RECONSTRUCTION OF BREIT-WHEELER SPECTRUM IN ELECTRON-LASER INTERACTION IN THE HIGH ELECTROMAGNETIC FIELD LIMIT

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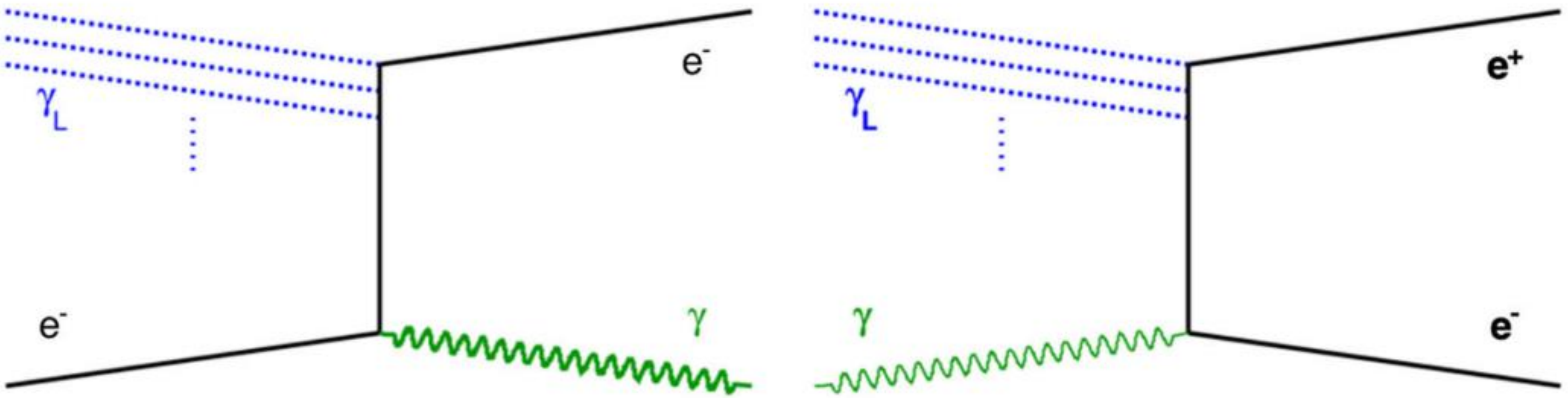
OUTLINE

- Topic of this presentation: use machine learning approach, a convolutional neural network, to reconstruct the Breit-Wheeler spectrum in LUXE electron-laser interaction
- Introduction
- Baseline results of the 20-layer ECAL from the conventional method (*EnergyFlow*) and the neural network
- Neural network result obtained with electromagnetic background
- Neural network results from ECAL with fewer layers

THE BREIT-WHEELER SPECTRUM

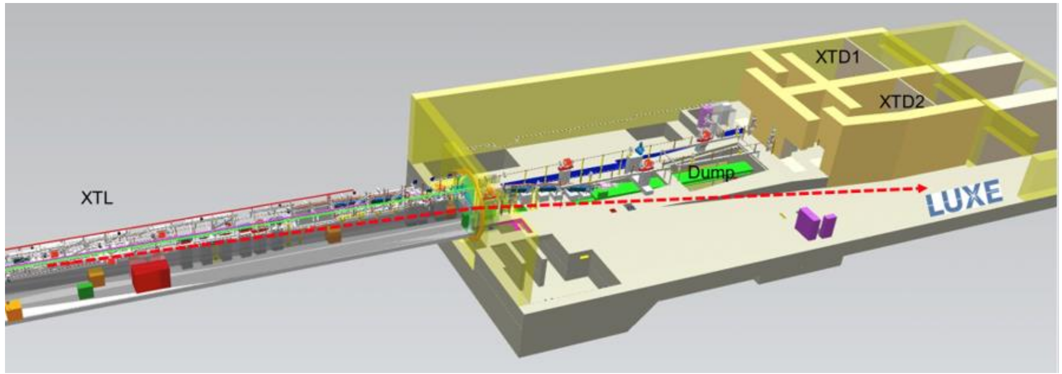
- One of LUXE interactions is between photons from high power laser and high energy electrons
- In which, non-linear Breit-Wheeler process creates electron-positron pairs
- Key measurement: energy spectrum of positrons from Breit-Wheeler pairs

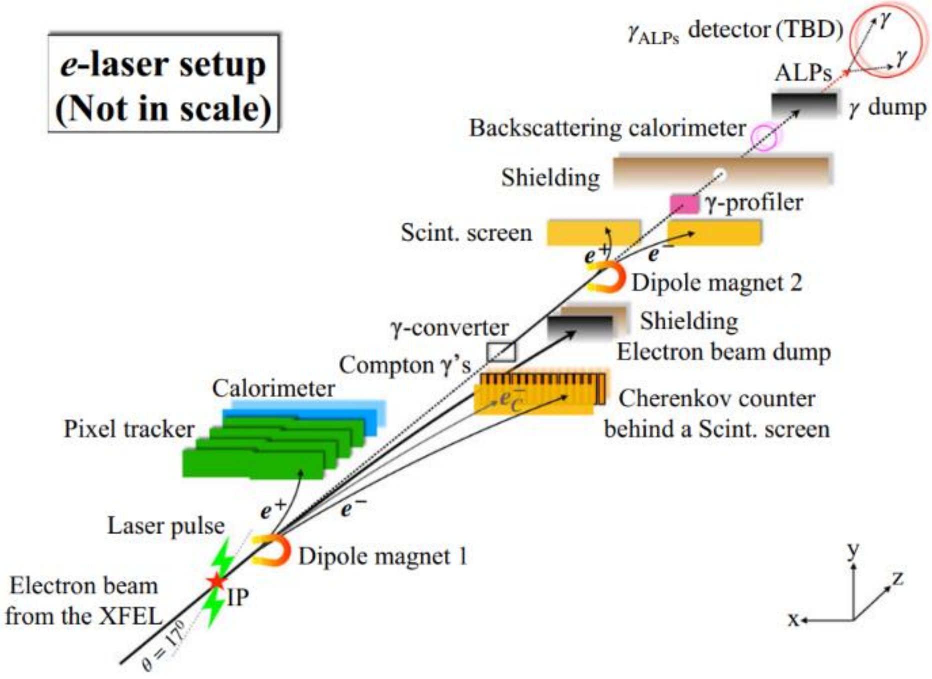


Schematic diagrams for the Compton process ($e + n\gamma_L \rightarrow e' + \gamma$) and the Breit–Wheeler process ($\gamma + n\gamma_L \rightarrow e^+e^-$)

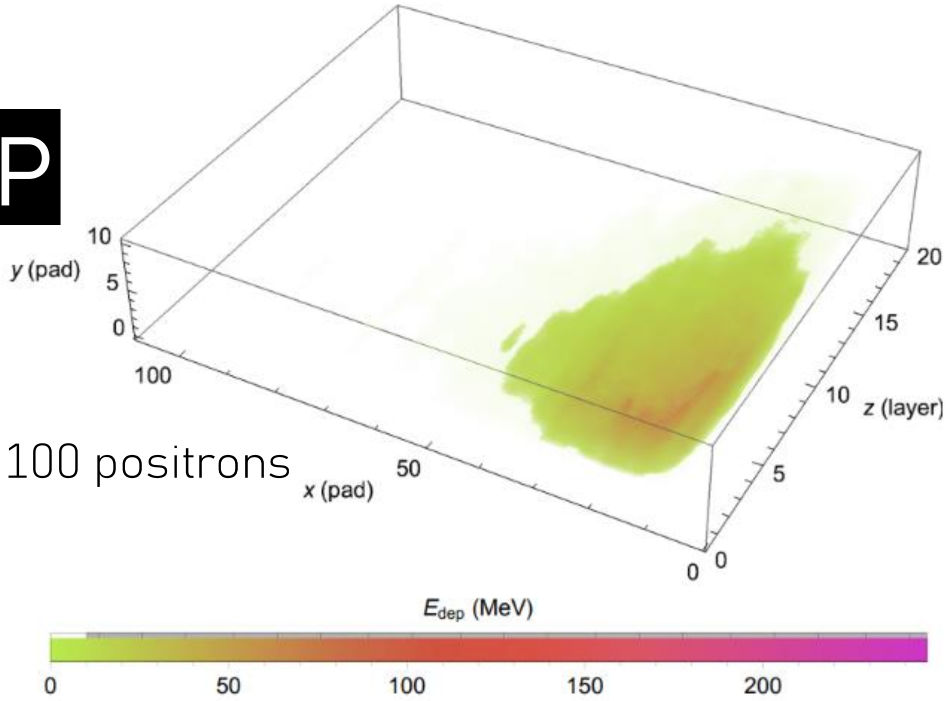
EXPERIMENTAL SETUP

positrons are measured with trackers and the ECAL



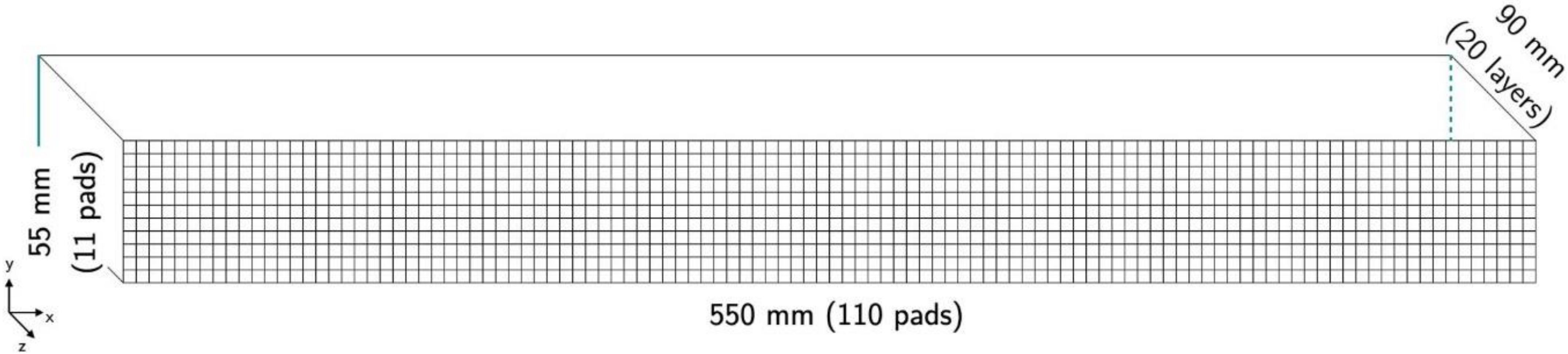


ECAL-P



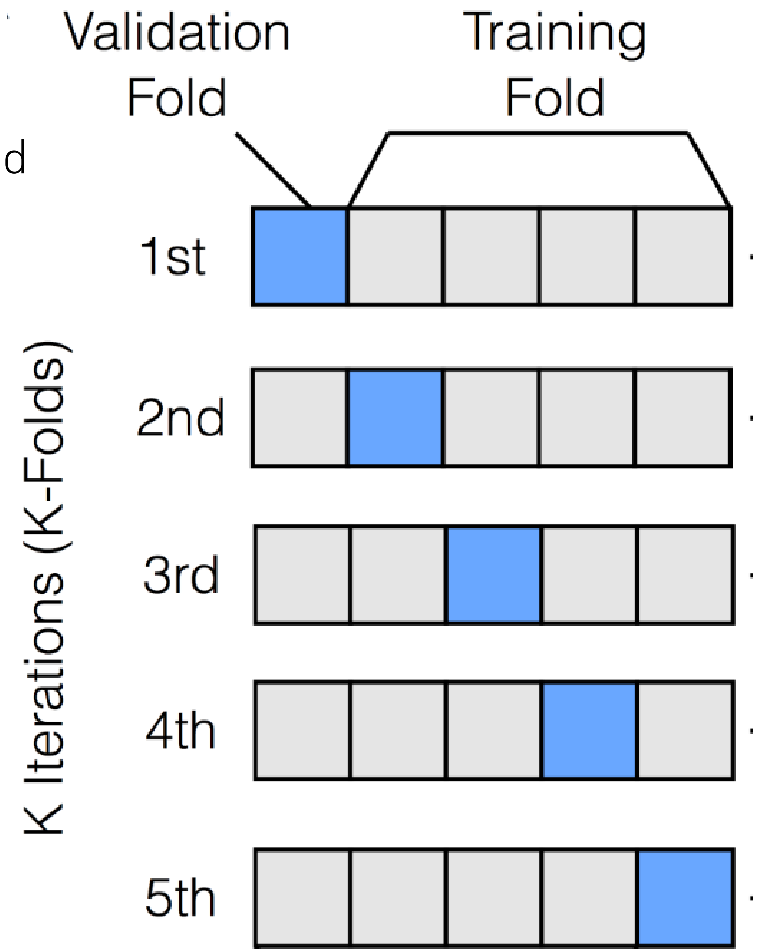
Shower image of 100 positrons
No background

- Positrons are showered in W and sampled in Si
- An old version of the ECAL-P is used (20 layers, 5x5 mm^2 pad)
- In the high multiplicity scenario, the showers overlap



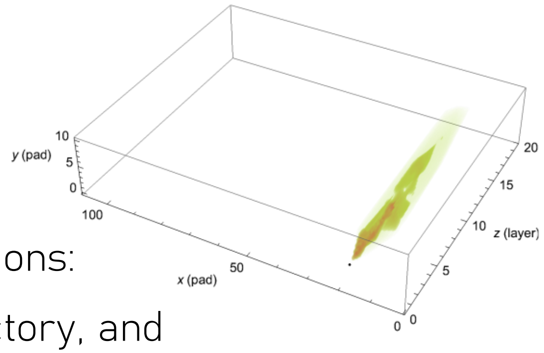
DATASET

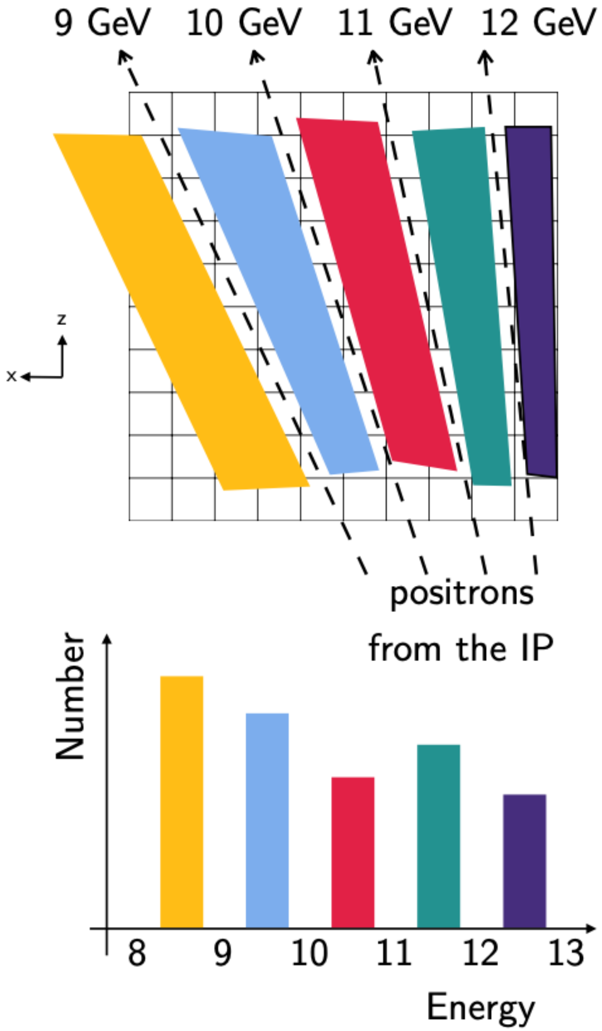
K-fold method
(*k* = 5)



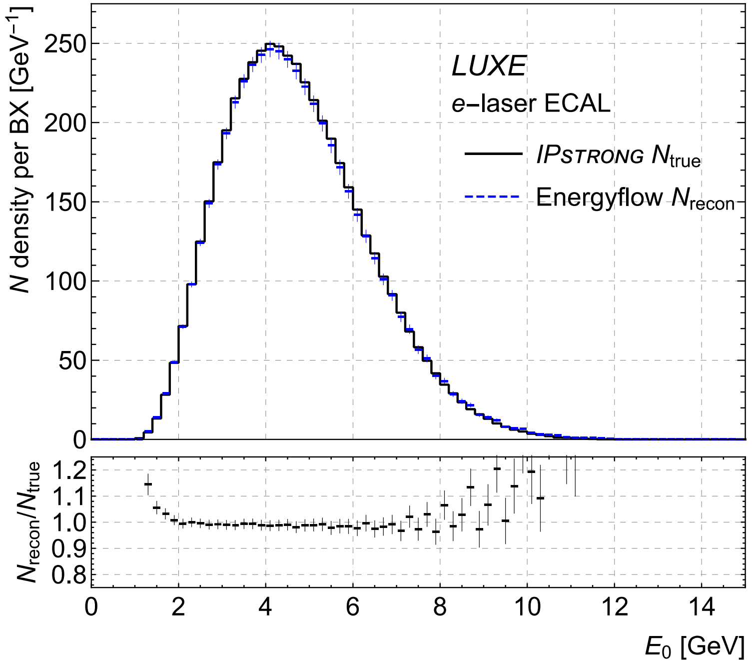
- The data the Neural Network was trained on was provided by LUXE Monte-Carlo generator IPstrong and geometrical simulation GEANT4
  - Not updated to the newer Ptarmigan due to lack of samples
- Machine learning is based on a convolutional neural network (CNN)
- The *k*-fold method, which gives the most unbiased estimates, is used to calculate the uncertainty
- Training with four fifths of all bunch-crossings (1 BX is called 1 “event”)

CONVENTIONAL METHOD: ENERGYFLOW



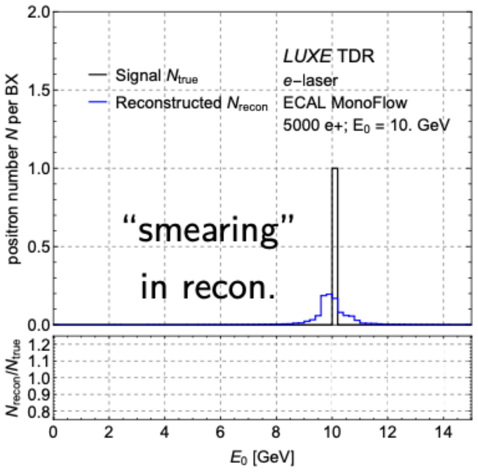


- A method presented in the CDR on the assumptions:
  - showers develop around a known e^+ trajectory, and
  - a known calibration ratio between e^+ energy and its deposits
- The number of positrons is estimated by assigning the E_{dep} of a pad to the e^+ energy bin
  - building a dependency between pad and e^+ energy,
  - collecting the deposits on a pad,
  - calculating the positron number contributed by the pad, and
  - going over the whole ECAL



CONVENTIONAL METHOD: ENERGYFLOW

reconstruction of one positron



- Essentially a hand-written neural network connecting the E_{dep} image with energy bin by physics knowledge and assumptions
- A convolution between the true energy spectrum and a smeared reconstruction
- The method performs fairly with the ECAL-P in CDR
- Difficulties with few-layer ECAL when the leakage is important and the sampling is insufficient

MACHINE LEARNING APPROACH

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Model architecture
========================================
==========================================================================================
Layer (type:depth-idx)                   Input Shape               Output Shape
==========================================================================================
Model                                    [128, 1, 110, 21]         [128, 60]
├─Conv2d: 1-1                            [128, 1, 110, 21]         [128, 8, 56, 11]
├─Conv2d: 1-2                            [128, 8, 56, 11]          [128, 16, 28, 6]
├─Linear: 1-3                            [128, 2688]               [128, 256]
├─Linear: 1-4                            [128, 256]                [128, 60]
==========================================================================================
Total params: 705,012
Trainable params: 705,012
Non-trainable params: 0
Total mult-adds (M): 118.36
==========================================================================================
Input size (MB): 1.18
Forward/backward pass size (MB): 8.12
Params size (MB): 2.82
Estimated Total Size (MB): 12.13
==========================================================================================
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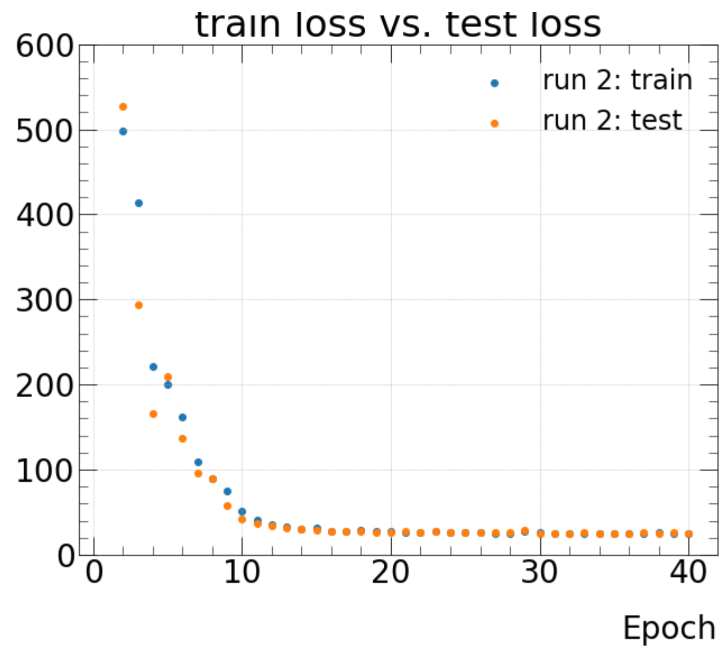


- The loss function decreases with training epoch and then starts to increase due to overfitting
- Stop training the neural network before overfitting
- The CNN based reconstruction is adaptive to fewer layers of ECAL and to the background

RESULTS

SPECTRUM

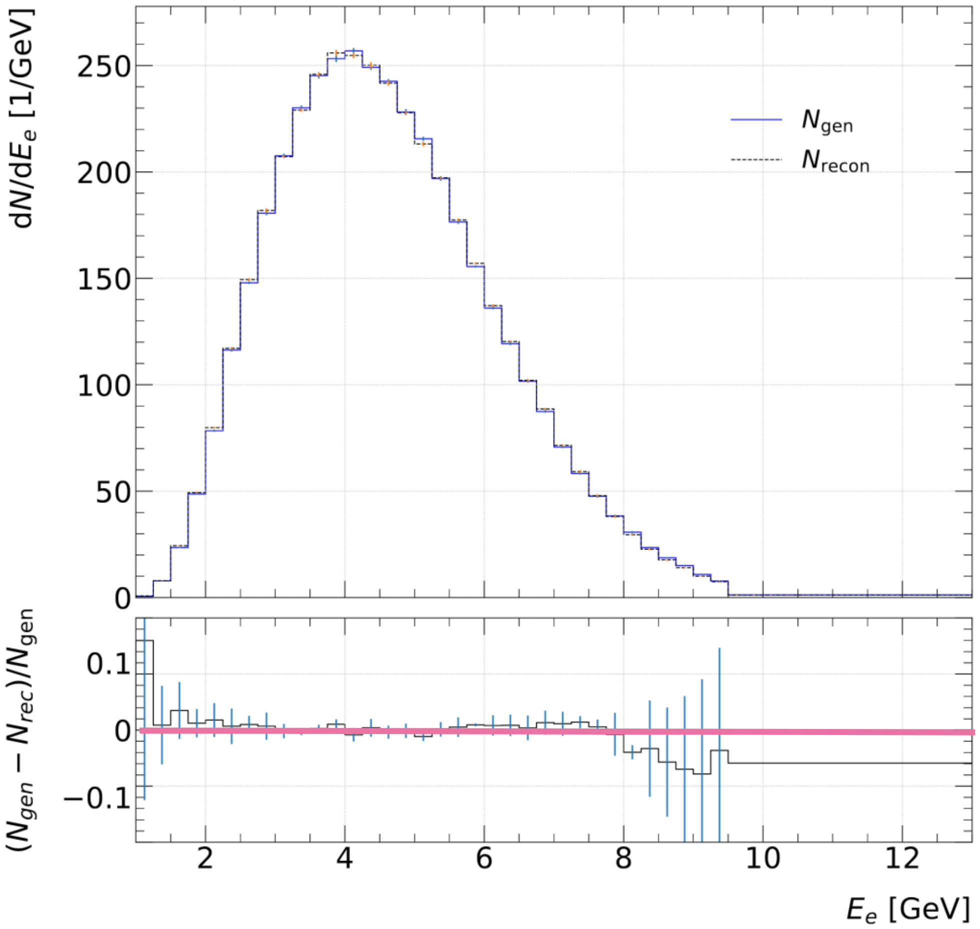
Conditions:

Electron beam energy E_{e-} = 16.5 GeV

laser focal waist w_0 = 3 um

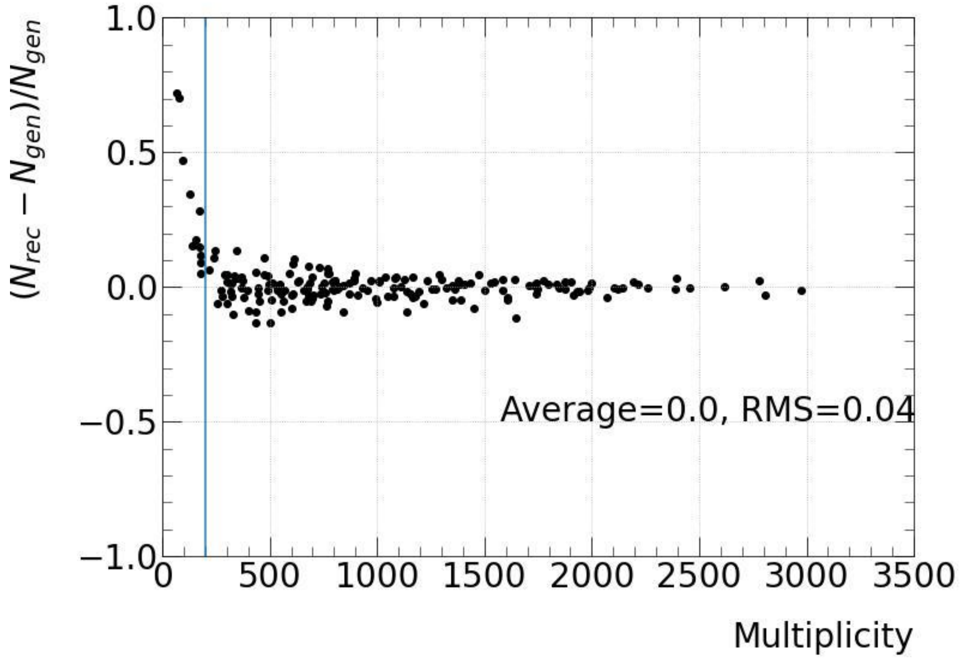
Intensity parameter xi = 4

20-layer ECAL without the background

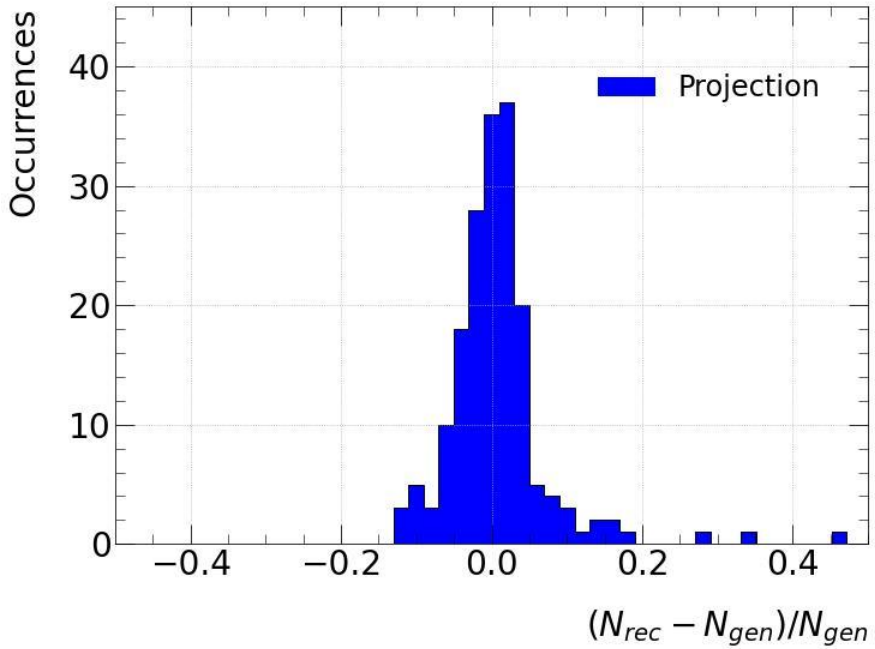


"gen" = generated by the MC (*IPstrong*)
"rec" = reconstructed by the CNN

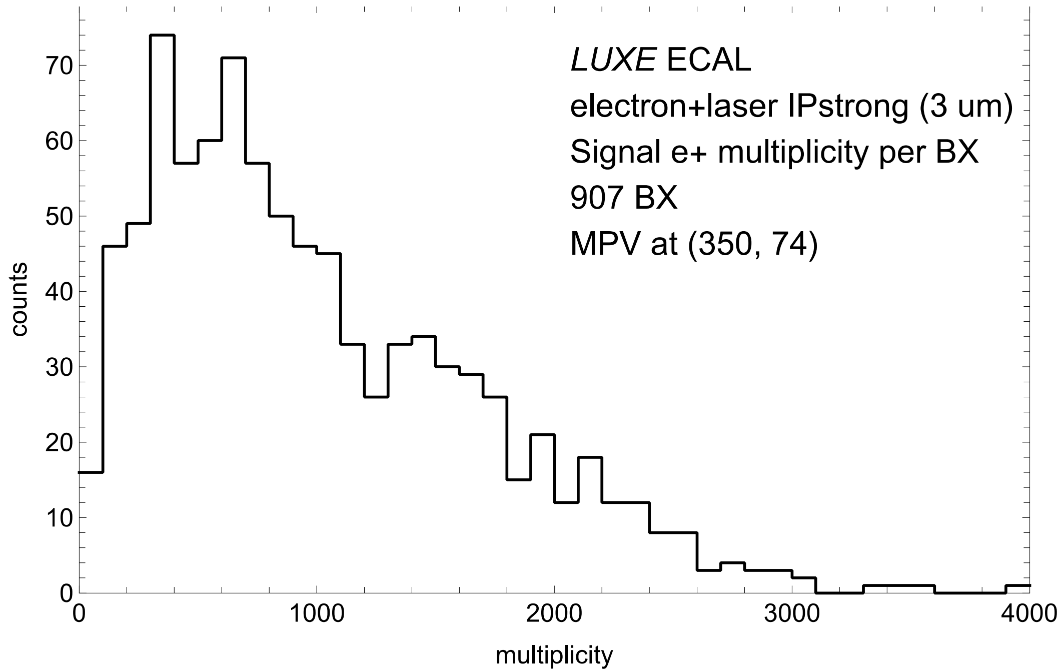
ERROR PROJECTION

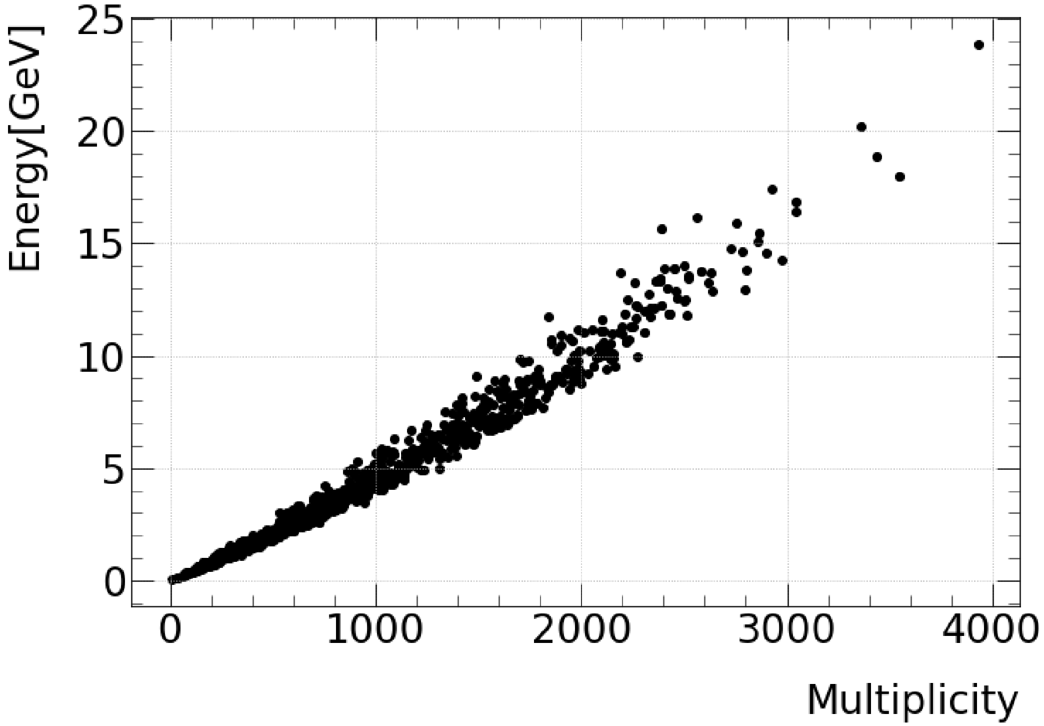


Calculation based on multiplicity greater than 200 (as seen by the line)



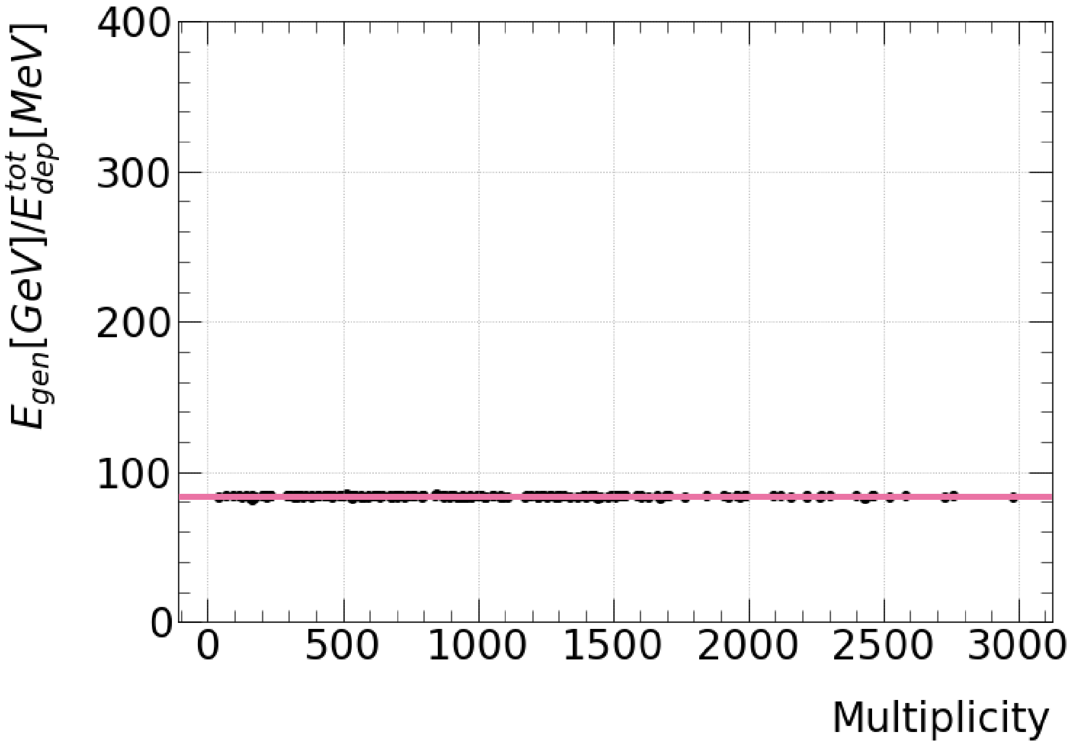
Higher multiplicity is easier for the CNN; classical methods is the other way around





MULTIPLICITY

Left: multiplicity distribution in IPstrong.   Right: Total reconstructed energy vs multiplicity



No. events: 181
Average: 83.9
RMS: 0.499

CALIBRATION RATIO

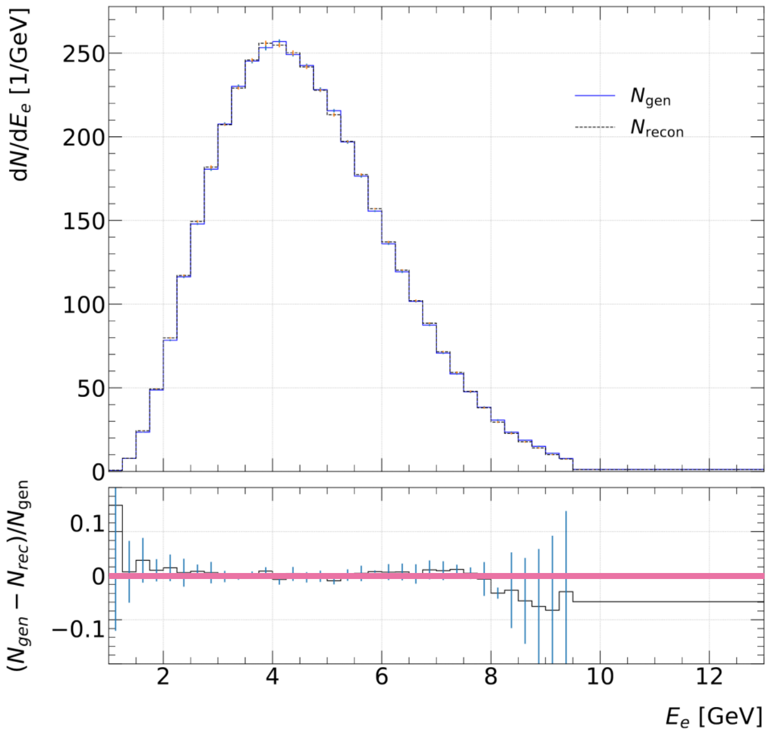
Defined as the ratio between positron energy and the total energy deposit inside the ECAL

RECONSTRUCTION WITH BACKGROUND AND FEWER LAYERS

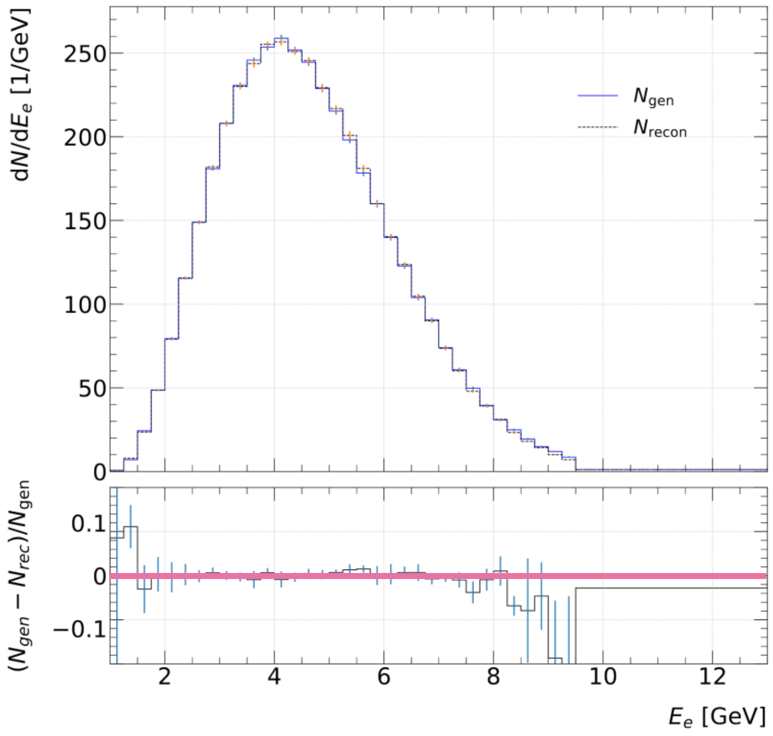
Background is contributed from electromagnetic processes, with random combinations to ~1000 samples from a 7-BX simulation

SPECTRUM

20-LAYER ECAL WITHOUT THE BACKGROUND

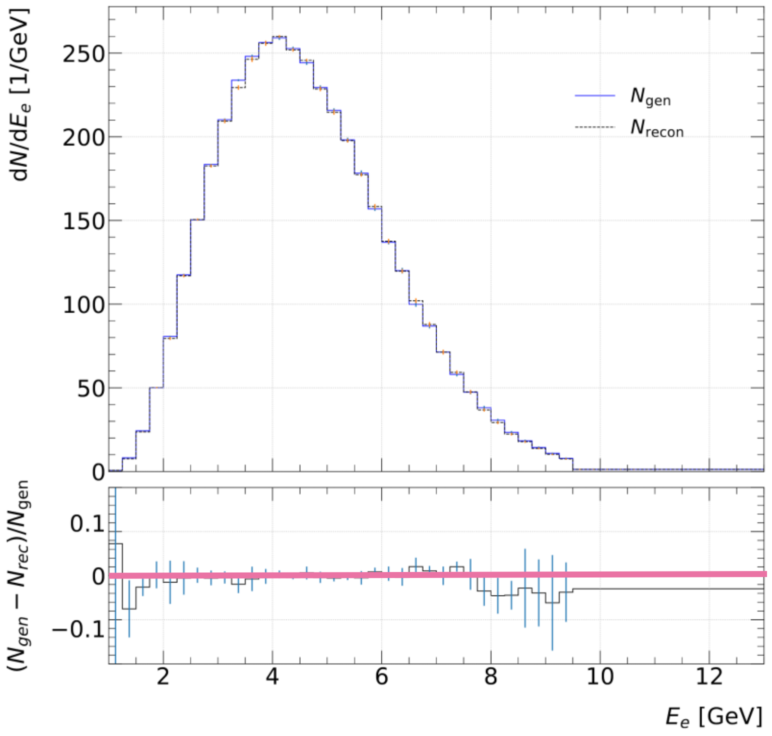


20-LAYER ECAL WITH THE BACKGROUND

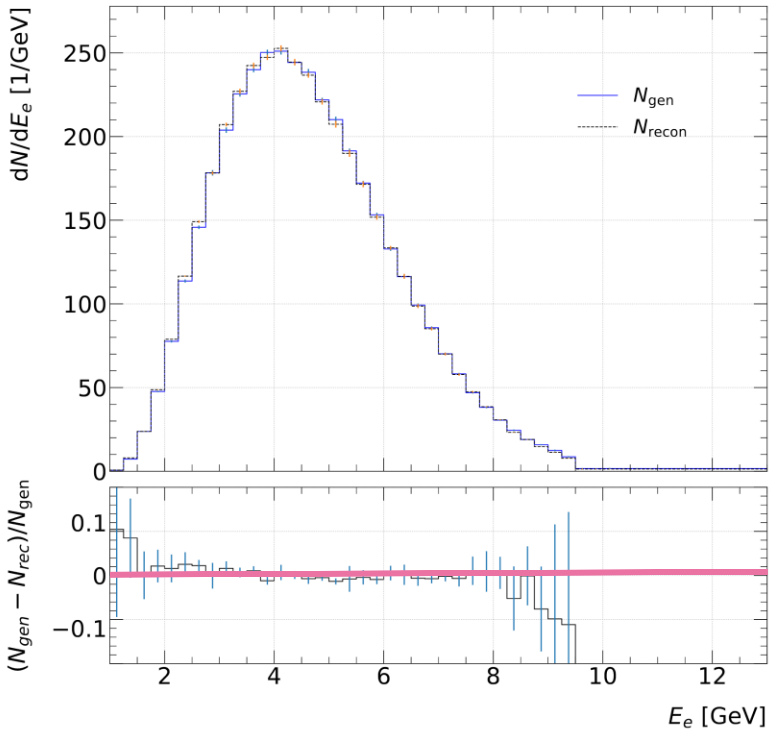


SPECTRUM

10-LAYER ECAL
WITH THE BACKGROUND

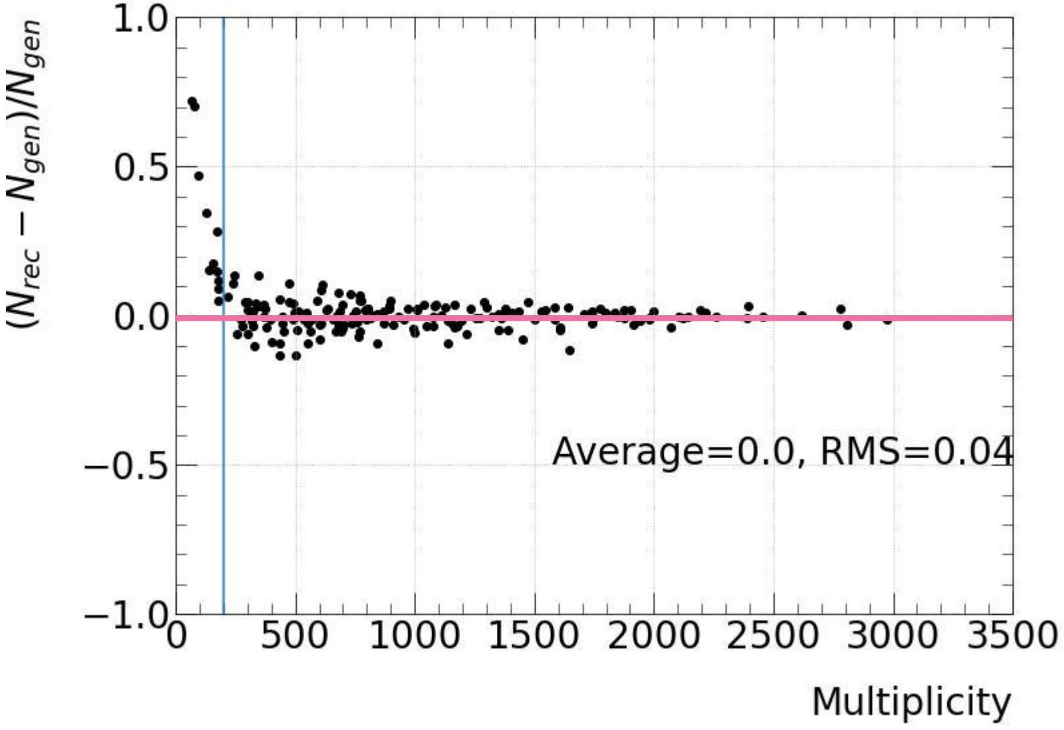


5-LAYER ECAL
WITH THE BACKGROUND

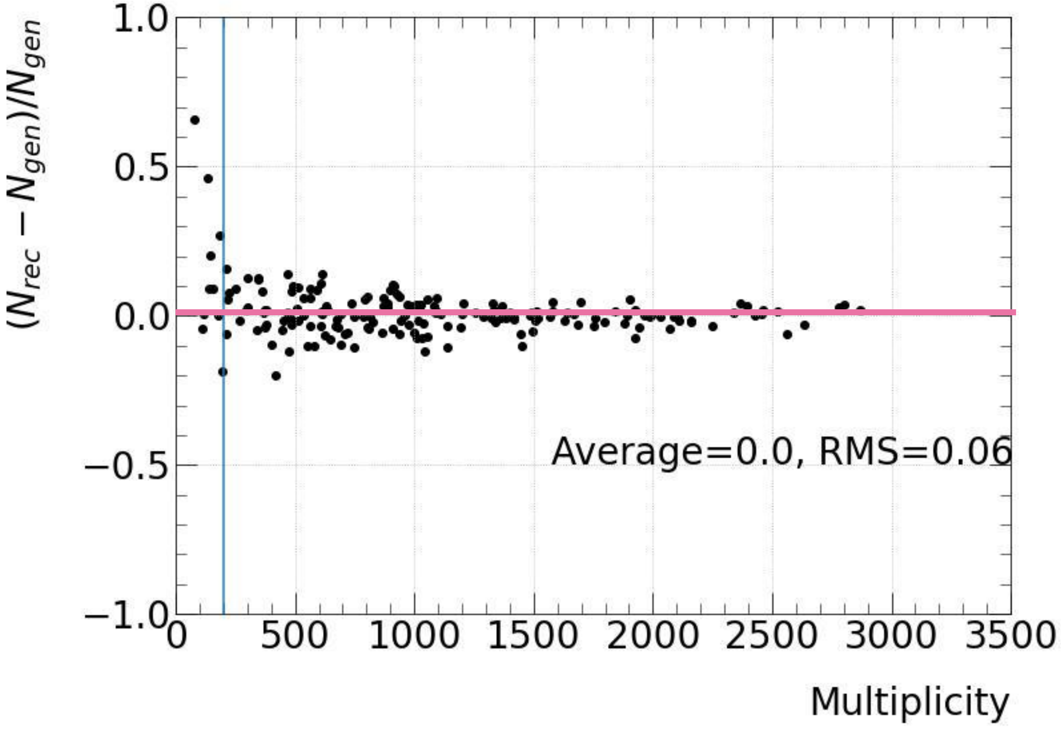


RECONSTRUCTION ERROR

20-LAYER ECAL WITHOUT THE BACKGROUND



20-LAYER ECAL WITH THE BACKGROUND



RECONSTRUCTION ERROR

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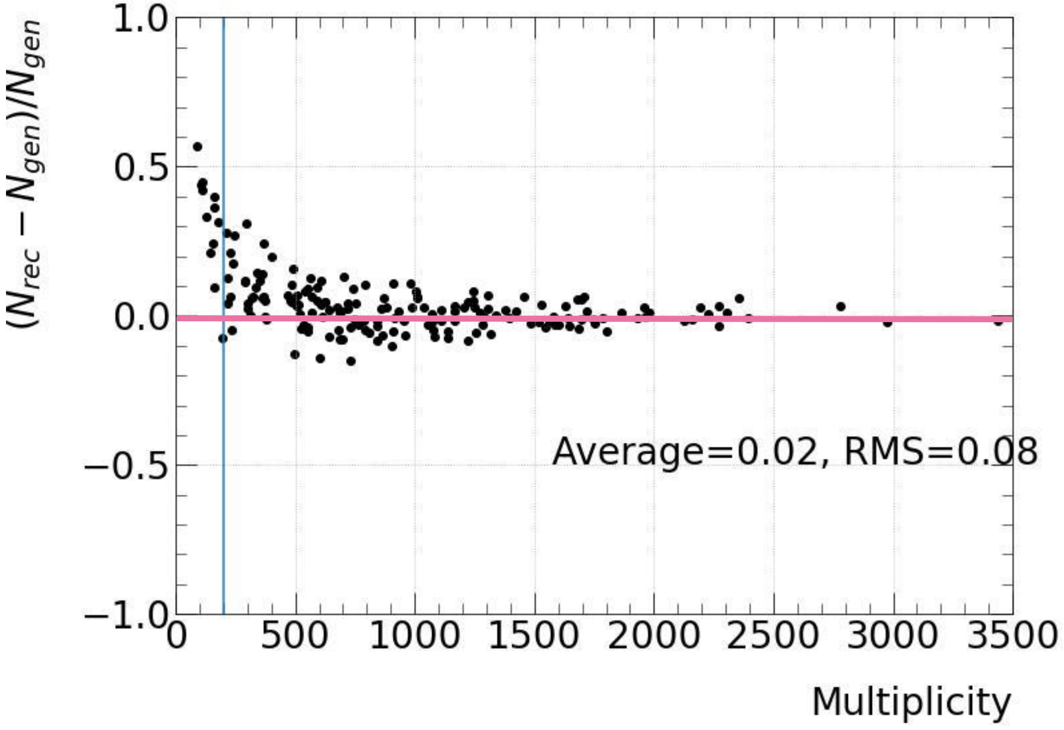

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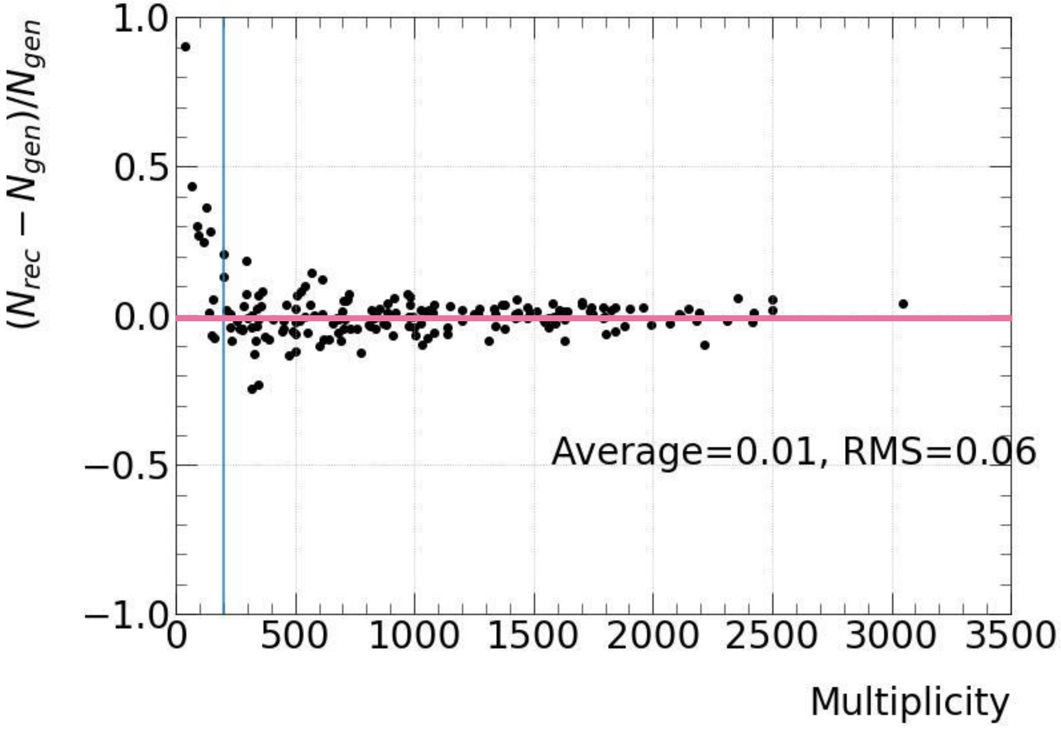
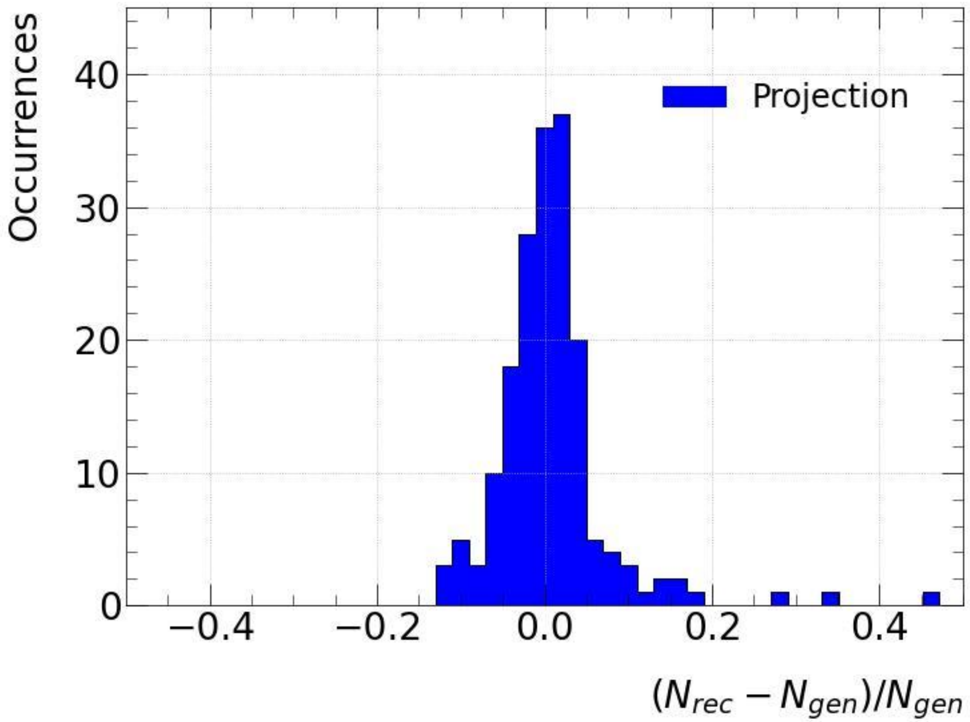


ERROR PROJECTION

20-LAYER ECAL WITHOUT THE BACKGROUND



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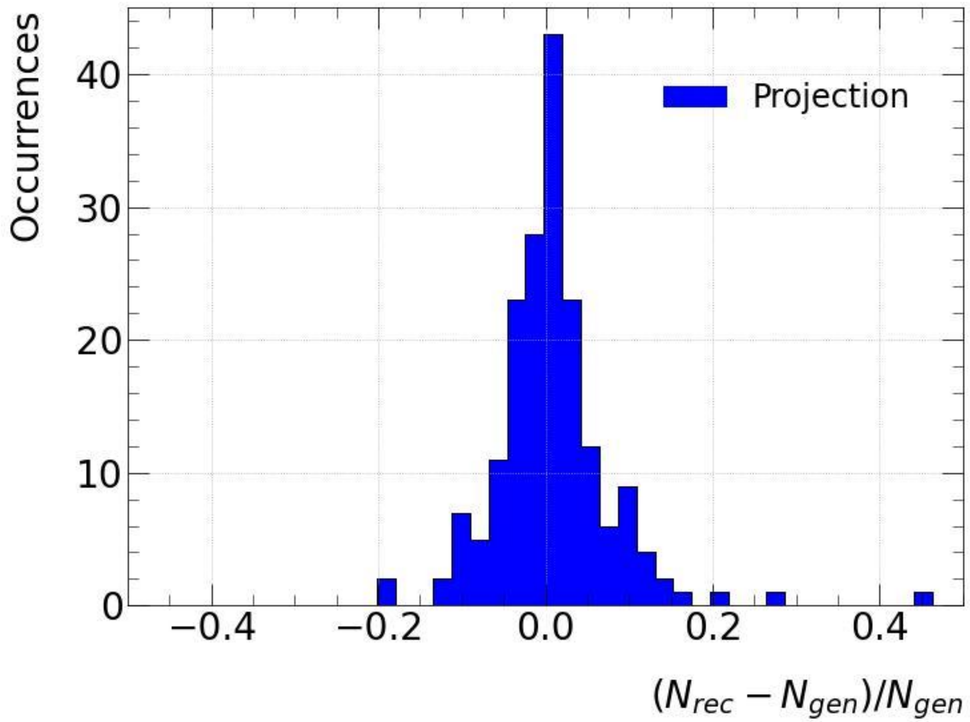

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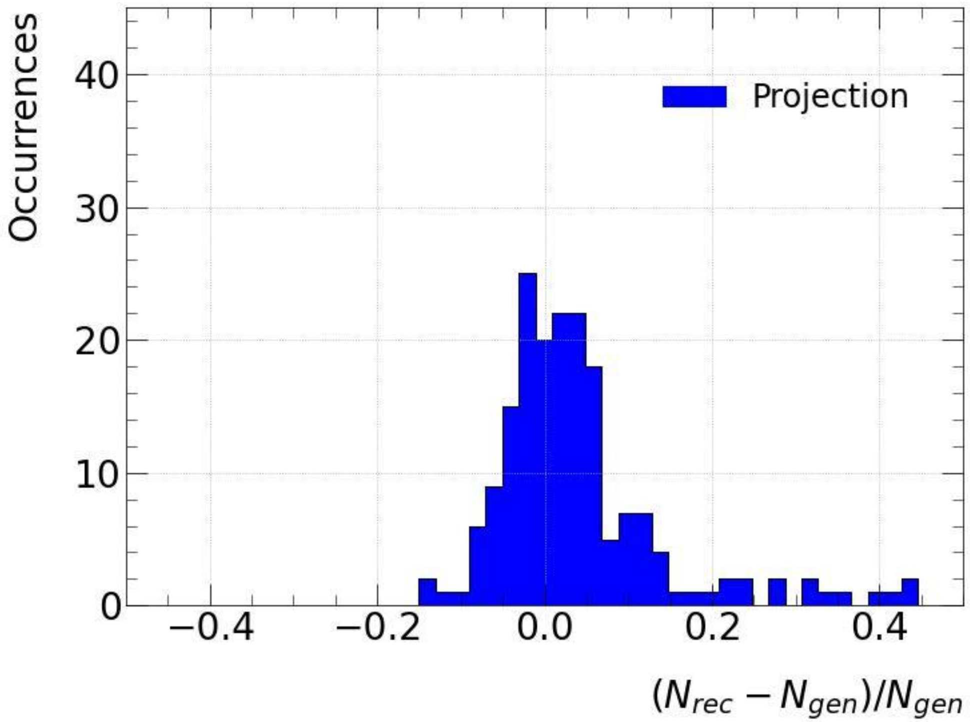

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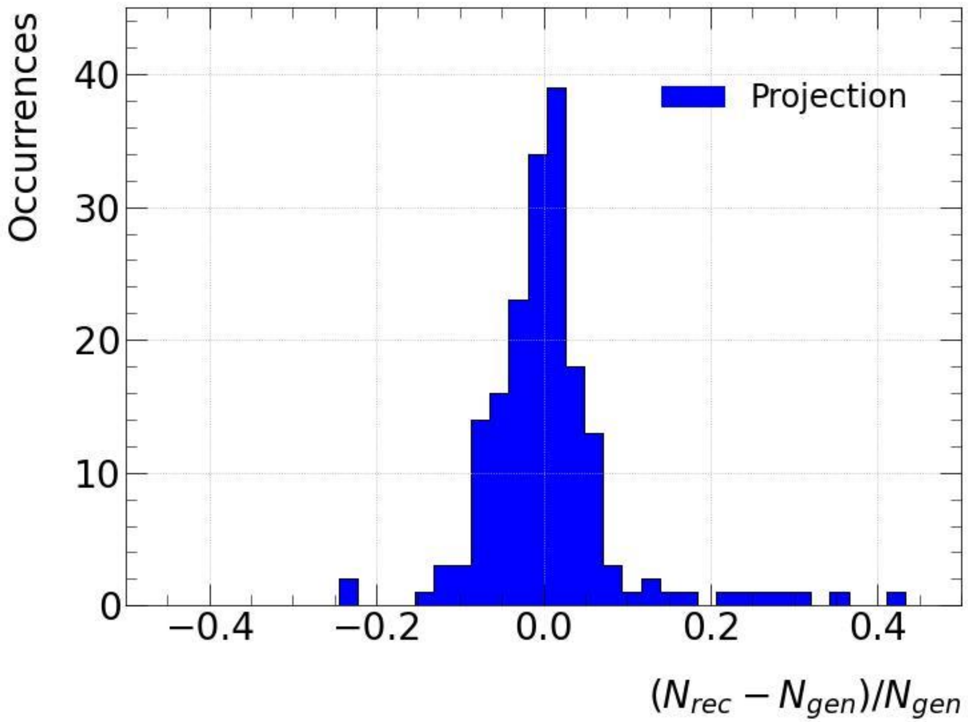
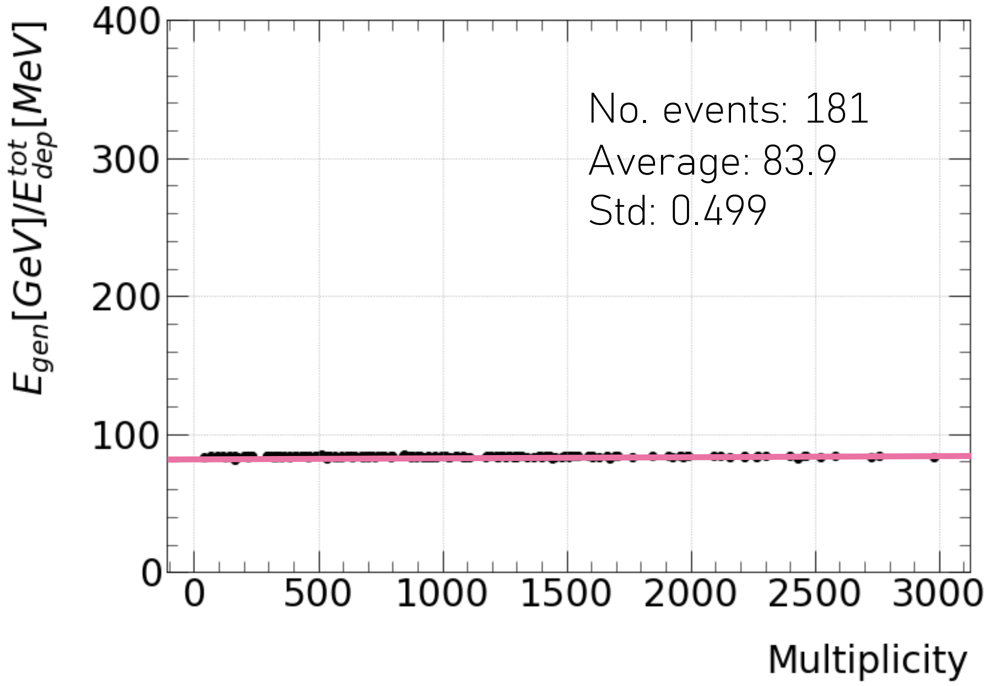


CALIBRATION RATIO

20-LAYER ECAL WITHOUT THE BACKGROUND



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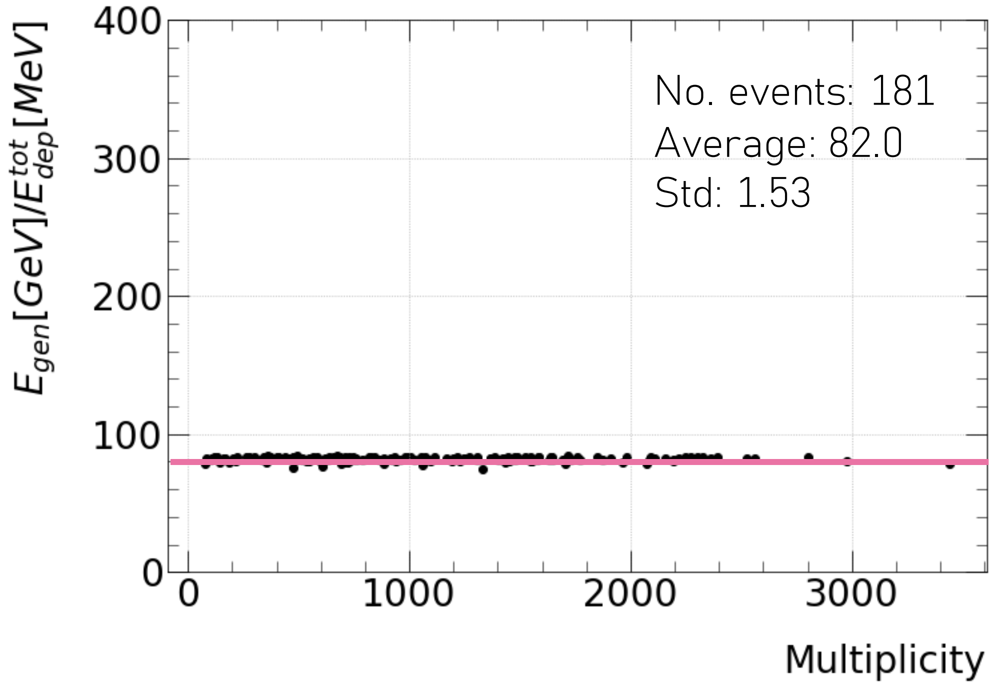

CALIBRATION RATIO

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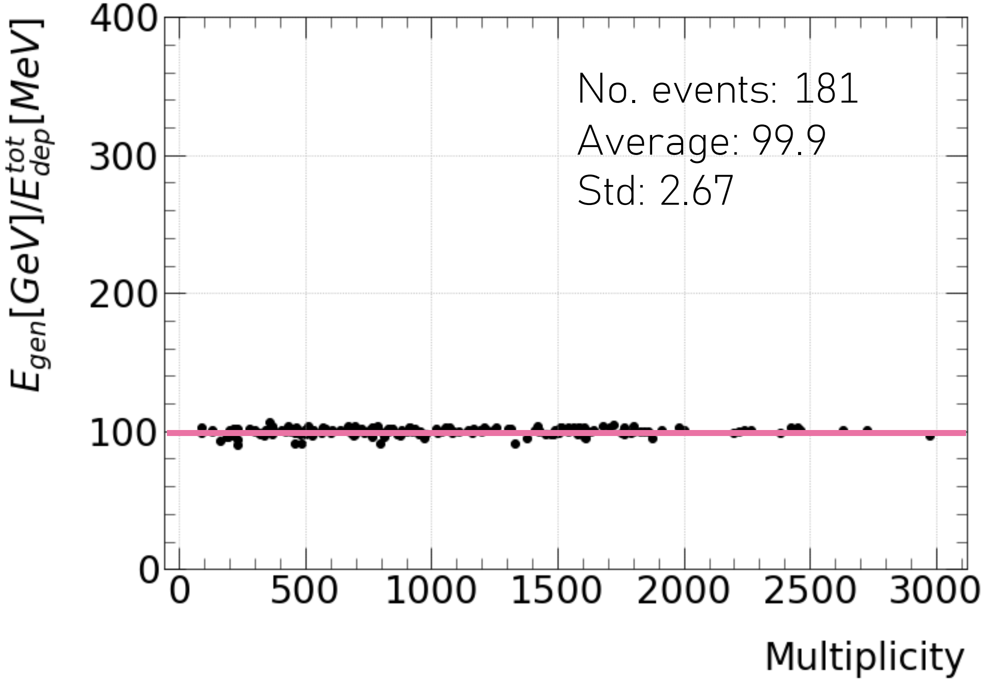
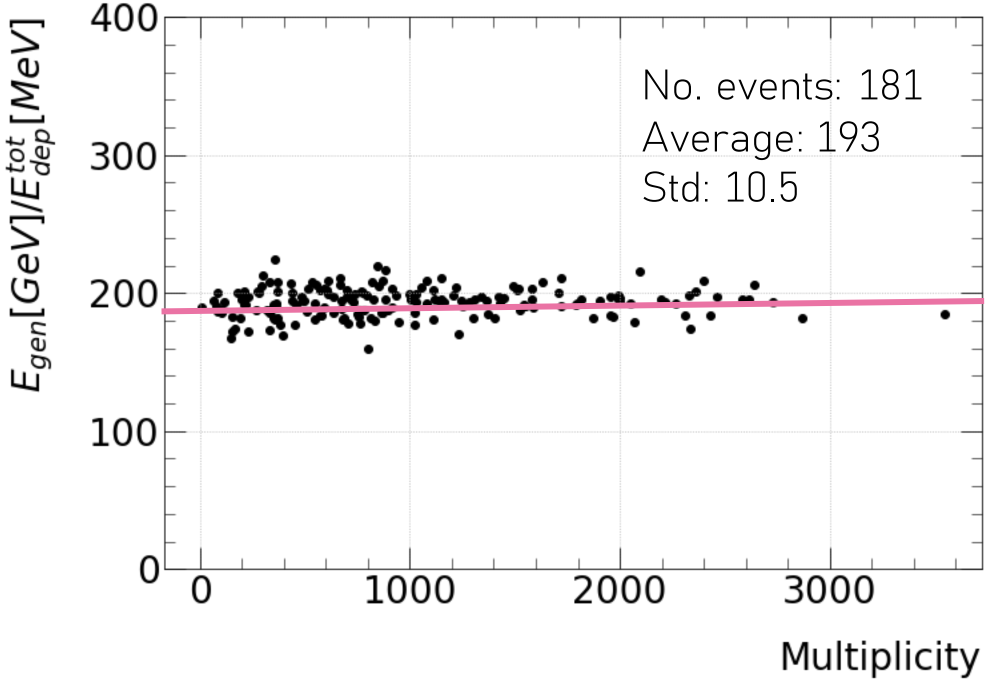


5-LAYER ECAL
WITH THE BACKGROUND



CONCLUSION

- Calculating the Breit-Wheeler Energy spectrum for many positrons is not an easy task
- There are classical methods which needs all the layers and data
- With our ML approach we are able to reconstruct the energy spectrum with the background and without the need of all the layers
- We need to add more data in the future:
  - Hadronic background
  - Ptarmigan spectrum
- Source codes available at GitHub: https://github.com/nirzaa/particles_repo/tree/paper_3micron_kfold