A direct test of time-reversal symmetry in the neutral K meson system with $\mathrm{K_S} \to \pi\ell\nu$ and $\mathrm{K_L} \to 3\pi^0$ at KLOE-2

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Motivation

A direct test of $\mathcal{T}$ symmetry – for spin 0 particles means an observation of asymmetry between one process and a process obtained by exchange of its initial and final states.

$$P(|a\rangle \to |b\rangle) \overset{?}{=} P(|b\rangle \to |a\rangle)$$

Kabir asymmetry at CPLEAR [1]

- Measured probability asymmetry of $\mathrm{K}^0 \to \overline{\mathrm{K}}^0$ and $\overline{\mathrm{K}}^0 \to \mathrm{K}^0$
- $< A_T^{exp} >= (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \times 10^{-3}$ [1]
- Controversy: asymmetry in $\mathrm{K}^0 \leftrightarrows \overline{\mathrm{K}}^0$ may be attributed both to $\mathcal{T}$ and $\mathcal{CP}$ violation!

$$\begin{tikzcd} \mathrm{K}^0 \to \overline{\mathrm{K}}^0 \arrow[r, "\mathcal{T}"] \arrow[d, "\mathcal{CP}"'] & \overline{\mathrm{K}}^0 \to \mathrm{K}^0 \arrow[dl, leftrightarrow, "\equiv"] \\ \overline{\mathrm{K}}^0 \to \mathrm{K}^0 & \end{tikzcd}$$

A test independent od $\mathcal{CP}$ violation

possible with transitions between flavour and $\mathcal{CP}$-definite states of neutral B and K mesons

BaBar measured a significant asymmetry in $\bar{B}^0 \leftrightarrows B_-$ [3, 4]. ⟵

⟶ KLOE-2 is capable of performing a significant test with neutral kaons! [2]

Testing $\mathcal{T}$ symmetry with neutral kaons

Strangeness eigenstates $\{\mathrm{K}^0, \overline{\mathrm{K}}^0\}$:

$$\mathcal{S}\,|\mathrm{K}^0\rangle = +1\,|\mathrm{K}^0\rangle$$
$$\mathcal{S}\,|\overline{\mathrm{K}}^0\rangle = -1\,|\overline{\mathrm{K}}^0\rangle$$

⟷ reversible transitions

$\mathcal{CP}$ eigenstates $\{\mathrm{K}_+, \mathrm{K}_-\}$:

$$|\mathrm{K}_+\rangle = \frac{1}{\sqrt{2}}\left[|\mathrm{K}^0\rangle + |\overline{\mathrm{K}}^0\rangle\right] \qquad \mathcal{CP} = +1$$
$$|\mathrm{K}_-\rangle = \frac{1}{\sqrt{2}}\left[|\mathrm{K}^0\rangle - |\overline{\mathrm{K}}^0\rangle\right] \qquad \mathcal{CP} = -1$$

- $\mathcal{CP}$-flavour transitions and their time-inverses are only connected by $\mathcal{T}$ conjugation
- Can be observed in an entangled system of neutral kaons

$$\begin{tikzcd} \mathrm{K}^0 \to \mathrm{K}_+ \arrow[r, "\mathcal{T}"] \arrow[d, "\mathcal{CP}"'] \arrow[dr, "\mathcal{CPT}"] & \mathrm{K}_+ \to \mathrm{K}^0 \\ \overline{\mathrm{K}}^0 \to \mathrm{K}_+ & \mathrm{K}_+ \to \overline{\mathrm{K}}^0 \end{tikzcd}$$

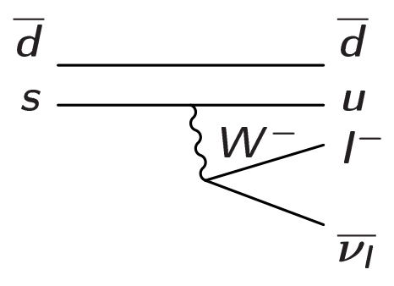
Identifying flavour states $\{\mathrm{K}^0, \overline{\mathrm{K}}^0\}$

by observation of semileptonic decays:

"ℓ^-" decay:

$\overline{\mathrm{K}}^0 \to \pi^+\ell^-\bar{\nu}_l$

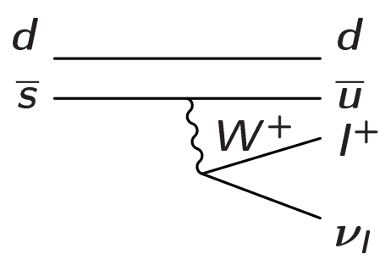
$\mathcal{S} = -1$



"ℓ^+" decay:

$\mathrm{K}^0 \to \pi^-\ell^+\nu_l$

$\mathcal{S} = +1$



Identifying $\mathcal{CP}$ states $\{\mathrm{K}_+, \mathrm{K}_-\}$

by observation of hadronic decays:

"$\pi\pi$" decay:

$\mathrm{K}_+ \to \pi^+\pi^-$, $\pi^0\pi^0$

$\mathcal{CP} = +1$

"$3\pi^0$" decay:

$\mathrm{K}_+ \to 3\pi^0$

$\mathcal{CP} = -1$

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

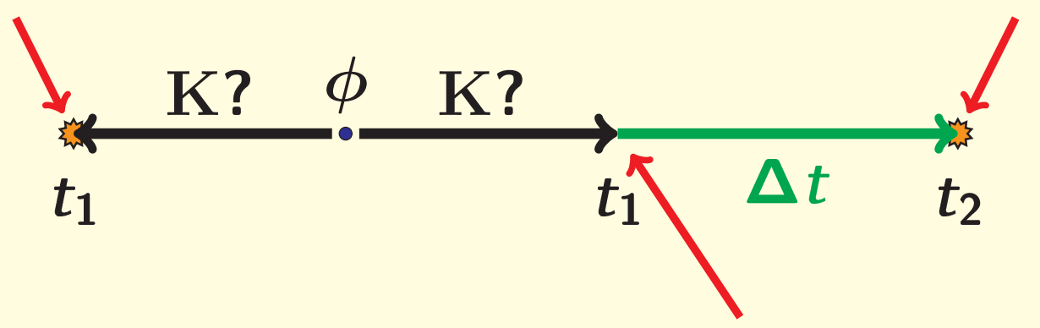
$$|\phi\rangle \to \frac{1}{\sqrt{2}}\Big(|\mathrm{K}^0(+\vec{p})\rangle\,|\overline{\mathrm{K}}^0(-\vec{p})\rangle - |\overline{\mathrm{K}}^0(+\vec{p})\rangle\,|\mathrm{K}^0(-\vec{p})\rangle \Big)$$

- Quantum entalglement in the EPR sense allows for identification of a state of the kaon without its decay.

Example: $|\overline{\mathrm{K}}^0\rangle \to |\mathrm{K}_-\rangle$ in time Δt

$K \to \pi^-\ell^+\nu$ decay tags $|\mathrm{K}^0\rangle$ state

$K \to 3\pi^0$ decay tags $|\mathrm{K}_-\rangle$ state



$|\overline{\mathrm{K}}^0\rangle$ state is known before kaon's decay

Reconstruction of events for the test

- The following proceses can be reconstructed for the $\mathcal{T}$ test:

$$\phi \to \mathrm{K_S K_L} \to \pi^+\ell^-\bar{\nu}\ 3\pi^0$$
$$\phi \to \mathrm{K_S K_L} \to \pi^-\ell^+\nu\ 2\pi$$
$$\phi \to \mathrm{K_S K_L} \to \pi^-\ell^+\nu\ 3\pi^0$$
$$\phi \to \mathrm{K_S K_L} \to \pi^+\ell^-\bar{\nu}\ 2\pi$$

- Good resolution of kaon decay times required
  - Obtained from decay vertex position
  - Decay vertex resolution of $\mathcal{O}(1cm)$ needed
- Good vertex reconstruction obtained using charged particle tracks for $\pi\ell\nu$ and $\pi^+\pi^-$ final states
- The $\mathrm{K_L} \to 3\pi^0$ decay only invovlves neutral particles and requires a specialized reconstruction method!

$\mathcal{T}$ test at KLOE-2

Possible transitions

	Transition	Identified by	$\mathcal{T}$-conjugate	Identified by
1	$\mathrm{K}^0 \to \mathrm{K}_+$	$(\ell^-, \pi\pi)$	$\mathrm{K}_+ \to \mathrm{K}^0$	$(3\pi^0, \ell^+)$
2	$\mathrm{K}^0 \to \mathrm{K}_-$	$(\ell^-, 3\pi^0)$	$\mathrm{K}_- \to \mathrm{K}^0$	$(\pi\pi, \ell^+)$
3	$\overline{\mathrm{K}}^0 \to \mathrm{K}_+$	$(\ell^+, \pi\pi)$	$\mathrm{K}_+ \to \overline{\mathrm{K}}^0$	$(3\pi^0, \ell^-)$
4	$\overline{\mathrm{K}}^0 \to \mathrm{K}_-$	$(\ell^+, 3\pi^0)$	$\mathrm{K}_- \to \overline{\mathrm{K}}^0$	$(\pi\pi, \ell^-)$

KLOE-2 will collect high statistics of events allowing to measure ratios of time-dependent probabilities of two transitions and their time-iverses through numbers of events identified by certain K decays in time interval Δt:

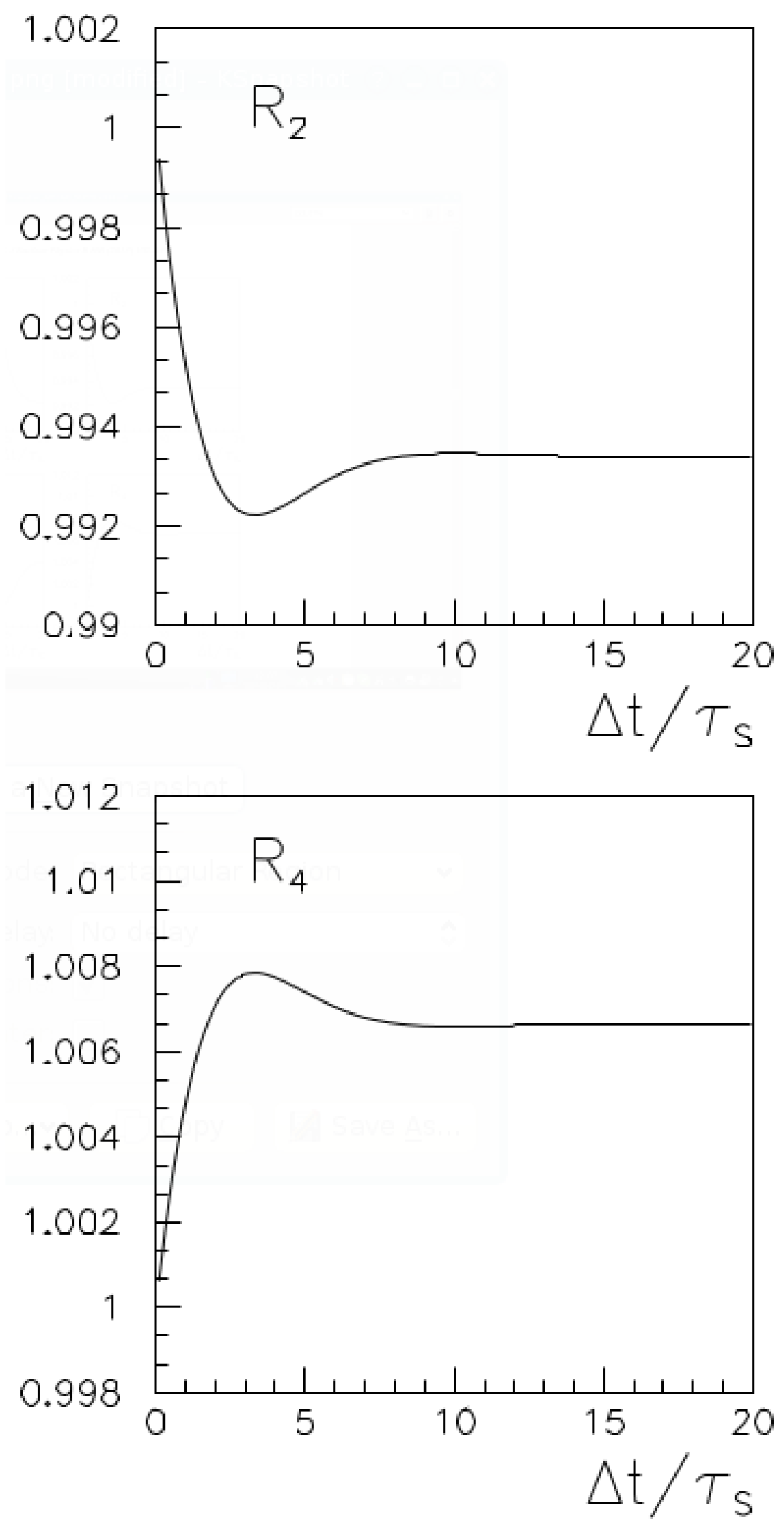
$$R_2(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} \sim \frac{\mathrm{I}(\ell^-, 3\pi^0; \Delta t)}{\mathrm{I}(\pi\pi, \ell^+; \Delta t)}$$
$$R_4(\Delta t) = \frac{P[\overline{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \overline{\mathrm{K}}^0(\Delta t)]} \sim \frac{\mathrm{I}(\ell^+, 3\pi^0; \Delta t)}{\mathrm{I}(\pi\pi, \ell^-; \Delta t)}$$

Asymptotic discrepancy of these ratios and 1 is a measure of $\mathcal{T}$ symmetry violation:

$$R_2(\Delta t) \xrightarrow{\Delta t \gg \tau_s} 1 - 4\Re\epsilon$$
$$R_4(\Delta t) \xrightarrow{\Delta t \gg \tau_s} 1 + 4\Re\epsilon$$

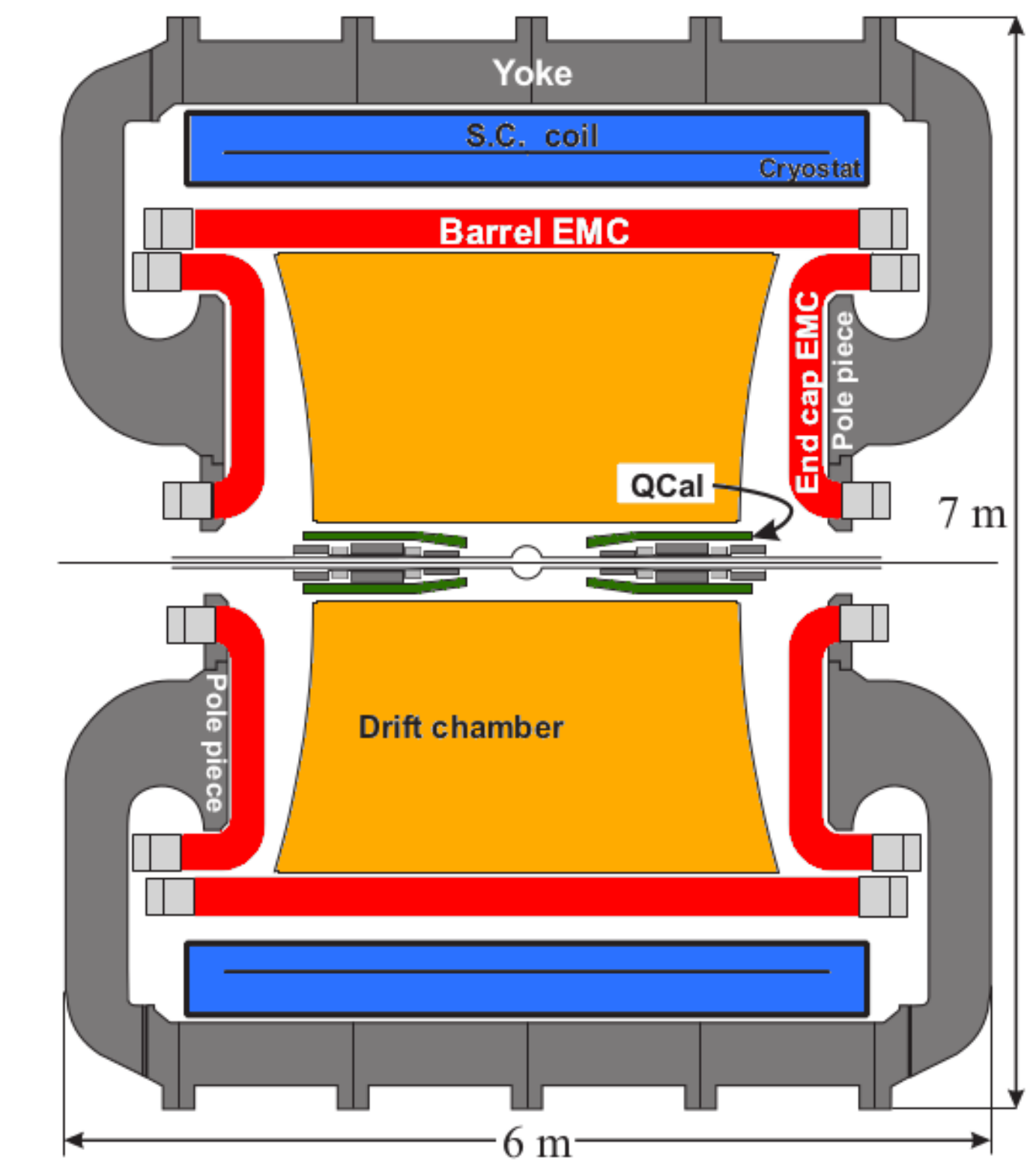
$\Re\epsilon \neq 0$ implies $\mathcal{T}$ violation[2].

Figure shows simulated behavior of the ratios expected for $10fb^{-1}$ of KLOE-2 data [2]. ⟶



KLOE Detector at DAΦNE

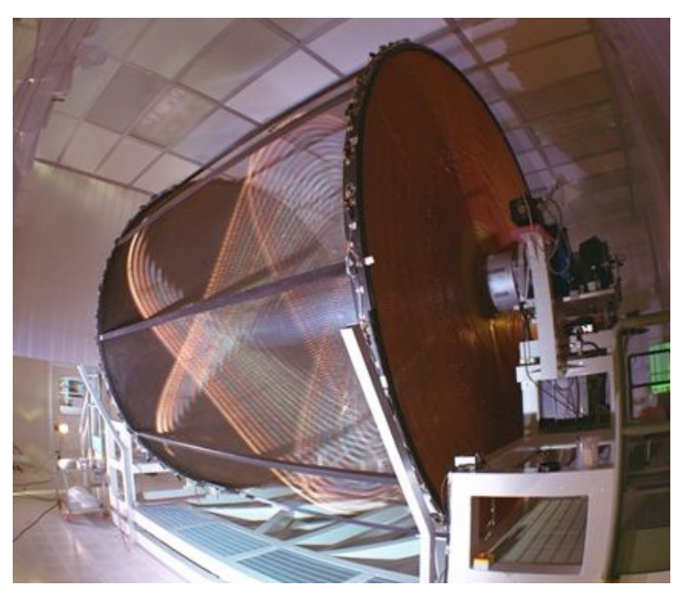
The KLOE (K LOng Experiment) detector is located at the DAΦNE e^+e^- collider in the National Laboratory of Frascati (LNF). DAΦNE is a ϕ-factory operating at the energy of the top of ϕ meson resonance, $\sqrt{s} \approx 1020$ MeV. In the years 1999–2006 KLOE has collected 2.5 fb^{-1} of data which corresponds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



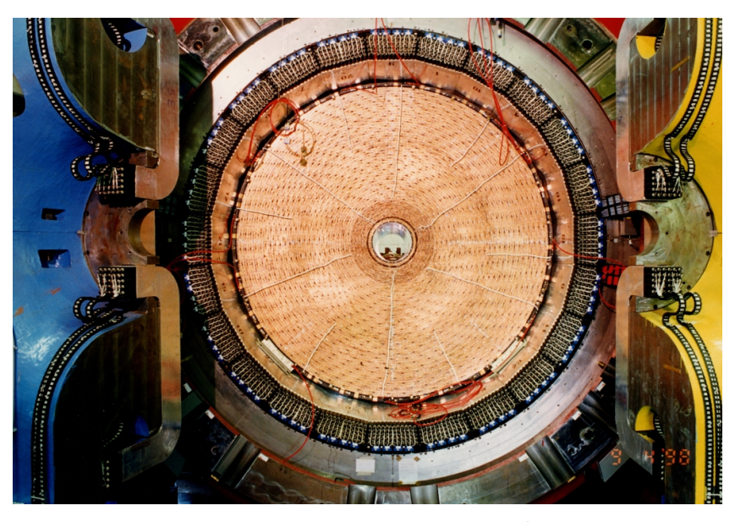
KLOE is a barrel-shaped detector whose basic components are the drift chamber and electromagnetic calorimeter immersed in magnetic field of 0.52 T.

Drift Chamber

- One of the largest DCs ever built
- 2 m radius ⇒ captures ~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



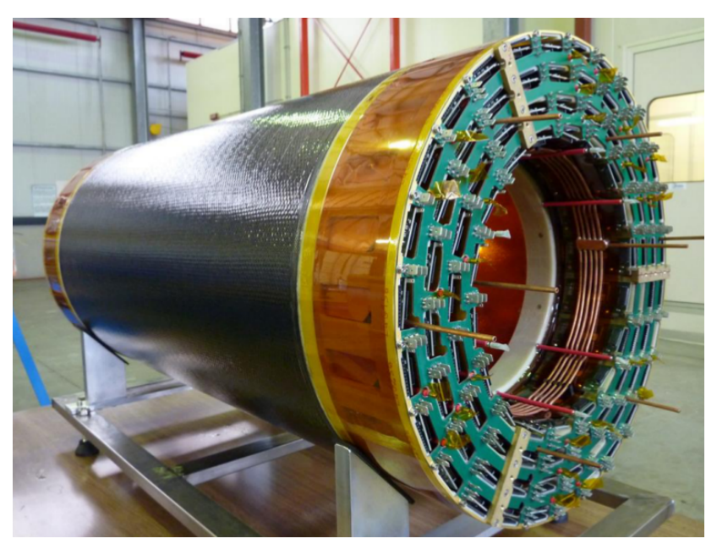
$$\sigma_t = \frac{54\ ps}{\sqrt{E[GeV]}} \oplus 140ps,$$
$$\sigma_E = \frac{5.7\% E}{\sqrt{E[GeV]}},$$
$$\sigma_x = \sigma_y = 1\,cm,$$
$$\sigma_z = \frac{1.2\ cm}{\sqrt{E[GeV]}}$$

- Lead-scintillating fiber sampling calorimeter
- Hermetically covers 98% of full solid angle

Upgrade to KLOE-2

Upgraded KLOE-2 detector[5] is starting operation with the following improvements:

- Triple higher luminosity of upgraded DAΦNE
- New C-GEM inner tracker [6] ⟶
- New calorimeters at small angles around beam pipe [7]



$\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ vertex reconstruction for $\mathrm{K_S K_L} \to \pi\ell\nu\ 3\pi^0$

- selection and analysis of $\mathrm{K_S} \to \pi e\nu$ decays to be adapted from [8]
- $\mathrm{K_L} \to 3\pi^0$ reconstruction must rely exclusively on calorimeter information
- **Reconstruction of $\mathrm{K_L} \to 3\pi^0$ similar to GPS positioning is possible:**

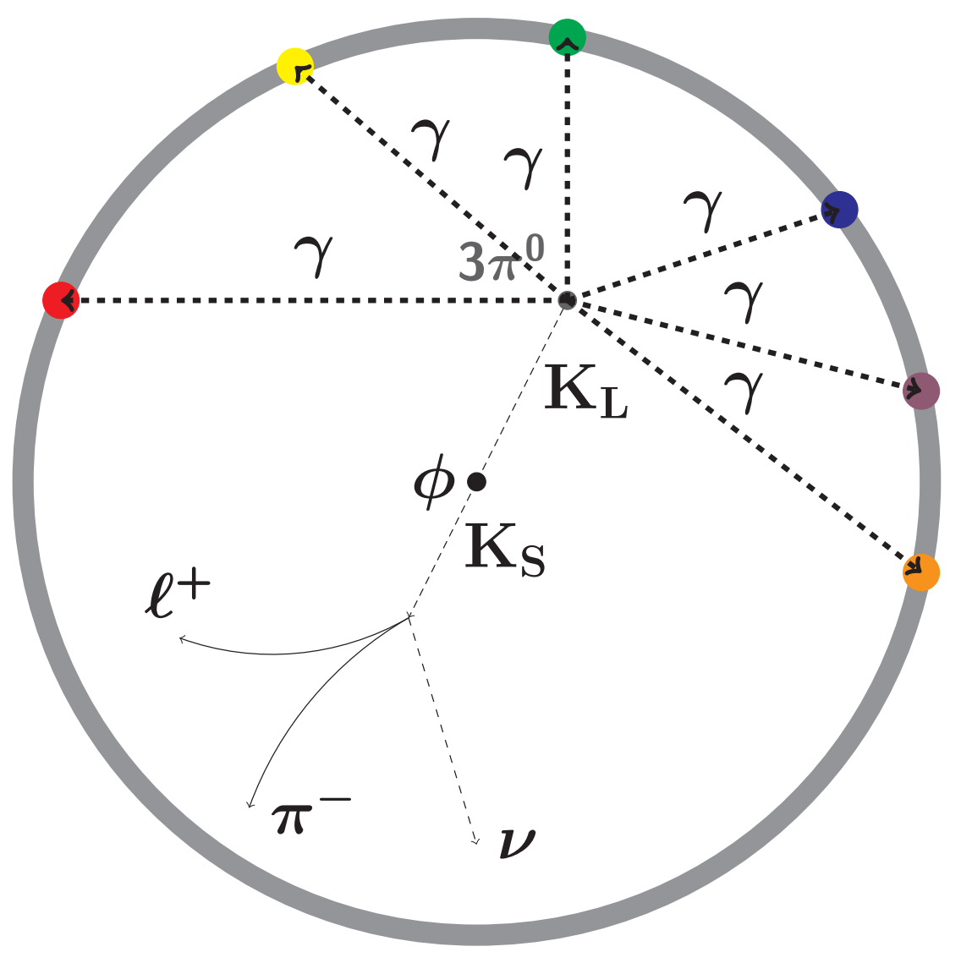
1. 6 clusters in the calorimeter from γ hits are the only direct information on the process recorded by the detector
2. For each cluster with location (X_i, Y_i, Z_i) and recording time T_i a set of possible origin points of its incident γ is a sphere with radius dependent on kaon decay time:

$$(T_i - t)^2c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2 \quad i = 1, \ldots, 6,$$

where the unknowns x, y, z, t correspond to $\mathrm{K_L}$ decay vertex location and time.

3. The $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ decay point and time are found as an intersection of spheres defined for all clusters. At least 4 clusters are required for reconstruction but additional 2 can be used to improve resolution.

1



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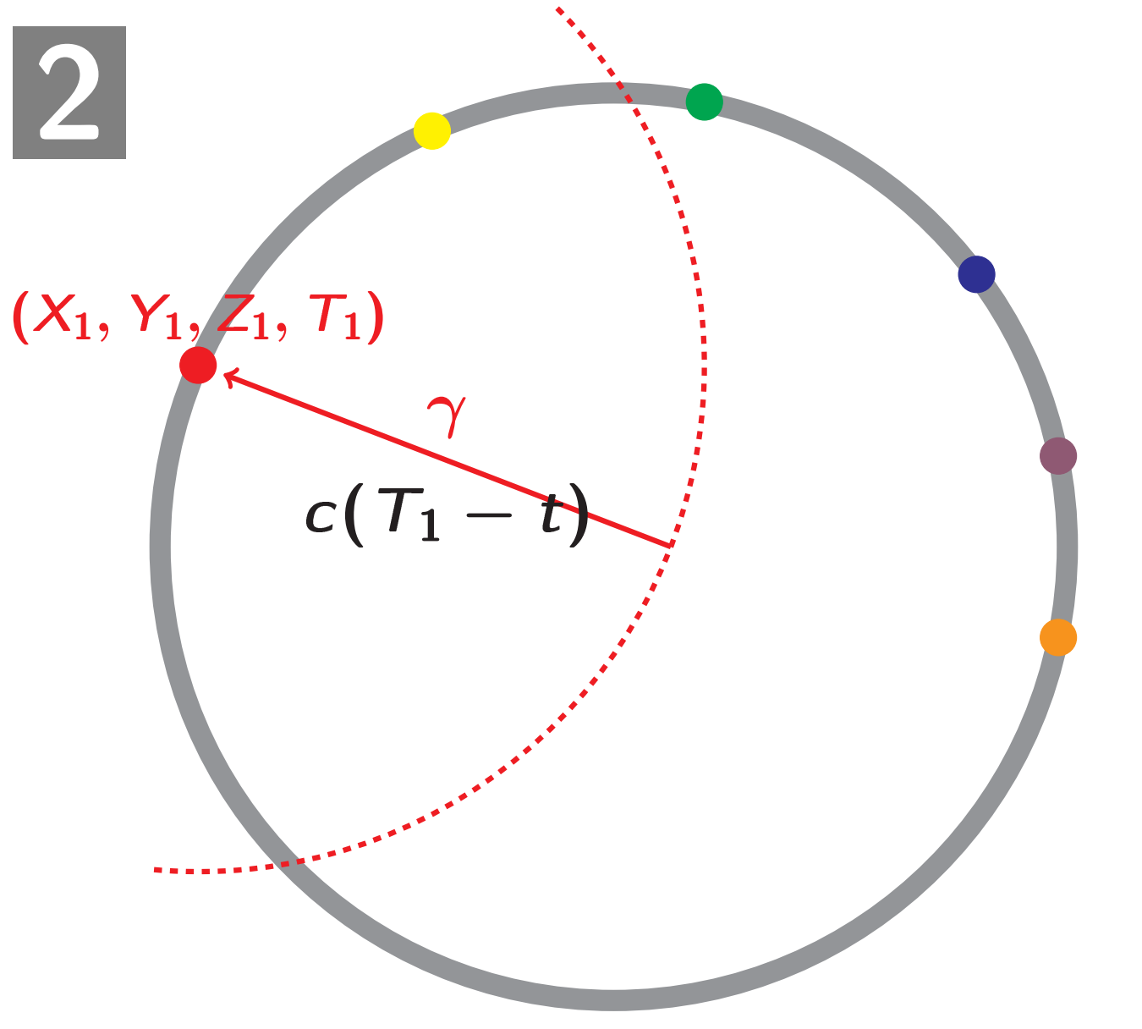

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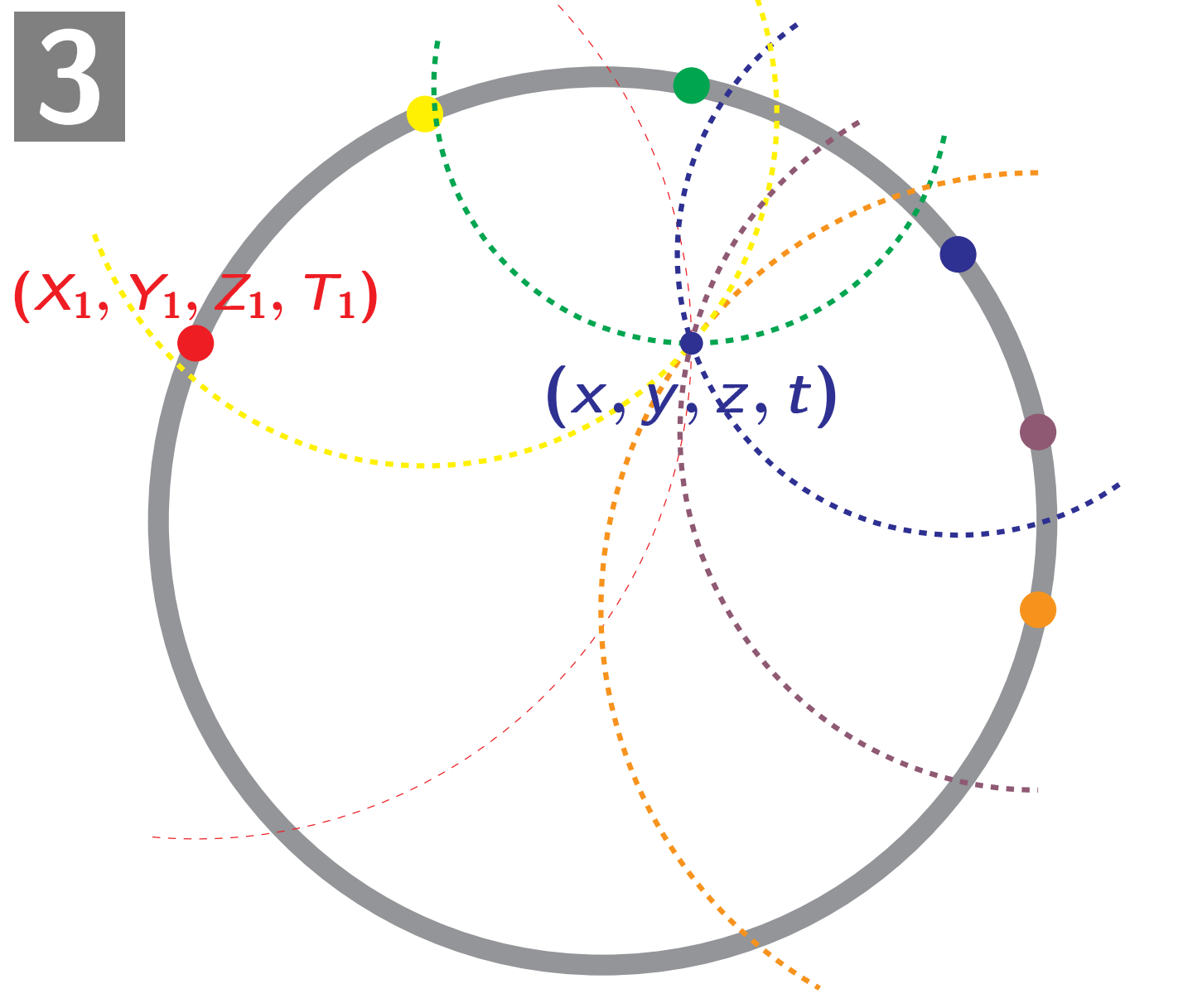

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[8] see a poster by D. Kamińska at this conference

Acknowledgements

This work was supported in part by the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3-CT- 2004-506078; by the European Commission under the 7th Framework Programme through the *Research Infrastructures* action of the *Capacities* Programme, Call: FP7-INFRASTRUCTURES-2008-1, Grant Agreement No. 227431; by the Polish National Science Centre through the Grants No. 0469/B/H03/2009/37, 0309/B/H03/2011/40, 2011/03/N/ST2/02641, 2011/01/D/ST2/00748, 2011/03/N/ST2/02652, 2013/08/M/ST2/00323 and by the Foundation for Polish Science through the MPD programme and the project HOMING PLUS BIS/2011-4/3.