

# Energy Reconstruction Using Timing and Shower Shape with SC and Neural Network

1. Role of Timing  
in Energy Reconstruction
2. Neural Network Setup

5. neural network setup



**MAX-PLANCK-INSTITUT**  
FÜR PHYSIK

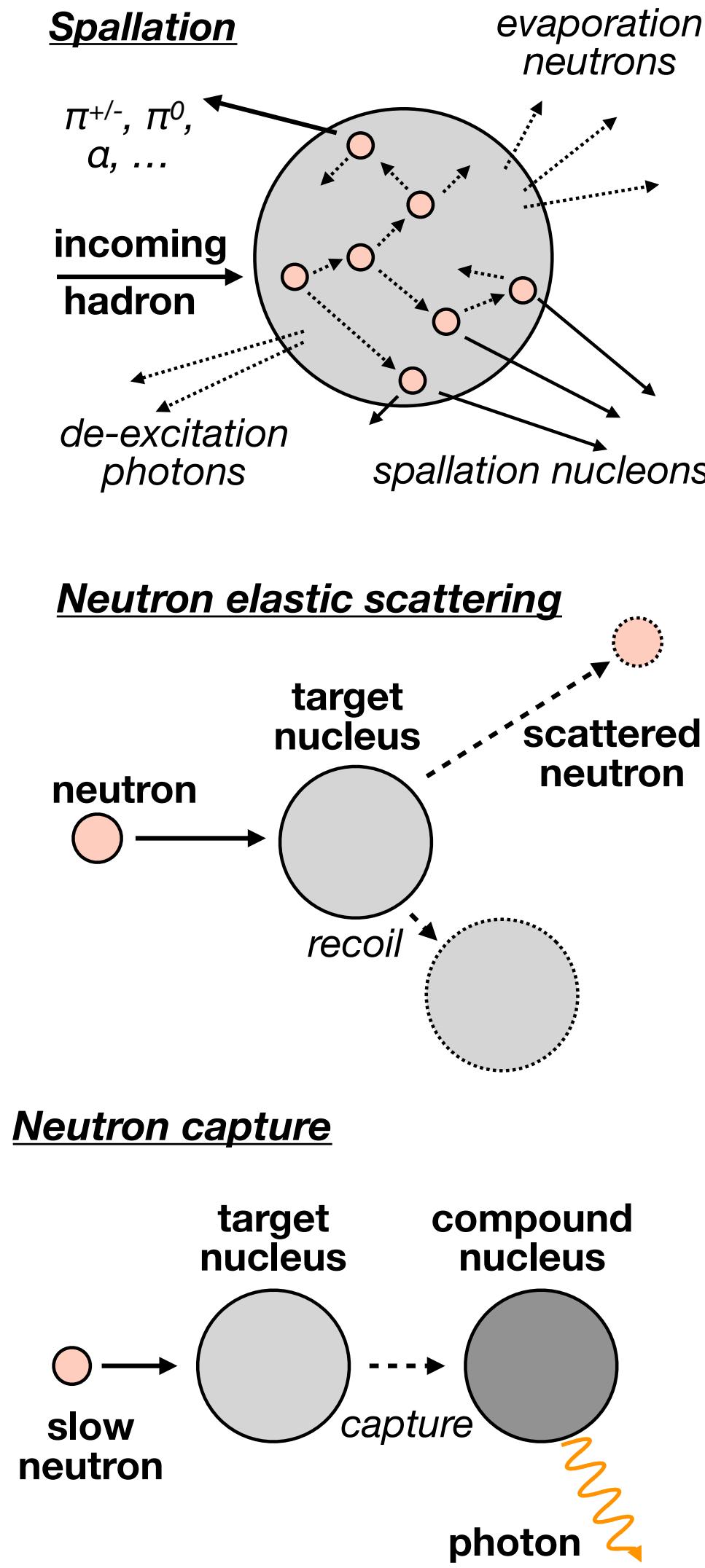
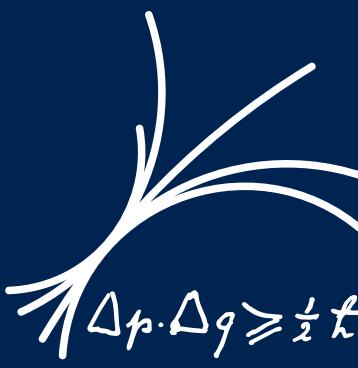
March 5th, 2020

*CALICE Meeting  
- Montreal -*

Christian Graf

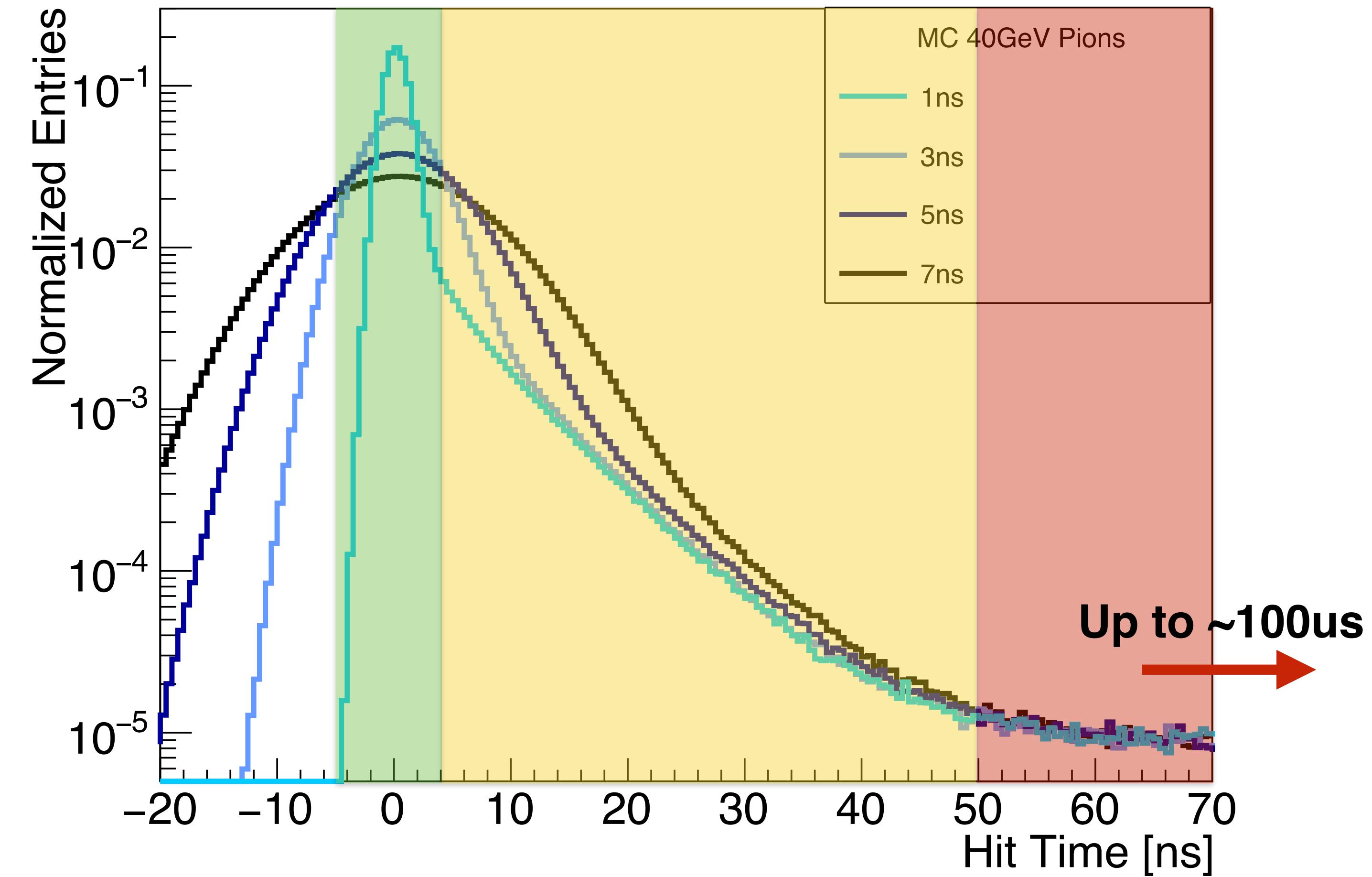


# Time Structure of Hadronic Showers



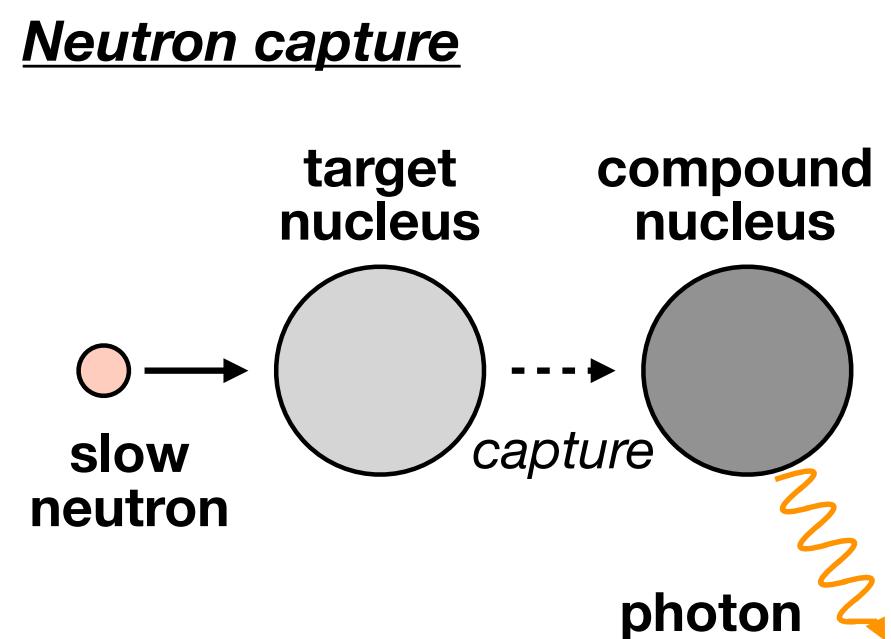
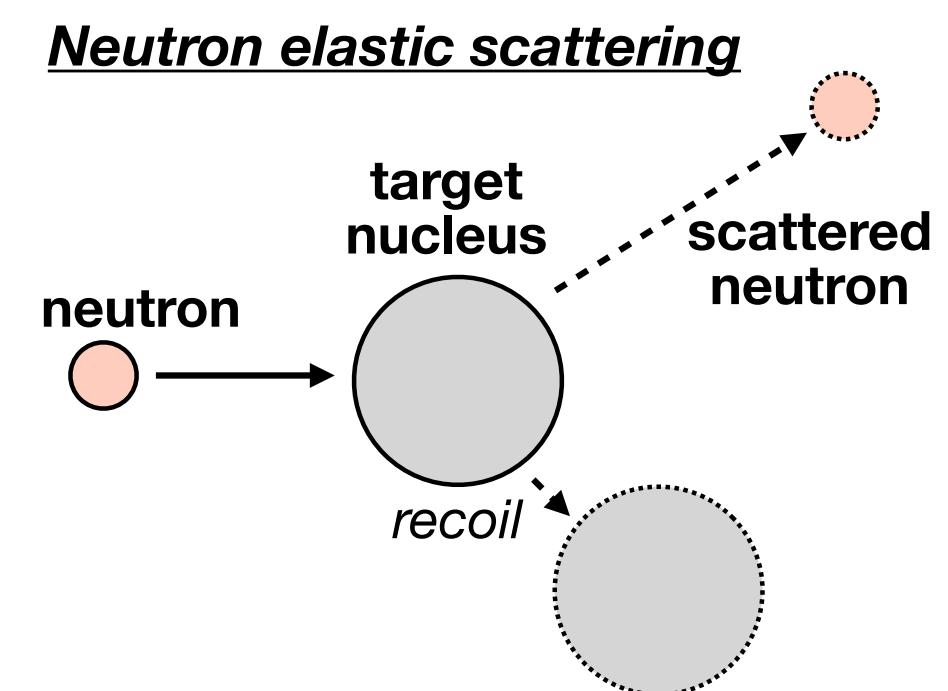
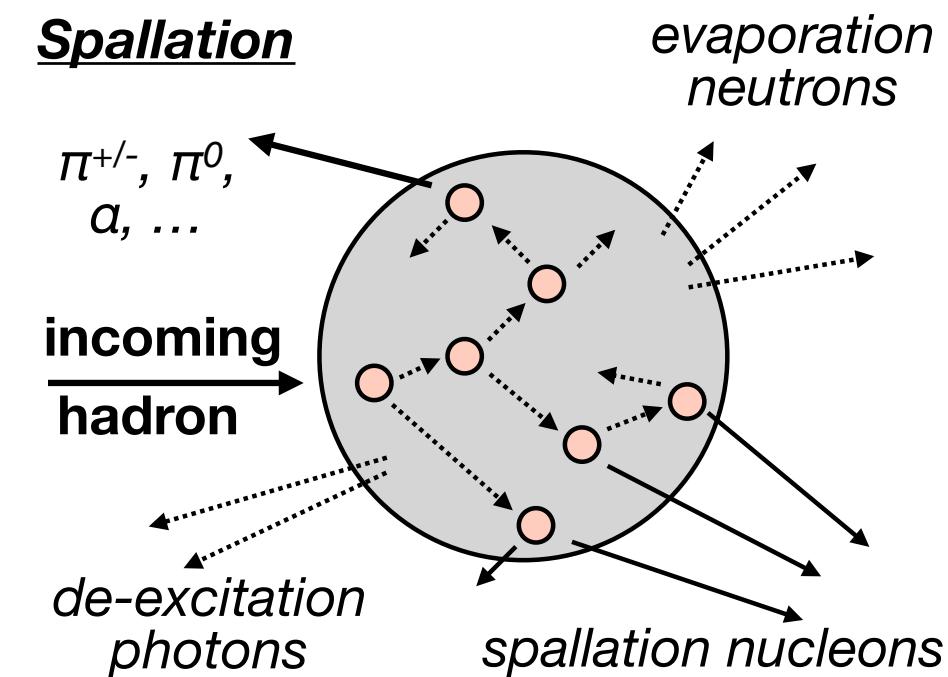
**Neutron elastic sc.**

**Neutron capture**





# Time Structure of Hadronic Showers



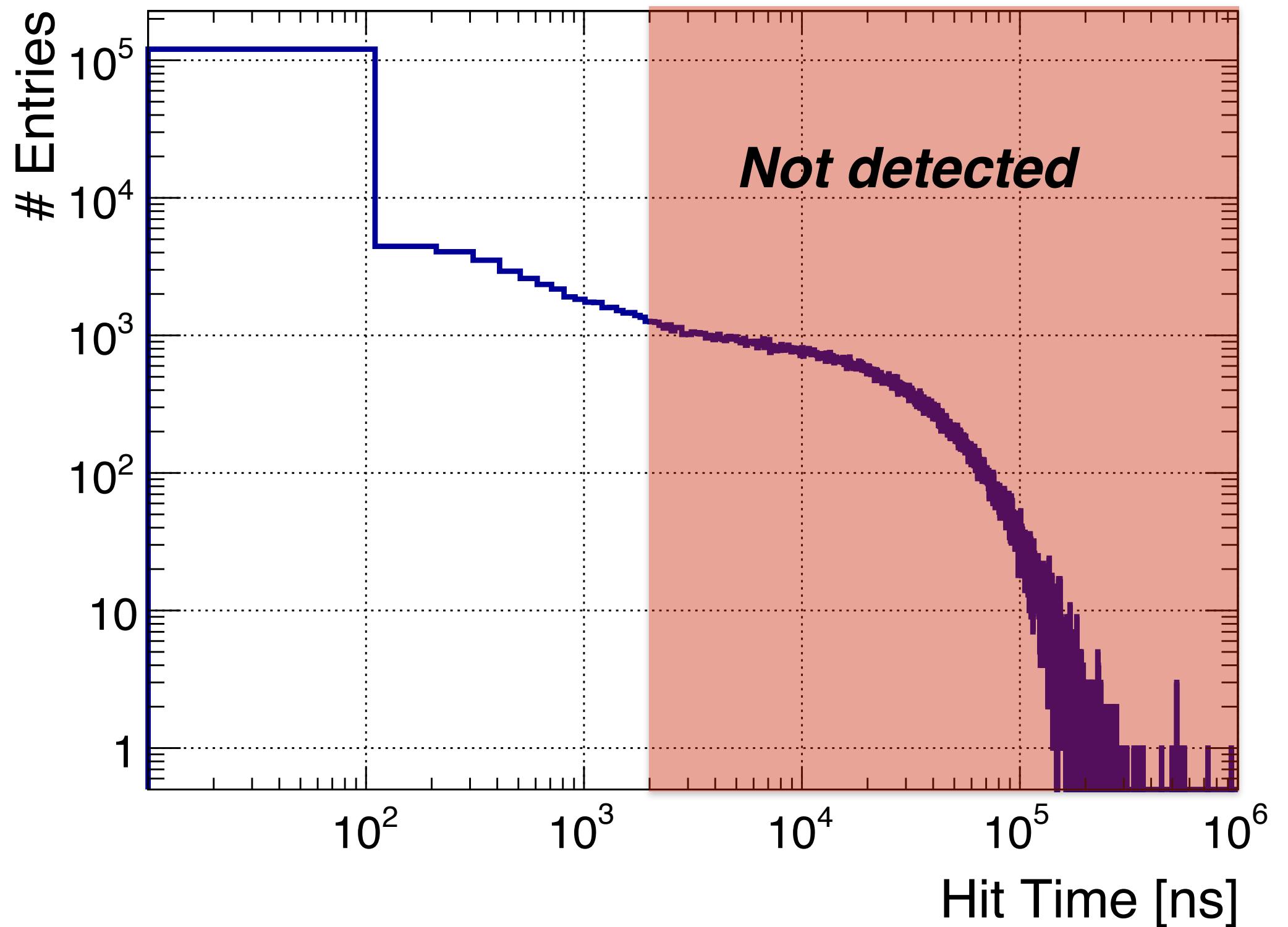
**Instantaneous**

**Nuclear binding energy lost**

**Neutron elastic sc.**

**Neutron capture**

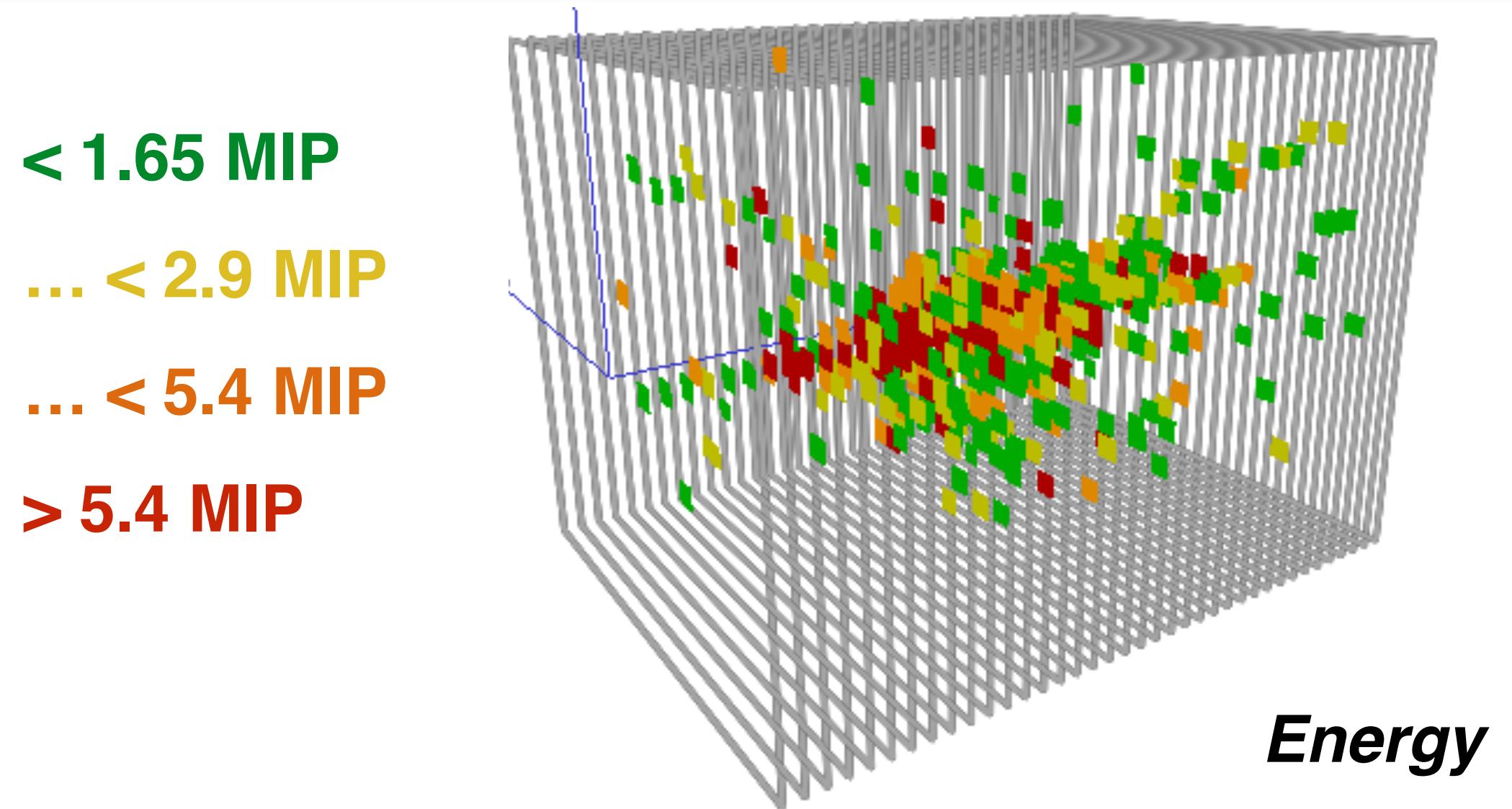
**Binding energy gained back**



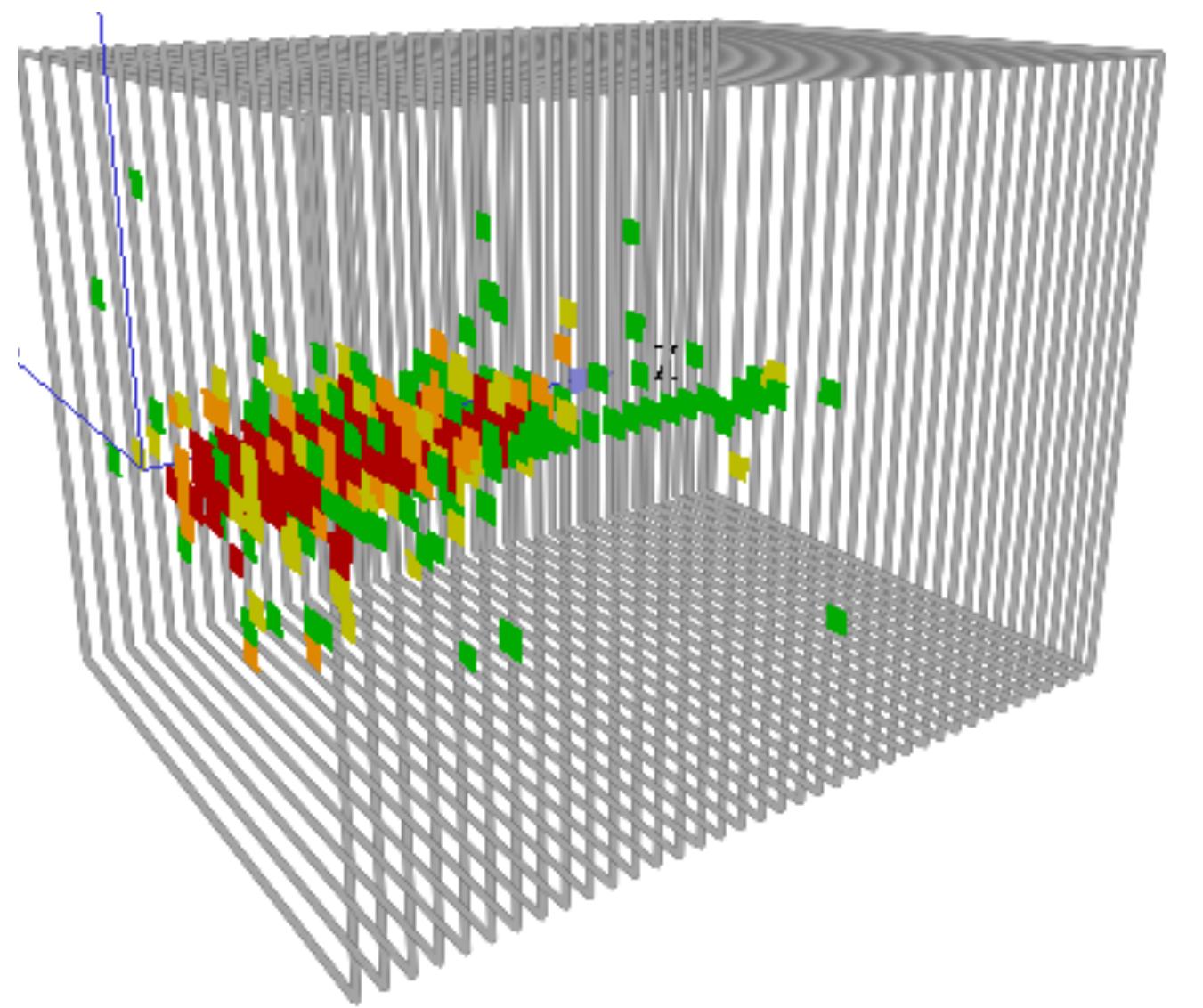
**Neutrons are an indication for:**

- Electromagnetic fraction
- Lost binding energies
- Most neutron captures too late for TB mode

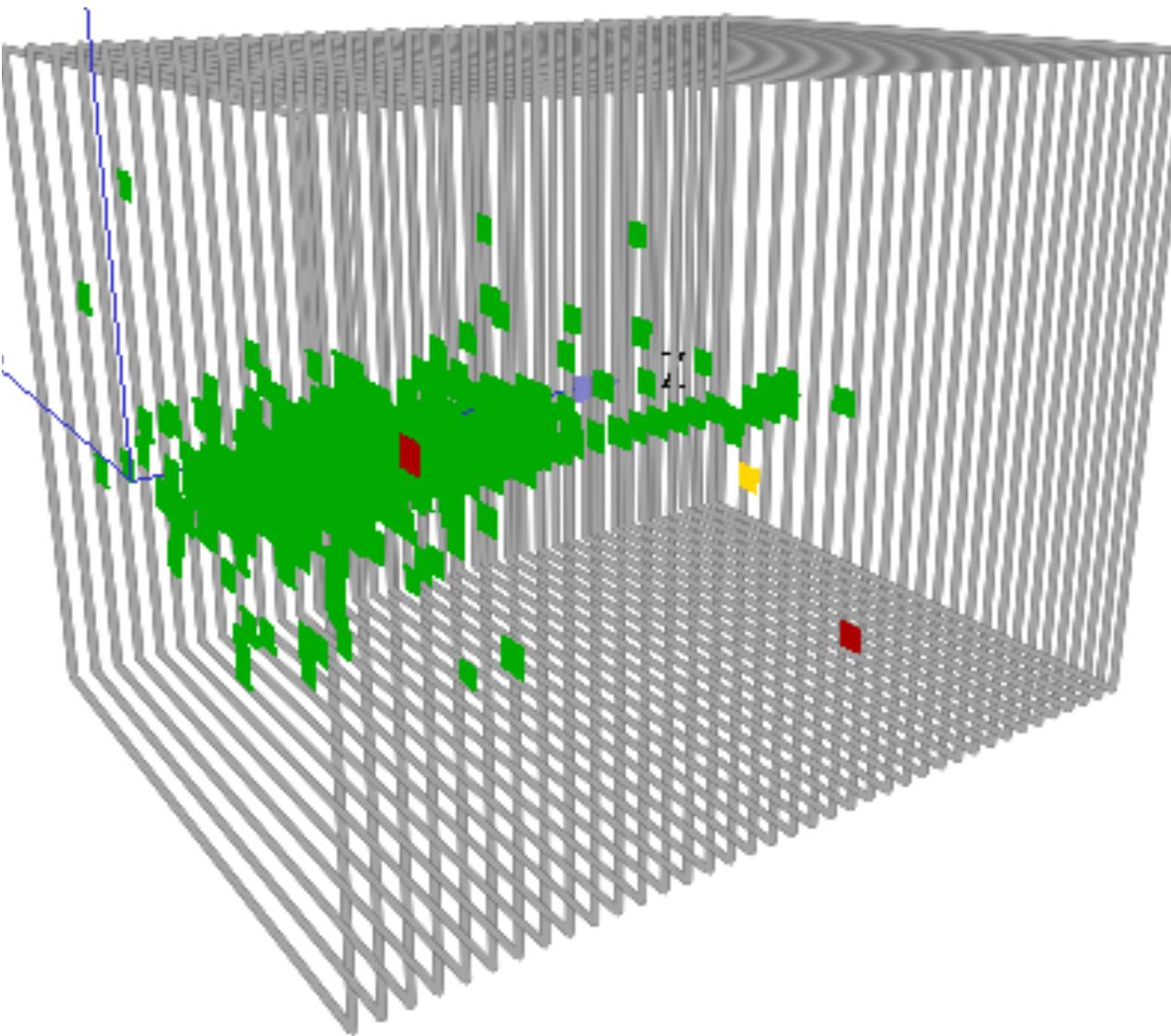
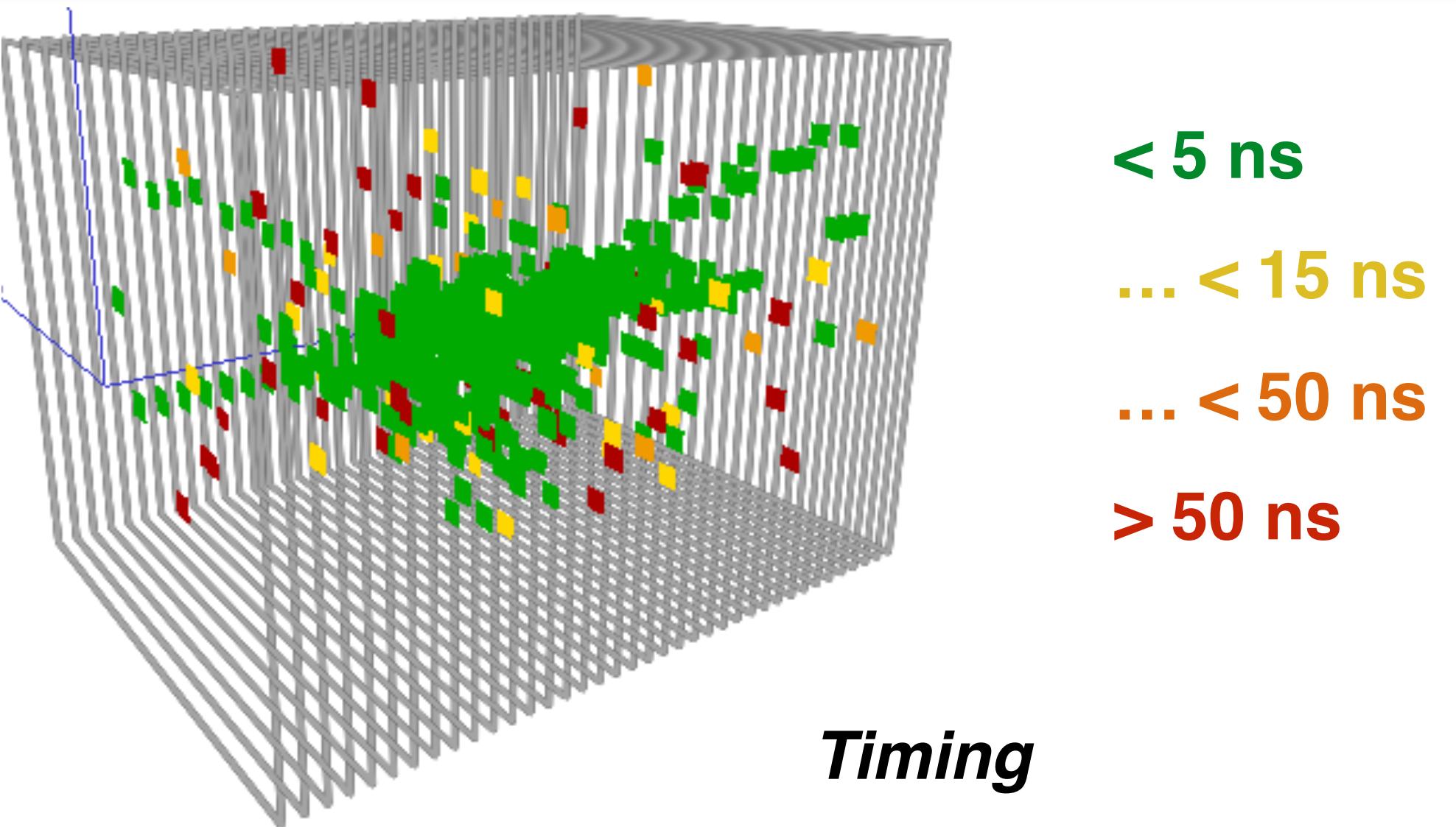
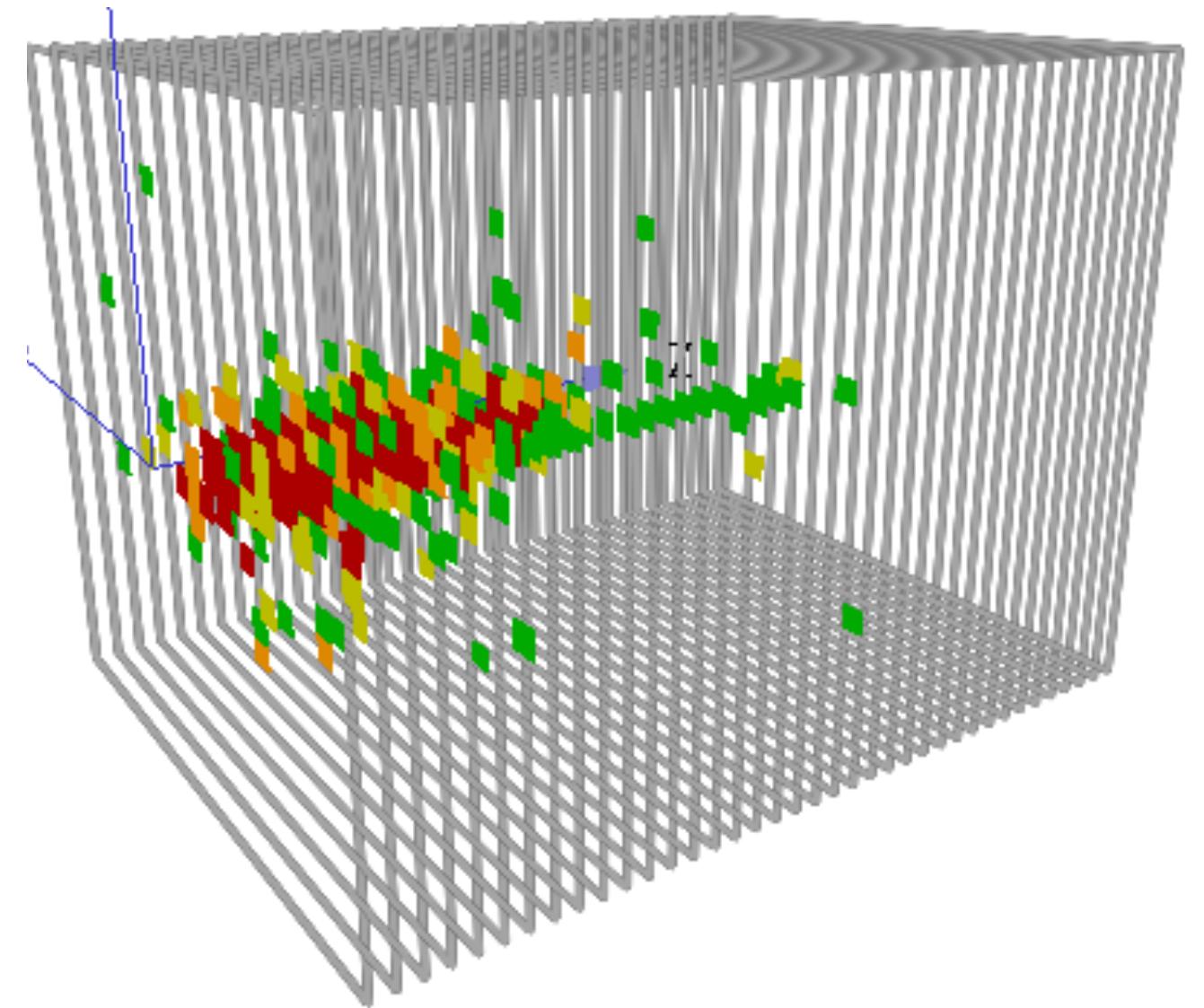
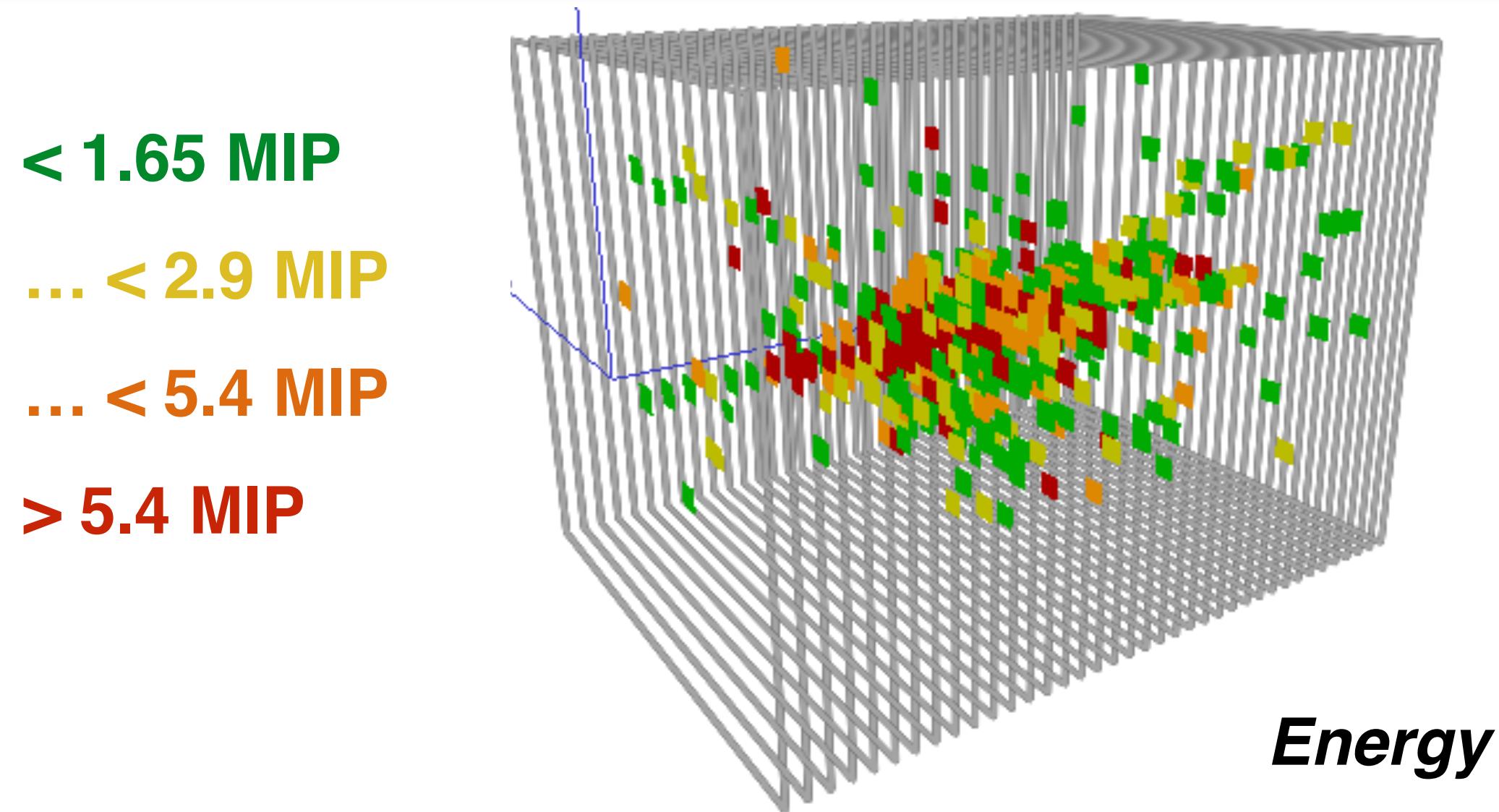
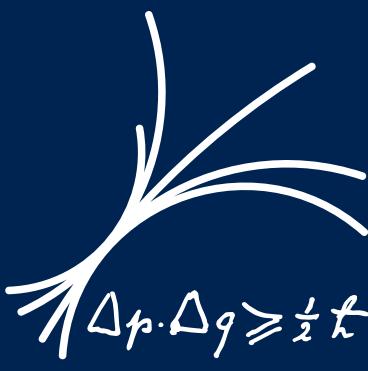
# Time Structure of Hadronic Showers



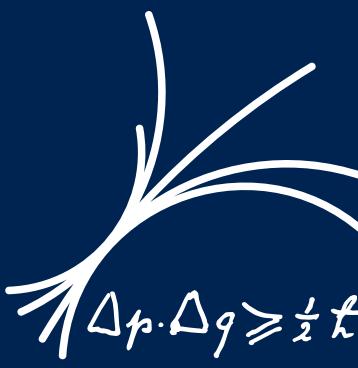
**Simulations**



# Time Structure of Hadronic Showers

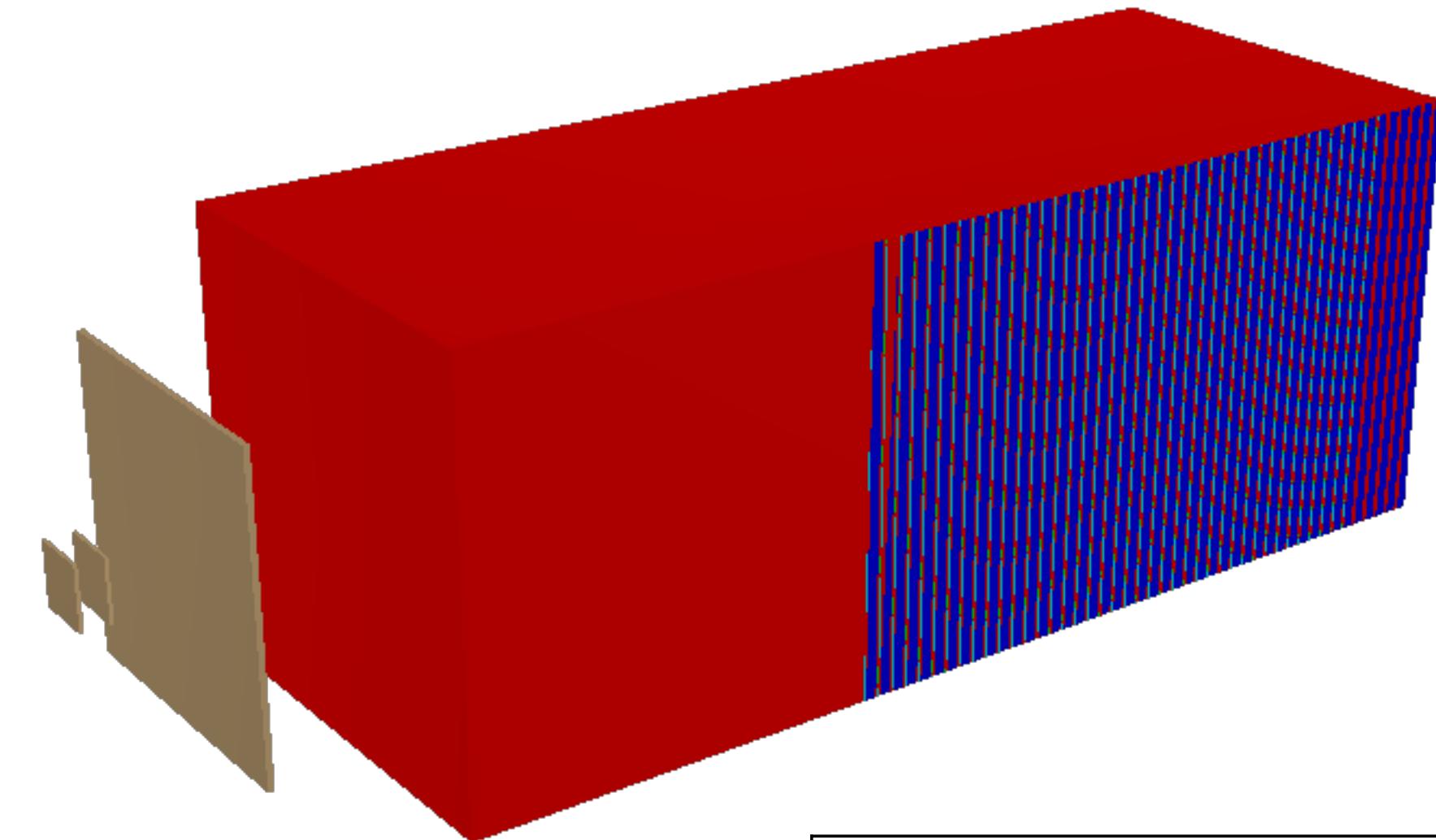


# Simulation



## Data:

- AHCAL May '18 test beam geometry with **60 layers** (reduce leakage)
- **10-85 GeV Pions** in 1GeV steps

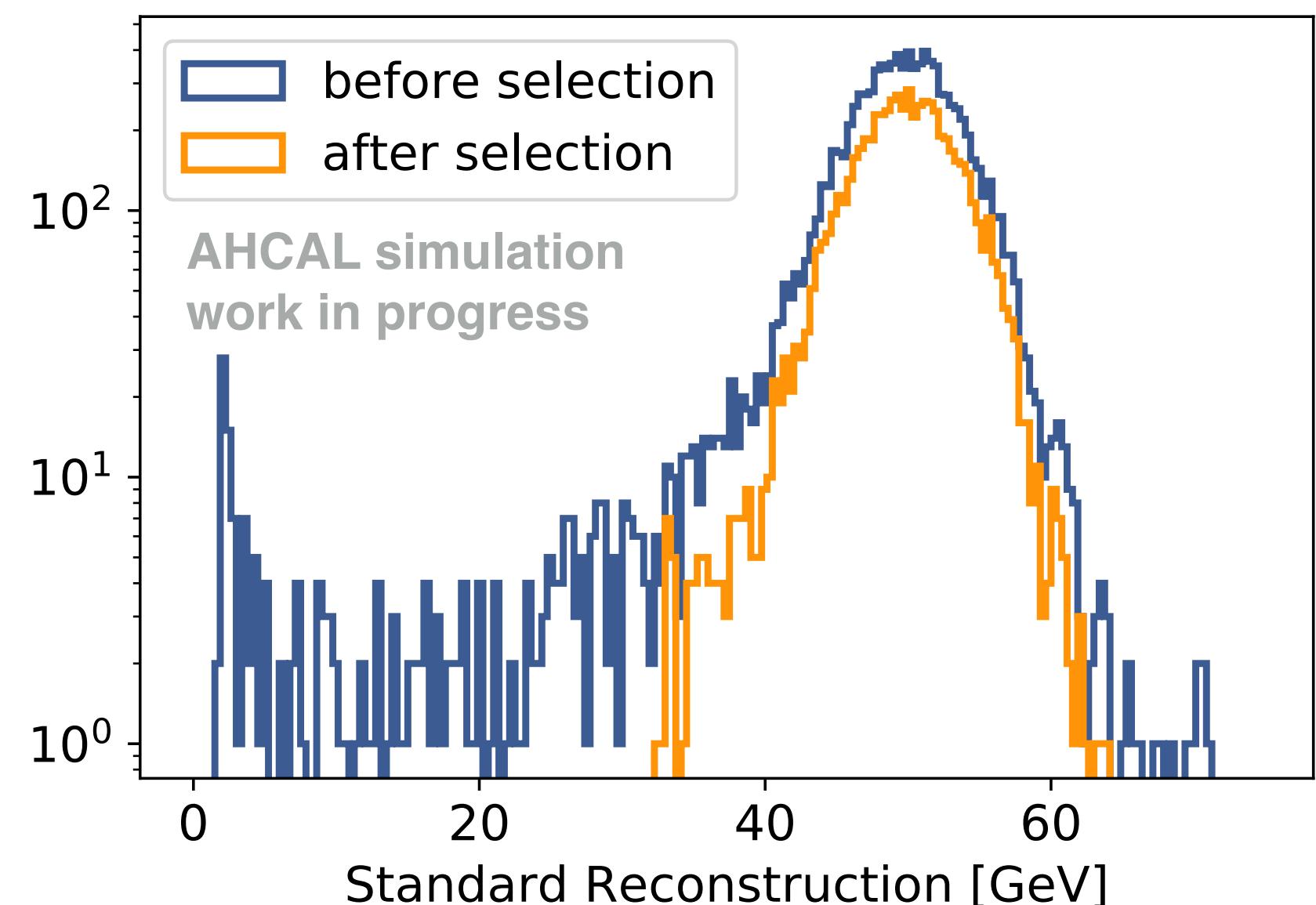


## Digitization:

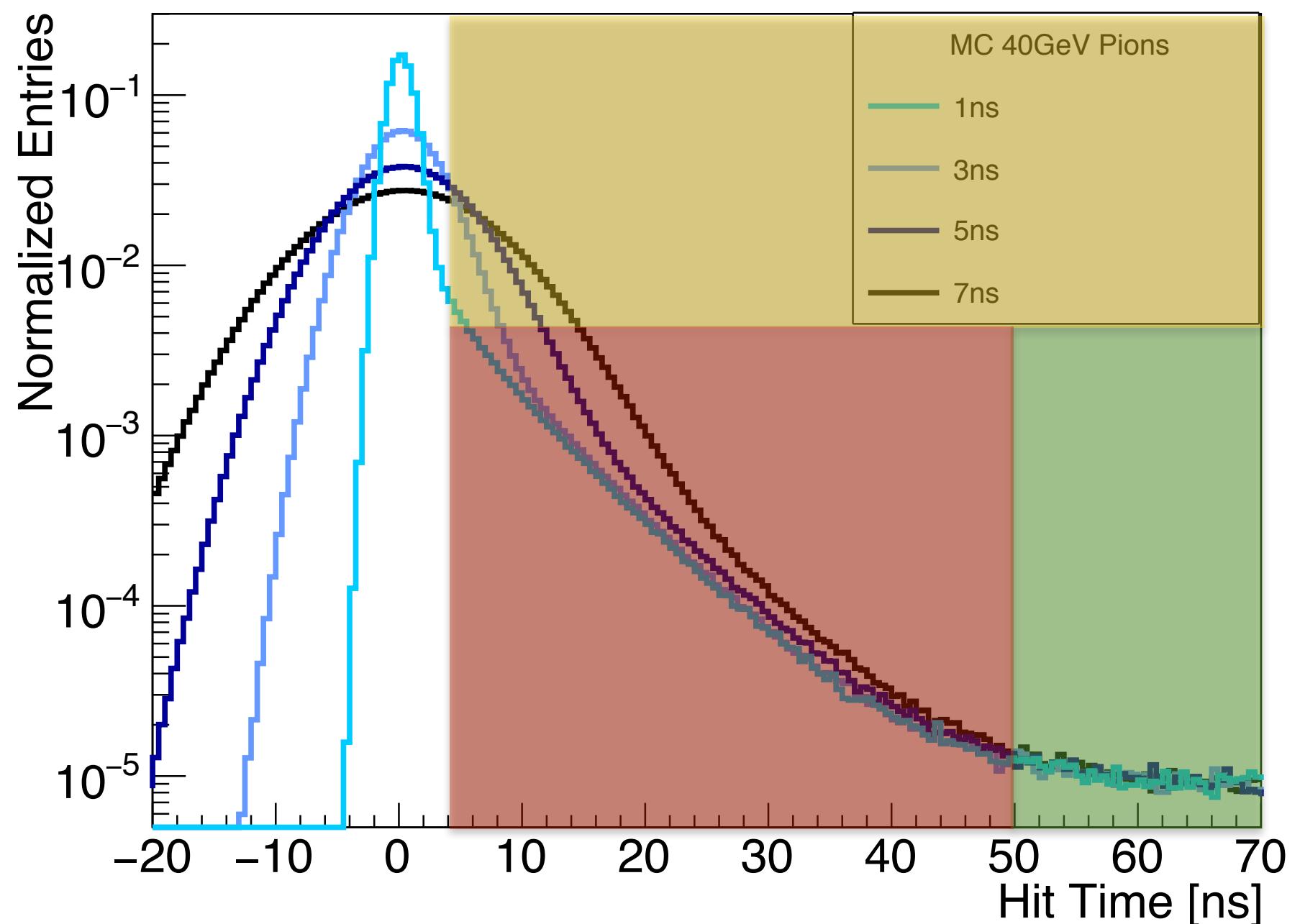
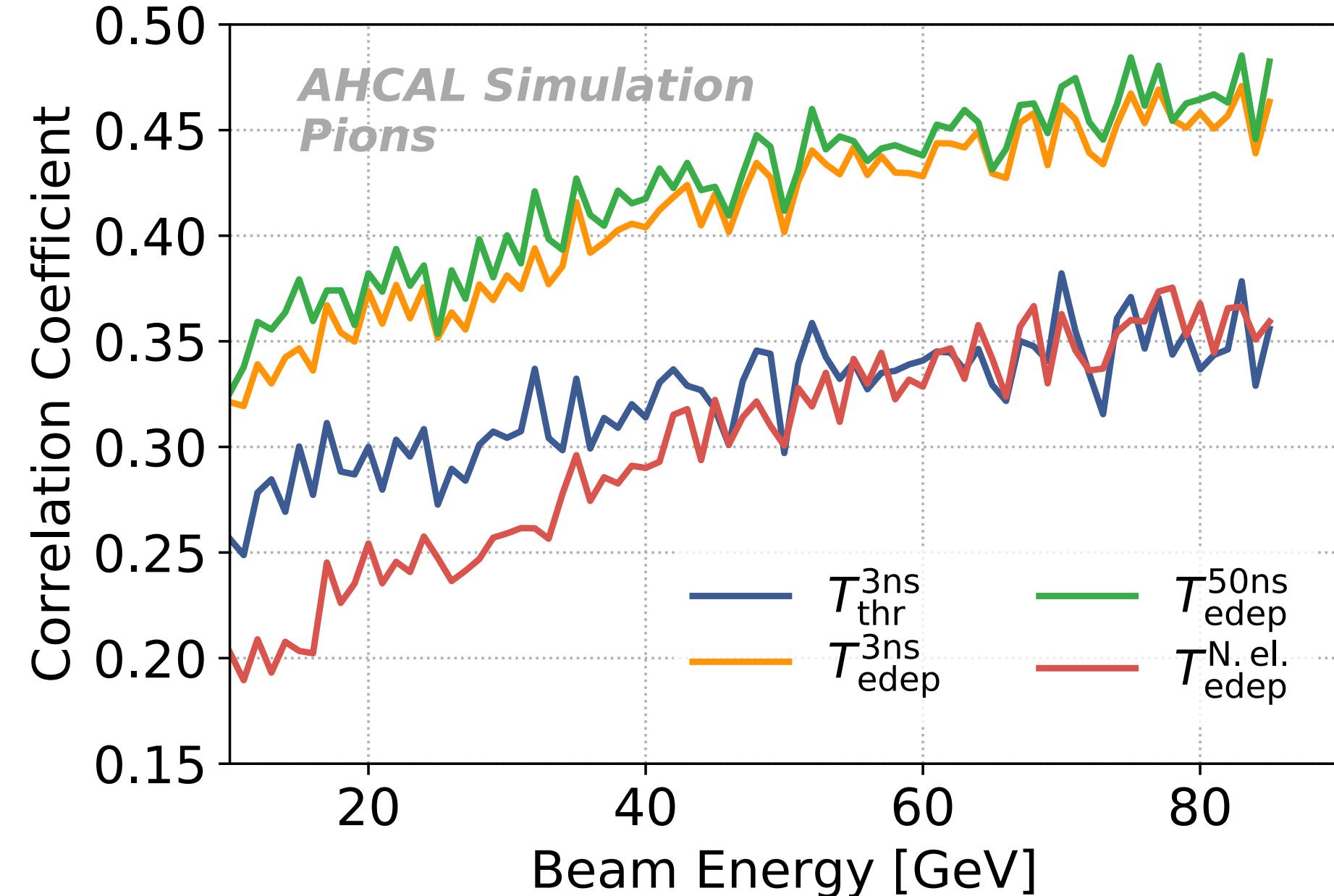
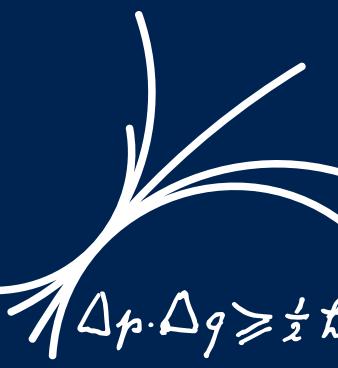
- **1ns** gaussian time smearing
- For now: ignore limited bunch crossing length in SPIROC

## Event selection:

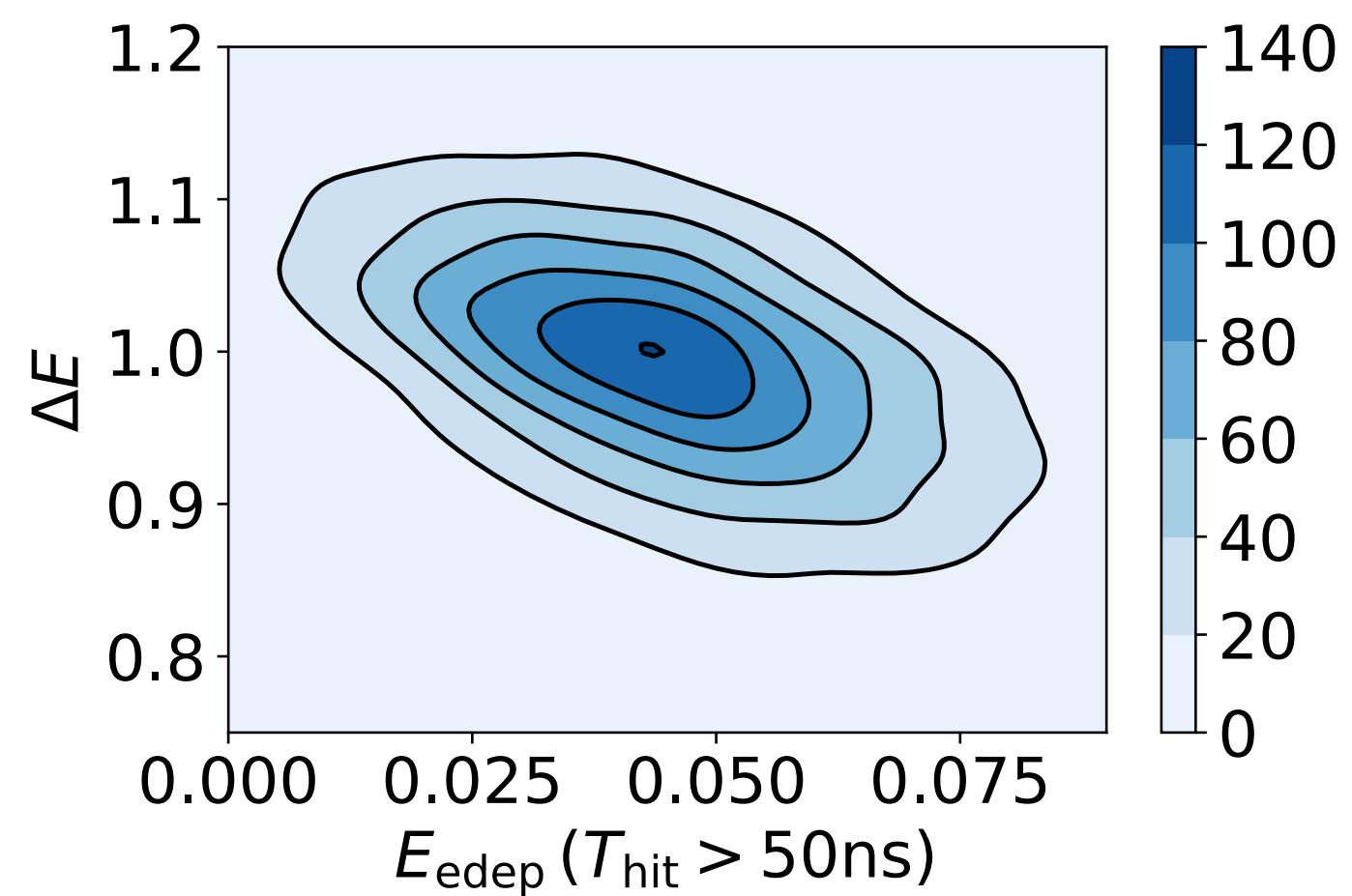
- Shower start before layer 15
- Cut on  $\pm 2.5\sigma$



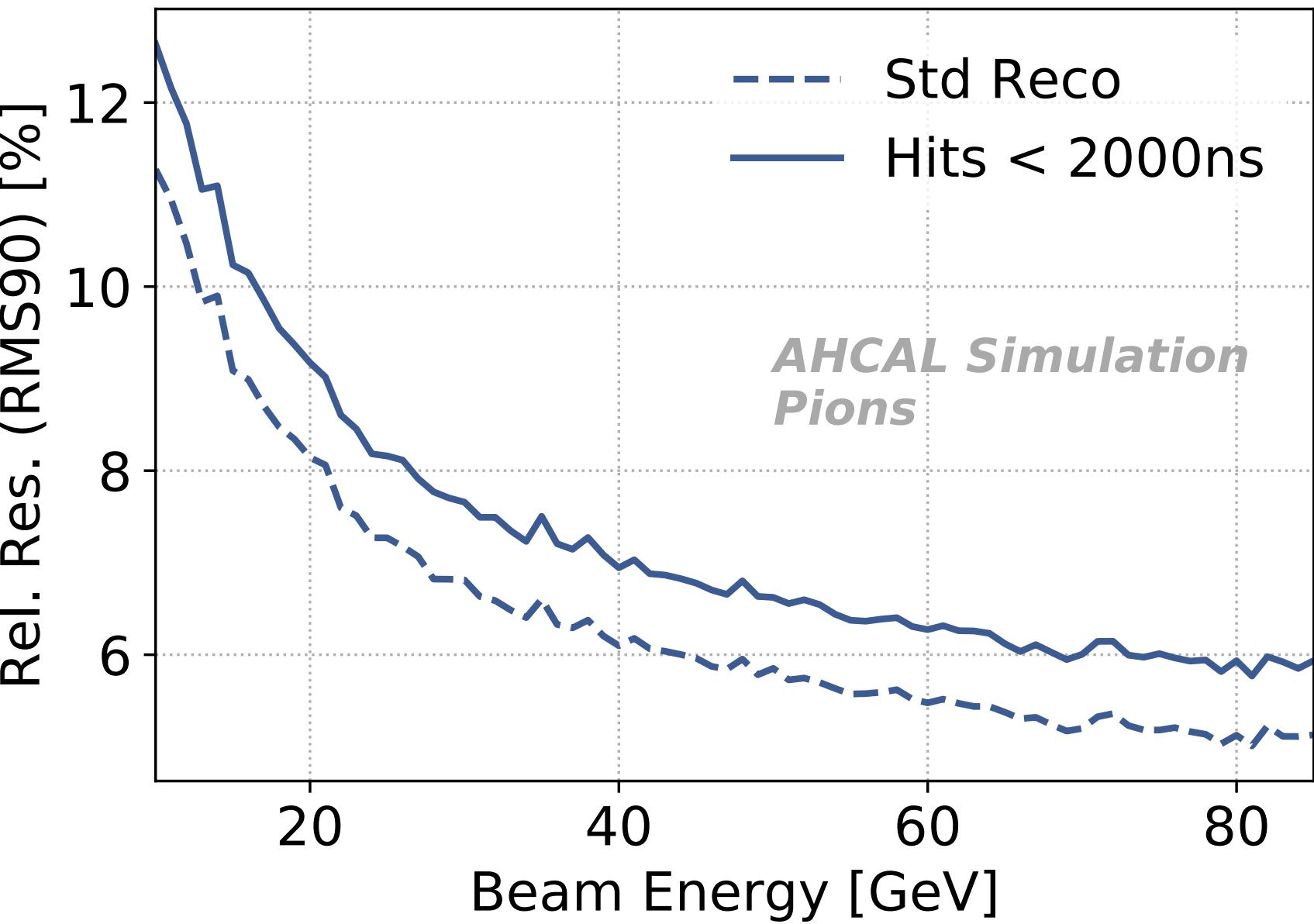
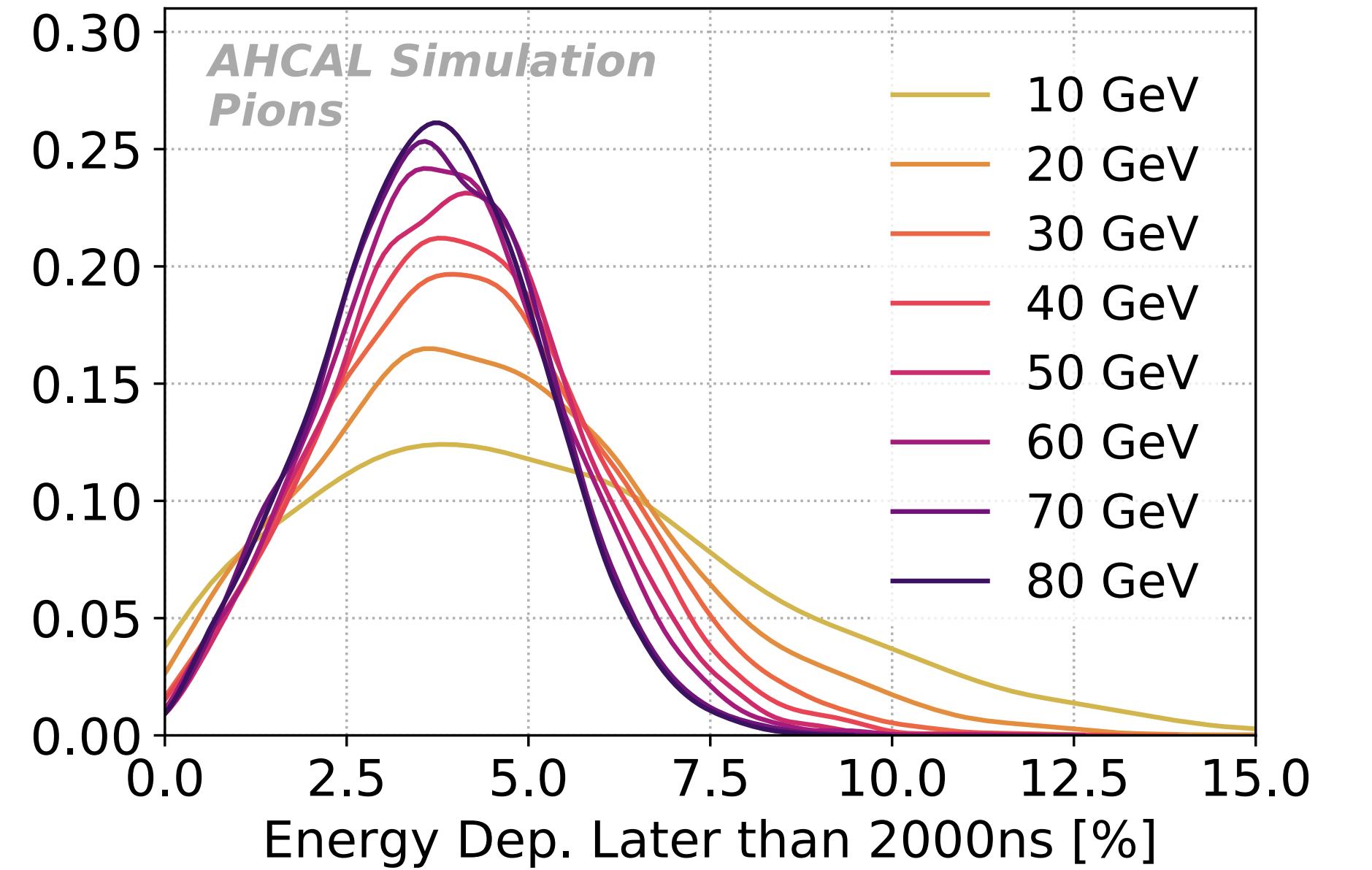
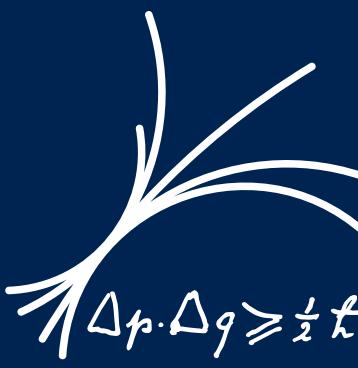
# Correlations



All hits, also very late ones  
**Clear correlation between time observables and reconstructed energy**  
**Neutron capture part is more predictive**



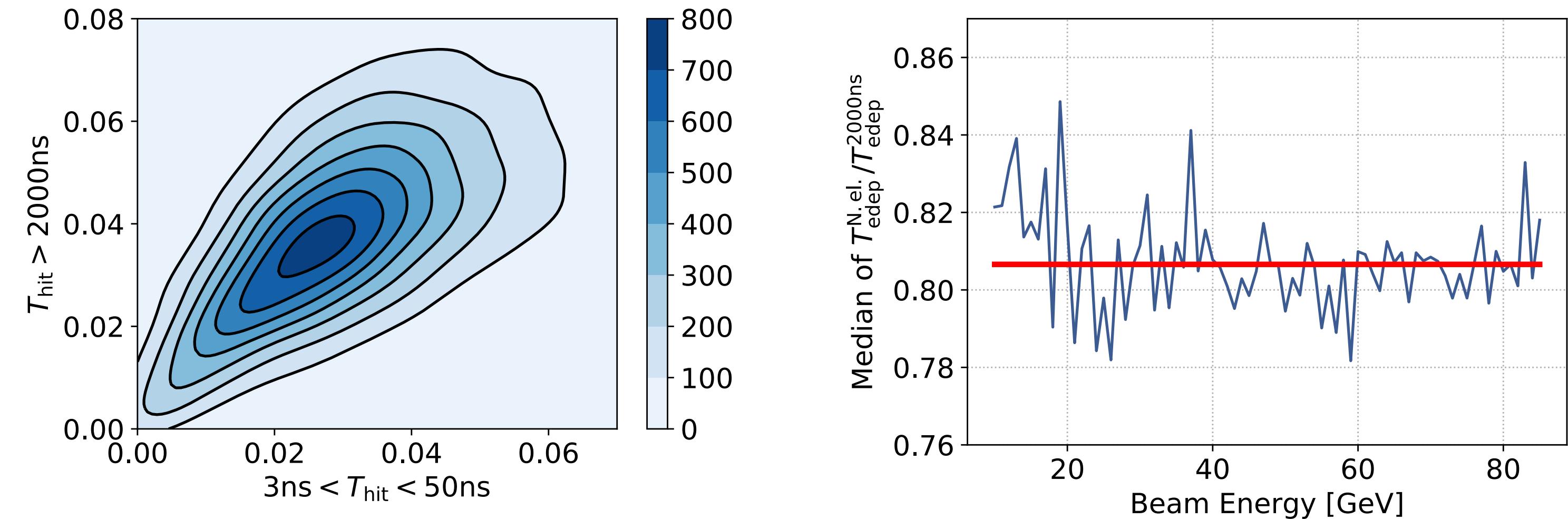
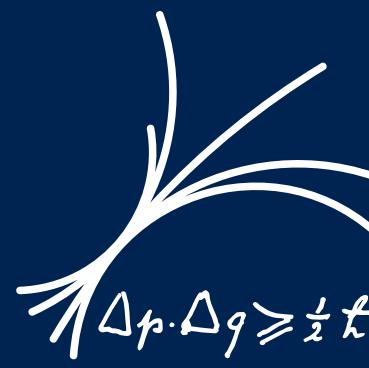
# Limited Integration Time



About **4% of the energy depositions later than 2000ns** with significant fluctuations

**~10% worse energy resolution** with limited integration time

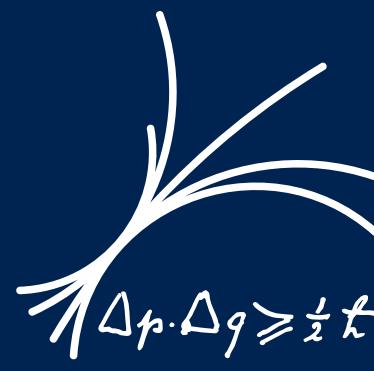
# Limited Integration Time



**Strong correlation** between neutron elastic scattering and neutron capture

Use neutron elastic part **to predict invisible neutron capture** part

# Global SC



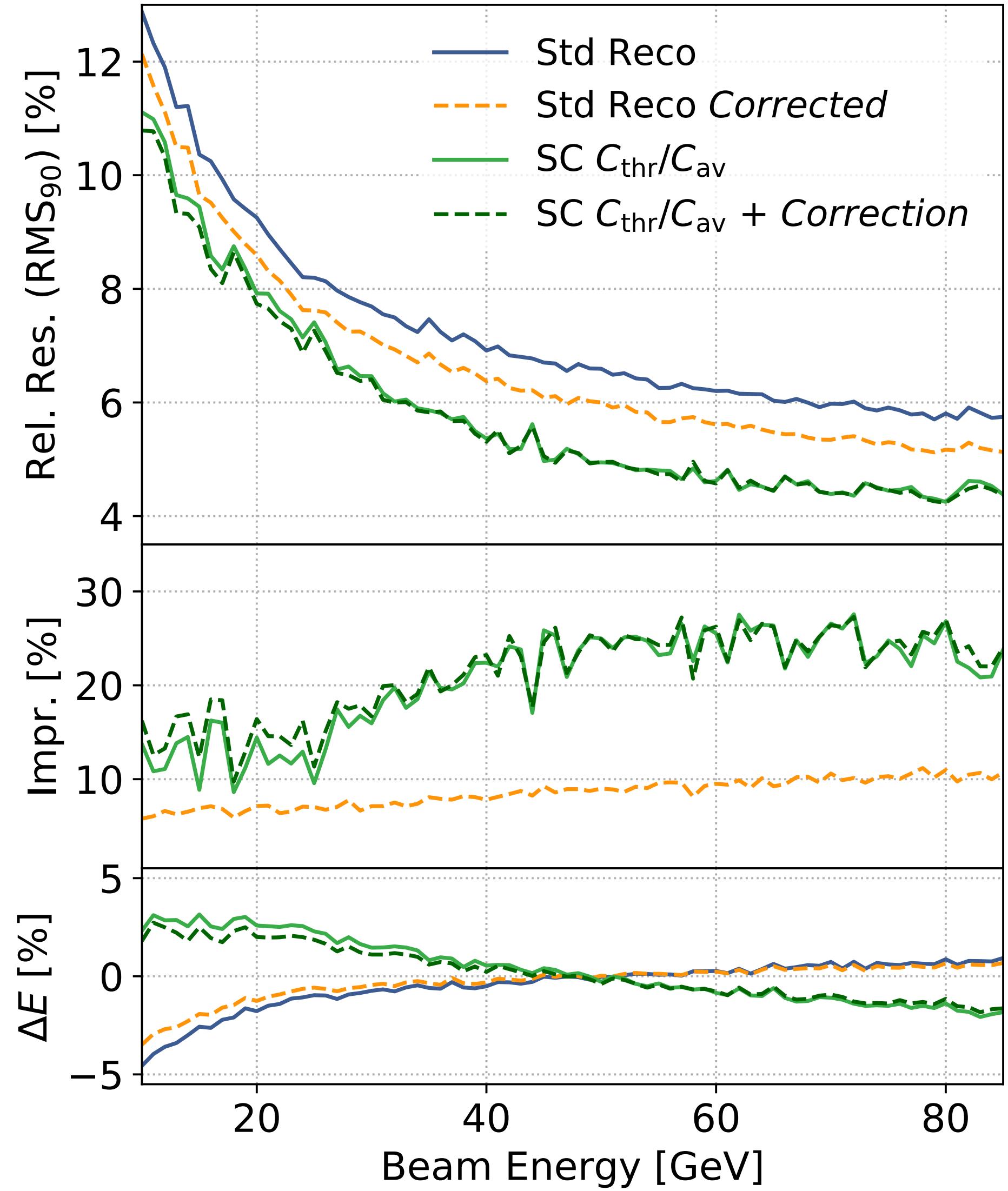
$$C_{thr}[> 5\text{MIP}] = \frac{N(E_{\text{hit}} > 5\text{MIP})}{N_{\text{total}}}$$

$$C = \frac{C_{\text{thr}}[> 5\text{MIP}]}{C_{\text{av}}}$$

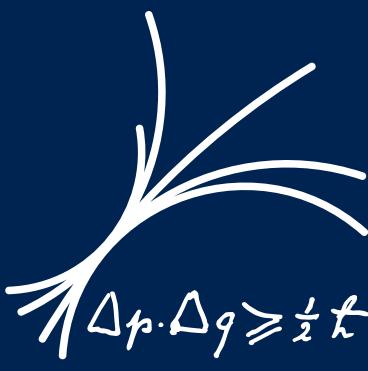
$$\chi^2 = \frac{(E_{\text{sum}} * (a + b * \text{feature} + c * \text{feature}^2) - E_{\text{beam}})^2}{E_{\text{beam}}}$$

**Simplified implementation of global software compensation: Energy independent**

$$C_{\text{av}} = \frac{N(E_{\text{hit}} > \overline{E}_{\text{hit}})}{N_{\text{total}}}$$



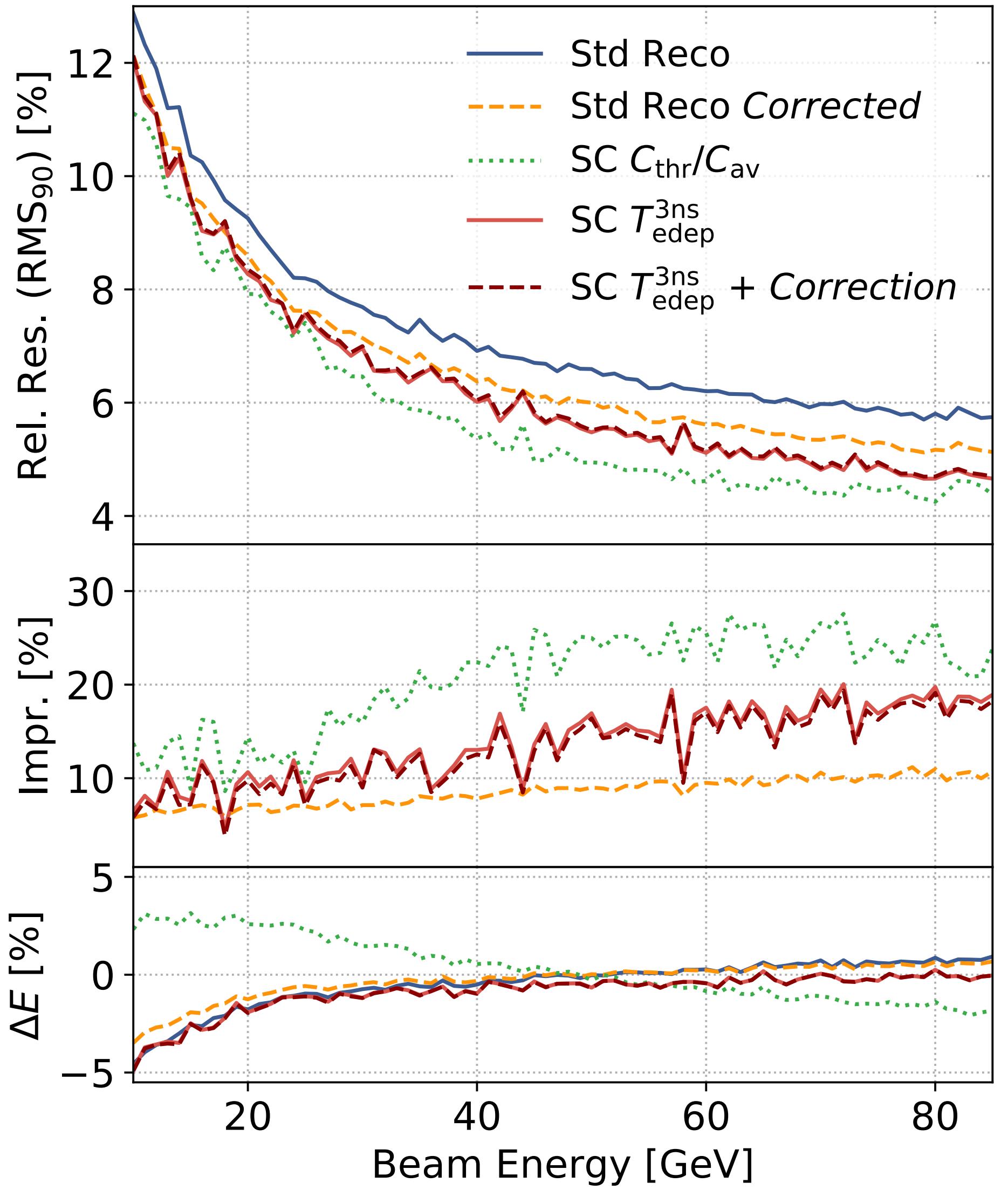
# Global SC Time



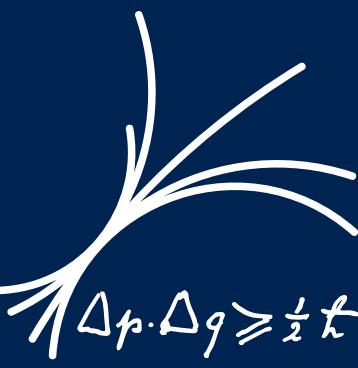
$$T_{\text{edep}}^{3\text{ns}} = \frac{E(E_{\text{hit}} > 3\text{ns})}{E_{\text{total}}}$$

$$\chi^2 = \frac{(E_{\text{sum}} * (a + b * \text{feature} + c * \text{feature}^2) - E_{\text{beam}})^2}{E_{\text{beam}}}$$

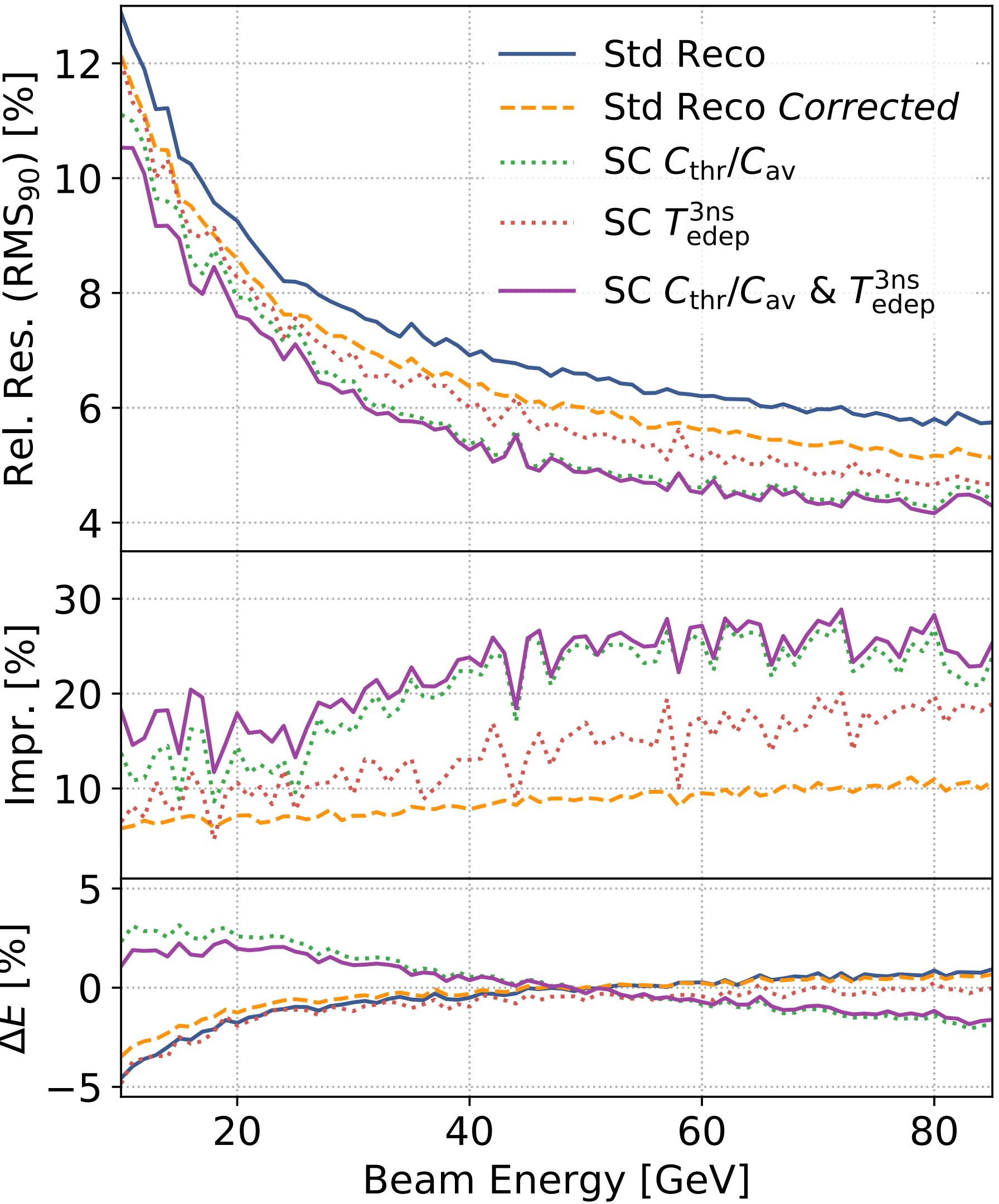
**Global SC works with hit time observables!**  
**Does not perform as good as the hit energy observables**



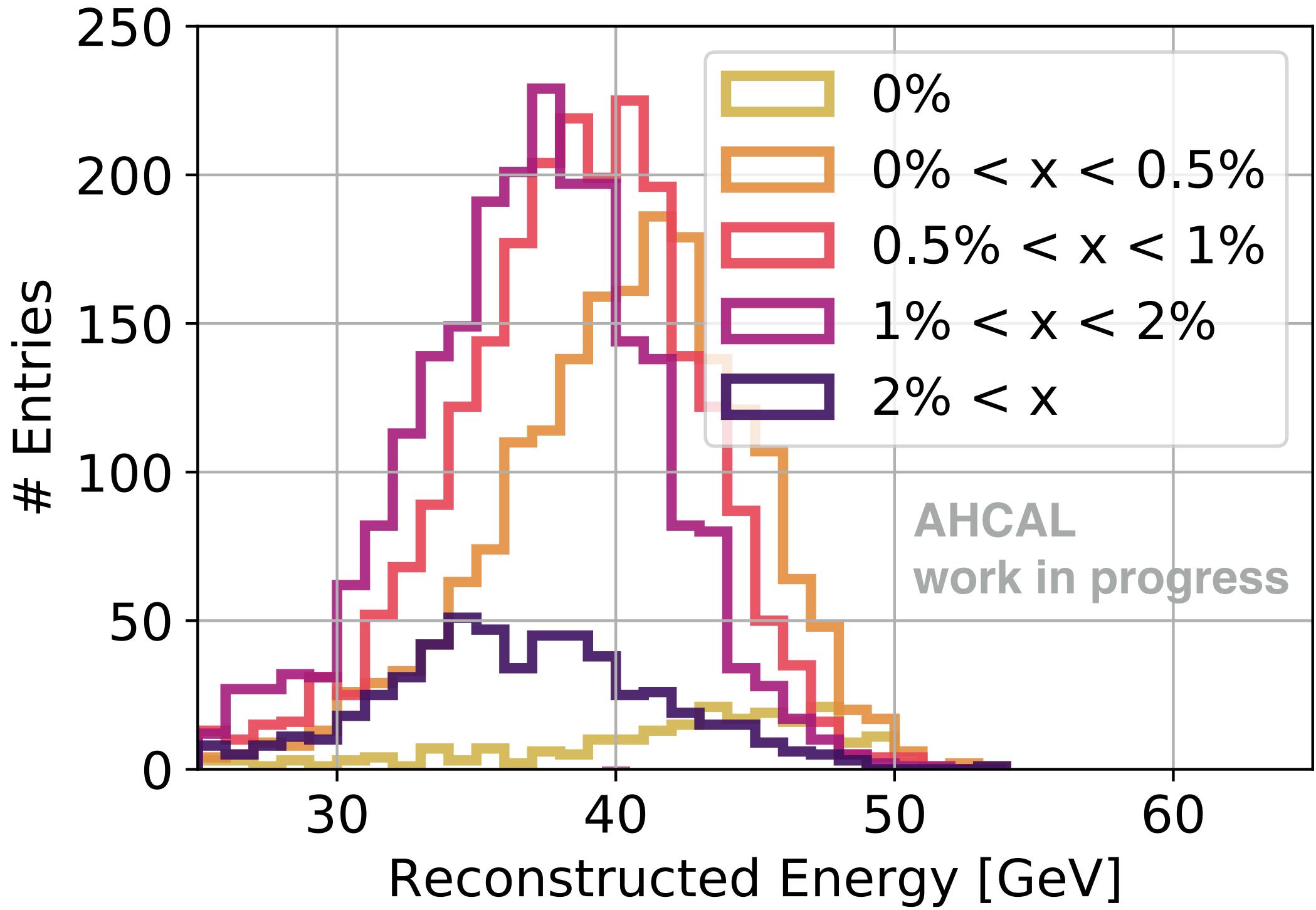
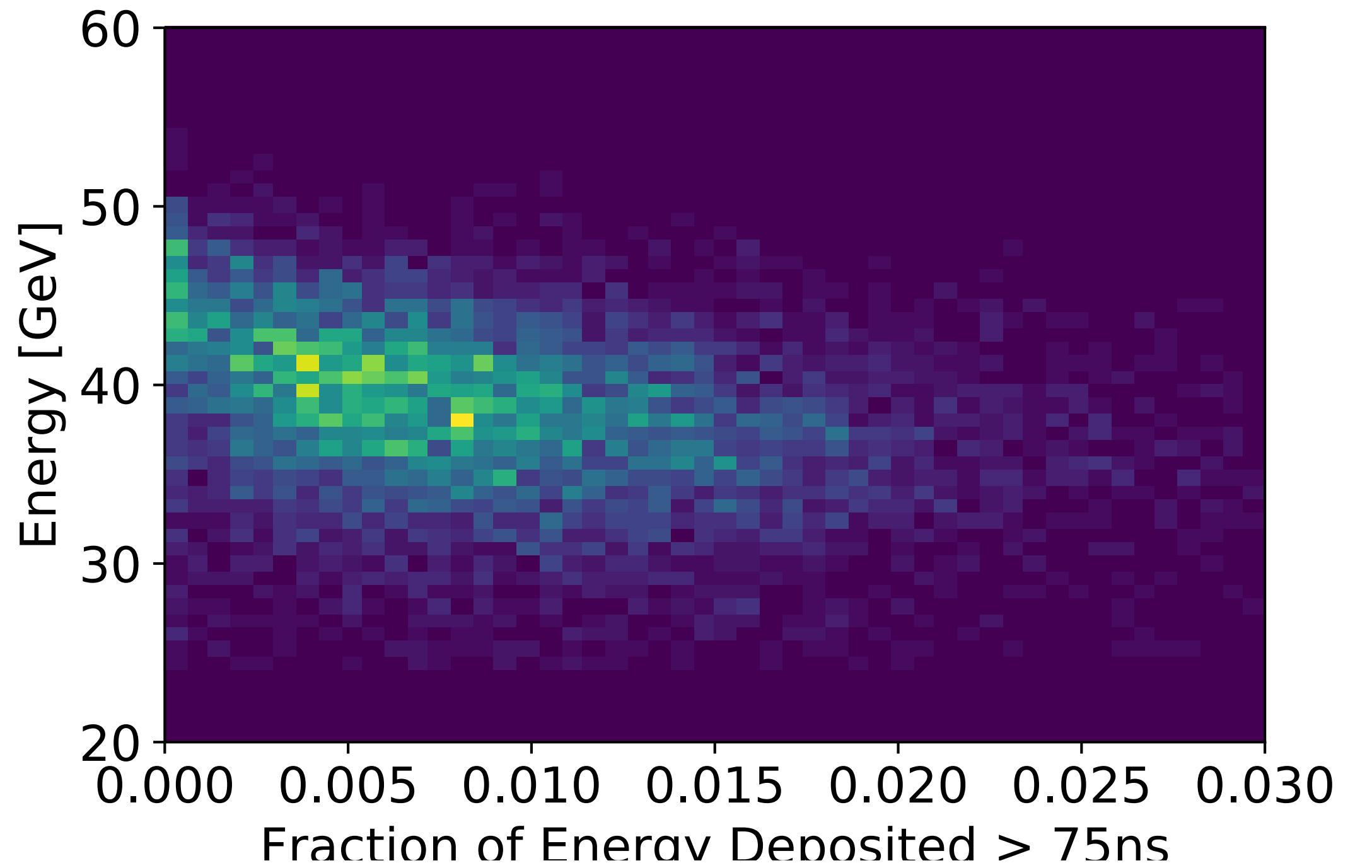
# Global SC Time



**Combining hit energy and hit time observables only gives minor improvement**



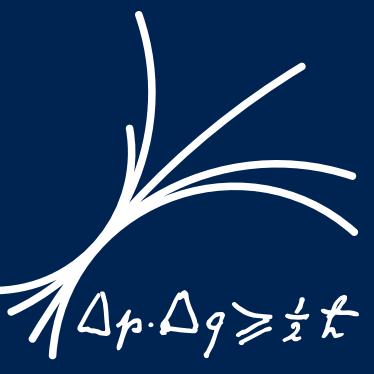
# Timing Correlation in Data



- **Correlation** between timing observables and  $E_{\text{reco}}$  also observed in data
- Limited statistics in late hits due to bad time resolution

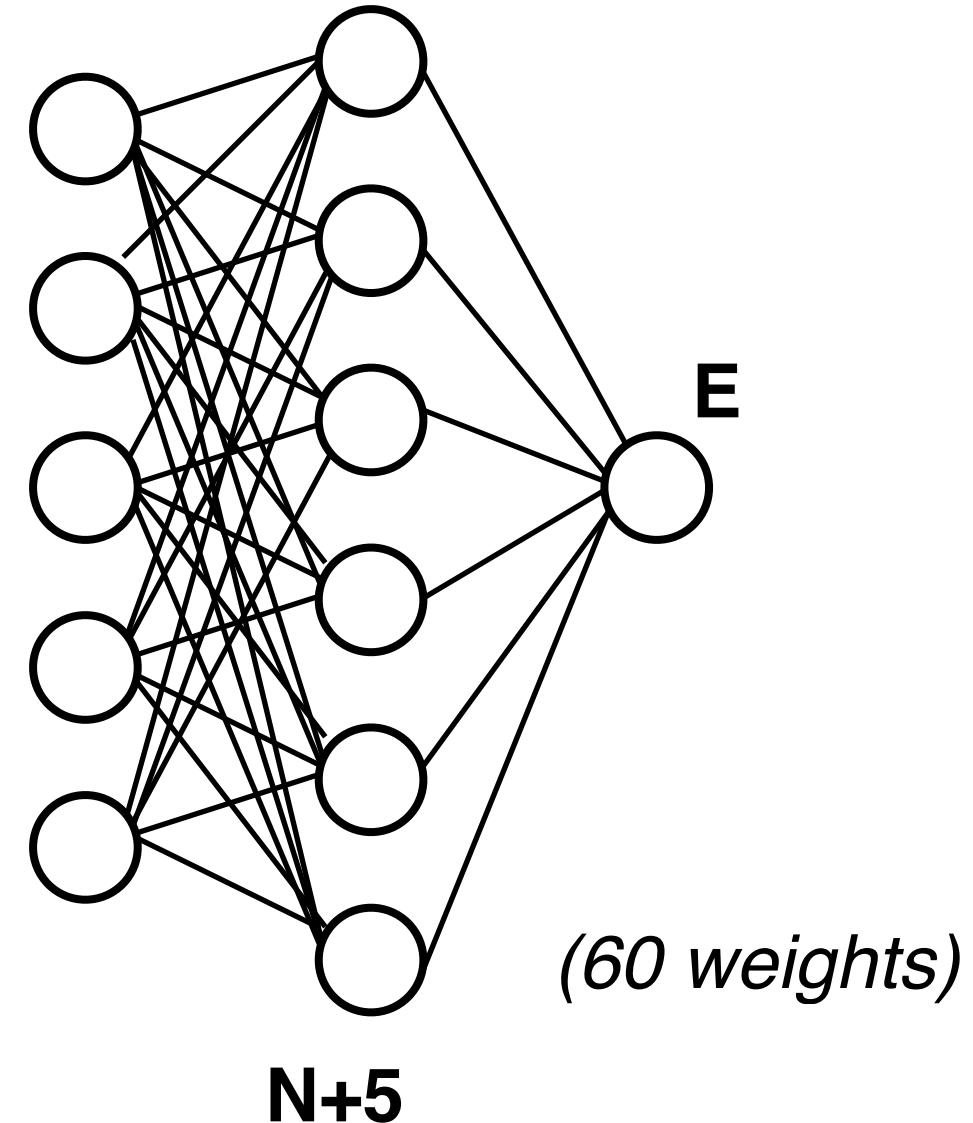
# Neural Network Approach

# Neural Networks in the AHCAL

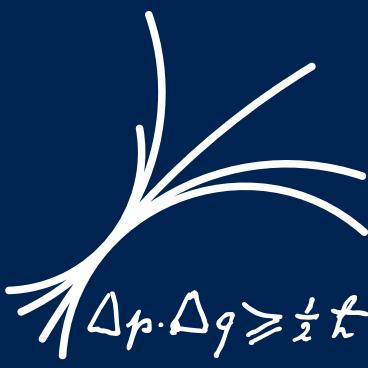


[Katja Seidel]

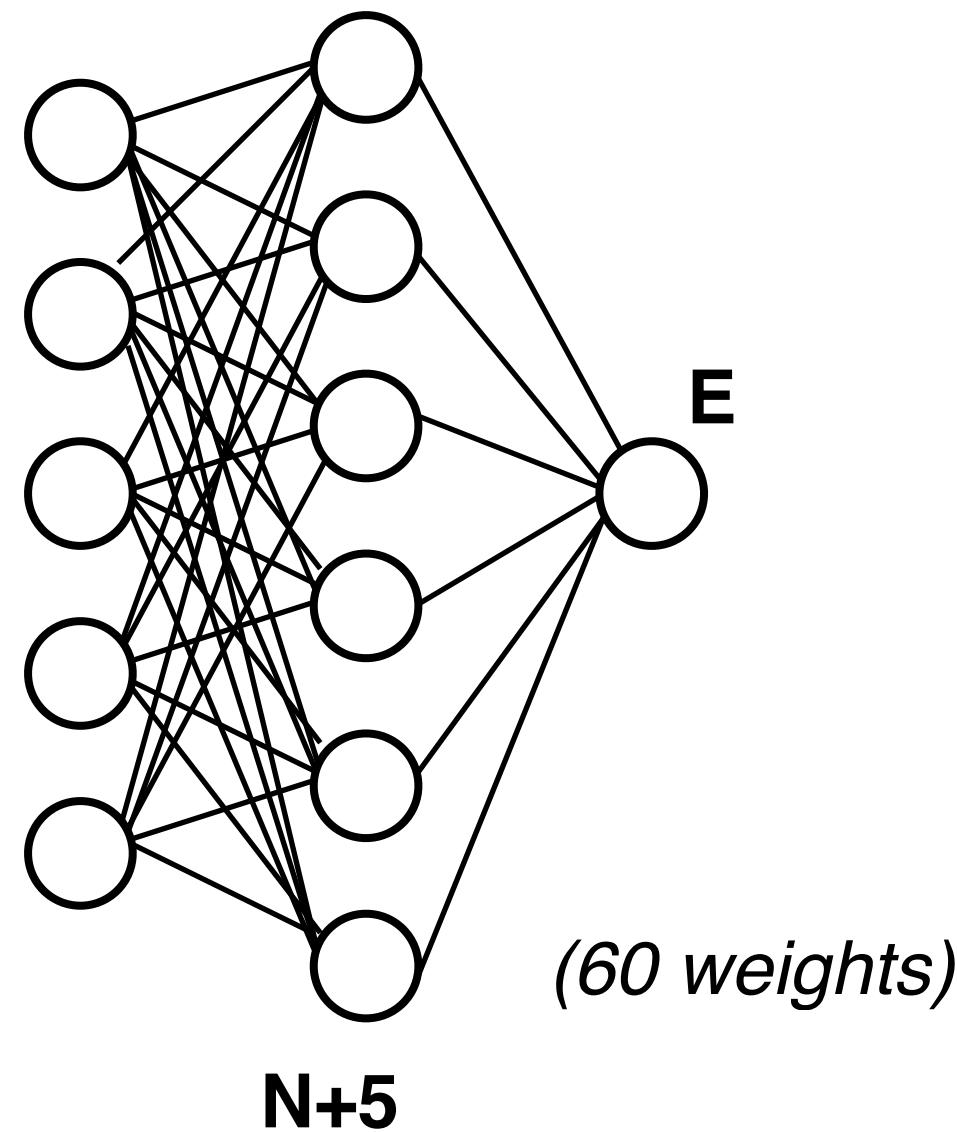
Complexity



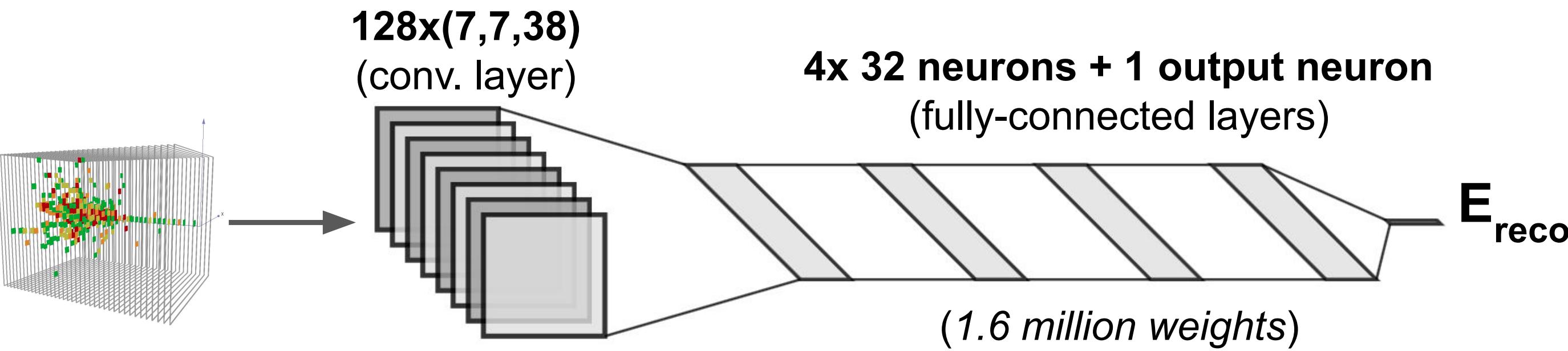
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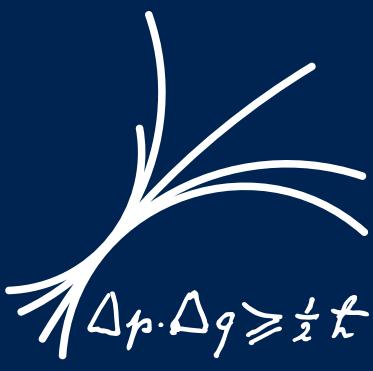


## Complexity

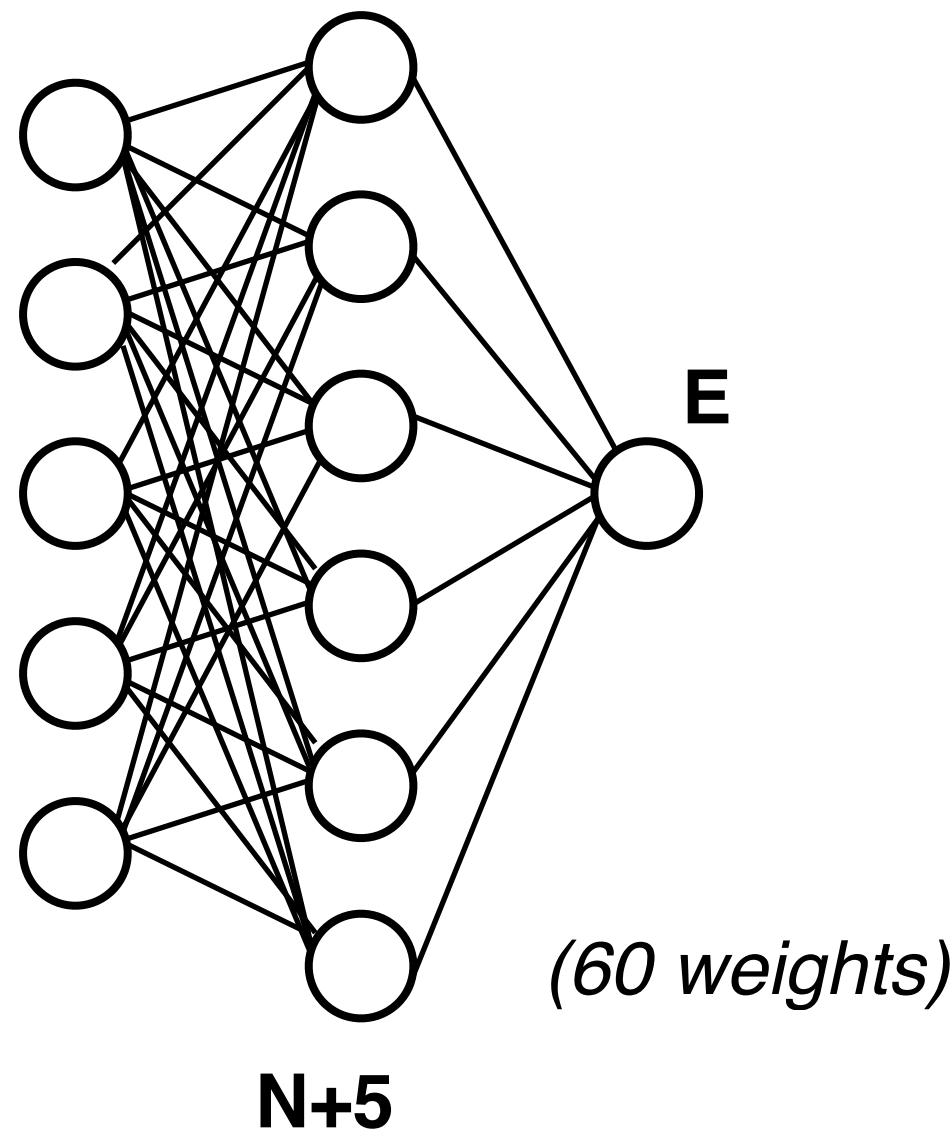


[Erik Buhmann]

# Neural Networks in the AHCAL



[Katja Seidel]



## Complexity

This Study

128      64

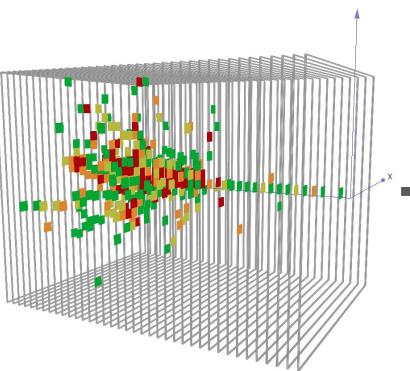
[...]

[...]

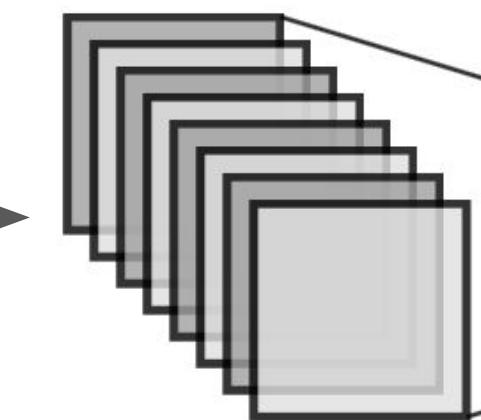
[...]

dE

(10k weights)



128x(7,7,38)  
(conv. layer)



4x 32 neurons + 1 output neuron  
(fully-connected layers)

E<sub>reco</sub>

(1.6 million weights)

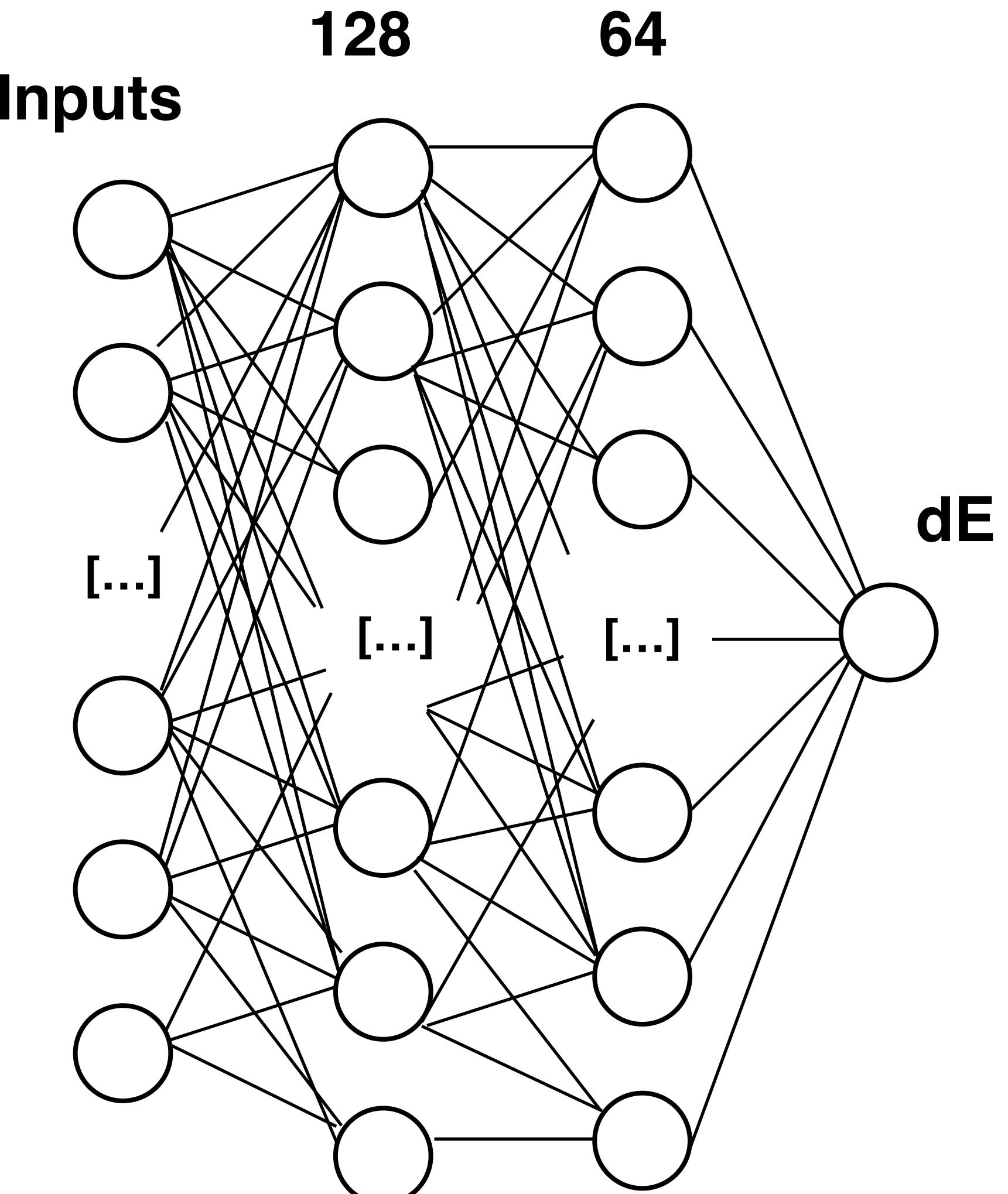
[Erik Buhmann]

# Neural Network: Architecture

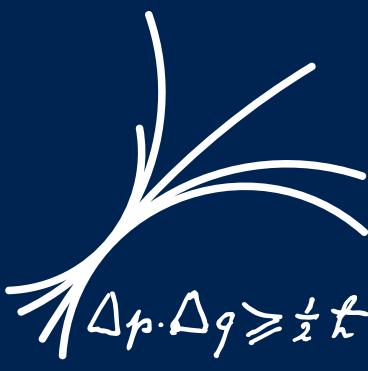


- Based on Keras (python)
- 2 fully connected hidden layers (128, 64 neurons)
- ~10'000 parameters
- Training on a laptop in minutes
- 1 GeV steps (10-85 GeV)

- **Energy independence:**
- Target variable:  $dE = E_{\text{reco}} / E_{\text{beam}}$
- Input features: energy independent

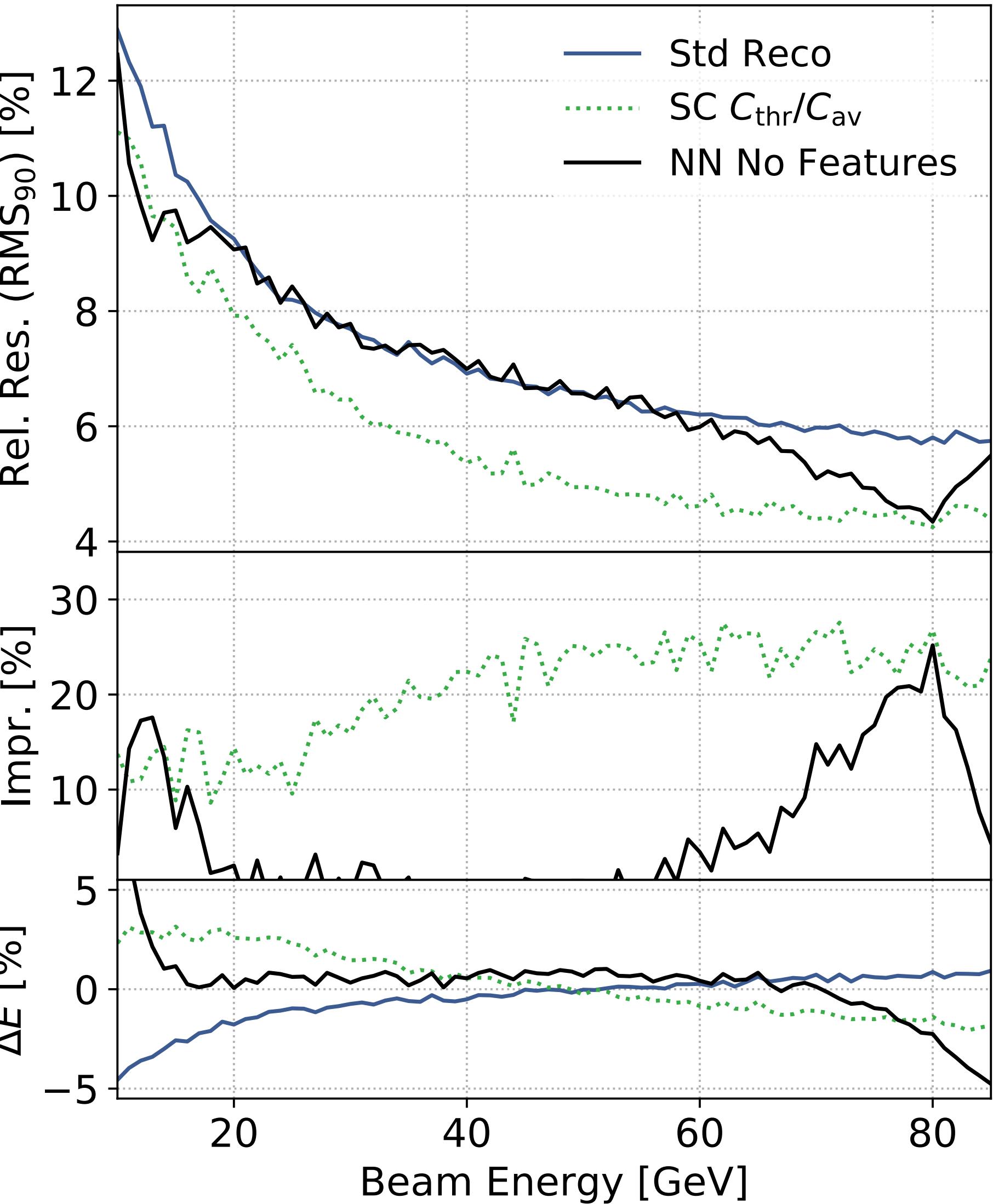


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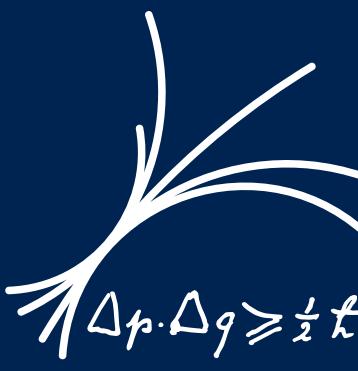


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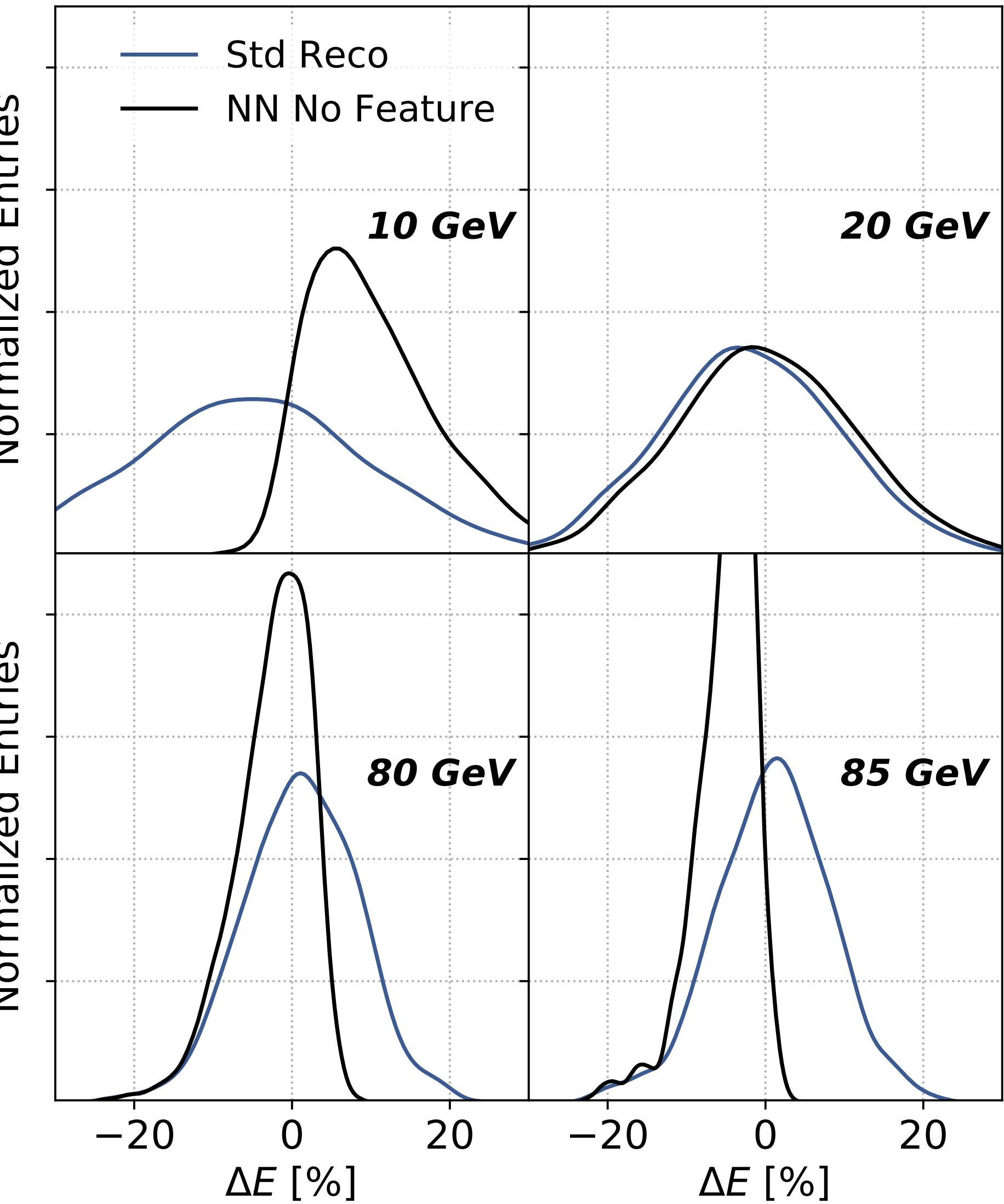


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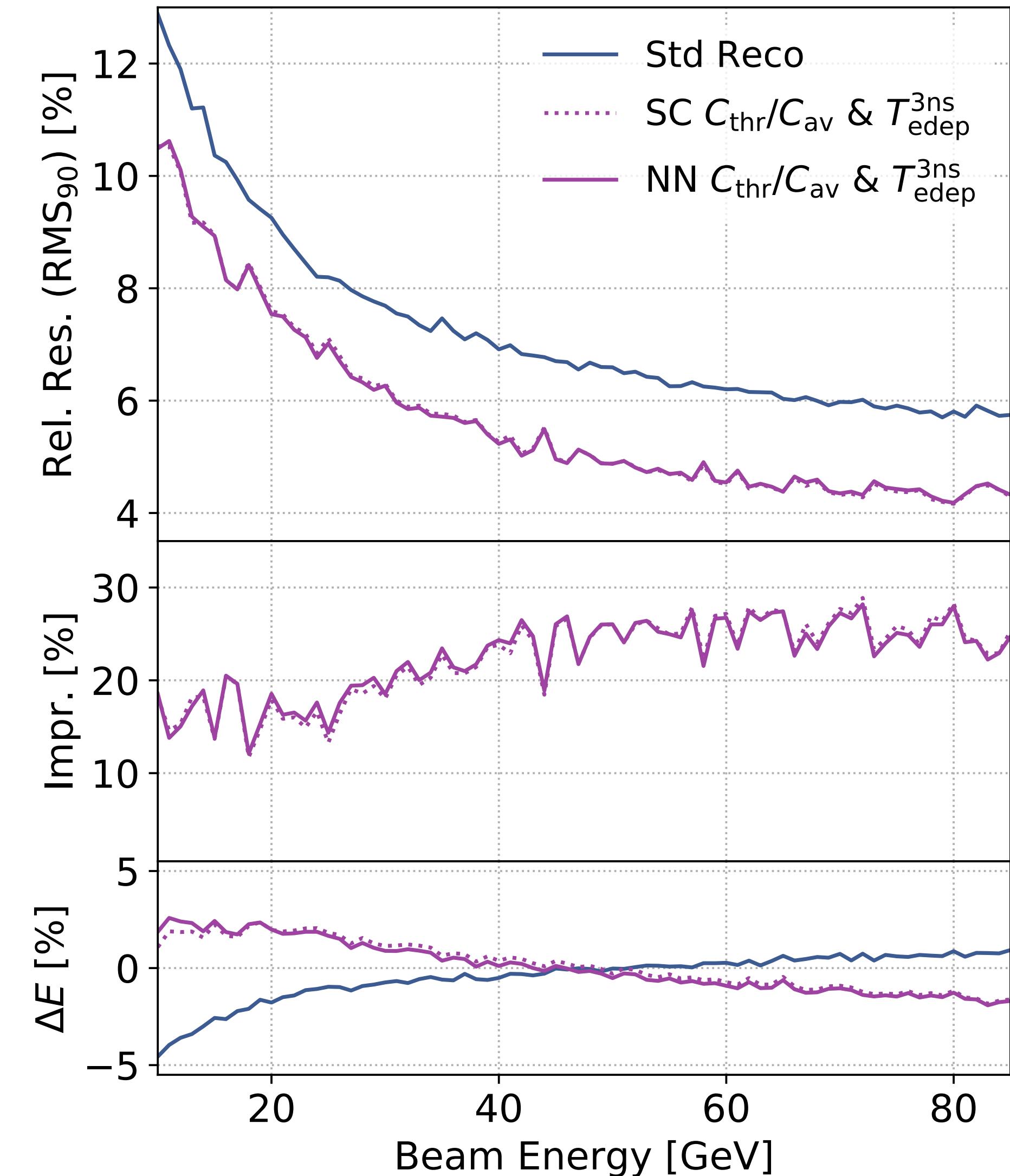
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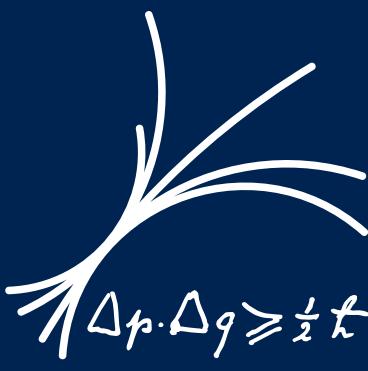
# Neural Network: Global Observables



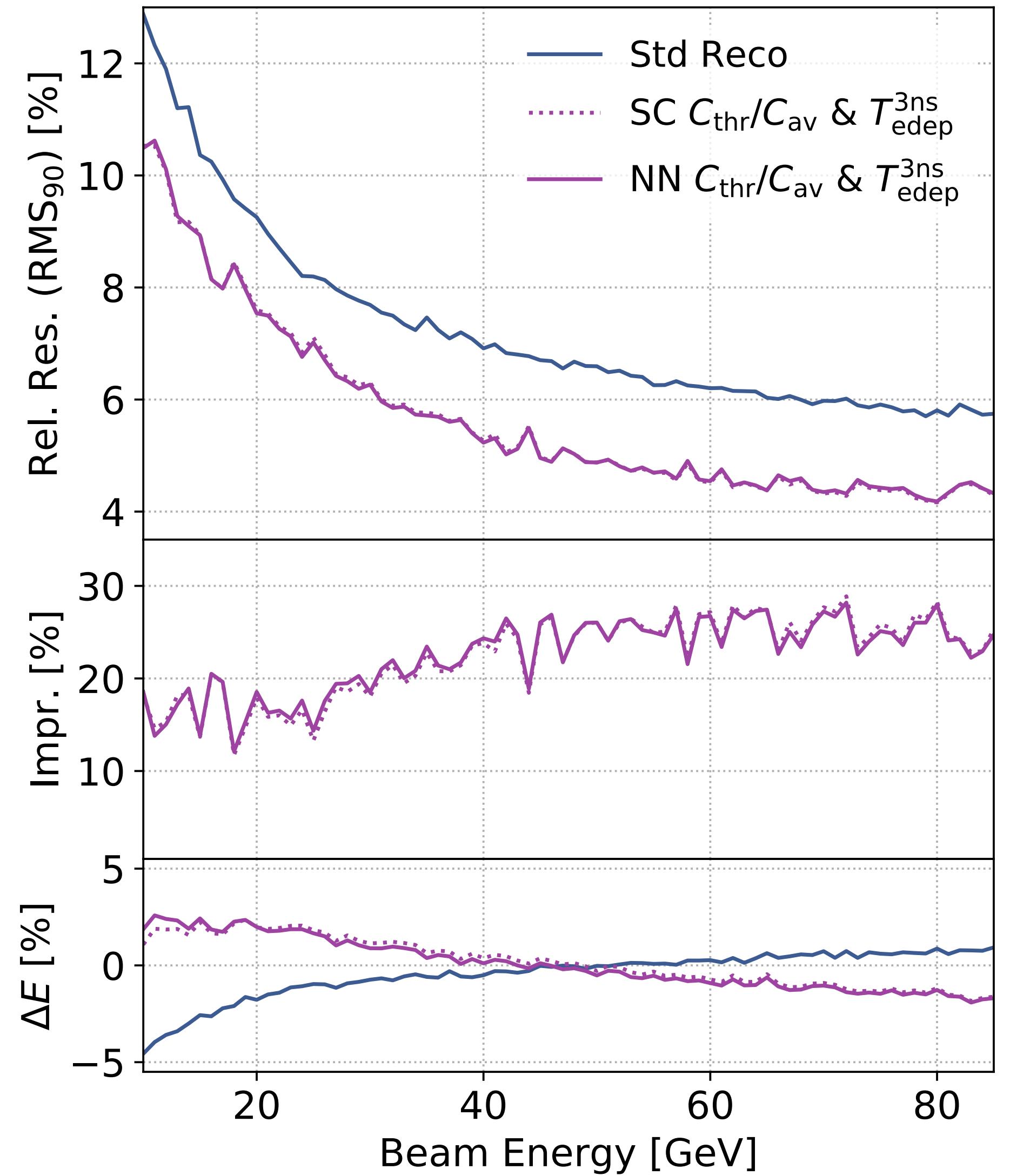
- **Similar performance** compared to global SC using the same variables



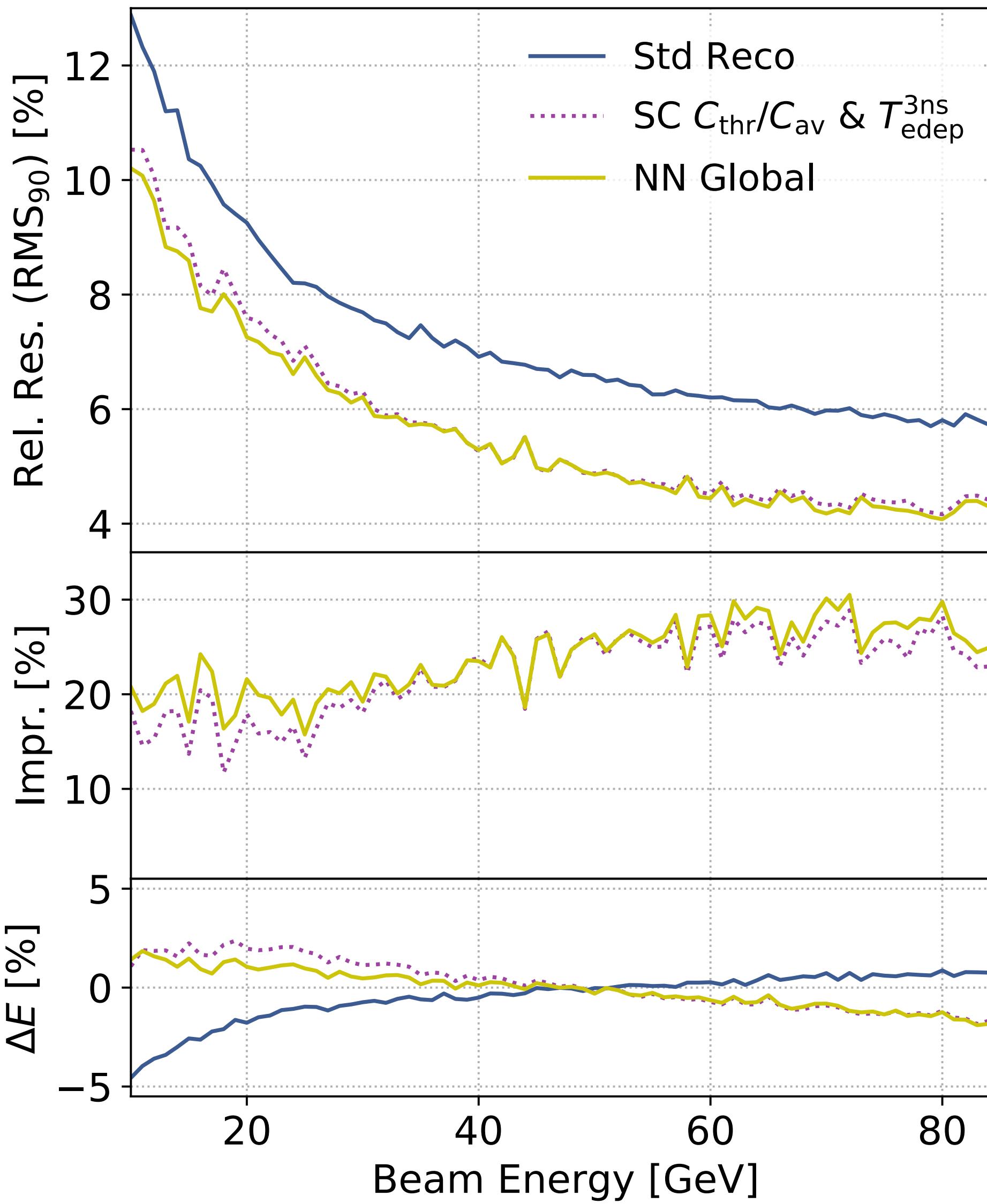
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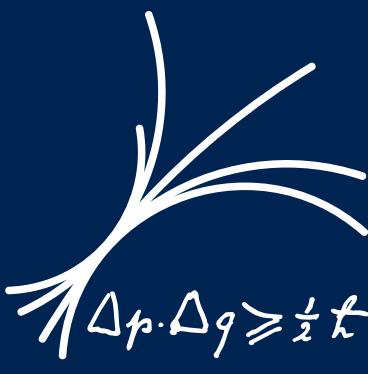
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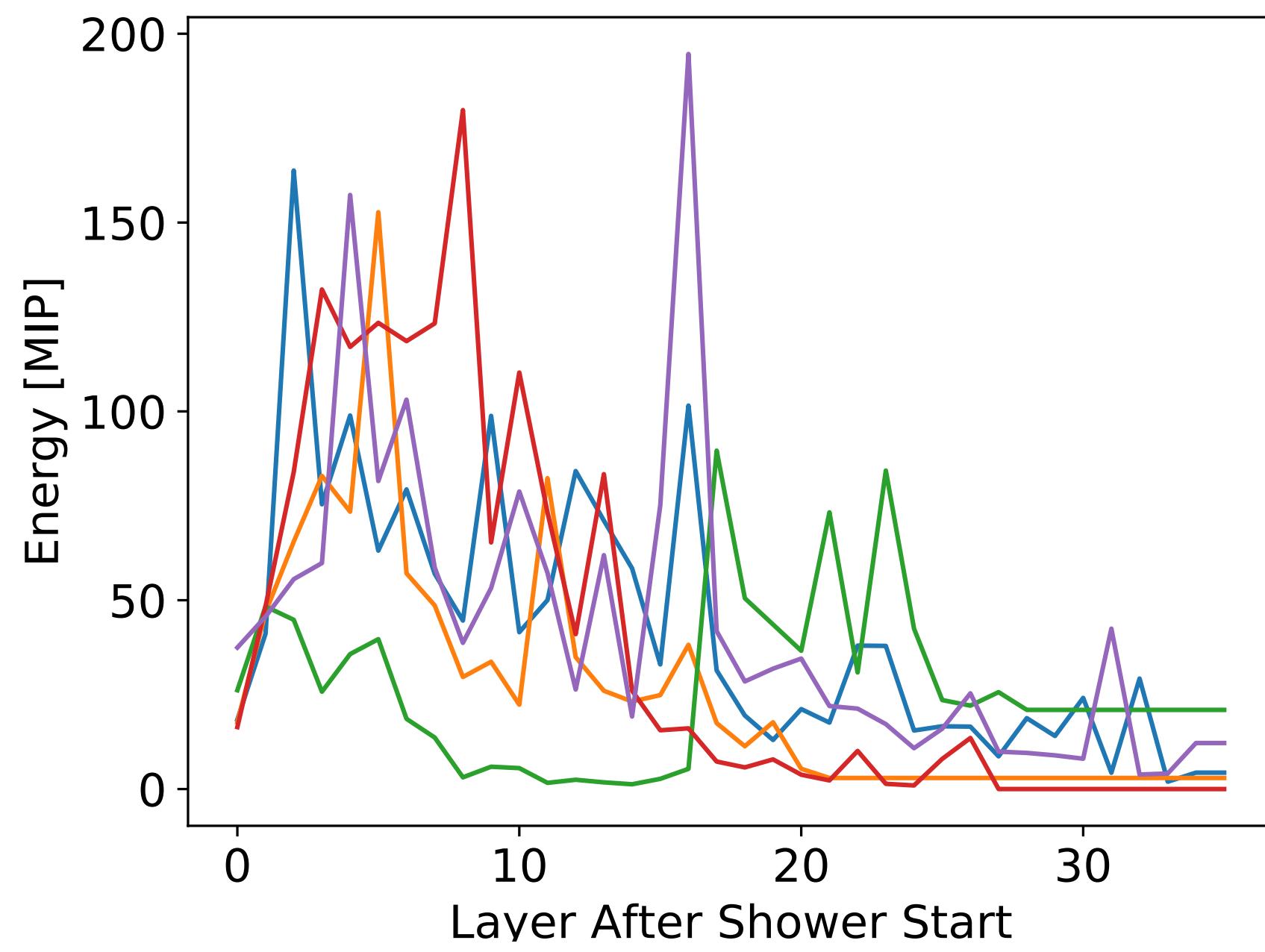
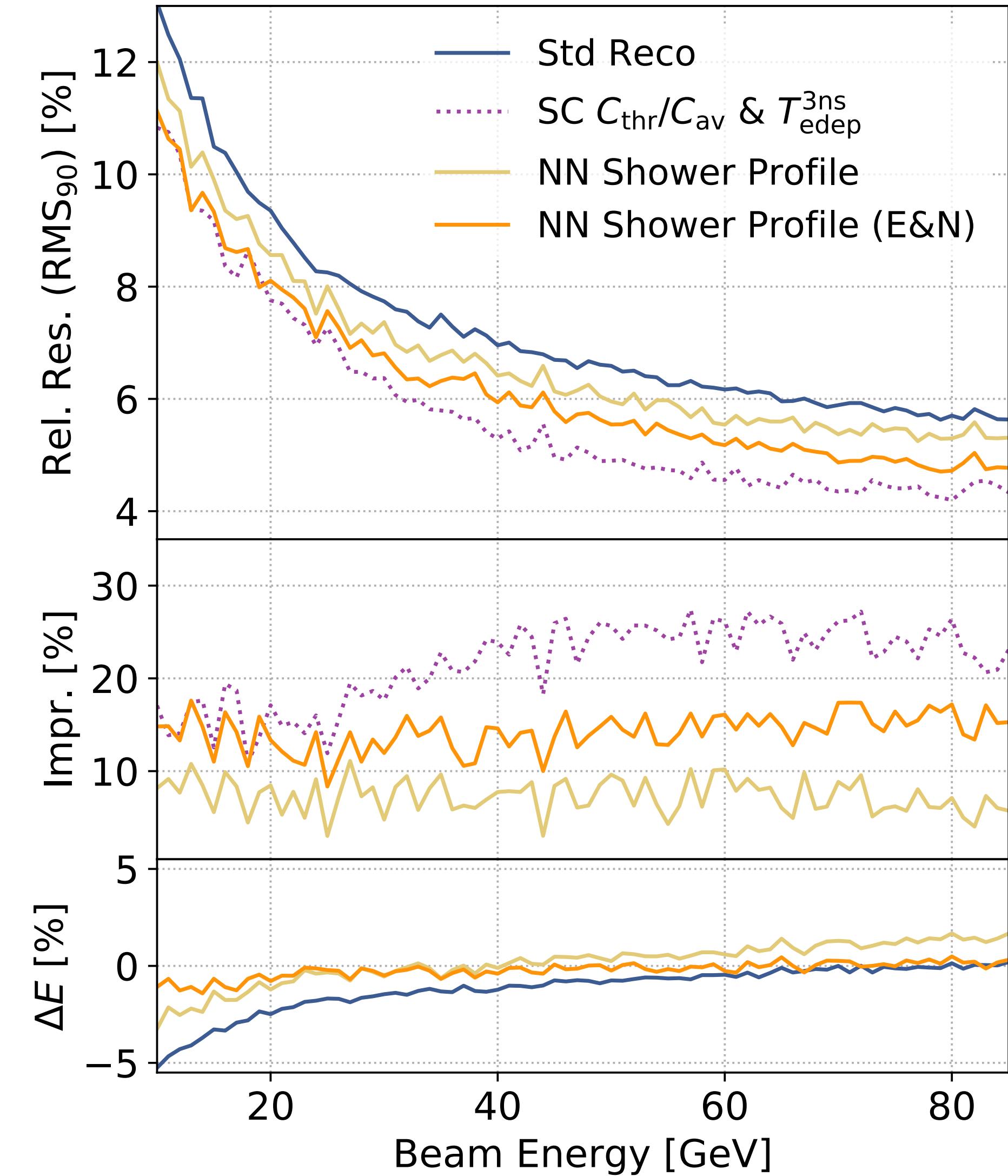
- Adding more features (shower Radius, shower Length, etc.) does **only slightly increase** the energy resolution



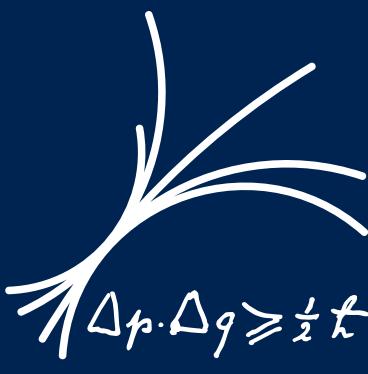
# Neural Network: Shower Profile



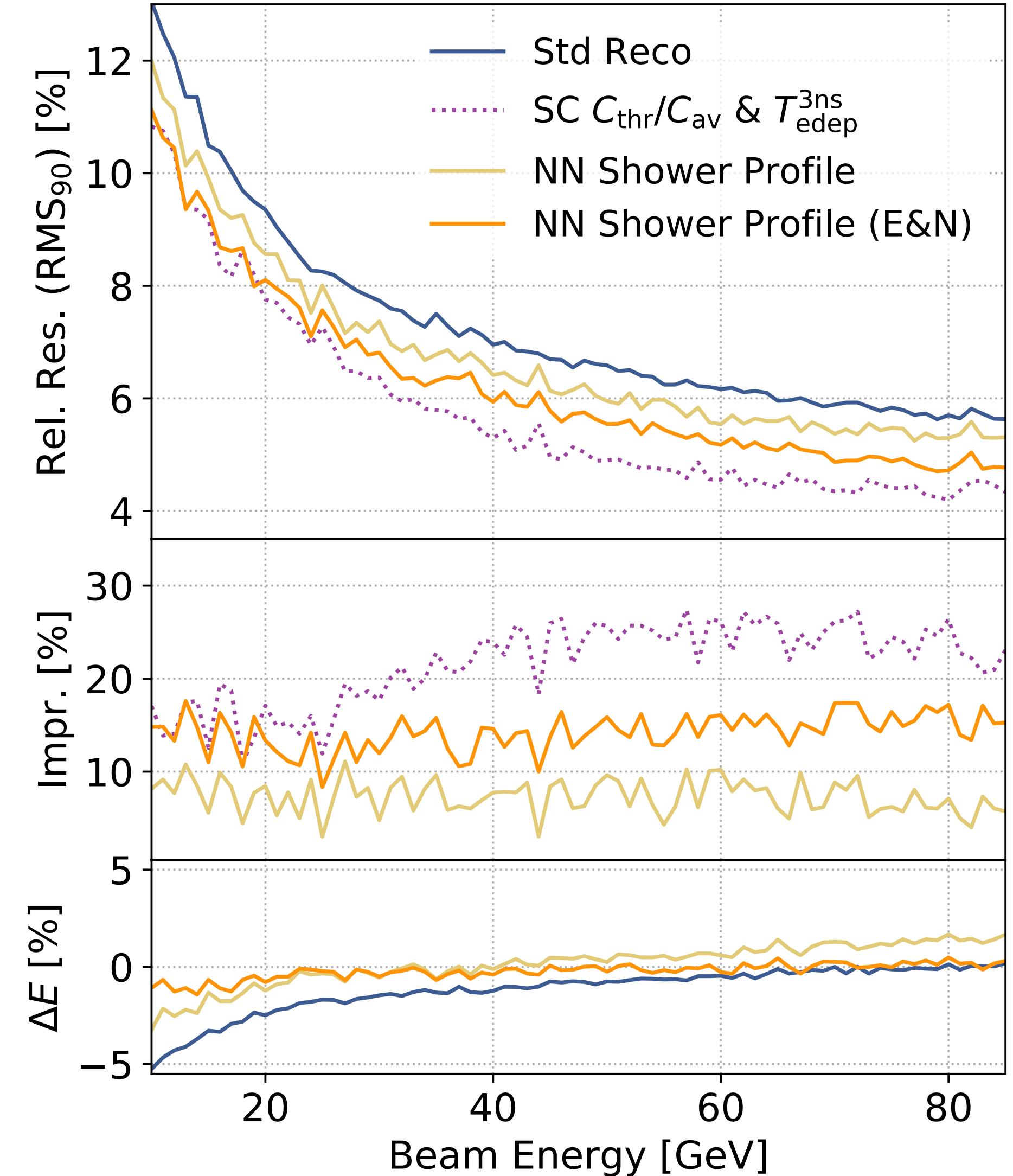
- Using whole **shower profile** to predict energy



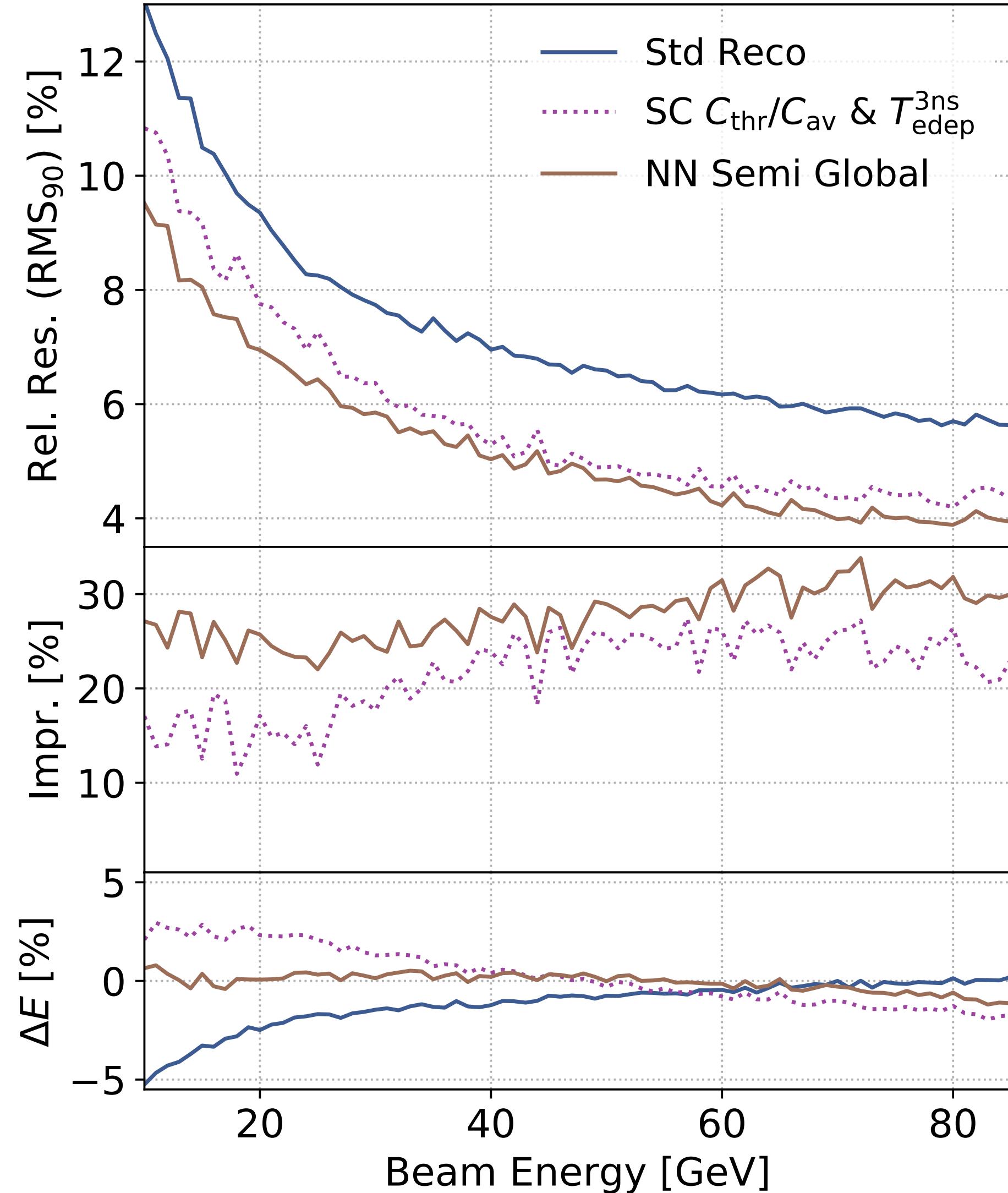
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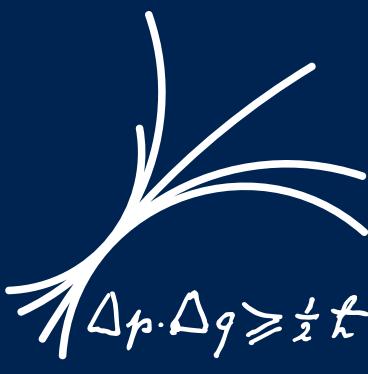
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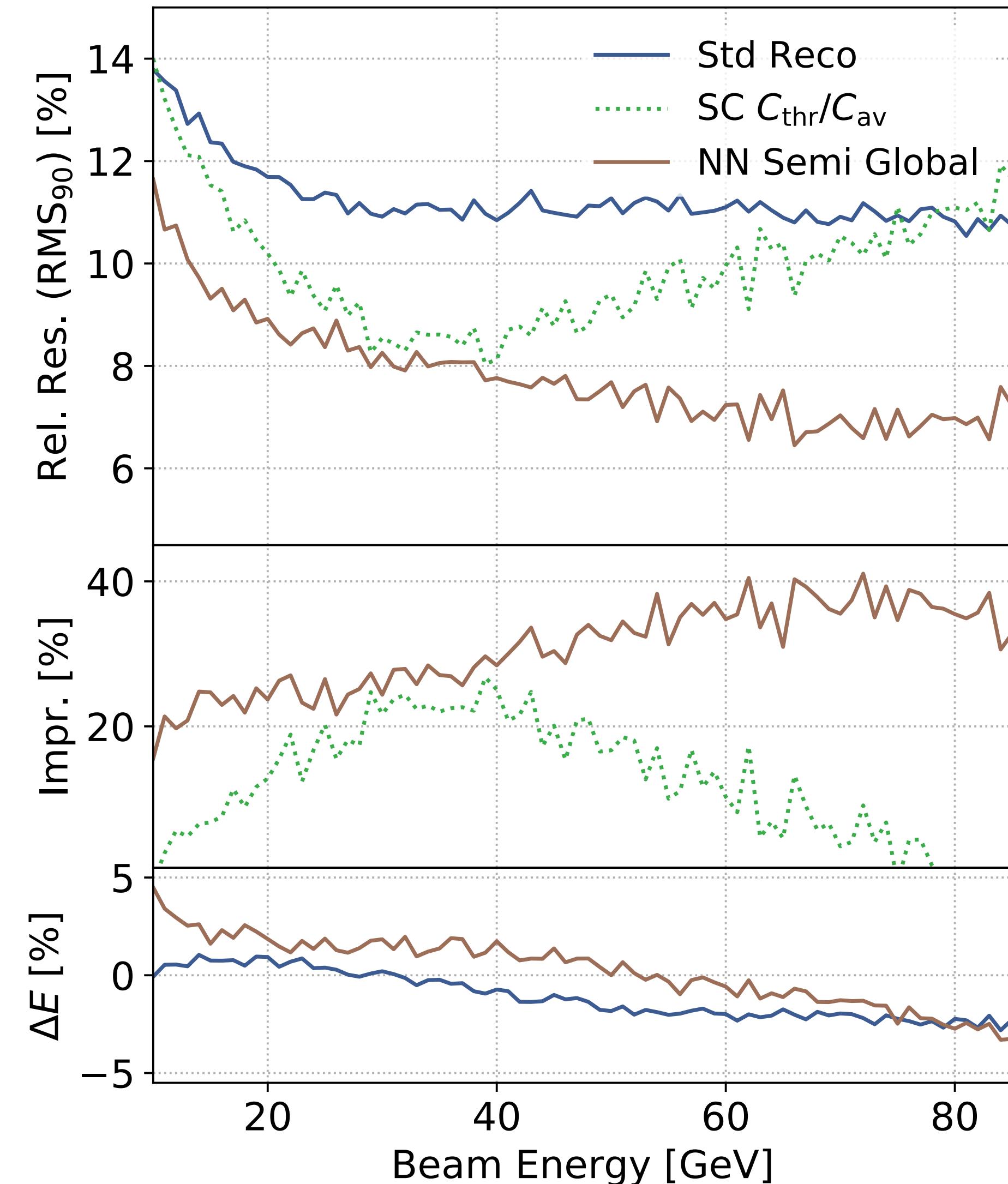
- Combining shower profiles with global features gives significant improvement



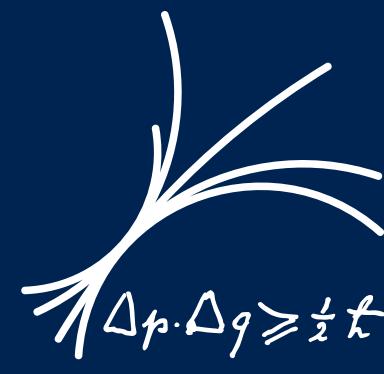
# Neural Networks



- Reducing to **38 layers**
- Leakage is significant
- **Large improvements**

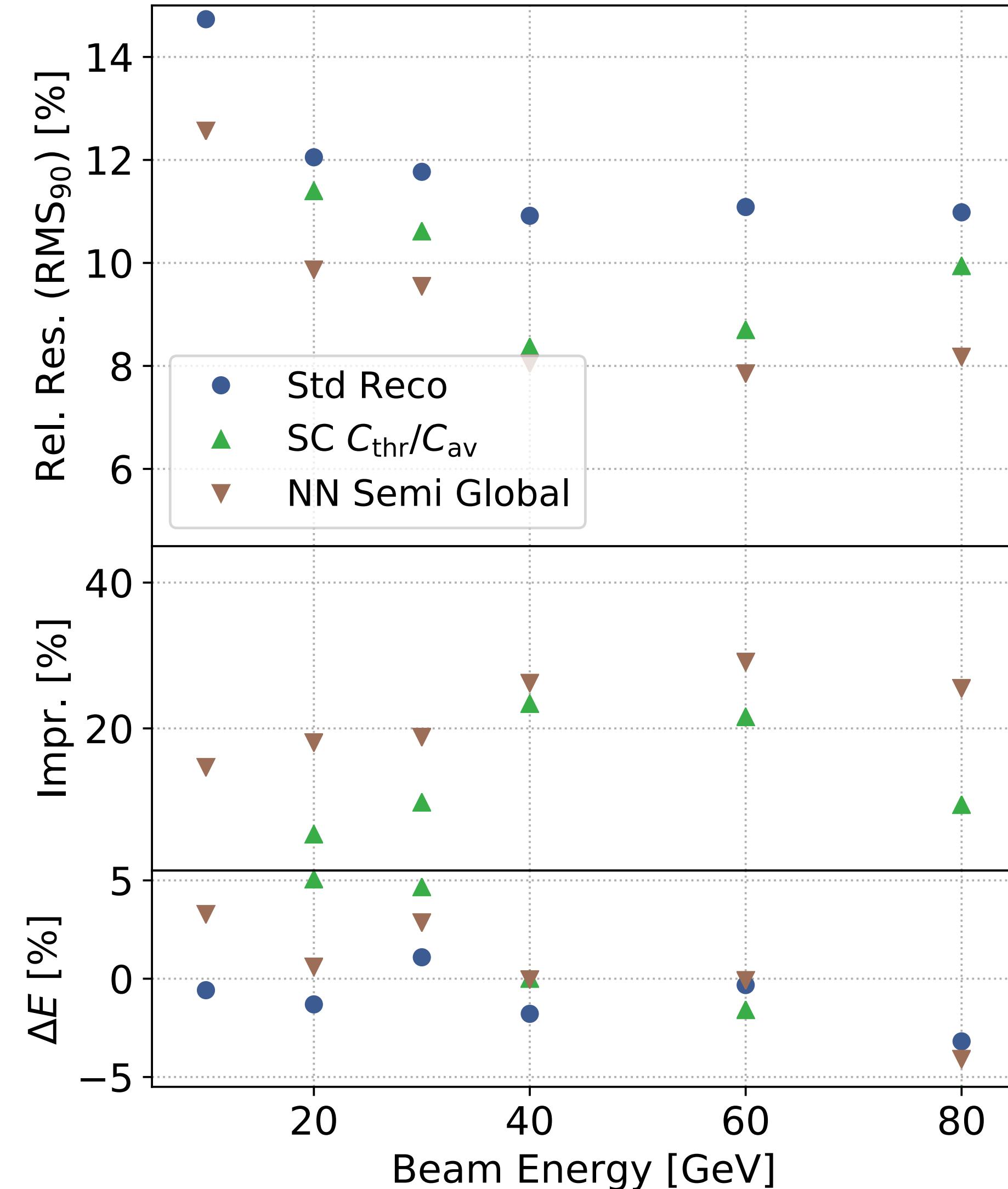
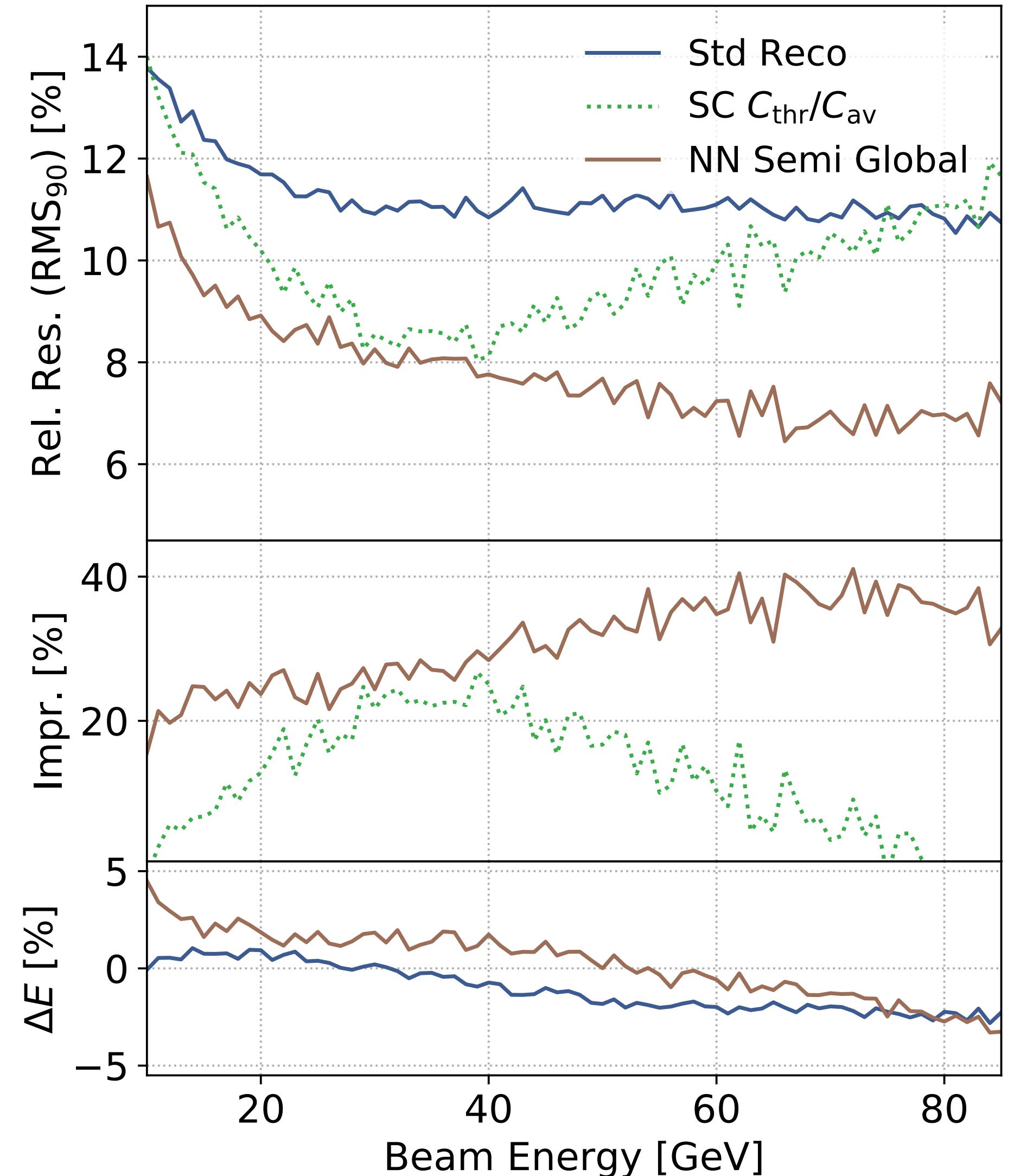


# Neural Network: On Data

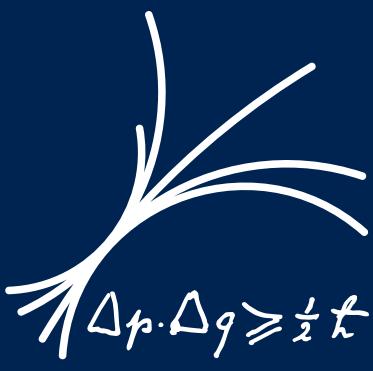


- Reducing to **38 layers**
- Leakage is significant
- **Large improvements**

- Trained on MC,  
applied to data:  
**improvements of up  
to 30%**
- Only minimal event  
selection



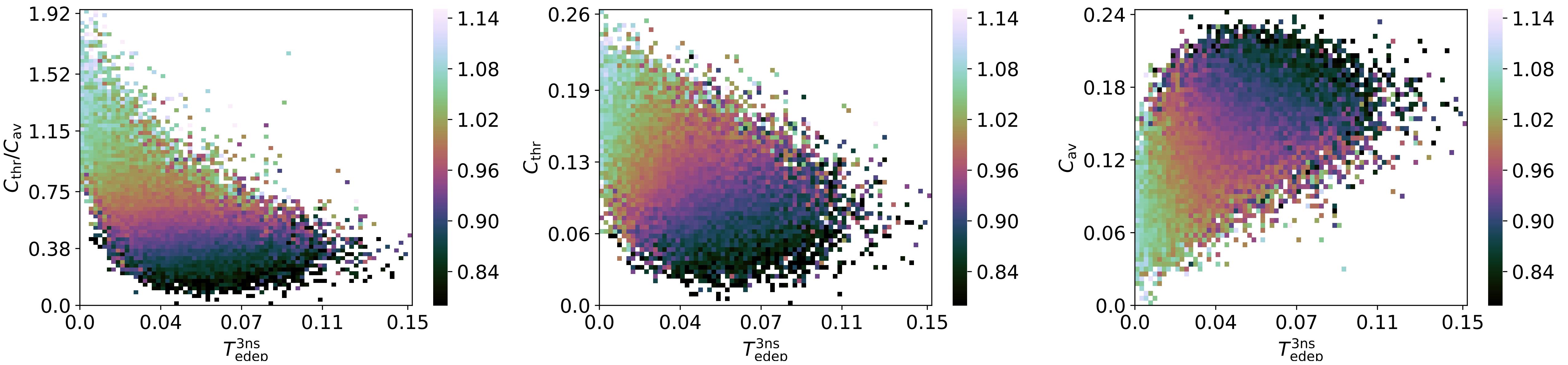
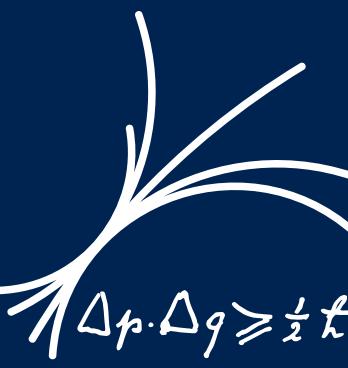
# Conclusions



- **Clear correlation** of hit time observables with reconstructed energy visible in simulation and data
- Energy reconstruction **can be improved** using time information
- Similar information can be extracted from **hit energy observables**
- **Neural network framework** shows similar performance than global SC given the same inputs
- **Shower profiles** can be used to improve energy reconstruction
- **Transferable** to data
- **Extendable**

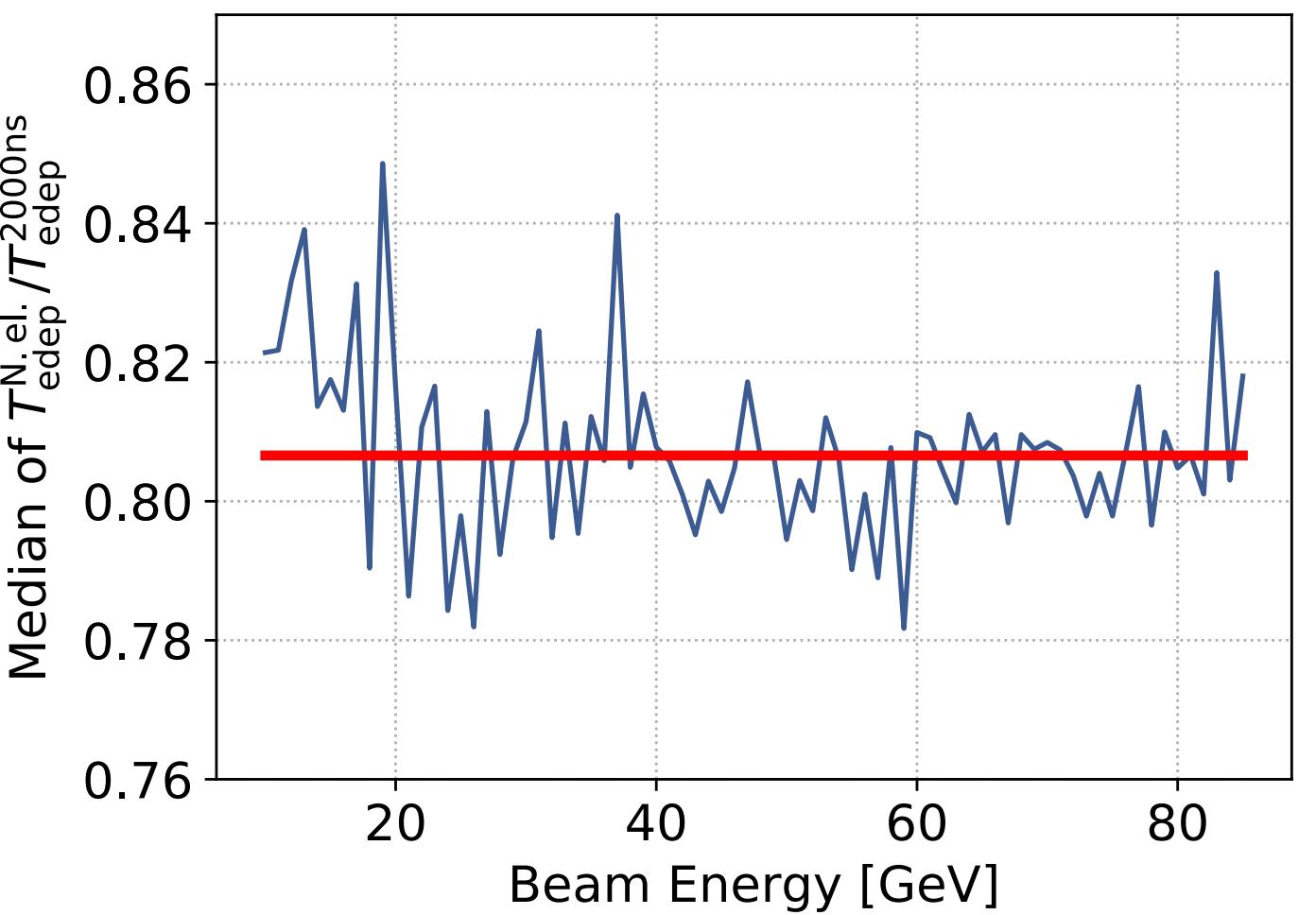
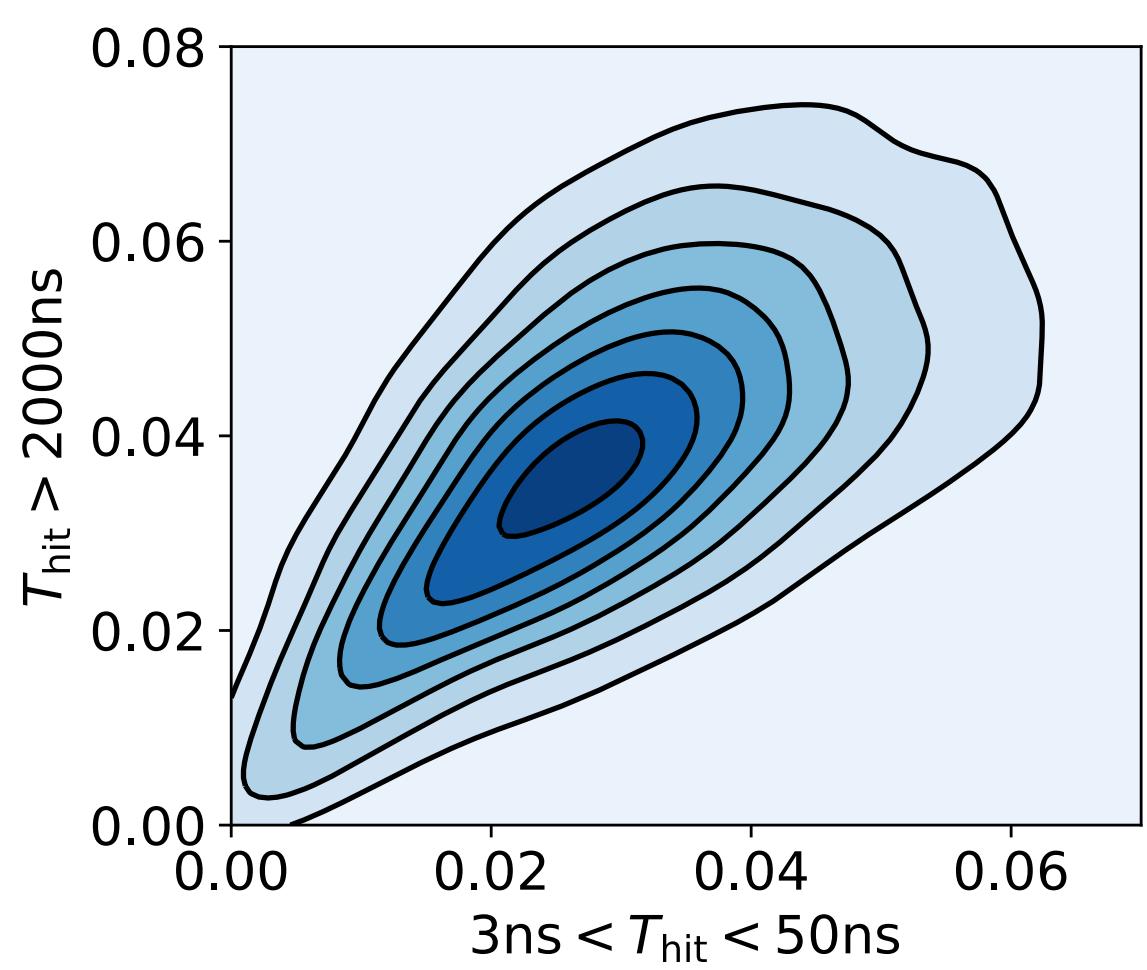
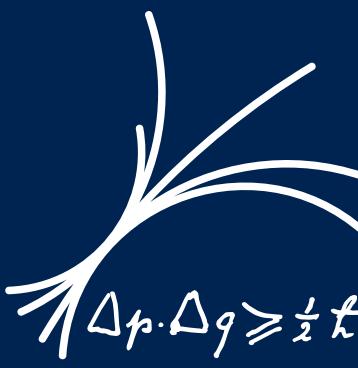
# Backup

# Global SC Time



**$C_{\text{thr}}/C_{\text{av}}$  includes most of the information of hit time observables.**  
 **$C_{\text{thr}}$  and  $C_{\text{av}}$  separately do not!**

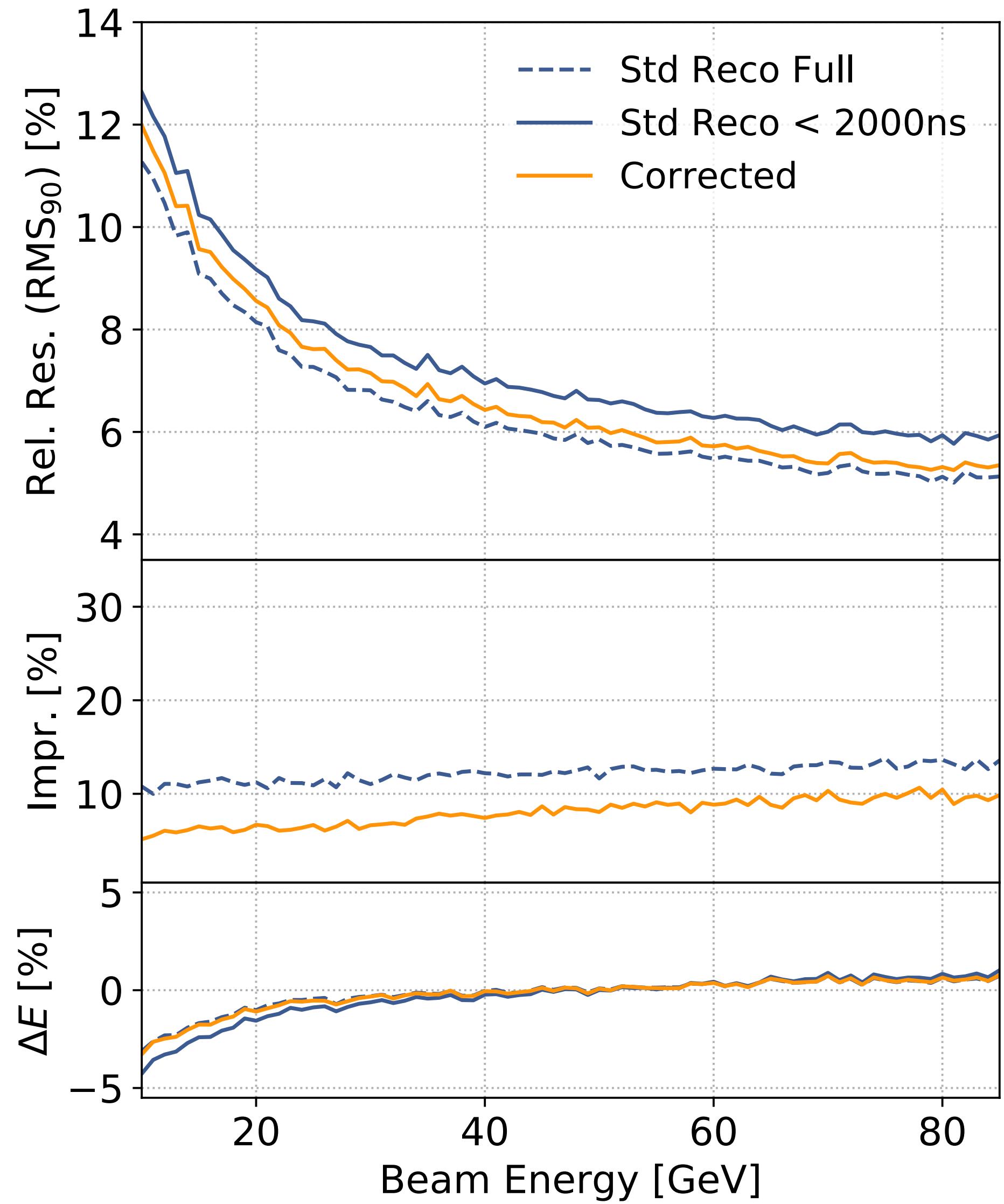
# Limited Integration Time



$$E_{\text{corrected}} = E_{\text{std. reco.}} + C * E(3\text{ns} > t_{\text{hit}} > 50\text{ns})$$

**Strong correlation** between neutron elastic scattering and neutron capture

Use neutron elastic part **to predict invisible neutron capture** part



# NN Energy Distributions

