ECAL Calibration with muons

Riccardo D'Amico, Paolo Gauzzi

DUNE Italia

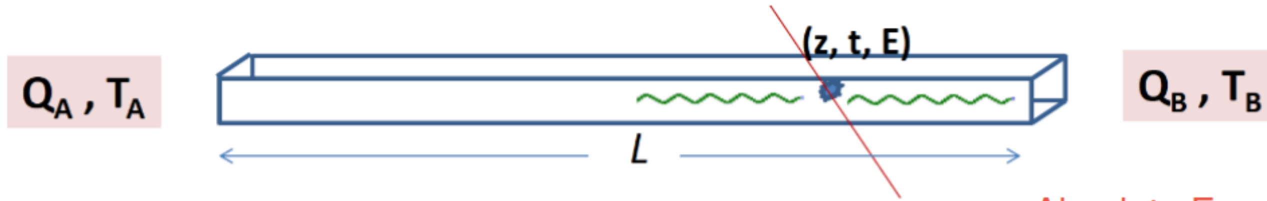
11/11/2025

Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

ECAL Calibration with muons

Energy Calibration:



Absolute Energy scale factor

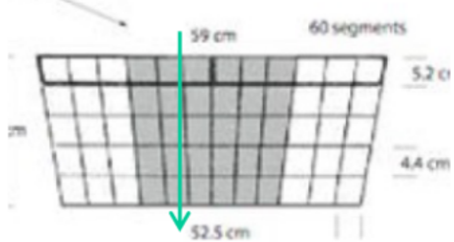
$$E_i^{(A,B)}[\mathrm{MeV}] = \frac{(Q_i^{(A,B)} - P_i^{(A,B)})[\mathrm{ADC\ counts}]}{C_i[\mathrm{ADC\ counts/MIP}]} K \times f_{MIP2MeV}[\mathrm{MeV/MIP}]$$

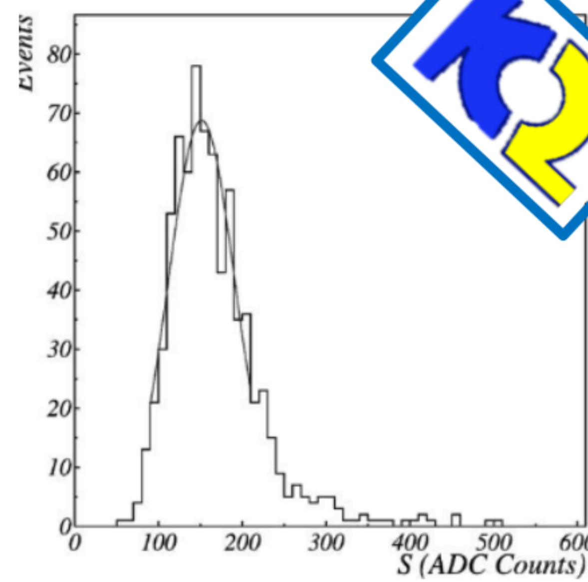
= Peak of MIP distribution

How it was done:

- Determined from cosmic ray muons ~ $10^4 \mu/s$ on ECAL
- crossing one column in barrel (100Hz).

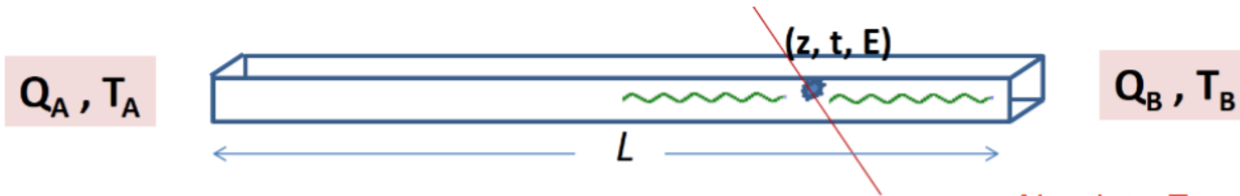
Golden MIP Sample





ECAL Calibration with muons

Energy Calibration:



Absolute Energy scale factor

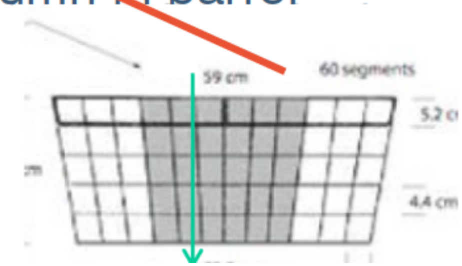
$$E_i^{(A,B)}[\mathrm{MeV}] = \frac{(Q_i^{(A,B)} - P_i^{(A,B)})[\mathrm{ADC\ counts}]}{C_i[\mathrm{ADC\ counts/MIP}]} K \times f_{MIP2MeV}[\mathrm{MeV/MIP}]$$

= Peak of MIP distribution

~~How it was done:~~

- ~~Determinated from cosmic ray muons ~ $10^4\,\mu/s$ on ECAL~~
- ~~crossing one column in barrel (100Hz).~~

Golden MIP Sample



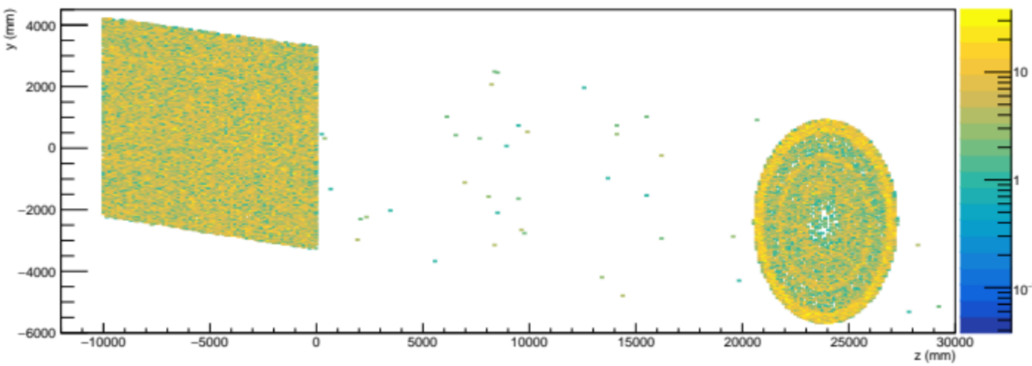
In SAND:

- Cosmic rays: underground reduction of a factor ~ 100 on ECAL (without selection).
- By rescaling KLOE numbers ~ 10 evts/cell of «Golden MIPs» in 24h.

Not enough

Other MiP sources → Muons from neutrino interactions

Neutrino production



$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

Removed TMS and NDLAr from the geometry (a conservative choice since they will also operate off-axis)

$$\mathcal{W}_{\text{NEAR-FID1}} = \Big\{ x \in [-3.20,\, 3.20]\ \text{m},\ y \in [-3.55,\, 3.05]\ \text{m} \Big\},$$

4k Files of 250 events each.
Each file equals to 7~8 x 10^13 POT (~1 spill) → 4k Spills ~ 1.3h of DataTaking.

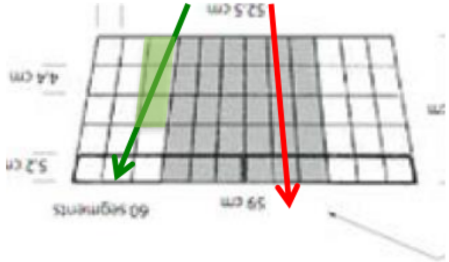
Selecting events with at least 1 muon cluster in ECal.

Region / volume	Events	Fraction [%]
ECAL volumes	35,536	37.70
Yoke	32,152	34.11
Rock	20,054	21.28
Tracker	3,945	4.19
Solenoid	1,893	2.01
GRAIN	632	0.67
Detector enclosure	43	0.05
Total selected	**94,255**	**100.00**

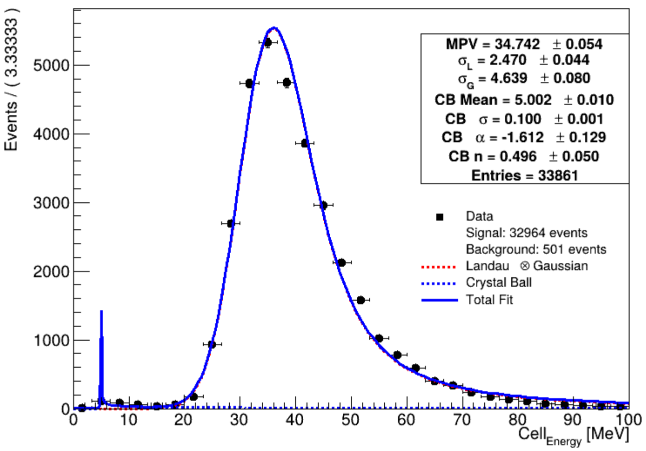
Energy Calibration:

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

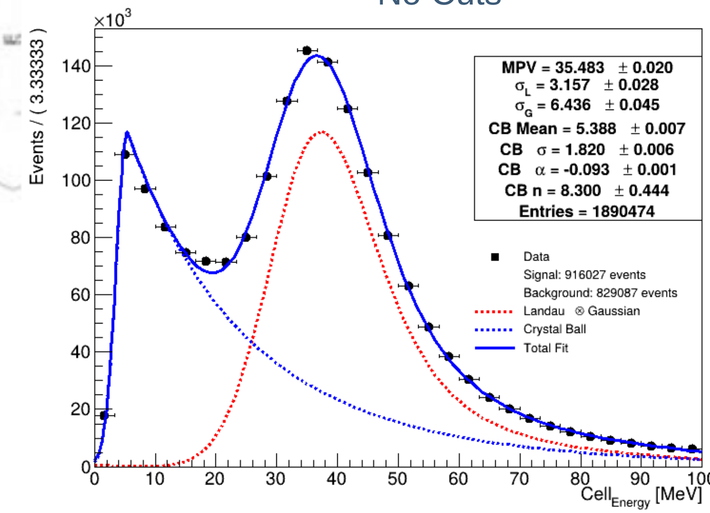
Cluster topology selection cuts



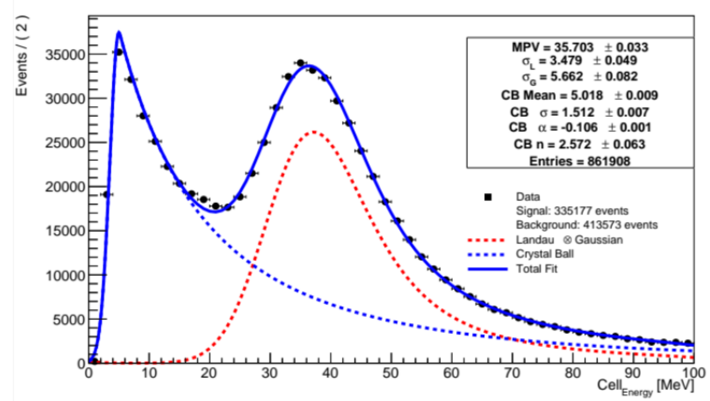
Golden MiP: Cluster of cells in 1 straight column



No Cuts



Clusters with at least 3 Cells in the same column



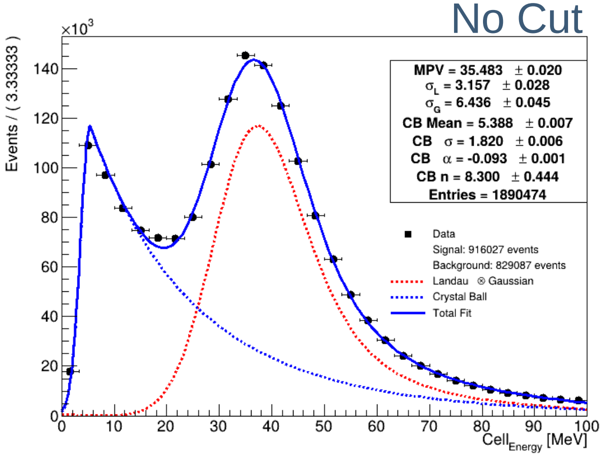
All cells grouped togheter → Monte Carlo cells are the same by construction.

These histograms must be obtained for each single cell.

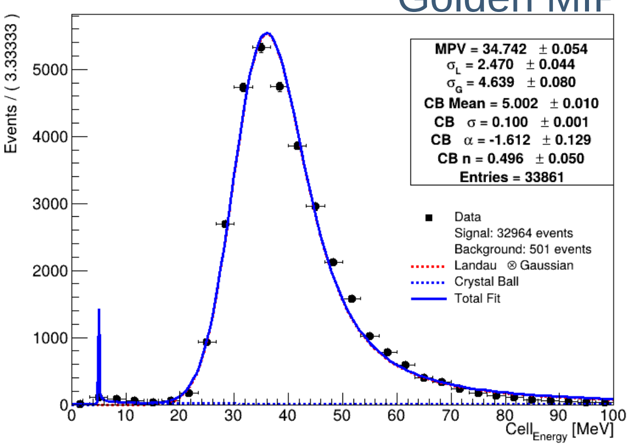
Energy Calibration:

Simulation

No Cut

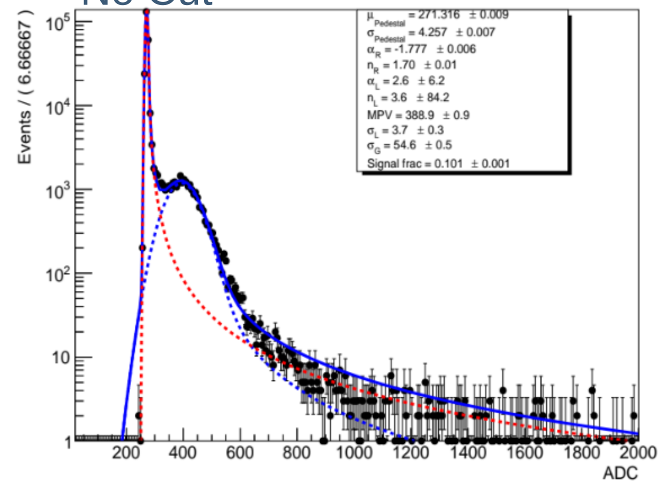


Golden MIP

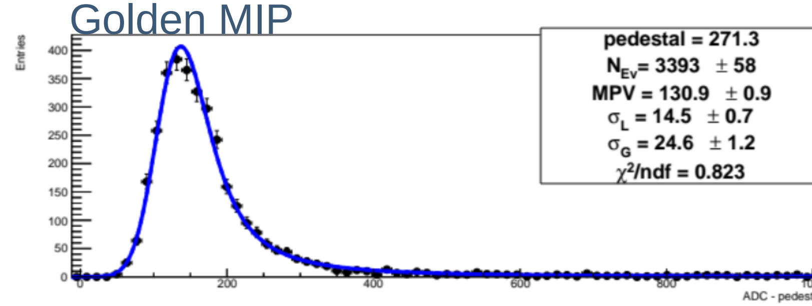


Real Data from Cosmic Ray Stand at LNF on Barrel 5

No Cut



Golden MIP



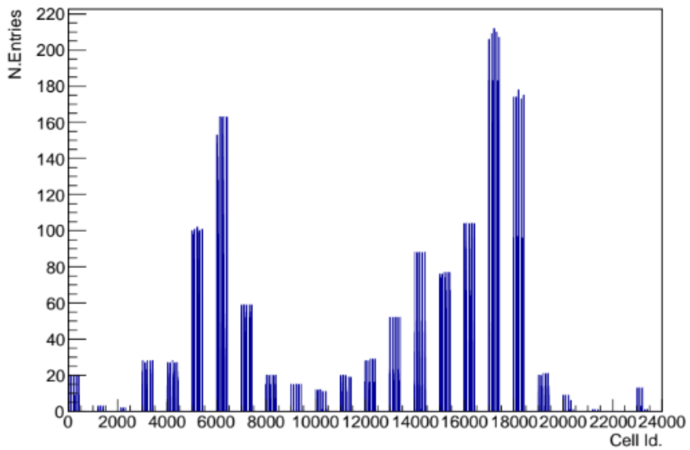
See previous talk on the [ECAL barrel Test Stand]

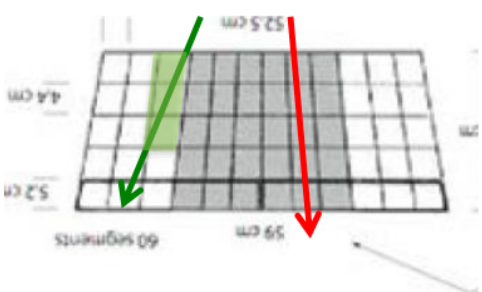
Energy Calibration: Barrel Cell Distribution

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

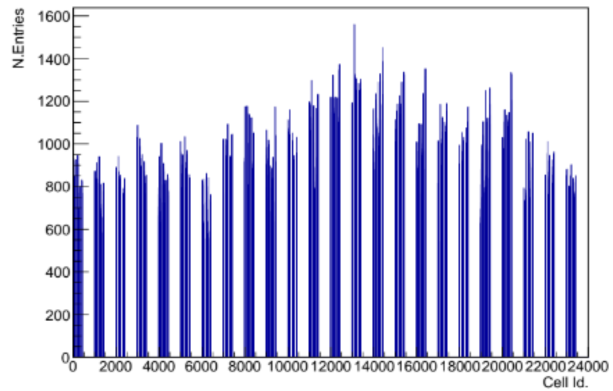
The cell distribution for each different selection varies. Golden MiPs can be found mostly only in the barrels along the beam direction and in endcap 1 (on the negative x)

Golden MIPs: Cluster of cells in 1 straight column



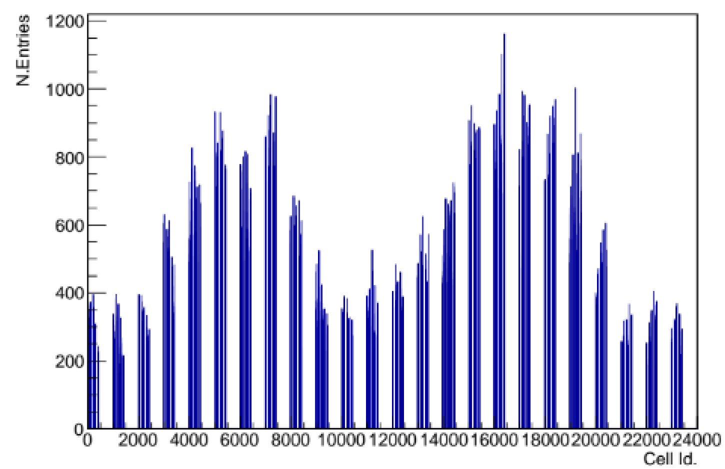


No Cuts



Without cuts the barrel histogram is mostly uniform

Clusters with at least 3 Cells in the same column

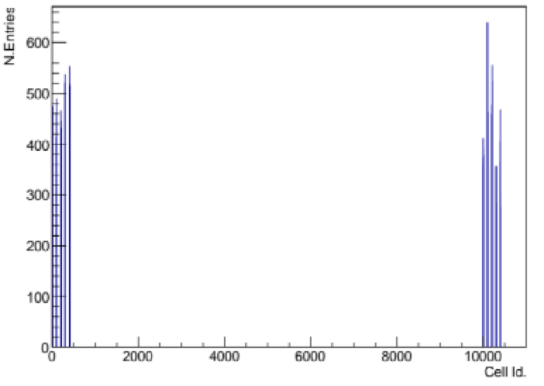


Energy Calibration: Endcap 0 Cell Distribution

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

The cell distribution for each different cuts varies a lot. Golden MiPs an be found mostly only in the barrels along the beam direction and in endcap 1 (on the negative x)

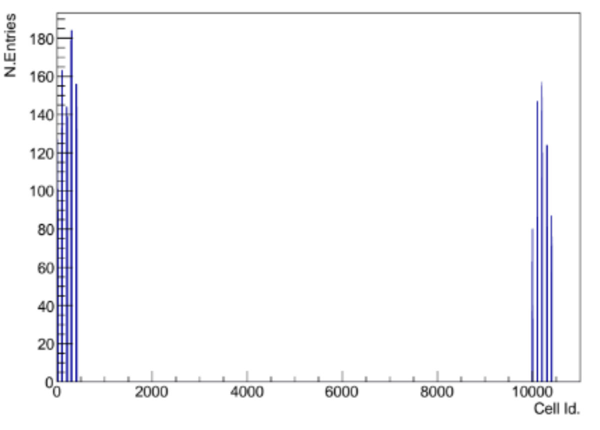
No Cuts



Golden MIPs: Cluster of cells in 1 straight column

Clusters with at least 3 Cells in the same column

NONE



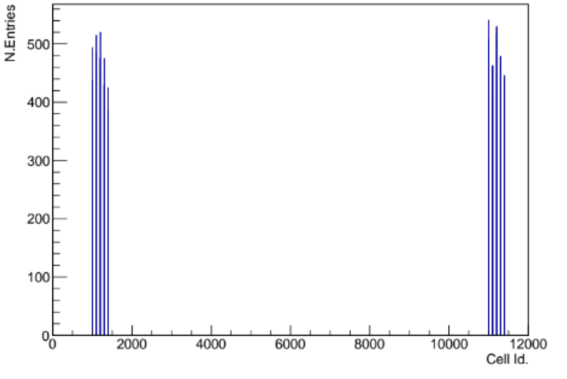
For **endcap 0** no single column found.

Energy Calibration: Endcap 1 Cell Distribution

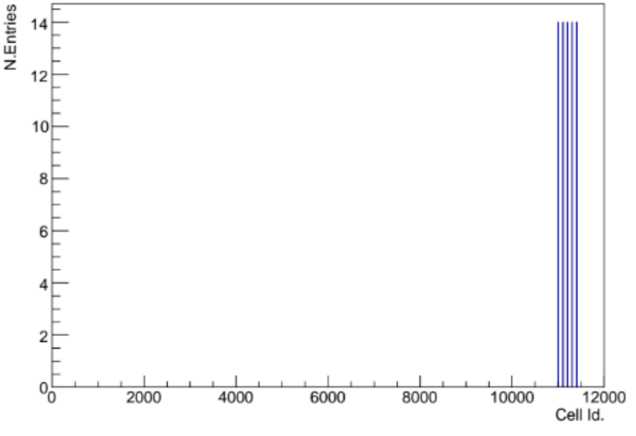
$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

The cell distribution for each different cuts varies a lot. Golden MiPs an be found mostly only in the barrels along the beam direction and in endcap 1 (on the negative x)

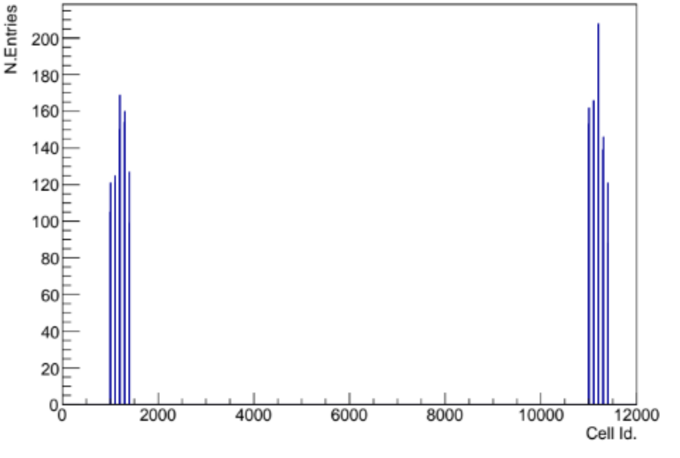
No Cuts



Golden MIPs: Cluster of cells in 1 straight column



Clusters with at least 3 Cells in the same column



For **endcap 1** some clusters of Golden MiPs are found.

Energy Calibration: Single Cells Histograms & Fit

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

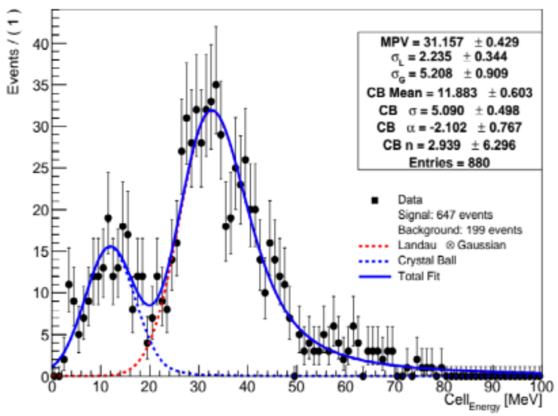
For each selected cut an histogram has been obtained for each cell.
A RooFit Script fits each cell histograms and saves the canvas, fit result and histogram in a new file. Another script organizes all histograms canvases and fit results in a rootfile, divided by detector ID and module ID in different folders.

```
<root-file>
|-- detX/                      # X = 0,1 for endcaps; X = 2 for barrel
|   `-- moduleYY/              # YY = module ID.
|       `--energy/
|          |-- fitResults/        # Per-cell fit objects
|          |   `-- fitResult_h_cell<Sel>_<cellID>
|          |-- canvases/          # Rendered canvases of fits/plots
|          |   `-- c_cell<Sel>_<cellID>
|          |-- histograms/        # Input histograms used in the fits
|          |   `-- h_cell<Sel>_<cellID>
|          `-- summary/           # Module-level overviews
|              `-- h_summary_<Sel>_moduleYY
```

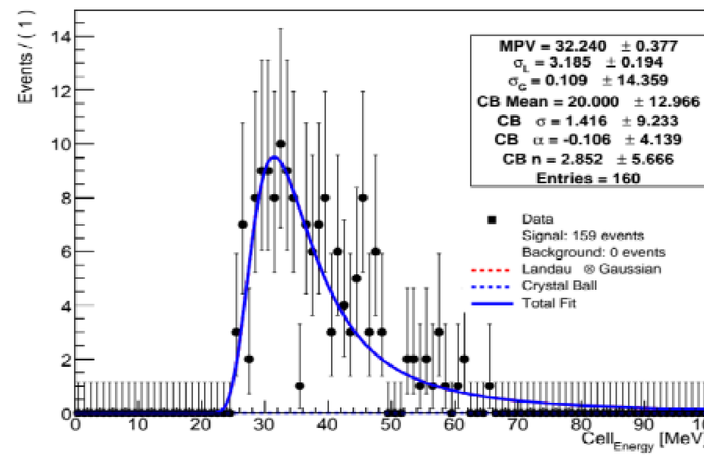
Energy Calibration: Single Cells Histograms & Fit

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

Some Results → Barrel Module 17, Layer 1, cell 5.

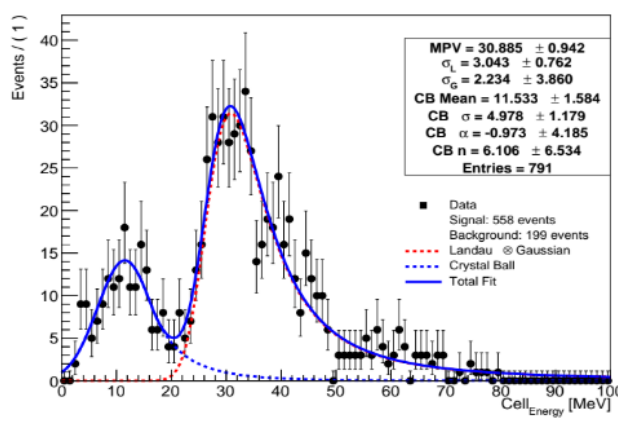


No Cut.



Golden Mip.

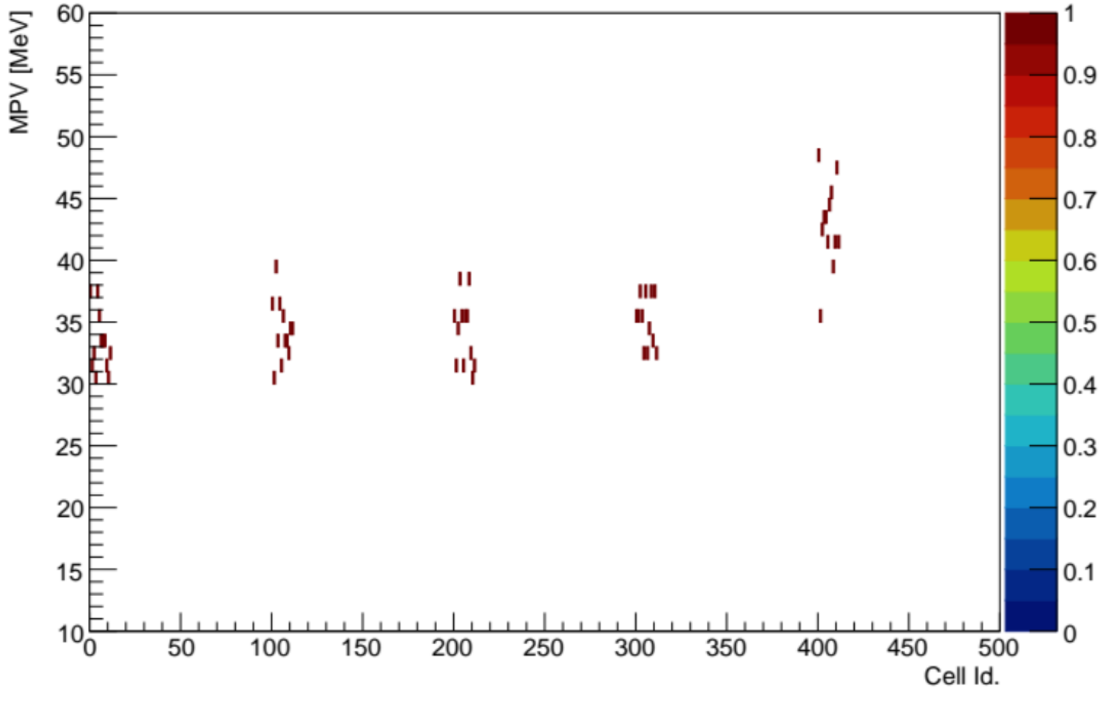
3Cell in 1 Column Cut.



Energy Calibration: Single Cells Histograms & Fit

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

Some Results → Barrel Module 17 Summay MPV.

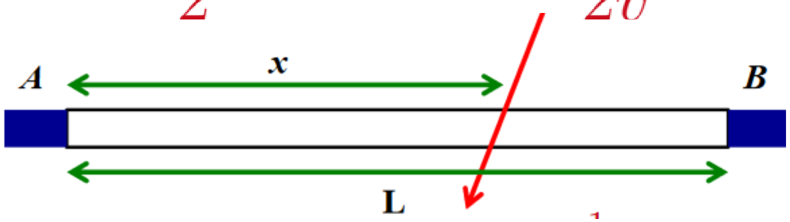


One can appreciate the increase of the MPV in layer 5 due to the increased thickness.

ECAL Calibration with muons

Time Calibration:

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

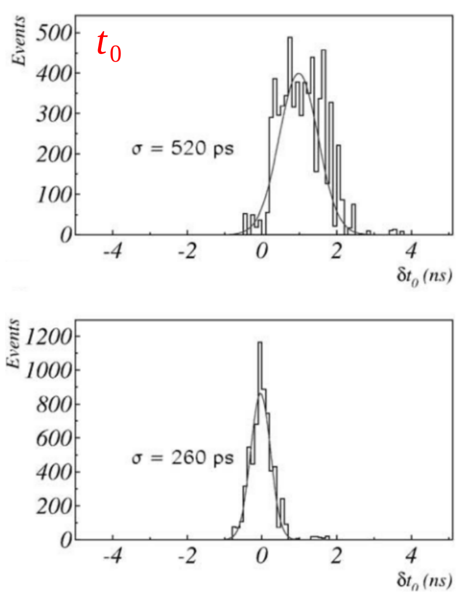


$$x = \frac{1}{2}v(t_A - t_B) + \frac{1}{2}L - \frac{1}{2}v\Delta t_0$$

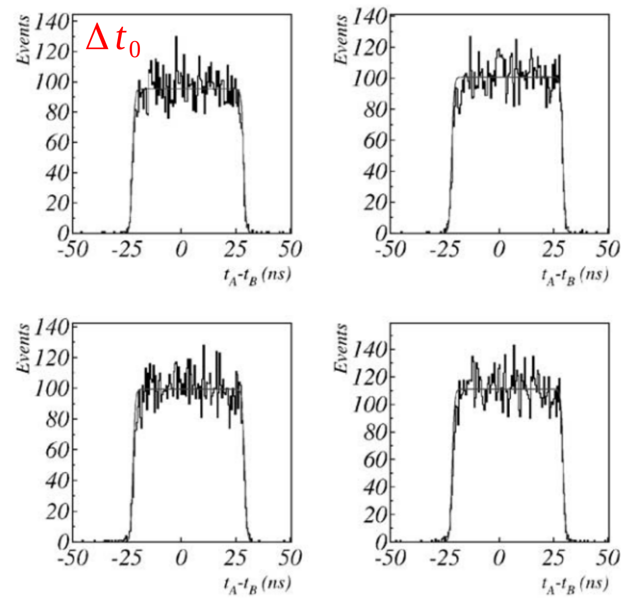
$$t_0 = \frac{1}{2}(t_A^0 + t_B^0)$$

$$\Delta t_0 = t_A^0 - t_B^0$$

Straight Track Study



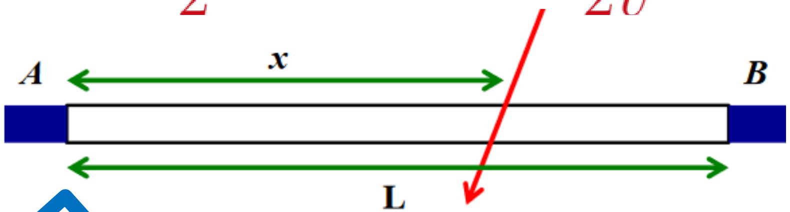
PMTs tdc difference



ECAL Calibration with muons

Time Calibration:

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

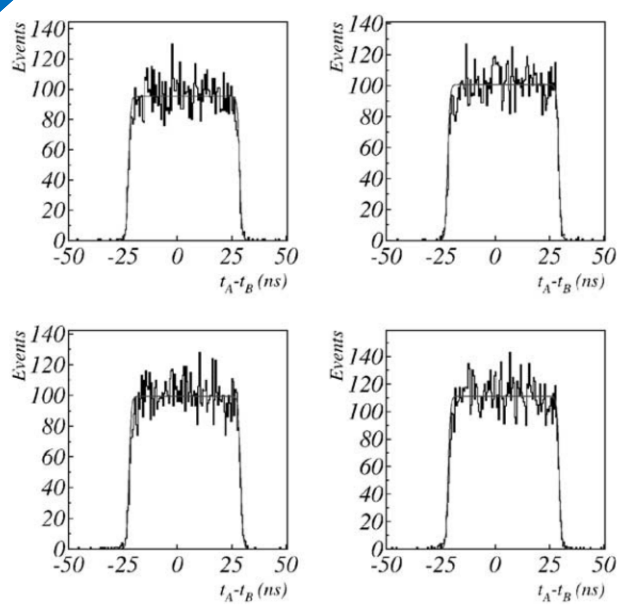


$$x = \frac{1}{2}v(t_A - t_B) + \frac{1}{2}L - \frac{1}{2}v\Delta t_0$$

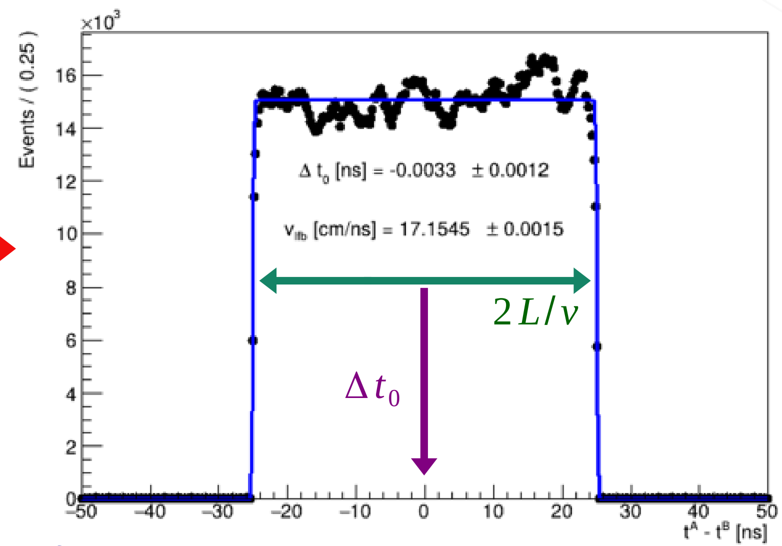
$$t_0 = \frac{1}{2}(t_A^0 + t_B^0)$$

$$\Delta t_0 = t_A^0 - t_B^0$$

PMTs tdc difference



No cluster topology cuts applied



$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

Time Calibration:

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

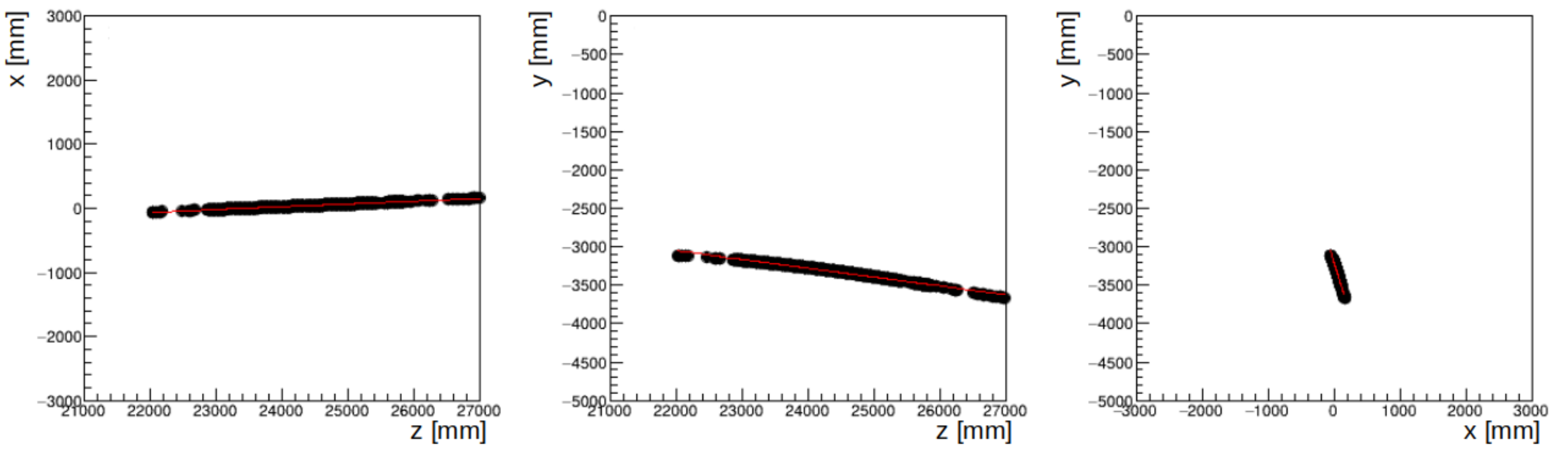
Time Calibration methodology:

- Select straight tracks that connect different parts of the ECAL;
- Linear fit on the cluster positions and on time vs z;
- Accumulate residuals for each cell → the center of the distribution yields t_0

Track Selection Method.

- Selecting events with at least 2 muon clusters;
- Selecting cells only from the 2 muon clusters.
- Using Monte Carlo Tracks to establish if the track is straight or not.
- At least 10 cells in the selection;

MC track



Time Calibration:

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume.

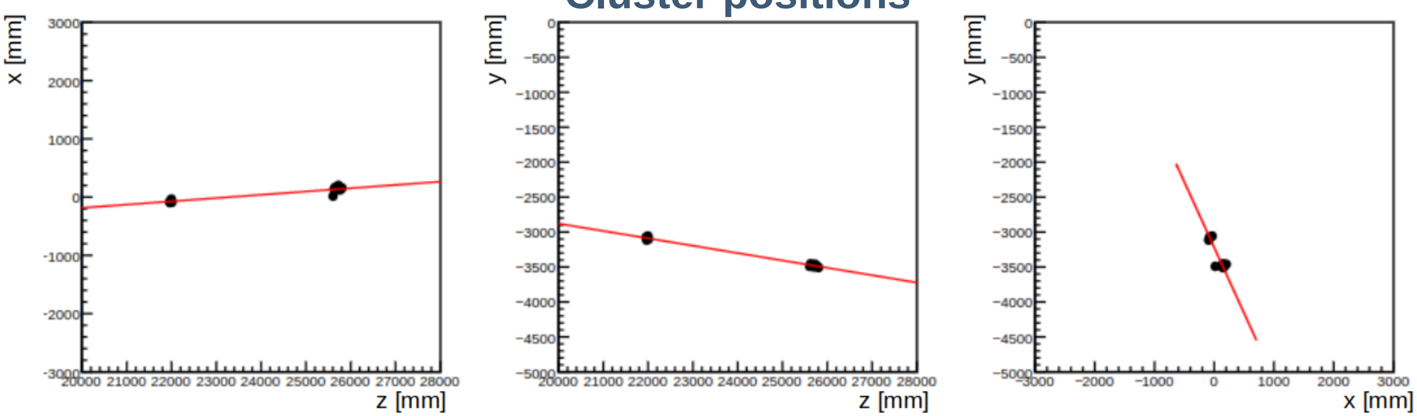
Time Calibration methodology:

- Select straight tracks that connect different parts of the ECAL;
- Linear fit on the cluster positions and on time vs z;
- Accumulate residuals for each cell → the center of the distribution yields t_0

Track Selection Method.

- Selecting events with at least 2 muon clusters;
- Selecting cells only from the 2 muon clusters.
- Using Monte Carlo Tracks to establish if the track is straight or not.
- At least 10 cells in the selection;

Cluster positions

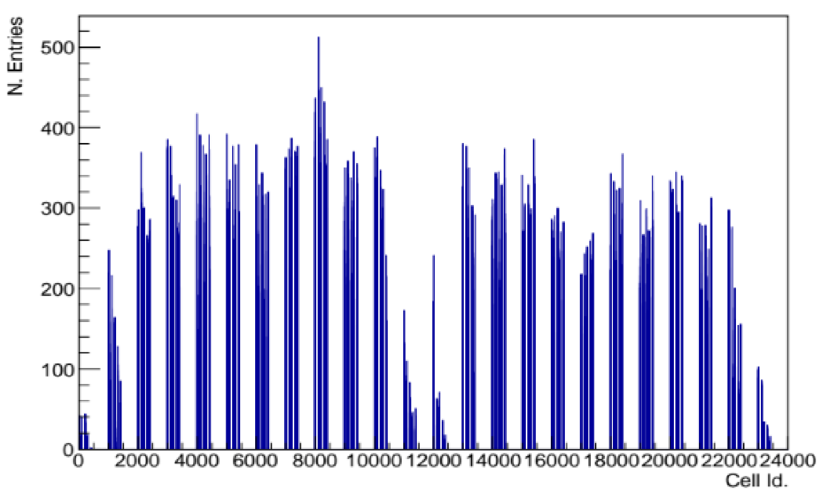


For each selected cell in an event it is saved the x, y and z position, the reconstructed time, reconstructed energy and id. A linear fit on the cell positions fixes the direciton in z.

Time Calibration: Cell Distribution

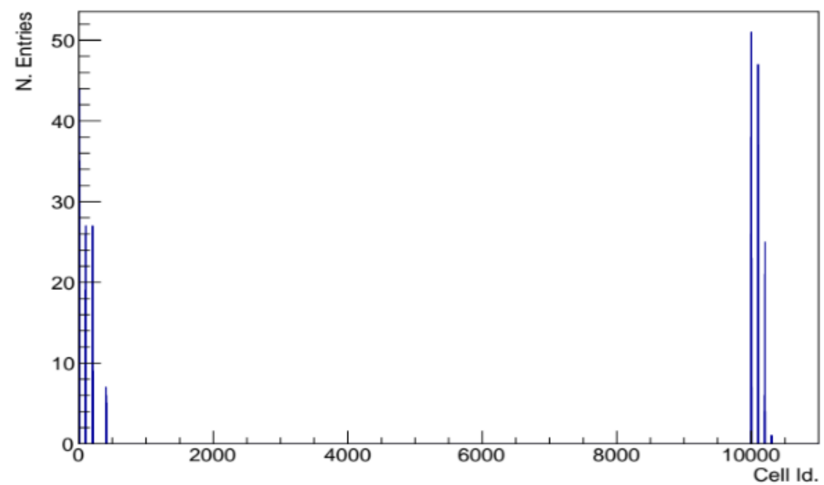
The cell distribution for selected tracks is as we expect, due to the straightness constraint the most populated cells are the ones on the direction of the beam. Modules 0,23 and 11,12
and the endcaps have low statistic.

Barrel

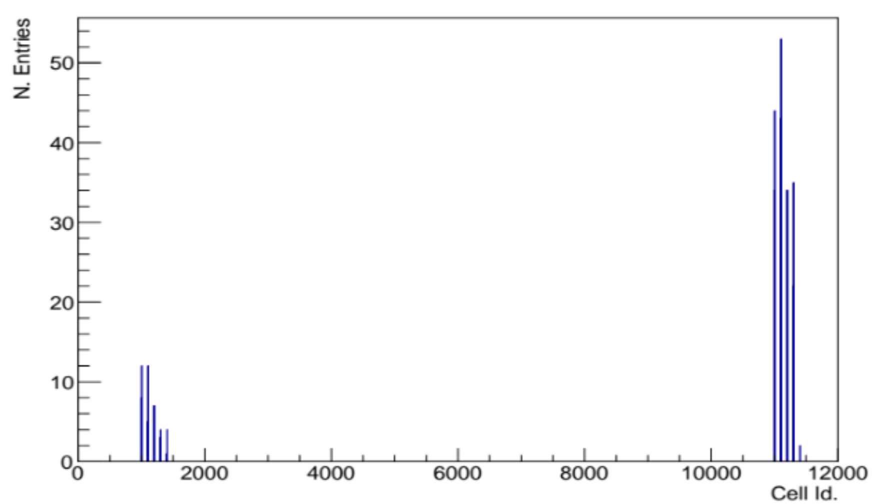


$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

Endcap 0

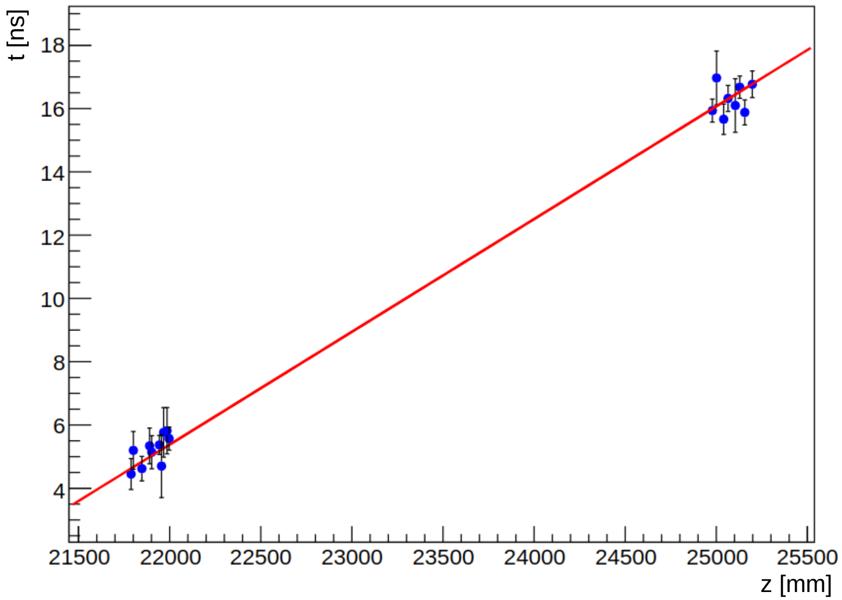


Endcap 1



Time Calibration:

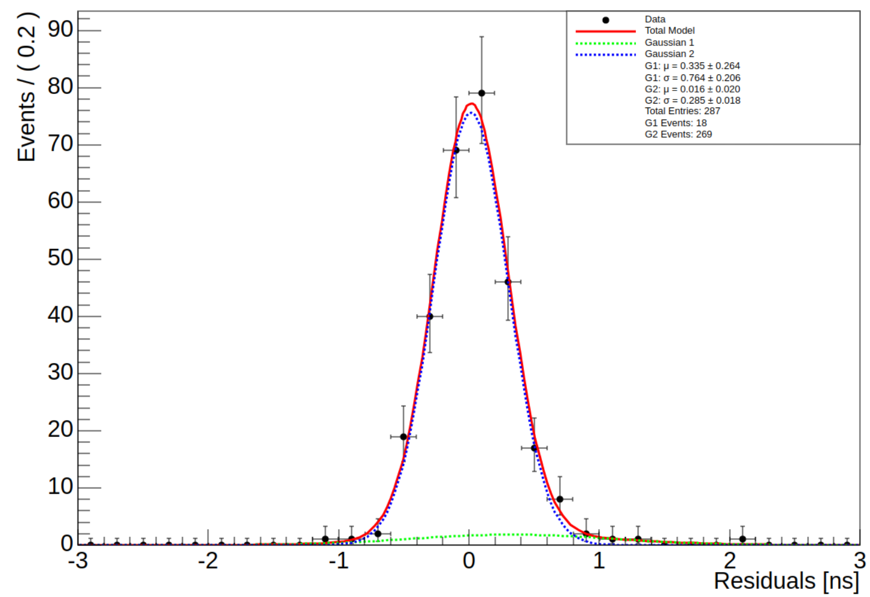
$10^6 \nu_\mu$ interacting in the rock and in the SAND volume



A linear fit is performed in t vs z.

The residuals of each point (=cell) from the fitted line are saved in an histogram for each cell ID.

- The residual histogram for each cell is fitted with a gaussian;
- Use the average to correct the cell t_0;
- Iterate the procedure to minimize the residuals;



Barrel Module 18, Layer 1, cell 10.

Time Calibration: Single Cells Histograms & Fit

$10^6 \nu_\mu$ interacting in the rock and in the SAND volume

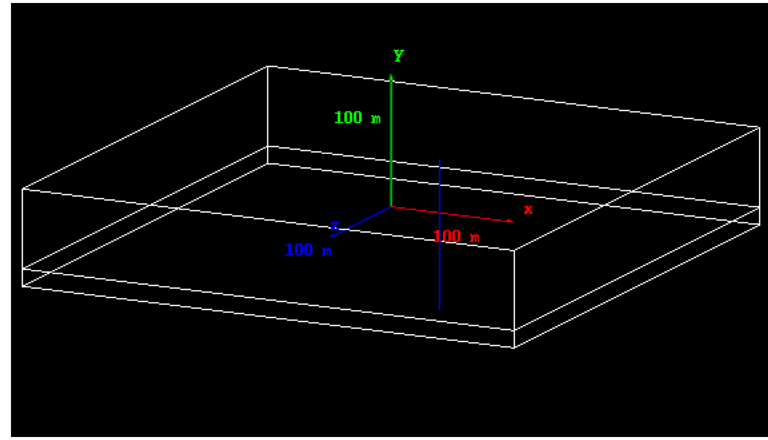
The results are stored in the same rootfile as before, in a separate directory, following the same structure.

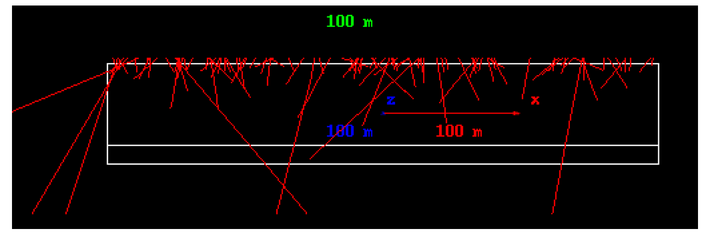
```
<root-file>
|-- detX/                        # X = 0,1 for endcaps; X = 2 for barrel
|   '-- moduleYY/                # YY = module ID.
|       '--energy/
|       '--time/
|          '--residual/
|             |-- fitResults/        # Per-cell fit objects
|            |   '-- fitResult_res_cell_<cellID>
|            |-- canvases/          # Rendered canvases of fits/plots
|            |   '-- res_cell_<cellID>
|            |-- histograms/        # Input histograms used in the fits
|               |   '-- hist_res_cell_<cellID>
|         '--tdcdiff/
|            |-- fitResults/        # Per-cell fit objects
|            |   '-- fitResult_tdcDiff_cell_<cellID>
|            |-- canvases/          # Rendered canvases of fits/plots
|            |   '-- tdcDiff_cell_<cellID>
|            |-- histograms/        # Input histograms used in the fits
|            |   '-- hist_tdcDiff_cell_<cellID>
```

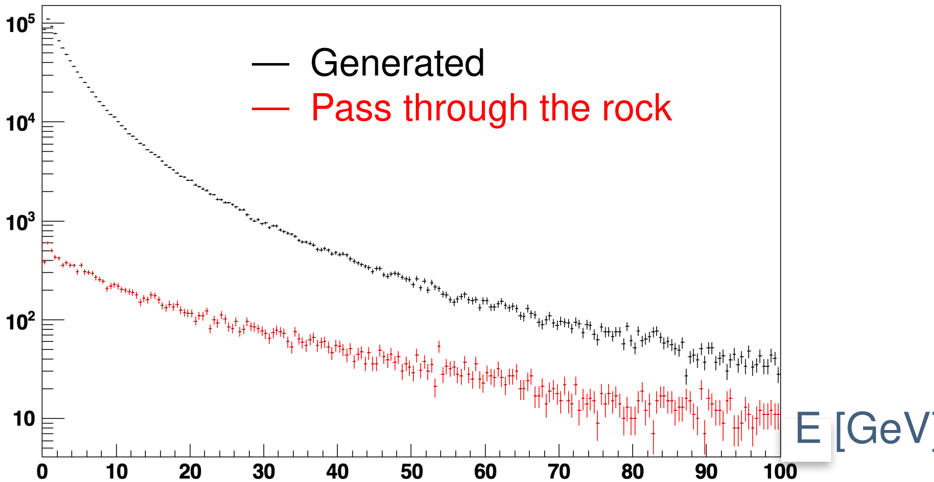
Cosmic μ with GEANT4

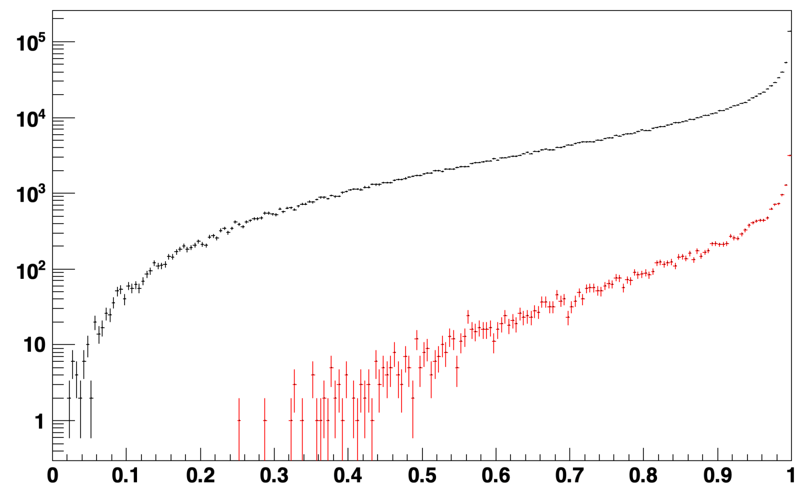
Very simple model:

- 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%

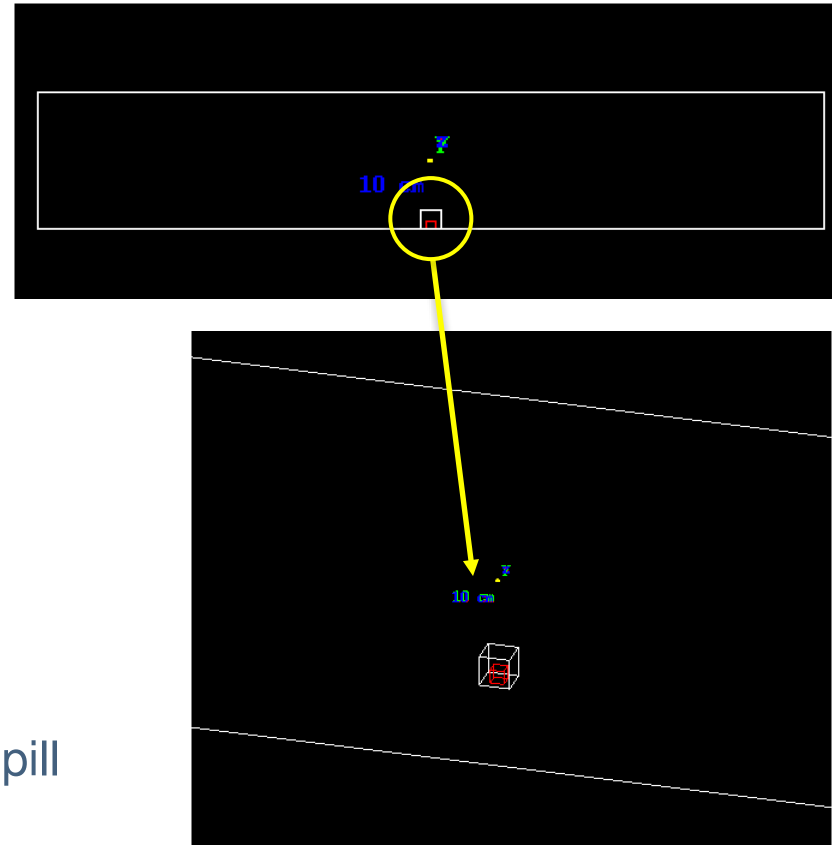
Cosmic μ simulation with GEANT4

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

- Generated 10^6 events on a surface of 50 × 50 m^2

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

- To collect cosmics we need data out of the spill



Next step: Interface with Edepsim and SAND geometry

Conclusions

- Preliminary Algorithms for Energy and Time Calibration Event selection;
- Fit results, canvases and histograms saved in organized files dividing Endcap and Barrels and Modules;

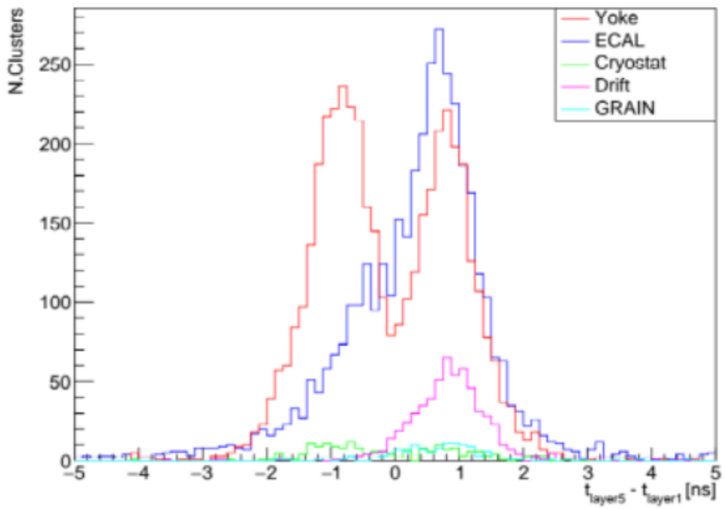
Next steps:

- Implement iteration algorithm for the time residual minimization;
- More Simulated Data;
- Cosmic ray integration;
- Energy Scale Calibration Factor Strategy;

Thank you

SPARE

ECAL Calibration Studies: Particles from outside the ECAL discrimination

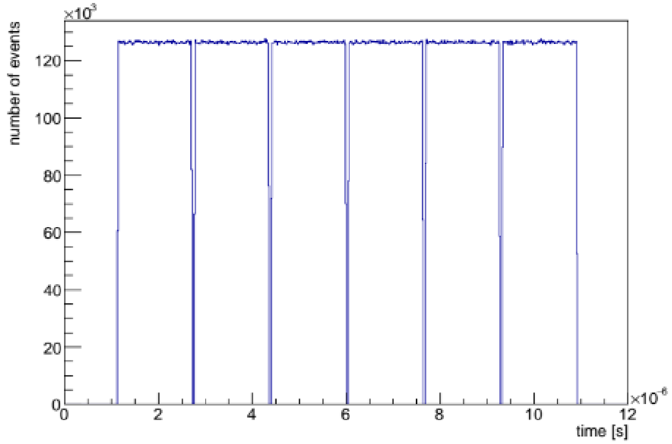


Study the Time difference between the cells in layer 1 and in layer 5.

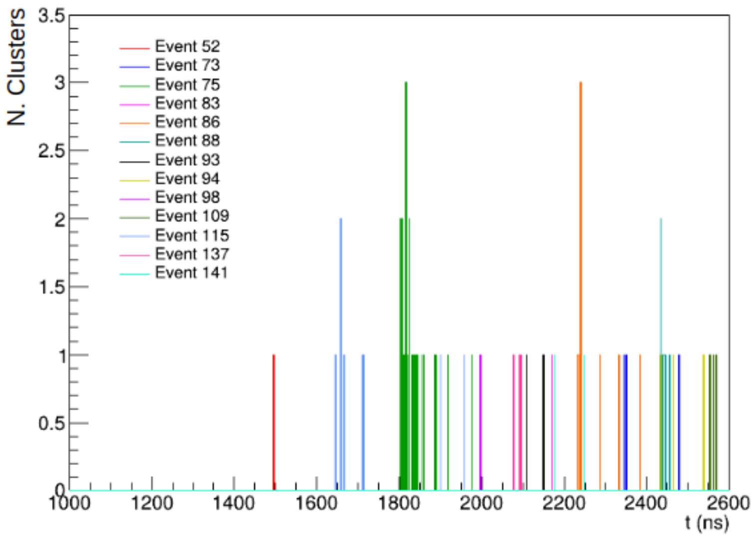
Keeping only events with all cluster with time difference > -0.5 ns

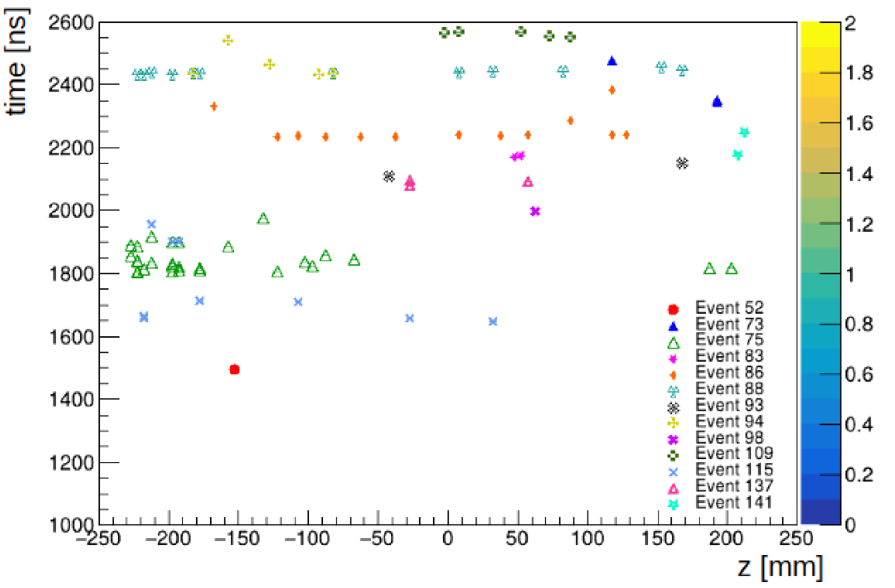
Region	Selected	After $\Delta t < -0.5$ cut	Kept [%]
Yoke	2609	471	18.1
ECAL	2686	1535	57.2
Cryostat	99	13	13.1
GRAIN	80	69	86.3
Tracker	408	364	89.2

ECAL Calibration Studies: Beam Overlay



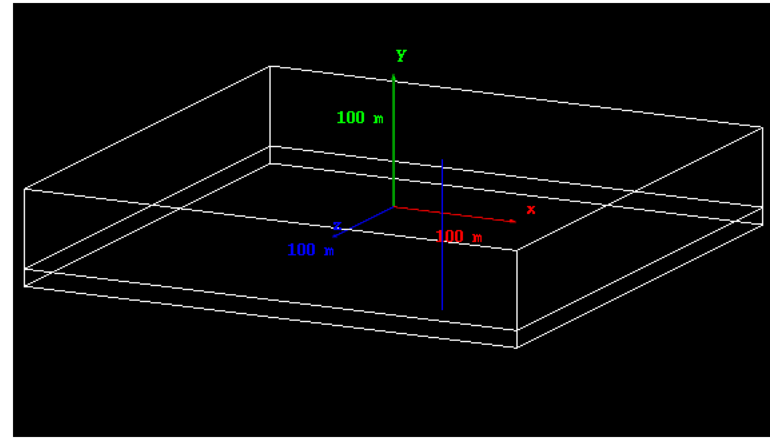
Study the peaks in the 1D cluster time distribution and the lines in the 2D cluster time vs z distribution to group clusters from the same event.





INFN Istituto Nazionale di Fisica Nucleare
Università degli Studi di Ferrara

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
- Muons generated on top of the rock box