A novel neutral vertex reconstruction algorithm for regeneration events in the $\mathrm{K_S K_L} \to \pi^+\pi^-\pi^0\pi^0$ channel

Aleksander Gajos

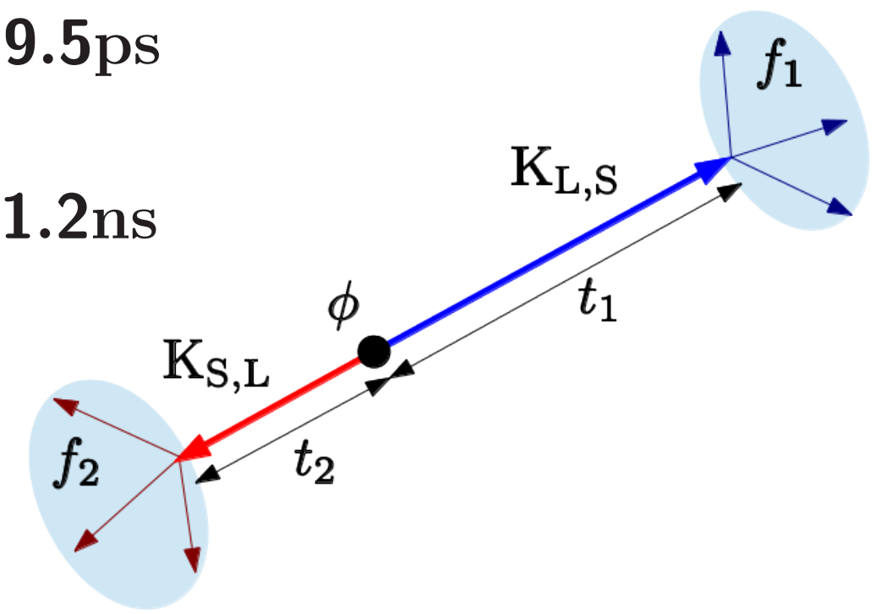
Jagiellonian University, Cracow, Poland
LNF-INFN, Frascati, Italy

Neutral kaon interferometry

Entangled kaons

$$|\mathrm{K_S}\rangle = \frac{1}{\sqrt{2(1+|\epsilon_S|^2)}}\left((1+\epsilon_S)\left|\mathrm{K}^0\right\rangle + (1-\epsilon_S)\left|\overline{\mathrm{K}}^0\right\rangle\right), \quad \tau_S \approx 89.5\mathrm{ps}$$

$$|\mathrm{K_L}\rangle = \frac{1}{\sqrt{2(1+|\epsilon_L|^2)}}\left((1+\epsilon_L)\left|\mathrm{K}^0\right\rangle - (1-\epsilon_L)\left|\overline{\mathrm{K}}^0\right\rangle\right), \quad \tau_L \approx 51.2\mathrm{ns}$$



Neutral kaon pairs produced in ϕ ($J^{PC} = 1^{--}$) decays are in an entangled state:

$$|i\rangle = \frac{\mathcal{N}}{\sqrt{2}}\left(|\mathrm{K_S}(+\vec{p})\rangle\,|\mathrm{K_L}(-\vec{p})\rangle - |\mathrm{K_L}(+\vec{p})\rangle\,|\mathrm{K_S}(-\vec{p})\rangle\right)$$

Probability of decays into f_1, f_2 final states in times t_1 and t_2 involves the interference term.

$$I(f_1,t_1;f_2,t_2) = C_{12}\Big[|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2|\eta_1||\eta_2| e^{\frac{\Gamma_S+\Gamma_L}{2}(t_1+t_2)} \cos(\Delta m(t_1-t_2) + \varphi_2 - \varphi_1)\Big]$$

The $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^0\pi^0$ process

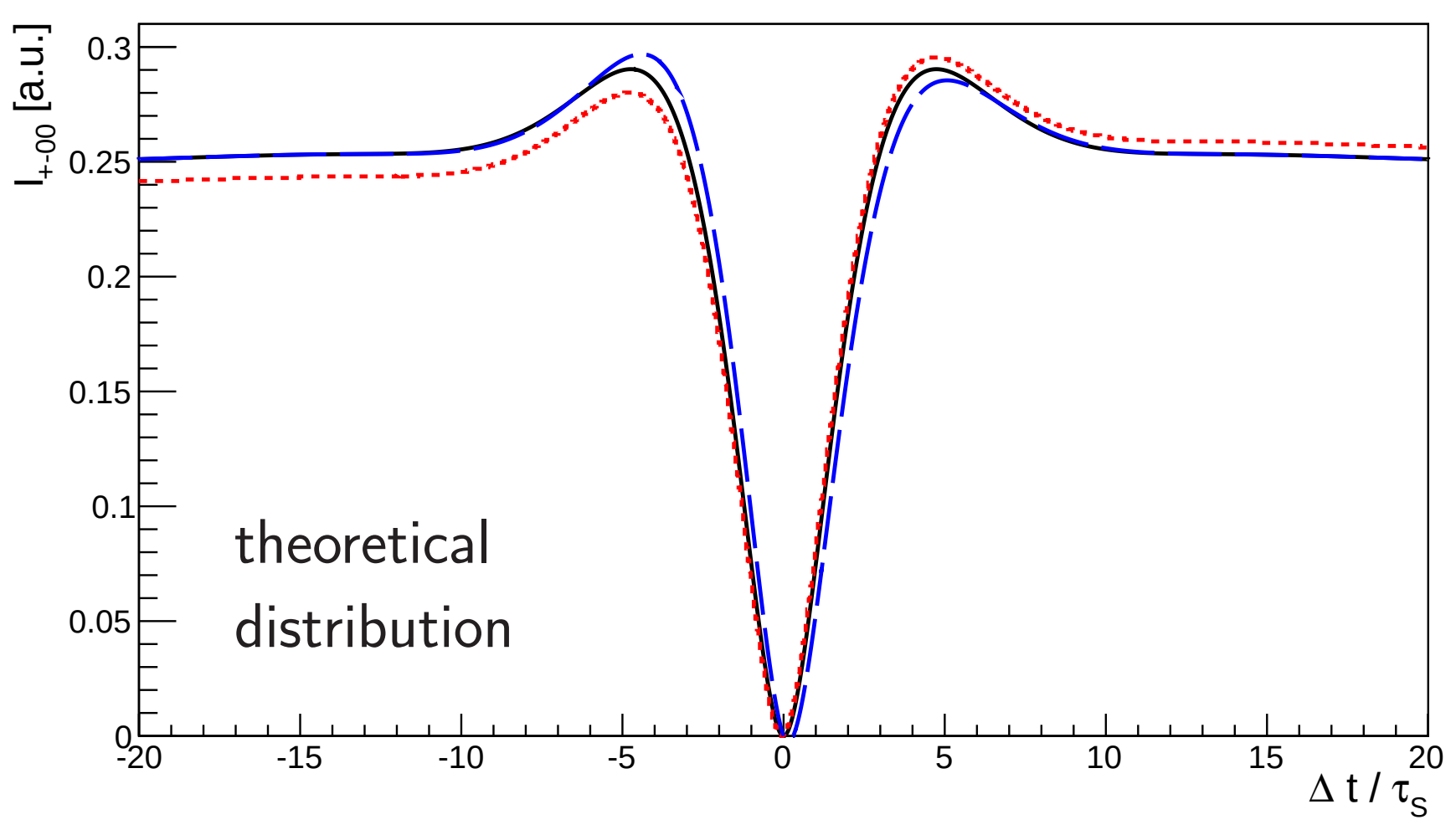
The probability distribution of the two neutral kaons decaying into final states $f_1 = \pi^+\pi^-$ and $f_2 = \pi^0\pi^0$ in times differing by $\Delta t = t_1 - t_2$ is asymmetric around $\Delta t = 0$ if the $\mathcal{CP}$ symmetry is violated.
$\mathcal{CP}$ symmetry violation is indicated by a nonzero value of the $\frac{\epsilon'}{\epsilon}$ parameter [1] whose real and imaginary parts can be simultaneously measured using the asymmetry function [2]:

$$A_{\epsilon'/\epsilon}(|\Delta t|) = \frac{I_{+-00}(\Delta t > 0) - I_{+-00}(\Delta t < 0)}{I_{+-00}(\Delta t > 0) + I_{+-00}(\Delta t < 0)} = A_R(|\Delta t|)\Re\left(\frac{\epsilon'}{\epsilon}\right) - A_L(|\Delta t|)\Im\left(\frac{\epsilon'}{\epsilon}\right)$$

This asymmetry of probability is sensitive to:

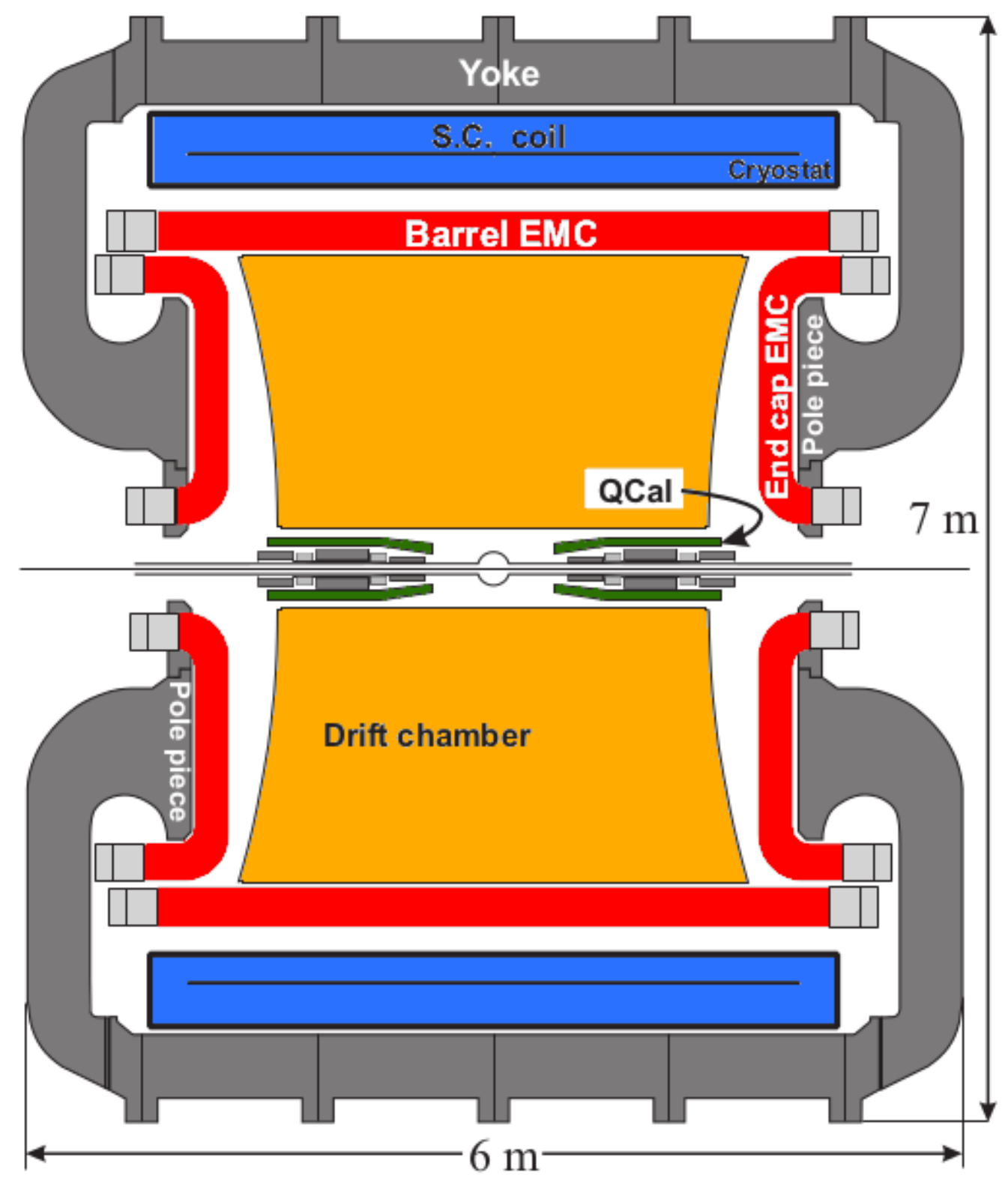
$\Im\left(\frac{\epsilon'}{\epsilon}\right)$ for $|\Delta t| < 5\tau_S$,

$\Re\left(\frac{\epsilon'}{\epsilon}\right)$ for $|\Delta t| \gg \tau_S$.



KLOE Experiment at DAΦNE

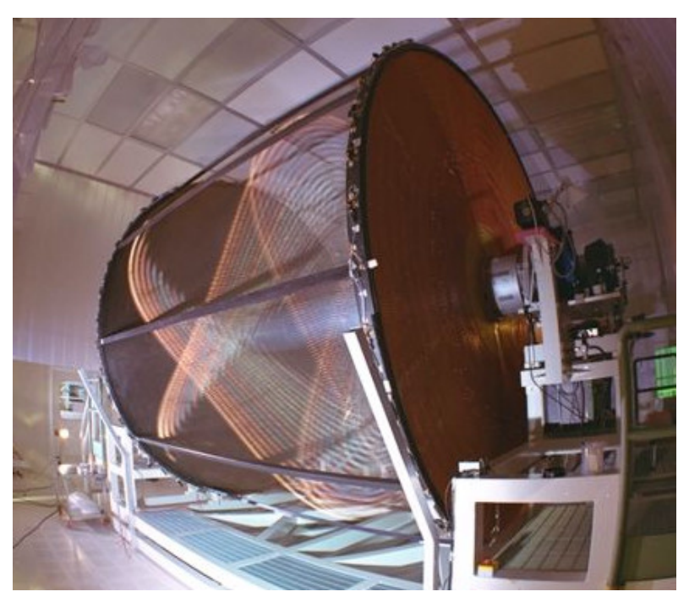
The KLOE (K LOng Experiment) detector is located at the DAΦNE e^+e^- collider in the National Laboratory of Frascati (LNF). DAΦNE is a ϕ-factory operating at the energy of the top of ϕ meson resonance, $\sqrt{s} \approx 1020$ MeV. In the years 1999–2006 KLOE has collected 2.5 fb^{-1} of data which corresponds to about 10^{10} ϕ mesons produced. Pairs of neutral kaons are produced in about 34% of ϕ decays.



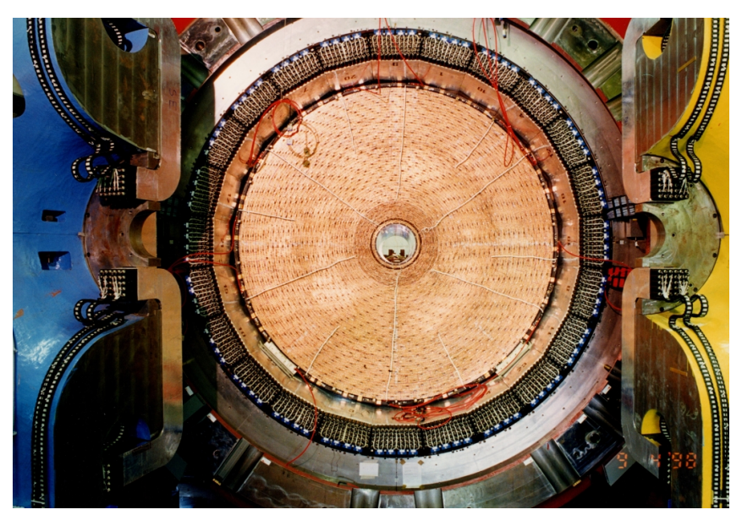
KLOE is a barrel-shaped detector whose basic components are the drift chamber and electromagnetic calorimeter immersed in magnetic field of 0.52 T.

Drift Chamber

- One of the largest DCs ever built
- 2 m radius in order to capture about 40% of $\mathrm{K_L}$ decays ($\lambda_{\mathrm{K_L}} \approx 3.5$ m).
- good momentum resolution $\frac{\sigma(p)}{p} = 0.4\%$
- $\sigma_{r,\varphi} = 150\mu m$, $\sigma_z = 3mm$



Electromagnetic Calorimeter



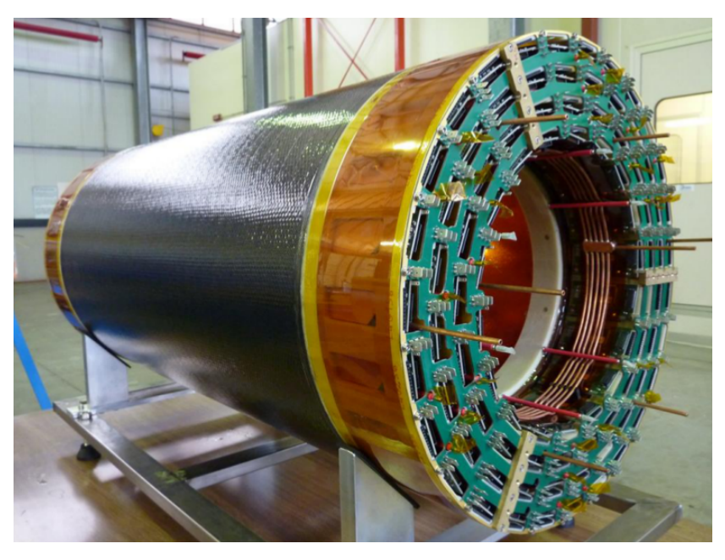
$$\sigma_t = \frac{54\ \mathrm{ps}}{\sqrt{E[\mathrm{GeV}]}} \oplus 140\mathrm{ps},$$
$$\sigma_E = \frac{5.7\%E}{\sqrt{E[\mathrm{GeV}]}},$$
$$\sigma_x = \sigma_y = 1\,\mathrm{cm},$$
$$\sigma_z = \frac{1.2\ \mathrm{cm}}{\sqrt{E[\mathrm{GeV}]}}$$

- lead-scintillating fiber sampling calorimeter
- hermetically covers 98% of full solid angle
- excellent timing resolution for reconstruction of $K \to \pi^0\pi^0$ vertex

KLOE-2

KLOE is presently being upgraded to become the KLOE-2 experiment with the following improvements:

- triple higher luminosity of upgraded DAΦNE
- new C-GEM inner tracker
- new calorimeters at small angles around beam pipe
- new High Energy Tagger and Low Energy Tagger detecors for γ-γ tagging



Acknowledgements

We acknowledge the support of the European Commission under 7th Framework Programme through the 'Research Infrastructures' action of the 'Capacities' Programme, Call: FP7-INFRASTRUCTURES-2008-1, Grant Agreement No. 283286
and the Foundation for Polish Science through the project HOMING PLUS BIS/2011-4/3.

Kaon regeneration at KLOE

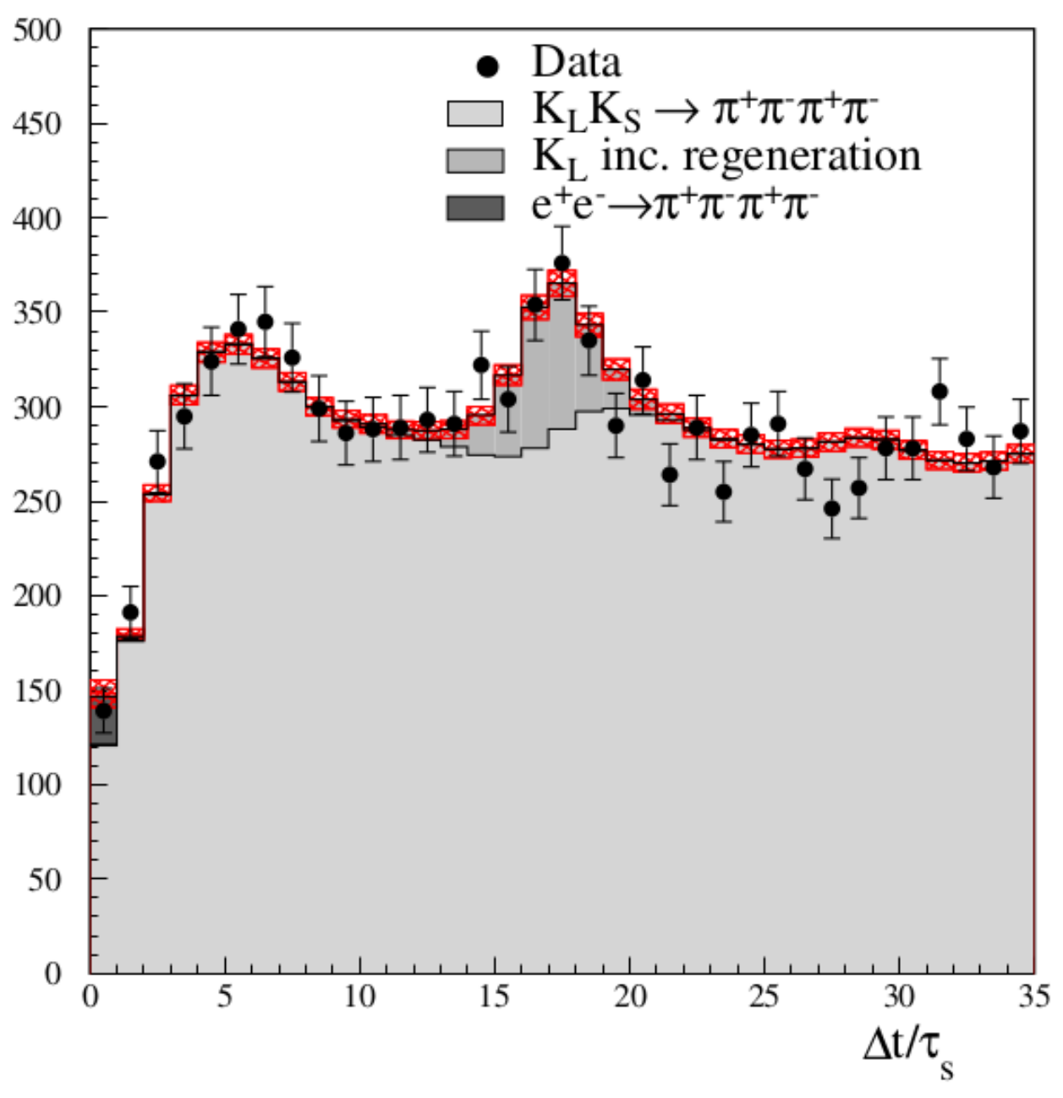
Regeneration mechanism

Regeneration of neutral kaons is a process of transformation of $\mathrm{K_L}$ into $\mathrm{K_S}$ (or $\mathrm{K_S}$ into $\mathrm{K_L}$) as a result of interaction with matter. It is caused by a difference in amplitudes for scattering on nucleons of the medium $f(\theta)$ and $\bar{f}(\theta)$ between the neutral kaon strangeness eigenstates K^0 and $\overline{\mathrm{K}}^0$ respectively.

$|i\rangle = |\mathrm{K_L}\rangle$ – an initially pure long-lived state after passing through matter is described by:

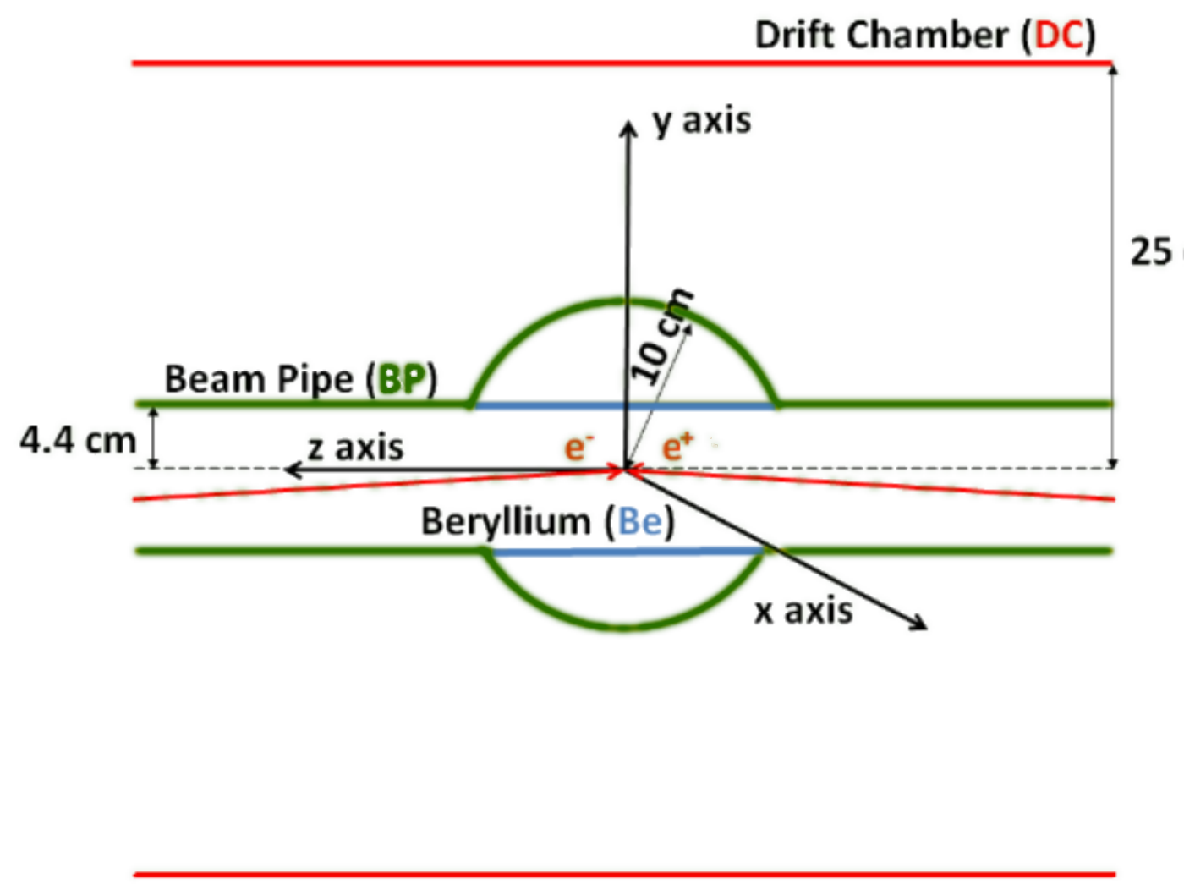
$$|f\rangle = |\mathrm{K_L}\rangle = \frac{f(\theta)+\bar{f}(\theta)}{2}|\mathrm{K_L}\rangle + \underbrace{\frac{f(\theta)-\bar{f}(\theta)}{2}}_{\neq 0}|\mathrm{K_S}\rangle\,,$$

where $\frac{f(\theta)-\bar{f}(\theta)}{2}$ is a non-zero regeneration amplitude which accounts for a $\mathrm{K_S}$ component arising in the $\mathrm{K_L}$ beam.



Regeneration in KLOE

Neutral kaon regeneration destroys quantum correlation between two kaons while leading to the same possible final states thus constituting an important background process in the interferometric studies of the $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^0\pi^0$ decay chain. As regeneration mostly occurs in material-dense parts of the detector located at fixed distance from the ϕ decay vertex, it leads to appearance of excesses of events in the decay intensity distribution at about $\Delta t = 17\tau_S$ [3].



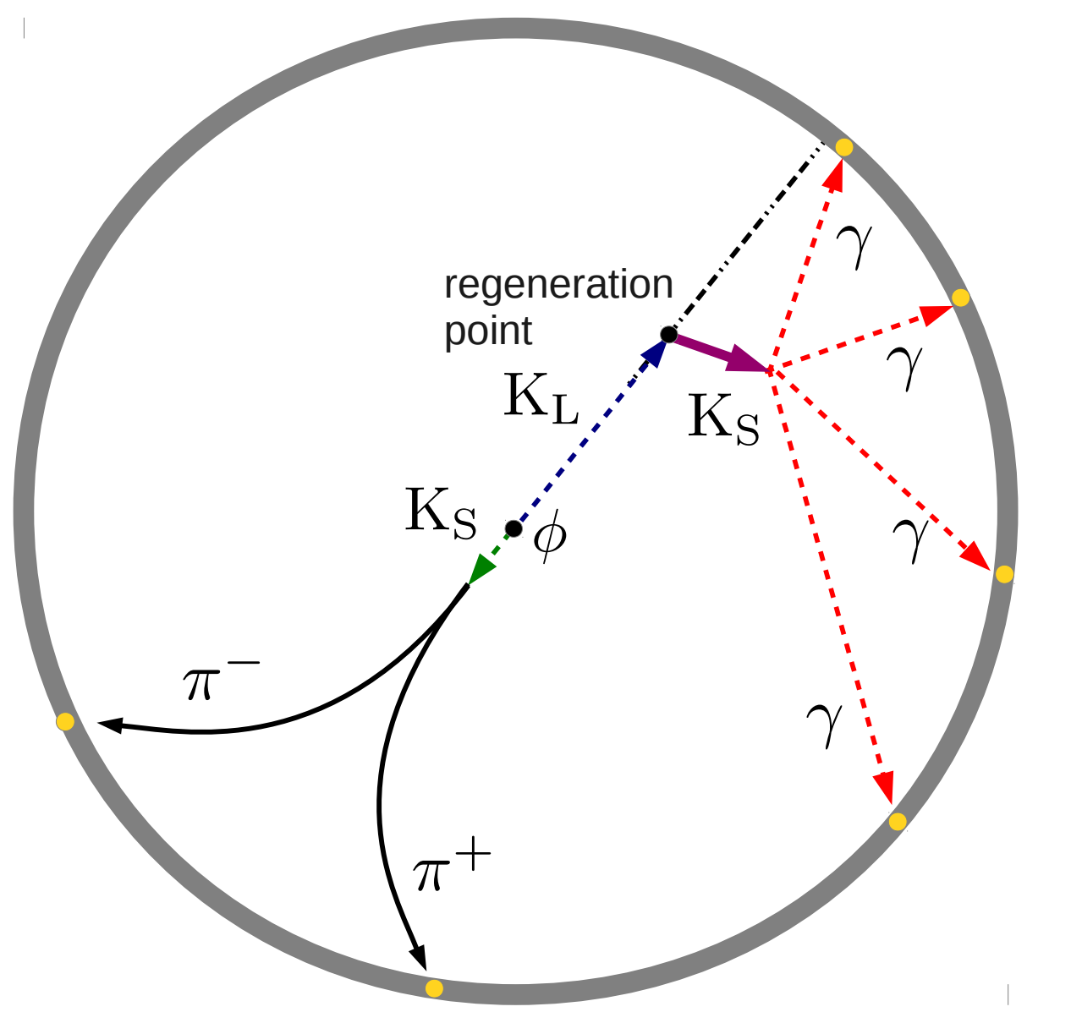
There are three parts of the KLOE detector which account for most of regeneration events:

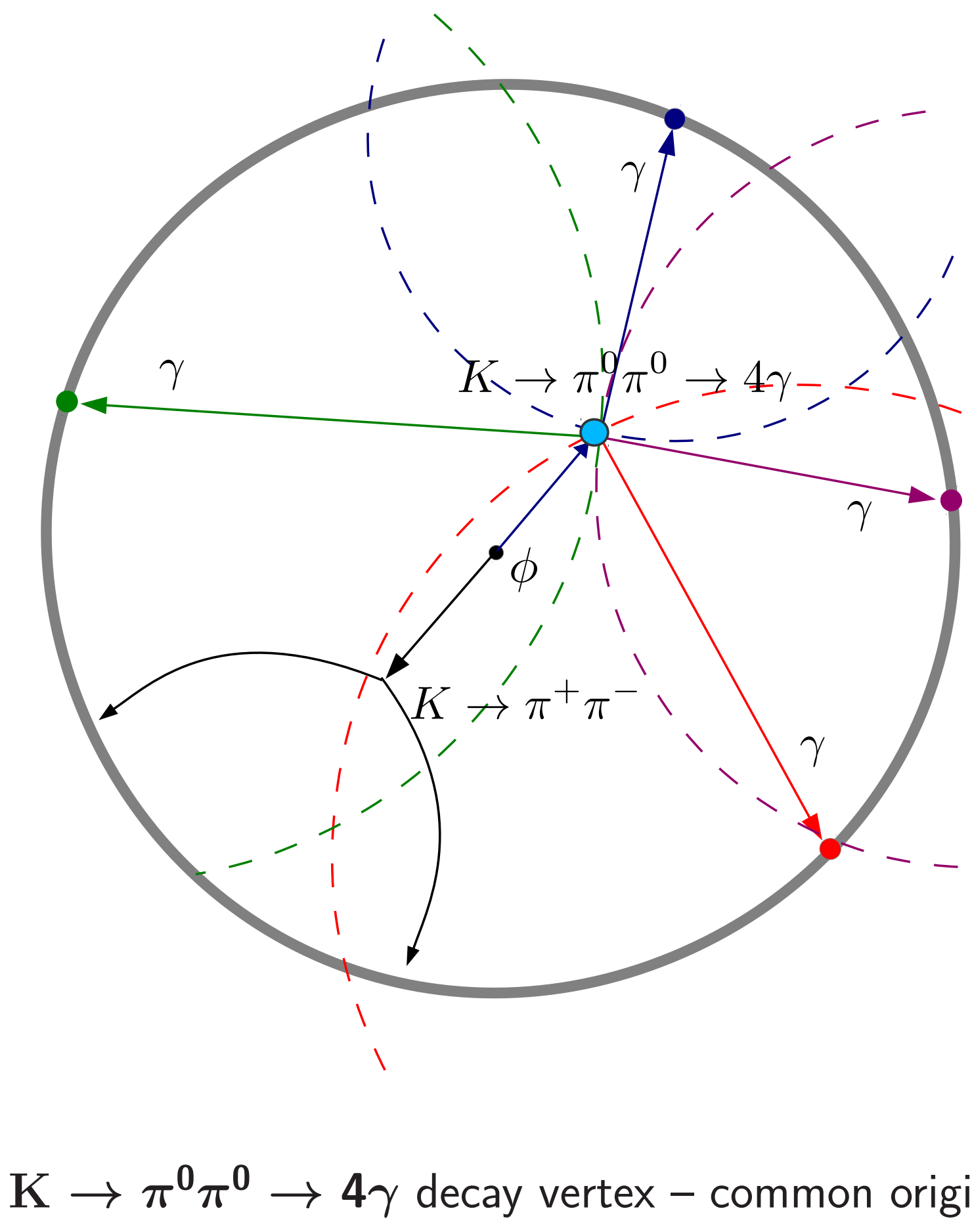
- beryllium foil of 50 μm thickness and cylindrical shape with $r_T = 4.4$ cm around the beam,
- spherical beam pipe of $R = 10$ cm surrounding the e^+e^- collision point, 0.5 mm thick layer of Be-Al alloy,
- drift chamber inner wall, cylindrical with $r_T = 25$ cm, made of carbon fiber and aluminum

New $\mathrm{K} \to \pi^0\pi^0$ decay vertex reconstruction

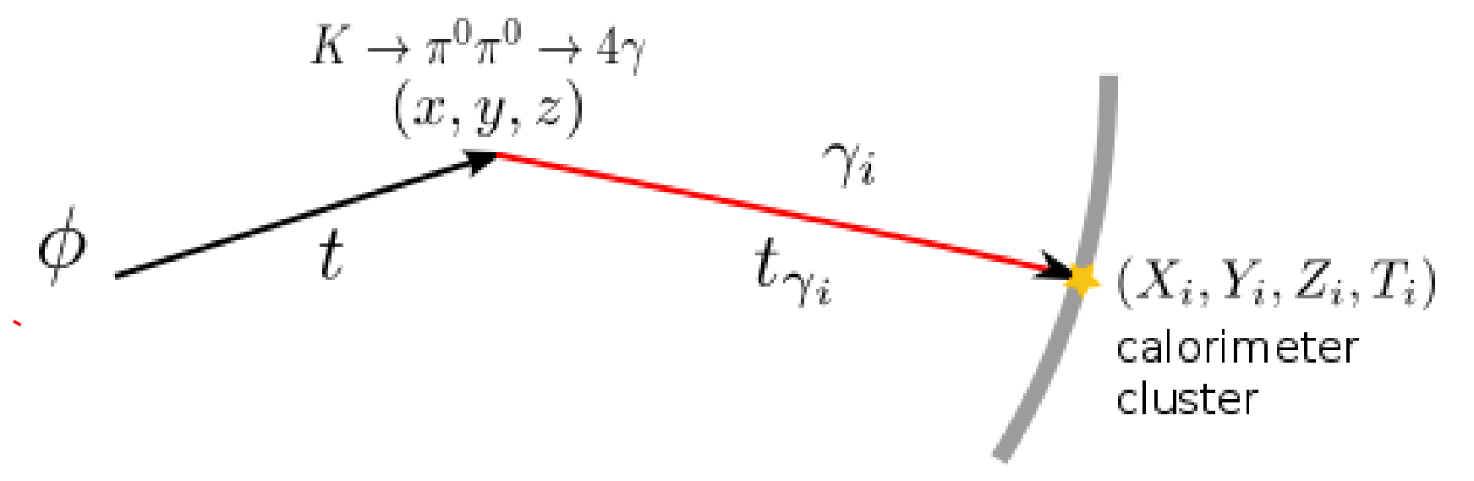
Motivation

- The standard method of the $\mathrm{K} \to \pi^0\pi^0 \to 4\gamma$ decay vertex reconstruction in KLOE utilizes the momentum direction of the tagging kaon to limit the search for vertex location to a line.
- In case of incoherent regeneration, however, the decay vertex of regenerated $\mathrm{K_S}$ may lie away from the original $\mathrm{K_L}$ momentum direction.
- Decay vertex reconstructed this way provides no means to recognize and reject regeneration.
- This raises a need for an auxiliary reconstruction algorithm which would only use the four calorimeter clusters from γ hits independently of this direction.





Reconstruction principle



- information available – 4 clusters:

$$X_i, Y_i, Z_i.T_i, \qquad i = 1,\ldots,4$$

- unknown – kaon decay vertex position (x,y,z), kaon flight time t
- cluster times: $T_i = t + t_{\gamma_i}$
- set of possible γ_i origin points - a sphere:

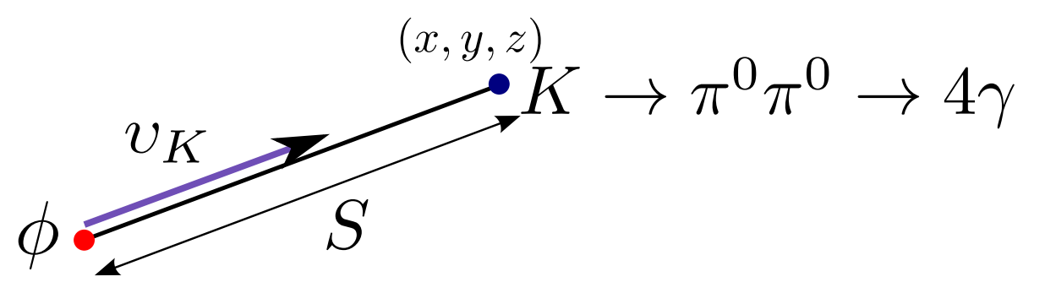
$$S\left((X_i.Y_i,Z_i), R = t_{\gamma_i}c\right)$$

- $\mathrm{K} \to \pi^0\pi^0 \to 4\gamma$ decay vertex – common origin point of four γs
  - vertex location (x,y,z) and kaon decay time t are solutions to system of 4 quadratic equations:

$$(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2 = (T_i - t)^2c^2, \qquad i = 1,\ldots,4,$$

- problem similar to intersection of 4 spheres but with spheres' radii parametrized by t
- geometrically two solutions for (x,y,z,t) possible → the physical one must be selected
  - selection possible by checking if the kaon could reach the (x,y,z) point with its velocity within its flight time t

$$\upsilon \cdot t - S = 0 \quad \text{for a physical vertex}$$



References

[1] G. D'Ambrosio, G. Isidori, and A. Pugliese, "CP and CPT measurements at DAPHNE," in *The second DAPHNE physics handbook*, L. Maiani, G. Pancheri, and N. Paver, eds., vol. 1 (1995) 63–95. `arXiv:hep-ph/9411389 [hep-ph]`.

[2] A. Di Domenico, "Handbook on neutral kaon interferometry at a Phi-factory," *Frascati Physics Series* **43** (2007) 1–38.

[3] KLOE Collaboration, F. Ambrosino *et al.*, "First observation of quantum interference in the process $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^+\pi^-$: A Test of quantum mechanics and CPT symmetry," *Phys. Lett.* **B642** (2006) 315–321, `arXiv:hep-ex/0607027 [hep-ex]`.