Studies of the neutral kaon regeneration with the KLOE detector

Izabela Balwierz
Marian Smoluchowski Institute of Physics, Cracow, Poland

The KLOE detector at the DAΦNE collider

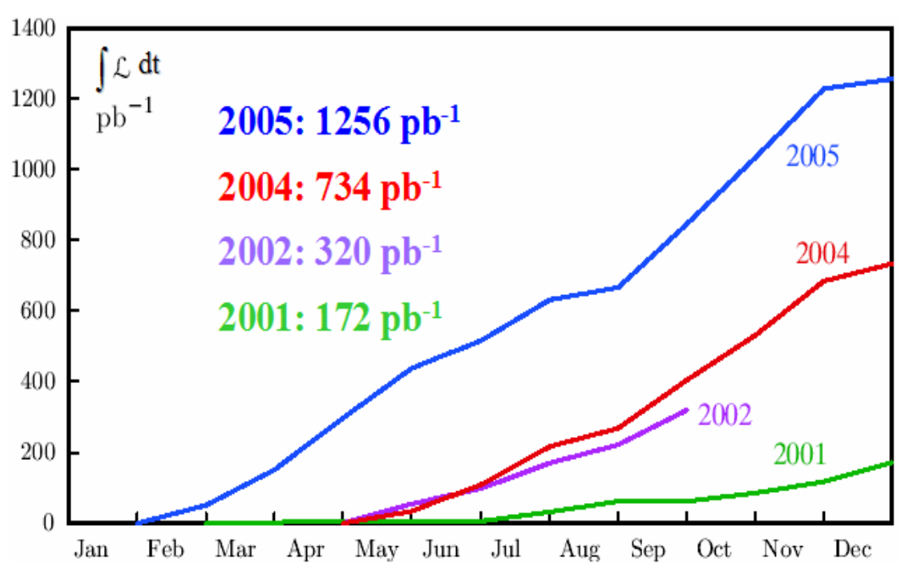

Fig. 1 KLOE integrated luminosity as a function of time

KLOE (**K** **LO**ng **E**xperiment) was located at the National Institute of Nuclear Physics (INFN) in Frascati near Rome. It was installed at the interaction point of the electron and positron beams of the DAΦNE (**D**ouble **A**nnular **Φ**-factory for **N**ice **E**xperiments) collider. KLOE started data taking in 1999 and concluded in 2006 with integrated luminosity of 2.5 fb^{-1} (Fig. 1), when the collider operated around the mass of the ϕ-meson equal to (1019.456±0.029) MeV.

The DAΦNE collider was a double-ring e^+e^- accelerator designed to obtain a peak luminosity of $\sim 5 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$. It consisted of three main components: a LINAC, an accumulation ring, and two collision rings (Fig. 2).

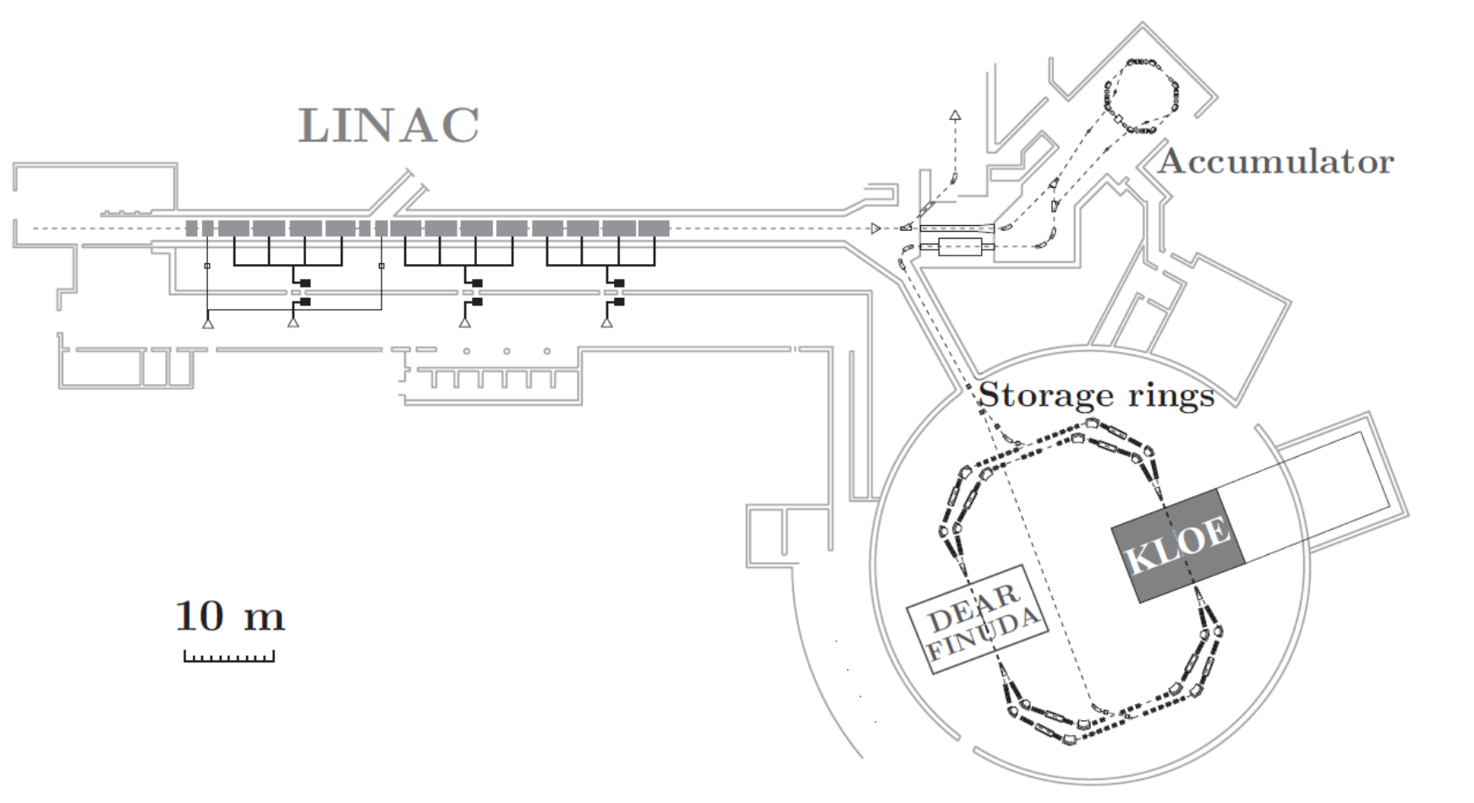

Fig. 2 The DAΦNE facility scheme.

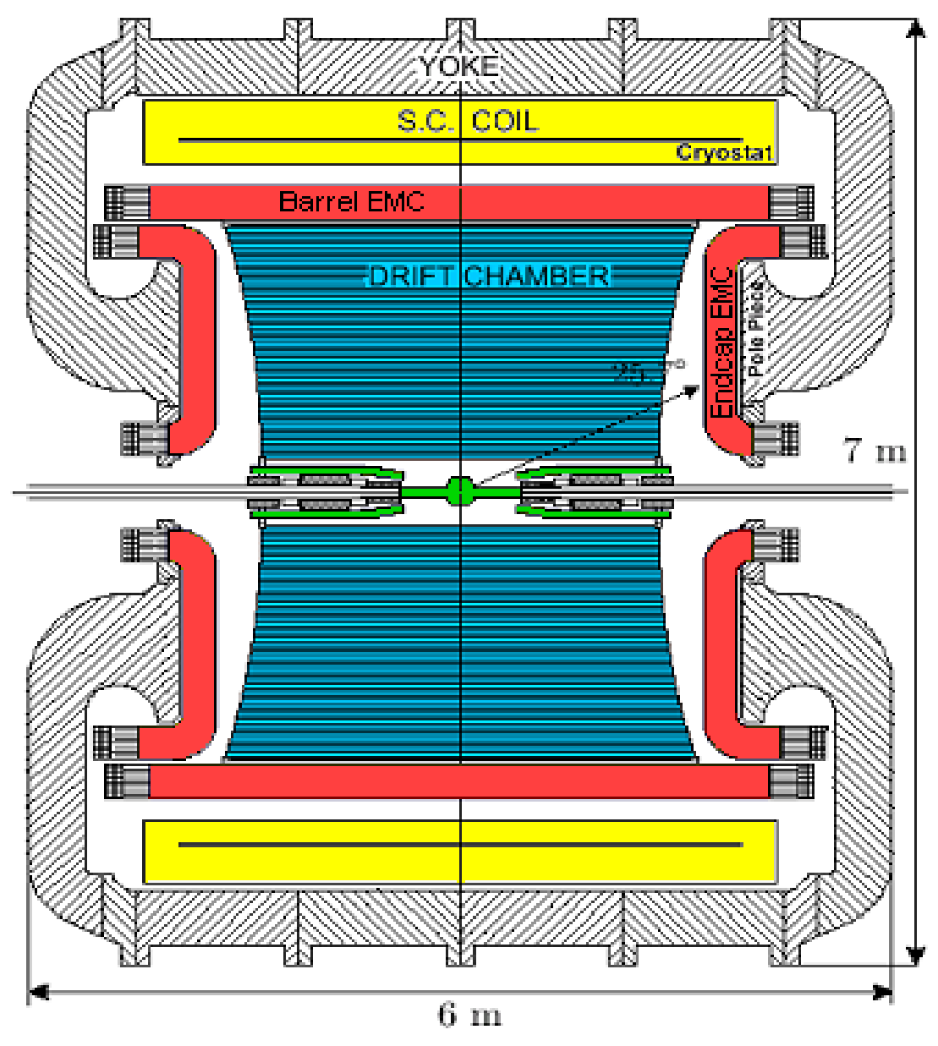

Fig. 3 Scheme of the KLOE detector.

The design of KLOE was driven by the intent of being a definitive high precision experiment for the K_L decays into charged and neutral particles, while the size was dictated by the mean decay length of the K_L meson ($\lambda_L \approx 3.4$ m).
The detector (Fig. 3) was composed of a cylindrical drift chamber (DC) (to register charged particles' tracks), surrounded by an a electromagnetic calorimeter (EmC) (to register particles' energies, times and positions), both inserted in a superconducting coil which produced an axial magnetic field of 0.52 T, parallel to the beam axis (to obtain particles' momenta).

$K_L \to K_S \to \pi^+\pi^-$ regeneration

One of the main sources of systematic errors in measurement of decoherence and *CPT*-violation parameters at KLOE is due to the poor knowledge of the incoherent regeneration in the KLOE cylindrical beam pipe made of beryllium (Fig. 6). In particular, for the measurement of the parameter *Im(ω)* this will be by far the dominant source of systematic uncertainty. This is due to the fact that when regeneration occurs, the K_L meson changes into the K_S meson that almost immediately decays into $\pi^+\pi^-$ ($K_L \to K_S \to \pi^+\pi^-$) and this disturbs the measurement $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ decays.

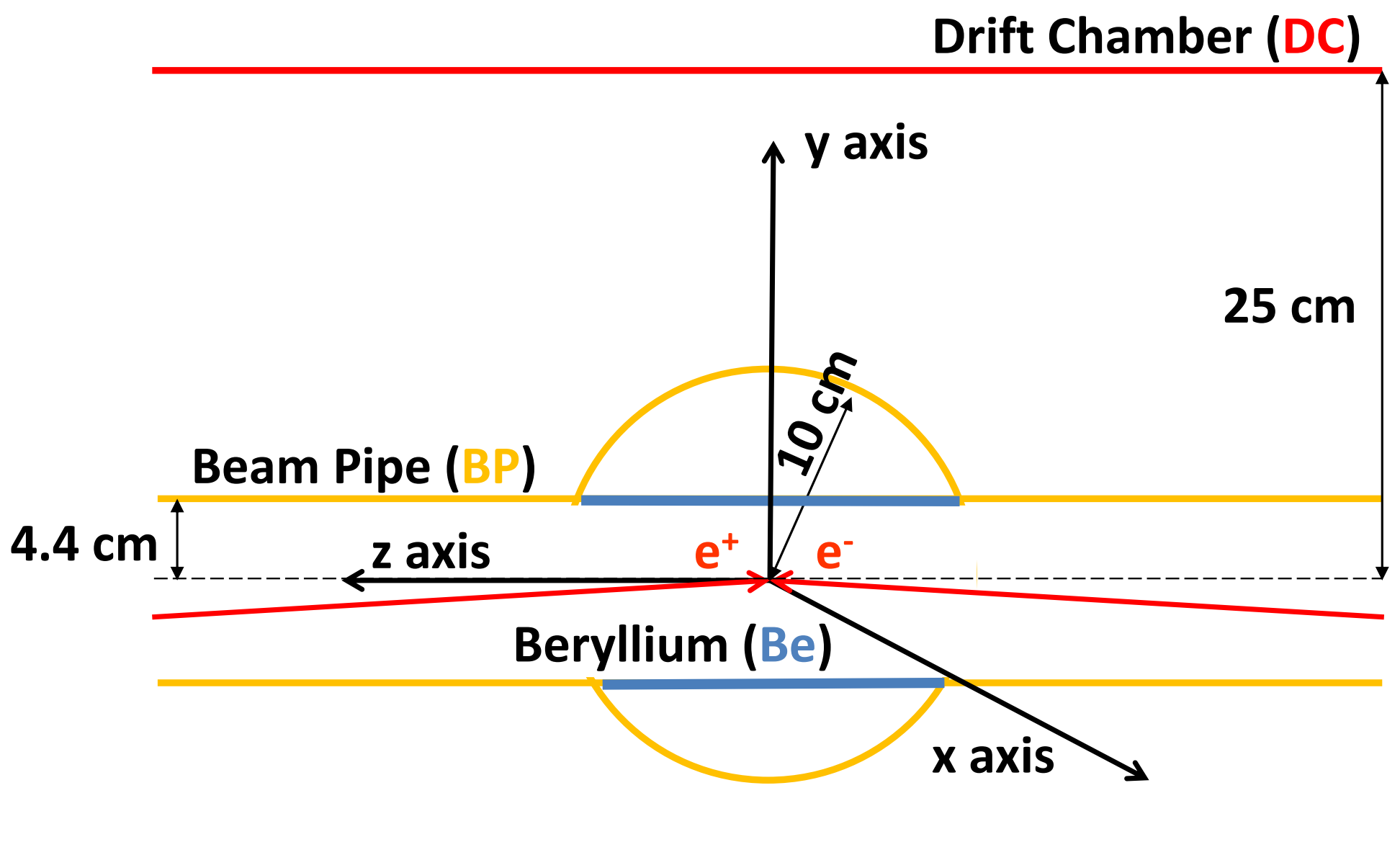

Fig. 6 Scheme of the regenerators' location at KLOE.

When long-lived neutral kaon is passing through material it undergoes repeated collisions with material nuclei. An incident pure K_L state is written in a form:

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

The two components K^0 and $\bar{K}^0$ are acting differently and the final state after scattering in the material reads:

$$|f\rangle = \frac{1}{2}[f(\theta) + \bar{f}(\theta)]|K_L\rangle + \frac{1}{2}[f(\theta) - \bar{f}(\theta)]|K_S\rangle,$$

where θ denotes the scattering angle and $f(\theta)$ the scattering amplitude for K^0 and $\bar{f}(\theta)$ for $\bar{K}^0$. This equation explicity shows that the emerging state containes a K_S component since $f(\theta) \neq \bar{f}(\theta)$.

The K_L mesons were produced in the center of the KLOE detector in the collision region of e^+ and e^- beams of the DAΦNE collider. The data sample comprising of $\sim 3.4 \cdot 10^8$ reconstructed neutral kaon pairs was used in this regeneration analysis. The K_L mesons were identified based on primary identification of the K_S meson decays into $\pi^+\pi^-$ close to the interaction point. This type of selection at KLOE is called tagging. After identification of K_S meson one searches for K_L that was produced with the opposite momentum vector in the ϕ rest frame (Fig. 7). The K_L decays are searched along the line of its supposed momentum, defined by the momentum of K_S and ϕ:

$$\vec{p}_{K_L^{tag}} = \vec{p}_\phi - \vec{p}_{K_S}$$

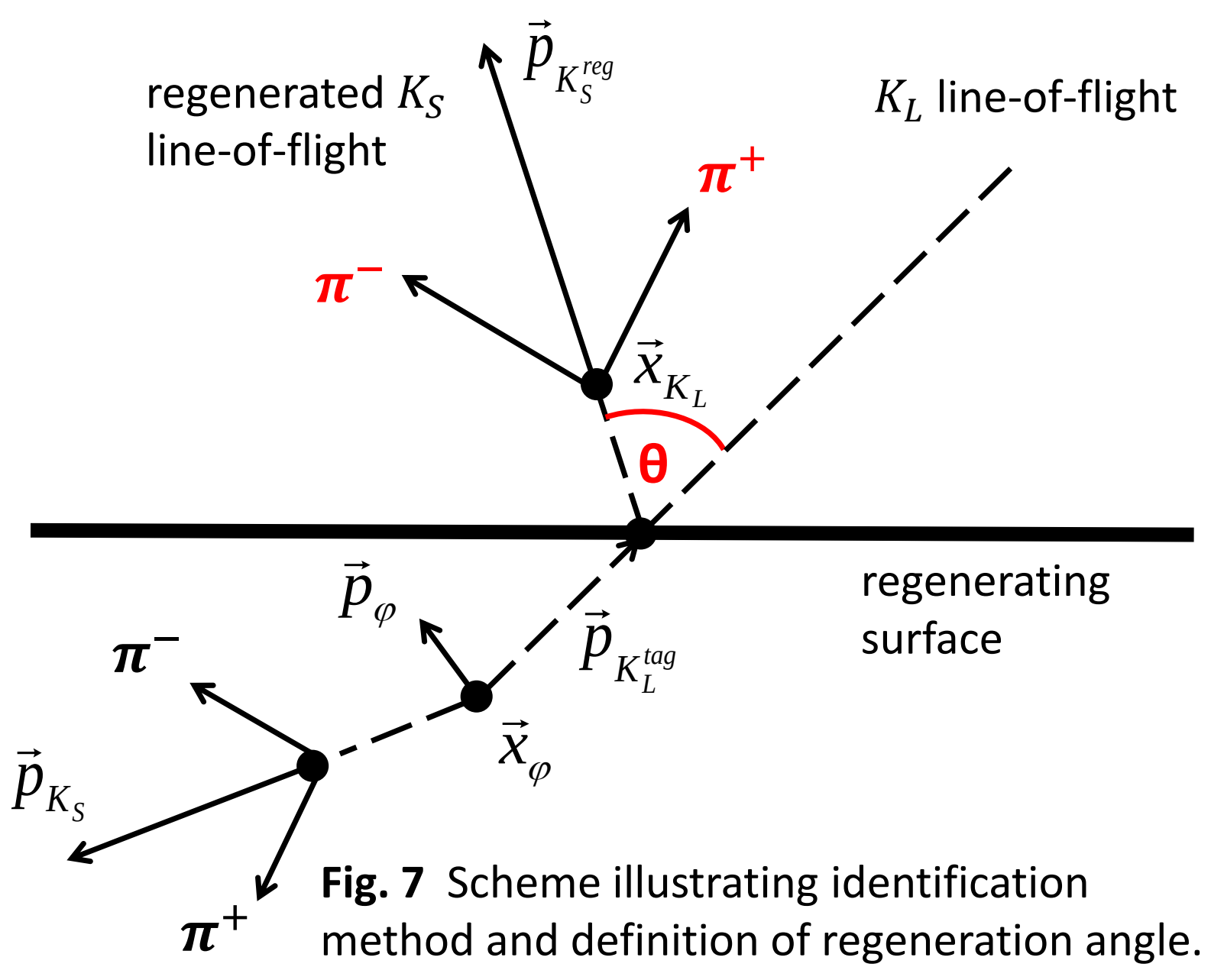

Fig. 7 Scheme illustrating identification method and definition of regeneration angle.

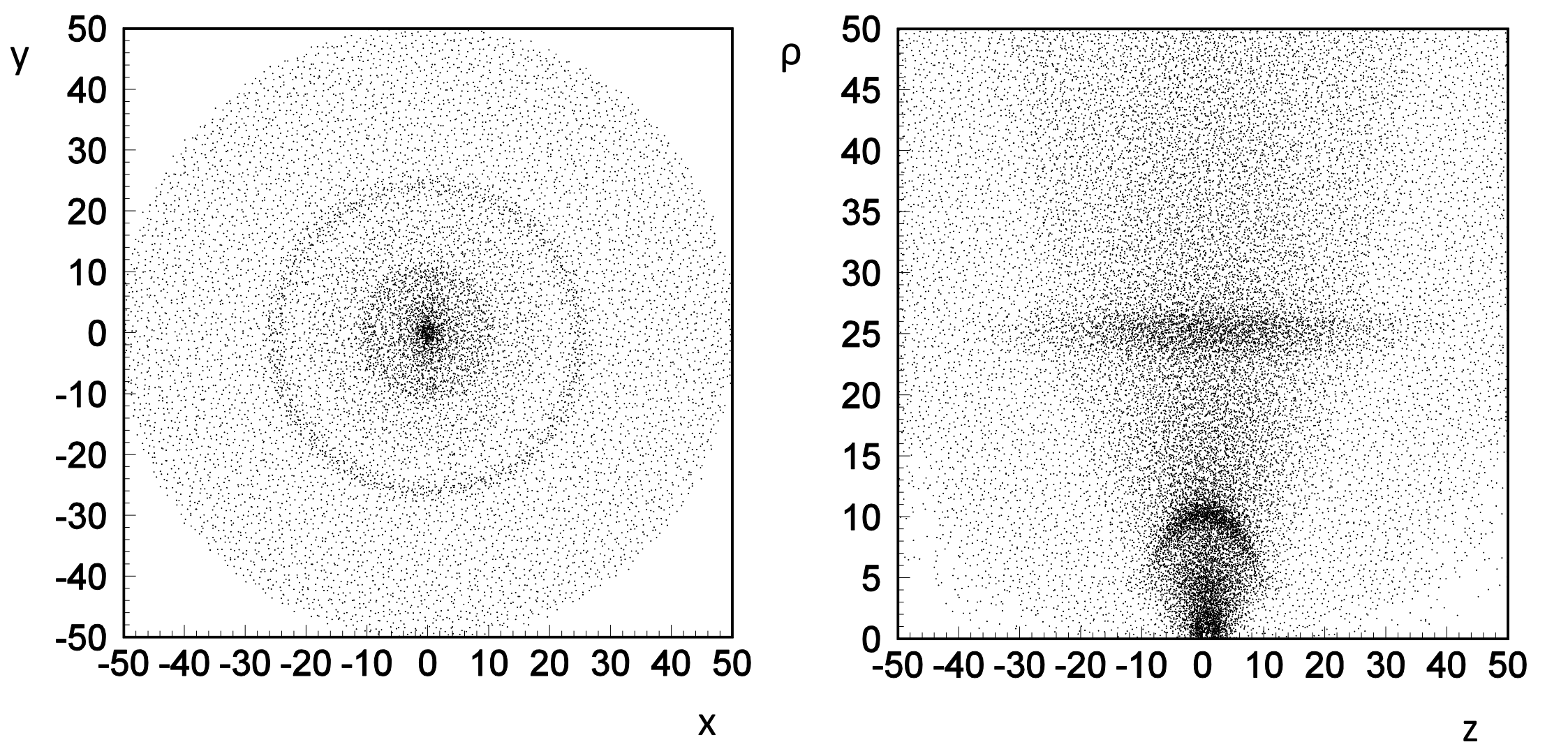

Fig. 8 Experimental spatial distributions of reconstructed K_L vertex in planes y-x and ρ-z, where ρ denotes cylindrical coordinate. The structure induced by the decay points of regenerated events is clearly visible. In the transverse (x-y) plane it is possible to see the cylindrical regenerators (Be and DC) as concentric rings with radii of 4.4 cm, 25 cm, respectively, and as a circle with radius of 10 cm, while in the polar plane (ρ-z) all the regenerators can be seen according to their geometry: lines for cylinders (Be and DC) and arcs for the spherical one (BP).

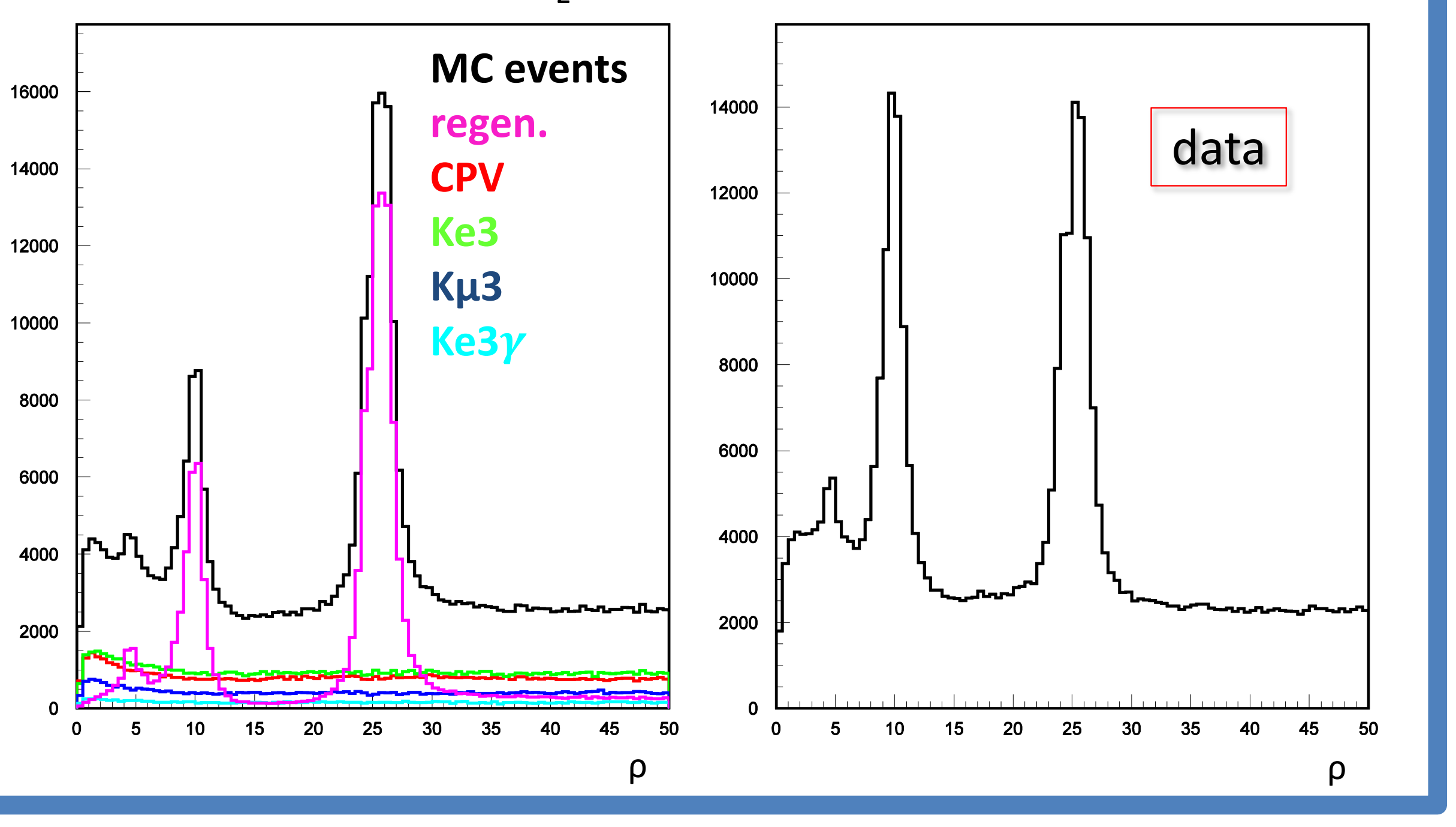

Fig. 9 Distributions of K_L decay distances in ρ coordinate after kinematic cuts. Experimental results are shown in the right panel and results of MonteCarlo simulations in the left panel. As the drift chamber inner wall and beryllium beam pipe are cylindrical, the regeneration in them is visible as symmetrical peaks. In MonteCarlo, regeneration as well as main background components originating from semileptonic and *CP*-violating events are shown. Absolute values of simulated contributions were adjusted according to the total luminosity and corresponding branching ratios.

The neutral kaon interferometry at KLOE

At KLOE, neutral kaons were produced in the decay of the ϕ meson. The simplest initial state of the two kaons, produced with momenta $+\vec{p}$ and $-\vec{p}$, can be expressed as [3]:

$$|i\rangle = 1/\sqrt{2}[|K^0(+\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(+\vec{p})\rangle|K^0(-\vec{p})\rangle].$$

The stranegness basis $\{|K^0\rangle, |\bar{K}^0\rangle\}$, suitable to describe kaons' production, can be changed to $\{|K_S\rangle, |K_L\rangle\}$ basis, appropriate to describe decays of kaons [3]:

$$|K_S\rangle = \frac{1}{\sqrt{2(1+|\varepsilon_S|^2)}}[(1+\varepsilon_S)|K^0\rangle + (1-\varepsilon_S)|\bar{K}^0\rangle],$$

$$|K_L\rangle = \frac{1}{\sqrt{2(1+|\varepsilon_L|^2)}}[(1+\varepsilon_L)|K^0\rangle - (1-\varepsilon_L)|\bar{K}^0\rangle].$$

where ε_S and ε_L are two small (of the order 10^{-3}) complex parameters describing the *CP* violation for K_S and K_L respectively. Then:

$$|i\rangle = N/\sqrt{2}\,[|K_S(+\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(+\vec{p})\rangle|K_S(-\vec{p})\rangle],$$

where $N = \sqrt{(1+|\varepsilon_S|^2)(1+|\varepsilon_L|^2)}/(1-\varepsilon_S\varepsilon_L) \approx 1$ is a normalization factor. Therefore, according to quantum mechanics, the double decay rate of the two kaons state into final states f_1 and f_1, $\phi \to K_S K_L \to f_1 f_2$, at kaons' proper decay time difference Δt, can be written as [3]:

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

where φ_1 and φ_2 are phases, Γ_1 and Γ_2 are decay widths, Δm is mass difference and:

$$C_{12} = \frac{|N|^2}{2}|\langle f_1|T|K_S\rangle\langle f_2|T|K_S\rangle|,\quad \eta_i = |\eta_i|e^{i\varphi_i} \equiv \frac{\langle f_i|T|K_L\rangle}{\langle f_i|T|K_S\rangle},$$

where *T* is the transition matrix whose explicit form is not needed here.

Search for decoherence and CPT violation in the process $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

If one now considers that both K_S and K_L decay into any identical final states $f_1 = f_2$, for example $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-$ which is *CP*-violating channel, one has that $\eta_1 = \eta_2 = \eta$ and $\varphi_1 = \varphi_2$. Hence, one obtains:

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

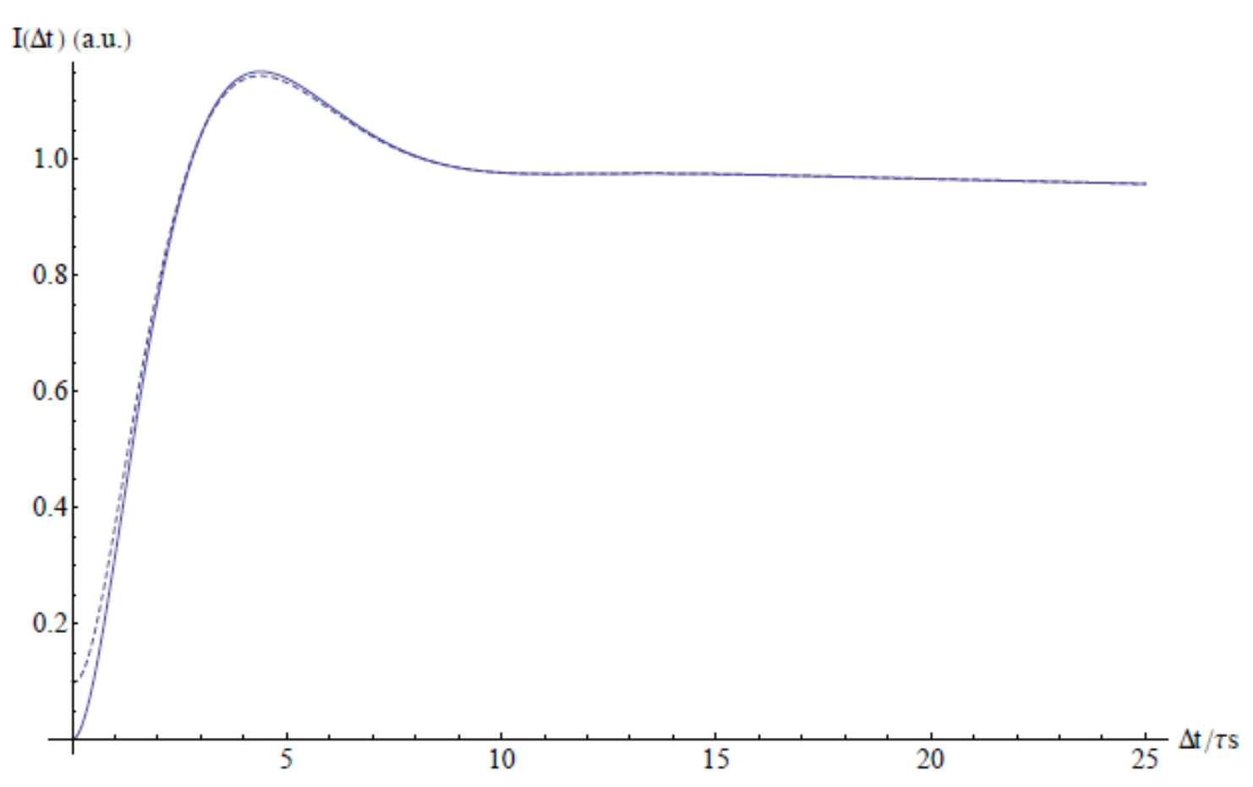

Fig. 4 Double decay rate as a function of Δt for $\zeta = 0$ (solid line) and $\zeta = 0.05$ (dashed line).

From the above equation results that two kaons cannot decay into the same final states at the same time, that is $\Delta t = 0$, since $I(f_1 = f_2, \Delta t = 0)$=0 (Fig. 4). What it really means is that, even though the two kaons are spatially separated, behaviour of one of them is dependent on what the other does. This counterintuitive correlation is of the type first pointed by *EPR* ans is called quantum entanglement.
Entanglement can be lost by decoherence that denotes the transition of a pure state into an incoherent mixture of states. The decoherence parameter ζ can be introduced by multiplying the interference term by factor (1-ζ):

$$I(f_1 = f_2, \Delta t) = \frac{C_{12}|\eta|^2}{\Gamma_S + \Gamma_L}[e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2(1-\xi) \cdot e^{-\frac{\Gamma_S+\Gamma_L}{2}|\Delta t|}\cos(\Delta m|\Delta t|)]$$

A value ζ=0 corresponds to the usual quantum mechanics case, while the ζ=1 is total decoherence.
Another phenomenological model introduces decoherence via a dissipative term *L(ρ)* in the Liouville–von Neumann equation for the density matrix of the state:

$$\dot{\rho}(t) = -iH\rho + i\rho H^+ + L(\rho)$$

Hawking suggested that at a microscopic level, in a quantum gravity picture, nontrivial space-time fluctuations could give rise to decoherence effects, which would necessarily entail a violation of CPT [2]. In the model of decoherence for neutral kaons one has 3 new CPTV paramameters α,β,γ:

$$L(\rho) = L(\rho; \alpha, \beta, \gamma)$$

In CPT violation induced by quantum gravity the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the *EPR* correlations to the kaon state:

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

The decoherence and CPT violation parameters have been measured at KLOE using interferometric methods by fitting the theoretical function to the distribution of the decay times (Δt) between *CP*-violating decays of K_L ($K_L \to \pi^+\pi^-$) and K_S decays into two charged pions in $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ reaction chain (Fig. 5). Current measurements show that there are no deviations from quantum mechanics [1, 2]:

$$\varsigma_{SL} = 0.018 \pm 0.040_{stat} \pm 0.007_{syst}$$

$$\varsigma_{0\bar{0}} = (1.0 \pm 2.1_{stat} \pm 0.4_{syst}) \cdot 10^{-6}$$

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

$$\gamma = (0.7 \pm 1.2_{stat} \pm 0.3_{syst}) \cdot 10^{-21}\, GeV$$

$$\text{Re}(\omega) = (-1.6^{+3.0}_{-2.1\,stat} \pm 0.4_{syst}) \cdot 10^{-4}$$

$$\text{Im}(\omega) = (-1.7^{+3.3}_{-3.0\,stat} \pm 1.2_{syst}) \cdot 10^{-4}$$

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

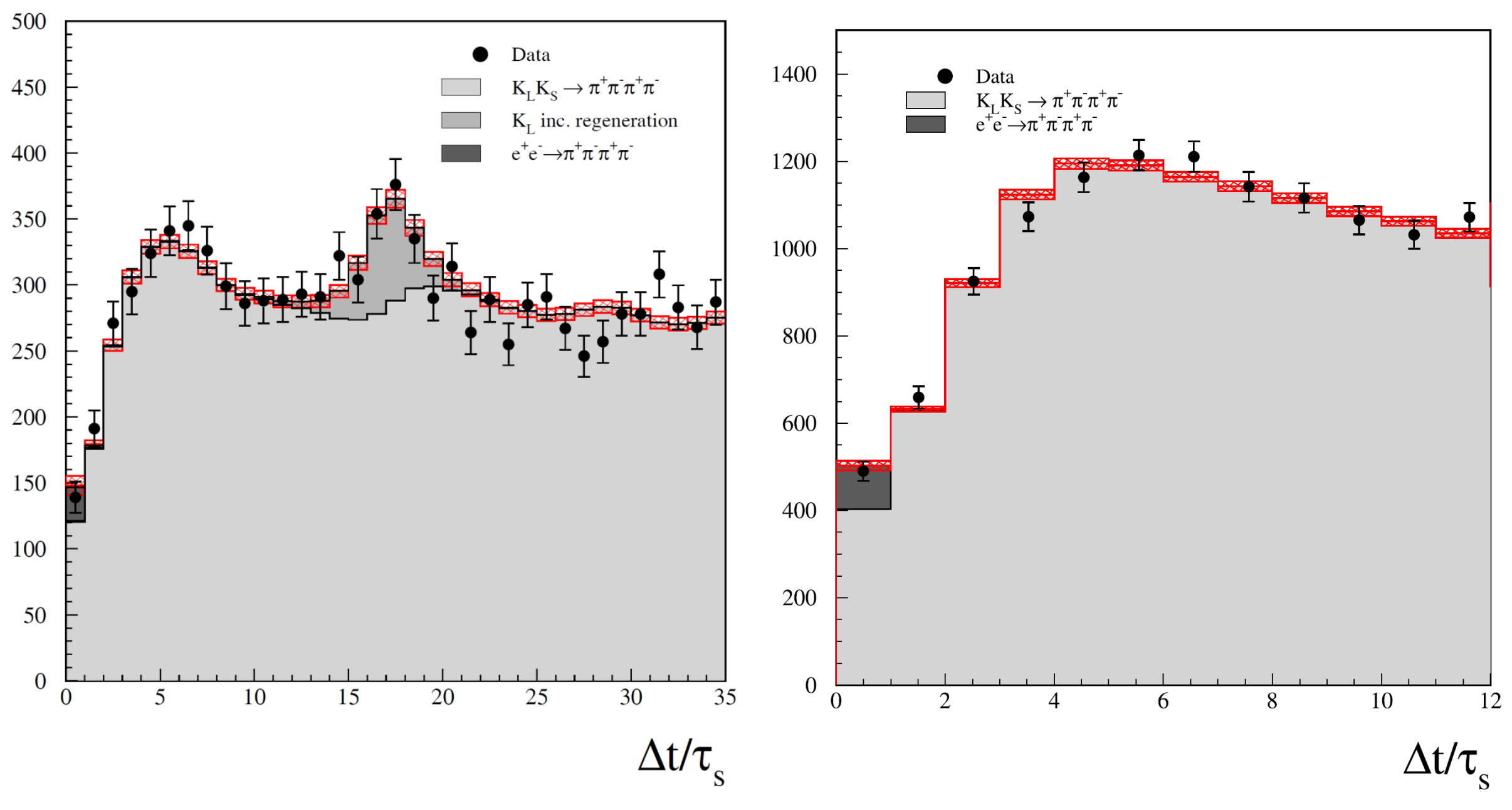

Fig. 5 Fit to Δt distributions of the events $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$. In the left panel the region from 0 to 35 life times of K_S is presented, whereas in the right panel the decoherence region is shown. The left figure is adapted from [1] and the right one from [2].

References

[1] F. Ambrosino et al. (KLOE Collaboration), *First observation of quantum interference in the process* $\boldsymbol{\varphi} \to \boldsymbol{K_S K_L \to \pi^+\pi^-\pi^+\pi^-}$ *: A test of quantum mechanics and CPT symmetry*, Physics Letters **B 642** (2006) 315-321

[2] A. Di Domenico (KLOE Collaboration), *CPT Symmetry and Quantum Mechanics Tests in the Neutral Kaon System at KLOE*, Foundations of Physics **40** (2010) 852-866

[3] A. Di Domenico*, Neutral kaon interferometry at a* $\boldsymbol{\varphi}$ *-factory*, Frascati Physics Series **43** (2007) 1-38