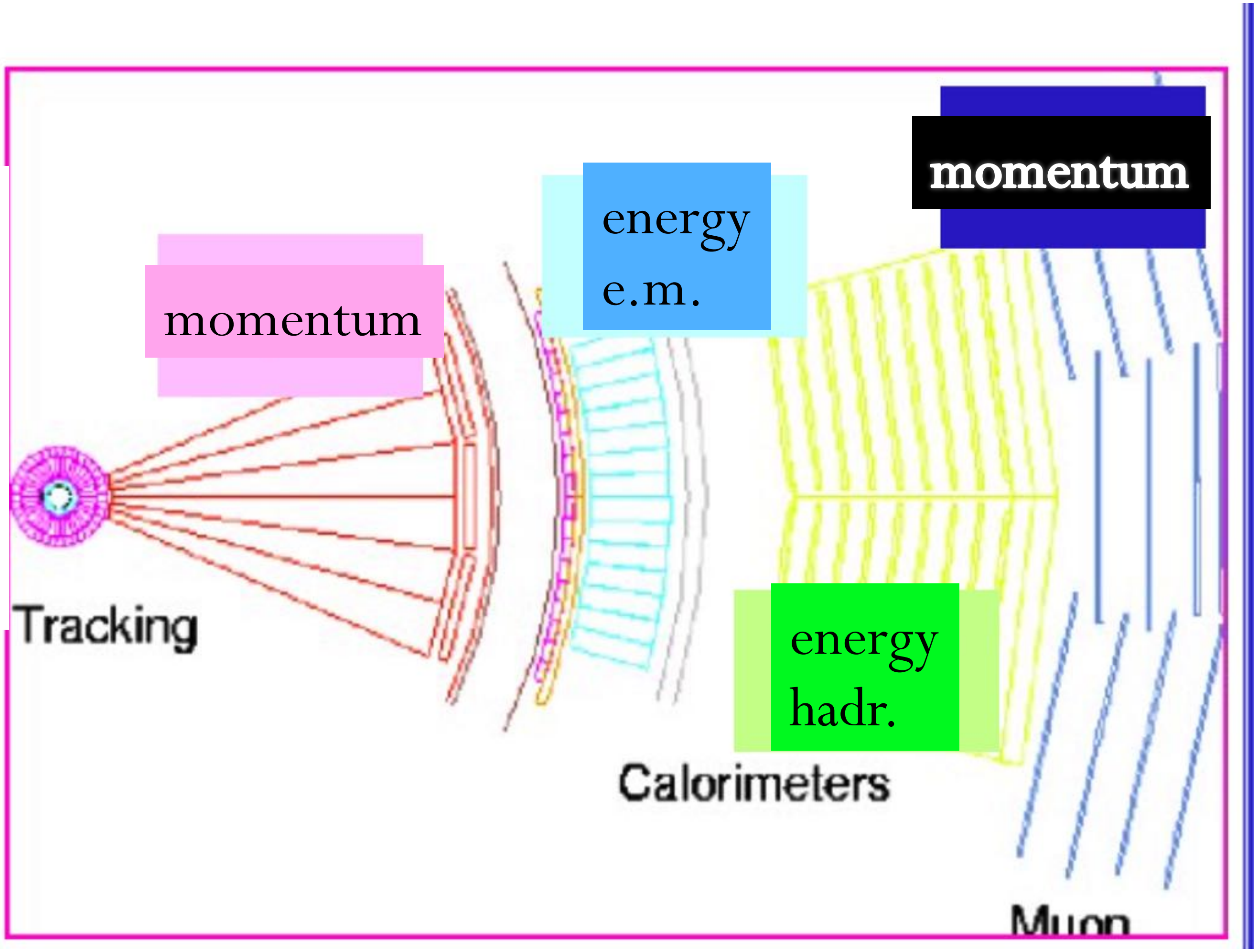
Designing an experiment

- Introduction

	p_c	E_{em}	E_h	p_μ
• $e^\pm$:	yes	yes	no	no
• γ :	no	yes	no	no
• $\pi^\pm$:	yes	mip	yes	no
• n :	no	mip	yes	no
• $\mu^\pm$:	yes	mip	mip	yes
• ν :	no	no	no	no

- ν from apparent unbalance in the event (hermeticity)



Momentum measurement

Momentum measurement

Assume a uniform magnetic field ***B*** in a region of dimension ***L*** and a particle of trasverse momentum $\boldsymbol{p_T}$ entering the region

$$p_T(GeV) = 0.3\rho(m)B(T)$$

We define the "sagitta" ***s*** and suppose to measure it through 3 points x_1, x_2 and x_3: $\boldsymbol{s} = x_2-(x_1+x_3)/2$

$$s = \frac{0.3BL^2}{8p_T}$$

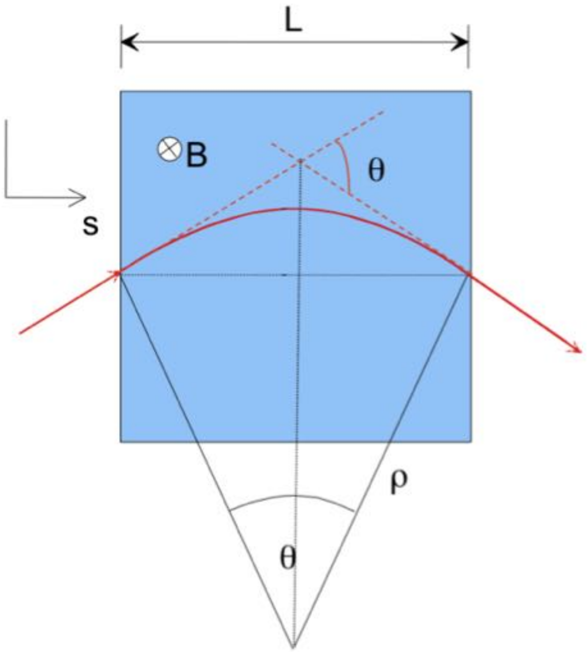
From ***s*** we get the transverse momentum, given the field ***B*** and the distance ***L*** between detectors 1 and 3

The resolution on $\boldsymbol{p_T}$ is:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{3}{2}}\sigma_X \frac{8p_T}{0.3BL^2}$$

In case of N points rather than 3, the resolution is:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{720}{N+4}}\sigma_X \frac{p_T}{0.3BL^2}$$



particle measurement : spectrometers

The Lorentz force bends a charged particle in a magnetic field ⇒ the particle momentum is computed from the measurement of a trajectory ℓ. Simple case:

- track ⊥ $\vec{B}$ (or ℓ = projected trajectory);
- $\vec{B}$ = constant;
- ℓ ≪ R (i.e. α small, s ≪ R, arc ≈ chord);
- then (p in GeV, B in T, ℓ R s in m) :

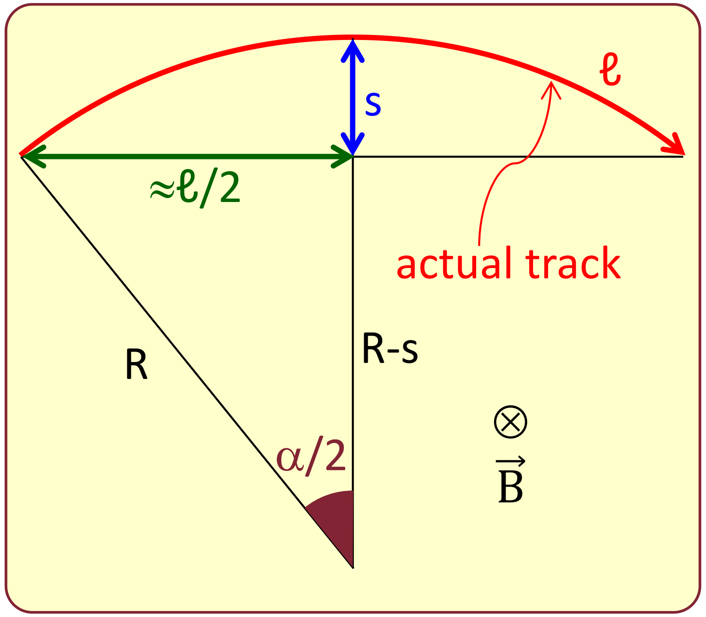
$$R^2 = (R-s)^2 + \ell^2/4 \rightarrow (R, \ell \gg s)$$

$$0 = \cancel{s^2} - 2Rs + \ell^2/4 \rightarrow$$

$$s = \frac{\ell^2}{8R} \simeq \frac{R\alpha^2}{8};$$

$$p = 0.3BR = 0.3B\frac{\ell^2}{8s};$$

$$\frac{\Delta p}{p} = \left|\frac{\partial p}{\partial s}\right|\frac{\Delta s}{p} = \frac{\cancel{p}}{s}\frac{\Delta s}{\cancel{p}} = \frac{\Delta s}{s} = \left(\frac{8\Delta s}{0.3B\ell^2}\right)p.$$



- e.g. B = 1 T, ℓ = 1.7 m, Δs = 200 μm →

  Δp/p =1.6 × 10^{-3} p (GeV);

- in general, from N points at equal distance along ℓ, each with error ε :

$$\frac{\Delta p}{p} \simeq \frac{\varepsilon p}{0.3B\ell^2}\sqrt{\frac{720}{N+4}}$$

(Gluckstern formula [PDG]).

Resolution of energy measurements through e.m. calorimetry

- In general the energy resolution of an e.m. calorimeter is given in terms of $\sigma(E)/E$.
- Main contributions:
  - $a/\sqrt{E}$ ➔ due to statistics: sampling fluctuations and/or number of photoelectrons fluctuations;
  - b/E ➔ tipically due to the fluctuations of a constant contribution to the energy (e.g. pedestal, electronic noise,…)
  - c ➔ constant term: due to systematics, calibration, containment.
- All three terms contribute. Normally c dominates at high energies, and a at low/intermediate energies. b is present only in specific cases.

Electromagnetic calorimetry

Table 31.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$\mathrm{Bi_4Ge_3O_{12}}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$\mathrm{PbWO_4}$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20–30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20–30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

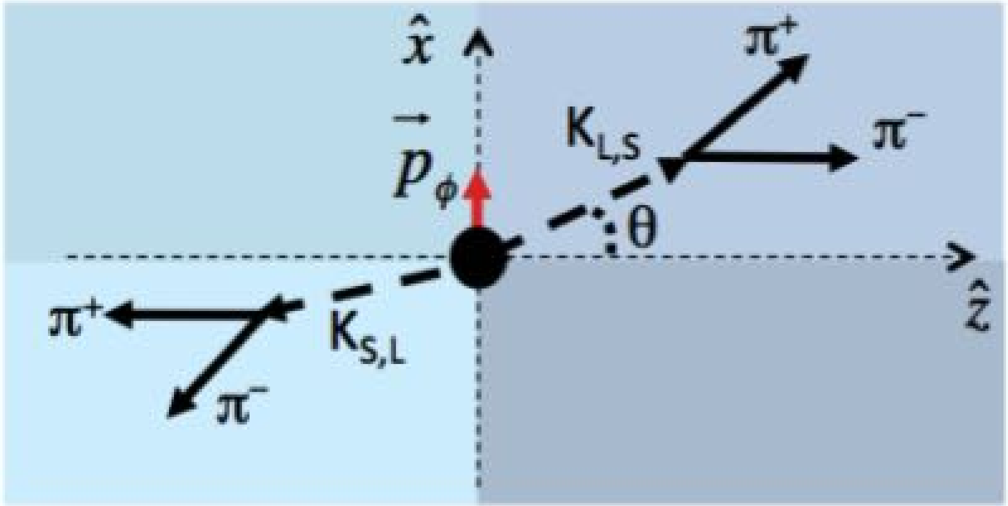
Designing an experiment

- examples

KLOE - I

- e^+e^- collisions at $\sqrt{s} = 1.02$ GeV $= M_\phi$
- Low multiplicity events well suited for "exclusive" analyses.
- Particles to detect (momentum range 50 ÷ 500 MeV):
  - Pions
  - Photons
  - Electrons
  - Muons
  - Charged kaons from $\phi \rightarrow K^+K^-$ (momentum = 130 MeV)
  - Neutral Kaons (see later)
- At these low momenta, there are not "hadronic showers", a pion is similar to a muon. On the other hand, electrons and photons are "e.m. showers".
- Strategy:
  - A tracking chamber in magnetic field to measure charged particles momenta (with some charged kaon discrimination through dE/dx measurement);
  - A calorimeter on its back to measure photons, and to help in the discrimination between pions, muons and electrons through time-of-flight;

KLOE - II



Specific KLOE case determines the detector overall dimensions:

$$\phi \rightarrow K_0 \overline{K}_0 \rightarrow K_S K_L$$

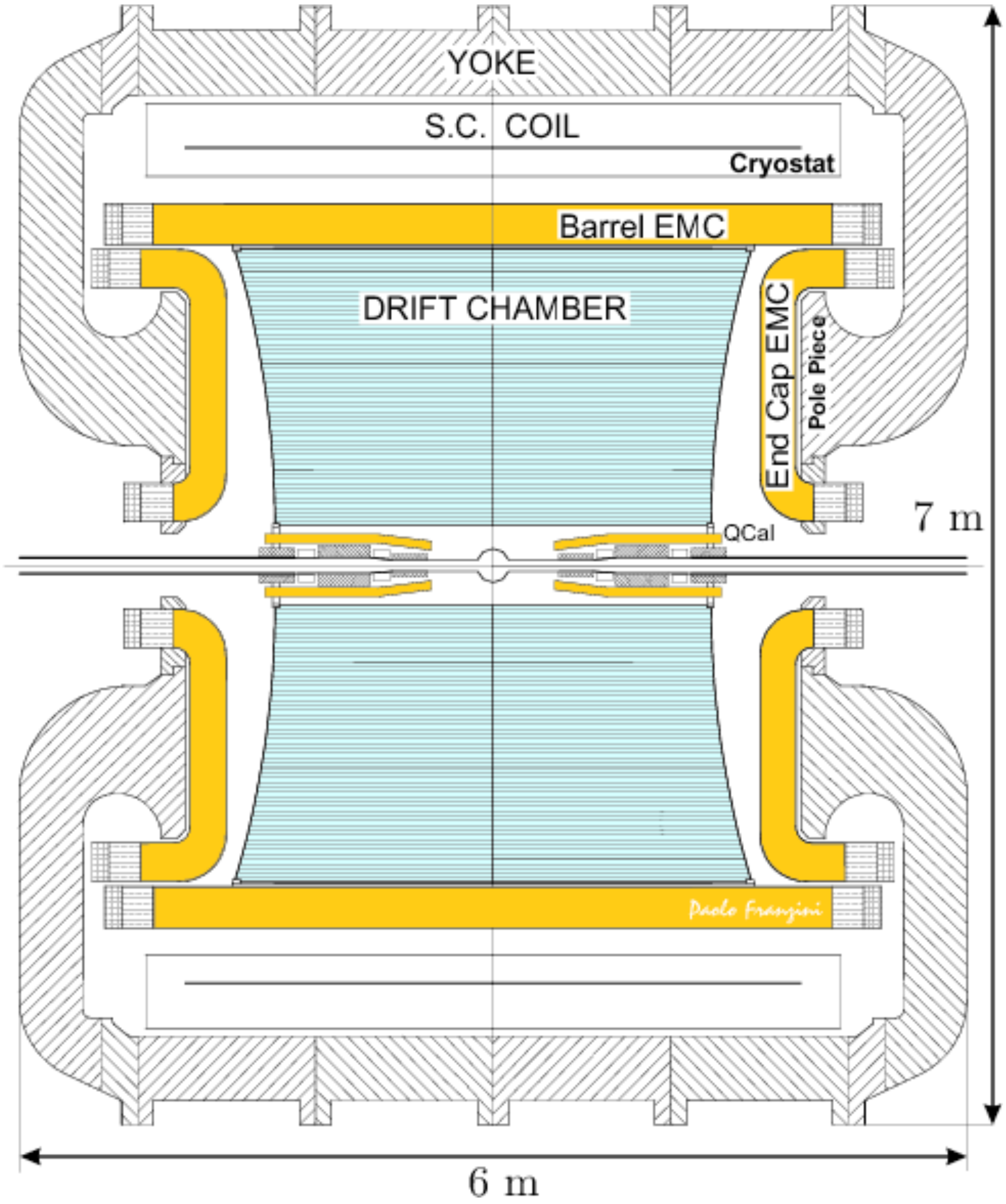
$p(K_0) = 110.6$ MeV/c

$\tau(K_S) = 0.8954 \times 10^{-10}$ s → $l(K_S) = \tau(K_S)\,\beta\gamma\, c = 6$ mm

$\tau(K_L) = 5.116 \times 10^{-8}$ s → $l(K_L) = \tau(K_L)\,\beta\gamma\, c = 3.4$ m

A>50% (acceptance on K_L) if R>2.3 m

$$A = \int_0^R f(r)dr = \frac{1}{l(K_L)} \int_0^R e^{-r/l(K_L)} dr = 1 - e^{-R/l(K_L)}$$



SuperConducting Coil + Return Yoke

- $B \approx 0.5\,T$
- typical curvature radii
- $R = p_T/0.3B = 33 \div 330$ cm

Drift chamber

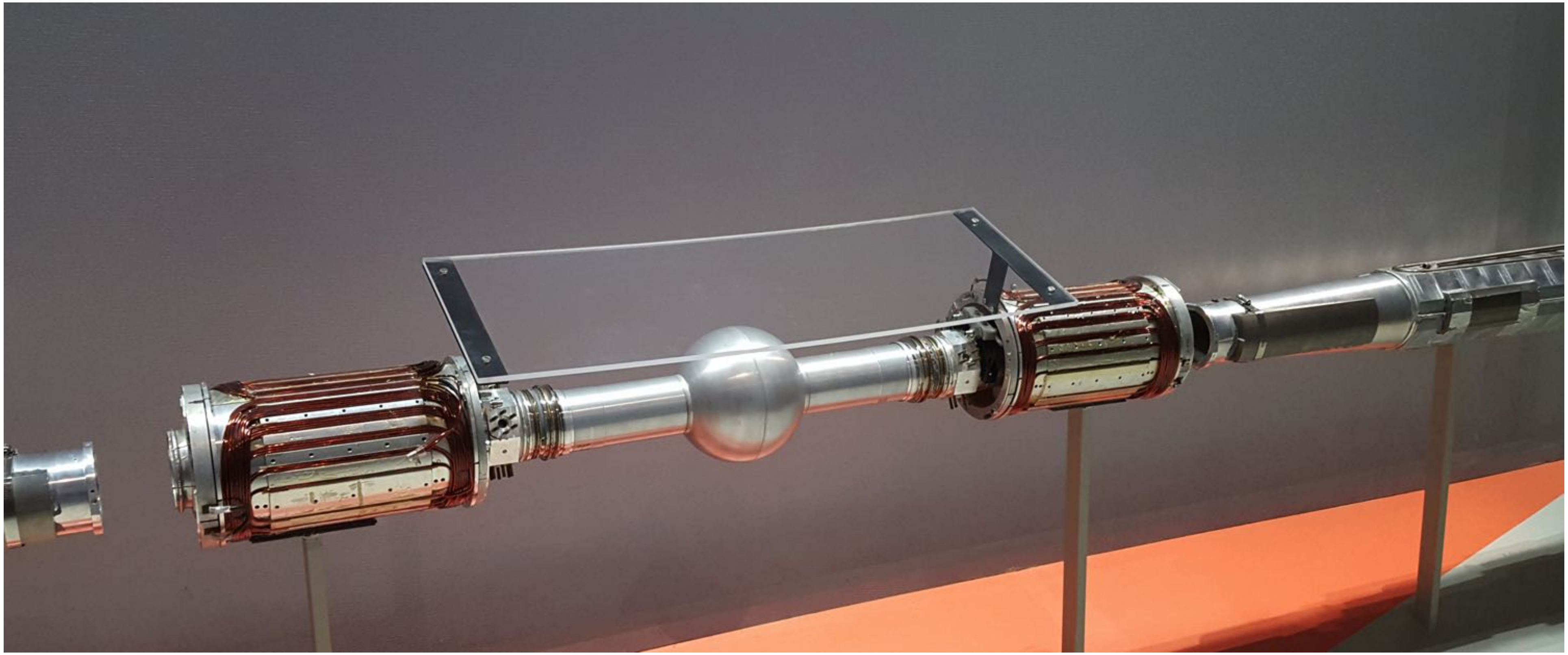
- $\approx 10^4$ wires in stereo configuration
- momentum measurement down to
  - 50 MeV
- typical track: ≈ 30 hits with 200 μm
- space resolution each.

Calorimeter

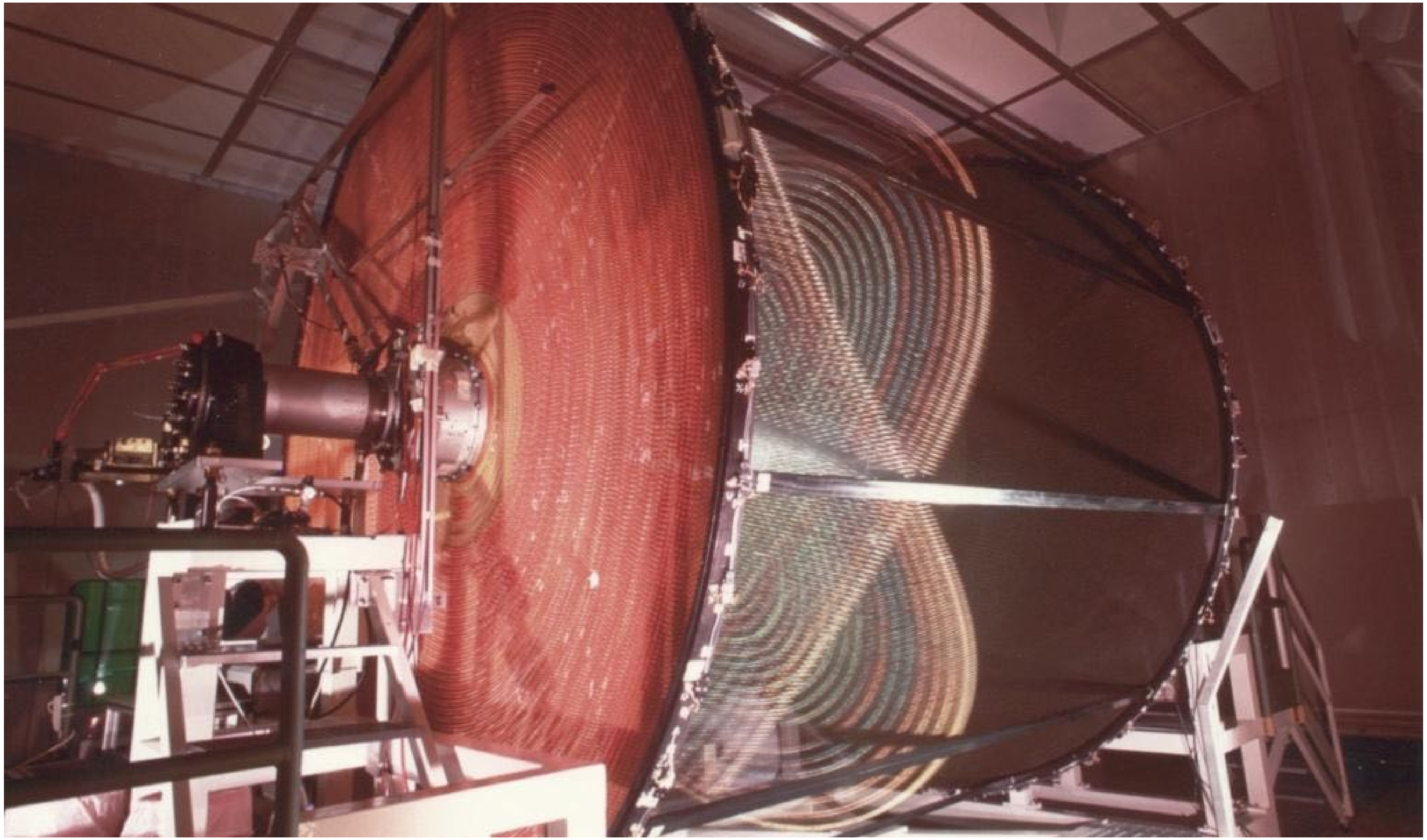
- Lead-Scintillating fibers calorimeter
- Read-out through 4880 PMTs
- Energy resolution (record for a sampling calorimeter)

$$\frac{\sigma(p_T)}{p_T} \approx 0.4\%$$

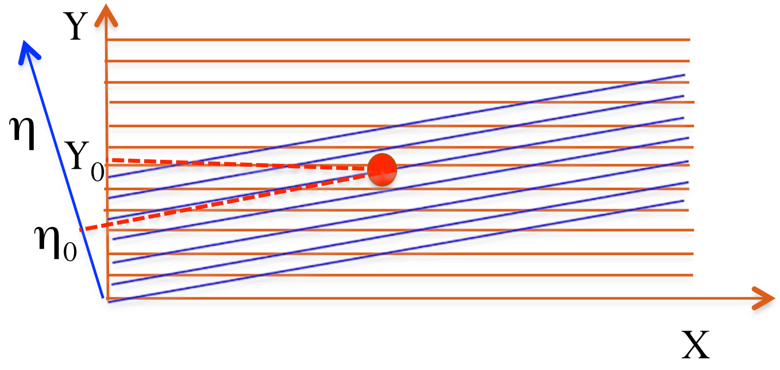
$$\frac{\sigma(E)}{E} \approx \frac{5.7\%}{\sqrt{E(GeV)}}$$



The KLOE drift chamber



Stereo wires



Measurement of two coordinates in the two views:

$Y = Y_0$

$\eta = \eta_0$

Each measurements is a line in the X-Y plane:

$Y = Y_0$

$Y = \eta_0 / \cos\theta + tg\theta\, X$

Risolvo il sistema e ottengo ($\sin\theta \approx \theta$, $\cos\theta \approx 1$)

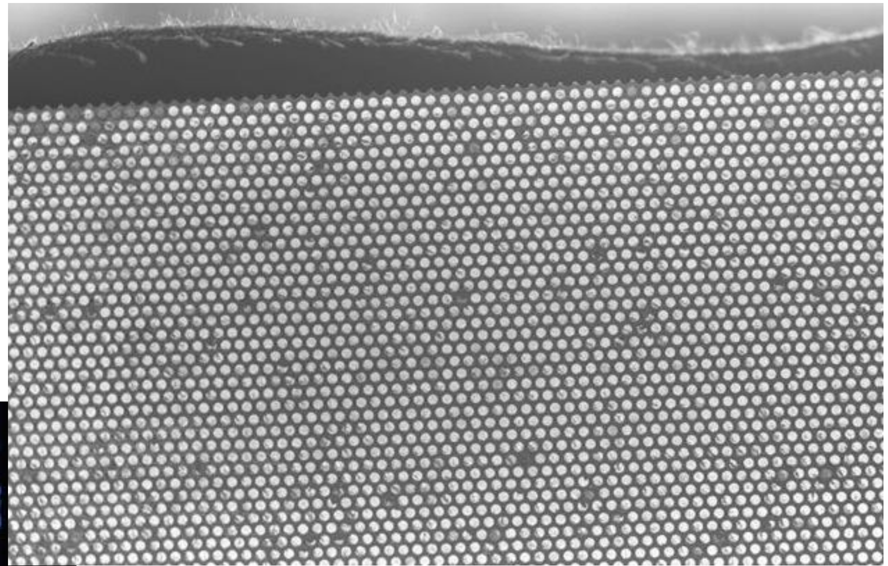
$X = (Y_0 \cos\theta - \eta_0)/\sin\theta \approx (Y_0 - \eta_0)/\theta$

NB: given $\sigma(Y_0) \sim \sigma(\eta_0)$

➔ $\sigma(X) = \sigma(Y_0)\, \sqrt{2}/\theta$

The KLOE calorimeter

The KLOE calorimeter



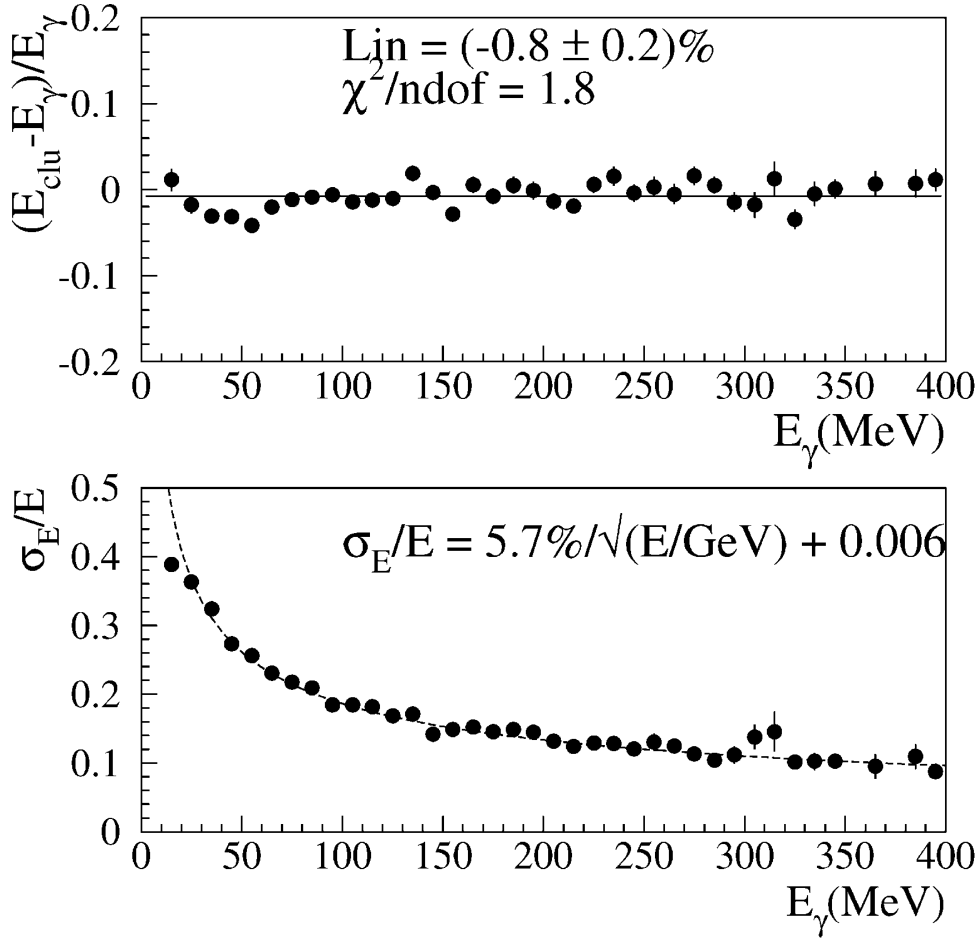


Fig. 1. $e^+e^- \to e^+e^-\gamma$: (a) Differential linearity vs. E_γ, (b) Energy resolution vs. E_γ.

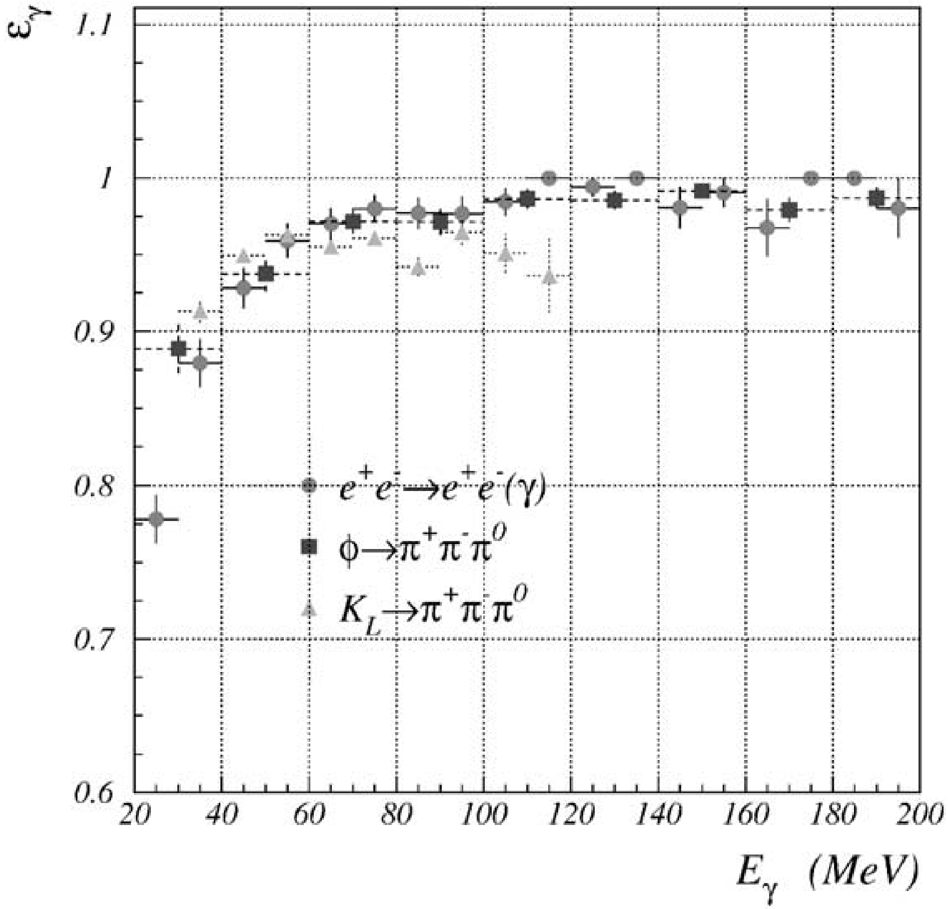


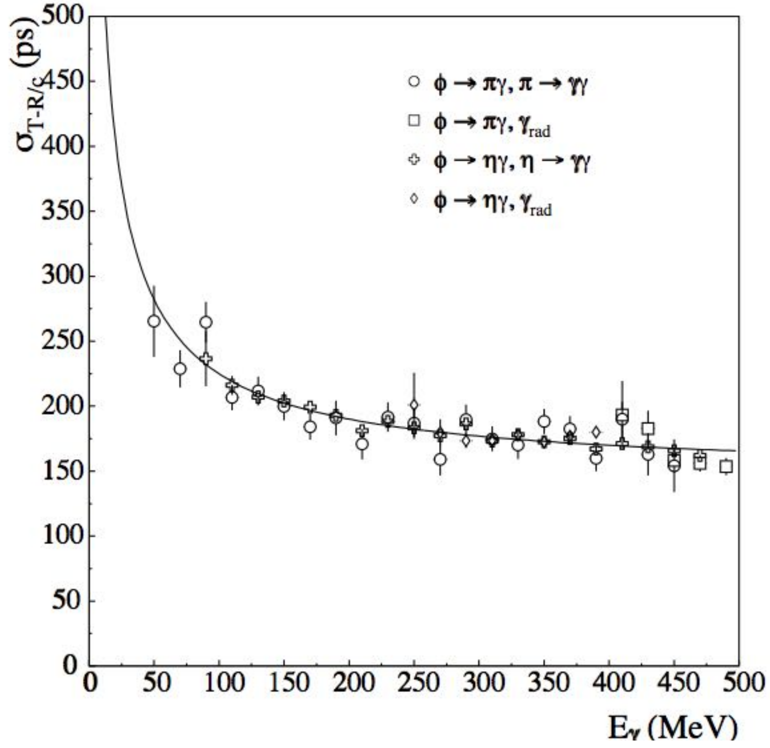
Fig. 38. Photons efficiency vs. energy for $e^+e^- \to e^+e^-\gamma$ events (circles), $\phi \to \pi^+\pi^-\pi^0$ (squares) and $K_L \to \pi^+\pi^-\pi^0$ (triangles).

KLOE calorimeter: Time-of-flight

Time resolution for scintillators:

- τ is the scintillator decay time;
- N_{pe} is the number of photoelectrons/MeV
- N is the total number of photoelectrons
  - $= N_{pe} \times E(\text{MeV})$
- tts = Transite Time Spread (PMT, guides,..)

$$\sigma(t) = (\tau + tts)/\sqrt{N} \approx const/\sqrt{E}$$



In KLOE:

- $\tau \approx 2$ ns
- $Npe \approx 2$/MeV
- $tts \approx 0.3$ ns

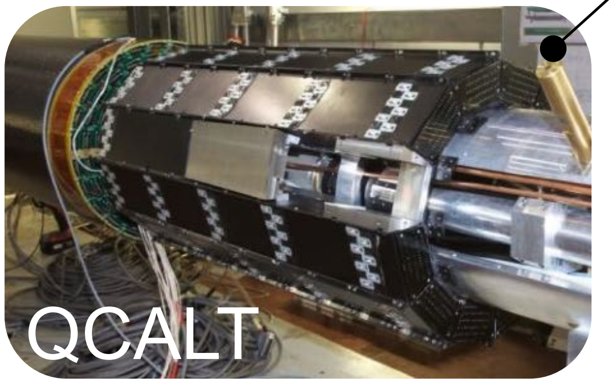
$$\sigma_t = 54 \text{ ps}/\sqrt{E \text{ (GeV)}} \oplus 140 \text{ ps}$$

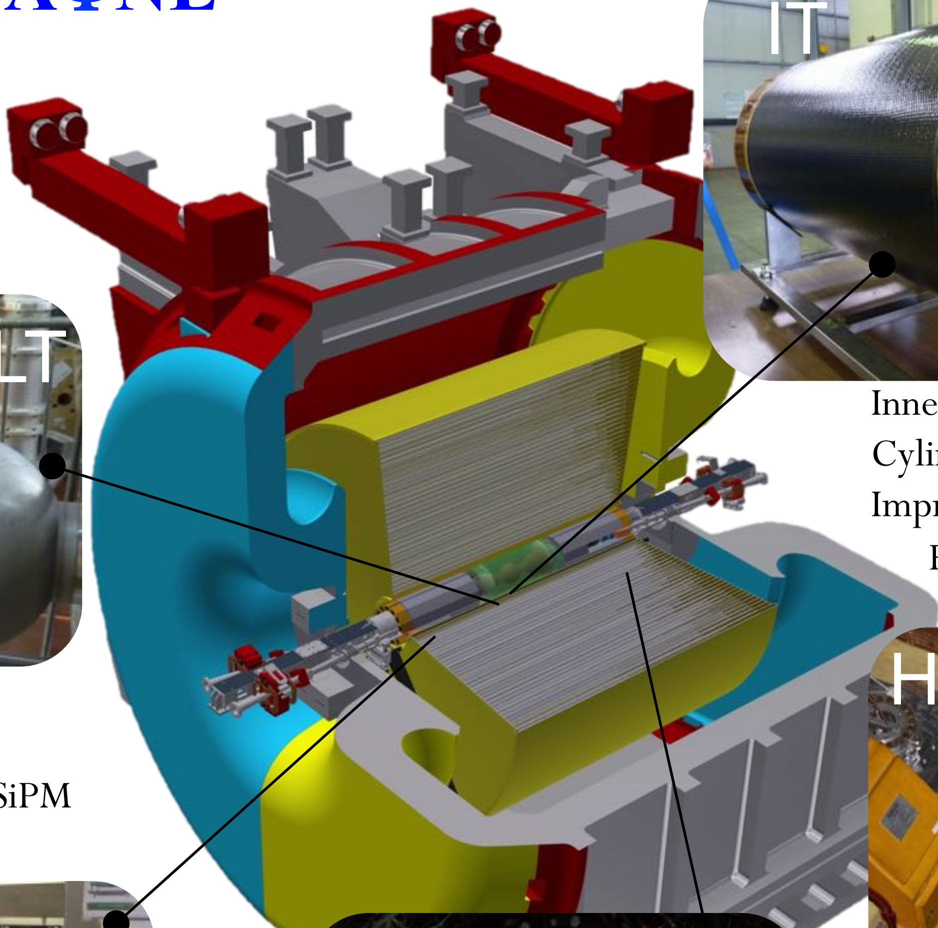
Spread in the “start” time

KLOE-2 at DAΦNE

LYSO Crystal w SiPM
Low polar angle

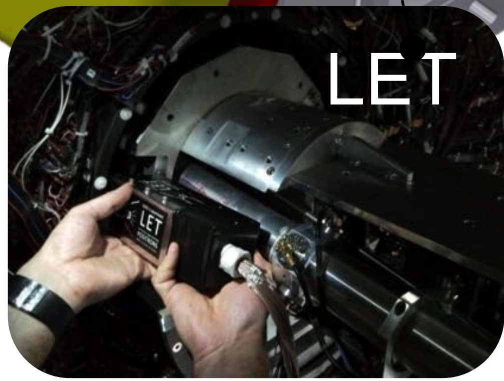
Tungsten / Scintillating Tiles w SiPM
Quadrupole Instrumentation



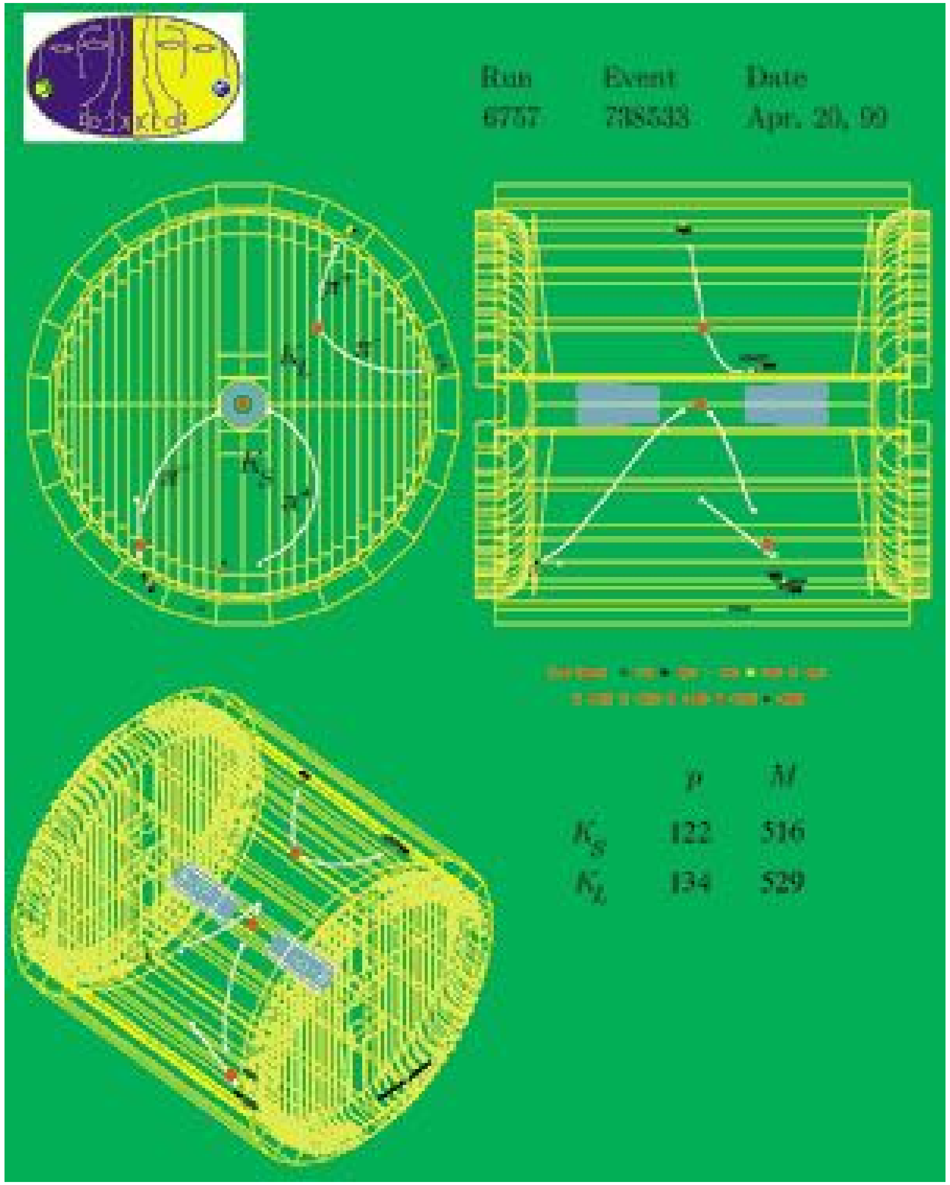


Inner Tracker – 4 layers of
Cylindrical GEM detectors
Improve track and vtx reconstr.
First CGEM in HEP expt.

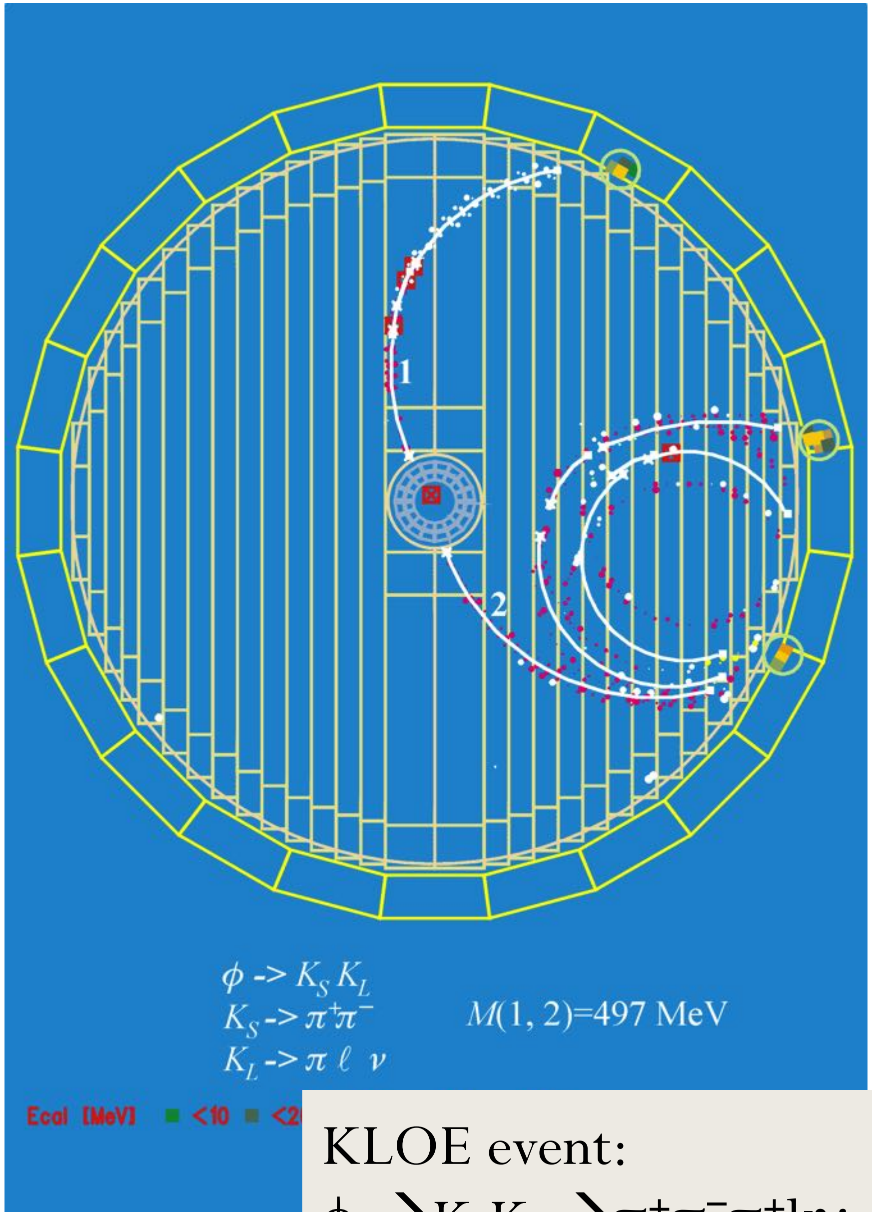
Scintillator hodoscope +PMTs



calorimeters LYSO+SiPMs at
~ 1 m from IP

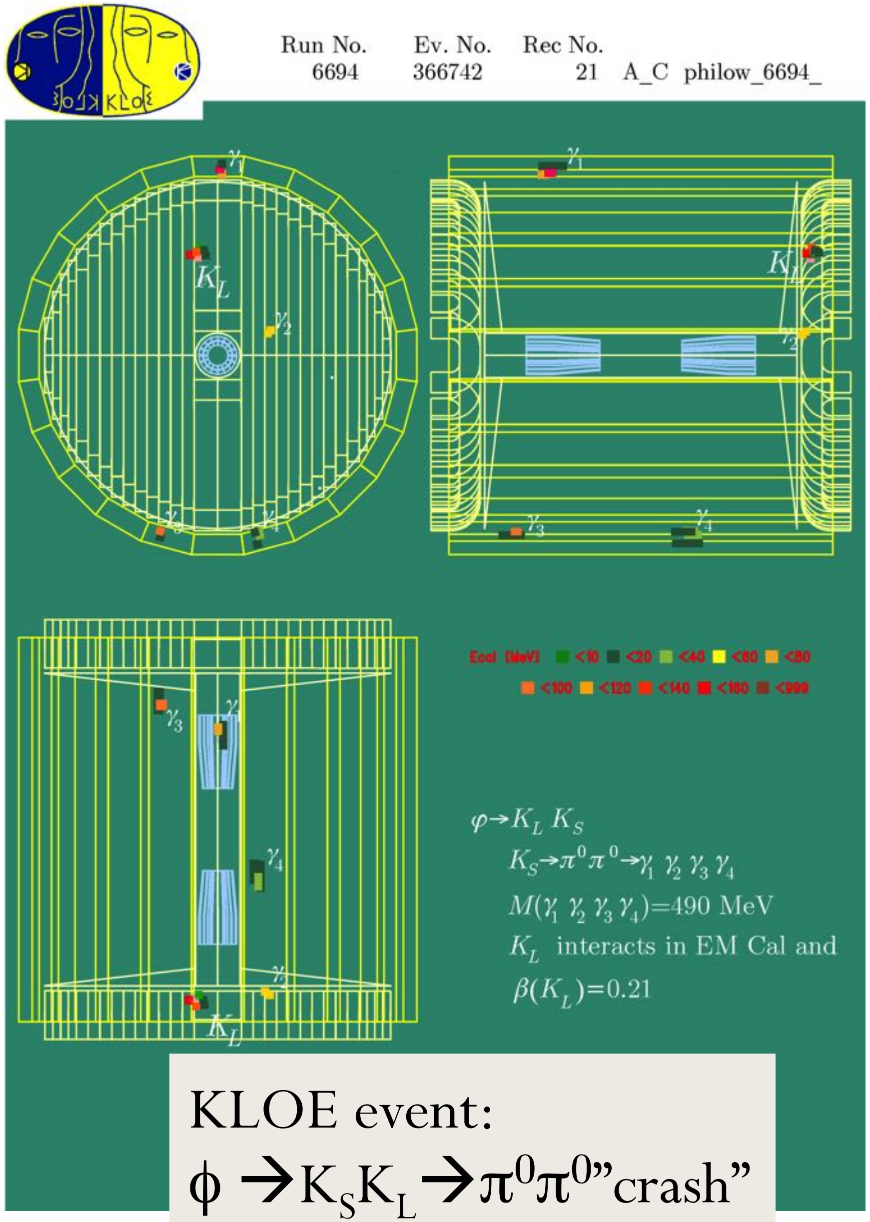


KLOE event:
$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^+\pi^-$



KLOE event:

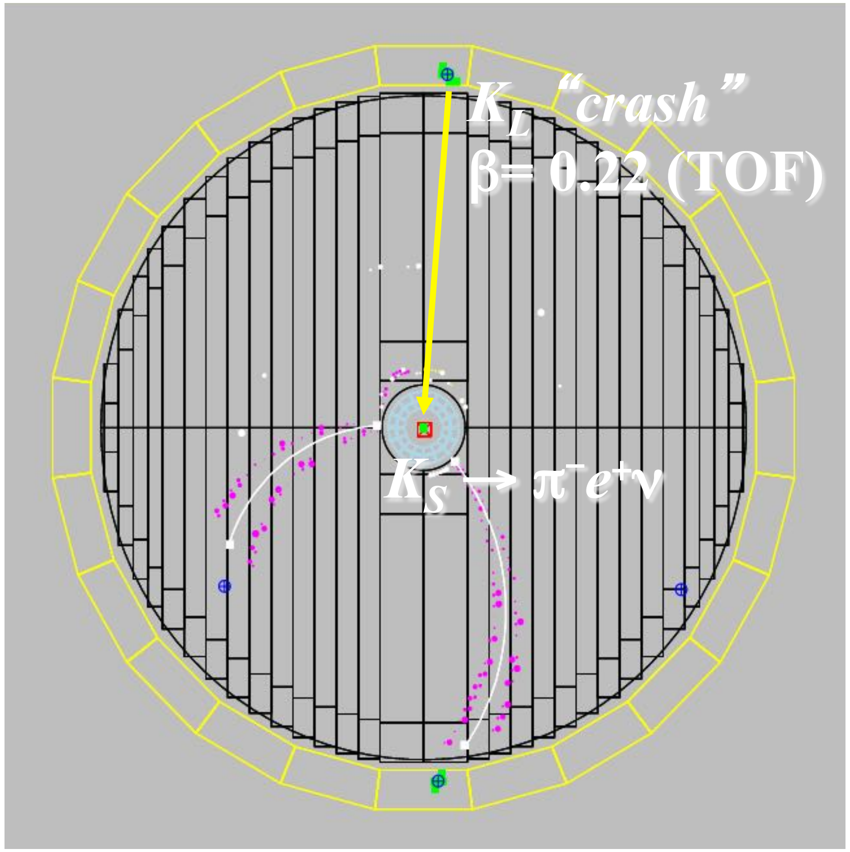
$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ l^- \nu$



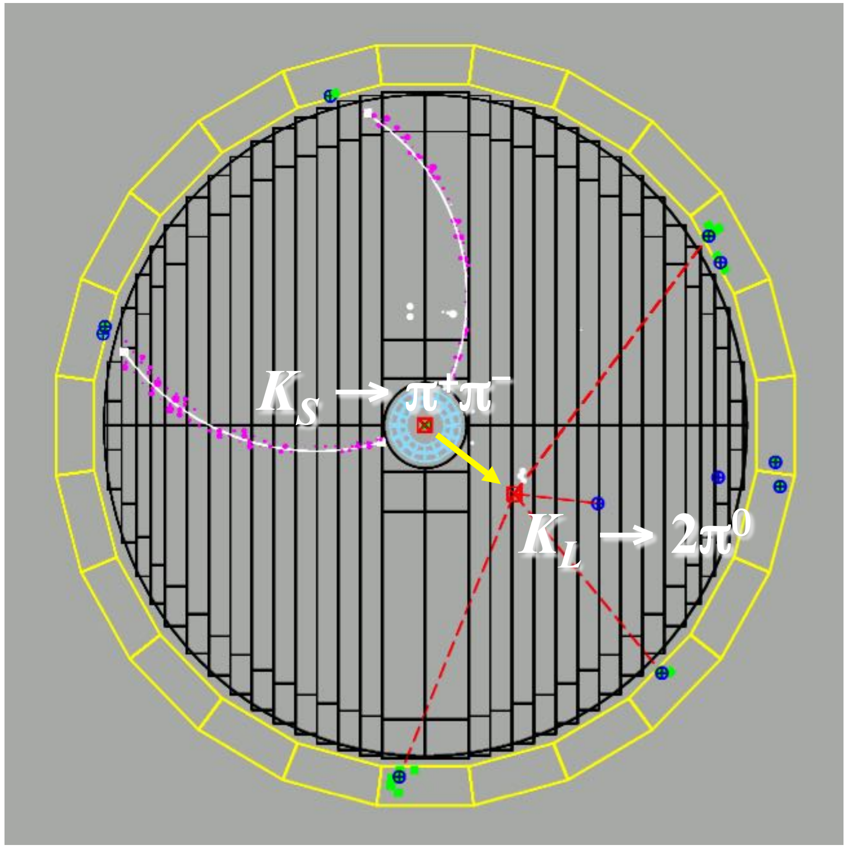
KLOE event:

$\phi \rightarrow K_S K_L \rightarrow \pi^0 \pi^0$"crash"

K_S and K_L Tagging at KLOE



K_S tagged by K_L interaction in EmC
Efficiency ~ 30% (largely geometrical)
K_S angular resolution: ~ 1° (0.3° in φ)
K_S momentum resolution: ~ 2 MeV



K_L tagged by $K_S \rightarrow \pi^+\pi^-$ vertex at IP
Efficiency ~ 70% (mainly geometrical)
K_L angular resolution: ~ 1°
K_L momentum resolution: ~ 2 MeV