Towards the optimization of a Muon Collider Calorimeter

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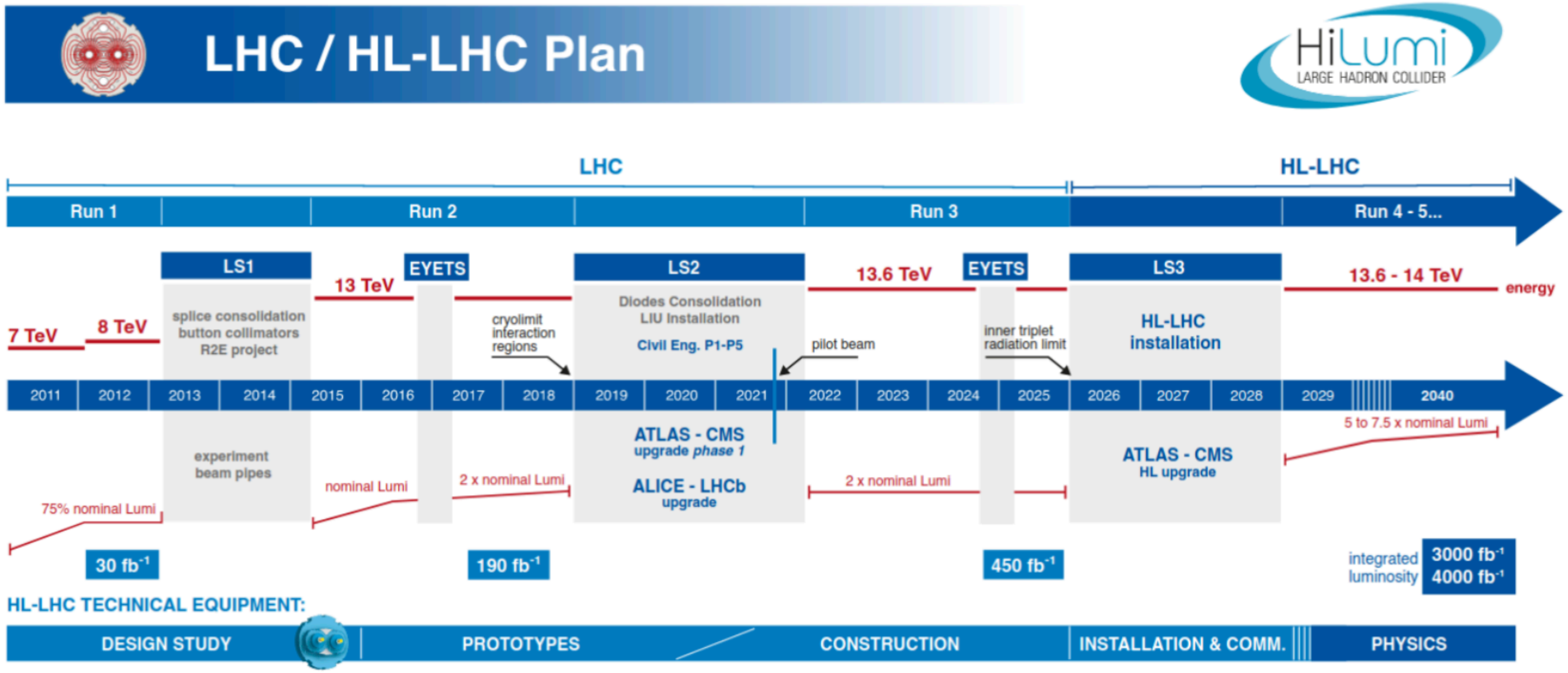
Muon Collider

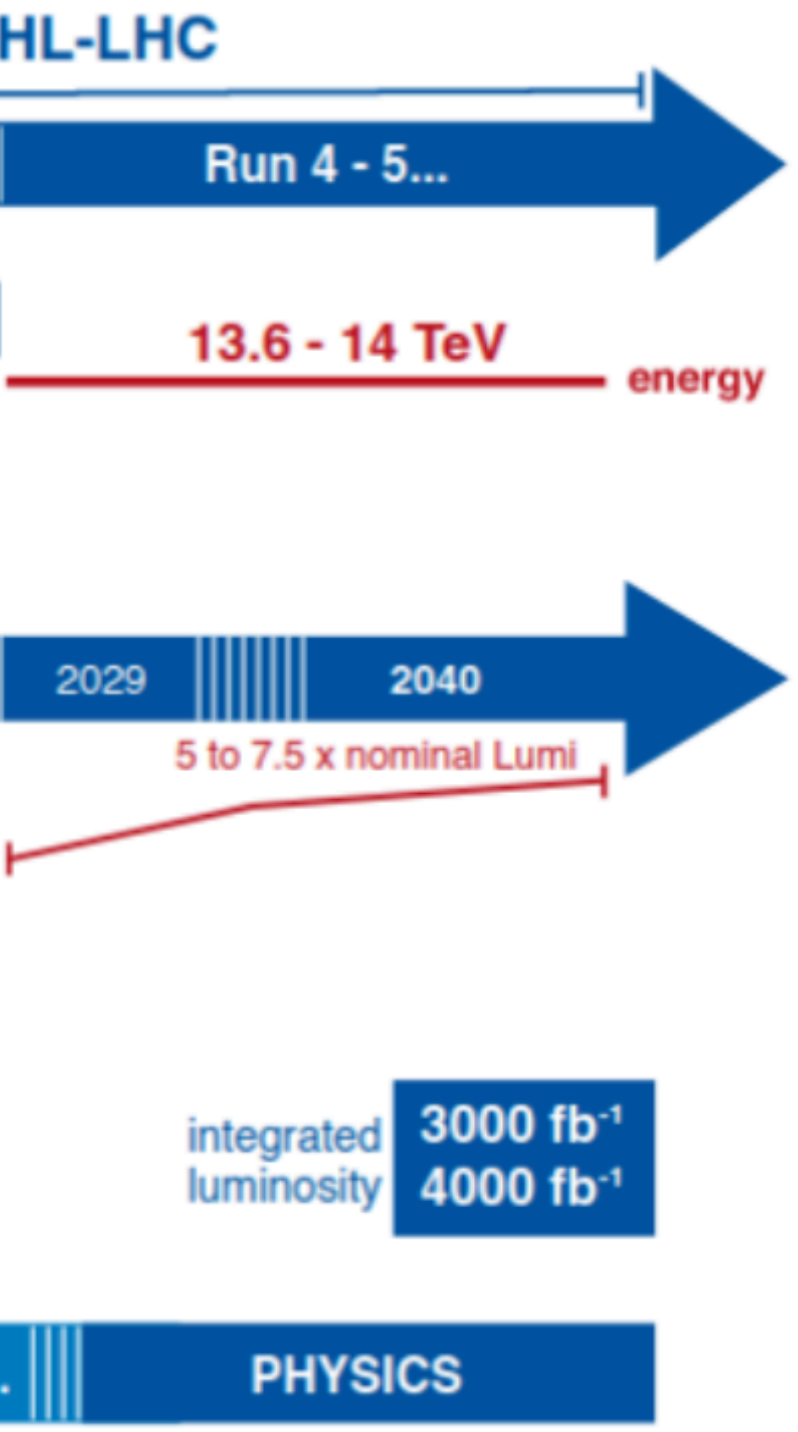
LHC & Future Colliders

- Discovery of the Higgs -> 3 main directions
    - **Precision Higgs** measurements
    - High **Luminosity** -> Reach high enough sensitivity for BSM effects to be visible
    - High **Energy** -> Expand the phase space to explore for direct searches

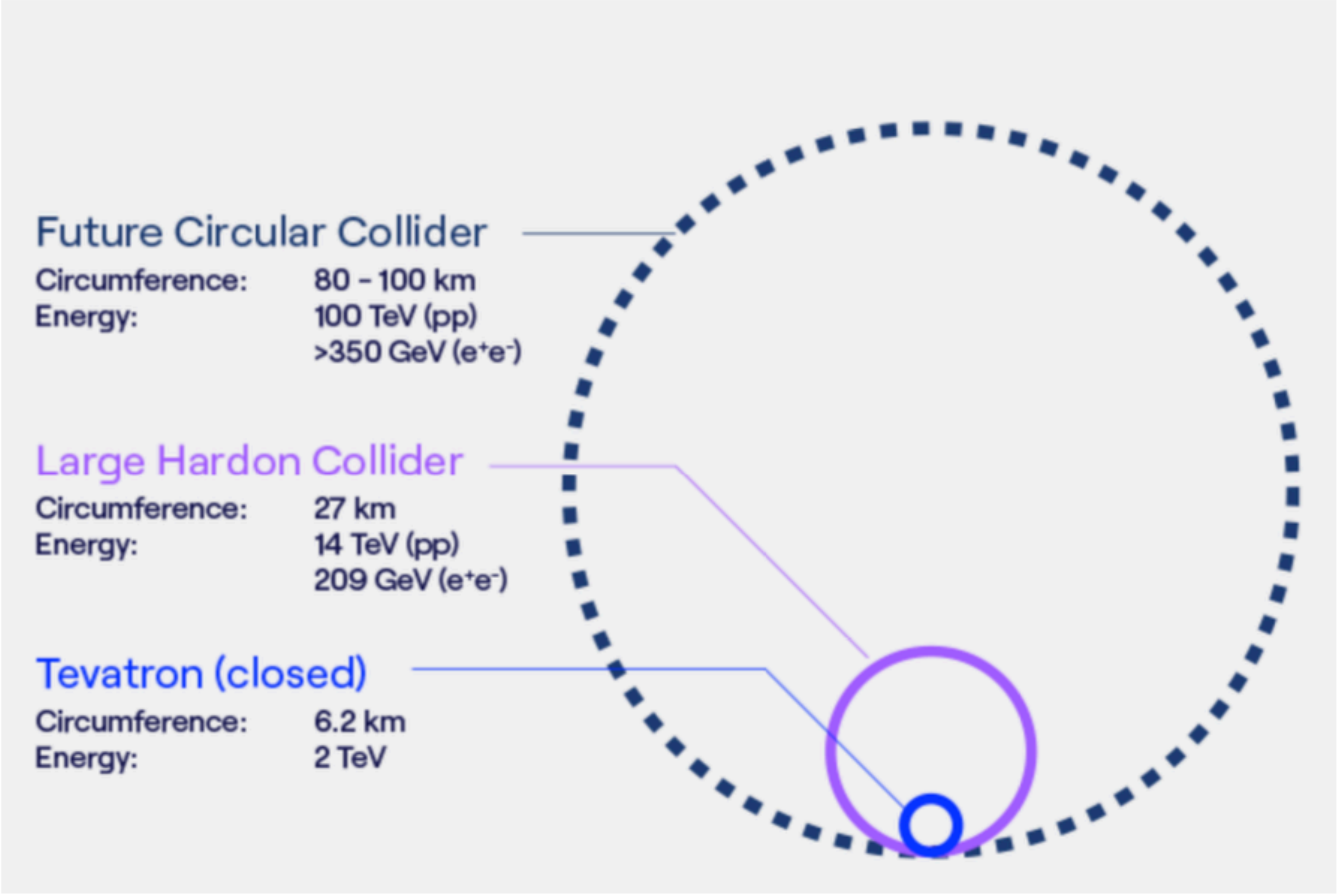


Muon Collider

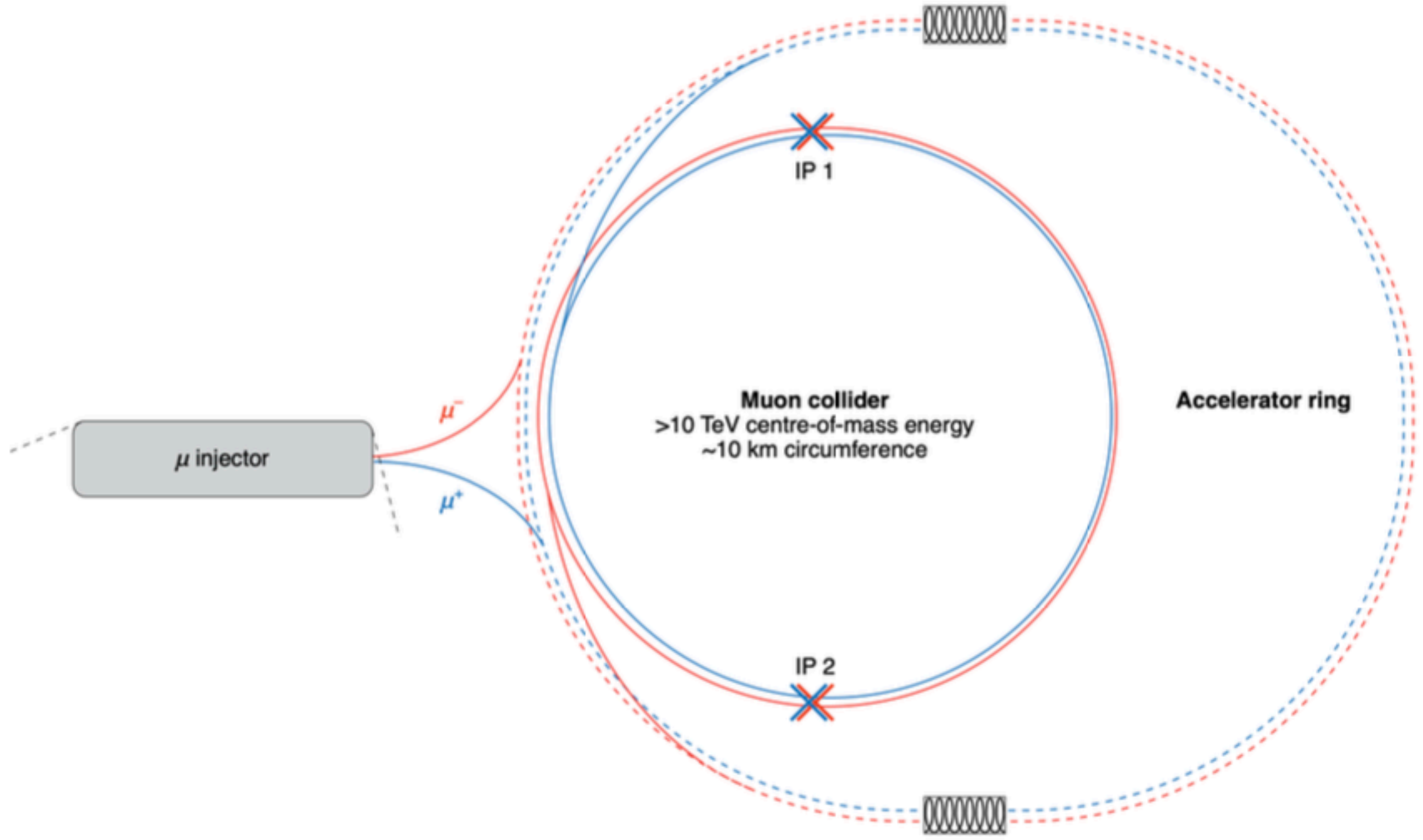
LHC & Future Colliders



- Efforts to plan next phases of research
  - Snowmass (2021 - US)
  - European Strategy for Particle physics (2022)
- Probably **lepton** collider
  - Precision measurement phase
- **FCC-ee** and **Muon Collider** envisioned to be operational by 2045 (https://arxiv.org/abs/2201.07895)



From https://fcc.web.cern.ch/overview



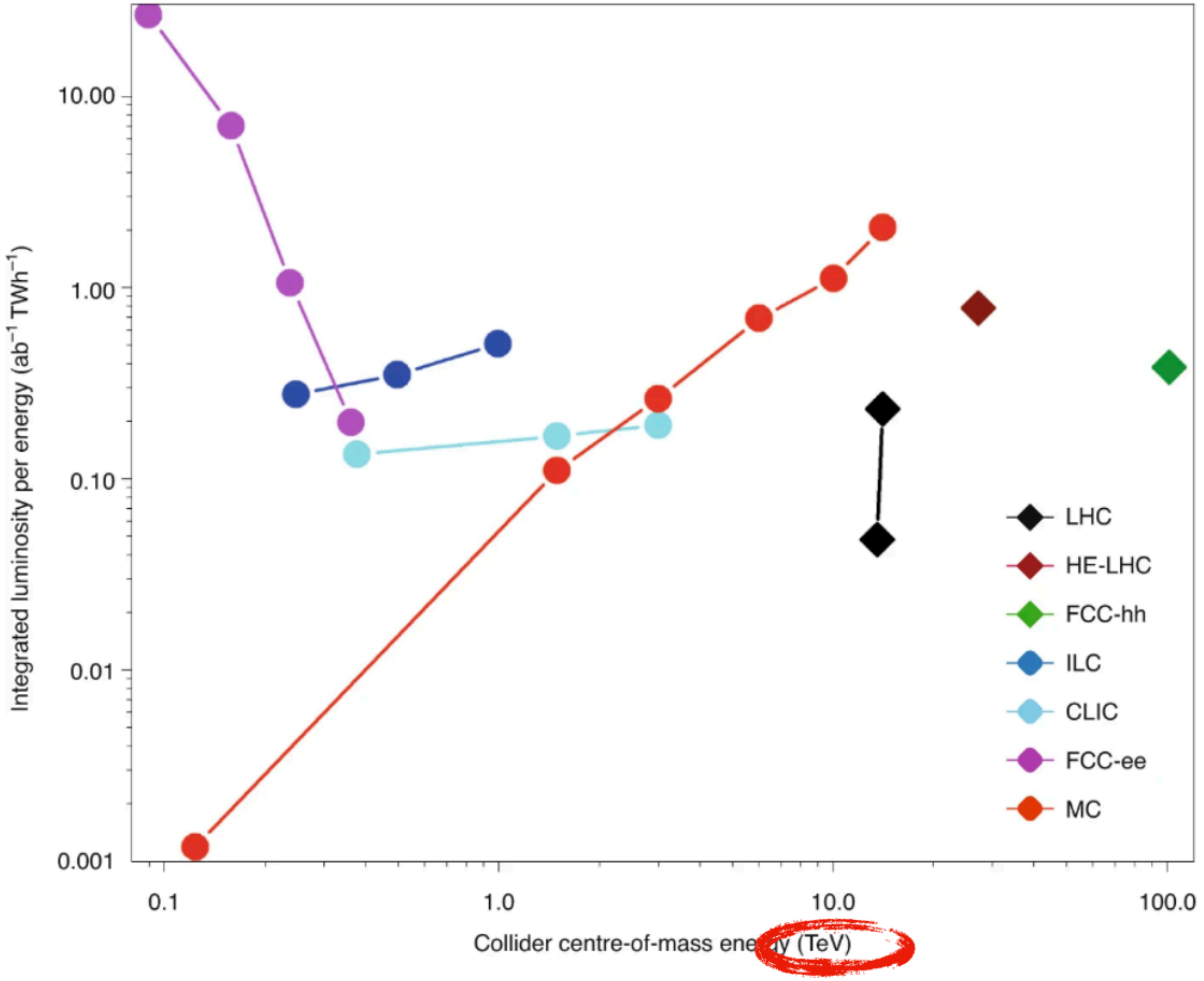
From https://doi.org/10.1038/s41567-020-01130-x

Muon Collider

Why a Muon Collider?

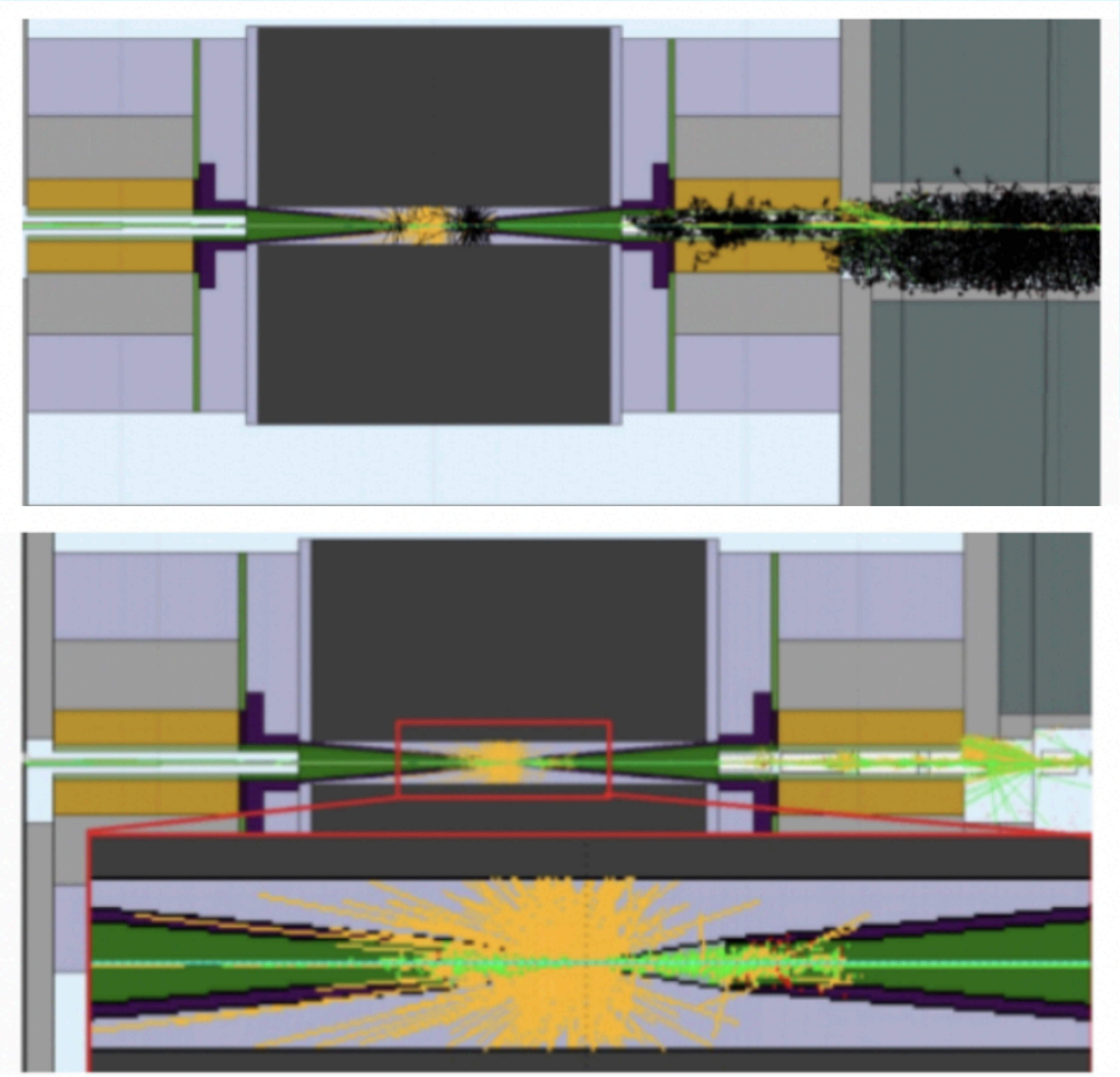
- Luminosity **increases with center-mass energy**
  - Competitive with LINACs
  - Most ‘physics-per-dollar’ potential
- Lepton Collider: **no pile-up** effects
- Rather old concept (1980s), regained interest with the Snowmass Process
- **Higgs** Factory
  - $\sigma(\mu\mu \to H) \simeq 40000\ \sigma\ (ee \to H)$
- **Dark Matter** portals
- New advanced **cooling** methods required to reduce transverse momentum of procuced muons

From https://doi.org/10.1038/s41567-020-01130-x



Muon Collider
The BIB problem

- TeV-scale Muon Collider as strong candidate among proposed Future Colliders (no pile-up, access to DM portals, Higgs factory)
- 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

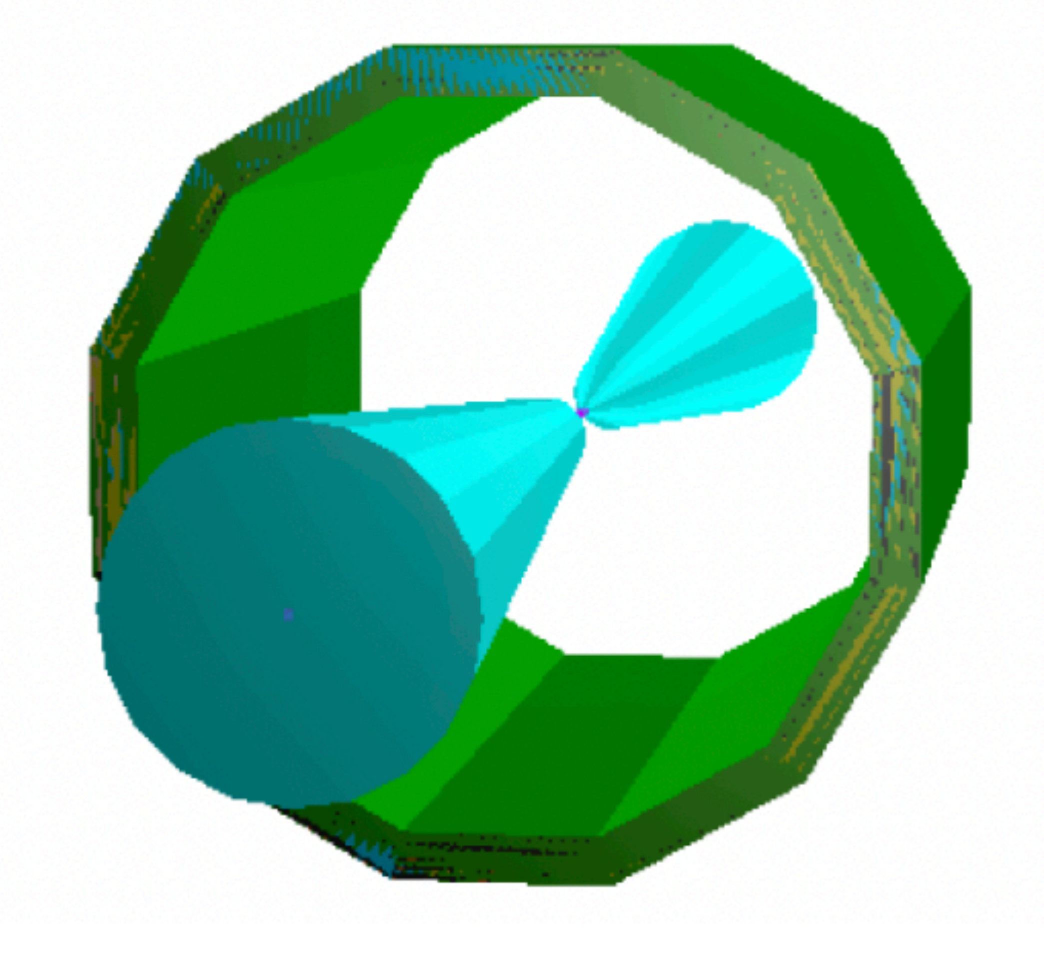


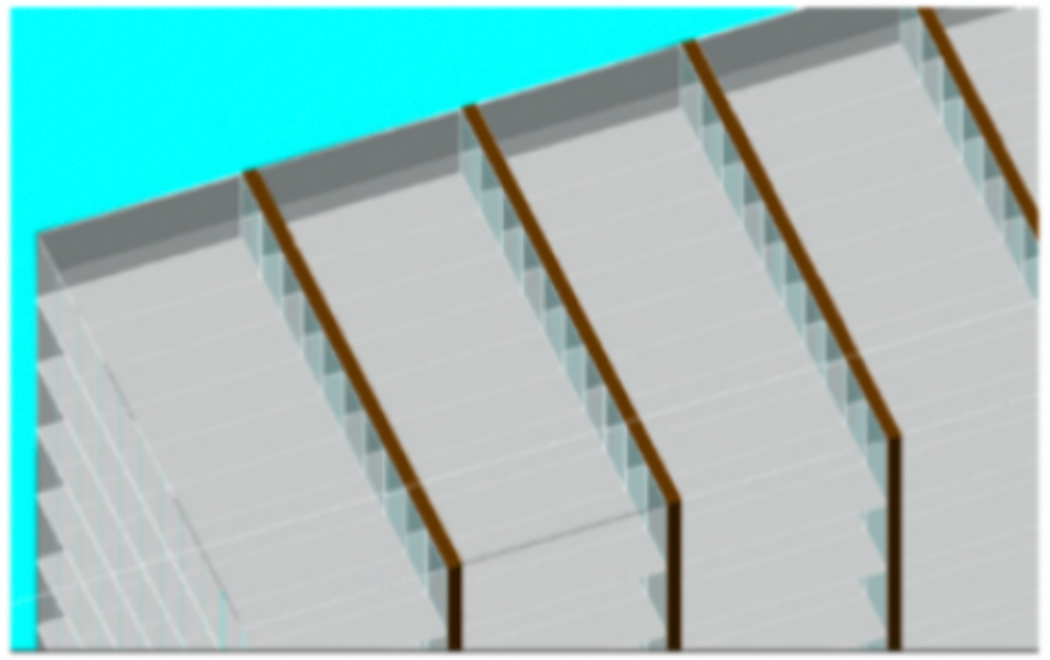
Visualizations from FLUKA BIB simulation. Black: neutrons, other: photons

Muon Collder

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

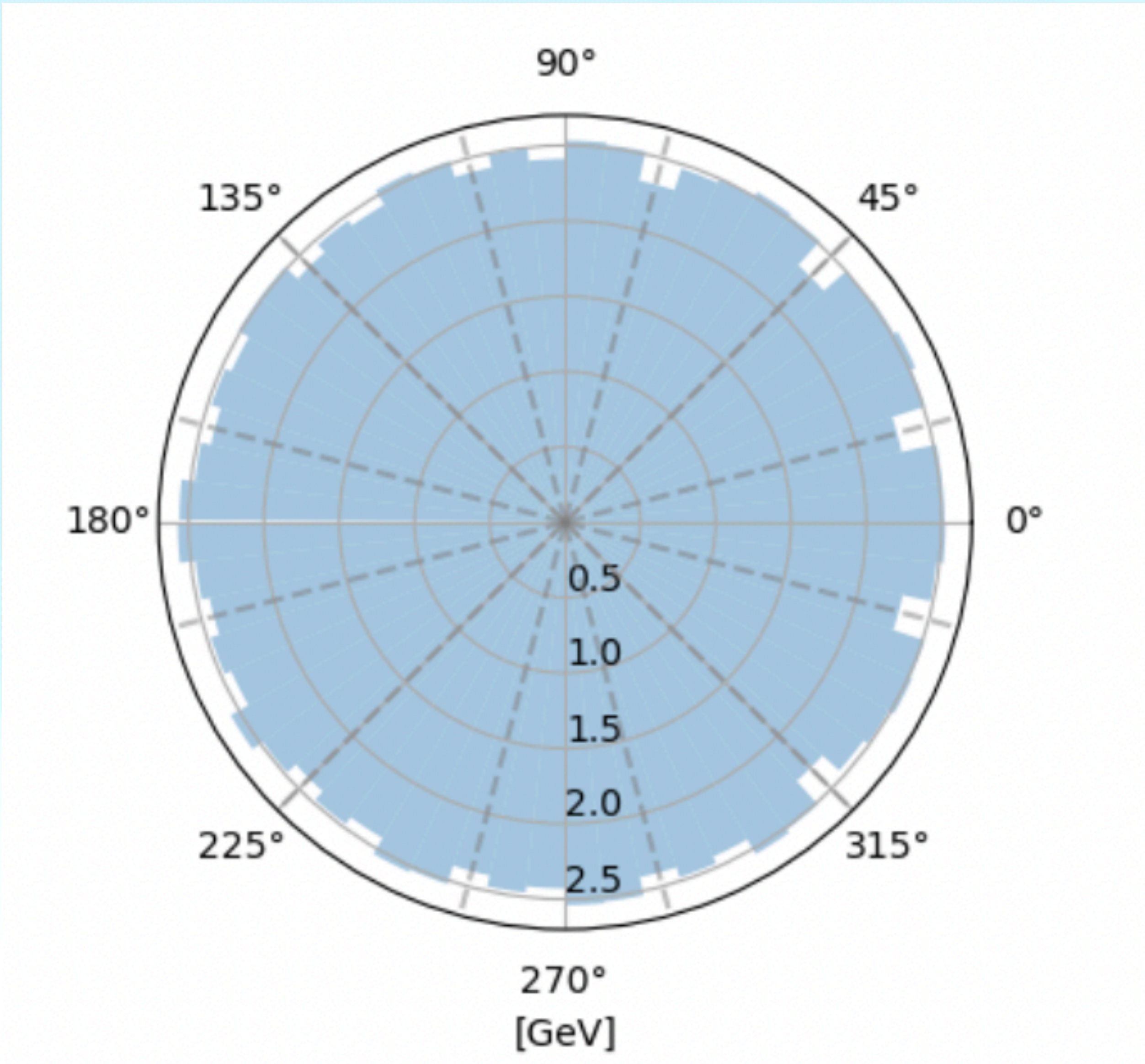


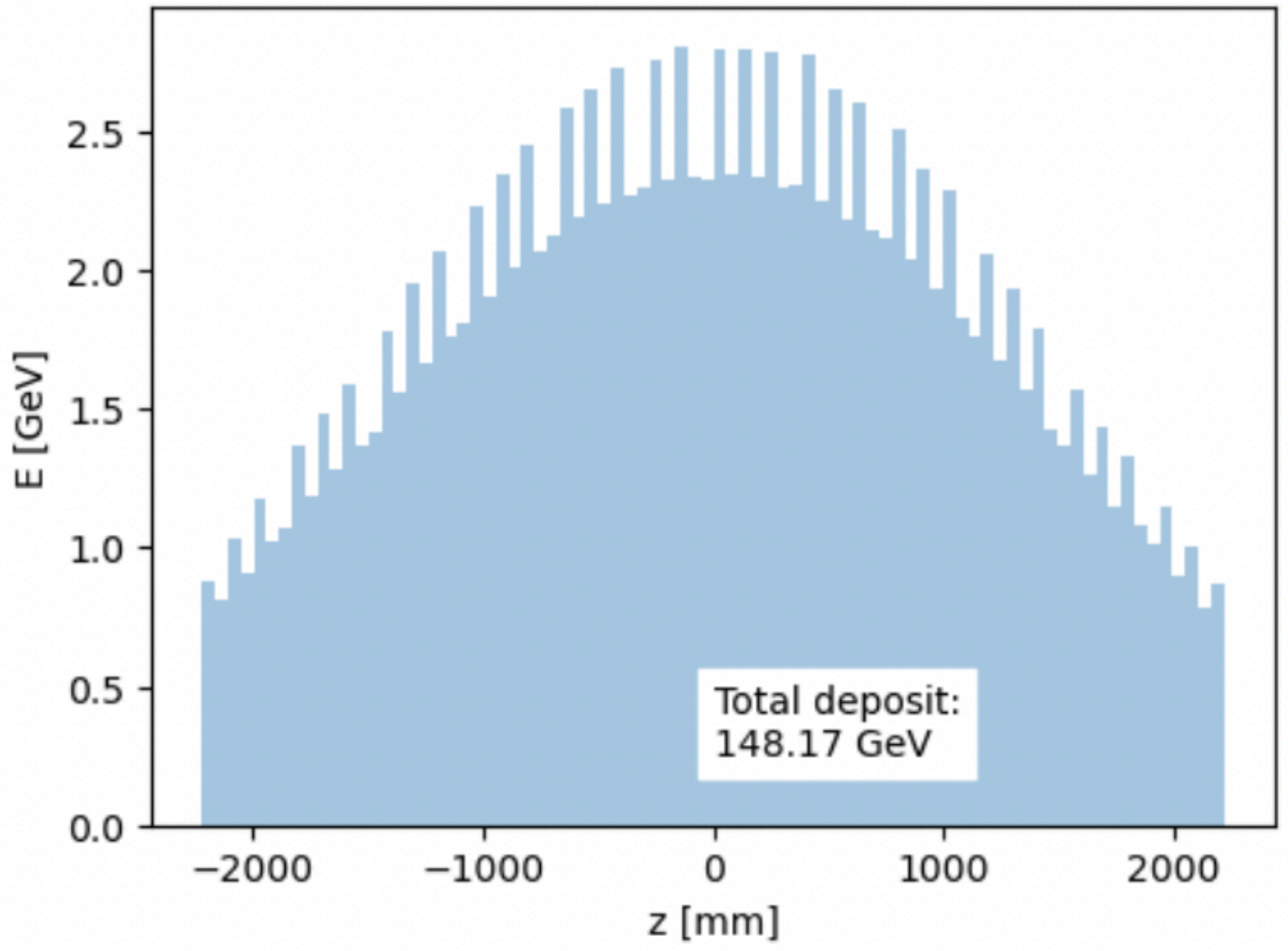


Muon Collider

BIB characterization

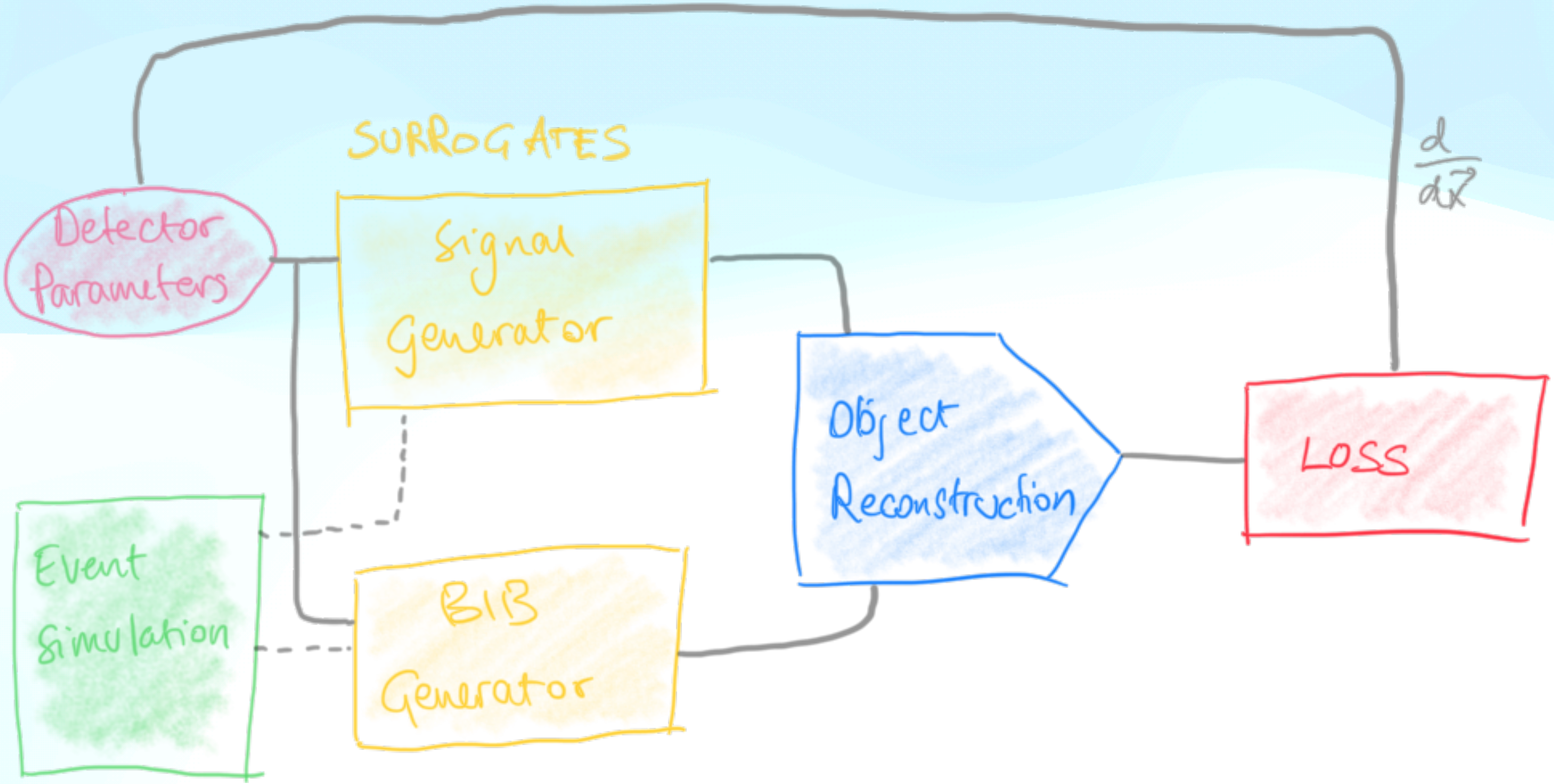
- Nozzle shields most radiation from endcaps, but area around interaction point remains unshielded
- BIB simulation at 1.5TeV center-of-mass energy. Energy deposits in ECal
- Still a considerable amount of energy deposited inside





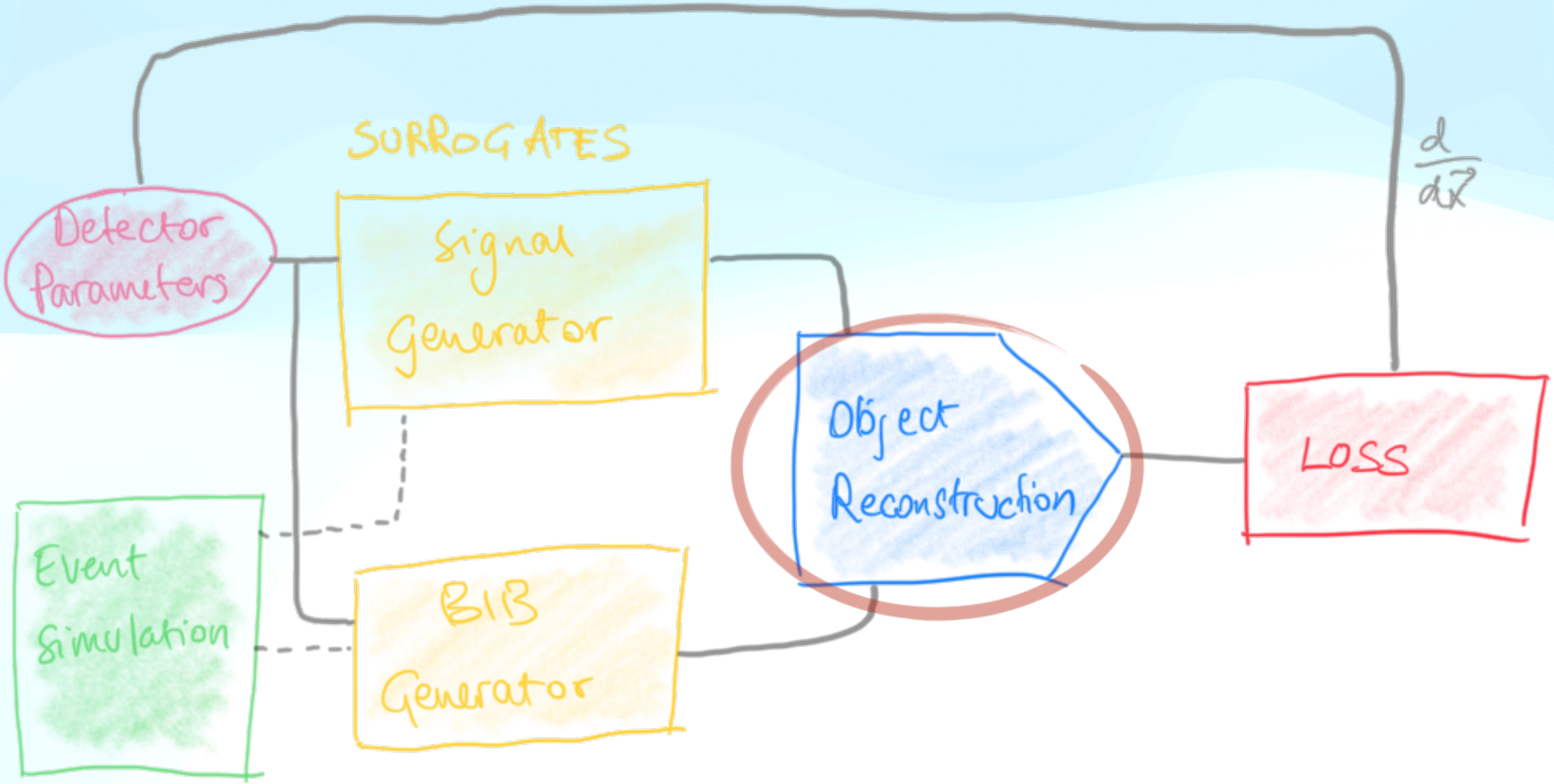
Muon Collider

Optimization Workflow



Testing a Reconstruction algorithm

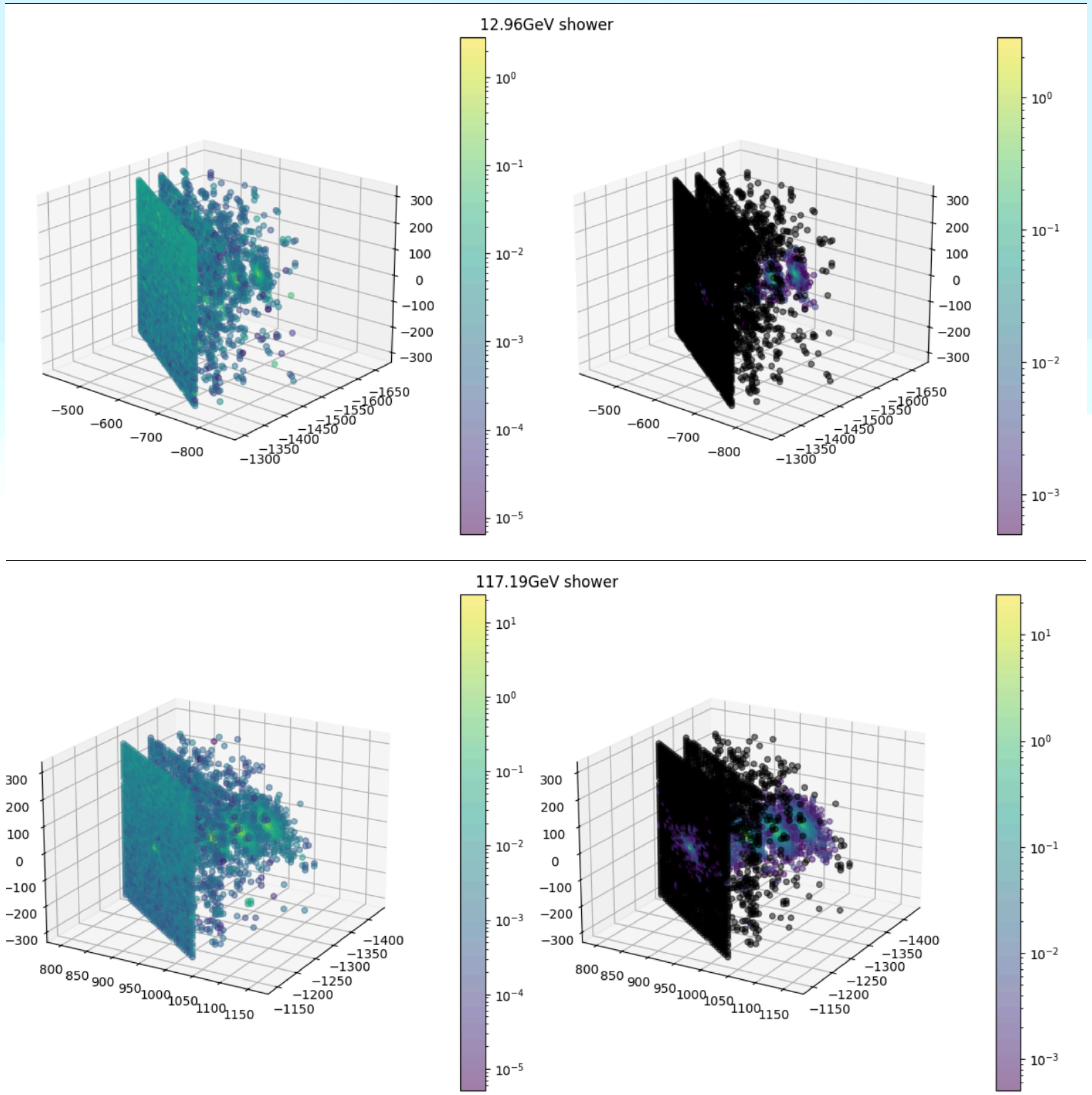
Object Condensation for reconstruction



Testing a Reconstruction algorithm

Dataset Generation

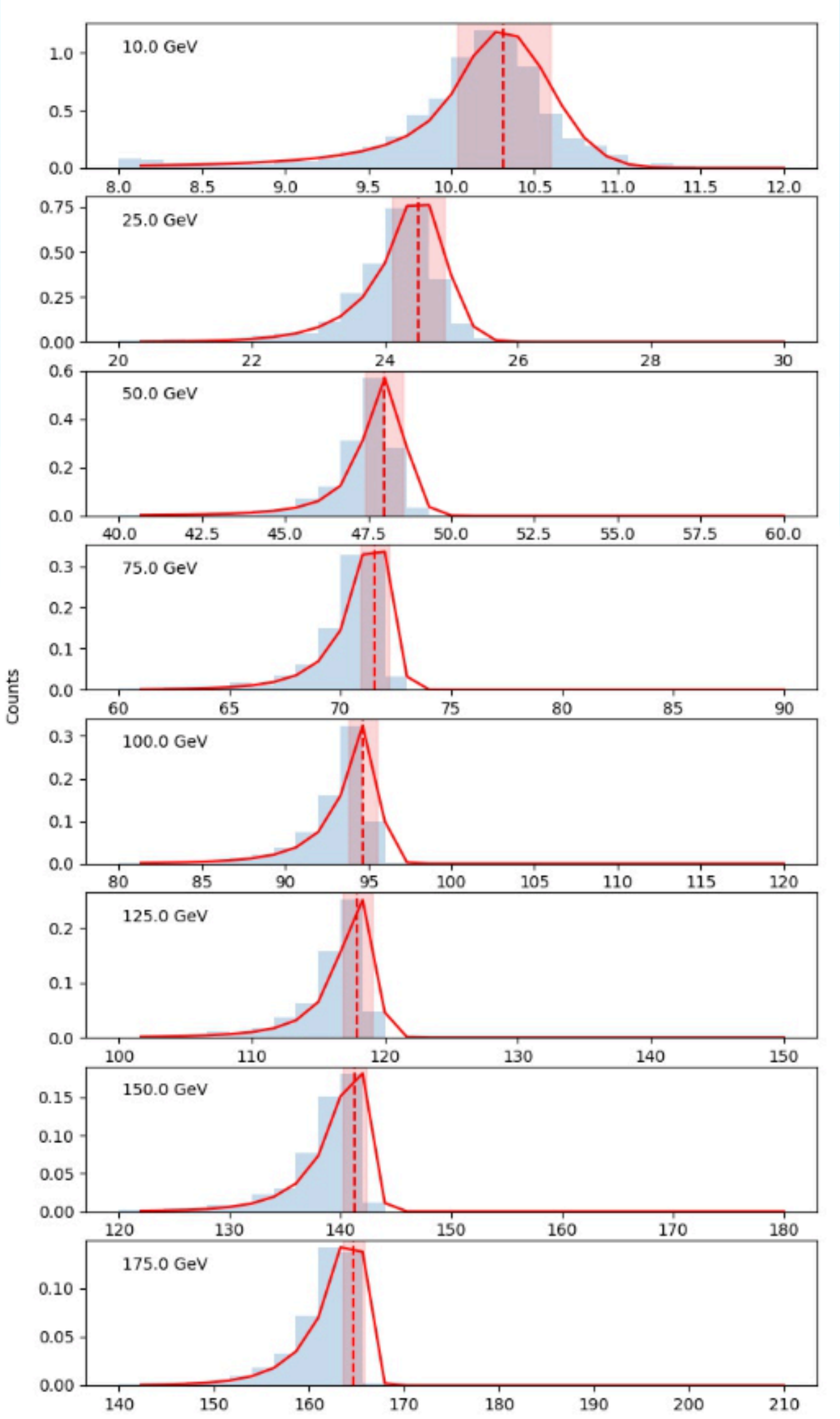
- Starting from Geant4 simulations of monochromatic photons in Crilin geometry
- Uniformly distributed in energy and transverse angle
- Developed code to produce overlay events superimposing BIB at 1.5TeV center-mass energy
- At low photon energies first layers of the shower are lost in BIB



Testing a Reconstruction Algorithm

Performance evaluation

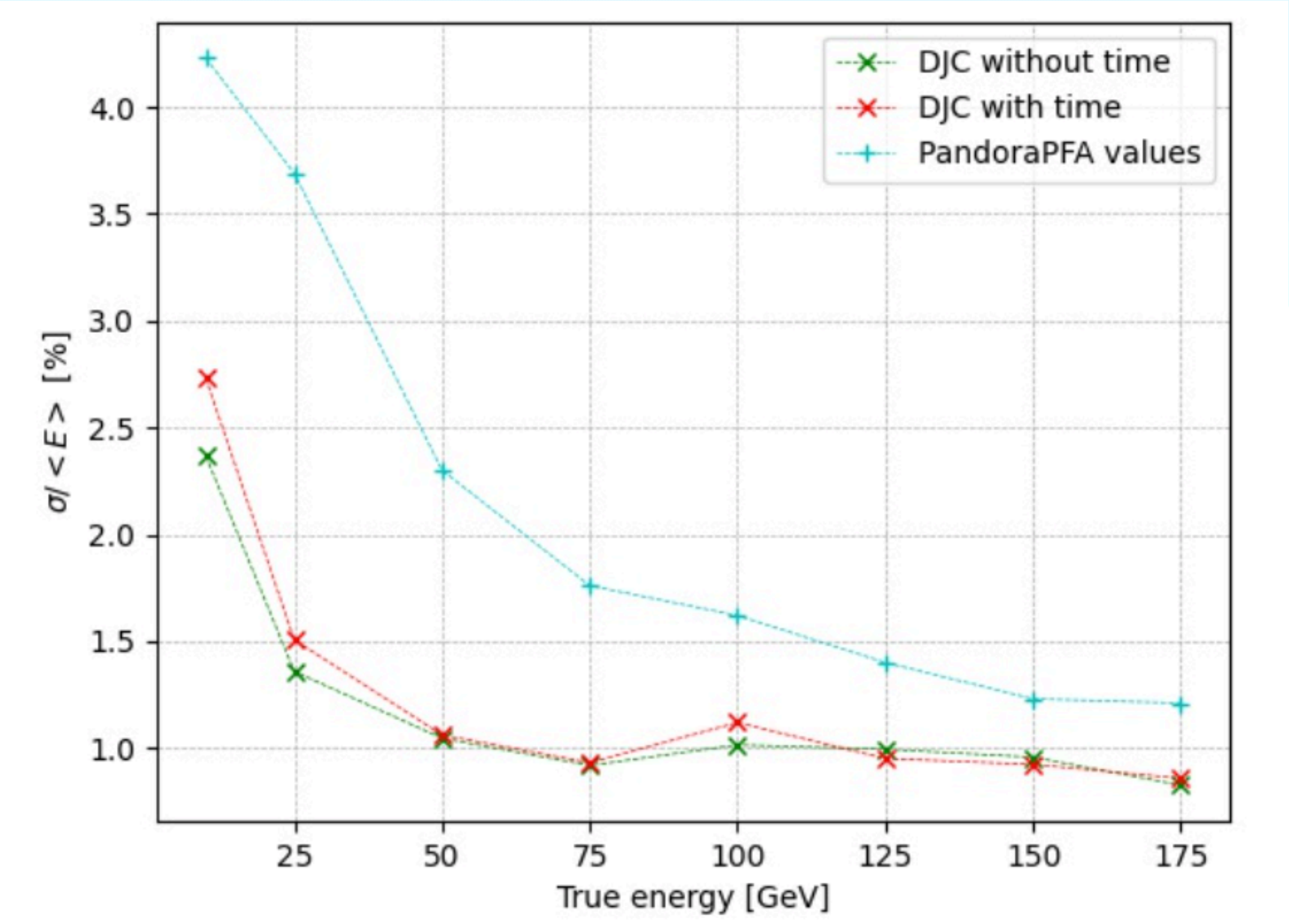
- Trained algorithm for 500 epochs on uniformly distributed energies
- Tested on 10k photons of single-point energies
- Plotted predicted primary energy per energy point
- Fitted distribution to a CrystalBall function



Testing a Reconstruction Algorithm

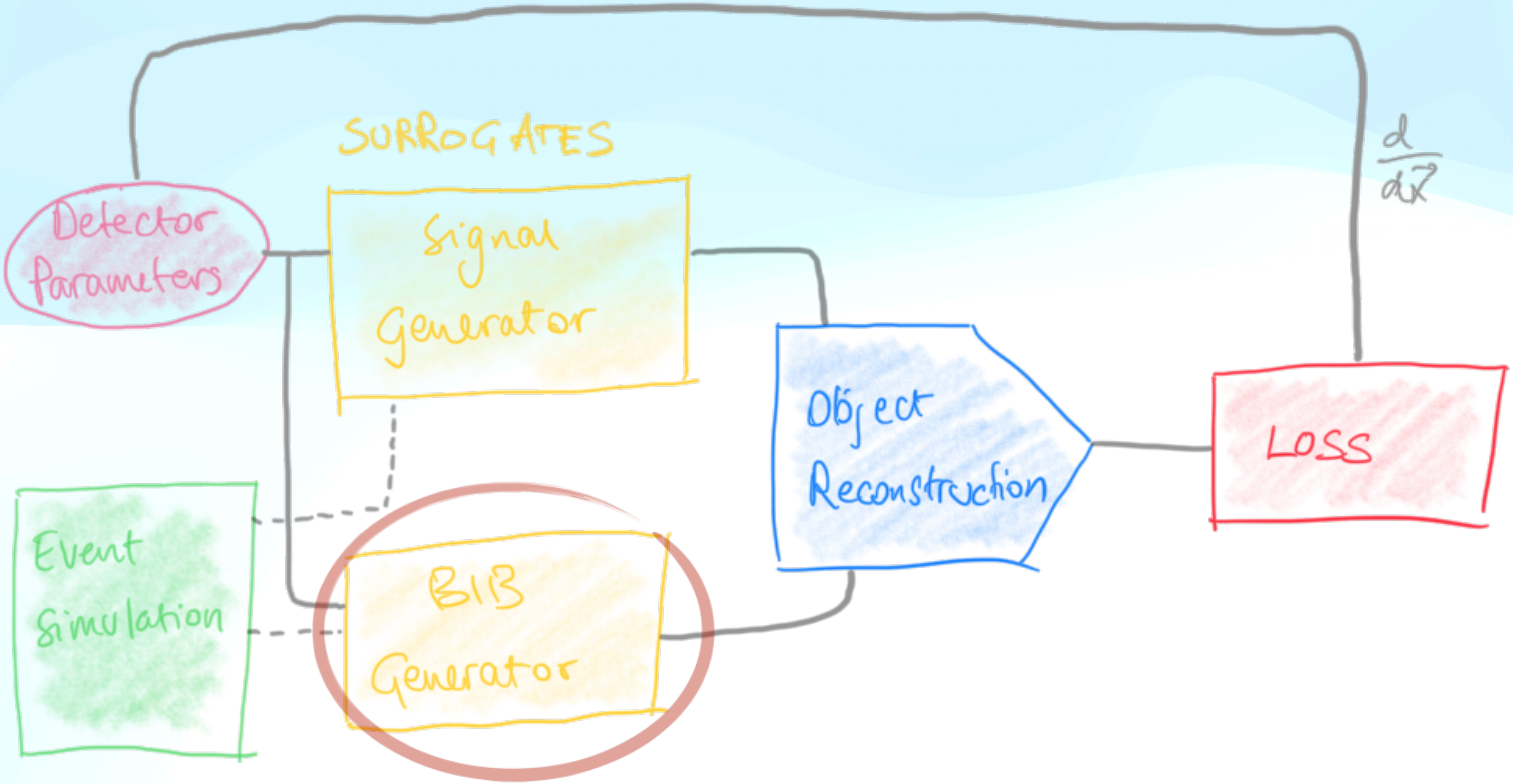
Performance evaluation

- Adapted GravNet architecture for reconstruction in granular calorimeters)
  arXiv:1902.07987
- Same analysis performed with and without timing information
- Compared with framework reconstruction made with Pandora+ParticleFlow on same data
- Significant improvement in resolution
- Time information does not seem to make a difference



Development of Surrogates

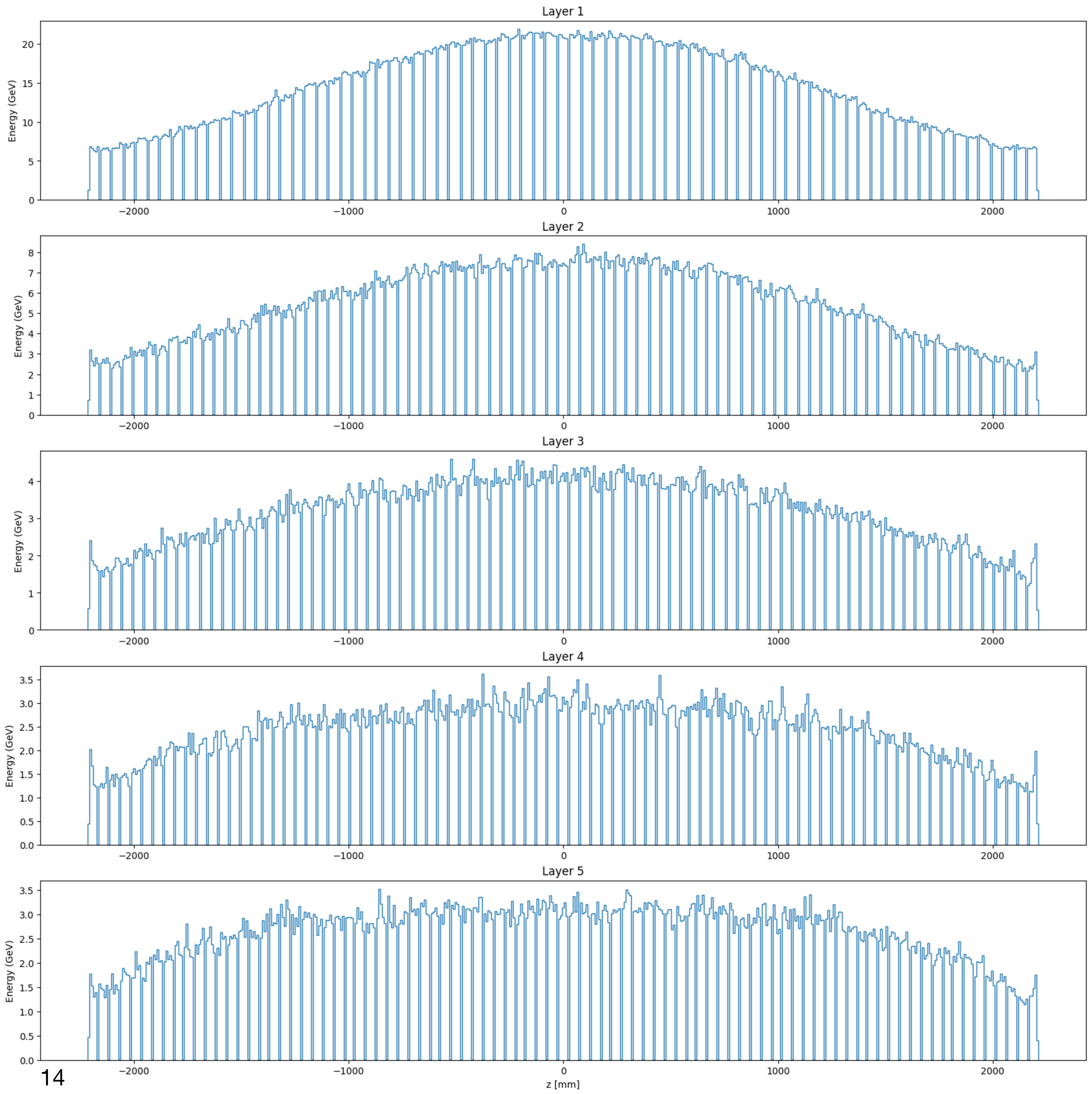
BIB generator



Development of Surrogates

BIB generator

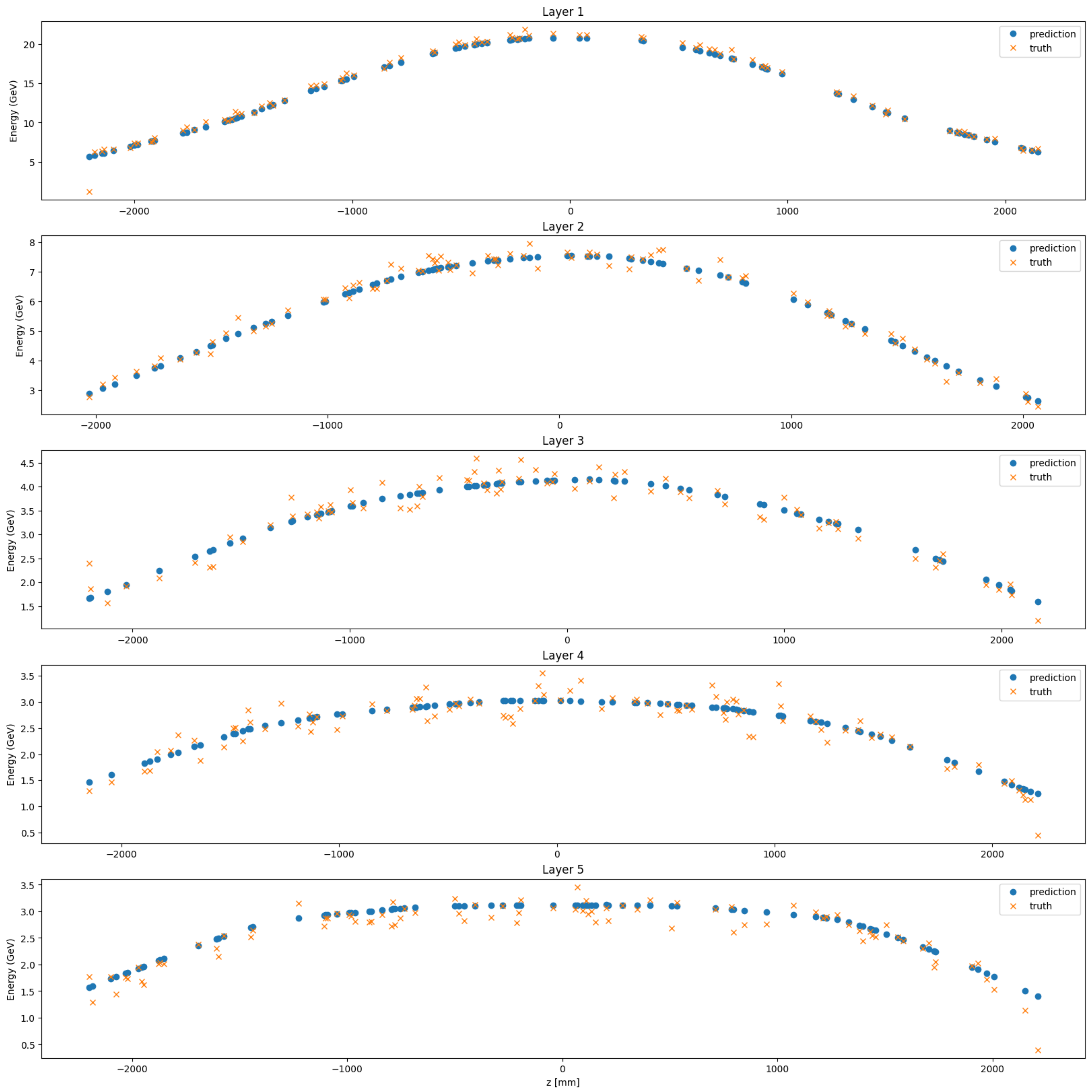
- Starting from 1.5 TeV Geant4 simulation
- Restricted to a single wedge due to cylindrical symmetry
- Neglecting transverse component (x) for the same reason

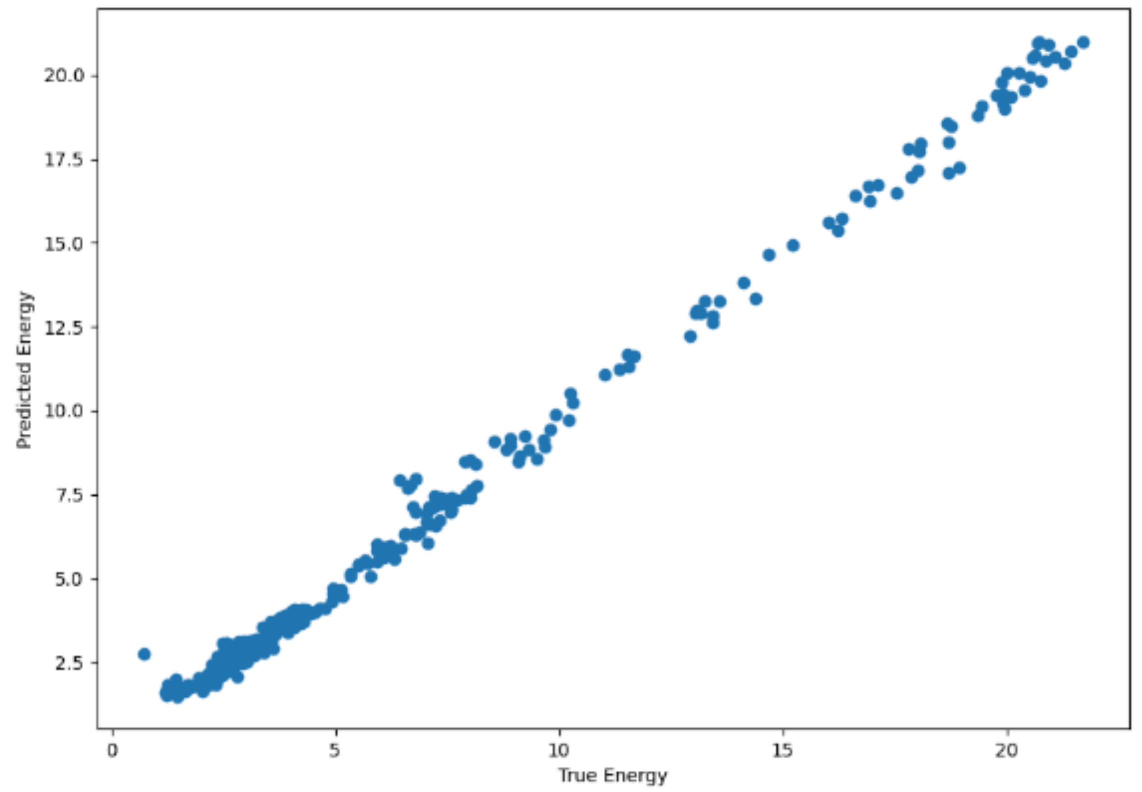


Development of Surrogates

BIB generator

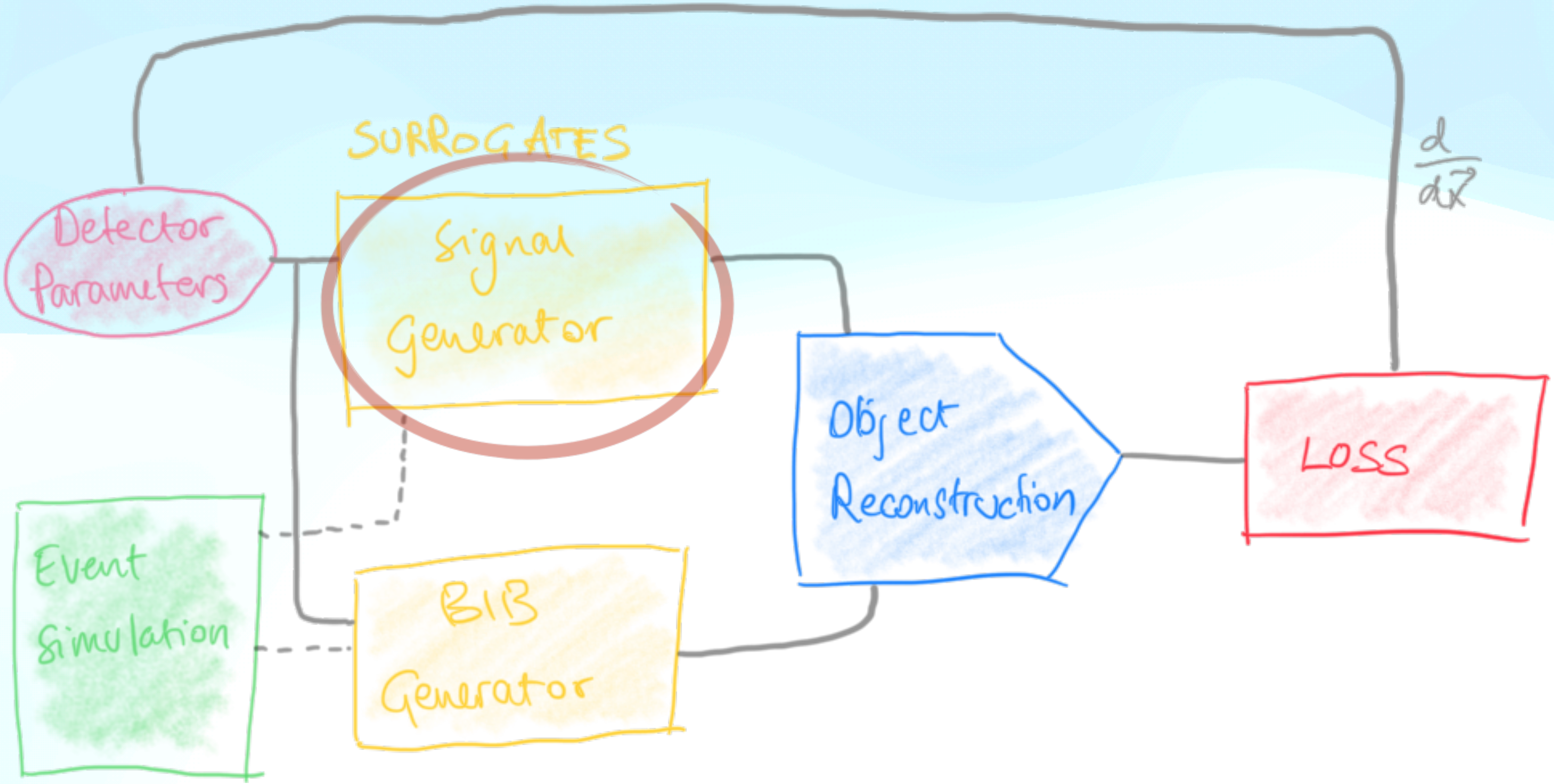
- Set up a simple DNN trained on the dataset
- For a coordinate pair (z,y) predict a BIB flux density value
- Decent performance on validation data





Development of Surrogates

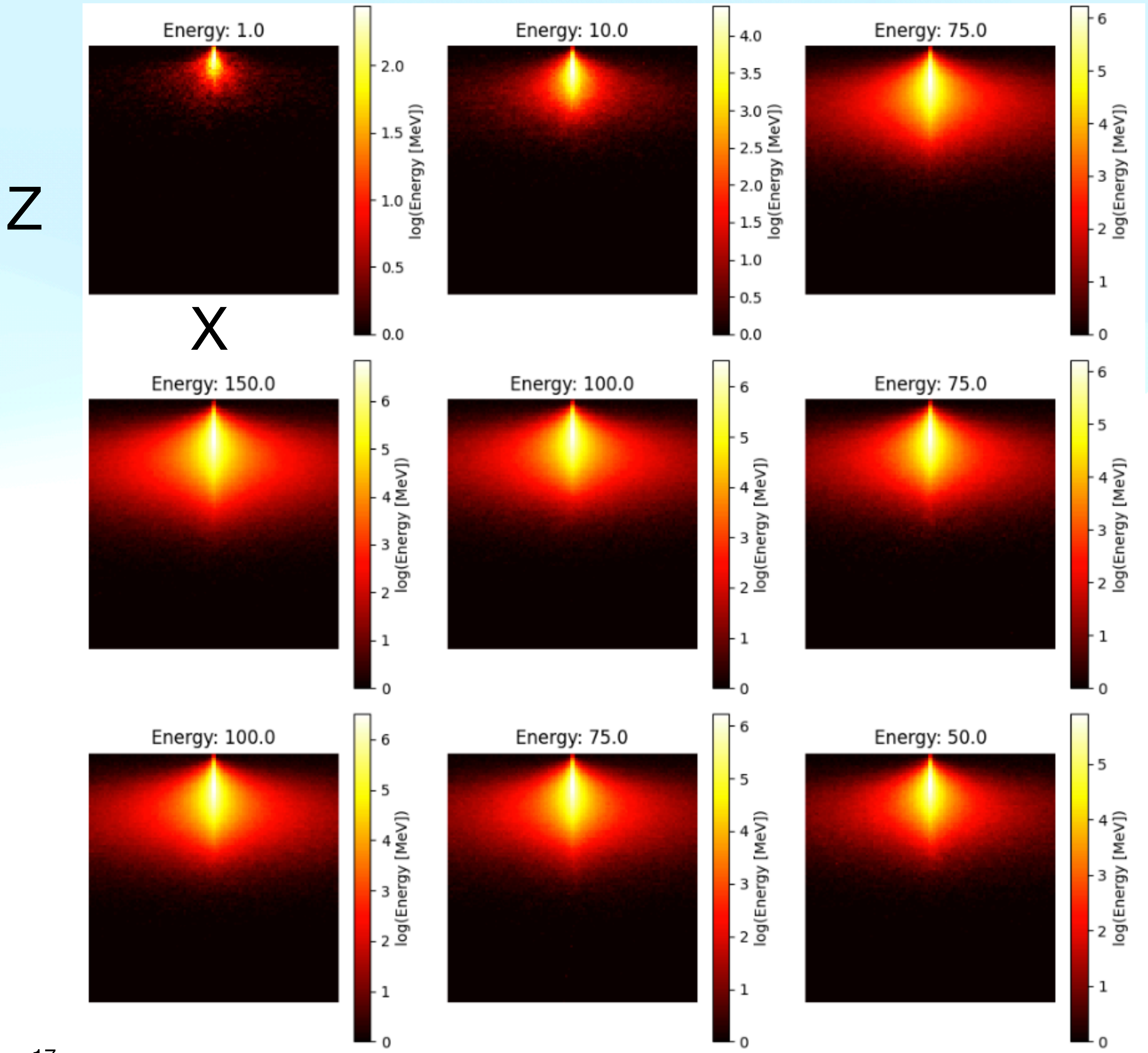
Signal generator



Development of Surrogates

Shower generator

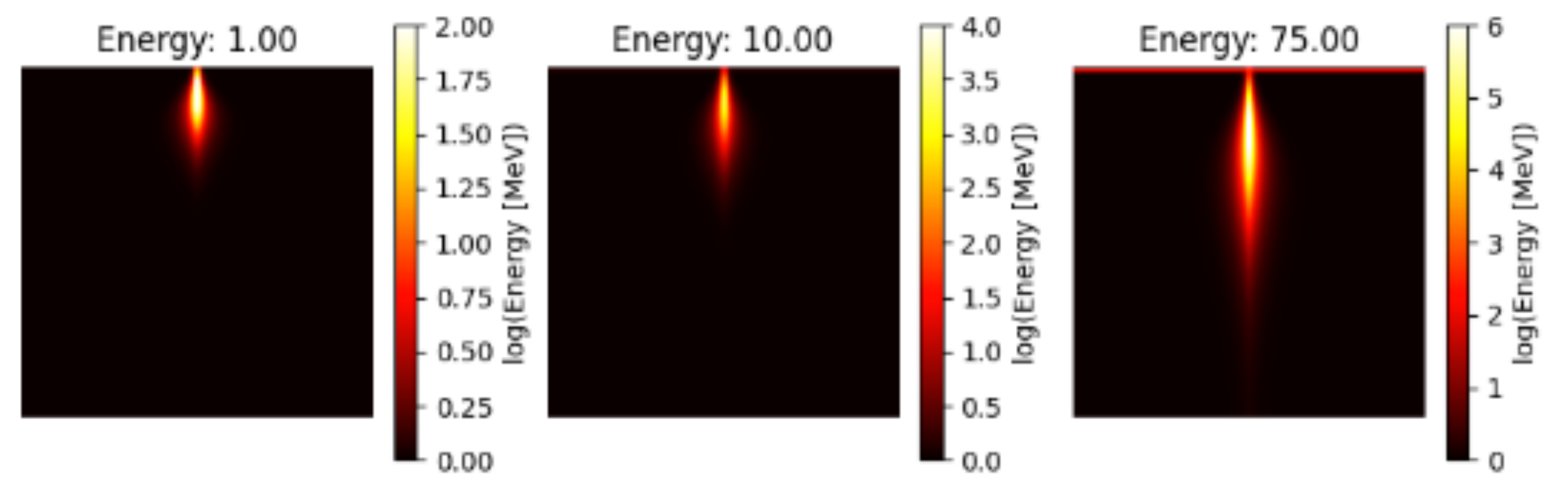
- Developed a simple Geant4 application to simulate monochromatic photons in a block of PbF_2
- Generated a datased of 40k monochromatic showers as 2D images
- Each generated event is bootstrap average of 100 Geant4 events



Development of Surrogates

Shower generator

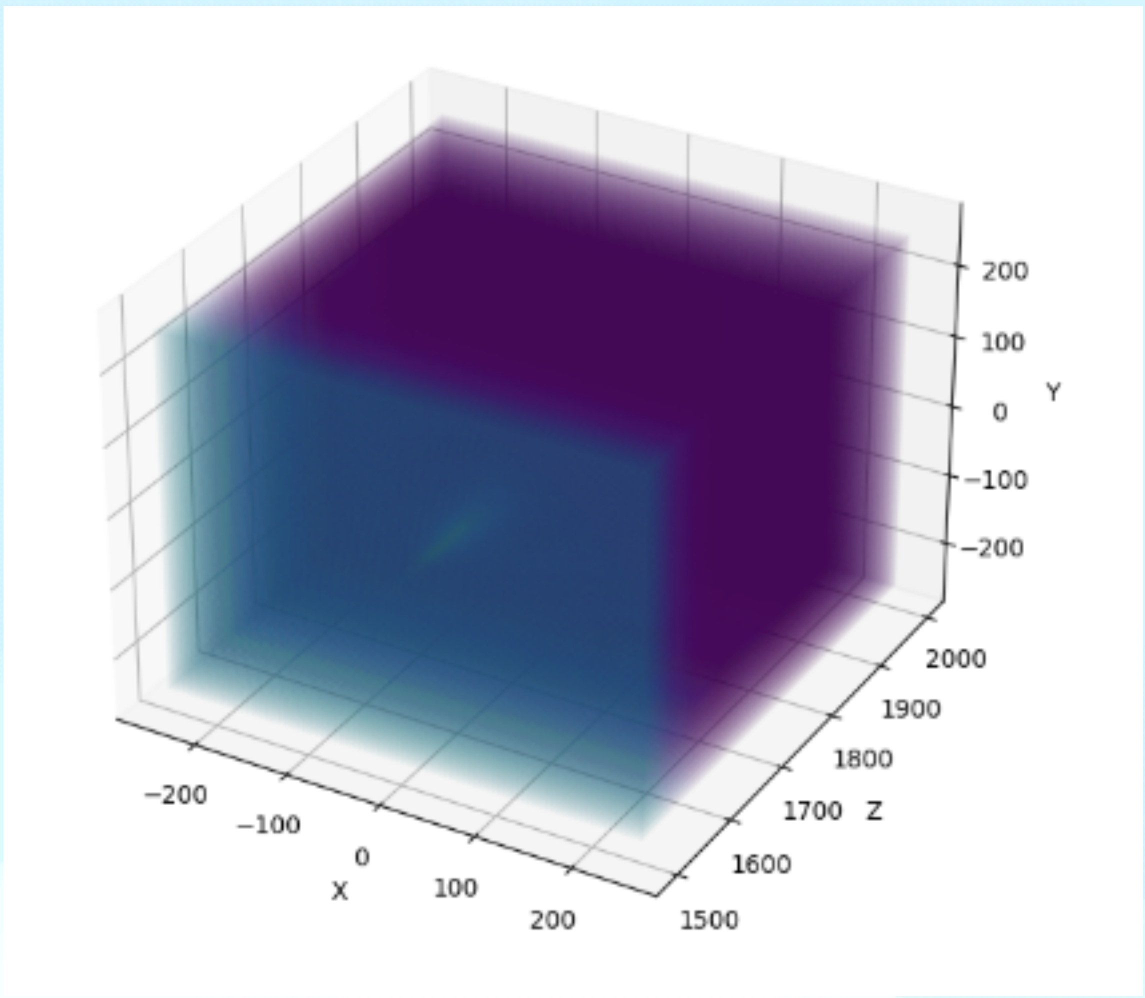
- Very basic model to generate a radial shower
- Suboptimal, but describes the core of the shower well enough
- Normalization enforced to match energy of primary photon

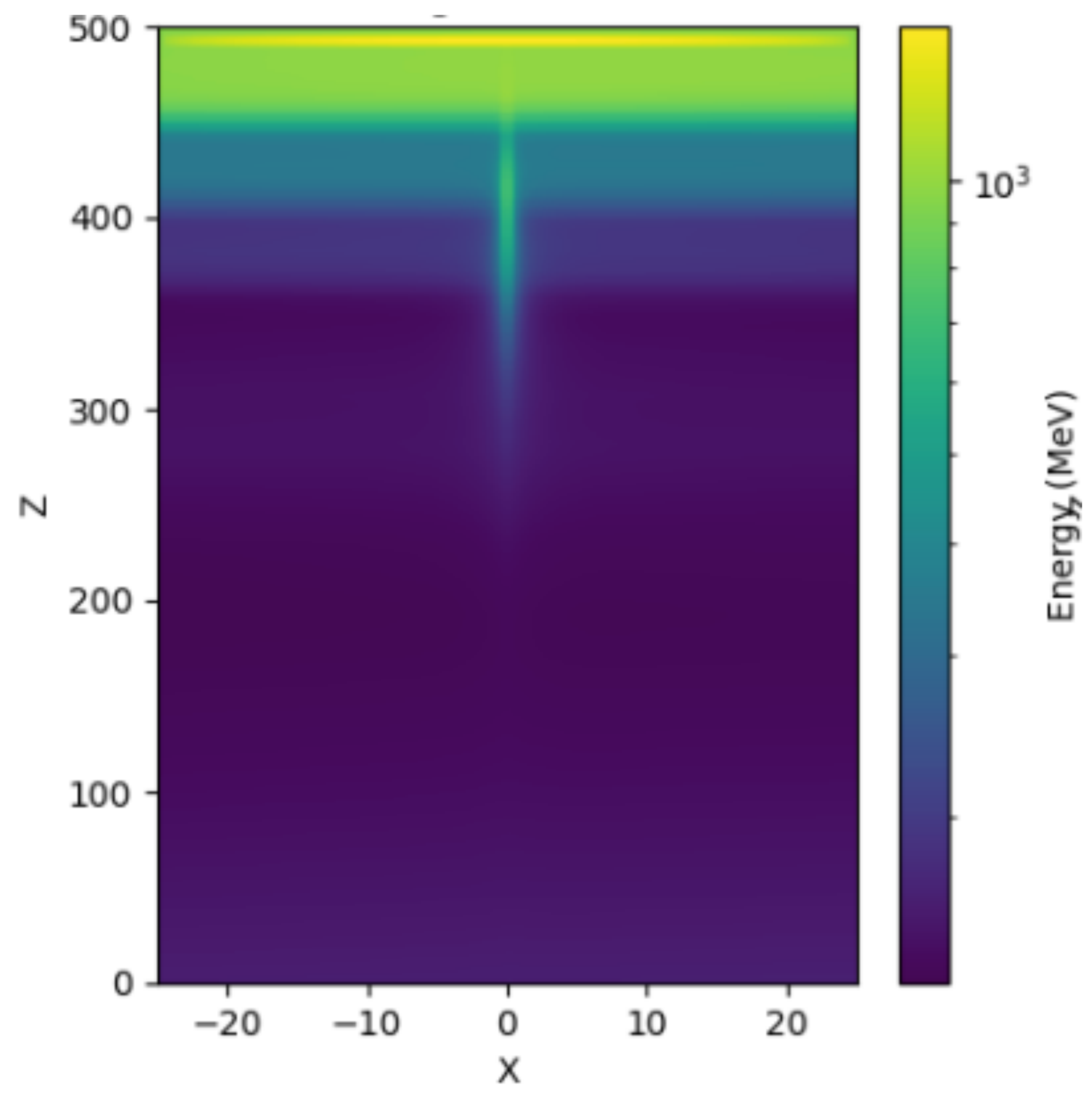


Pipeline Implementation

Generator module

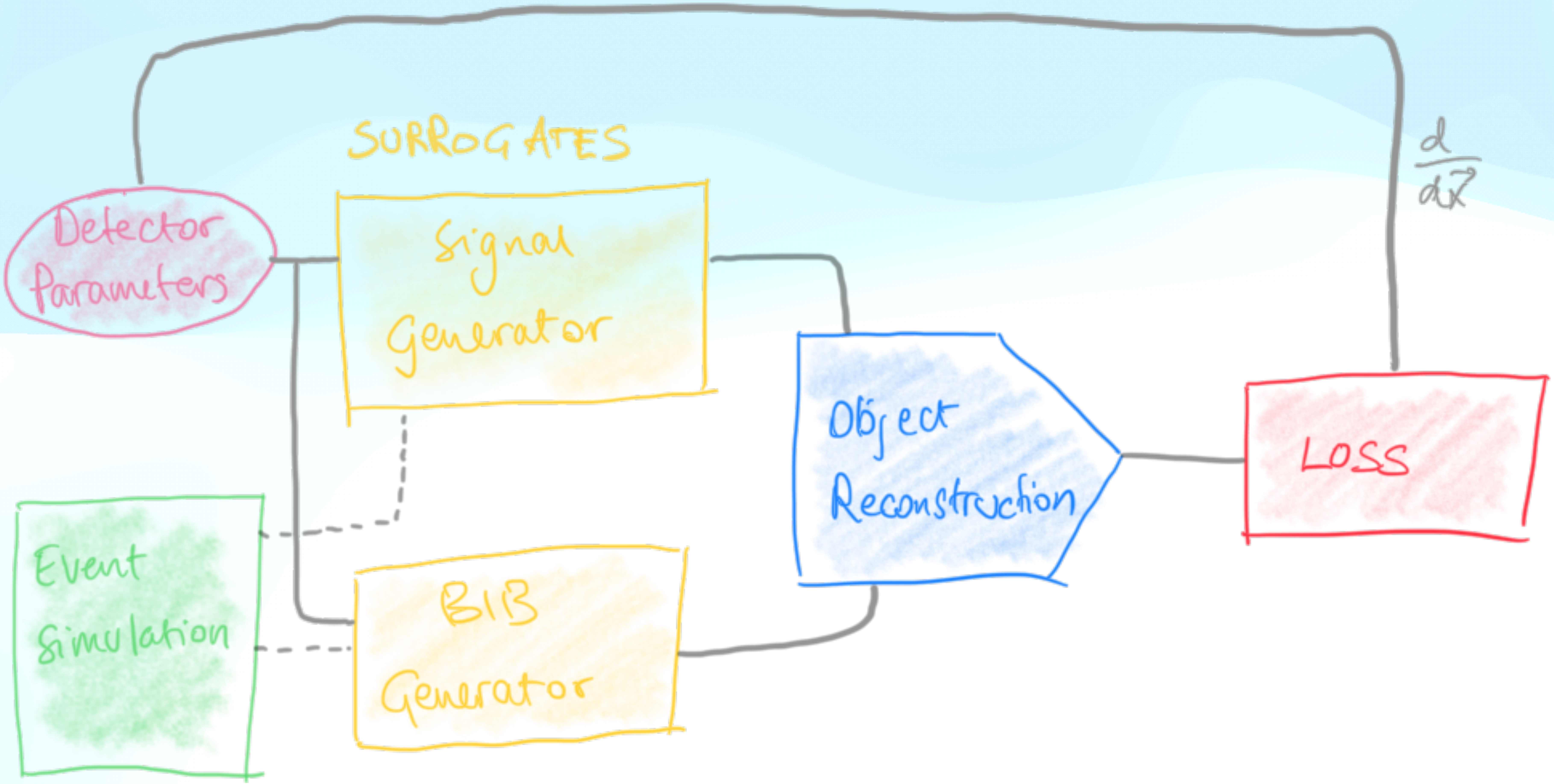
- Developed a generator module implementing the overlay of BIB and shower generators
- Using Tensorflow and ensuring differentiability of operations
- Evaluate the deposits on a grid with arbitrary spacing
- Currently working on implementing reconstructor in the pipeline





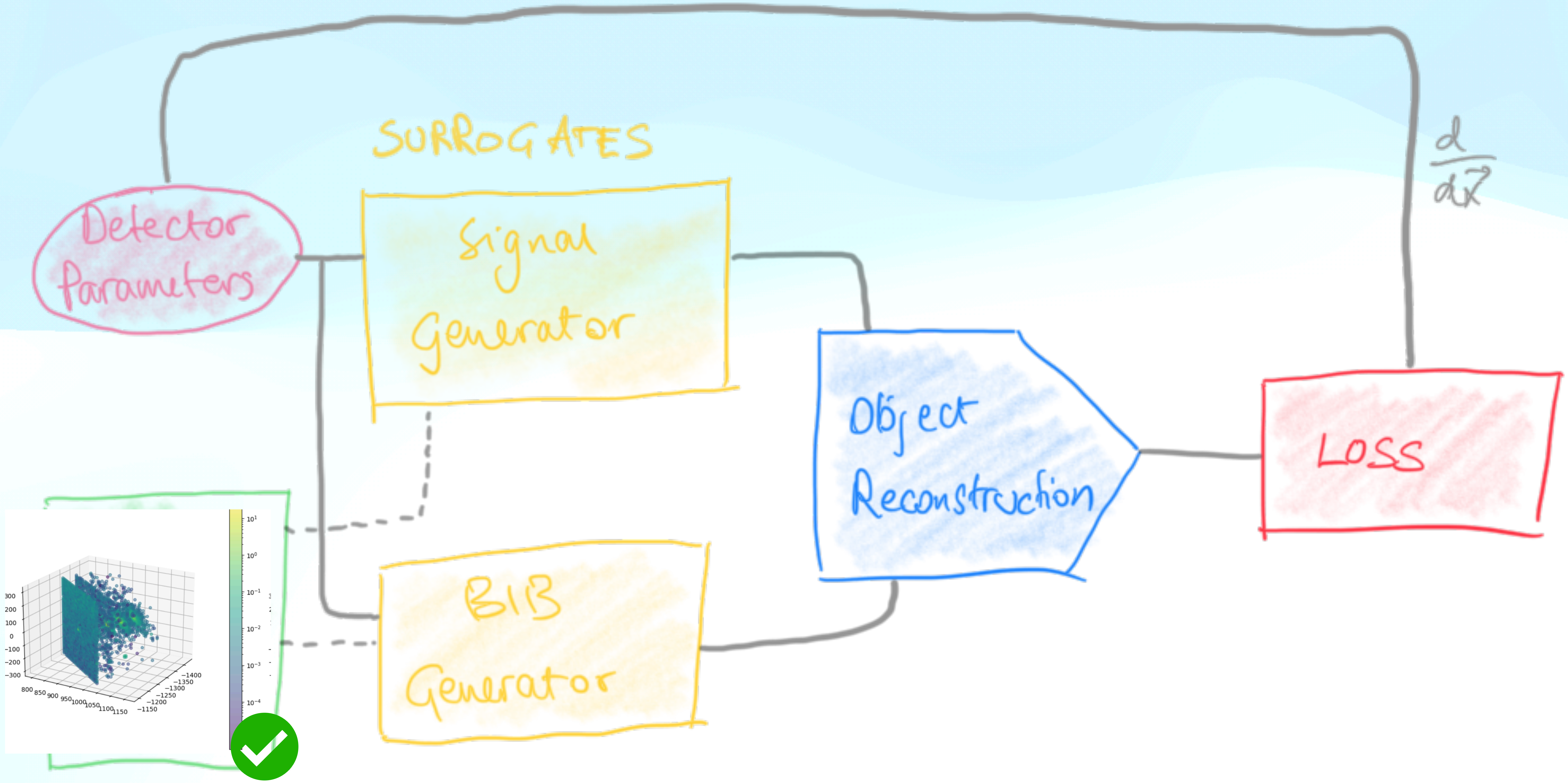
Pipeline Implementation

Current Status



Pipeline Implementation

Summary and Status



Pipeline Implementation

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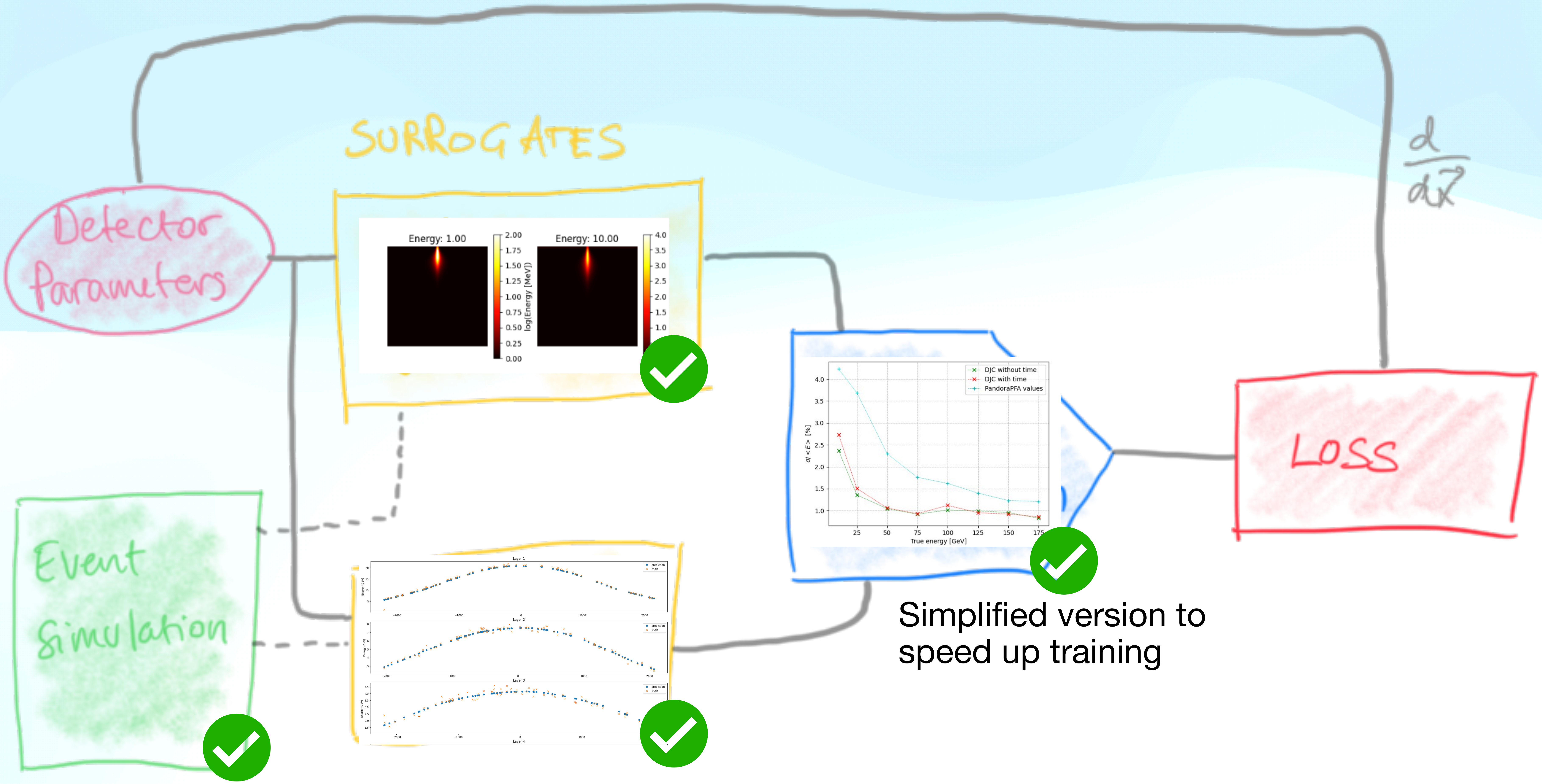
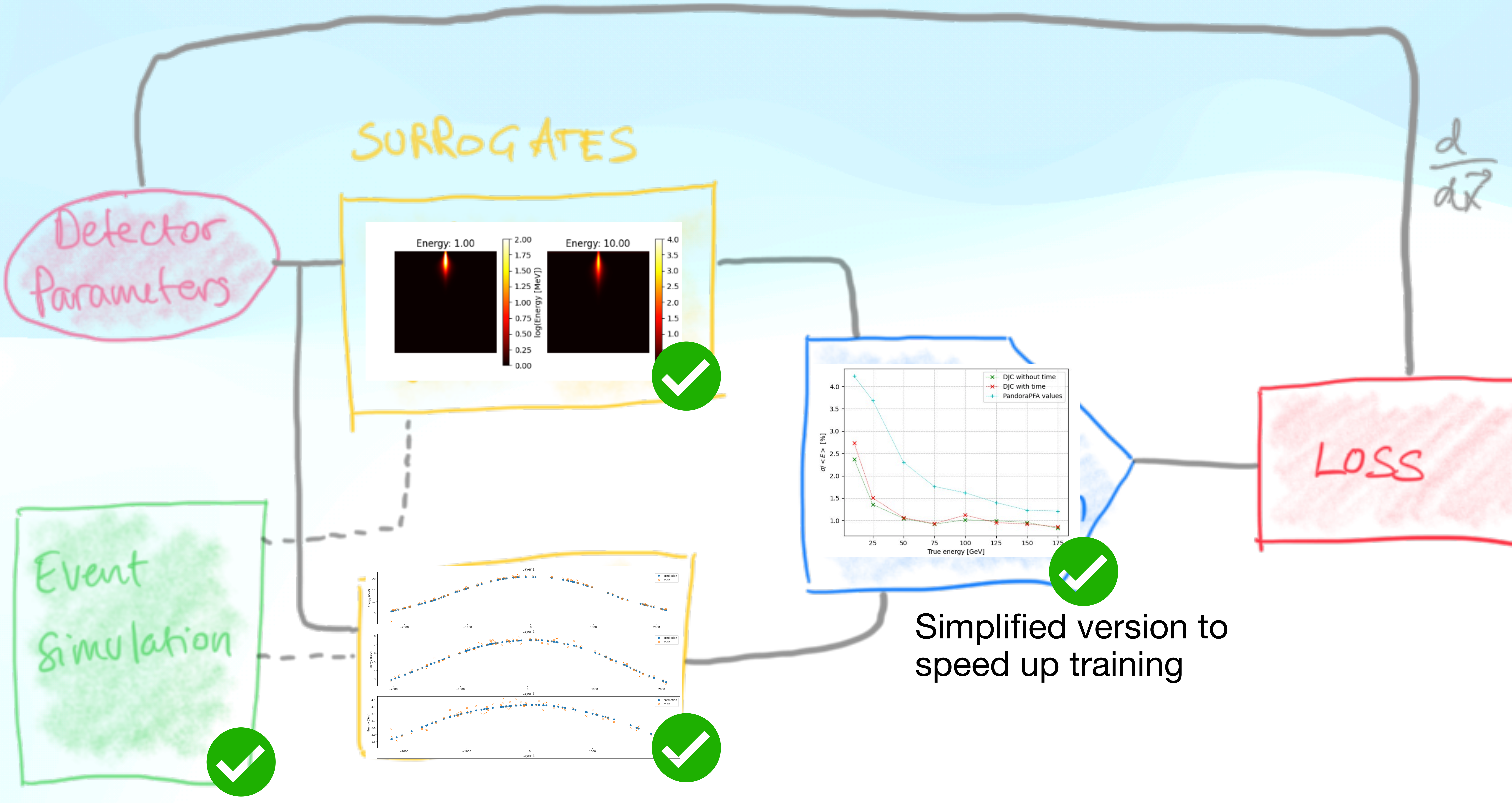


Pipeline Implementation

Summary and Status



- Photon Reconstruction efficiency
- Material cost

Summary

- Developed all necessary surrogates to run pipeline
- Need to fix the final details to launch optimization cycle
- Come up with a sensible loss, to model also material cost
- Target is to present a proof of concept. Further
- Improve surrogate accuracy
- Generalize to higher center-of-mass energies

Summary

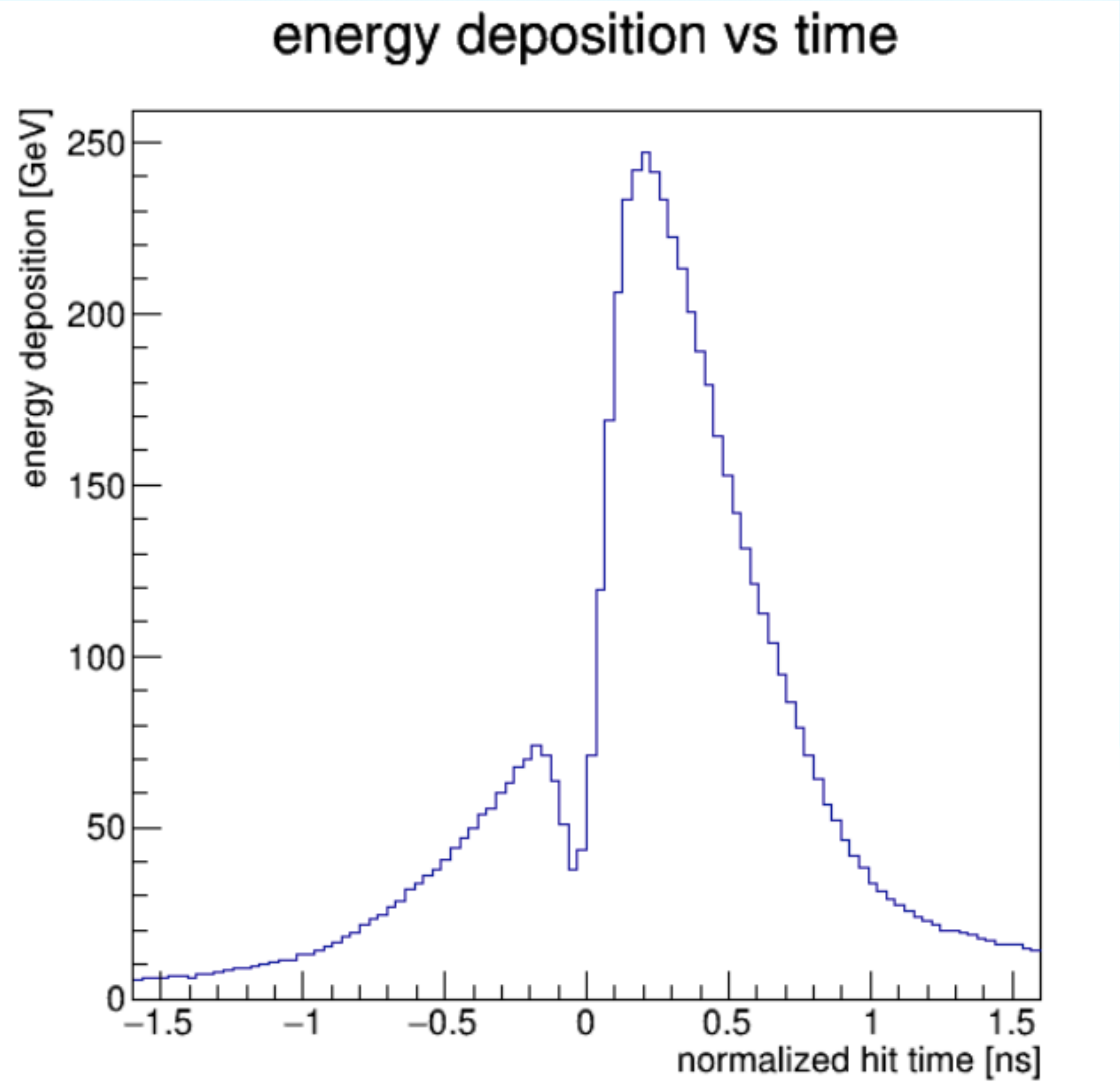
- Work ongoing, developed all necessary surrogates to run pipeline
- Need to fix the final details to launch optimization cycle
- Come up with a sensible loss, to model also material cost
- Target is to present a proof of concept. Further
- Improve surrogate accuracy
- Generalize to higher center-of-mass energies

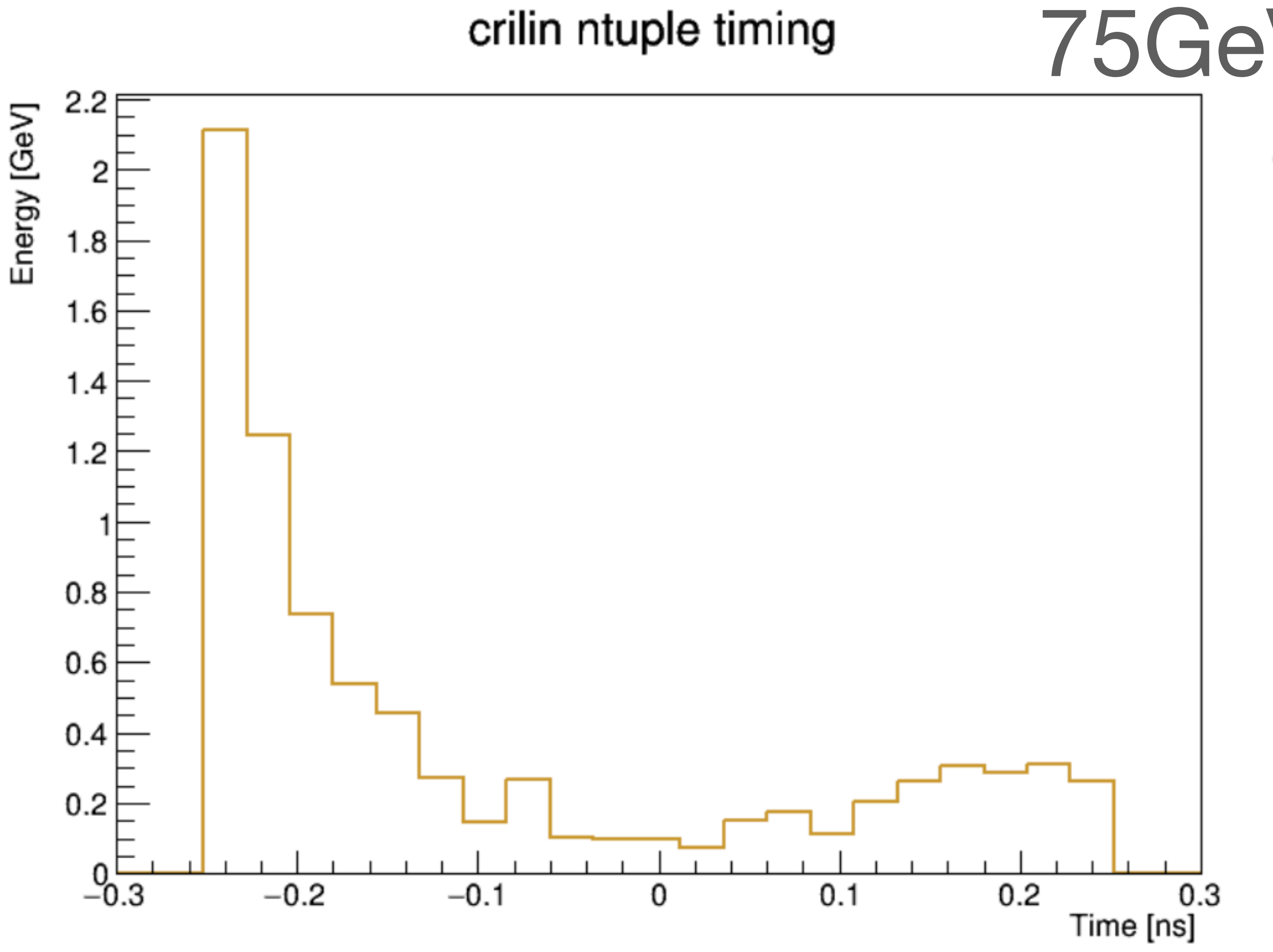
BACKUP

Testing a Reconstruction Algorithm

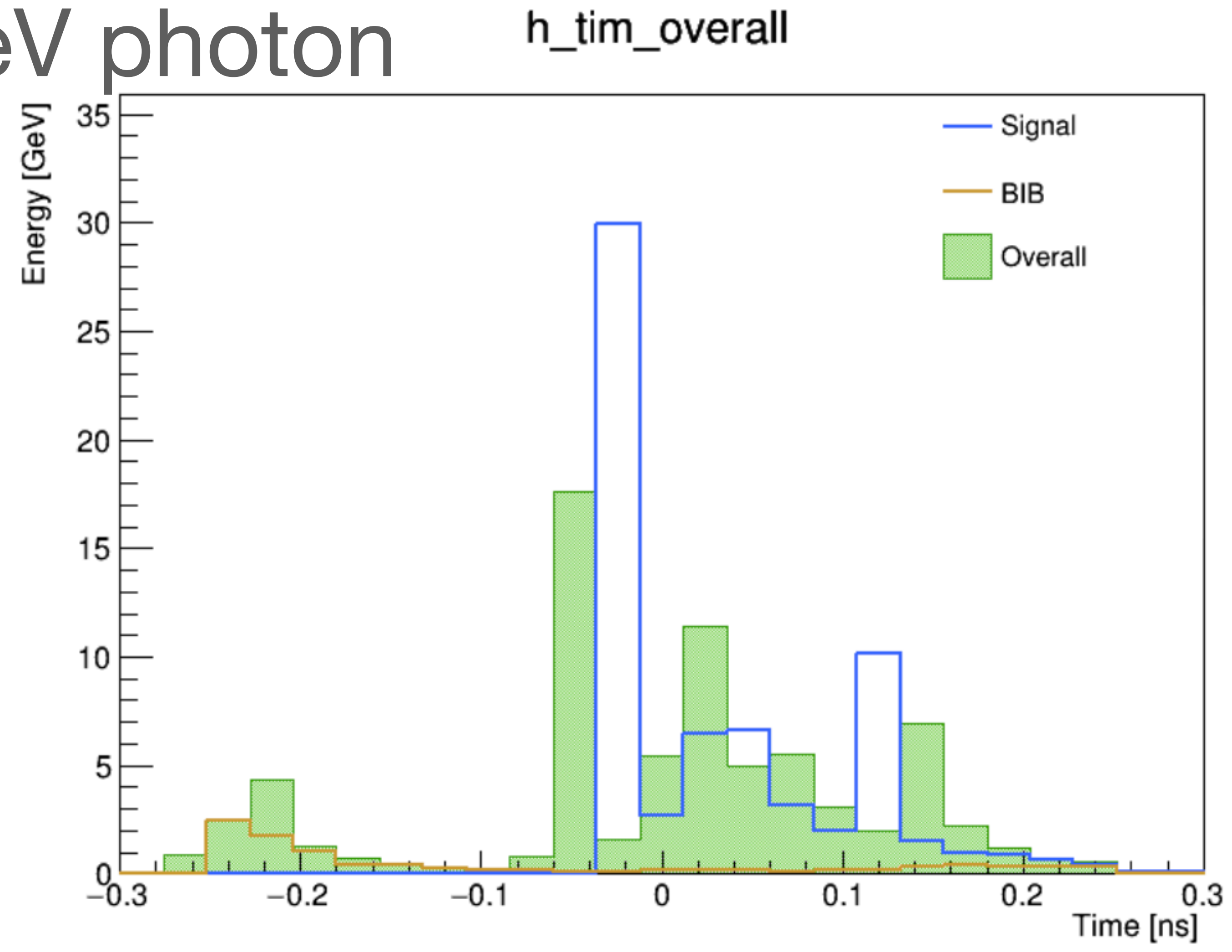
Dataset Generation - A few notes

- Applied timing cut on BIB to reduce background
- Restricted to a [-250, 250]ps window
- Implemented basic digitization:
  - Time for each cell assigned to first registered hit; energy then integrated over the whole window
  - Gaussian smearing of 20ps





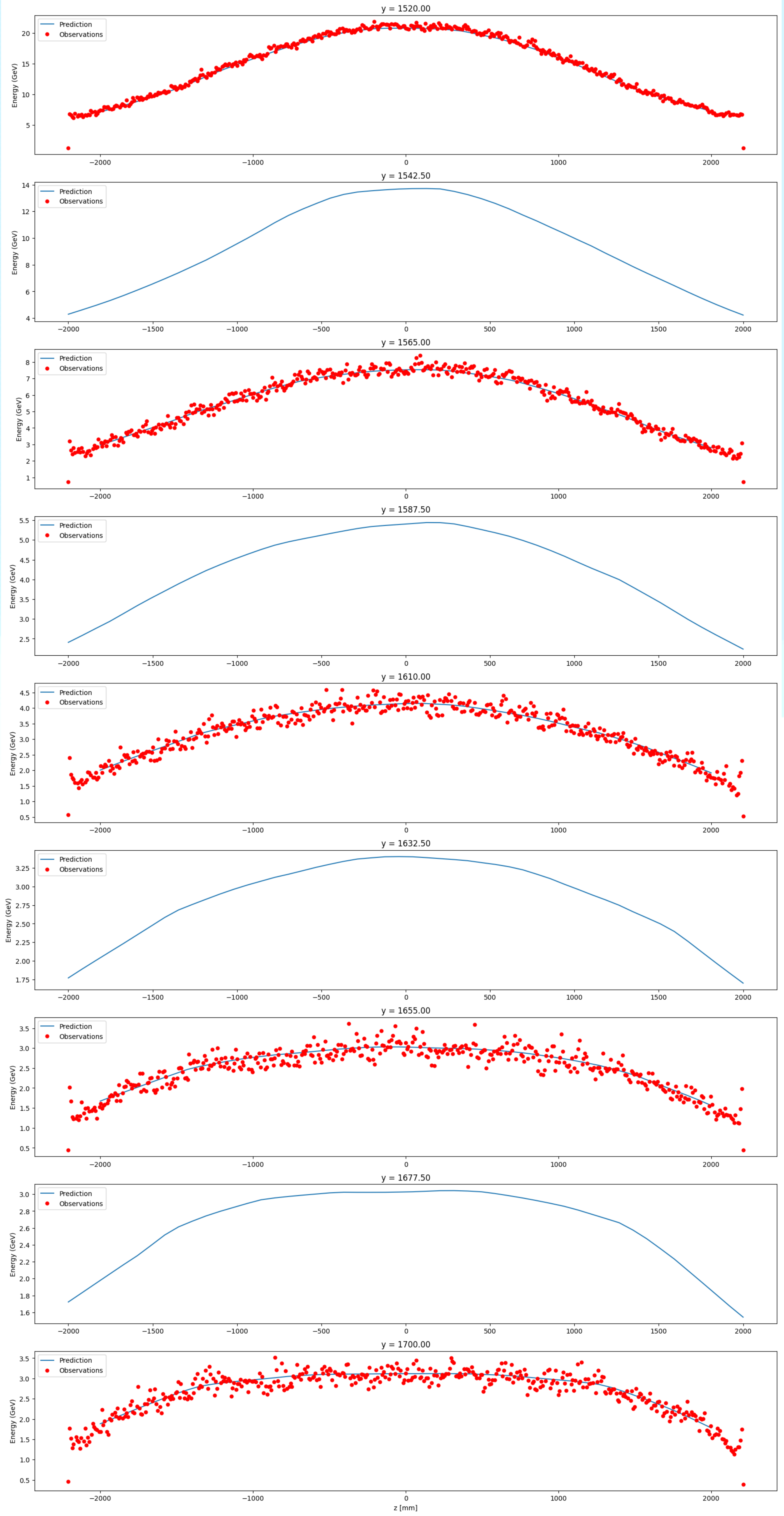
75GeV photon



Development of Surrogates

BIB generator

- Most importantly, we need to be able to interpolate when modifying the geometry
- Tested inference on intra-layer values to check consistency



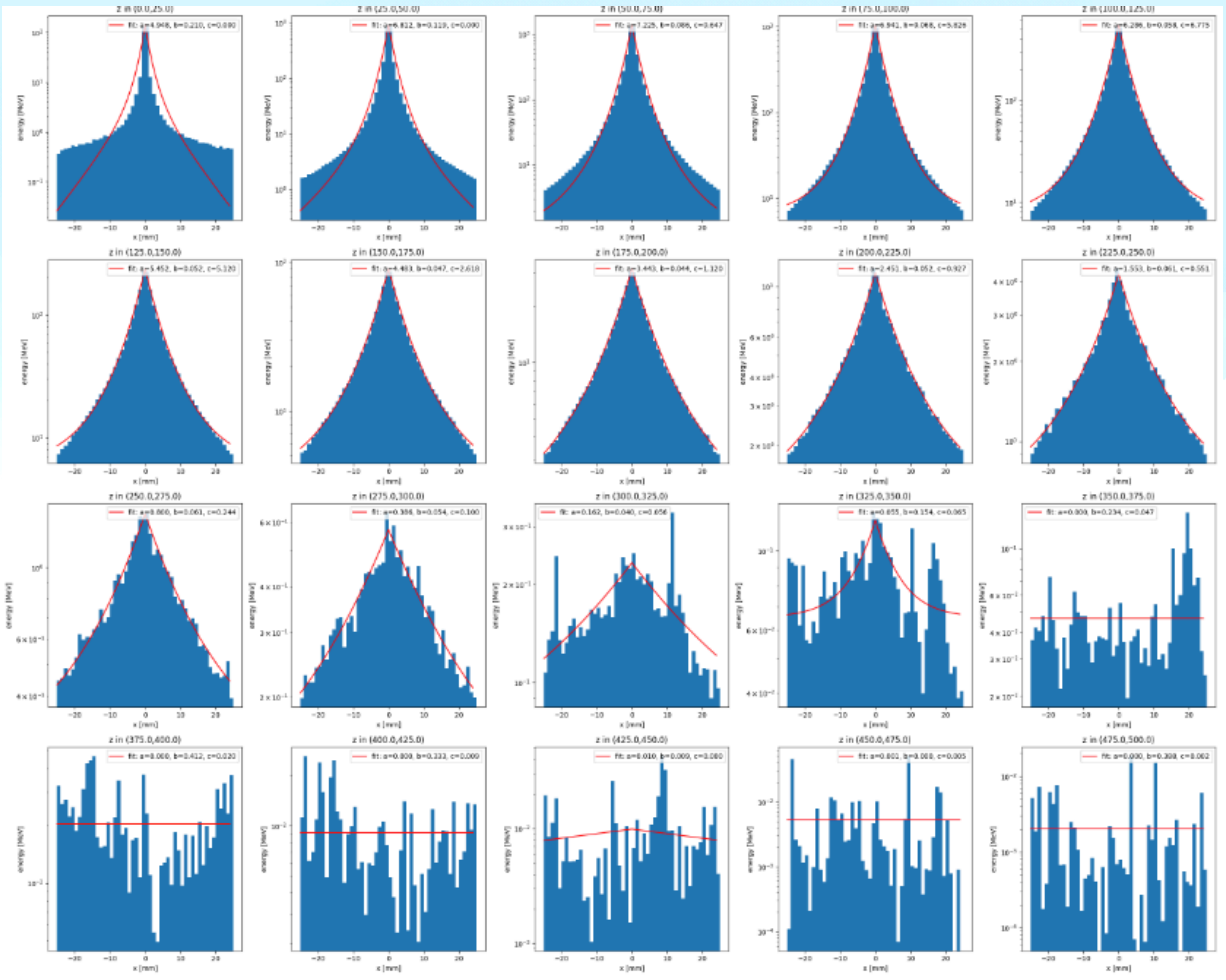
Development of Surrogates

Shower generator

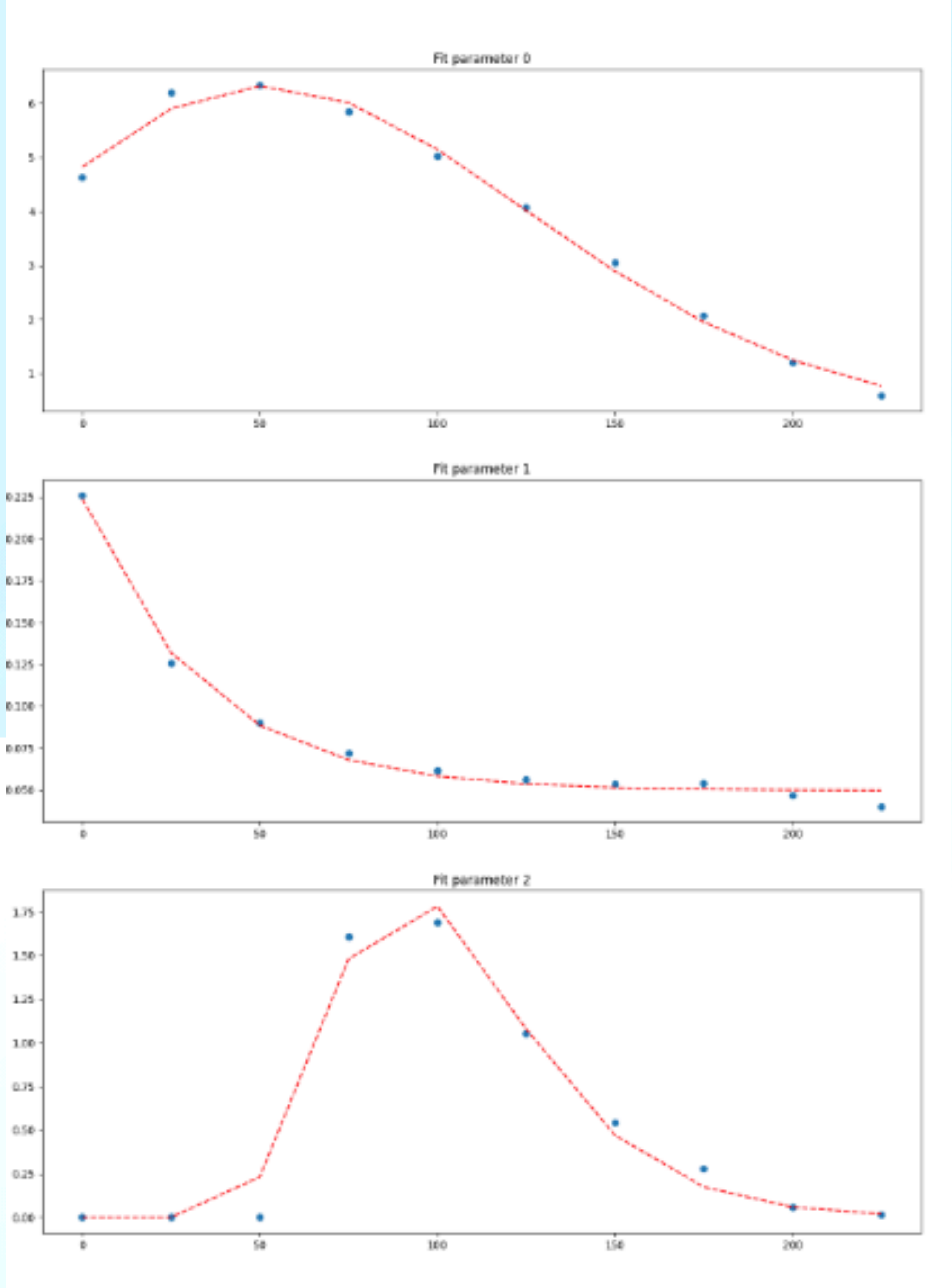
- Fitted the transverse energy distribution for 20 bins along the z-axis

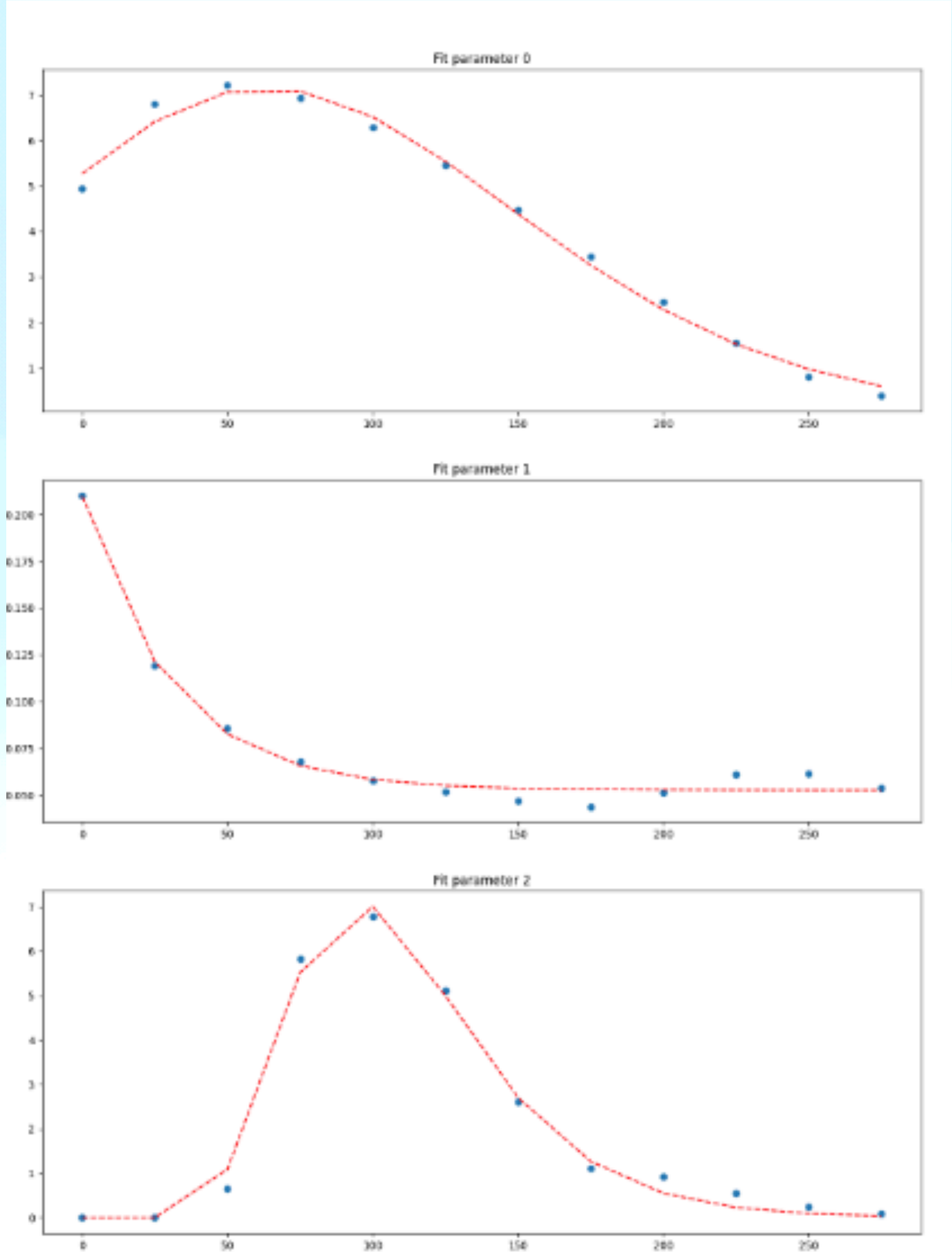
- Model the fitted coefficients as function of z, as well as the primary energy (see backup for plots)

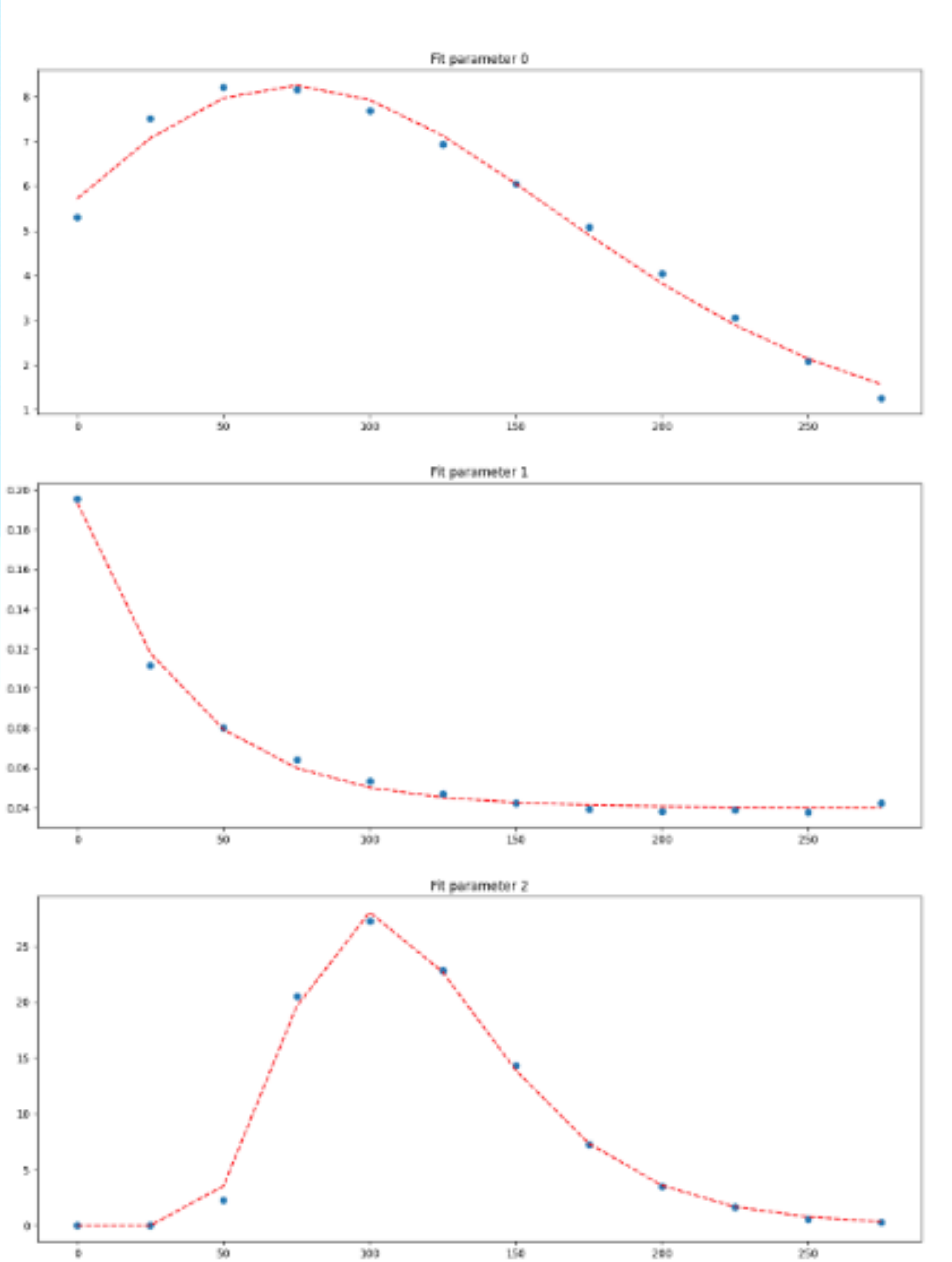
- Image for a 50GeV photon



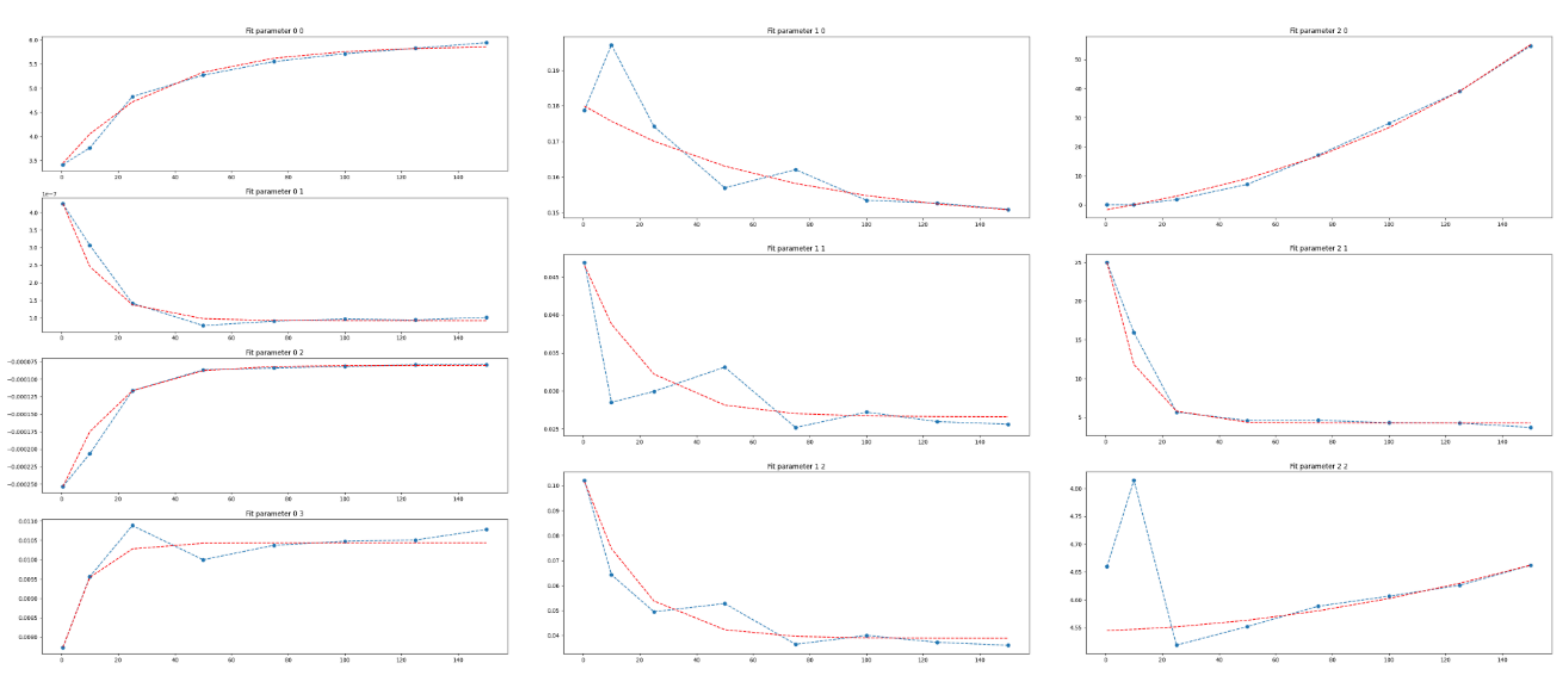
Evolution of fitted parameters along z, for 25, 75 and 150 GeV







Energy dependence of z-coefficients



Pipeline Implementation

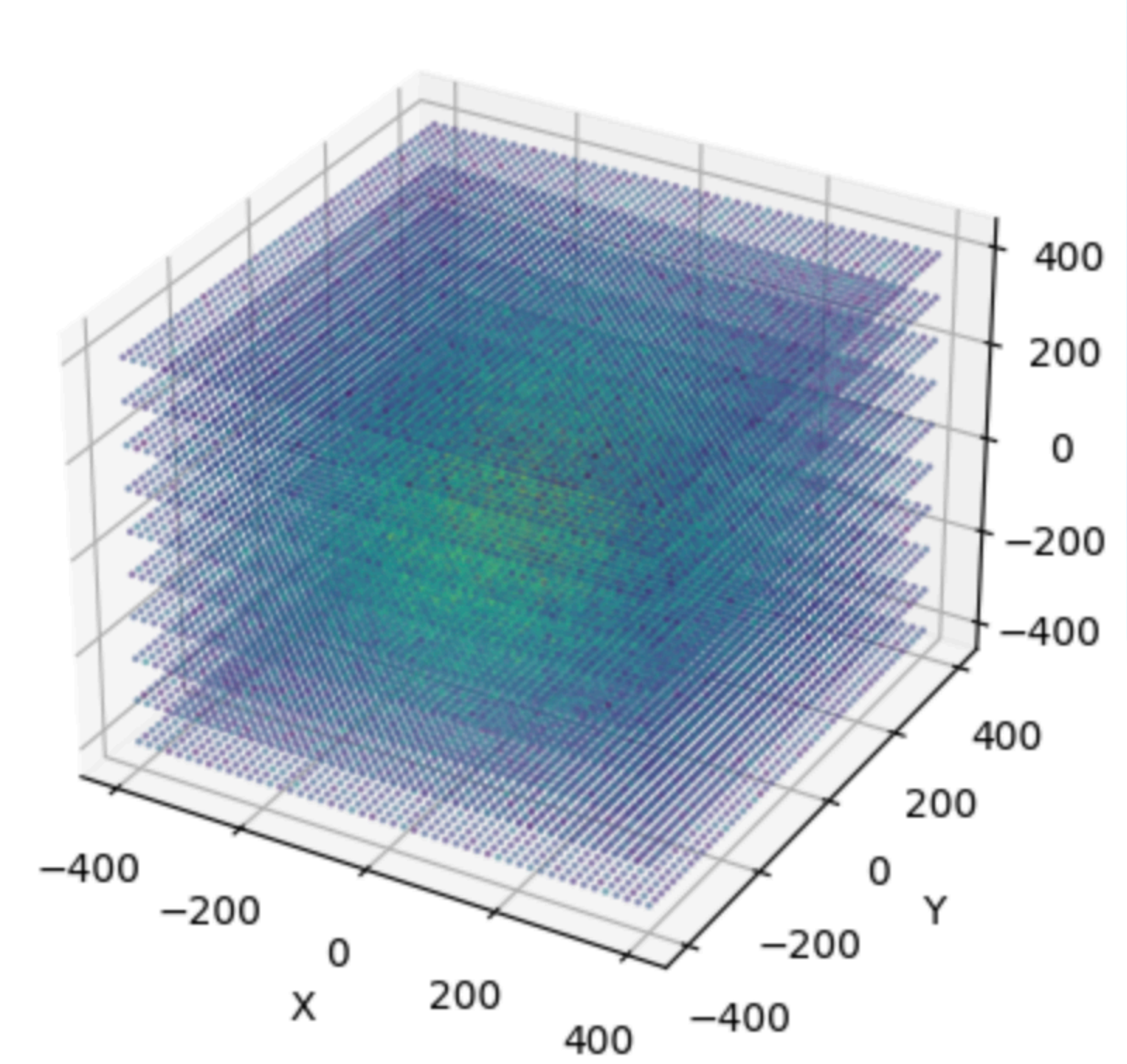
Optimization skeleton

- **Concept**: Representing geometry as a 3D grid of voxel centroids
- Optimize grid spacing parameters

  [dx, dy, dz]

- **Example**: Maximize reconstruction performance of distribution parameters

Initial spacing: [1.0 1.0 1.0]



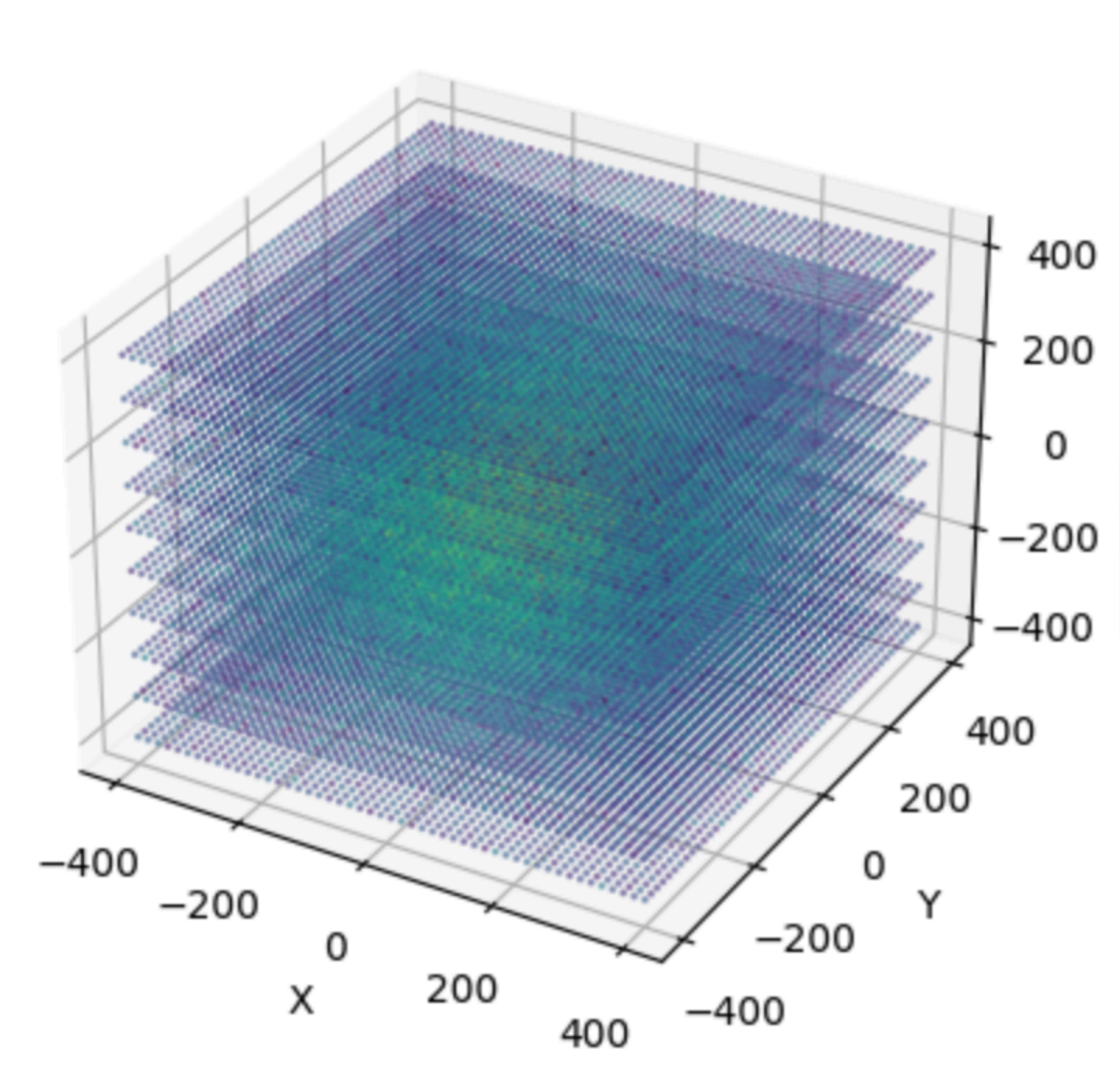

```
sigma_x = 100.
sigma_y = 120.
sigma_z = 100.
```

Pipeline Implementation

Optimization skeleton

- **Distribution**: 3D gaussian centered in 0 and with $\sigma_x=\sigma_z\neq\sigma_y$
- Evaluated on each grid point
- Superimposed with random noise on each voxel

```
Initial spacing:  [1.0   1.0   1.0]
```




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

Pipeline Implementation

Optimization skeleton

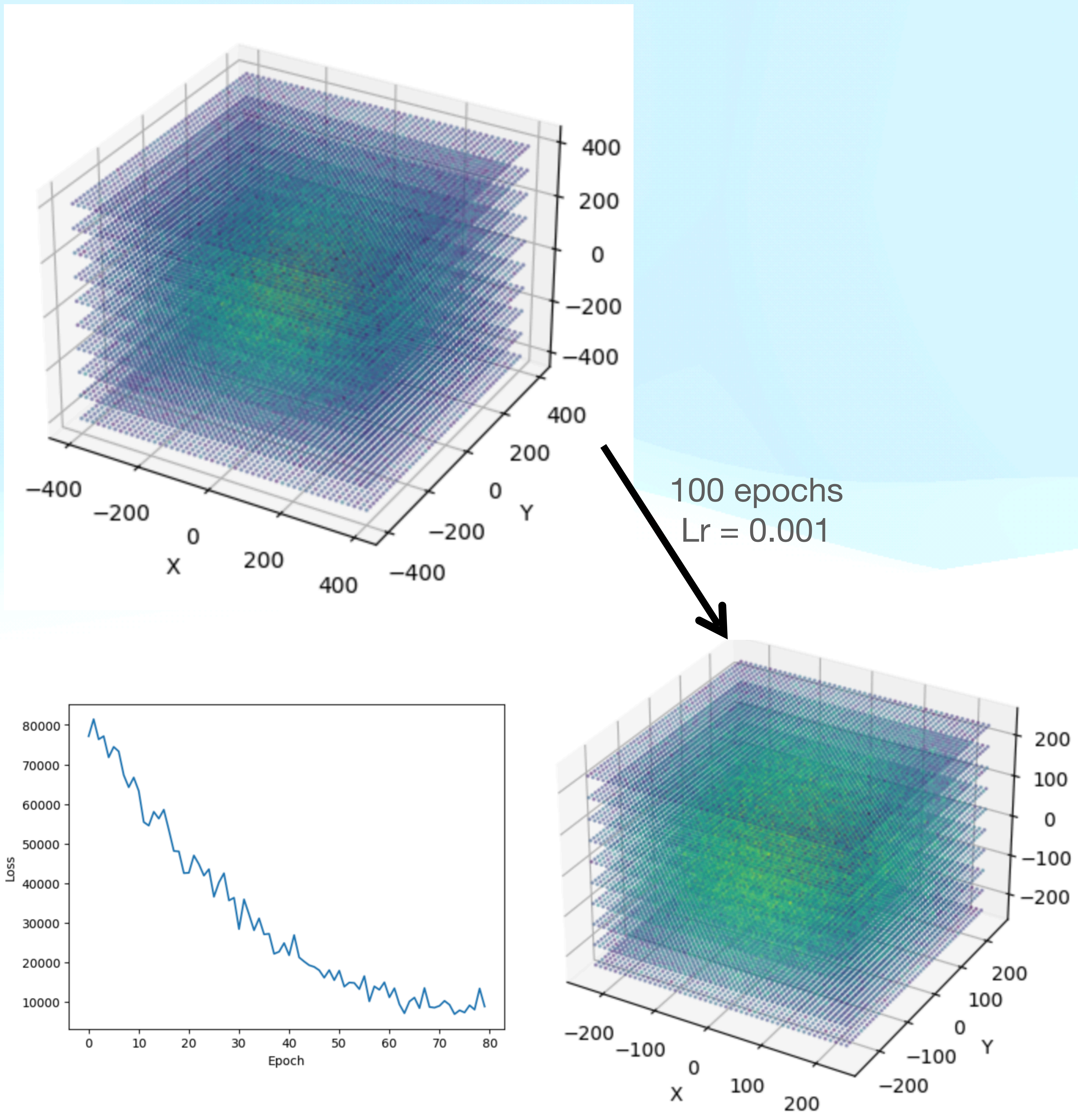
- **Reconstruction**: Use maximum-likelihood estimators to infer the gaussian parameters $\widehat{\mu}, \widehat{\sigma}$

- **Evaluating loss:** MSE for gaussian parameters + regularizer to prevent spacing to collapse towards degeneracy

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

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

```
Initial spacing:  [1.0   1.0   1.0]
```




```
Final spacing:  [0.47563136 0.5433373  0.44885612]
```

Object Reconstruction
Lighter Version

- Kept GNN core architecture
- Adapted end part to produce one scalar output
- Infer energy of primary photon in presence of BIB
- Simplify loss to speed up - clustering replaced by simple MSE