Report from SAND Calibration WG

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for the SAND Calibration WG

SAND General Meeting
January 14, 2025

Outline

1. **Updates on the studies for ECAL Calibration** (R.D'Amico – P.Gauzzi)
2. **Grain Calibration with muons** (A.Surdo)
3. **Conclusions**

ECAL calibration in SAND

Calibration constants cell by cell determined with cosmic muons and muons from beam

MIPs from cosmic rays: muon flux at surface ~ 0.02 μ/(s cm^2)

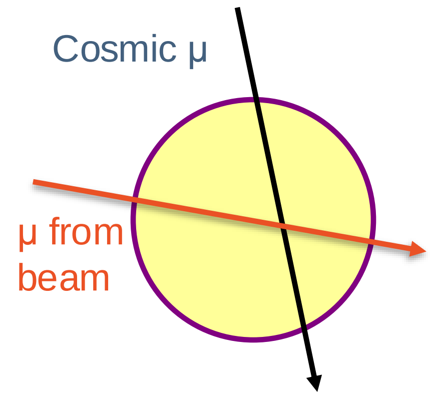
⇒ ~ 10^4 μ/s on ECAL (⇒ 100 Hz of "golden mips" in KLOE)

- 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)

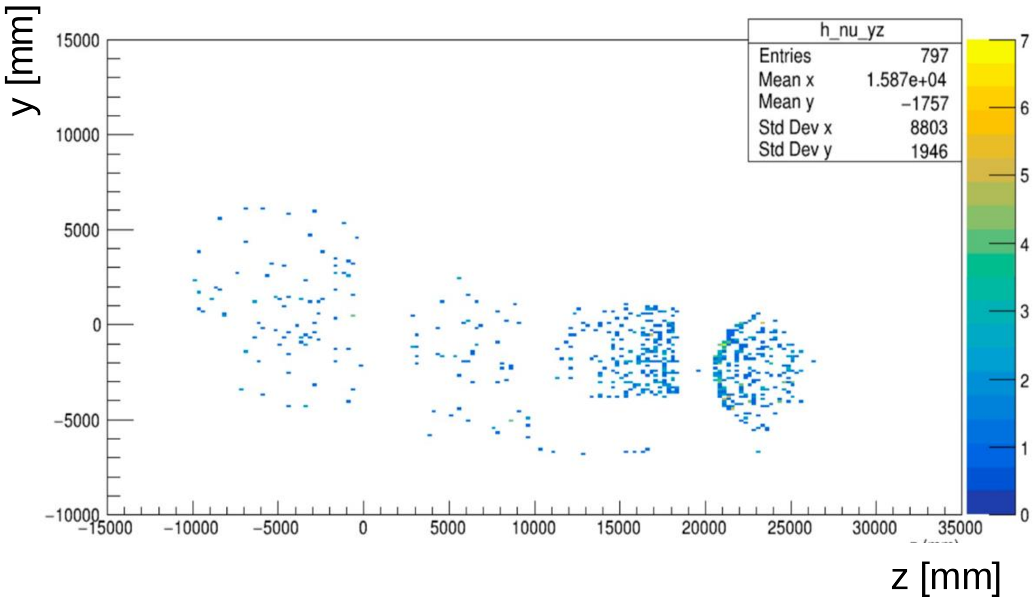
- We need also muons from beam for the modules around the median plane and for the endcaps



MIPs from beam

- Generation of 25000 ν_μ events in the generation window = DUNE_ND_HALL (X and Y in ~ -6.0 – 6.0 m) and to cut at Z > -10 m ⇒ 797 events with at least 1 cluster from μ in the ECAL

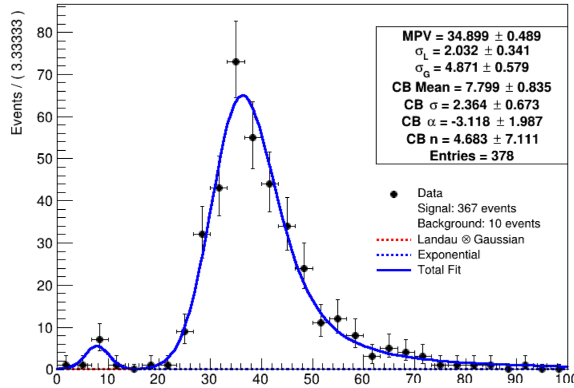
Vertices	
Rock	104
Fe Yoke	224
ECAL upstream modules	86
TMS	278
Cryostat/Solenoid	28
Others	57



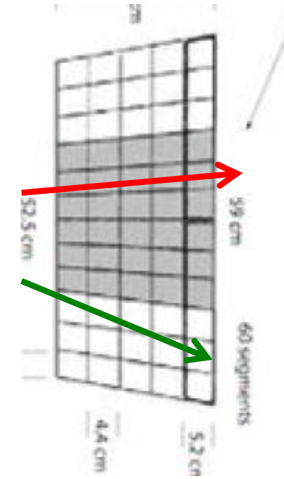
- ~ 800 evts in 30 spills means ~ 26 muons/spill
- 2 × 10^6 good muons in 24 hours of beam

MIPs from beam

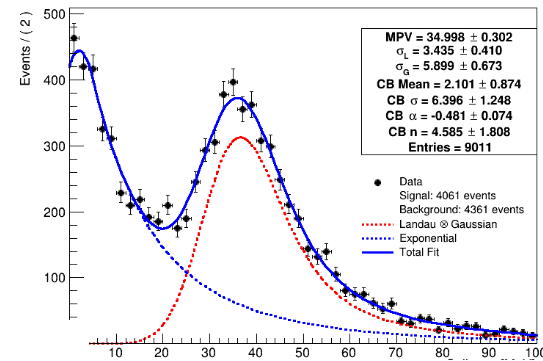
- Golden mips: all the cluster cells in the same column
- Low statistics
- Clean distribution
- Good peak fit



E_{cell} [MeV]

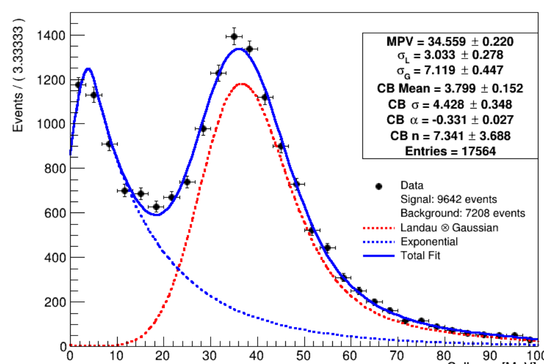


- Less stringent selection: at least 3 cells in the same column
- Peak still clear



E_{cell} [MeV]

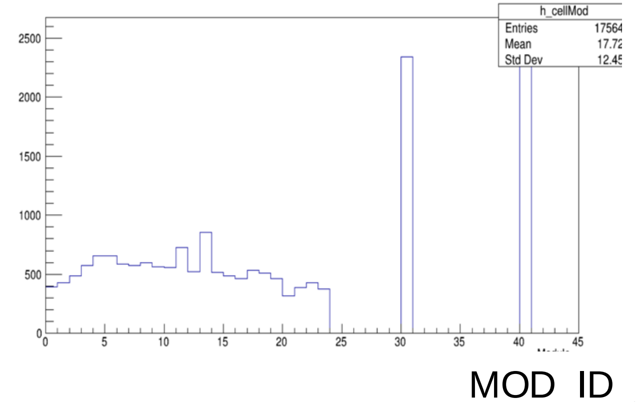
- No conditions on muon clusters

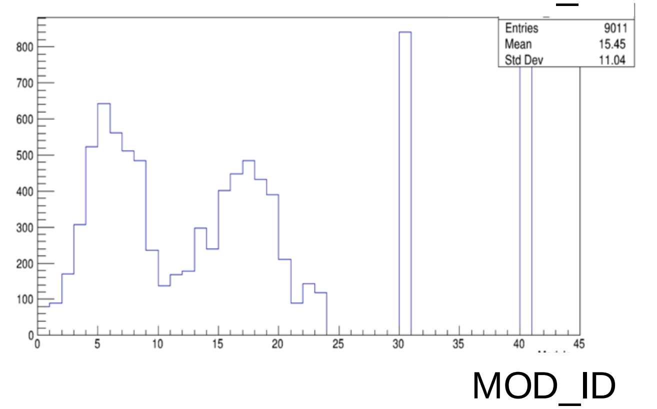


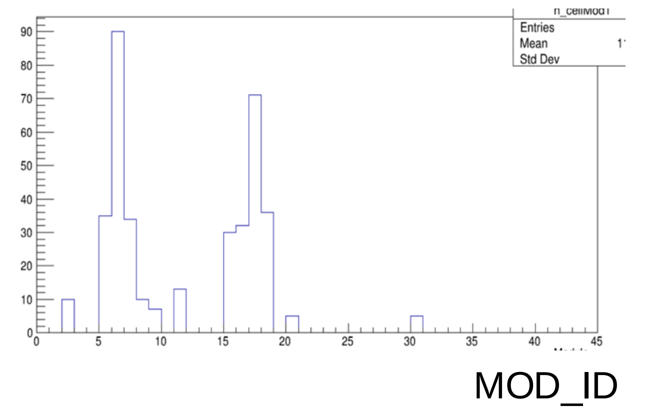
E_{cell} [MeV]

MIPs from beam

- Occupancy:
  - No conditions on muon clusters
  - At least 3 cells in one column
  - Golden mip selection



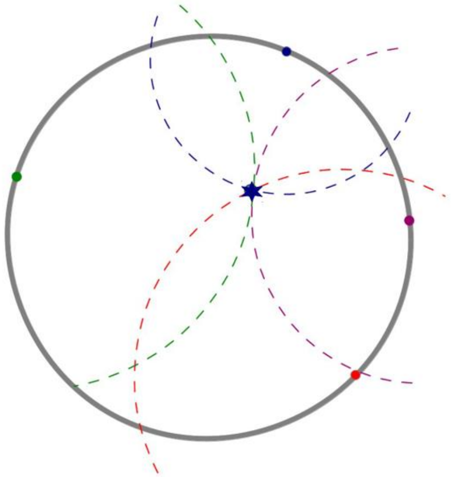




Energy scale calibration in SAND

- 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

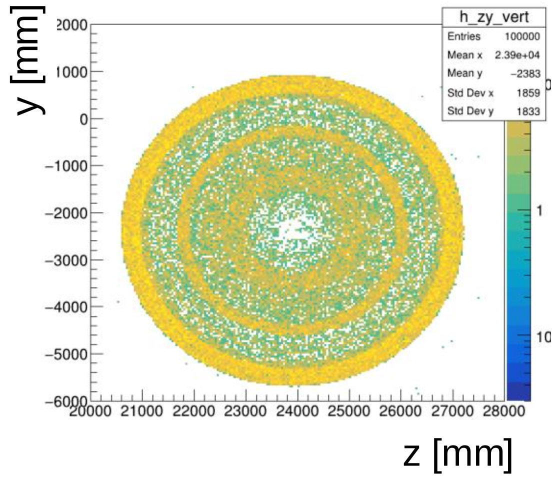
  ⇒ ~ 50% of π^0 have at least one $\gamma \to e^+e^-$. (from DUNE-doc-13262 A Near Detector for DUNE)
- High energy electrons from ν_e interactions ⇒ need the momentum measurement in the tracker

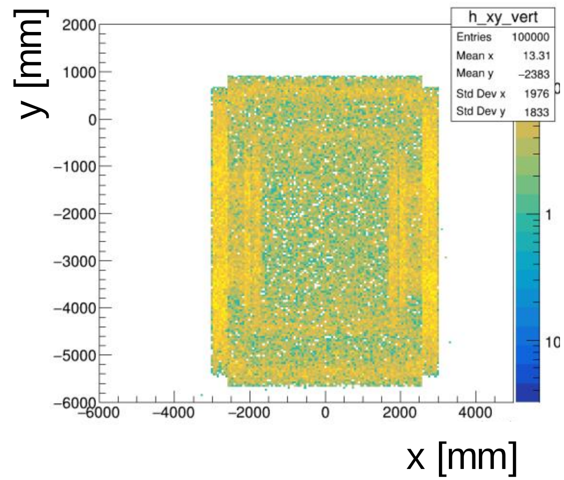


- Possibility to exploit $K^0 \to \pi^0\pi^0 \to 4\gamma$
- From a naive rescaling of $K^0 \to \pi^+\pi^-$ ⇒ $O(10^5)$ evts in 5 years of FHC data-taking
- Reconstruct a vertex with the ECAL only, back-propagating each of the 4 photons, but the times of the ECAL cells must be very well aligned

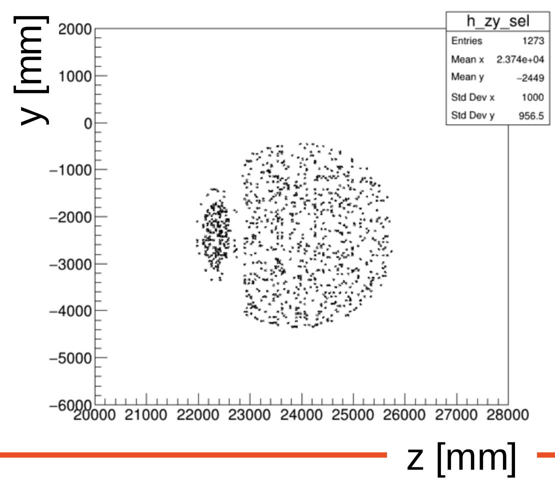
MC sample

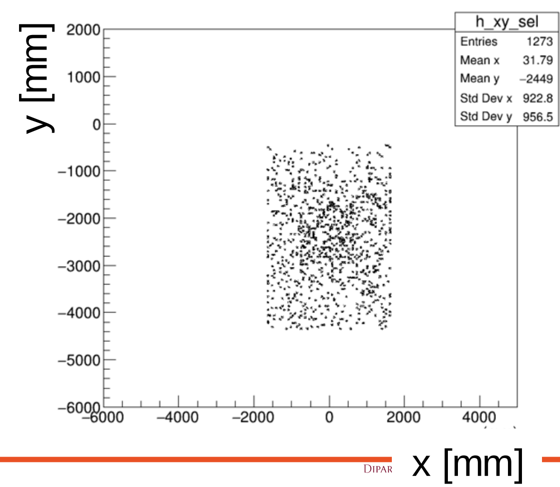
- Generated 100000 ν_μ events with vertices in in the SAND volume (TOP_VOLUME = volSAND), POTs ~ 10^{17} ⇒ ~ 30 min of beam





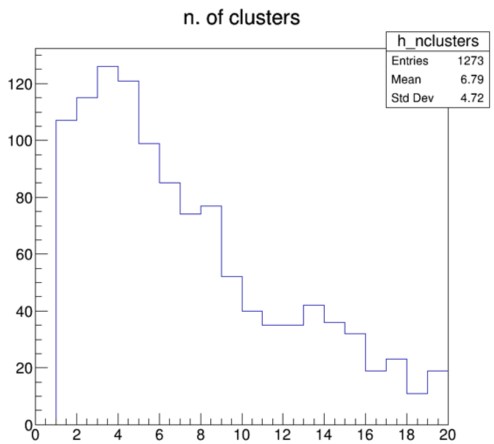
- Select vertices inside the ECAL ⇒ 1273 events

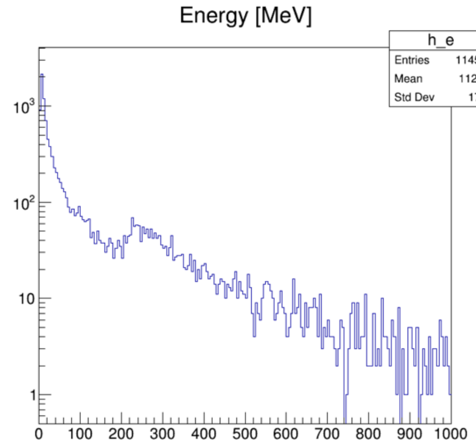


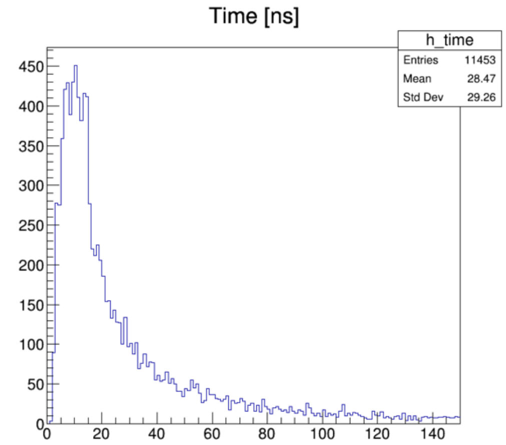


MC sample

- Clusters in the ECAL



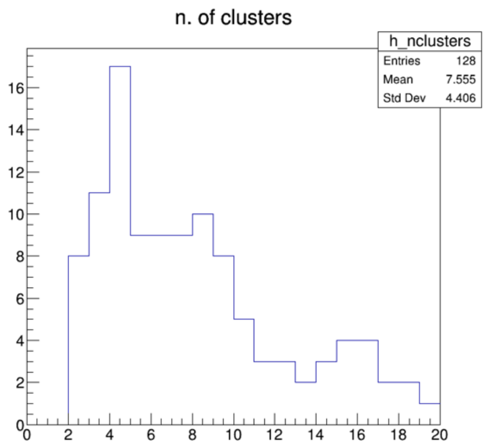


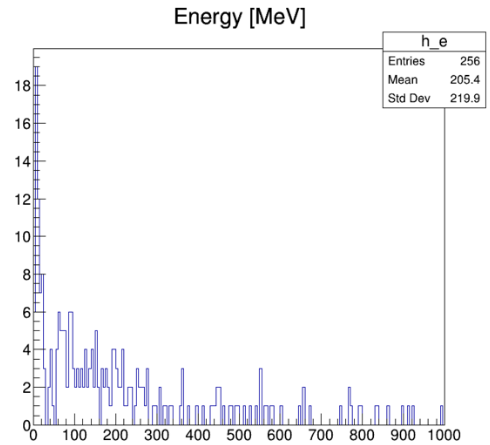


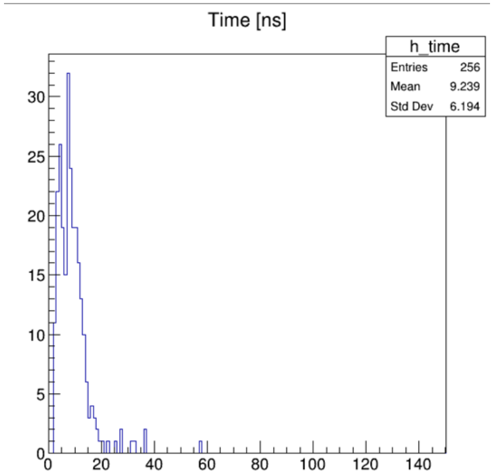
Cluster particle (main contribution)								
e^+/e^-	μ^+/μ^-	γ	K_L	π^+/π^-	K^+/K^-	n	p	Λ
360	1260	2105	56	3033	128	3016	1491	4

Photons from π^0's

- Look at the parent of the cluster particle: select events with 2 photons from a π^0 decay ⇒ 128 events (256 clusters)







- Energy not well calibrated because I used an old version of SANDRECO

- Work in progress (waiting for the new version)

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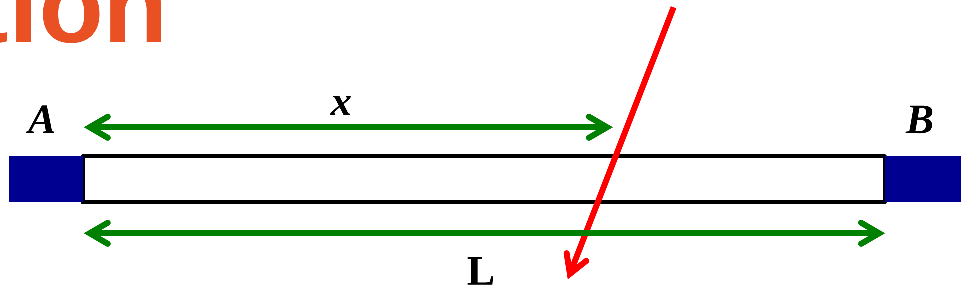
Time calibration



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

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

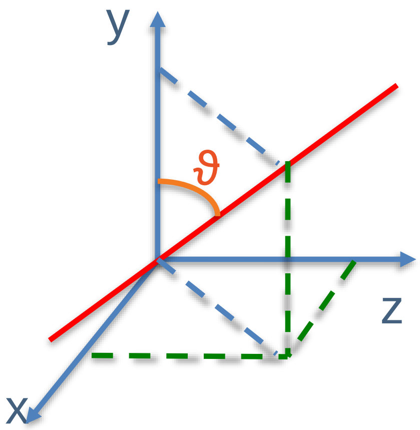
$$t_0 = \frac{1}{2}(t_A^0 + t_B^0)$$

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

- Alignment of times in the ECAL requires to determine the t_0's cell by cell
- Select straight tracks (p > 6 GeV) with 2 clusters, connecting as much as possible different regions of the ECAL
- Also in this case we could use beam muons together with cosmics
- Global offset ⇒ t^0_G to be determined

Time calibration

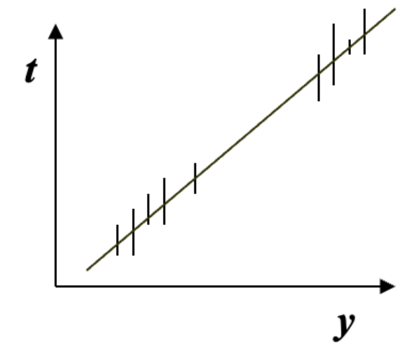
1. 3D linear fit of the straigth track to get the ϑ angle
2. Linear fit: t vs y (or z), at least 5 + 5 points / track



$$t = T_0 + \frac{y}{c\cos\theta}$$

$$T_0 = \frac{\sum_i (t_i - t_i^0 - \frac{y_i}{c\cos\vartheta}) E_i}{\sum_i E_i}$$

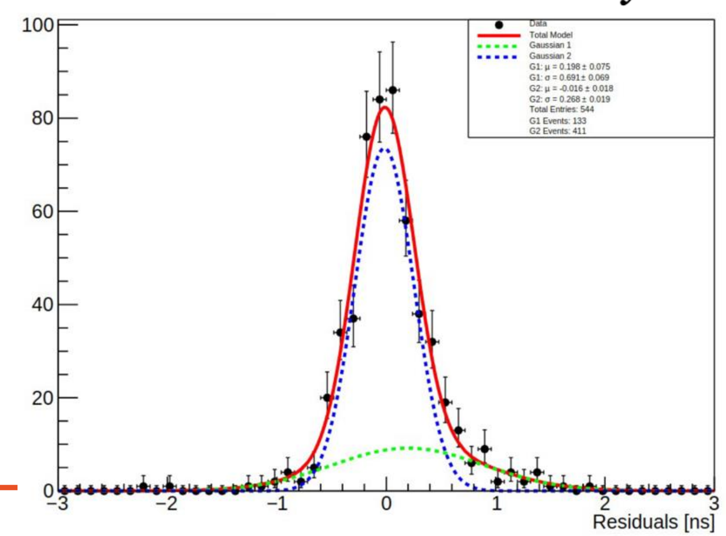
(Energy-weighted average)



3. Histograms of the residuals (one histo. per cell)

$$\Delta y_i = t_i - t_i^0 - T_0 - \frac{y_i}{c\cos\vartheta}$$

- The center of the distribution is the correction to the t^0_i
- Iterate the procedure: re-run the ECAL reconstruction and clustering with the t^0_i 's updated and go to step 1.



Next steps (ECAL)

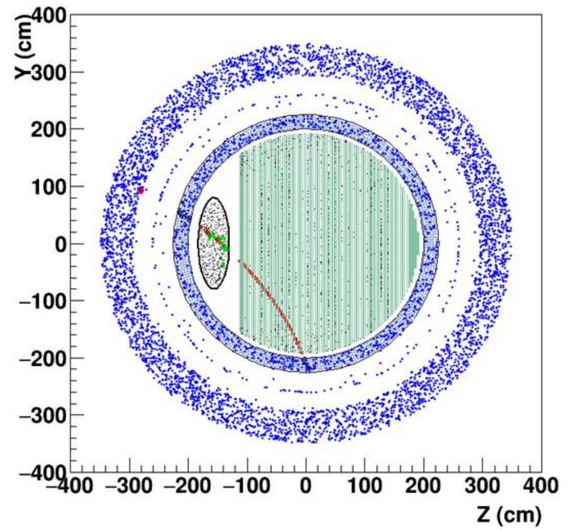
- Generate few x 10^6 events for more statistics of muons from beam (waiting for the implementation of the last version of the ECAL Digitization which includes the real Endcap geometry)

- Continue the study of γ's from π^0 decays for the absolute energy scale

- Start the discussion on ideas for the global t_0 determination
- Other items:
  - Generate events from beam flux
  - Study cosmic muons with MC

GRAIN calibration with muons

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: $\langle dE/dx \rangle \sim 2$ 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 ~ 4 ·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

Muon beams to test GRAIN calibration

Simulation of different muon beams crossing GRAIN with:

- Monochromatic muons (1 GeV)
- Different impact points on GRAIN surface
- Different beam directions and path-lengths inside the LAr

.. in order to study the dependence on:

- track location and distances from the cameras (geometric acceptance)
- path-length inside GRAIN (energy deposit) for different track orientations
- …

Scintillation light photons propagated in LAr and collected by the photo-sensor system through *OptMen* code

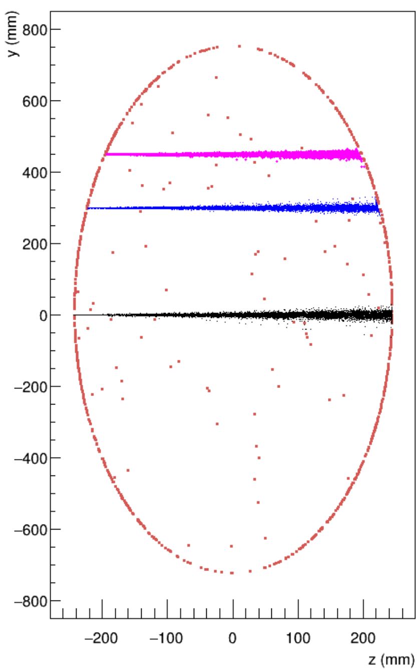
Simulation of the Lens-camera setup with proper SiPM-PDE and Electronics

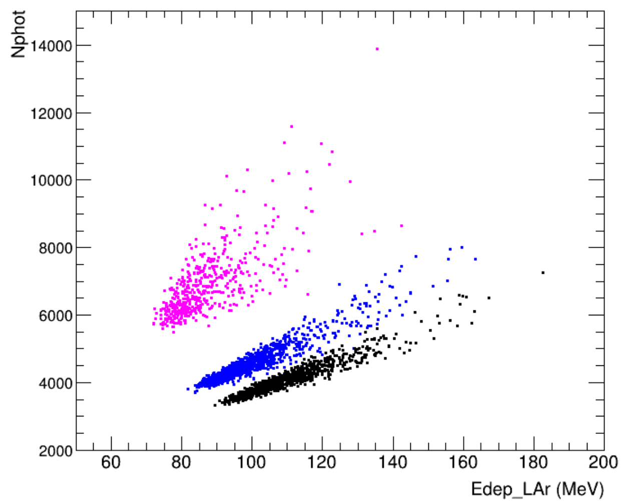
Simulation of Muon beams

1) Beam of 1 GeV muons **along Z axis** (X=Y = 0)

2) Beam of 1 GeV muons parallel to Z axis, at **Y = 30 cm**

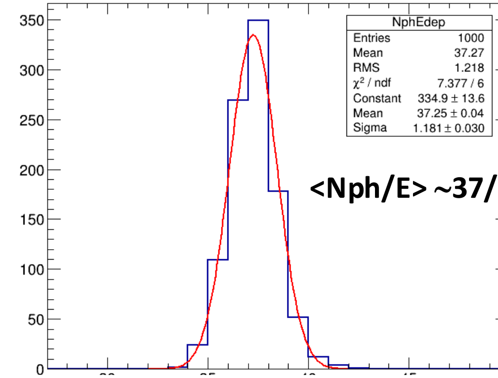
3) Beam of 1 GeV muons parallel to Z axis, at **Y = 45 cm**





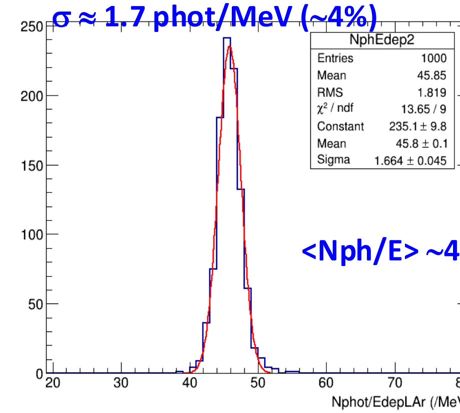
Large spread for Beam_3 in the correlation btw EdepLAr and Nphot!

... due to very near cameras?



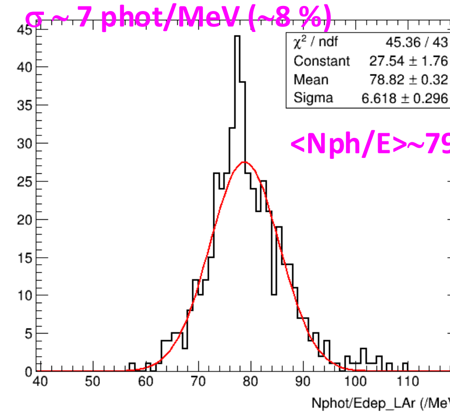
<Nph/E> ~37/MeV

σ ≈ 1.7 phot/MeV (~4%)



<Nph/E> ~46/MeV

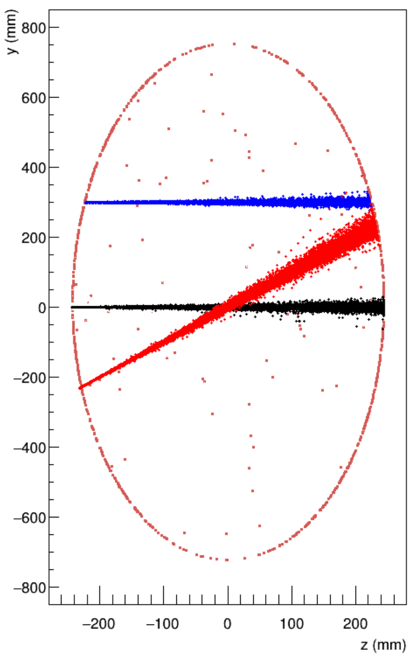
σ ~ 7 phot/MeV (~8 %)

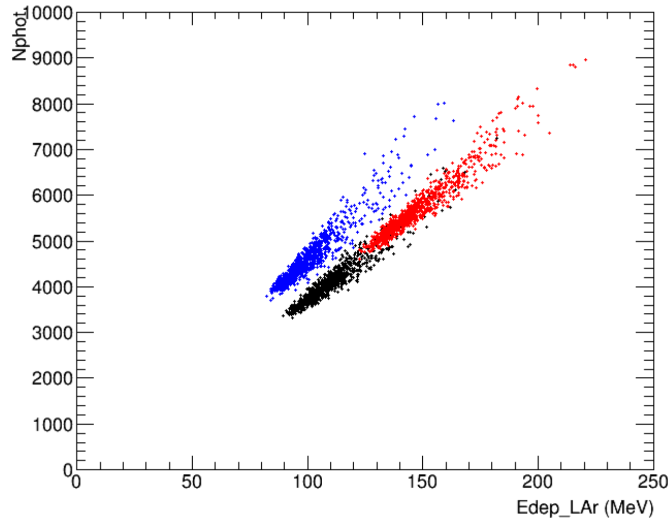


<Nph/E>~79/MeV

Simulation of Muon beams

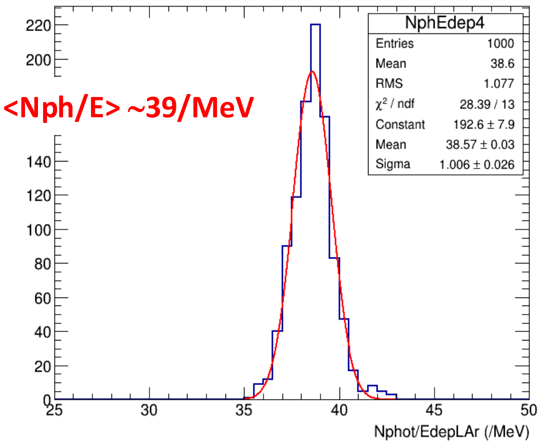
4) Beam of 1 GeV **inclined muons crossing the center**





σ ≈ 1 phot/MeV (~2%)

<Nph/E> ~39/MeV



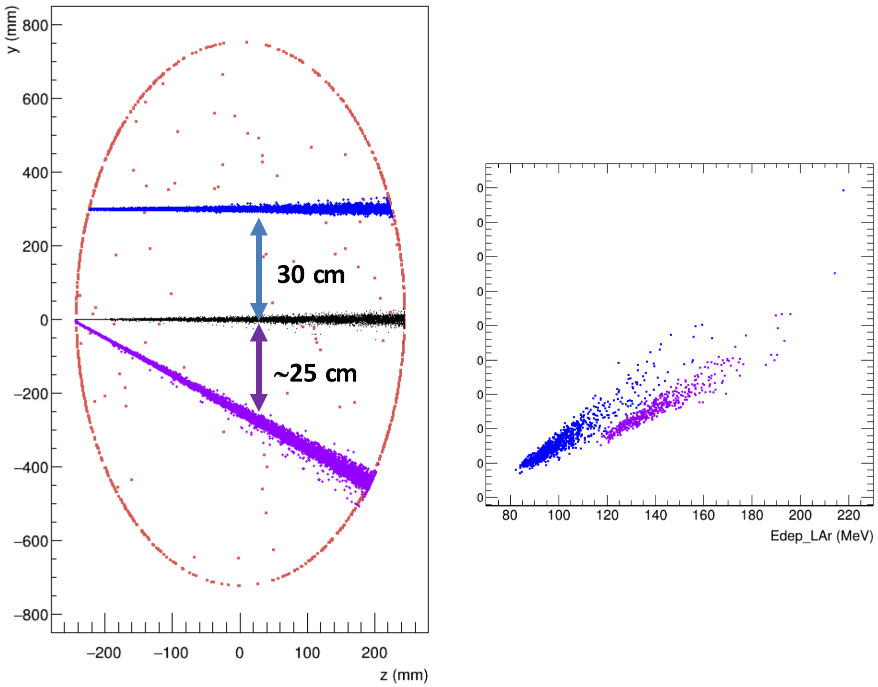
It is remarkable that the beams through GRAIN center (black and red) give aligned correlations one each other

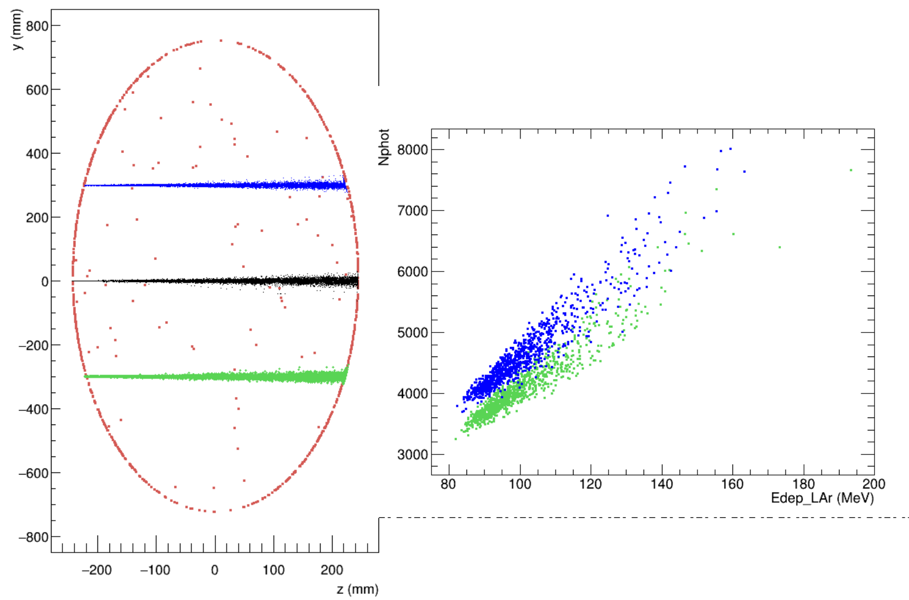
⇒The distance from GRAIN center could be a parameter which affects calibration curves

Simulation of Muon beams

5) Beam of 1 GeV **inclined muons, distant from the center**

6) Beam of 1 GeV horizontal muons, ad **Y = – 30cm** (to be compared with Beam_2)





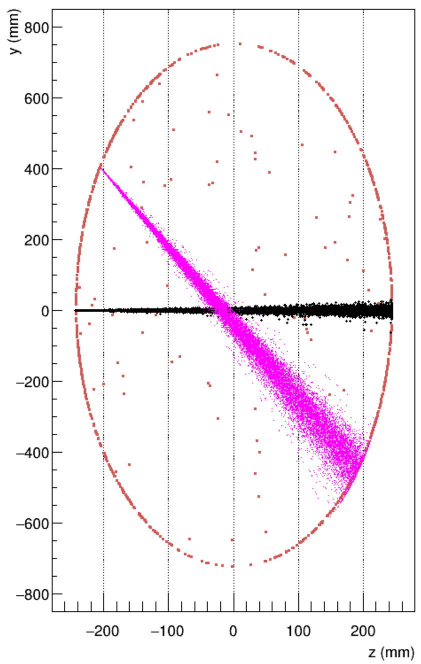
Beams 1 and 5 (blue and violet) give not perfect aligned correlations one each other
(distance from center not equal and camera-layouts not asimmetric ..)

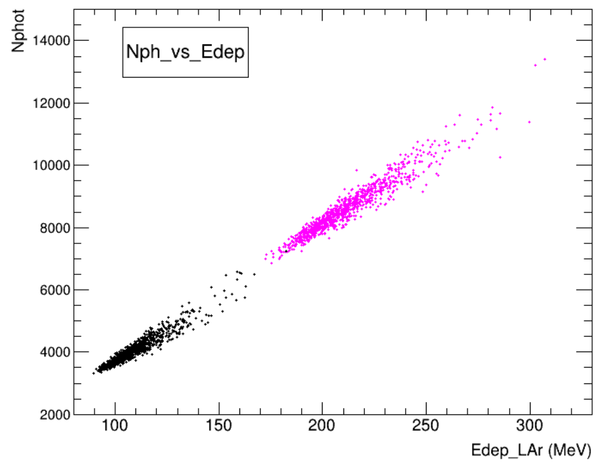
Difference due to the **asimmetry** btw **Top and Bottom** camera layouts
(14 on the Top, 7 on the Bottom)

Simulation of Muon beams

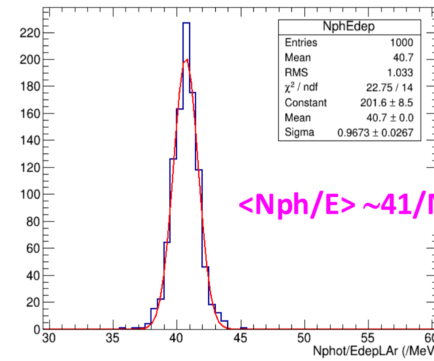
7) Beam of 1 GeV **very inclined muons, crossing GRAIN center**

$\Rightarrow$ **comparison with Beam 1**





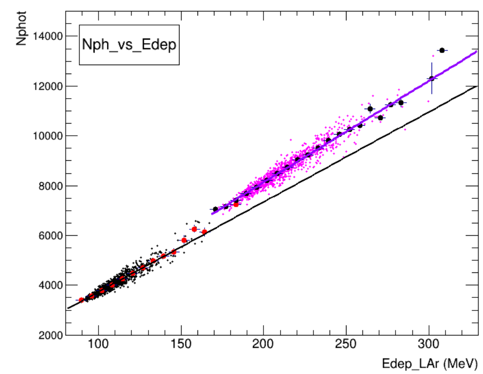
σ ≈ 1 phot/MeV (~2.4 %)



<Nph/E> ~41/MeV

Again, the beams through GRAIN center give aligned correlations one each other

(despite very different directions)



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Conclusions (Simulation of Muon beams in GRAIN)

- ✓ The test of the procedure with simulated muon beams shows that the calibration method with muons could work, in principle
- ✓ For muon pathlengths inside GRAIN not far from the center, a tight correlation (i.e. calibration curve) between EdepLAr and Nphot is obtained
- ✓ Larger spreads observed for tracks very near to the cameras ..
- ✓ It is remarkable that the calibration curves seem aligned for the same distance from GRAIN center ($\rightarrow$ a parameter to be used)
- ✓ Observed the effect of the asimmetry Top/Bottom in the Lens-camera system

Conclusions

- ECAL:
  - Studies of Energy and Time calibration with muons in progress
  - Studies of Energy scale calibration with γ's from π^0 decays started
  - Next step: strategy for t_0 global determination
- GRAIN:
  - Studies on calibration with muons in progress
  - In particular the dependence of the response on track location and path length inside GRAIN and on the distance from the cameras is studied
- Other items to be addressed in the future:
  - Calibration of the inner tracker
  - Intercalibration among subdetectors (timing)
  - Organize the software for calibration and define a place for calibration constants

Spares

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: ……
- Next meeting: Thursday, January 16, at 3:30 p.m. CET (8:30 a.m. CT)
- WG mailing list: dune-nd-sand-calibration@fnal.gov

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

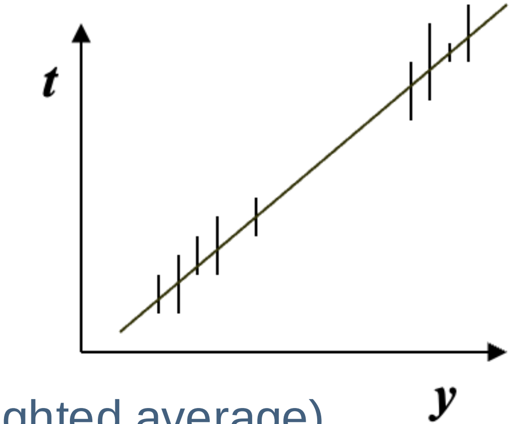
Time calibration

2. Linear fit: t vs y (at least 5 + 5 points / track)

$$t = T_0 + \frac{y}{c\cos\theta}$$

$$T_0 = \frac{\sum_i (t_i - t_i^0 - \frac{y_i}{c\cos\vartheta})E_i}{\sum_i E_i}$$

(Energy-weighted average)

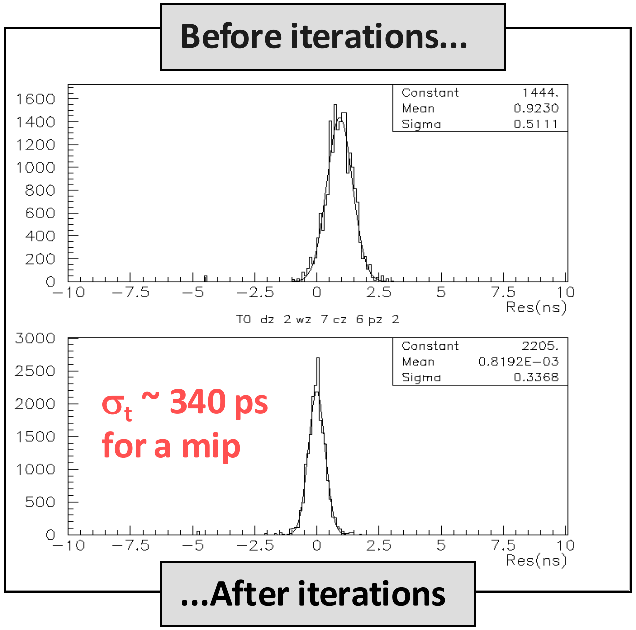


3. Histograms of the residuals (one per cell)

$$\Delta y_i = t_i - t_i^0 - T_0 - \frac{y_i}{c\cos\vartheta}$$

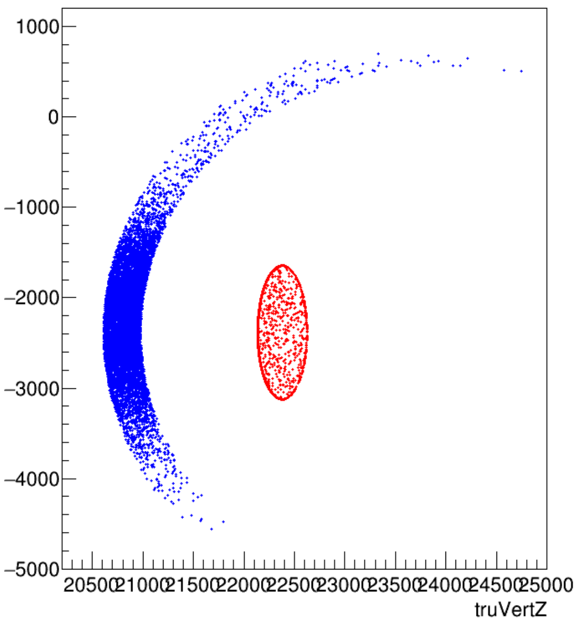
- The center of the distribution is the correction to the t^0_i
- Iterate the procedure: re-run the ECAL reconstruction and clustering with the t^0_i 's updated and go to step 1.

- Stop when the corrections are compatible with zero



Events with the muon entering GRAIN

Vertex in the Magnet yoke

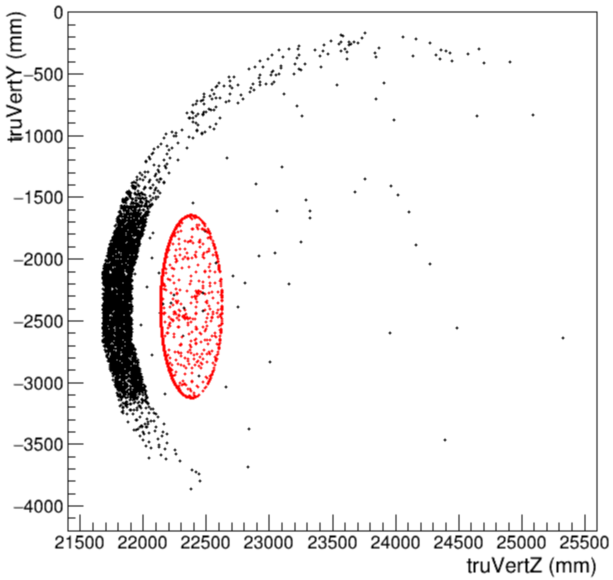


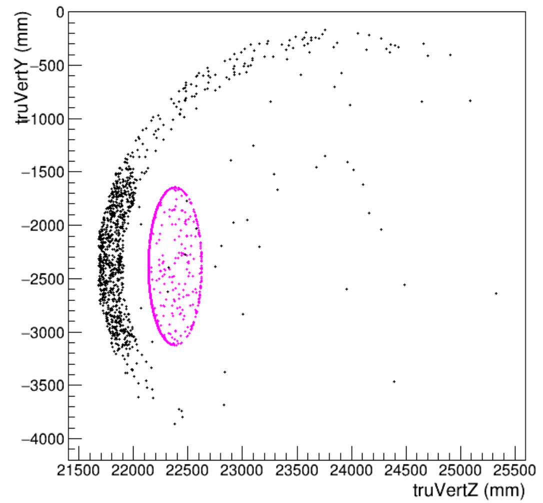
Total interaction events: 441,000

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

Clean muons: ~ 10,000 (2.3%)

Vertex in ECAL



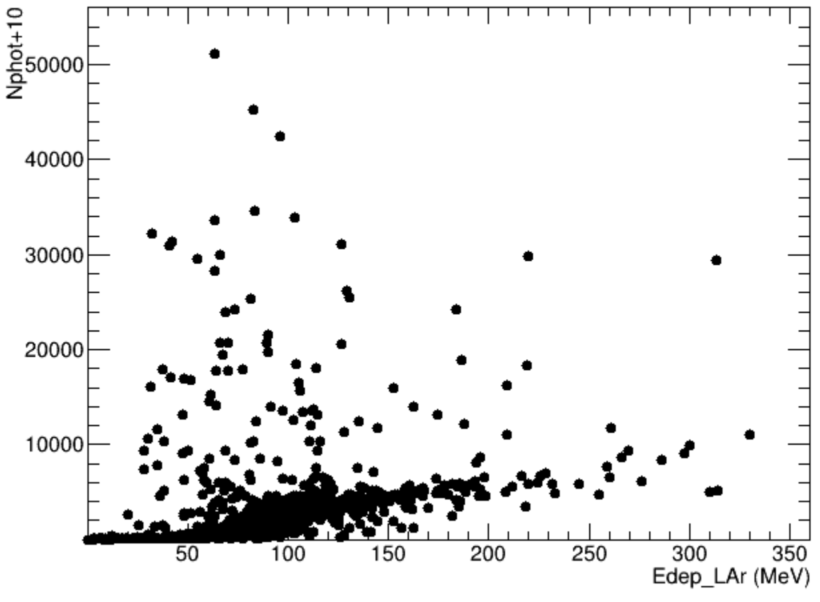


Total interaction events: 200,000

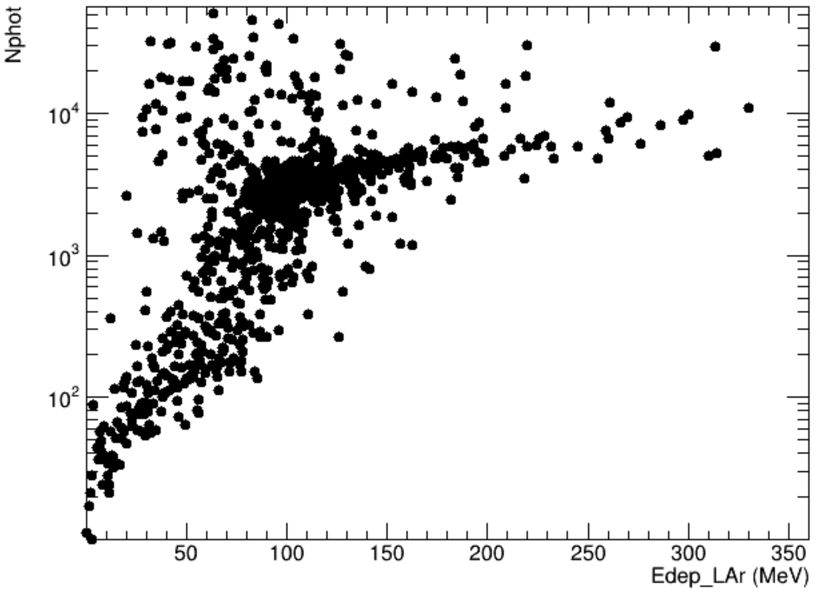
Muons entering GRAIN: ~ 6,000 (3%)

Clean muons: ~ 1,500 (0.8%)

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 $\times 10^{13}$ 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 $\times 10^{13}$ 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) …

- 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