Towards the optimization of a Muon Collider Calorimeter

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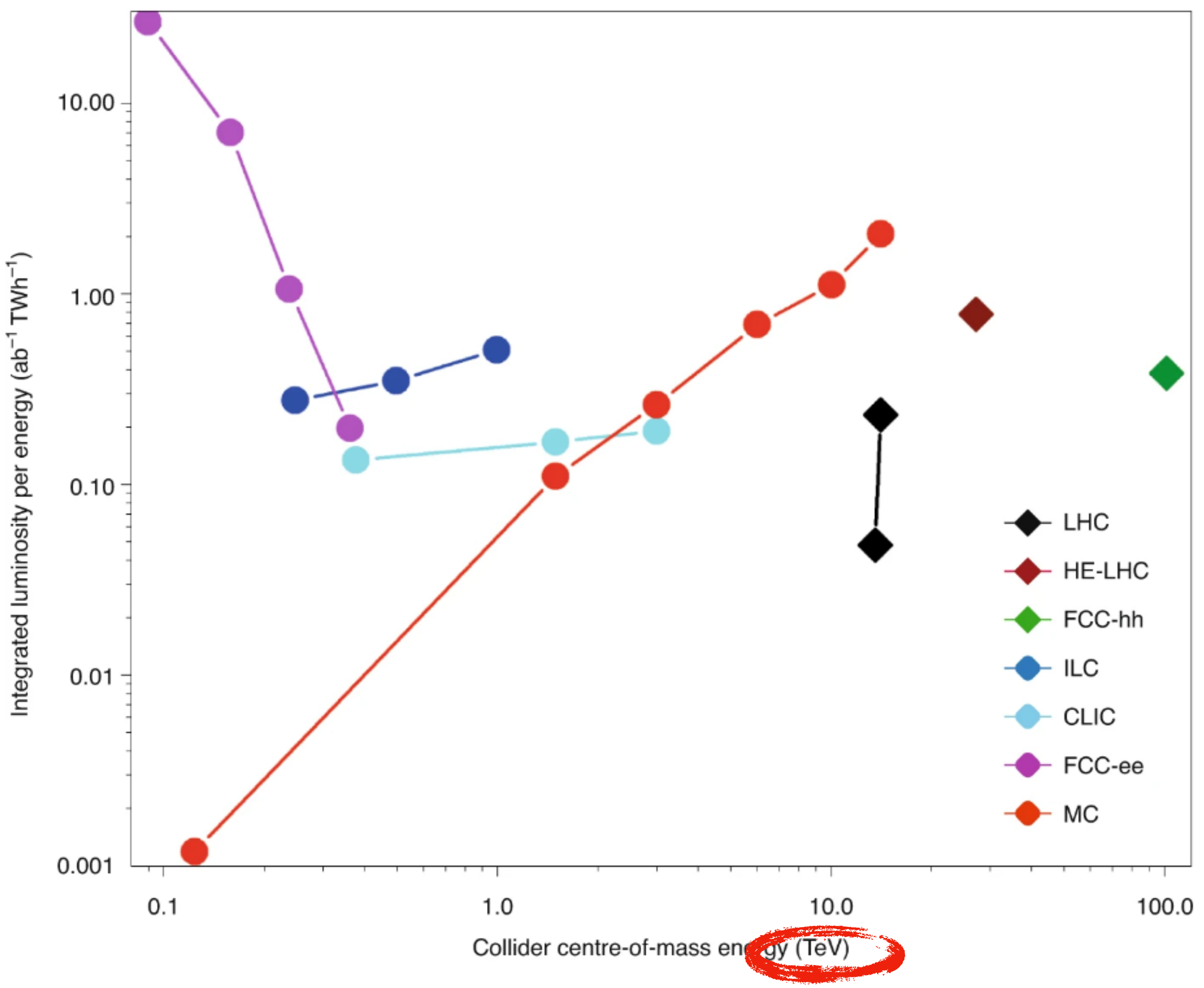
MODE

Introduction

Why a Muon Collider?

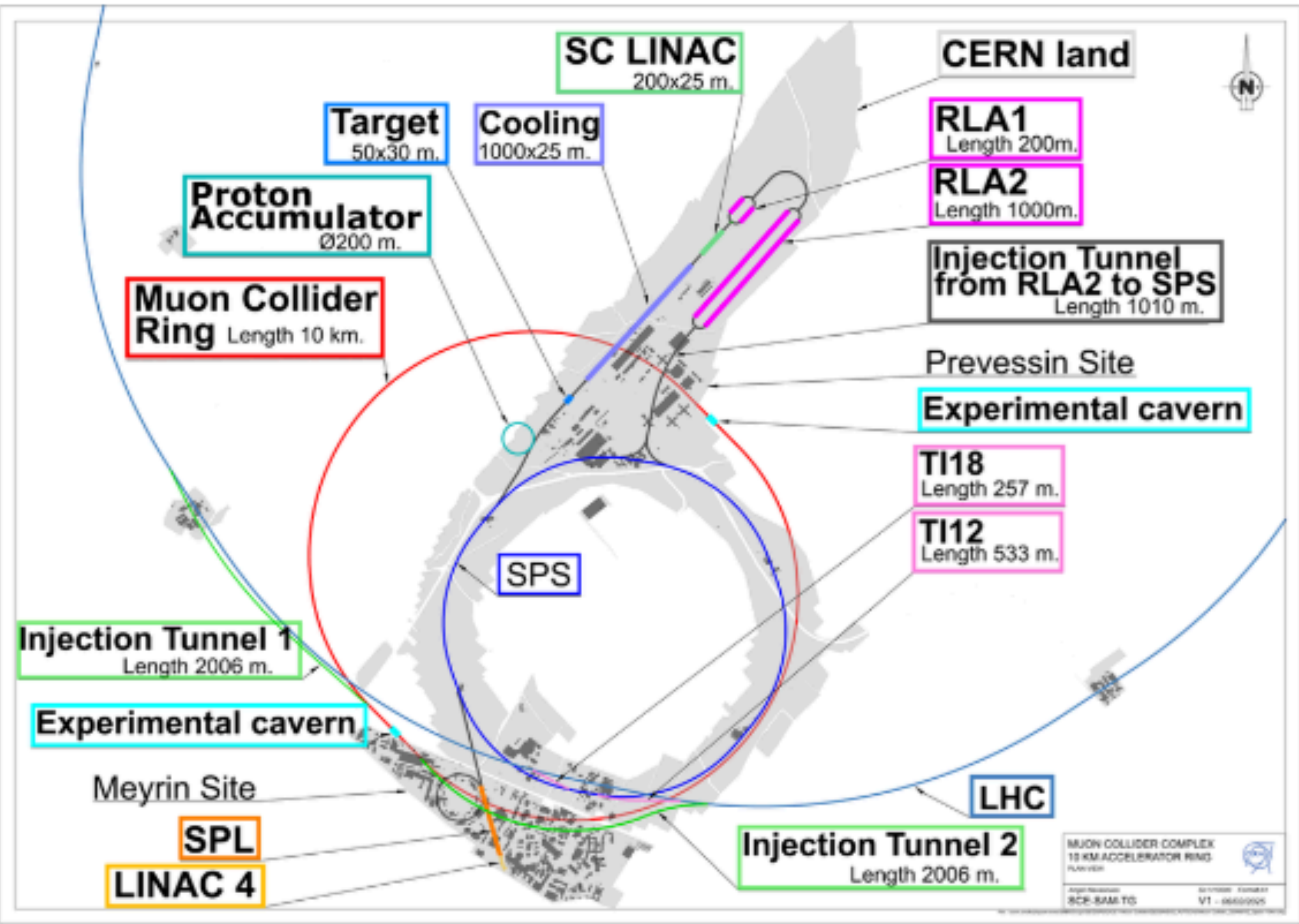
- Luminosity increases with center-mass energy
    - Competitive with LINACs
    - Most 'physics-per-dollar' potential
- Heavier than electrons: less radiative losses -> Higher center mass energies
- Lepton Collider: no pile-up effects
- Rather old concept, regained interest within the post-LHC debate (Snowmass, European Strategy): possibility to have a lepton collider working at TeV scale
- Higgs Factory
    - $\sigma(\mu\mu \to H) \simeq 40000\ \sigma(ee \to H)$
- Possibility for BSM measurements

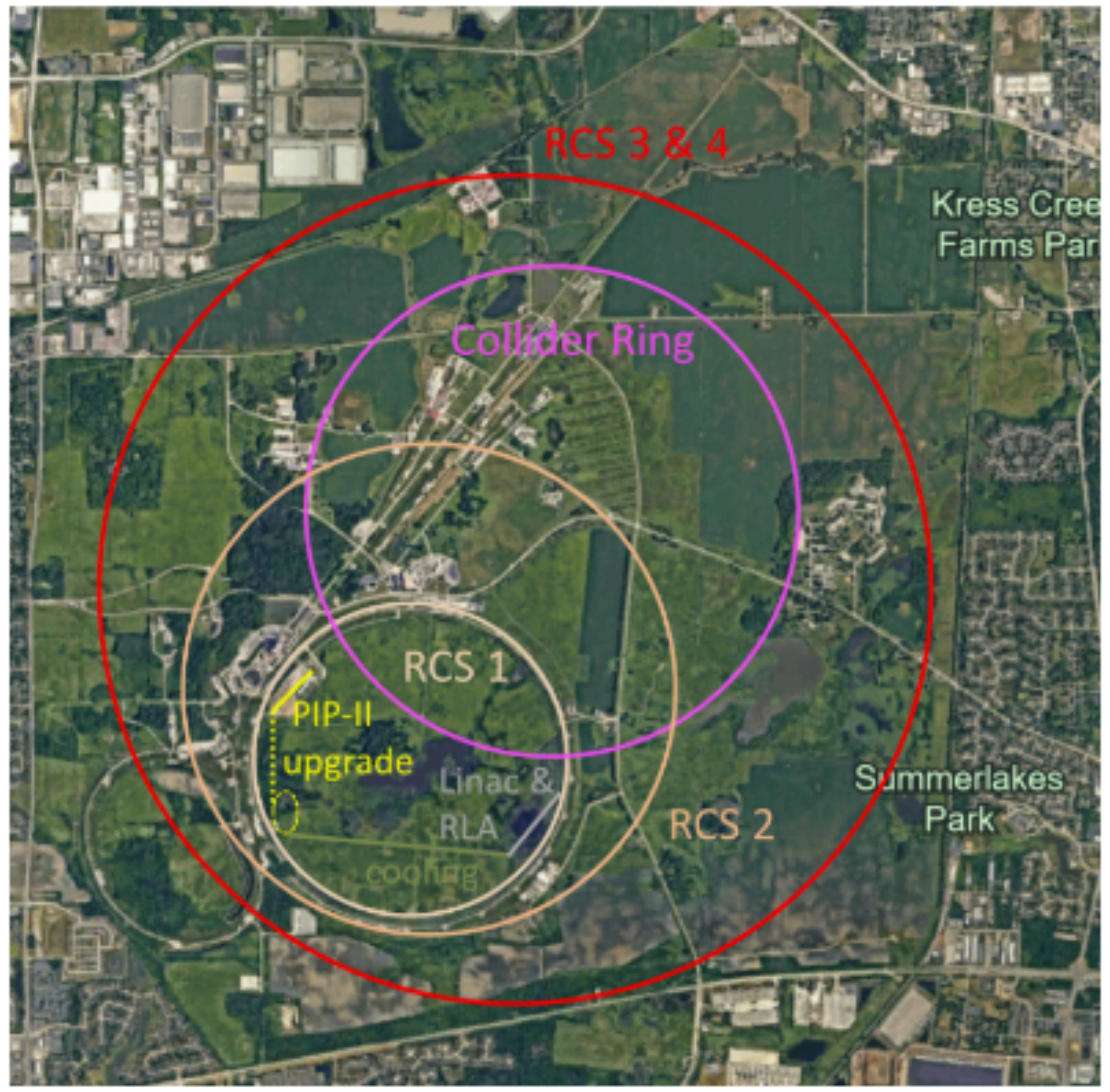


Introduction

Why a Muon Collider?

- Beamline plans for CERN(left) and Fermilab(right).
- O(10km) rings for TeV-scale collision

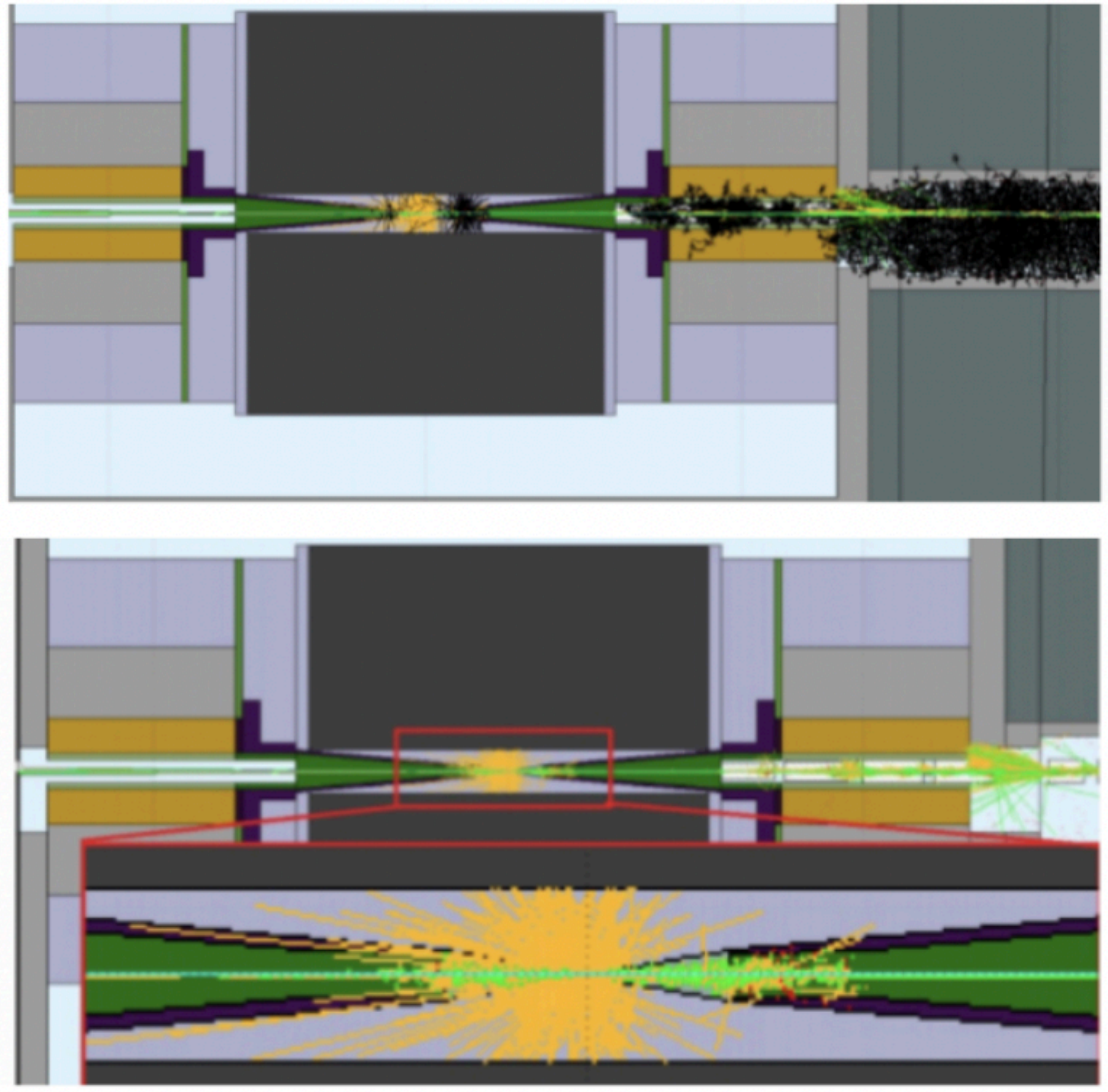




What

Summary of the problem

- Finite lifetime of the muon (2.2μs) implies a cloud of high-energy decay product along the beamline, which interferes with the instrumentation (Beam-Induced Background - BIB)
- During preliminary Machine-Detector Interface design, a double-cone nozzle has been included to shield the detector from BIB radiation

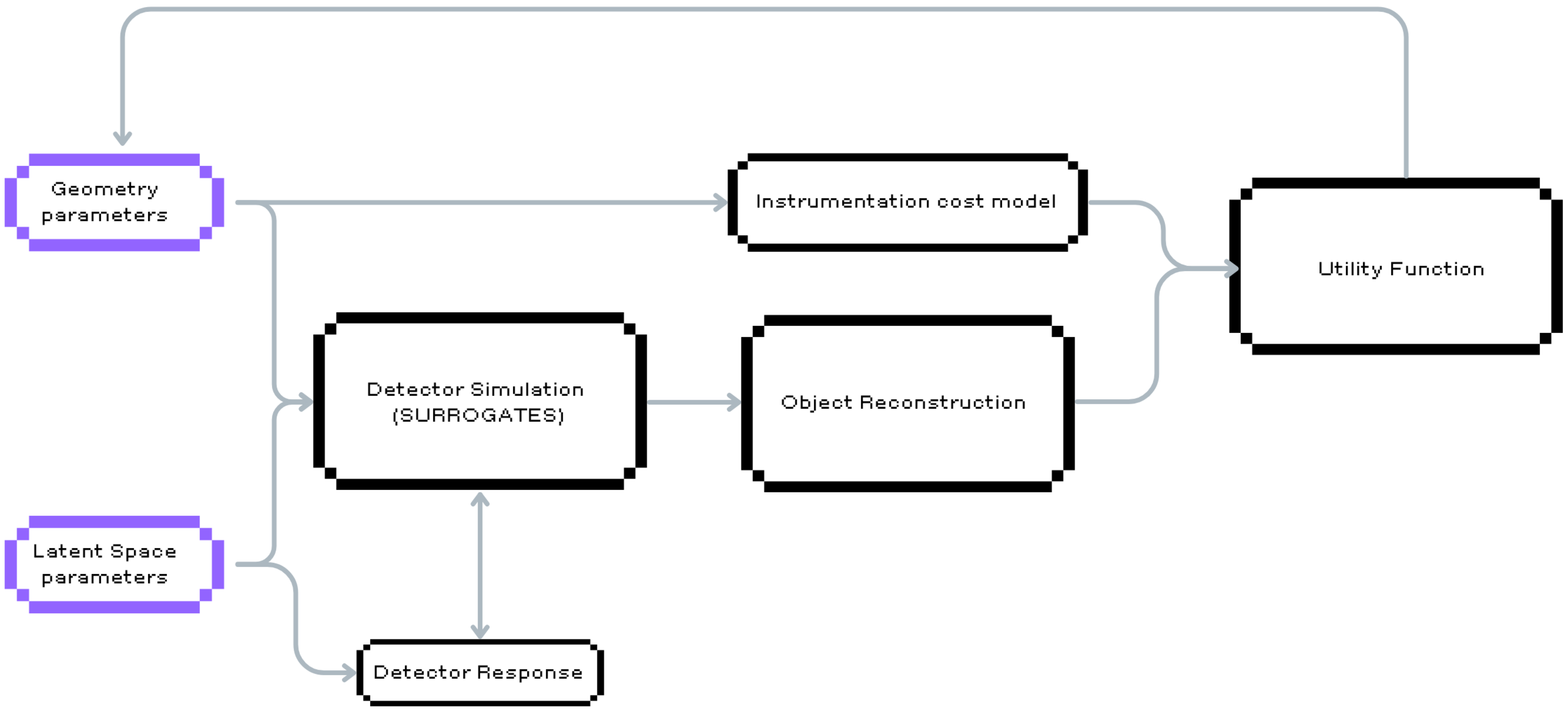


Visualizations from FLUKA BIB simulation. Black: neutrons, other: photons

What

Pipeline scheme

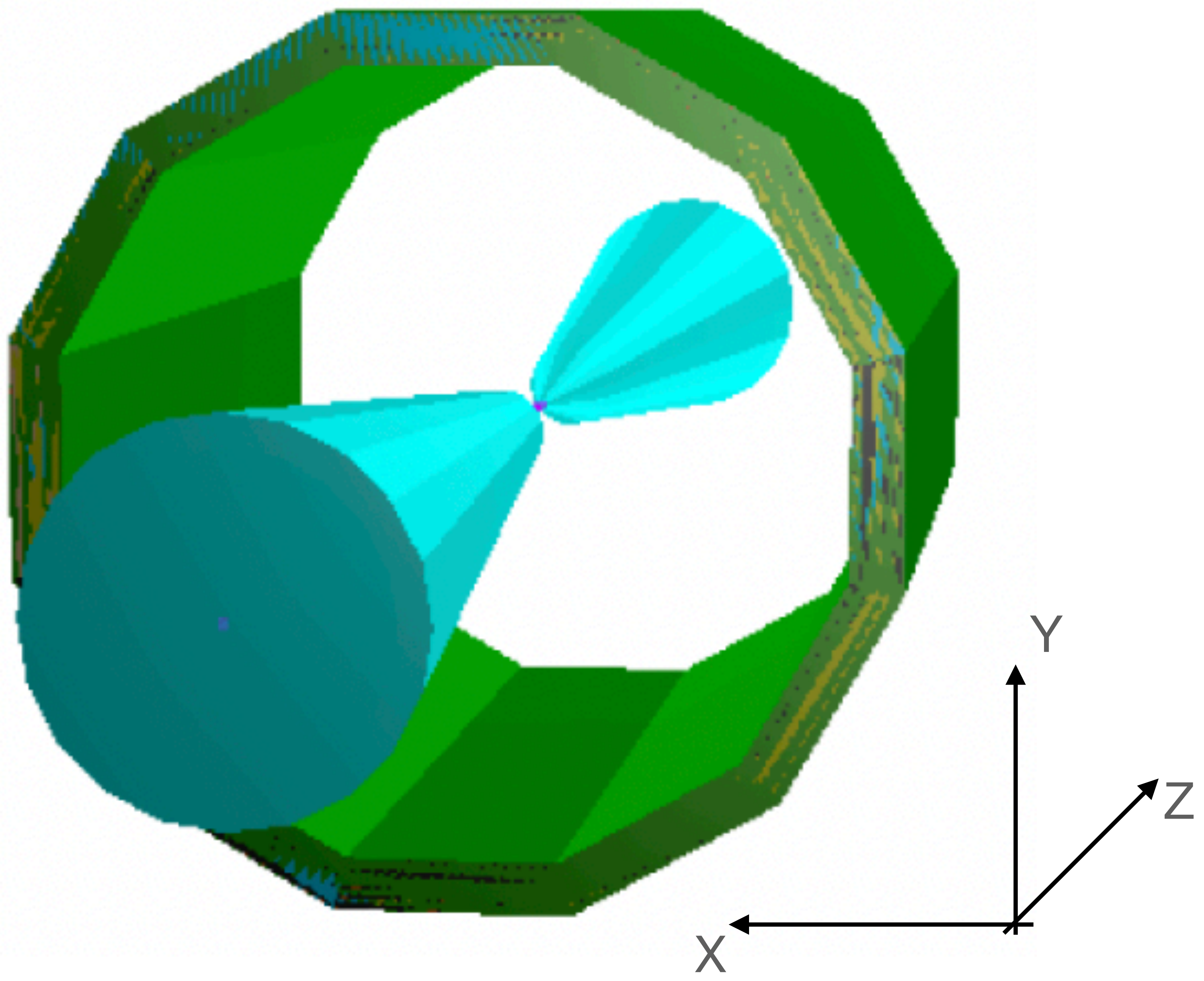
- End objective: design optimization study approached with AD techniques
- Development of a pipeline to propose an optimal configuration in terms of signal-to-background discrimination and instrumentation cost
- Use single monochromatic photons as benchmark

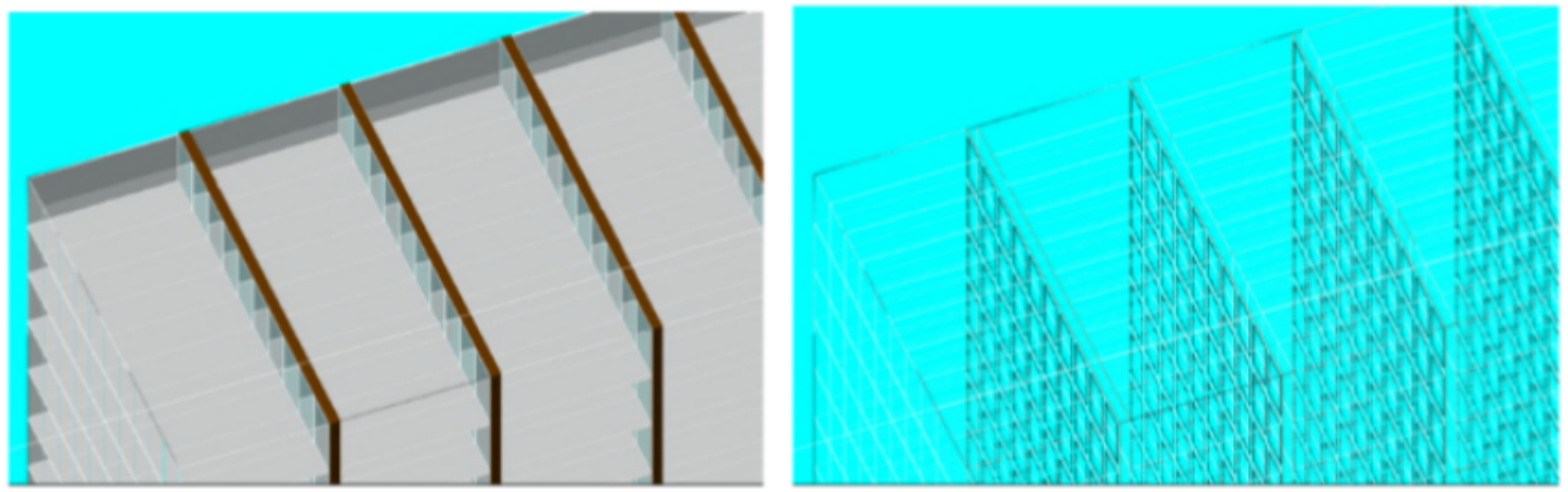


What

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 dodecagonal prism
- 5 layers per wedge
- Modular design, easy to modify and rearrange

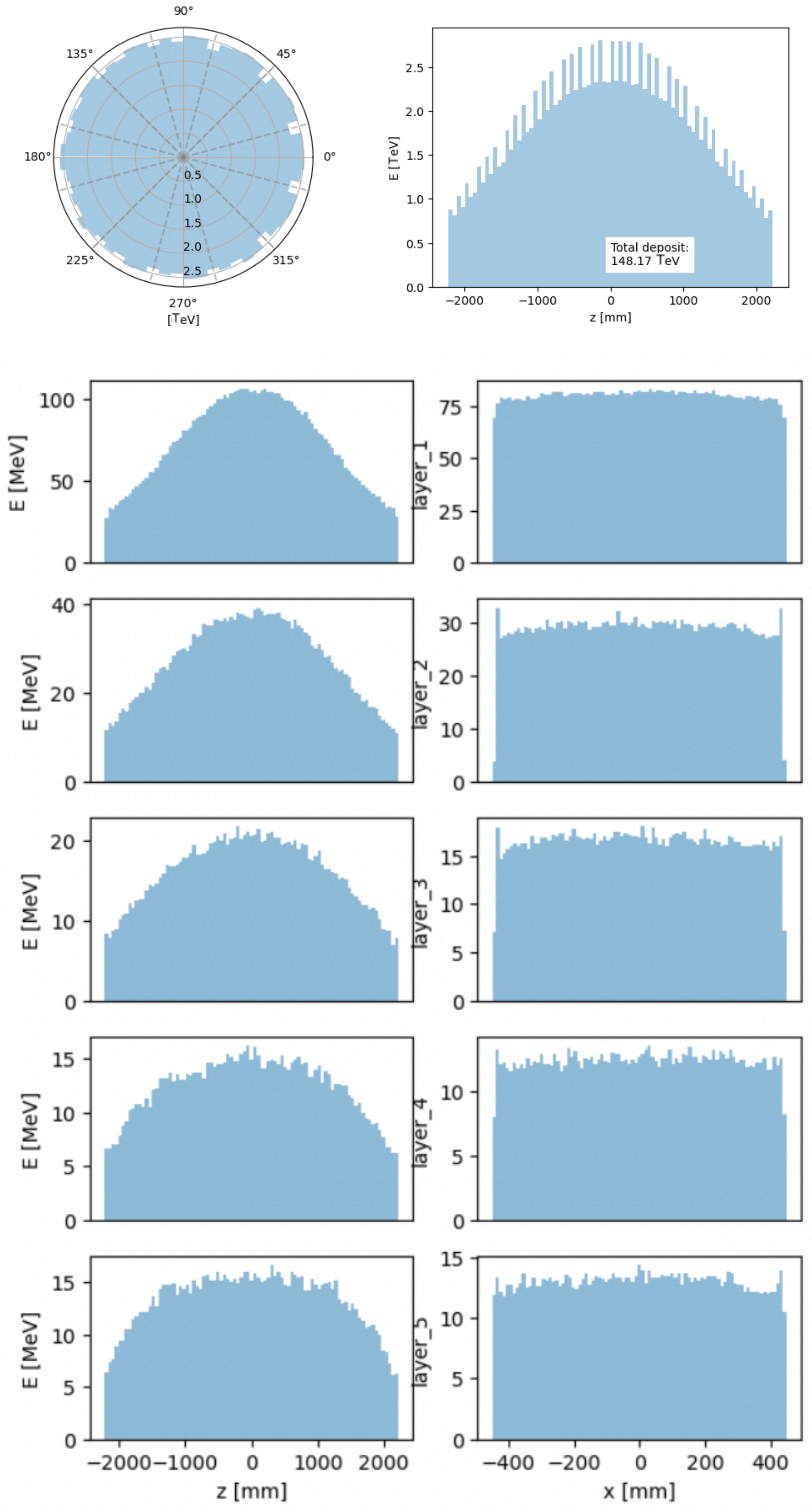




Modules

BIB Generation

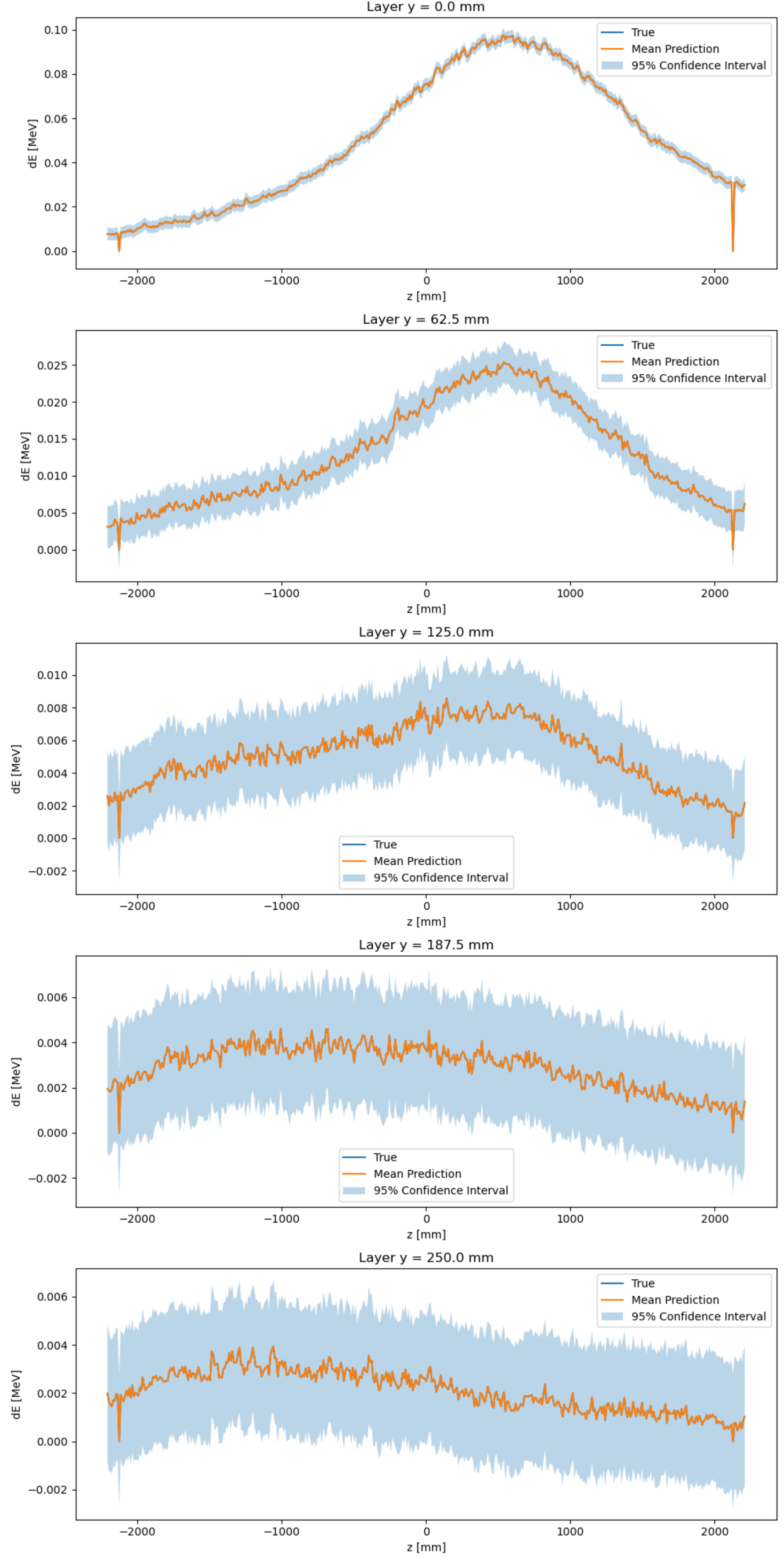
- Starting from a 750GeV FLUKA beam simulation, fed to a Geant4 detector model.
- Muon decays within 5m from interaction point
- Symmetrized to simulate contributions from both sides
- Cylindrical symmetry allows to limit the problem to a single wedge



Modules

BIB Generation

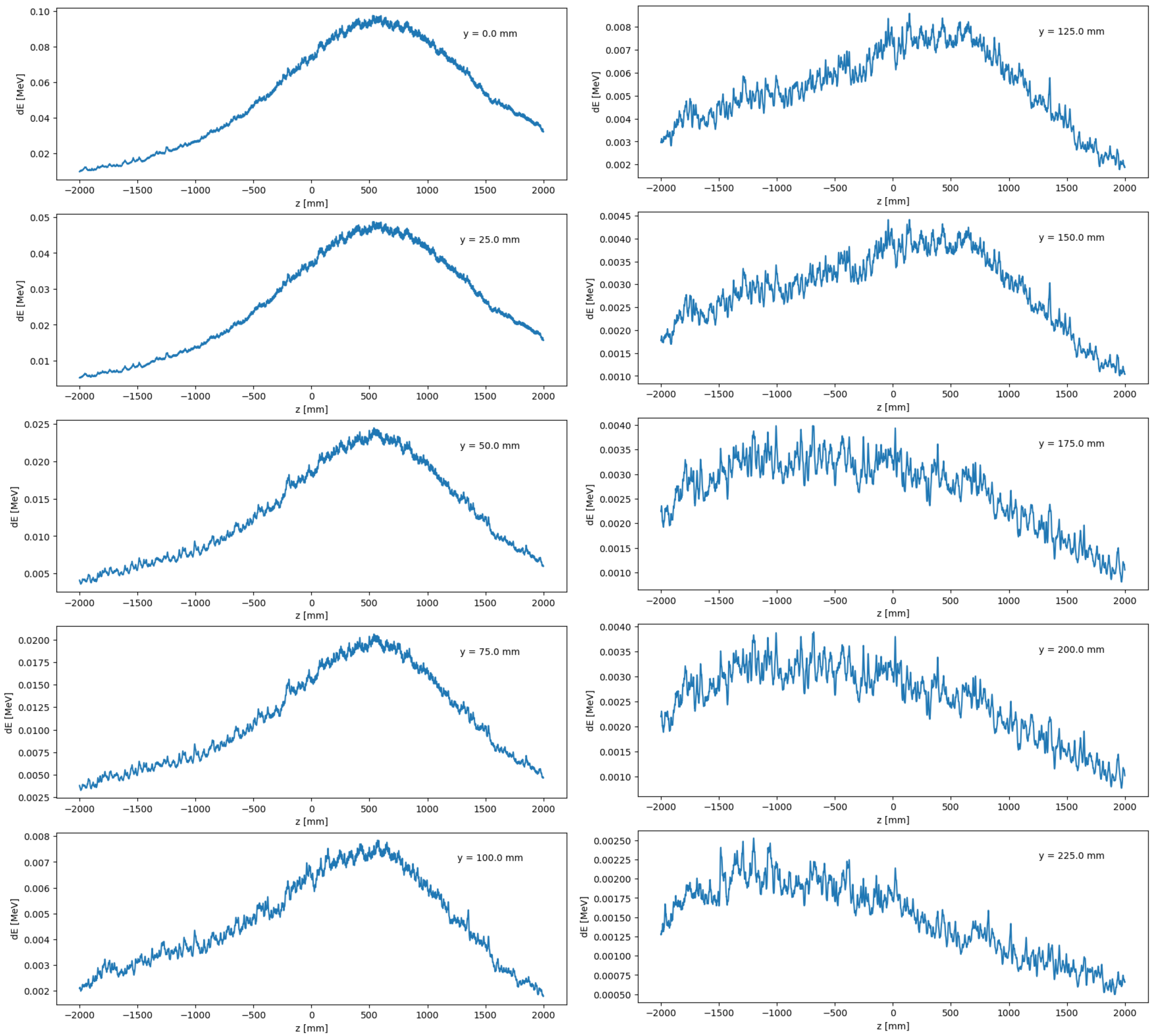
- Model the BIB flux across the 5 layers by training a Gaussian Process
- Predicts BIB energy density given a (z,y) coordinate pair - uniform along the x direction
- Main motivation for a GP is ability to interpolate between layers



Modules

BIB Generation

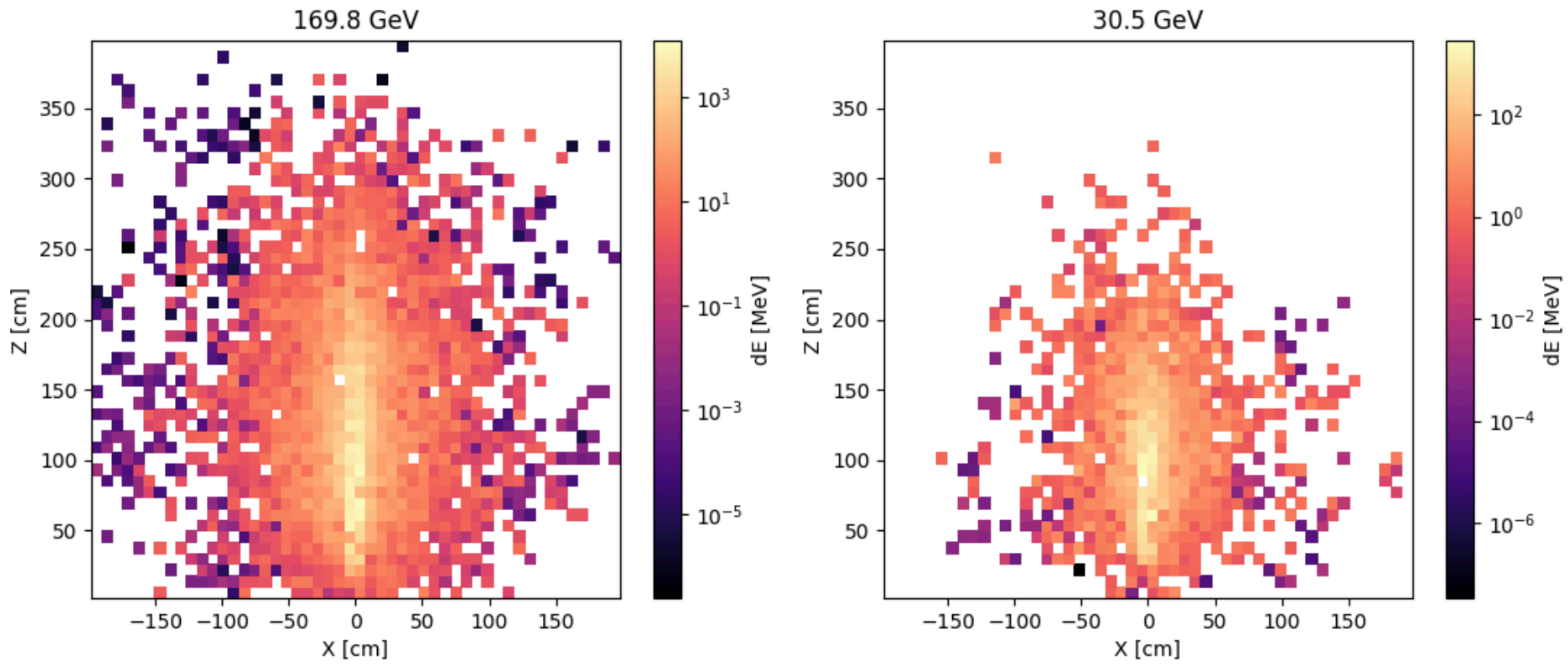
- Simulation is heavy (O(TB) for single event), and does not provide information on intra-layer BIB depositions
- Validation: total deposit on the detection area matches simulation
- Shapes and magnitudes are reasonable, allows us to work



Modules

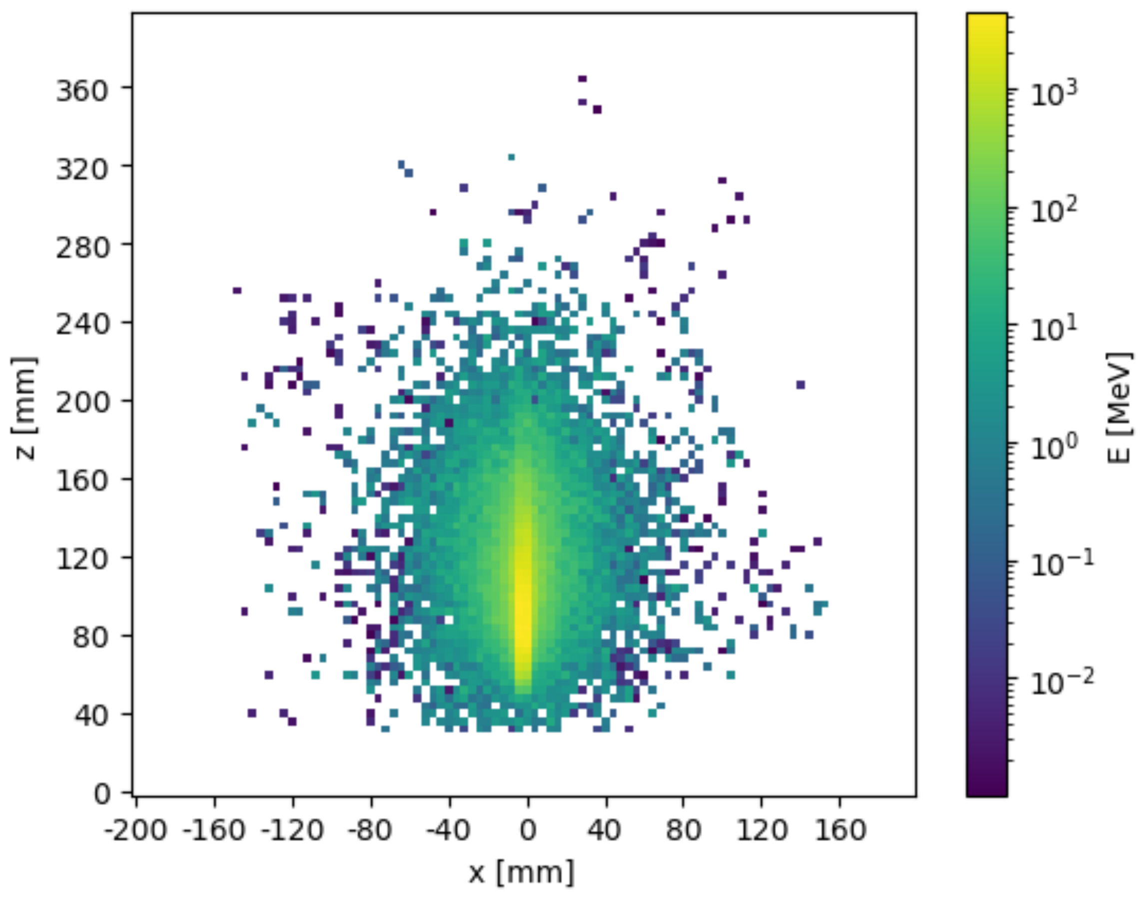
Shower Generation

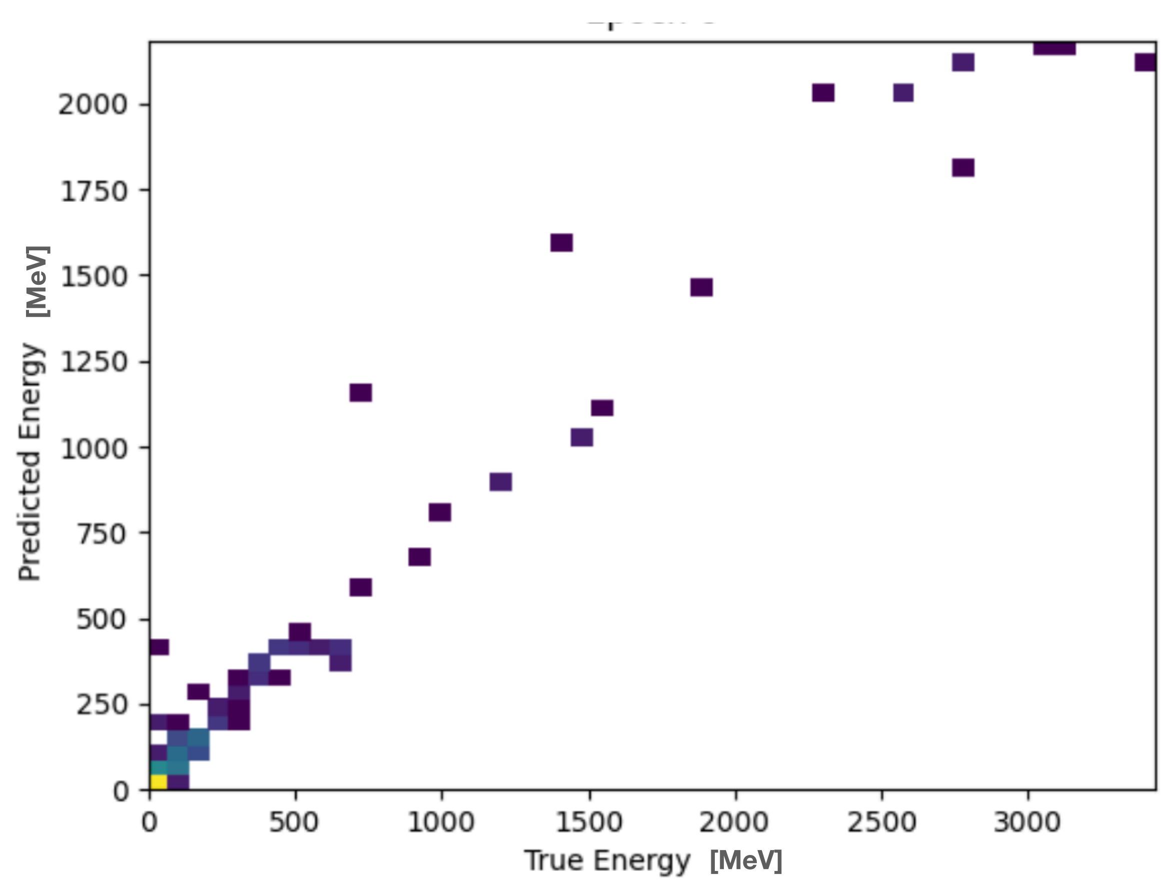
- For signal events we chose single monochromatic photons, energy uniformly distributed in [10,175]GeV.
- Use Geant4 to produce a dataset of 10k photons entering orthogonally in a PbF2 block.
- Saved as 2D images



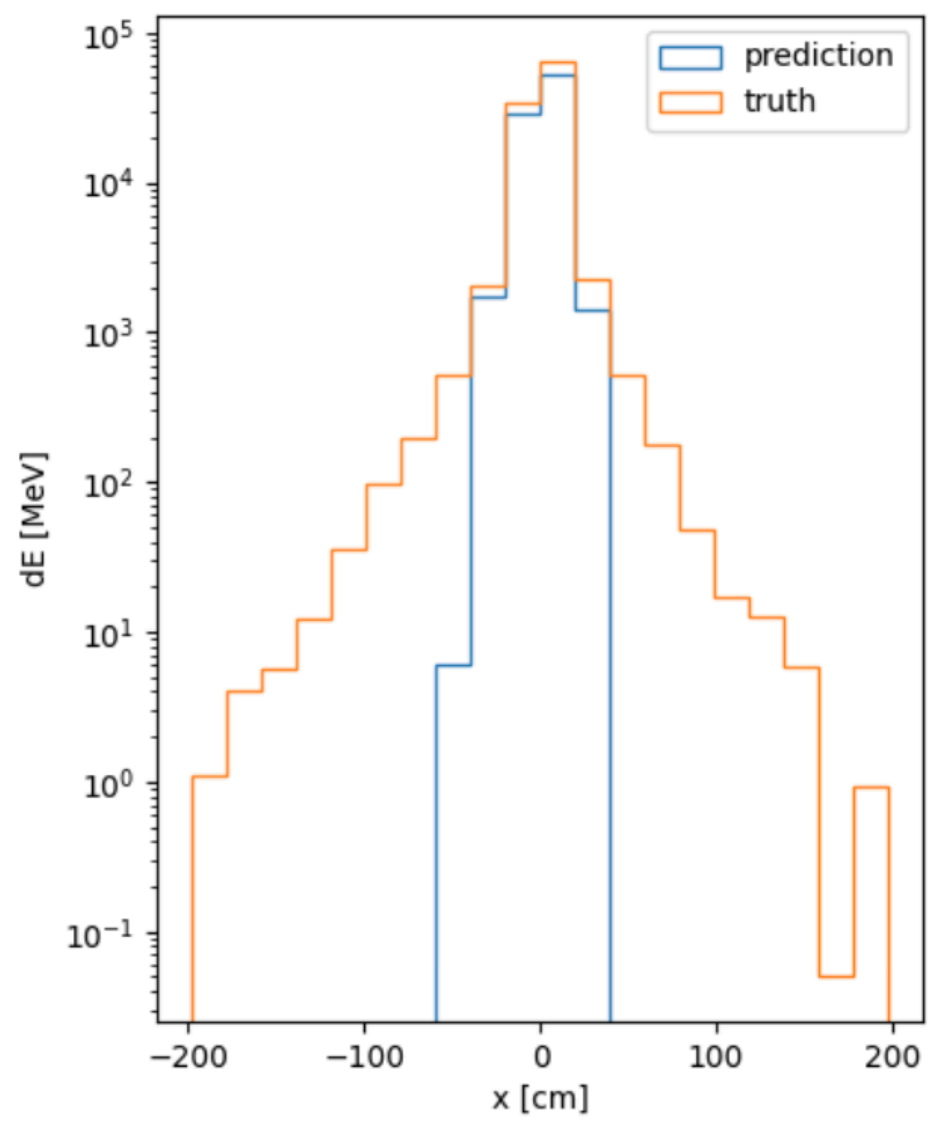
Modules

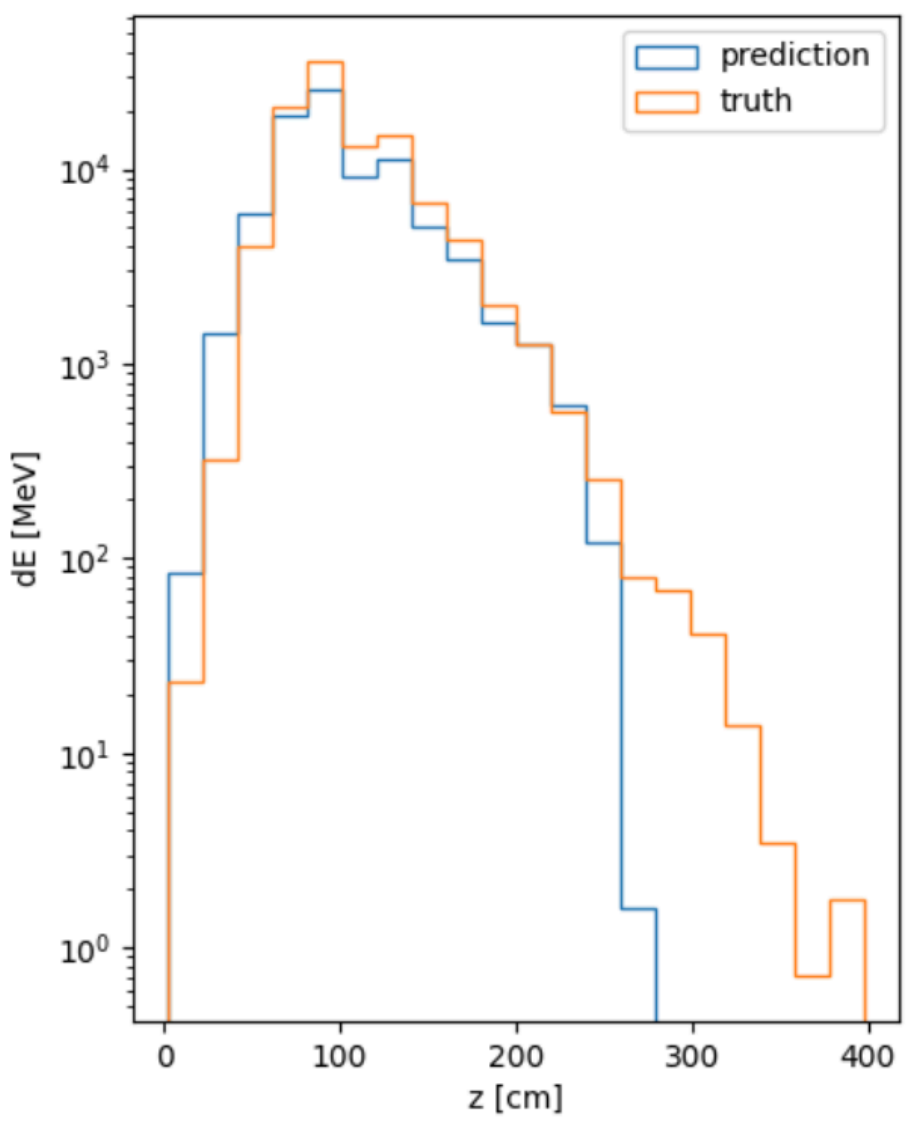
Shower Generation





- Use the dataset to train a simple GravNet-based GNN to generate photon showers given an input energy.
- Not extremely precise, but
  - Fast
  - Describes well enough shower bulk
  - Total deposit matches the target
- To be patched with conditional DDPM (Denoising Diffusion Models). See Xuan Tung's talk at this year's MODE workshop (https://indico.cern.ch/event/1481852/contributions/6464894/)

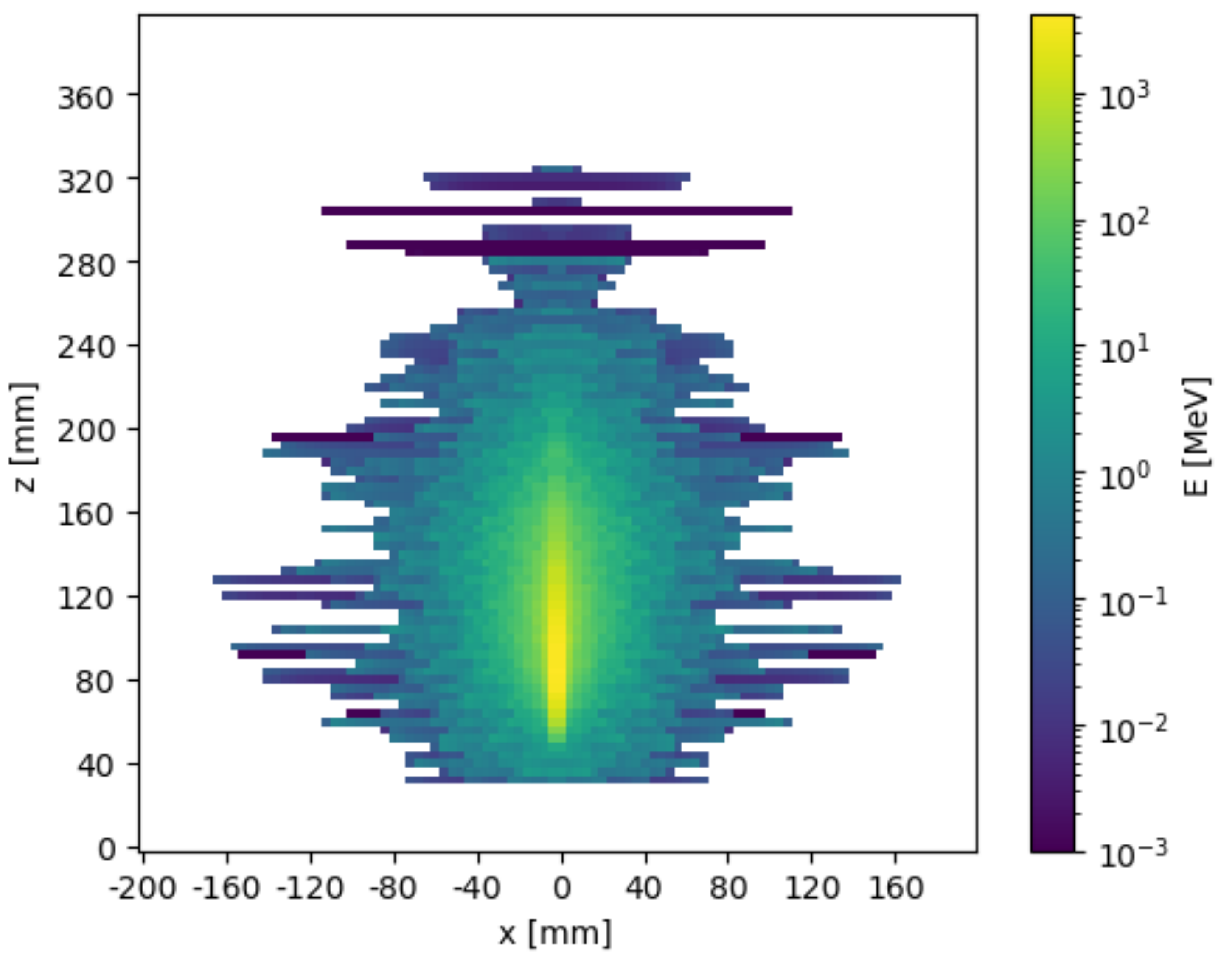


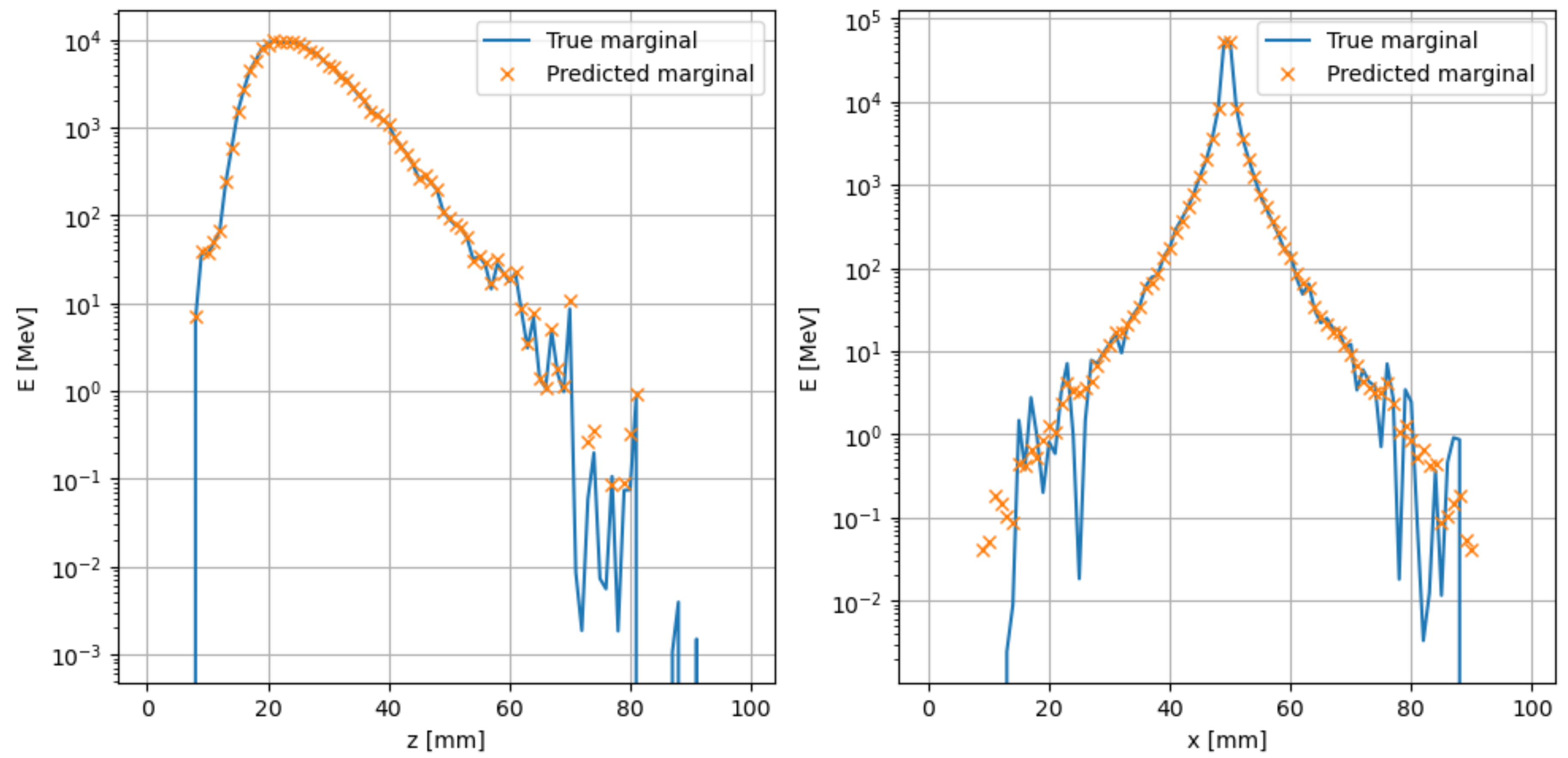


Modules

Shower Generation

- To reconstruct the 3D shower shape from a marginal distribution we set up a minimal chi2 regressor
- Enforce cylindrical symmetry by introducing a numerical Jacobian modulating inferred 3D deposits
- X- and Z-marginals match the original distribution





Modules

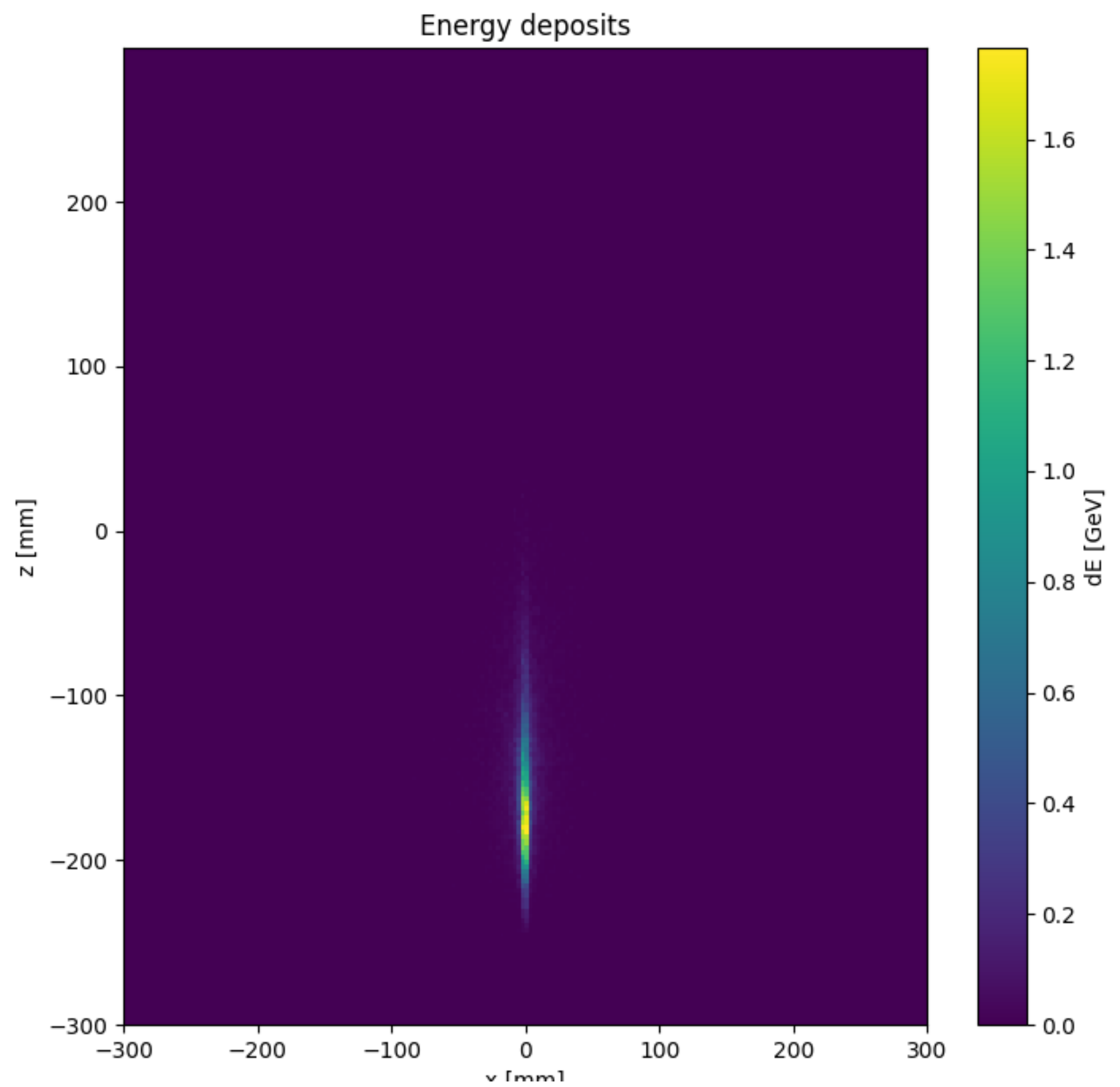
Shower Generation

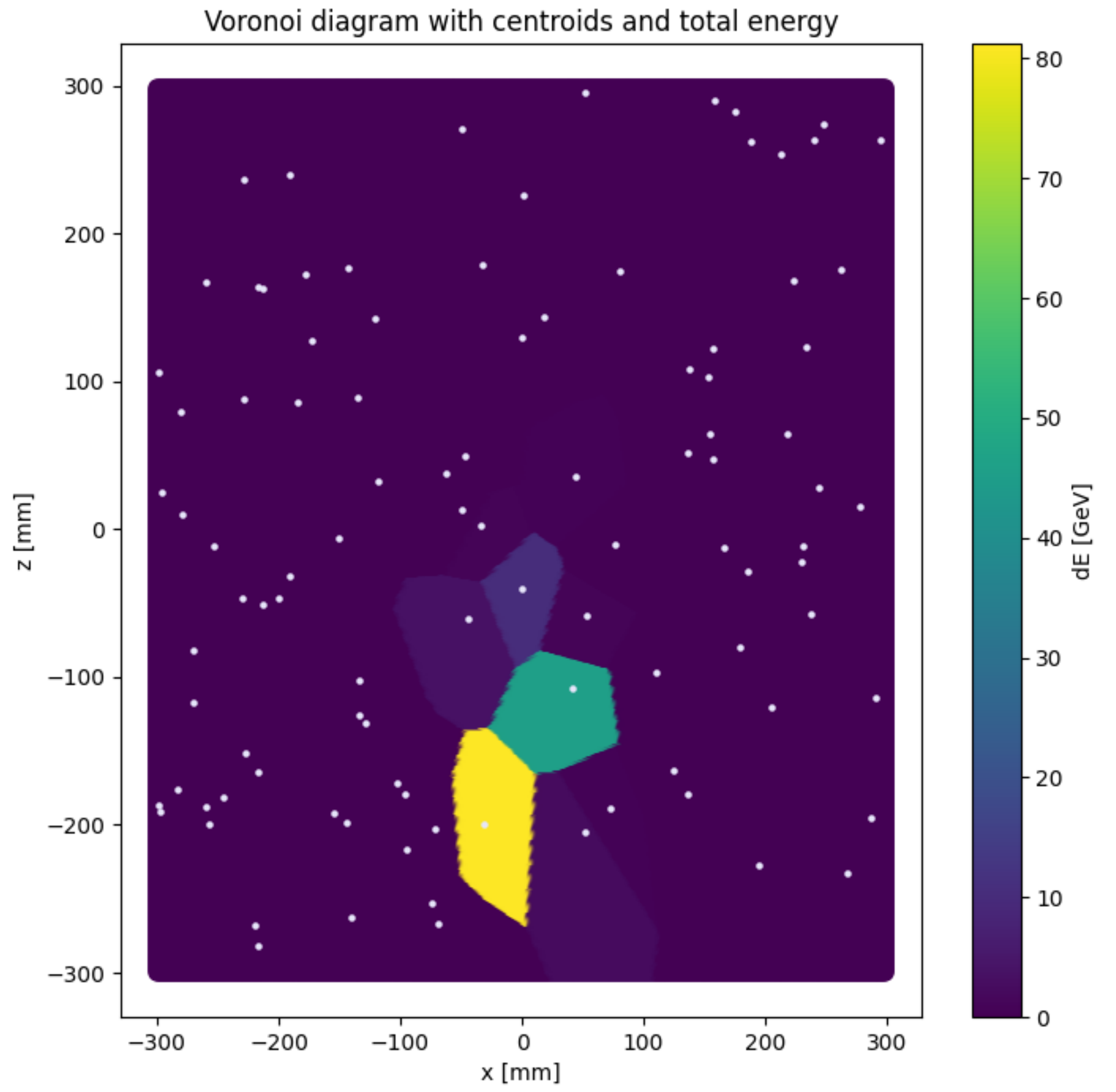
- Looking at slices of the simulated volume, shower features and symmetries are respected
- Cylindrical symmetry is correctly restored

Modules

Voxels and Event overlay

- Voxel structure is encoded through Voronoi regions identified by the voxel centers.
  - Boundaries defined as median planes between centers
- Objective is using centers as free parameters and thus optimize voxel location and extension
- In a (800x800x200)mm3 volume

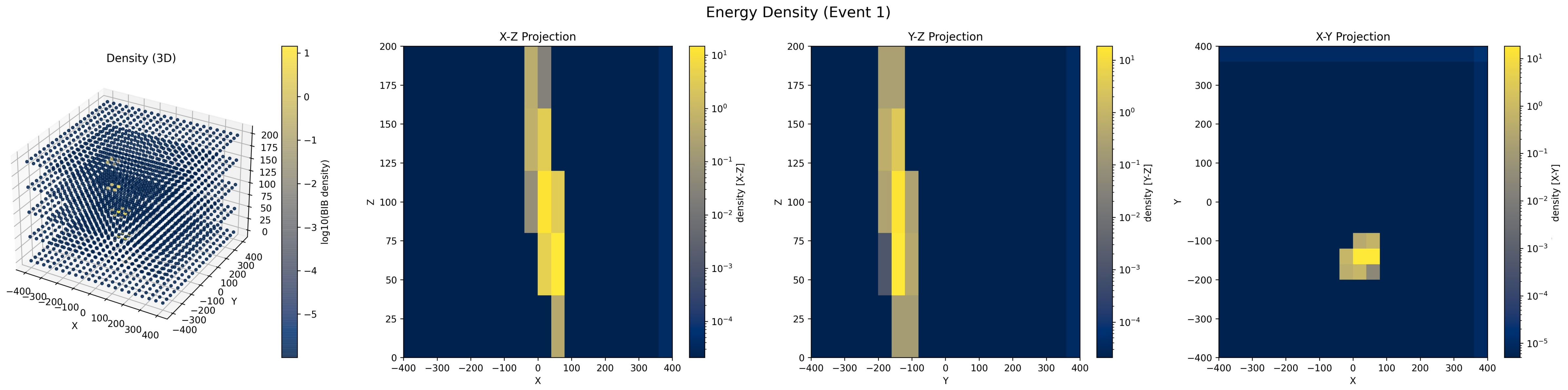


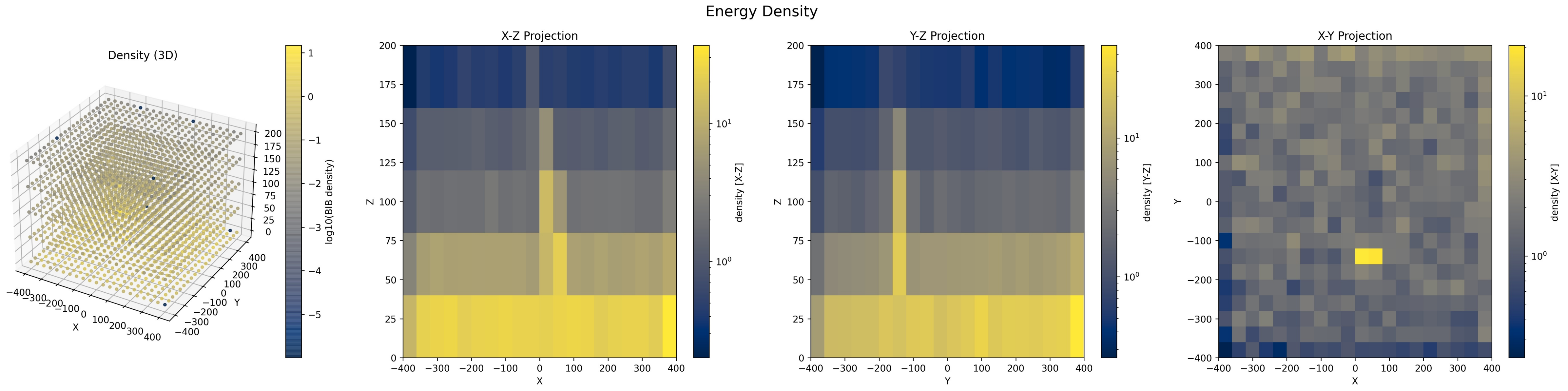


Modules

Voxels and Event overlay

- 3D generated shower is randomized and assigned to Voronoi voxel
  - Rotated: ϕ~[0,30]deg θ~[0,360]deg
  - Entrance point randomly selected in a 20cm cube of base plane
- BIB density evaluated at voxel center, and scaled by voxel volume



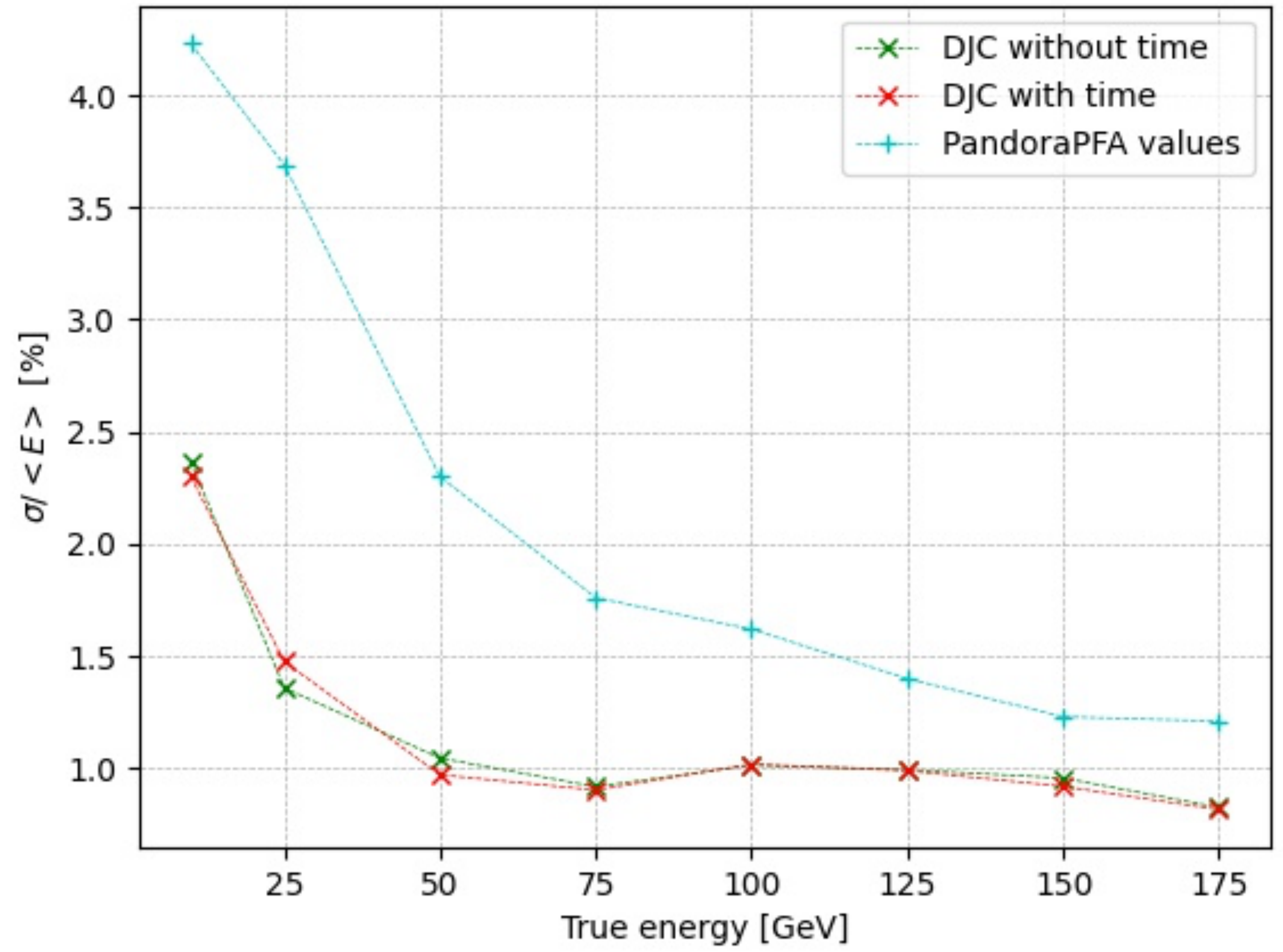


Modules

Reconstruction

https://arxiv.org/abs/2204.01681

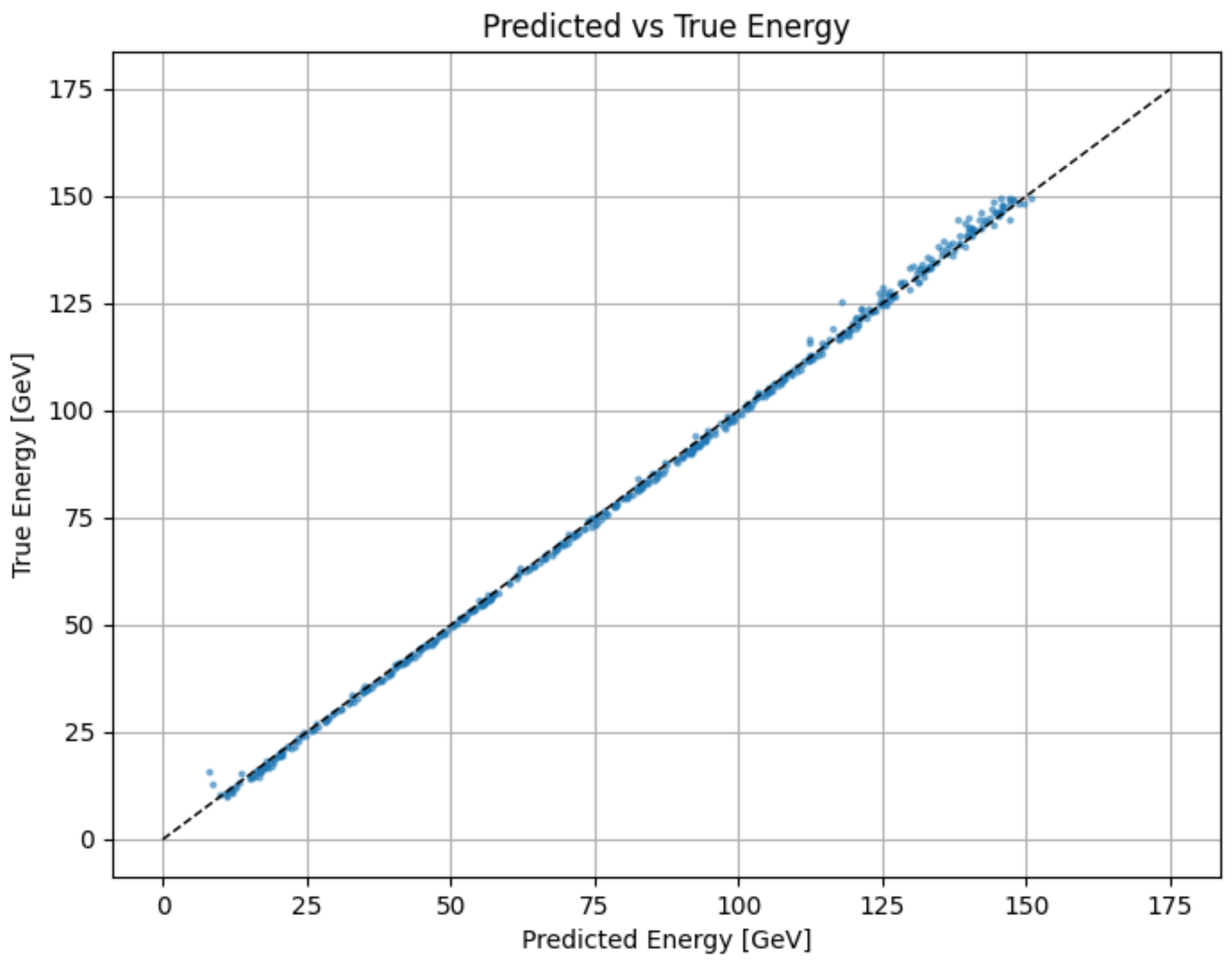
- Employed DeepJetCore for object reconstruction:
    - Signal photon vs BIB discrimination
    - Trained on 10k photons uniformly distributed in [10, 175]GeV
    - Tested on 8 fixed energy points
- Both signal and BIB overlayed from Geant4 simulations
    - Similar performance wrt collaboration framework on full BIB dataset
    - Significant improvement if we apply the same time window cut [-250,250]ps



Modules

Reconstruction

- With our framework clustering is trivial (only one cluster by definition)
- Kept the same architecture, adapted to simply regress a signal fraction associated to each cell deposit
- Trained on 10k events, generated with the developed surrogates on randomized centroid configuration (gaussian sampling centered at regular grid points, std the original cell dimension)
- Very good reconstruction performance, stable throughout different configurations



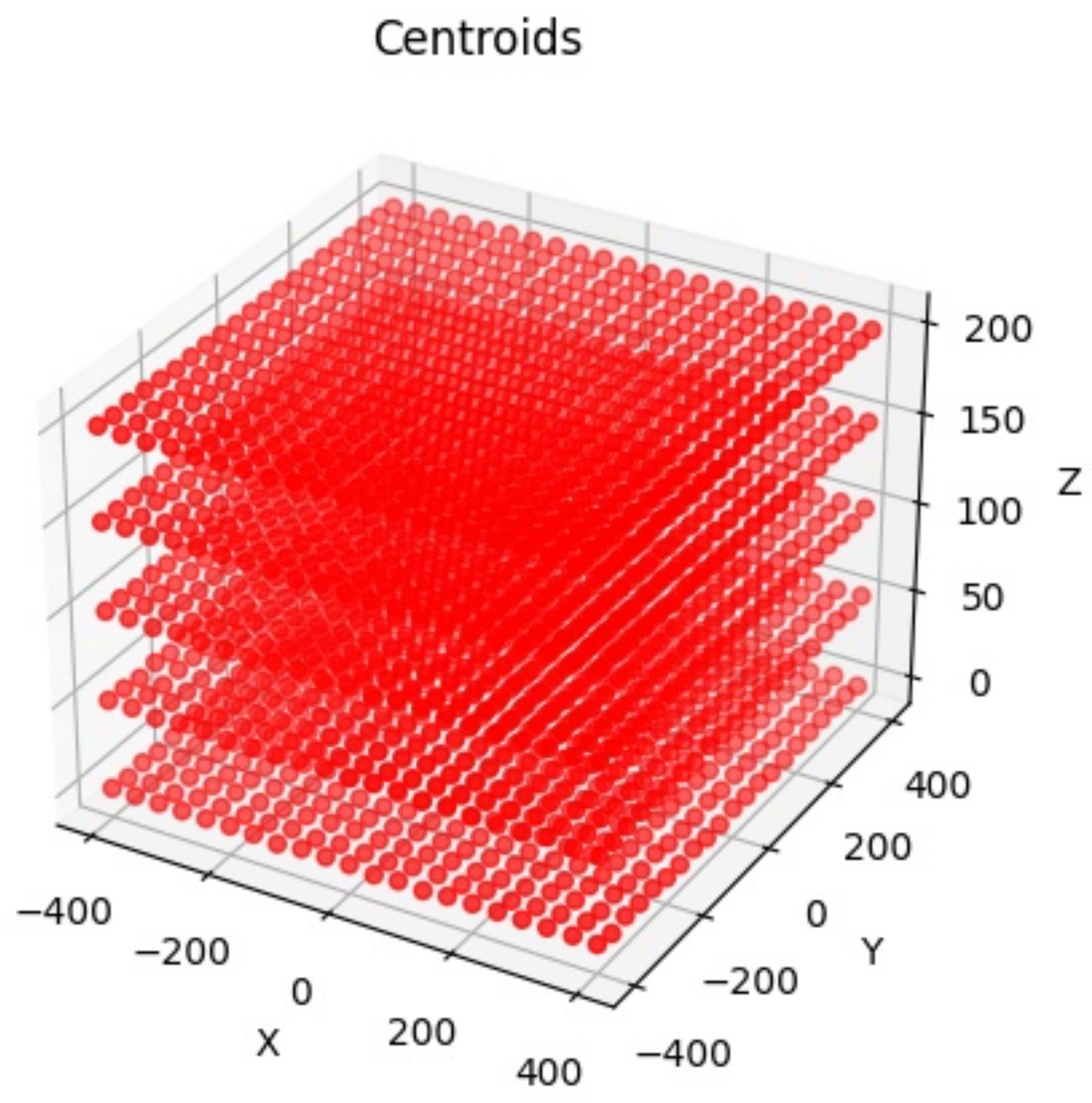
Testing the Pipeline

First run setup

- Defined a basic utility function as energy reconstruction resolution $\mathscr{L} := \frac{|E_{pred} - E_{true}|}{E_{true}}$

- Used initial configuration that mocks the original calorimeter design (4x4x5)cm cells in a 40x40x20cm3 volume (Limited by GPU memory)

- Launched an optimization cycle over 300 epochs with linearly decaying learning rate (1.->0.1)



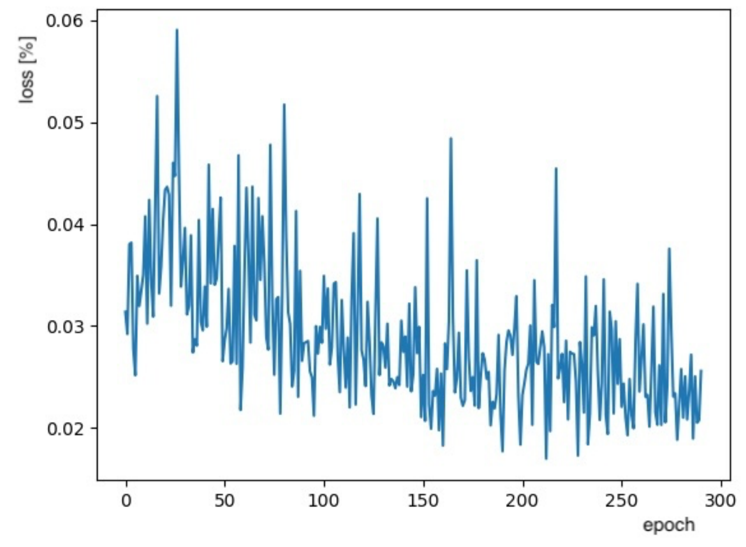
Testing the pipeline

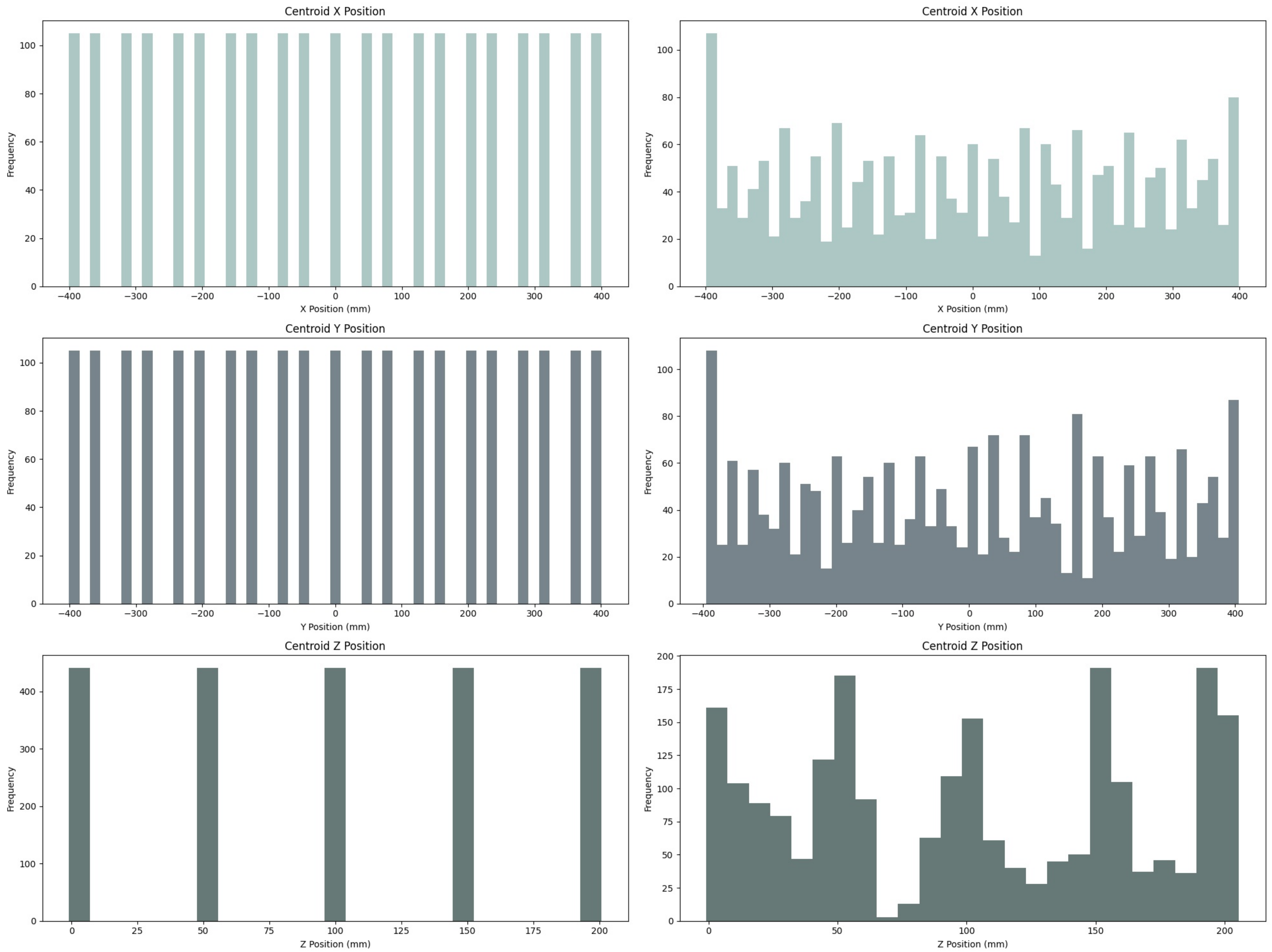
First run Results

- Good news: pipeline works, gradients flow through and loss diminishes

- Still extremely noisy: Reconstruction solid enough to properly reconstruct photons, although we have already a small gain

- Can draw first considerations on how voxels diffuse



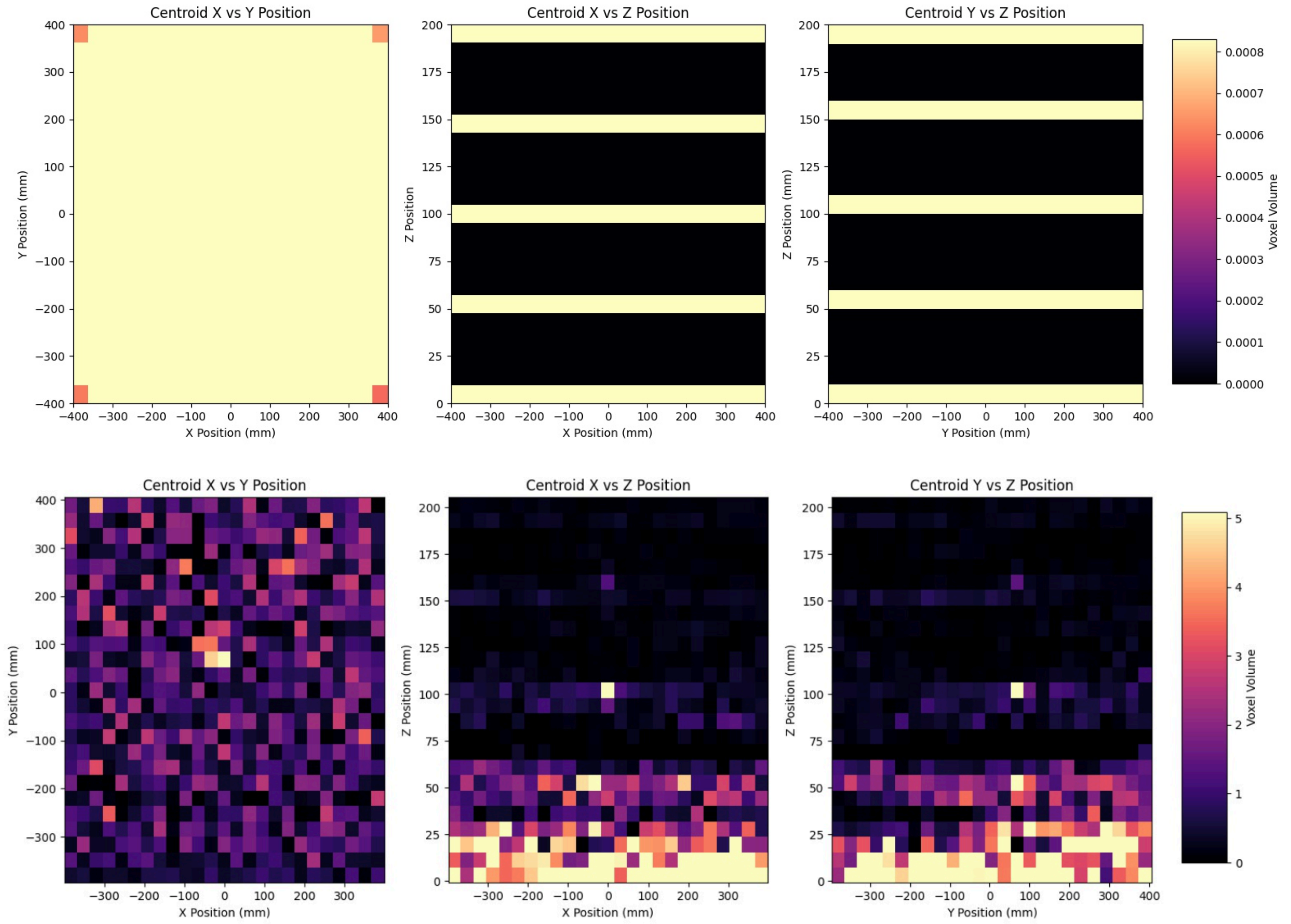


Testing the pipeline

First run Results

- Looking at volume maps, voxels on the bottom block tend to diffuse upwards
- Left with less, broader cells in the lower region
- There most information is lost due to BIB. Lower cells can play also as absorbers, increasing granularity on the layers above to collect information where signal is clearer.

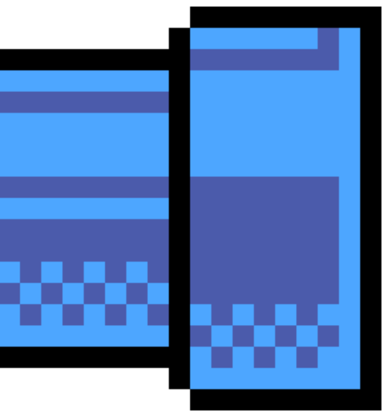
Note: not same scale, max of top plot is normalized to 1



Wrap up

Summary and conclusions

- Presented a **proof-of-concept** for a SGD-based optimization pipeline. Results are still preliminary, but provide a starting point for more realistic studies
- **Surrogate** models provide fast, differentiable tools for event simulation
- Solid reconstruction performance, allows for more complicated utility definition. Explore multi-target functions, discussing with collaboration and encoding **geometrical** limitations and preferences. Implementation of **position** reconstruction as well.



Thank you!

Backup

2D image to 3D shower

Chi2 regressor

Algorithm 2 Reconstruction of 3D Energy Distribution from a Marginal using Cylindrical Symmetry

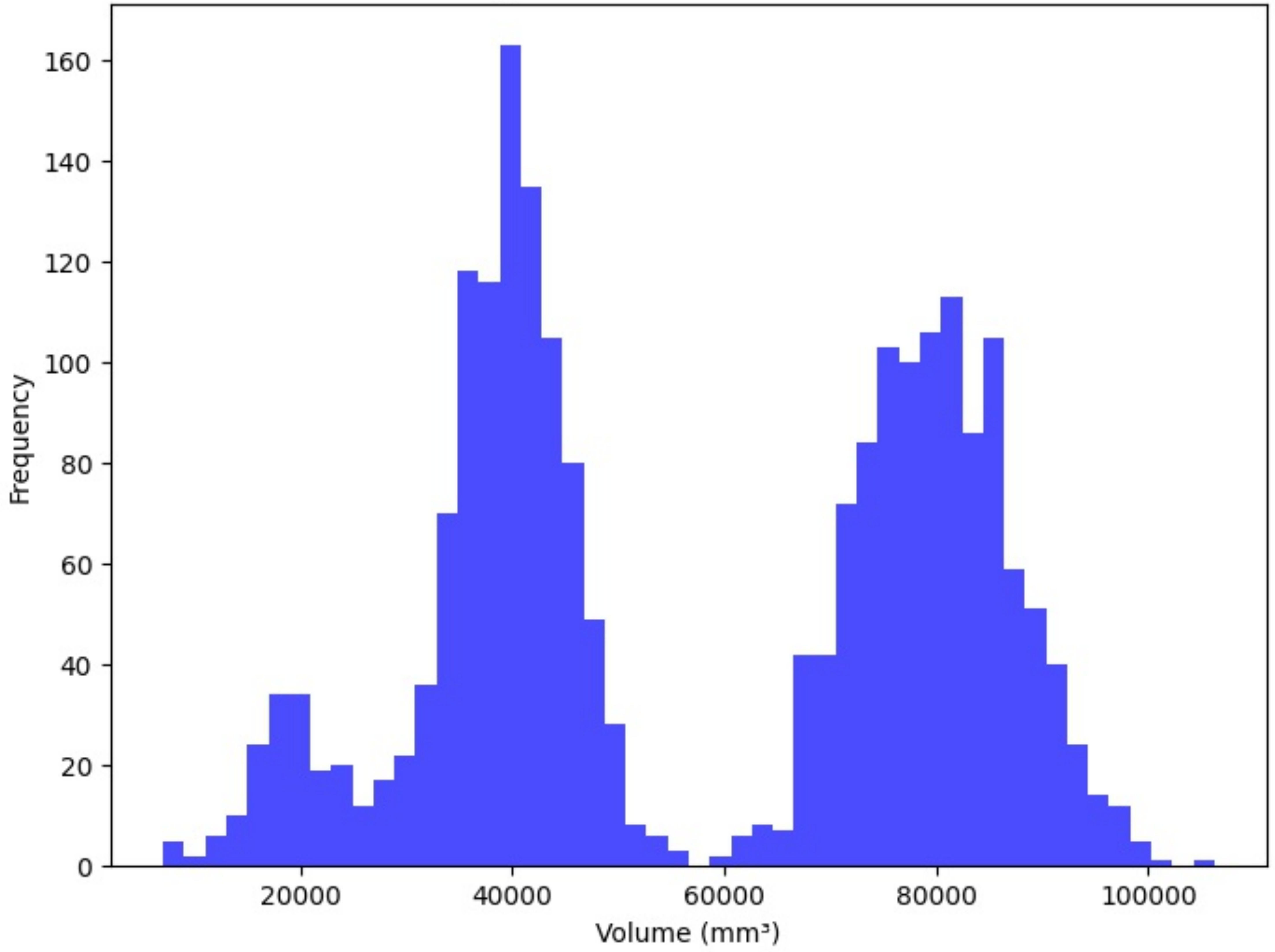
Input: Target marginal image $f_Y(x,z) \in \mathbb{R}^{n \times m}$
Output: Predicted 3D distribution $E(x,y,z) \in \mathbb{R}^{n \times m \times p}$

1: **procedure** InflateShower(f_Y)
2: Precompute cylindrical ring fractions f via uniform sampling
3: Initialize density tensor ρ as trainable variable
4: **for** $t = 1$ to T (training steps) **do**
5: Compute predicted marginal: $\hat{f}_{Y\,i,j} = \sum_k \sum_m \sum_l f_{ijkl}\, \rho_{lm}$
6: Compute loss: $L = \sum_{ij} \left(\hat{f}_{Y\,ij} - I_{ij}\right)^2.$
7: Update ρ using Adam optimizer and gradients from L
8: Enforce physicality: $\rho \leftarrow \max\{\rho, 0\}$
9: **end for**
10: Reconstruct full 3D energy volume: $E_{ijk} = \sum_m \sum_l f_{ijkl}\, \rho_{lm}$
11: **return** E
12: **end procedure**

Voxel volume estimation

Monte-Carlo sampling for Voronoi volumes

- Voxel volumes are estimated through Monte Carlo sampling
- Draw 200k points over detection volume
- Assign each to the closest voxel center
- At initial configuration 3 type of voxels, depending on whether they occupy a central, edge or corner position



Muon Collider details

Muon production beamline

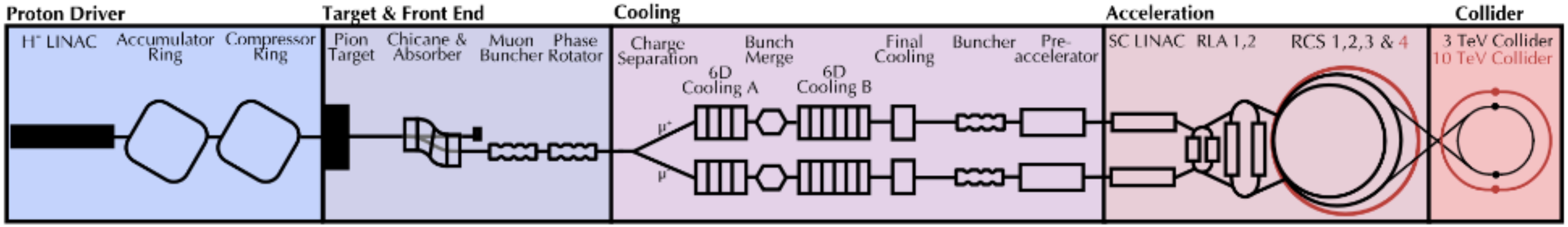


Figure 3.2: Schematic layout of the Muon Collider system. From [96]

Muon Collider details

Envisioned timeline

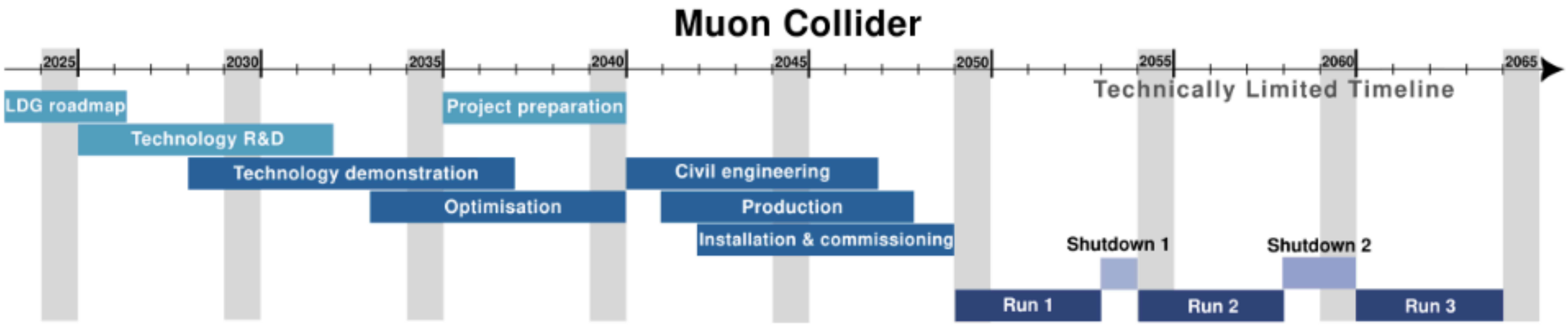


Figure 3.1: Proposed R&D and construction milestones needed to enable a first 3 TeV stage by 2050, assuming a successful demonstration of cooling, magnets, and detectors

Muon Collider details

Target parameters

- Scenario 1: Energy staging. First run at 3TeV, there are physics case studies, lower instrumentation cost at beginning.
- Scenario 2: luminosity staging. Less performing magnets, but already at full energy. Full cost required at beginning. Estimated factor 3 loss in luminosity

Parameter	Symbol	Unit	Scenario 1 Stage 1	Scenario 1 Stage 2	Scenario 2 Stage 1	Scenario 2 Stage 2
Center-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	10	10
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	2.1	21	5(tbc)	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_r	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\epsilon_{\parallel}$	eV	0.025	0.025	0.025	0.025
RMS transverse emittance	$\epsilon_{\perp}$	μm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP beta function	β	mm	5	1.5	tbc	1.5
IP beam stile	σ	μm	3	0.9	tbc	0.9
Protons on target/bunch	N_p	10^{14}	5	5	5	5
Proton energy in target	E_p	GeV	5	5	5	5

Table 3.1: Tentative target parameters for a Muon Collider at different energies.