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A new dimension in shower reconstruction

Update about software compensation with CNN

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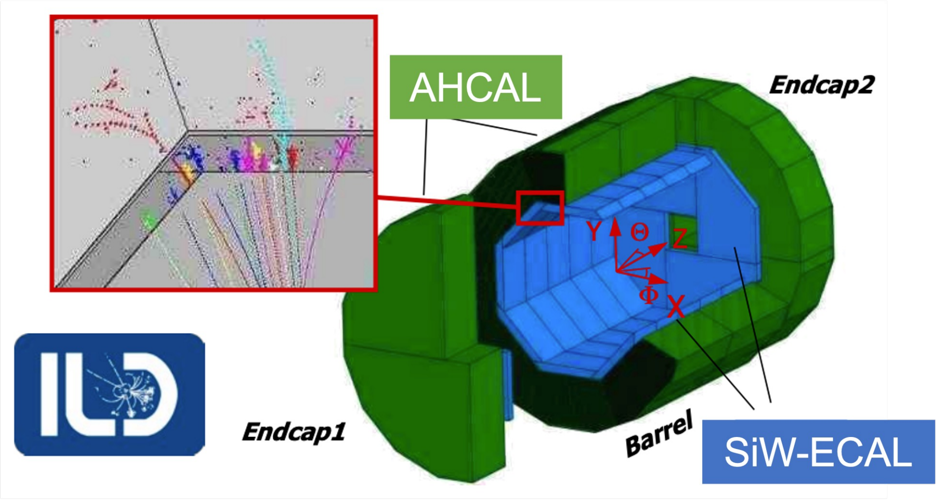
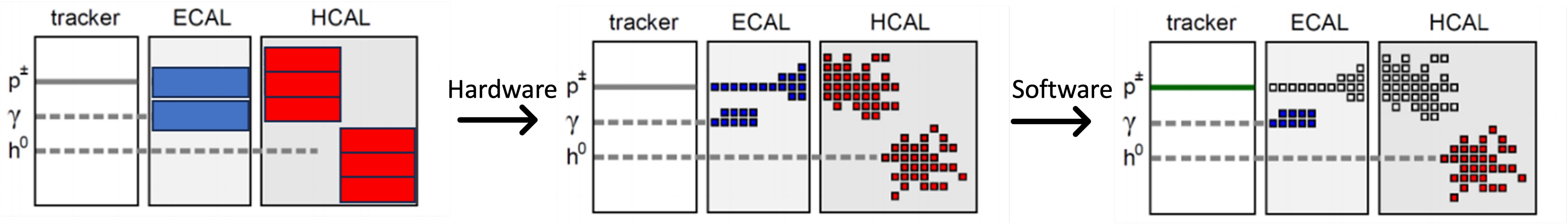
Part I: Previous study

Motivation

- What is PFA?
  - PFA: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
    - 60% charged particles → Tracker
    - 30% photons → ECAL
    - 10% neutral hadrons → HCAL
  - High granularity calorimeter (imaging):
    - SiW-ECAL + AHCAL in ILD system



- $E_{ECAL} + E_{HCAL}$ as part of PFA & intrinsic performance of calorimeter   Ref: arXiv:2107.10207v3
- In my case: software compensation in the ECAL-HCAL calorimeter system with dual-branch CNN

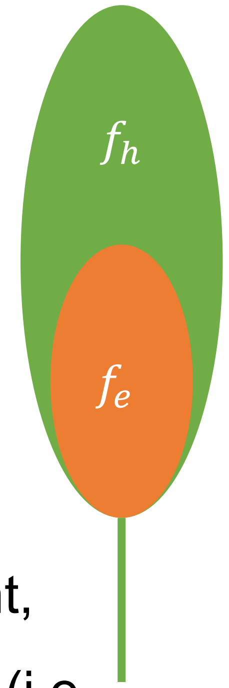


SC Algorithm

Software Compensation Algorithm:

- For a hadron (π^+) in a non-compensating calorimeter
  - Have electromagnetic components (e) and hadronic components (h), e/h >1
    - $\pi = f_{em} \cdot e + (1 - f_{em}) \cdot h$
    - $E_{rec} = \frac{e}{\pi} \cdot E_{dep} = \frac{e}{f_{em} \cdot e + (1 - f_{em}) \cdot h} \cdot E_{dep} = \frac{e/h}{1 + f_{em}(e/h - 1)} \cdot E_{dep}$
      - e/h: a constant value which depends on calorimeter
      - f_{em}: generated by π^0 in hadronic shower, fluctuates strongly from event to event, measured as the ratio of the energy deposited by electromagnetic components (i.e., photons and $e^{\pm}$ from $\pi^0 \rightarrow \gamma\gamma$ decays) to the total deposited energy.

$$f_{em} = \frac{\sum_i^{em} E_i}{\sum_i^{all} E_i} \ (em\ is\ \gamma, e^{\pm})$$



SC Algorithm

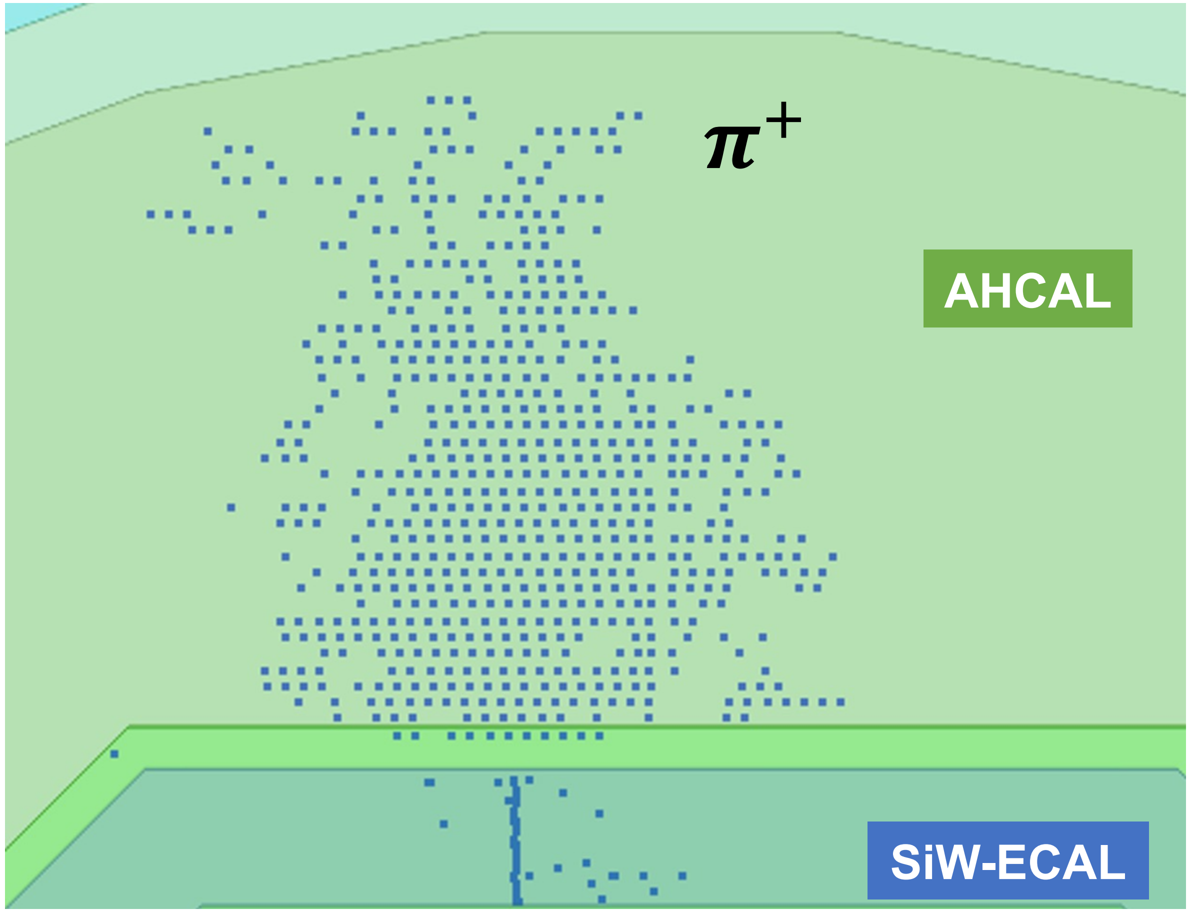
Software Compensation Algorithm :

- In my case, a hadron in a system (SiW-ECAL + AHCAL):

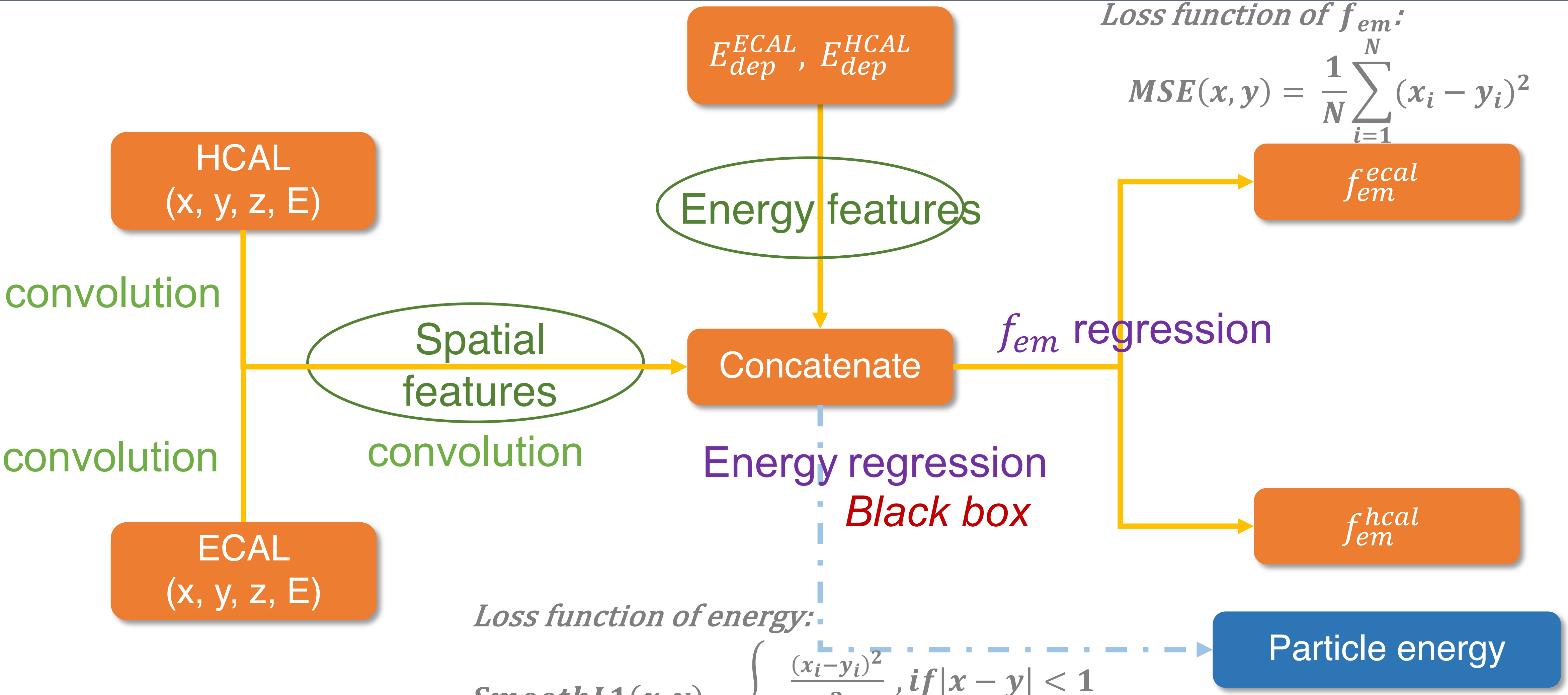
- $$E_{rec} = \frac{\left(\frac{e}{h}\right)^{ECAL}}{1 + f_{em}^{ECAL}\cdot\left(\left(\frac{e}{h}\right)^{ECAL} - 1\right)} \cdot E_{dep}^{ECAL} + \frac{\left(\frac{e}{h}\right)^{HCAL}}{1 + f_{em}^{HCAL}\cdot\left(\left(\frac{e}{h}\right)^{HCAL} - 1\right)} \cdot E_{dep}^{HCAL}$$

- f_{em}^{ECAL}
- f_{em}^{HCAL}

- $\left(\frac{e}{h}\right)^{ECAL}$
- $\left(\frac{e}{h}\right)^{ECAL}$



Model



Loss function of f_{em}:

$$MSE(x,y) = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2$$

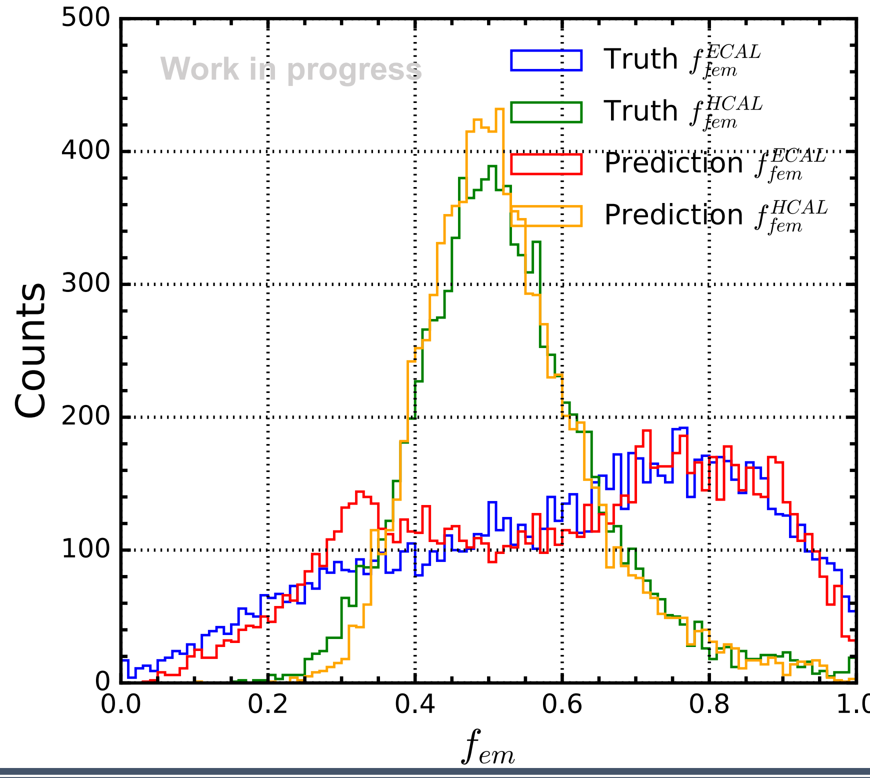
Loss function of energy:

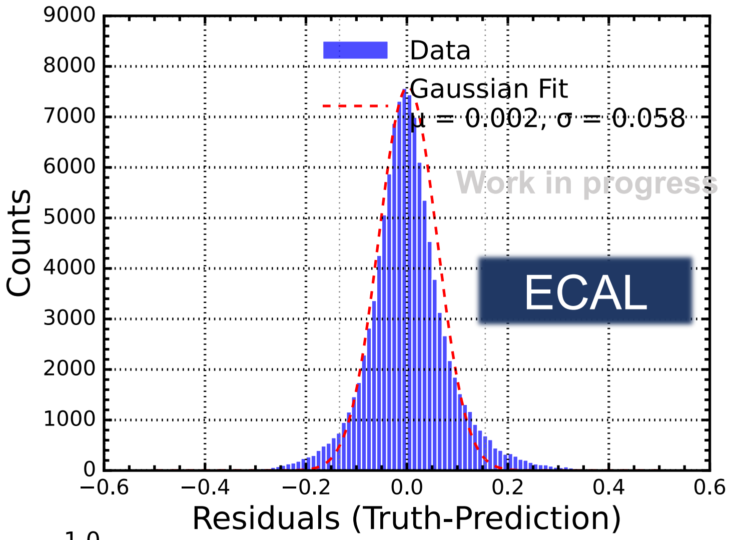
$$SmoothL1(x,y) = \begin{cases} \frac{(x_i-y_i)^2}{2}, if|x-y| < 1 \\ |x-y| - 0.5, otherwise \end{cases}$$

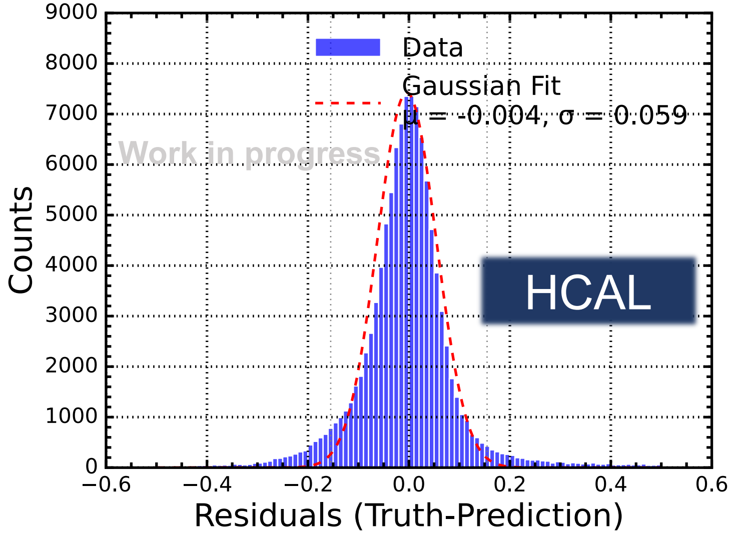
f_{em} regression results

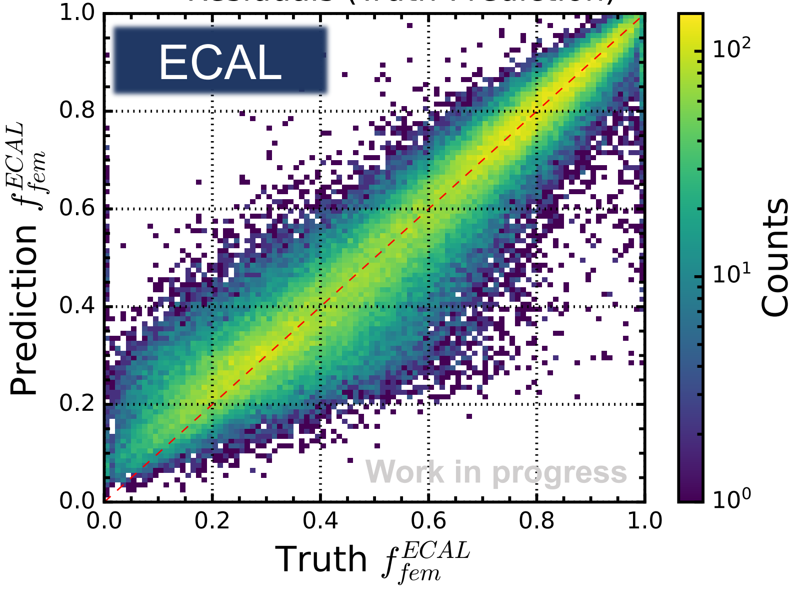
Results of f_{em}^{ECAL} and f_{em}^{HCAL} :

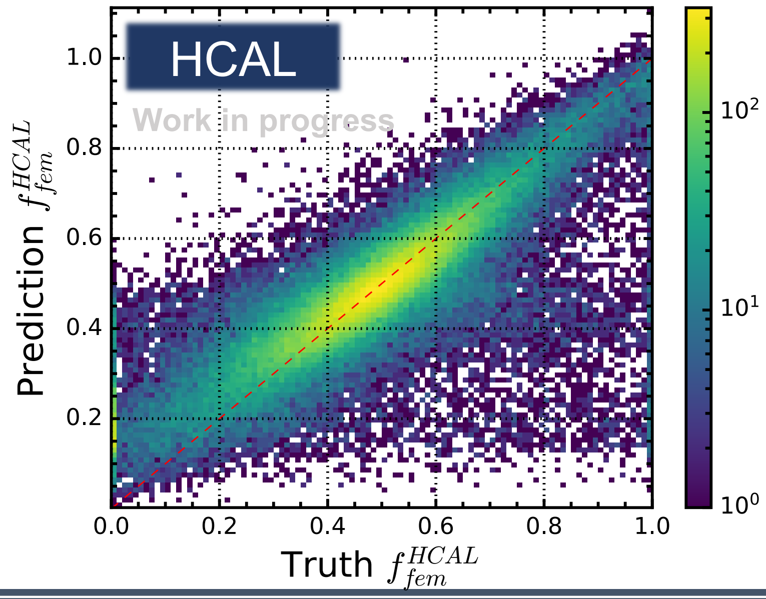
- Overall, the model shows good consistency between truth and prediction











Part II: e/h study

SC Algorithm

Software Compensation Algorithm :

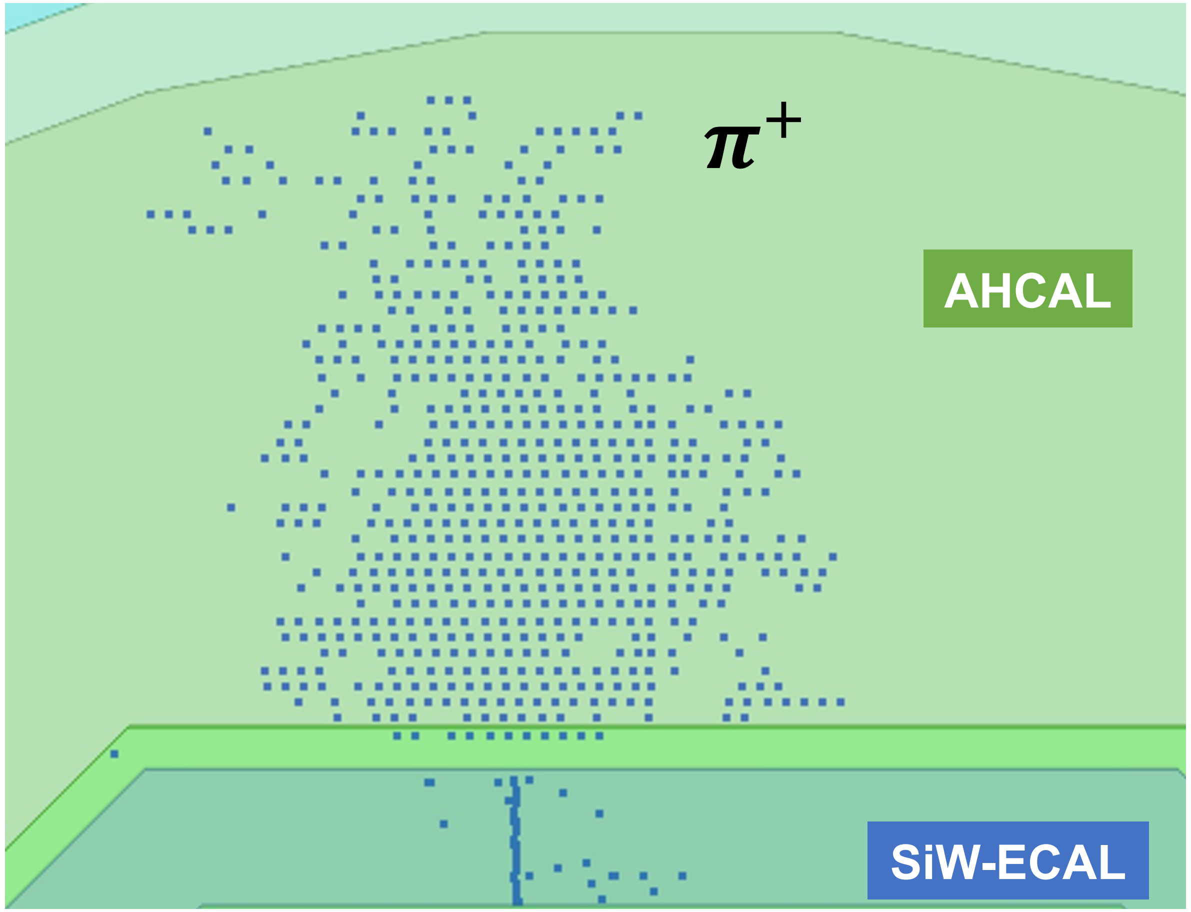
- In my case, a hadron in a system (SiW-ECAL + AHCAL):

  - $E_{rec} = \dfrac{\left(\frac{e}{h}\right)^{ECAL}}{1 + f_{em}^{ECAL} \cdot \left(\left(\frac{e}{h}\right)^{ECAL} - 1\right)} \cdot E_{dep}^{ECAL} +$

$$\frac{\left(\frac{e}{h}\right)^{HCAL}}{1 + f_{em}^{HCAL} \cdot \left(\left(\frac{e}{h}\right)^{HCAL} - 1\right)} \cdot E_{dep}^{HCAL}$$

- f_{em}^{ECAL}
- f_{em}^{HCAL}

- $\left(\frac{e}{h}\right)^{ECAL}$
- $\left(\frac{e}{h}\right)^{HCAL}$



How to get e/h?

For e/h:

- Definition: $\frac{e}{h} = \frac{Calorimeter\ response\ to\ an\ electromagnetic\ shower}{Calorimeter\ response\ to\ a\ hadronic\ shower} = \frac{\langle E_{vis}(e)\rangle}{\langle E_{vis}(\pi)\rangle}$
- Considering different W thicknesses in ECAL:
  - $\left(\frac{e}{h}\right)^{ECAL}$ for first 20 layers
  - $\left(\frac{e}{h}\right)^{ECAL}$ for last 10 layers
  - $\left(\frac{e}{h}\right)^{HCAL}$

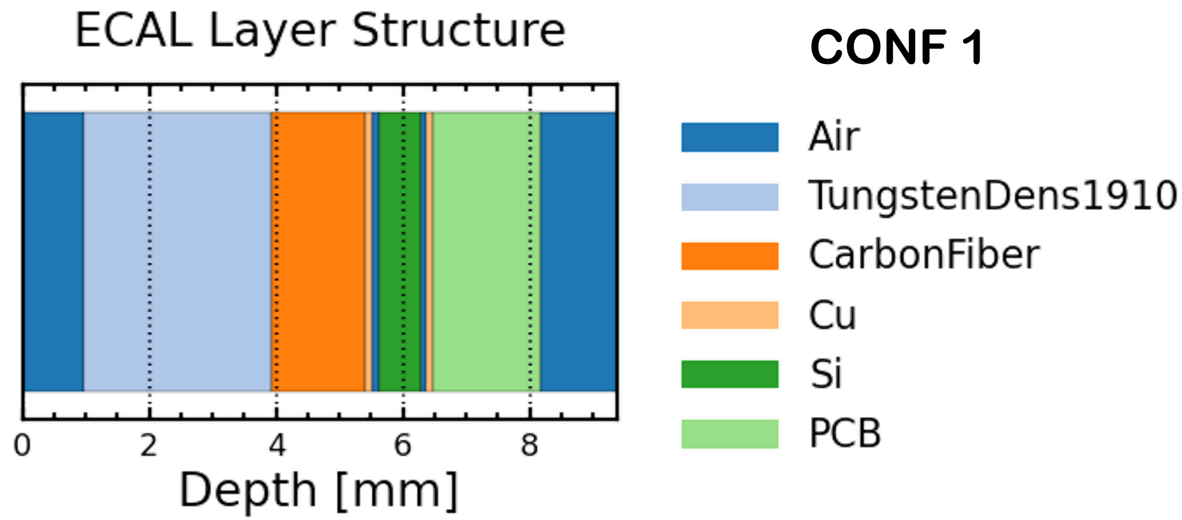
In the current ILD detector system,

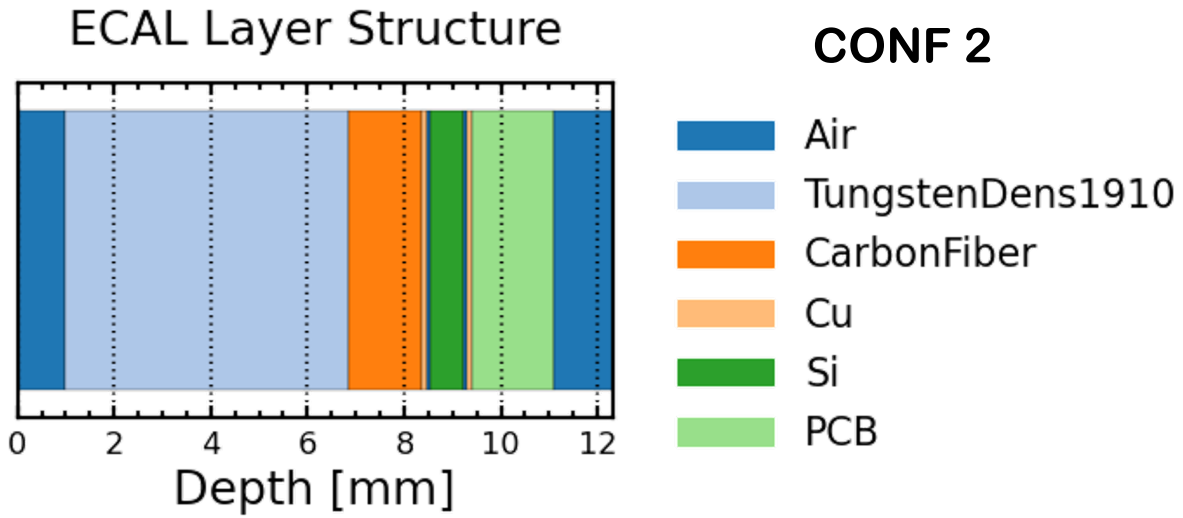
- The ECAL and HCAL dimensions are limited.
- The nuclear interaction length is not sufficient to fully contain hadronic showers.
- As a result, pions and even electrons may not be fully absorbed, leading to energy leakage.

	#. Layers	Length	Cell size	Active material	Absorber	Type
SiW-ECAL	30 in 20 cm	~ $1\lambda_I$	0.5×0.5 cm^2	Silicon	Tungsten	Non-Compensating
AHCAL	48 in 1 m	~ $5\lambda_I$	3×3 cm^2	Scintillator	Steel	Non-Compensating

ECAL Configuration

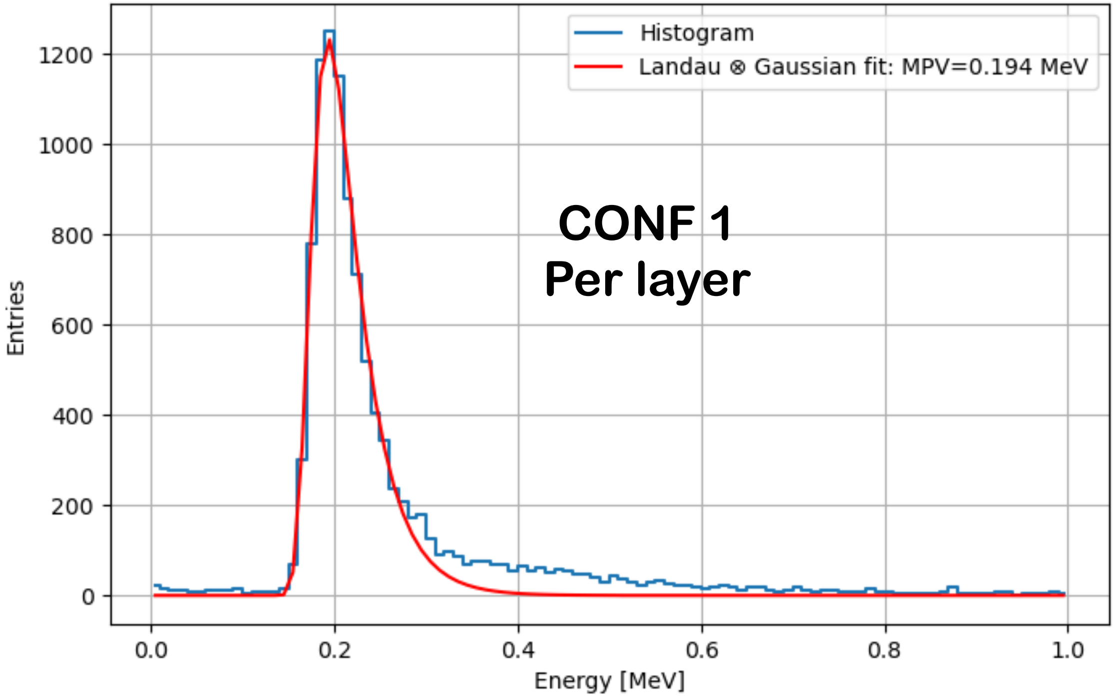
	CONF1	CONF2
#. Layers	200 in 2 m	200 in 3 m
Length	~ $10\lambda_I$	~ $16\lambda_I$
W thickness	2.94 mm/layer	5.88 mm/layer
Cell size	$0.5\times0.5\ cm^2$	$0.5\times0.5\ cm^2$

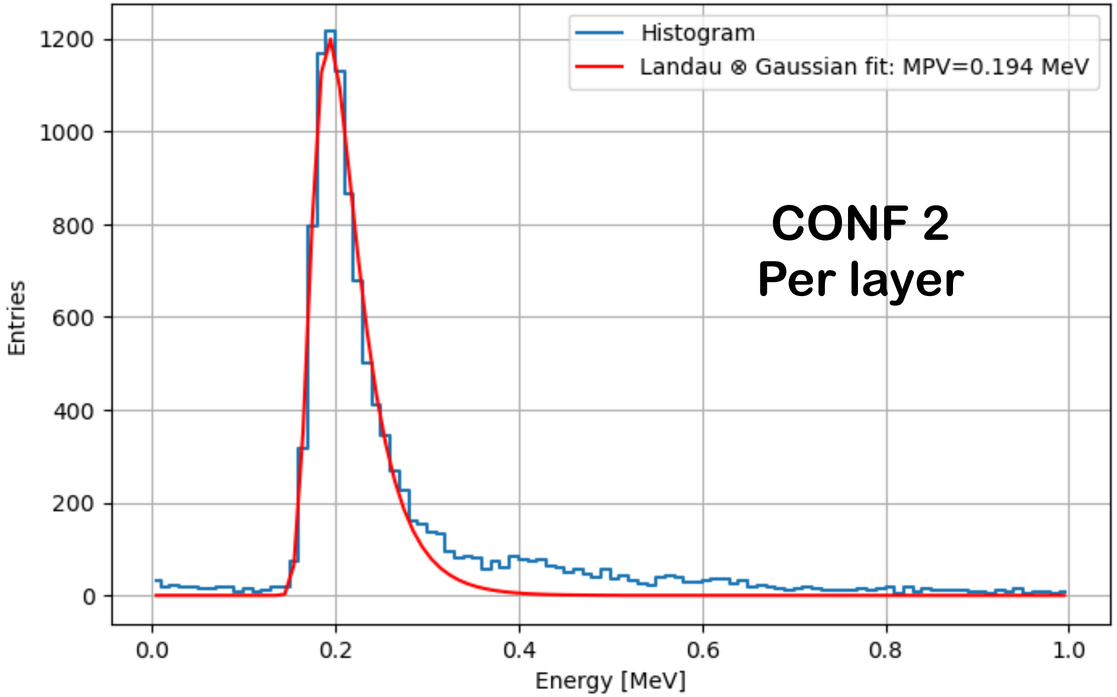




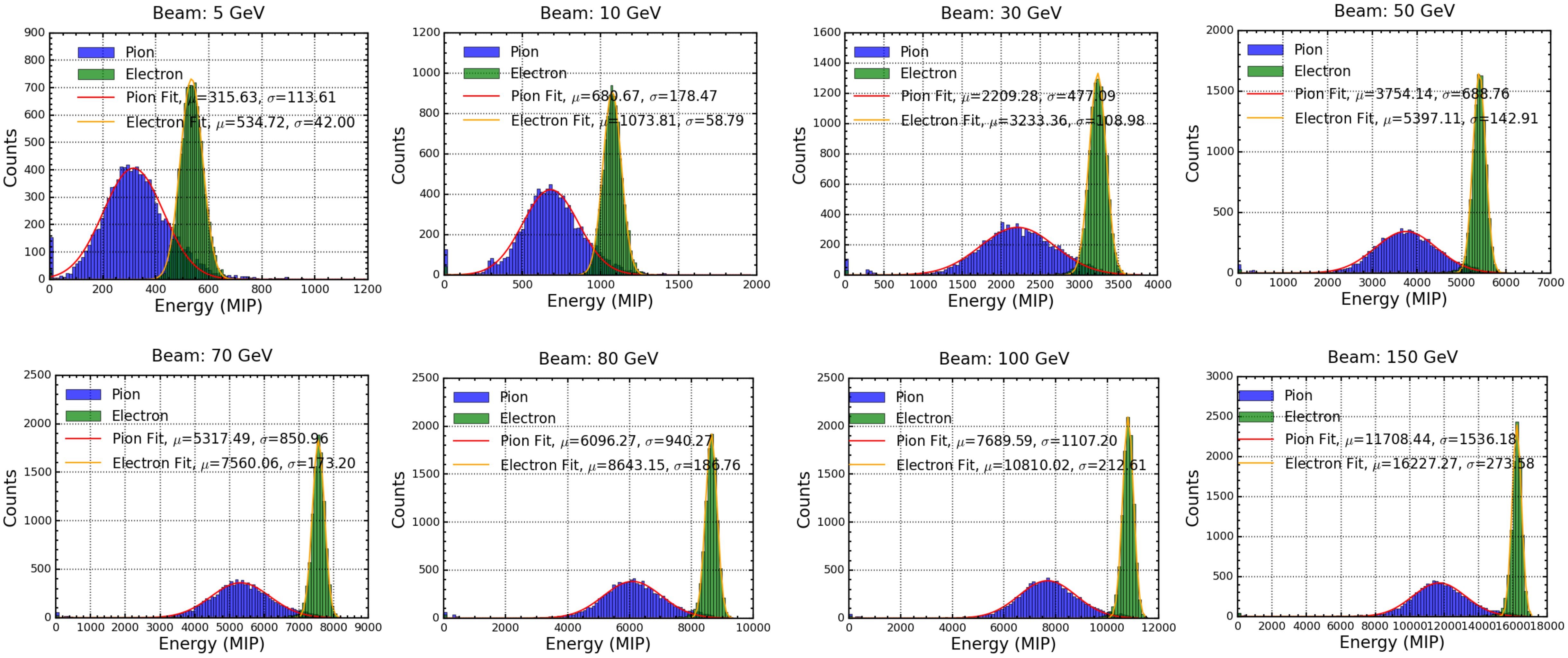
MIP Value

- use 100 GeV muon for MIP
- MIP = 0.194 MeV
- 0.5 MIP for noise cut

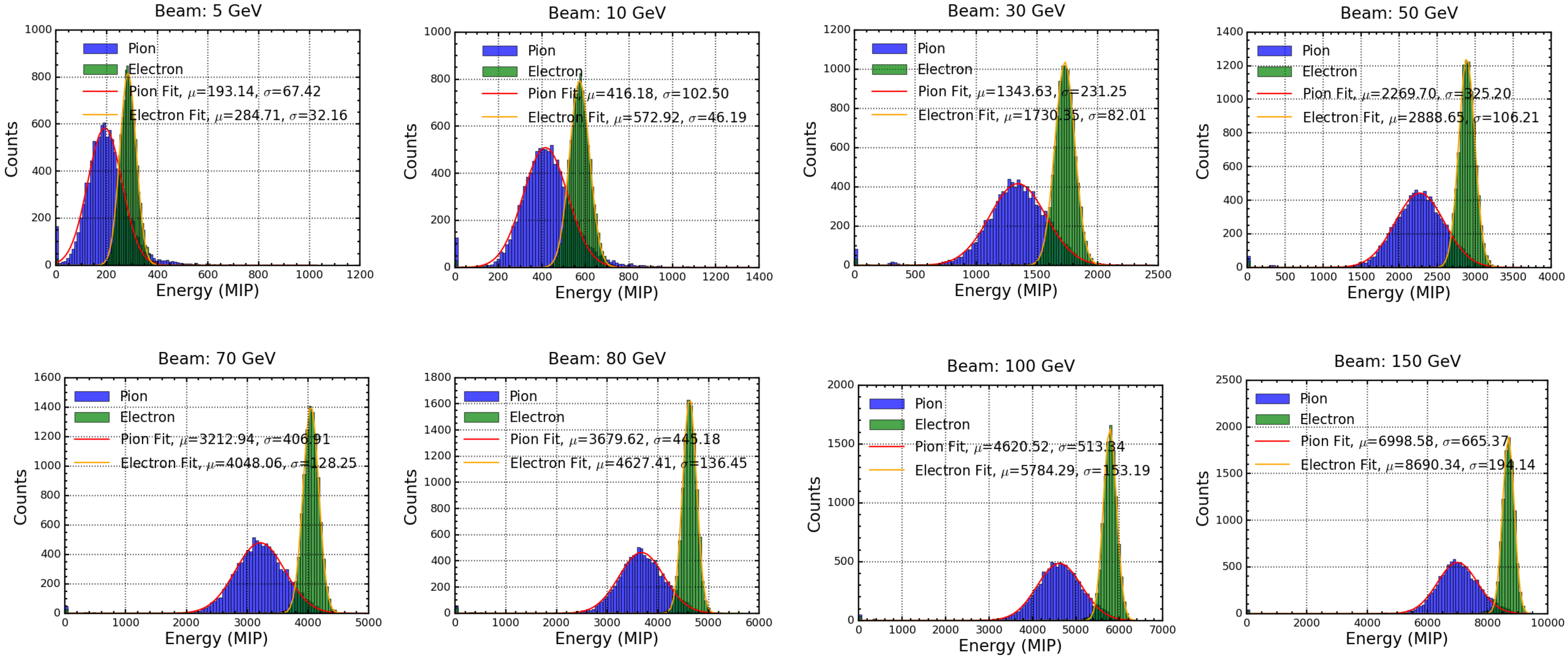




ECAL CONF1


Beam: 5 GeV
Pion
Electron
Pion Fit, μ=315.63, σ=113.61
Electron Fit, μ=534.72, σ=42.00
Counts
Energy (MIP)
Beam: 10 GeV
Pion
Electron
Pion Fit, μ=680.67, σ=178.47
Electron Fit, μ=1073.81, σ=58.79
Counts
Energy (MIP)
Beam: 30 GeV
Pion
Electron
Pion Fit, μ=2209.28, σ=477.09
Electron Fit, μ=3233.36, σ=108.98
Counts
Energy (MIP)
Beam: 50 GeV
Pion
Electron
Pion Fit, μ=3754.14, σ=688.76
Electron Fit, μ=5397.11, σ=142.91
Counts
Energy (MIP)
Beam: 70 GeV
Pion
Electron
Pion Fit, μ=5317.49, σ=850.96
Electron Fit, μ=7560.06, σ=173.20
Counts
Energy (MIP)
Beam: 80 GeV
Pion
Electron
Pion Fit, μ=6096.27, σ=940.27
Electron Fit, μ=8643.15, σ=186.76
Counts
Energy (MIP)
Beam: 100 GeV
Pion
Electron
Pion Fit, μ=7689.59, σ=1107.20
Electron Fit, μ=10810.02, σ=212.61
Counts
Energy (MIP)
Beam: 150 GeV
Pion
Electron
Pion Fit, μ=11708.44, σ=1536.18
Electron Fit, μ=16227.27, σ=273.58
Counts
Energy (MIP)

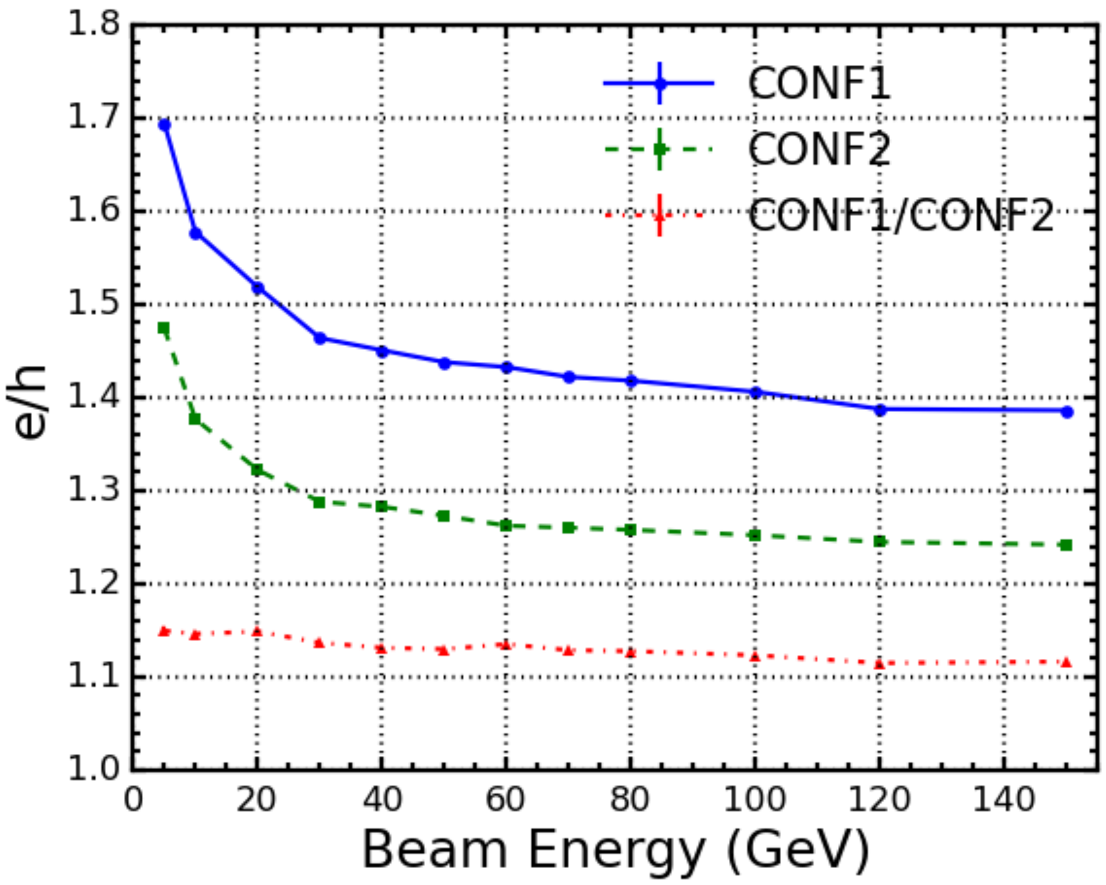
ECAL CONF2



Beam: 5 GeV
Pion
Electron
Pion Fit, μ=193.14, σ=67.42
Electron Fit, μ=284.71, σ=32.16
Counts
Energy (MIP)
Beam: 10 GeV
Pion
Electron
Pion Fit, μ=416.18, σ=102.50
Electron Fit, μ=572.92, σ=46.19
Counts
Energy (MIP)
Beam: 30 GeV
Pion
Electron
Pion Fit, μ=1343.63, σ=231.25
Electron Fit, μ=1730.35, σ=82.01
Counts
Energy (MIP)
Beam: 50 GeV
Pion
Electron
Pion Fit, μ=2269.70, σ=325.20
Electron Fit, μ=2888.65, σ=106.21
Counts
Energy (MIP)
Beam: 70 GeV
Pion
Electron
Pion Fit, μ=3212.94, σ=406.91
Electron Fit, μ=4048.06, σ=128.25
Counts
Energy (MIP)
Beam: 80 GeV
Pion
Electron
Pion Fit, μ=3679.62, σ=445.18
Electron Fit, μ=4627.41, σ=136.45
Counts
Energy (MIP)
Beam: 100 GeV
Pion
Electron
Pion Fit, μ=4620.52, σ=513.34
Electron Fit, μ=5784.29, σ=153.19
Counts
Energy (MIP)
Beam: 150 GeV
Pion
Electron
Pion Fit, μ=6998.58, σ=665.37
Electron Fit, μ=8690.34, σ=194.14
Counts
Energy (MIP)

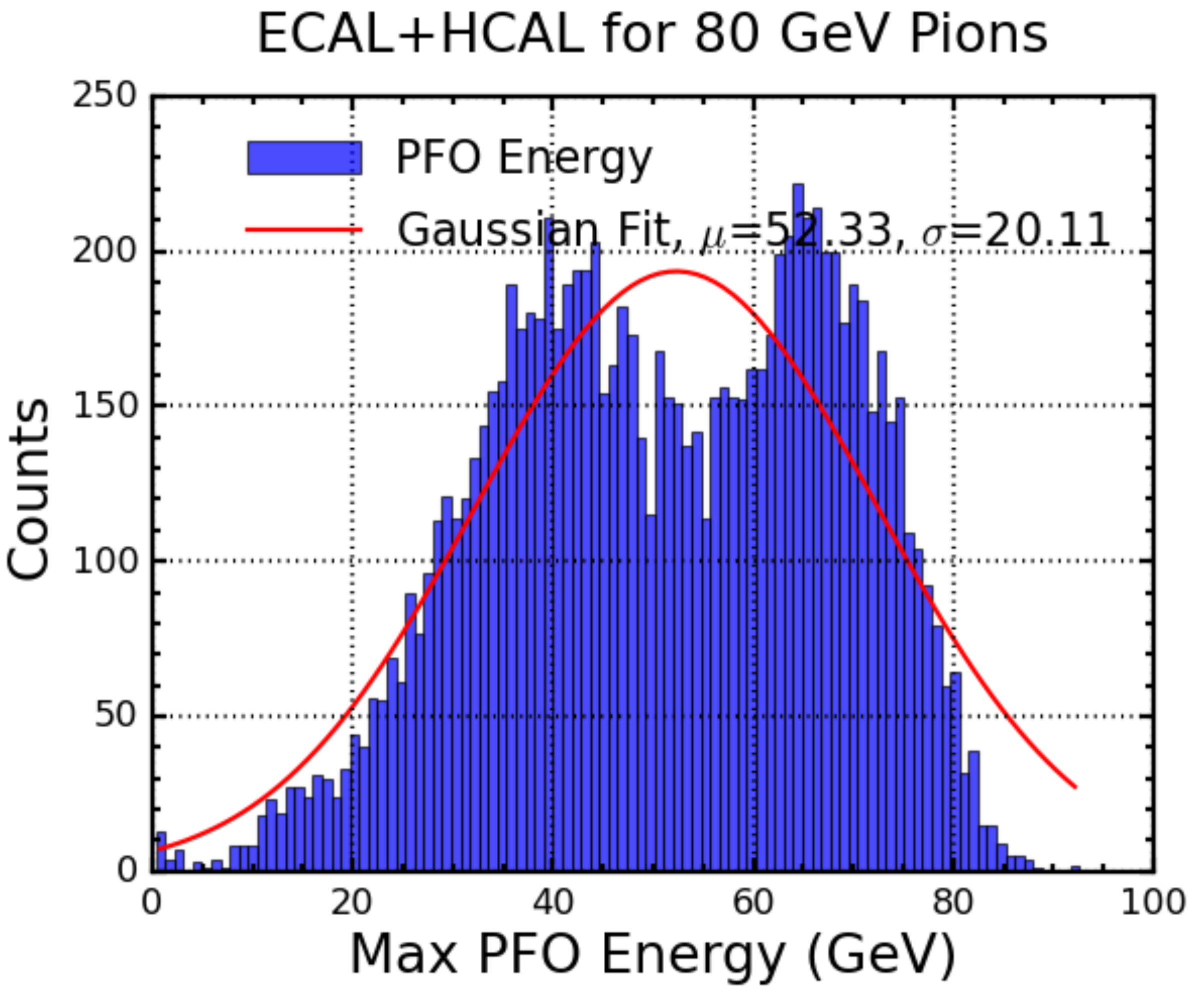
e/h

- CONF1_e/h > CONF2_e/h
- Both e/h in CONF1 and CONF2 are not constant, but with energy increasing, the e/h tends to be stable
- e/h of CONF1/CONF2 is stable



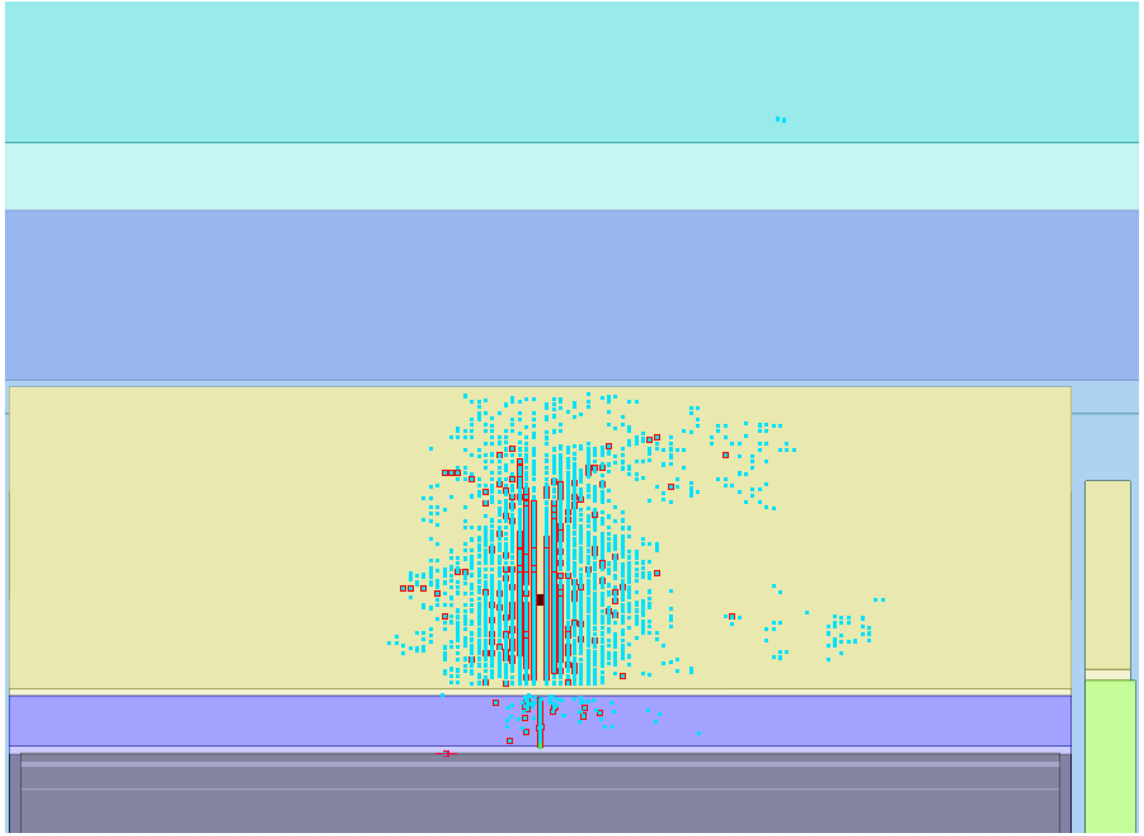
Part III: two peaks study

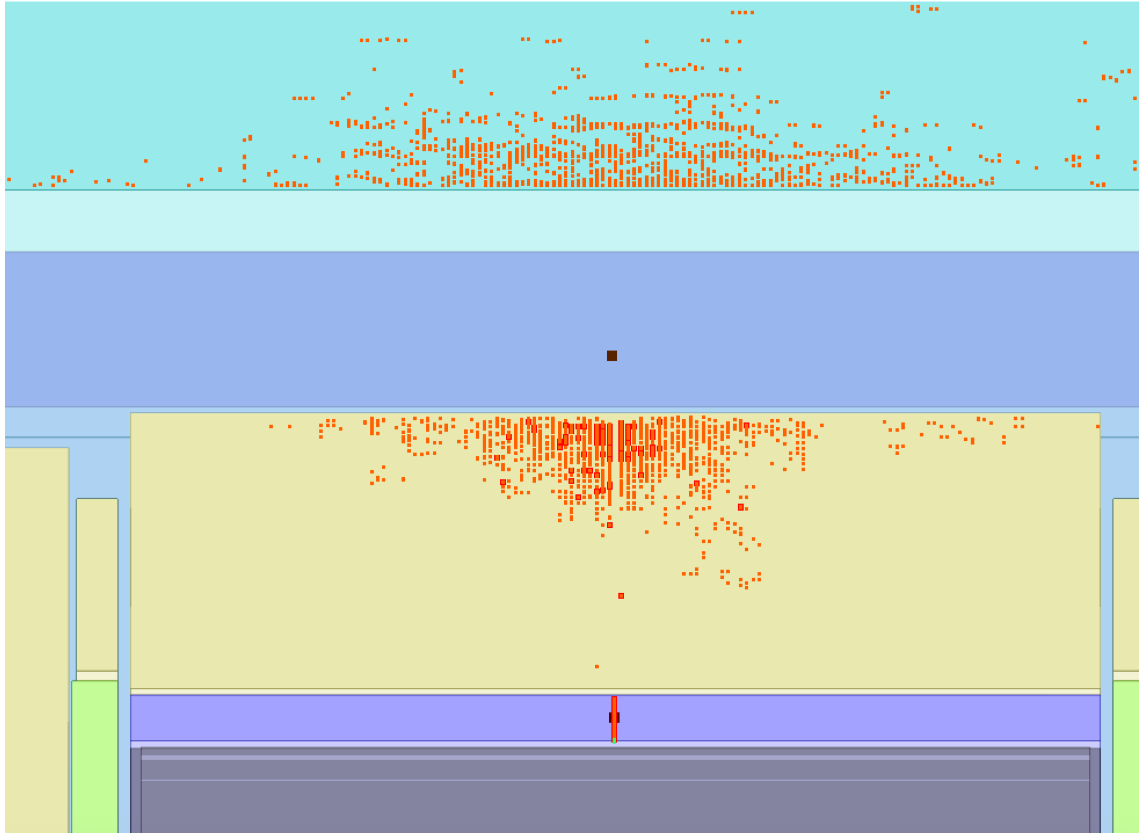
Strange 2 peaks?



Why 2 peaks?

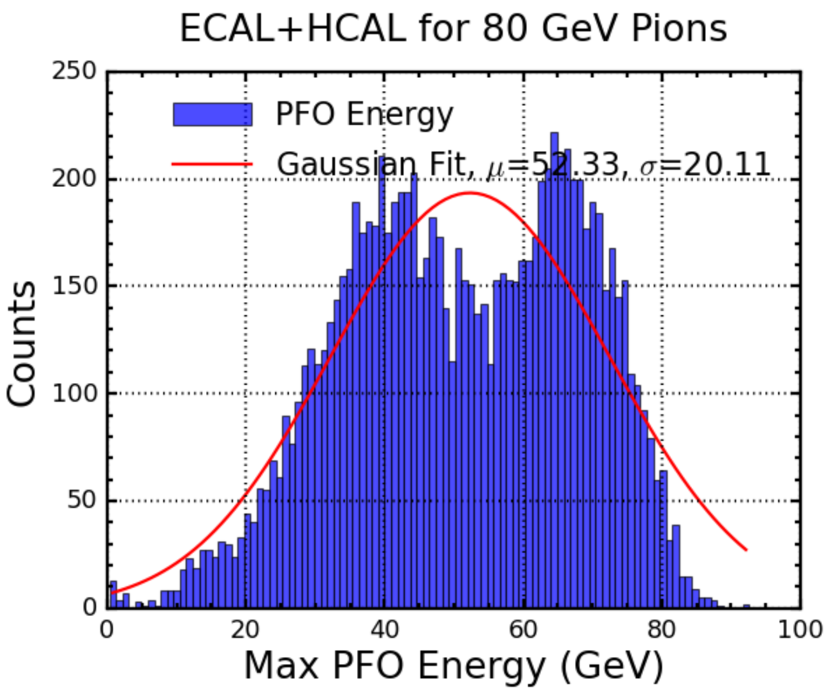
- The gap in the middle of the HCAL.
- In my previous code, I set: *SIM.vertexSigma = [5.0*mm, 0.0, 10.0*mm, 0.0]* and *SIM.gun.position = (2.0, (1804.8-10.)*mm, 2.0),* it's not larger enough.

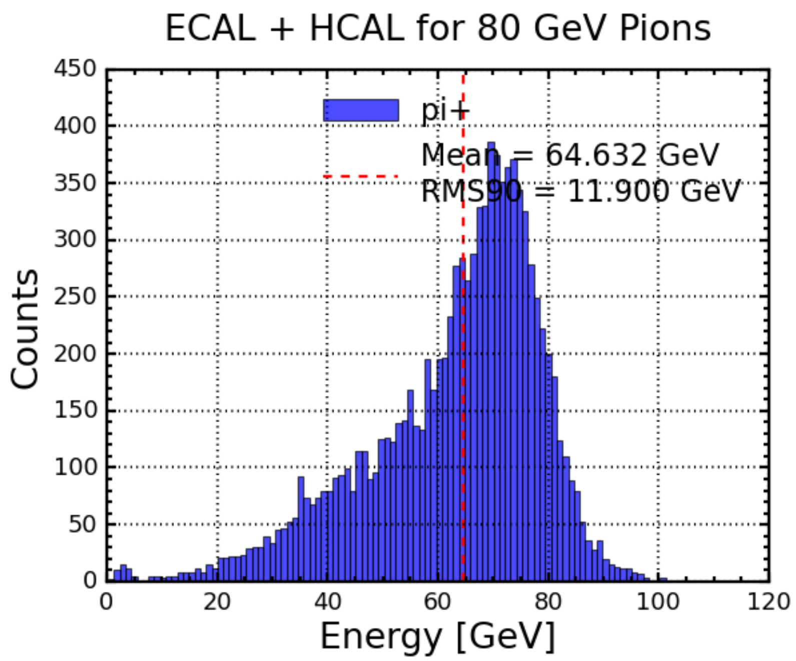


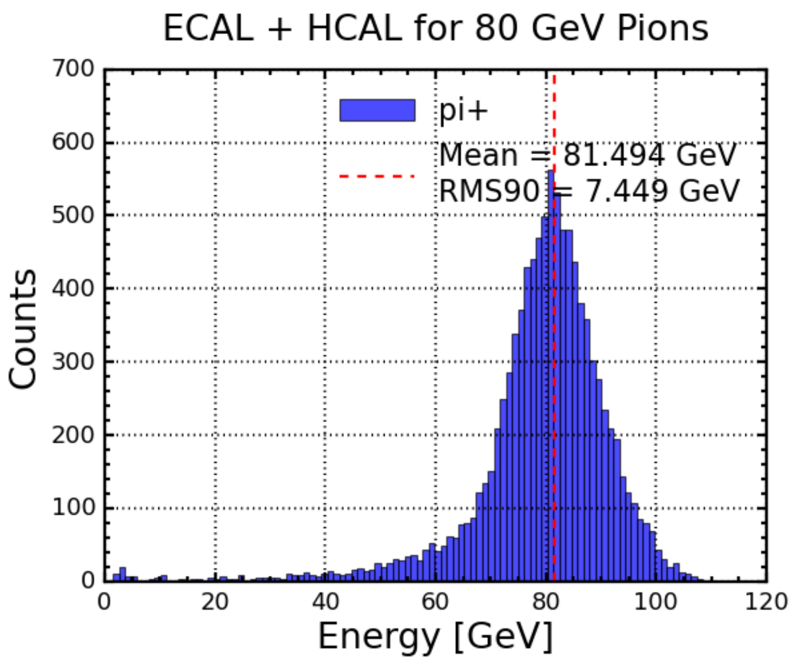


The effect of the gap is significant

Gun position	(2.0, (1804.8-10.)*mm, 2.0)	(17.0, (1804.8-10.)*mm, 17.0)	(17.0, (1804.8-10.)*mm, 17.0)
vertexSigma	[5.0*mm, 0.0, 10.0*mm]	[14.0*mm, 0.0, 28.0*mm]	[150.0*mm, 0.0, 470.0*mm]

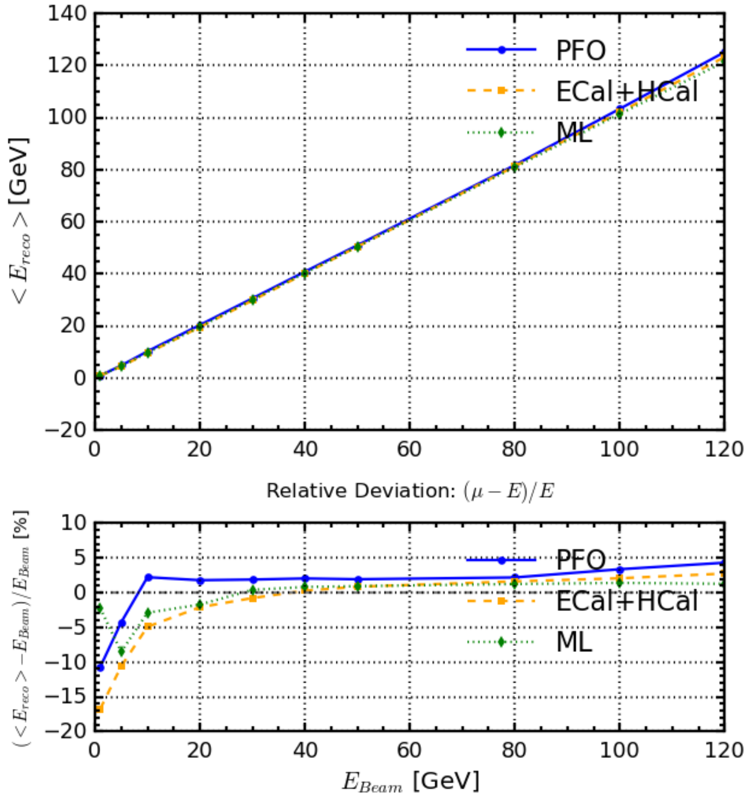


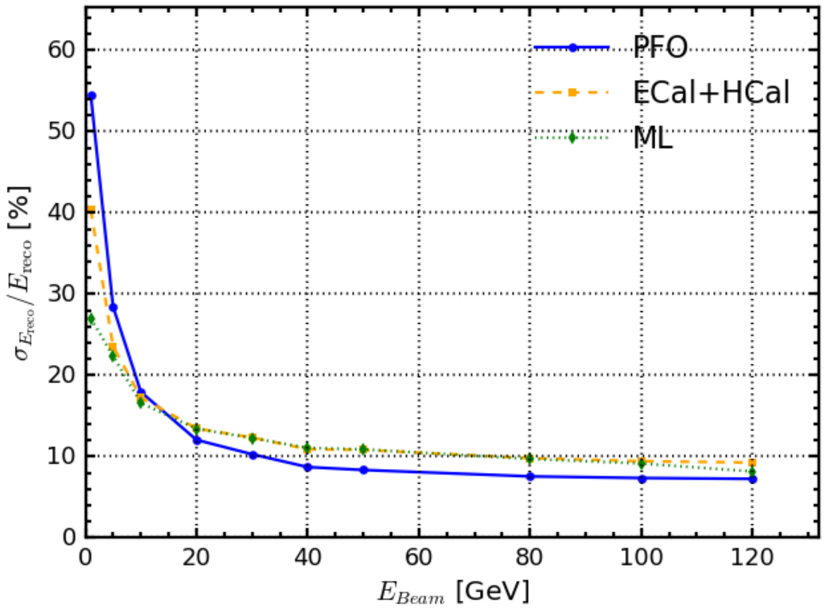




Preliminary results

- For ML approach, predicting energy directly, no fem information.
- The ML model is the old one (using the small smear, the shower is not complete), need re-training.
- Energy measurement performances of Pandora and summing all the energy deposition become much better than before.





Summary

Summary

- Established a full software compensation chain using a dual-branch CNN with Si-W ECAL + AHCAL system
- f_{em} regression model shows accurate prediction, showing strong potential for energy reconstruction
- Energy regression: get very preliminary results, showing potential; low and high energy regions require further improvement
- Performed simulation and reconstruction for semi-infinite ECAL.
- Studied the e/h ratio of ECAL with different tungsten thicknesses.
- Investigated the origin of the double-peak structure.

Plans

Plans

- Conducted new simulation with larger injection position smearing and retrained the model.
- Applied the e/h ratio for energy reconstruction.
- Explored the potential of using timing information to improve reconstruction performance.

Thanks!

ECAL Layer Structure		
Air	:	0.980 mm
TungstenDens1910	:	2.940 mm
CarbonFiber	:	1.500 mm
Cu	:	0.100 mm
Air	:	0.100 mm
Si	:	0.650 mm
Air	:	0.100 mm
Cu	:	0.100 mm
PCB	:	1.700 mm
Air	:	1.200 mm

Preliminary results of energy reconstruction:

- Very preliminary → strong limitations at low & high energies
- Further refinement and validation required