ECAL Calibration

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April 5, 2024

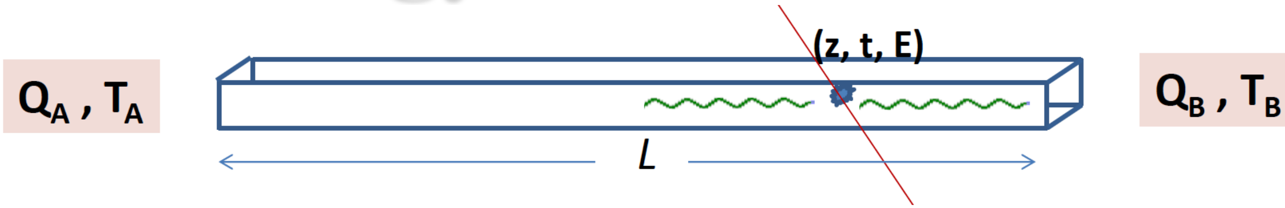
Calibration of the calorimeter in KLOE

1. MIPs (cosmic muons) for energy response calibration and relative time offsets calibration of the EMC cells

2. Electrons (510 MeV energy) from Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) for cross-calibration of the energy response

3. Photons of 510 MeV from $e^+e^- \rightarrow \gamma\gamma$ for absolute energy scale, and for refining the time calibration

Energy reconstruction



$$E_i^{(A,B)}[\text{MeV}] = \frac{(Q_i^{(A,B)} - P_i^{(A,B)})[\text{ADC counts}]}{C_i[\text{ADC counts/MIP}]} K \times f_{MIP2MeV}[\text{MeV/MIP}]$$

- **Each cell readout at both ends (*A*, *B*): *Q* = collected charge, *P* = pedestal, C_i = calibration constant, *K* = absolute energy scale factor**

$$E_i = \frac{1}{2}\left(\frac{E_i^{(A)}}{w_A(z)} + \frac{E_i^{(B)}}{w_B(z)}\right)$$

Cell energy, corrected for the attenuation along the fibers

$$w(z) = Ae^{-\frac{z}{\lambda_1}} + (1-A)e^{-\frac{z}{\lambda_2}}$$

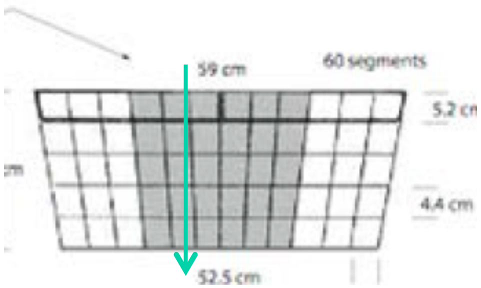
($A \approx 35\%$, $\lambda_1 \approx 50$ cm, $\lambda_2 \approx 4$ m)

- **Clustering algorithm to join contiguous cells in position and time,**

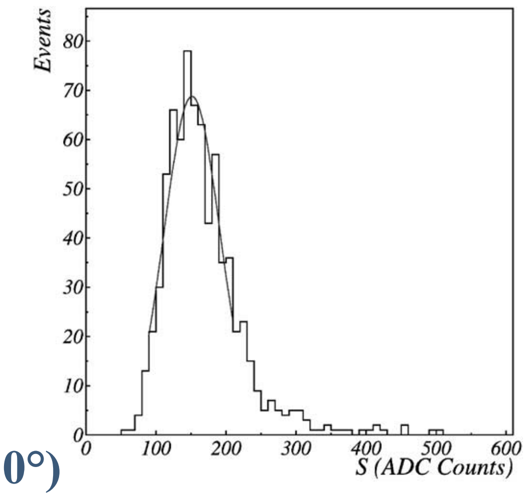
$$E_{cl} = \sum_i E_i \qquad t_{cl} = \frac{\sum_i t_i E_i}{\sum_i E_i} \qquad \vec{r}_{cl} = \frac{\sum_i \vec{r}_i E_i}{\sum_i E_i}$$

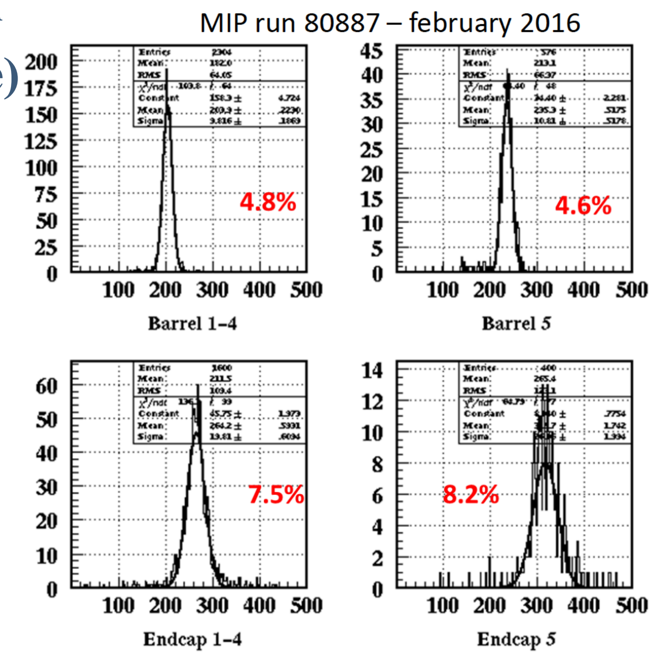
Energy calibration

- **Calibration constants C_i determined with cosmic rays, Data-taking without circulating beams: muons = MIPs**
- **2.5 kHz of cosmics**
  ⇒ online selection of "golden" MIPs, ~ 100 Hz



μ crossing one column (almost orthogonal to the module, within 10°) at the module center (± 20 cm in the longitudinal coordinate)



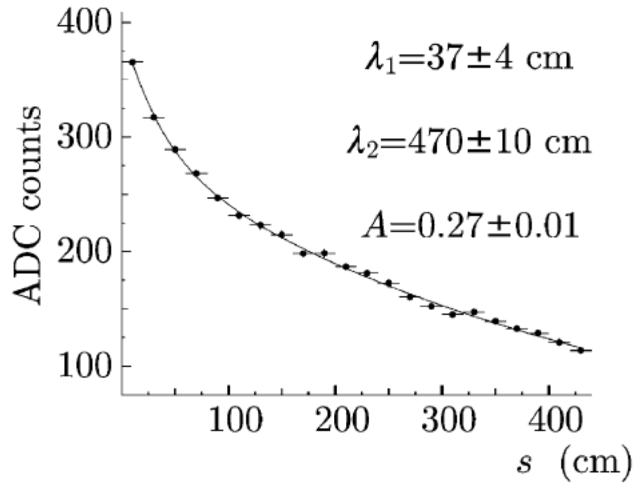


- **1 day data-taking ⇒ ~ 10^3 evts/cell**
- **C_i = peak of the MIP distribution**
  ⇒ ~ 1 – 2 % accuracy

- **Repeated every few months**
- **Used to equalize HVs to have uniform trigger thresholds**

Energy calibration

- Attenuation curves measured for each calorimeter channel
- Double exponential parametrization



$$w(z) = Ae^{-\frac{z}{\lambda_1}} + (1-A)e^{-\frac{z}{\lambda_2}}$$

$$w\left(z = \frac{L}{2}\right) \simeq 0.5$$

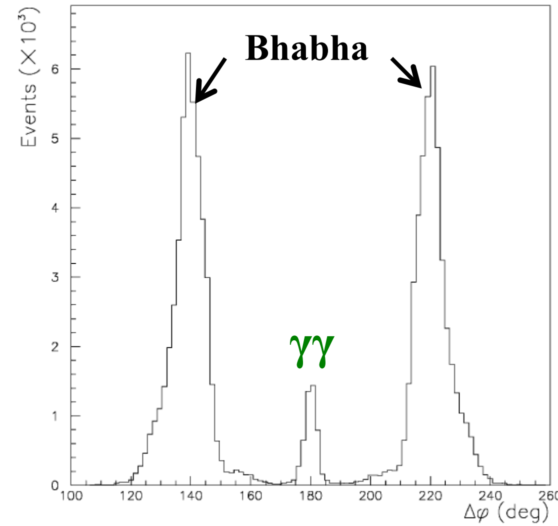
- Light yield at each readout side:
  ~ 1 p.e./MeV deposited energy at the cell center

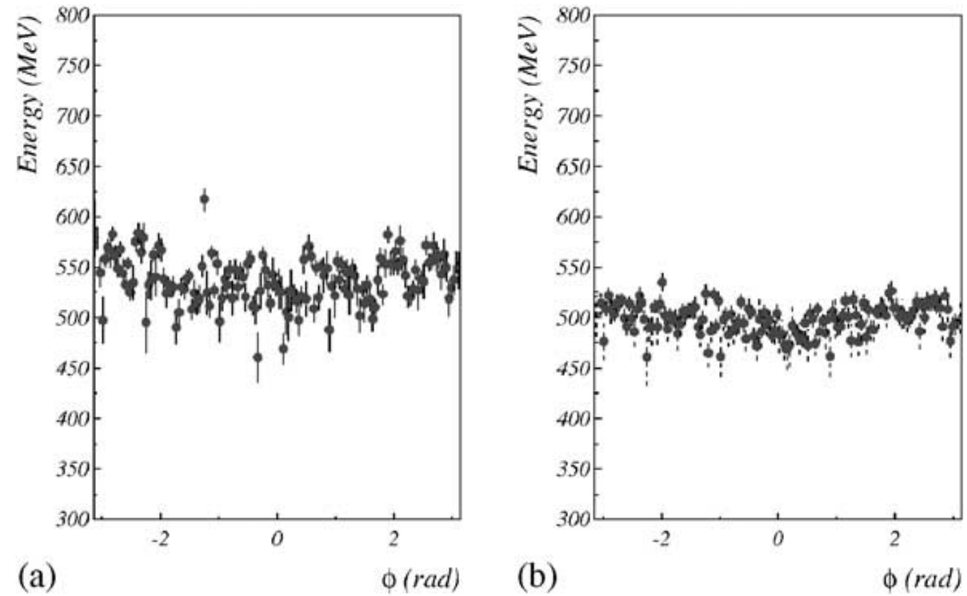
Energy calibration

- Average energy scale: $f_{MIP2MeV}$ = 38 MeV/MIP crossing a cell at the center (measured at test beams)

- Corrections to the C_i with the Bhabha scattering events ($e^+e^- \to e^+e^-$): showers of 510 MeV
  - select the peak of the distribution and correct for the ratio Peak/(510 MeV)
  - iterative procedure (3 iterations)

- Repeated every run (every 1 or 2 hours) (~ 100 nb^{-1} in KLOE, ~ 1 pb^{-1} in KLOE-2)
- 4 — 5 × 10^4 Bhabha evts in the Barrel $O(10^5)$ in the Endcaps





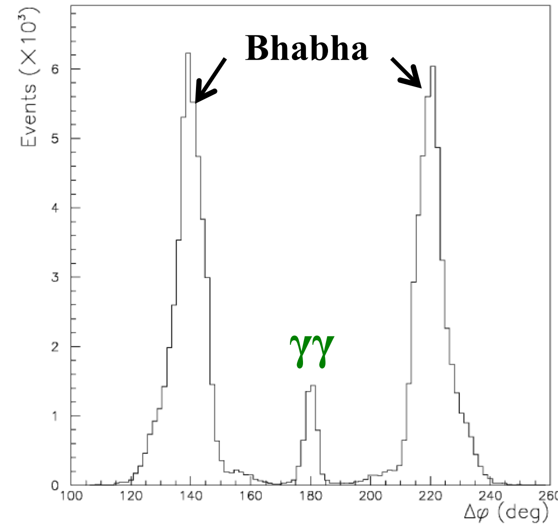
Energy calibration

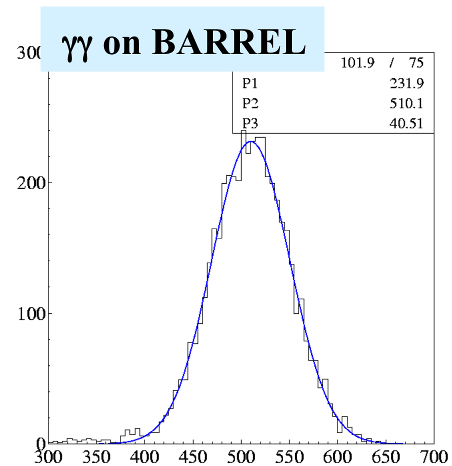
- **Electrons lose energy in the material before the ECAL⇒ peak for $e^{\pm} \sim 503 - 504$ MeV**

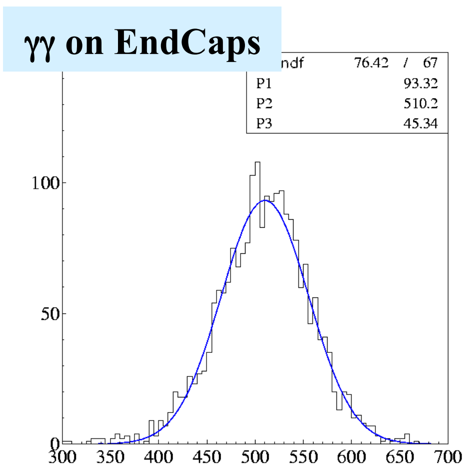
- **Absolute energy scale K fixed at cluster level with the $e^{+}e^{-} \rightarrow \gamma\gamma$ events**

- **γ's don't lose energy in the material before the calorimeter ⇒ fix the peak at 510 MeV**

- **$10^{3} - 10^{4}$ γγ events in one run**

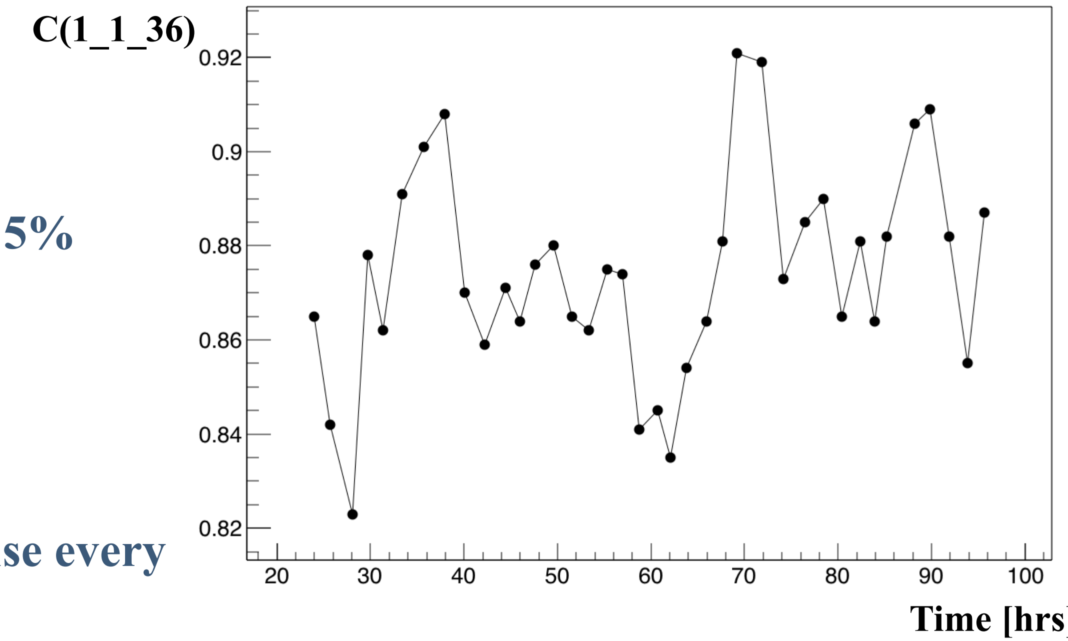






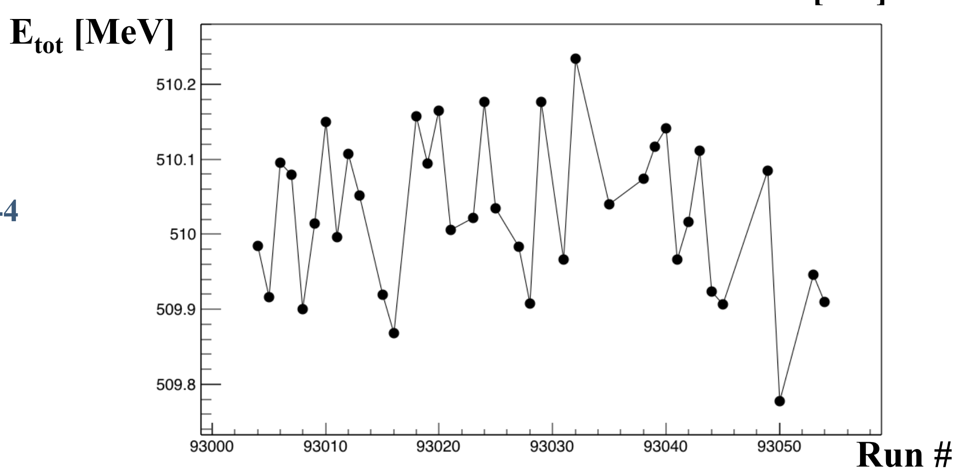
Energy calibration

- Typical calibration constant variations (1 barrel channel)



Max variations ~ ± 5%

- Not a problem in KLOE because every run was calibrated



Max variations $< 4 \times 10^{-4}$

Energy resolution

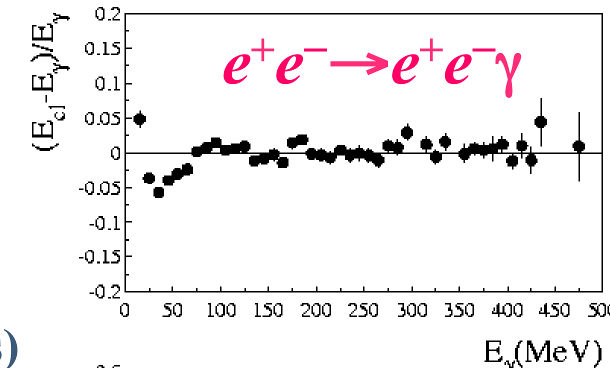
- **Linearity of the response and energy resolution measured with radiative Bhabha scattering ($e^+e^-\rightarrow e^+e^-\gamma$) by detecting the charged tracks in the drift chamber**

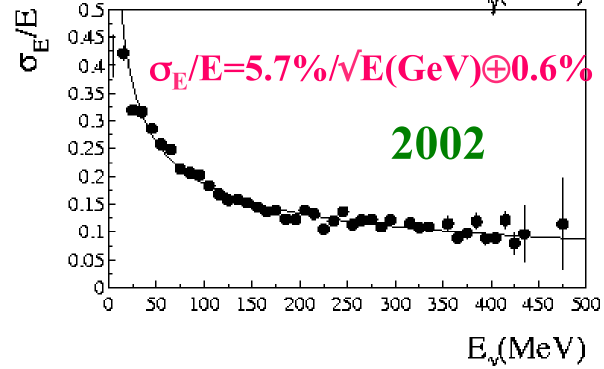
- **Linearity within 1% for E > 70 MeV** $\dfrac{E_{cl}-E_\gamma}{E_\gamma}$

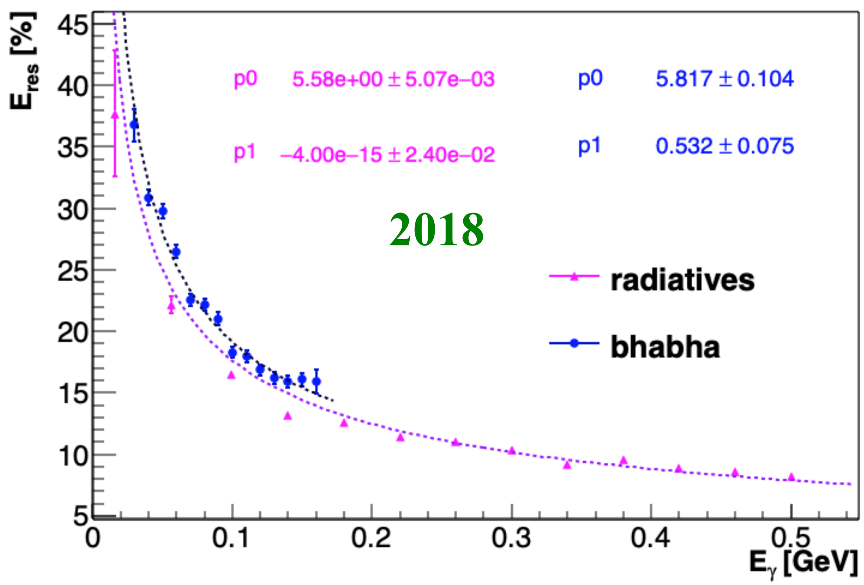
$$E_\gamma = \sqrt{s} - E_+ - E_-$$

E_+ and E_- from p_+ and p_- measured in the Drift chamber (much better resolution for charged tracks)

- **For $E = 100$ MeV $\Rightarrow \sigma_E = 18$ MeV**







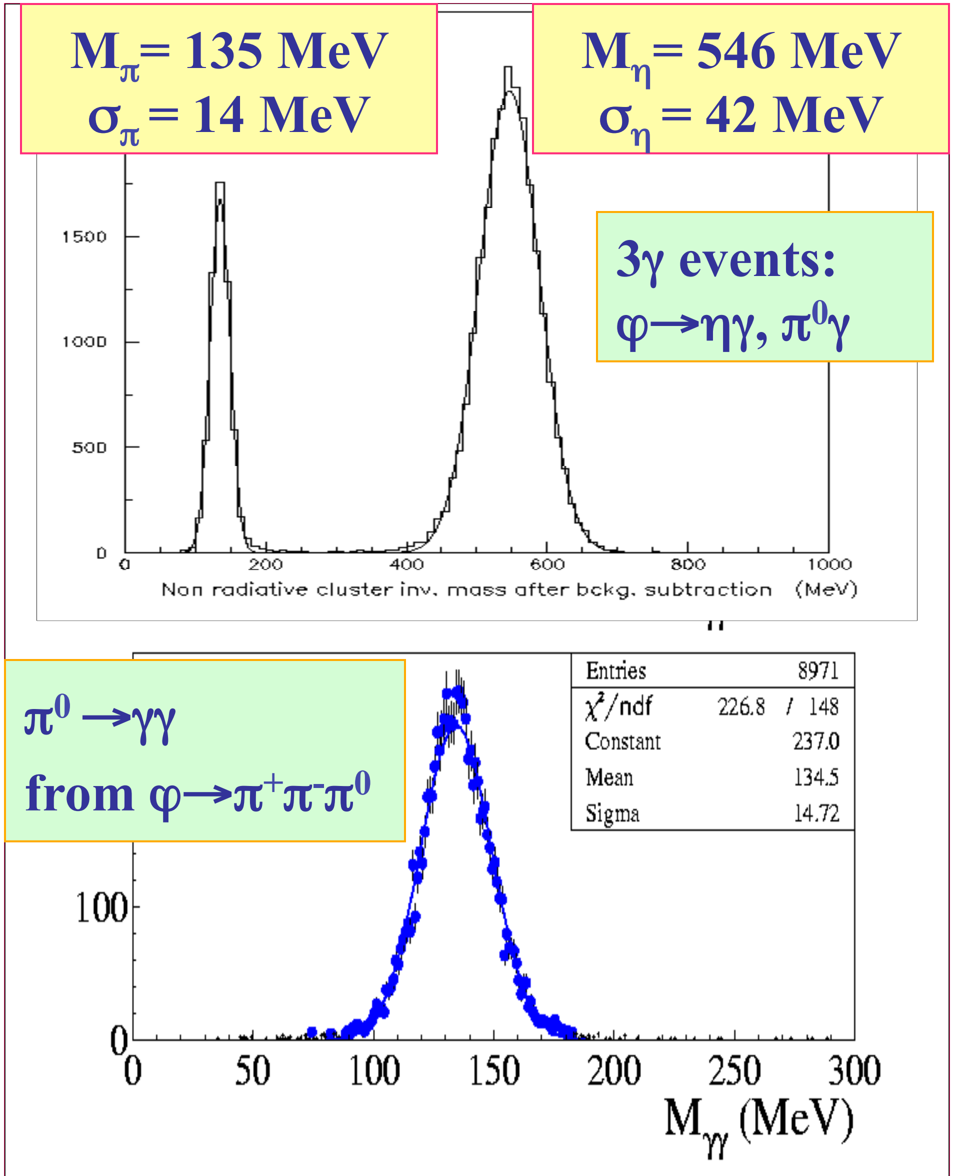
Mass resolution

$M_\pi = 135$ MeV
$\sigma_\pi = 14$ MeV

$M_\eta = 546$ MeV
$\sigma_\eta = 42$ MeV

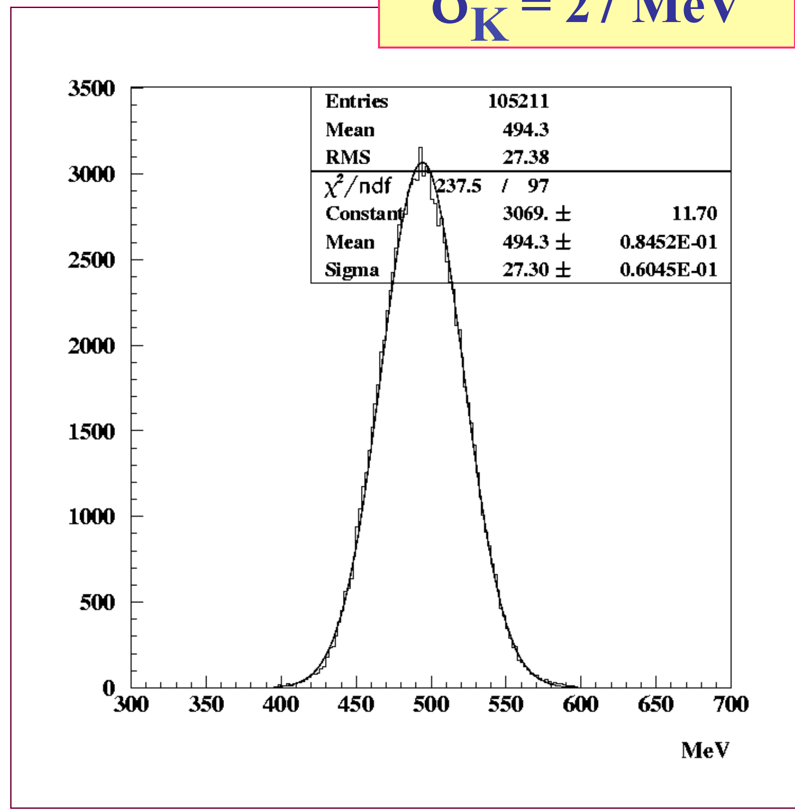
3γ events:
$\varphi \to \eta\gamma,\ \pi^0\gamma$

$\pi^0 \to \gamma\gamma$
from $\varphi \to \pi^+\pi^-\pi^0$

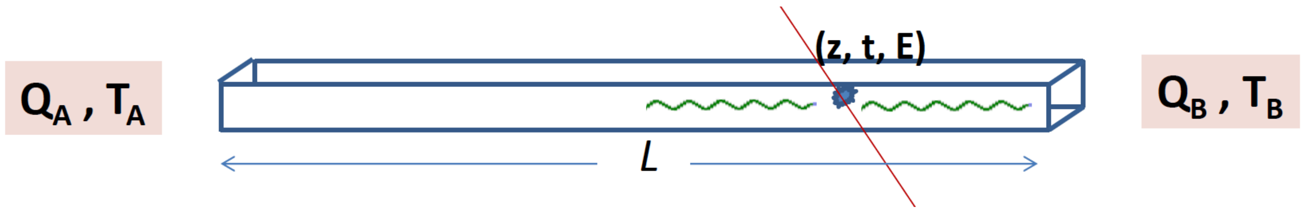


$K_S \to \pi^0\pi^0$

$M_K = 494$ MeV
$\sigma_K = 27$ MeV



Time reconstruction



$$t_{A,B}[ns] = (T_{A,B} - T^0_{A,B})[\text{TDC counts}] \times c_{A,B}[\text{ns/TDC count}]$$

$T_{A,B}$ = arrival time at the PMTs

$c_{A,B}$ = 53 ps/TDC count (measured in lab. before the installation)

$$t_A = t + \frac{z}{v} + t^0_A + t^0_G$$

$$t_B = t + \frac{L-z}{v} + t^0_B + t^0_G$$

t = Time-of-Flight

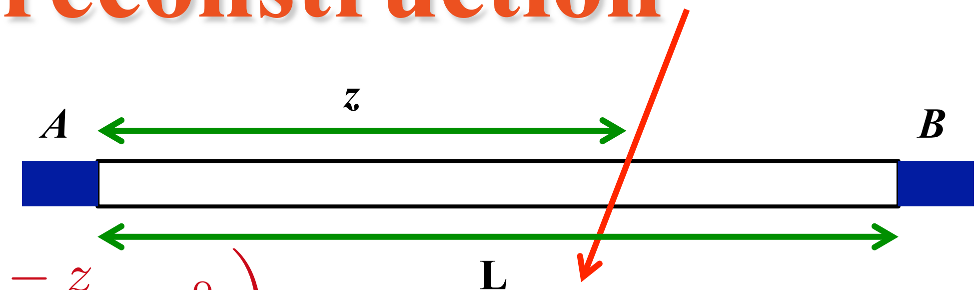
$t^0_{A,B}$ = time offsets

v = effective light velocity in the scintillating fibers

t^0_G = global time offset to be determined event by event

Z-coordinate reconstruction

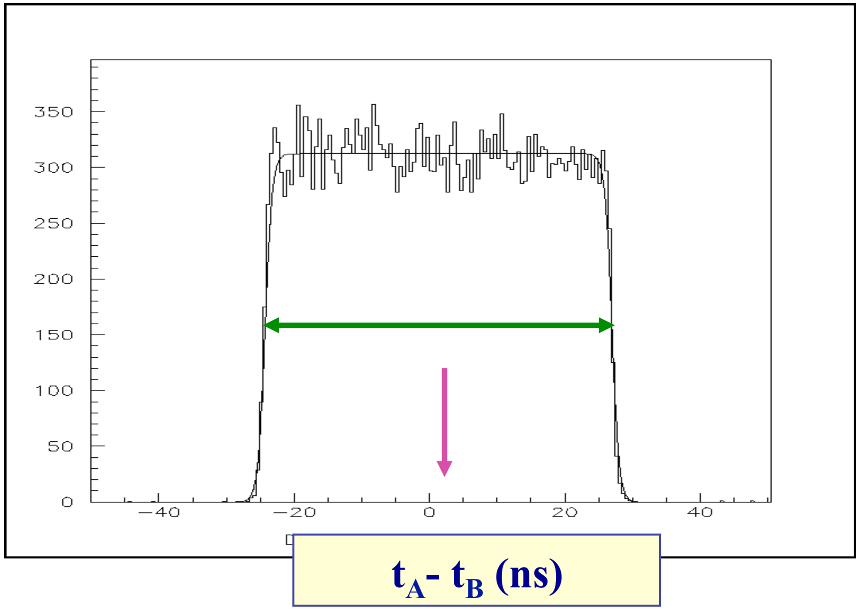
- Time difference



$$\frac{1}{2}(t_A - t_B) = \frac{1}{2}\left(t + \frac{z}{v} + t_A^0 - t - \frac{L-z}{v} - t_B^0\right)$$

$$z = \frac{1}{2}v(t_A - t_B) - \Delta t_0 \qquad \left[\Delta t_0 = \frac{1}{2}\left(t_A^0 - t_B^0 - \frac{L}{v}\right)\right]$$

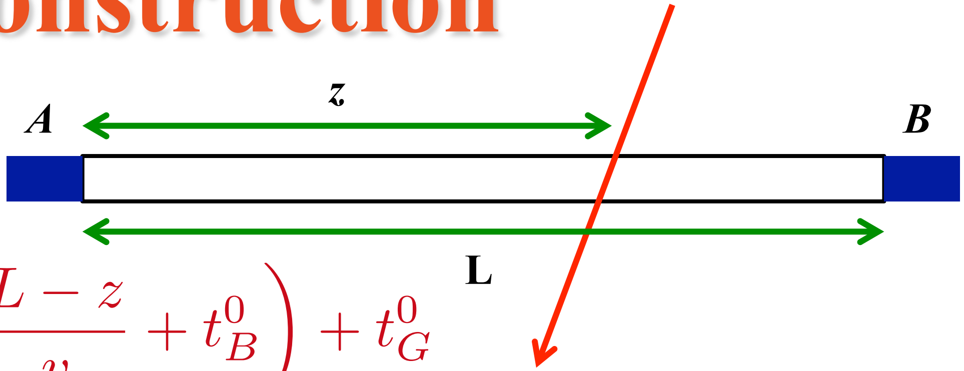
- **Calibration with cosmic rays**
  ⇒ **uniform illumination of the calorimeter**
- **Δt_0 is the center of the distribution**
- **v is obtained from the width of the distribution**



- **10^6 cosmics, 10 min run (once per day)**

⇒ v = 16.7 cm/ns

Time reconstruction

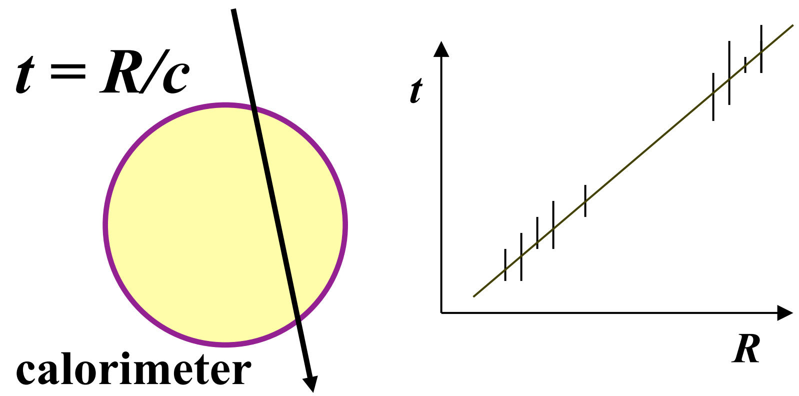


- Sum of the times:

$$\frac{1}{2}(t_A + t_B) = \frac{1}{2}\left(t + \frac{z}{v} + t_A^0 + t + \frac{L-z}{v} + t_B^0\right) + t_G^0$$

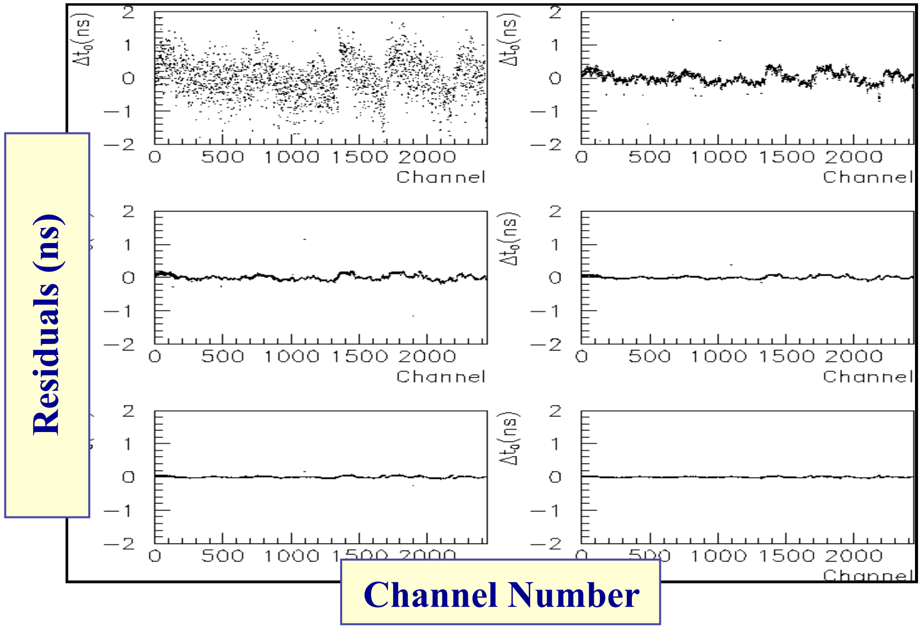
$$t = \frac{1}{2}(t_A + t_B) - \frac{L}{2v} - t_0 - t_G^0 \qquad \left[t_0 = \frac{1}{2}(t_A^0 + t_B^0)\right]$$

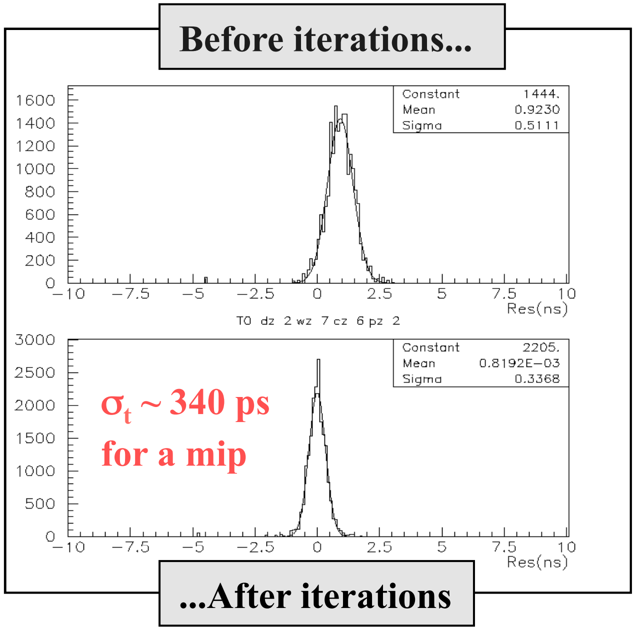
- **Select high momentum cosmic rays (p > 7 GeV) as almost straight tracks in the drift chamber, illuminating the whole calorimeter**
- **5 + 5 time measurements per each track**
- **Linear fit of *t* vs *R* to determine the time offsets t_0**
  Iterative minimization of fit residuals



Time calibration

- After 5 iterations:

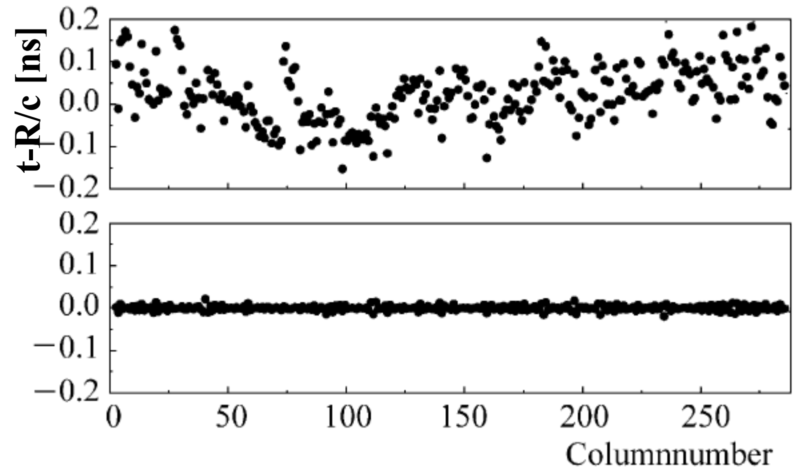




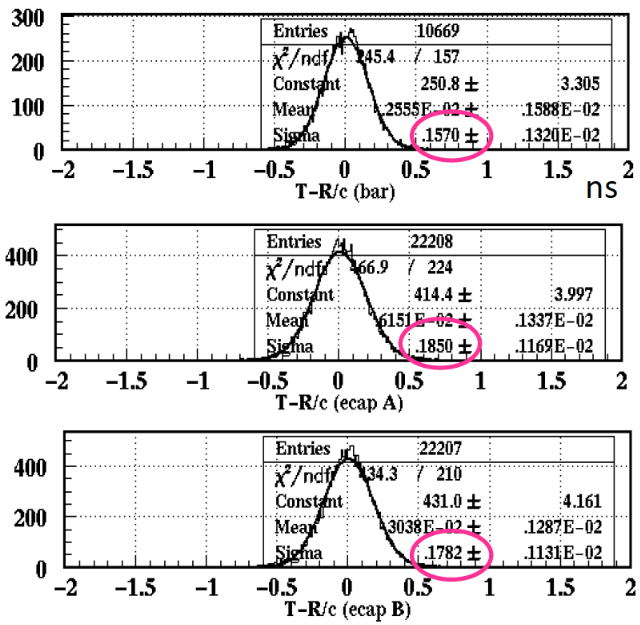
- t_0's determination at ~ 80 ps

Fine calibration of offsets

- Done at cluster level with $e^+e^- \rightarrow \gamma\gamma$ events
- Set t-r/c to zero for all γ clusters
- Iterative procedure (3 iter.)
- t_0's determination at ~ 20 ps

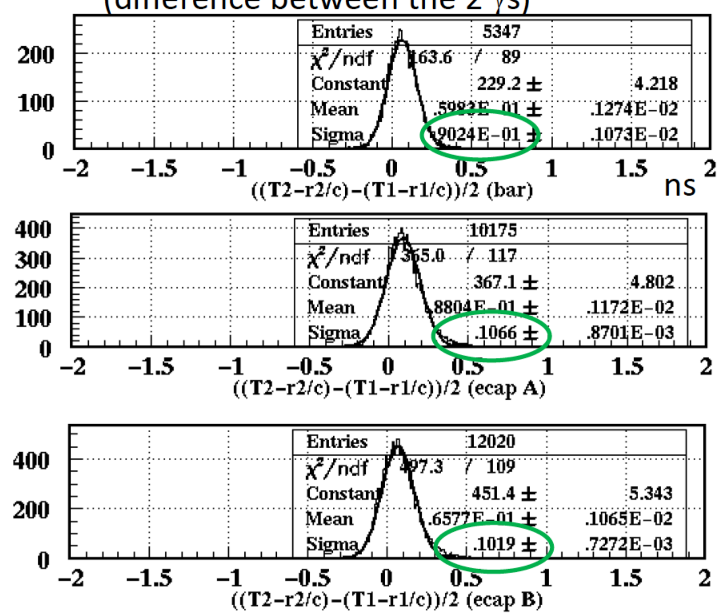


Time resolution:



Intrinsic Time resolution:

(difference between the 2 γs)



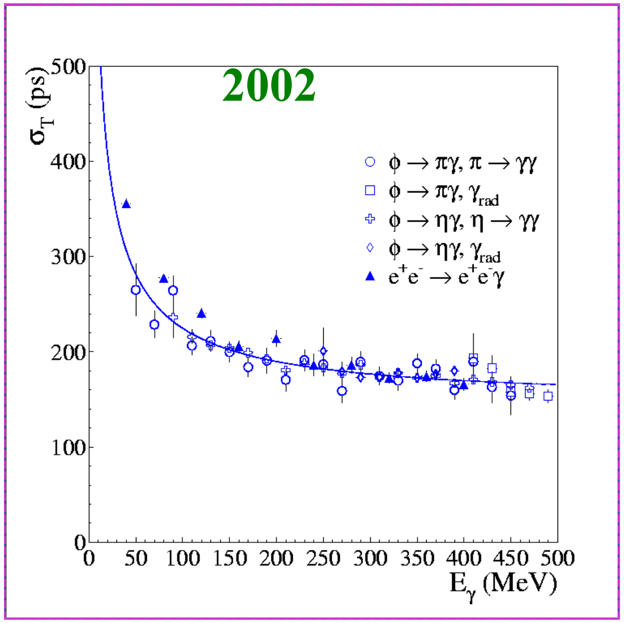
Time resolution

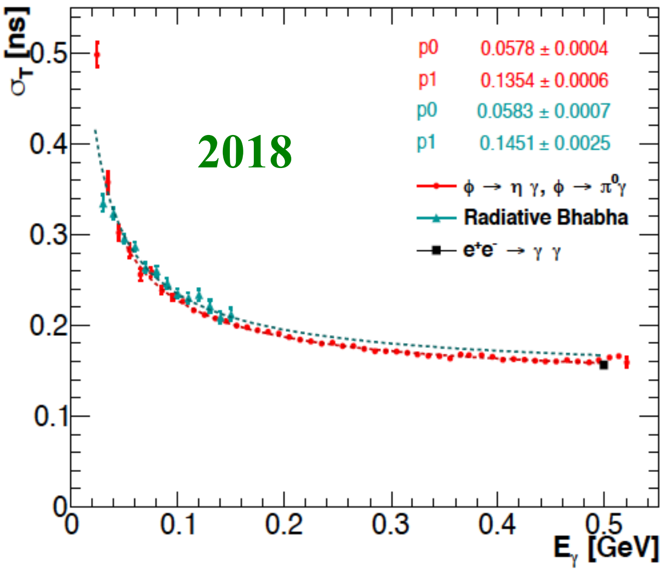
- **Measured with different processes: $\phi \rightarrow \pi^0\gamma$ ($\pi^0 \rightarrow \gamma\gamma$), $\phi \rightarrow \eta\gamma$ ($\eta \rightarrow \gamma\gamma$), $\phi \rightarrow \pi^+\pi^-\pi^0$, $e^+e^- \rightarrow e^+e^-\gamma$**

$$\sigma_t = \frac{57\ \mathrm{ps}}{\sqrt{E\ [\mathrm{GeV}]}} \oplus 140\ \mathrm{ps}$$

- **The constant term has two contribution: a term common to all the cells, due to the spread of the DAΦNE Interaction Point position, and a proper constant term, uncorrelated among cells, due to a residual miscalibration**

$$140\ \mathrm{ps} = 92\ \mathrm{ps} \oplus 105\ \mathrm{ps}$$



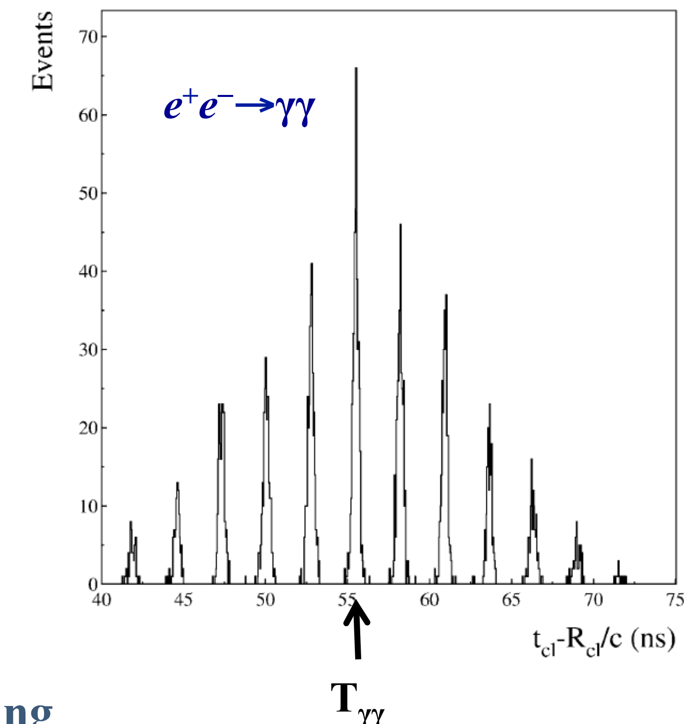


Global t_0 determination

- The trigger signal is synchronized with a clock from the radiofrequency of DAΦNE of 2.7 ns period (T_{RF})
- Typical multipeak time distribution of the events

$$t = \frac{1}{2}(t_A + t_B) - \frac{L}{2v} - t_0 - t_G^0$$

- Time needed to a photon from the interaction point to reach the calorimeter: 6 − 9 ns
- Time needed to Kaons (or the decay products) to reach the calorimeter can be as high as 30 − 40 ns
- How to associate the event to the correct beam crossing ?
  - First, choose (arbitrarily) one of the peaks ($T_{\gamma\gamma}$)
  - For each event assume that the first particle arriving at the calorimeter is a prompt photon (coming from the Interaction Point), and determine the integer *k* by imposing:



$$t - \frac{R}{c} = 0 \;\Rightarrow t_G^0 = T_{\gamma\gamma} + kT_{RF}$$

Summary

	Frequency	Duration	# of events
MIP run	every few months (2-3 times/year)	~ 24 hrs	10^3 evts/cell
Cosmics for timing	once per day	10 min	10^6 evts
Bhabha's	each run from normal data-taking	1 – 2 hrs	10^4 evts Barrel 10^5 evts EndCap
$\gamma\gamma$	each run from normal data-taking	1 – 2 hrs	10^3 – 10^4 evts

ECAL Calibration in SAND

MIPs from cosmic rays:

- muon flux at surface ~ 0.02 μ/(s cm^2)

- with an effective cross-section of the ECAL for vertical muons of ~ 5×10^5 cm^2
  ⇒ ~ 10^4 μ/s on ECAL (⇒ 100 Hz of "golden mips" in KLOE)

- Underground reduction of a factor of about 100
  ⇒ ~ 100 μ/s on ECAL (without any selection)

- Rough estimate by rescaling the KLOE numbers
  ⇒ 1 day (24 hrs): ~ 10 evts/cell

- Relaxing the "golden mip" selection: in few days ~ 10^3 evts/cell

ECAL Calibration in SAND

MIPs from beam (rock, magnet and Fe yoke, upstream ECAL modules)

Cut	ECAL Events	ECAL ε (%)	Rock muons Events	Rock muons ε (%)	Magnet events Events	Magnet events ε (%)
No cut	2.23	100.0	1447.26	100.000	50.82	100.000
μ in ECAL FV	2.23	100.0	12.73	0.880	18.92	37.229
STT & ECAL hits	1.63	72.9	6.05	0.420	3.443	6.775
NN cut	1.56	95.5	0.10	0.007	0.07	0.136

Table 40: Number of events per spill (9.6 μs, 7.5×10^{13} pot) and selection efficiency for the signal from ν_μ CC in the front barrel ECAL and the backgrounds from rock muons and magnet events.

(from DUNE-doc-13262, A Near Detector for DUNE)

~ 1.5×10^3 μ/spill (1 spill = 9.6 μs every 1.2 s) without any selection

- **Can we use also charged π's as MIPs ?**
- **Maybe a MC study could be useful**
- **Could be useful a calibration with cosmics of all the modules with the final FE electronics before re-assembling the ECAL**

Energy scale calibration

- γ's from π^0 decays, invariant mass reconstruction (need a vertex from the STT)

- γ + electrons: ~ 30% of photons from π^0 convert in the STT
  $\Rightarrow$ ~ 50% of π^0 have at least one $\gamma \rightarrow e^+e^-$
  (from DUNE-doc-13262, A Near Detector for DUNE)

- High energy electrons from ν_e interactions
  $\Rightarrow$ need the momentum measurement in the STT

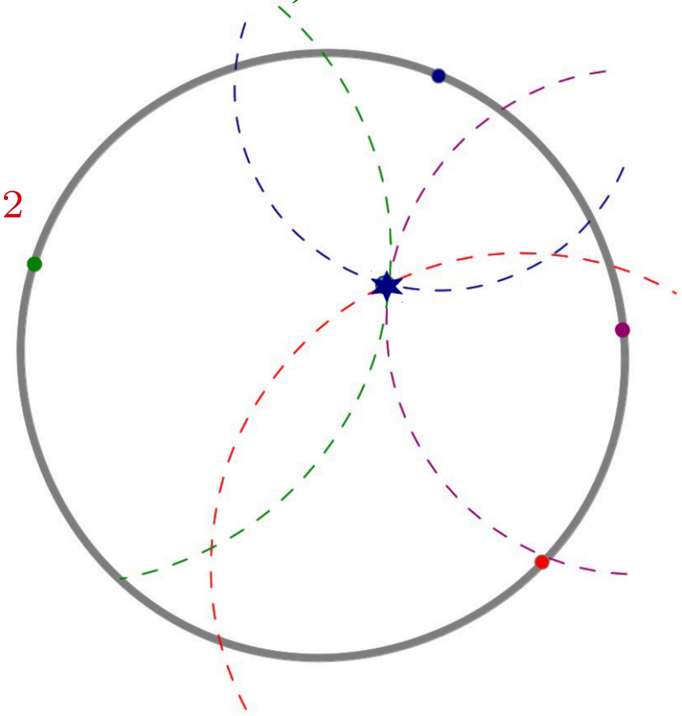
Energy scale calibration

- Exploit $K^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$
- How many expected events ?

  From a naive rescaling of $K^0 \rightarrow \pi^+\pi^- \Rightarrow O(10^5)$ evts in 5 years of FHC data-taking (from DUNE-doc-13262, A Near Detector for DUNE)
- Reconstruct a vertex with the ECAL only
- Back propagate each of the 4 photons

$$(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2 = c^2(T_i - t_K)^2$$

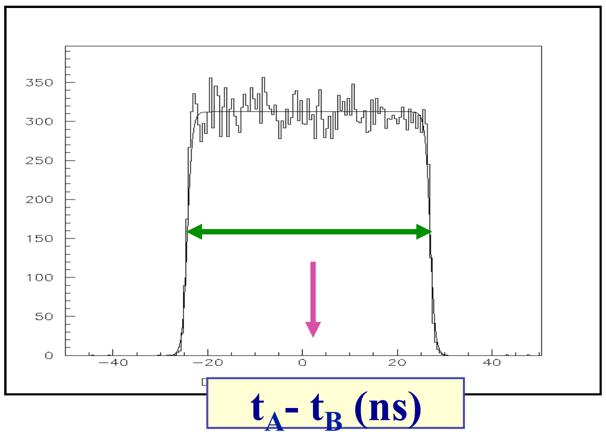
- Times of the ECAL cells must be very well aligned

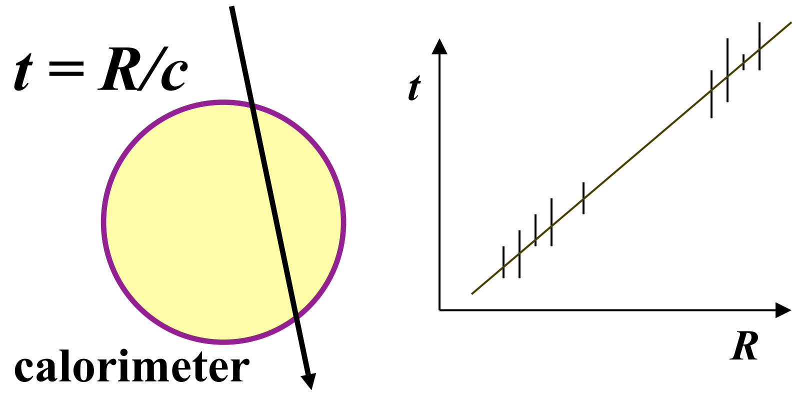


- Also $\Lambda \rightarrow n\pi^0$? (factor of ~2 more than K^0, but the neutron could be a complication)

Time Calibration

- Alignment of the t_0's: MIPs from cosmics and other beam particles





- Fine calibration of t_0's non-trivial: we need events connecting different parts of the ECAL
- Maybe events with π^0 decaying into γ (and $e^{\pm}$) could be used, with the information of the vertex in the STT

Conclusions

For energy and time calibration we need:

- **MIPs (from cosmics and from beam)**
- **π^0 reconstruction (from γ and $e^{\pm}$), $K^0 \rightarrow \pi^0\pi^0$**
- **electrons from ν interactions**

MC studies needed for all these points