

# CNN-Based Hadron Energy Regression for the ILD SiW-ECAL and AHCAL System

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IJCLab, France

For ILD Software Meeting

2026/5/18

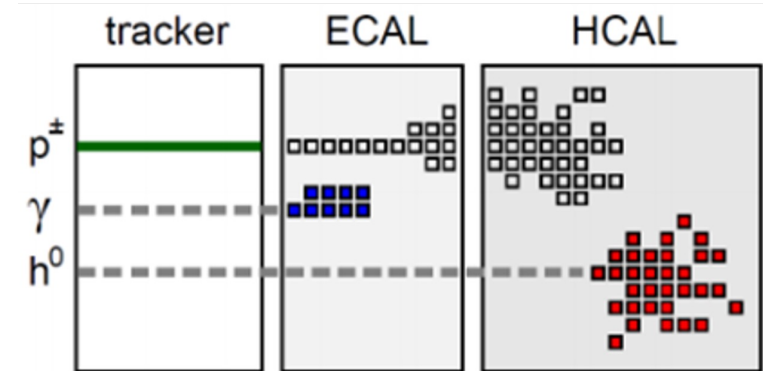
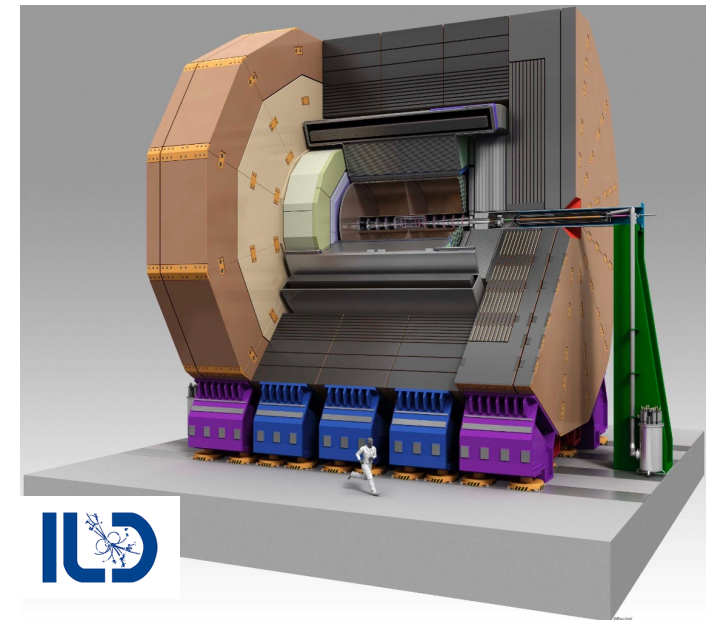




# Why Calorimeter Energy Reconstruction Matters?

- Future Higgs factories rely on detectors to measure the energies of final-state particles.
- These particles are combined into jets, and jet energy resolution is a key physics performance target.
- Pandora Particle-Flow Algorithm (PFA):
  - $\sigma_{\text{jet}}^2 = \sigma_{p^\pm, \text{tracker}}^2 + \sigma_{\gamma, \text{ECAL}}^2 + \sigma_{h^0, \text{HCAL}}^2 + \sigma_{\text{confusion}}^2$ 
    - $\sigma_{\text{ECAL}}, \sigma_{\text{HCAL}}$ : key ingredients and limiting factors
- An essential metric for detector R&D
  - Detector design optimization
  - Technology comparison

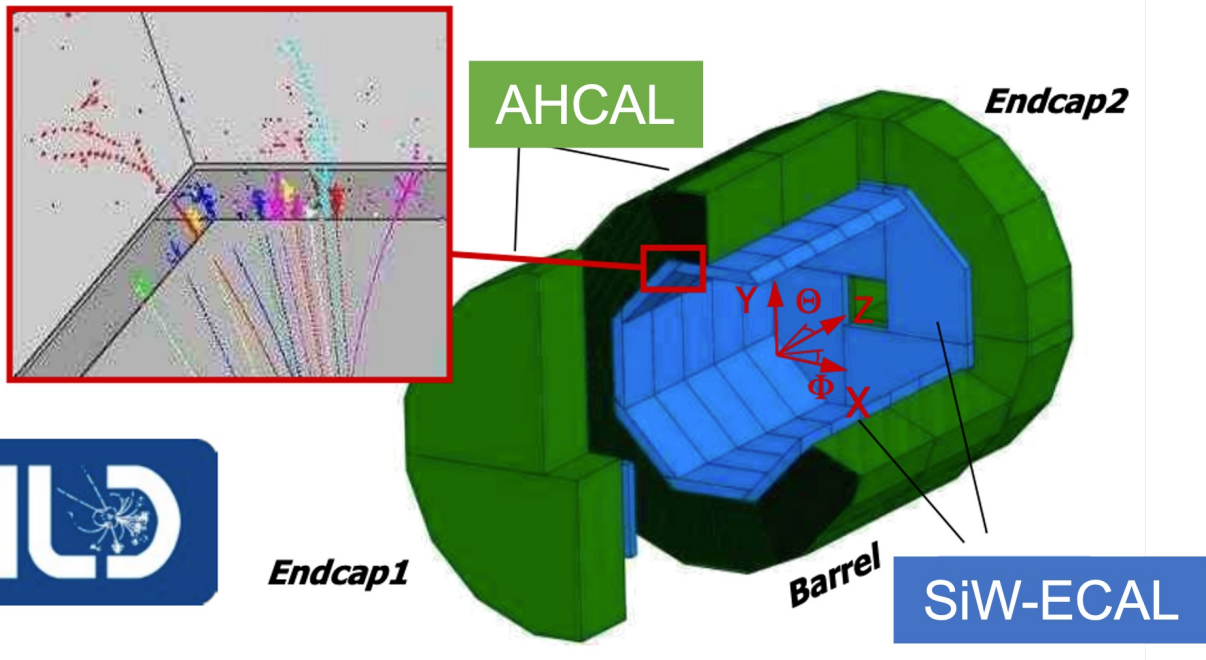
[Pandora PFA: arXiv:0907.3577](https://arxiv.org/abs/0907.3577)





# ILD Calorimeter system

	Active material	Absorber	Cell size	#. Layers	Length	Type
SiW-ECAL	Silicon	Tungsten	0.5×0.5 cm <sup>2</sup>	30 in 20 cm	~ 1λ <sub>I</sub>	Non-Compensation
AHCAL	Scintillator	Steel	3×3 cm <sup>2</sup>	48 in 1 m	~ 5λ <sub>I</sub>	Non-Compensation



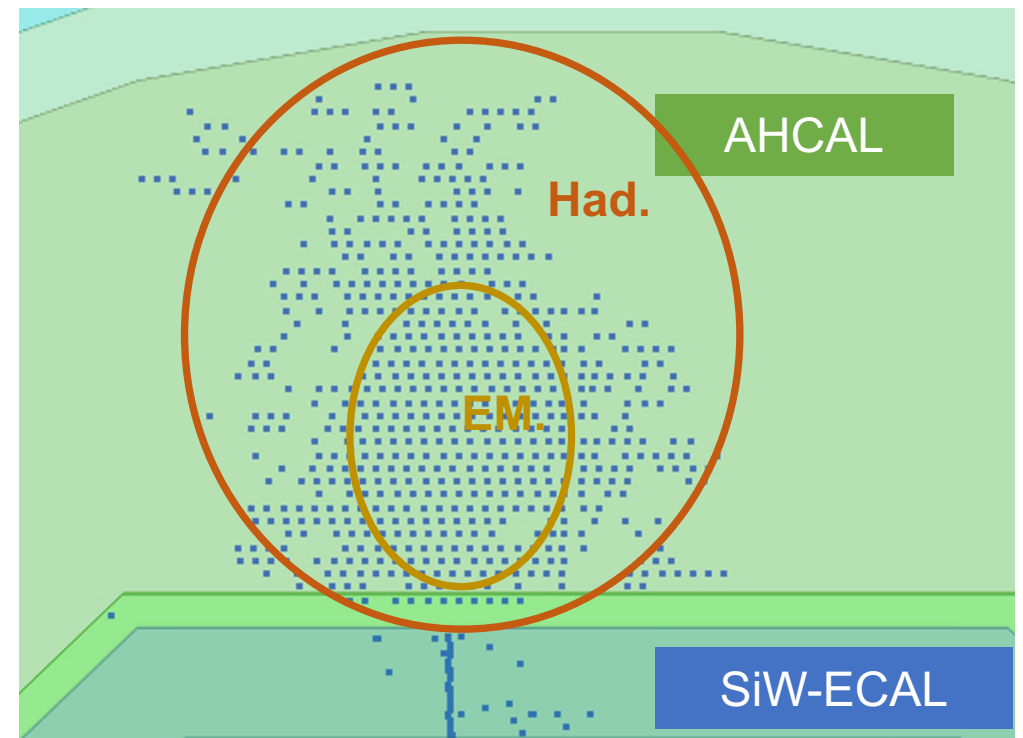
- Detector overview:
  - Combined SiW-ECAL + AHCAL system in ILD
  - High-granularity imaging calorimeter
- **Goal:** study hadron energy reconstruction in the realistic combined system (In PFA calorimeter design, ~55% particles interact in the ECAL)



# Challenges in Hadron Energy Reconstruction

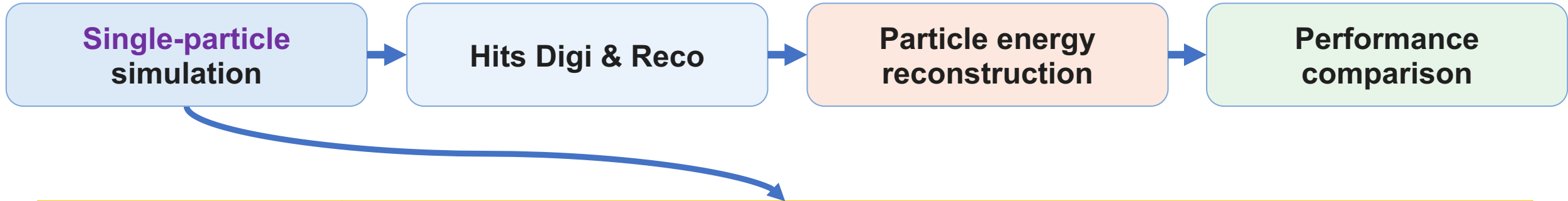
- Hadron showers contain:
  - **Electromagnetic(EM)** components  
( $\pi^0 \rightarrow \gamma\gamma$ )
  - **Hadronic** components
- The EM fraction fluctuates significantly event by event
- However, **Non-compensating** calorimeters:
  - Different response to EM and hadronic components ( $e/h \neq 1$ )
- Therefore, large variations in detector response, which degraded the hadron energy resolution

**My work:**  
*CNN-based approach for the full ECAL + HCAL system  
(realistic detector setup)*





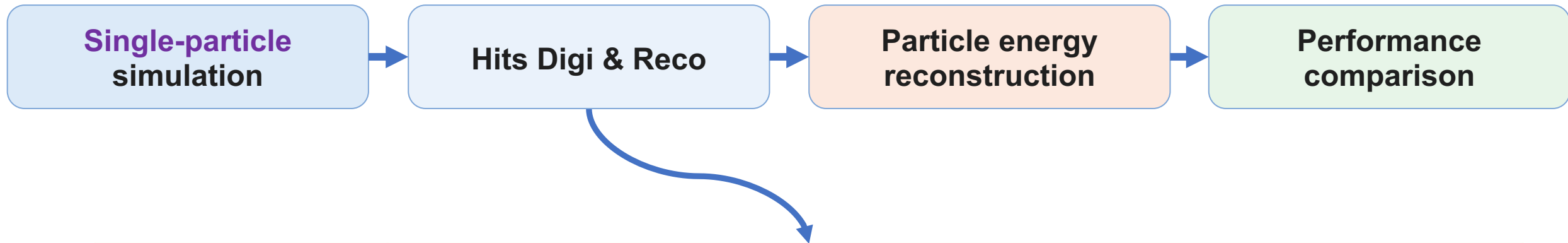
# Samples preparation based on ILD software



<b>Calorimeters</b>	SiW-ECAL and AHCAL				
<b>Incident position</b>	ECAL surface (with position smear in X-Z plane to avoid cracks)				
<b>Incident angle</b>	Perpendicular along the y-axis				
<b>Particle</b>	$\pi^+$	$e^-$	$K^-$	$K_L^0$	
<b>Energy</b>	<b>0.2 GeV – 200 GeV</b> (1k uniform E points)	3-150 GeV	3-150 GeV	3-150 GeV	3-150 GeV
<b>Num. of events</b>	<b>1M</b>	230k	230k	230k	230k
<b>Used for</b>	<b>Train &amp; Validation</b>	Evaluation	Evaluation	Evaluation	Evaluation



# Reco-level calorimeter hit observables



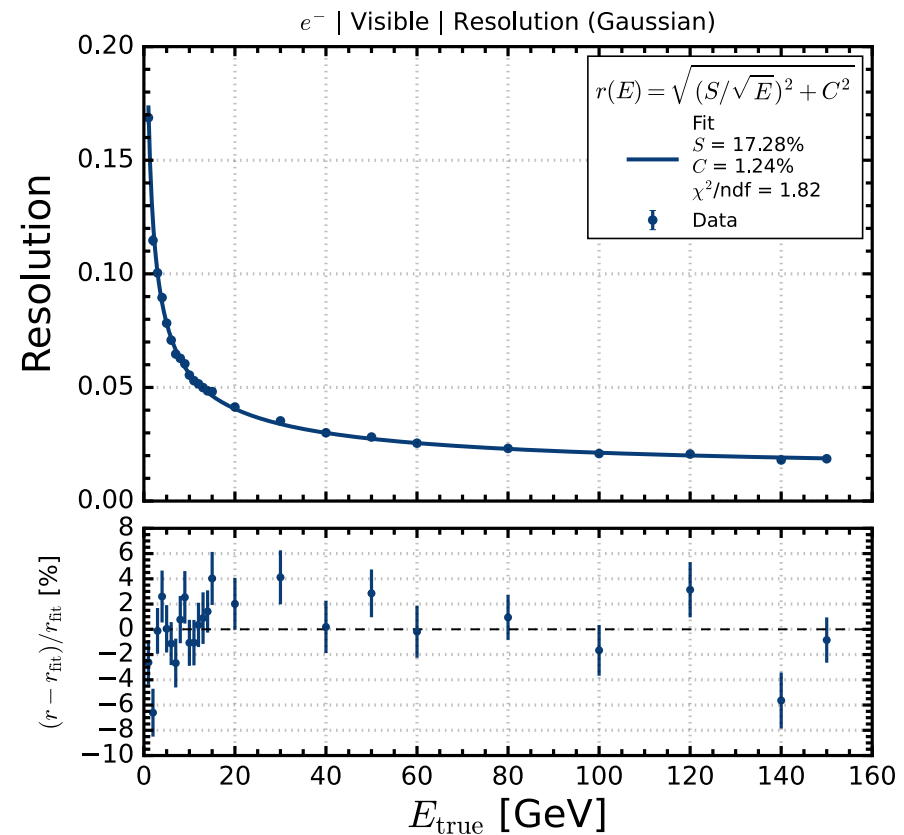
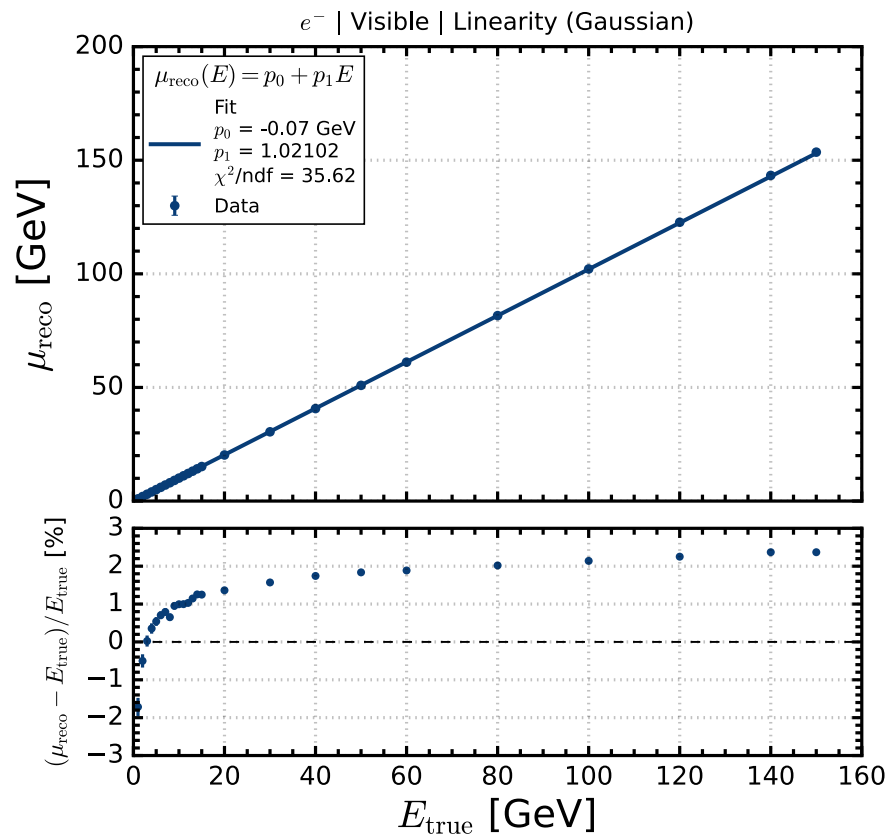
<b>X, Y, Z</b>	Reconstructed hit position in detector coordinates
<b>E</b>	Calibrated reconstructed hit energy with <b>0.5 MIP</b> threshold
<b>T</b>	<b>Earliest contribution</b> within the integration window, relative to the generator-level production time of the incident particle



# Detector response and reconstruction work properly

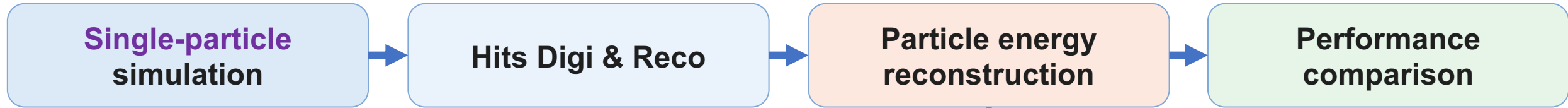
At EM scale (electrons), evaluating the reconstruction performance

- Summing of all the visible hits
- Linearity: within 2.5%; Resolution: S=17.3%, C=1.2%

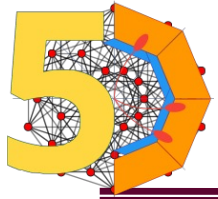




# Reconstruction Methods



<b>Visible (baseline)</b>	$E = \sum_{\text{all\_hits}} E_{\text{hit}}$
<b>CNN w/o time</b>	$(E, x, y, z)$
<b>CNN w. time</b>	$(E, T, x, y, z)$



# Irregular calorimeter data → CNN input ?

CNN input requirements:

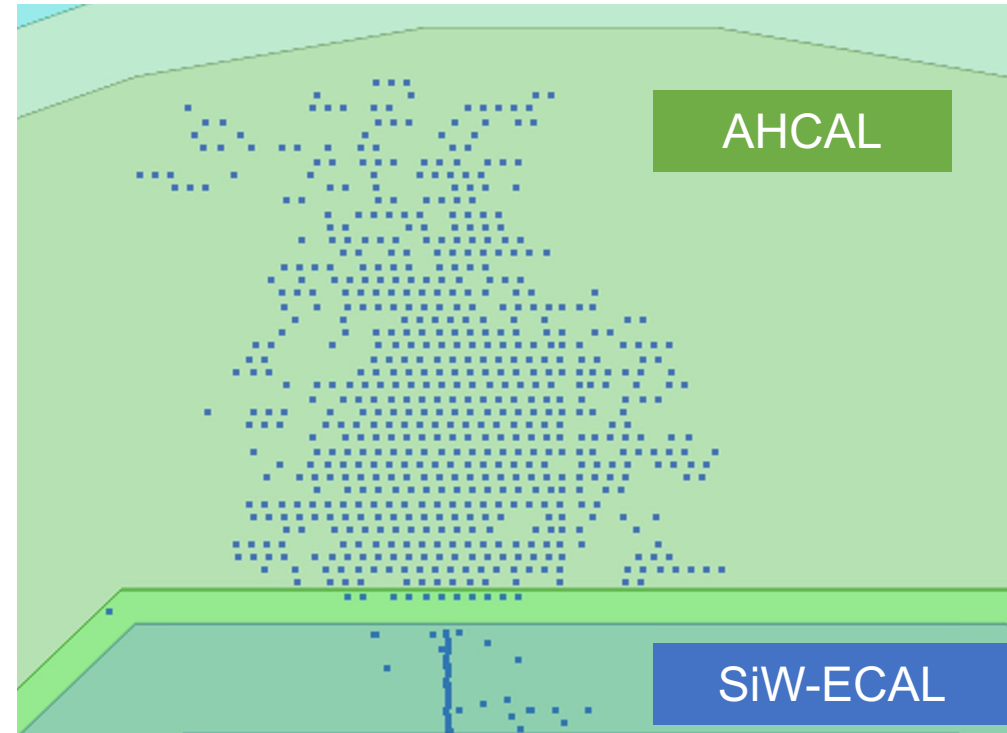
- Regular grid format
- Operate within a fixed spatial window

However, Detector reality: calorimeter data are irregular

- Discrete hits with non-uniform geometry
- Different granularity in ECAL and HCAL

Therefore, calorimeter hits need a structured representation for CNN input

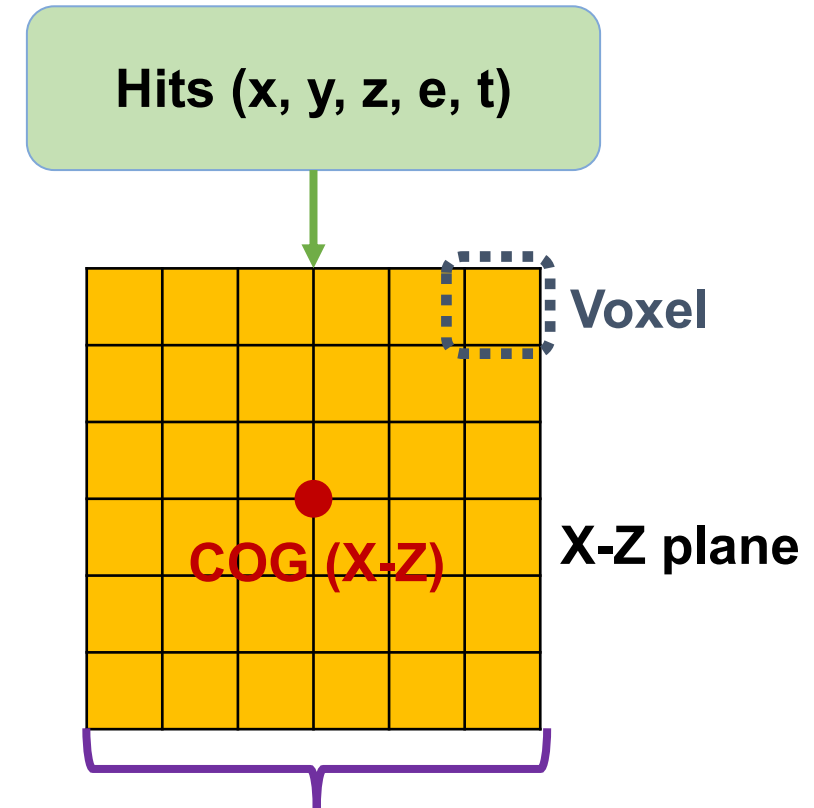
- Voxelization





# How to perform voxelization?

- Voxelization:
  - Transform shower hits to calorimeter images
- 💡 **Detector-aware** representation
  - Transverse plane: local windows centered on the shower COG
  - Longitudinal direction: native detector segmentation retained
  - Preserve different granularity and geometry



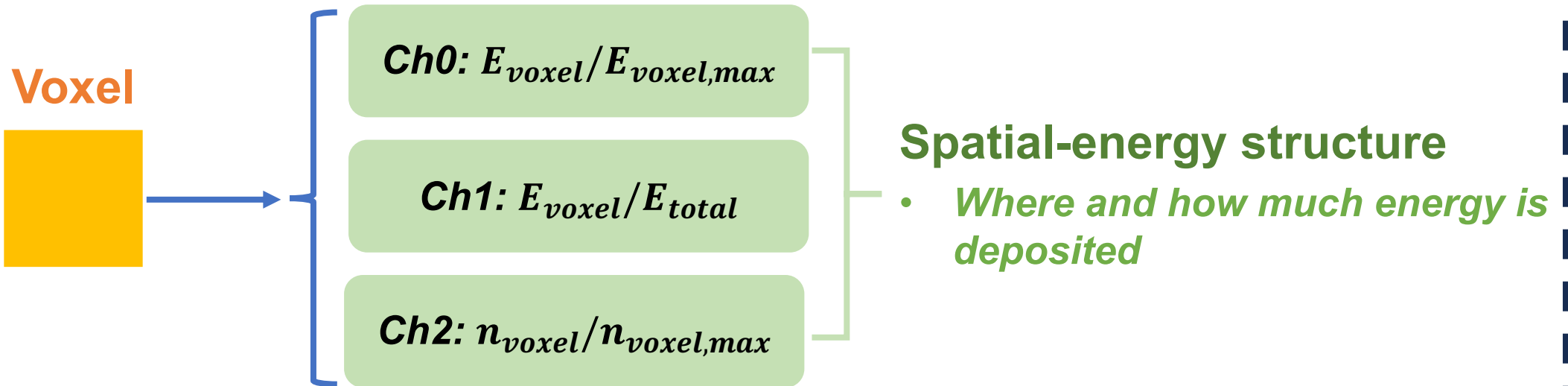
	Bins (mm <sup>2</sup> )	Windows (mm <sup>2</sup> )
ECAL	5 × 5	200 × 200
HCAL	30 × 30	1200 × 1200



# What information is encoded into the voxel?

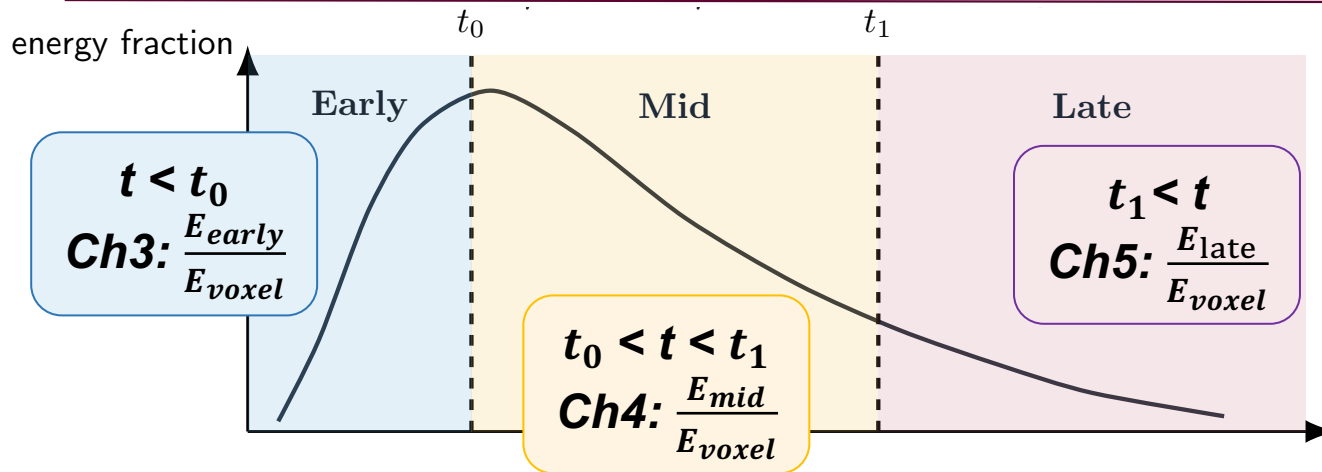
	(x, y, z)	E	t
EM component	Narrow, compact, shorter	Higher density	Prompt
Hadronic component	Broader, longer	Lower, spread out	Delayed components

*For CNN w/o timing information:*



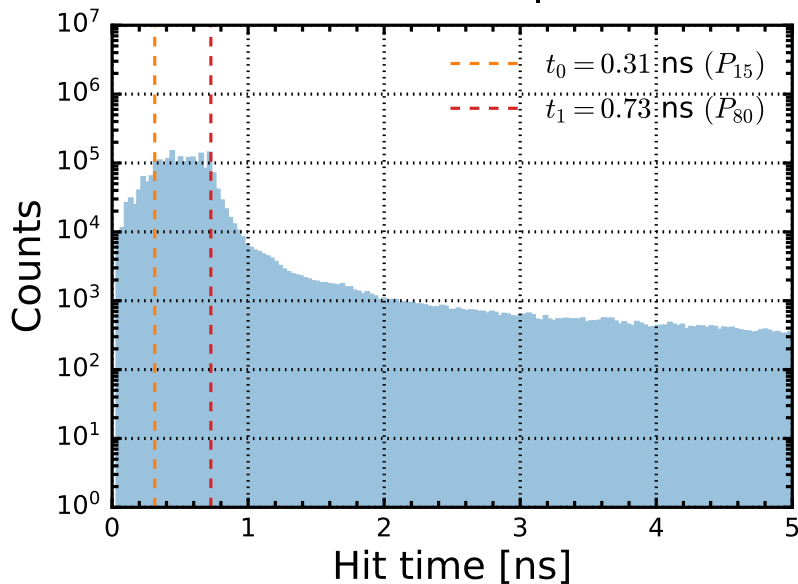


# How to implement time?

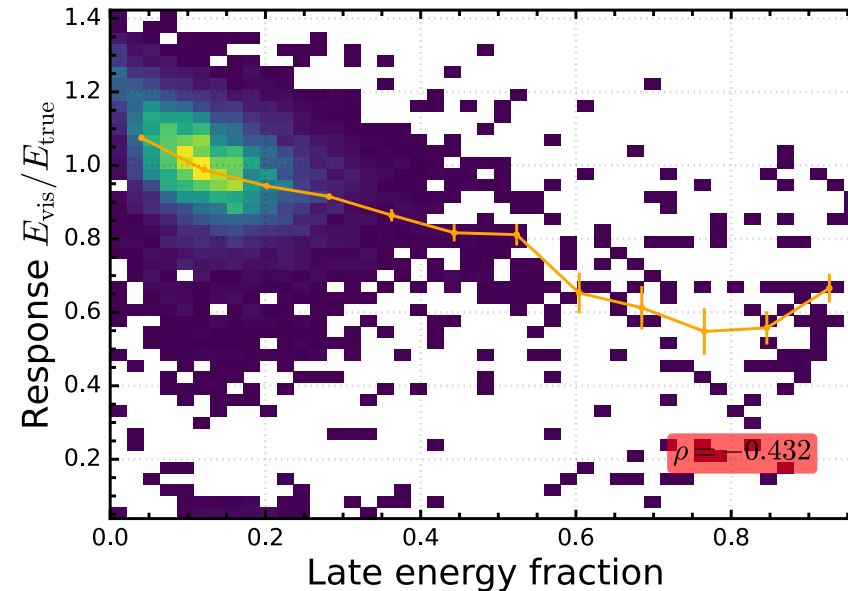
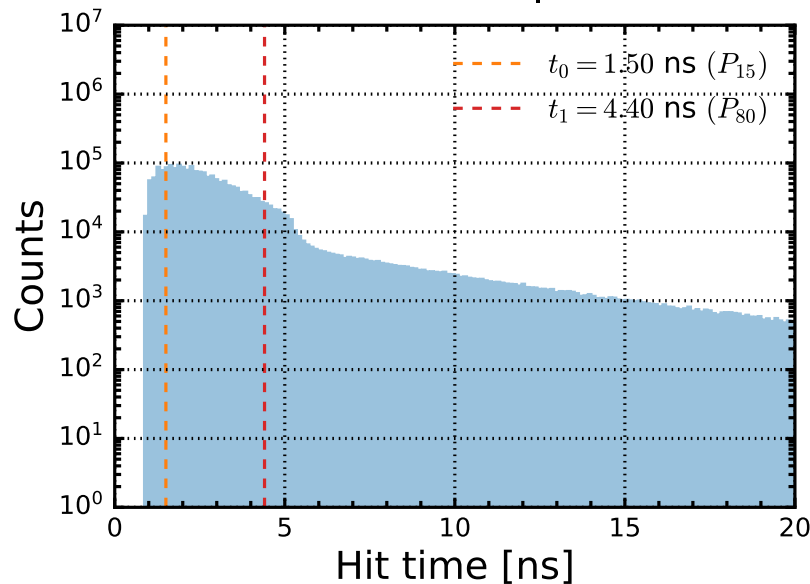


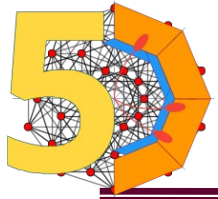
- Timing is encoded through threshold-defined shower components.
  - Choice:  $t_0 = t_{P_{15}}$ ,  $t_1 = t_{P_{80}}$
- Prompt/main/late energy fractions show correlations with the visible calorimeter response.

40.00 GeV  $\pi^+$  | ECAL



40.00 GeV  $\pi^+$  | HCAL





# What information is encoded into the voxel?

*For CNN w. timing information:*

**Voxel**



**Ch0:**  $E_{voxel}/E_{voxel,max}$

**Ch1:**  $E_{voxel}/E_{total}$

**Ch2:**  $n_{voxel}/n_{voxel,max}$

**Ch3:**  $E_{early}/E_{voxel}$

**Ch4:**  $E_{mid}/E_{voxel}$

**Ch5:**  $E_{late}/E_{voxel}$

## Spatial-energy structure

- *Where and how much energy is deposited*

## Spatial-time-category structure

- *How the energy is distributed in time*
- *Use perfect time for upper-bound study*



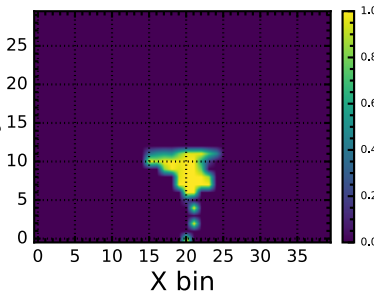
# Time-Separated Spatial Patterns

- Temporal structure of the shower is converted into a set of **time-resolved spatial and energy maps** (*combine time with spatial-energy structure*).
- The model can learn where different time components tend to appear and how they are distributed across the ECAL and HCAL.

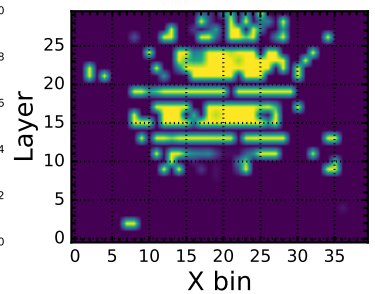
## Longitudinal

$\pi^+$  single event | X-Y plane |  $E_{true} = 80.002$  GeV | response=1.010

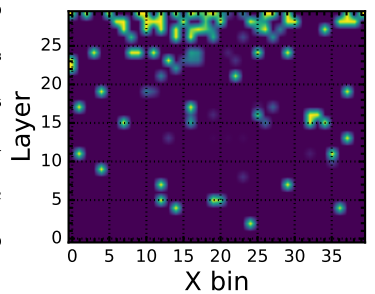
ECAL Prompt energy frac



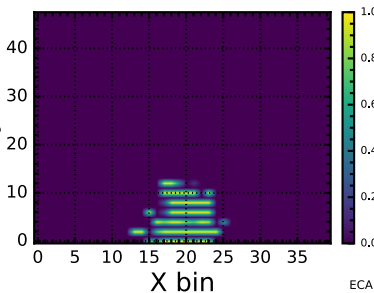
ECAL Main energy frac



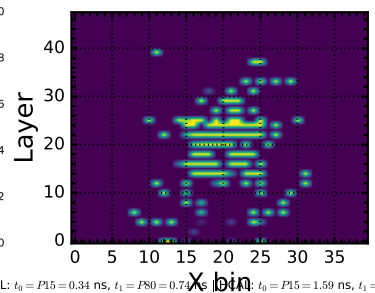
ECAL Late energy frac



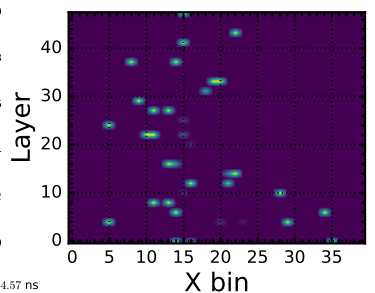
HCAL Prompt energy frac



HCAL Main energy frac



HCAL Late energy frac

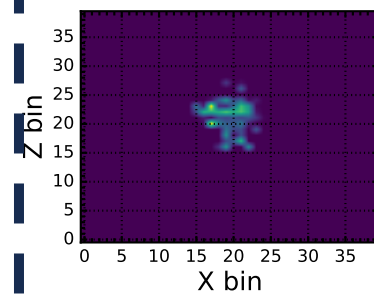


ECAL:  $t_0 = P15 = 0.34$  ns,  $t_1 = P80 = 0.74$  ns,  $t_2 = P15 = 1.59$  ns,  $t_3 = P80 = 4.57$  ns

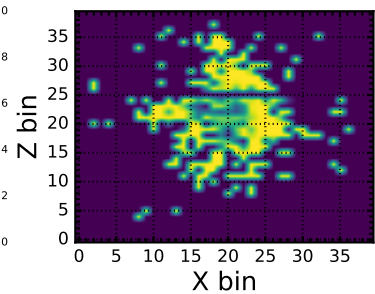
## Transverse

$\pi^+$  single event | X-Z plane |  $E_{true} = 80.002$  GeV | response=1.010

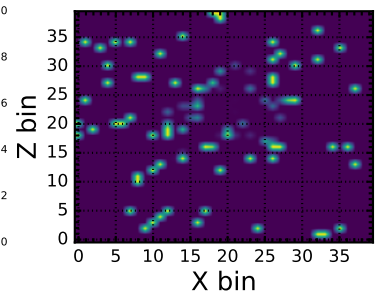
ECAL Prompt energy frac



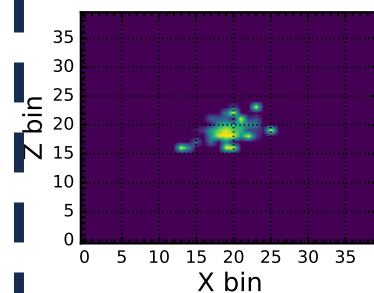
ECAL Main energy frac



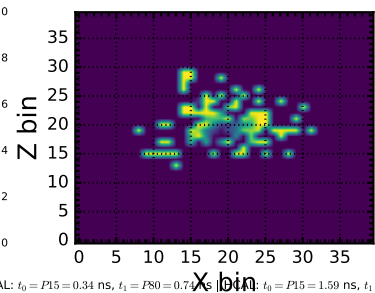
ECAL Late energy frac



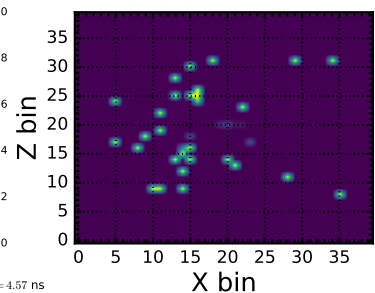
HCAL Prompt energy frac



HCAL Main energy frac



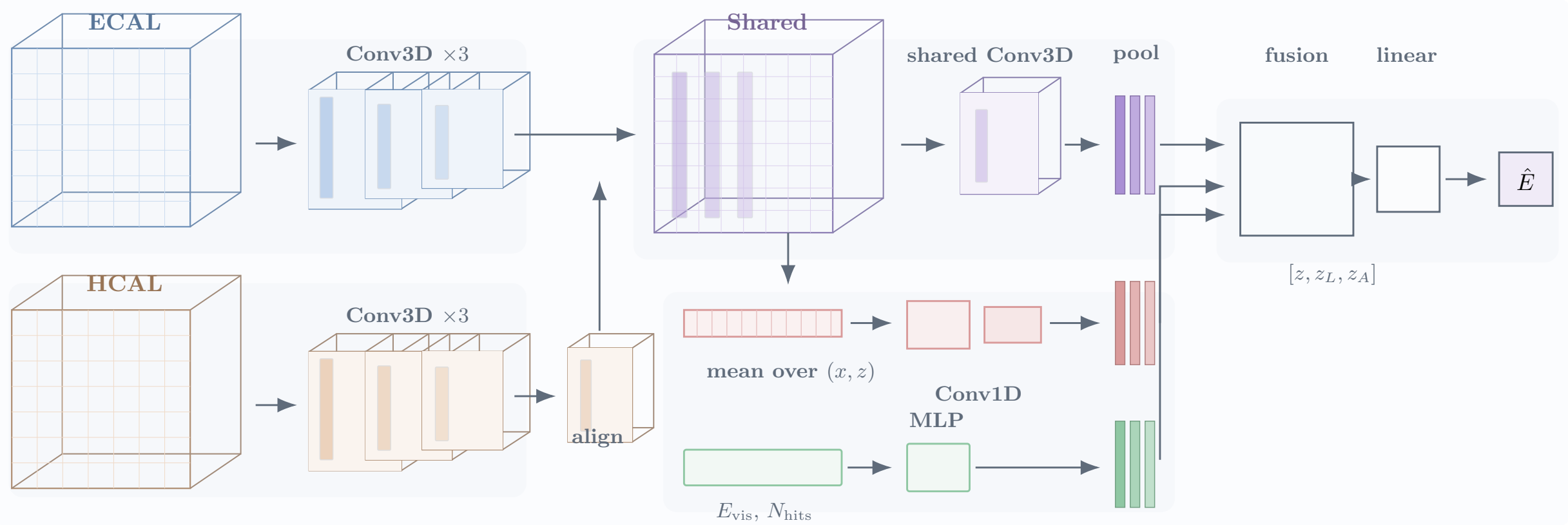
HCAL Late energy frac



ECAL:  $t_0 = P15 = 0.34$  ns,  $t_1 = P80 = 0.74$  ns,  $t_2 = P15 = 1.59$  ns,  $t_3 = P80 = 4.57$  ns



# Dual-branch CNN model



- Inputs:**
- Voxelized shower images from **ECAL** and **HCAL**
  - Global features:  $E_{\text{dep}}$ ,  $N_{\text{Hits}}$

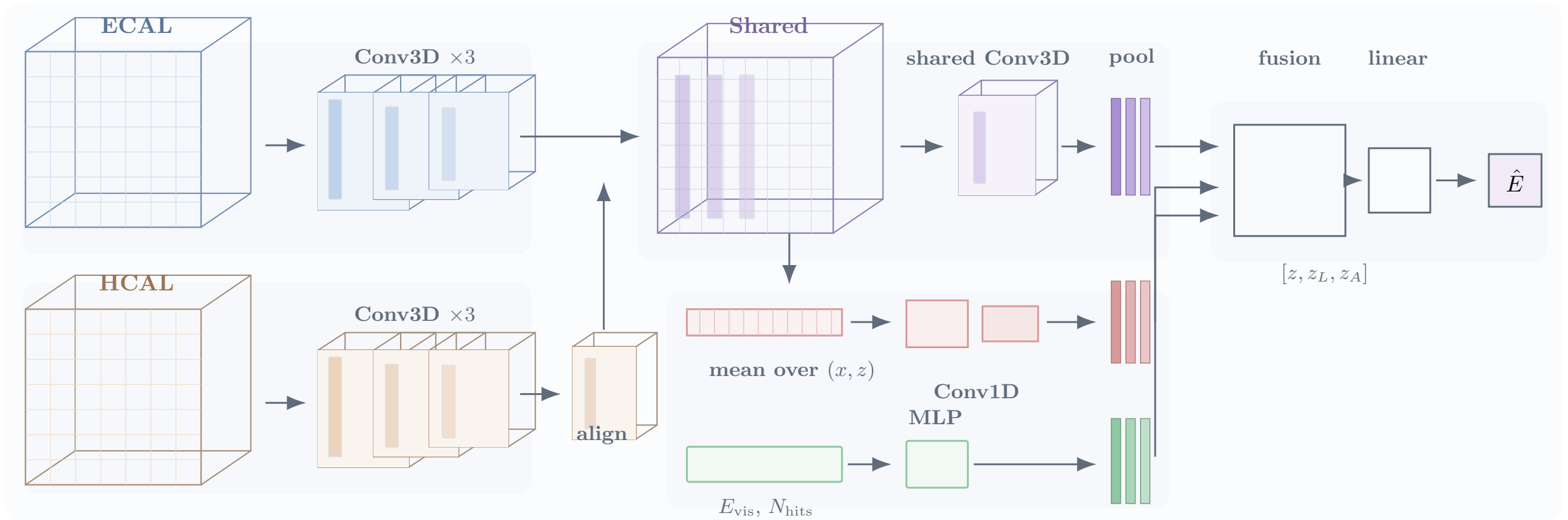
**Optimization objective:**

- $Loss = 0.5 r^2$
- $r = \begin{cases} (\hat{E}_i - E_i)/E_i, & E_i \geq 0.7 \text{ GeV} \\ \hat{E}_i - E_i, & E_i < 0.7 \text{ GeV} \end{cases}$



# Dual-branch CNN model

💡 Calorimeter-aware design, balance and exploit the complementary information from the two calorimeters.

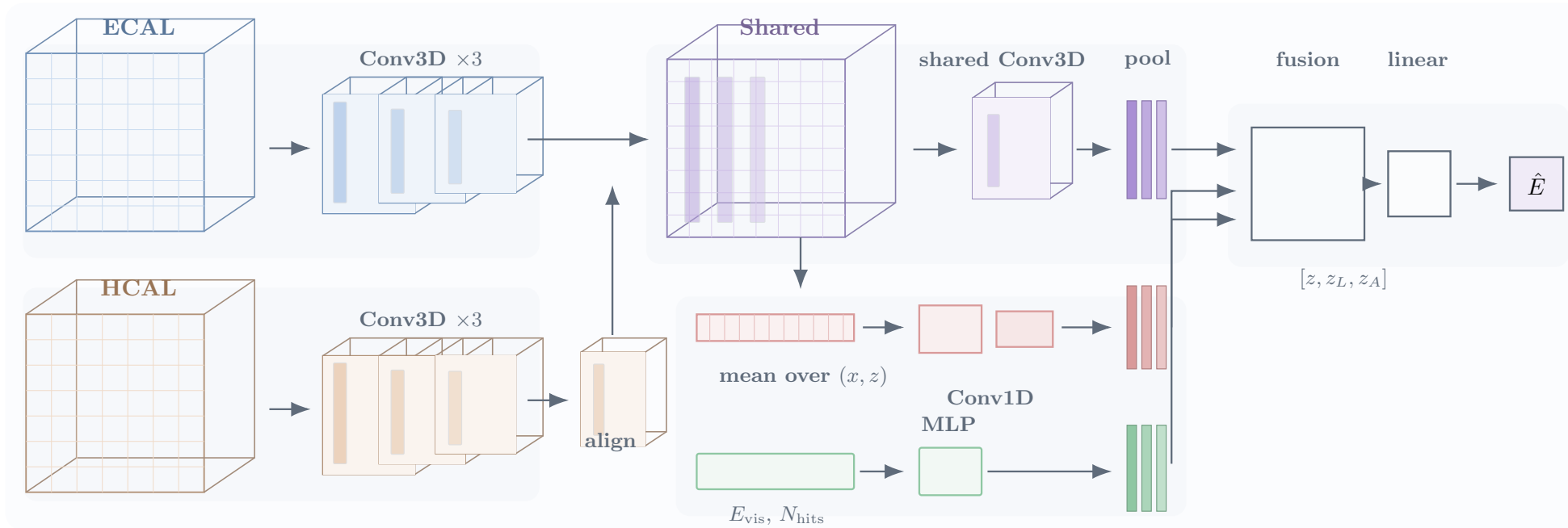


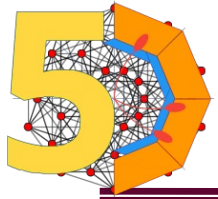


# What physical information can CNN potentially learn?

## Potentially Learned features:

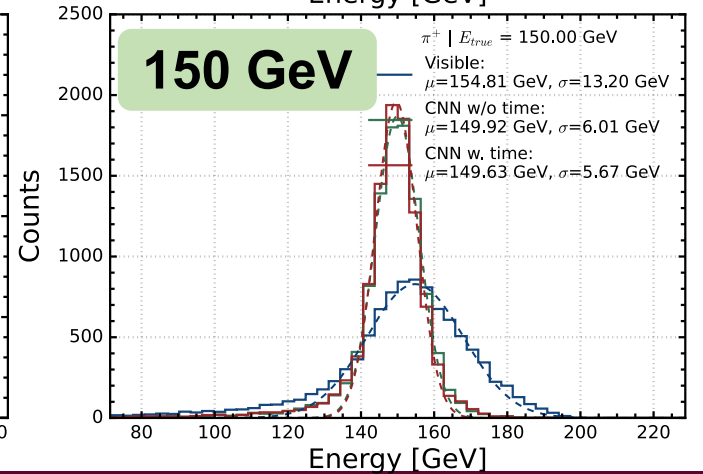
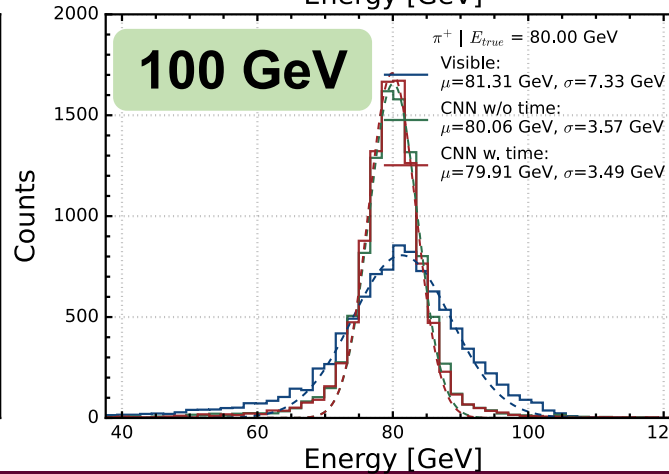
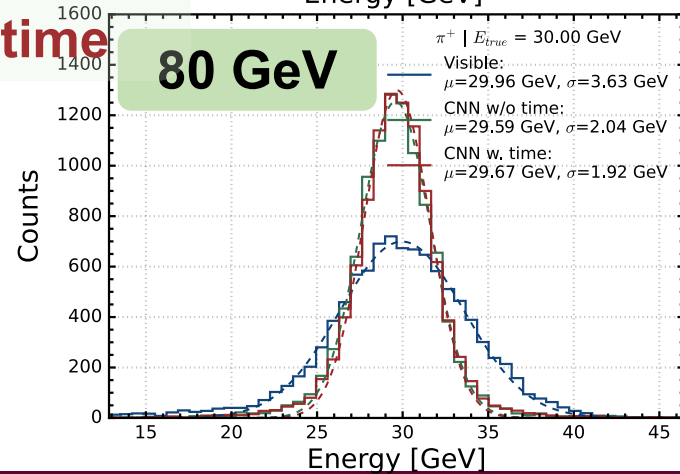
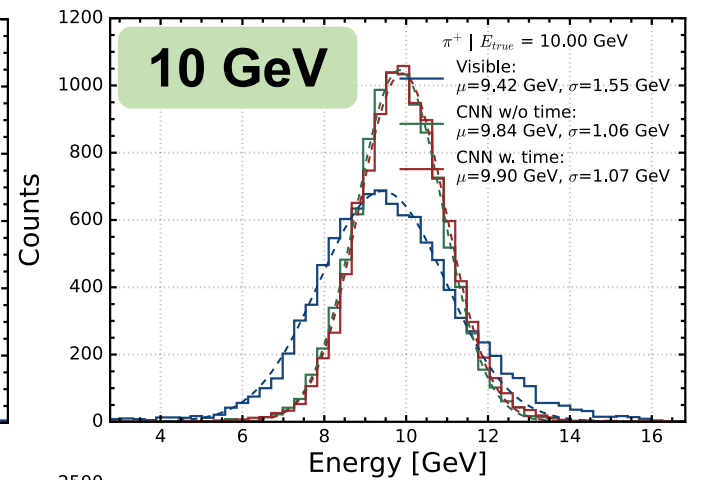
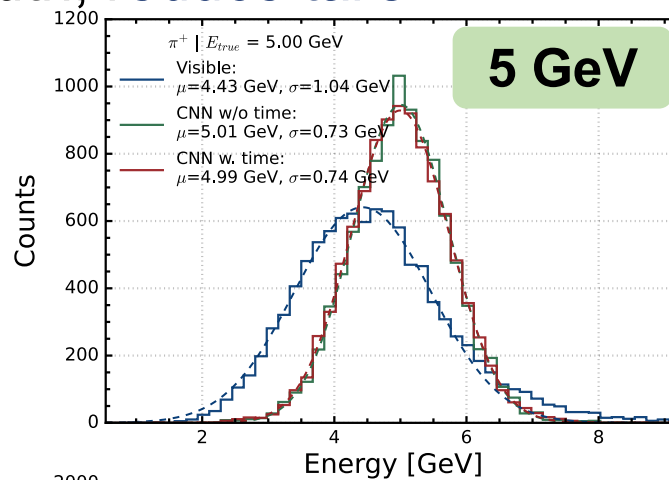
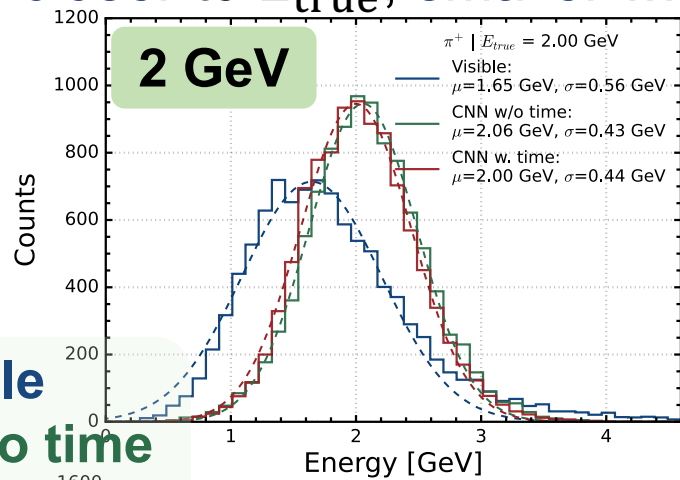
- ECAL/HCAL energy sharing
- Shower start and depth
- Longitudinal spread
- *prompt / main / late spatial-time patterns (only for CNN w. time information)*
- Local density and topology
- Leakage tendency
- Electromagnetic vs non-electromagnetic mixture



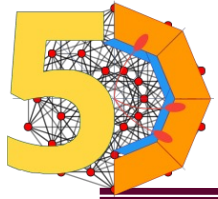


# Energy Distribution of $\pi^+$ : CNN vs Baseline

- Metric: Gaussian fit to the reconstructed energy distribution
- CNN shows better performance:
  - mean closer to  $E_{true}$ ; smaller width; reduce tails

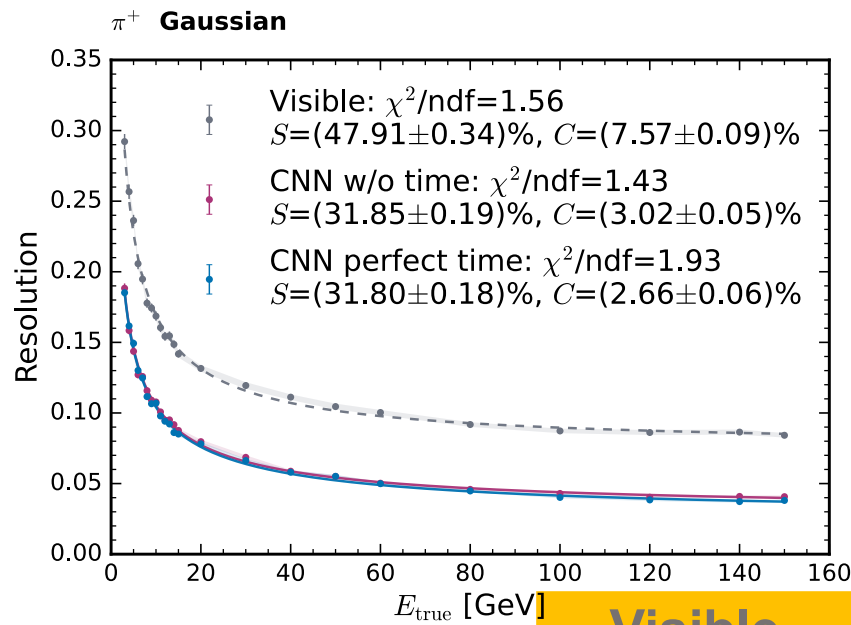
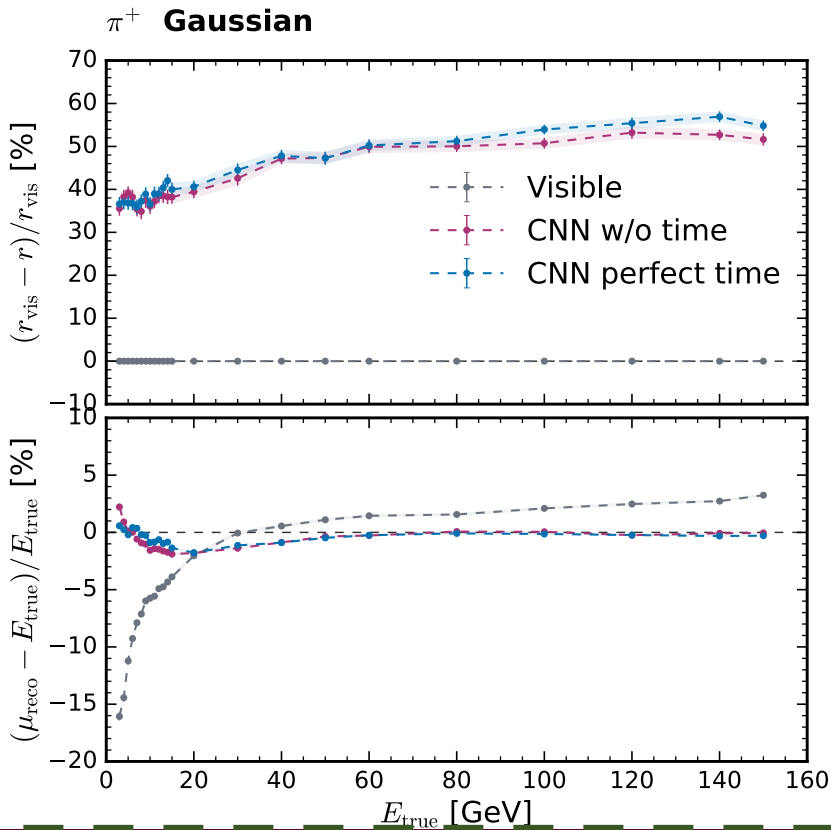


**Blue: visible**  
**Green: CNN w/o time**  
**Red: CNN w. time**



# CNN Gain for $\pi^+$ over Baseline

- CNN significantly outperforms visible-energy baseline in both linearity and resolution. (40% - 60% improvement in resolution)
- The dominant gain comes from the spatial-energy shower structure.
- Timing only provides a modest additional improvement over the no-time CNN.

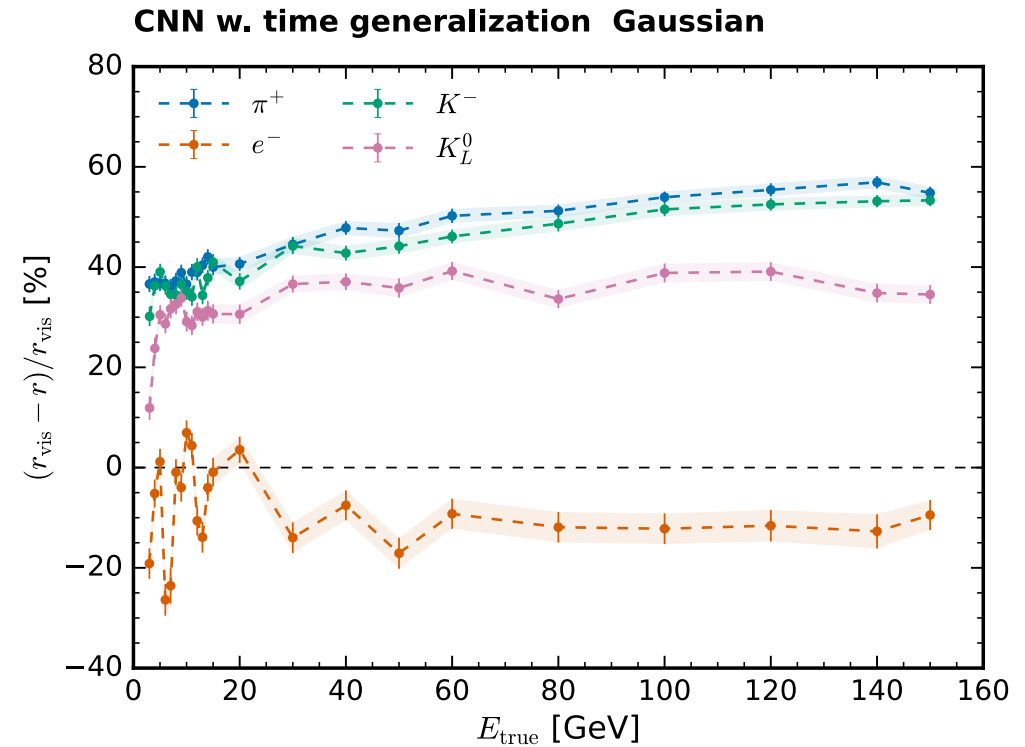
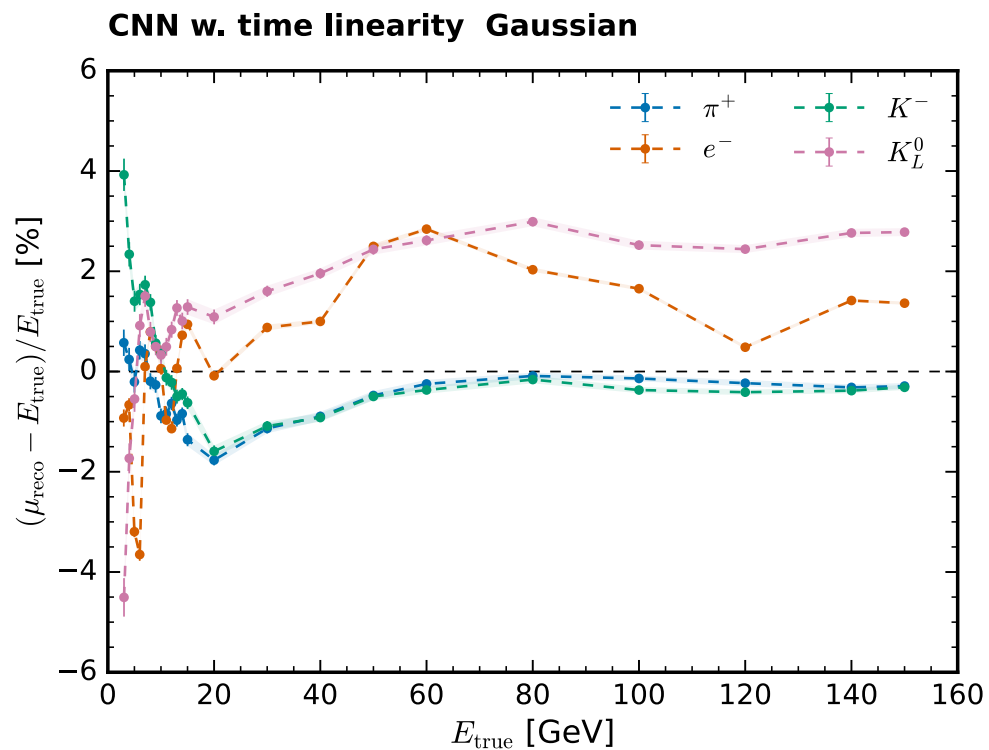


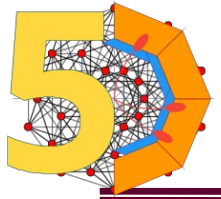
	Resolution	
	S	C
Visible	47.7%	7.6%
CNN w/o T	31.9%	3.0%
CNN w. T	31.8%	2.7%



# Generalization across particles

- The model trained on  $\pi^+$  performs **best on  $K^-$** , still **improves  $K_L^0$** , and shows a slight **degradation for  $e^-$** .
- This indicates that the model has learned **genuine hadronic shower features** relevant for energy reconstruction and shows robustness to kaon-induced showers which have lower EM component.



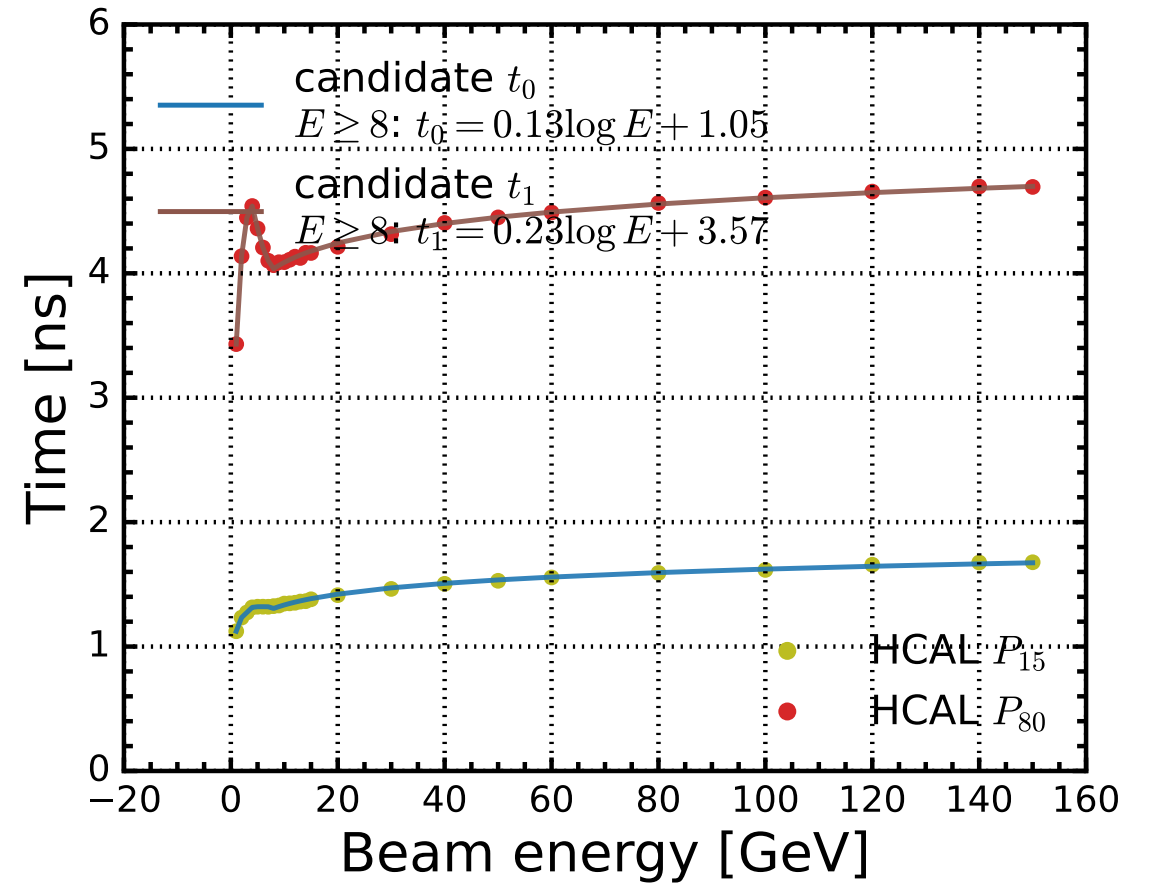
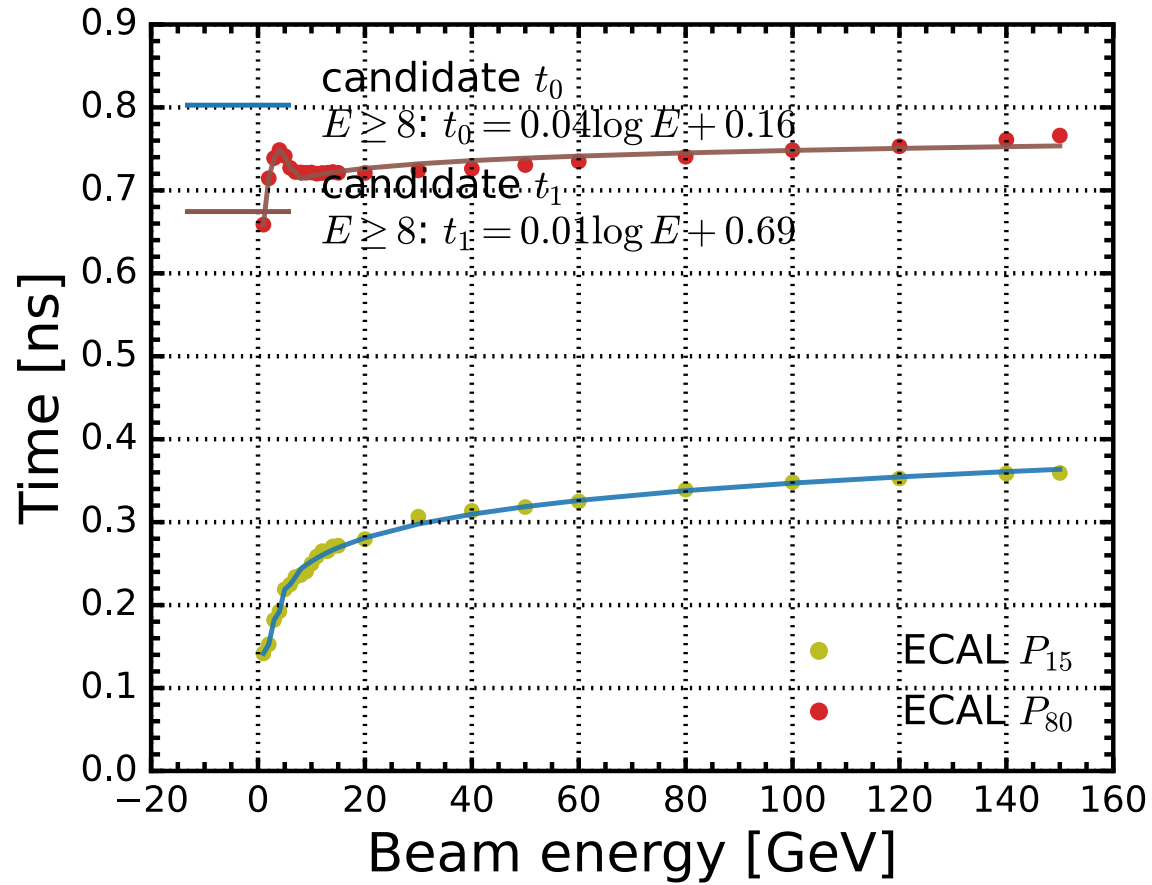


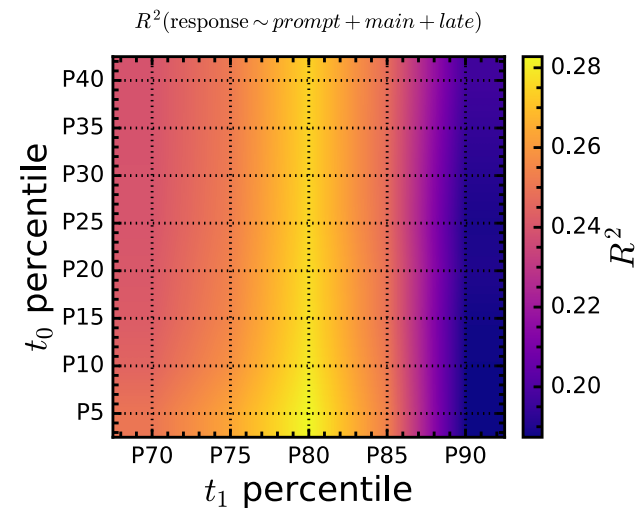
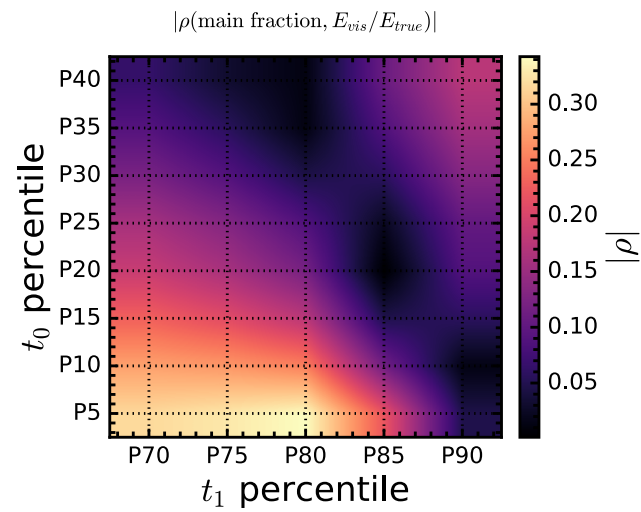
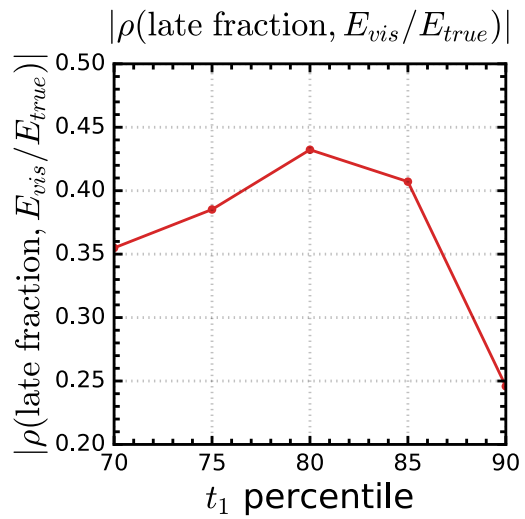
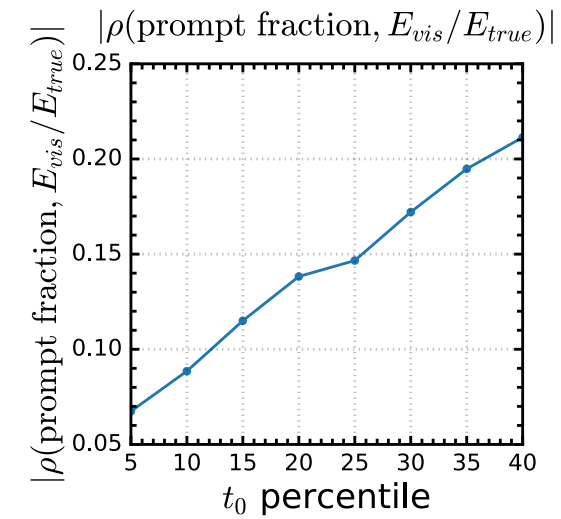
# Summary

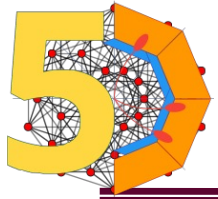
- A **CNN-based energy regression** model has been developed for the ILD SiW-ECAL + AHCAL system.
- For single-particle  $\pi^+$ , the CNN provides around **50% improvement** over visible-energy baselines from 3 GeV to 150 GeV.
  - Linearity at **2%** level and a Gaussian-fit resolution of about  **$31.8\%/\sqrt{E} \oplus 2.7\%$** .
- The model remains effective even for showers with a reduced electromagnetic component. The generalization behavior supports that the network learns **genuine hadronic shower features**.
- Timing carries some additional information, especially in the late component, but the current bin-based timing encoding provides only a modest extra gain; the dominant improvement comes from the spatial-energy shower structure.

# Thanks!

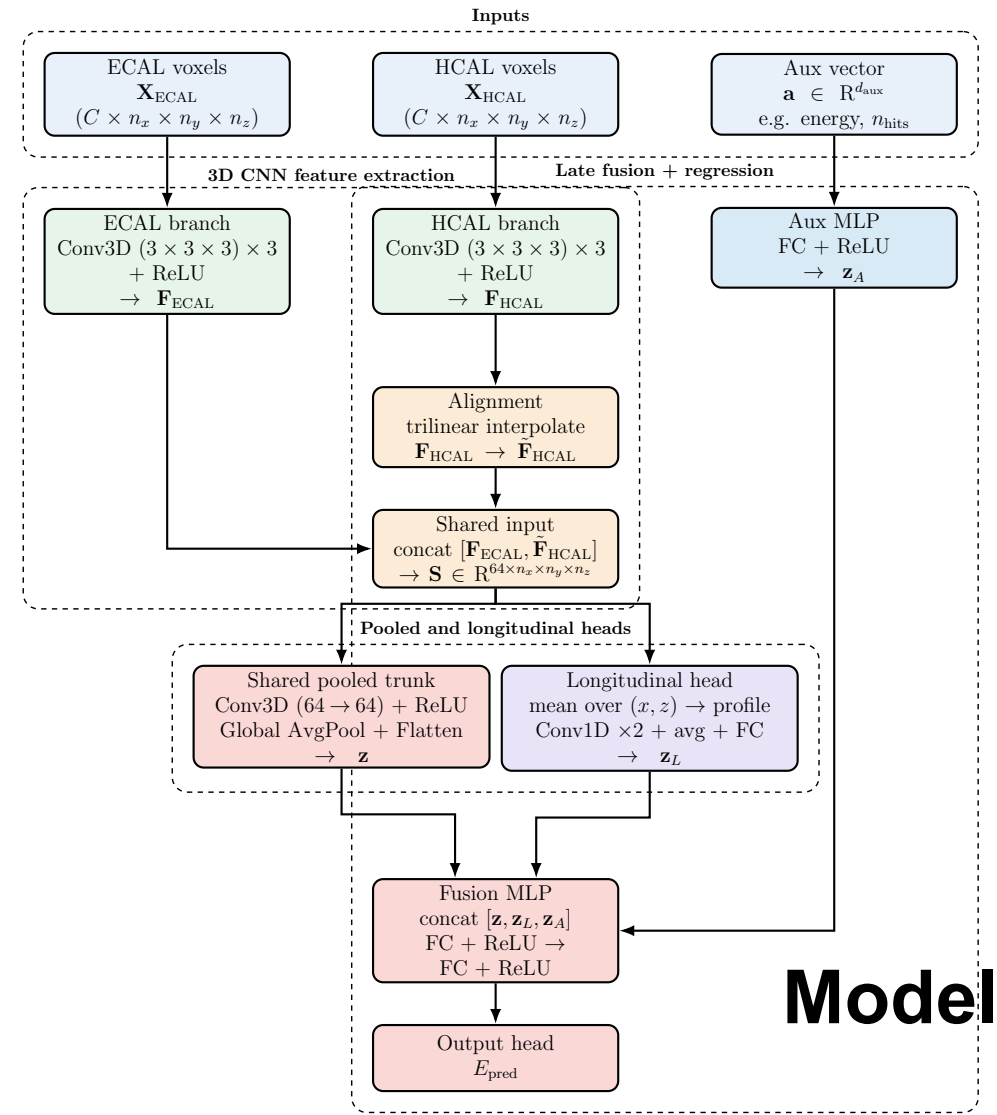
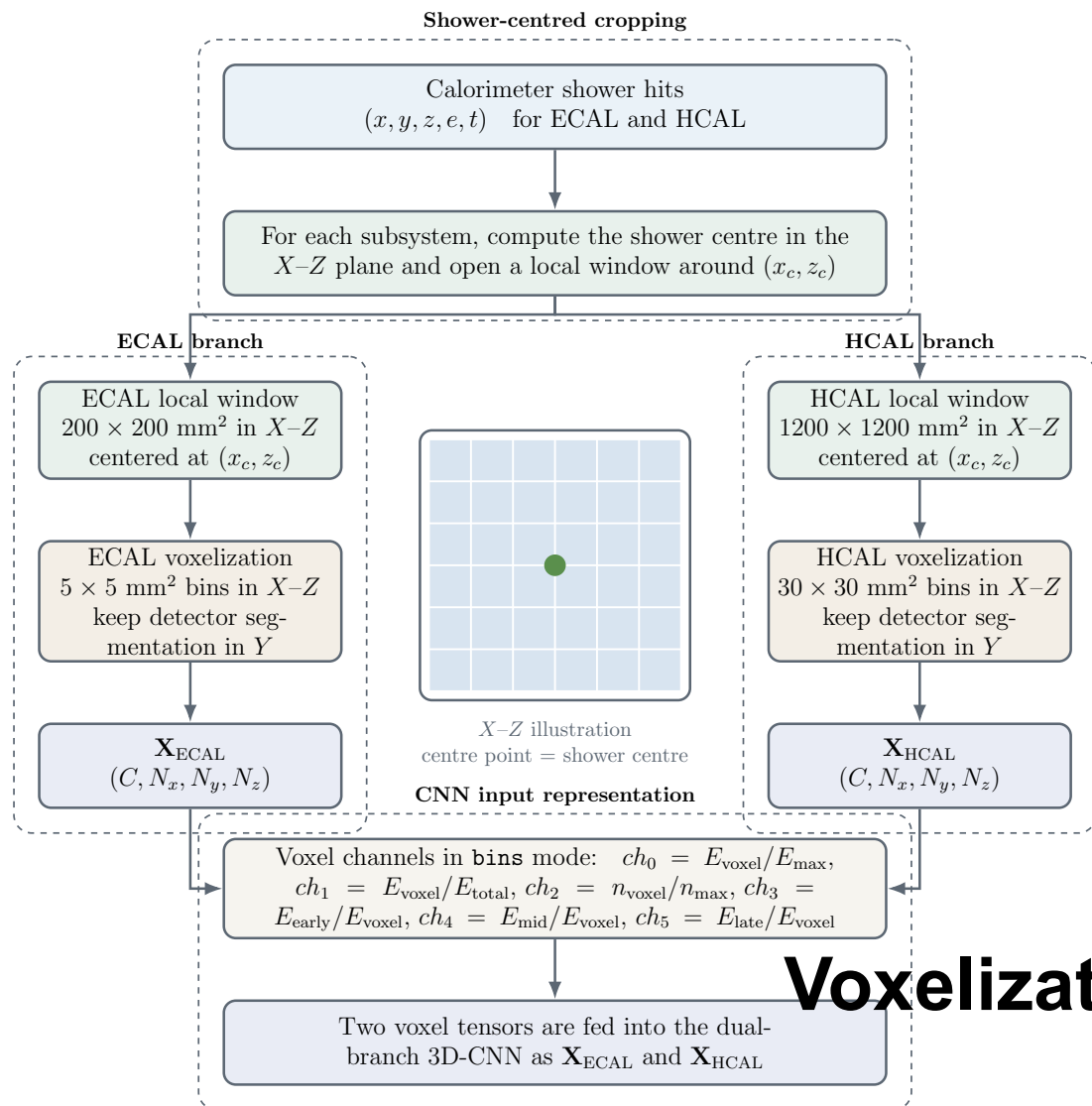
# Backup







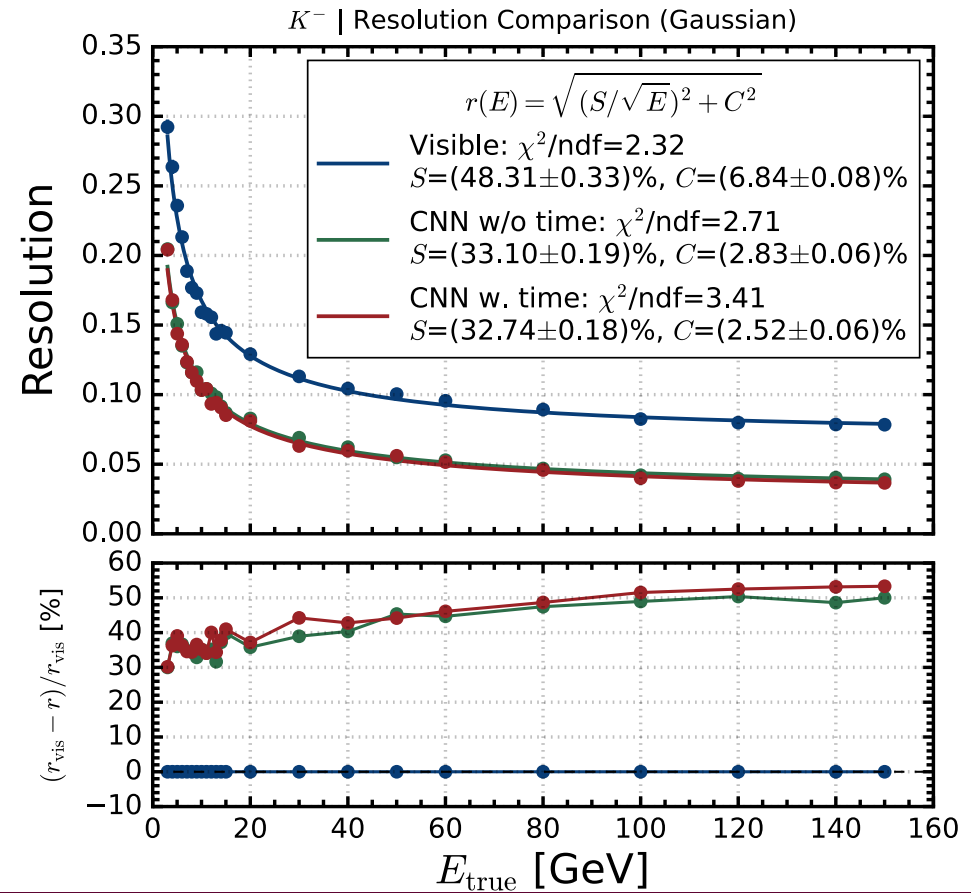
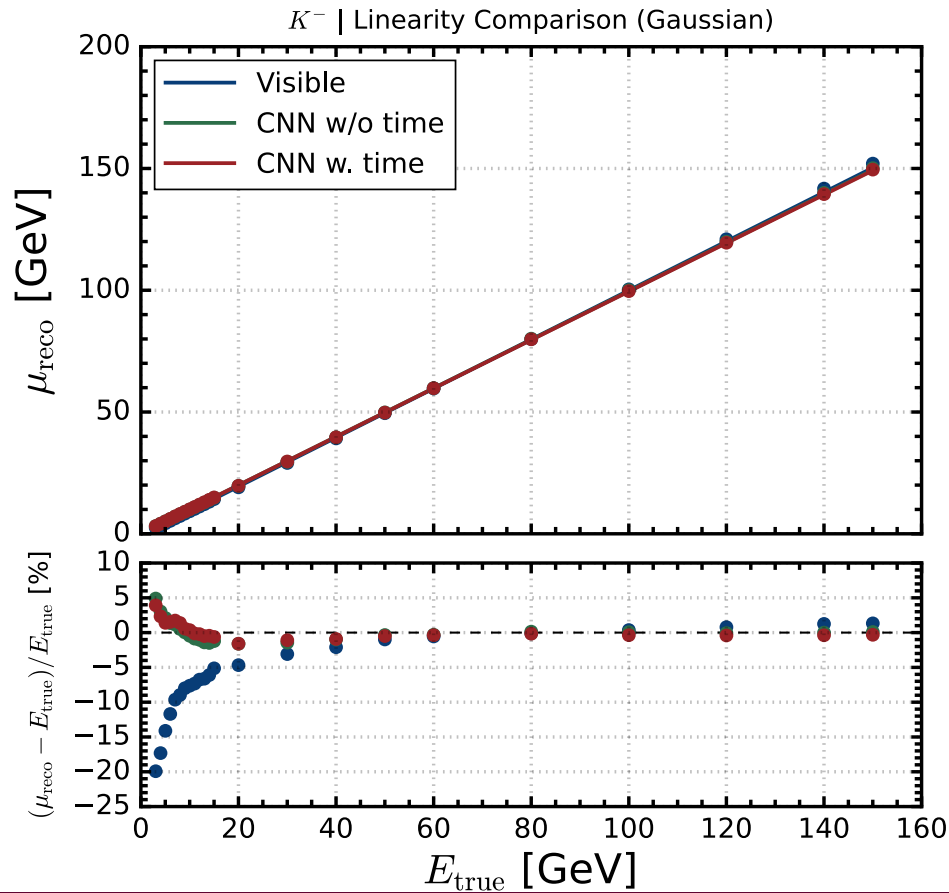
# Voxelization strategy and model





# Transfer to $K^-$ (Model trained on $\pi^+$ )

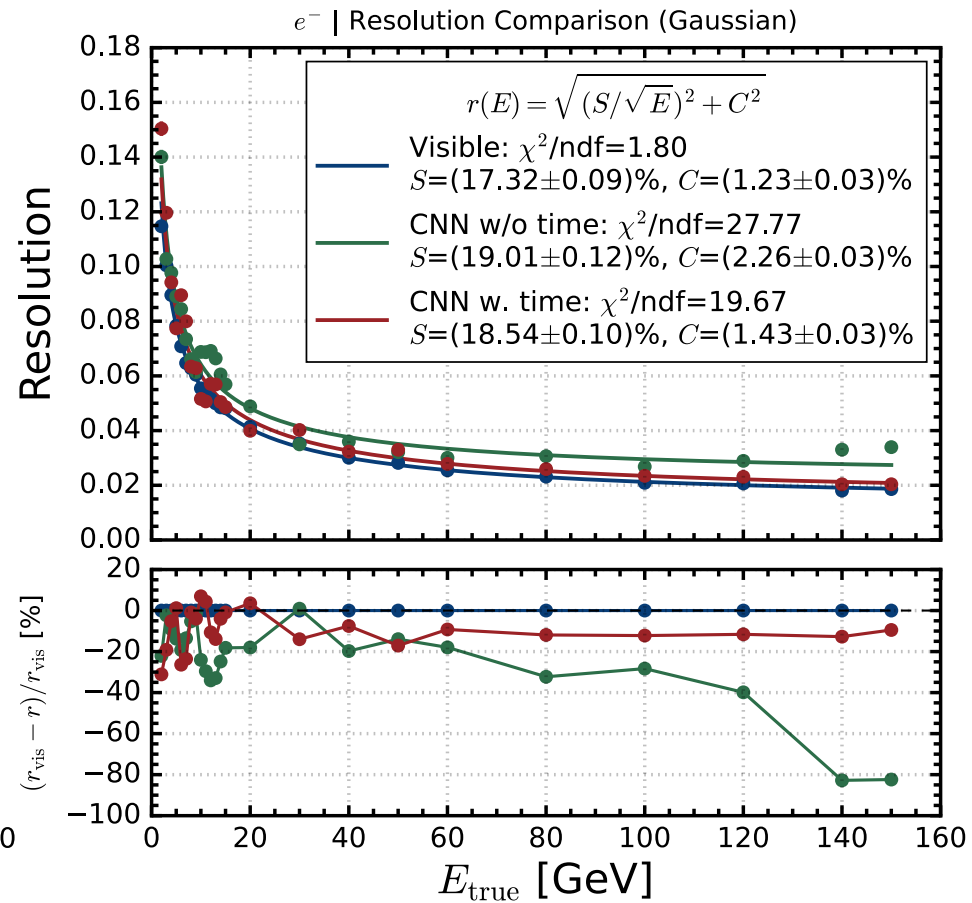
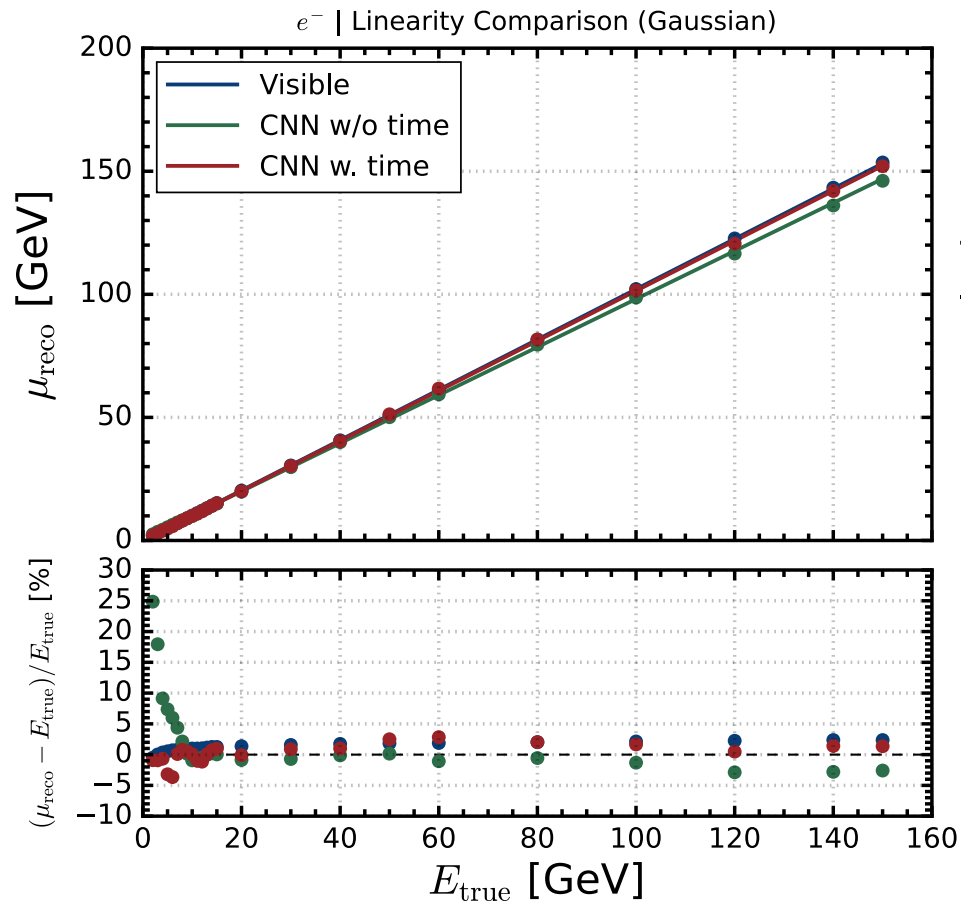
- The model generalizes well to  $K^-$ , which is the most similar to  $\pi^+$  among the tested particles.
- The performance remains strong:
  - linearity at the few-% level and clear resolution improvement over the visible baseline.

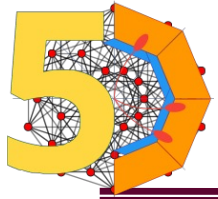




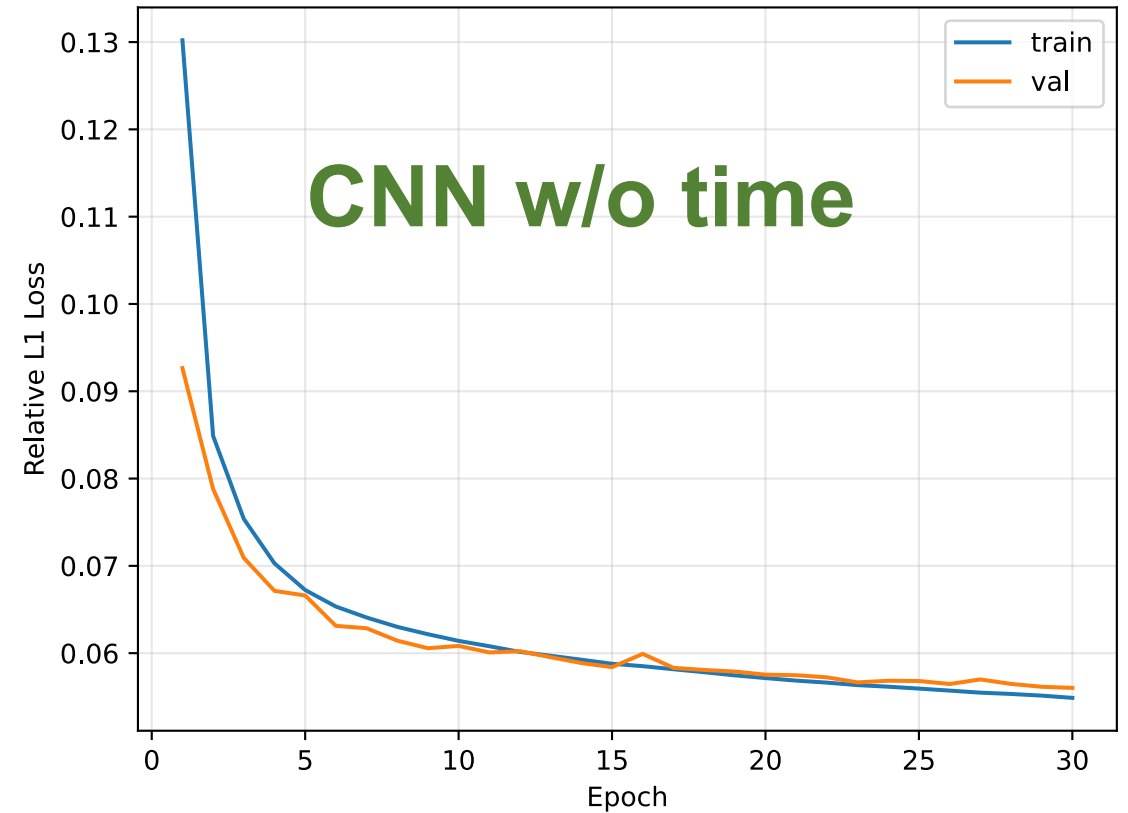
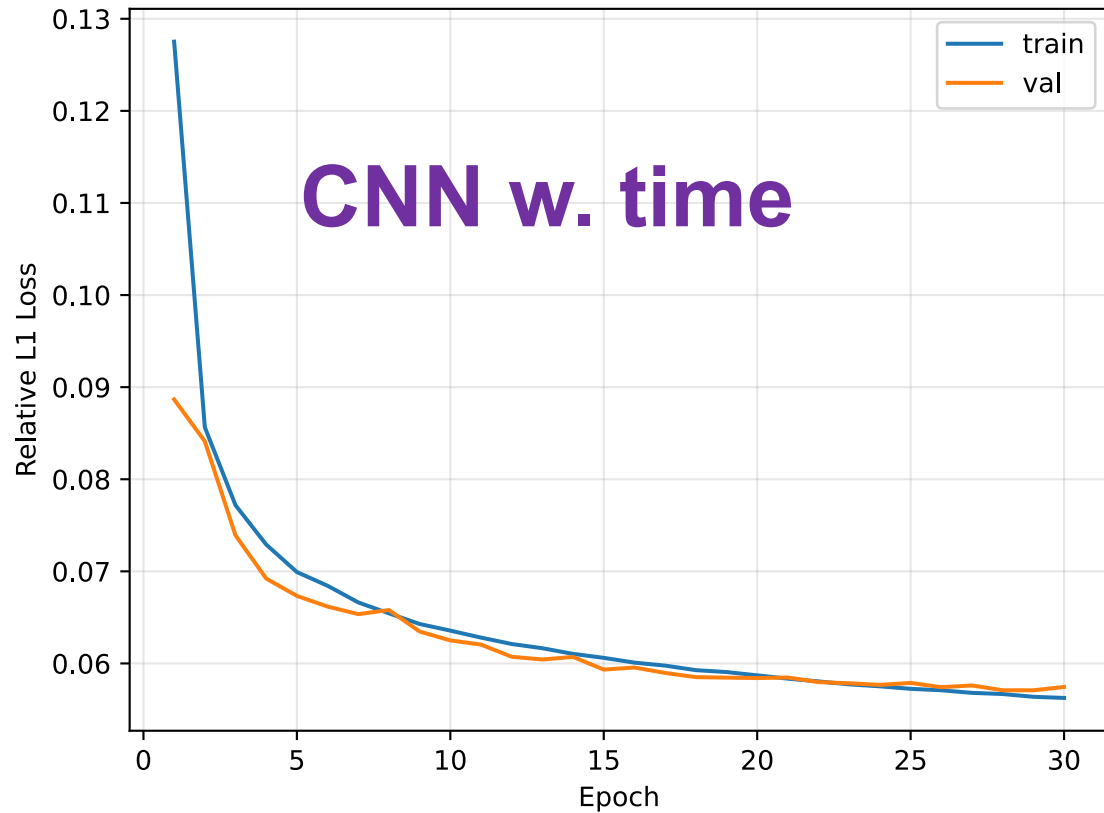
# Transfer to $e^-$ (Model trained on $\pi^+$ )

- The model trained on hadronic showers does not provide gain for  $e^-$ .
- This is physically expected, since electromagnetic showers have a very **different spatial development** and much **smaller event-by-event response fluctuations** than hadronic showers.





# Loss curve





# Time gain

