Electromagnetic showers resolution: update

Ginevra De Lauretis - FD sim/reco - 02.12.24

Introduction

Previous presentation in September at FD sim/reco: https://indico.fnal.gov/event/66234/
Interest in understanding the effects that affects EM shower resolution for the neutrino energy measurement.
To do that the idea is to simulate electrons interactions in a large enough volume with no leakage and then introduce systematically the different effects impacting on the resolution

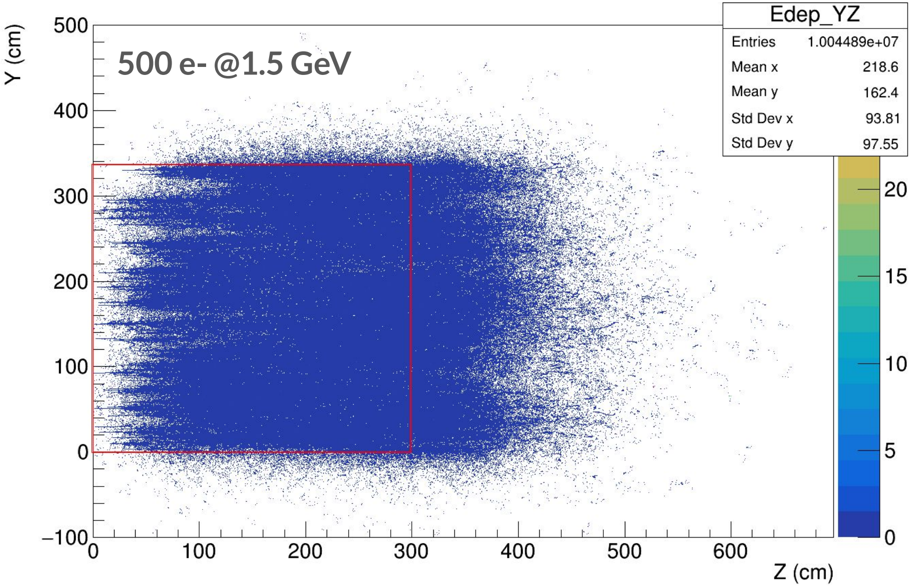
1. 500 electrons generated for three different energy values (0.5, 1.5, 3.0 GeV) with vertices distributed uniformly in one of the CRP planes.

2. Volume large enough → no leakage

3. Add one by one the detector resolution effects:
   a. Recombination
   b. CRP gaps
   c. Signal digitization

4. Cut on topology to check the effect of photonuclear interactions in the shower development

5. Fiducial border effects



Recap on the simulation

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 (future simulations will have to be corrected since these dimensions 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

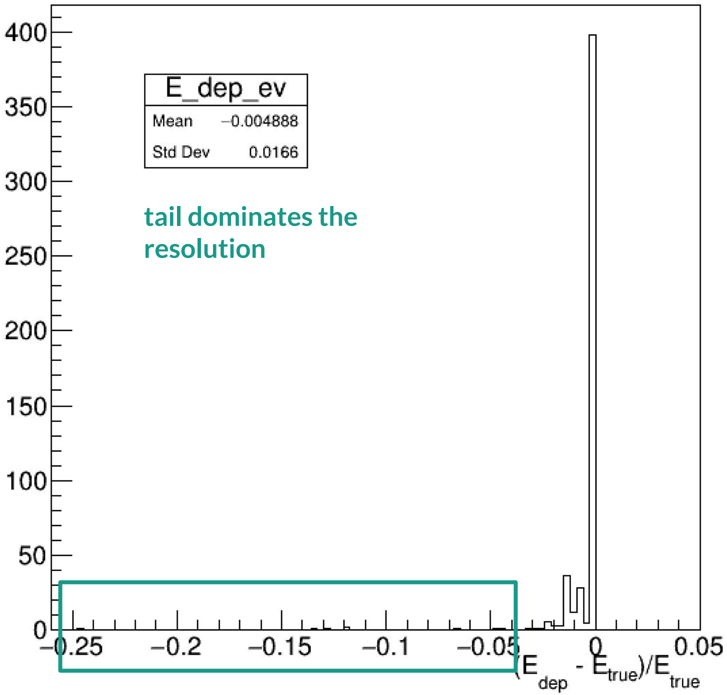
} **Number of electrons N_e** in the active volume and in the gaps after recombination

- ➔ recob::Hits_gaushit_Reco1
- ➔ recob::Hits_gaushit_Reco2

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

Photonuclear interactions of the ɣs in the shower

At the G4 level, differently than muons, we noticed that sometimes the initial energy was not recovered
This is due to photonuclear interactions of some of the ɣs in the shower
The effect has a strong impact also on the next steps of the simulation



These events have a nuclear product in the G4 record, related to photonuclear interactions of the ɣs

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 of G4 are also reproduced by FLUKA

% 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%

CRP gaps impact after recombination (IonAndScint)

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**

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Effect of CRP gaps after having removed the events with photonuclear interactions

→ **The impact of the CRP gaps on the resolutions is at the level of ~1% for all the energies**

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

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

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3. 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

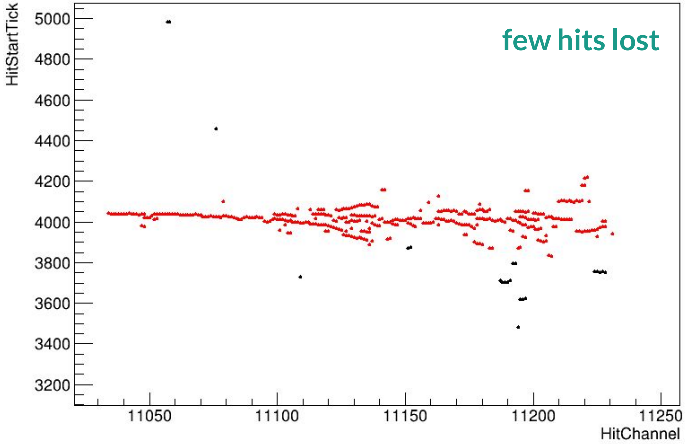
Result is coherent with the Japanese paper on LAr ionization chamber and with the FLUKA simulations

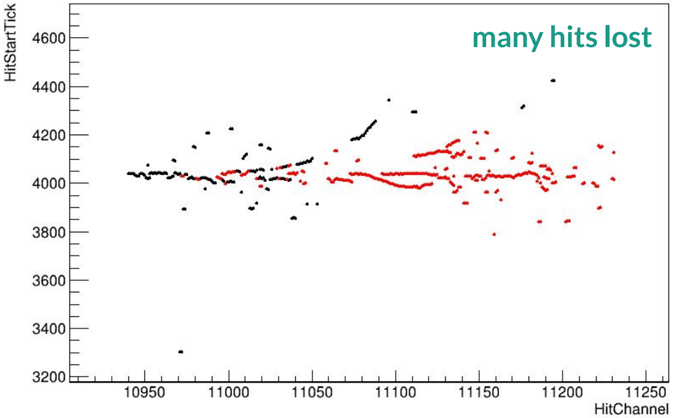
Reco2 selection of hits

With the second reconstruction step (Pandora) I compared the number and the energy of the hits selected by the reconstruction with the total number and the energy of hits present at a reco1 level

Res [%]	All topologies		$N_{nuclei} = 0$	
E_0[GeV]	Hit reco1	Hit reco2	Hit reco1	Hit reco2
0.5	2.60	12.83	1.97	12.48
1.5	2.93	4.54	1.40	2.38
3.0	1.69	2.73	1.00	1.48

The resolution becomes much worst especially at low energy due to the fact that an important fraction of the hits (hits in black in the event displays) are often not associated with the reconstructed shower



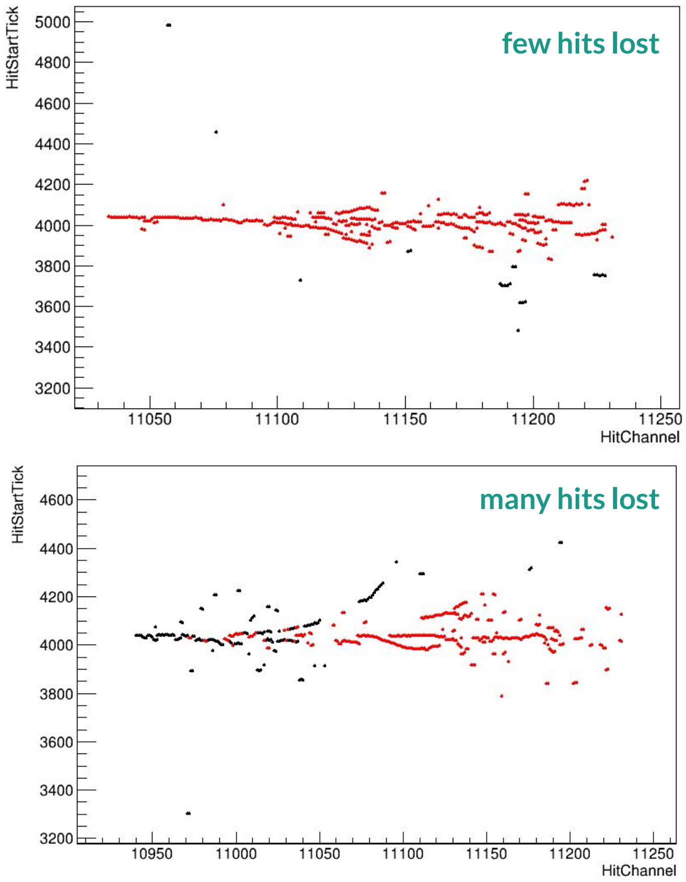


Reco2 selection of hits

The table below shows the fractions in terms of numbers and total energy of the hits selected by the reco2 normalized to the total number and the energy of hits present at a reco1 level

	Fraction [%]	
E_0[GeV]	Hits	Hit energy
0.5	90.7	93.7
1.5	93.7	97.3
3.0	93.2	97.7

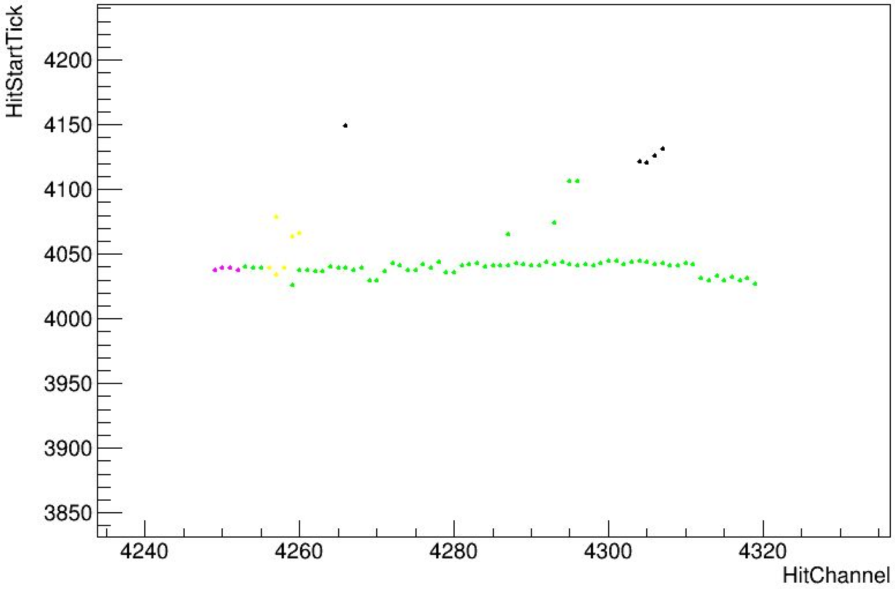
Even if these average fractions may look high the missing about 10% of the hits on average and the related fluctuations event by event have a strong impact on the resolution



Reco2 selection of hits

We can highlight three main problems:

- ➔ **The track of the electron before showering is not always associated with the shower itself**
- ➔ Peripheral hits in radius are sometimes lost
- ➔ Showers are sometimes divided in more pieces due to the presence of gaps inside them



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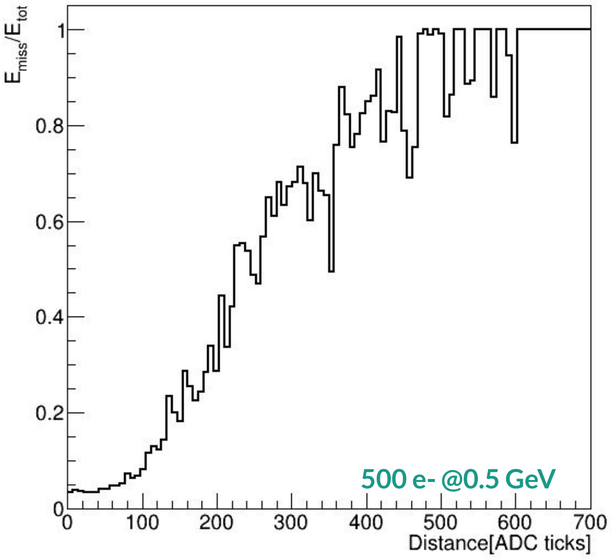

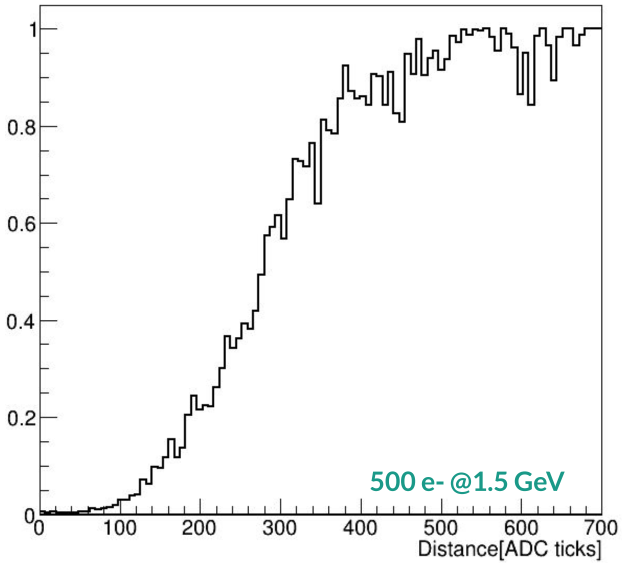

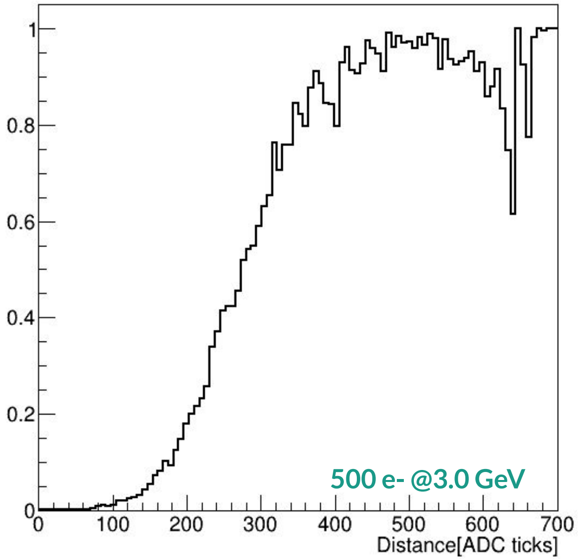

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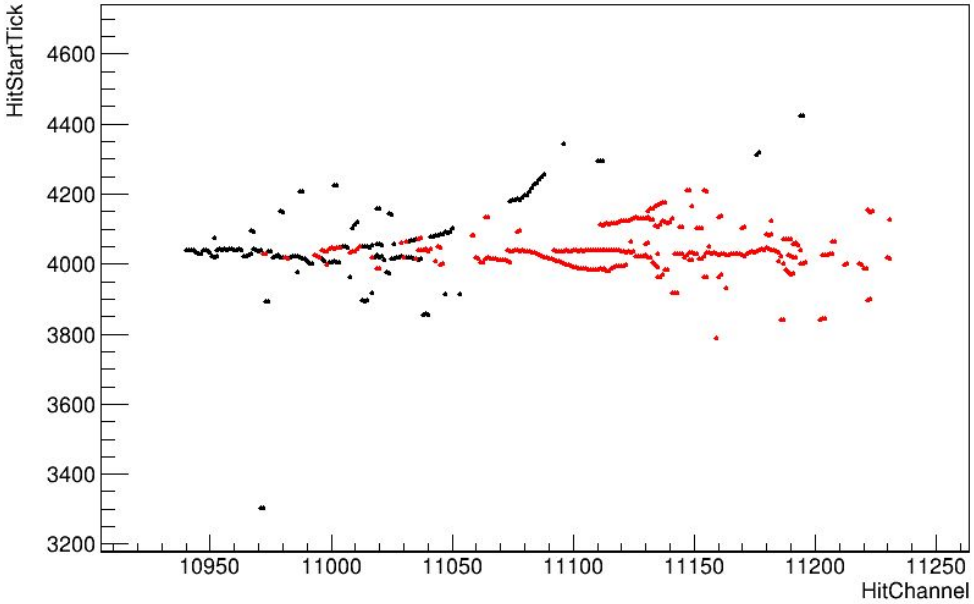

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These three issues might be due to the fact that in LAr there is:

- Finer granularity;
- Higher radiation length (X0=14 cm)

with respect to ILC calorimeters for which the algorithm was developed

➔

- ➔ Less compact showers which might present gaps and larger radial extension
- ➔ Electron track before showering is visible in the calorimeter

Pandora Particle Flow Calorimetry

Historical development of Pandora Particle Flow Calorimetry for jets reconstruction in ILC detectors

→ from Particle Flow Calorimetry and the Pandora PFA Algorithm, Thomson, M.A, NIMA 611 (2009) https://arxiv.org/pdf/0907.3577

Base energy reconstruction as much as possible on the measurement of charged particles in the tracking devices:

- Calorimeter for separation of signals by charged and neutral particles
- Overlap between showers compromises correct assignment of calo hits → high granularity to separate them

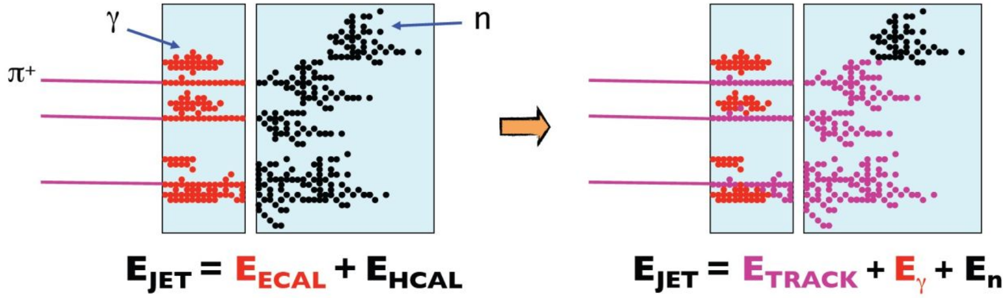
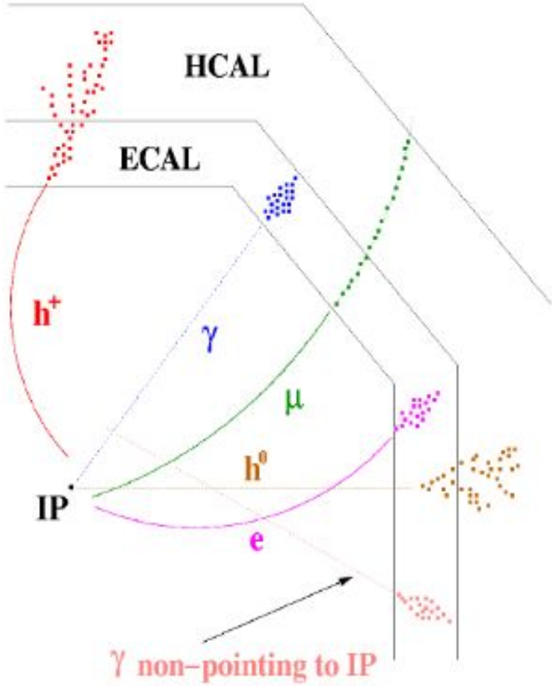


Figure 2.2 – The transition from traditional calorimetry to the fine granular Particle Flow calorimetry.



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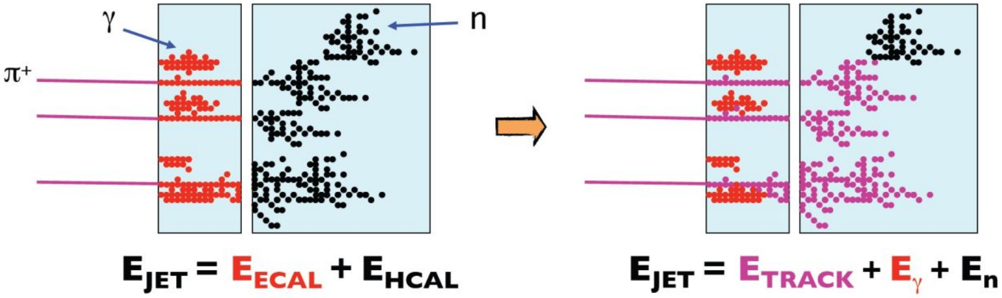

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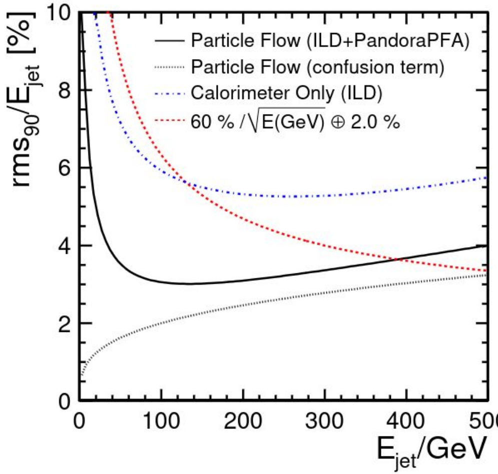

Figure 10: The empirical functional form of the jet energy resolution obtained from PFlow calorimetry (PandoraPFA and the ILD concept). The estimated contribution from the confusion term only is shown (dotted). The dot-dashed curve shows a parameterisation of the jet energy resolution obtained from the total calorimetric energy deposition in the ILD detector. In addition, the dashed curve, $60\,\%/\sqrt{E(\mathrm{GeV})} \oplus 2.0\,\%$, is shown to give an indication of the resolution achievable using a traditional calorimetric approach.

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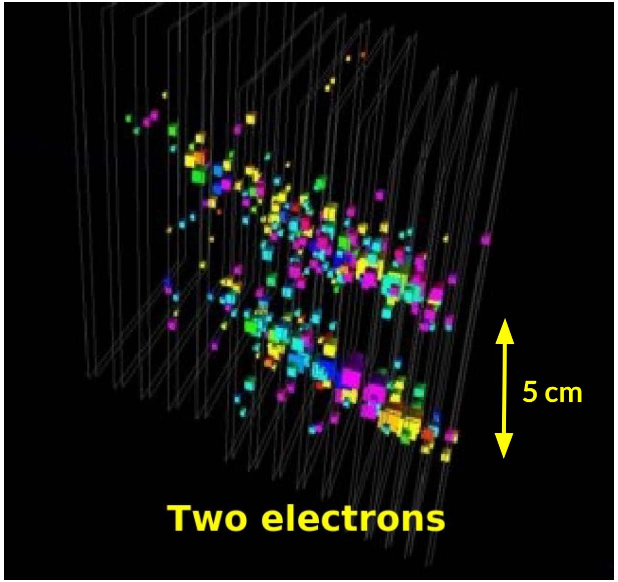


https://indico.in2p3.fr/event/4711/attachments/25403/31285/seminar_lpnhe.pdf

example: SiW electromagnetic calorimeter with 5x5 mm^2 cells

X0(W)=0.35cm → **Short X0, much more compact showers than in LAr with 14 cm**

Next steps and conclusions

This work was conducted in order to assess the impact of the different effects related to the physics of the interaction as well as the detector and the reconstruction on the energy resolution for EM showers.

- ➔ **Recombination** fluctuations impact of the level of a fraction of percent and do not play a major role in the energy resolution
- ➔ The physics of the electromagnetic showers has a much stronger impact than recombination due to the presence of fluctuations generated by **photonuclear interactions** of the ɣs of the shower with the LAr nuclei
- ➔ Sampling fluctuations due to **CRP gaps** have an effect at the level of ~1%
- ➔ Signal **digitization** also does not play a significant role, affecting the resolution at the level of about 0.1-0.2 %

- ➔ It looks then achievable at the hits level a resolution of less than 3% at 1 GeV (like shown by ICARUS and by the Japanese pure LAr calorimeter) for contained events (relevant for the second oscillation maximum)
- ➔ The reconstruction achieving 3% resolution is being demonstrated for QE events (most of the population at the second oscillation maximum) with a simple box hit collection algorithm

- ➔ Higher level reconstruction with Pandora has presently a strong impact in degrading resolution especially at lower electron energies. This may be improved by a further tuning of the algorithm to the larger X0 in LAr.

Backup slides

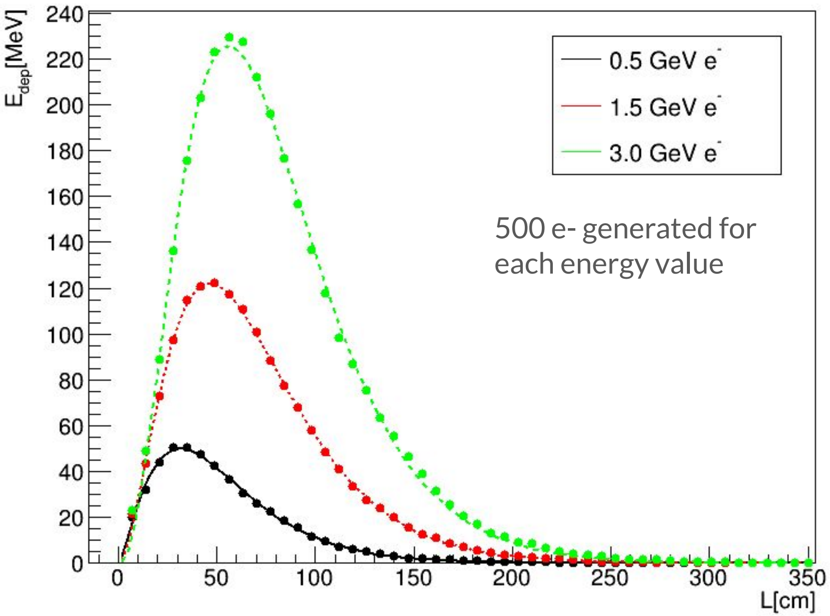
Longitudinal containment (result of the simulations)

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

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

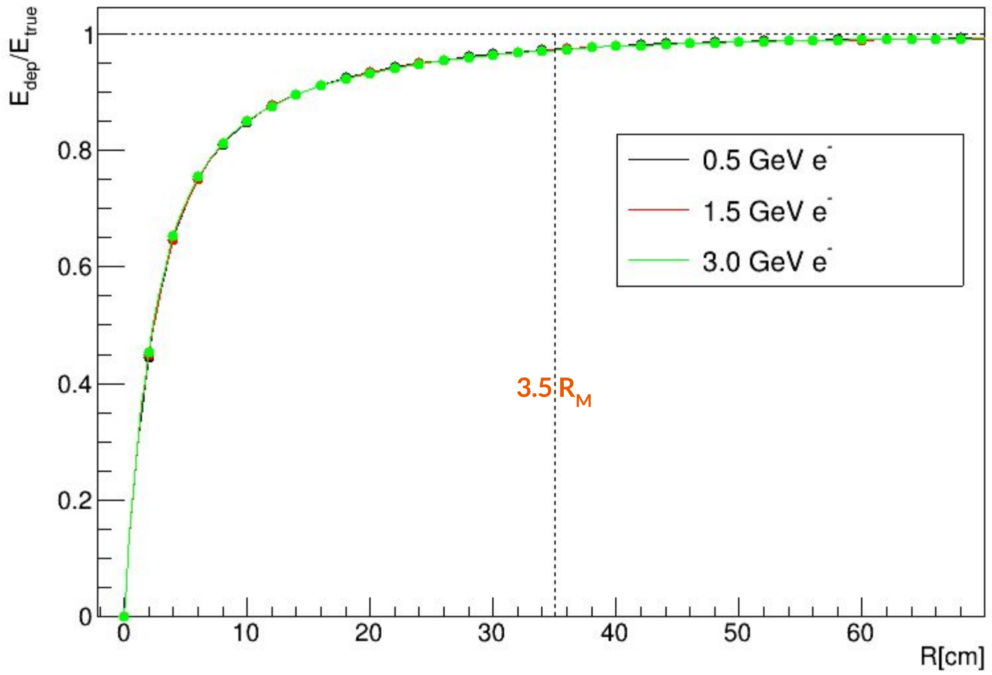


500 e- generated for each energy value

	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 %