HCAL performance study with and without tungsten absorber Using software compensation

ePIC Calo Nov 1, 2023

Bishnu Karki

In Collaboration with:

LBNL - B. Nachman, F. Torales-Acosta et al.

LLNL- A. Angerami, R. Soltz, P. Karande et al.

U.S. DEPARTMENT OF ENERGY | Office of Science

DOE grant award number DE-SC0022355

UC RIVERSIDE

Methodology for software compensation studies

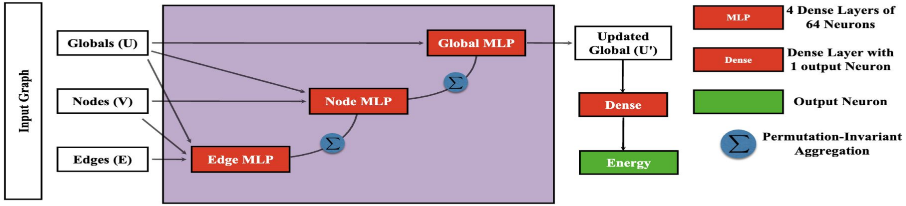
- What we mean by **"software compensation"** is described in the following:

  "for intrinsically non-compensating calorimeters, compensation can be achieved by so-called "off-line weighting" or "software compensation" techniques. These techniques assign different weights to electromagnetic and hadronic energy deposits on an event-by event basis. The differing spatial structure of the electromagnetic and hadronic components of particle showers can be used to characterise the origin of energy deposits…",

  CALICE Collaboration 2012 JINST 7 P09017

- Rather than do it "by hand" like what was done by CALICE (very time consuming), we implement software compensation using Graph-Neural Networks as described in https://arxiv.org/abs/2310.04442.

  Using GNNs is more efficient, optimal way to find the *"weights"* that minimize the resulting energy resolution but is the same principle than the traditional CALICE method (nothing mysterious).



DD4HEP simulation details

- Data used:
  - π^+ simulation with ECAL in front of HCAL
  - Polar angle 10 -30 deg
  - Absorber thickness = 16 mm
  - Scintillator thickness= 4 mm
  - Total Number of absorber layers = 64
  - Transverse segmentation = 5 cm x 5 cm

- Case study for two different configurations for Fe/W mixtures in HCAL
  - 0W + 64 Fe
  - 4W + 60 Fe
- Simulation validated by reproducing the CALICE result, calorimeter of similar design (see previous presentation)

- **ECAL :**
  - Tungsten-power/scintillating fiber technology ,17 cm deep, 22 X_0 (See Ref.)
  - In all studies ECAL is placed in front of HCAL
- Energy is digitized and minimum cuts on energy (E>0.5 MIP) and time (t<150 ns) hits are applied. A “hit” in HCAL is a segment (HCAL has 8 segments).

- **Caveat:** Not currently using the exact, current ePIC model for ECAL or HCAL. We intend to repeat study with current ePIC forward geometry and digitization models. What we present today is a proof of concept, which we will seek to refine. In conversation with Friederike, we planned to redo the study with an official ePIC tag, and share the trained modes to ePIC for reproducibility. We expect such follow up study to not change much.

Goal:

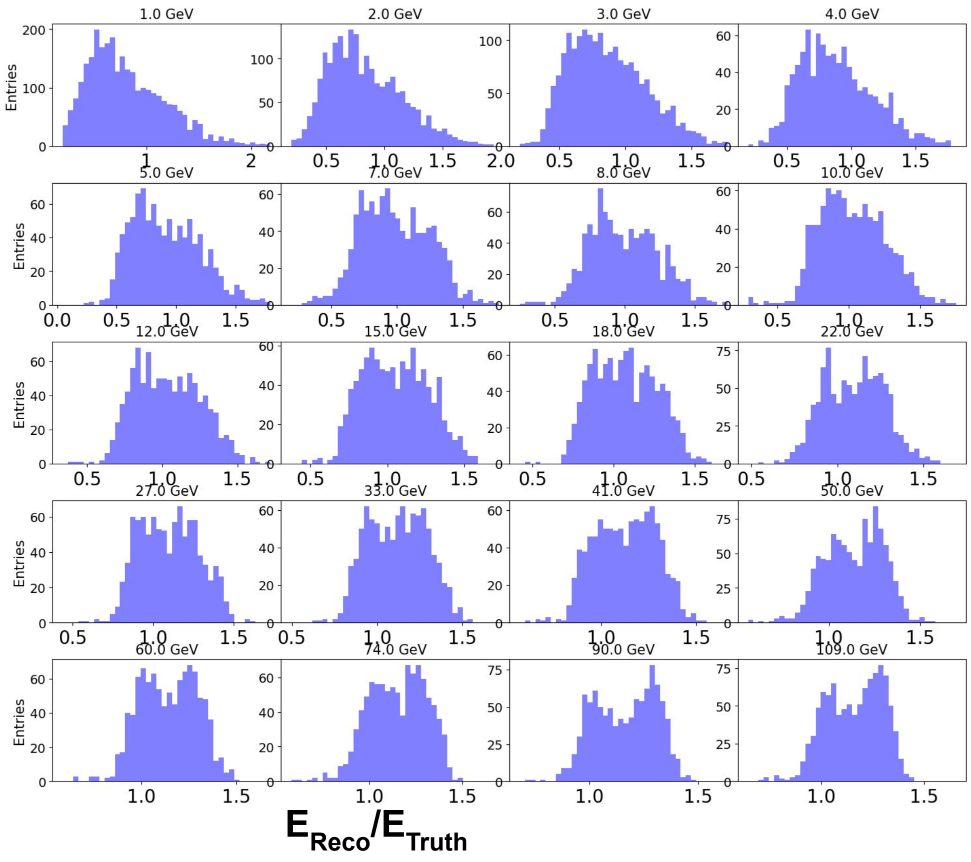
- Compare two HCAL configurations: one has 4 W layers in front (default) and the other has no W layers (and instead more it has more Fe layers)

- The question we want to pursue is: how does the performance compare <u>after</u> software compensation?

- We seek to address the comment from recent final-design review: ***"Implement software compensation as soon as possible and re-assess the benefits of the tungsten section."***

Baseline energy reconstruction

Absorber 0W + 64 Fe



Baseline energy reconstruction

$$E_{Reco} = \left[\frac{\sum E_i}{SF}\right]_{HCal} + \left[\frac{\sum E_i}{SF}\right]_{ECal}$$

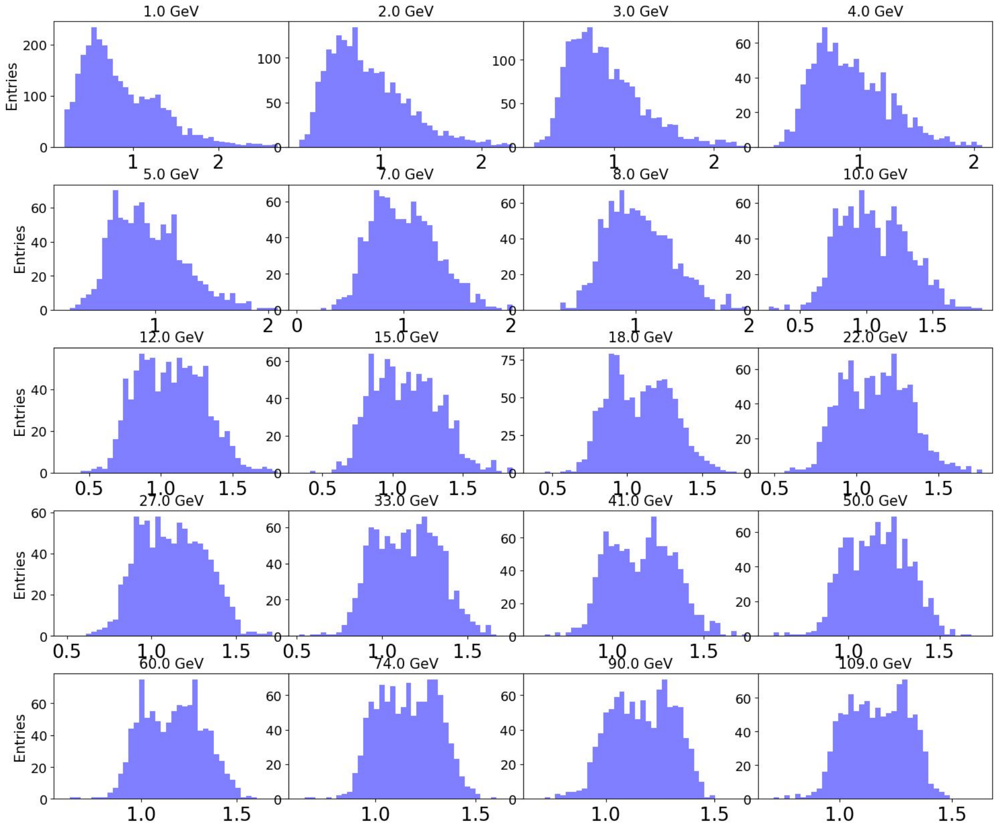
$$\text{Sampling Fraction} = \left(\frac{\sum \text{Cell Energy}}{E_{Truth}}\right)_{\text{at 40 GeV electron}}$$

HCal		ECal
Fe layers	2.4%	3%

Due to presence of ECal in front of HCal the simplest energy reconstruction (baseline) yields poor energy resolution

Baseline energy reconstruction

Absorber 4W + 60 Fe



E_{Reco}/E_{Truth}

Baseline energy reconstruction

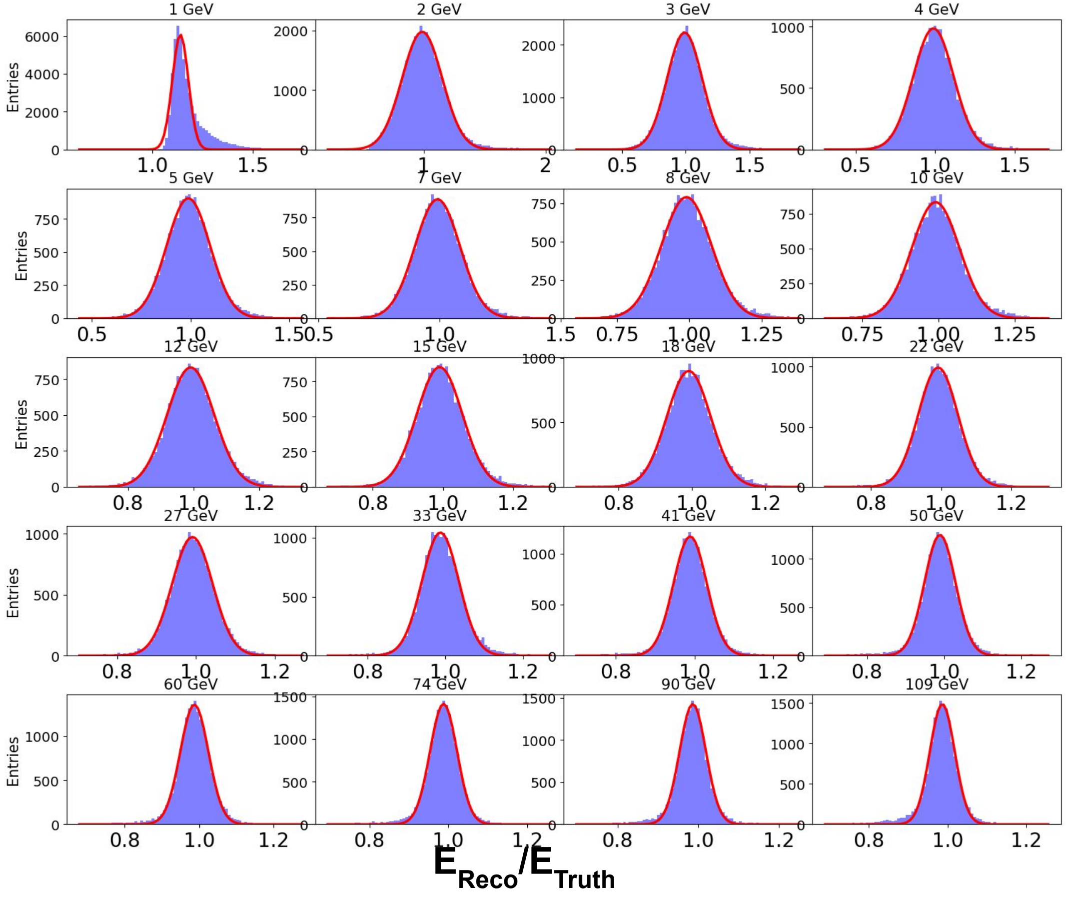
$$E_{Reco} = \left[\frac{\sum E_i^W}{SF_W} + \frac{\sum E_i^{Fe}}{SF_{Fe}}\right]_{HCal} + \left[\frac{\sum E_i}{SF}\right]_{ECal}$$

$$\text{Sampling Fraction} = \left(\frac{\sum \text{Cell Energy}}{E_{Truth}}\right)_{\text{at 40 GeV electron}}$$

HCal		ECal
W layers	0.9%	3%
Fe layers	2.4%	

Due to presence of ECal in front of HCal the simplest energy reconstruction (baseline) yields poor energy resolution

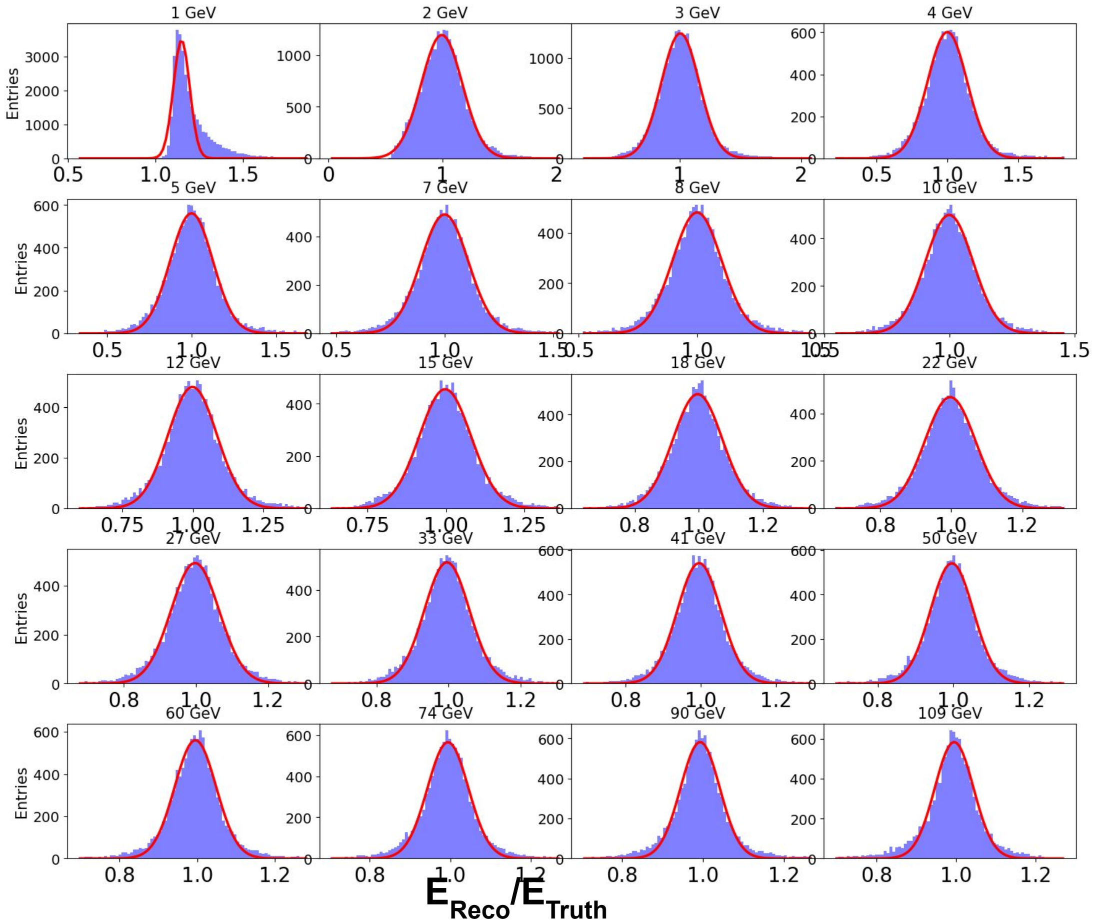
Energy prediction using Graphnet
Absorber 0W + 64 Fe



- Data features:
  - Calo config: Ecal + Hcal
  - Polar angle: 10 < $\boldsymbol{\theta}$ < 30 deg

- Model:
  - Graphnet
  - Output: Energy regression

Energy prediction using Graphnet
Absorber 4W + 60 Fe

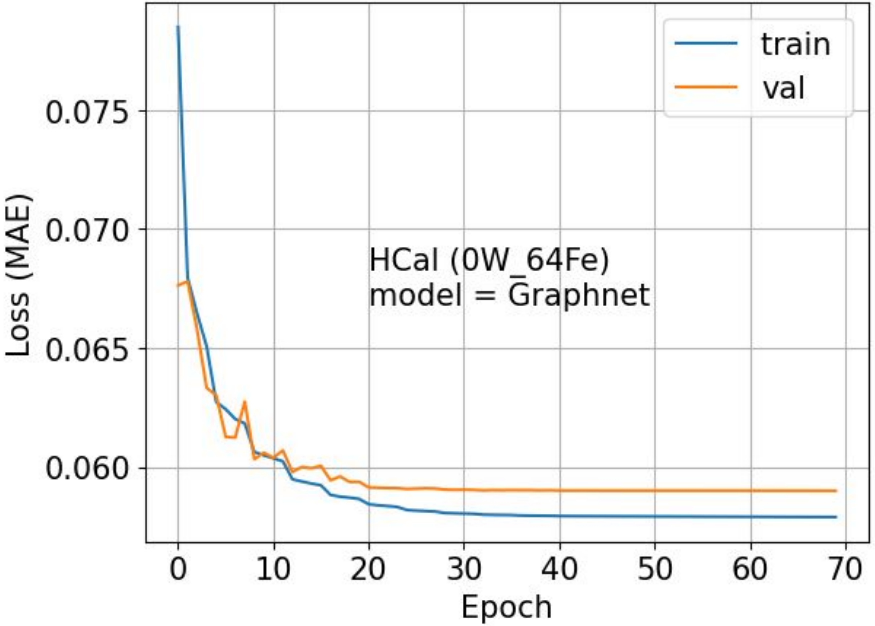


- Data features:
  - Calo config: Ecal + Hcal
  - Polar angle: 10 < $\boldsymbol{\theta}$ < 30 deg

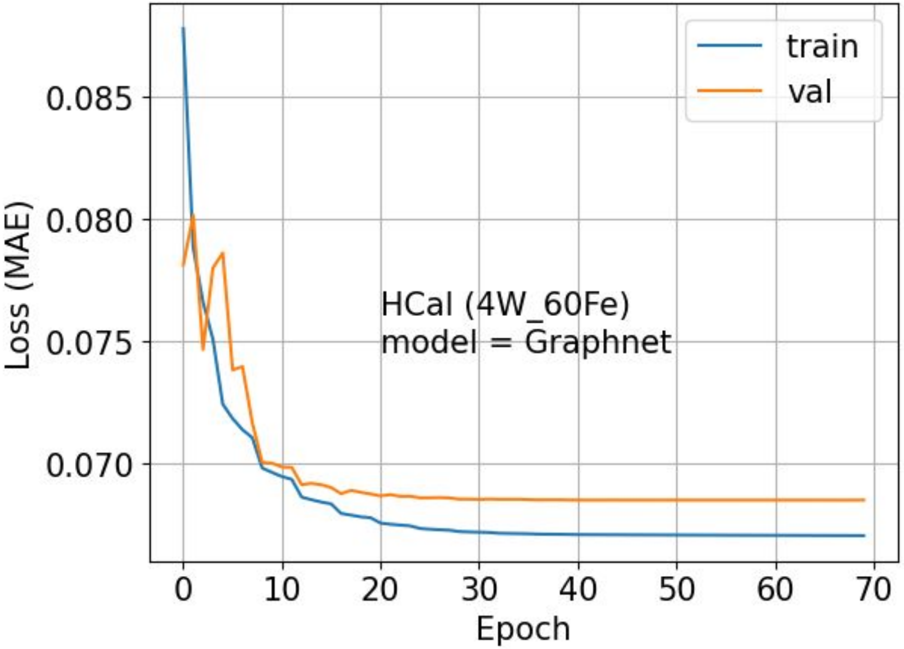
- Model:
  - Graphnet
  - Output: Energy regression

Comparison of loss for different absorber combination using Graphnet model

ECAL + (0W + 64 Fe) HCAL



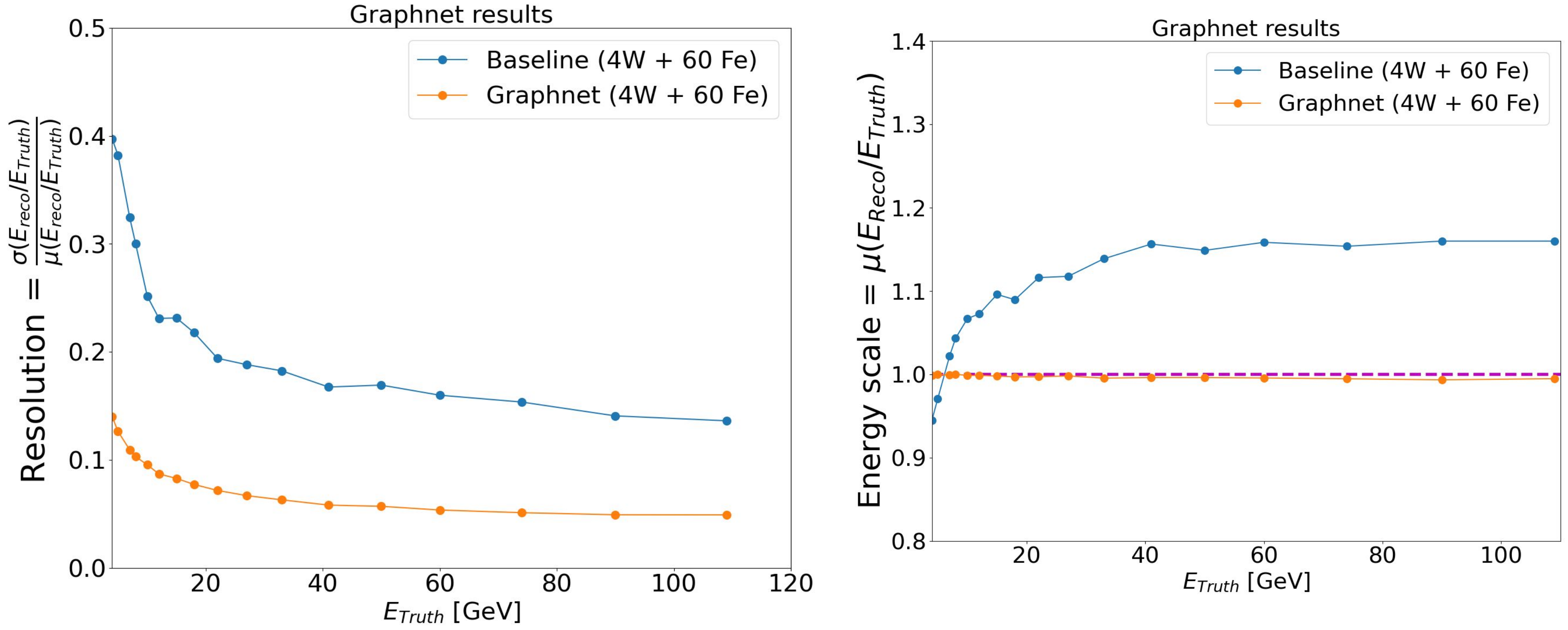
ECAL + (4W + 60 Fe) HCAL



Slightly worse loss for the model with W (reflected in resolution)

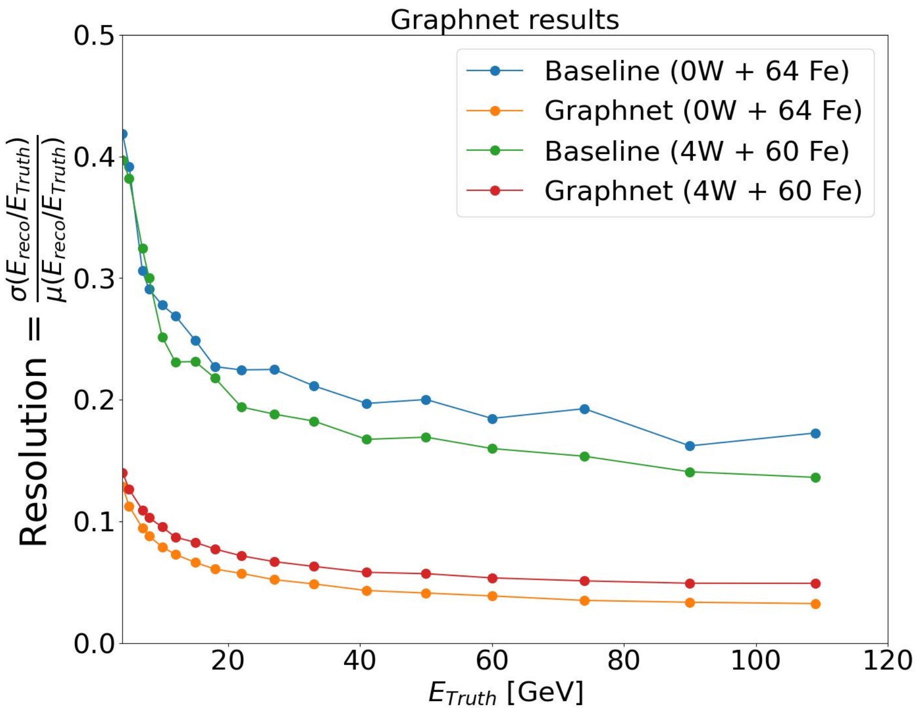
Software compensation using ML based model (Graphnet)

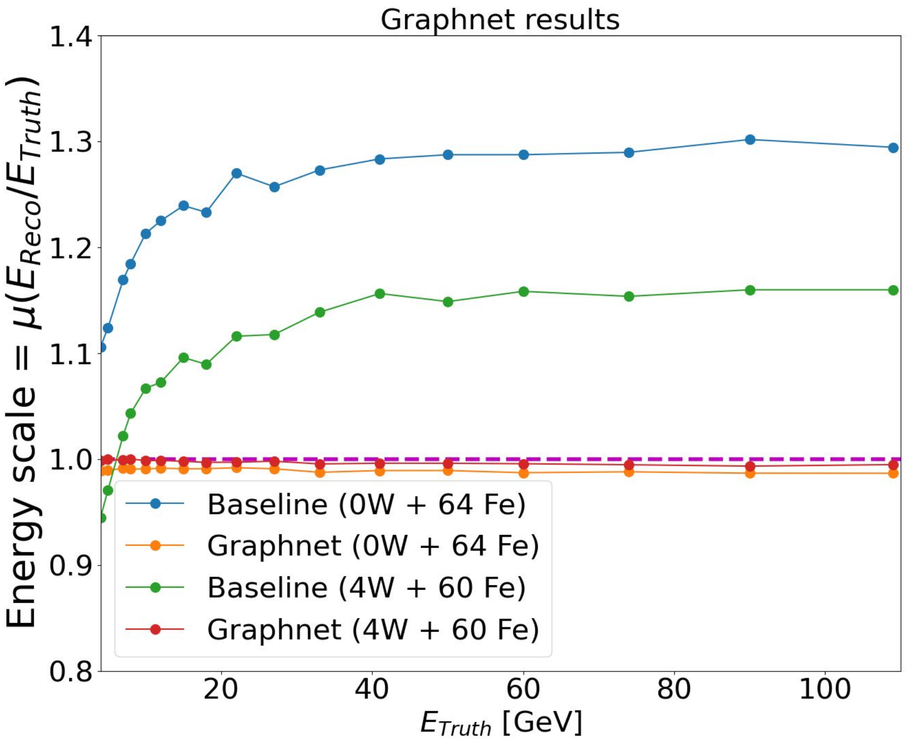
ECAL + (4W + 64 Fe) HCAL



Software compensation fixes scale (i.e. it is unity for both hadrons and electrons)
The resulting resolution is improved

Performance comparison between 0W and 4W results





Energy resolution with “0W_64Fe” yields better resolution than “4W_60Fe”(left plot) and basically the same level of “compensation” (right plot)

Preliminary conclusions

After comparing two configurations:
a) ECAL + HCAL (4W + 60Fe), total=7.7 λ
b) ECAL + HCAL (0W + 64Fe), total=7.5λ

We conclude that while option a) has better performance with a simple “strawman” reconstruction (better resolution and scale closer to unity), the situation is different after using software compensation. After software compensation, both a) and b) have scale at unity (i.e. compensated response). On the other hand option b) yields better resolution.

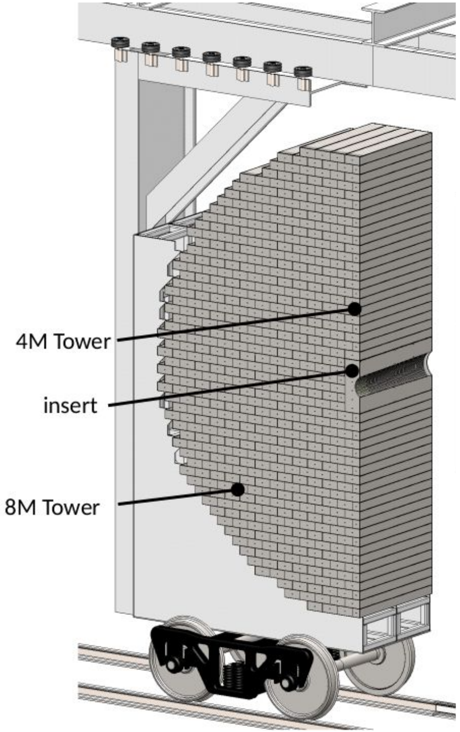
Our preliminary conclusion is that the W section has no beneficial impact for HCAL for the energy range studied.

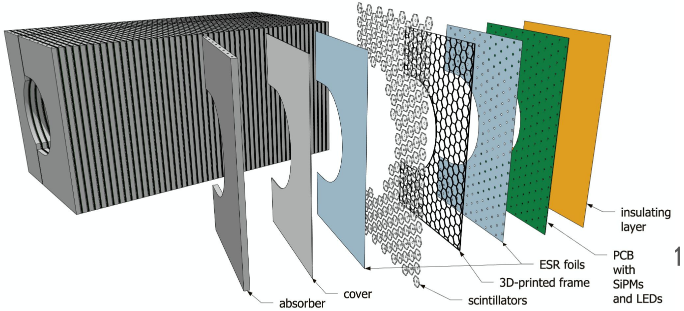
Case study for Insert

- Insert has 64 Z segments, each readout independently.
- Absorber thickness 16 mm and scintillator thickness= 3 mm
- Pions generated between 3.20 < η* < 3.90

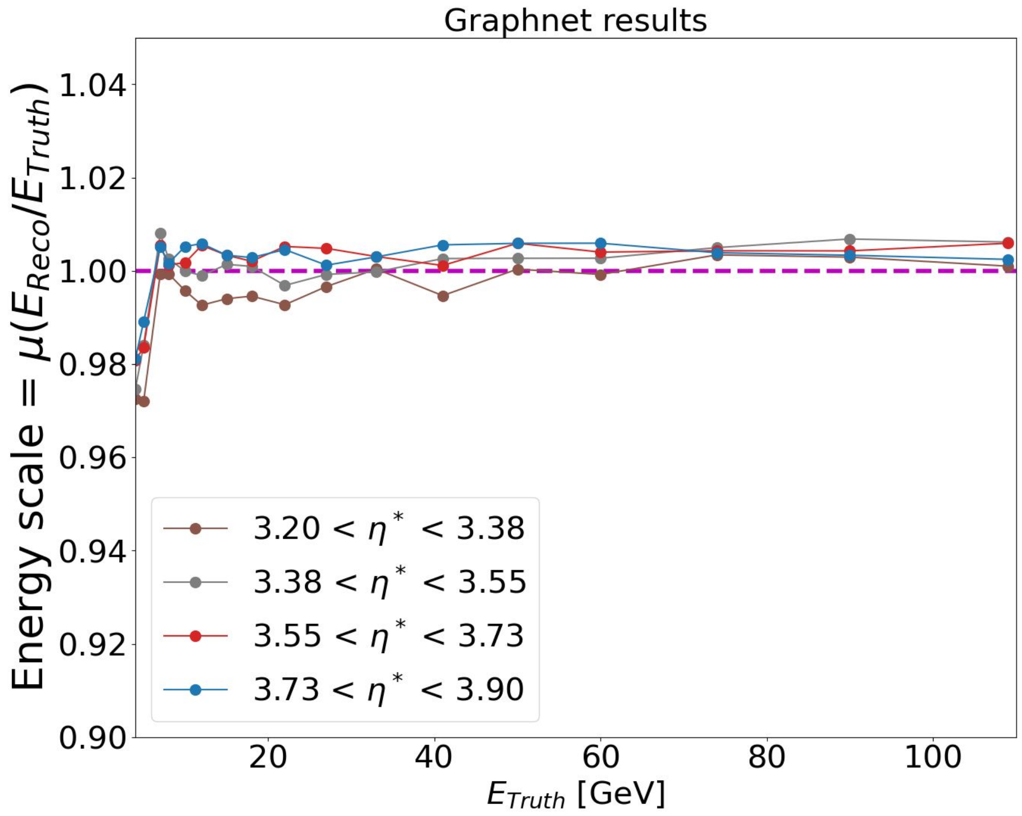
Question: what are the benefits of the W section (10 W)?

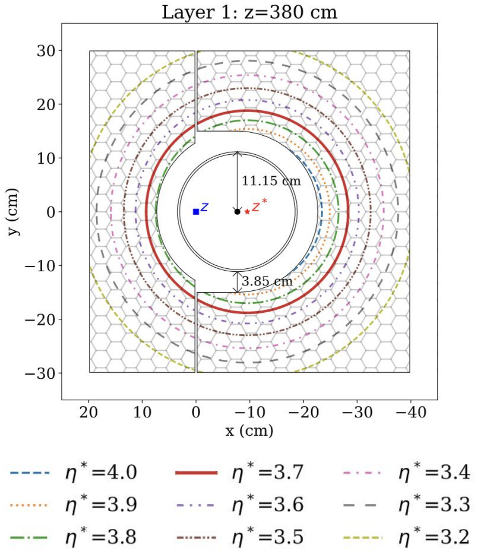
Note that the situation might be different here because we are dealing with possible leakages into the beampipe. Original motivation of W sections was to make showers as narrow as possible, and compensate the detector via hardware

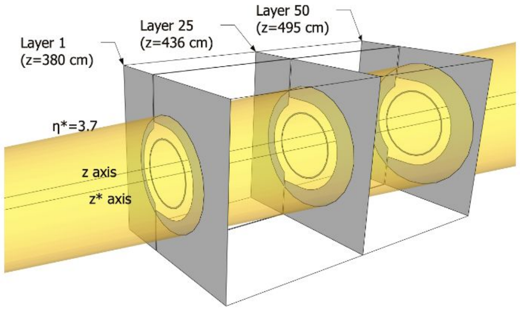




Energy scale as function of η for ECAL + Insert (0W + 64Fe) case

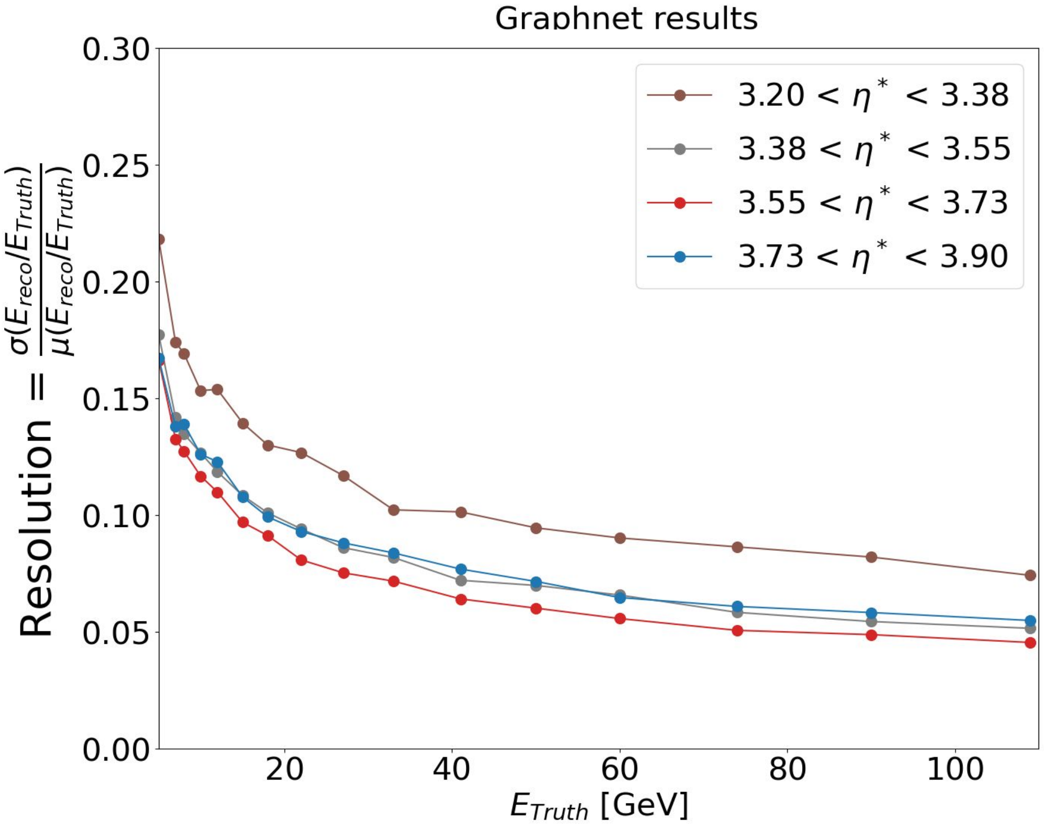


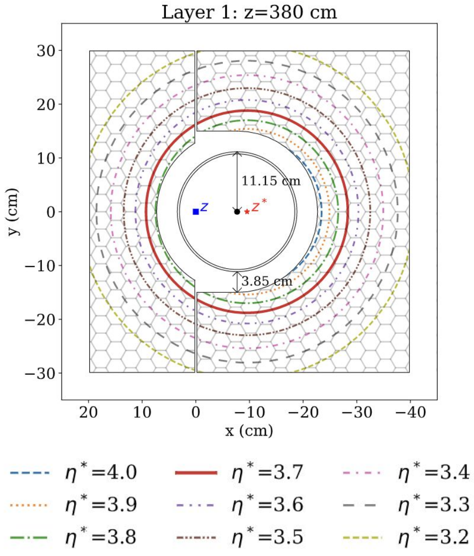


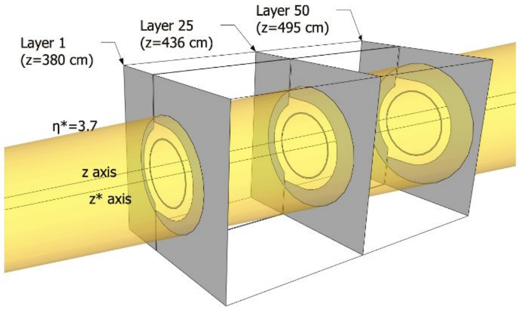


Graphnet yields compensated response across all rapidity range of interest.

Energy resolution as function of η for ECAL + Insert (0W + 64Fe) case







Some dependence on pseudorapidity is naturally expected as we get closer to edges

Conclusion

- We simulated forward ePIC forward calorimeters (ECal + HCal) using DD4HEP. Implemented AI/ML based software compensation technique on HCal
  - Fixes the energy scale, same energy response for electron and hadron
  - Improves the energy resolution

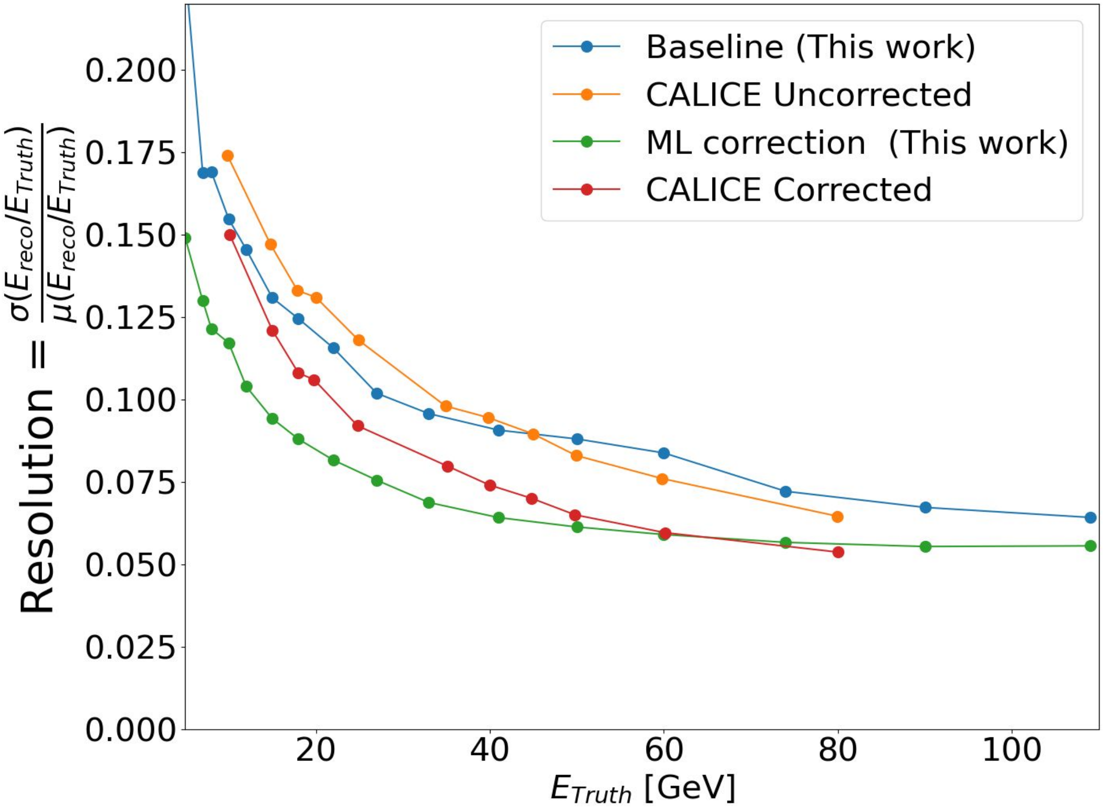
- Case study for two different combinations of Fe/W mixture was presented
  - Energy resolution for “0W_64Fe” is about 25% better relative to “4W_60Fe”

Our preliminary conclusion is that the W section has no beneficial impact for HCAL for the energy range studied.

- Insert study still ongoing but “pure Fe” already yields reasonable results.

Backup

Validation of simulation and ML based software compensation against CALICE test-beam data



[CALICE Result]

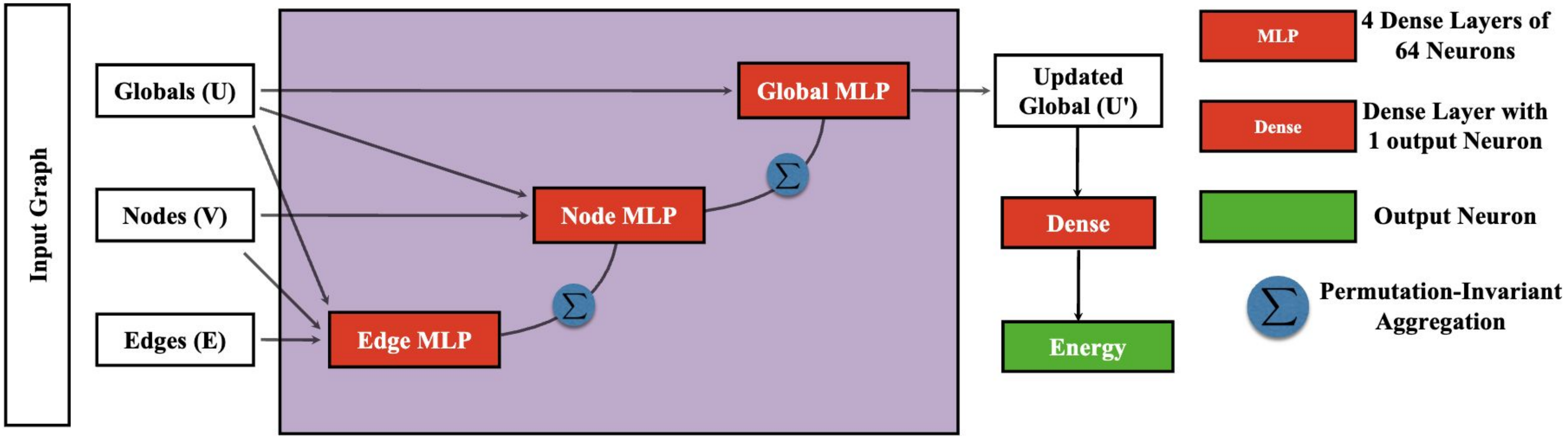
Implemented CALICE setup in our simulation

Agreement between uncorrected (simplest reconstruction)

ML based reconstruction shows better performance compared to traditional reconstruction

Energy regression

AI/ML based models (Graphnet model)



- In addition to node information cell hits (E, X, Y, Z) set of nearest neighbour of a cell are feeded as input
- Data set continuous in energy is used for training
- Separate data set discrete in energy is used for inference.

HCAL performance study with and without tungsten

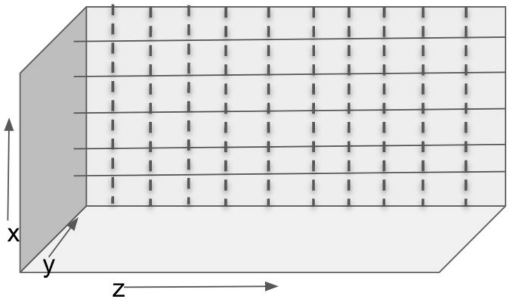
- Data used:
  - π^+ simulation with ECAL in front of HCAL (SiPM on tile technology similar to CALICE design)
  - Polar angle 10 -30 deg
  - Absorber thickness = 16 mm
  - Scintillator thickness= 4 mm
  - Total Number of absorber layers = 64
  - Transverse segmentation = 5 cm x 5 cm

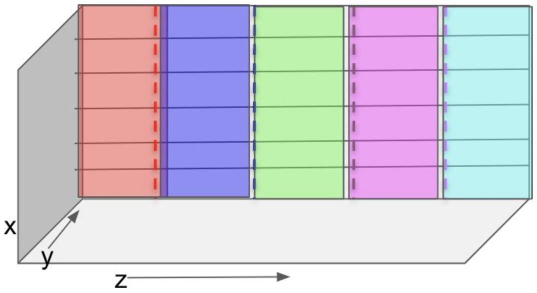
- Case study for two different configurations for Fe/W mixtures in HCAL
  - 0W + 64 Fe
  - 4W + 60 Fe
- Simulation validated by reproducing the CALICE result, calorimeter of similar design (see previous presentation)

- **ECAL :**
  - Tungsten-power/scintillating fiber technology ,17 cm deep, 22 X_0 (See Ref.)
  - In all studies ECAL is placed in front of HCAL

Varying longitudinal segmentation

Regrouping illustration with 5 z sections





E	Z	Y	X
[[0.028	3821.500	300.000	-1100.000]
[0.058	3844.900	300.000	-1100.000]
[0.092	3938.500	300.000	-1100.000]
[0.070	3961.900	300.000	-1100.000]
[0.109	3868.300	300.000	-1100.000]
[0.132	3891.700	300.000	-1100.000]
[0.116	3915.100	300.000	-1100.000]
[0.001	4429.900	300.000	-1100.000]
[0.001	4359.700	300.000	-1100.000]
[0.003	4055.500	300.000	-1100.000]
[0.016	4008.700	300.000	-1100.000]
[0.032	3985.300	300.000	-1100.000]
[0.003	4032.100	300.000	-1100.000]
[0.003	4125.700	300.000	-1100.000]
[0.001	4172.500	300.000	-1100.000]
[0.003	4078.900	300.000	-1100.000]
[0.001	4149.100	300.000	-1100.000]
[0.001	4640.500	300.000	-1100.000]
[0.001	4242.700	300.000	-1100.000]
[0.002	4102.300	300.000	-1100.000]
[0.001	4195.900	300.000	-1100.000]
[0.001	4336.300	300.000	-1100.000]
[0.001	4289.500	300.000	-1100.000]]

Re-grouping →

Esum	Z centers	Y	X
[[0.656	3933.820	300.000	-1100.000]
[0.016	4158.460	300.000	-1100.000]
[0.003	4383.100	300.000	-1100.000]
[0.001	4607.740	300.000	-1100.000]]

Regrouping in real world is just summing SiPMs outputs