Energy Regression with CNN in 5D SiW-ECAL + AHCAL of ILD

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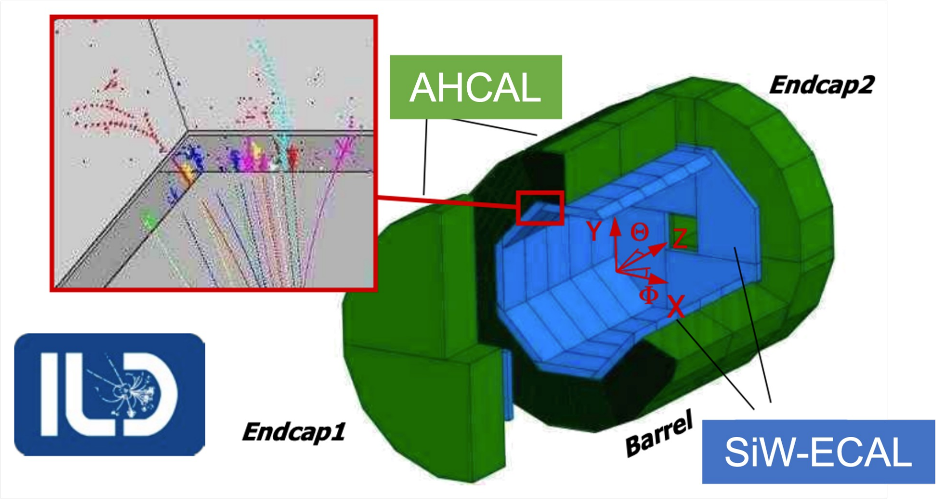
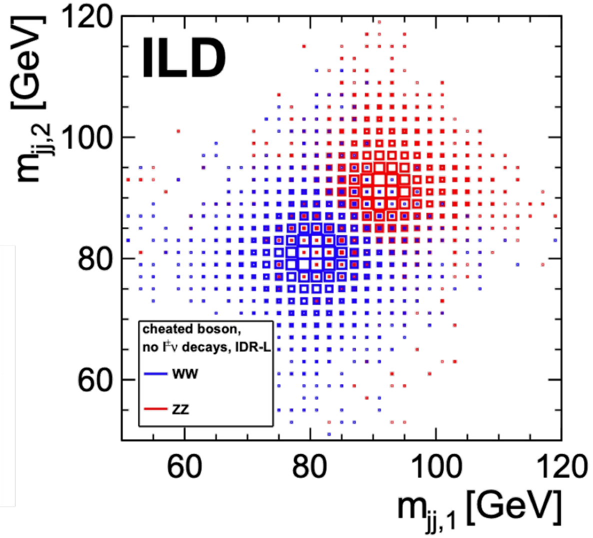
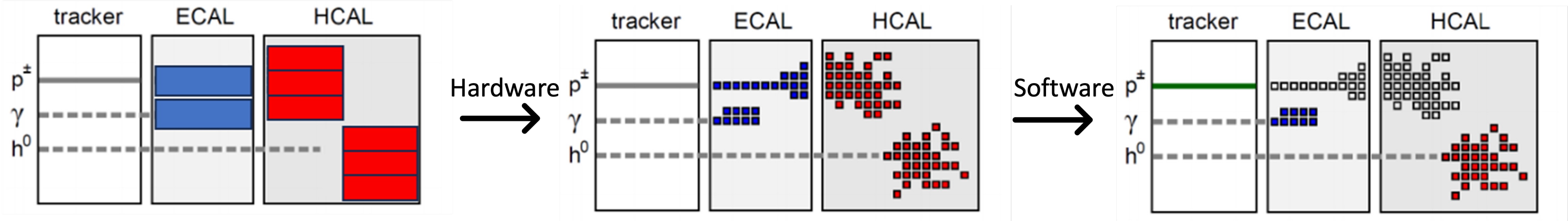
Motivation

- High-precision energy measurements is essential for $W/H/Z$ studies in future Higgs factory
- Benchmark: 3% Jet energy resolution
- A major option: Particle Flow Algorithm (PFA) + PFA-oriented detector system
  - PFA: $E_{jet} = E_{tracker} + E_{ECAL} + E_{HCAL}$
  - High granularity calorimeter (imaging):
    - SiW-ECAL + AHCAL
- $E_{ECAL} + E_{HCAL}$ as part of PFA & intrinsic performance of calorimeter





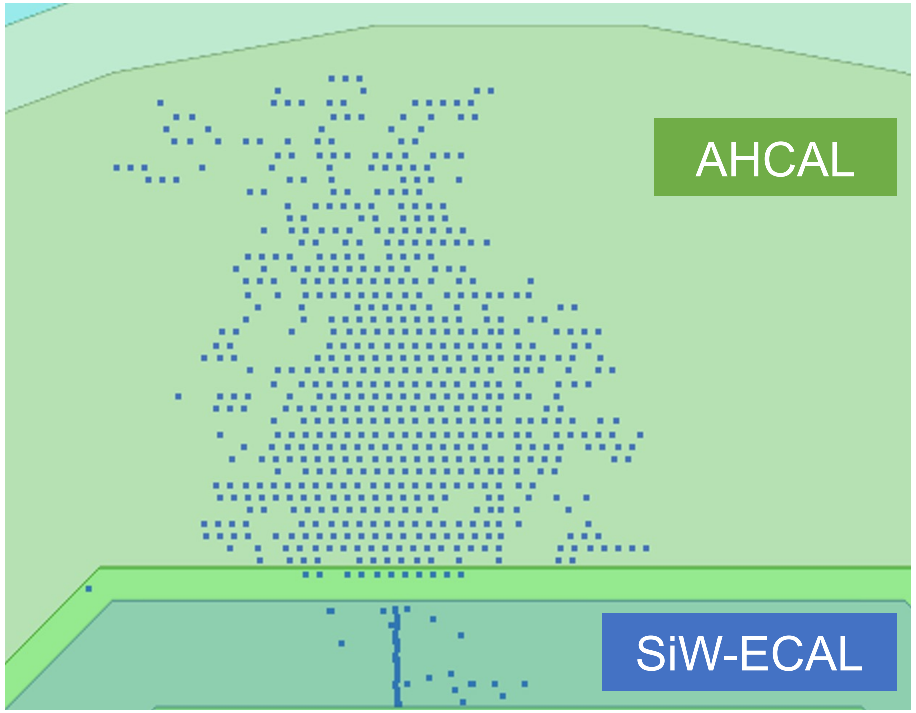


Detector

	#. 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

Detector introduction:

- Configuration: details in table; Energy resolution of hadron < $60\%/\sqrt{E}$
- Different response for electro-magnetic/hadronic shower, degrade energy measurement precision



How to improve the energy reconstruction performance?

Methods

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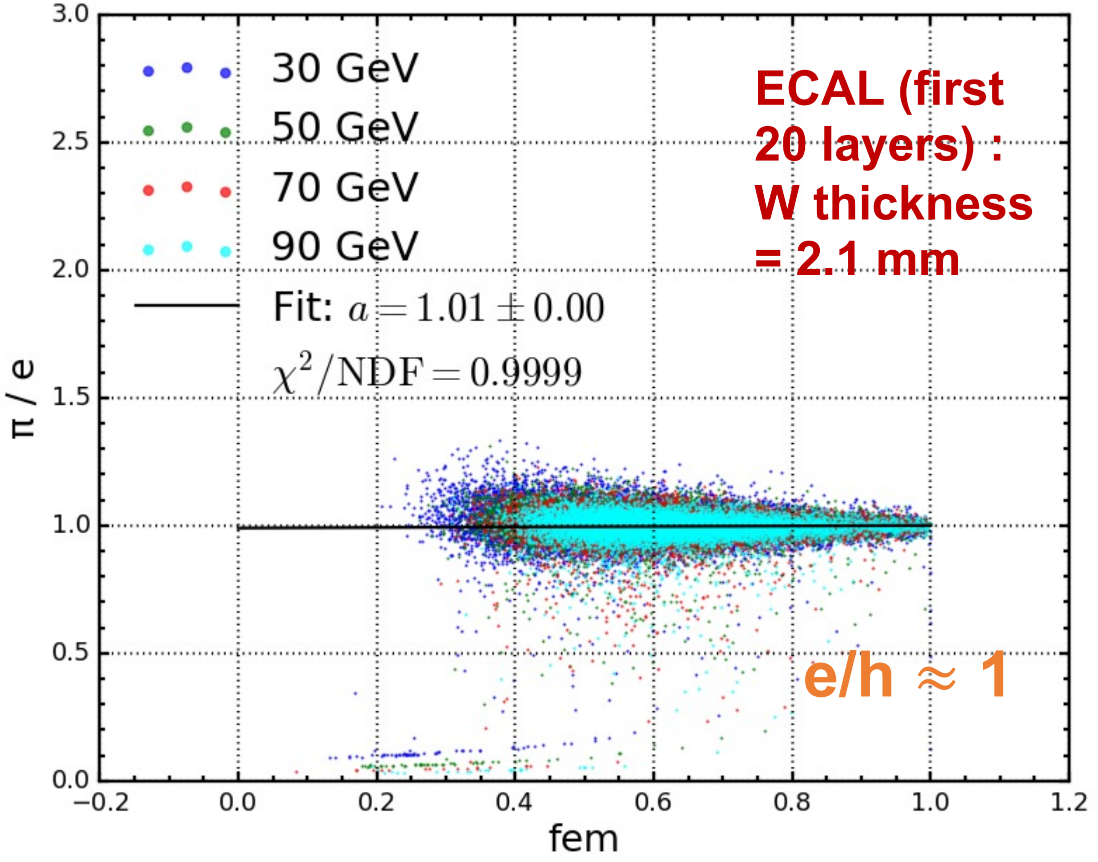
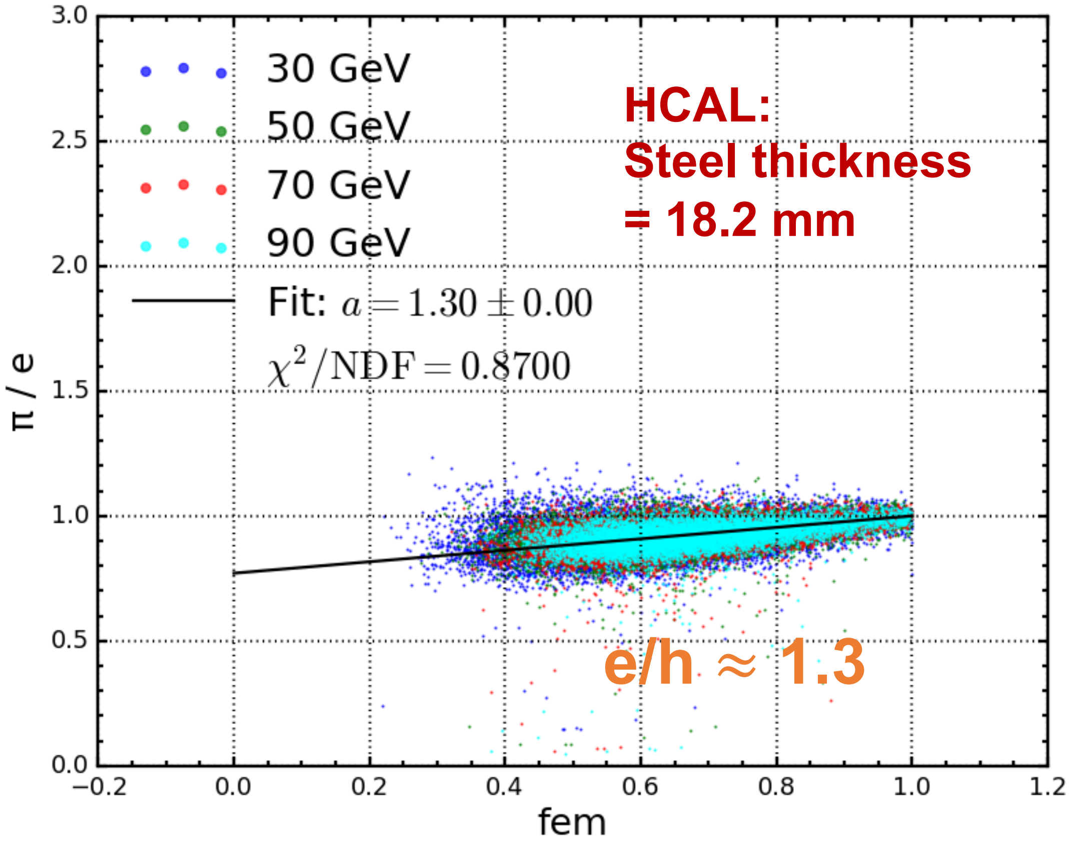
<tr><td>Total energy deposition (Vis)</td><td colspan="3">$$E = \sum_{all\_hits} E_{hit}^{ECAL} + \sum_{all\_hits} E_{hit}^{HCAL}$$</td></tr>
<tr><td>Pandora PFA (PFO)</td><td colspan="3">Use standard Pandora PFA reconstruction, choose the PFO with largest energy, ignore other PFOs</td></tr>
<tr><td rowspan="2">Software Compen (truth fem)</td><td colspan="3">$$E_{rec} = \frac{(e/h)_{ECAL}}{1+f_{em\_ECAL}((e/h)_{ECAL}-1)} \cdot E_{ECAL} + \frac{(e/h)_{HCAL}}{1+f_{em\_HCAL}((e/h)_{HCAL}-1)} \cdot E_{HCAL}$$ (Individual-SC)</td></tr>
<tr><td colspan="3">$$E_{rec} = \frac{e}{\pi} \cdot E_{dep} = \frac{e}{f_{em} \cdot e + (1-f_{em}) \cdot h} \cdot E_{dep} = \frac{e/h}{1+f_{em}(e/h-1)} \cdot E_{dep}$$ (Global-SC)</td></tr>
<tr><td>CNN(ML w/o time)</td><td colspan="3">(E, x, y, z)</td></tr>
<tr><td rowspan="2">CNN (ML w time)</td><td rowspan="2">(E, T, x, y, z)</td><td>Moments</td><td>Absolute time</td></tr>
<tr><td>Bins</td><td>sigma = Max(0.04, 0.10 /$\sqrt{E}$)
t = t + rng.normal(0, sigma)</td></tr>
</table>

Individual e/h

$$\frac{(e/h)_{ECAL}}{1+f_{em\_ECAL}((e/h)_{ECAL}-1)} = 1$$

$$\frac{(e/h)_{HCAL}}{1+f_{em\_HCAL}((e/h)_{HCAL}-1)} = \frac{1.3}{1+0.3\cdot f_{em\_HCAL}}$$





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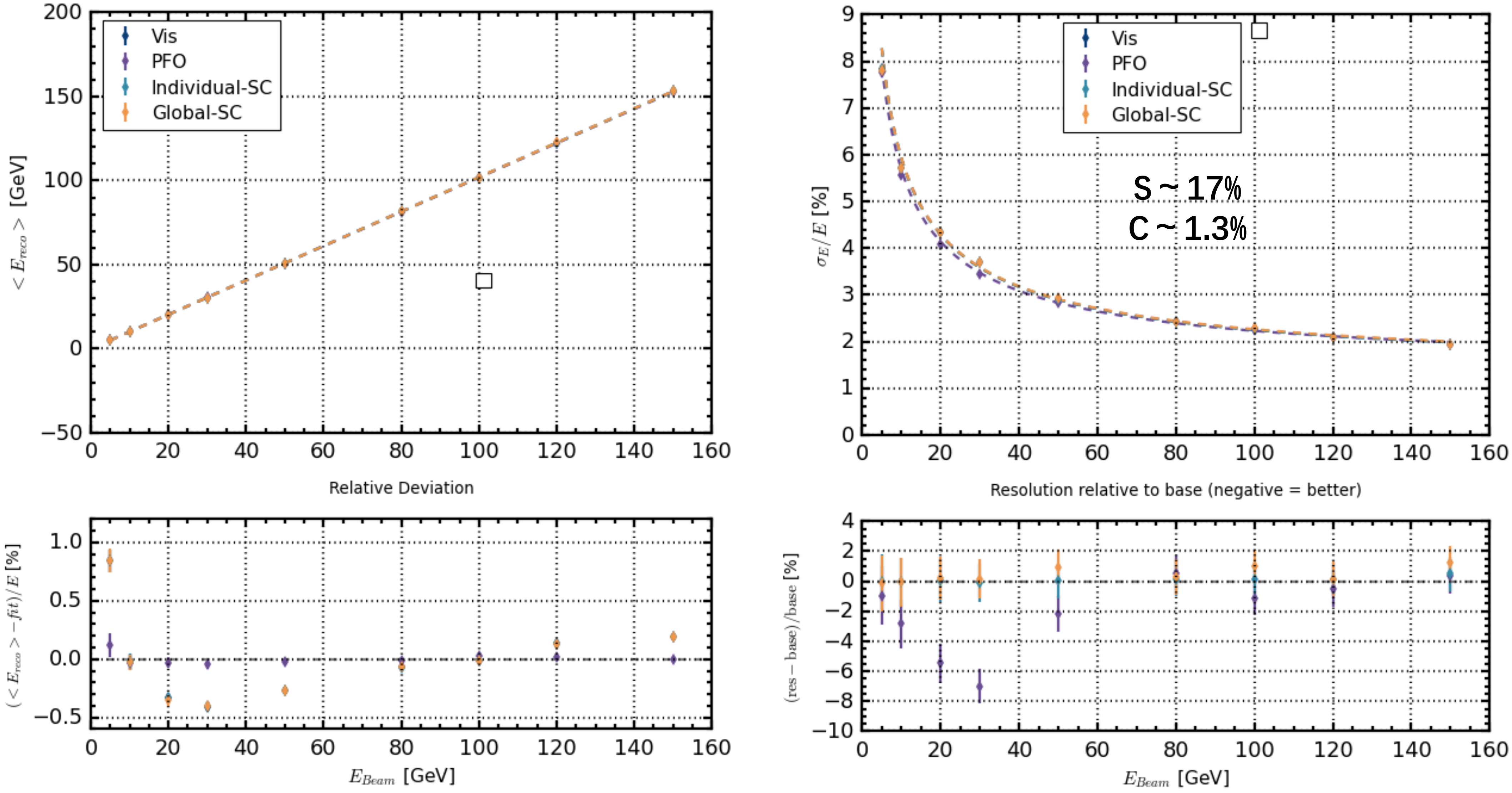
Dataset

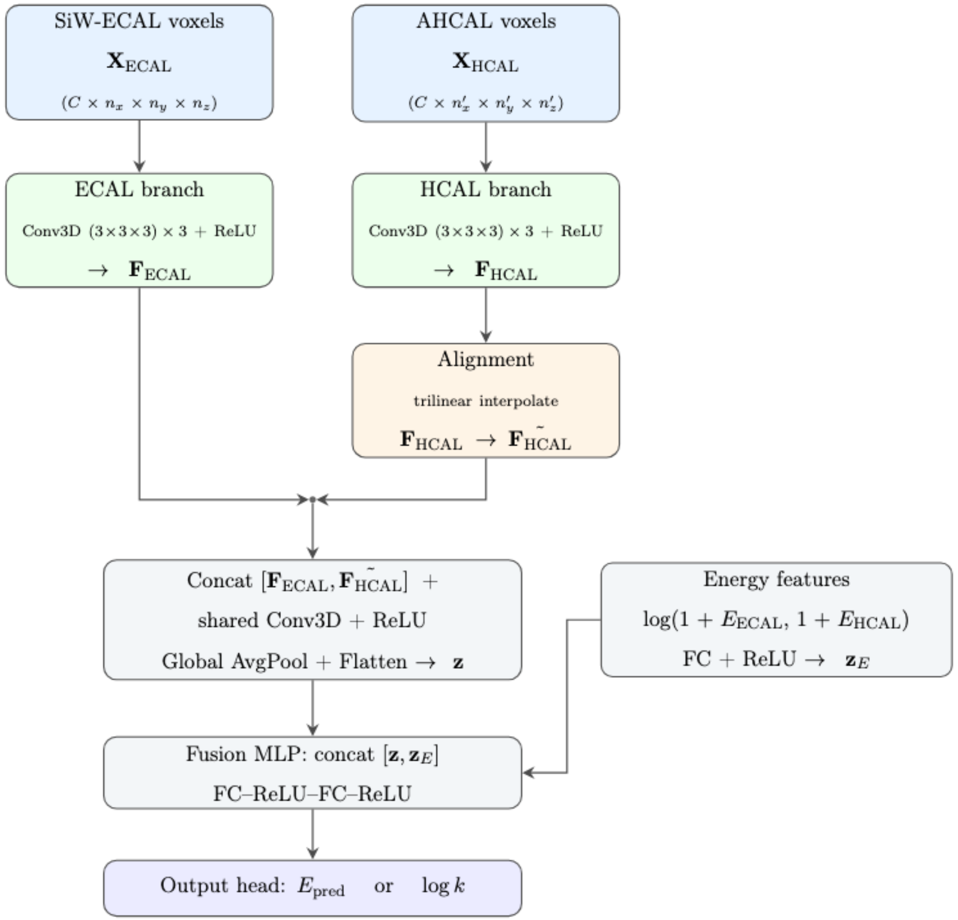
Data set	
Particle	Pi+ / e- / k- in ILD ECAL + AHCAL system (ILD_l5_o1_v02)
Train set	0.2 GeV to 200 GeV (1000 events / 1000 uniform energy points); only pi+
Test set	1,2,3,4,5,6,7,8,9,10,11,12, 13,14,15, 20,30,40,50,80,100,120,150 GeV 10000 events / energy; pi+ / e- / k-

Electron Samples - well calibration



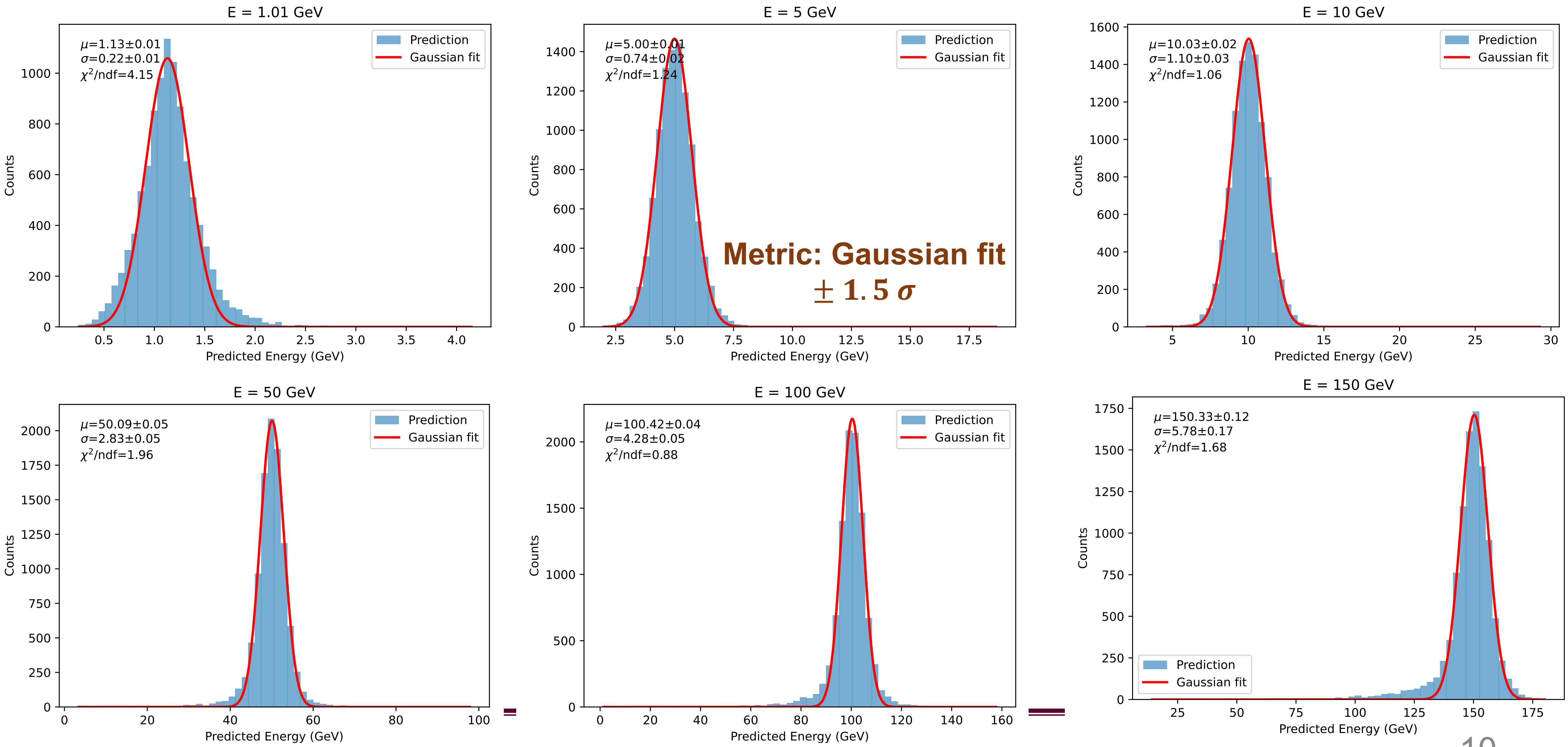
CNN Model (Trained by pi+)

Dual-branch ECAL+HCAL 3D-CNN (schematic)



Model	CNN (ML w/o time)	CNN (ML w. time)	
Input information	(E, x, y, z)	(E, T, x, y, z)	
		Moments	Bins
Channels	$[\text{ch}_0, \text{ch}_1]$	$[\text{ch}_0, \text{ch}_1, T_{\text{mean}}, T_{\text{rms}}]$	$[\text{ch}_0, \text{ch}_1, \text{ch}2, \text{ch}3, \text{ch}4]$
	$\text{ch}_0 = \frac{E_{\text{voxel}}}{v_{max}}$, $\text{ch}_1 = \frac{E_{\text{voxel}}}{E_{\text{total}}}$ v_{max}: voxel with max energy E_{total}: total energy in Cal	$T_{\text{mean}} = \frac{\sum_{i\in\text{voxel}} E_i t_i}{\sum_{i\in\text{voxel}} E_i + \epsilon}$ $T_{\text{rms}} = \sqrt{\frac{\sum_{i\in\text{voxel}} E_i t_i^2}{\sum_{i\in\text{voxel}} E_i + \epsilon} - T_{\text{mean}}^2 + \epsilon}$	$\text{ch}_2 = \frac{E_{\text{early}}}{E_{\text{voxel}}}$, $\text{ch}_3 = \frac{E_{\text{mid}}}{E_{\text{voxel}}}$, $\text{ch}_4 = \frac{E_{\text{late}}}{E_{\text{voxel}}}$, $E_{\text{early}}: t < t_0$, $E_{\text{mid}}: t_0 \le t < t_1$, $E_{\text{late}}: t \ge t_1$
	Absolute time, sigma = Max(0.04, 0.10 /$\sqrt{E}$), t = t + rng.normal(0, sigma)		

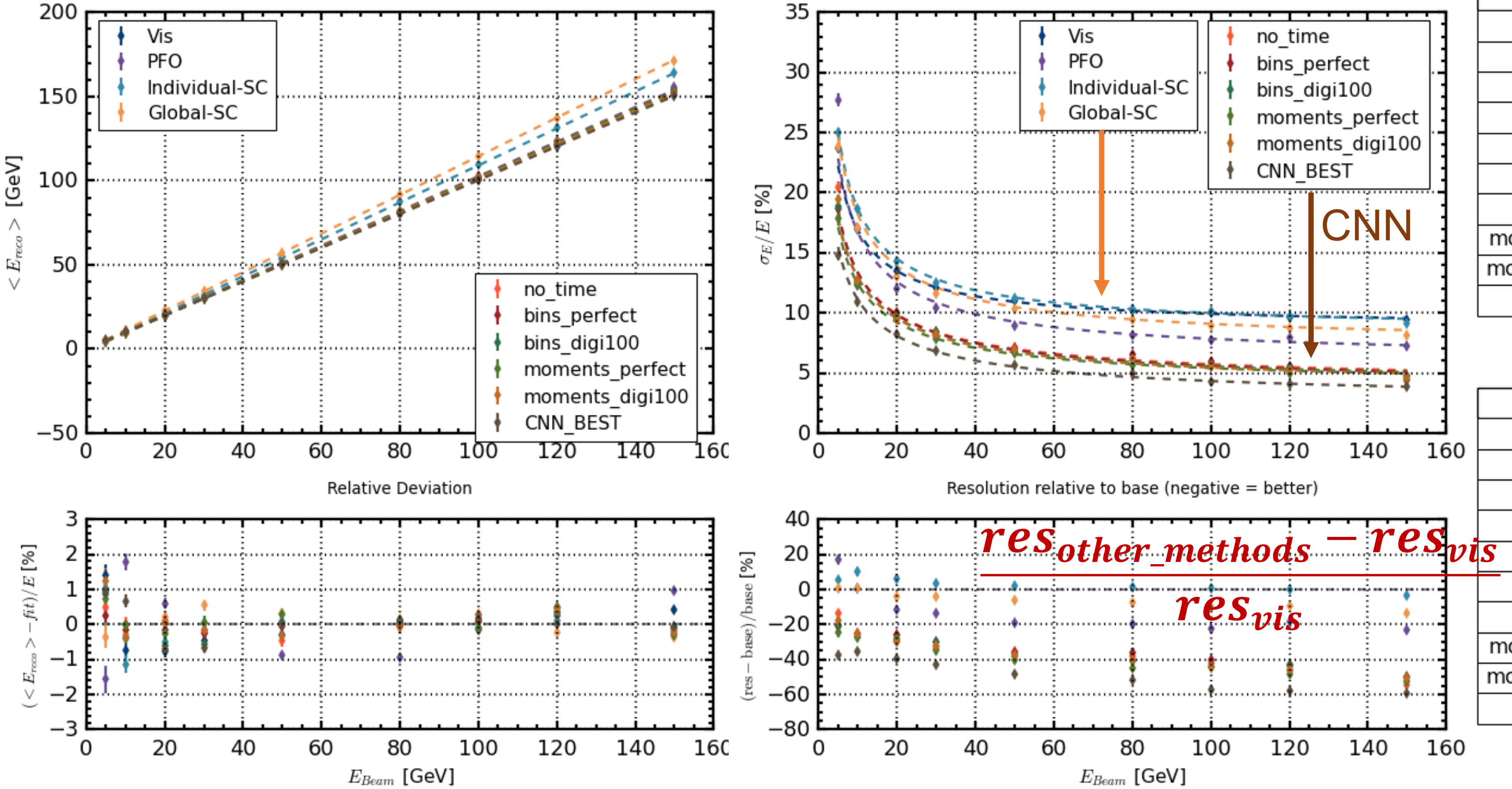
Distribution of predicted pion energy



Metric: Gaussian fit $\pm 1.5\,\sigma$

Pion samples

- CNN energy regression improves systematically
- Linearity within 2%; Resolution: 20% - 50% improvement
- No big difference between w. or w/o time.



Linearity

Method	a	b	chi2/ndf
Vis	1.0277 ± 0.0006	-0.751 ± 0.013	13.49
PFO	1.0280 ± 0.0005	-0.283 ± 0.015	56.63
HCAL-SC	1.0982 ± 0.0006	-0.737 ± 0.014	5.69
Global-SC	1.1469 ± 0.0006	-0.199 ± 0.014	5.76
no_time	1.0216 ± 0.0005	-0.332 ± 0.013	5.68
bins_perfect	1.0108 ± 0.0005	-0.175 ± 0.010	3.71
bins_digi100	1.0100 ± 0.0005	-0.219 ± 0.012	10.26
moments_perfect	1.0231 ± 0.0006	-0.409 ± 0.010	2.51
moments_digi100	1.0141 ± 0.0005	-0.269 ± 0.012	8.48
CNN_BEST	1.0031 ± 0.0004	-0.066 ± 0.011	18.04

Resolution

Method	S	C	chi2/ndf
Vis	45.64 ± 0.54%	8.81 ± 0.06%	0.89
PFO	49.22 ± 0.56%	6.10 ± 0.07%	17.09
HCAL-SC	52.57 ± 0.58%	8.48 ± 0.07%	3.15
Global-SC	52.51 ± 0.49%	7.41 ± 0.06%	3.99
no_time	40.22 ± 0.54%	4.07 ± 0.11%	7.99
bins_perfect	40.33 ± 0.47%	3.90 ± 0.10%	5.64
bins_digi100	38.97 ± 0.56%	3.94 ± 0.10%	4.20
moments_perfect	37.32 ± 0.37%	3.91 ± 0.11%	3.54
moments_digi100	39.14 ± 0.44%	3.79 ± 0.10%	3.59
CNN_BEST	34.11 ± 0.40%	2.67 ± 0.09%	2.10

Loss function

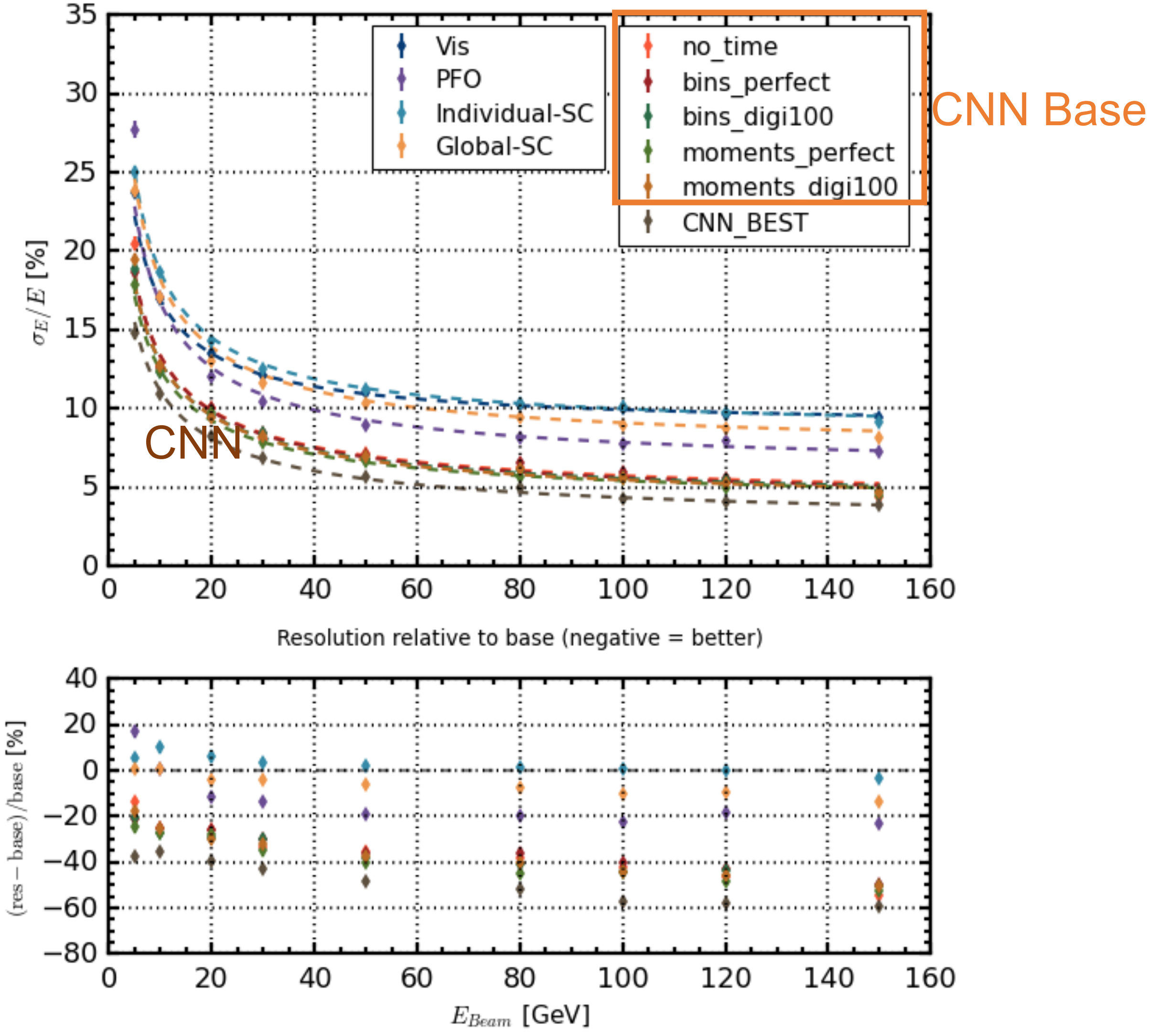
Optimization objective: relative error

$$L_{Huber} = \frac{1}{N}\sum_i \mathrm{Huber}\left(\frac{\widehat{E}_i - E_i}{E_i}\right),$$

$$\text{where Huber(r) is defined as Huber}(r) = \begin{cases} \frac{1}{2}r^2, |r| < \delta \\ \delta(|r| - \frac{1}{2}\delta), |r| \geq \delta \end{cases}$$

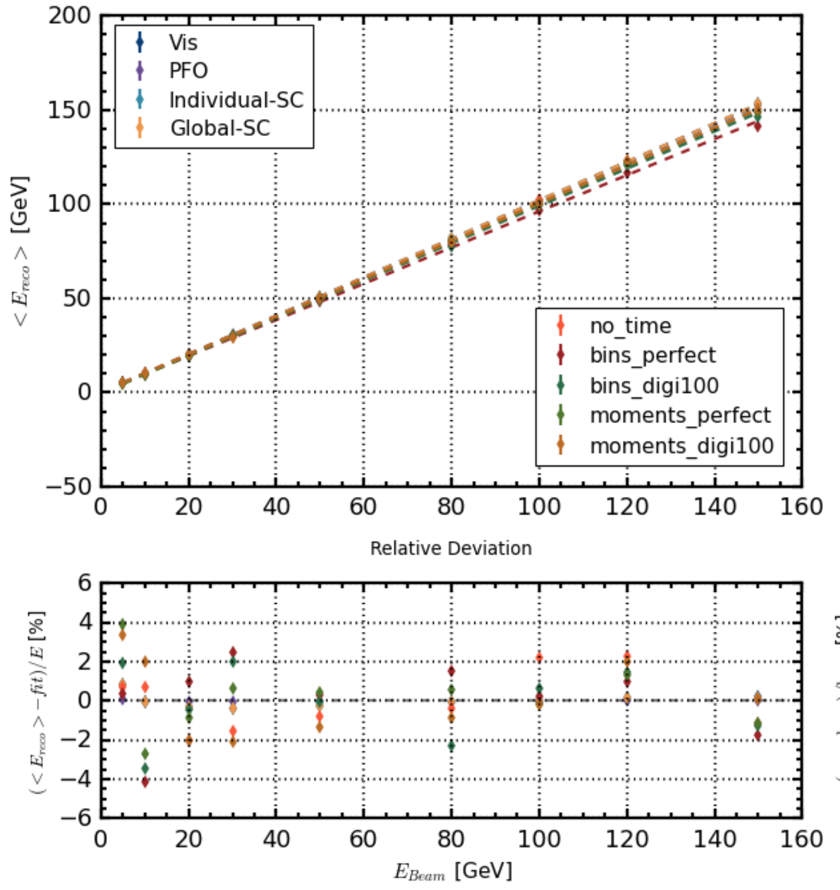
$\widehat{E}_i$: predicted energy value of i_th sample
E_i: true energy value of i_th sample
δ: threshold

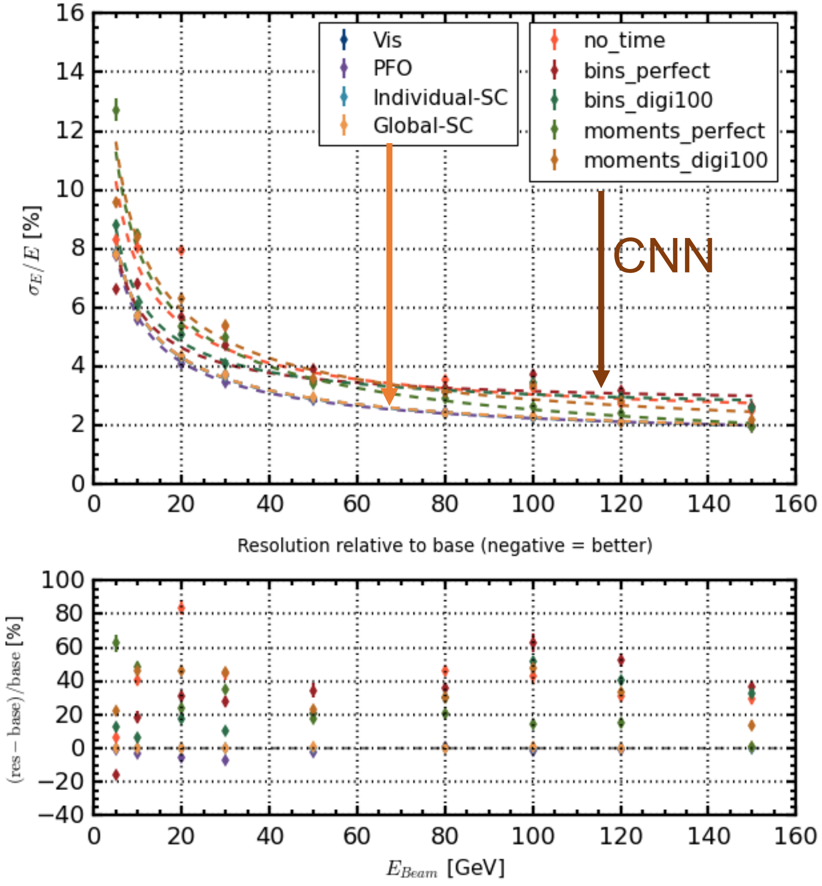
CNN Best: $E_i = \max(E_{true}, 1.0)$
CNN Base: $E_i = \max(E_{true}, 0.2)$



E samples

- CNN model(trained by pion samples) doesn't perform well on electron samples.
- Dedicated compensation for hadronic showers, hadron-specific physics correction
- Over-compensation for electrons





Linearity

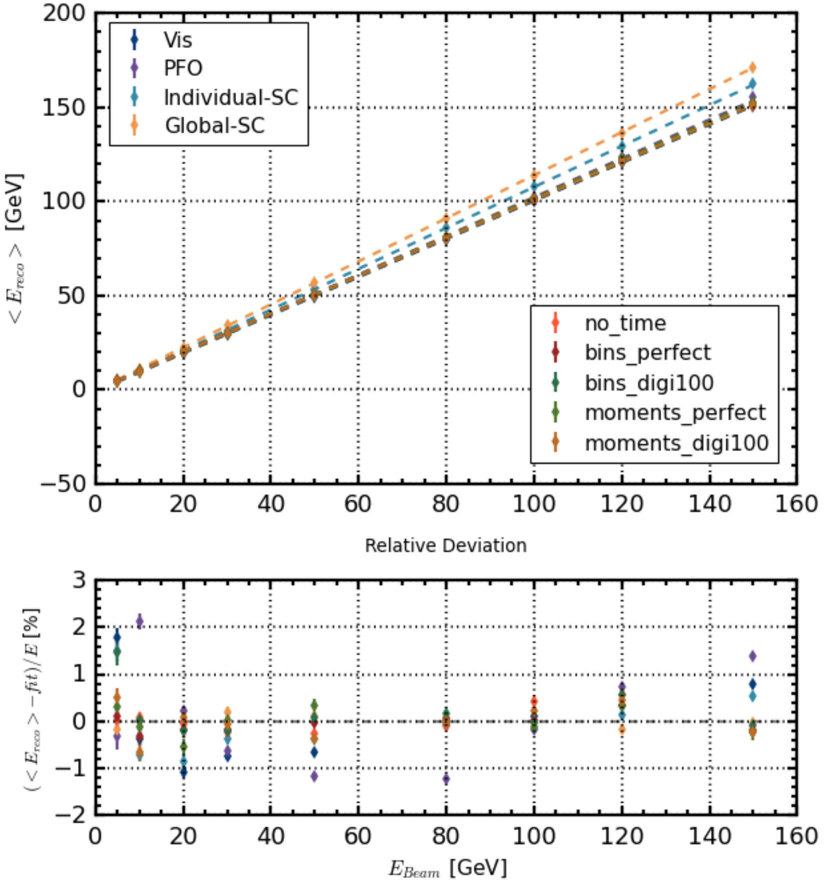
Method	a	b	chi2/ndf
Vis	1.0212 ± 0.0001	-0.121 ± 0.004	59.69
PFO	1.0186 ± 0.0001	-0.027 ± 0.004	0.83
HCAL-SC	1.0212 ± 0.0001	-0.121 ± 0.004	58.99
Global-SC	1.0219 ± 0.0001	-0.122 ± 0.004	58.43
no_time	0.9998 ± 0.0003	0.175 ± 0.006	627.27
bins_perfect	0.9599 ± 0.0003	0.208 ± 0.006	714.82
bins_digi100	0.9902 ± 0.0002	0.070 ± 0.006	950.27
moments_perfect	1.0074 ± 0.0002	-0.488 ± 0.008	415.91
moments_digi100	1.0037 ± 0.0002	0.146 ± 0.007	866.51

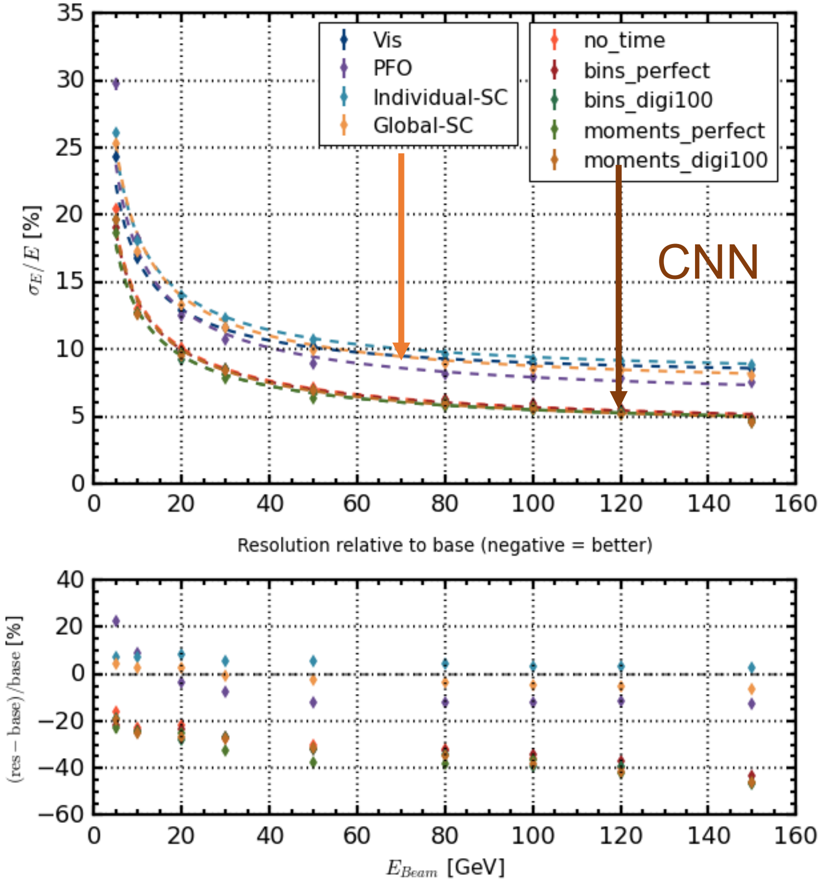
Resolution

Method	S	C	chi2/ndf
Vis	18.20 ± 0.12%	1.29 ± 0.02%	7.78
PFO	17.29 ± 0.12%	1.39 ± 0.02%	3.20
HCAL-SC	18.17 ± 0.12%	1.30 ± 0.02%	7.38
Global-SC	18.19 ± 0.12%	1.32 ± 0.02%	8.36
no_time	22.18 ± 0.29%	2.08 ± 0.06%	72.94
bins_perfect	16.98 ± 0.30%	2.68 ± 0.05%	41.30
bins_digi100	18.69 ± 0.27%	2.41 ± 0.05%	10.40
moments_perfect	25.36 ± 0.16%	-0.00 ± 63.70%	13.96
moments_digi100	25.55 ± 0.25%	1.30 ± 0.08%	37.22

Kaon samples

- CNN model(trained by pion samples) performs well on kaon- samples.
- Linearity within 2%; Resolution: 20% - 40% improvement.
- But a bit worse compared with working on pi+ samples.





Linearity

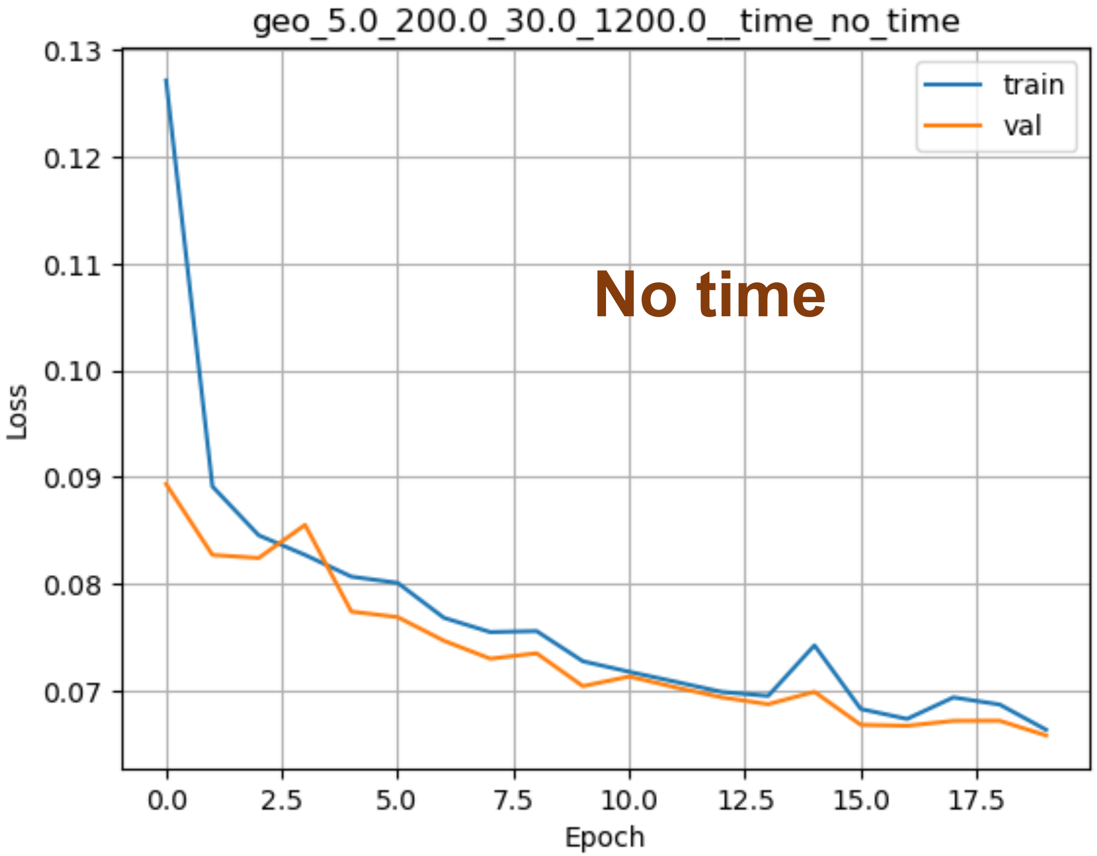
Method	a	b	chi2/ndf
Vis	1.0119 ± 0.0004	-0.811 ± 0.009	62.72
PFO	1.0296 ± 0.0003	-0.625 ± 0.011	193.33
HCAL-SC	1.0862 ± 0.0004	-0.866 ± 0.010	24.51
Global-SC	1.1433 ± 0.0004	-0.345 ± 0.010	1.70
no_time	1.0174 ± 0.0005	-0.259 ± 0.008	5.59
bins_perfect	1.0090 ± 0.0003	-0.104 ± 0.007	6.37
bins_digi100	1.0093 ± 0.0002	-0.241 ± 0.008	24.66
moments_perfect	1.0216 ± 0.0005	-0.325 ± 0.013	5.05
moments_digi100	1.0121 ± 0.0003	-0.193 ± 0.010	16.18

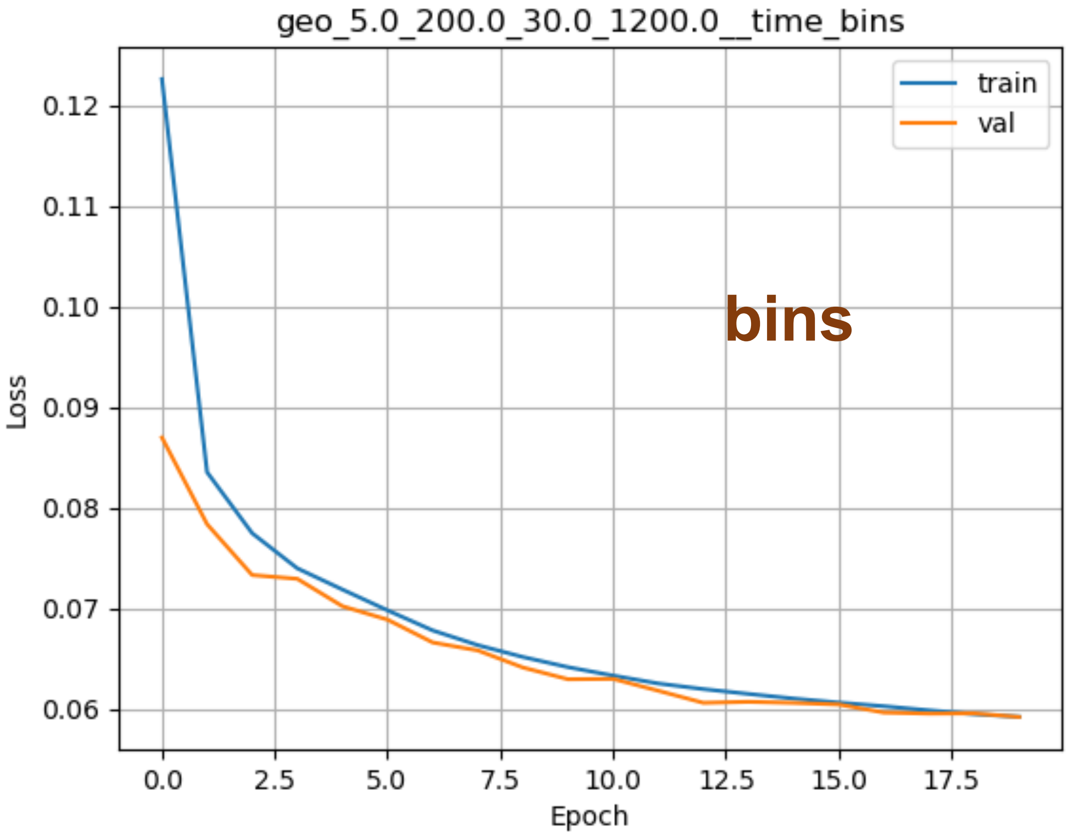
Resolution

Method	S	C	chi2/ndf
Vis	48.76 ± 0.39%	7.54 ± 0.05%	5.53
PFO	51.96 ± 0.42%	5.92 ± 0.06%	47.19
HCAL-SC	53.42 ± 0.42%	7.61 ± 0.05%	3.72
Global-SC	51.73 ± 0.35%	6.81 ± 0.05%	5.73
no_time	42.18 ± 0.37%	3.76 ± 0.12%	10.47
bins_perfect	41.10 ± 0.34%	3.88 ± 0.07%	7.94
bins_digi100	39.11 ± 0.31%	3.83 ± 0.04%	13.25
moments_perfect	39.13 ± 0.54%	3.82 ± 0.10%	4.06
moments_digi100	41.75 ± 0.41%	3.55 ± 0.08%	8.40

Effects of Time

Time helps with generalization and convergence stability, but it is not revolutionary.





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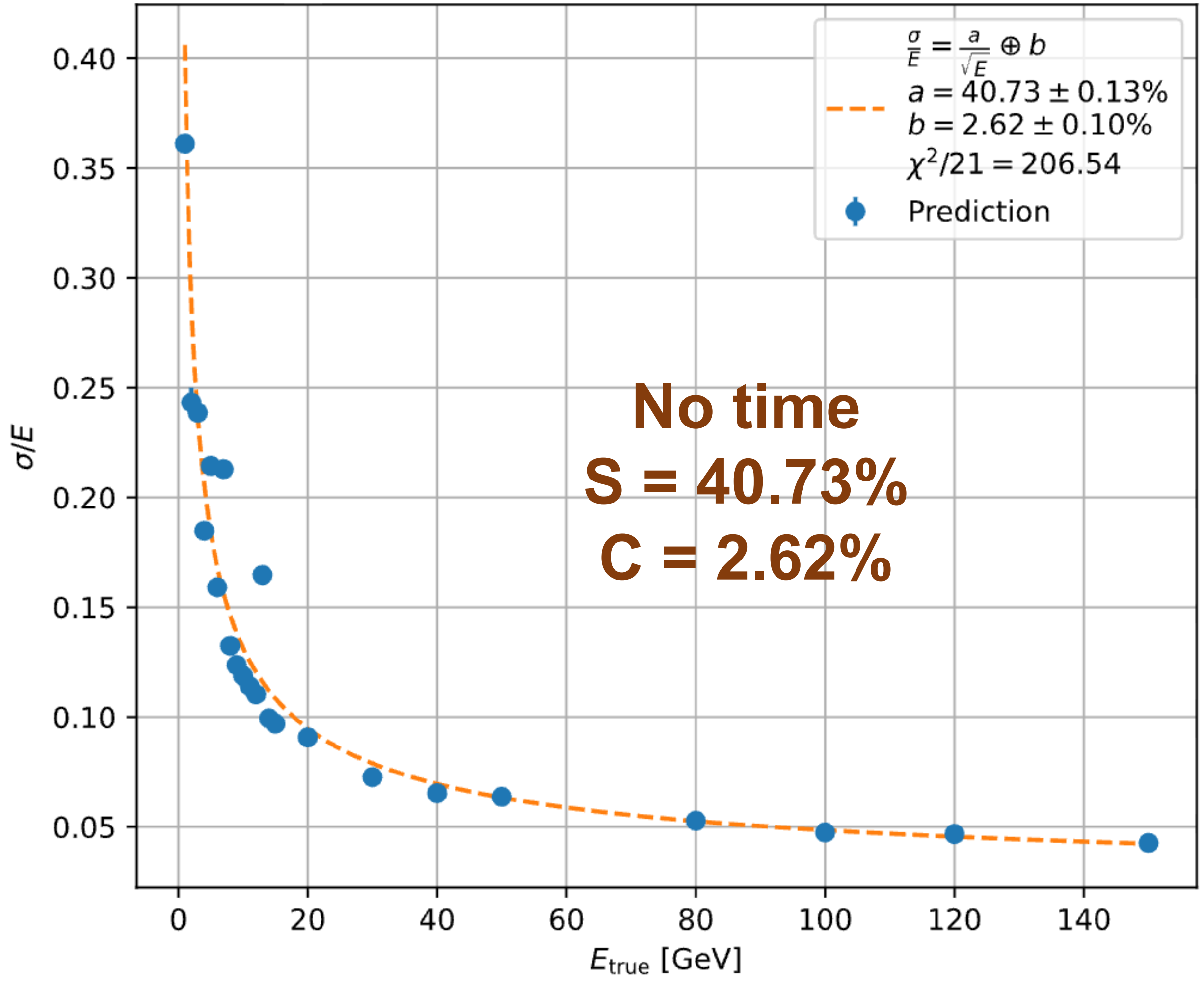
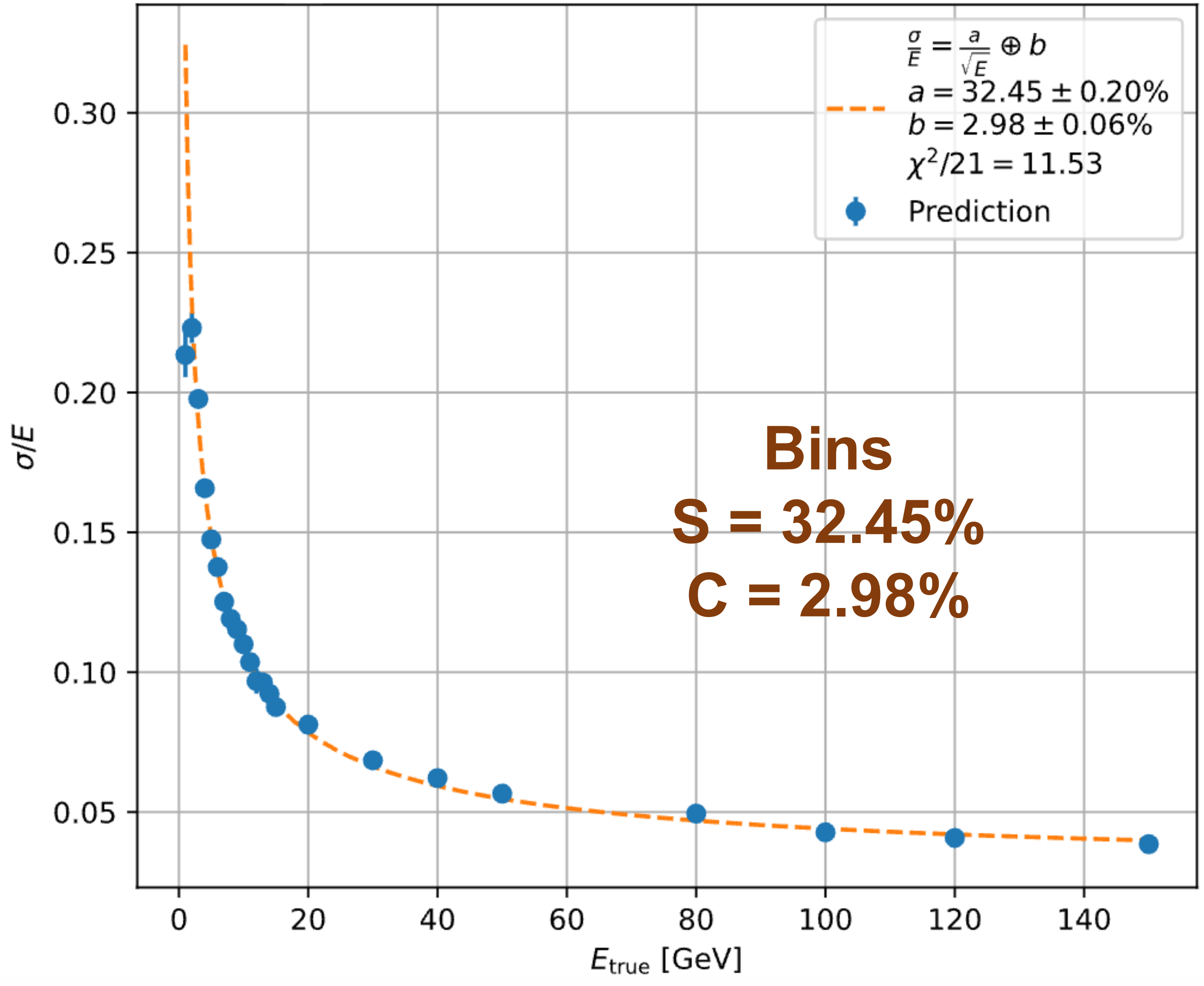




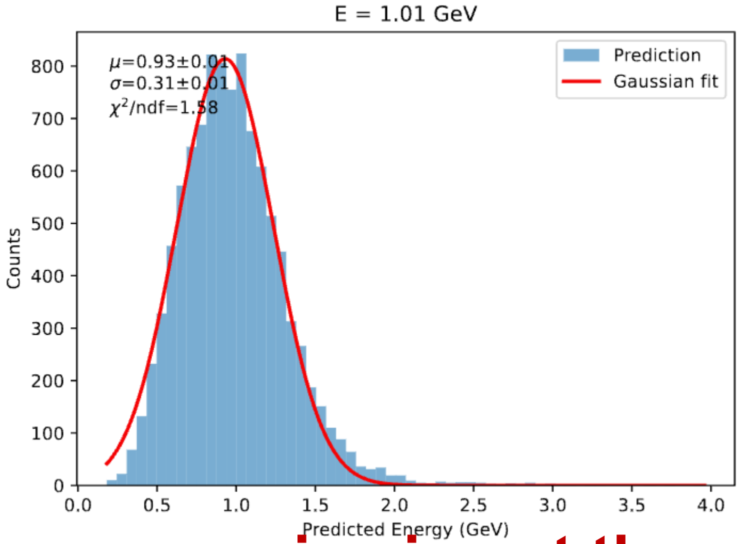
Summary

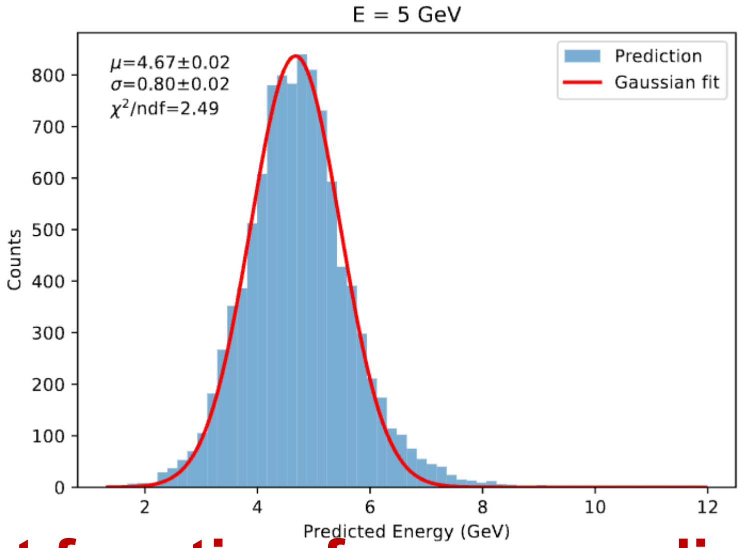
- The CNN significantly reduces the stochastic (S) and constant (C) terms for π, which essentially corresponds to an implicit software compensation.
  - EM sub-shower information generated by π^0
  - Differences in shower topology
  - Differences in the temporal structure of hadronic vs EM
- The performance degradation observed for e^- demonstrates that the model has learned hadronic physics rather than simply performing a trivial fit.
- Timing information looks not very helpful, maybe need further optimization

Thanks!

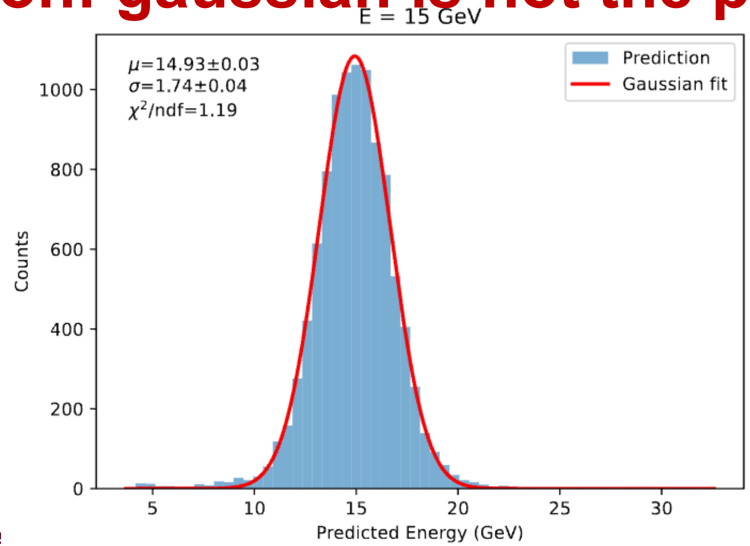
Backup

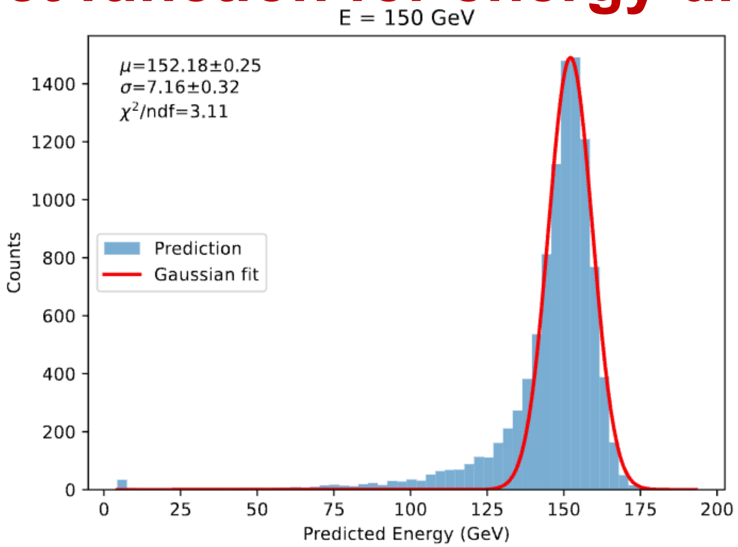
Energy distribution





One reason: gaussian is not the perfect function for energy distribution.



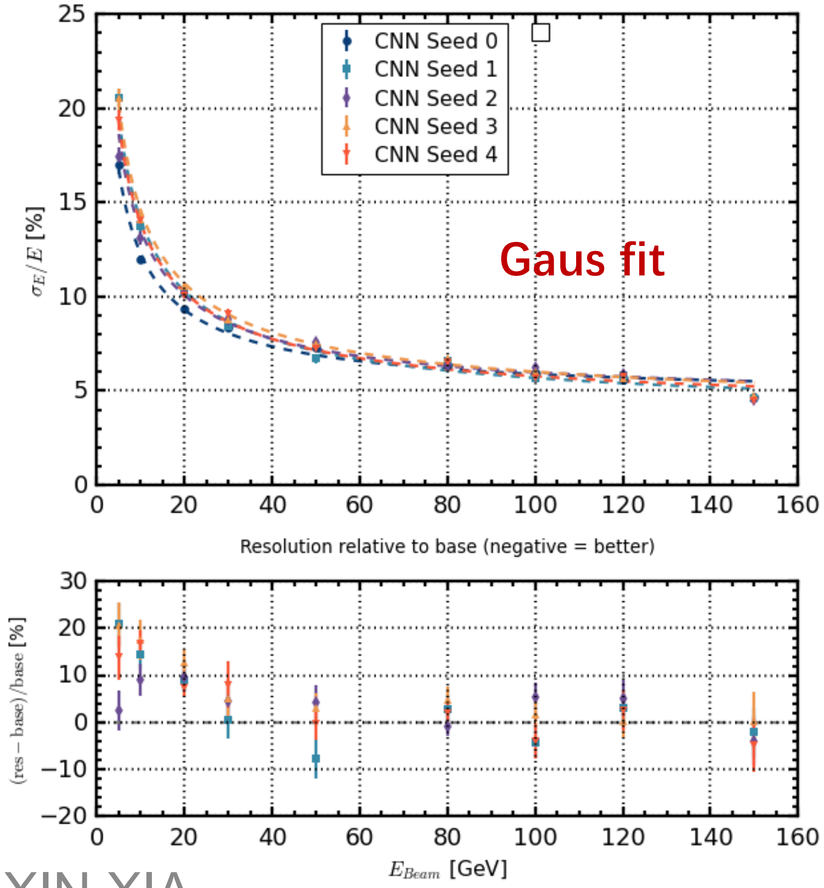


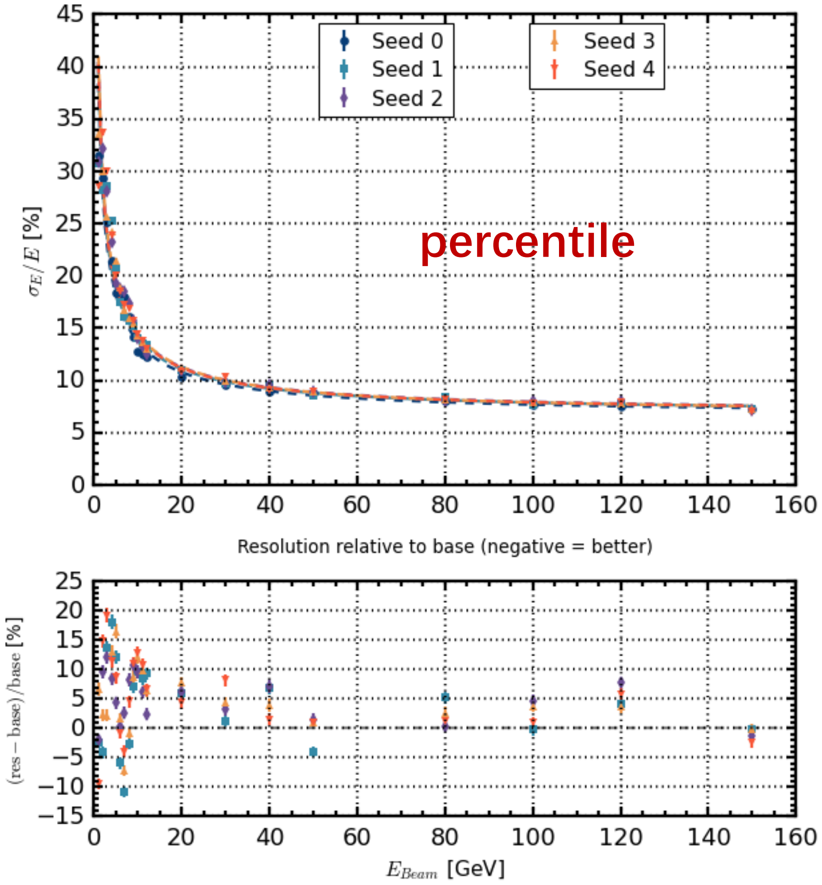
Seeds Problems

One reason: gaussian is not the perfect function for energy distribution.

Method	S	C	chi2/ndf
CNN Seed 0	35.99 ± 0.51%	4.65 ± 0.10%	4.02
CNN Seed 1	42.92 ± 0.60%	3.72 ± 0.13%	5.84
CNN Seed 2	40.51 ± 0.69%	4.40 ± 0.11%	9.89
CNN Seed 3	44.32 ± 0.62%	4.05 ± 0.11%	3.30
CNN Seed 4	42.22 ± 0.53%	3.94 ± 0.14%	4.81

Method	S	C	chi2/ndf
Seed 0	37.79 ± 0.10%	6.68 ± 0.03%	115.50
Seed 1	39.02 ± 0.10%	6.83 ± 0.03%	176.54
Seed 2	39.86 ± 0.11%	6.87 ± 0.03%	188.67
Seed 3	40.43 ± 0.11%	6.77 ± 0.03%	89.66
Seed 4	39.62 ± 0.11%	6.83 ± 0.03%	288.36



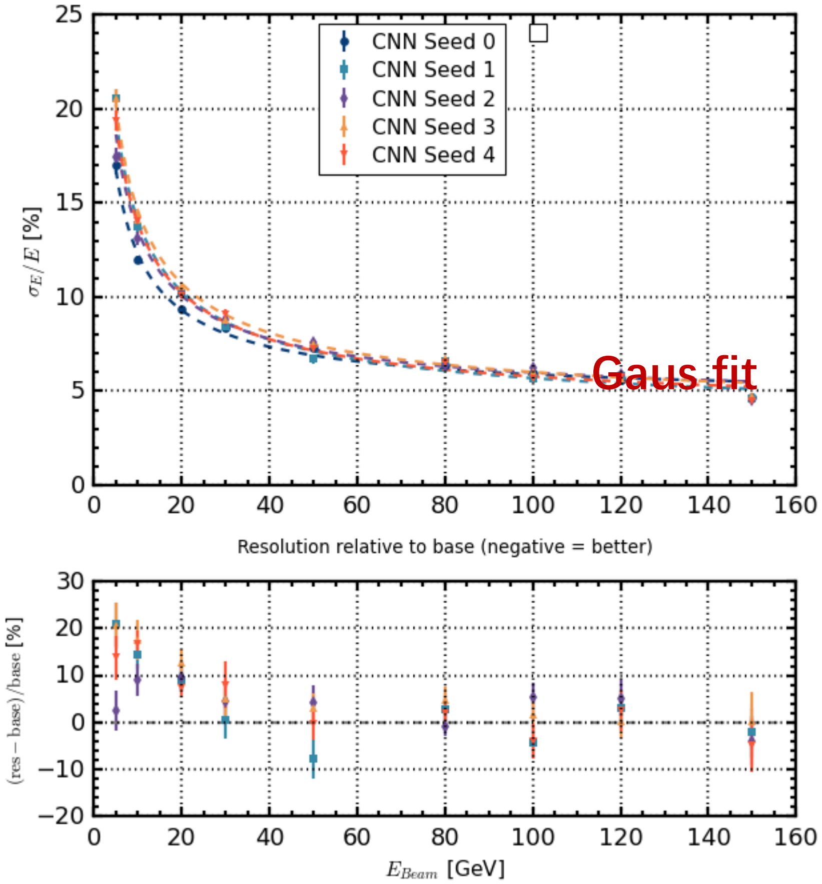


Seeds Problems

- **The model only predict the energy for each event. And then get the energy distribution for each energy point. Then choose different way to get the sigma/mean value. Then use $\frac{\sigma}{\mathrm{E}} = \frac{\mathrm{S}}{\sqrt{\mathrm{E}}} \oplus \mathrm{C}$ to fit the whole energy range. Each step introduces differences, which are reflected in S and C.**

Seeds Problems

Different seed, different results. Significant in lower energies.



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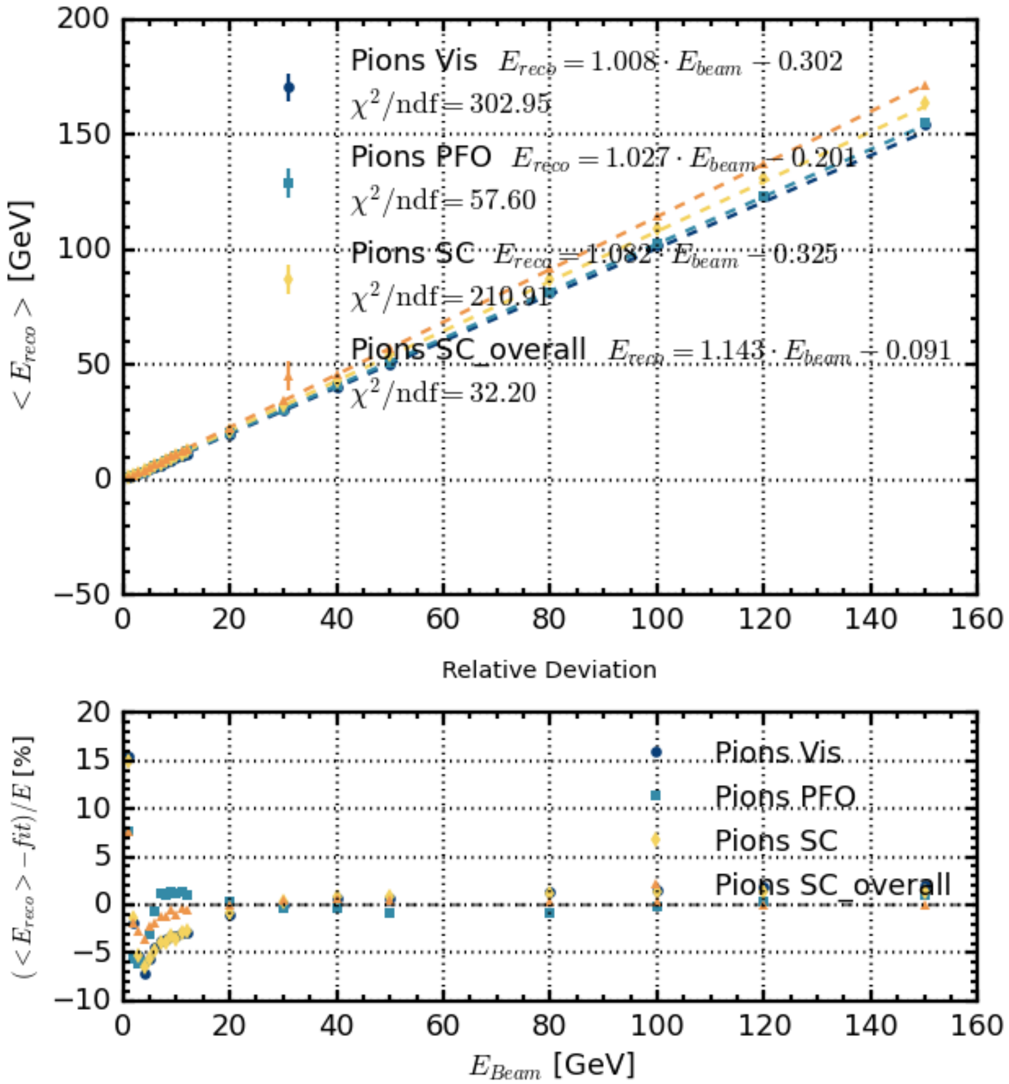
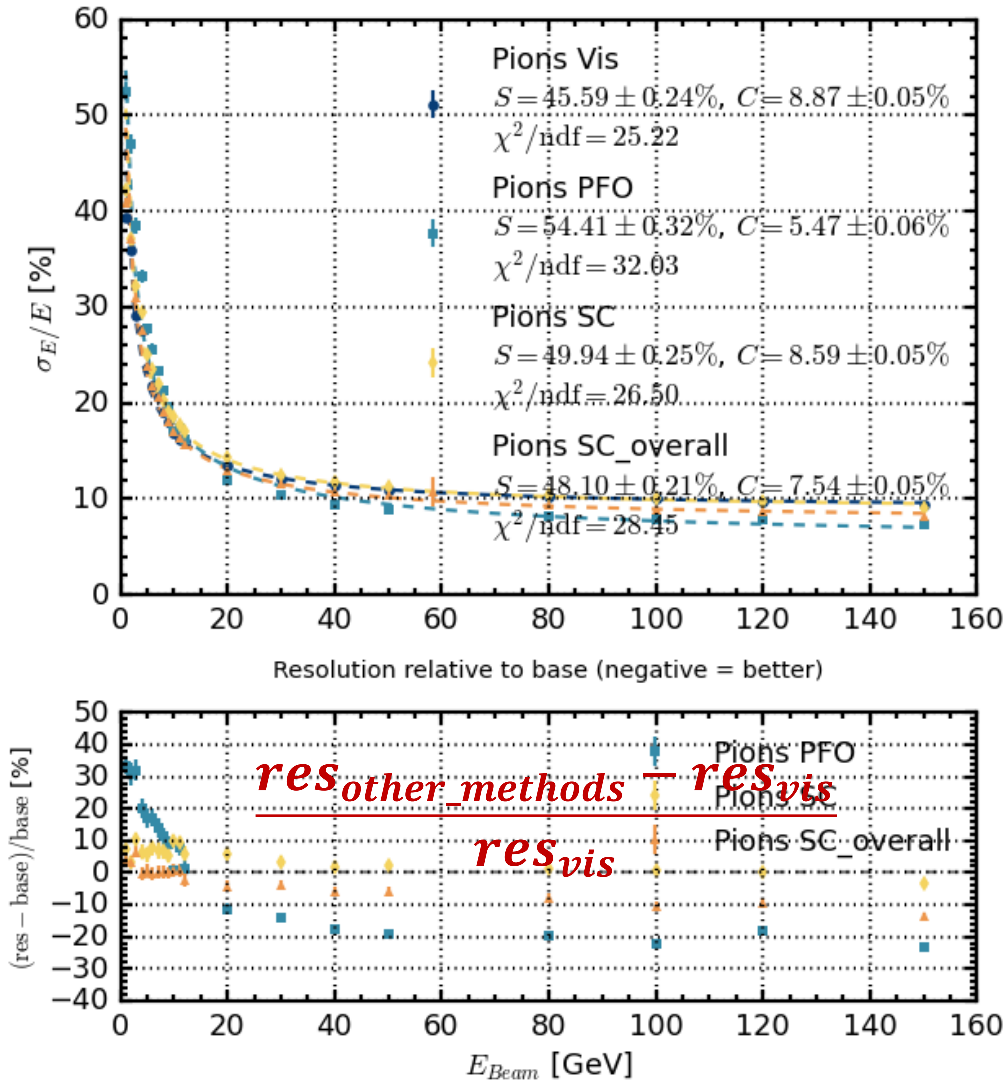
Seeds Problems

The information of low energy is less than high energy, model can get several solutions from the less information, it’s hard to converge to only one solution.

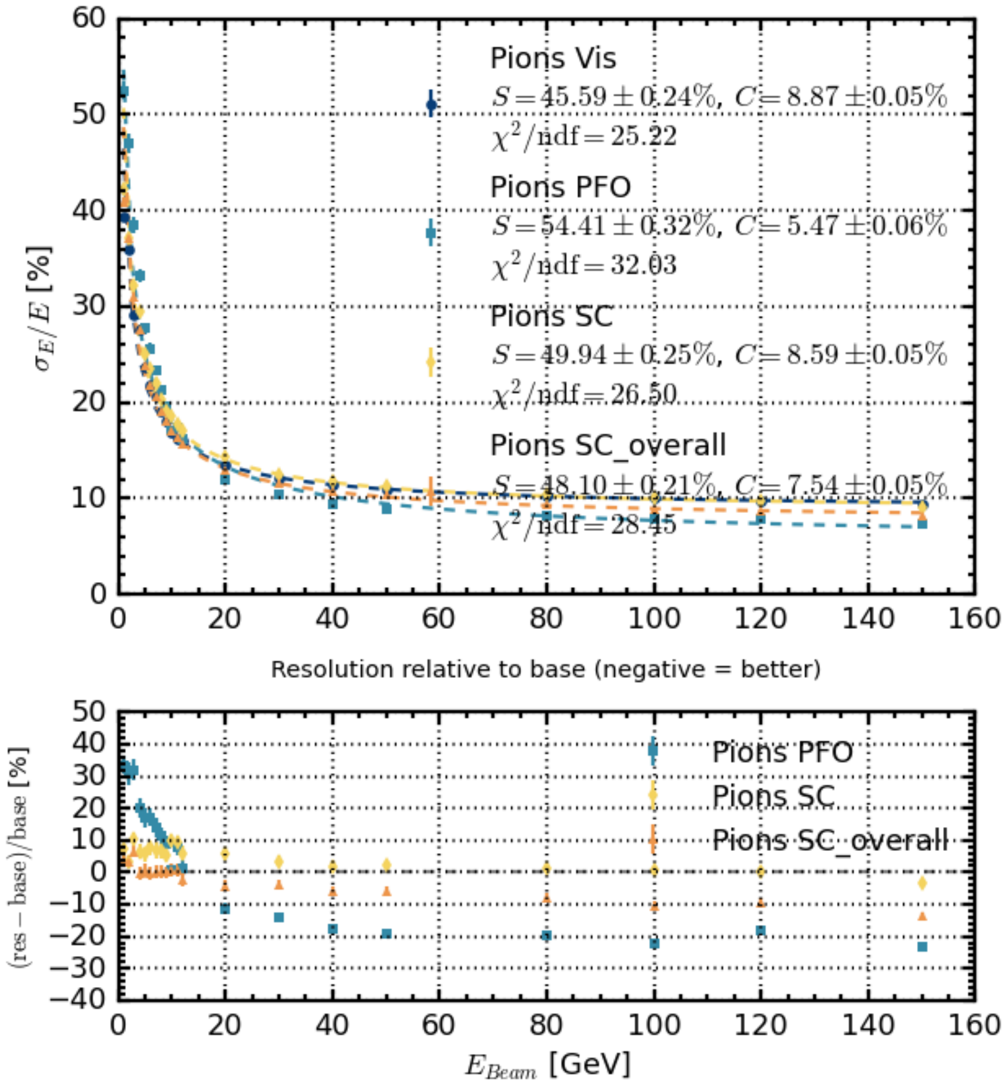
Use different seeds, the first few batches determine which solution the model will choose.

Pion+ Samples





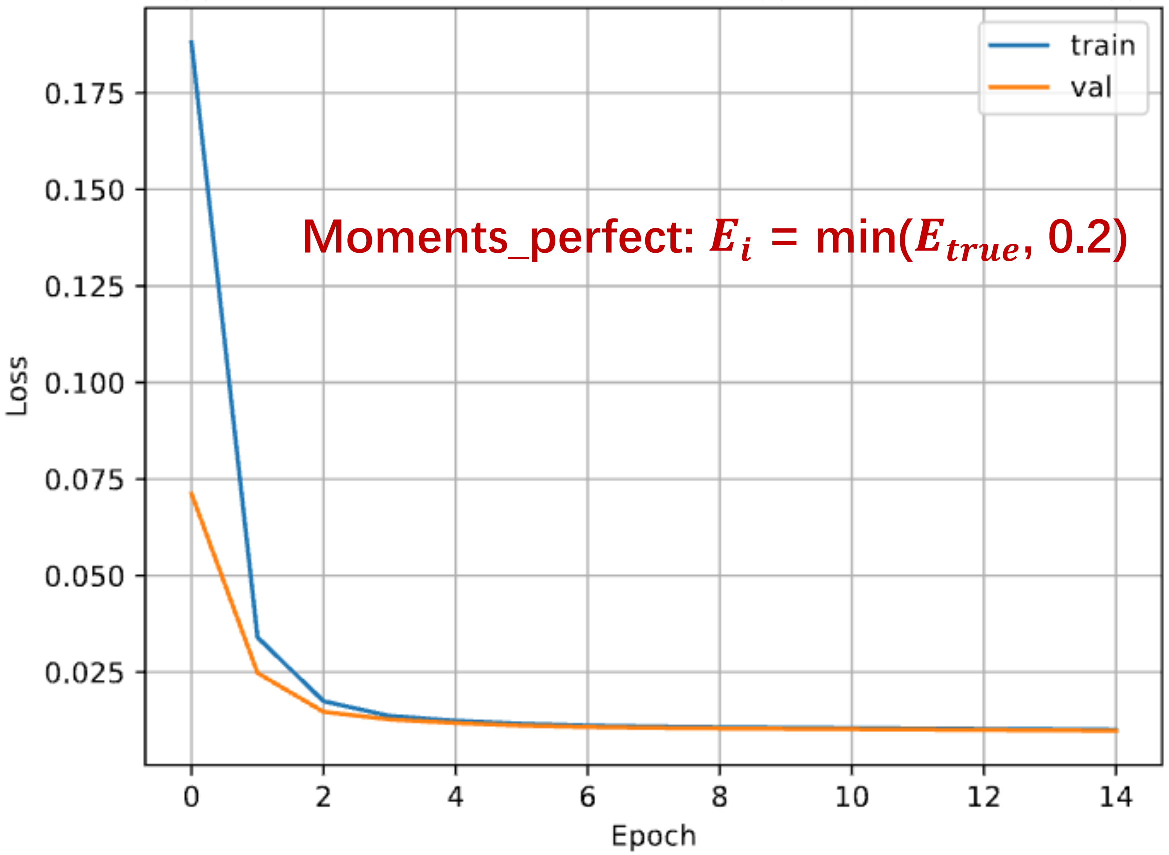
Pion+ Samples

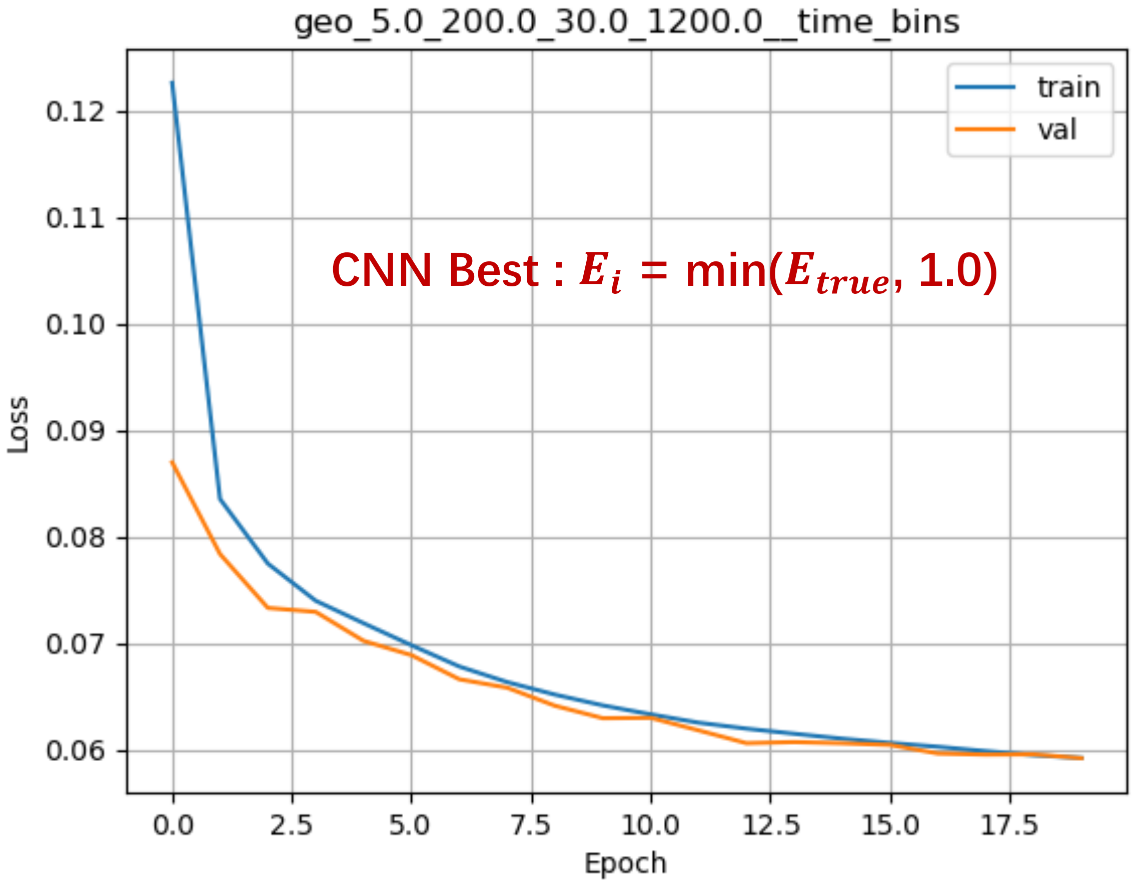


For the traditional methods:

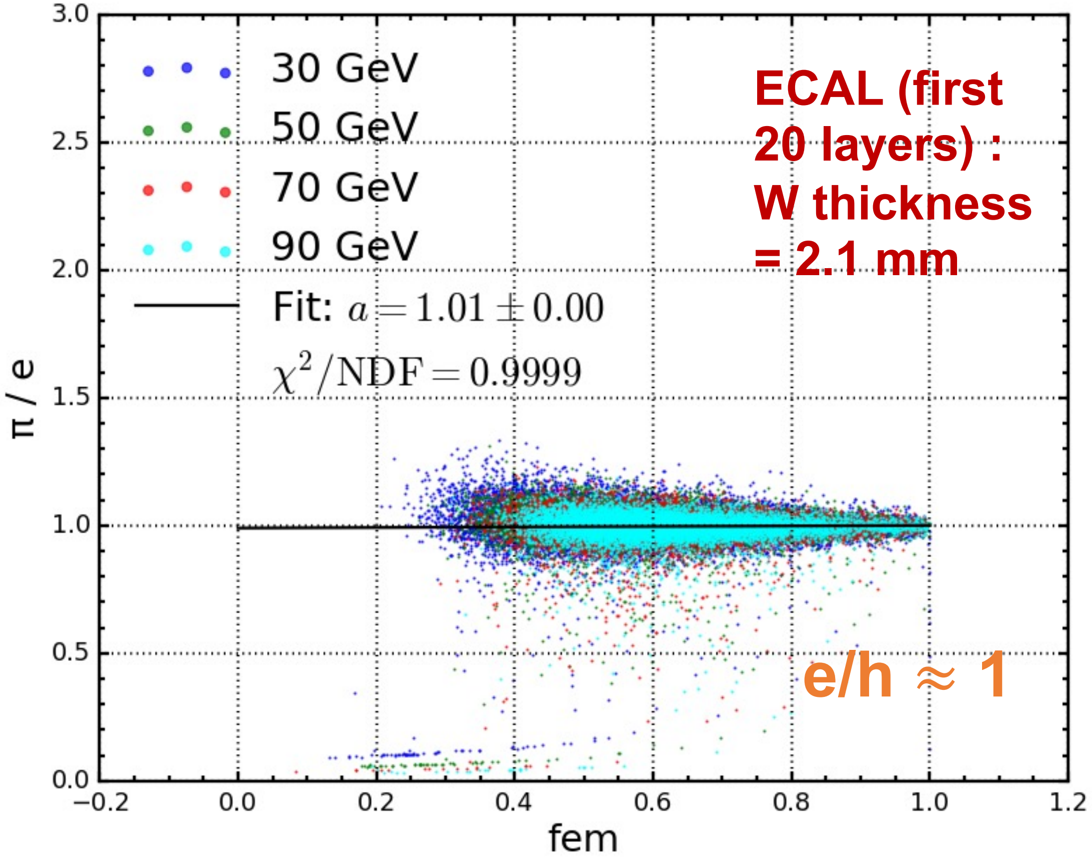
- PFO shows the best performance, improves ~20%
- HCAL-Only SC has no improvement, and even worse at lower energies.
- Global SC improves ~10%
- Why HCAL-Only SC worse? Global SC better?

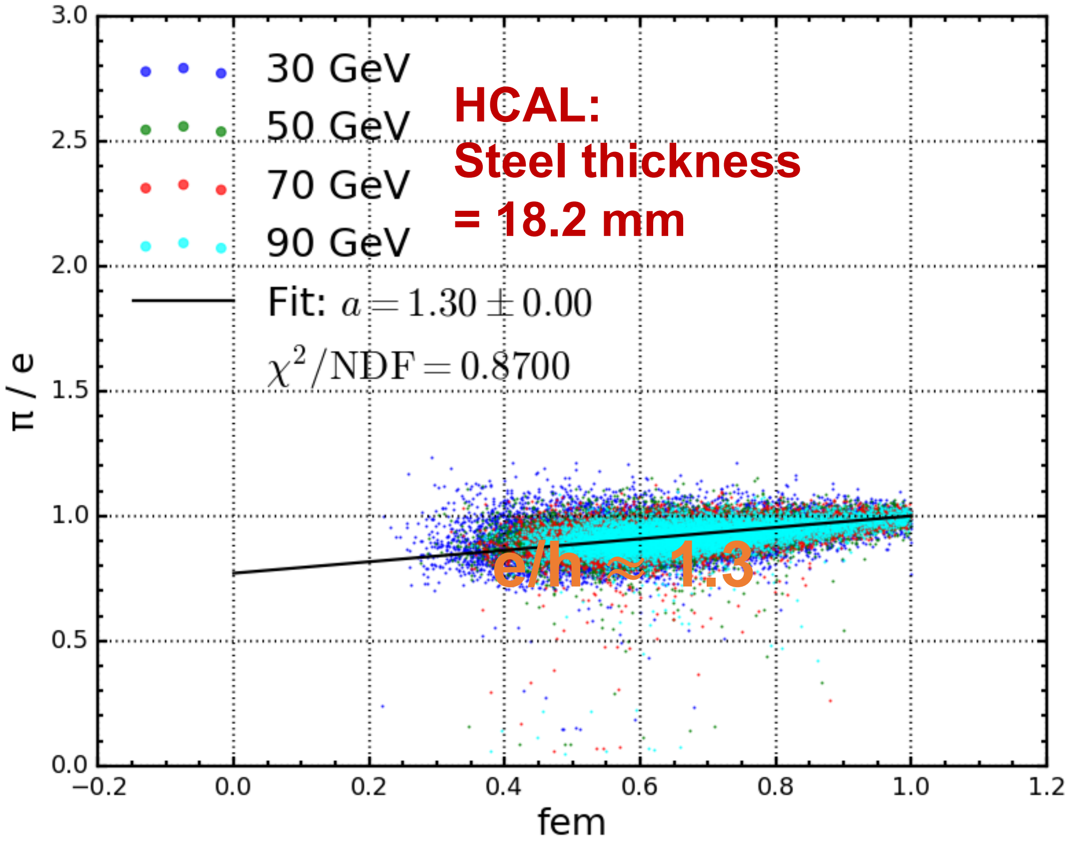
Loss function curve





Individual e/h





My Guess - Disrupt the correlation

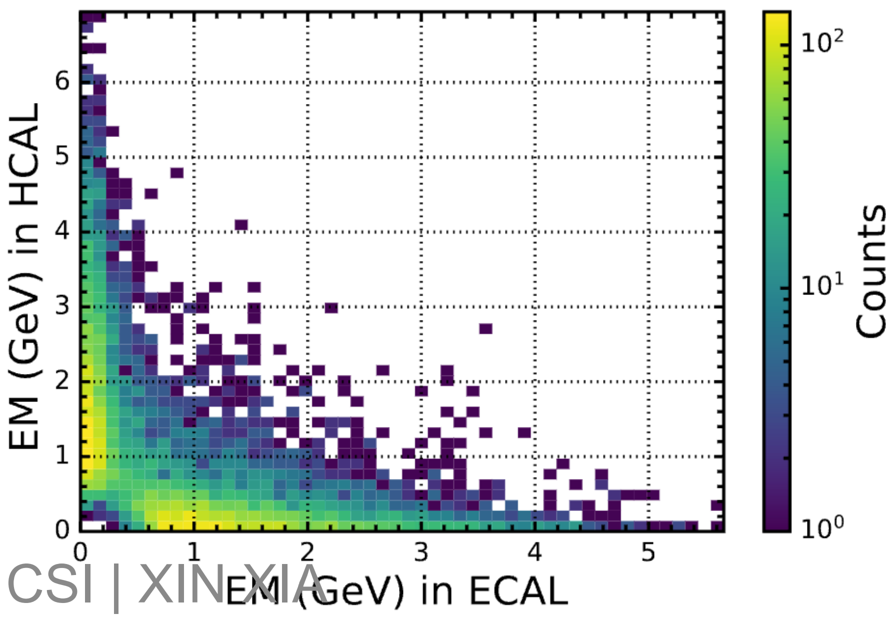
- $E_{Vis} = E_{ECAL} + E_{HCAL}$
- $E_{SC} = E_{ECAL} + w(f_{em})E_{HCAL}$
  - $E_{ECAL} = e_{ECAL}E_{em}^{ECAL} + h_{ECAL}E_{had}^{ECAL}$,
  - $E_{HCAL} = e_{HCAL}E_{em}^{HCAL} + h_{HCAL}E_{had}^{HCAL}$
  - $E_{em}^{HCAL} \uparrow,\ E_{em}^{ECAL} \downarrow$
  - $Var(E_{ECAL} + E_{HCAL}) = Var(E_{ECAL}) + Var(wE_{HCAL}) + 2Cov(E_{ECAL}, wE_{HCAL})$

$$f_{em\_ECAL} = \frac{EM\ in\ ECAL}{E_{ECAL}}$$

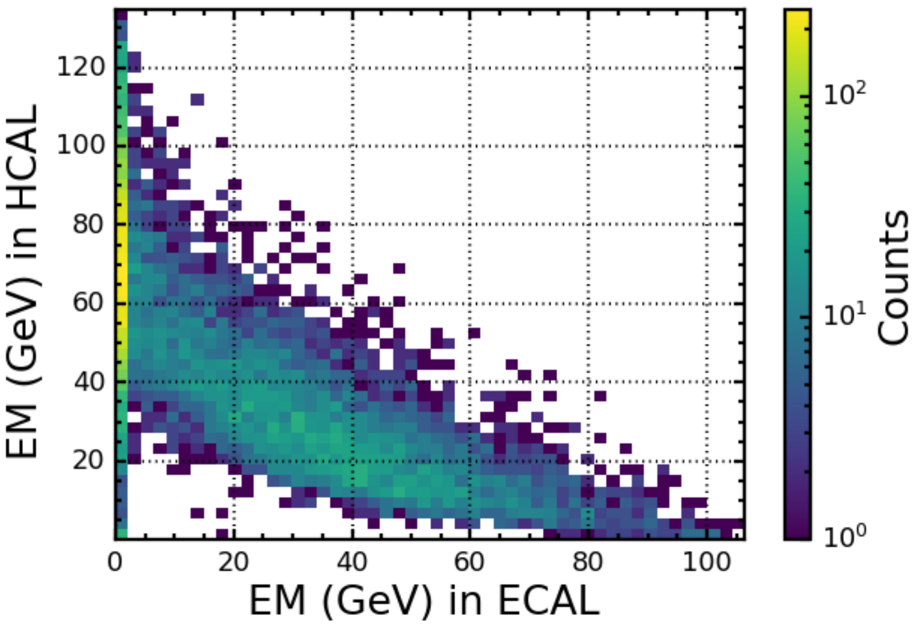
$$f_{em\_HCAL} = \frac{EM\ in\ HCAL}{E_{HCAL}}$$

$$f_{em\_global} = \frac{f_{em\_ECAL} * E_{ECAL} + f_{em\_HCAL} * E_{ECAL}}{E_{ECAL} + E_{ECAL}}$$

5 GeV Pions Correlation: -0.54



100 GeV Pions Correlation: -0.75



My Guess - Disrupt the correlation

- $E_{Vis} = E_{ECAL} + E_{HCAL}$
- $E_{SC} = E_{ECAL} + w(f_{em})E_{HCAL}$
  - $E_{ECAL} = e_{ECAL}E_{em}^{ECAL} + h_{ECAL}E_{had}^{ECAL}$,
  - $E_{HCAL} = e_{HCAL}E_{em}^{HCAL} + h_{HCAL}E_{had}^{HCAL}$
  - $E_{em}^{HCAL} \uparrow, \; E_{em}^{ECAL} \downarrow$
  - $Var(E_{ECAL} + E_{HCAL}) = Var(E_{ECAL}) + Var(wE_{HCAL}) + 2Cov(E_{ECAL}, wE_{HCAL})$

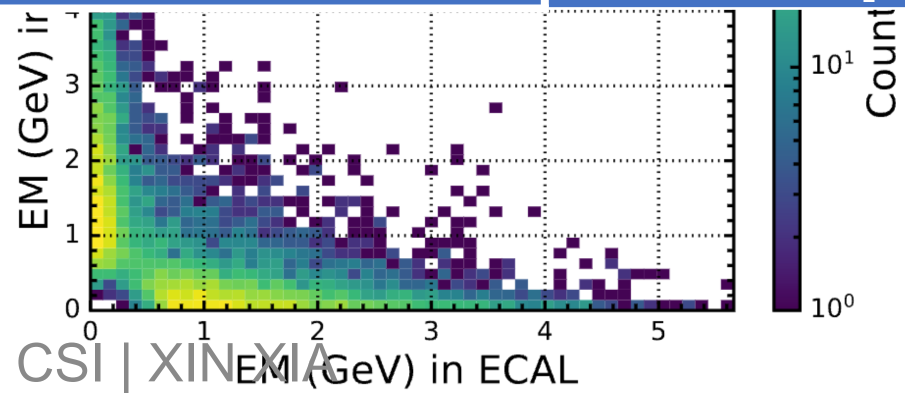
$$f_{em\_ECAL} = \frac{EM\ in\ ECAL}{E_{ECAL}}$$

$$f_{em\_HCAL} = \frac{EM\ in\ HCAL}{E_{HCAL}}$$

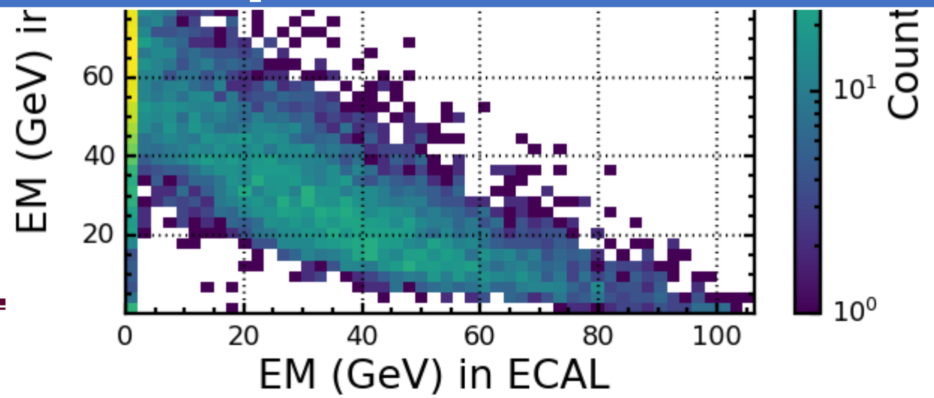
$$f_{em\_global} = \frac{f_{em\_ECAL} * E_{ECAL} + f_{em\_HCAL} * E_{ECAL}}{E_{ECAL} + E_{ECAL}}$$

Software Compen (truth fem)	
	$E_{rec} = \frac{e}{\pi} \cdot E_{dep} = \frac{e}{f_{em} \cdot e + (1 - f_{em}) \cdot h} \cdot E_{dep} = \frac{e/h}{1 + f_{em}(e/h - 1)} \cdot E_{dep}$ (Global-SC)
	$E_{rec} = \frac{(e/h)_{ECAL}}{1 + f_{em\_ECAL}((e/h)_{ECAL} - 1)} \cdot E_{ECAL} + \frac{(e/h)_{HCAL}}{1 + f_{em\_HCAL}((e/h)_{HCAL} - 1)} \cdot E_{HCAL}$ (HCAL-SC)

5 GeV Pions Correlation: -0.54



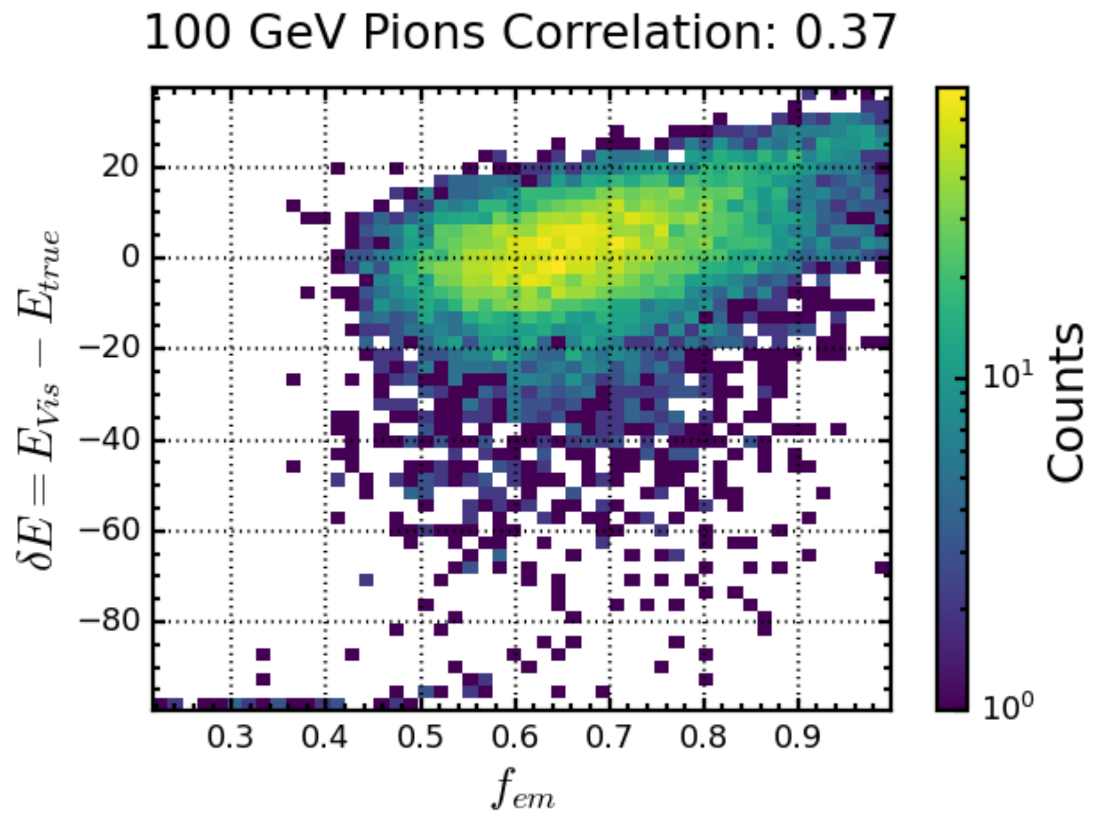
100 GeV Pions Correlation: -0.75

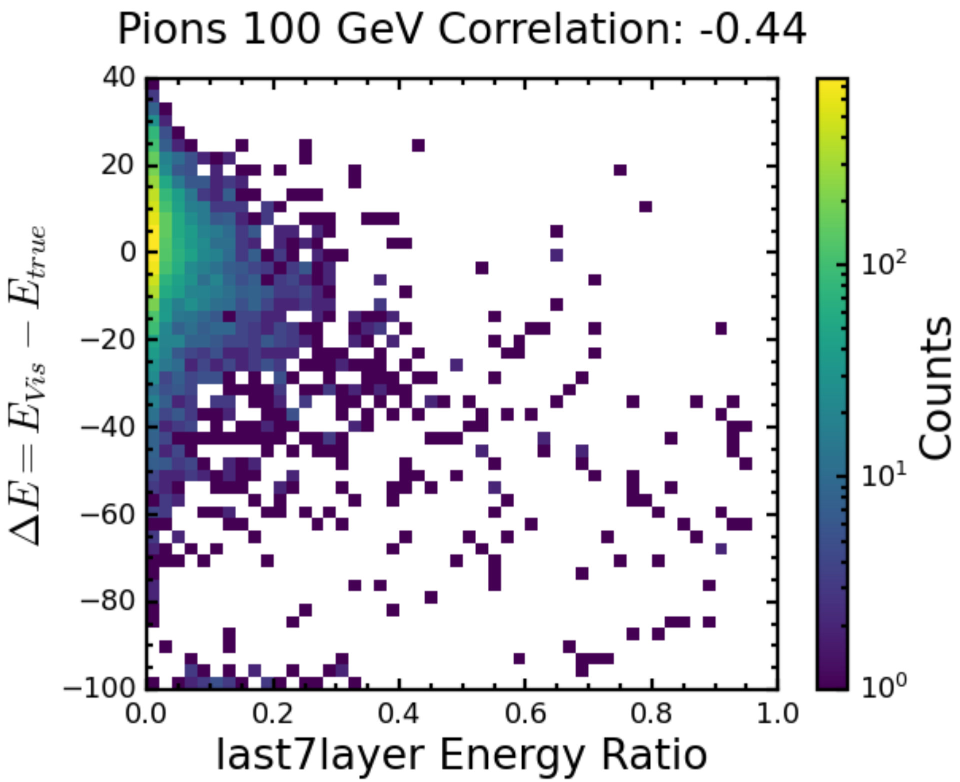


My Guess

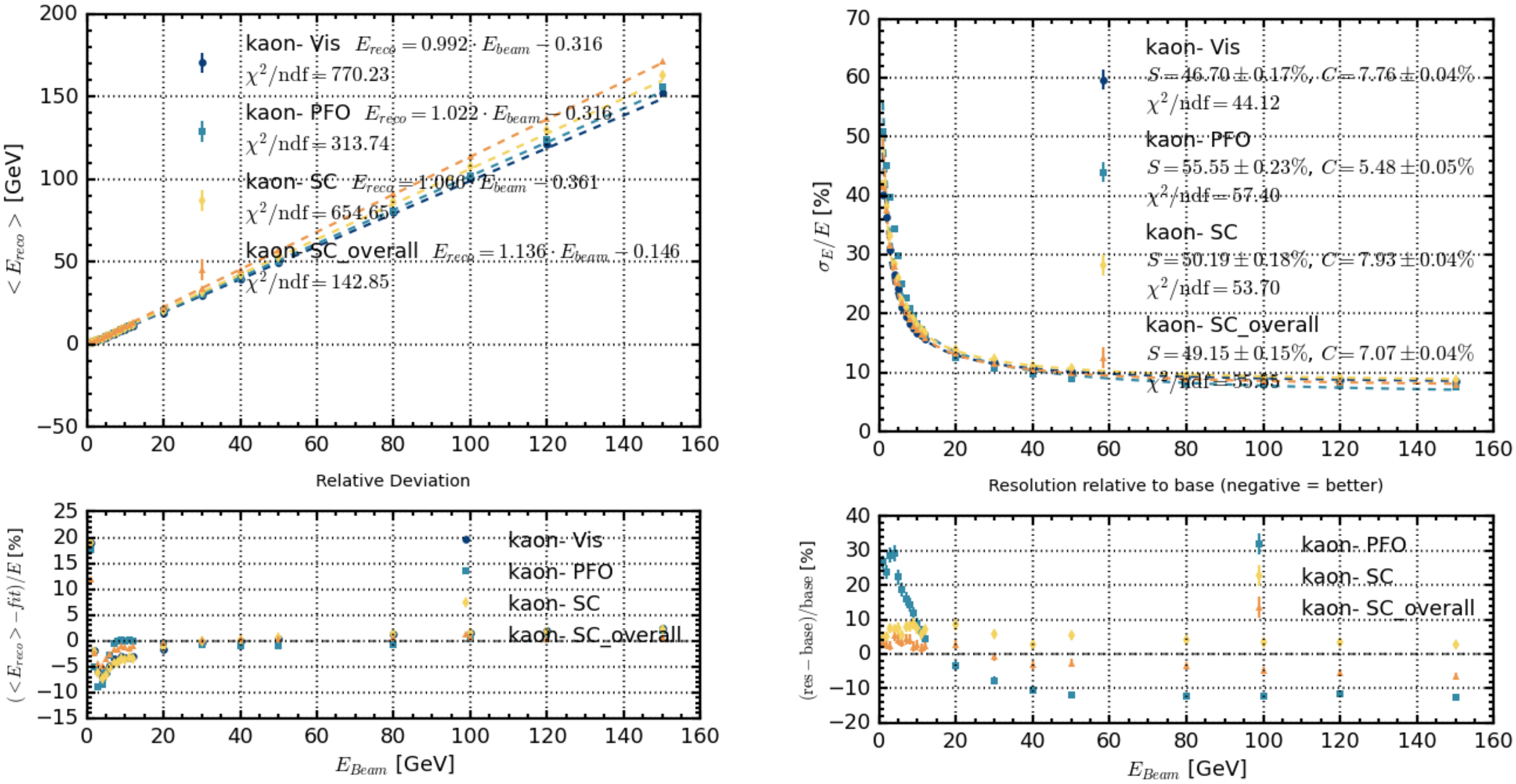
Why Global-SC better but not so good?

- $\mathbf{f_{em}} \uparrow, \mathbf{\Delta E > 0}, \frac{e}{h} \neq 1$
- But weak correlation & energy leakage

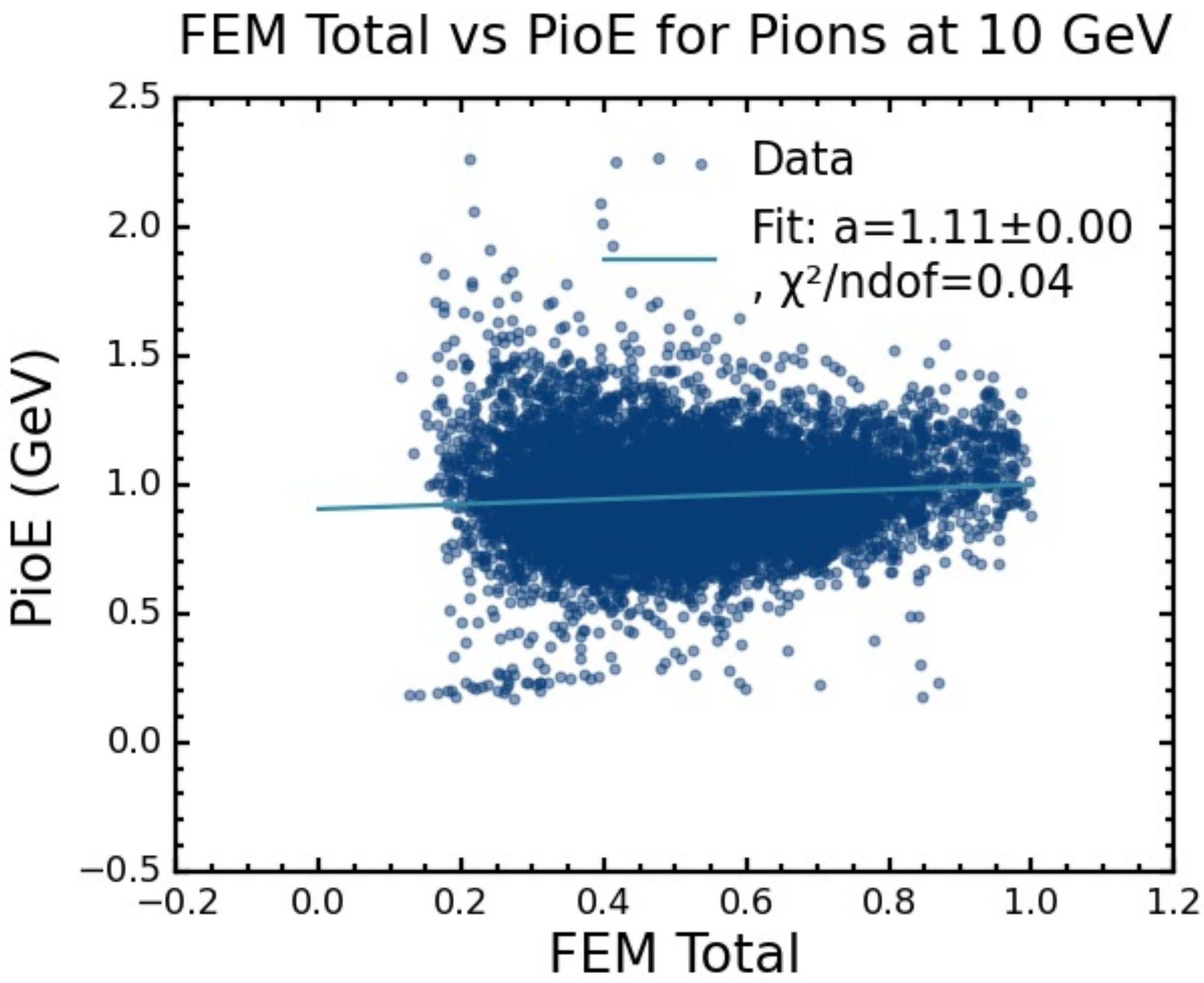




Kaon- samples



Global e/h


FEM Total vs PioE for Pions at 10 GeV
Data
Fit: a=1.11±0.00
, χ²/ndof=0.04
PioE (GeV)
FEM Total
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2