The KLOE Electromagnetic Calorimeter

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on behalf of the KLOE Collaboration

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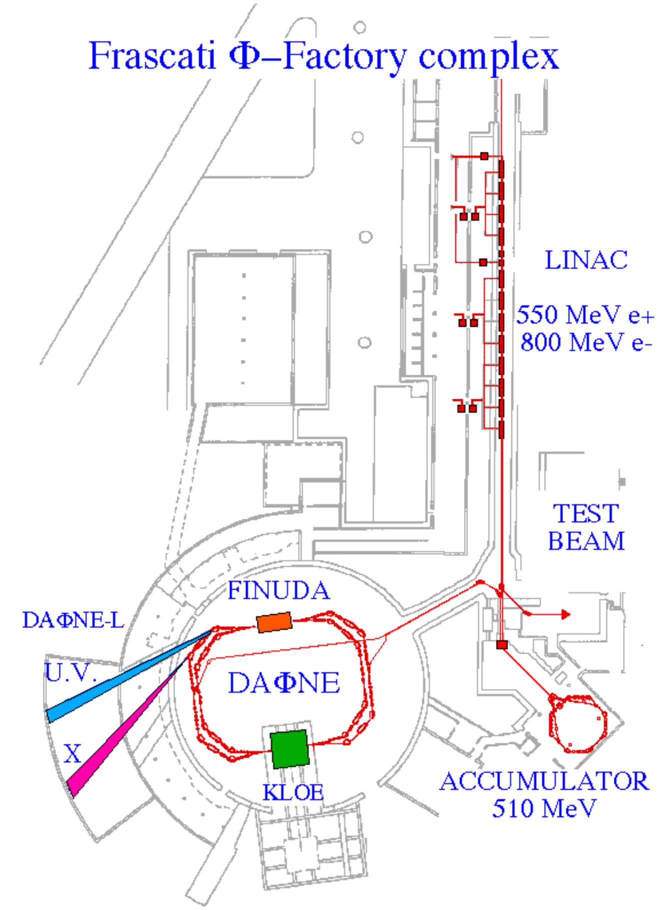
The DAΦNE Φ-Factory (I)

e^+e^- **collider at** $\sqrt{s} = M_\phi =$ **1020 MeV**

Design parameters:

$E_{\rm BEAM}$ (MeV)	510
Max n. of bunches	120
Bunch spacing (ns)	2.715
Bunch current (mA)	40
Single bunch L (cm^{-2}s^{-1})	$4 \cdot 10^{30}$
Total L (cm^{-2}s^{-1})	$\mathbf{5 \cdot 10^{32}}$



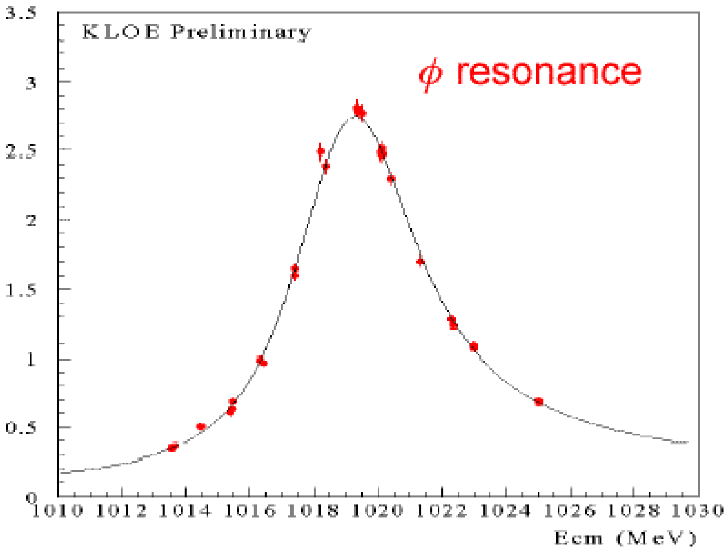
The DAΦNE Φ-Factory (II)

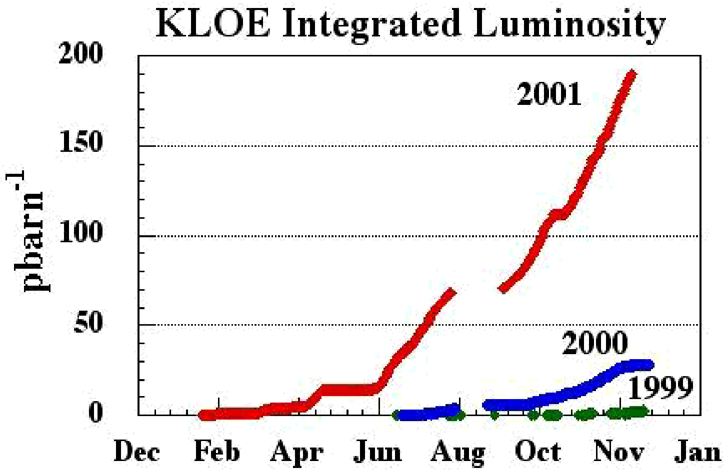
Present Performances:

$L_{max}\ (cm^{-2}s^{-1})\ \sim 6 \cdot 10^{31}$

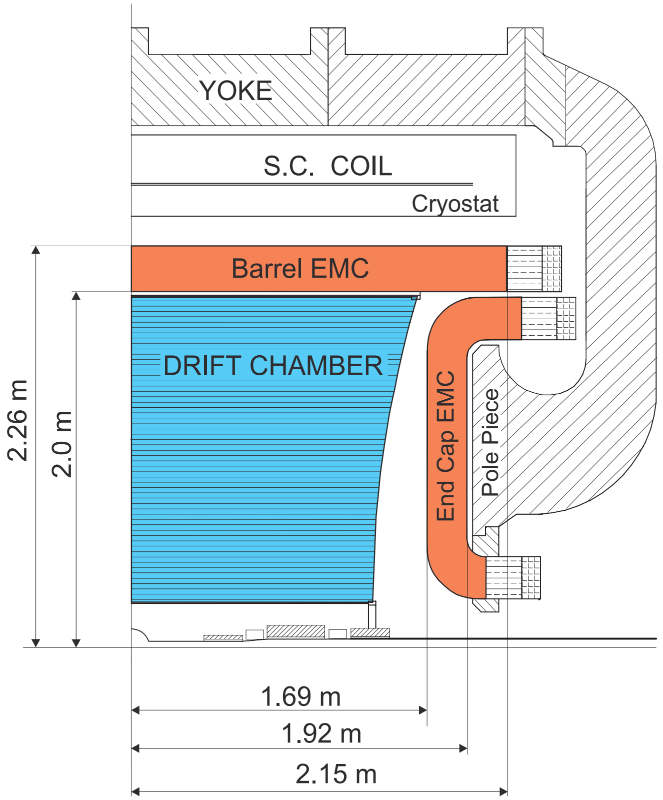
$\int L\ dt(day)\ \sim 2.5\ pb^{-1}$

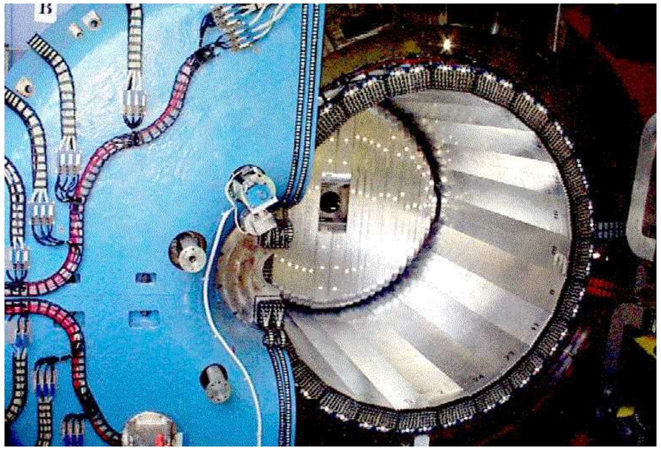
$\int L\ dt(tot) \sim 180\ pb^{-1}$





The KLOE Detector





Lead/Scintillating Fiber Calorimeter

$\sim$ **0 MeV** $< E_\gamma <$ **510 MeV**

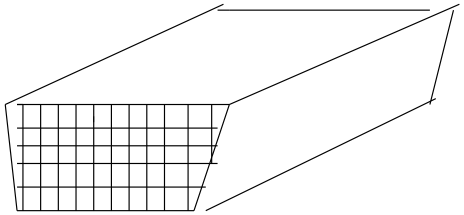
50 MeV/c $< |\vec{p}_{charged}| <$ **250 MeV/c**

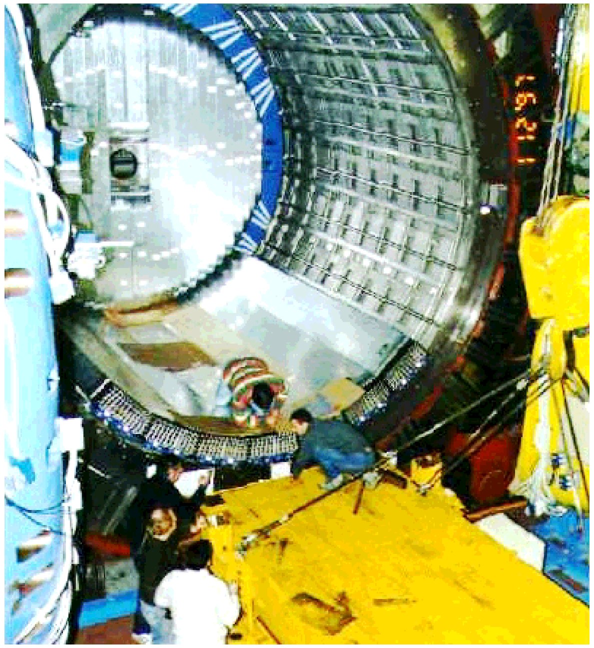
He-iC_4H_{10} Drift Chamber

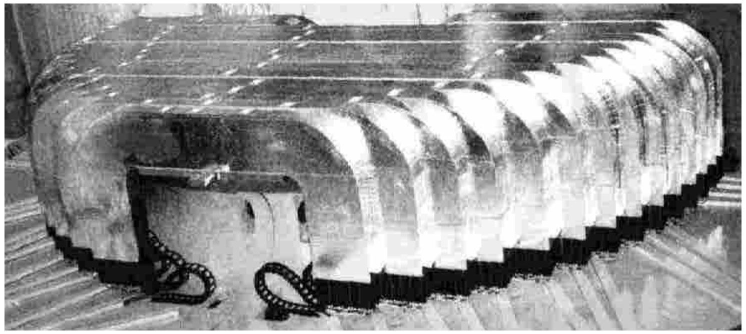
The KLOE Calorimeter

The Barrel: $\Longrightarrow$

- 24 modules of trapezoidal section.
- $(23\times\ 60\ \times\ 430)$ cm^3.
- 5 planes $\times$ 12 columns each.
- $43^\circ < \vartheta < 90^\circ$.
- 2880 read-out channels.





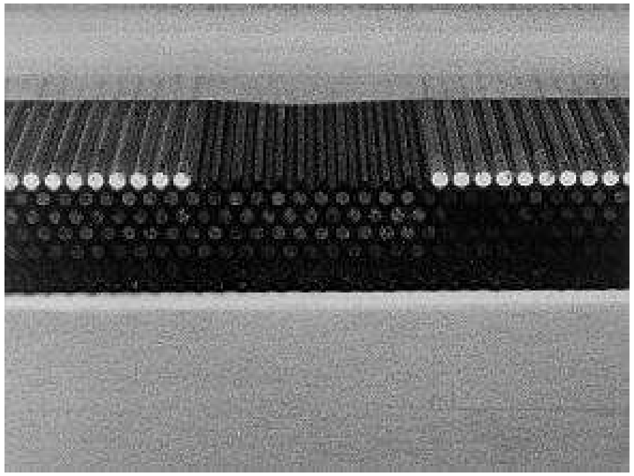


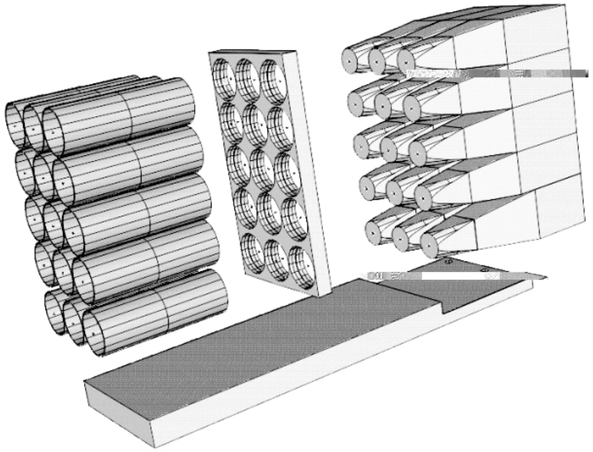
$\Longleftarrow$ **The EndCap:**

- 64 C-shaped modules.
- $(23\ \times\ (8.8,13.2,26.8)\ \times\ (80\ \rightarrow\ 400))$cm^3.
- 2000 read-out channels.

The KLOE Calorimeter: structure and readout

- Very fine sampling lead-scintillating fibers calorimeter with a volume ratio: Fiber:Lead:Glue=50:40:10.
- $\overline{\rho} \sim 5$ g/cm^3, $X_0 \sim 1.6$ cm.
- Sampling fraction for a minimum ionising particle: $\sim 15\%$.
- Fibers allow superior timing accuracy because of single mode propagation.





- Light is collected at both calorimeter ends by light guides coupled to PM's with a granularity of (4.4 $\times$ 4.4) cm^2.
- For each readout cell two time signals, $t^{A,B}$ and two amplitude signals $S^{A,B}$ are recorded from the corresponding PM's signals.

Reconstruction of energy:

The energy signal, E, on each side of a cell i is given by:

$$E_i^{A,B}(\text{MeV}) = \frac{S_i^{A,B} - S_{0,i}^{A,B}}{S_{M,i}} \times k_E$$

- $S_i^{A,B}$ = response in ADC counts.
- $S_{0,i}^{A,B}$ = zero offsets of the amplitude scale.
- $S_{M,i}$ = response to a mip crossing the cell center.
- k_E = sets the energy scale in MeV.

The cell energy, E_i, is taken as the mean of the signals at both ends:

$$E_i(\text{MeV}) = (E_i^A A_i^A + E_i^B A_i^B)/2$$

- $A_i^{A,B}$ = correction factor due to the attenuation along the fiber length.

- Energy zero-offsets are obtained from cosmic rays triggered runs without circulating beams (low occupancy runs).
- The energy calibration is performed using minimum ionizing particles and electromagnetic showers.

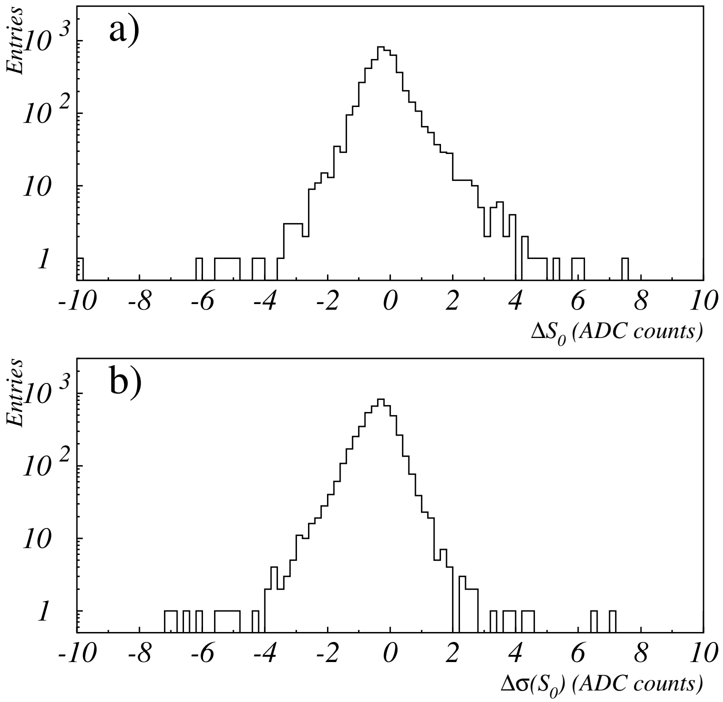
Zero Offset determination:

- Energy zero-offsets are obtained daily from cosmic ray runs without circulating beams in few minutes of data taking.
- The energy scale offsets S_0 and their fluctuations σ_{S_0} are computed from data.

⇒ Most of the offset rms fluctuations are below 4 ADC counts $\sim$ 1 MeV.

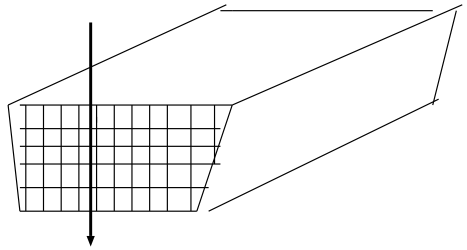
⇒ Noisy channels ($\sigma_{S_0} > 20$ counts) are 10 out of 4880 channels.

⇒ Long term drifts are below 1-2 counts per month.



- **Amplitude zero-offset stability:**
- Offset differences for two runs one month apart (a).
- Offset rms fluctuation (b).

Energy Calibration:



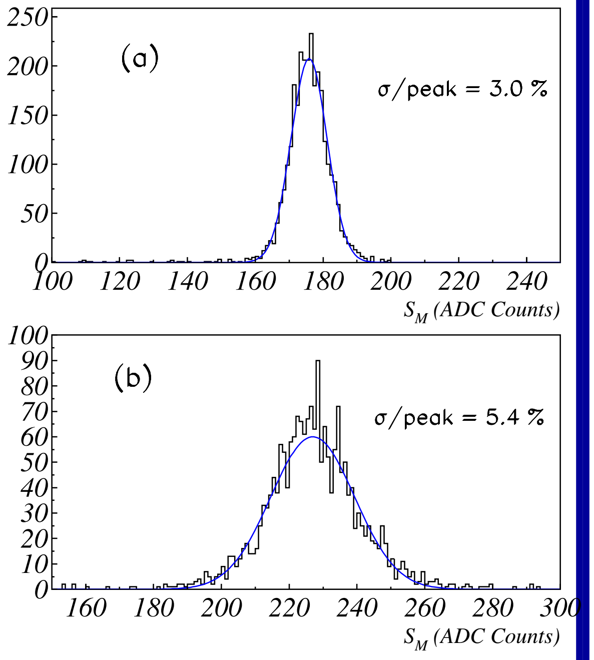
Equalization with mips:

High quality minimum ionizing particle are selected. They are requested to:

- cross the modules at center;
- be almost orthogonal to the calorimeter surface;
- cross one column only.

Response of channels is equalized in term of integrated charge per unit path length.

$\Longrightarrow$ Equalization to better than 5% is obtained by a gain-equalization iterative procedure.



(a) Barrel
(b) EndCap

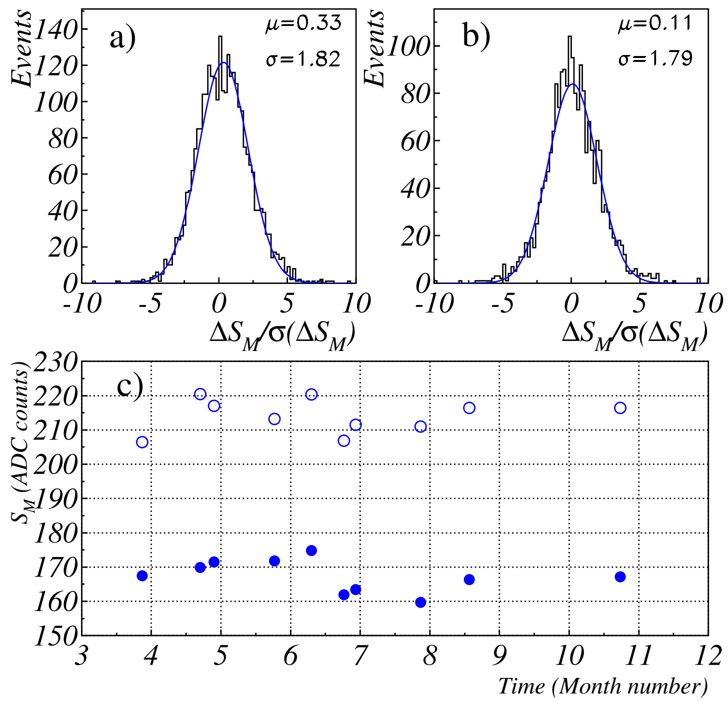
Energy Calibration:

Stability of Calibration using mips:

The change in the calorimeter response without changing the HV has been studied over an interval of two months.

The mean values do not change whereas a broadening $\times$ 1.8 of the widths is observed indicating that individual PMs gains have drifted of $\sim 2-4\%$.

The long term response variations are below 5%. $\Longrightarrow$



- **Calibration stability:**
- Barrel and Endcap over 2 months interval (up).
- Average value of S_M during one year (down).

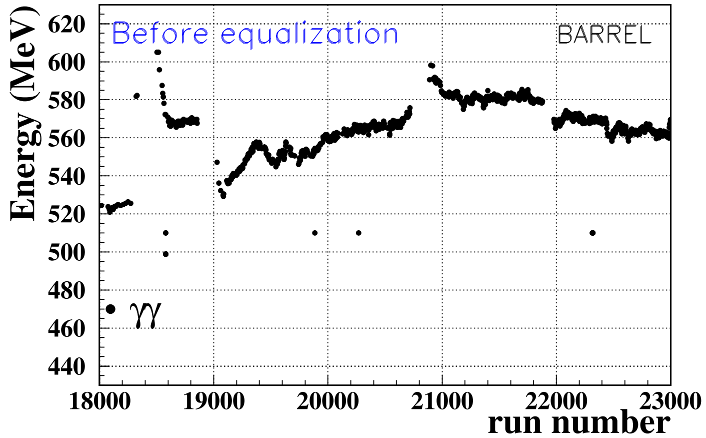
Energy Calibration:

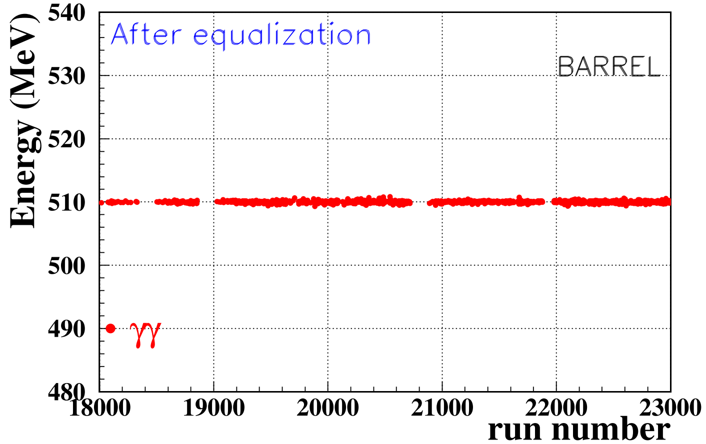
Calibration with electromagnetic showers:

Fine corrections to the mips equalization constants are obtained using $e^+e^- \to e^+e^-$ events. An iterative procedure equalizes calorimeter columns.

The energy scale is set imposing $M_\phi/2$ on the peak of photon energy distribution for $e^+e^- \to \gamma\gamma$ events.

The scale factor of $\sim$ 40 MeV /mip results in a light yield of $\sim$ 1 p.e. per MeV deposited at calorimeter center.





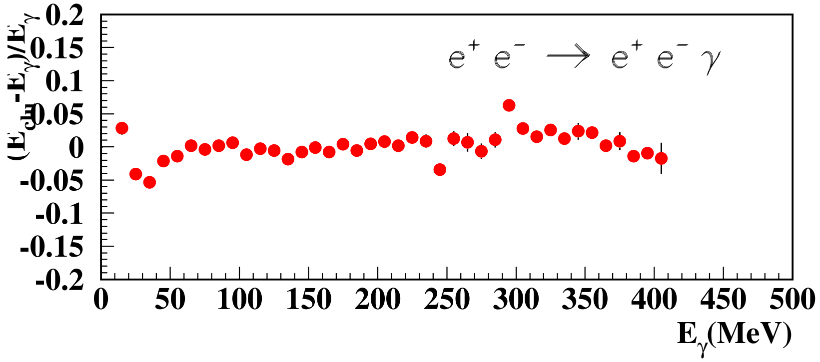
Energy Resolution and Energy Response:

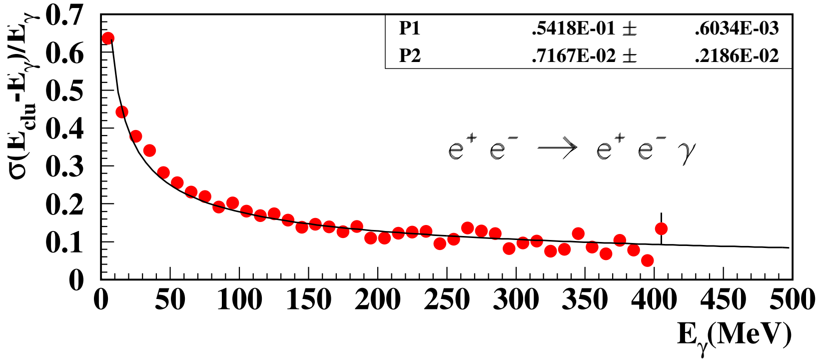
Energy resolution and linearity are obtained using photons from radiative bhabha events $e^+e^- \rightarrow e^+e^-\gamma$.

Photons position and energy are determined with high accuracy using event reconstruction from tracking information.

Linearity is of $\sim 1\%$ for $E_\gamma > 50$ MeV; deviation from linearity of $\sim 4-5\%$ are observed below 50 MeV.

The resolution is dominated by sampling fluctuations with contributions from photoelectron statistics.





$$\sigma(E)/E = 5.4\%/\sqrt{E(GeV)}$$

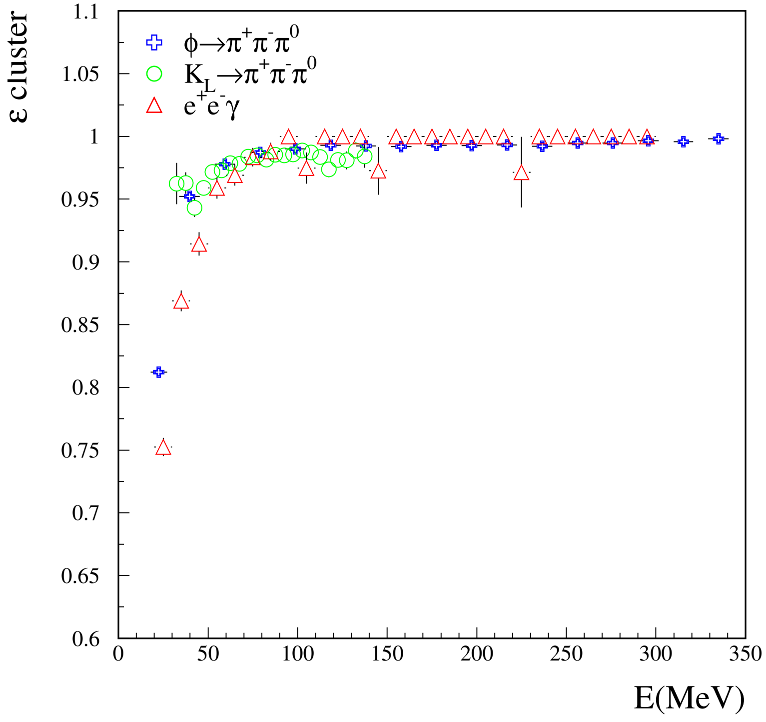
Photon Detection Efficiency:

Photon detection efficiency is measured using $e^+e^- \to e^+e^-\gamma$, $\phi \to \pi^+\pi^-\pi^0$ and $K_L \to \pi^+\pi^-\pi^0$ events.

The energy and direction of one of the two photons is evaluated using tracking information of the charged pions and the direction of the other photon.

The efficiency is evaluated as the number of detected clusters divided by the number of produced photons.

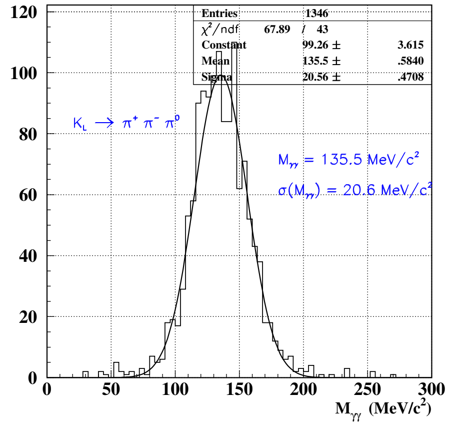
Cluster efficiencies obtained with the three samples are in agreement within the errors.



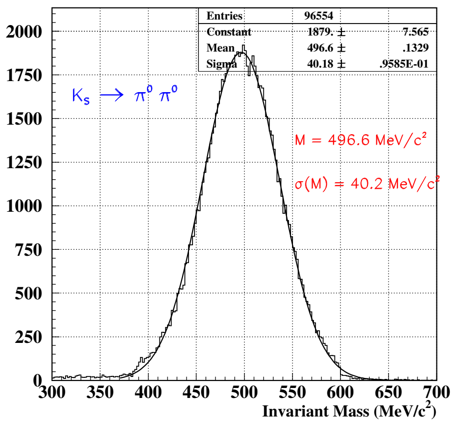
Efficiency > 99 % is reached for cluster energies > 80 MeV.

Masses:

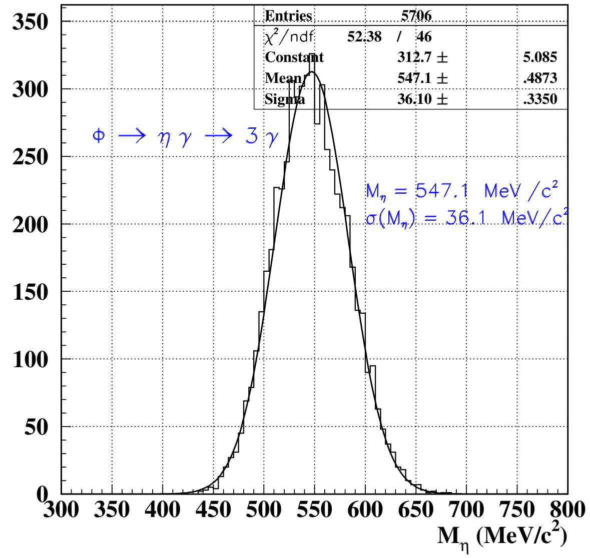
M_{π^0} from $K_L \rightarrow \pi^+\pi^-\pi^0$



M_{K_S} from $K_S \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$



M_η from $\phi \rightarrow \eta\gamma \rightarrow 3\gamma$



Reconstruction of time and position:

- The time and the coordinate along the fiber direction for each cell are given by:

$$\begin{aligned} t(\mathrm{ns}) &= \frac{t^A + t^B}{2} - \frac{t_0^A + t_0^B}{2} - \frac{L}{2v_f} \\ s(\mathrm{cm}) &= \frac{v_f}{2}(t^A - t^B - t_0^A + t_0^B) \end{aligned}$$

- $t^{A,B} = c^{A,B} \times T^{A,B}$ with $c^{A,B}$ = TDC calibration constants (~ 53 ps/count).
- v_f = light velocity in the fibers (~ 17 cm/ns).
- L = cell length.
- $t_0^{A,B}$ = time offsets.

- The arrival time and position of a particle is obtained by proper energy weighting of the cells belonging to a shower.

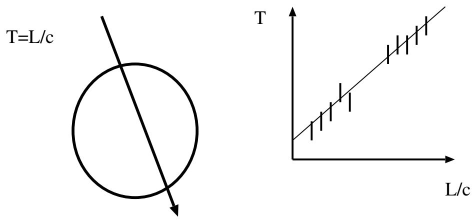
Time Equalization with Cosmic Rays:

- The v_f and the time offsets are measured using cosmic rays of high momentum ($|\vec{p}| > 7$ GeV/c).

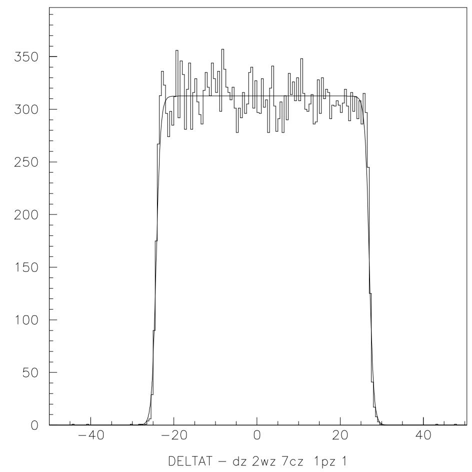
- For each cell we measure:

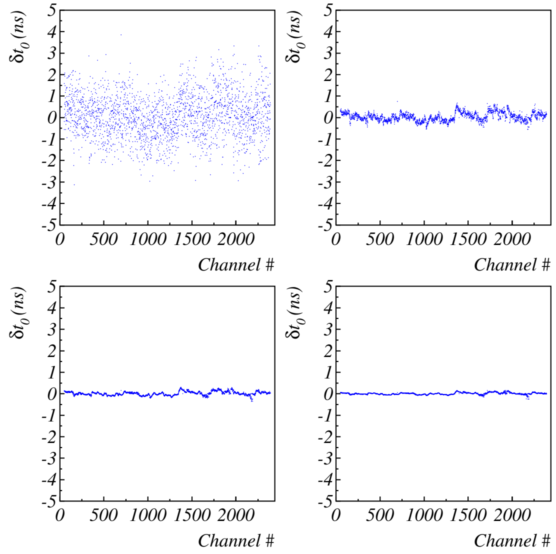
1) $\Delta t_{AB} = t_A - t_B = \Delta t^0_{AB} + 2z/v_f$

2) $t - L/c = (t^0_A + t^0_B)/2$



Minimization of time residuals of a 10^6 events run ($\sim$ 10 minutes of data taking) allow to determine the time offsets with a statistical uncertainty of $\sim$ 50 ps and v_f at 0.1% level.

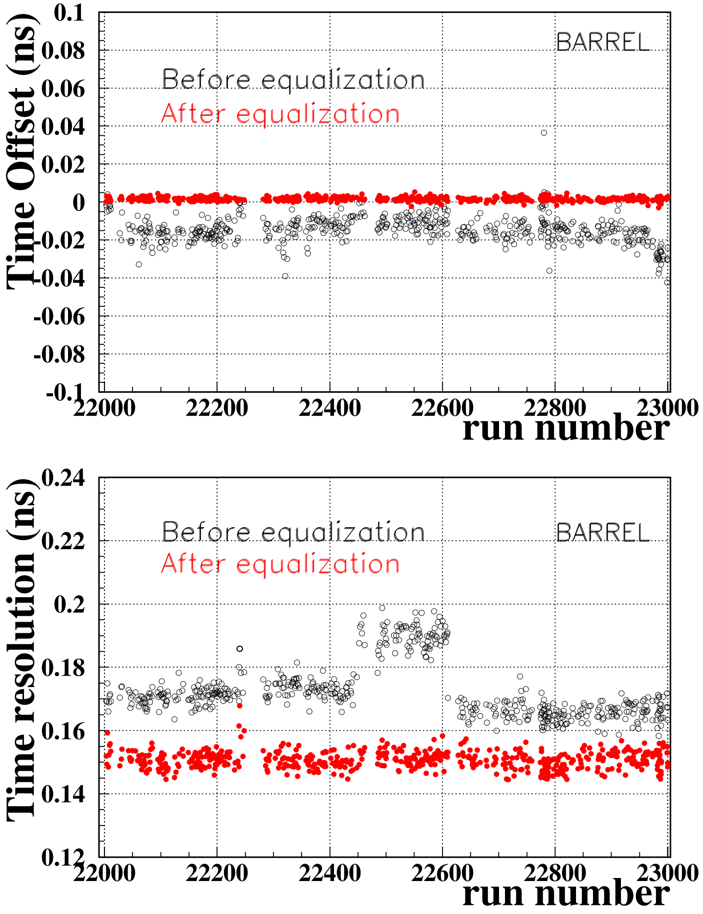




Time Equalization with $e^+e^- \to \gamma\gamma$ events:

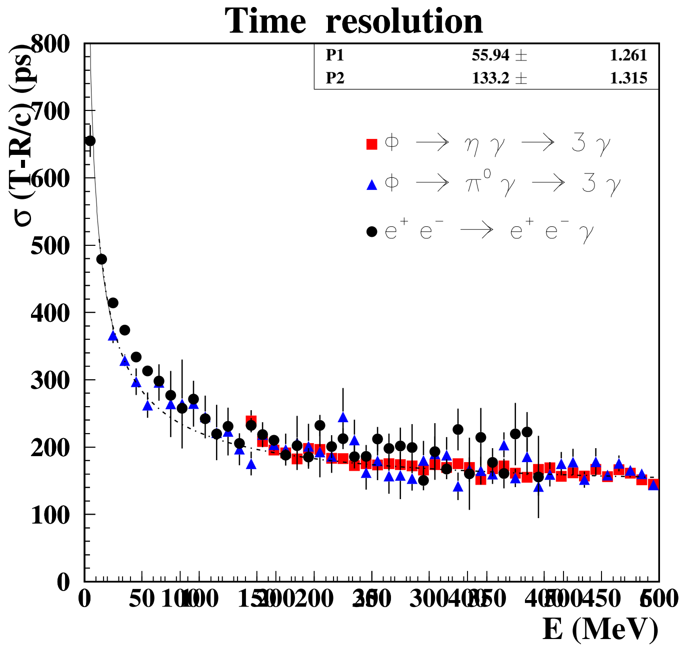
- $e^+e^- \to \gamma\gamma$ events are used to find the fine corrections to the time offsets obtained with cosmic rays.
- Minimization of time residuals $(T - R/c)$ is obtained with an iterative procedure.
- These corrections are evaluated run by run.

$\Rightarrow$ The accuracy of the method is $\sim$ 20 ps for 100 nb^{-1} of collected data.



Time Resolution:

- Time resolution is measured using the $T - R/c$ distributions of prompt photons.
- Three different data samples are used: $\phi \to \pi^0\gamma$, $\phi \to \eta\gamma \to 3\gamma$, $e^+e^- \to e^+e^-\gamma$.



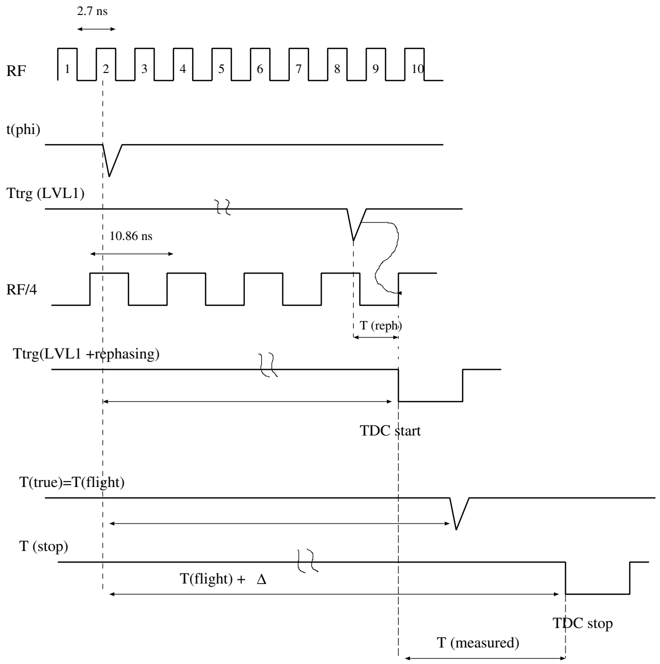
→ The constant term is due to the finite luminous point length (σ_z(IP) $\sim$ 1.5 cm) that affects both T and R/c term.

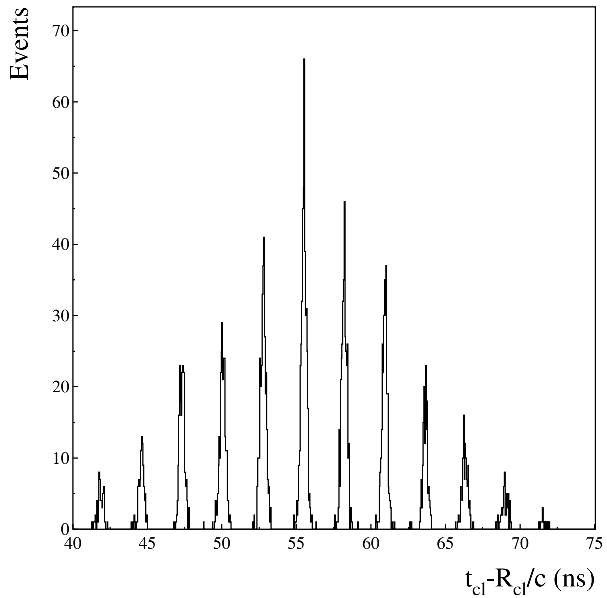
→ The intrinsic time resolution is dominated by sampling fluctuations.

$$\boxed{\sigma_t(E) = 56\text{ps}/\sqrt{E(\text{GeV})} \oplus 133\text{ps}}$$

Absolute Time Scale (I):

- The period between bunch crossings at DAΦNE is $T = n \times 2.715$ ns, $n = 1, 2, \ldots$ so the trigger and DAQ must run in asynchronous mode.
- The trigger signal is synchronized with a clock phased-locked with the DAΦNE radio frequency.
- The time (T_0) of the bunch crossing for every event is reconstructed offline and the particle arrival times are corrected for it.

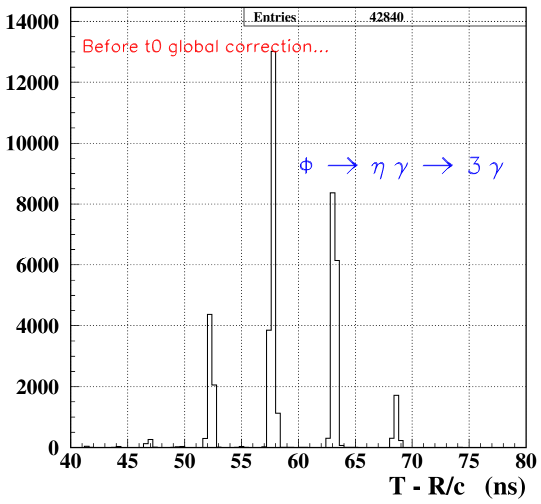


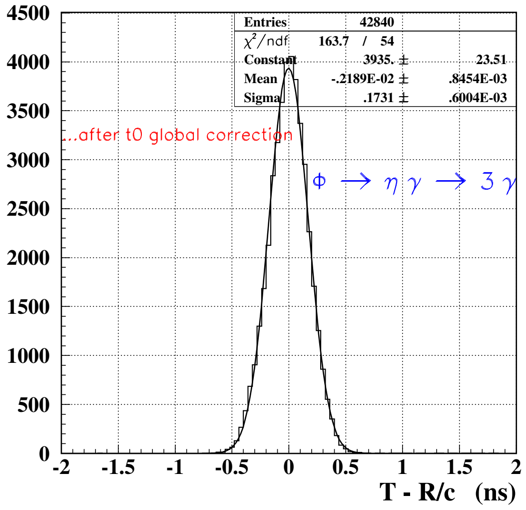


Absolute Time Scale (II):

- The first determination of the T_0 is provided by the calorimeter since drift chamber needs a rough estimate of it ($\pm$ 10 ns) to start tracking.
- We use the first cluster in time and assume that it belongs to a neutral prompt particle:

$$T_0^{(0)} = R(first)/c - T(first)$$

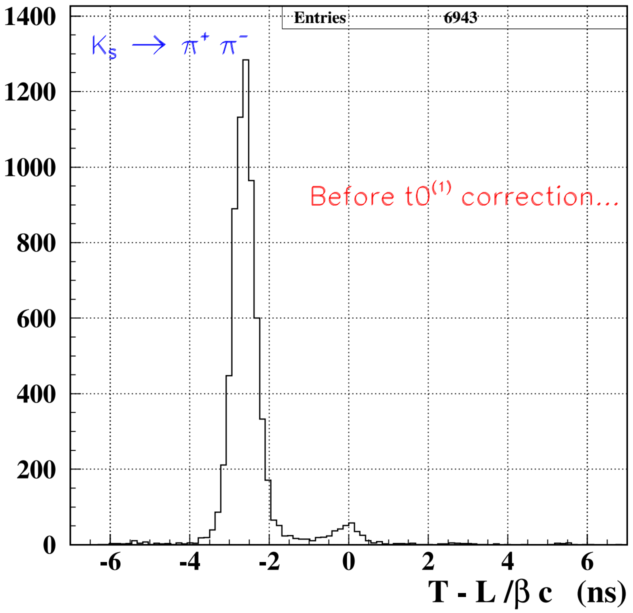


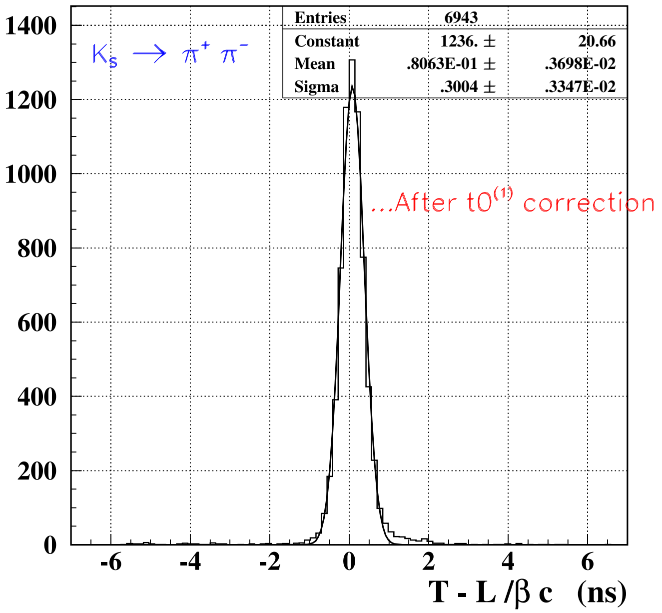


Absolute Time Scale (III):

A correction to T_0 is given after tracking and some PID using for the proper track length L and β of the particle:

$$T_0^{(1)} = L(first)/\beta c - T(first)$$





Absolute Time Scale (IV):

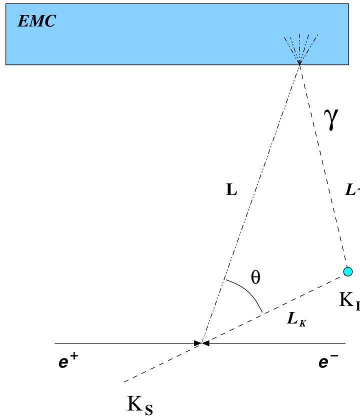
- Timing capability of the calorimeter if fully exploited in the reconstruction of the decay path L_K in the neutral channels:

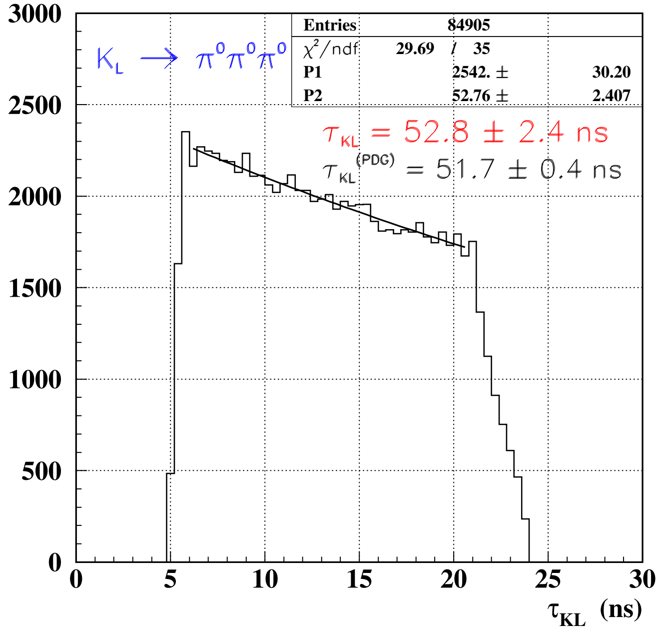
$$K_L \rightarrow \pi^0\pi^0, \pi^0\pi^0\pi^0, \gamma\gamma$$

- The L_K can be determined by measuring time and position of a single photon:

$$\begin{cases} L^2 + L_K^2 - 2LL_K\cos\theta & = L_\gamma^2 \\ L_K/\beta + L_\gamma & = ct \end{cases}$$

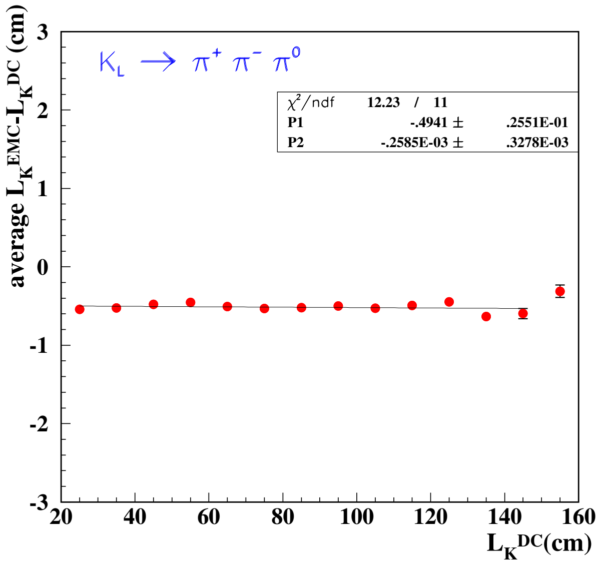
- In the case of more than one photon, an over-constrained determination can be done.



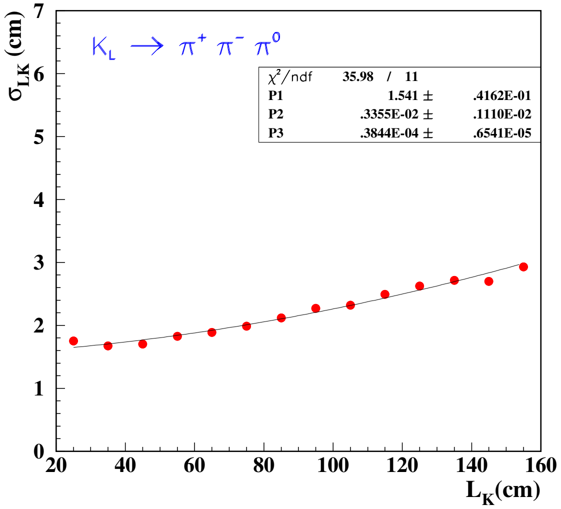


Absolute Time Scale (IV):

- Absolute time scale is monitored comparing the position of the vertex reconstructed by the calorimeter L_K^{EMC} with the one reconstructed by the DC L_K^{DC} in the channel $K_L \to \pi^+\pi^-\pi^0$.



The time scale is correct within $\sim$ 5 mm in the whole FV. $\Longrightarrow$

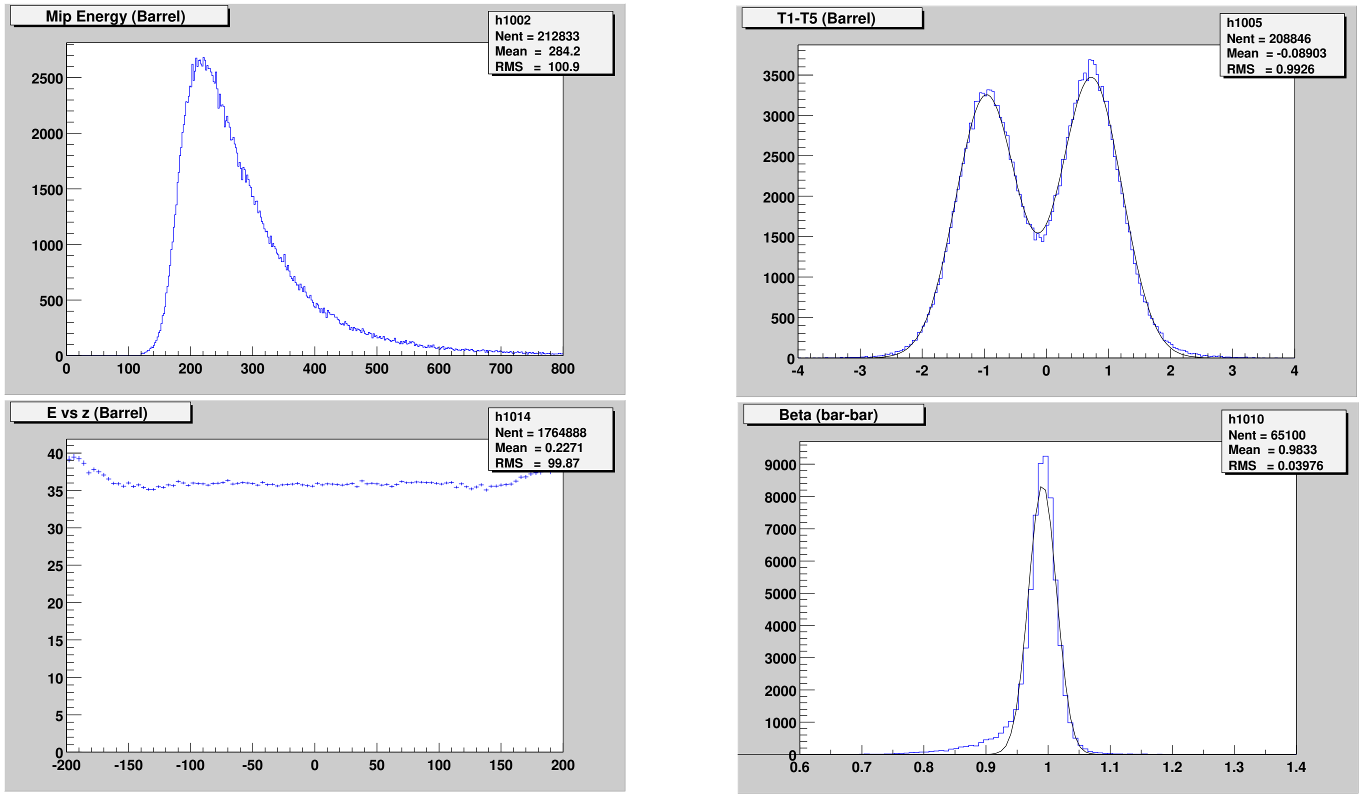


$\Longleftarrow$ The width of the $L_K^{EMC} - L_K^{DC}$ distribution is dominated by the photon vertex resolution:

$$< \sigma(L_K^{EMC}) > \sim 2 \text{ cm}$$

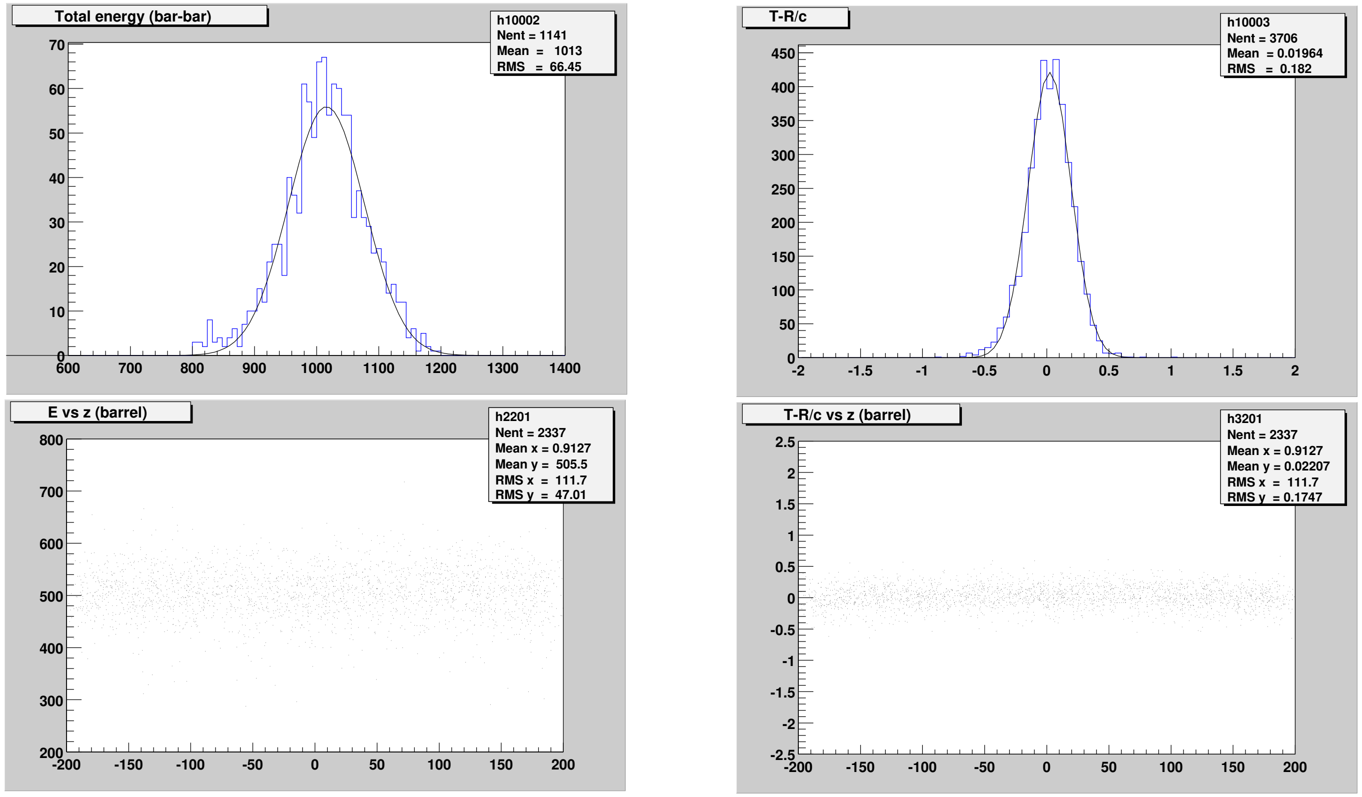
Online Monitor:

MIPS are used to continuously monitor the calorimeter calibration during data taking.



Online Monitor :

$e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \gamma\gamma$ events are used to monitor the calorimeter performances during data taking:



Conclusions:

- The KLOE Calorimeter is kept in operation for more than 4 years.
- It is calibrated run by run and continuously monitored.
- The measured performances are in good agreement with the specifications:

$\Rightarrow$ Energy Resolution: $\sigma(E)/E \sim 5.4\%/\sqrt{E(\mathrm{GeV})}$.

$\Rightarrow$ Time resolution: $\sigma_t(E) \sim 54$ ps $/\sqrt{E(\mathrm{GeV})}$.

$\Rightarrow$ Photon detection efficiency: $\epsilon > 99\ \%$ for $E_\gamma > 80$ MeV.

$\Rightarrow$ Linearity: $\sim 1\%$ for $E_\gamma > 50$ MeV.

$\Rightarrow$ Good time and energy stability.

- Good reliability has been reached:
  $\sim 0.1\%$ bad channels over $4880\times$ (preamp, SDS, ADC, TDC) channels.