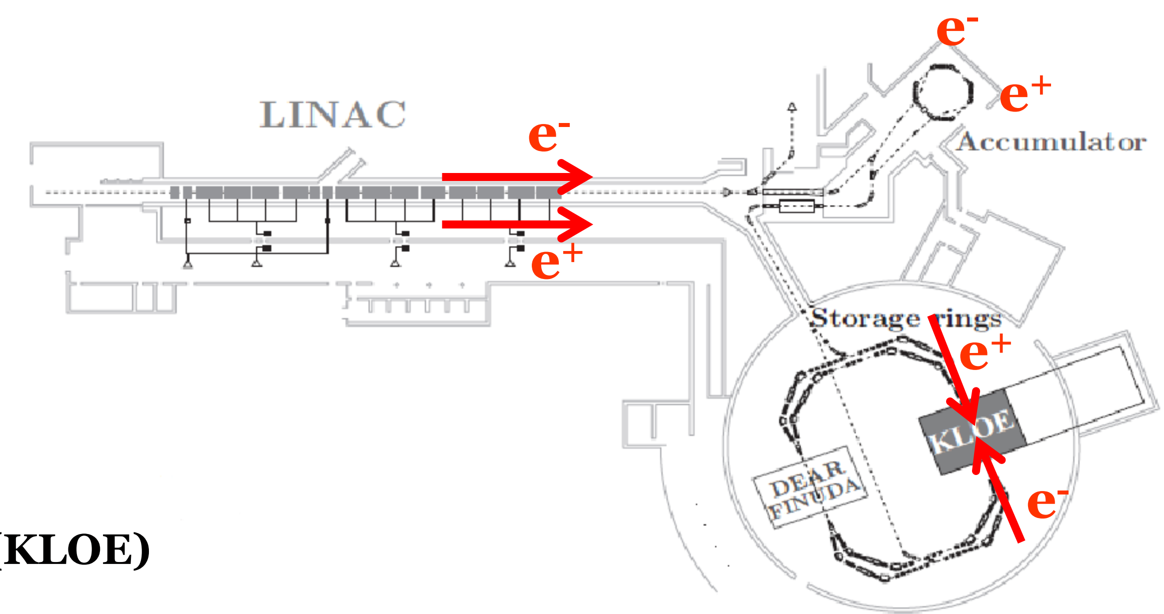
1) The Frascati ϕ-factory facility

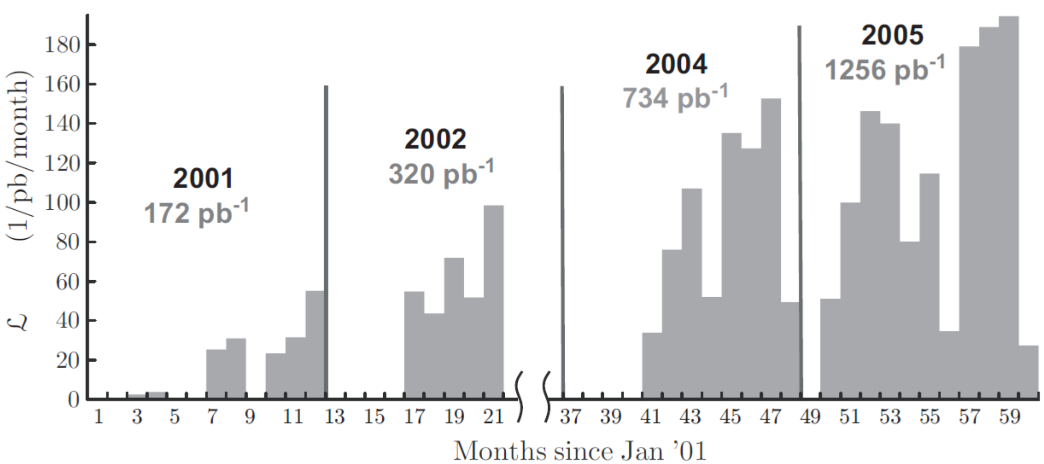
The KLOE detector at the Frascati ϕ-factory DAFNE

$$e^+e^- \to \phi \to K^0\overline{K}^0$$

- e^+e^- collider
- $\sqrt{s} = m_\phi = 1.019$ GeV
- $\sigma(e^+e^- \to \phi) \approx 3.1$ μb
- BR$(\phi \to K^0\overline{K}^0) \approx 34\%$



Integrated luminosity (KLOE)



KLOE Data-taking periods:

- 2001-2002 - p(ϕ) ~12 MeV
- 2004-2005 - p(ϕ) ~15 MeV
- 2006 - √s =1.0 GeV

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

→ ~ 2.6×10^9 kaon pairs

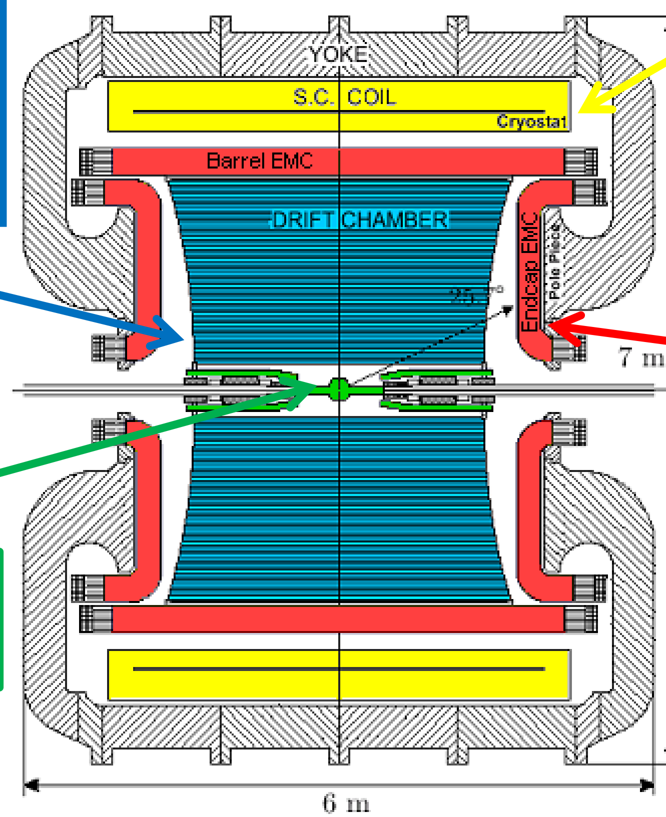
The KLOE detector

Drift Chamber

4 m diameter × 3.3 m length
helium based gas mixture
momentum: $\frac{\sigma_p}{p} = 0.4\%$
$\sigma_x{}^{hit} \cong 150\ \mu\text{m (xy), 2 mm (z)}$
vertex: $\sigma_x{}^{vtx} \cong 1\text{ mm}$

SC Magnet

B = 0.52 T



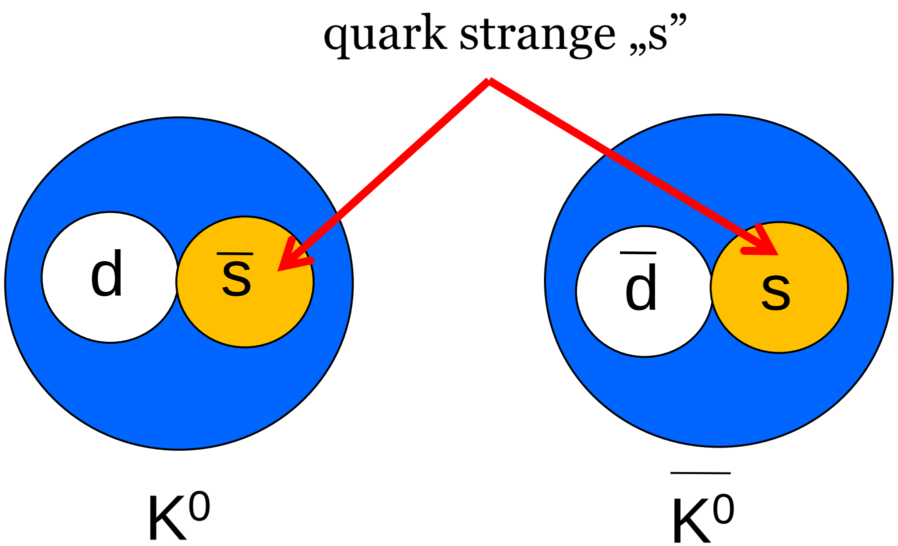
Interaction point (IP)

10 cm radius Be&Al sphere

Electromagnetic calorimeter

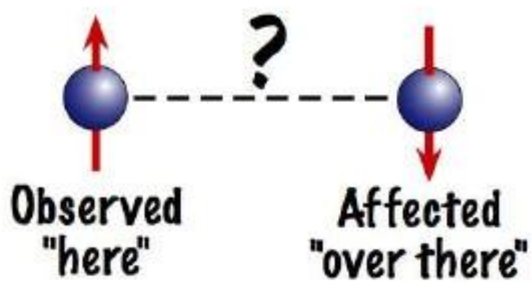
4π solid angle coverage
lead layers & scintillating fibers
energy: $\sigma_E \cong 5.7\%/\sqrt{E(\text{GeV})}$
time: $\sigma_t \cong \frac{54\text{ ps}}{\sqrt{E(\text{GeV})}} \oplus 50\text{ ps}$

Quantum entanglement of neutral kaons



$$\varphi \rightarrow K^0 \overline{K}^0$$

Strangeness:
S(φ) = 0
S(K^0) = +1
S($\overline{K}^0$) = -1



Short- and long-lived states of kaons

$$\left|K_S\right\rangle = \alpha\left|K^0\right\rangle + \beta\left|\overline{K}^0\right\rangle, \quad \left|K_L\right\rangle = \alpha\left|K^0\right\rangle - \beta\left|\overline{K}^0\right\rangle$$

$$CP = +1 \qquad\qquad CP = -1$$

$$2\pi \qquad\qquad 3\pi$$

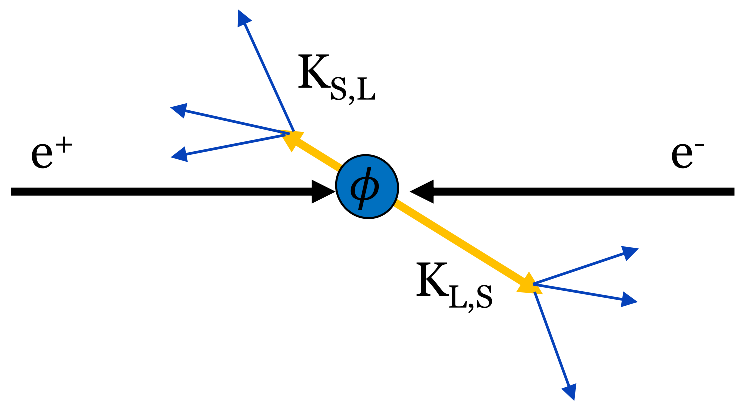
$$\tau_S = 0.09ns \qquad\qquad \tau_L = 51.7ns$$

⇒ mean decay length (p_K = 110 MeV/c): $K_L = 3.37m$, $K_S = 0.6cm$.

The detection of a kaon at large (small) times tags a K_S (K_L)
⇒ possibility to select a pure K_S beam

Neutral kaons at a ϕ-factory

- Production of the vector meson ϕ in e^+e^- annihilations:



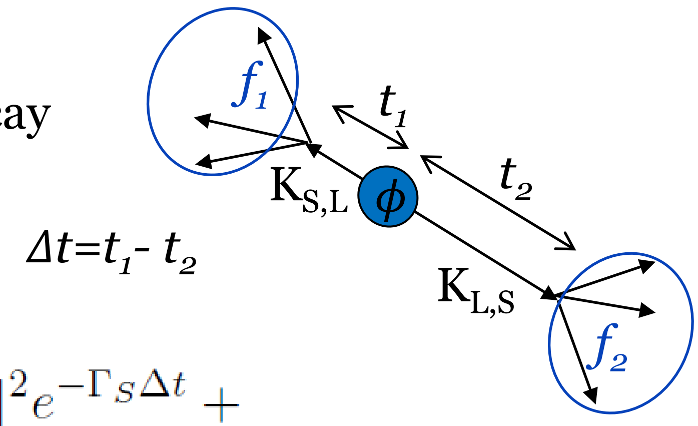
- BR($\phi \to K^0\overline{K^0}$) ~ 34%
- neutral kaon pairs produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:

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

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

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

Neutral kaon interferometry



- $t_1(t_2)$ is the proper time of one (the other) kaon decay into f_1 (f_2) final state

- Decay intensity distribution:

$$I(f_1, f_2; \Delta t \geq 0) = \frac{C_{12}}{\Gamma_S + \Gamma_L}\left[|\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} + - 2|\eta_1||\eta_2| e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t} \cos(\Delta m \Delta t + \varphi_2 - \varphi_1) \right]$$

$$\eta_i = |\eta_i| e^{i\varphi_i} = \langle f_i | T | K_L \rangle / \langle f_i | T | K_S \rangle$$

$$C_{12} = \frac{|N|^2}{2} \left| \langle f_1 | T | K_S \rangle \langle f_2 | T | K_S \rangle \right|^2$$

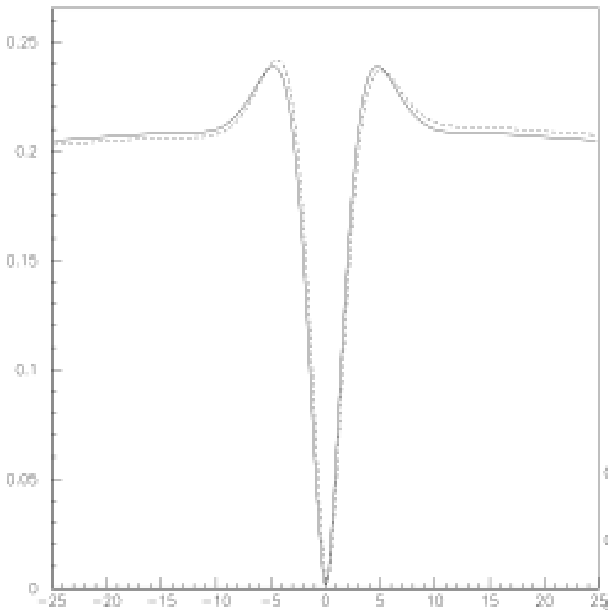
characteristic interference term at a ϕ-factory => interferometry

- From this distribution for various final states f_i one can measure the following quantities:

$$\Gamma_S\ ,\ \Gamma_L\ , \Delta m\ , \ |\eta_i|\ , \Delta\varphi$$

Neutral kaon interferometry: main observables

$I(\Delta t)$ (a.u)



$$\phi \to K_S K_L \to \pi^+\pi^- \ \pi^0\pi^0$$

$$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$$

CP, CPT

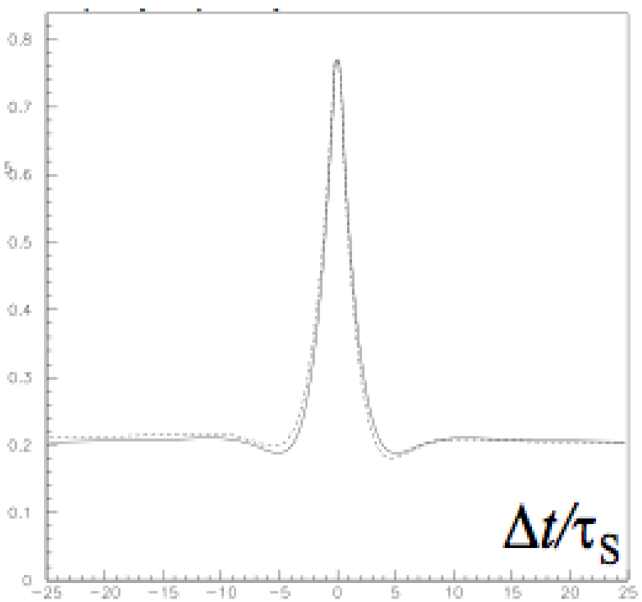
$$\Re\delta + \Re x_-$$

$$\Im\delta + \Im x_+$$

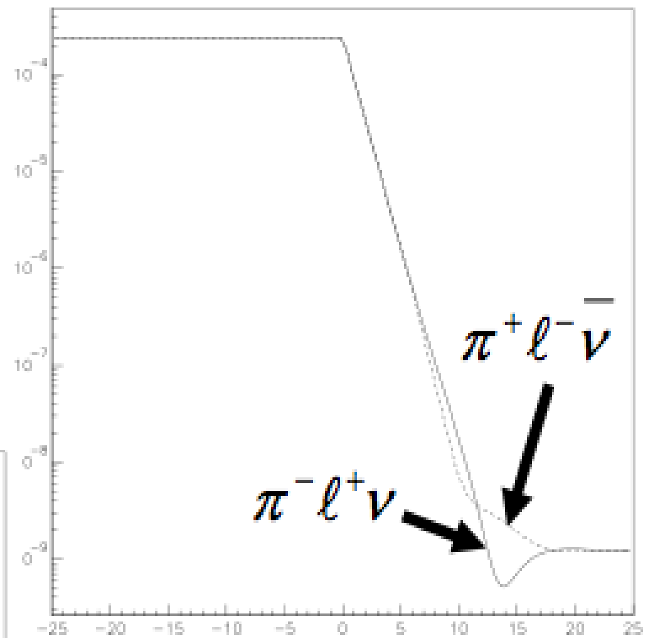
CPT

$$\phi \to K_S K_L \to \pi^+\ell^-\bar{\nu} \ \ \pi^-\ell^+\nu$$

$I(\Delta t)$ (a.u)



$I(\Delta t)$ (a.u)



$$\phi \to K_S K_L \to \pi\pi \ \ \pi\ell\nu$$

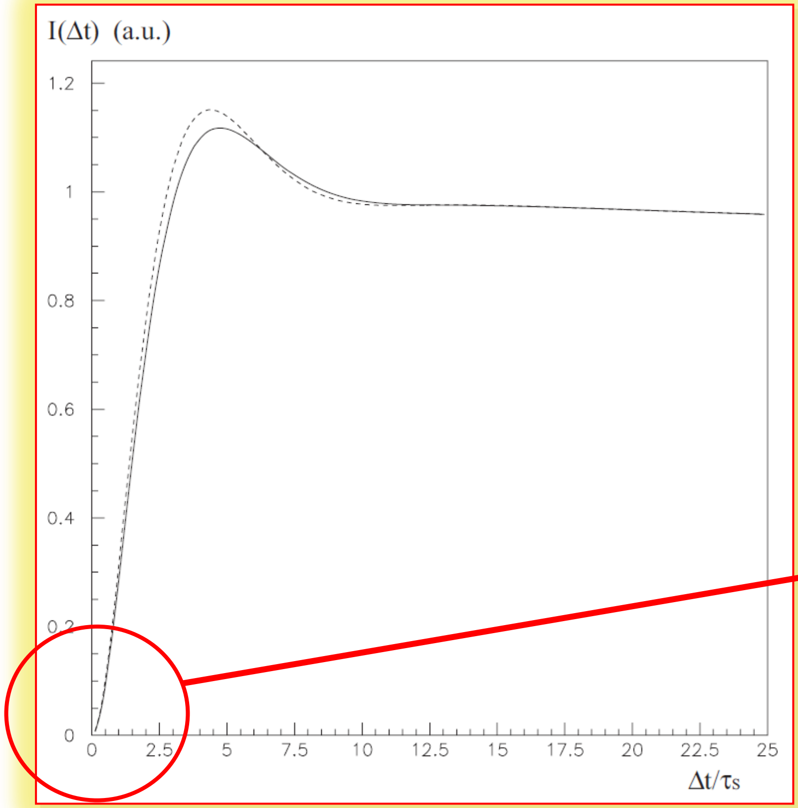
$$A_L = 2(\Re\varepsilon - \Re\delta - \Re y - \Re x_-)$$

$\varphi_{\pi\pi}$ **CP, CPT**

2) Search for decoherence and CPT violation in entangled neutral kaons

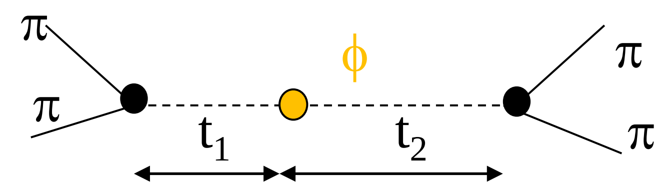
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \; \pi^+\pi^-$: the same final states

$$I(f_1 = f_2, \Delta t \geq 0) = I(f_1 = f_2, \Delta t \leq 0) = \\ = \frac{C_{12}|\eta|^2}{\Gamma_S + \Gamma_L}\left\{e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2e^{-\frac{\Gamma_S+\Gamma_L}{2}|\Delta t|}\cos(\Delta m|\Delta t|)\right\}$$



Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

$\Delta t = |t_1 - t_2|$



$I(\Delta t=0)=0$

EPR correlation:

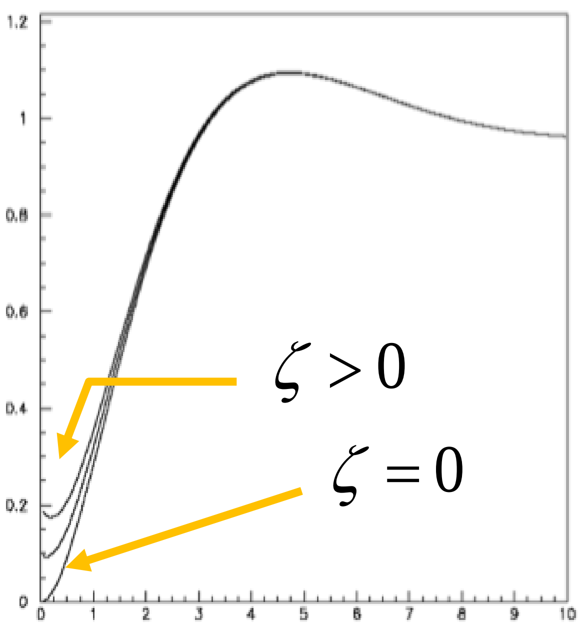
no simultaneous decays (Δt=0) in the same final state due to the destructive quantum interference

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

$$I(f_1 = f_2; |\Delta t|) = \frac{C_{12}|\eta|^2}{\Gamma_S + \Gamma_L}\left[e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2e^{-\frac{(\Gamma_S+\Gamma_L)}{2}|\Delta t|}\cos(\Delta m|\Delta t|)\right]$$

$$I(\pi^+\pi^-, \pi^+\pi^-; \Delta t) \propto e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2(1 - \zeta_{SL})e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t}\cos(\Delta m|\Delta t|)$$

I(Δt) (a.u.)



$\Delta t/\tau_S$

Decoherence parameter:

$\zeta = 0 \quad \to \quad$ QM

$\zeta = 1 \quad \to \quad$ total decoherence

The decoherence parameter measures the amount of deviation from the predictions of quantum mechanics.

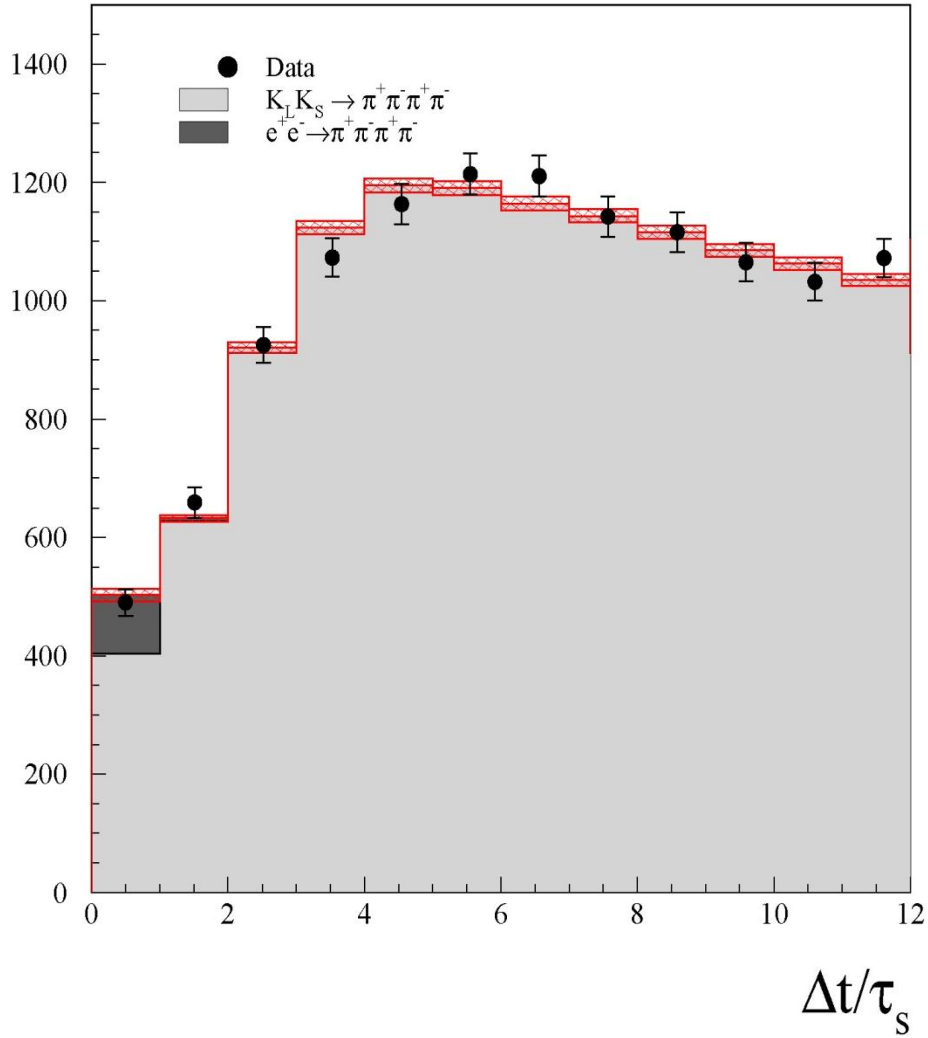
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: test of quantum coherence

- Analysed data: L=1.5 fb^{-1}
- Fit of $I(\pi^+\pi^-, \pi^+\pi^-; \Delta t)$

PLB 642(2006) 315

KLOE result: J.Phys.Conf.Ser.171:012008,2009

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



- From CPLEAR data (PR D60 (1999) 114032):

$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$

- In the B-meson system, BELLE coll. obtains (PRL 99 (2007) 131802) :

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

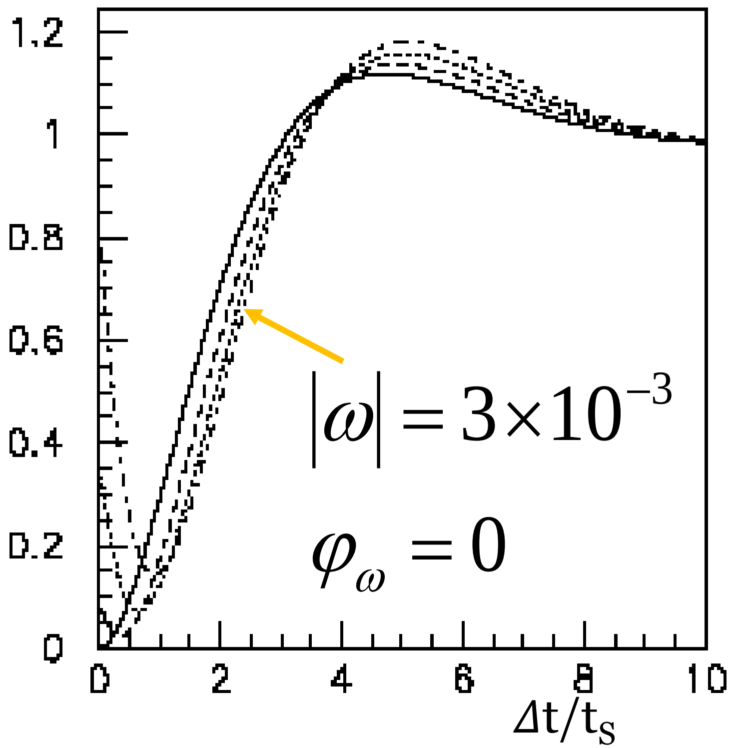
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: CPT violation in entangled K states

- There are several hypothesis of possible CPT violation sources. One of them are quantum gravity effects that could induce loss of information about the initial state that is in striking conflict with quantum mechanics and its unitarity principle.
- It can be shown that this kind of decoherence necessarily implies CPT violation in the sense that the quantum mechanical operator generating CPT transformation cannot be consistently defined.
- This could affect the entanglement of the kaon pair. In fact the resulting loss of particle-antiparticle identity could induce a breakdown of the correlation of initial state imposed by Bose statistics (EPR correlations) to the kaon state.
- As a result the initial state gains also small symmetric term [Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180]:

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right] \longrightarrow \begin{aligned} |i\rangle &\propto \left(K^0\overline{K}^0 - K^0\overline{K}^0\right) + \omega\left(K^0\overline{K}^0 + K^0\overline{K}^0\right) \\ &\propto \left(K_S K_L - K_L K_S\right) + \omega\left(K_S K_S - K_L K_L\right) \end{aligned}$$

$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$: CPT violation in entangled K states

I($\pi^+ \pi^-$, $\pi^+ \pi^-$;Δt) (a.u.)



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

- One expects at most:

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

- In some microscopic models of space-time foam arising from non-critical string theory [Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014] :

$$|\omega| \sim 10^{-4} \div 10^{-5}$$

- The maximum sensitivity to ω is expected for $f_1=f_2= \pi^+ \pi^-$

$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$: CPT violation in entangled K states

- Analysed data: 1.5 fb^{-1}
- Fit of $I(\pi^+\pi^-,\pi^+\pi^-;\Delta t,\omega)$

KLOE result: PLB 642(2006) 315
J.Phys.Conf.Ser.171:012008,2009

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

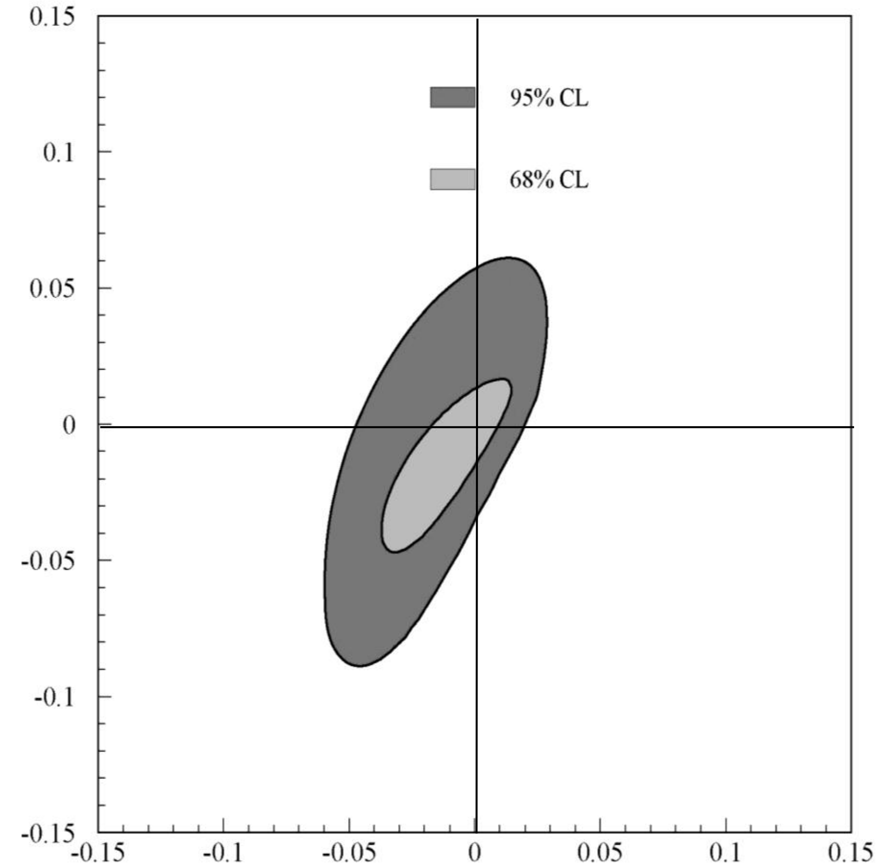
$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

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

- In the B system

[Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

$$-0.0084 \le \Re\omega \le 0.0100 \quad \text{at } 95\%\ \text{C.L.}$$

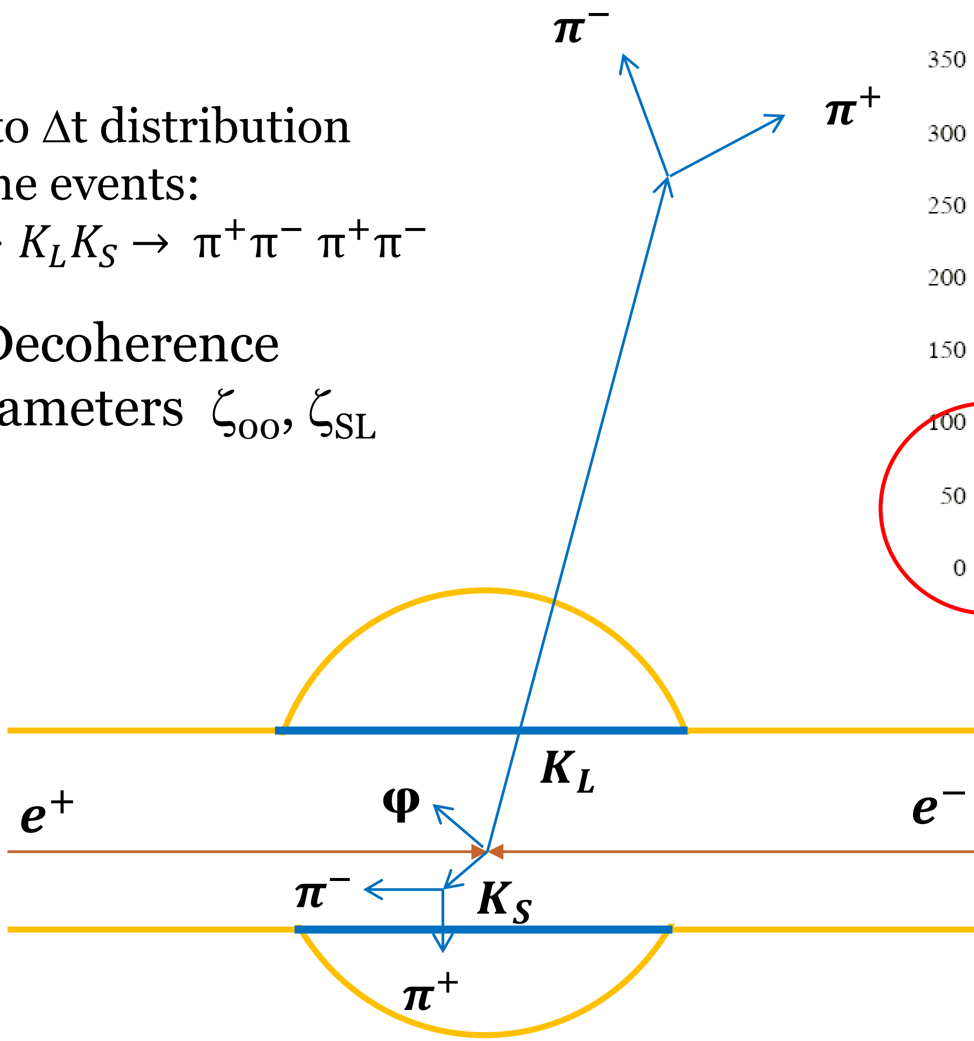


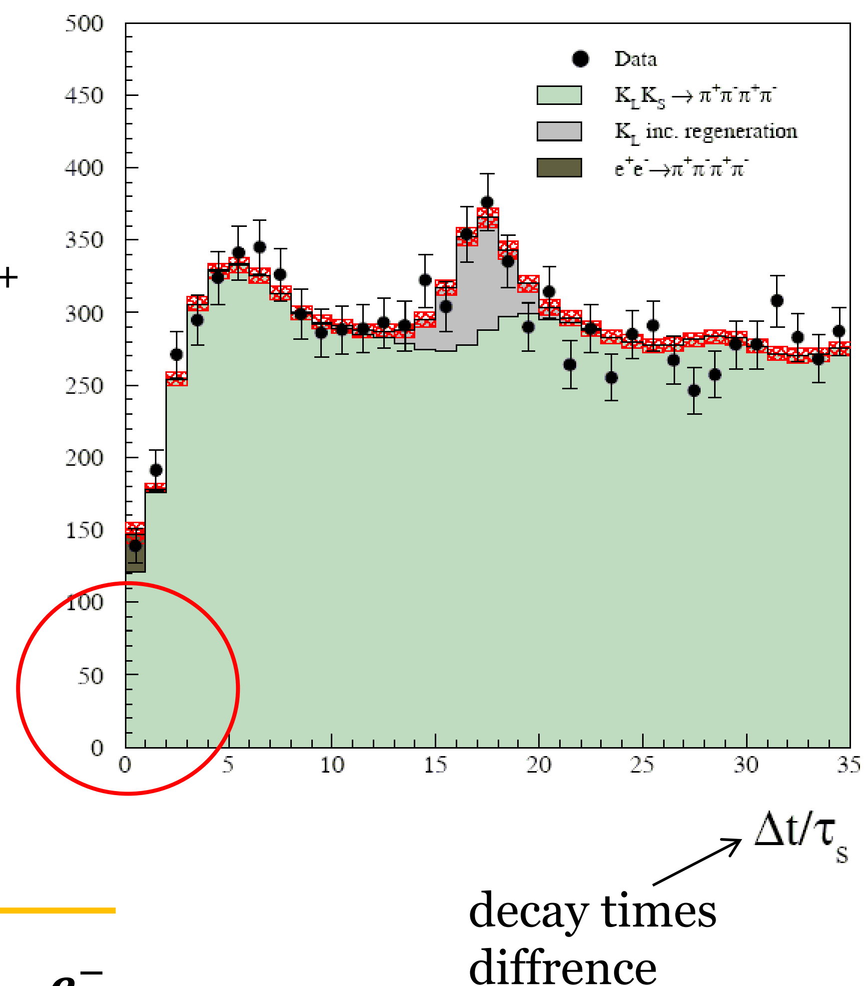
3) Studies of systematic effects - regeneration

Motivation for the regeneration studies

Fit to Δt distribution of the events:
$\varphi \rightarrow K_L K_S \rightarrow \pi^+\pi^- \pi^+\pi^-$

⇒ Decoherence parameters ζ_{00}, ζ_{SL}

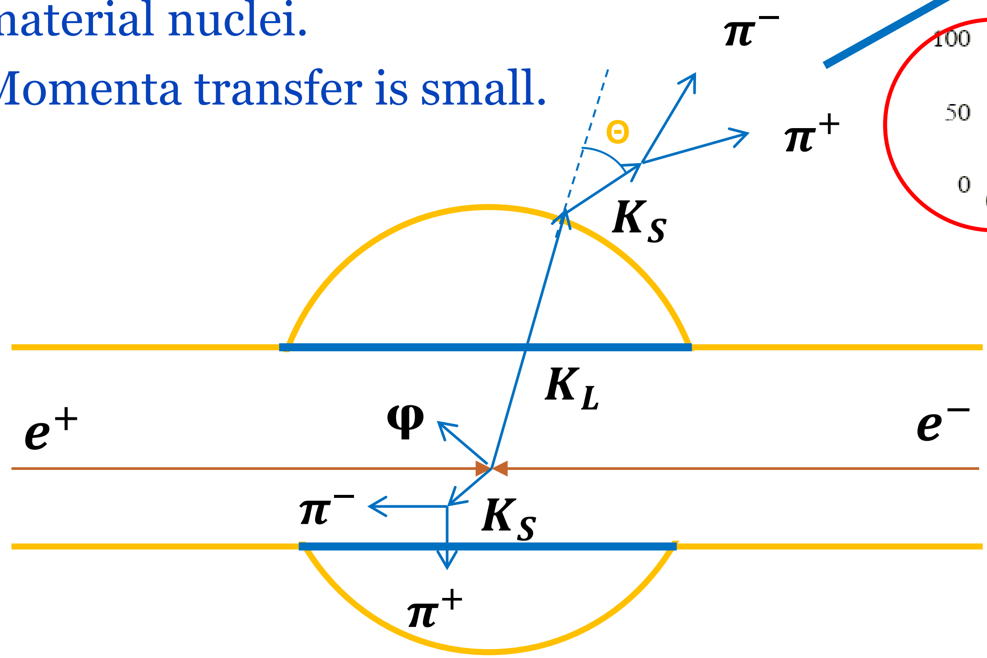


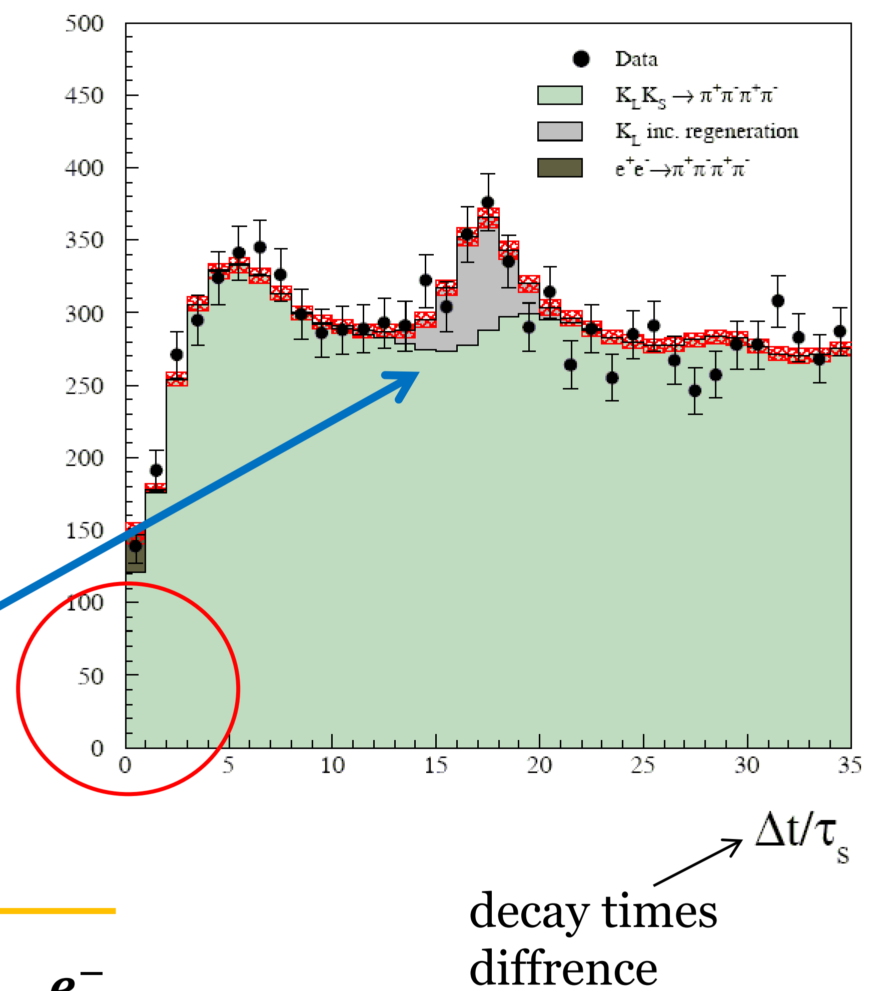


Motivation for the regeneration studies

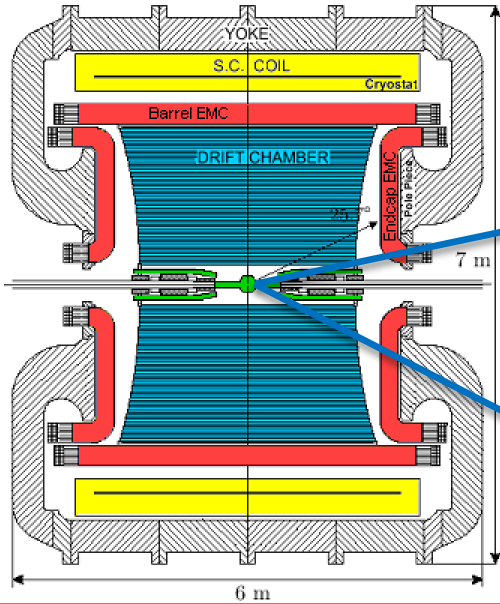
Incoherent regeneration:

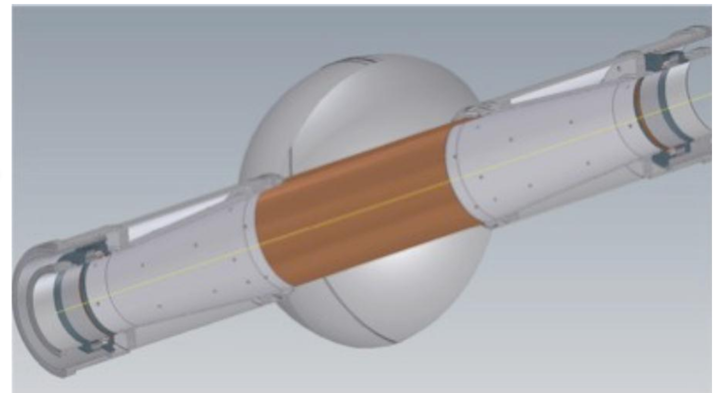
- K_L changes into K_S
- Particle direction changes under **θ angle**.
- It is elastic scattering on material nuclei.
- Momenta transfer is small.

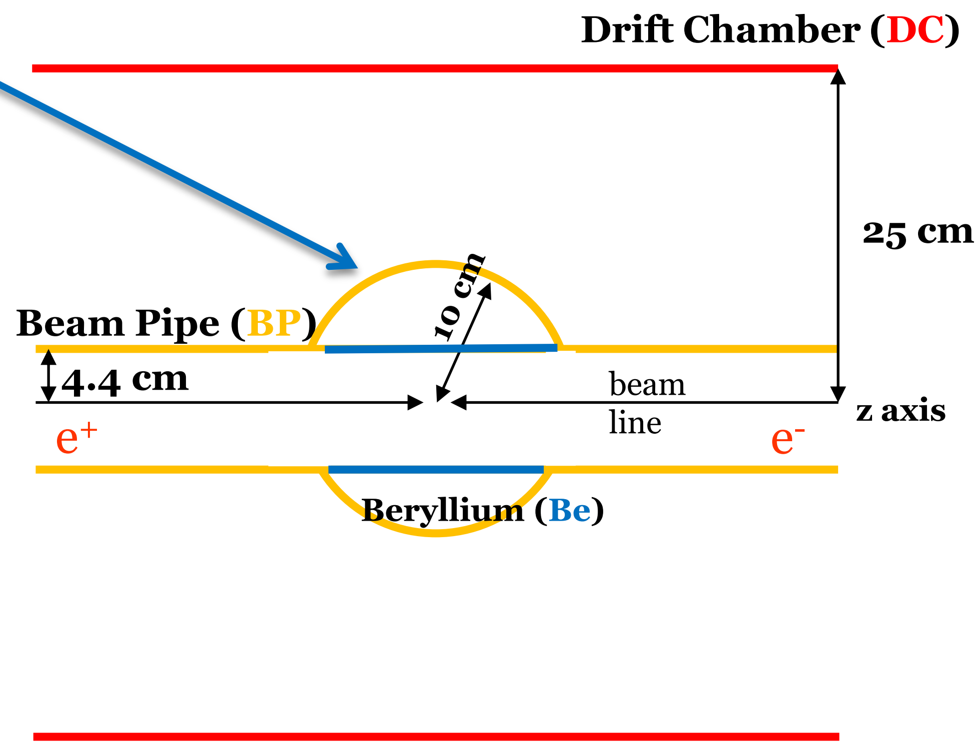




Regenerators at KLOE





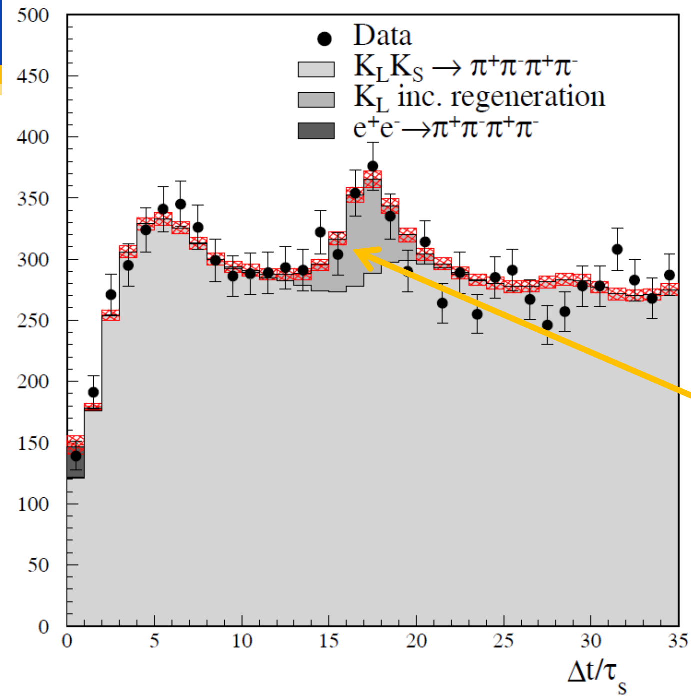


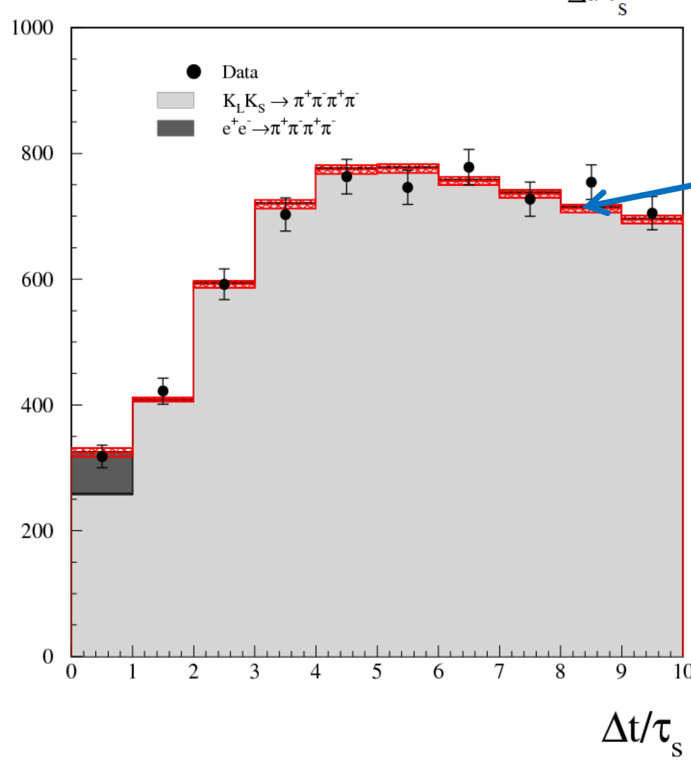
- **DC** **cylinder**-shape, 25 cm radius
  - 750 μm of C
  - 150 μm of Al
- **BP** **sphere**-shape, 10 cm radius
  - 62% Be
  - 38% Al

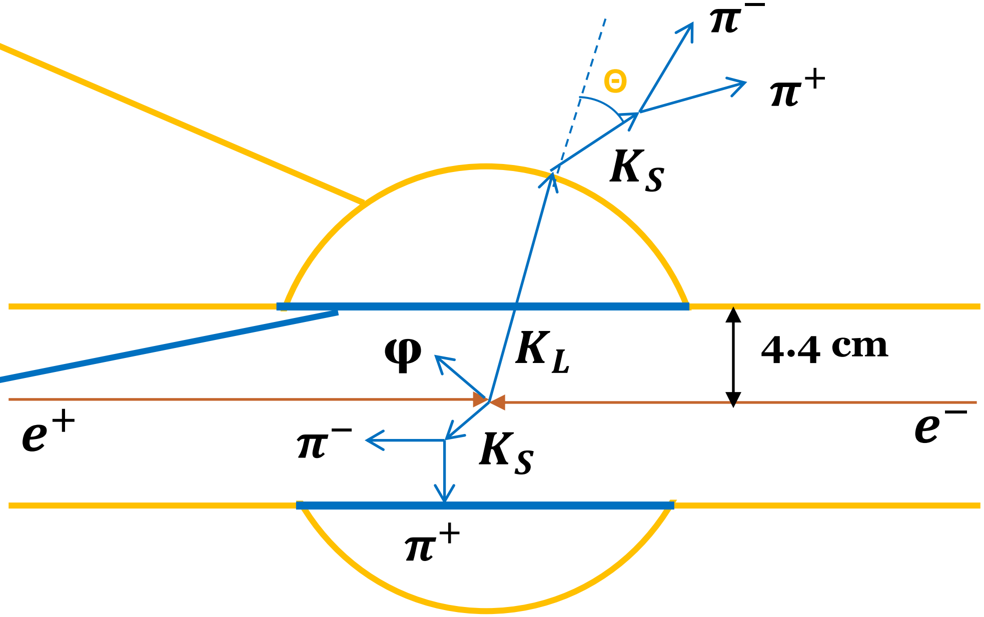
  thickness: 500 μm
- **Be** **cylinder**-shape

	OLD	**NEW**
thickness:	60 μm	30 μm
radius:	4.4 cm	3.7 cm

K_S regeneration at KLOE







KLOE 2004-2005 data

Fit to Δt distribution of the events $\varphi \to K_L K_S \to \pi^+\pi^-\ \pi^+\pi^-$

Experimental and theoretical cross-section situation

K_L momentum at KLOE: 110MeV/c

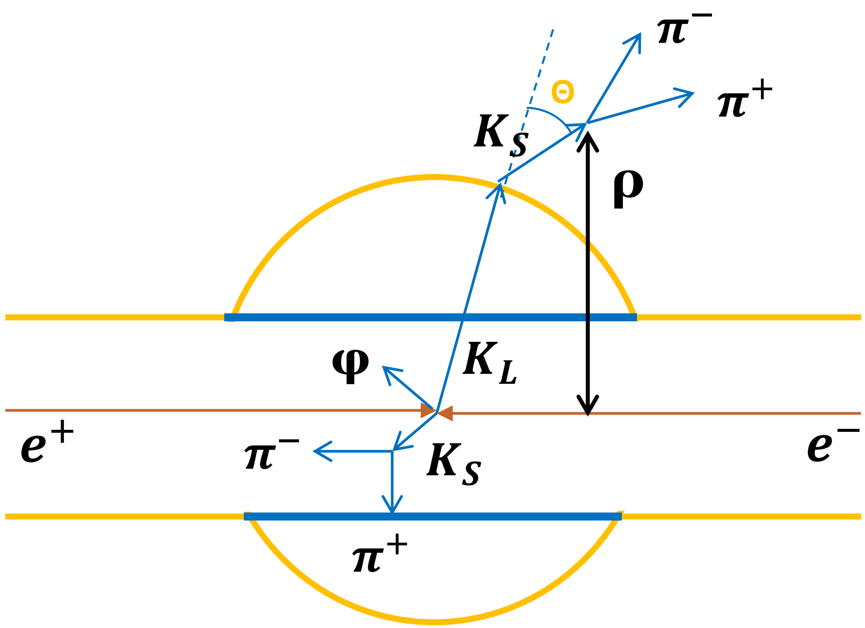
Theoretical evaluations by R. Baldini and A. Michetti ('96):

$$\sigma_{\text{reg}}^{\text{Be}} = 40.7 \pm 1.1\,\text{mbarn}$$

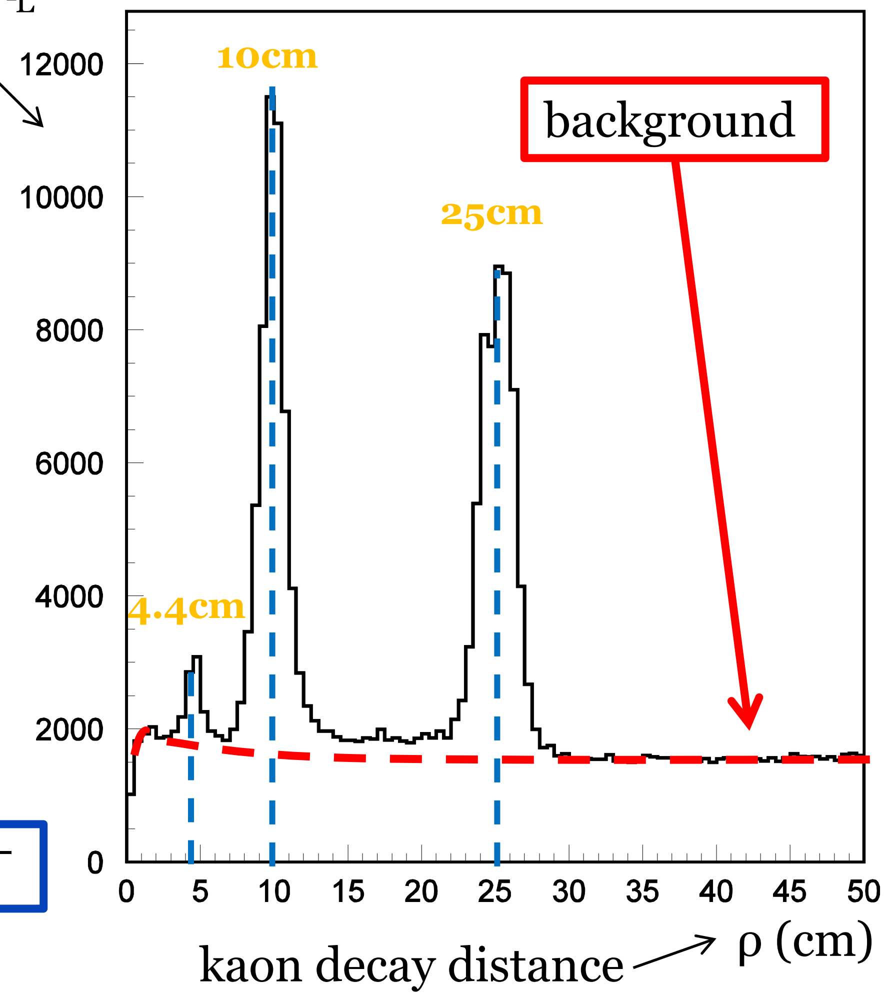
Novosibirsk CMD-2 result ('99) - only existing measurement at this momentum value:

$$\sigma_{\text{reg}}^{\text{Be}} = 55.1 \pm 7.7\,\text{mbarn}$$

How to calculate the regeneration cross section?



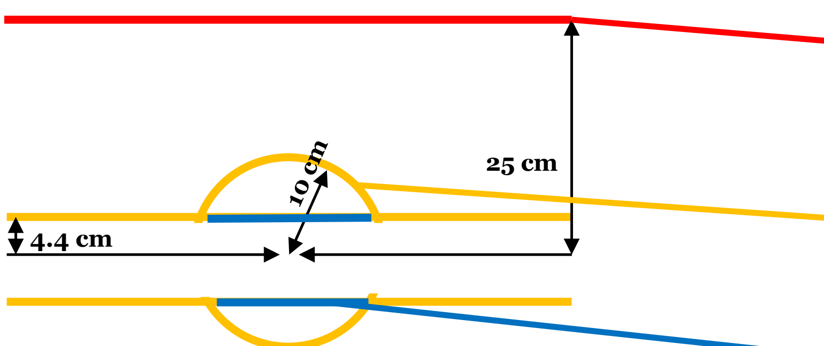
number of registered decays of K_L

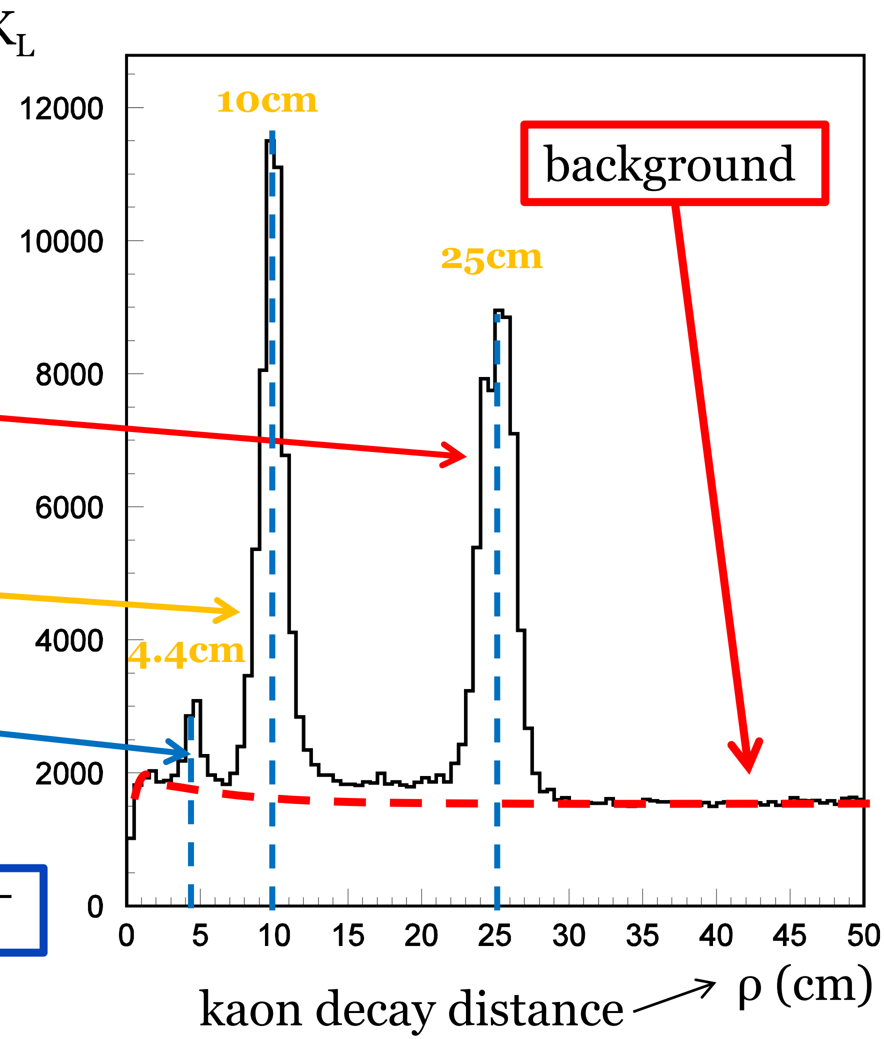


$$e^+ e^- \to \varphi \to K_L K_S \to K_S^{reg}\, \pi^+\pi^- \to \pi^+\pi^-\pi^+\pi^-$$

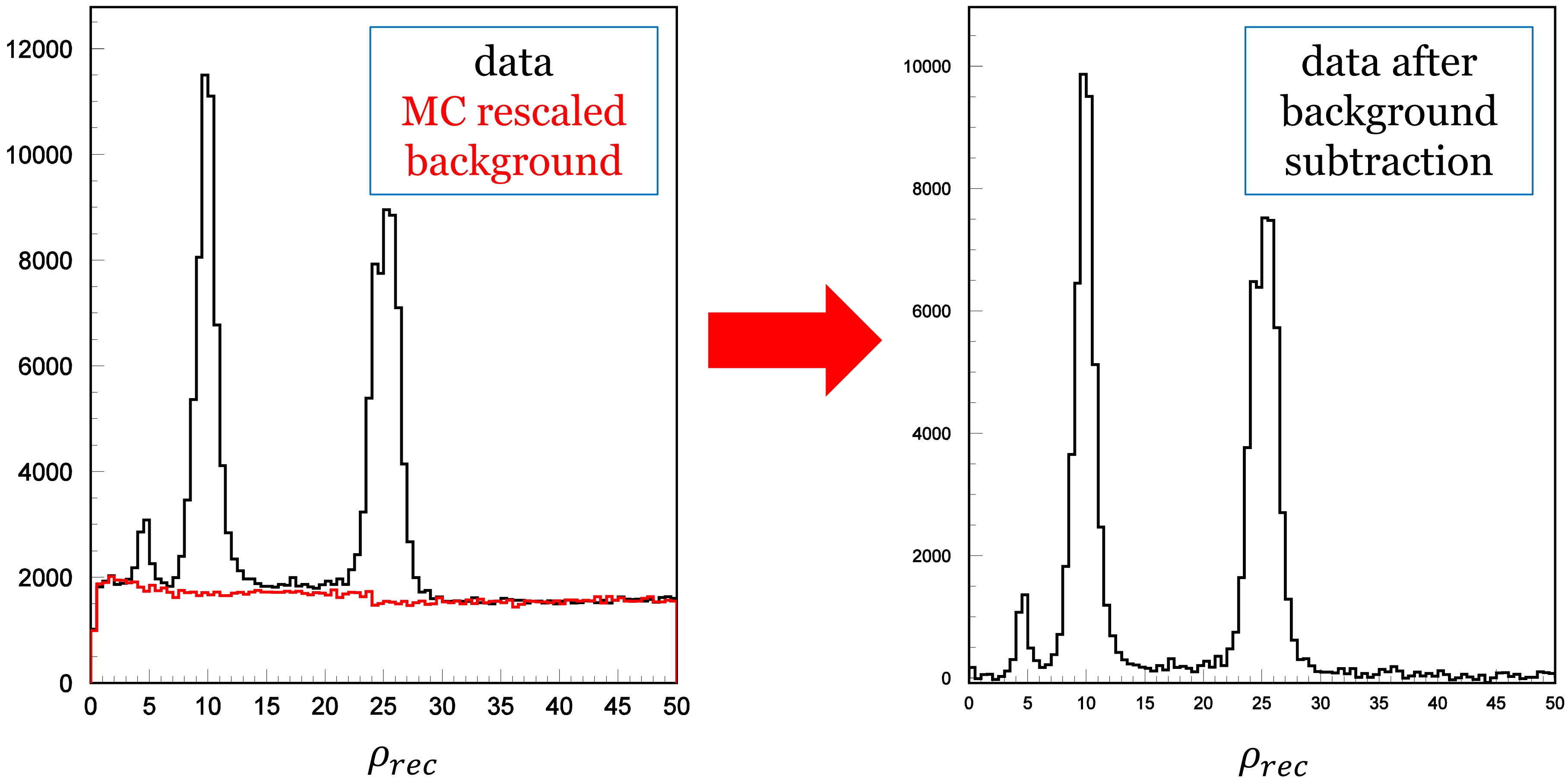
How to calculate the regeneration cross section?

$$P_{reg} = \frac{N_{reg}}{N_{K_L}}$$





$$e^+ e^- \to \varphi \to K_L K_S \to K_S^{reg}\, \pi^+\pi^- \to \pi^+\pi^-\pi^+\pi^-$$


data
MC rescaled
background
12000
10000
8000
6000
4000
2000
0
0
5
10
15
20
25
30
35
40
45
50
ρ_{rec}
data after
background
subtraction
10000
8000
6000
4000
2000
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5
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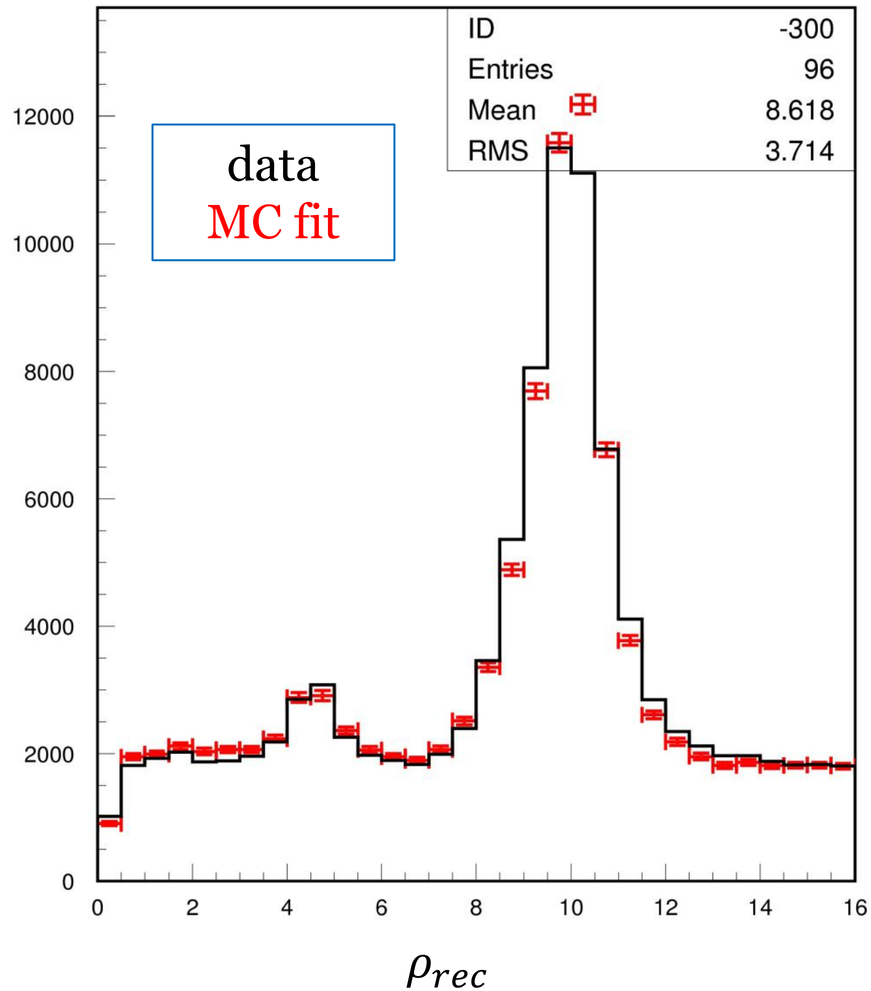
45
50
ρ_{rec}



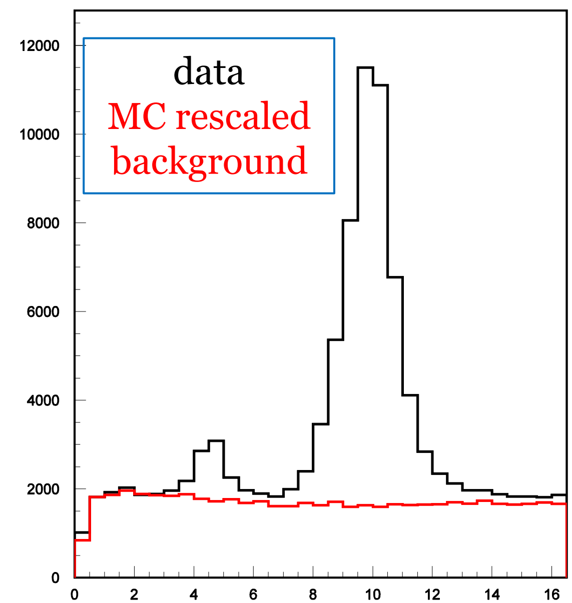
Transverse radius distribution fitting

fit to ρ∈(0;16)cm

⇒ fixed background shape (Ke3+ Ke3γ, Kμ3, CPV)

⇒ 2 scale factors: Be regen. & BP regen.

⇒ ratio between Be and BP regeneration



4) KLOE-2 plans

KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:

- new scheme of the interaction region (crabbed waist scheme) at DAΦNE
- increase L by a factor x 3 demonstrated by a successful experimental test

KLOE-2 Plan (approved and funded):
- extend the KLOE physics program at DAΦNE upgraded in luminosity
- collect ~5 fb–1 of integrated luminosity in the next 3-4 years

Physics program (see **EPJC 68 (2010) 619-681**)

- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K_S decays
- η,η' physics
- Light scalars, γγ physics
- Dark forces
- Hadronic cross section at low energy, muon anomaly ⇒ Caterina Bloise talk

Detector upgrade:

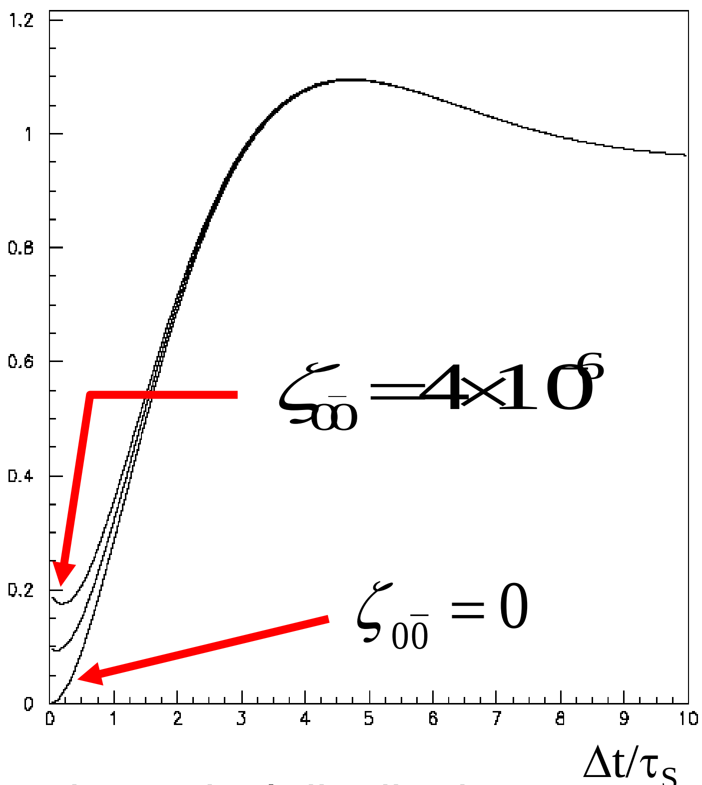
- γγ tagging system
- inner tracker

  ⇒ Erica De Lucia talk
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)

Interferometry at KLOE-2: $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

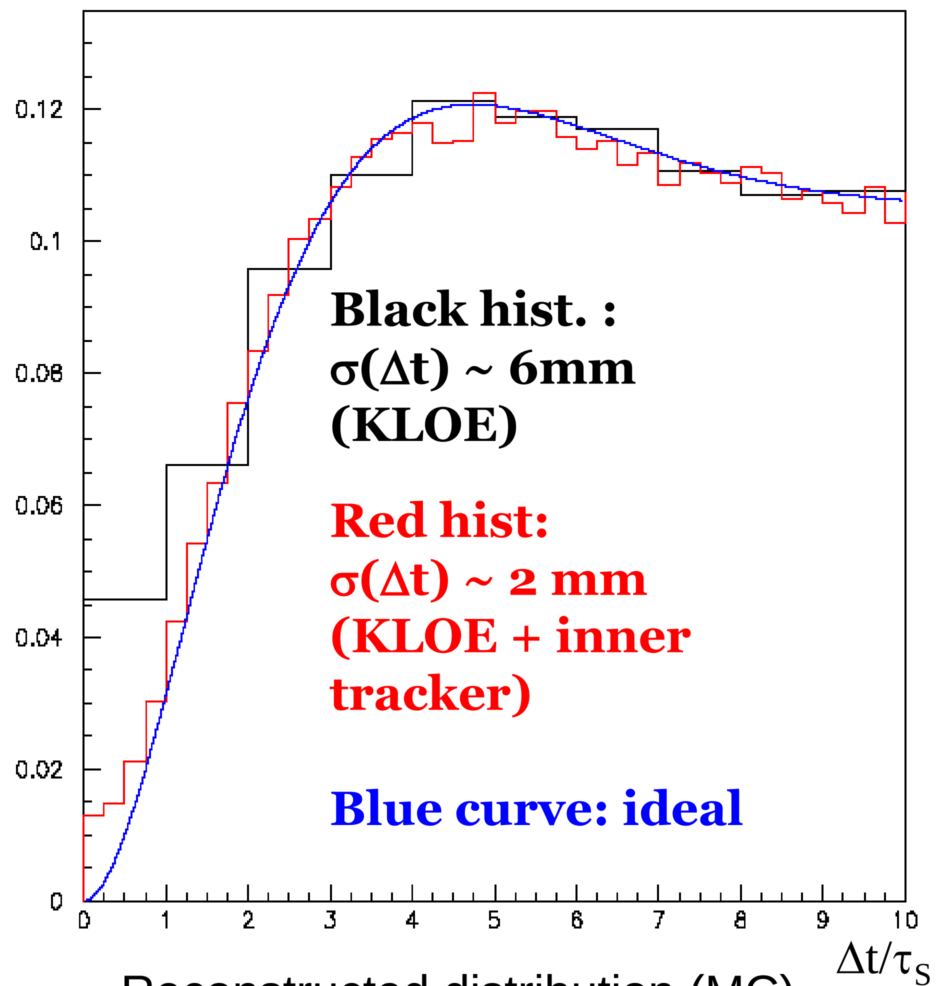
Possible signal of decoherence concentrated at very small Δt

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



Theoretical distribution

$I(\pi^+\pi^-, \pi^+\pi^-;\Delta t)$ (a.u.)



Reconstructed distribution (MC)

Summary

- The entangled neutral kaon system is an excellent laboratory for the study of CPT symmetry and the basic principles of Quantum Mechanics;

- Several parameters related to possible
  - decoherence
  - CPT violation (due to quantum gravity effects)

  have been measured at KLOE, in same cases with a precision reaching the interesting Planck's scale region;

- All results are consistent with no CPT violation and no decoherence.

- KLOE-2 at DAFNE upgraded in luminosity is going to start taking data;

- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program.


Thank you