Report from SAND Calibration WG

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for the SAND Calibration WG

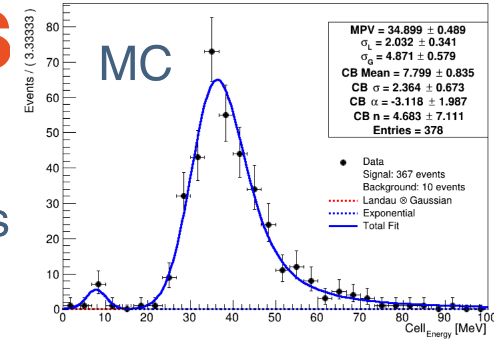
Meeting annuale della
Collaborazione DUNE Italia
LNF - November 11, 2025

SAND Calibration WG

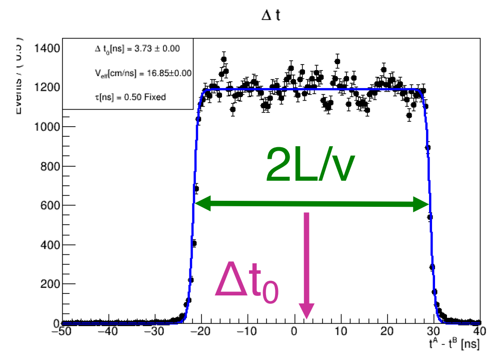
- Calibration: from detector signals to physical variables
  - ECAL: energy, time and positions of the particles
  - GRAIN: tracks, time, energy, ...
  - Tracker : r-t relations, track momentum, dE/dx for PID, ...
  - Timing alignment among the subdetectors
- Define a strategy for each subdetector:
  - Sources: cosmics, particles from beam, …
  - Choose suitable processes (given the expected fluxes of particles in the detector, e.g. for the ECAL: cosmic μ's as MIPs, MIPs from the beam, electrons and photons ....)
- Set a calibration procedure (Which level of precision ? How much time expected ?)
- People: ECAL - P.Gauzzi – R.D'Amico GRAIN: A.Surdo, Tracker: ……
- WG meetings generally every three weeks, on Thursday at 5 p.m. CET
- WG mailing list: dune-nd-sand-calibration@fnal.gov

ECAL calibration with MIPs

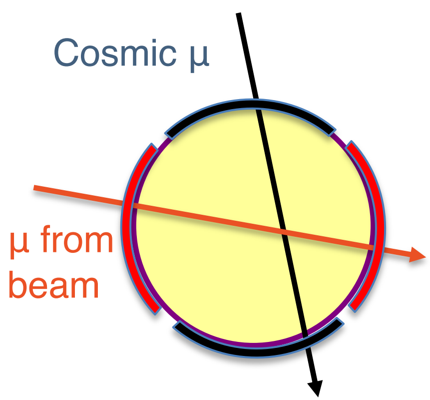
- ECAL: 4880 readout channels (PMTs), 2440 cells
- MIP peaks to equalize the Energy response of the ECAL cells



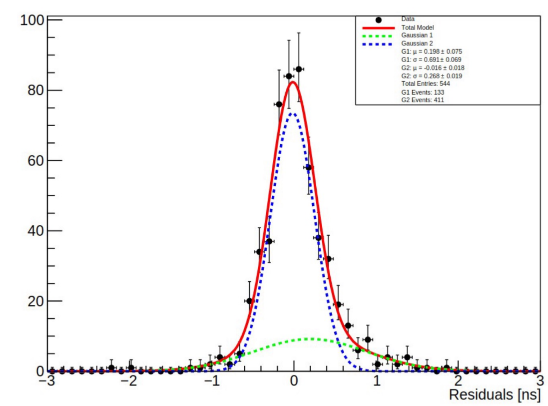
- Time calibration: 2 sets of constants to determine
- t_0's and Δt_0's for timing alignment of the cells and for calibration of the coordinate along the fibres



- We need muons from beam and from cosmic rays



- MC study of calibration with muons
  ⇒ see R.D'Amico's talk

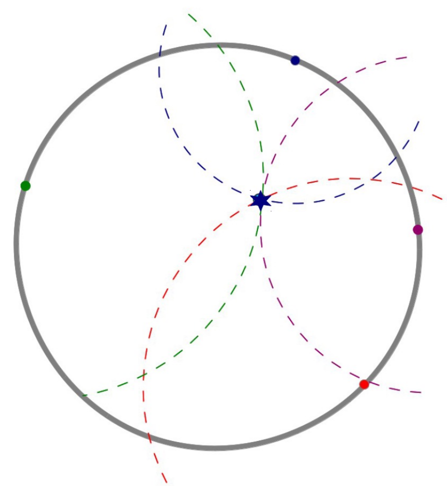


Energy scale calibration in SAND

- γ's from π^0 decays, invariant mass reconstruction (need a vertex from the tracker)
- γ + electrons: ~ 30% of photons from π^0 convert in the tracker

  ⇒ ~ 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 ⇒ need the momentum measurement in the tracker

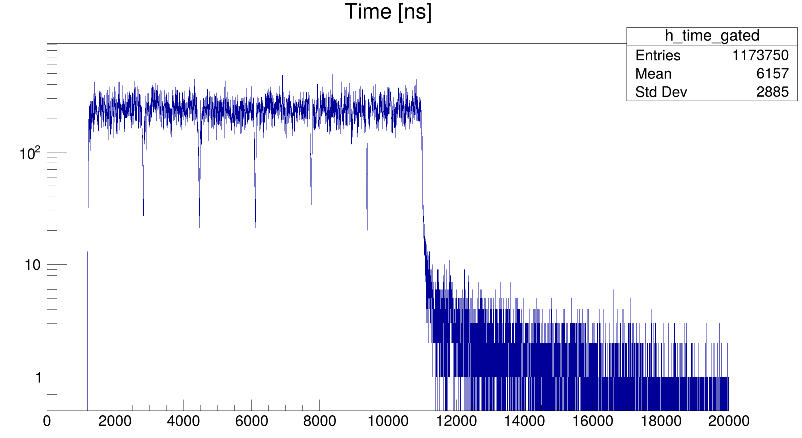
- Also exploit $K^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$
- From a naive rescaling of $K^0 \rightarrow \pi^+\pi^-$ ⇒ $O(10^5)$ evts in 5 years of FHC data-taking
- Reconstruct a vertex with the ECAL only, back-propagating each of the 4 photons, but the times of the ECAL cells must be very well aligned

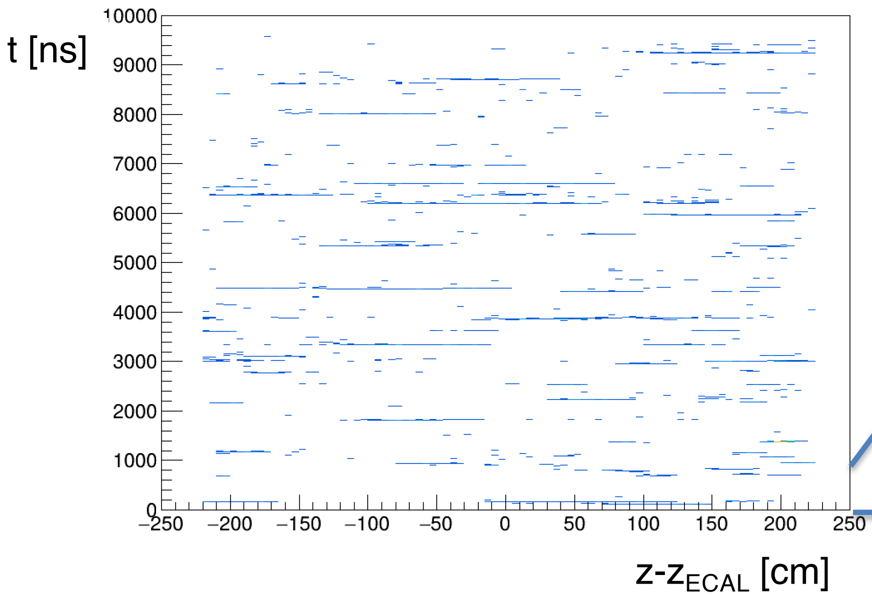


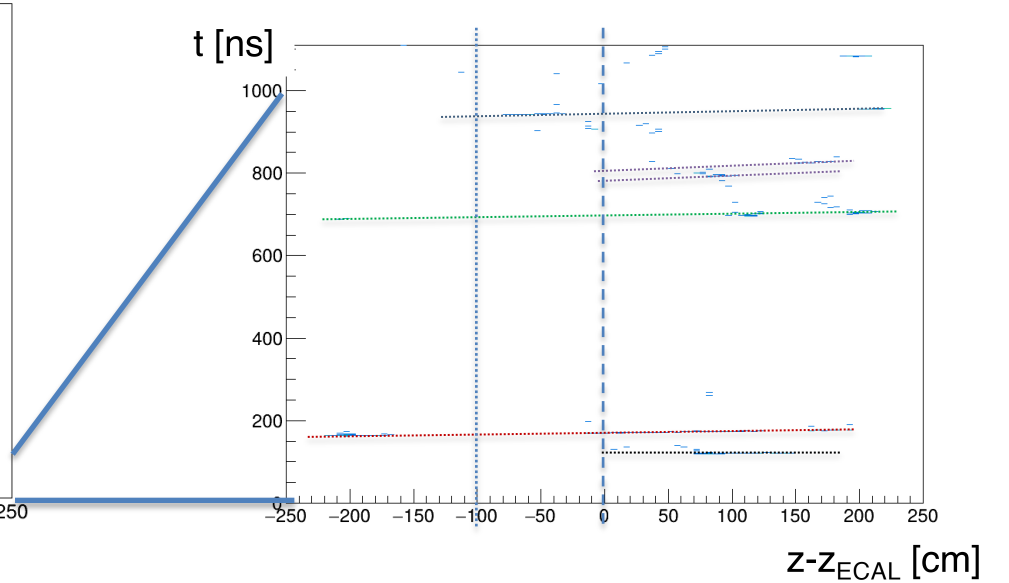
ECAL global t_0

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

- Global t_0, to be determined for each event
- The clusters will have the time distribution of the spill
- On average 88 ν interactions/spill in the SAND volume (FHC mode, 1.2 MW)
- Cell time vs Z coordinate:







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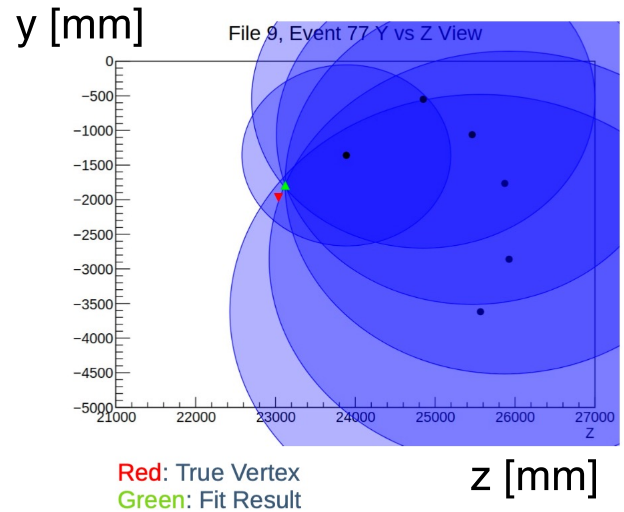
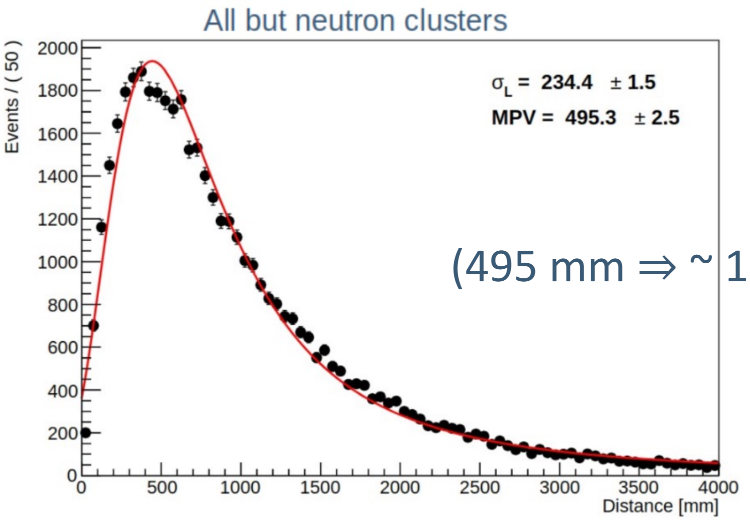
ECAL: Global t_0

- A complementary approach is to find the vertex of the ν interaction and compute the global t_0 from it
- Take the apex of each cluster as the center of a sphere, find the intersection of all the spheres with a fit.

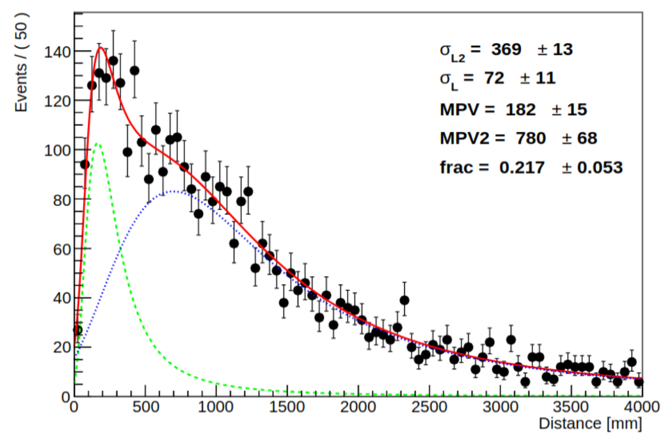


5×10^5 ν_μ interacting in the tracker volume: select events with at least 3 clusters (all particles except neutrons)



(495 mm ⇒ ~ 1.7 ns on t_0)

3×10^4 ν_μ interacting in the whole SAND (all particles except neutrons)



(780 mm ⇒ ~ 2.5 ns uncert. on t_0)

GRAIN calibration with muons

Expected muon flux from the beam and CRs

✓ Different contributions of the target masses in SAND for beam neutrinos

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

Table 1.29: Total number of ($\nu_\mu + \bar{\nu}_\mu + \nu_e + \bar{\nu}_e$) CC+NC events expected within a single beam (9.6 μs, 7.5 $\times$ 10^{13} POT) in the various detector components for both the FHC and RHC beam modes.

Detector element	Mass	FHC	RHC
Magnet	511 t	68.9	36.6
ECAL	100 t	13.5	7.2
LAr+STT	8.2 t	1.1	0.59
STT fiducial volume	5.5 t	0.74	0.39
Total	619.2	83.5	44.39

- From the interaction rate /spill in Magnet yoke and ECAL, a quite low number of clean muons are expected to cross GRAIN per spill (≤ 1 μ / spill)

Table 1.34: Number of events per spill (9.6 μs, 7.5 $\times$ 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.

	ECAL		Rock muons		Magnet events	
Cut	Events	ε (%)	Events	ε (%)	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

- Further contribution from rock μ's (~ 1.7/spill) ...

✓ **Contribution from Cosmic Rays ...**

CR Muon flux at surface ~ 0.01 μ/(s cm^2) +
underground reduction of ~ 100
Effective area of GRAIN for <60^o CR muons:
~3×10^4 cm^2⇒ ~3 μ/s are expected to cross GRAIN

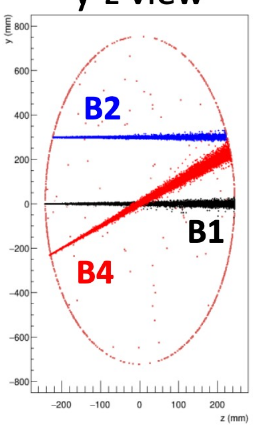
Drawback: smaller acceptance by the tracker for a precise track reconstruction

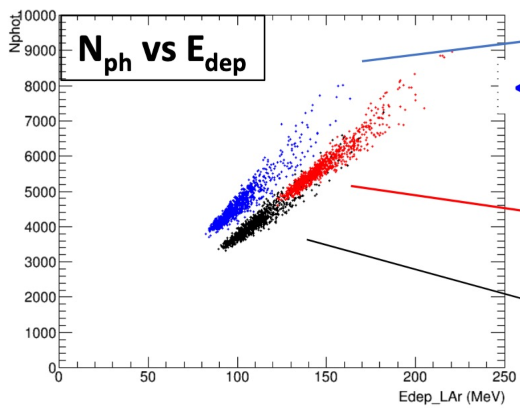
Main contribution only if inter-spill DAQ were ON

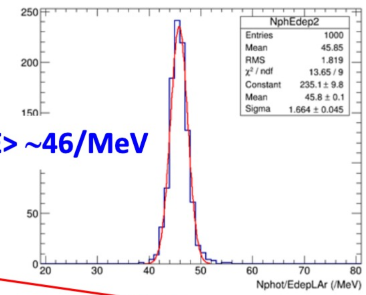
Muon beams with different positions and inclinations

MC samples of monochromatic muons of 1 GeV

See talk by A.Surdo

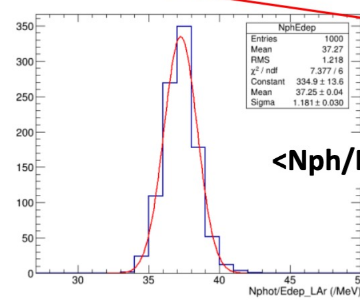






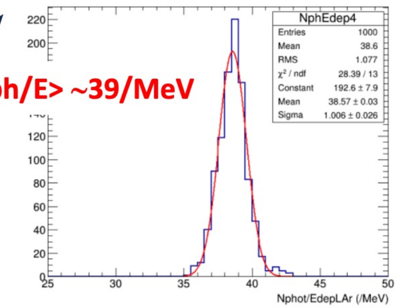
<Nph/E> ~46/MeV

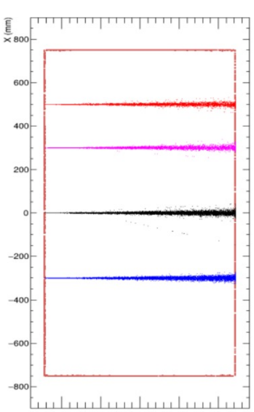
Similar calibration constants for beams at same average distance from GRAIN center
... no matter their inclination

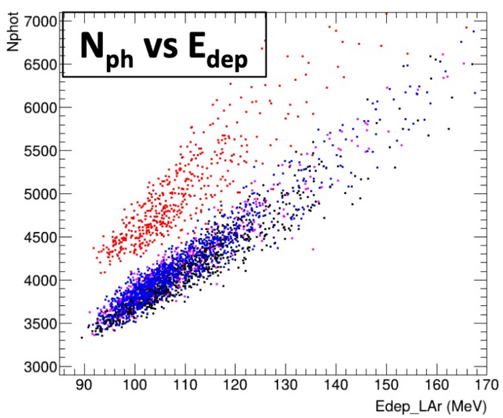


<Nph/E> ~37/MeV

<Nph/E> ~39/MeV





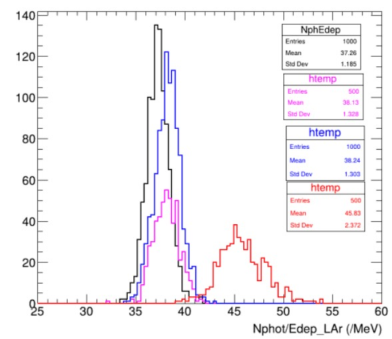


<Nph/E> ~37/MeV

<Nph/E> ~38/MeV

<Nph/E> ~38/MeV

<Nph/E> ~46/MeV



Conclusions

ECAL

- Calibration with muons (see Riccardo's presentation)
- First MC tests for a global t_0 determination

  (with ECAL alone, the method will improve by using the info from the tracker)
- Next steps:
  - Start the study of the energy scale calibration
  - Define the number of constants and the amount of data to be saved in a DB

GRAIN

- Studying the calibration with muons (see Antonio's talk)

Strategy of time alignment among the subdetectors has to be studied

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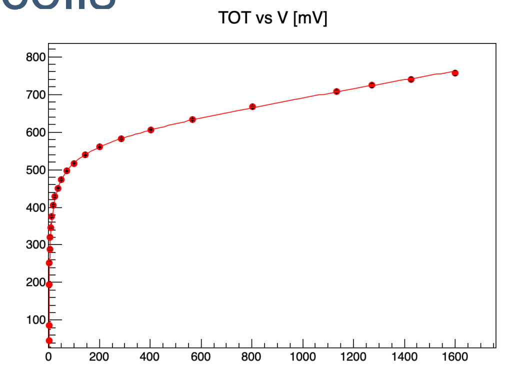
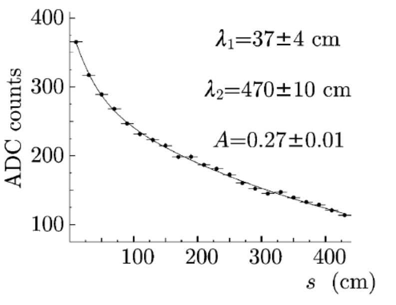
ECAL calibration constants

- ECAL: 4880 readout channels (PMTs), 2440 cells
- Pedestals: 1 constant/readout channel
- ToT calibration: 5th order polynomial,

  6 constants/readout channel



- Attenuation curve: 3 constants/readout channel

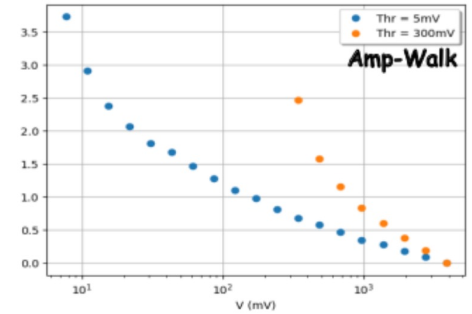


- c_i [counts/MIP]: 1 constant/cell, but two sets of constants, for ADC and for ToT
- K: absolute energy scale (few values for the whole ECAL)

ECAL calibration constants (II)

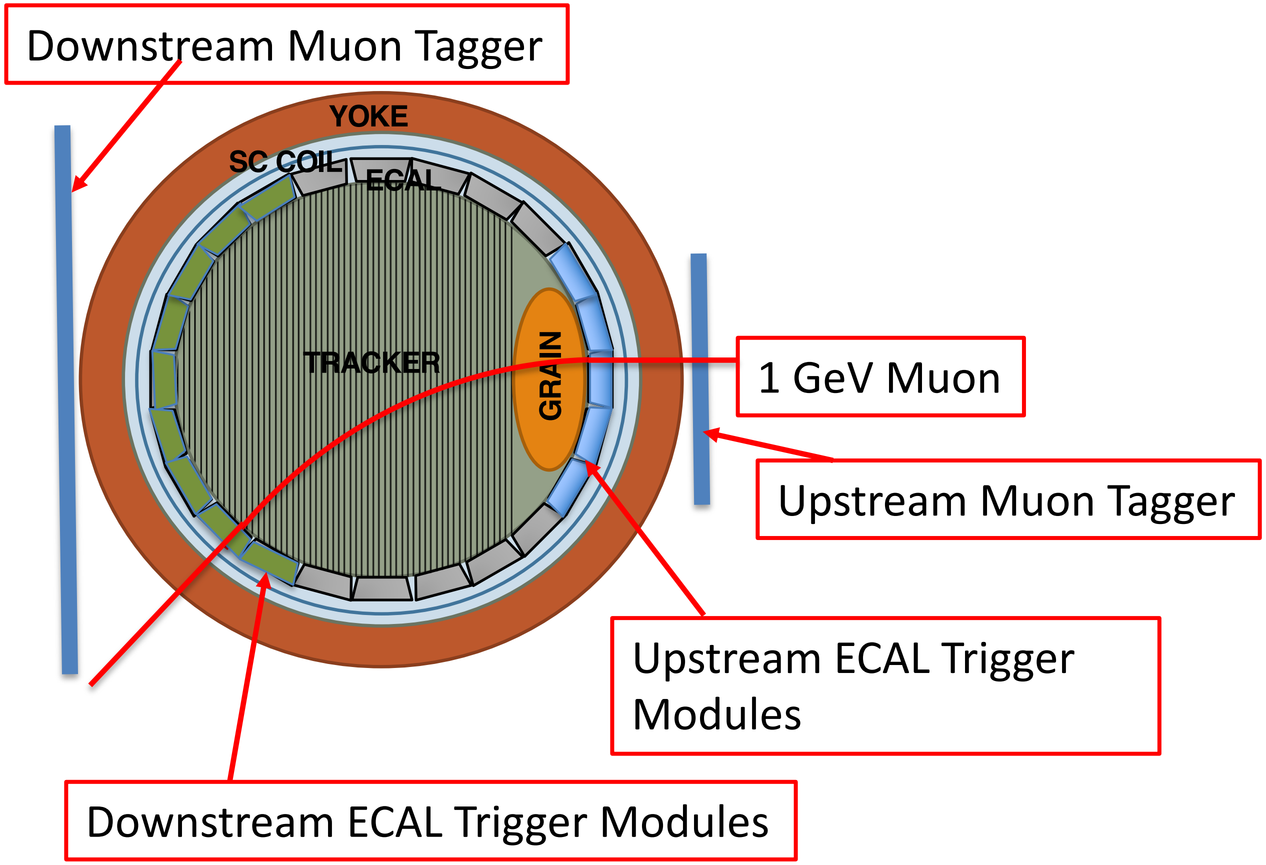
$$t_{A,B}\ [\mathrm{ns}] = c_{A,B}\ [\mathrm{ns/(TDC\ count)}](T_{A,B} - T_{A,B}^{(P)})\ [\mathrm{TDC\ counts}]$$

- T_P , time offsets due to cables, electronics: 1 constant/readout channel
- $C_{A,B}$[ns/count]: 1 constant/readout channel
- Time-walk corrections: polynomial fit, few constants/readout channel
- t_0's from MIPs: 1 constant/cell
- Δt_0's : 1 constant/cell
- Global T_0: 1 value/event



Scheme

- Upstream ECAL
  - In-time hits in 3 out of 4 layers
    - ~10ns window
  - Ignore outer (upstream) layer
- Downstream ECAL
  - In-time hits in 4 out of 5 layers
    - ~10ns window
- Coincidence
  - Upstream left and right
  - Downstream left and right
  - Pick out 100ns window for event-builder

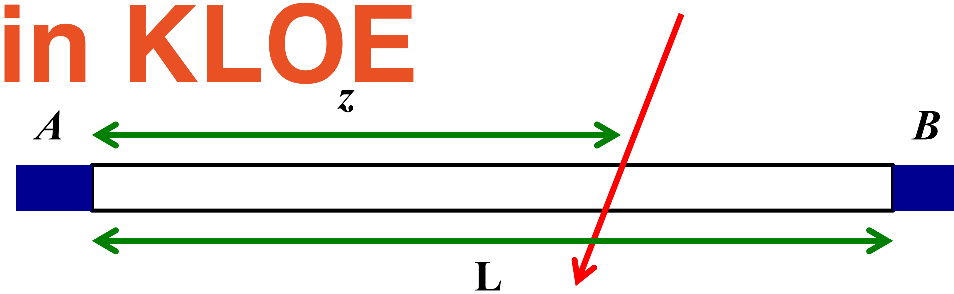


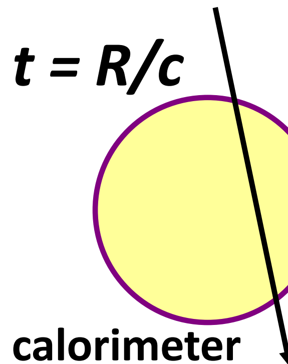
Time calibration in KLOE

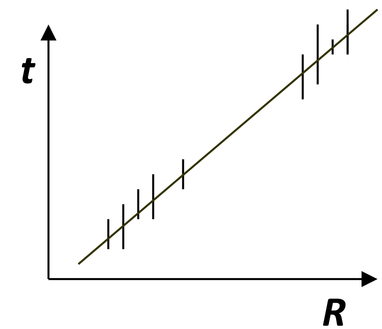
- MIPs: uniform illumination of the ECAL for time and z-coord. calibration

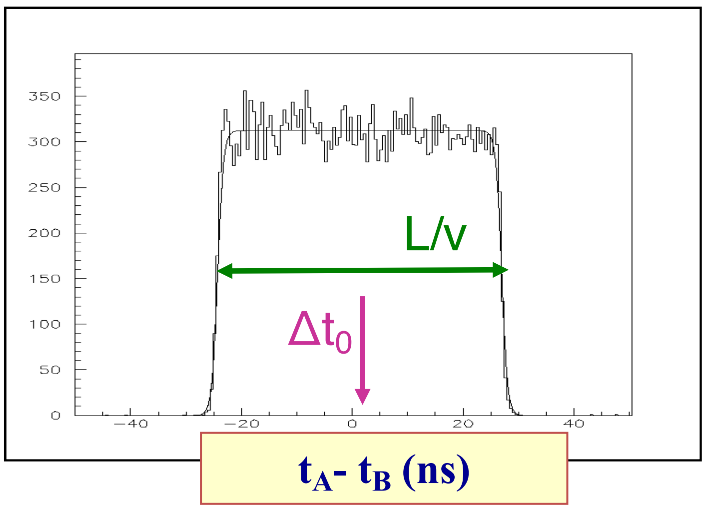
$$t = \frac{1}{2}(t_A + t_B) - \frac{L}{2v} - t_0 - t_G^0$$

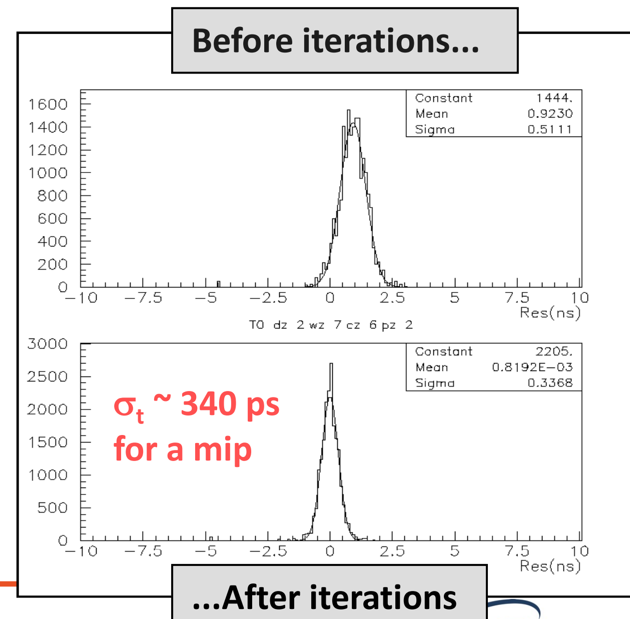
$$z = \frac{1}{2}v(t_A - t_B) - \Delta t_0$$





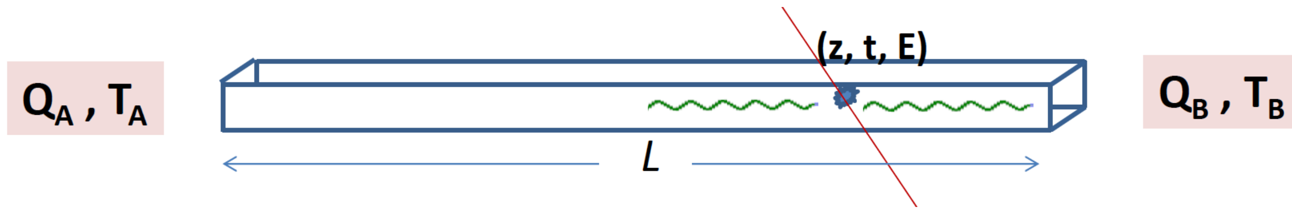






- Fine determination with Bhabha and γγ t_0's at ~ 20 ps

Energy calibration in KLOE



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

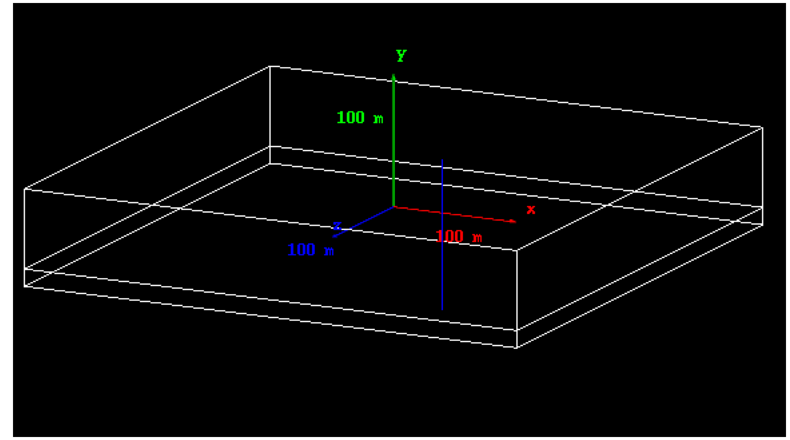
- C_i = peak of the MIP distribution
- **Corrections to the C_i with the Bhabha scattering events ($e^+e^- \to e^+e^-$): showers of 510 MeV**
- **Absolute energy scale K fixed at cluster level with the $e^+e^- \to \gamma\gamma$ events**

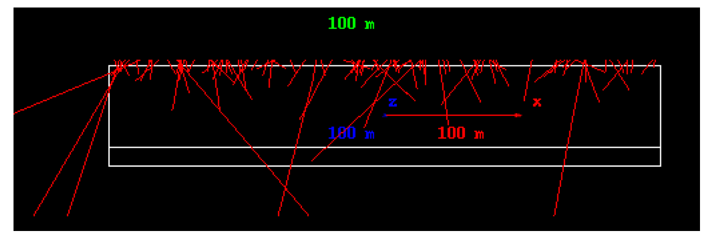
$$\Rightarrow \mathrm{Calib.\ Const.} = \frac{K}{C_i}$$

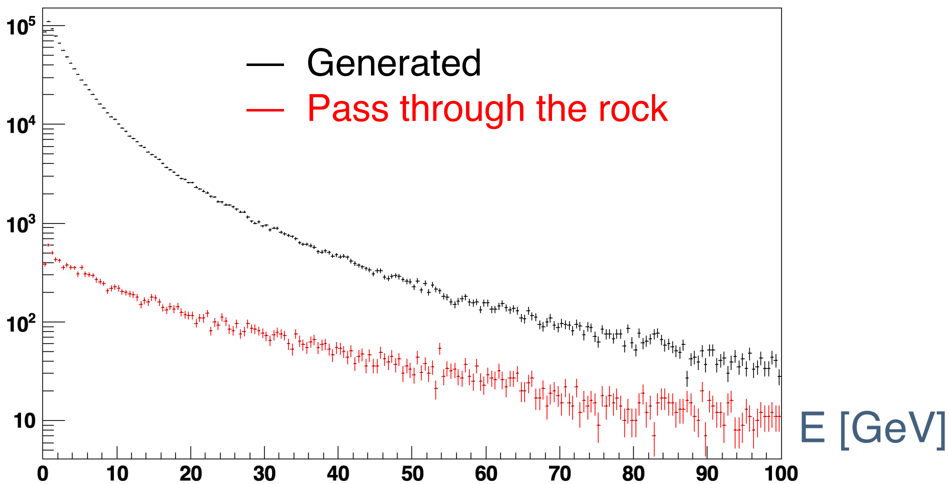
Cosmic μ with GEANT4

Very simple model:

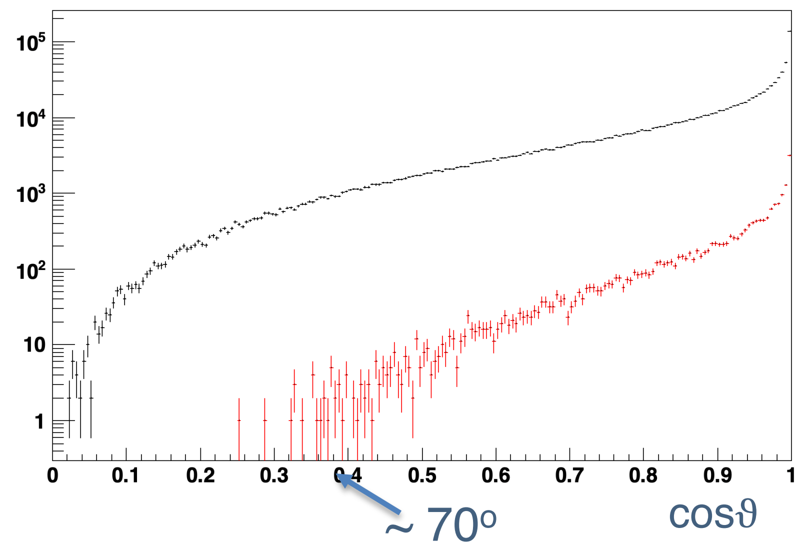
- Box of Standard Rock, 60 m thick (52% O, 27% Ca, 12% C, 9% Mg, density 2.65 g/cm^3)
- Box of air 10 m thick
- 10^6 muons generated on top of the rock box







Events surviving	16965	1.7%
MIPs (p_μ > 300 MeV)	16583	1.7%
p_μ > 1 GeV	15983	1.6%
Straight tracks (p_μ > 6 GeV)	12228	1.2%



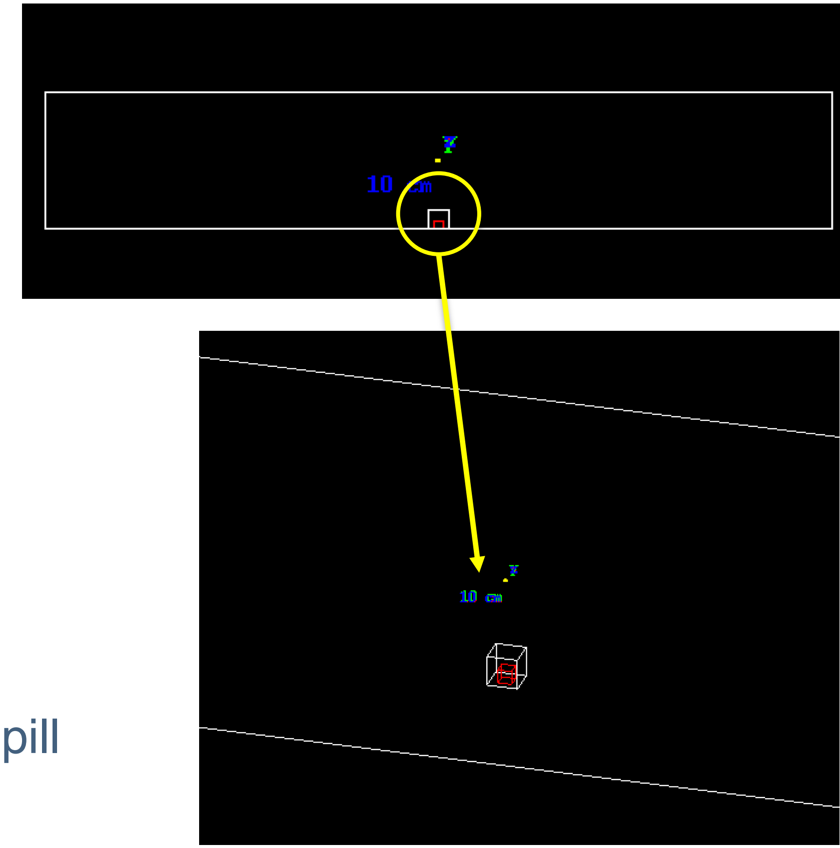
Cosmic μ simulation with GEANT4

- Simplified model of the hall (a cube of air of $10 \times 10 \times 10\ m^3$ embedded in the rock)
- Red box representing the SAND: cube $4.5 \times 4.5 \times 4.5\ m^3$ inside the air cube

- Generated 10^6 events on a surface of $50 \times 50\ m^2$

- 95 events on SAND volume ($\sim 10^{-4}$)
- Rescaling the muon flux at the surface ($\sim 0.02\ \mu/(s\ cm^2)$) $\Rightarrow$ ~ 40 – 50 μ/s on ECAL

- To collect cosmics we need data out of the spill



Next step: Interface with Edepsim and SAND geometry

Cosmic μ with GEANT4

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