Towards the optimization of a Muon Collider Calorimeter

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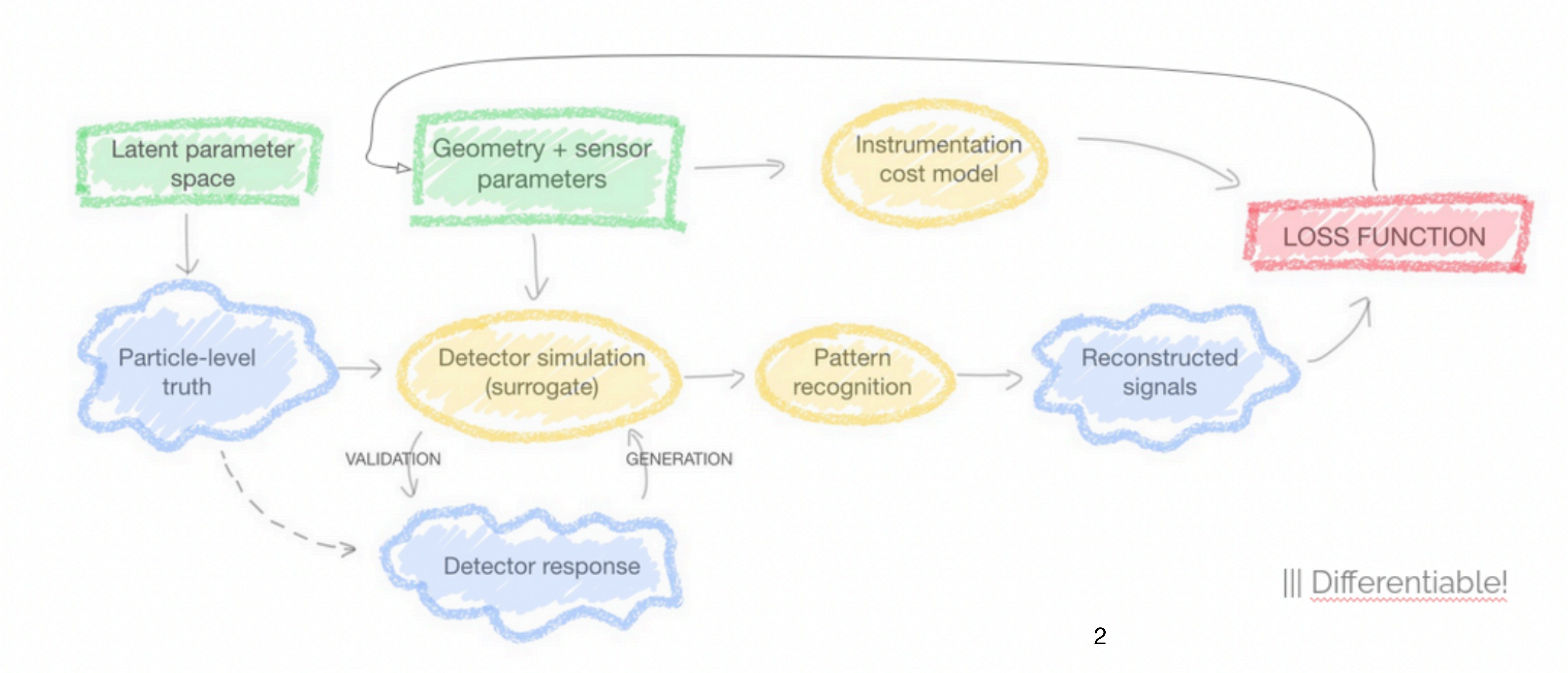
Muon Collider

Optimization Workflow

- End objective: design optimization study approached with AD techniques
- Development of a pipeline to propose an optimal configuration in terms of signal-to-background discrimination and instrumentation cost



- Based on **3** main **core methods**
- Provide information encoded in a **utility function**
- Minimized using **automatic differentiation** techniques

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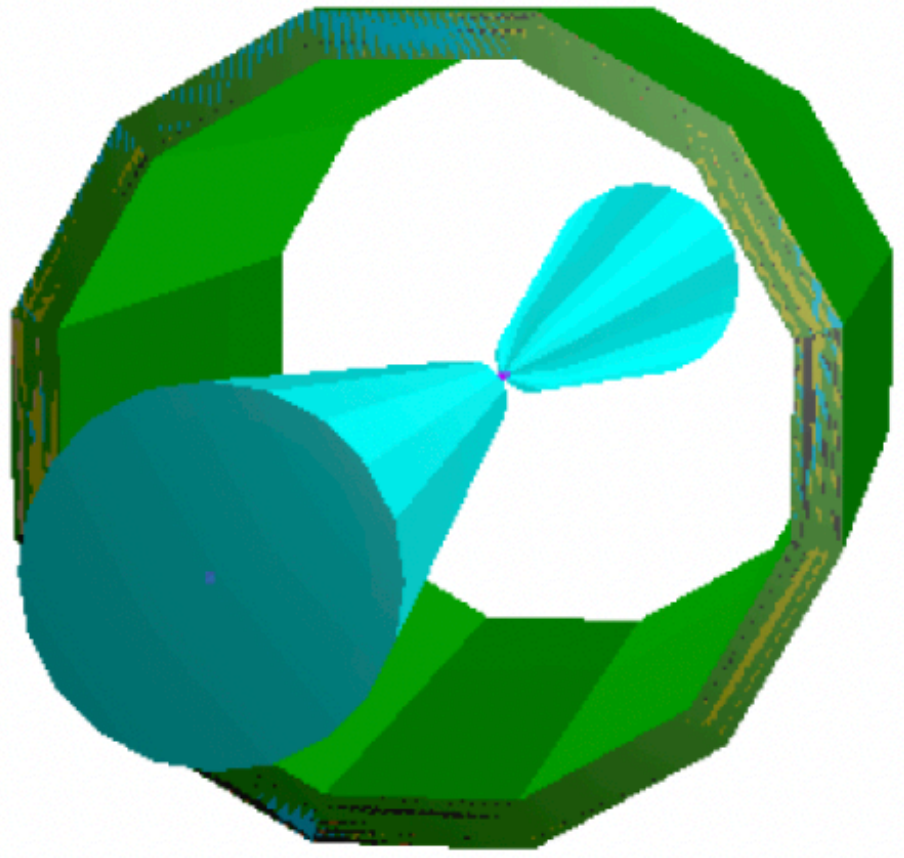
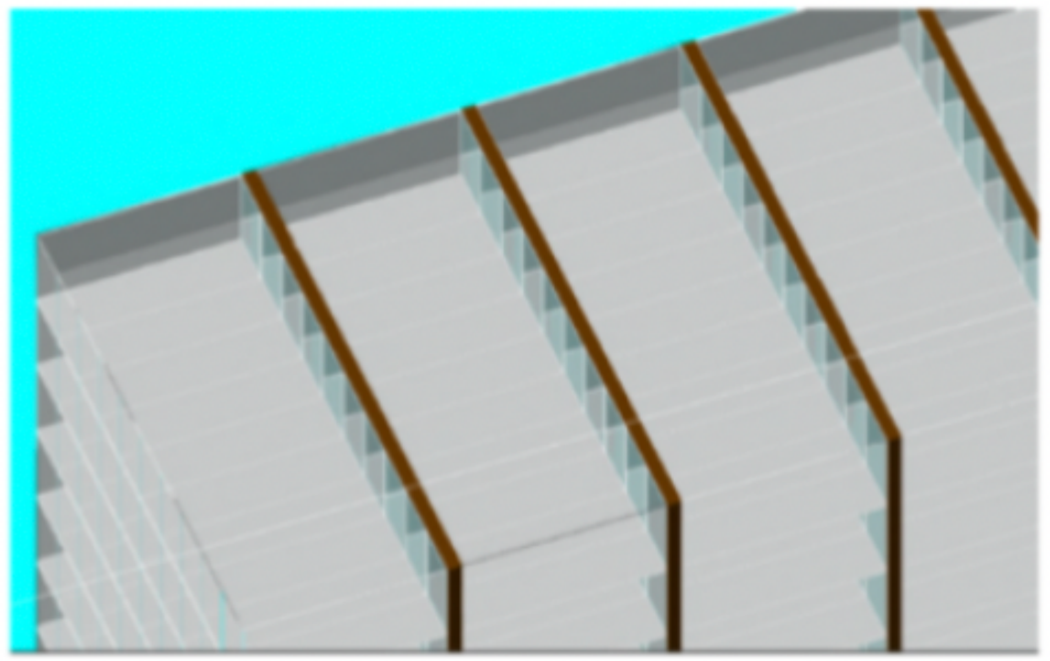
CRILIN: reference design

- Reference design chosen for our studies is CRILIN for the Electromagnetic Calorimeter (ECal)
- Array of 1x1x4.5cm^3 PbF_2 voxels, arranged in a dodecahedron
- 5 layers per wedge
- Modular design, easy to modify and rearrange





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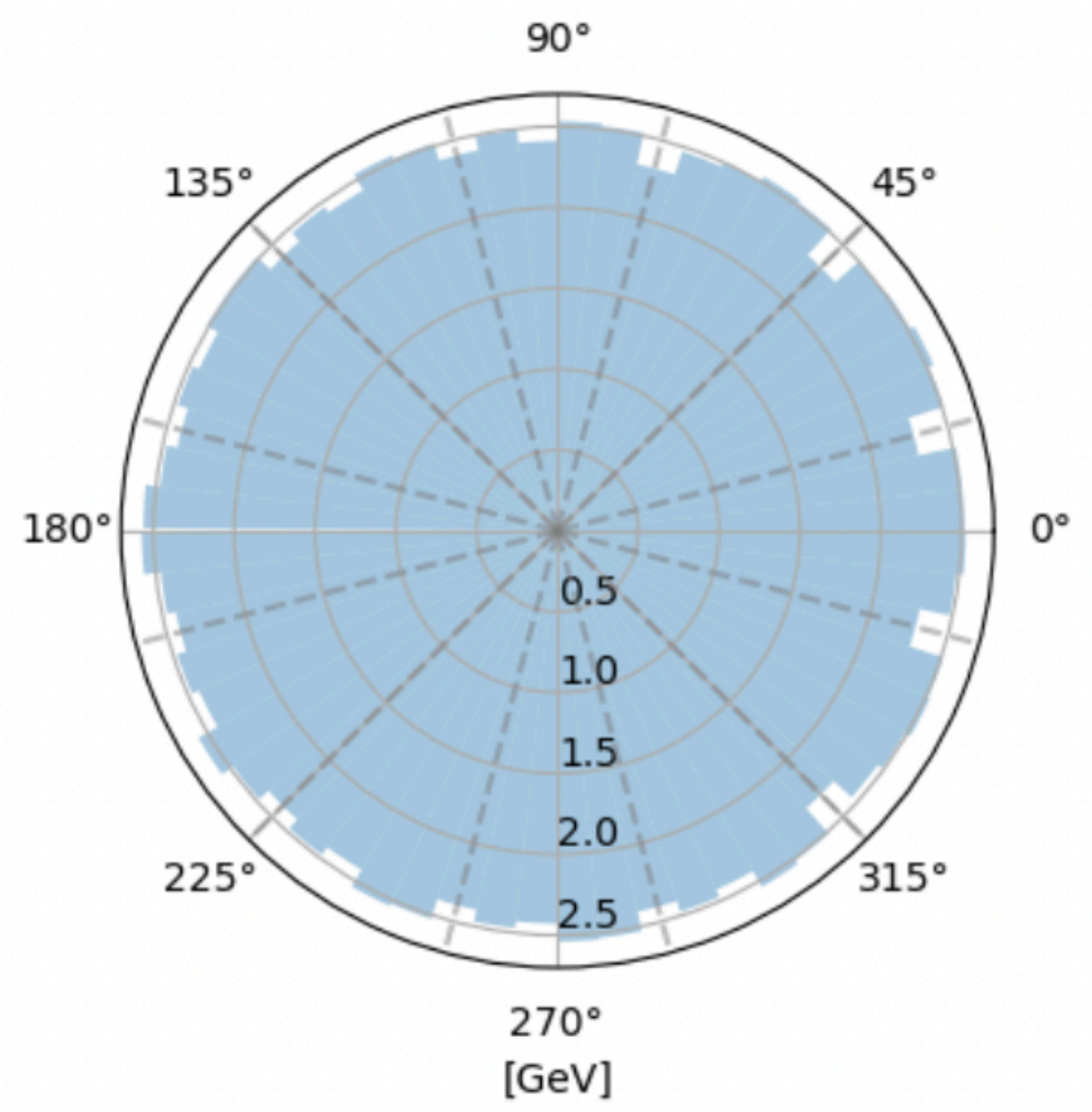
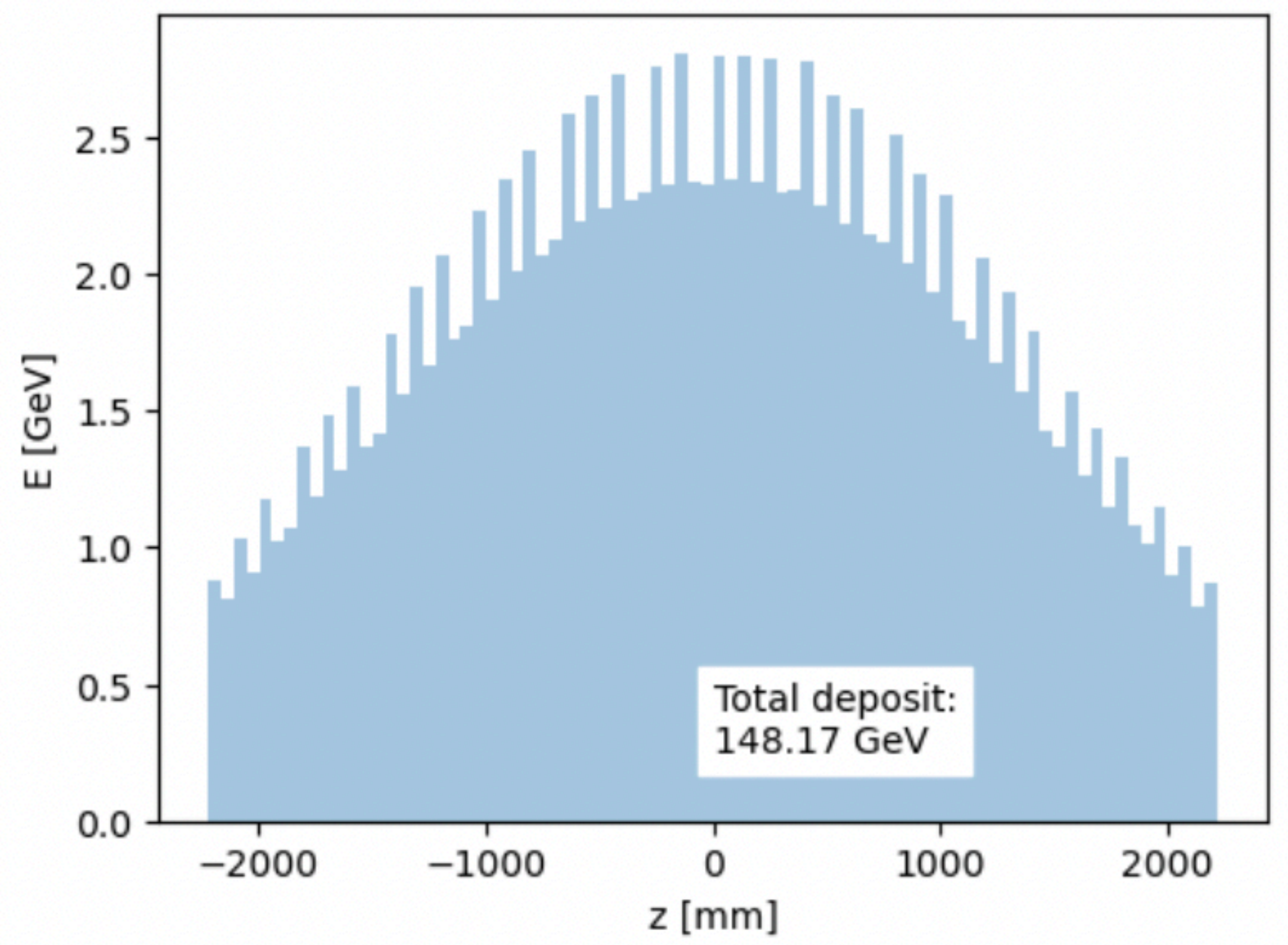
BIB characterization

- Nozzle shields most radiation from endcaps, but area around interaction point remains unshielded
- BIB **simulation at 1.5TeV** center-of-mass energy. Energy deposits in ECal
- Still a considerable amount of energy deposited inside
- Non-uniform distribution alongside z-axis suggests that homogeneous voxels might be suboptimal





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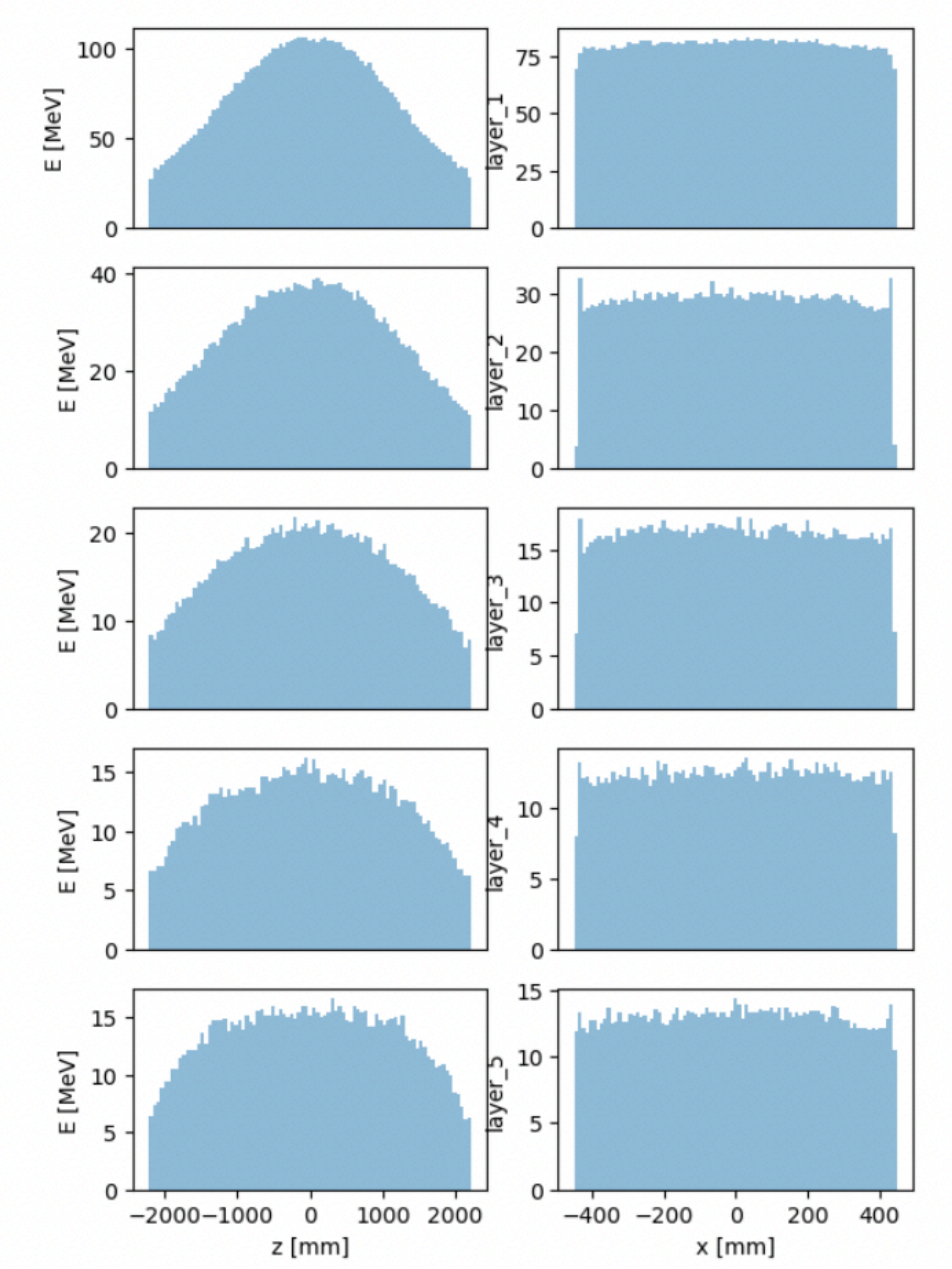
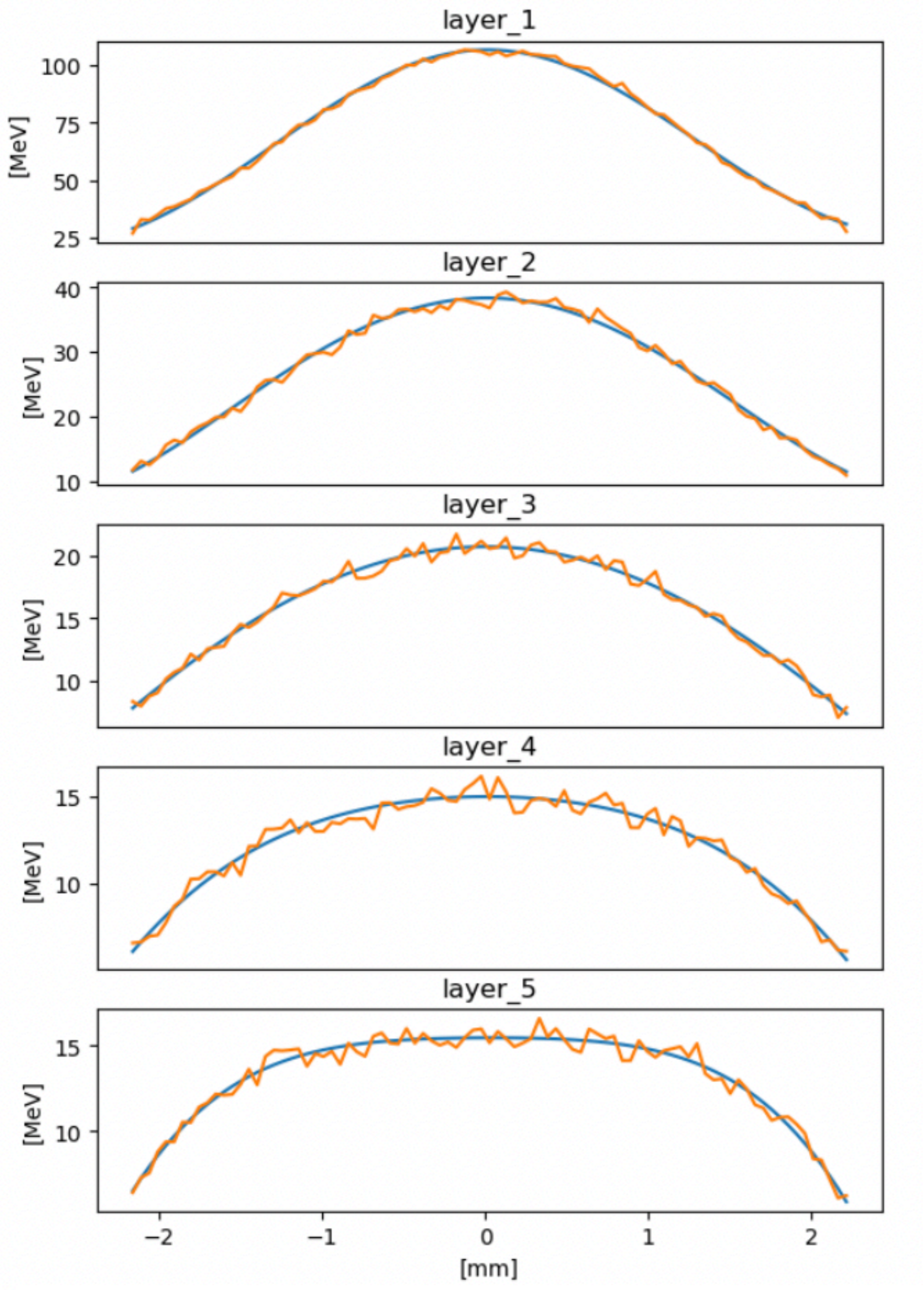
Fitting BIB distribution

- Starting from 1.5TeV BIB simulation
- **Cylindrical symmetry** lets us neglect transverse direction: focus on a **single wedge** and model component along beam axis.
- 5-parameter **fit** to a gaussian superimposed to a 2nd order polynomial



$$f(z) = p_1 e^{-\frac{z^2}{p_2^2}} + p_3 z^2 + p_4 z + p_5$$



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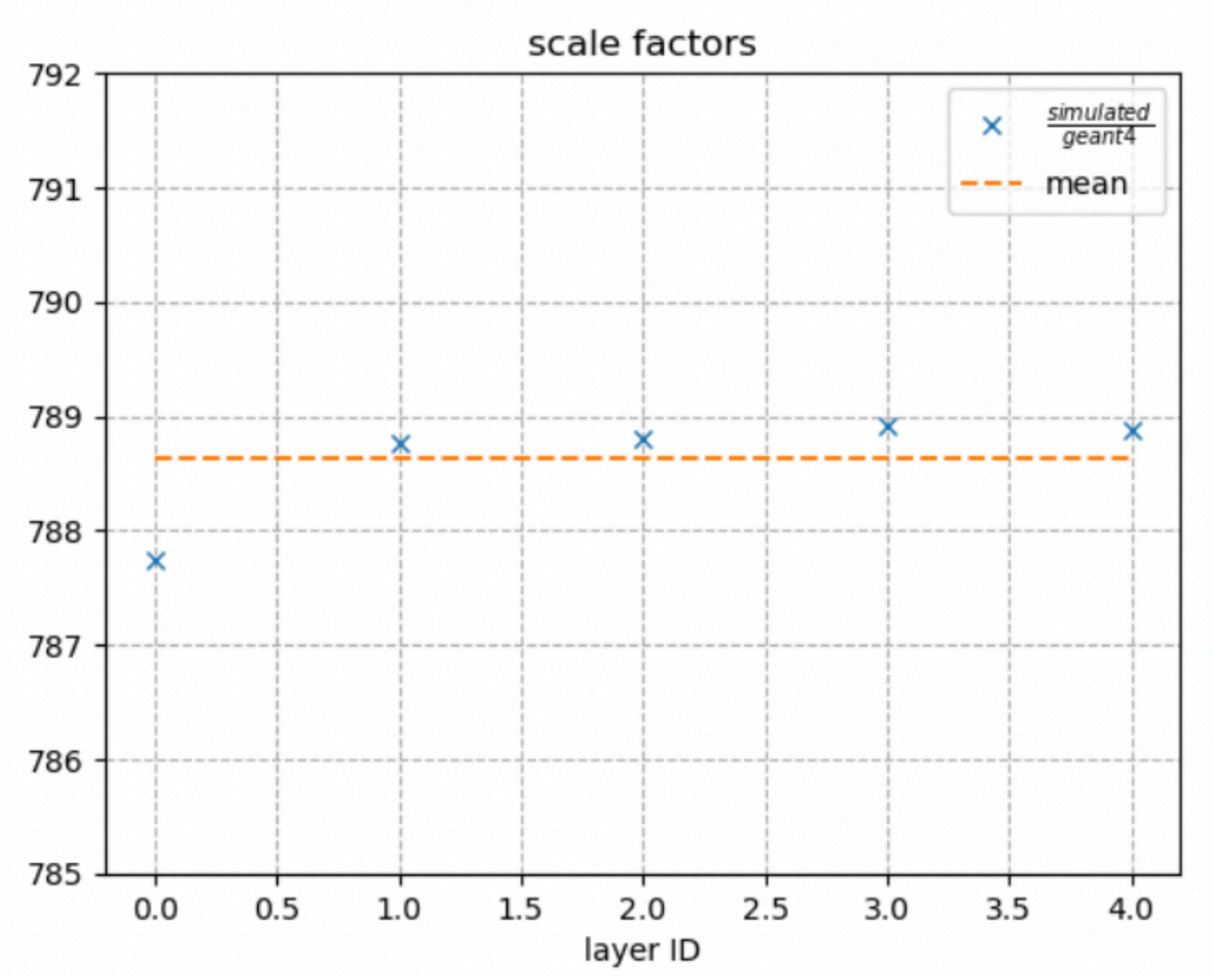
BIB simulation and checks



- Evaluate parametrization in a grid. Since we have neglected transverse direction, parametrizations will be accurate **up to a normalization constant**
- Constraint: parametrized deposition **match** layer-by-layer the **Geant4 deposition**
- Normalization constant can be explained by the transverse bin multiplicity (~80) times a bin width geometric factor (10mm)

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Object Condensation for reconstruction

- To reconstruct signals in ECal we test **DeepJetCore**, a package developed for the **reconstruction of jets** in the High-Granularity Calorimeter for the CMS upgrade for the High-Luminosity LHC runs

- Core is a **Graph Neural Network** that **clusters** the data, whose dimensionality has been reduced by filter layers.

- Clustering performed through the identification of **one condensation point for each object**, and the subsequent minimization of a loss function

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OC: Dataset Generation

- The dataset chosen to **train** the algorithm is **10000 photon events**, distributed uniformly in [10,175]GeV
- Photons are generated with Geant4, with **rapidity 0** and uniformly distributed in the transverse angle ϕ
- **BIB parametrization superimposed**
- Geometric **cuts**:
  - 2σ of total signal deposition in ϕ
  - 40cm band along z-axis

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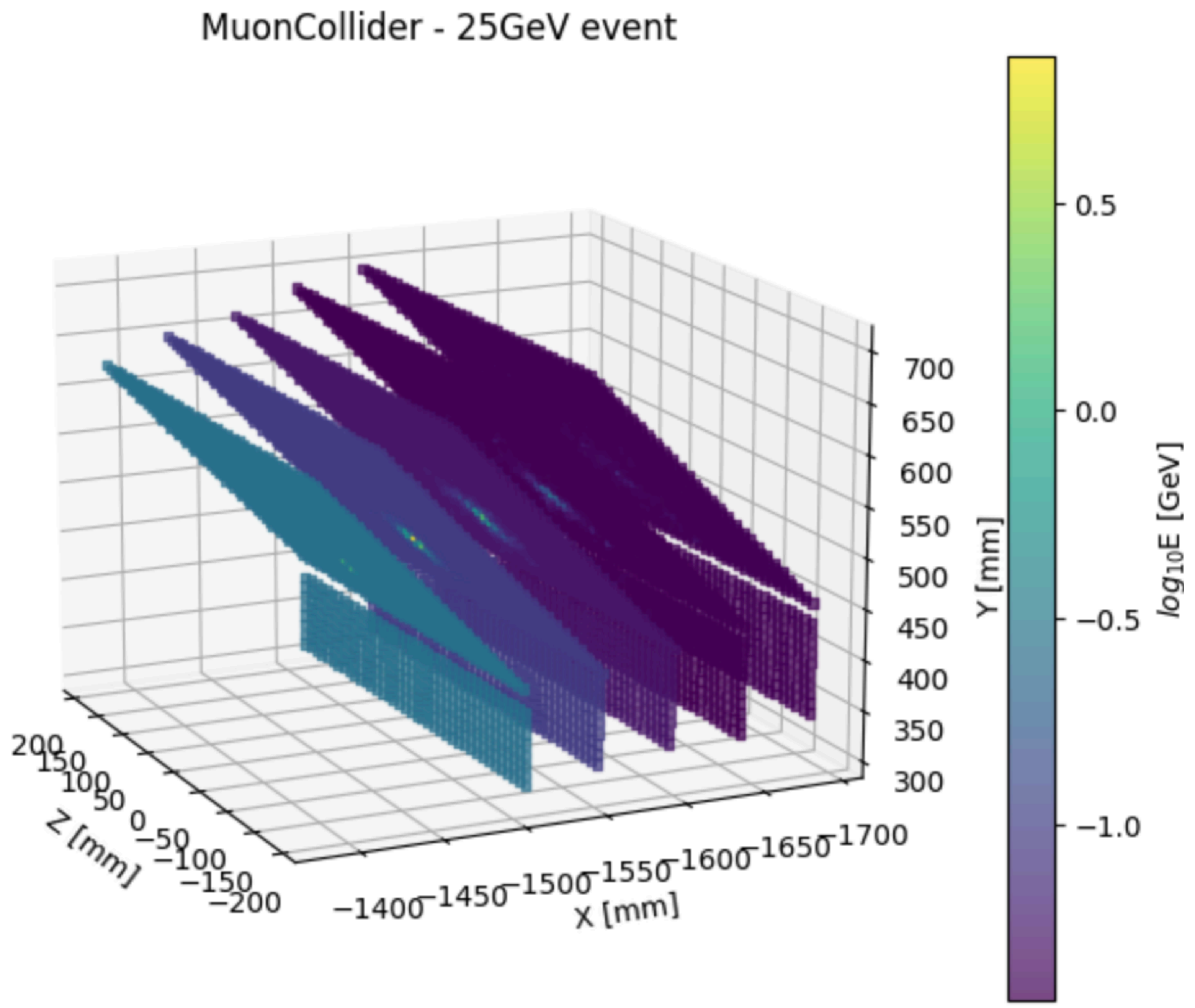
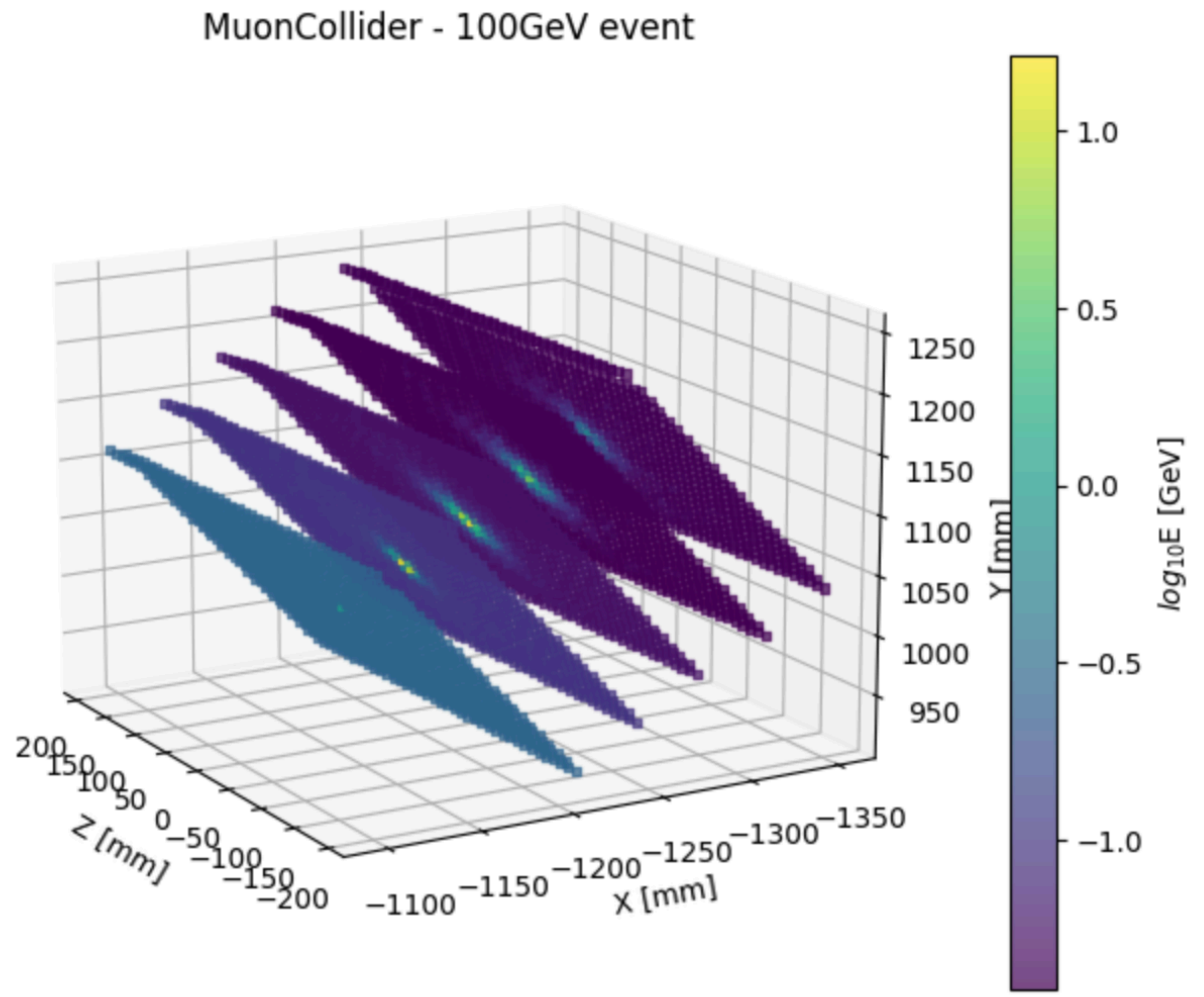
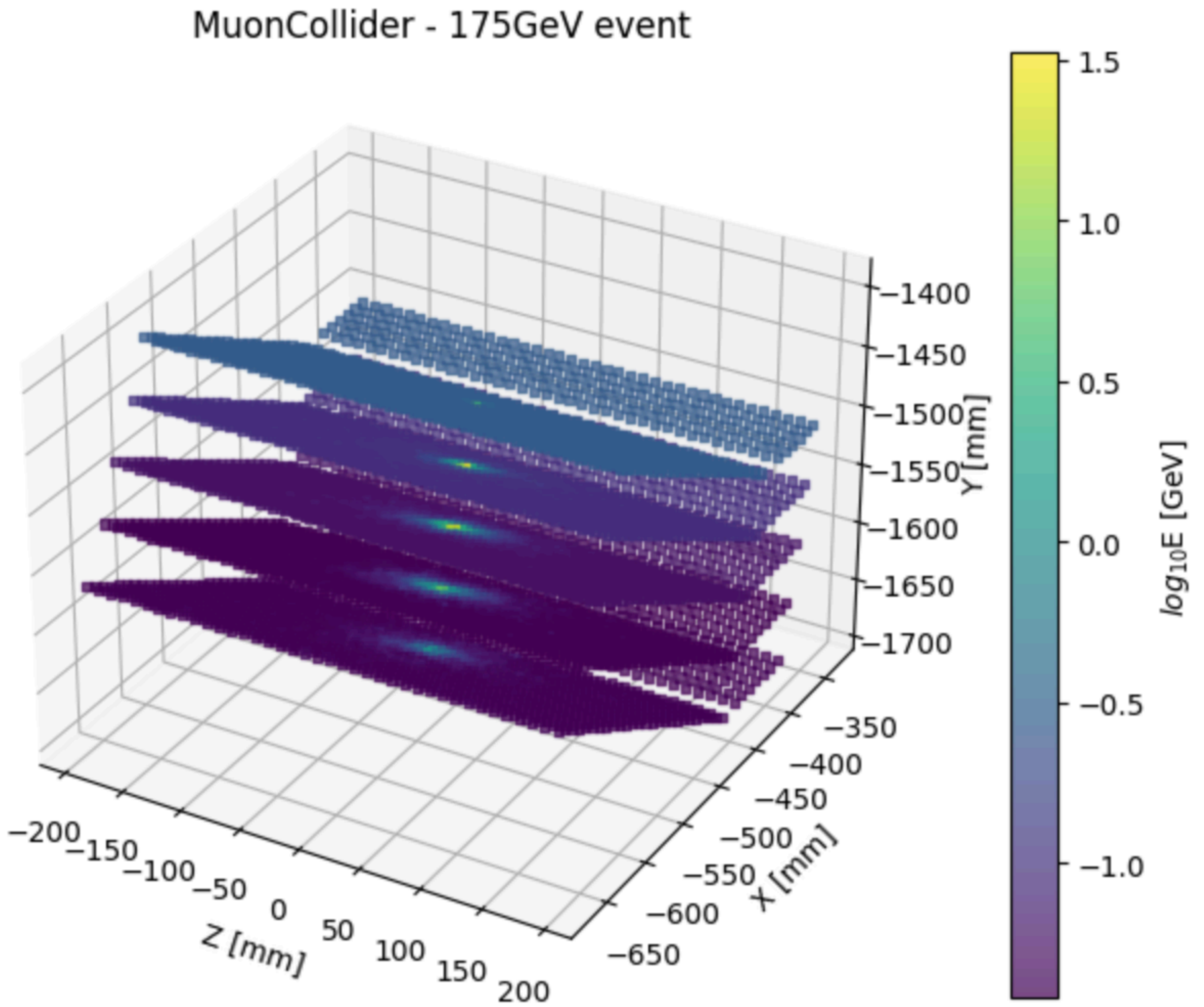
OC: Dataset Generation







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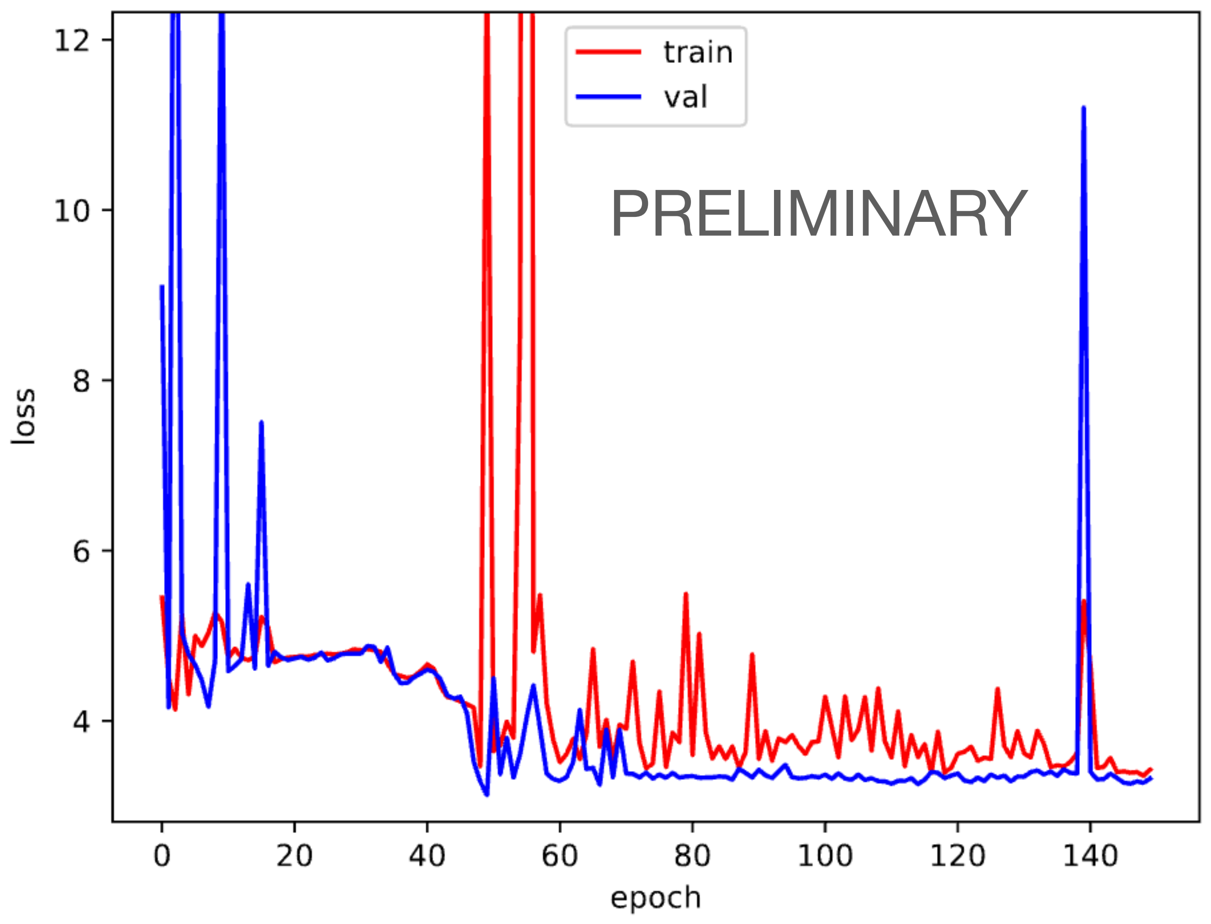
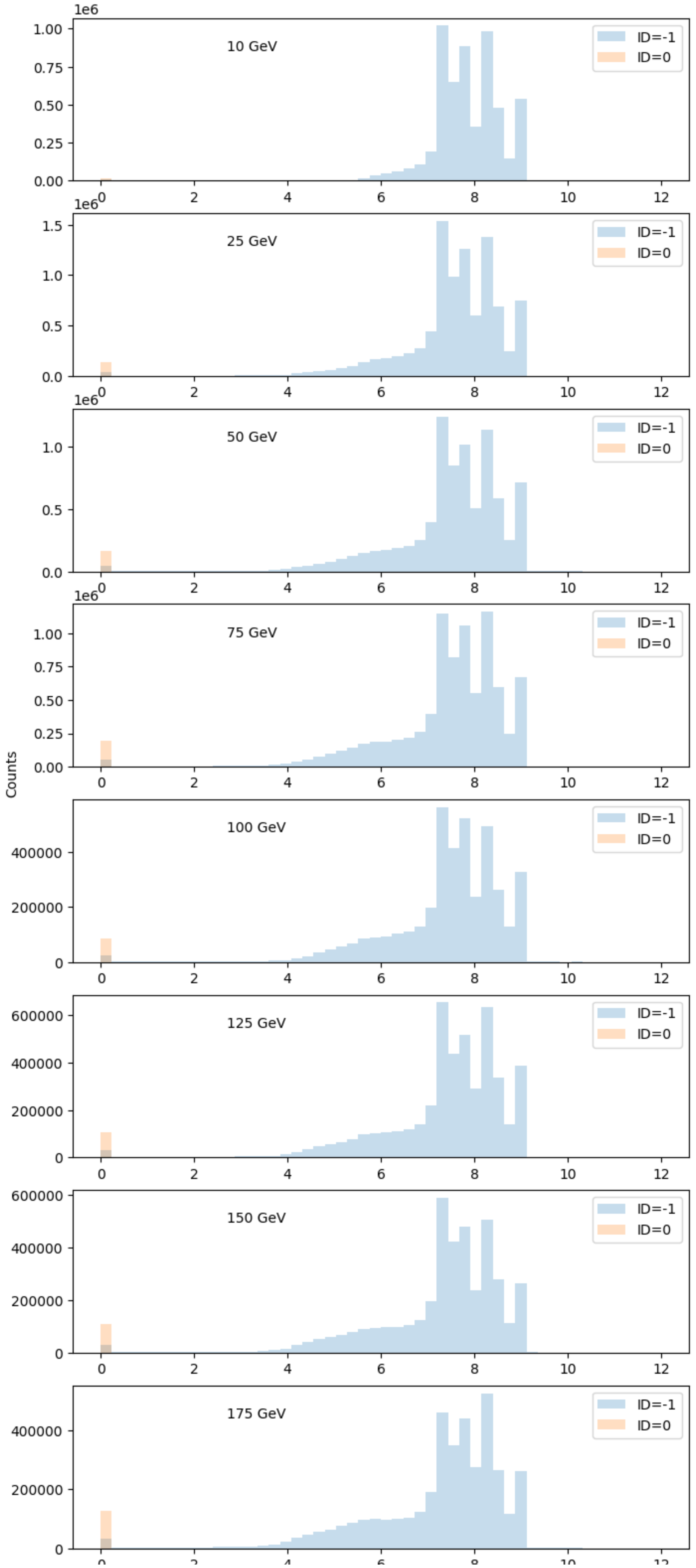
OC: Clustering





- Trained for **150 epochs** with learning_rate=1E-3
- Jumps in loss due to **too big learning step**
  - Next training down 2 orders of magnitude
- Performance evaluated on **1k monochromatic photons** for **8 energy points**
- Decent signal (ID=0) vs background (ID=1) **separation**

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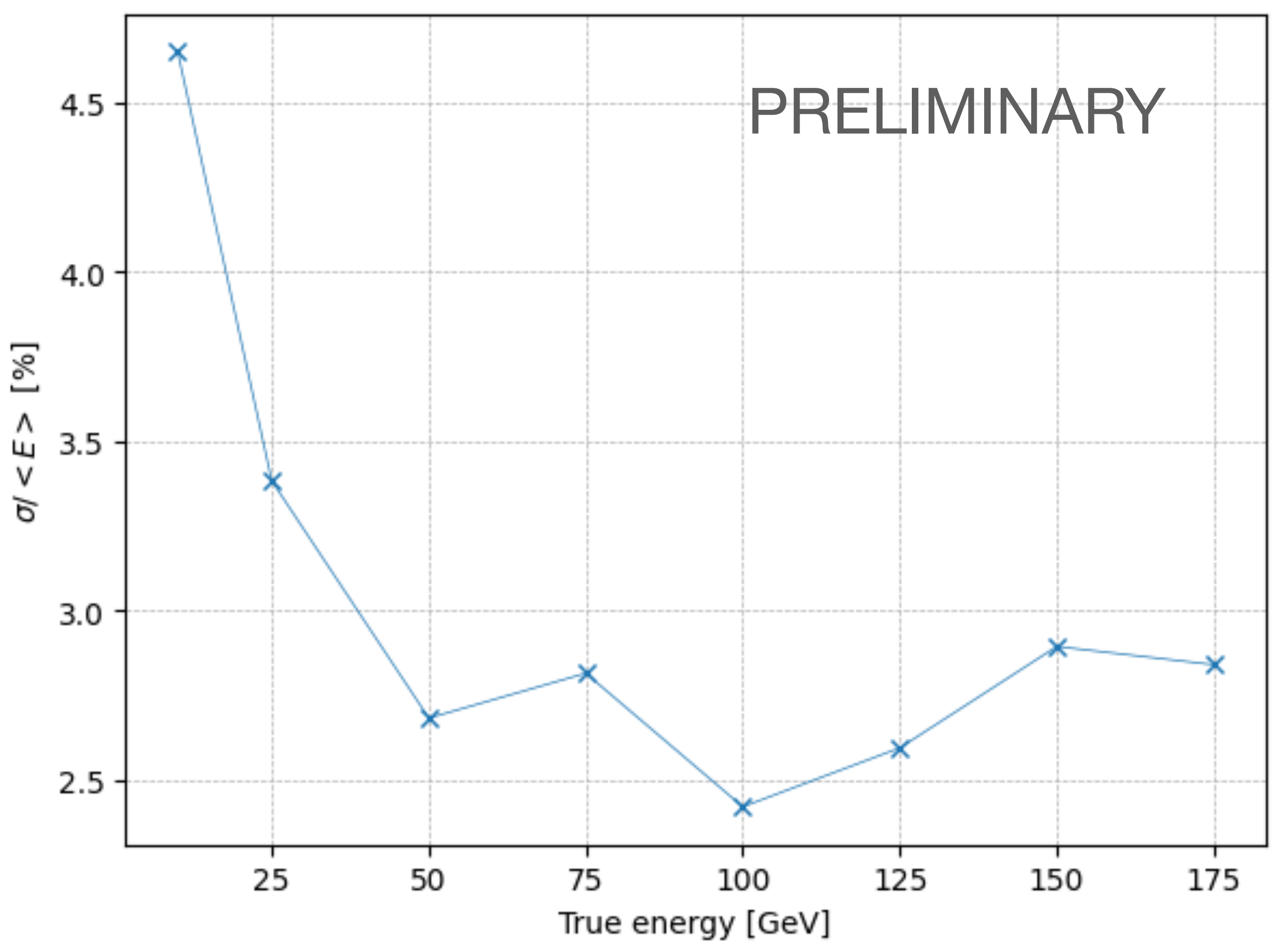
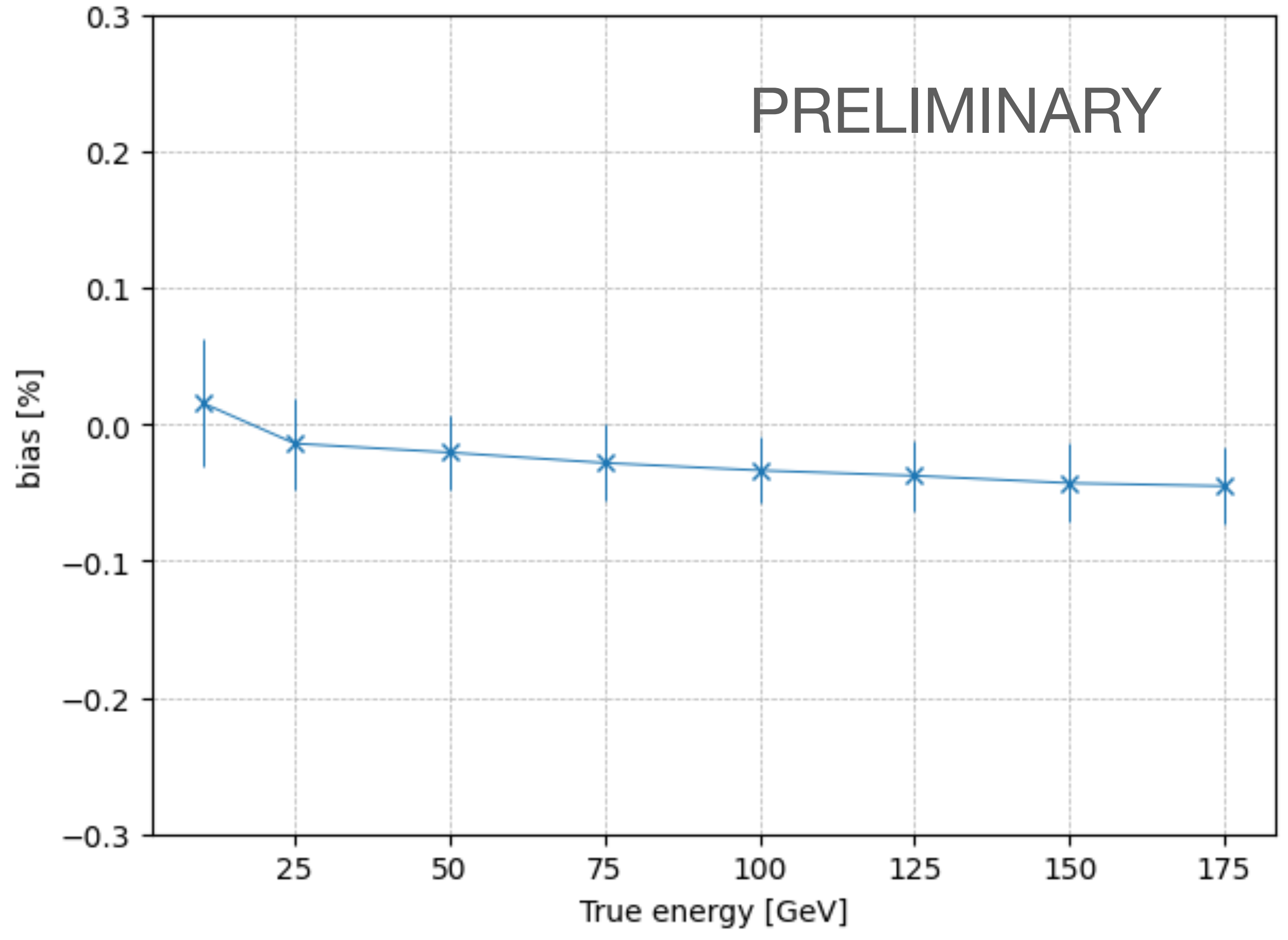
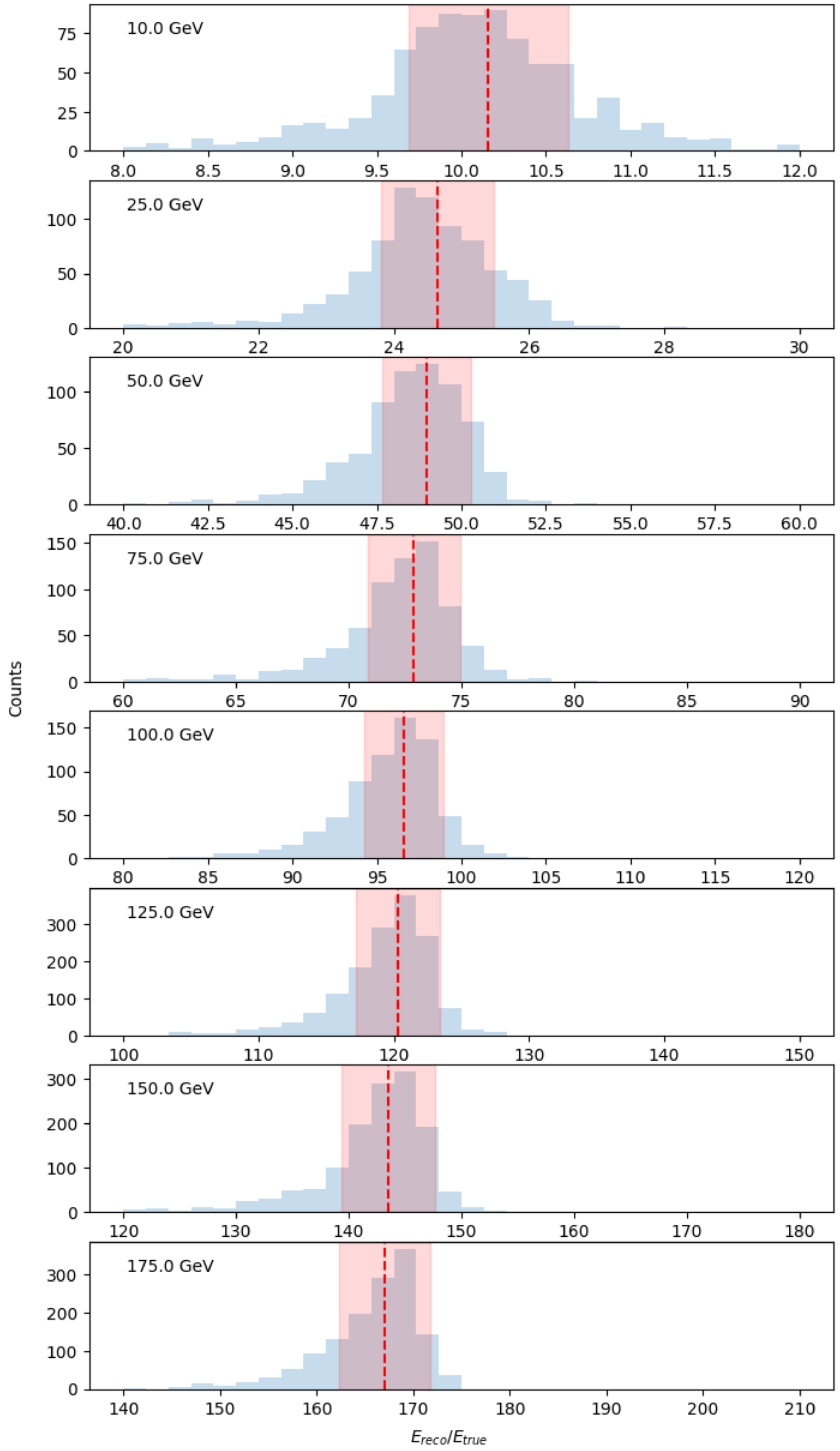
OC: Energy reconstruction

- Primary **energy** inferred by summing the energy **deposits for signal-labeled hits**
- **Degrades at lower energies**, where signal and BIB deposits become comparable
- Calculate standard deviation and RMS error around each peak to **evaluate resolution**







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OC: Energy reconstruction

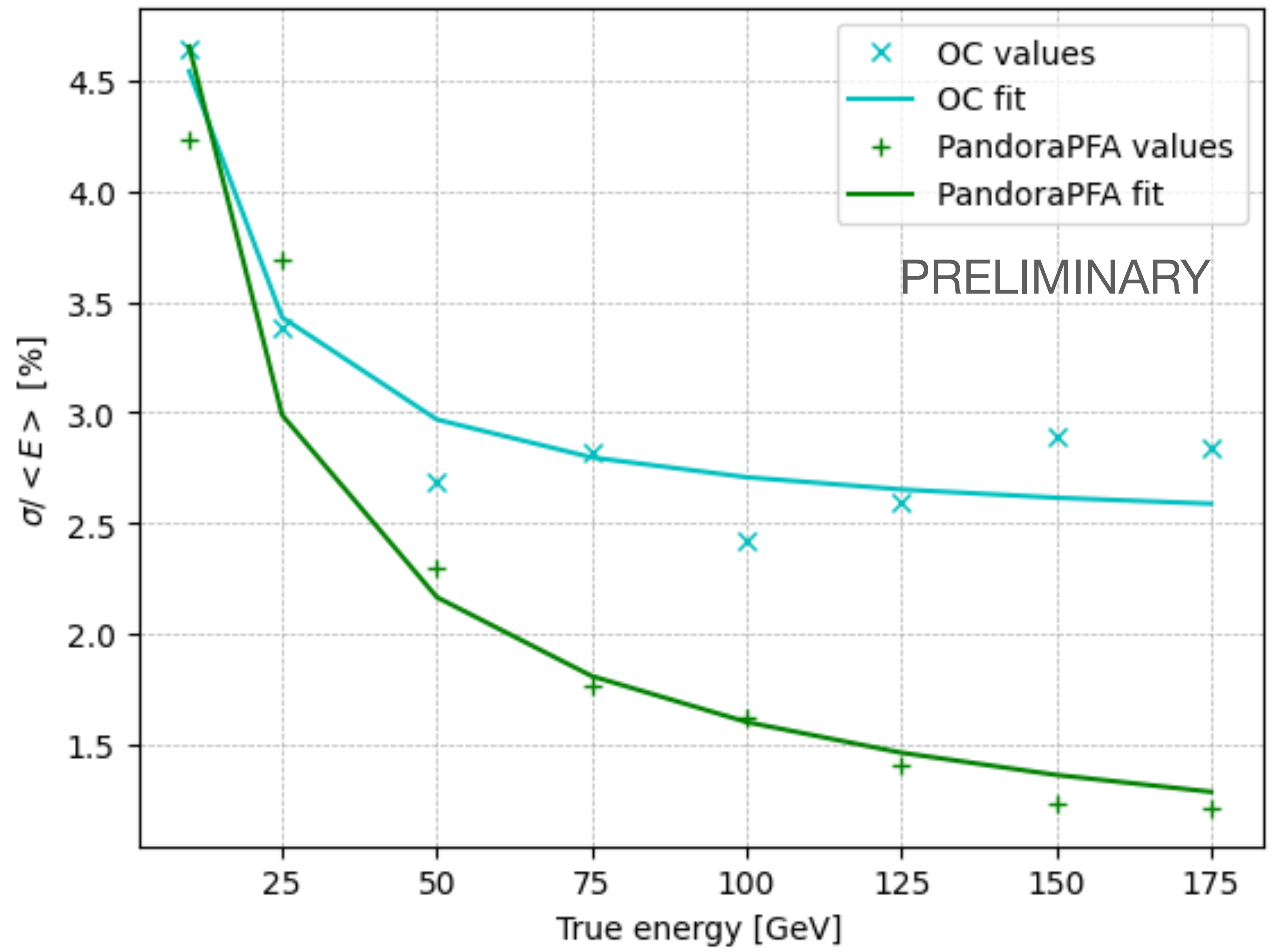
- Fit to obtain resolution function parameters:

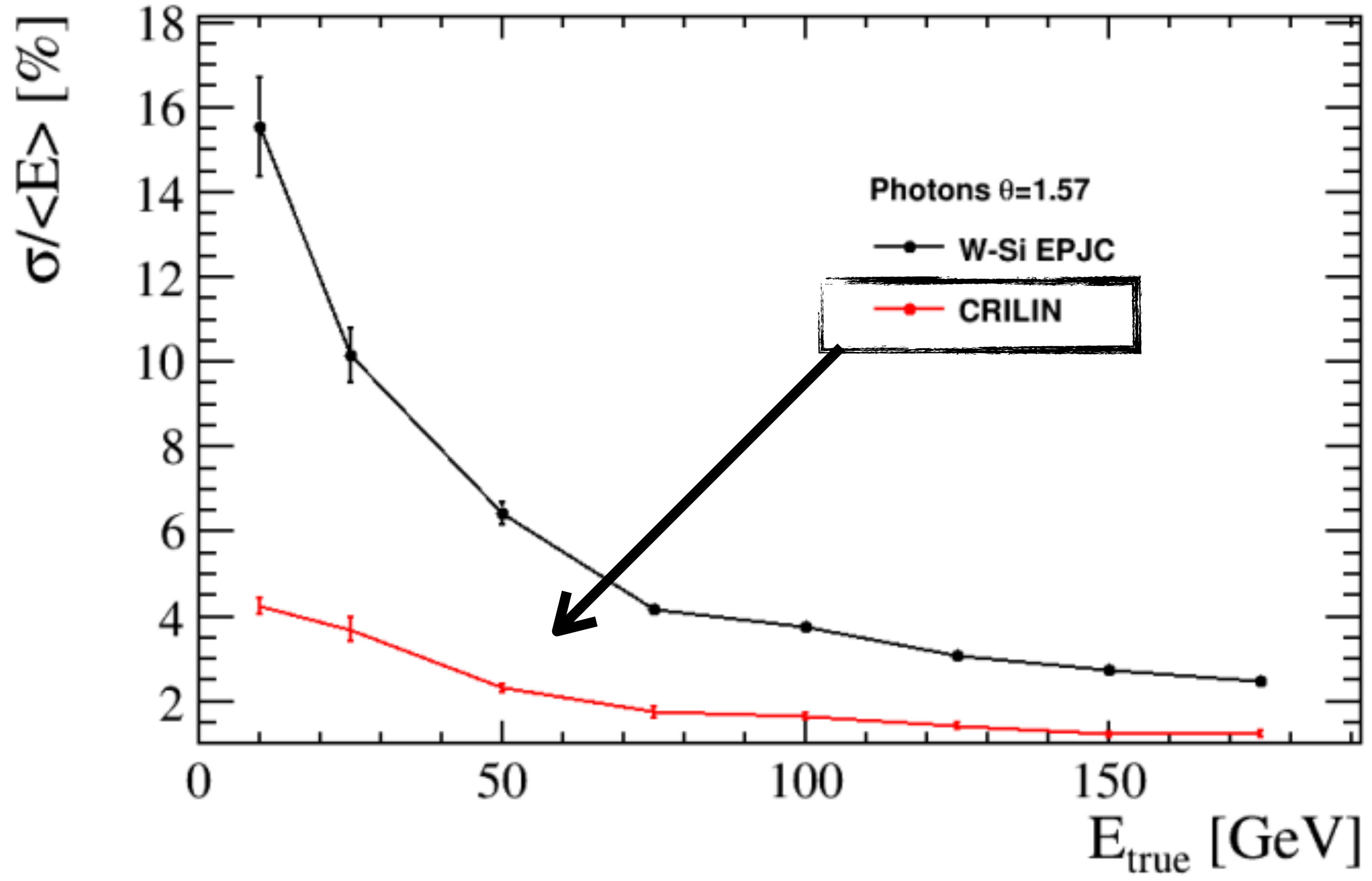
$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2}$$

$$a = 0.14, \quad b = 0.025$$

- Comparable performance with PandoraPFA and BIB preprocessing

$$a = 0.14, \quad b = 0.006$$





Courtesy of L. Sestini, Muon Collider Collaboration - INFN Padova

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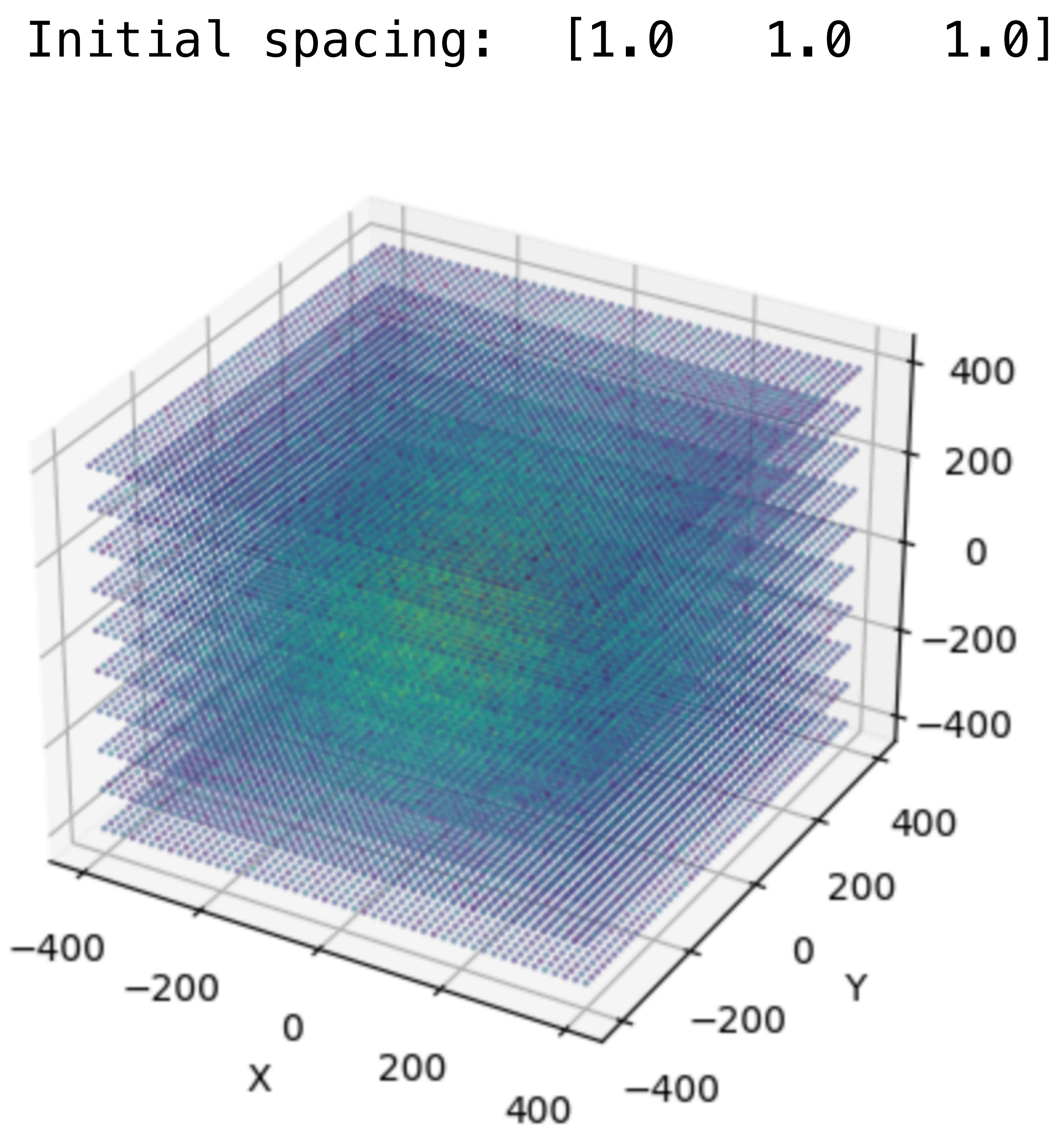
Towards setting up a pipeline

- Idea: represent Crilin detector as a 3D grid of voxels, and optimizing the spacing (Δx,Δy,Δz) between them.

- Started to work on a toy model:

  - **Defining the geometry**: simple 3D grid with custom # voxels

  - **Evaluating a function on the grid**: 3D gaussian with $\sigma_x \neq \sigma_y \neq \sigma_z$ + random noise




```
sigma_x = 100.
sigma_y = 120.
sigma_z = 100.
```

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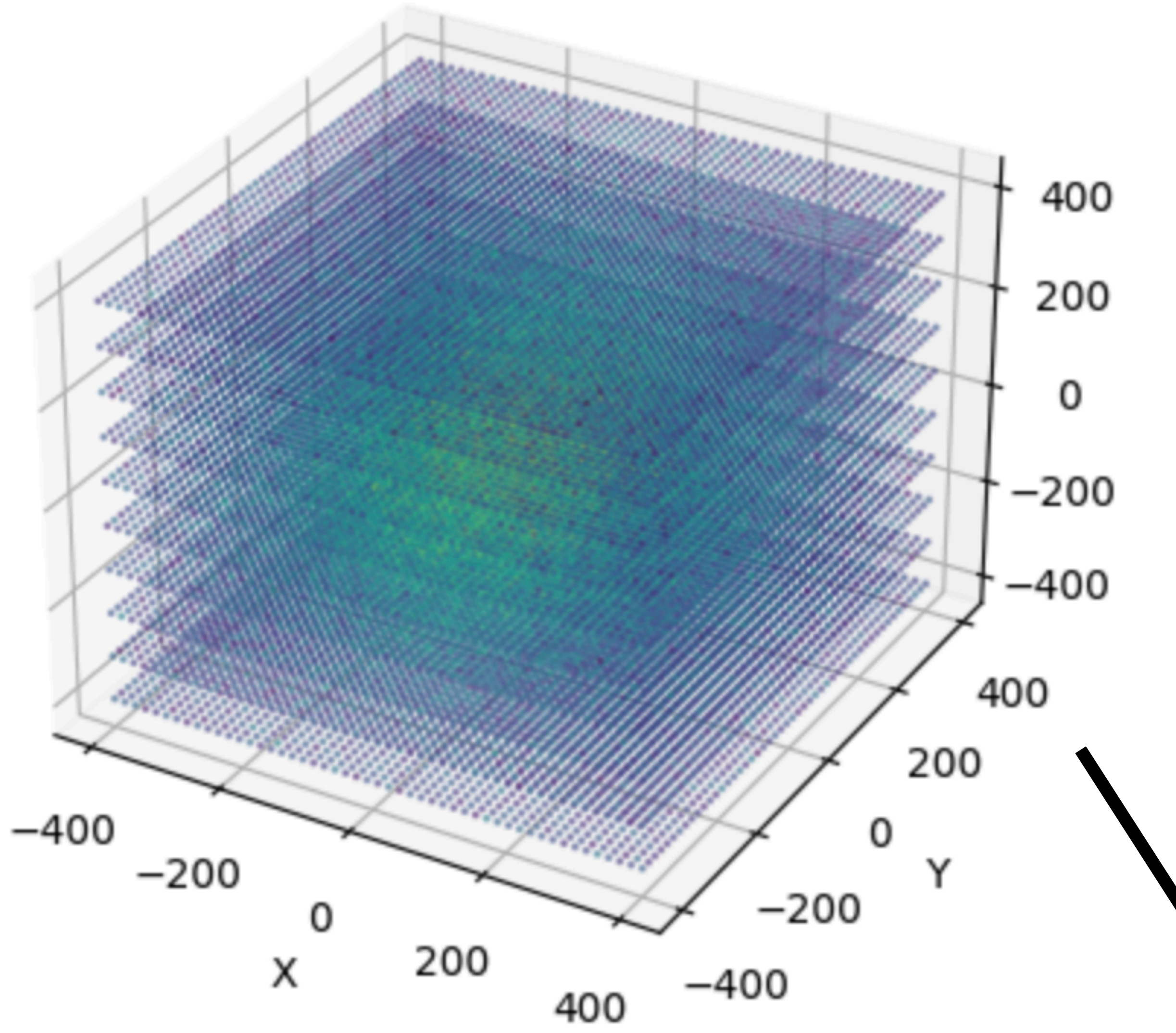
Towards setting up a pipeline

- **Reconstruction**: Use maximum-likelihood estimators to infer the gaussian parameters $\hat{\mu}, \hat{\sigma}$
- **Evaluating loss:** MSE for gaussian parameters + regularizer to prevent spacing to collapse towards degeneracy

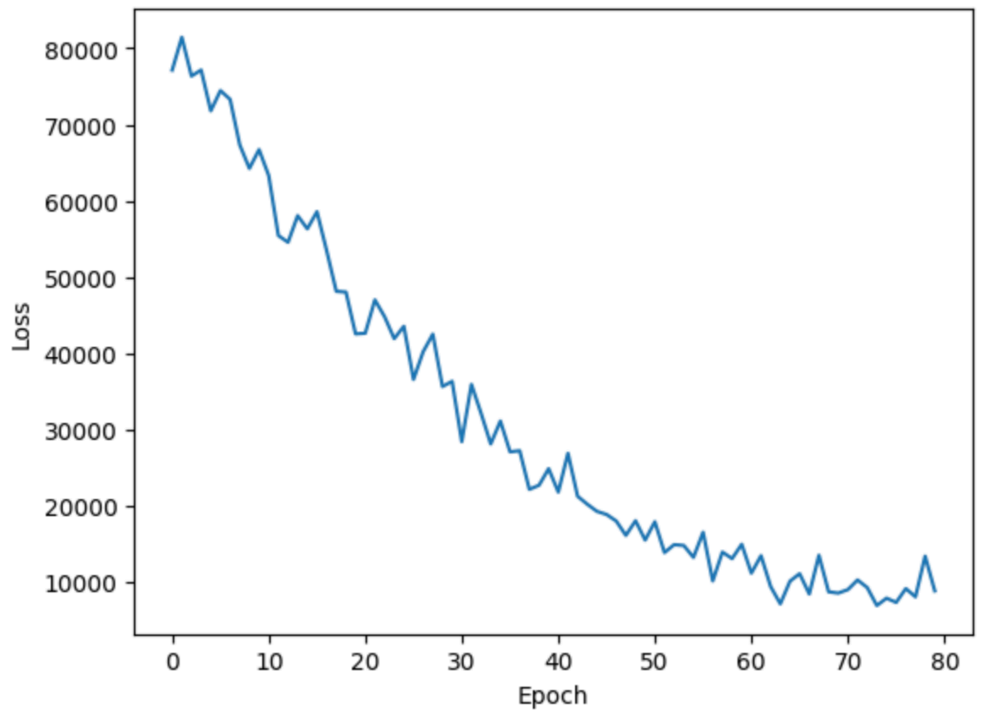
$$\sum_{i=x,y,z} (\hat{\mu}_i - \mu_i)^2 + (\hat{\sigma}_i - \sigma_i)^2 + \frac{1}{\Delta x_i^2}$$

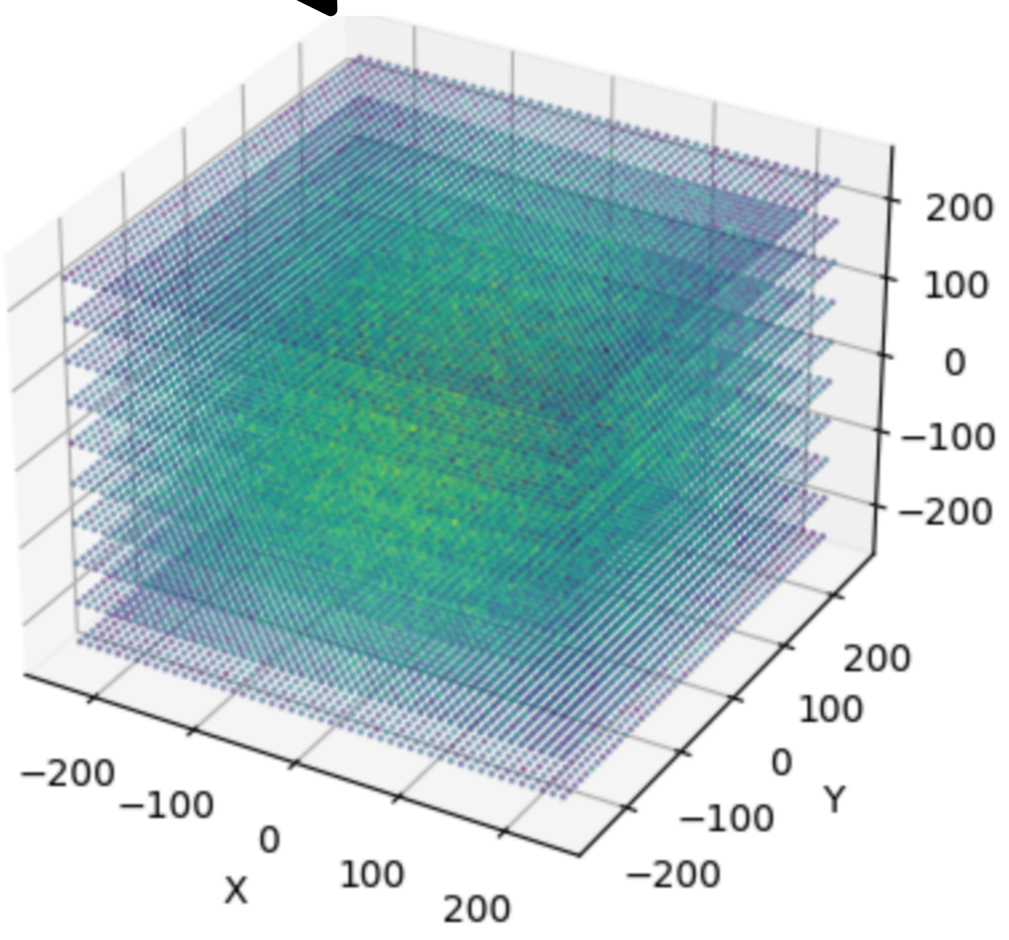
- **Minimization** of loss and identification of ideal parameters

Initial spacing: [1.0 1.0 1.0]



100 epochs
Lr = 0.001





Final spacing: [0.47563136 0.5433373 0.44885612]

Summary

- Still work to do to come up with a design
- Differentiable blocks are however taking shape
- Tests on OC promising. Need to play with parameters, and generalize to N photons.
- Toy pipeline model to be upgraded with more realistic loss and signal generation
- If it proves successful, we are able to implement the full ECal geometry

Summary

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- Tests on OC promising. Need to play with parameters, and generalize to N photons.
- Toy pipeline model to be upgraded with more realistic loss and signal generation
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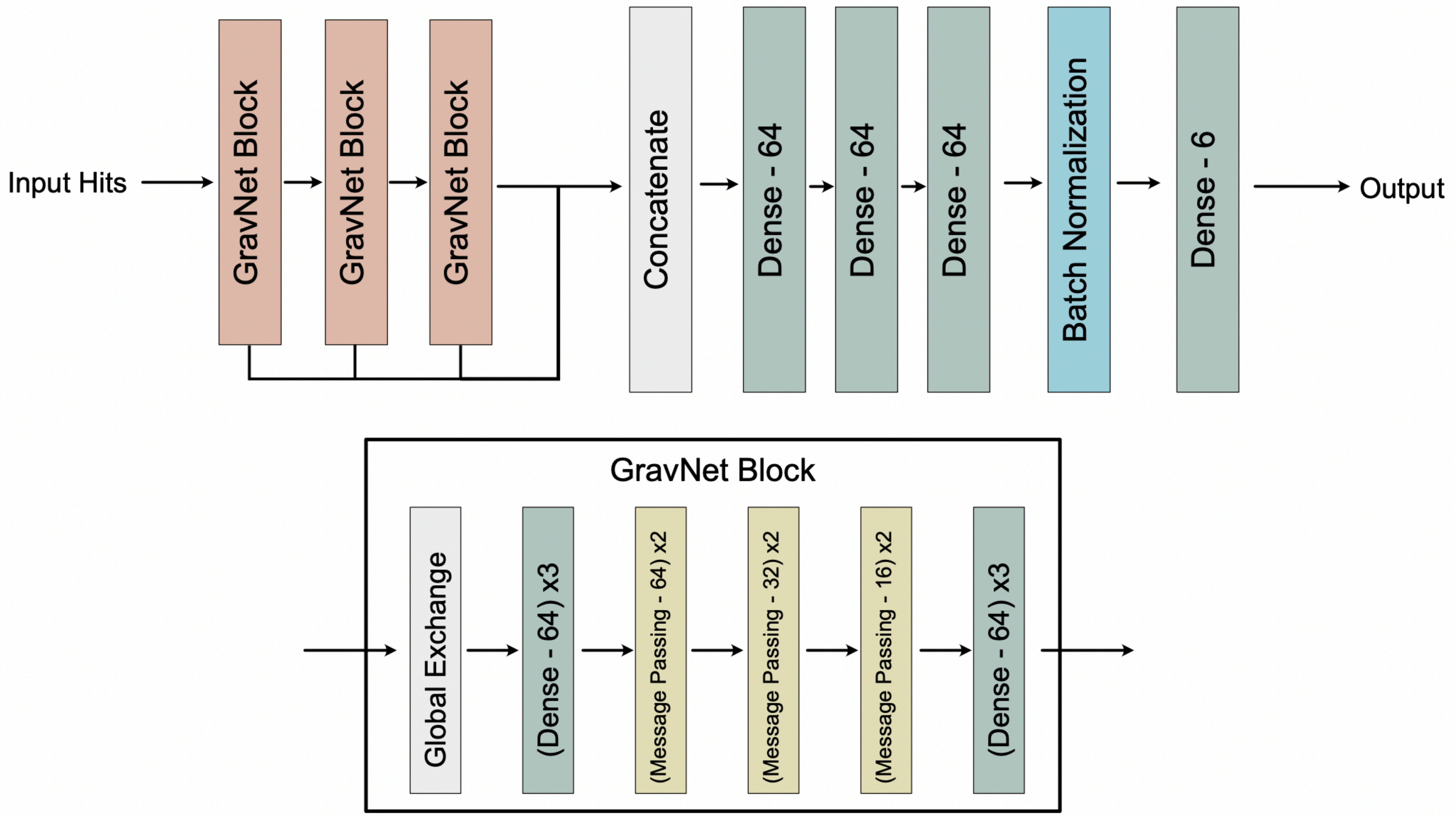
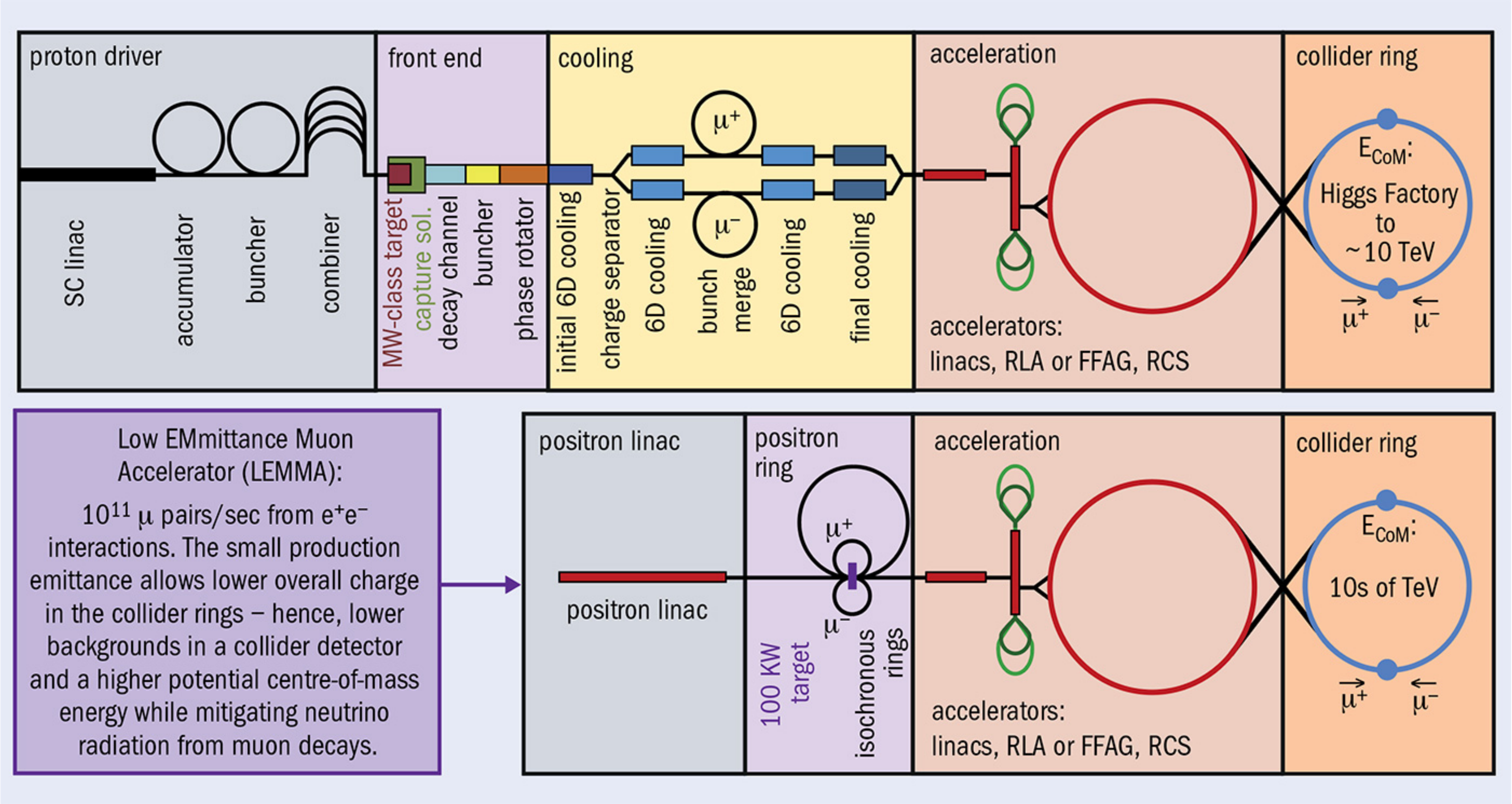
Thank you!

Backup

DJC Architecture



Muon Collider baseline



- Muon production - mMAo Muon Accelerator Program
  - Proton beam on a target, muons from pion decay
  - High emittance, advanced cooling needed
- Alternative - LEMMA