The KLOE calorimeter

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*A sampling calorimeter based on Lead and **Scintillating fibres** to detect photons $20 < E_\gamma < 500$ MeV*

"History"

1992-1995 Prototype tests
1995-1997 Calorimeter construction
1998 Calorimeter installed in KLOE
1999-… KLOE data taking (~ 500 pb^{-1} integrated luminosity)

M.Adinolfi et al.:NIM A 482 (2002) 364-386

1) Motivations and Requirements

KLOE: e^+e^- collisions at $\sqrt{s} = M(\phi) = 1020$ MeV
final states:

49% $K^+K^- \to \mu\nu,\ 2\pi,\ 3\pi$

34 % $K_S K_L \to \pi^+\pi^-, \pi^0\pi^0$

$\to \pi\mu\nu,\ \pi e\nu,\ \pi^+\pi^-\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-, \pi^0\pi^0$

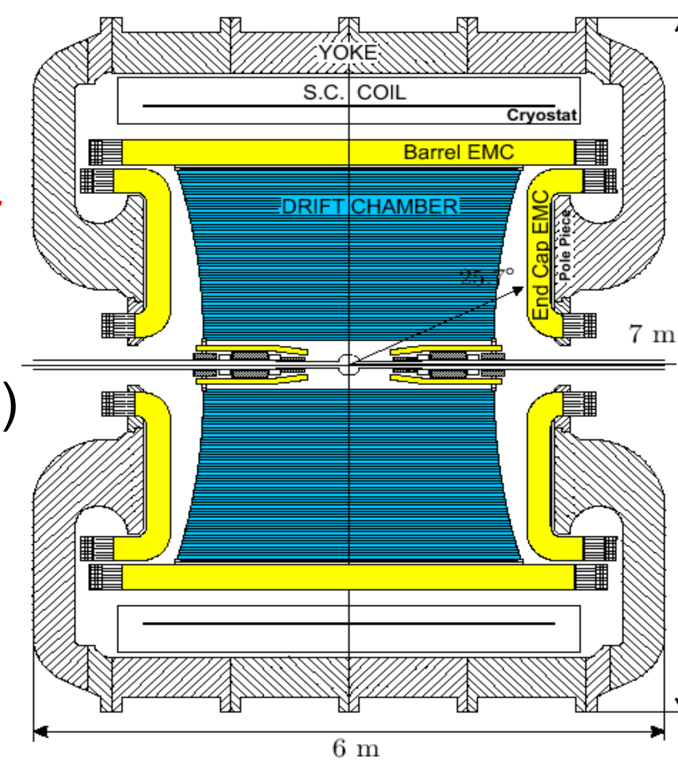
15% $\pi^+\pi^-\pi^0$

1% $\eta\gamma \to \gamma\gamma\gamma,\ \pi^0\pi^0\pi^0\gamma,\ \pi^+\pi^-\pi^0\gamma$

other decays $\to$ …

Charged particles: pions muons electrons up to **500 MeV**
: charged kaons p = **110 MeV/c**
Neutral particles: photons **20** < E < **500 MeV**
: K_L (λ_L = **340 cm**) p = **110 MeV/c**

The KLOE detector:
Drift Chamber
E.M. Calorimeter
Q.Calorimeter
Magnetic field
= **0.52 T** (solenoid)



Requirements on the calorimeter:

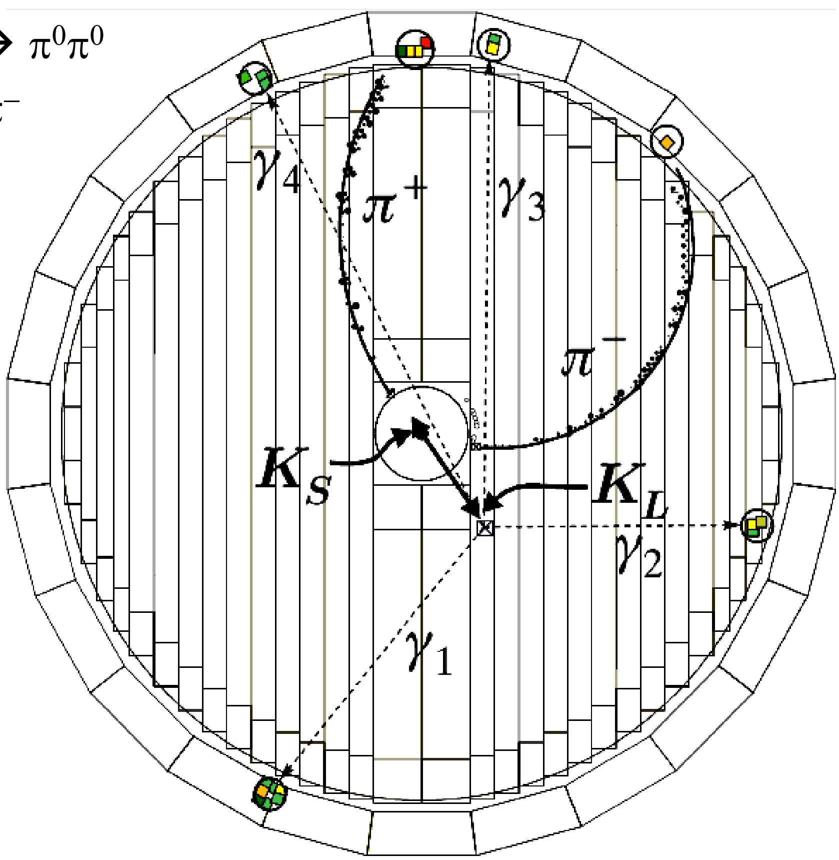
0. Hermeticity (photon counting, 2 π^0 vs 3 π^0 decays)
1. Efficiency for photons **20** < E < **500 MeV**
2. Energy resolution **< 7%/$\sqrt{E}$** in this range
3. Time resolution ~ **100 ps** in this range
4. Fast response (main trigger device)
5. Charged particle identification (π vs e vs μ)

→Identification of $K_L \rightarrow \pi^0\pi^0$ decay in the "fiducial volume"

Event

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

$\rightarrow \pi^+\pi^-$

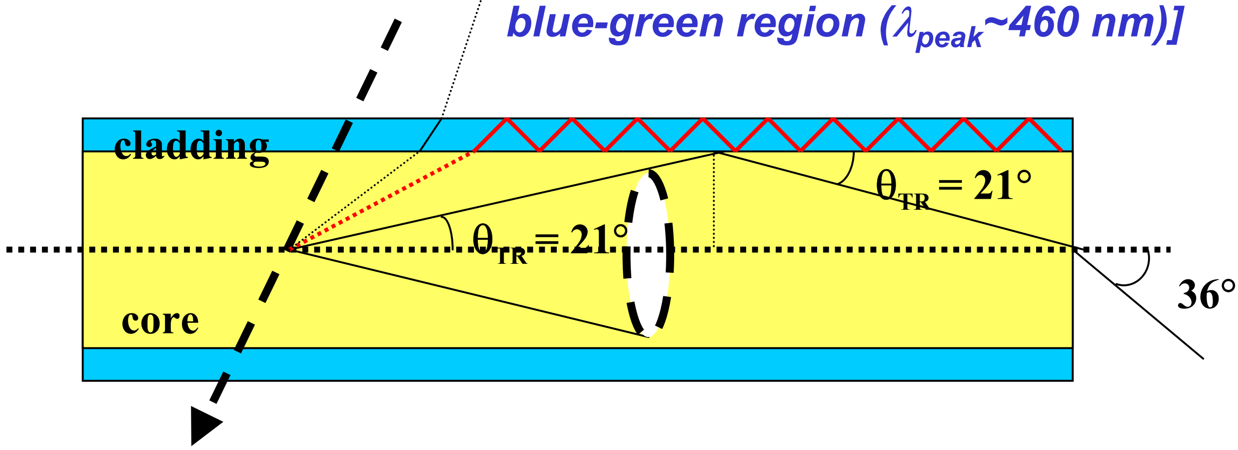


→Identification of $\pi^+\pi^-\gamma$ events respect to $e^+e^-\gamma$ background

→Identification of $K_S \rightarrow \pi l \nu$ respect to $K_S \rightarrow \pi^+\pi^-$ (**10^3** times more frequent)

2) Working principle and Calorimeter structure

(1) Scintillating fiber (1mm diameter) [emitting in the blue-green region (λ_{peak}~460 nm)]



n(core=**polystirene**) = **1.6** n(cladding=**PMMA**) = **1.49**

Only **~3%** of photons produced are trapped in the fiber

But :

(a) ~ uni-modal propagation at **21°** ➔ small transit time spread

(b) Small attenuation (λ ~ **4-5 m**)

(c) Cladding light removed by optical contact with glue n(glue) ~ n(core)

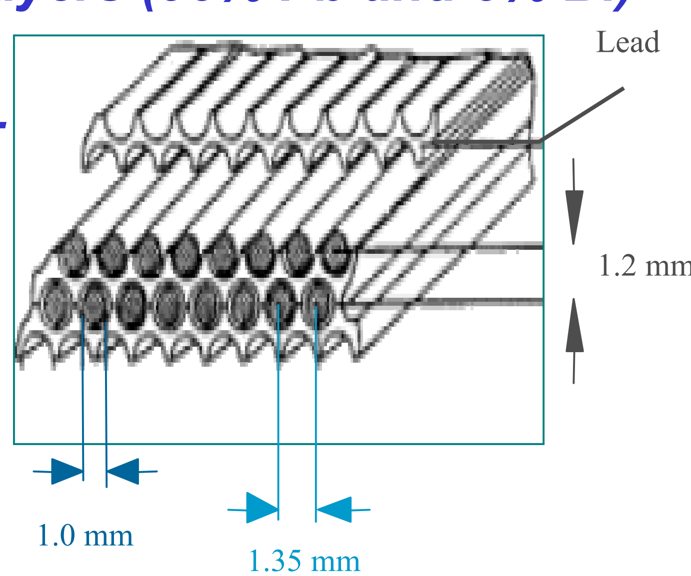
Fibers used: *Kuraray SCSF-81* *Pol.Hi.Tech. 00046*

15.000 km of fibers

(fully tested: *A.Antonelli et al., NIM A370 (1996) 367*)

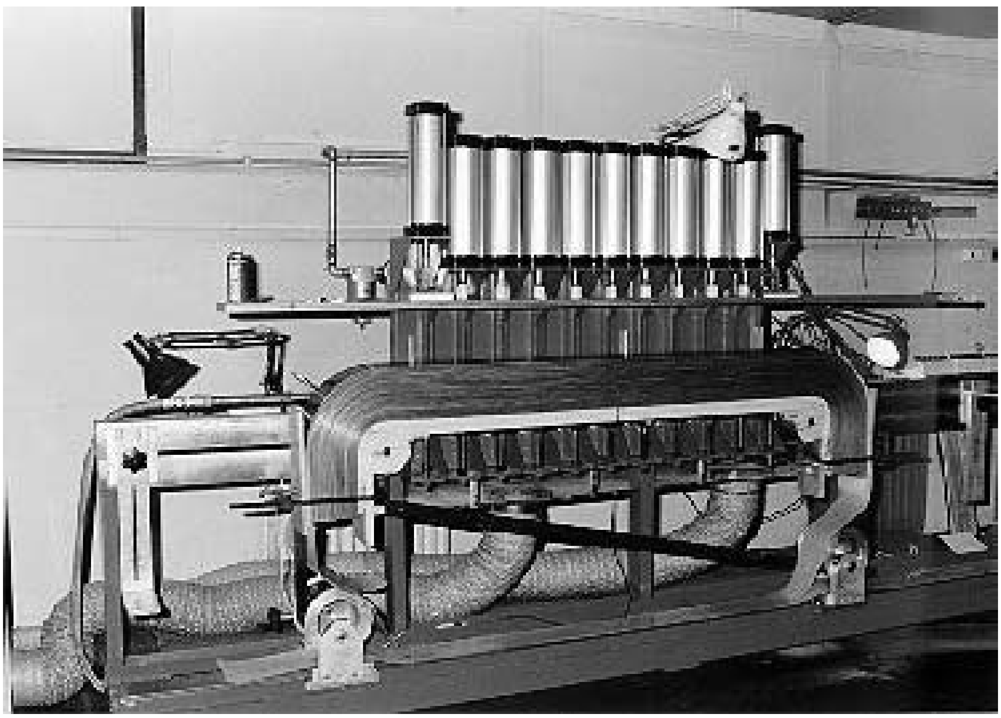
(2) Lead: 0.5mm grooved layers (95% Pb and 5% Bi)

(3) Glue: Bicron BC-600ML + hardener (28%) (1.5 h pot life)



Construction scheme:

lead foil + glue + fiber layer
repeat **10-15** layers
wait for glue curing with **1.1 atm** pressure (pistons)
90° bending (in case of end-cap modules)
repeat up to ~ **200 layers** (one module complete)



Assembly station for End-Cap modules

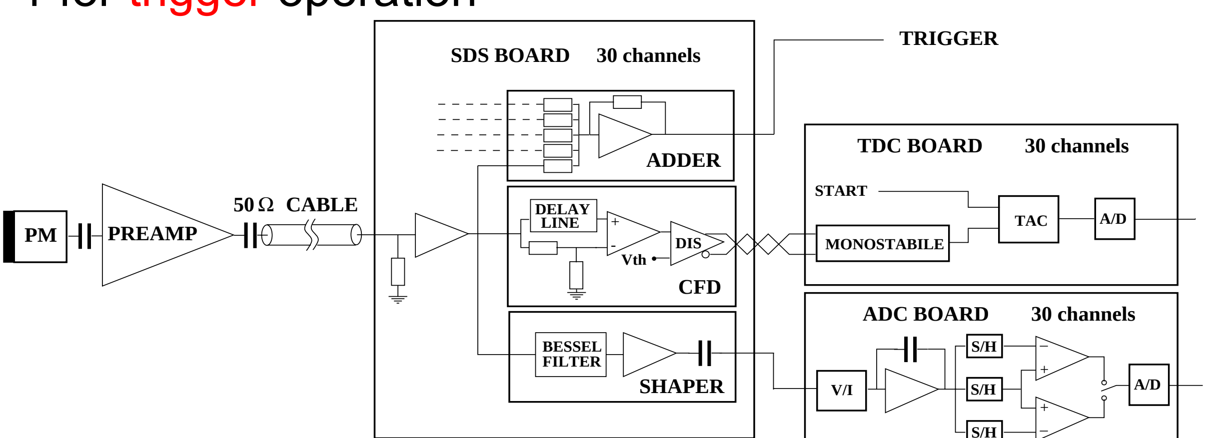
Properties of the resulting structure:

Lead : Fiber : Glue volume ratio = **42 : 48 : 10**
Density = **5 g / cm^3**
Radiation Length = **1.5 cm**
Module thickness = **23 cm (~ 15 r.l.)**

Plexiglass light guides (**n=1.6**, **20 cm** length [Winston cone])
Glued on both sides (after milling) ➔ **4.4 X 4.4 cm^2** granularity:

Fine-mesh photomultipliers **(1.5')** Hamamatsu **R5960**
Working in **B=0.1-0.2T** and **$0 < \theta < 30^o$** (**Q.E.~25%** , **G~5 x10^6**)
Fully tested (see *A.Antonelli et al. NIM A379 (1996) 511*)

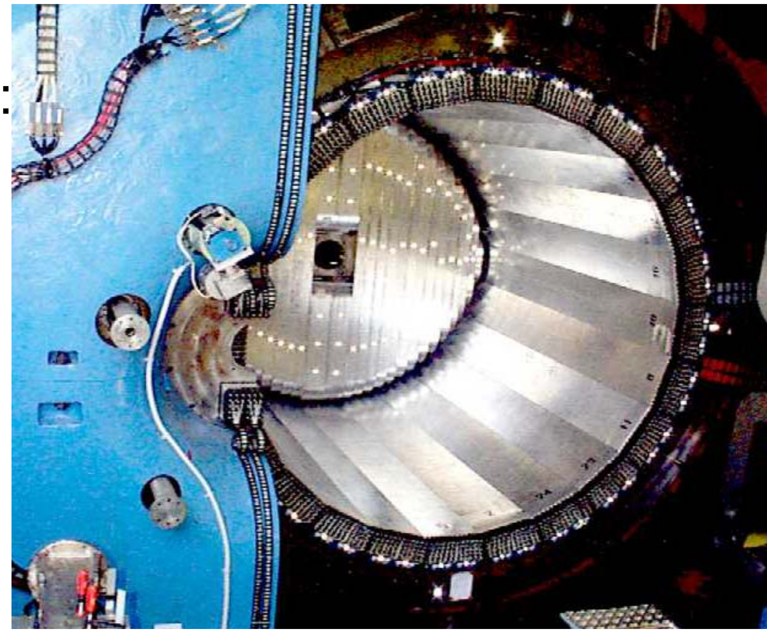
Readout scheme:
The signal is splitted in 3 parts:
1 for energy measurement
1 for time measurement (discriminated: threshold = **4 mV**)
1 for trigger operation



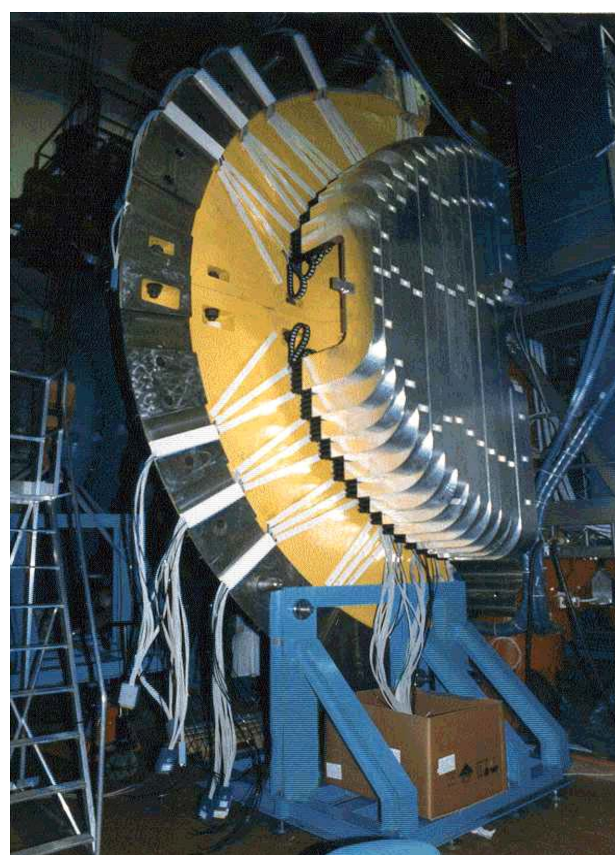
➔ **4880** read-out channels: light guides + PMT + electronics

General Structure:

All modules ➔ fibers almost ⊥ to the incoming particle



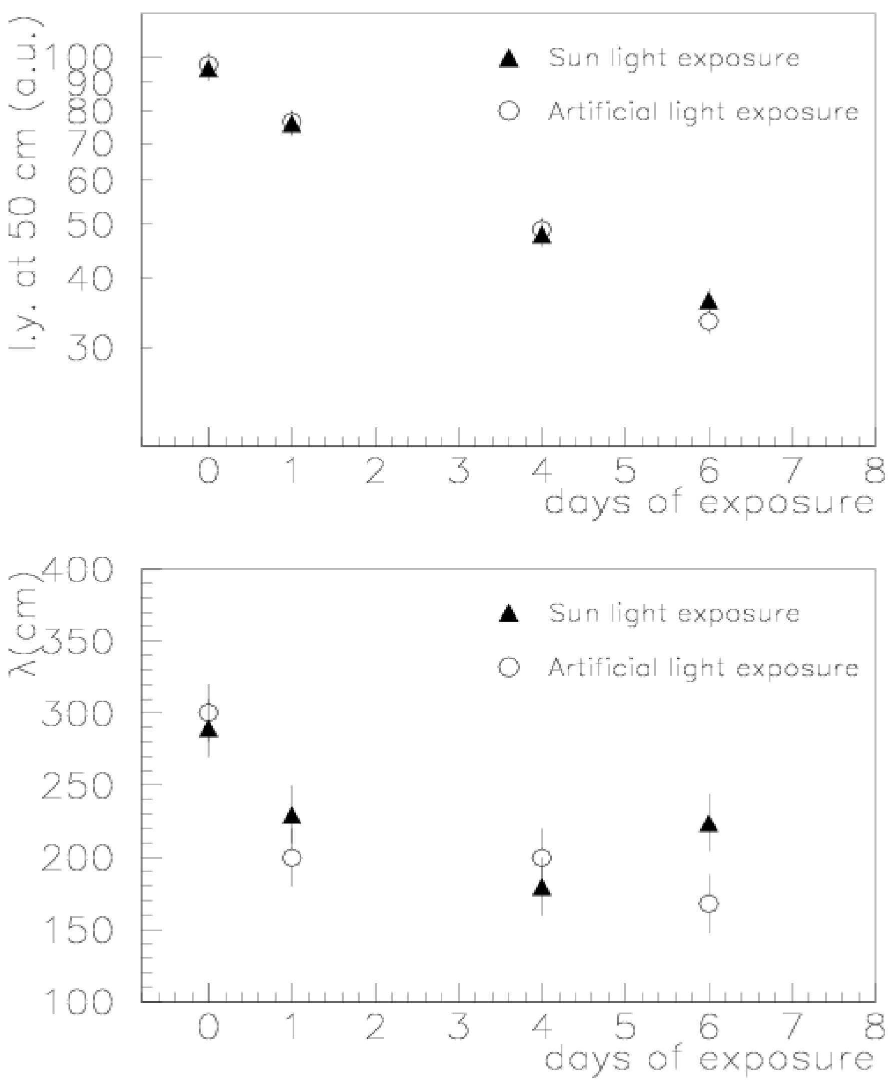
(1) Barrel: **24** modules:
Trapezoidal section
(52 – 59) X 23 cm²
4.3 m length
➔ cylinder
diameter = 4 m
length = 4.3 m



(2) End-Caps:
32 modules each:
Rectangular sections
(9-27) X 23 cm²
0.7-3.9 m length (bent on both sides)
➔ 2 circles of 4 m diameter

Damage induced by UV light irradiation:
problem for Kuraray fibers only

➔ filtering at the windows during fiber manipulation and calorimeter construction



Calorimeter expected performance:

Light Yield ➔ Efficiency:

P1) Sampling fraction (for e.m. showers) ~ **12%**

P2) Intrinsic light yield ~ **5x10^3 photons / MeV**
P3) Collection efficiency ~ **3%**
P4) Absorption @ 2 m ~ **50%**

P5) PMT q.e. ~ **25%**

➔ Light Yield = (1 / 2)*P1*P2*P3*P4*P5
~ 1 p.e. / MeV /side @ 2 m

Discriminator threshold ~ **3 – 4 p.e.**
➔ below 10 MeV photons, sizeable efficiency loss

Resolutions:

1) Energy resolution : dominated by sampling fluctuations:

$$\frac{\sigma_E}{E} = \left(\frac{4.2\%}{\sqrt{E(GeV)}}\right)_{sampling} \oplus \left(\frac{2.5\%}{\sqrt{E(GeV)}}\right)_{p.e.} \oplus \ldots$$

(see *A.Antonelli et al. NIMA 354 (1995) 352*)

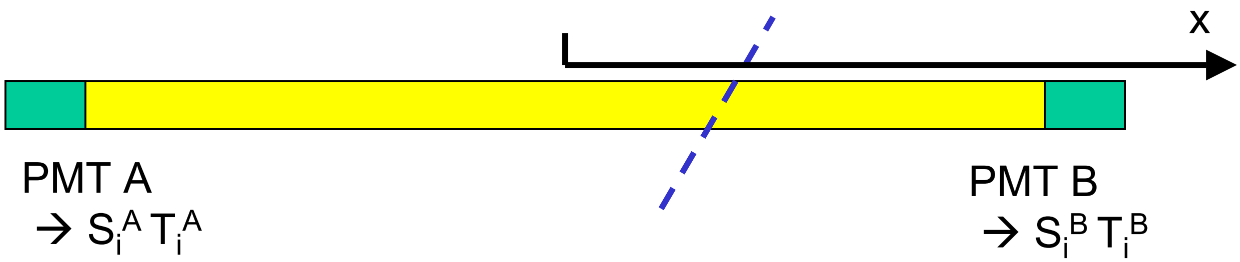
2) Time resolution: dominated by p.e. statistics.

$$\sigma_t = \frac{\tau_{decay} \oplus \sigma_{fiber} \oplus \sigma_{l.g.}}{\sqrt{N(p.e.)}} \approx \frac{2.2ns}{\sqrt{N(p.e.)}} \approx \frac{50\,ps}{\sqrt{E(GeV)}}$$

$$\tau_{decay} \approx 2.2ns >> \sigma_{fiber}, \sigma_{l.g.}$$

(see *A.Antonelli et al. NIMA 370 (1996) 367*)

3) Operation in the Experiment



Reconstruction of Energy Time and Impact position:

1) Energy:

$$E_i(MeV) = \frac{E_i^A A_i^A(x) + E_i^B A_i^B(x)}{2}$$

where:

$$E_i^{A,B} = \frac{S_i^{A,B} - S_{o,i}^{A,B}}{S_{M,i}^{A,B}} \times \kappa_E$$

and:

$A_i(x)$ = attenuation factor
$S_{0,i}$ = channel ADC pedestal
$S_{M,i}$ = calibration constant from cosmic rays M.I.P.s
κ_E = overall energy scale

2) Time:

$$t_i(ns) = \frac{t_i^A + t_i^B}{2} - \frac{t_{0,i}^A + t_{0,i}^B}{2} - \frac{L}{2v}$$

where:

t_i = **c_i x T_i** times in ns (after conversion from TDC counts)
$t_{0,I}$ = time offsets
L = module length
v = light velocity in the fibers

3) Impact position:

along the fiber direction:

$$s_i(cm) = \frac{v}{2}\left(t_i^A - t_i^B - t_{0,i}^A + t_{0,i}^B\right)$$

transverse to fiber direction:
→ center of the cell

Groups of hit cells ➔ energy cluster

$$E_{cl} = \sum_{i=1}^{N} E_i \qquad s_{cl} = \frac{\sum_{i=1}^{N} E_i s_i}{E_{cl}}$$

$$t_{cl} = \frac{\sum_{i=1}^{N} E_i t_i}{E_{cl}} \qquad x_i, y_i = \frac{\sum_{i=1}^{N} E_i x_i, y_i}{E_{cl}}$$

Constants to be determined and calibrated:

$\mathbf{S_{0,I}}$	ADC pedestals per channel
$\mathbf{S_{M,I}}$	ADC response to M.I.P.s per channel
A(x)	attenuation curve per channel
κ_E	absolute energy scale (ADC → MeV)
$\mathbf{c_i}$	TDC calibration constants (TDC → ns)
$\mathbf{t_{0,I}}$	TDC offset per channel
L	module length
v	light velocity in the fibers

Calibration procedure:

(0) Pre-Calibration and response equalization with cosmic rays

(1) Routinely cosmic ray runs M.I.P.s Every 1-2 weeks

→ $\mathbf{S_{M,I}\ t_{0,I}\ v\ \ A(x)}$

(2) $e^+e^- \rightarrow \gamma\gamma$ events: source of monochromatic 510 MeV photons → $\kappa_E\ \mathbf{c_i}$

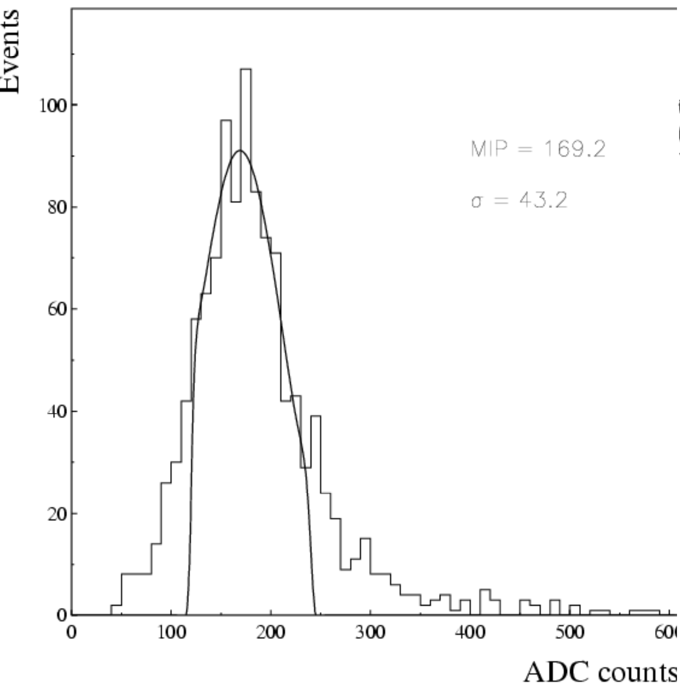
Every **200 nb^{-1}** (~ 1 h)

➔ write Cal.DB after 1-2 hours from end of run

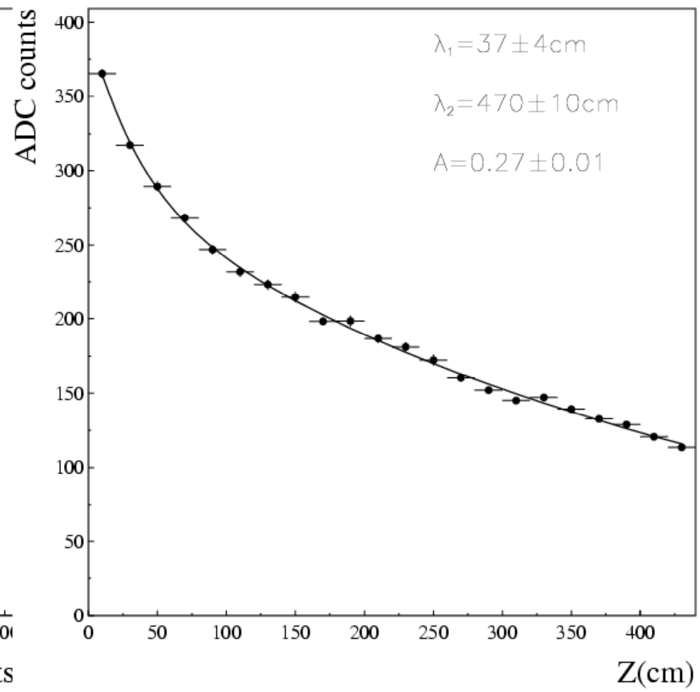
➔ starts data reconstruction

Cosmic Ray Calibration:

1) Energy: a M.I.P. crossing a cell (4.4 cm path)

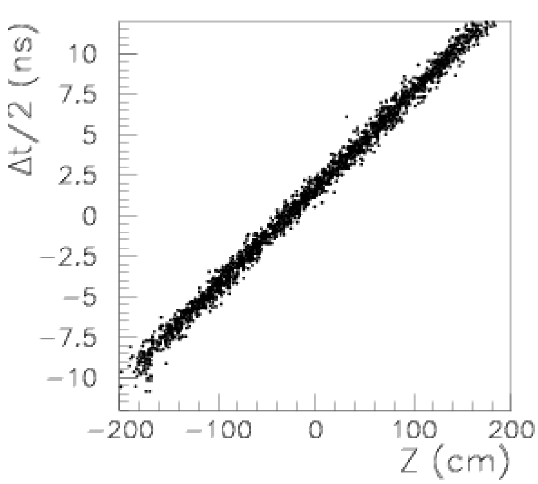


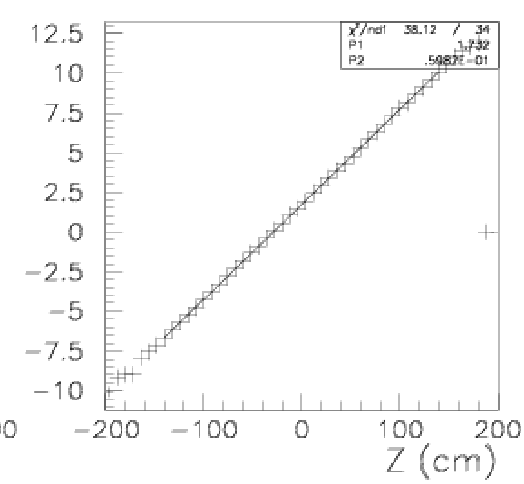
M.I.P. spectrum



M.I.P. peak vs. Z

2) Time: Z obtained by external informations (from D.C.)





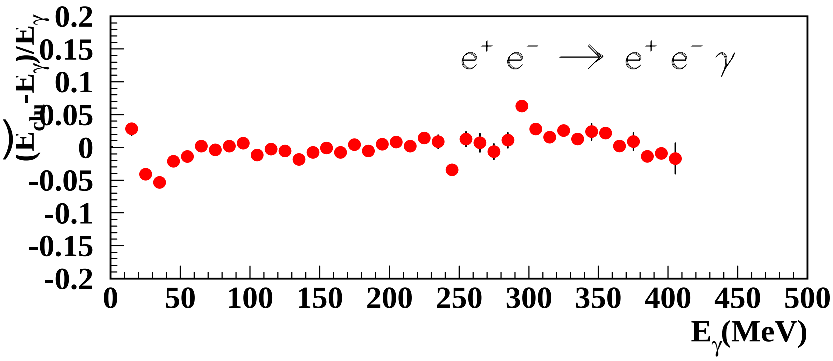
$t^A - t^B$ vs Z ➔ slope = 1/v ➔ **<v> = 16.75 cm / ns**

[v ~ (c / n) x cos (21^o) ~ (30 / 1.6) x 0.93 = 17.4]

Energy measurement:

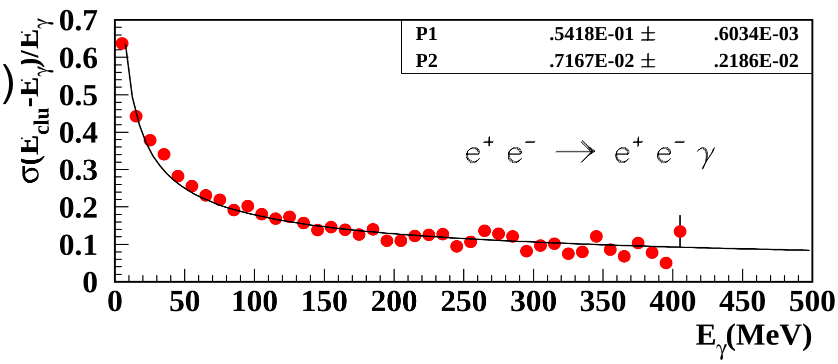
Absolute energy scale fixed by $e^+e^- \rightarrow \gamma\gamma$ peak
Linearity checks using D.C. information

Linearity:
from $e^+e^-\gamma$
(slight deviation (within 4%) below 80 MeV)



Resolution:
from $e^+e^-\gamma$
(mostly end-cap resolution)

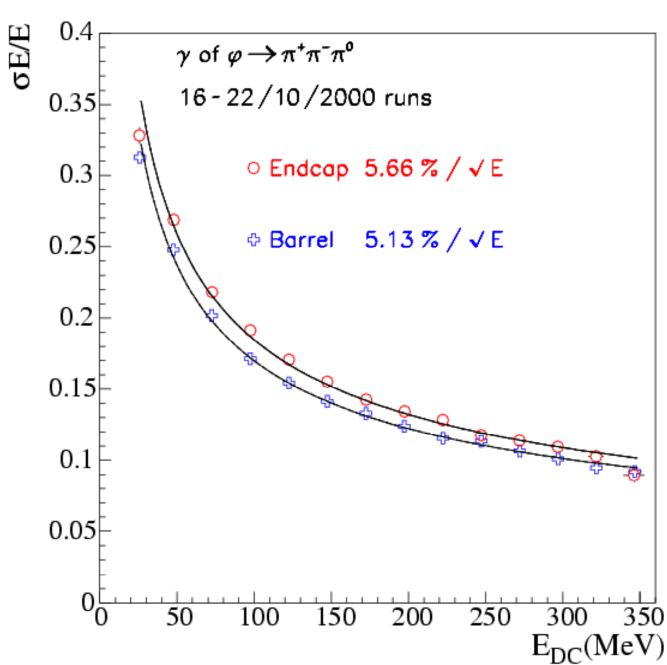
$$\frac{\sigma_E}{E} = \frac{5.4\%}{\sqrt{E(GeV)}}$$



Resolution:
from $\pi^+\pi^-\pi^0$
(barrel vs end-cap)

$$\left(\frac{\sigma_E}{E}\right)_{BARREL} = \frac{5.1\%}{\sqrt{E(GeV)}}$$

$$\left(\frac{\sigma_E}{E}\right)_{END-CAP} = \frac{5.7\%}{\sqrt{E(GeV)}}$$

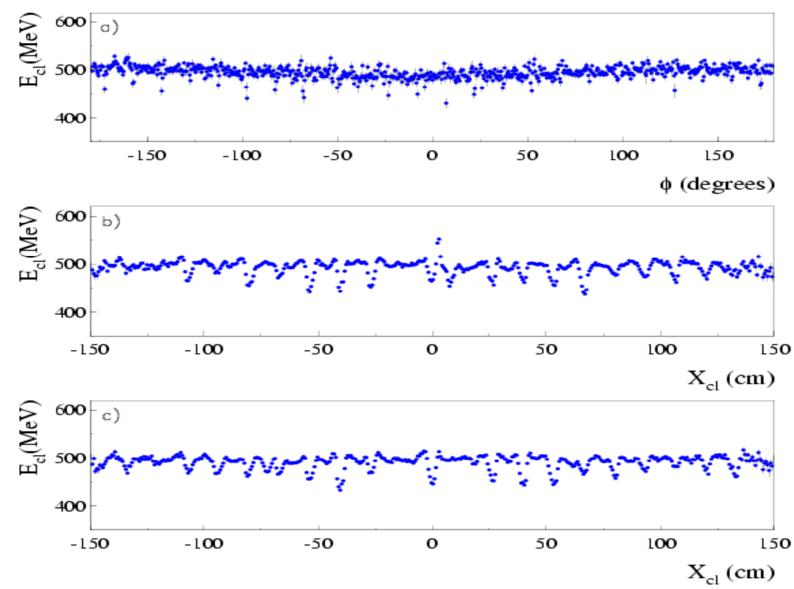


Uniformity of the energy response: holes between modules
➔ worsening of end-cap resolution compared to barrel

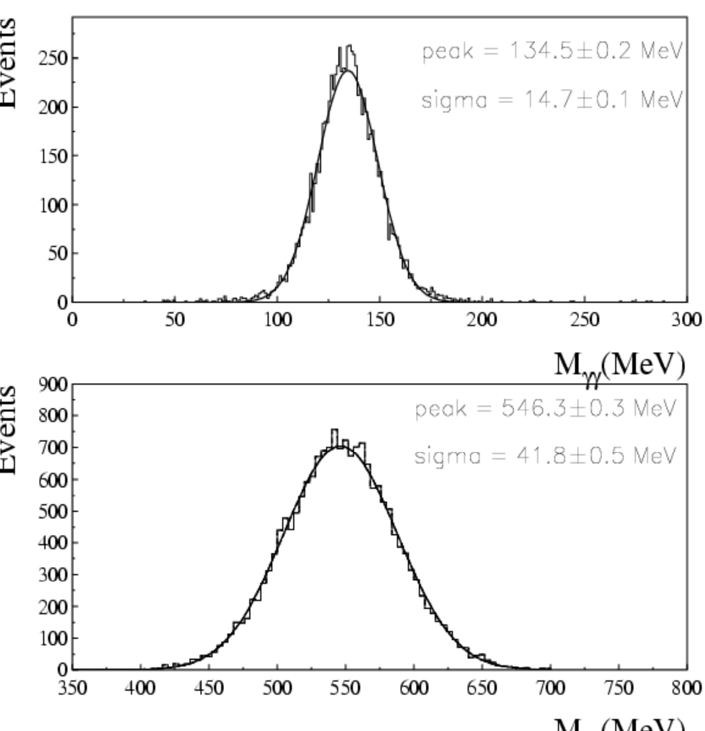
BARREL
(E vs ϕ)

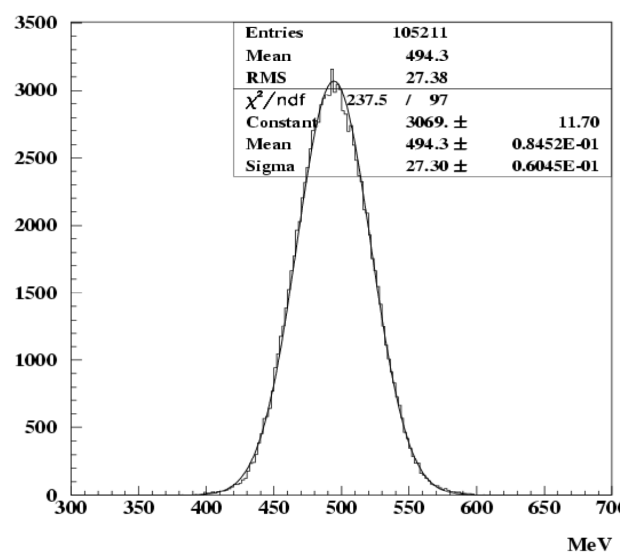
END-CAP 1
(E vs X)

END-CAP 2
(E vs X)



Energy response checks: particle invariant masses:
M (π^0 ➔ $\gamma\gamma$)   M (η ➔ $\gamma\gamma$)   M (K_S ➔ $\pi^0\pi^0$ ➔ $\gamma\gamma\gamma\gamma$)





(δM / M) = **-0.3% -0.7% -0.2%**
(π^0) (K_S) (η)

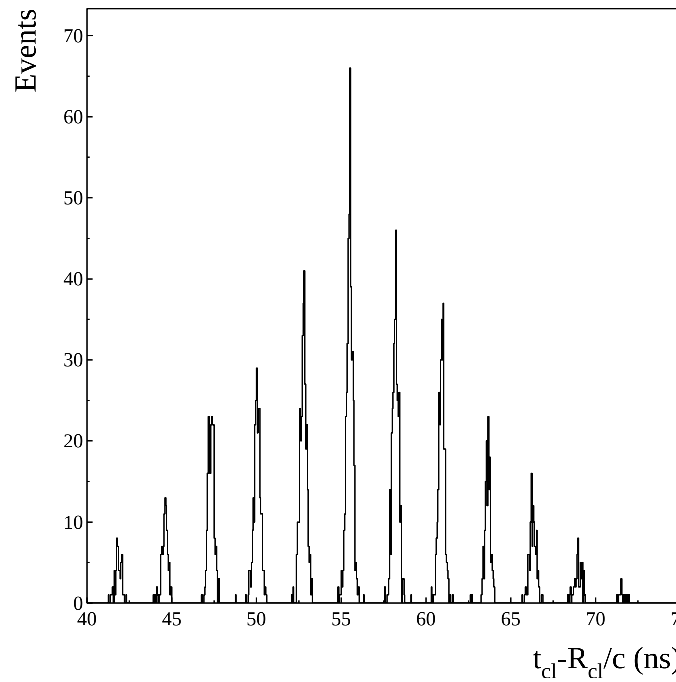
Time Measurement

The beams are bunched: collisions every **n x 2.715** ns (n = 1 or 2)
RadioFrequency fixed to **368.3… MHz** (known at level 10^{-6})
The event time scale is ~ **30-50 ns** >> interbunch timing
➔ Every event you need to know the "real" t0

$e^+e^- \rightarrow \gamma\gamma$ events:
T-R/c raw spectrum (n = 1)

Fourier analysis
(1) "Period" Δt
→ absolute time scale calibration

(2) "Phase" t0

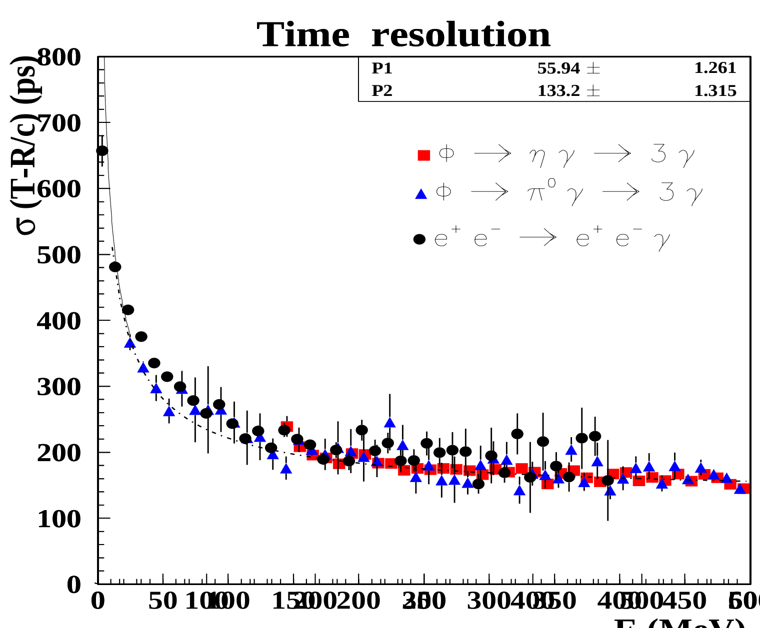


For every event:
t – R/c (of the promptest particle) ➔ find the right t0

Time resolution:

$$\sigma_t = \frac{55\,ps}{\sqrt{E(GeV)}} \oplus 130\,ps$$

The constant term is:
50 ps intercalibration
120 ps bunch time fluctuations

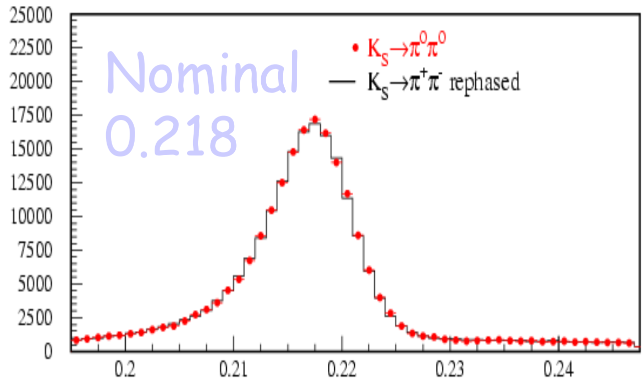


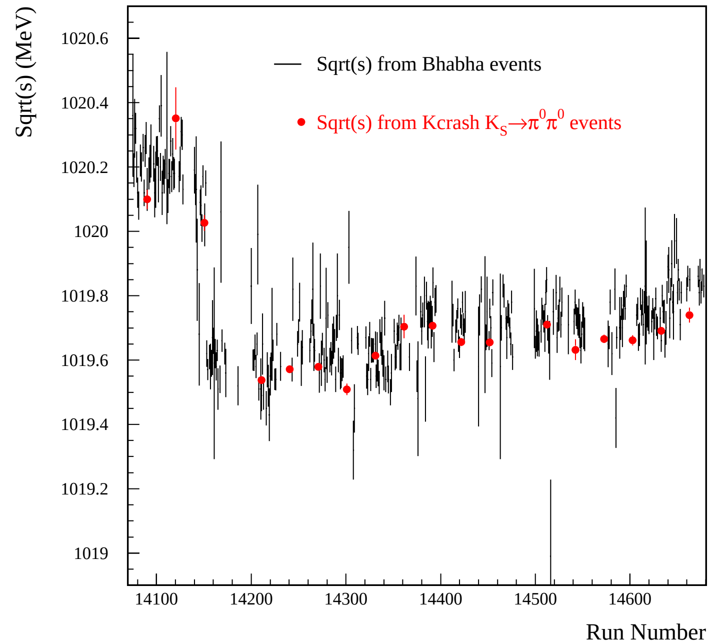
Examples of time performance:

(1) Measurement of K_L "crash"

➔ K_S tagging

➔ $\sqrt{s}$ measurement





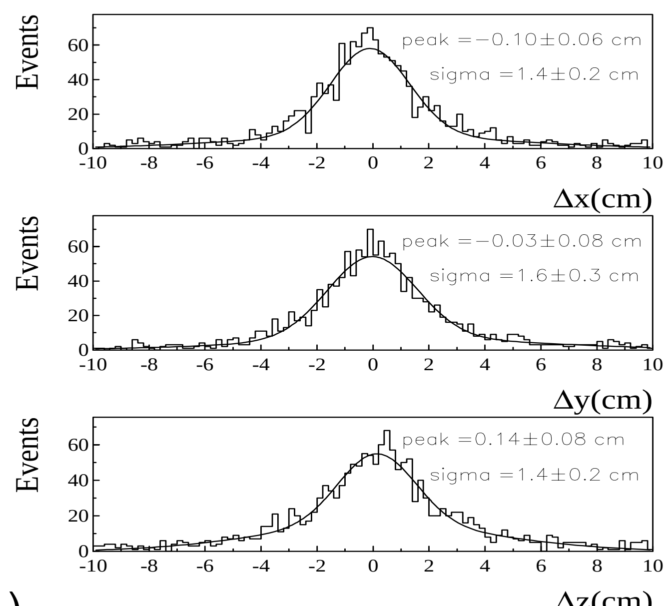
(2) Measurement of the

$K_L \to \pi^0\pi^0$ decay vertex

check done using

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

compare charged and neutral vertex ➔ 1.5 cm resolution

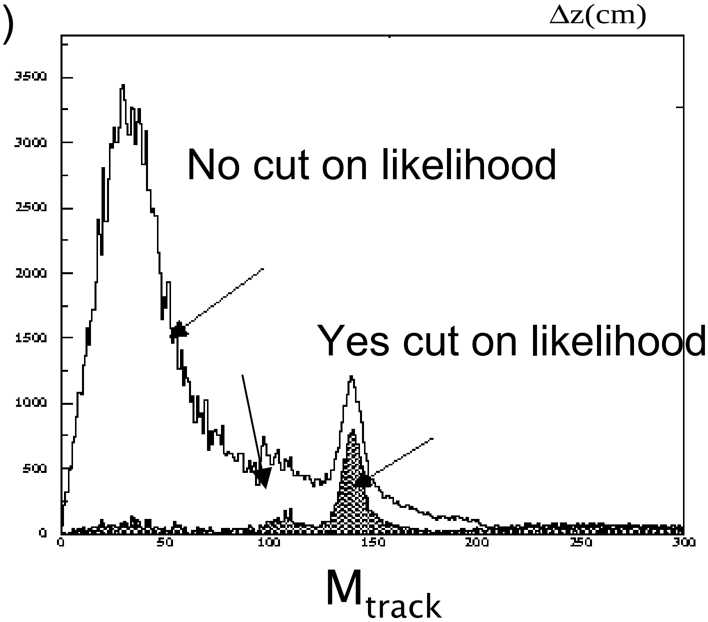


(3) π – e separation ($\pi^+\pi^-\gamma$ vs. $e^+e^-\gamma$)

Likelihood function based on:

- Time of flight
- Energy deposit profile

The π peak clearly emerges
With strong background reduction



Photon efficiency

Measured using the extrapolated energy and position by D.C. in

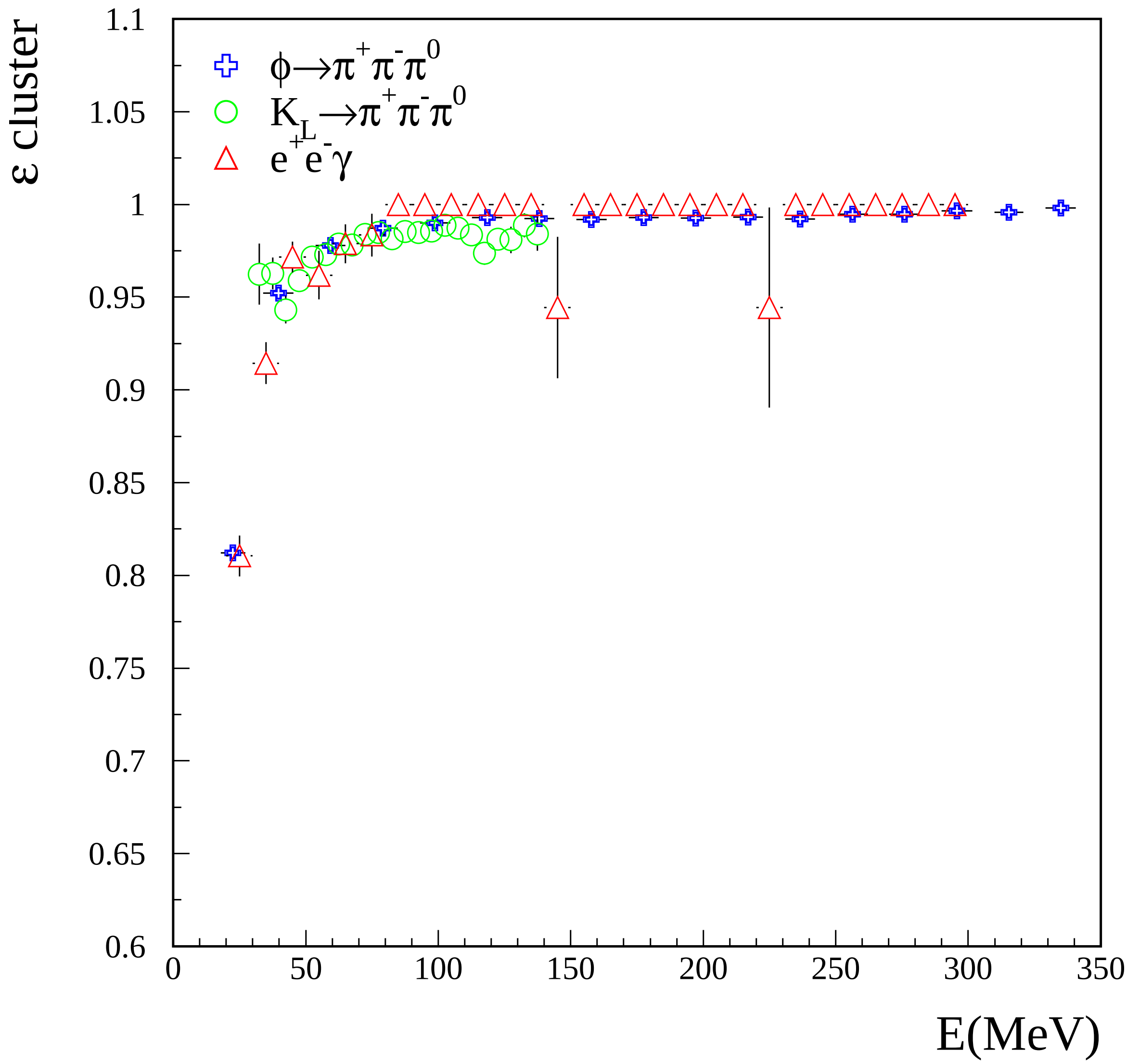
(1) $\pi^+\pi^-\pi^0$ final states (2 tracks + 2 photons)

(2) $e^+e^-\gamma$

(3) $K_L \rightarrow \pi^+\pi^-\pi^0$

➔ e = 100% (> 98%) E > 80 MeV

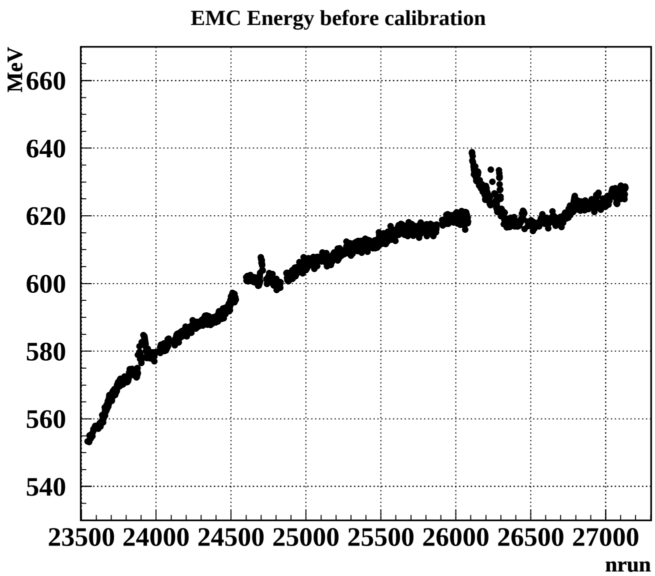
➔ e = 100% → 80% E = 80 → 20 MeV

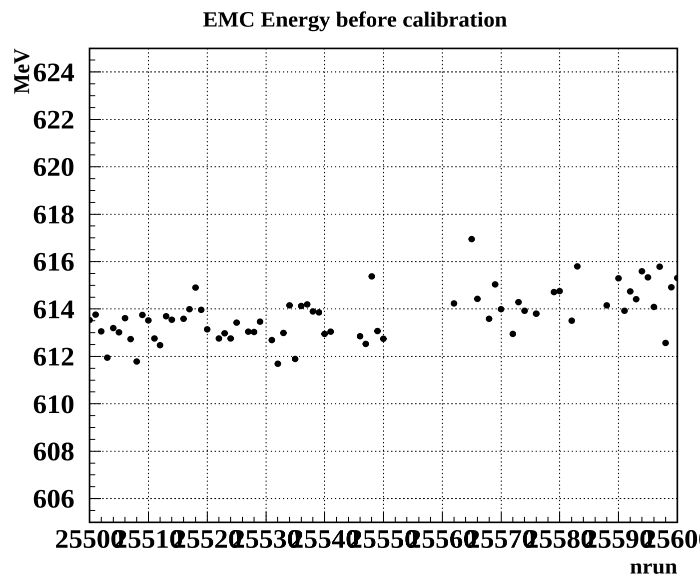


Response stability

long term operation = 4 years @ **L = 2 x 10^{30} → 7 x 10^{31} cm^{-2} s^{-1}**
high rate operation ~ MHz / channel (hotter regions)
Failure rate ~ 1 / 5000 channels per year (no PMT broken up to now)

(1) Stability of energy response



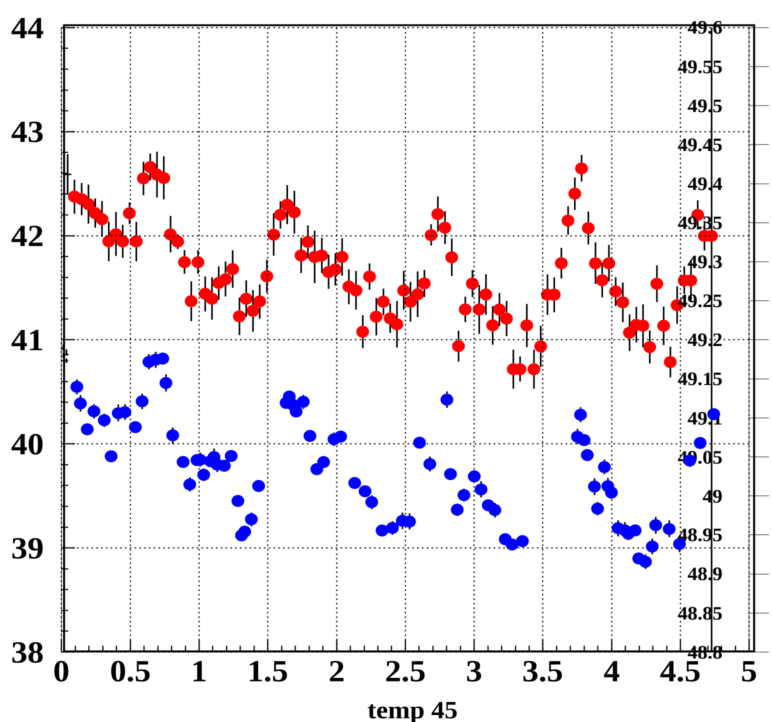


Energy scale variations (a.u.) during 6 months operation:
~ 10% (maybe PMT gain)

Short term variations (a.u.) in 1 week:
<< 1%

(2) Stability of time response

Daily variations of t0 global
±**200 ps** fully correlated with
TDC crate temperature
± **1 deg**



Summary and Conclusions

The Lead - Scintillating fibre technique has proven to:

→ match the requirements from KLOE physics
  Energy resolution
  Time resolution
  Photon efficiency

→ is solid and reliable