Estimating energy resolution: electromagnetic showers resolution

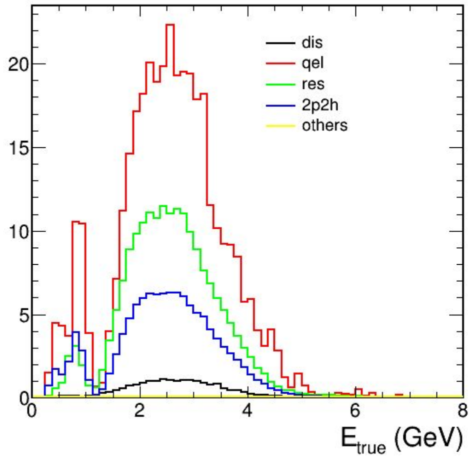
Ginevra De Lauretis - DUNE France - 16.10.24

Introduction

In my work on the study of the neutrino energy reconstruction from final state particles related to neutrino interaction models I am using a smeared resolution to take into account the detector resolution effect

$$K \rightarrow K\left(1 + \sigma\, Gauss\,(0,1)\right)$$

Particle	Energy	Resolution
Electrons, Photons, ...	All	$\sigma = \left(\frac{0.15}{\sqrt{E(MeV)}} \oplus 1\right)\%$
Neutral hadrons (neutrons...)	All	$\sigma = \frac{30}{\sqrt{E(GeV)}}\%$
Charged hadrons (protons...)	$K < K_1$	$\sigma = 3\%$
	$K_1 < K < K_2$	$\sigma = 1\%$
	$K > K_2$	$\sigma = \frac{30}{\sqrt{E(GeV)}}\%$



My interest is to advance on the definition of the best smearing parameters, in particular for the EM showers, which constitute a particularly important point for veCC-QE events in the region of the 2nd oscillation max which is the topic of my analysis

Trying to understand the various contributions which affect EM shower resolution

Introduction

Some values for the resolutions of electromagnetic showers quoted in DUNE publications:

- DUNE CDR was quoting 15%/sqrt(E[GeV]) + 2%
- Long-baseline neutrino oscillation physics potential of the DUNE experiment 8%/sqrt(E[GeV]) + 4%
- DUNE TDR 8% (spectrum averaged)

For the basic principles of calorimetry (see Calorimetry for particle physics, Fabjan, Gianotti, 2003)

The past DUNE figures look pessimistic even to what achieved in lead/scintillator **sampling calorimeters**:

UA2 : Pb/scint., 26 lead plates of 3.5 mm thickness alternated with scintillator plates 4mm thick
Longitudinal containment 17 X0, resolution 14%/sqrt(E GeV) + 1%

Shaslik: Pb/scint, 75 lead plates 1.5mm thickness, alternated with 75 scintillator plates 4mm thick, fine light readout with 100 WLS fibers. Longitudinal containment 20 X0, resolution 5.6% %/sqrt(E GeV) + 1%

As well as in other **sampling calorimeters**:

ATLAS Lead/Lar sampling calorimeter, accordion geometry. Longitudinal containment 22 X0, resolution 10%/sqrt(E GeV) + 0,7%

Introduction

In **homogeneus calorimeters** resolutions are better:

- NOMAD: Lead glass (Cerenkov light) (yield: 1400 photoelectrons/GeV) longitudinal containment 19 X0, resolution 2.7%/sqrt(E GeV) + 1% (dominated by photostatistics 1400 photoelectrons/GeV)

Note that the charge statistics in a LAr TPC is much higher ~ 30 M e-/GeV

Some LAr TPC measured resolutions:

- Pure LAr calorimeter: Resolution 2.4% at 1 GeV (measurement taken with a LAr ionization chamber by Japanese groups)
- ICARUS LArTPC with full showers containment homogeneous LAr calorimeter, res = 3%/sqrt(E GeV) +1%

Beyond reconstruction effects in Pandora which could be hopefully further improved, what's the most realistic resolution to use for EM showers corresponding to the real detector performance?

Which are the intrinsic limitations of a LAr TPC which determine its resolution beyond the primary statistics?

→ The idea is to simulate electrons interactions in a large enough volume with no leakage and then introduce the different effects that affects the resolution (see next slide)

Effects impacting calorimetric resolution

1. **Containment**
2. Sampling fluctuations
3. Statistics

→ fluctuations on the lateral or longitudinal leakage for which part of the shower is not seen

Shower maximum: $t_{max} \simeq \ln \frac{E_0}{\epsilon} + t_0$

1 Gev → T_{max} ~ 3.49 X0 = 49 cm
2 Gev → T_{max} ~ 4.18 X0 = 58.5 cm

Longitudinal containment: $t_{95\%} \simeq t_{max} + 0.08Z + 9.6$

1 Gev → $T_{95\%}$ ~ 14.53 X0
2 Gev → $T_{95\%}$ ~15.22 X0

~ 2.5/3 m needed for full containment!

Lateral containment: given by Molière radius, 99% of the energy is contained laterally in a radius of 35 cm

→ In the simulation the detector can be made as large to contain the entire shower, this means for DUNE to get a longitudinal containment of about >3m and lateral of >70 cm diameter

In the DUNE FD module there will be 2 categories of events:

- fully contained in the fiducial volume
- events affected by leakage

Effects impacting calorimetric resolution

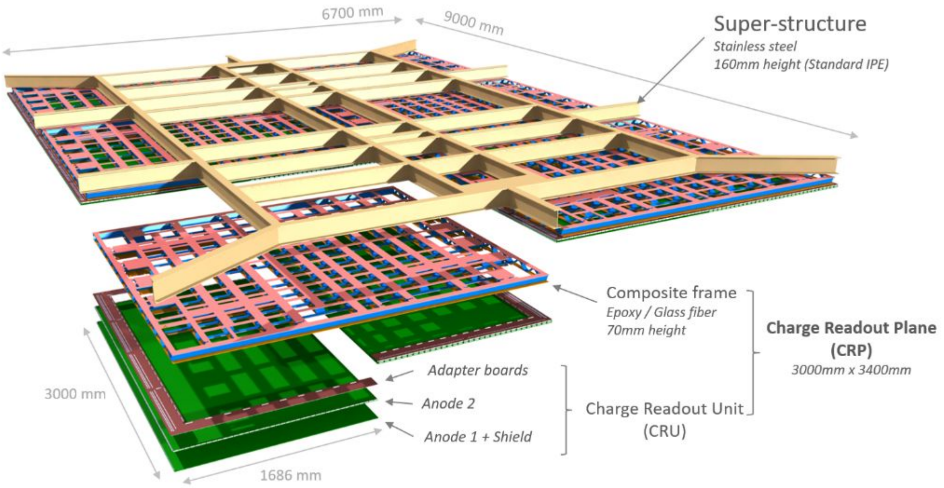
1. Containment
2. **Sampling fluctuations**
3. Statistics

Normally there should not be sampling fluctuation in LArTPC but we have dead regions in which we cannot measure the charge deposited by the shower

In DUNE VD FD module there are sampling fluctuations at the CRP boundaries (every 3 m)

- ~1.6 cm gap between 2 CRP
- ~ 3.2 cm gap between superstructures

It is not yet clear what will happen to the charge deposited in these gaps, probably part of it will go to the nearest anode (topic under investigation)



Effects impacting calorimetric resolution

1. Containment
2. Sampling fluctuations
3. **Statistics**

→ statistical fluctuations on the measured deposited charge or due to other effects (as recombination)

- Statistics of the generated charge is huge, not a limiting factor (compared to the 1400 pe/GeV of NOMAD)
- However recombination depends on the local charge density which fluctuates → fluctuations independent on the primary statistics

→ Fluctuations in recombination may be the strongest effect for a LarTPC bringing to the resolution measured by the LAr ionization chamber cited before of 2.4%/sqrt(E)

Reminder: recombination depends on the drift field intensity and on the orientation of ionization with respect to the electric field axis and can be modeled with Birks law

$$\mathcal{R} = \frac{A}{1 + \frac{k}{\mathcal{E}} \frac{\mathrm{d}E}{\mathrm{d}x}}$$

with $A = 0.800 \pm 0.003$ and $k = 0.0486 \pm 0.0006$ $(\mathrm{kV/cm})(\mathrm{g/cm^2})/\mathrm{MeV}$, as measured by the ICARUS collaboration [49]. This parametrization is valid in the range $0.1 < \mathcal{E} < 1.0$ kV/cm and $1.5 < \mathrm{d}E/\mathrm{d}x < 30$ $\mathrm{MeV/(g/cm^2)}$

How to understand the EM shower resolution ?

1) Simulate a large enough volume with no leakage and understand the resolution for electrons of various energies in the range 0.5 - 3.0 GeV

2) Introduce **recombination** in the simulation and understand its effect

3) Introduce the **CRP gaps** and quantify the effect of the sampling fluctuations

4) Introduce the fiducial border effects (tradeoff between fiducial volume and resolution, maybe the events in the border regions (to be understood which dimensions to put) will have to be treated differently and we should not make an “average resolution” including them and averaging over the entire sample.

5) Introduce the **first stage of the reconstruction** step and recover the hit energy to understand its effect

General informations on the simulation

Thanks also to Dom and Laura for the help provided on this!

Geometry is the 1x8x6 CRP (taken from official VD simulations):

- ➔ standard_g4_dunevd10kt_1x8x6_3view_30deg.fcl
- ➔ in order to store the deposits of energy in the CRP gaps the geometry was modified for us thanks to Viktor Pec
- ➔ the CRP gaps are 10mm large (this does not correspond to reality)

Getting the informations from LArSoft branches:

- ➔ sim::SimEnergyDeposits_largeant_LArG4DetectorServicevolTPCActive_G4
- ➔ sim::SimEnergyDeposits_largeant_LArG4DetectorServicevolTPCEnclosure_G4

} **Energy deposits E_{dep}** in the active volume and in the gaps (EDep, EDepOut) at the true level of the G4 simulation

- ➔ sim::SimEnergyDeposits_IonAndScint

} **Number of electrons N_e** in the active volume and in the gaps after recombination

- ➔ recob::Hits_gaushit_Reco1

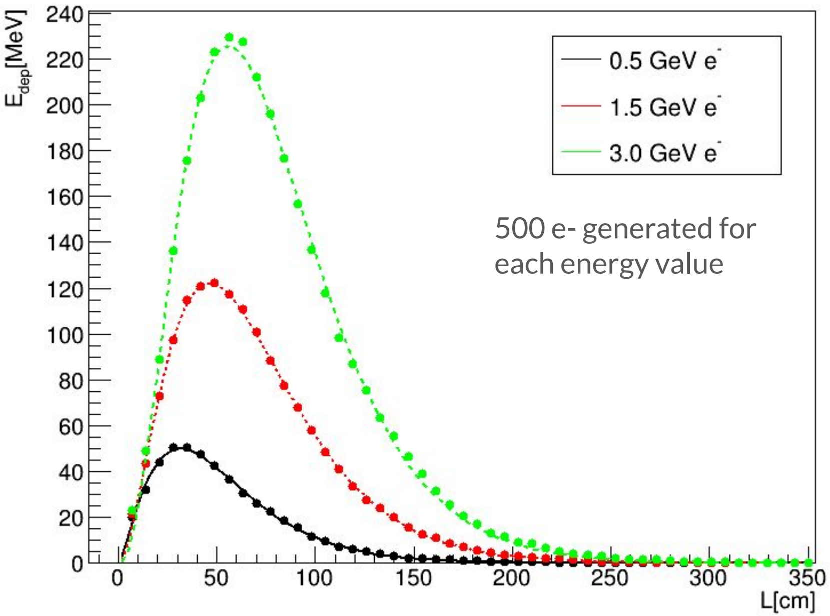
} **Hit integral** in the active volume after the first step of the reconstruction

Longitudinal containment (result of the simulations)

Shower maximum: $t_{max} \simeq \ln \frac{E_0}{\epsilon} + t_0$

Longitudinal containment: $t_{95\%} \simeq t_{max} + 0.08Z + 9.6$

to fit ➔ $$\frac{dE}{dt} = E_0 c t^{\alpha} e^{-\beta t} \quad \begin{cases} t = \frac{x}{X_0} \\ \alpha \sim \beta t_{max} \end{cases}$$

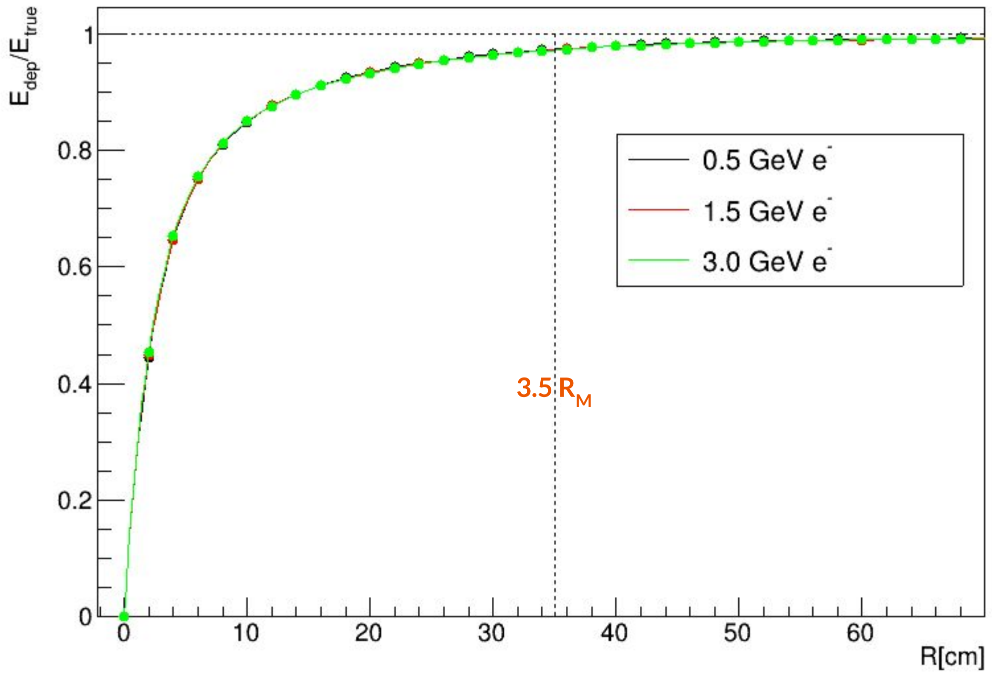


500 e- generated for each energy value

	E_0	E_{left} [20 X0]	α/β (fit)	x_{max}(expected)
➔	0.5 GeV	0.02 %	31.3 cm	32.2 cm
➔	1.5 GeV	0.08 %	46.2 cm	47.5 cm
➔	3.0 GeV	0.12 %	56.0 cm	57.2 cm

good agreement with theoretical values

Transversal evolution



Along the transversal axis I should have that 99% of the energy is contained laterally in a radius of 35 cm (3.5 R_M)

In LAr Molière radius R_M=10 cm

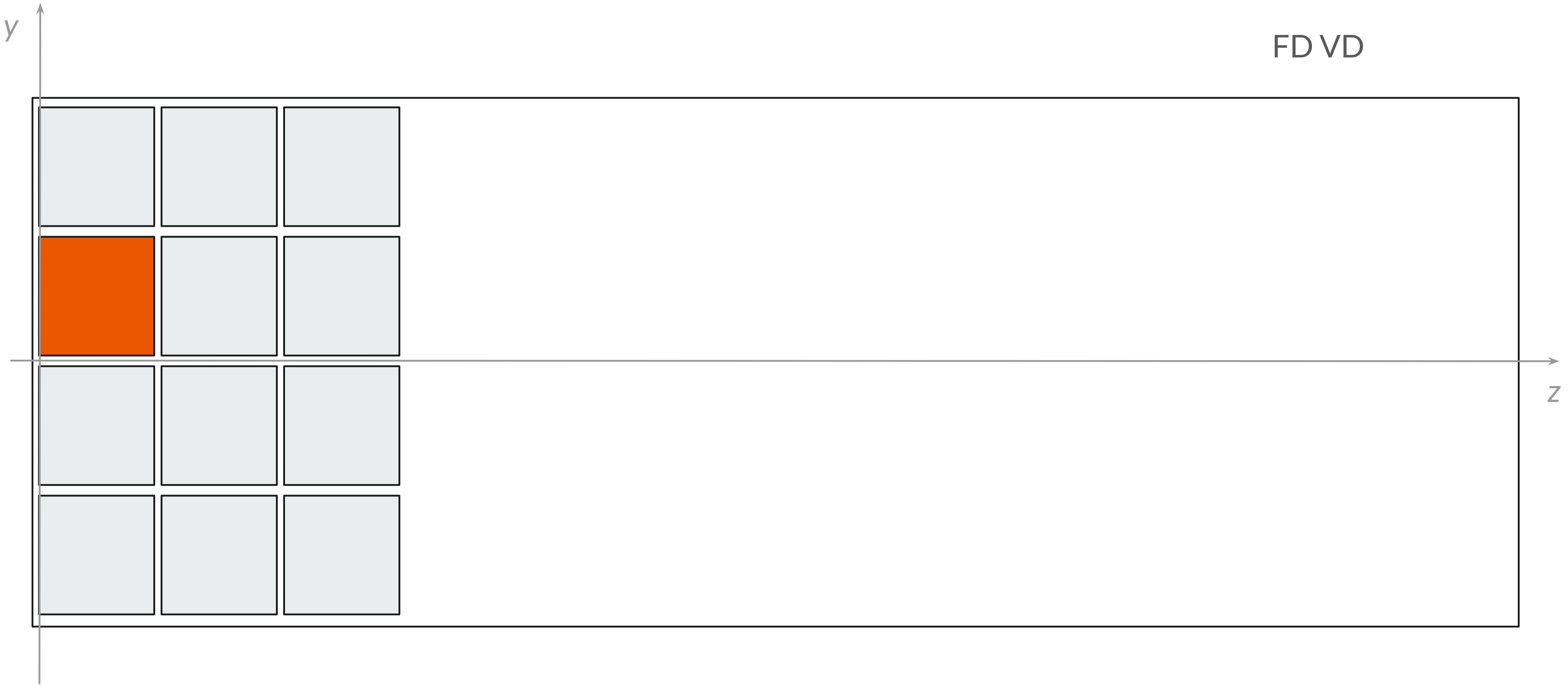
(→ https://lar.bnl.gov/properties/)

PDG quotes 9.04 cm in LAr

	Energy	E_{lost} [36cm]	E_{lost} [40cm]
➔	0.5 GeV	2.50 %	1.63 %
➔	1.5GeV	2.57 %	1.71 %
➔	3.0 GeV	2.61 %	1.73 %

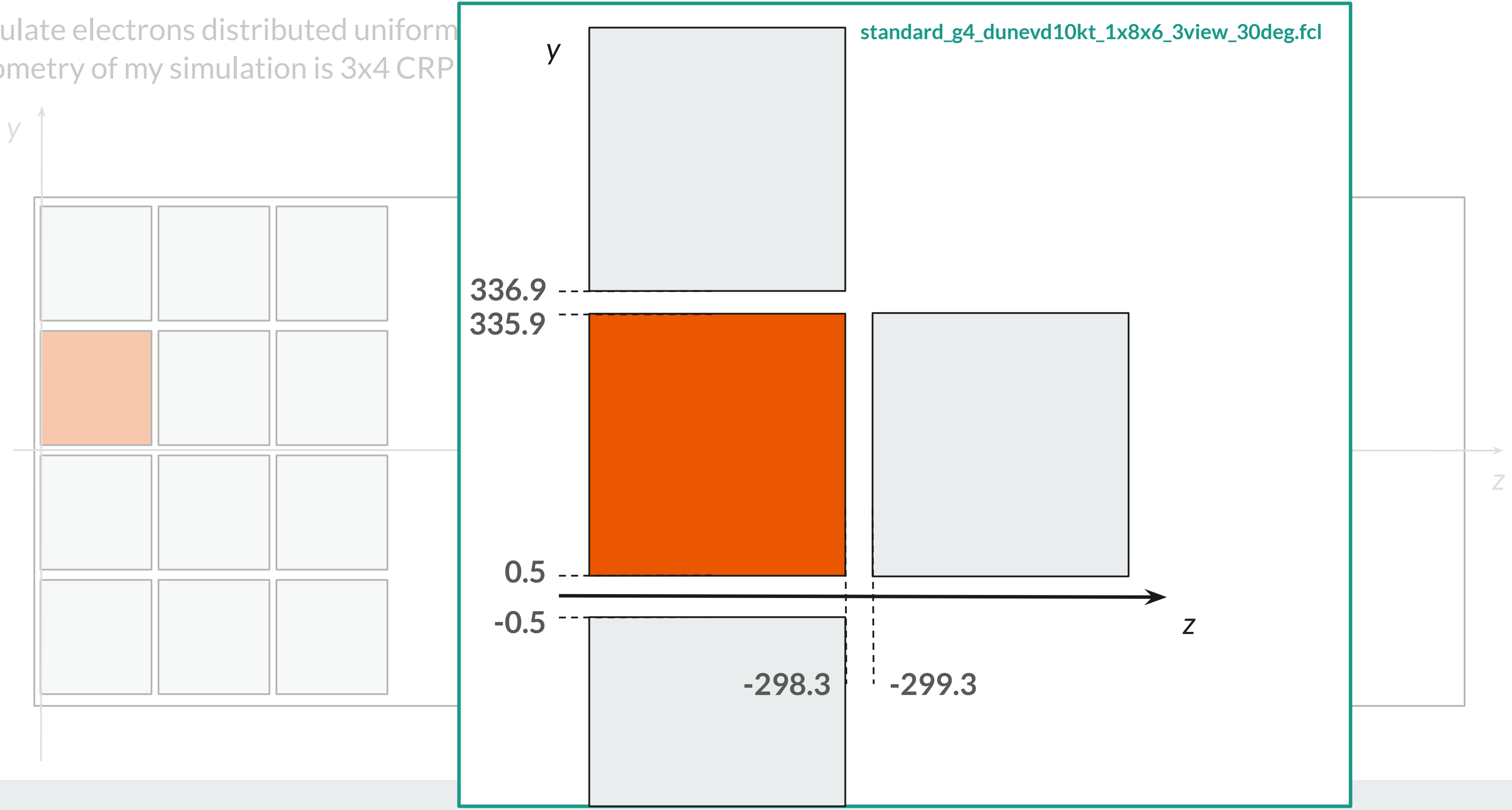
Electrons vertices uniformly distributed on YZ plane

Simulate electrons vertices distributed uniformly in one CRP.
Geometry of my simulation is 3x4 CRP (6x8 CRM) → standard_g4_dunevd10kt_1x8x6_3view_30deg.fcl

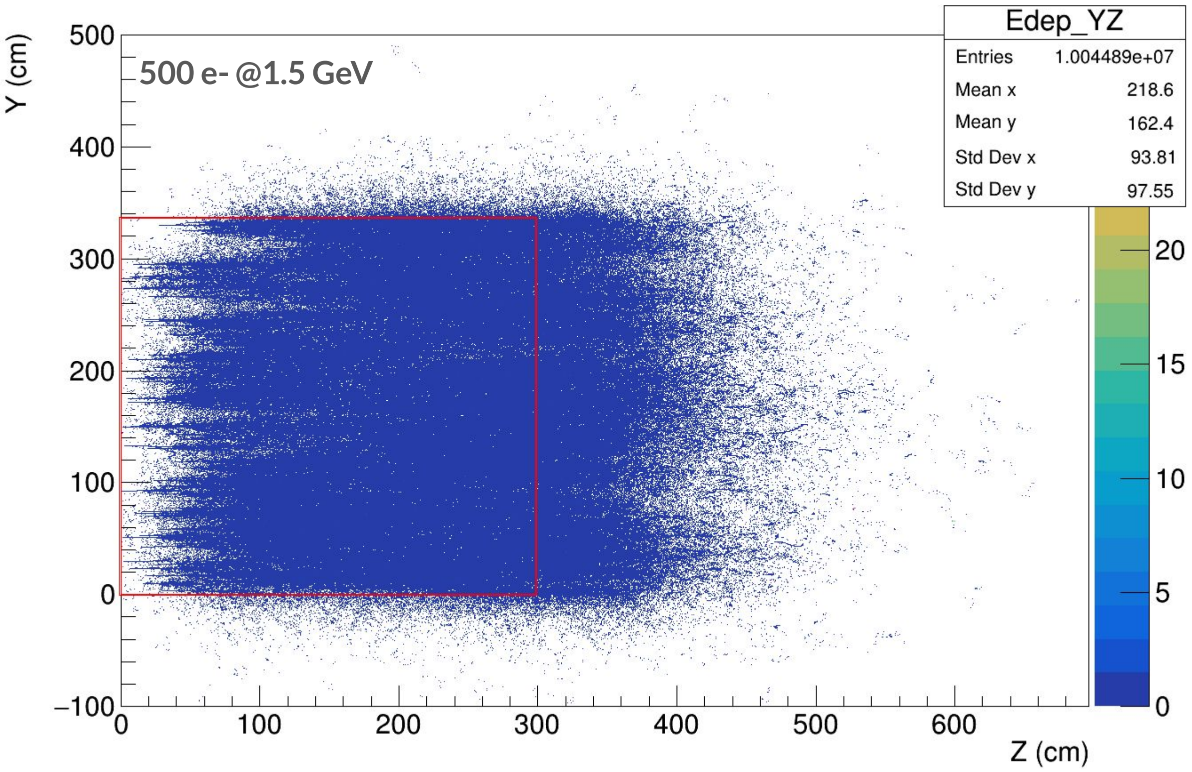


Electrons vertices uniformly distributed on YZ plane

Simulate electrons distributed uniform
Geometry of my simulation is 3x4 CRP

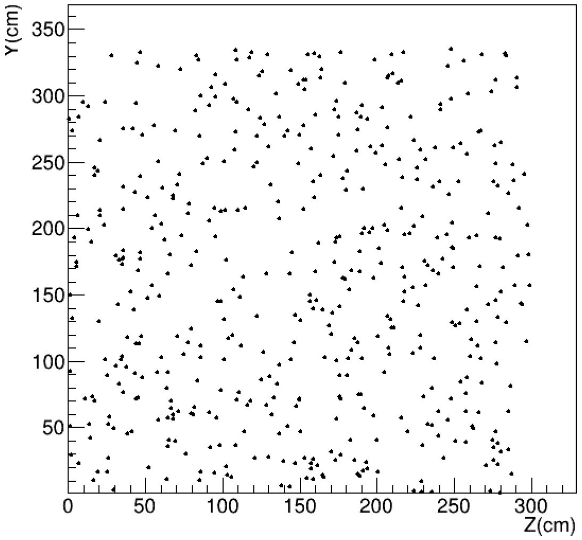


Electrons vertices uniformly distributed on YZ plane



500 electrons generated with vertices distributed uniformly in one of the CRP planes for 3 different energy values (0.5, 1.5,3.0 GeV)

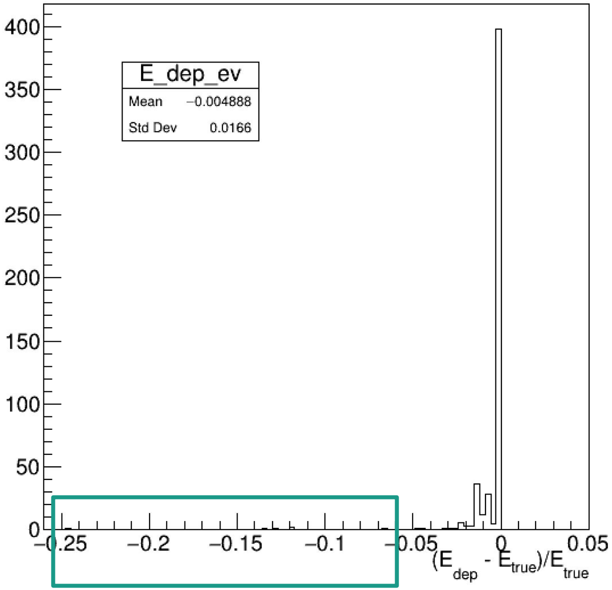
Vertices distribution in CRP plane

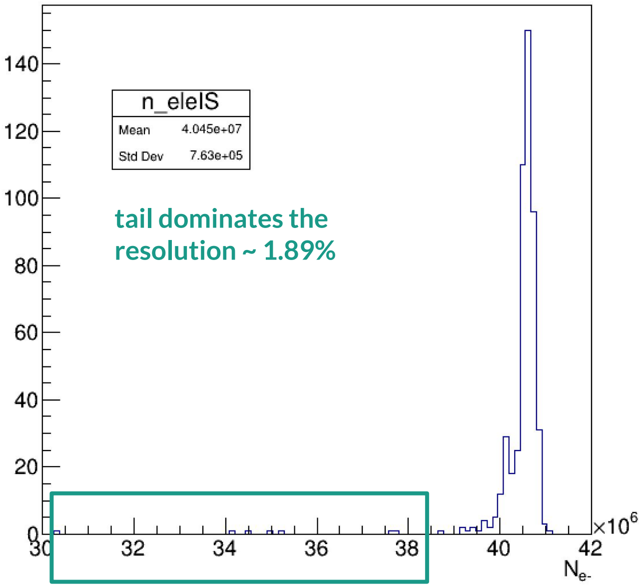


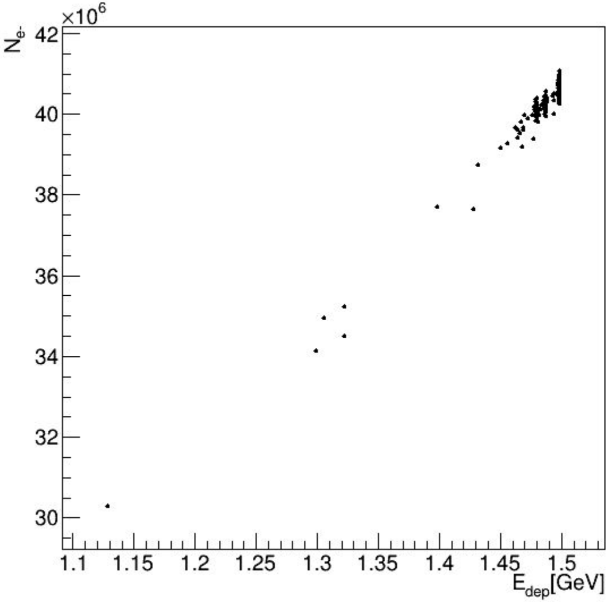
Photonuclear interactions of the ɣs in the shower

At the G4 level, differently from muons, sometimes the initial energy is not recovered → These events have a nuclear product in the G4 record

Photonuclear interactions of the ɣs → these are a violation that the primary statistics simply corresponds to (E/23.6 eV) R







Tried to apply a topology cut by removing these events to see how the resolution is affected

We have been checking with the help of Paola Sala that the amount of photonuclear effects and simulation results are also reproduced by FLUKA

CRP impact on IonAndScint (I&S) information (after recombination)

Res [%]	All topologies			$N_{nuclei} = 0$		
E_0[GeV]	no gaps	with gaps	diff	no gaps	with gaps	diff
0.5	2.93	3.26	**0.33**	0.60	1.64	**1.04**
1.5	1.89	2.21	**0.32**	0.36	1.28	**0.92**
3.0	1.10	1.54	**0.44**	0.26	1.26	**1.00**

% events	0.5 GeV	1.5 GeV	3.0 GeV
with neutrons	3.8%	9.2%	23.60%
with protons	0.2%	1.0%	1.40%
with nuclei	7.8%	18.8%	38.40%

Effect of CRP gaps after having removed the events with photonuclear interactions
→ **Both before and after recombination the impact of the CRP gaps is still at the level of ~1%**

Note that the CRP gaps dimensions in the simulations does not correspond to the real ones: impact might be stronger than that

Fluctuations on recombination do not seem to play a major role on the resolution

Impact of recombination and signal digitization

Res [%]	All topologies			$N_{nuclei} = 0$		
E_0[GeV]	G4	I&S	Hit	G4	I&S	Hit
0.5	1.93	2.38	2.66	1.61	1.71	**1.97**
1.5	2.73	3.11	3.36	1.22	1.28	**1.40**
3.0	1.50	1.68	1.82	0.85	0.89	**1.00**

CRP gaps included

% events	0.5 GeV	1.5 GeV	3.0 GeV
with neutrons	4.4%	13.6%	23.20%
with protons	0.2%	1.4%	1.0%
with nuclei	7.2%	23.8%	37.40%

I&S takes into account fluctuations in the recombination due to local charge density

→ fluctuations on recombination do not seem to play a major role on the resolution

The same holds true for signal digitization whose impact is less than ~0.3% (this is a good news)
Hit is reconstructed with Hit::HitSumADC

→ The most important physical contribution to the resolution ~ 2% is given by the fluctuations due to photonuclear interactions which have a stronger weight when the primary statistic is lower at 0.5 GeV

Result is coherent with the Japanese paper on LAr ionization chamber and with the FLUKA simulations

Conclusions

We are trying to make a global assessment of the effects affecting EM calorimetry in a LArTPC related to the performance of the detector and not of the bias of the reconstruction (Pandora) which should be largely improved in order to match the performance of the detector

→ Understanding the various contributions and the intrinsic EM showers resolution in LArTPC beyond current performance of Pandora reconstruction;
→ The current detector performance is underestimated in the reconstruction. The improvement of Pandora is a big task which will require important efforts for the next years in the collaboration.

Next steps:

- Work in progress to finalize the assessment of the gaps in collaboration with Anselmo, studying with gap dimensions corresponding to the real ones
- Proceed with the second reconstruction step
- Show that a simple hits collection algorithm can achieve the natural detector performance for ν_eCCQE fully contained events independently on the shower reconstruction of Pandora
- Show also where Pandora loses parts of the shower
- Finalize the assessment of leakage fluctuations