

GRAIN calibration with muons

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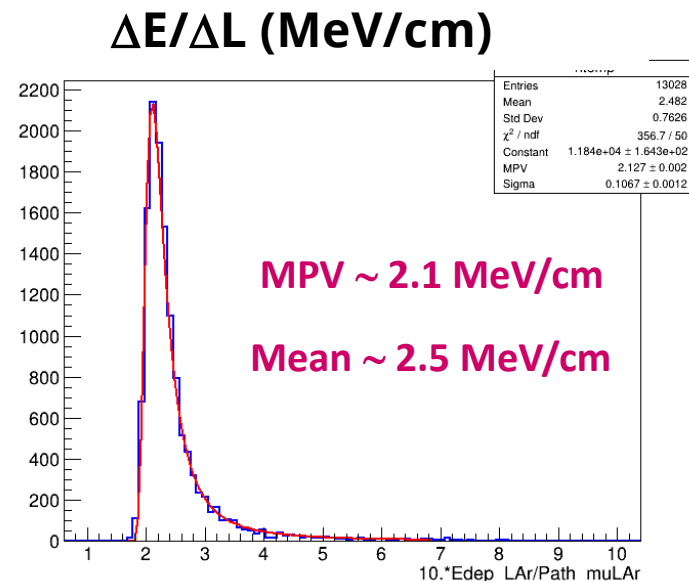
INFN - Lecce Group

DUNE-Italy Collaboration Meeting

LNF, 10-12 November 2025

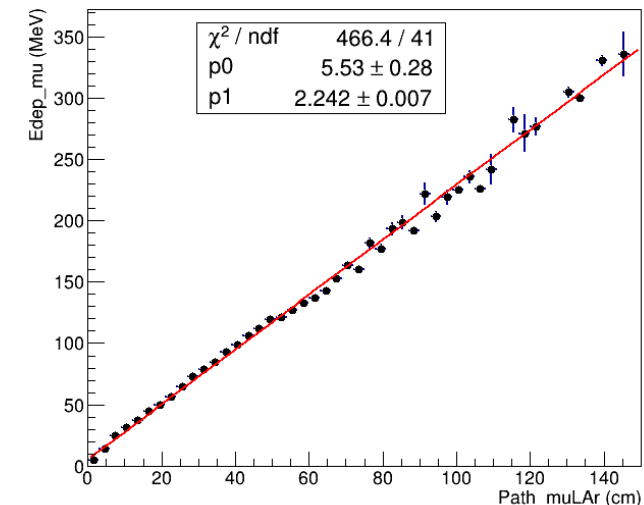
Use of muons for GRAIN calibration

- ✓ Natural energy calibration probe: **MIPs crossing the LAr volume**
 - muons from the beam interactions outside GRAIN (detectors, rock, ..)
 - cosmic ray muons
- ✓ Specific energy loss by muons in LAr



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

Relation btw ΔL and ΔE

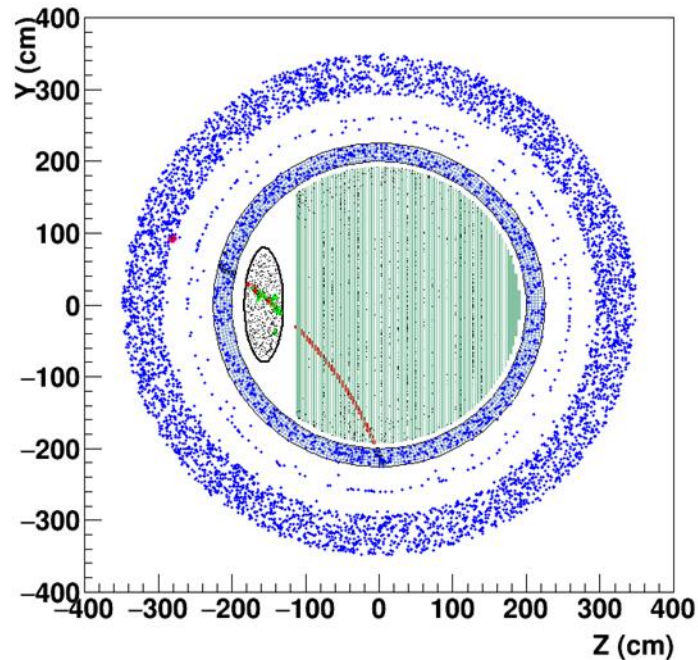


Correlation useful to extract muon energy deposit from Track-length

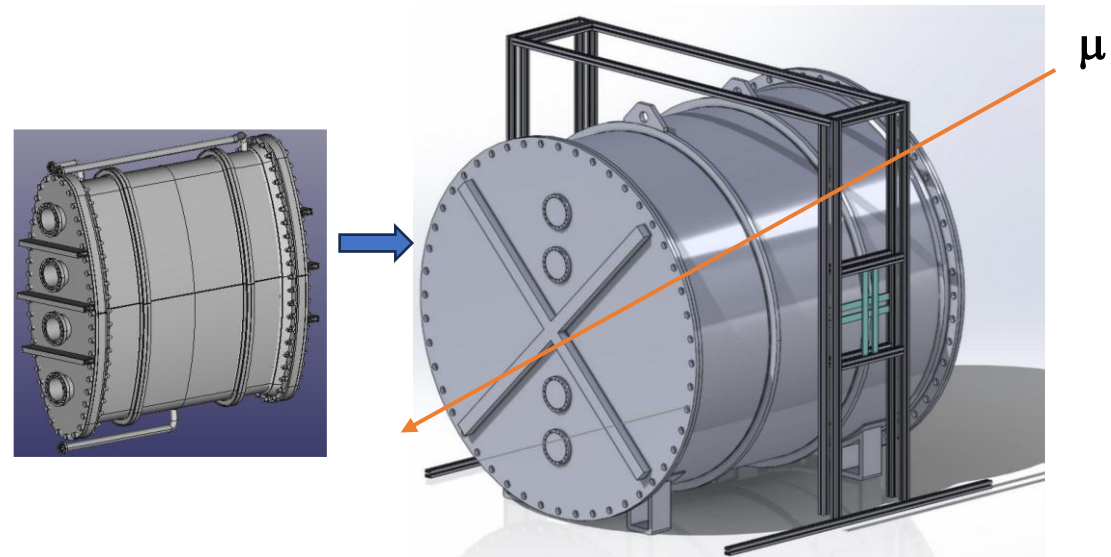
Muons crossing GRAIN

- Muons as MIPs crossing LAr volume in GRAIN are easily available both on the ν beam and in **GRAIN prototypes (ARTIC and LNL)**

Muon from ν interaction in the yoke and crossing GRAIN



Full-scale GRAIN prototype at LNL



Expected muon flux from the beam and CRs

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

Table 1.29: Total number of ($\nu_\mu + \bar{\nu}_\mu + \nu_e + \bar{\nu}_e$) CC+NC events expected within a single beam spill ($9.6 \mu\text{s}$, 7.5×10^{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

	Magnet Yoke		ECAL		Yoke + ECAL		GRAIN	
Total/spill	69		14		83		0.14	
CC + (NC)	51	(18)	10	(4)	61	(22)	0.1	(0.04)
Evts in ECAL	12 (24%)		10 (100%)		22 (36%)			
Evts in GRAIN	2.2 (4,4%)		2.0 (19%)		4.2 (6,9%)		0.1	
μ 's from rock	~1.7/spill in GRAIN (*)							

- 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 / spill)

Table 1.34: Number of events per spill ($9.6 \mu\text{s}$, 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.

Cut	ECAL		Rock muons		Magnet events	
	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 ($\sim 1.7/\text{spill}$)

✓ Contribution from Cosmic Rays ...

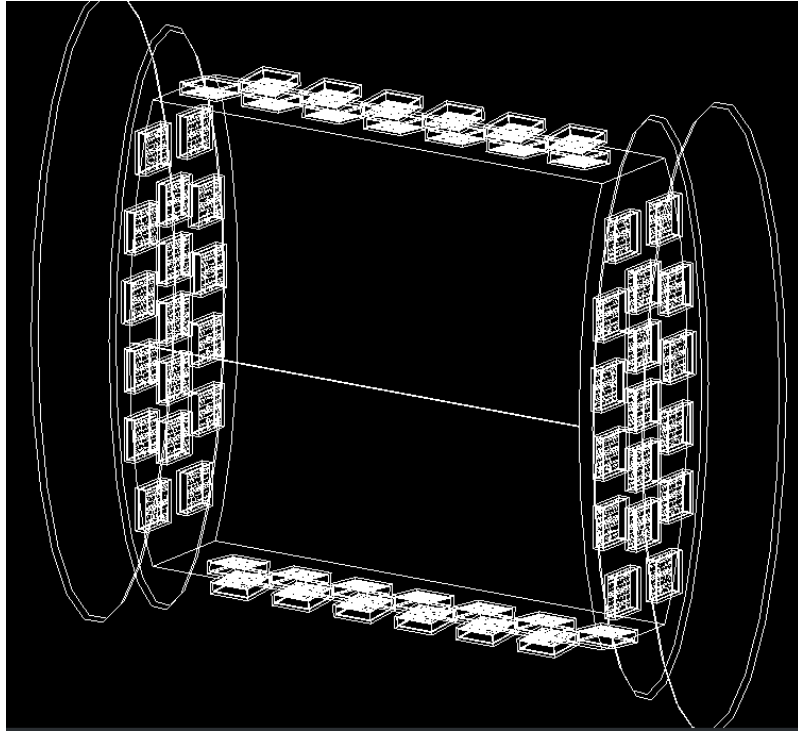
CR Muon flux at surface $\sim 0.01 \mu/(\text{s cm}^2)$ +
underground reduction of ~ 100

Effective area of GRAIN for $<60^\circ$ CR muons:
 $\sim 3 \times 10^4 \text{ cm}^2 \Rightarrow \sim 3 \mu/\text{s}$ are expected to cross GRAIN

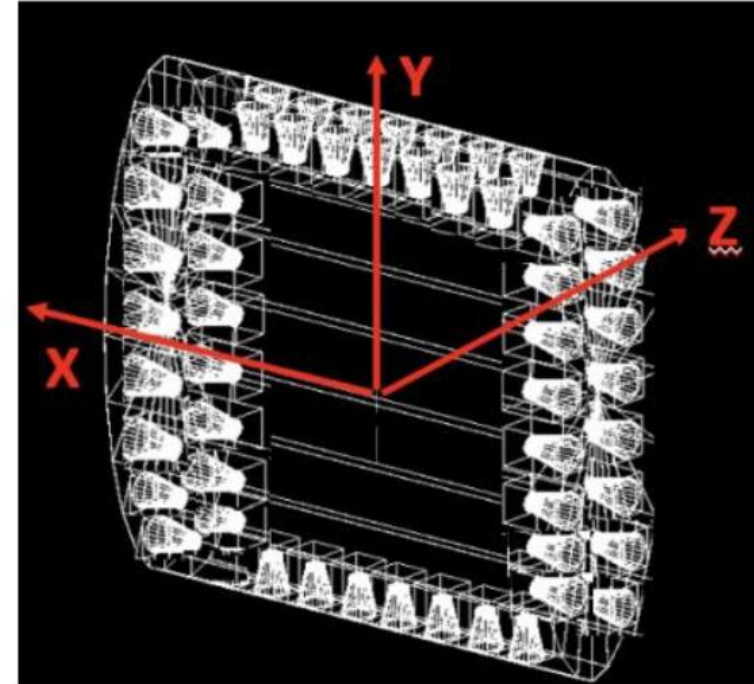
Drawback: smaller acceptance by the tracker for a precise track reconstruction

- Main contribution only if inter-spill DAQ were ON

GRAIN Detector readout by photosensors



Coded masks



Lenses

- 1024 SiPM matrix
- SiPM 3x3 mm² area
- mask of same size and hole pitch as SiPM matrix
- 60 cameras inside GRAIN, total 62k channels

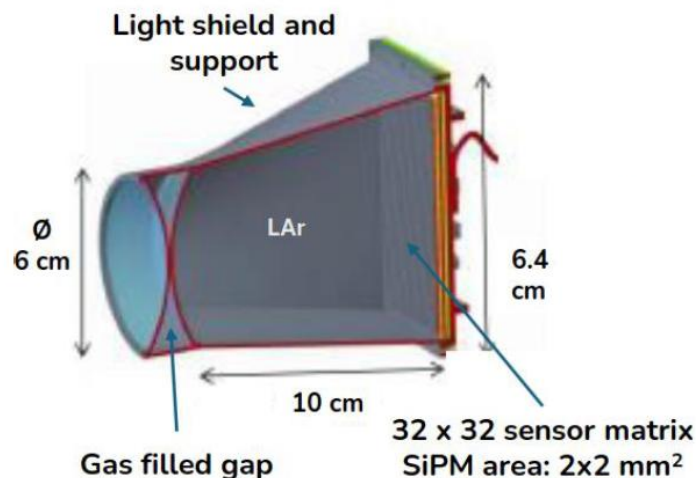
- 53 cameras for maximum coverage:
 - 16 pairs on the sides (at optimal distance)
 - 7 pairs on top
 - 7 single cameras on bottom
- 32 x 32 SiPM matrix, with 2 mm pixels and 20% PED

Imaging setup: Lens-camera system

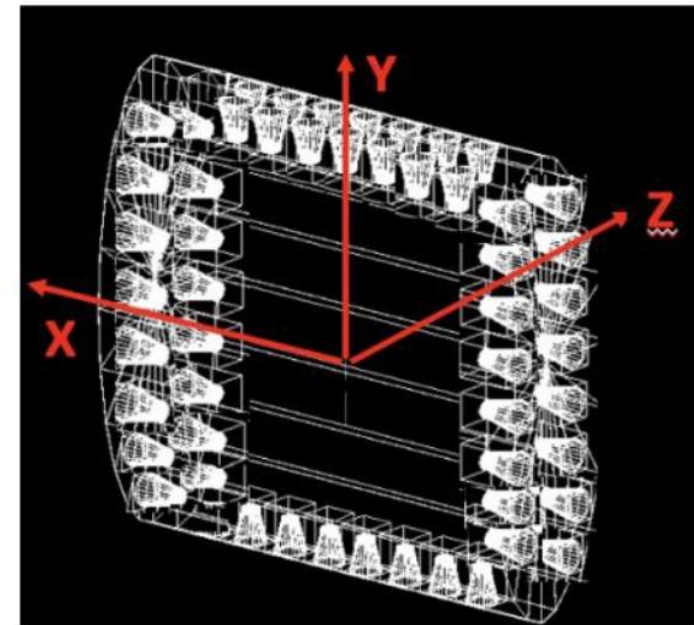
Scintillation light photons propagated in LAr and collected by the photo-sensor system through *OptMen* code

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

- **Sensor matrix:**
 - 32 x 32 Silicon Photomultipliers (SiPM)
 - SiPM active area: $2 \times 2 \text{ mm}^2$
PDE $\approx 0.1 - 0.2$

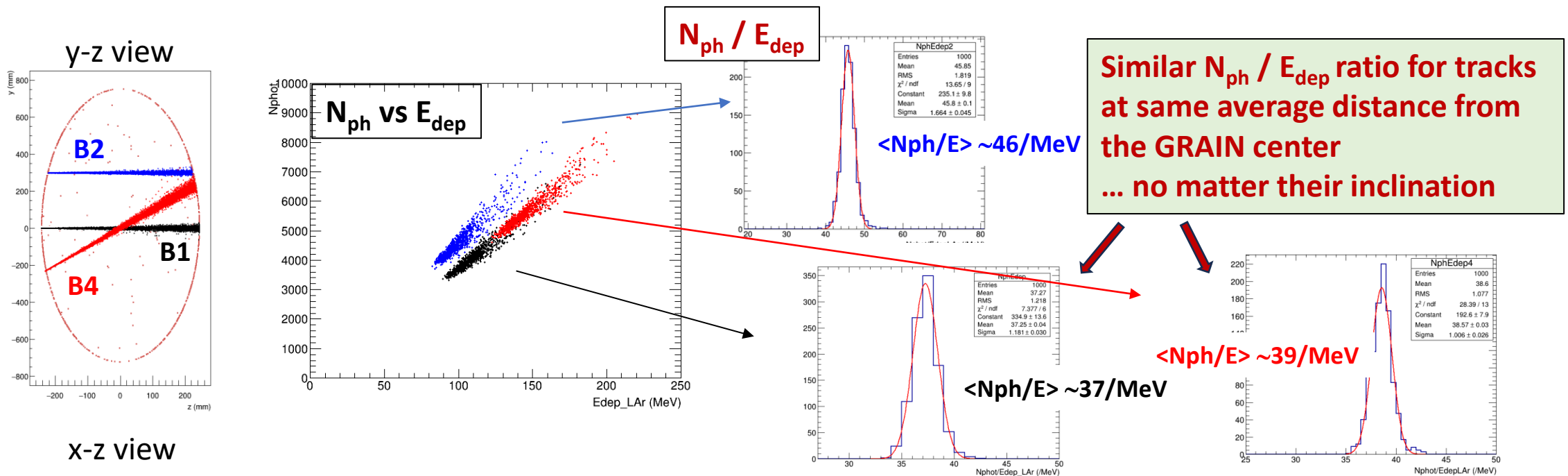


Total # of 53 cameras in GRAIN



Simulation of muon beams crossing GRAIN

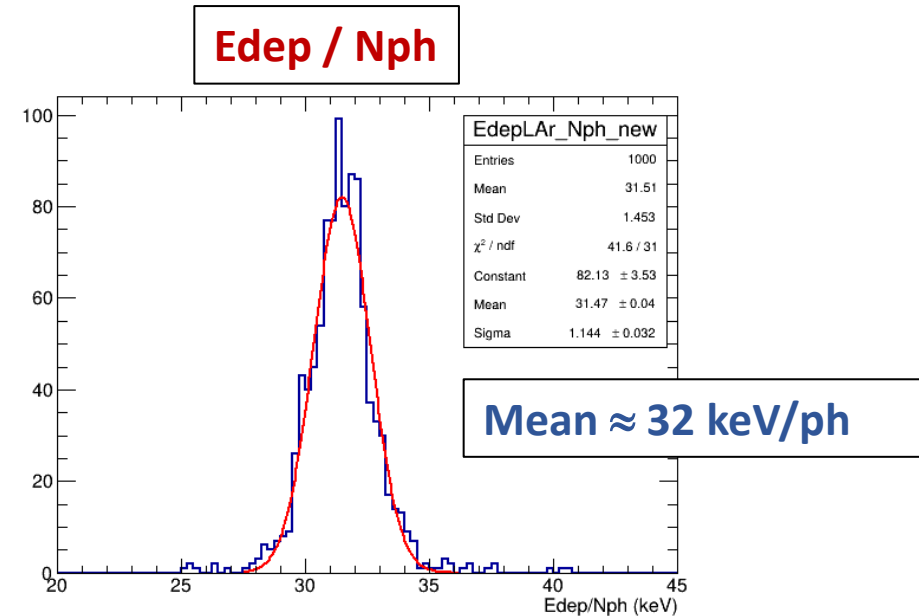
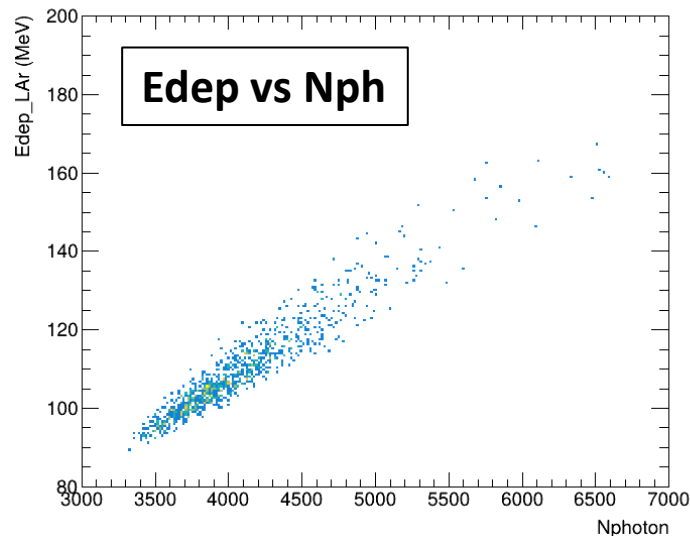
- Scintillation photon emission $f \sim 4 \cdot 10^4$ ph/MeV
- The photon collection depends on the energy deposit location inside GRAIN, according to the camera layout
 $\Rightarrow$ The calibration constants are functions of the position and orientation of the track related to the scintillation light emission



Calibration constants for energy estimate

Mean of the distribution of ($\text{Edep_LAr} / \text{Nphoton}$) taken as **calibration constant** for a given position inside GRAIN

Random beam



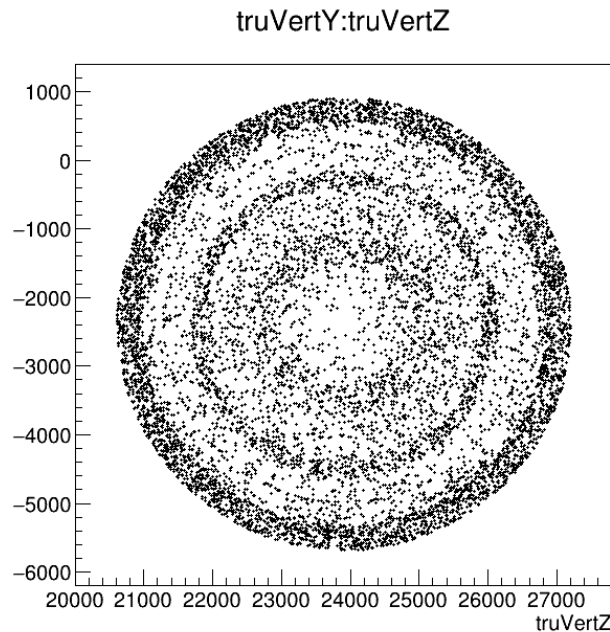
➡ The "constants" are parametrized with the distance from GRAIN center, to account for dependence on the average position of deposited energy (the track) on X and Y axes

- Assumption: track position and length reconstructed in GRAIN (by combining information also from Tracker and Ecal)

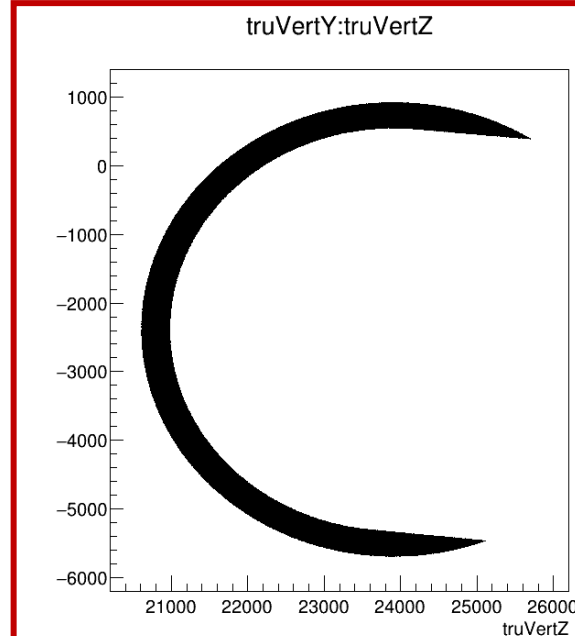
Monte Carlo simulation of ν interactions

- ✓ Three samples of ν_μ CC interactions in whole SAND, in the Magnet yoke and in ECAL were generated through GENIE

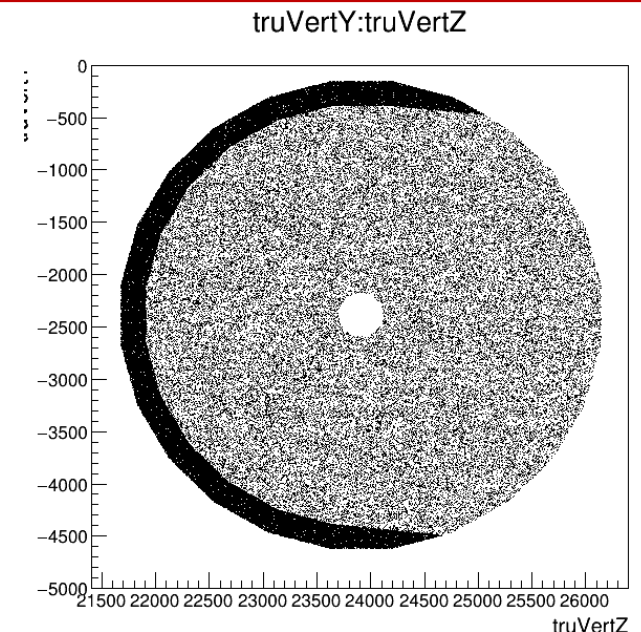
Distribution of interaction vertexes:



SAND



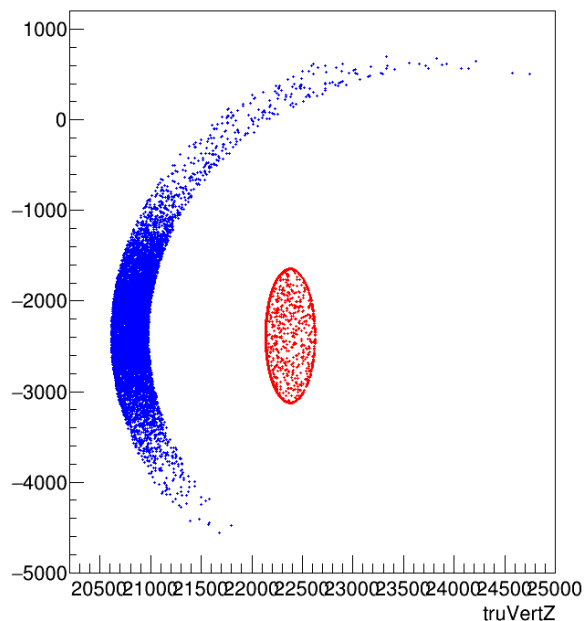
**Magnet yoke
(no end-caps)**



ECAL (including end-caps)

Events with the muon entering GRAIN

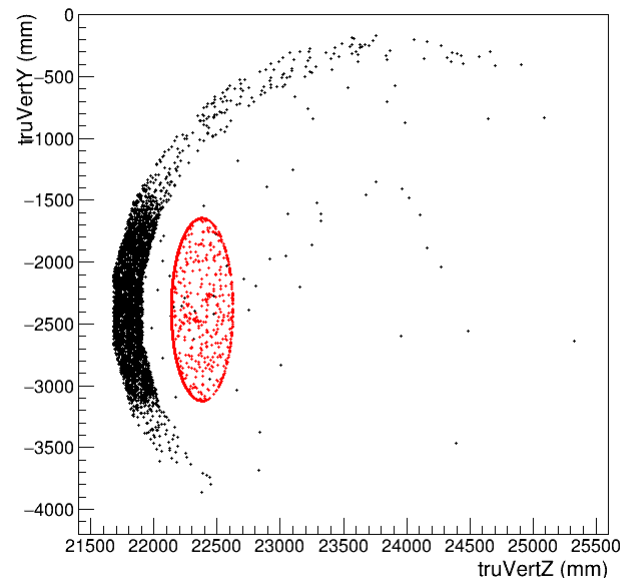
Vertex in the Magnet yoke



Total interaction events: 441,000
Muons entering GRAIN: $\sim 13,000$ (3%)

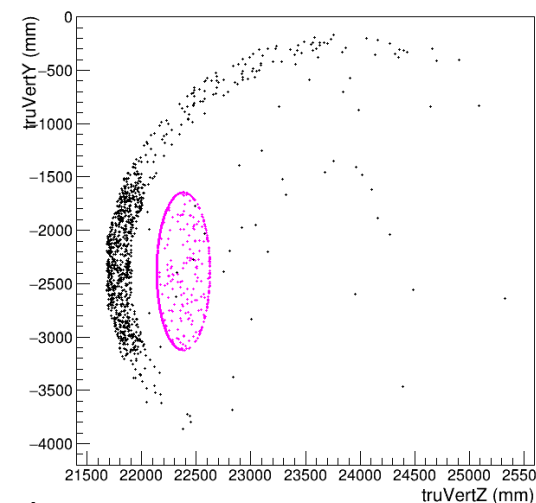
└ Clean muons: $\sim 10,000$ (2.3%)

Vertex in ECAL



Total interaction events: 200,000
Muons entering GRAIN: $\sim 6,000$ (3%)

└ Clean muons: $\sim 1,500$ (0.8%)



Calibration constants for any position in X-Y plane

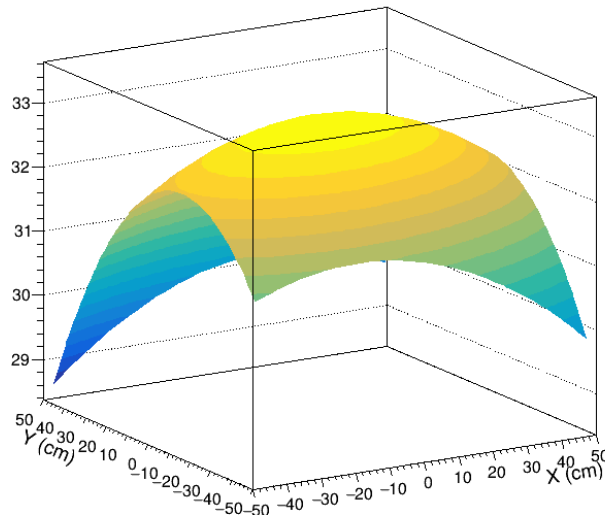
The GRAIN surface $\Delta X = (-50\text{cm}, 50\text{cm})$ and $\Delta Y = (-50\text{cm}, 50\text{cm})$ was subdivided into 100 cells (10cm x 10cm) and the sample of Yoke muons spread-out on the whole area was used

The average calibration constant was estimated in each cell from the Gaussian fit of the distribution of (Edep/Nphot) ratio for the muons crossing the cell

Fit of the most probable values of (Edep/Nphot) ratios in the grid with a 2D function of X and Y coord

→ quadratic function used as a calibration function: $F_{cal}(x,y) = a \cdot x^2 + b \cdot y^2 + c \cdot xy + d \cdot x + e \cdot y + f$

$[0] \cdot x^2 + [1] \cdot y^2 + [2] \cdot xy + [3] \cdot x + [4] \cdot y + [5]$



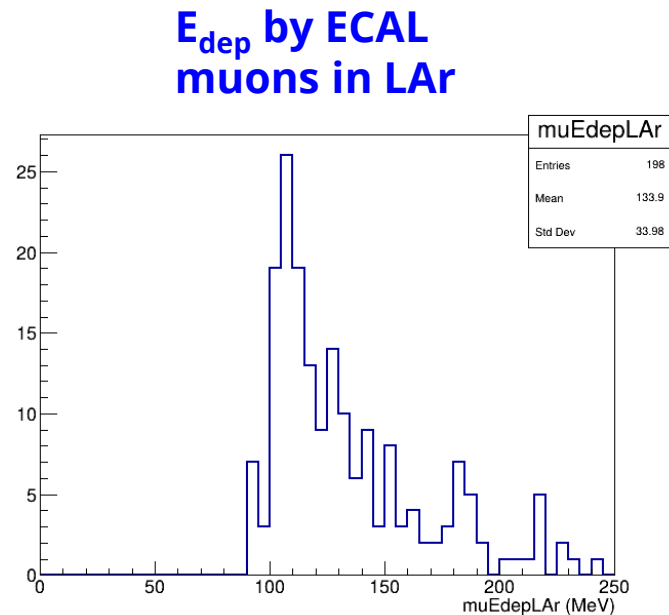
- Muons from ν interaction in Yoke
- → Realistic muon distribution in GRAIN from ν beam
- Event statistics not huge, anyway enough to obtain the parametric function fitting the grid points

a	=	-3.9e-04
b	=	-1.0e-03
c	=	2.7e-04
d	=	-1.44e-04
e	=	-1.4e-04
f	=	33.1

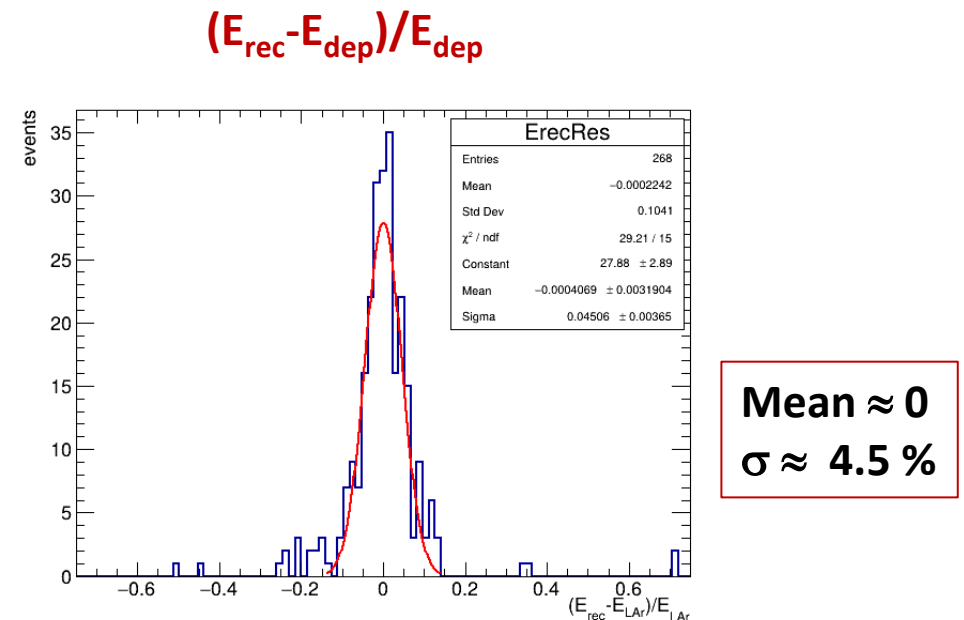
Test of the Calibration function on ECAL μ 's

- Calibration function tested on the sample of isolated muons from ν interactions in ECAL, as an independent muon sample

- Reconstruction of deposited energy in GRAIN for the ECAL muons



applying the above calibration function



Cut: muons entering GRAIN with $E_{\mu} > 300 \text{ MeV}$ and within 35cm from Z axis are selected

Muons useful for GRAIN calibration

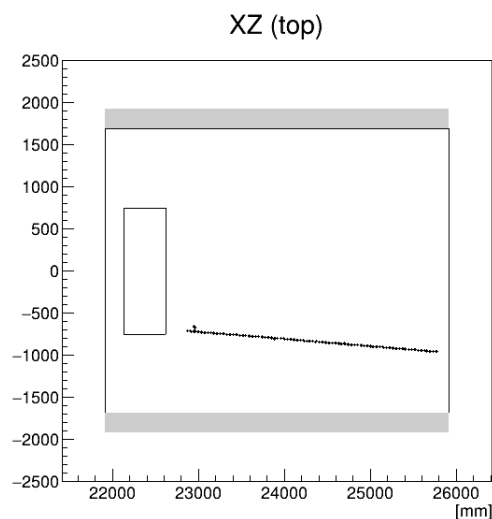
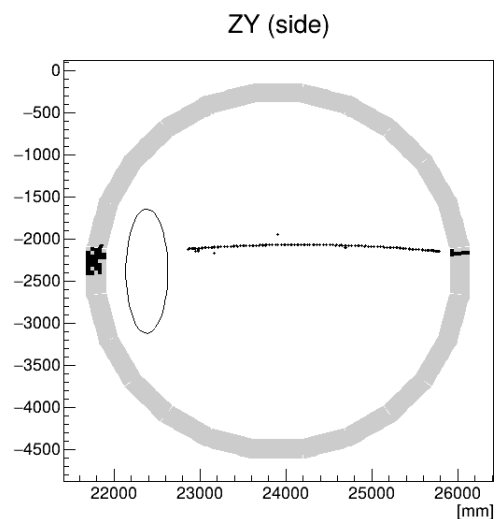
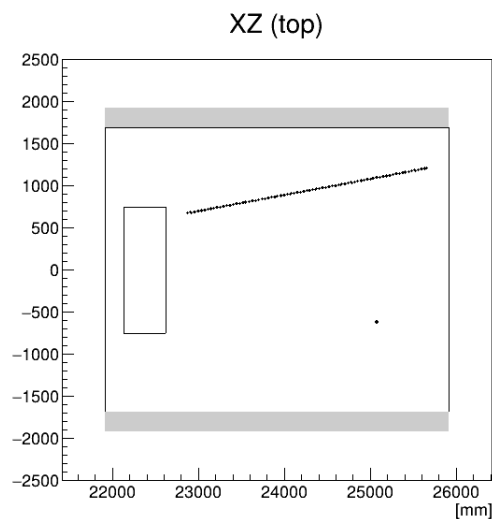
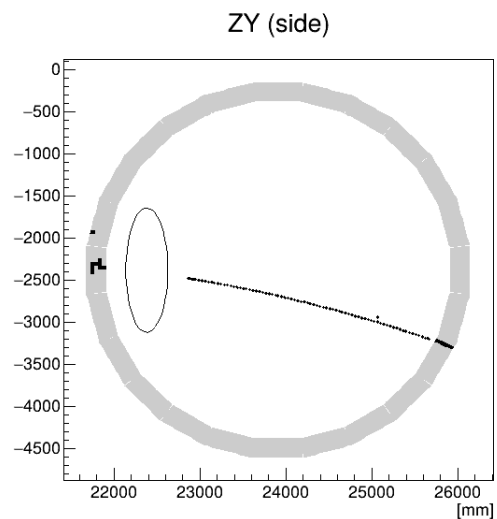
Requirements for muons to calibration purposes:

- produced outside GRAIN (from ν interactions in ECAL, in the Yoke, in front detectors, in the rock, from cosmic rays, ..)
- with enough energy to reach and cross GRAIN as isolated particles
- with a minimum track length in the SAND Tracker, to ensure a precise measurement of the pathlength inside GRAIN LAr volume (combining the information from ECAL, GRAIN, Tracker)

Selection of "calibration muons"

- ✓ In the real experiment, a proper selection of events with muons useful for GRAIN calibration will be needed, both for ν beam muons and cosmic muons
- ✓ Possible selection criteria for ν beam muons (without use of MC info):
 - events with at most 1 cluster (with no more than 3 nearly contiguous cells) in the innermost layer of the upward ECAL
 - energy deposit occurring in GRAIN
 - a single track reconstructed in the Tracker, such that:
 - length > $L_{\min} = 15$ (or 30) hits
 - geometrically crosses the GRAIN volume
 - matches the cluster in ECAL

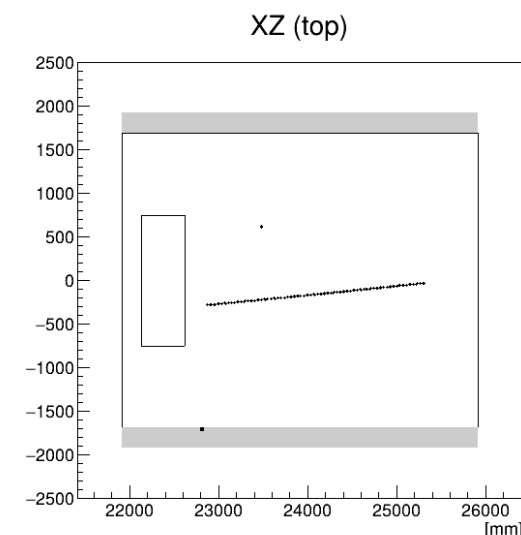
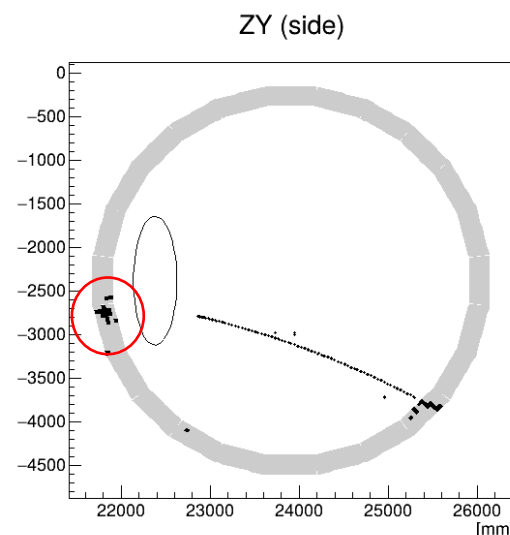
Events with ν interaction in ECAL



Accepted events

Rejected event

(> 1 cluster in innermost ECAL layer)



Events selection tests

- ✓ The above selection criteria were tested on the MC sample of ν interactions in the Yoke and ECAL

➤ Results:

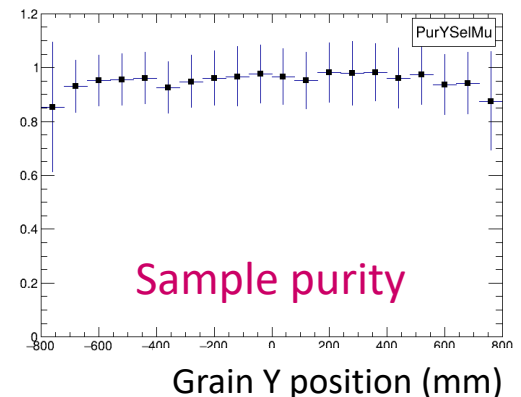
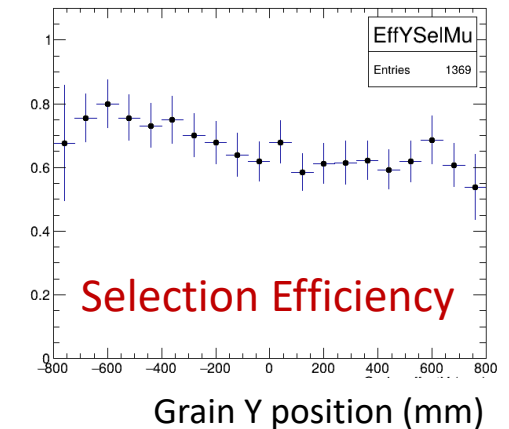
- **Efficiency:**

- Events with ν interactions in **Yoke**: $\approx 72\%$
- Events with ν interactions in **ECAL**: $\approx 54\%$

- **Purity** of selected sample:

- Events with ν interactions in **Yoke**: $\approx 94\%$
- Events with ν interactions in **ECAL**: $\approx 68\%$

Yoke muons



Events selection tests

- ✓ Additional selection cut in order to increase purity for ECAL sample:
 - events with at least 1 cluster in the 4th layer of the upward ECAL, matching the track (to ensure the muon production occurred up to that layer)
- Updated results:
 - **Efficiency:**
 - Events with ν interactions in **Yoke**: $\approx 72\%$
 - Events with ν interactions in **ECAL**: $\approx 35\%$
 - **Purity** of selected sample:
 - Events with ν interactions in **Yoke**: $\approx 95\%$
 - Events with ν interactions in **ECAL**: $\approx 72\%$

Conclusions

✓ What presented:

- Muons (from beam or cosmic rays) as natural probes for GRAIN calibration
- A possible calibration procedure investigated and tested, using simulated muons from beam ν interactions in the Yoke and ECAL
- Definition of the basic requirements for calibration muons
- Possible event selection criteria for calibration muons from neutrino beam

✓ Nest steps:

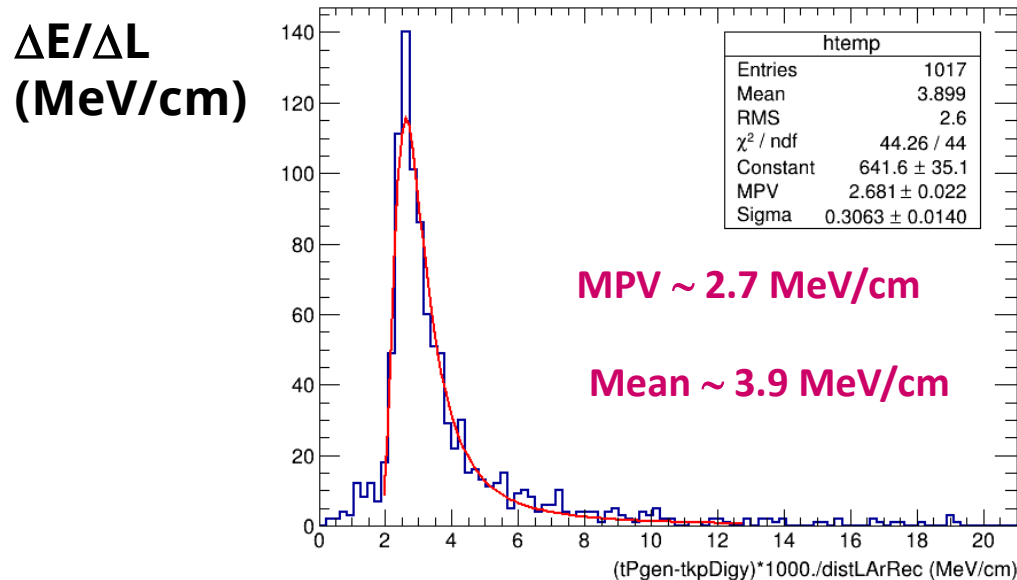
- evaluation of track-length inside GRAIN for selected events
- estimate of energy deposit from Edep vs Pathlength relation

BACKUP

Muons crossing LAr volume

➤ Precise determination of $\langle dE/dx \rangle$ in LAr

From MC simulation of SAND, for a μ crossing GRAIN:

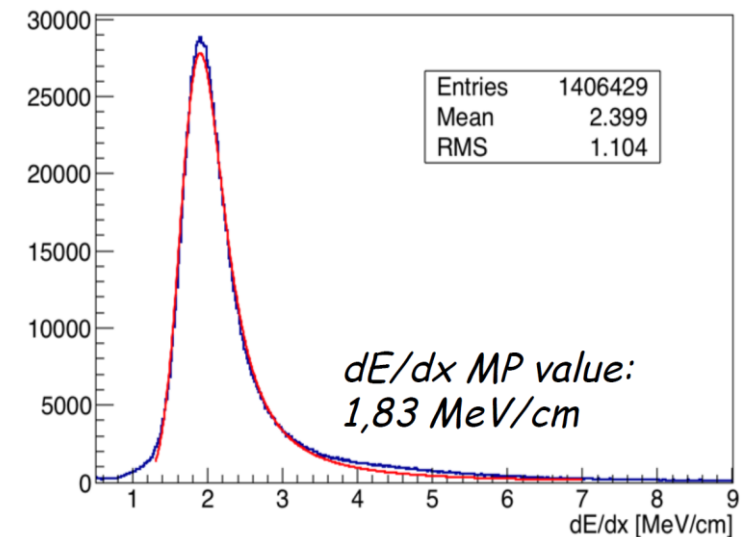


ΔL : pathlength in GRAIN LAr

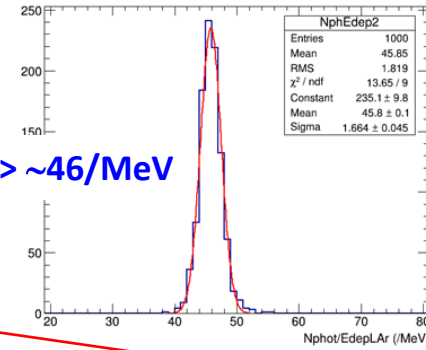
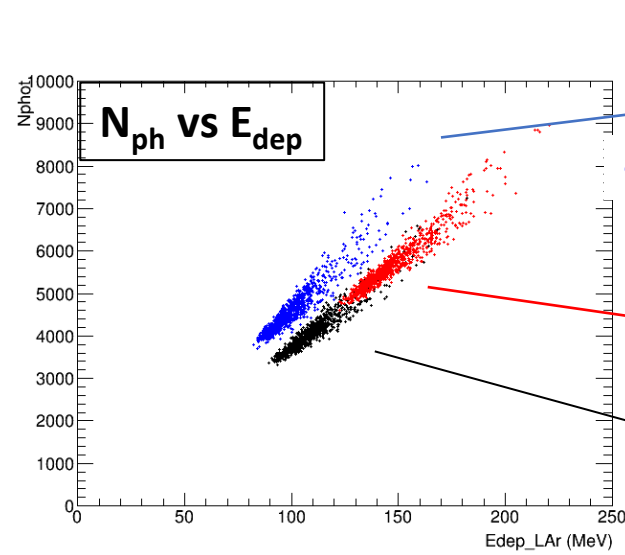
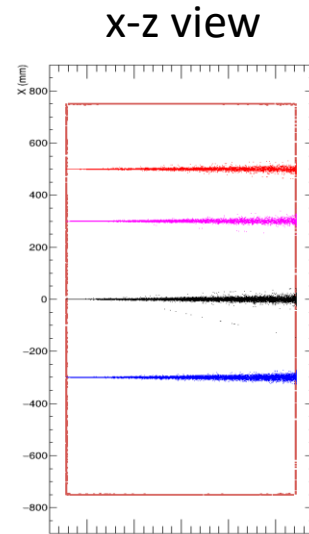
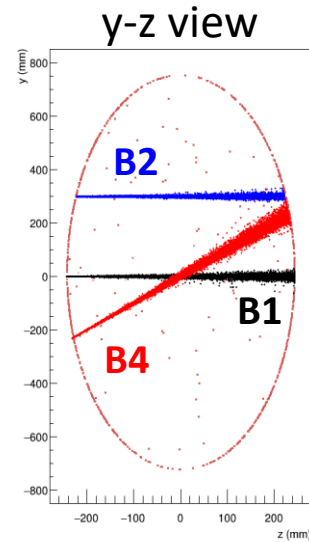
ΔE : energy loss by the muon in ΔL

From ICARUS

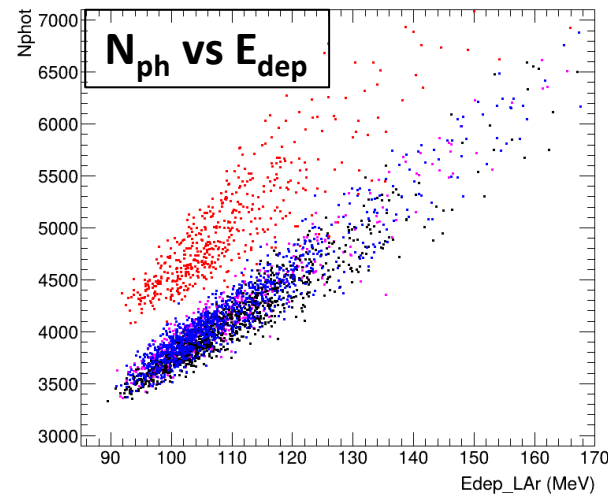
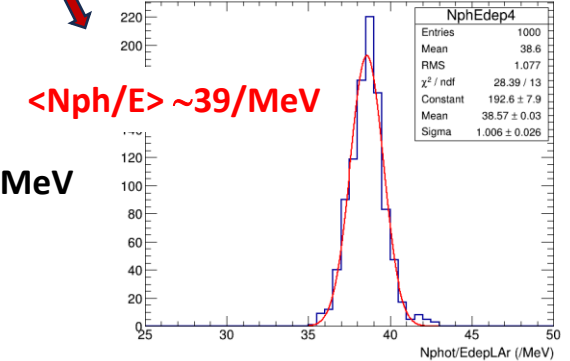
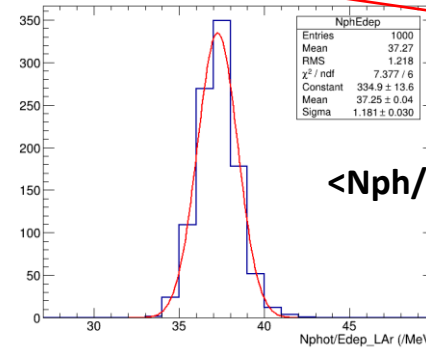
Full 3D reconstruction on selected muon tracks crossing LAr volume



Muon beams with different positions and inclinations



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

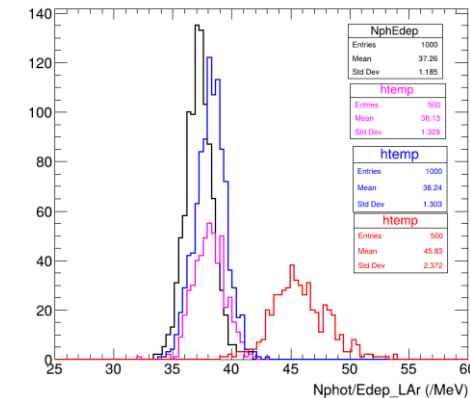


$\langle N_{ph}/E \rangle \sim 37/\text{MeV}$

$\langle N_{ph}/E \rangle \sim 38/\text{MeV}$

$\langle N_{ph}/E \rangle \sim 38/\text{MeV}$

$\langle N_{ph}/E \rangle \sim 46/\text{MeV}$



Events selection tests

- ✓ Preliminary event selection for calibration muons: pure purity for ECAL sample due to interactions in ECAL internal layers with particles entering GRAIN but not tracked ...

