Report from SAND Calibration WG

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for the SAND Calibration WG

SAND General Meeting
November 12, 2024

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 ?)
- Reference people: ECAL - P.Gauzzi, GRAIN: A.Surdo, Tracker: ……
- WG meetings generally every three weeks, on Thursday at 3 p.m. CET (8 a.m. CT)
- WG mailing list: dune-nd-sand-calibration@fnal.gov

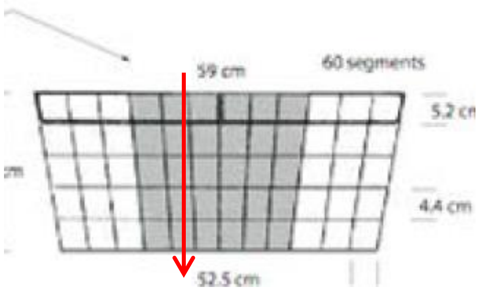
Studies on ECAL Calibration

R.D'Amico – P.Gauzzi

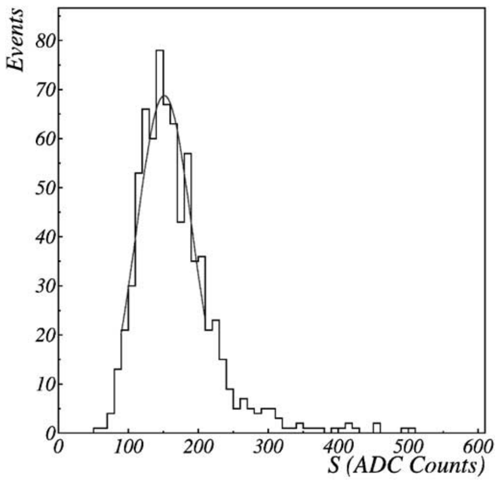
ECAL calibration in KLOE

- Calibration constants C_i determined with cosmic rays,
  Data-taking without circulating beams: muons = MIPs

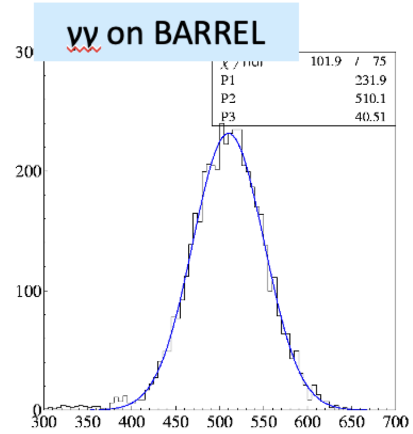
- 2.5 kHz of cosmics ⇒ "golden" MIPs, ~ 100 Hz



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



- Average energy scale 38 MeV / MIP crossing a cell at the center (measured at test beams)
- Absolute energy scale set with Bhabha scattering events ($e^+e^- \to e^+e^-$) and $e^+e^- \to \gamma\gamma$: showers of 510 MeV
- Repeated every run (every 1 or 2 hours)
- 4 — 5 × 10^4 Bhabha evts in the Barrel
  $O(10^5)$ in the Endcaps
  $10^3 – 10^4$ γγ events in one run

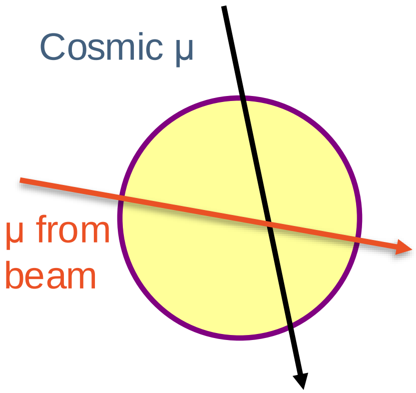


ECAL calibration in SAND

MIPs from cosmic rays: muon flux at surface ~ 0.02 μ/(s 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 (no 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



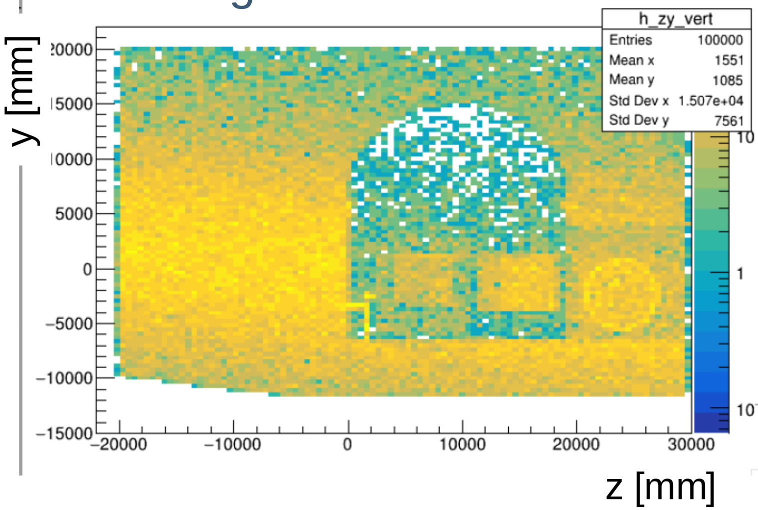
MIPs from beam (rock, magnet and Fe yoke,

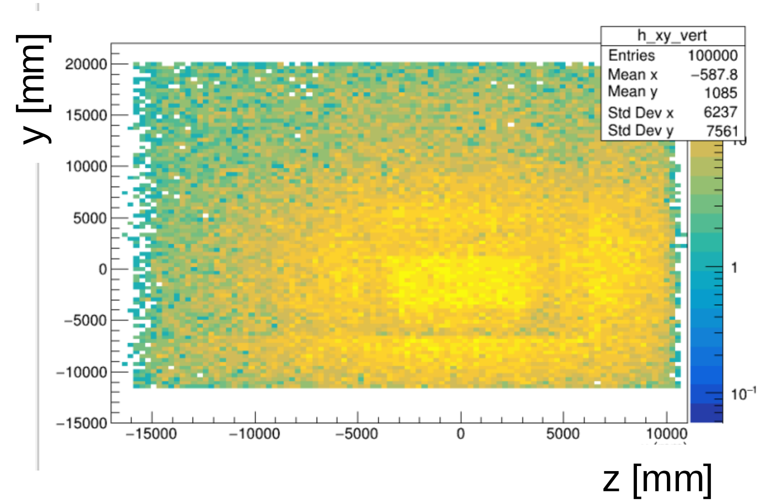
upstream ECAL modules)

- We need also muons from beam for the modules around the median plane and for the endcaps
- Started MC study of the rate of muons from beam events reaching the ECAL

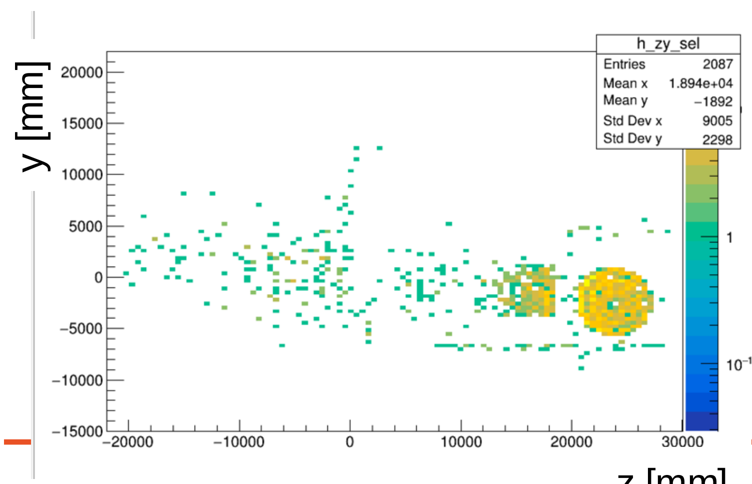
MIPs from beam

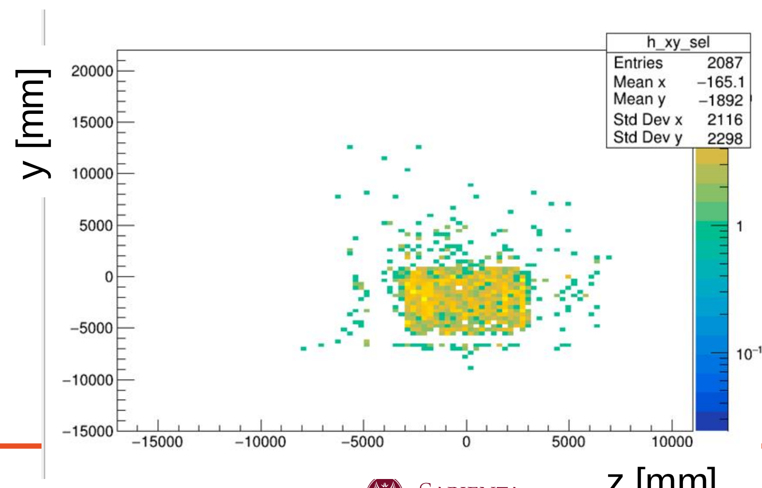
- Generation of 100000 ν_μ events with vertices in the hall and in the rock surrounding the hall



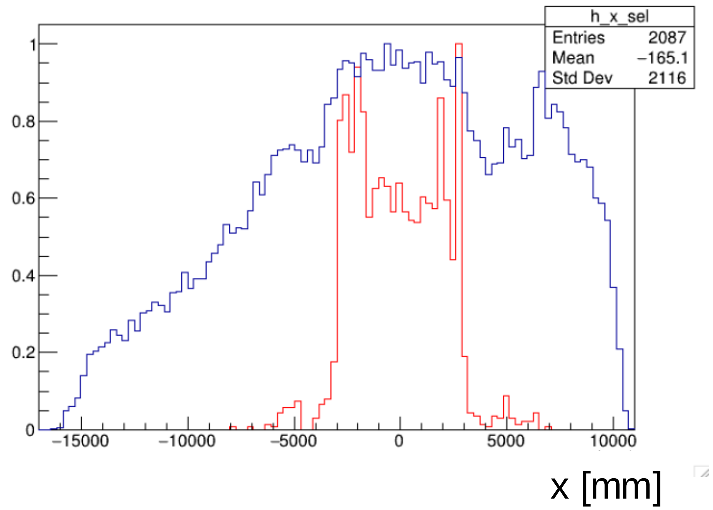


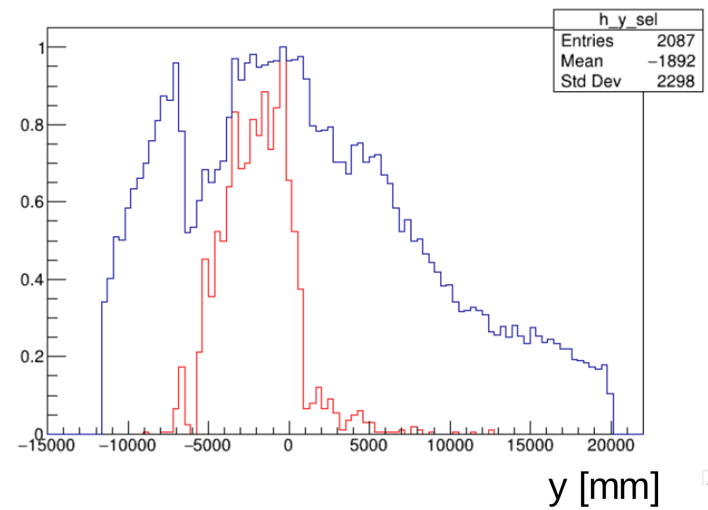
- Selecting events with at least a muon in the ECAL ⇒ ~ 2000 evts.



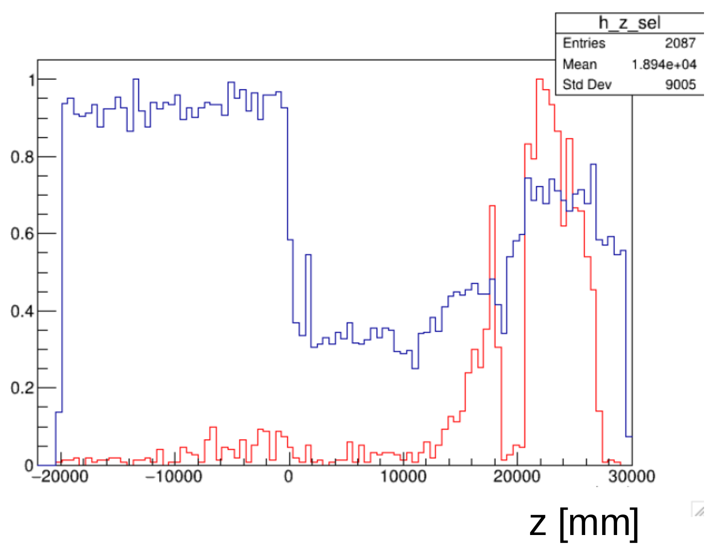


MIPs from beam





- All events
- Events with at least one muon in the ECAL

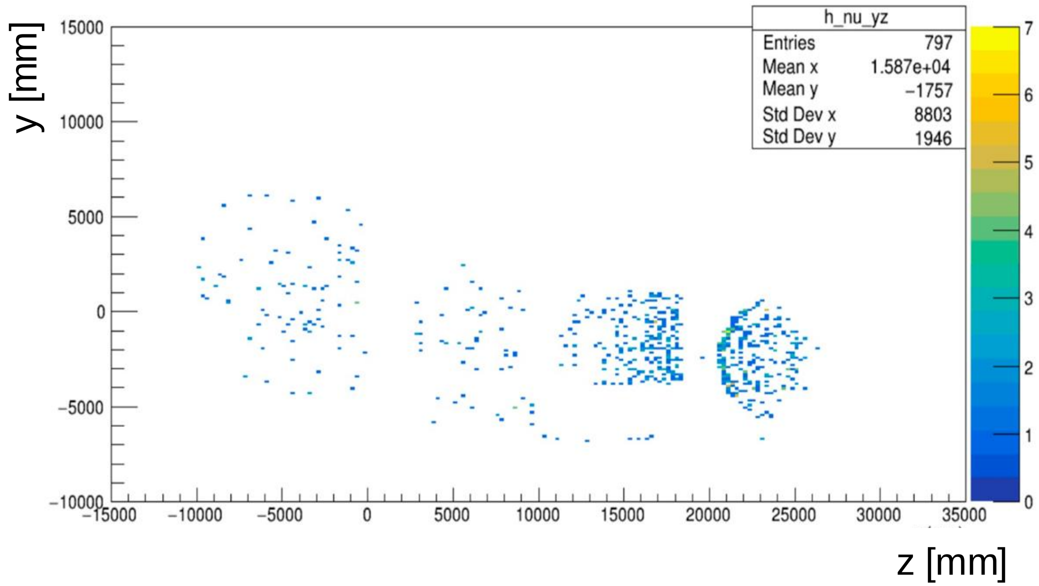


- We can restrict the generation window to DUNE_ND_HALL (X and Y in ~ -6.0 – 6.0 m) and to cut at Z > -10 m

MIPs from beam

- Generation of 25000 ν_μ in that window ⇒ 797 events with at least 1 cluster from μ
- This small sample corresponds to ~ 2 × 10^{15} POTs, ~ 30 spills (FHC mode, 1.2 MW)

Vertices	
Rock	104
Fe Yoke	224
ECAL upstream modules	86
TMS	278
Cryostat/Solenoid	28
Others	57



- ~ 800 evts in 30 spills means ~ 26 muons/spill
- 2 × 10^6 good muons in 24 hours of beam

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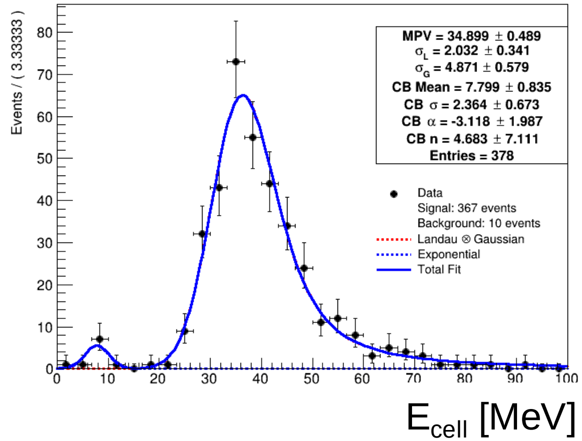
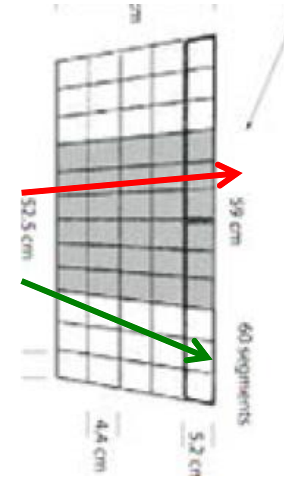
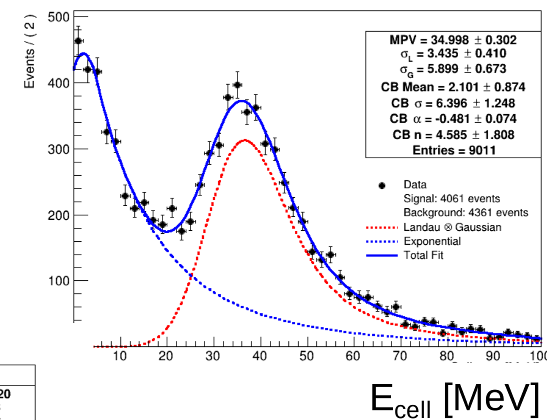
MIPs from beam

- Golden mips: all the cluster cells in the same column
- Low statistics
- Clean distribution
- Good peak fit

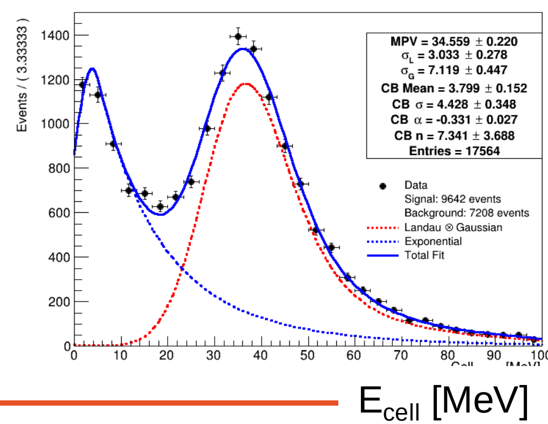






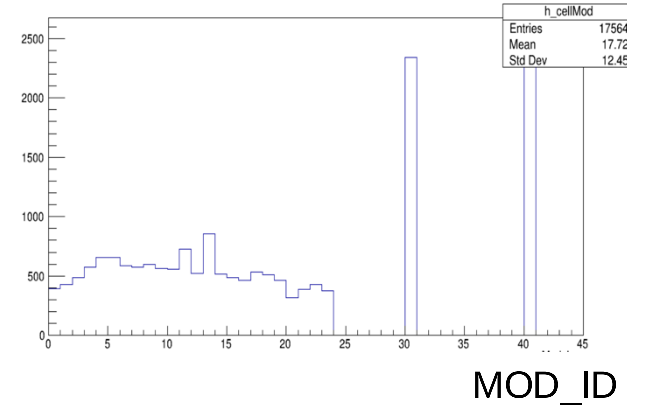
- Less stringent selection: at least 3 cells in the same column
- Peak still clear

- No conditions on muon clusters

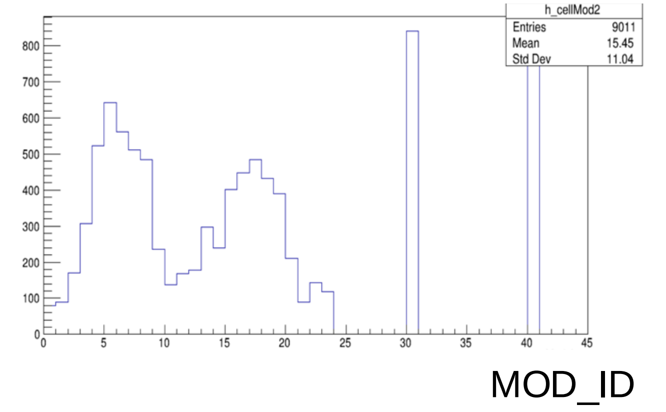


MIPs from beam

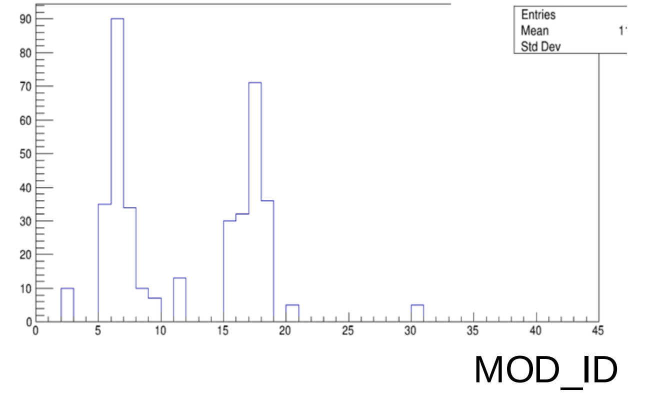
- Occupancy:
  - No conditions on muon clusters



  - At least 3 cells in one column



  - Golden mips



- Next step: generate few x 10^6 ν_μ events

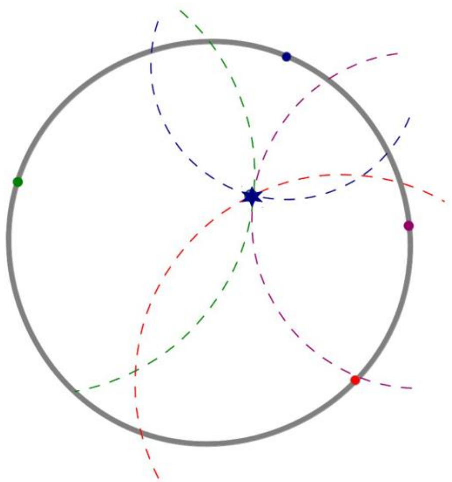
Energy scale calibration in SAND

- 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

  $\Rightarrow$ ~ 50% of π^0 have at least one $\gamma \rightarrow e^+e^-$. (from DUNE-doc-13262 A Near Detector for DUNE)

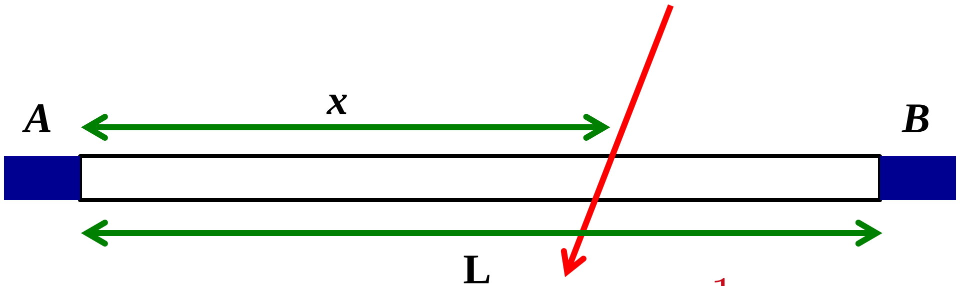
- High energy electrons from ν_e interactions $\Rightarrow$ need the momentum measurement in the tracker

- Possibility to exploit $K^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$
- From a naive rescaling of $K^0 \rightarrow \pi^+\pi^-$ $\Rightarrow$ $O(10^5)$ 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



Time calibration

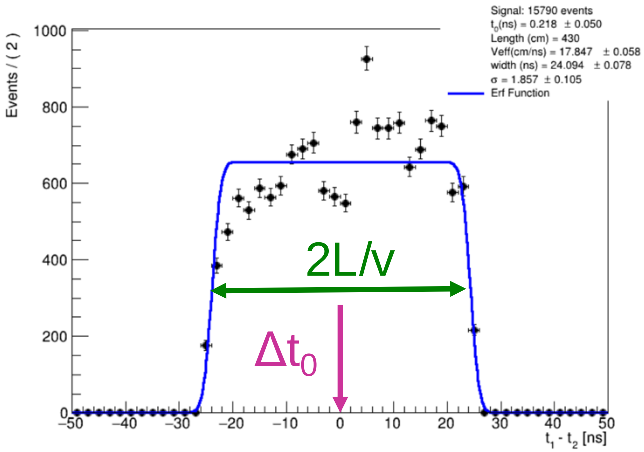
- MIPs: uniform illumination of the ECAL for calibration of time and coordinate along the fibers



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

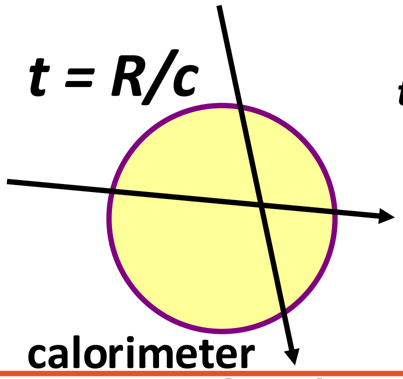
$$t_0 = \frac{1}{2}(t_A^0 + t_B^0)$$

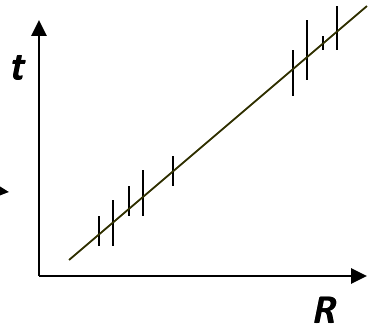
$$\Delta t_0 = \frac{1}{2}(t_A^0 - t_B^0)$$



Fit function: sum of two Error functions
Width ⇒ 2L/v , L =430 cm fixed,
v free parameter ≈ 17 cm/ns

- t_0's from fit of straight tracks (p > 6 GeV): cosmic muons and beam muons





GRAIN calibration with muons

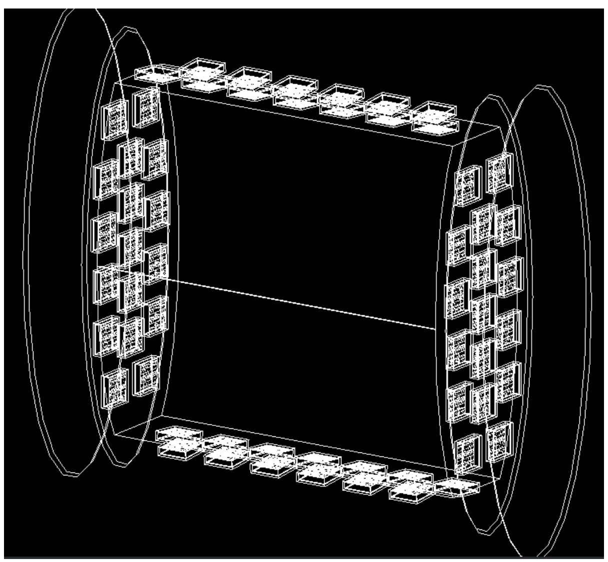
A.Surdo

The case of GRAIN

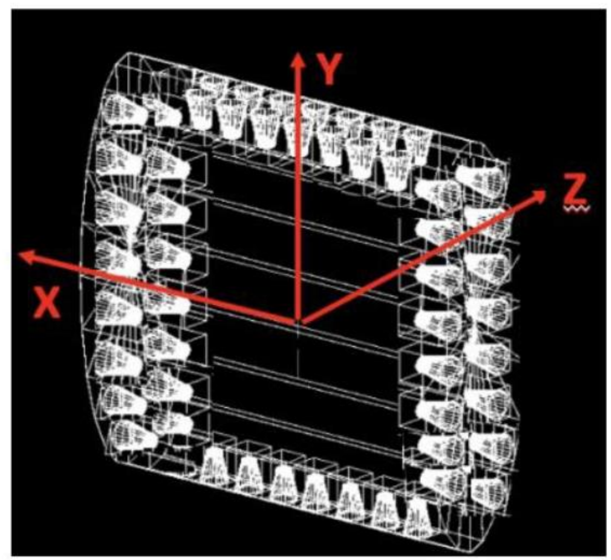
Event features to be reconstructed from detector signals: **interaction vertex**, **tracks**, **time**, **energy deposit** (transferred directly to the LAr and/or carried out by the outgoing tracks)

Detector: **SiPM matrices** collecting the scintillation light photons in the whole sensitive LAr volume through lenses and/or coded masks

Coded masks



Lenses



Energy deposit evaluation

- ✓ In principle, two possible approaches (probably complementary and interleaved):

a) **Calorimetric** measurement of total released energy
Extract the whole energy released in GRAIN from the total number of collected photons by all SiPM matrices

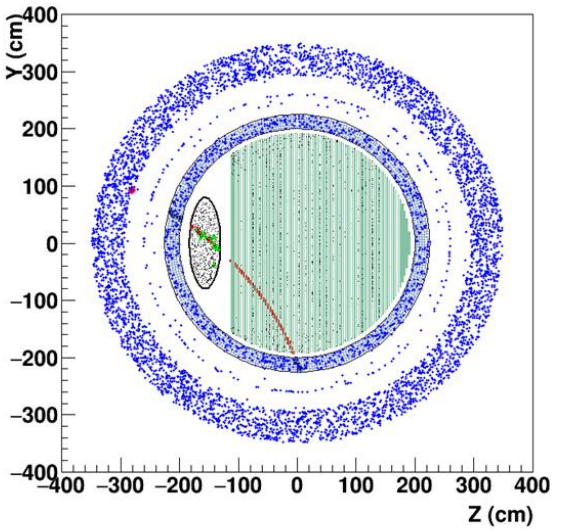
a) **Track-by-track** energy loss evaluation
For each reconstructed track, evaluate the associated amount of collected photons

- ✓ In both cases, several factors must be taken into accounts:

- relation between energy deposit and scintillation light emission
- positions of interaction vertex and track propagation through the volume (absorption of photons, geometrical acceptance, ..)
- SiPM photon detection efficiency

Use of muons for calibration

Muon from ν interaction in the yoke and crossing GRAIN



✓ Most obvious process to be considered:

MIPs crossing the LAr volume

- muons from the beam interaction outside GRAIN
- cosmic ray muons

✓ Specific energy loss for a generic material: $<dE/dx> \sim 2$ MeV/(g·cm^{-2})

Can be estimated from MC simulation or measured from experimental data.

For LAr:

dE/dL ~ 2.5 MeV/cm $\Rightarrow N_0 \sim 10^5$ ph /cm   Photon emission per unitary pathlength
(assuming $f \sim 4 \cdot 10^4$ ph/MeV)

➢ The relation between muon Pathlength and Energy loss exploited to get knowledge of energy deposit in LAr, to be related to the amount of detected photons

A possible plan

Possible method to be implemented:

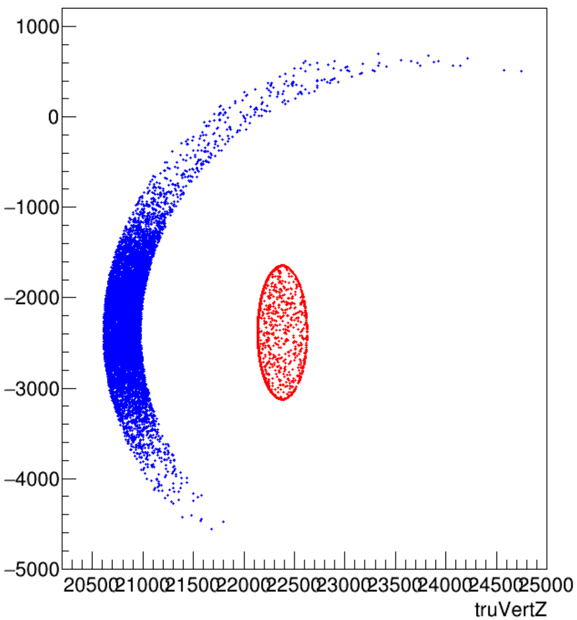
- Reconstruct the tracks in the event ("*SandReco*")
- Select the events with a clean muon track generated outside and crossing GRAIN
- Estimate the track **Pathlength (ΔL)** and the corresponding **Energy Loss (ΔE_{loss})** in LAr
- Correlate the total **collected photons** to the **deposited energy** in LAr, in order to calibrate photo-sensor response

To test this procedure:

- MC samples of ν_μ CC interactions both in ECAL and magnet Yoke were generated
- The events with a muon crossing GRAIN are then selected, and **ΔL** and **ΔE_{loss}** are evaluated from *EdepSim* information related to the muon trajectory
- The subsample of events is considered in which the muon crosses GRAIN not accompanied by other particles
- By using the photo-sensor setup (including layout, efficiencies and electronics), the number of photons collected by all SiPM matrices is finally correlated to ΔE_{loss}

Events with the muon entering GRAIN

Vertex in the Magnet yoke

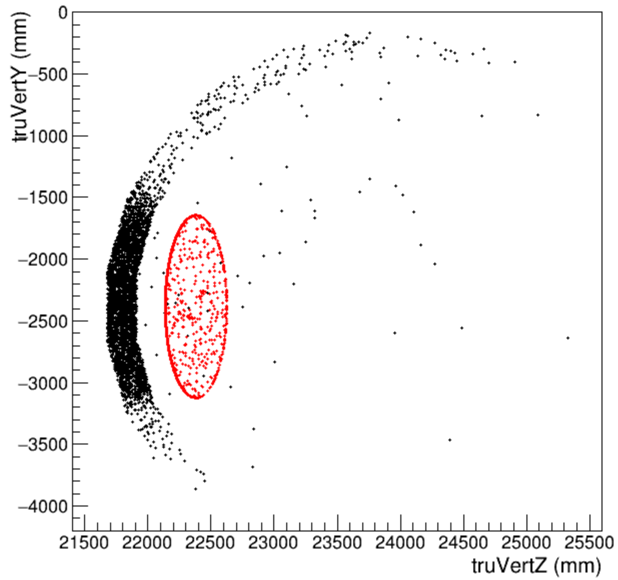


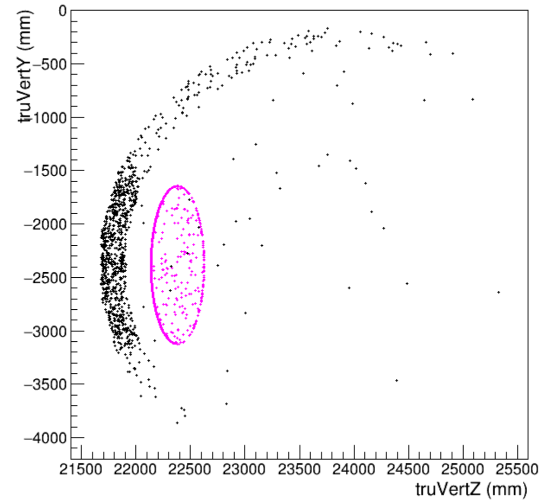
Total interaction events: 441,000

Muons entering GRAIN: ~ 13,000 (3%)

Clean muons: ~ 10,000 (2.3%)

Vertex in ECAL





Total interaction events: 200,000

Muons entering GRAIN: ~ 6,000 (3%)

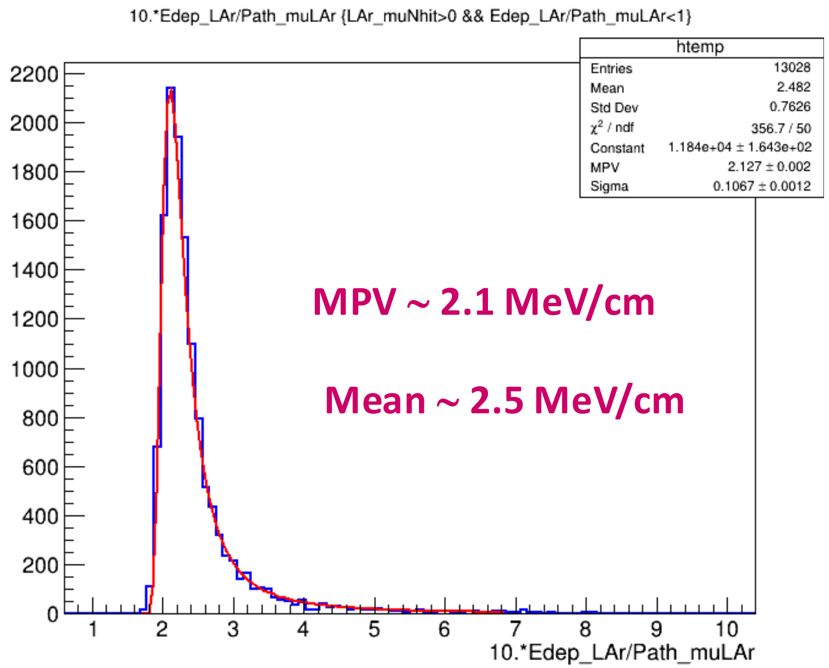
Clean muons: ~ 1,500 (0.8%)

Energy deposit evaluation

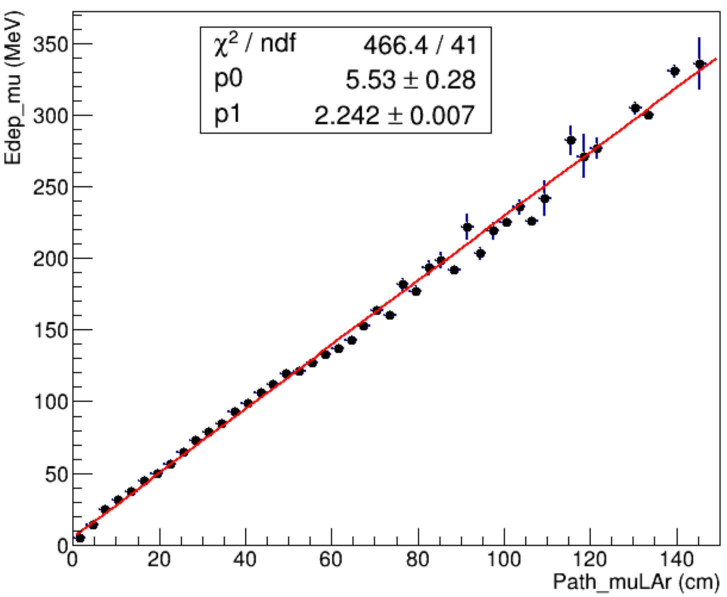
Selection of events with the muon entering the GRAIN volume:

➢ **Precise determination of <dE/dx> by the muons crossing GRAIN**

ΔE/ΔL (MeV/cm)



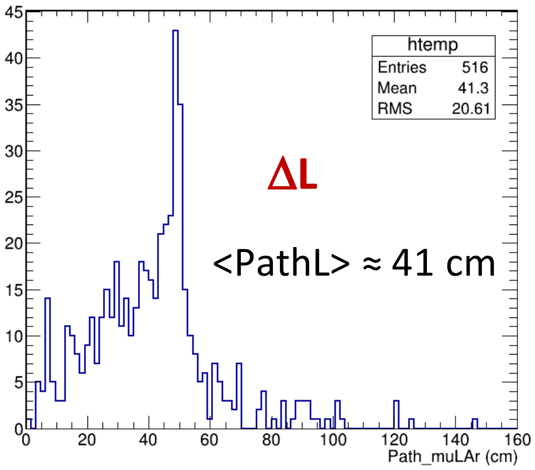
Relation btw ΔL and ΔE



ΔL: pathlength in GRAIN LAr
ΔE: energy loss by the muon in ΔL

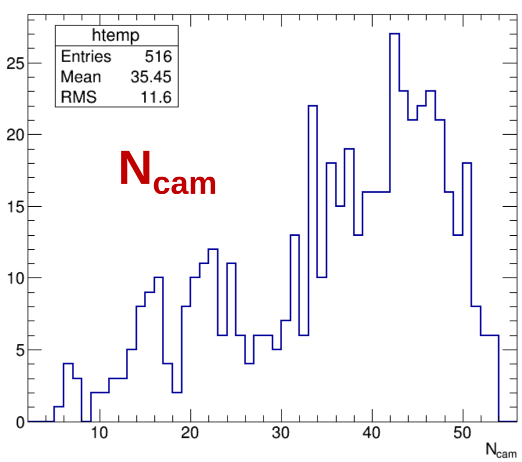
Calibration curve to extract muon energy from Track-length

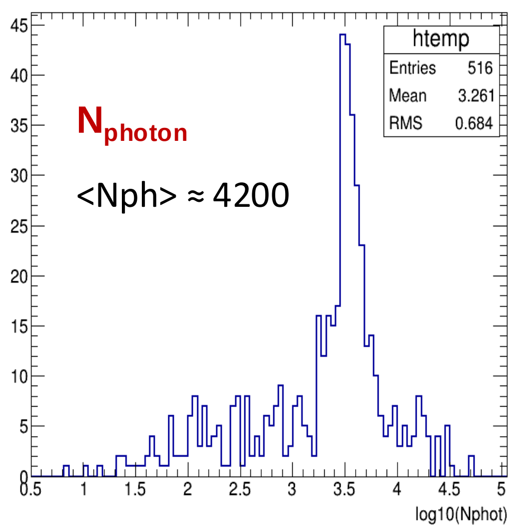
Muon Pathlength in GRAIN and Collected photons

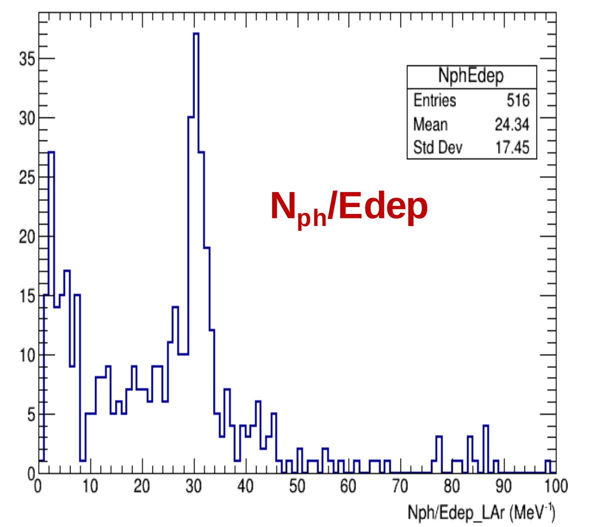


Photons collected by the 53 cameras in GRAIN

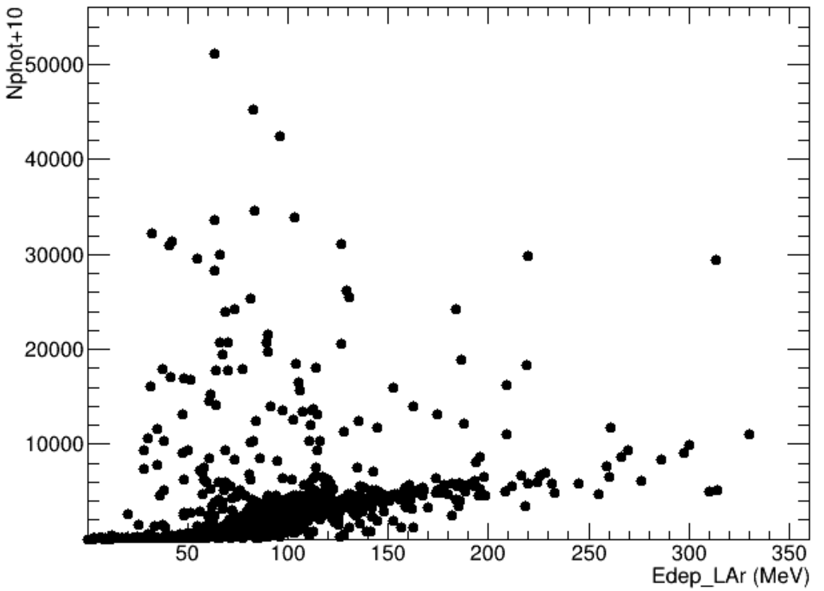
- Average number of fired cameras ≈ 35
- Average number of photons ≈ 4200
- Significant fraction with low number of photons



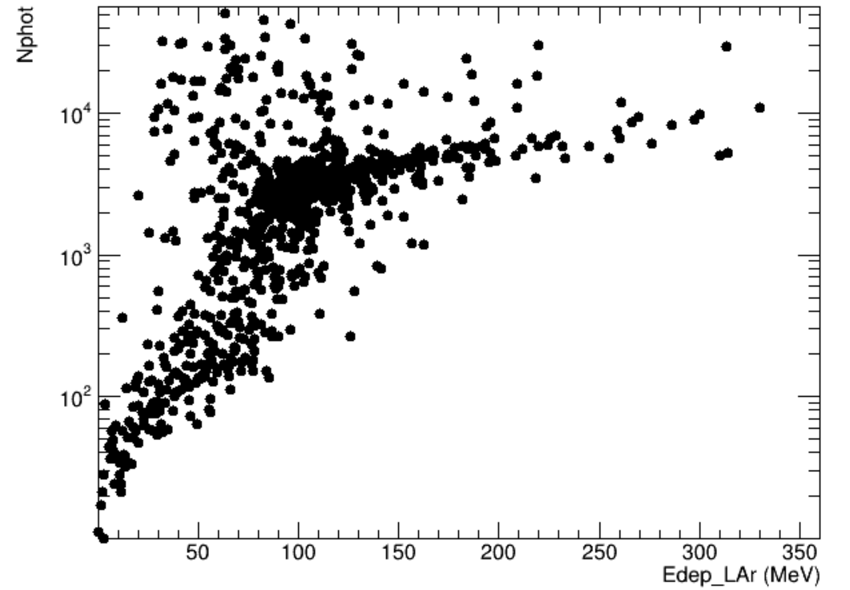




Correlation btw detected photons and deposited energy



Log scale for N $_{phot}$



- Not a so narrow correlation
- Possible effects from track position vs geometrical acceptance

Apparently, different behaviours ?

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 × 10^{13} POT) in the various detector components for both the FHC and RHC beam m

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

Table 1.34: 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.

	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) …

- 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)

✓ **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° 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

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Conclusions

- ECAL: Evaluating the rate of good muons from beam events

  Next steps:

  - Produce few x 10^6 events to increase the statistics
  - Define a strategy to calibrate the Endcaps and the modules with low statistics
  - Start the study of the energy scale calibration

- GRAIN: Two approaches considered: the calorimetric measurement of total energy and the Track-by-track energy loss evaluation

  - A possible procedure for energy calibration proposed and preliminarily tested, based on the Monte Carlo simulation of ν_μ interactions in ECAL and Yoke, and the Lens-camera system response (including geometrical layout, PDE, electronics, ..)
  - Study in progress, results too preliminary to get conclusions on the method validity

  Next step: use of muon beams from MC crossing GRAIN with fixed pathlength and direction

- Strategy of time alignment with the other subdetectors has to be studied

Spares

ECAL calibration

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

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

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)

- By requiring hits in the STT and ECAL ⇒ ~ 11 muons/spill