High Fidelity Simulation of High Granularity Calorimeters with High Speed

LCWS Workshop

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17.03.2021

arxiv:2005.05334

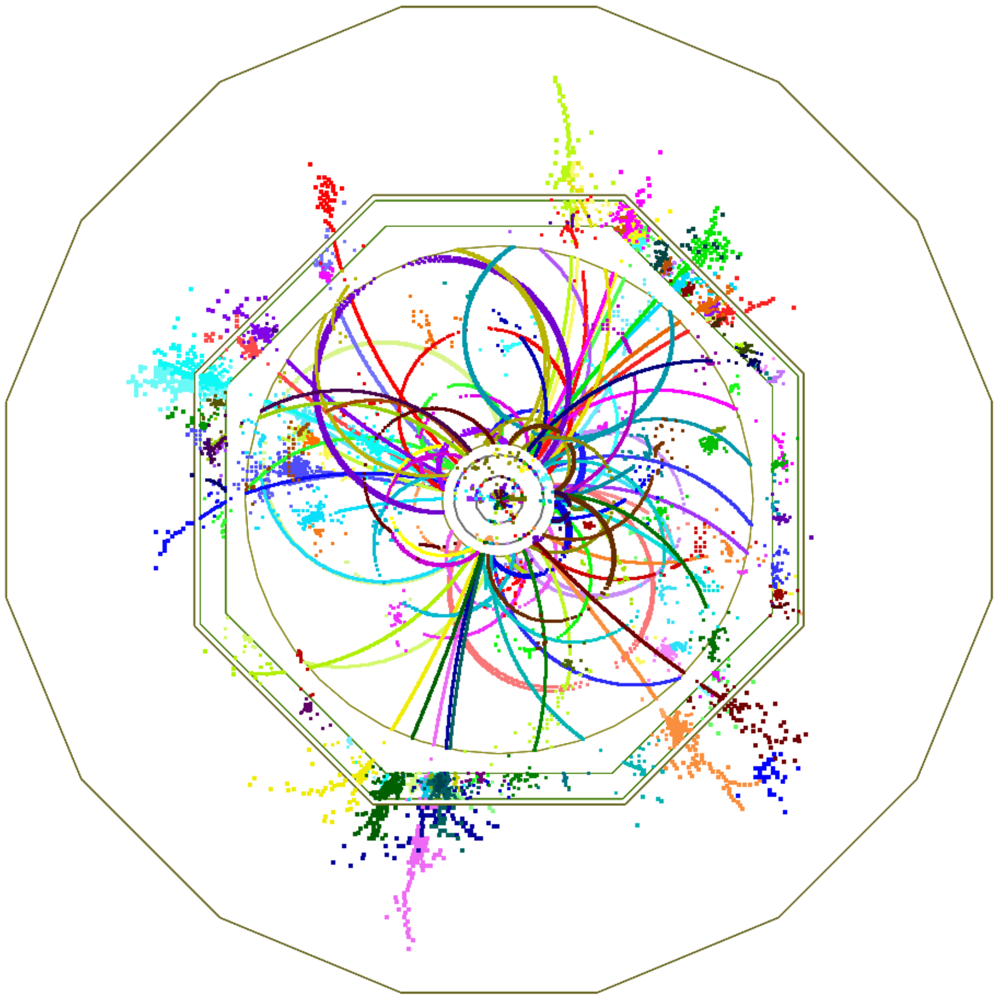
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

UHH CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

High Granularity Calorimeter

Very fine segmentation of channels

- Reconstruct all individual particle showers
- Optimised for Particle Flow Approach (PFA)
    - ✓ Improve overall precision



Examples:

- ILD detector at ILC (Higgs Factory):
    - ✳ Si-W ECAL (5x5mm) + Scintillator-Steel HCAL (30x30mm)
- CMS High Granularity Calorimeter (HGCAL)

Shower Simulation

- Particle showers in the calorimeter are simulated by Geant4
  - ✓ First-principle **physics** based simulation
- Very CPU intensive, due to large number of interacting particles

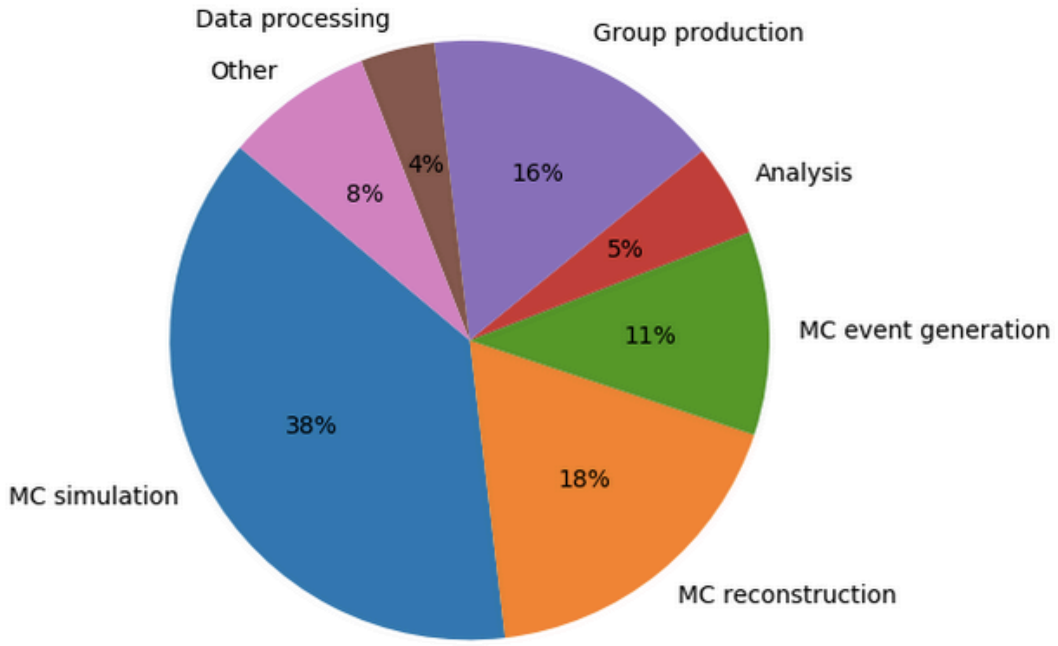


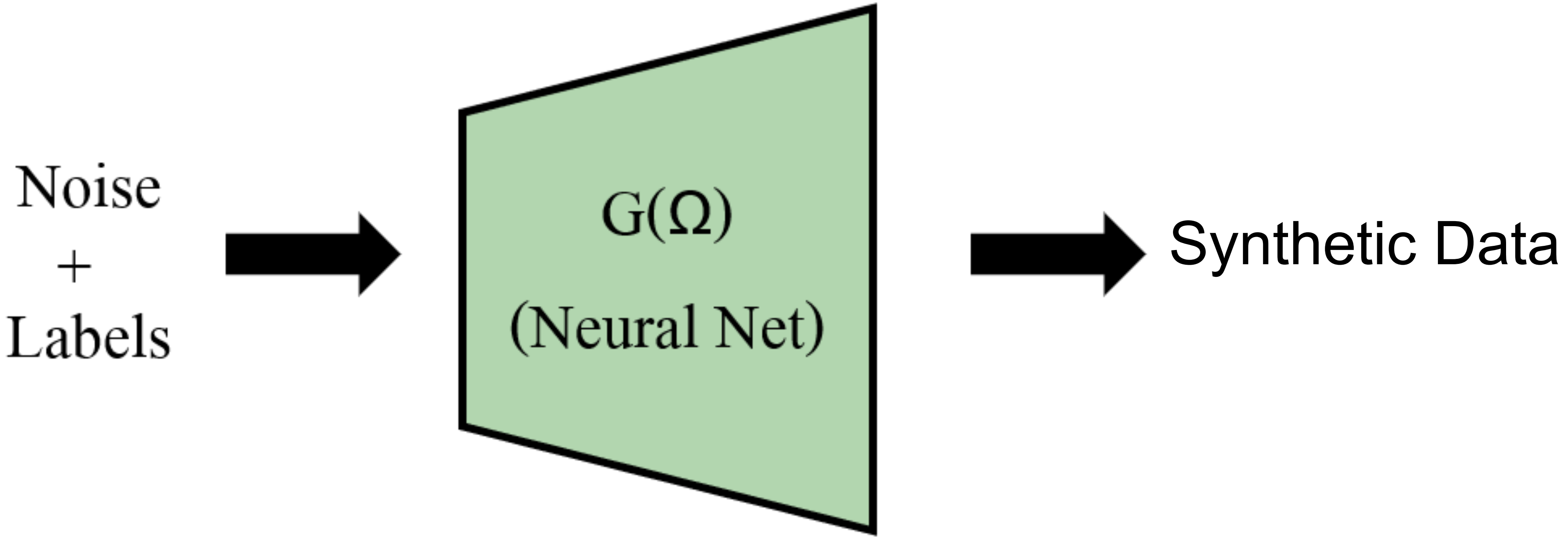
Figure from D.Costanzo, J.Catmore, LHCC meeting

Goal:

- Reproduce accurate shower simulations with a faster, powerful **generator**; based on state-of-the-art generative models
- **Enormous** amounts of **CPU time** could be potentially saved!

Generative Models

- Promising solution: **generative models**
  - Generate new samples following the distribution of original data
  - Map random noise to data
  - Conditioning

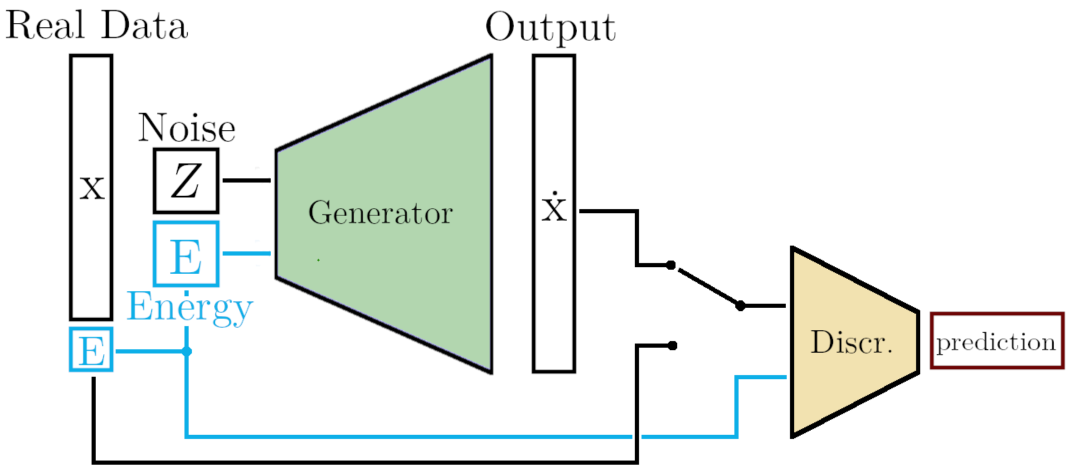


Generative Models

GAN and WGAN

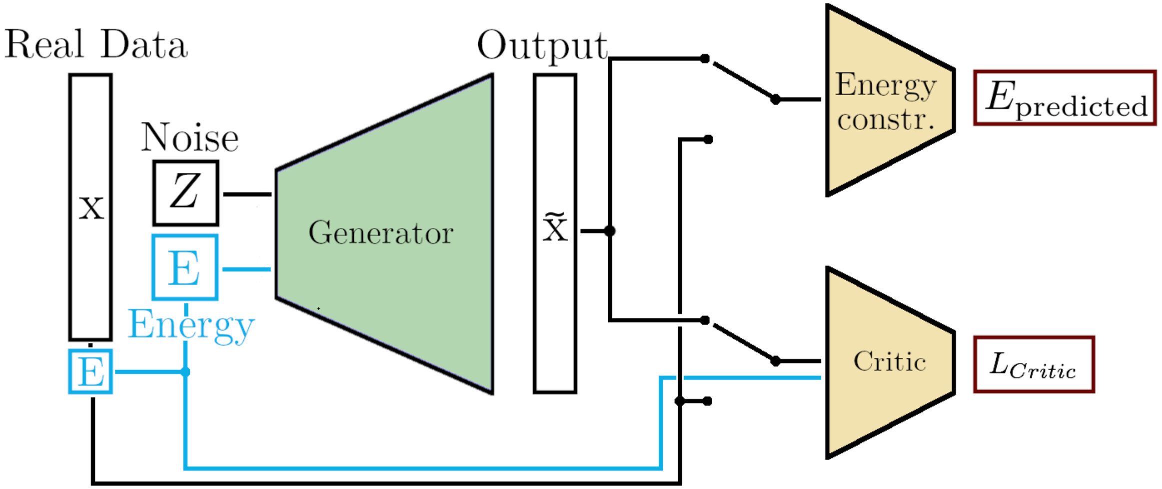
Generative Adversarial Network (GAN)

- Generator generates new fake images from noise
- Discriminator tries to differentiate: Fake or Real ?
  - ➡ Binary classification



Wasserstein GAN (WGAN)

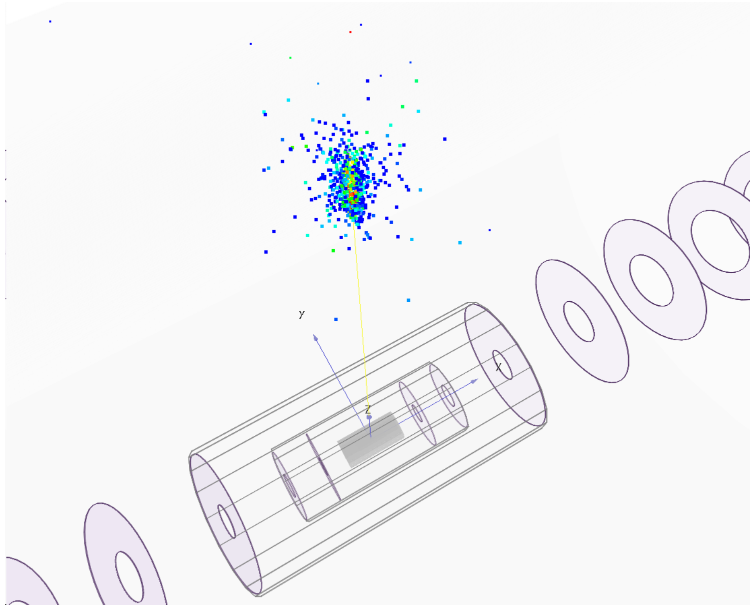
- Alternative to classical GAN training
  - ➡ Helps improve the stability of the training
  - ➡ Use Wasserstein-1 distance as a loss function
  - ➡ Critic network does regression (i.e. gives a score)
- Second network to constrain the energy

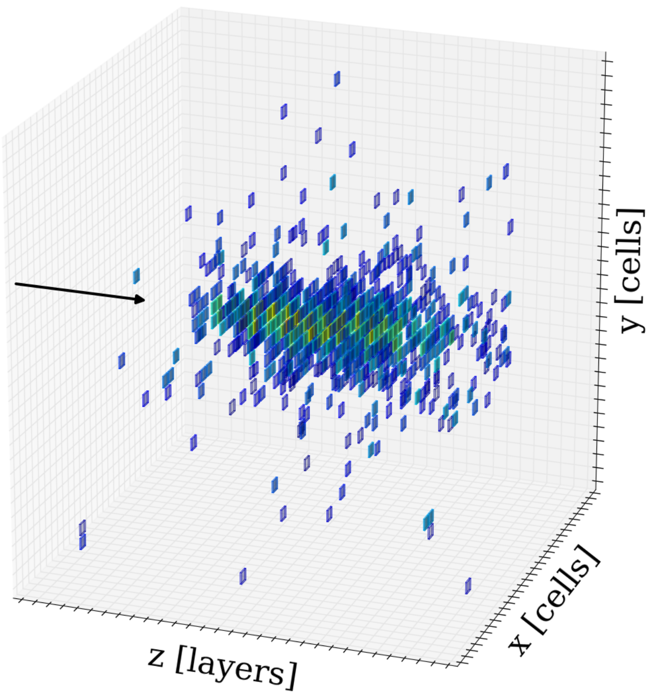


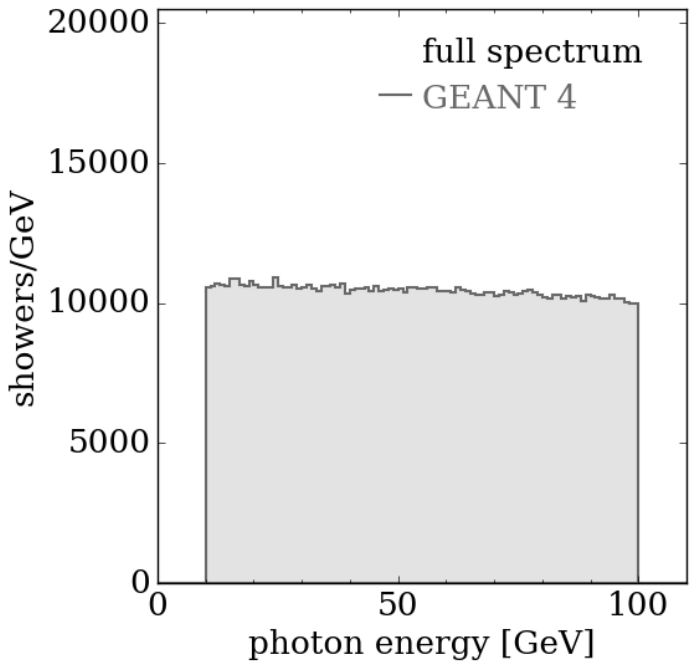
Training Data

Geant4 Simulation

- Shooting photon perpendicular to the ILD-ECAL (Si-W)
    - ◉ Constant incident point
    - ◉ 950k photon showers
    - ◉ Photon energy: 10-100 GeV, continuous!
    - ◉ 30x30x30 pixels, centered on beam

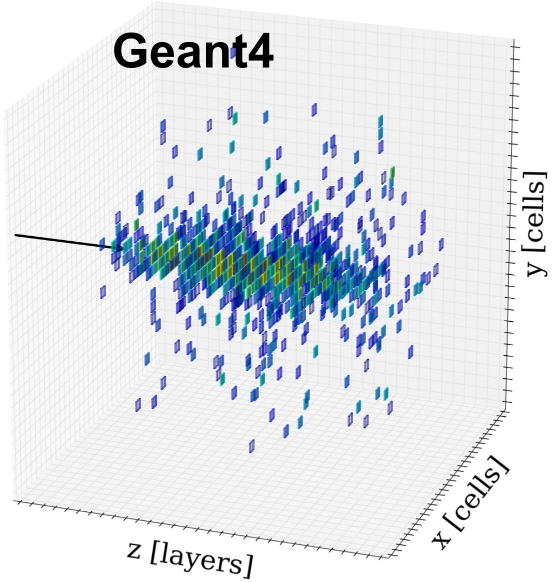


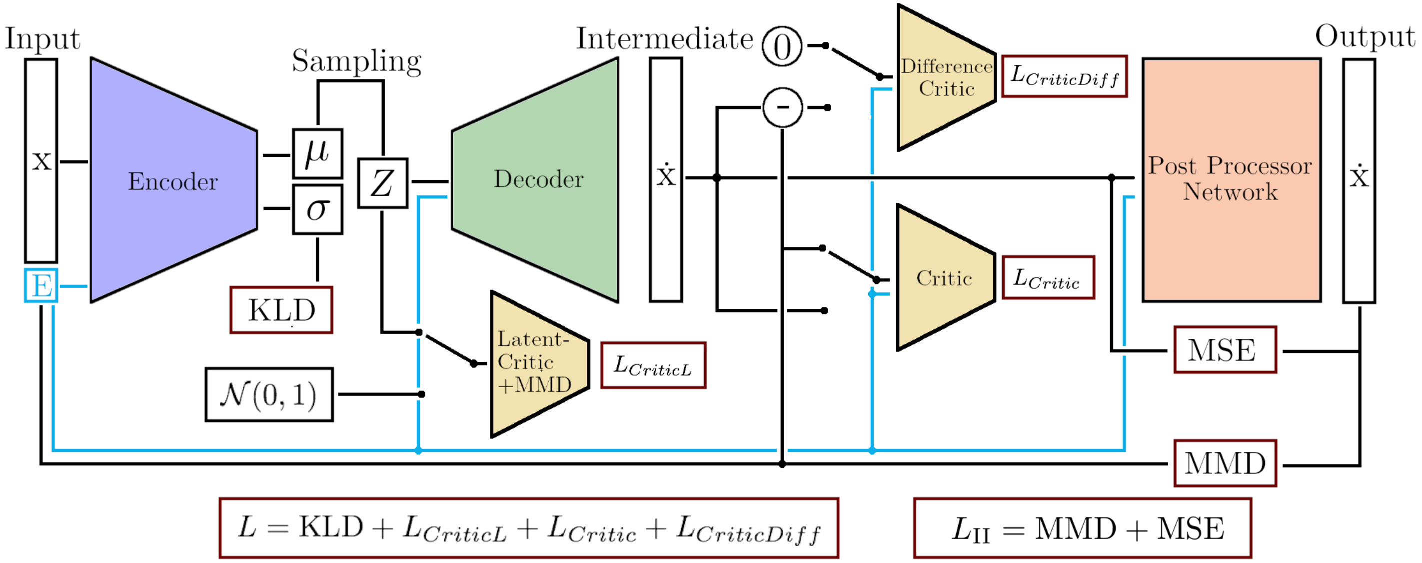


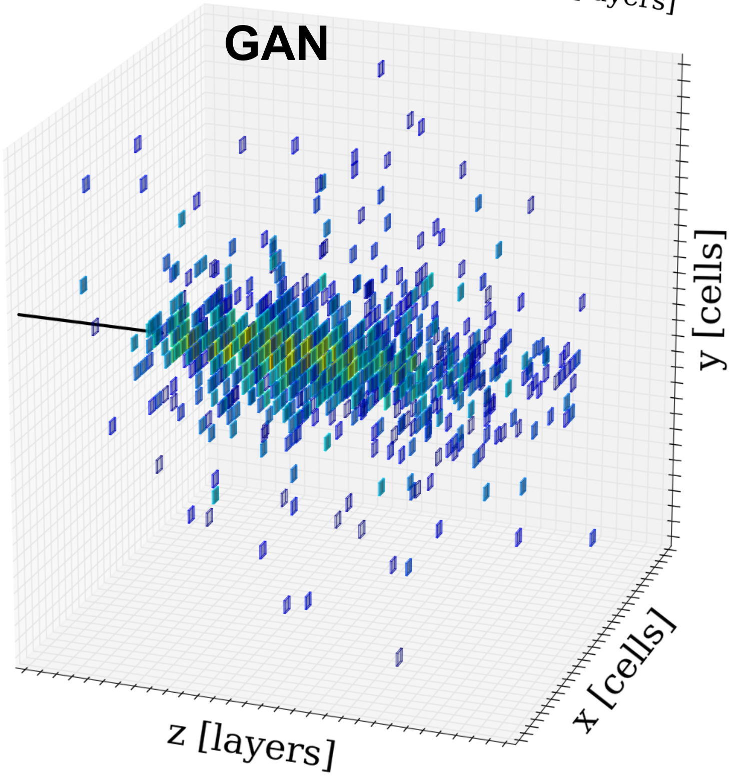


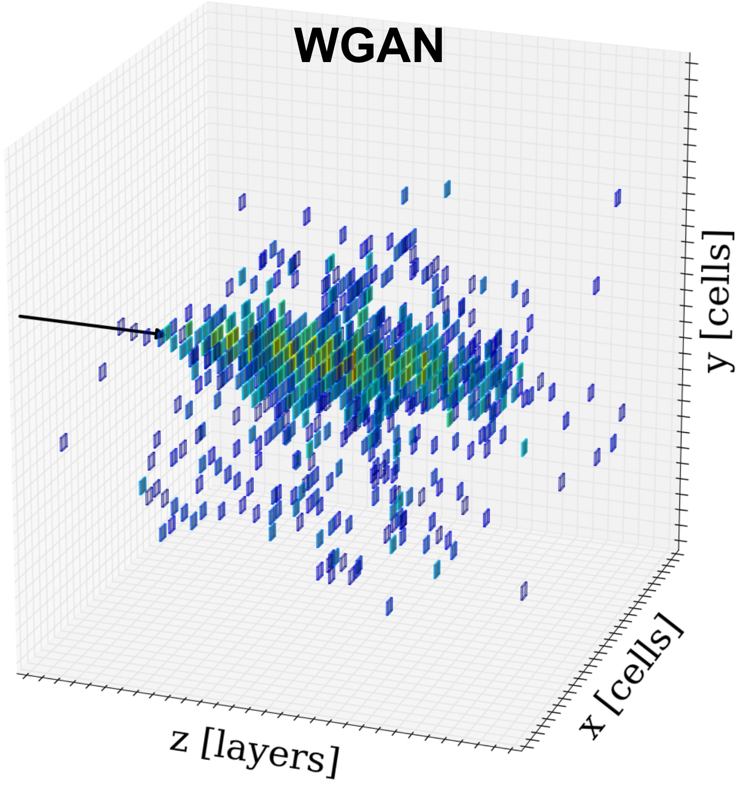
Results

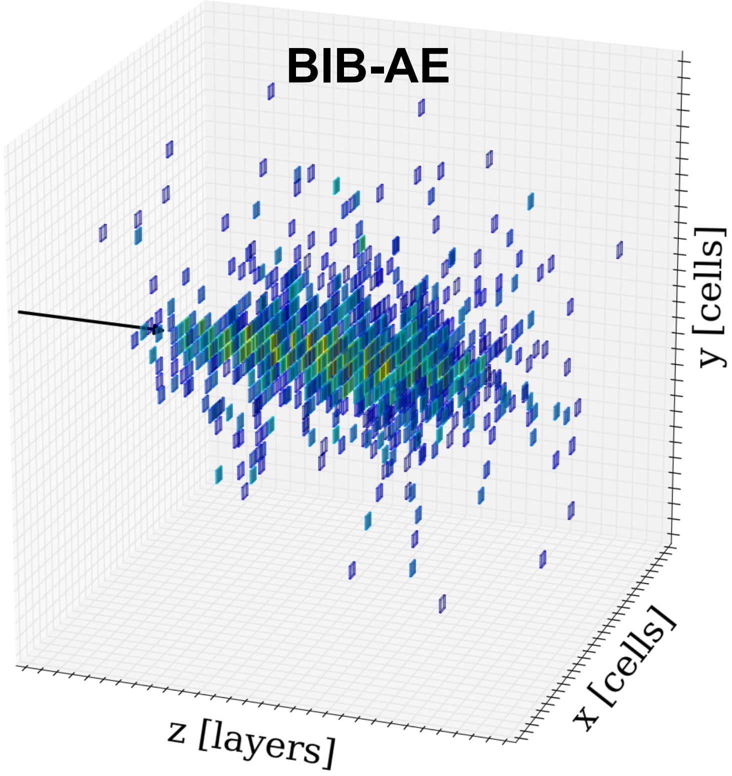
realistic???



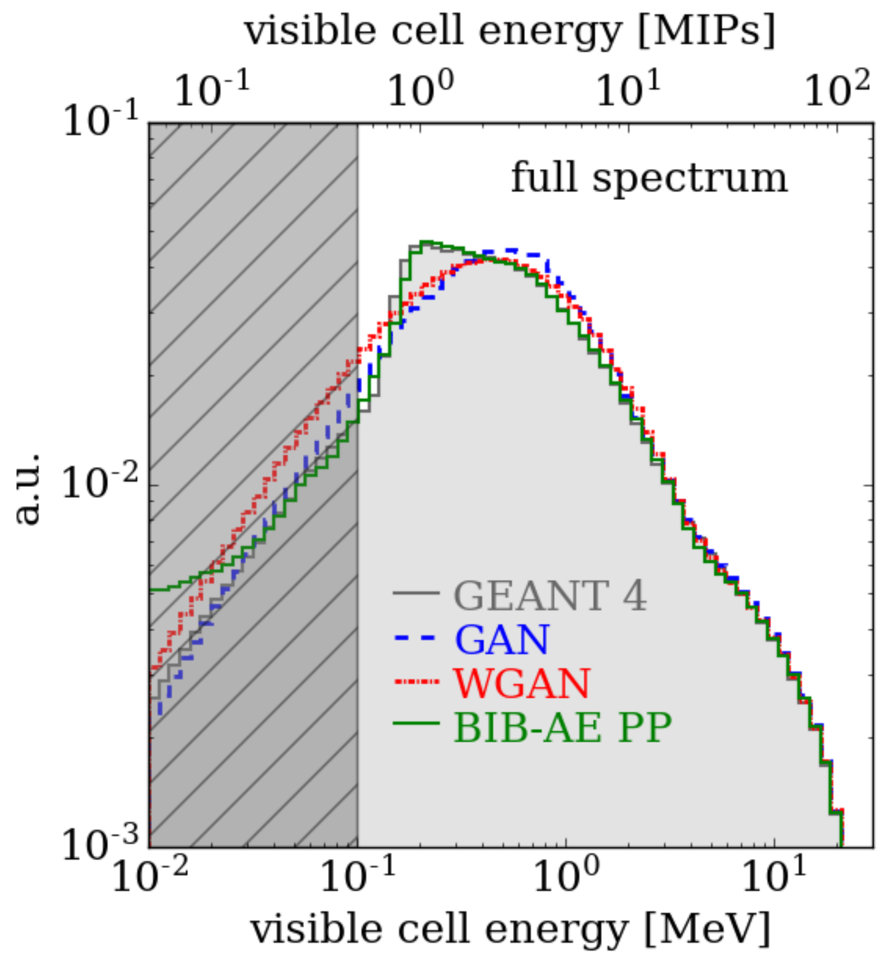


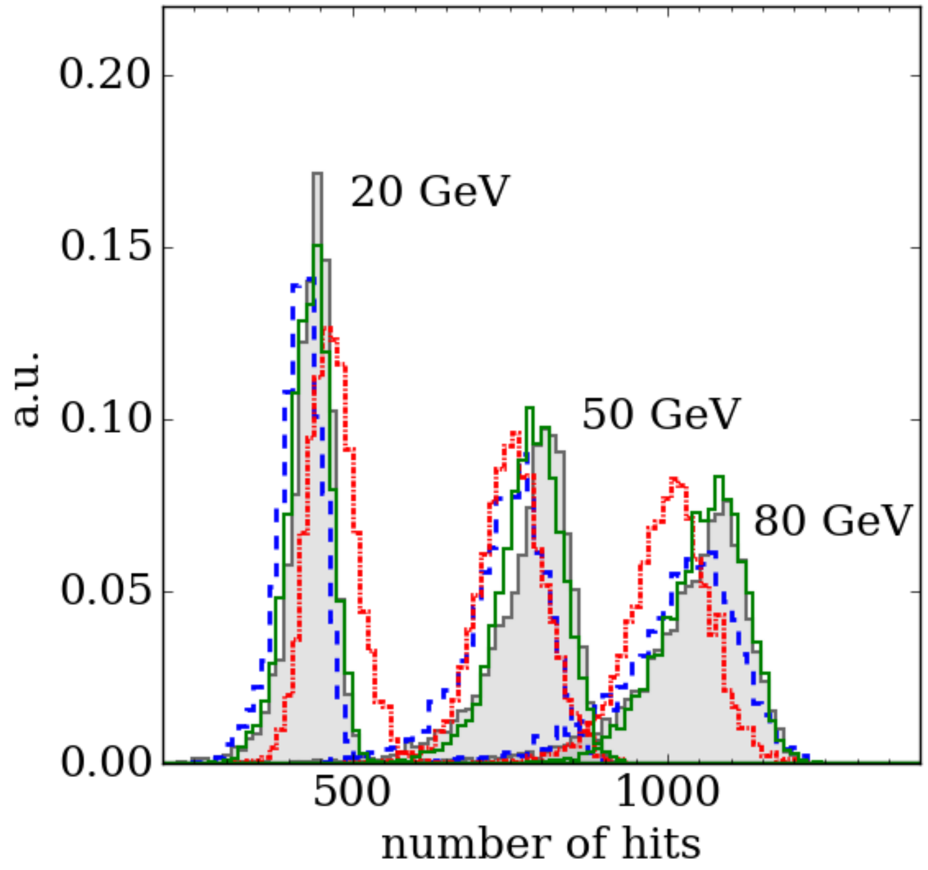






Results: Cell energy and Number of hits

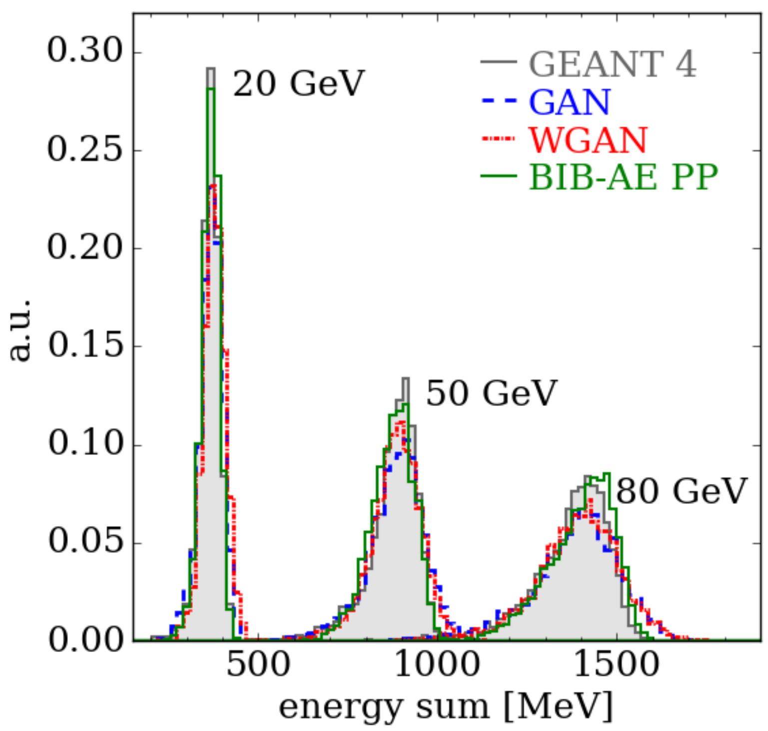


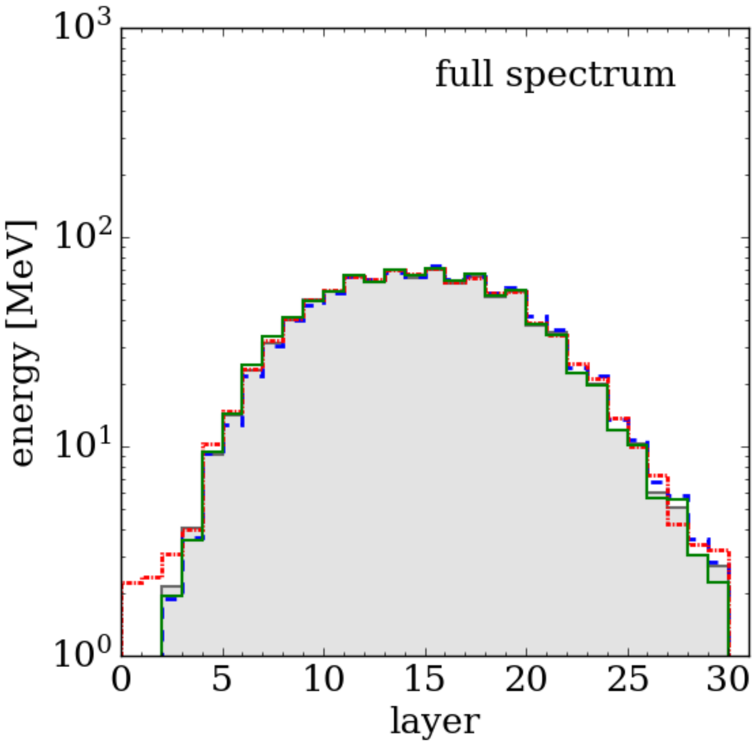


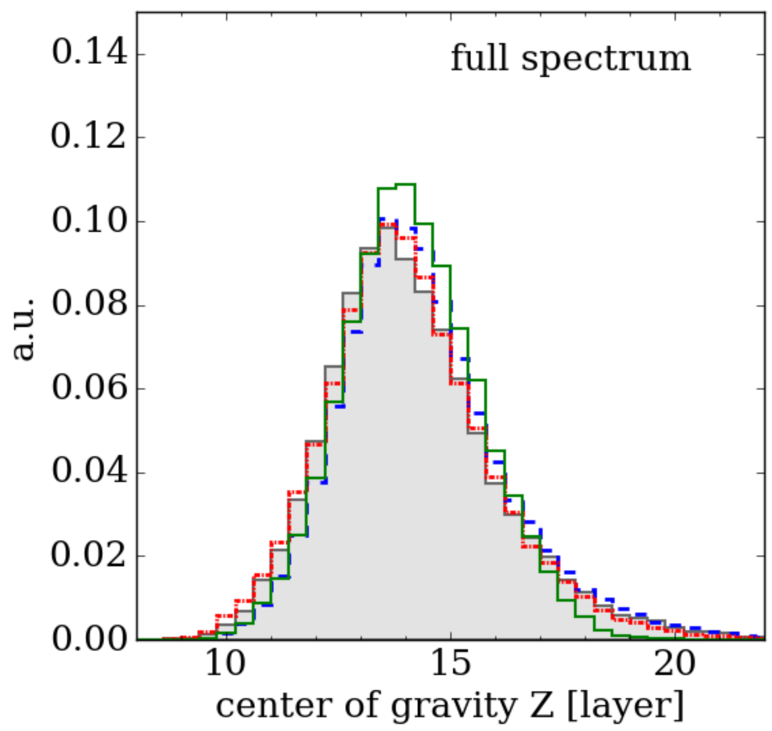
- Both GAN and WGAN fail to capture MIP bump around 0.2 MeV
- ✓ BiB-AE is able to produce this feature thanks to Post-Processing network

- GAN and WGAN slightly underestimate the total number of hits
- ✓ BiB-AE reproduces the shape and width

Results: Other important distributions







✓ the shape, center and width of the peak are well reproduced for all models

✓ reproduce the bulk of the distributions very well.

- slight deviations for the WGAN appear around the edges

- Deviations for BiB-AE:
  - ✓ Explainable via latent space encoding
  - ✓ Recent publication [arxiv: 2102.12491]

Computation Time

Simulator	Hardware	Batch Size	15 GeV	Speed-up	10-100 GeV Flat	Speed-up
GEANT4	CPU	N/A	1445.05 ± 19.34 ms	-	4081.53 ± 169.92 ms	-
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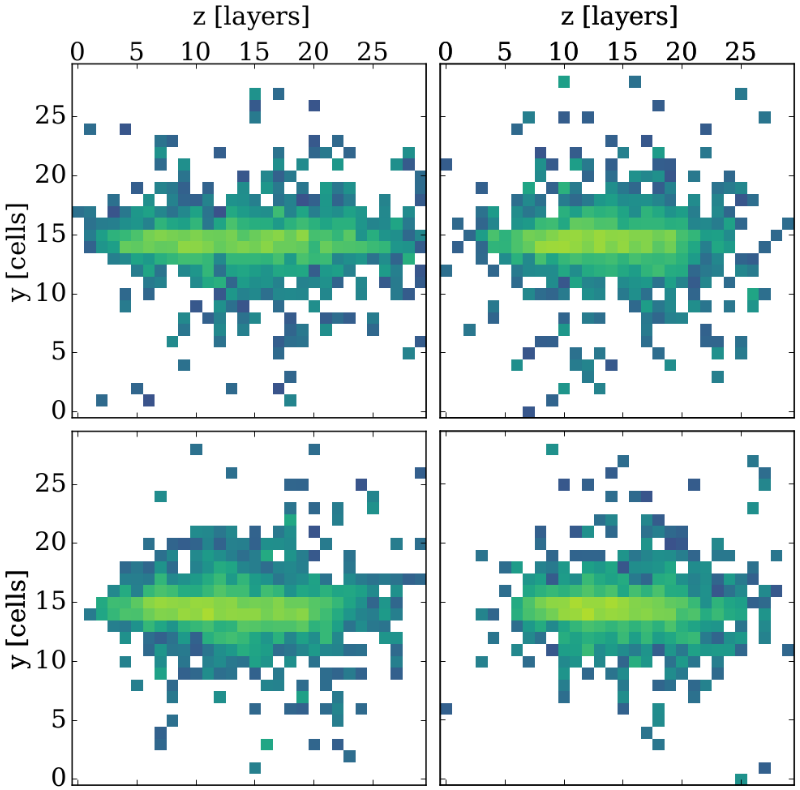
For 10-100 GeV showers, BiB-AE and WGAN

- 3 orders of magnitude speed-up on **GPU**
- 2 orders of magnitude speed-up on **CPU**

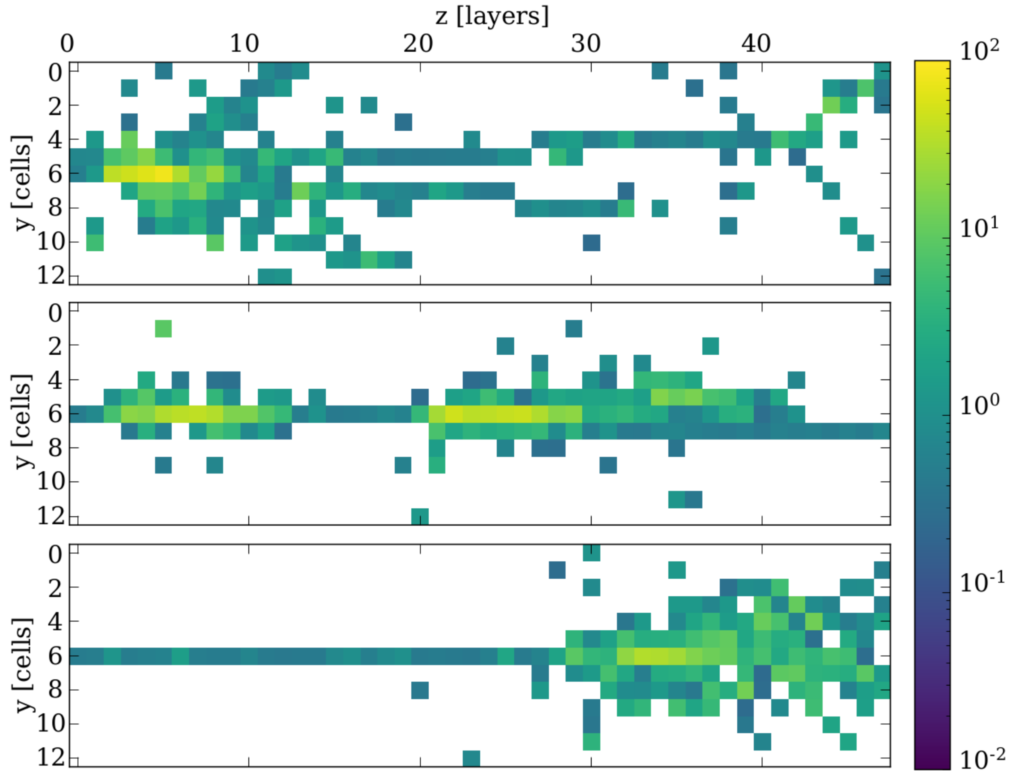
Hadron Showers

very preliminary

- After success with GAN based simulation for electromagnetic showers, we started to address hadronic (pion) showers
- Much more complex shower structure
- Currently training with a smaller 3D image containing only the **shower core**
- Started with GAN, WGAN, BIB-AE and alternatives

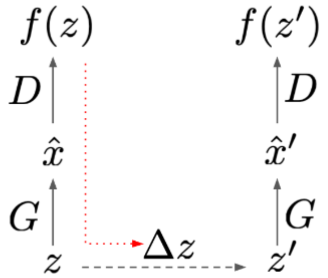


photon showers **vs.** **pion showers**



A new WGAN

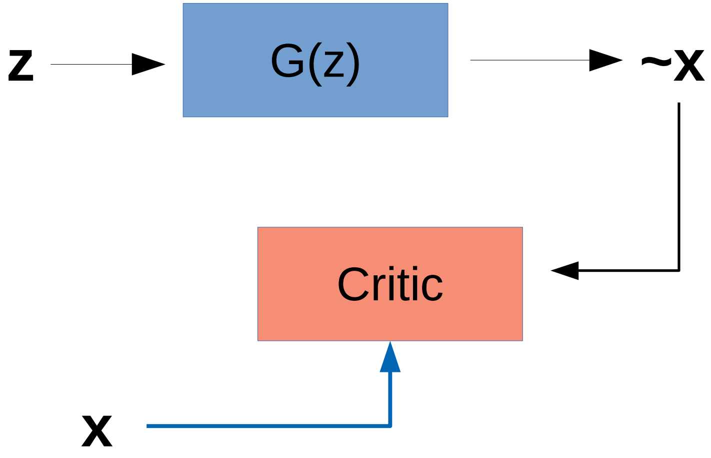
- Trained on pion showers. Approx half a million
- Shower is 48x13x13
- Architectures
  - very similar to WGAN in our “getting high paper”
  - Latent Optimized WGAN, inspired by DeepMind

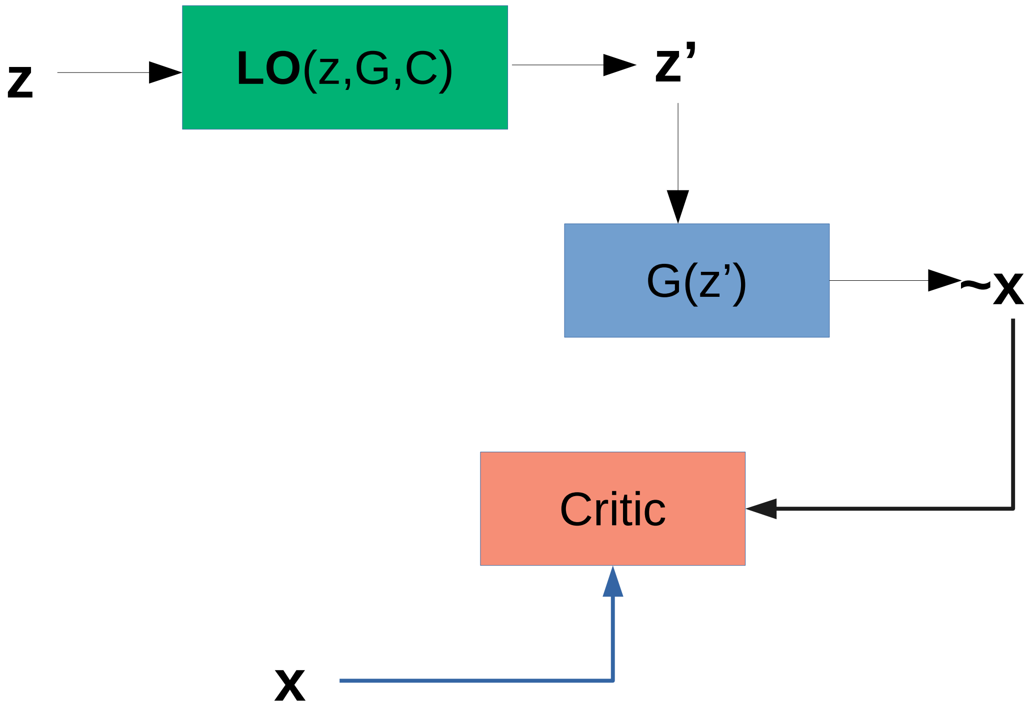


arXiv: 1912.00953

Figure 3: (**a**) Schematic of LOGAN. We first compute a forward pass through G and D with a sampled latent z. Then, we use gradients from the generator loss (dashed red arrow) to compute an improved latent, z'. After we use this optimised latent code in a second forward pass, we compute gradients of the discriminator back through the latent optimisation into the model parameters θ_D, θ_G. We use these gradients to update the model. (**b**) Truncation curves illustrate the FID/IS trade-off

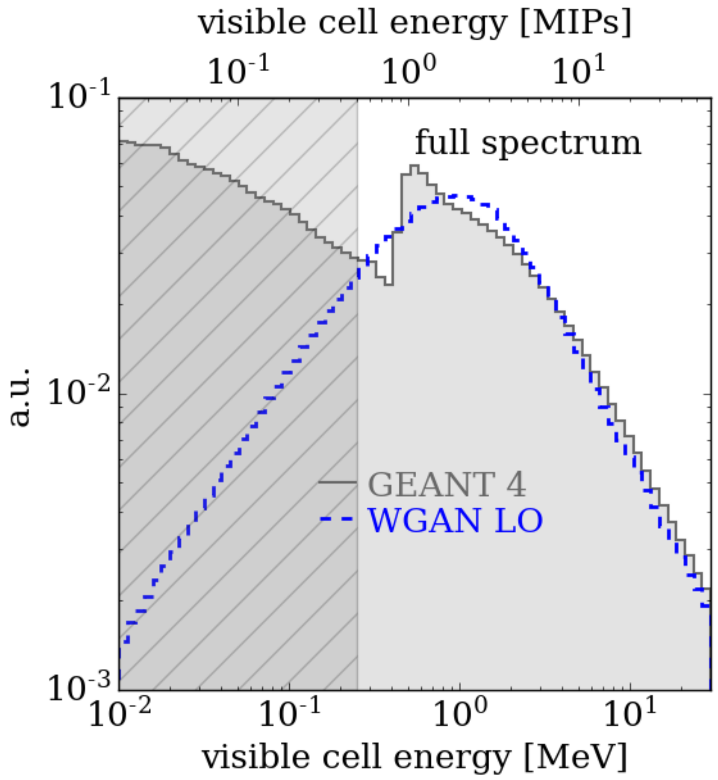
Our classical WGAN

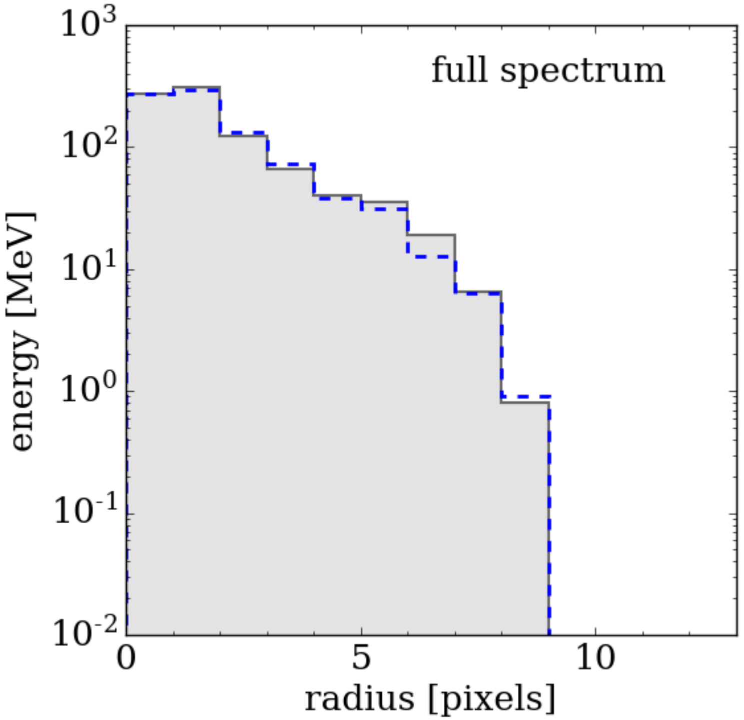


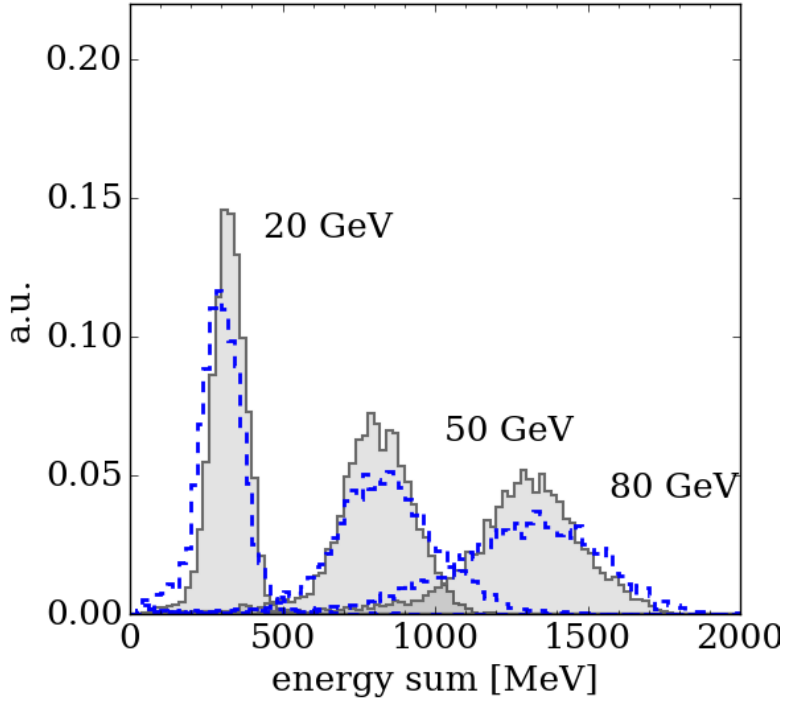


Hadron Showers

very preliminary results



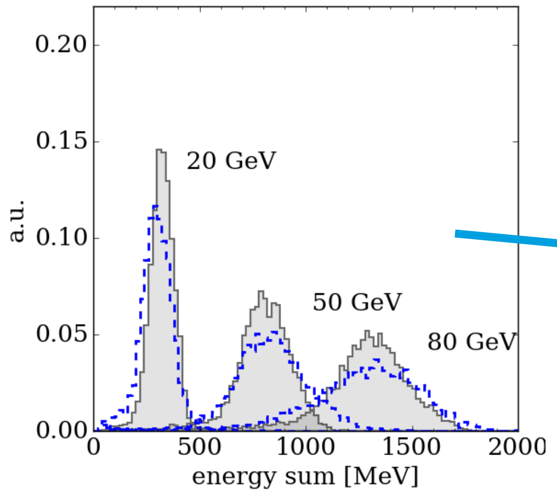


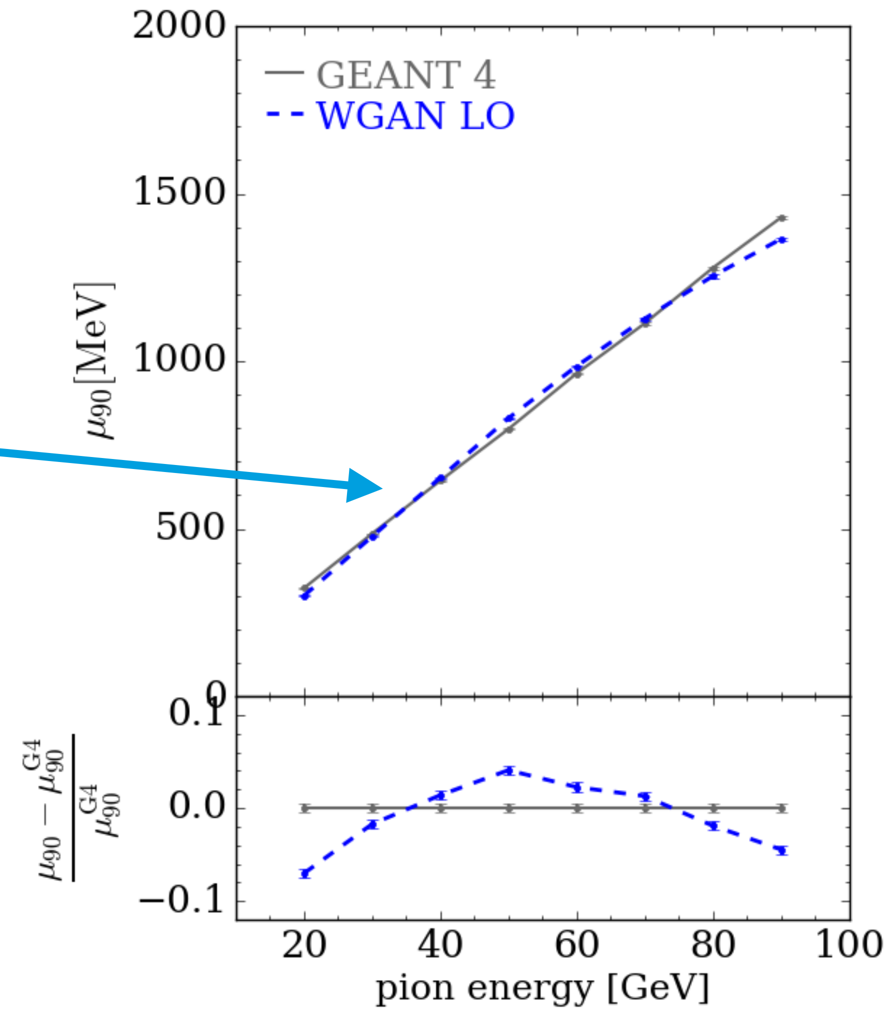


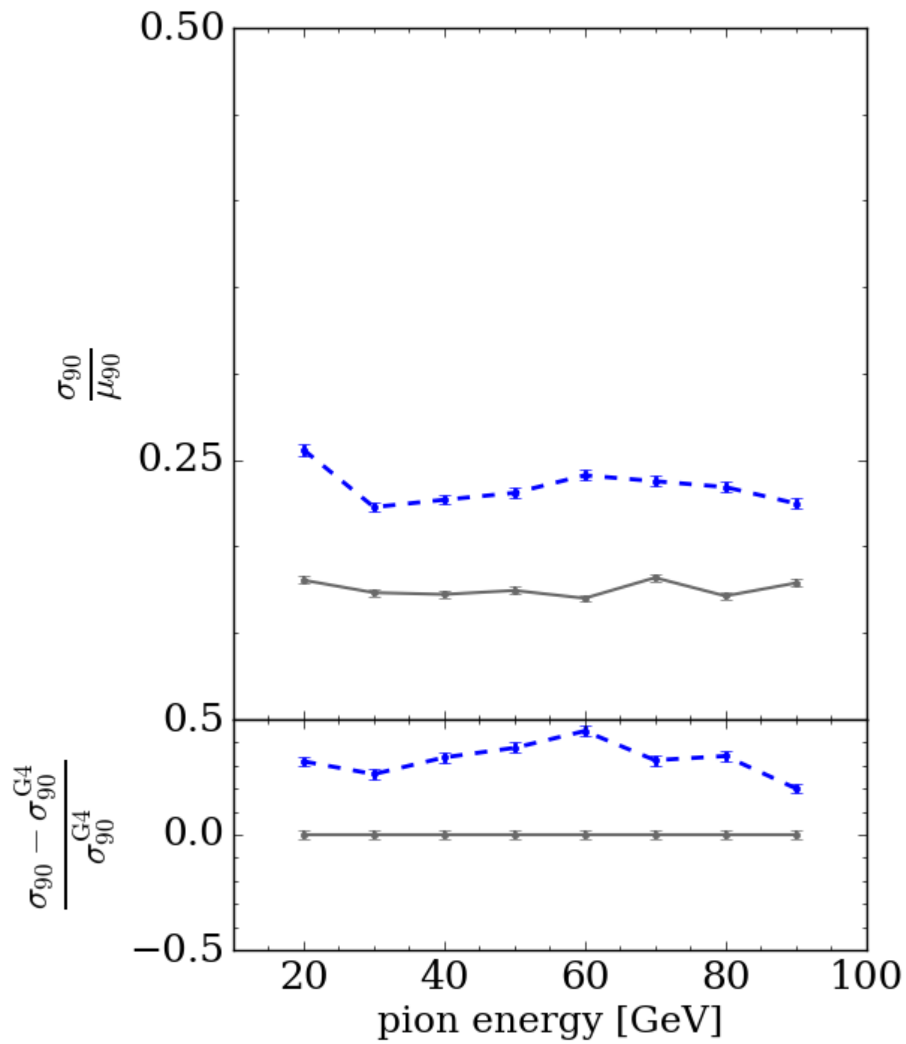
✓ Difficult to model MIP peak, but encouraging results for first attempts!!

Hadron Showers

very preliminary results



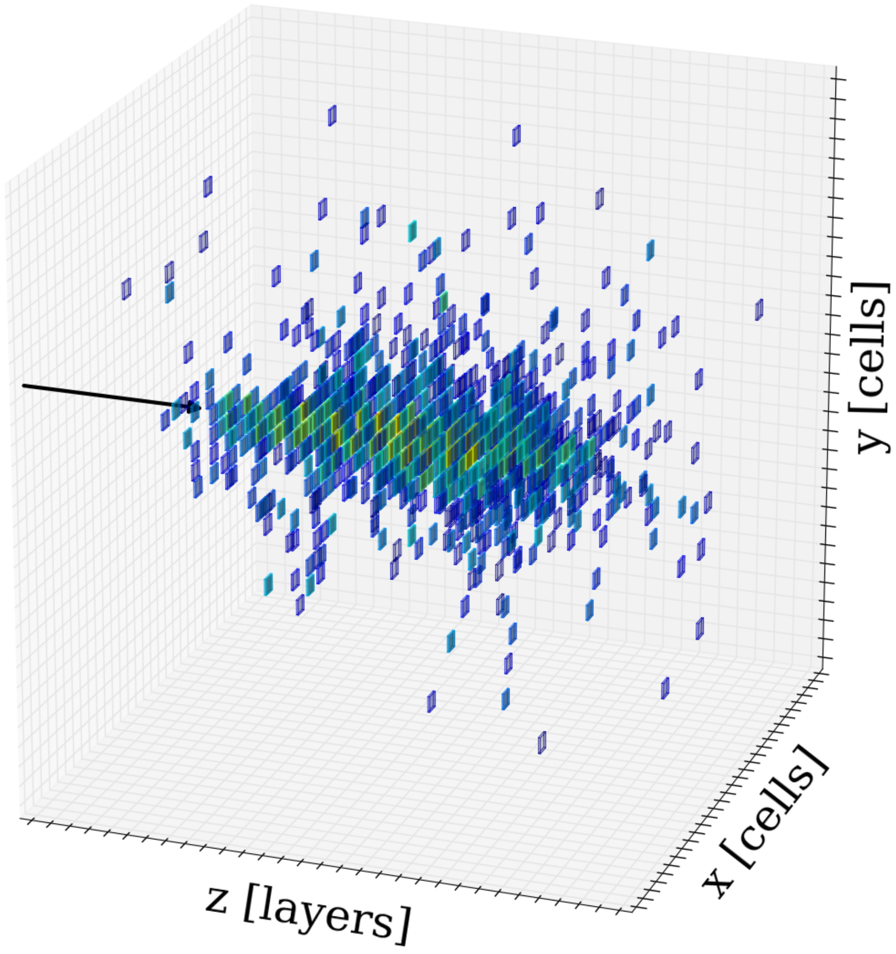




✓ Linearity is overall in a good agreement, room for improvements for the relative width

Conclusion

- Application of generative models to high resolution EM shower simulation
  - ✓ Modelling of MIP peak and high fidelity
  - ✓ Speedup: 3 orders of magnitude
- Architectures:
  - ◉ GAN
  - ◉ WGAN
  - ◉ BIB-AE (**New!**)
- Future Plans:
  - ◉ condition on incident position/angle
  - ◉ hadron showers (**Promising results!**)
  - ◉ integrate into existing tools / frameworks



Paper: [arxiv:2005.05334] (submitted to journal, soon to be published)

Backup

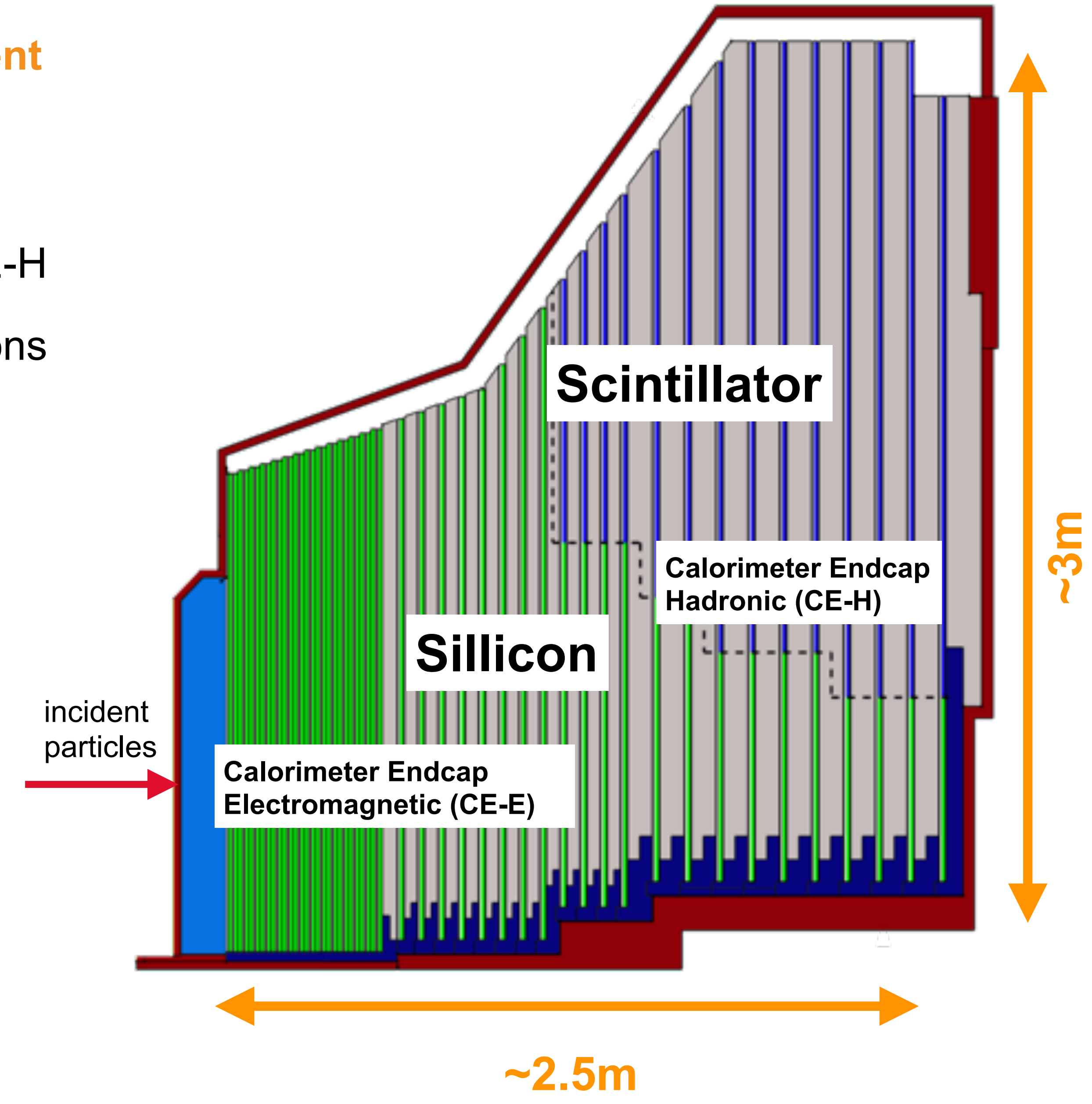
New Challenge: CMS HGCal

Planned High Granular Calorimeter for CMS Experiment

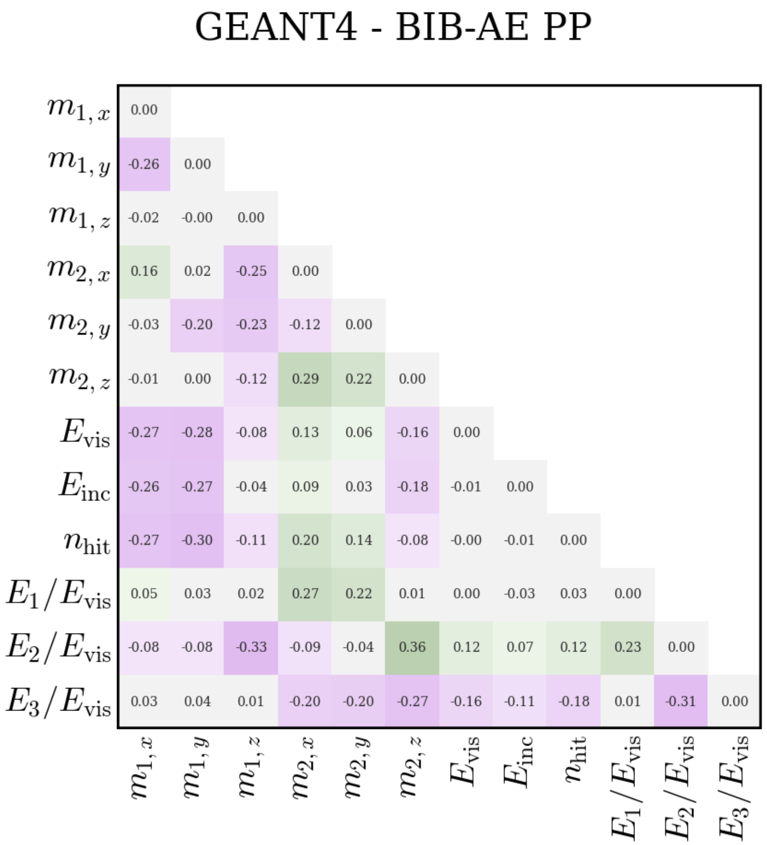
- HGCAL is a **sampling** calorimeter
- Silicon sensors in CE-E and high radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H
- 3D imaging calorimeter with timing capabilities

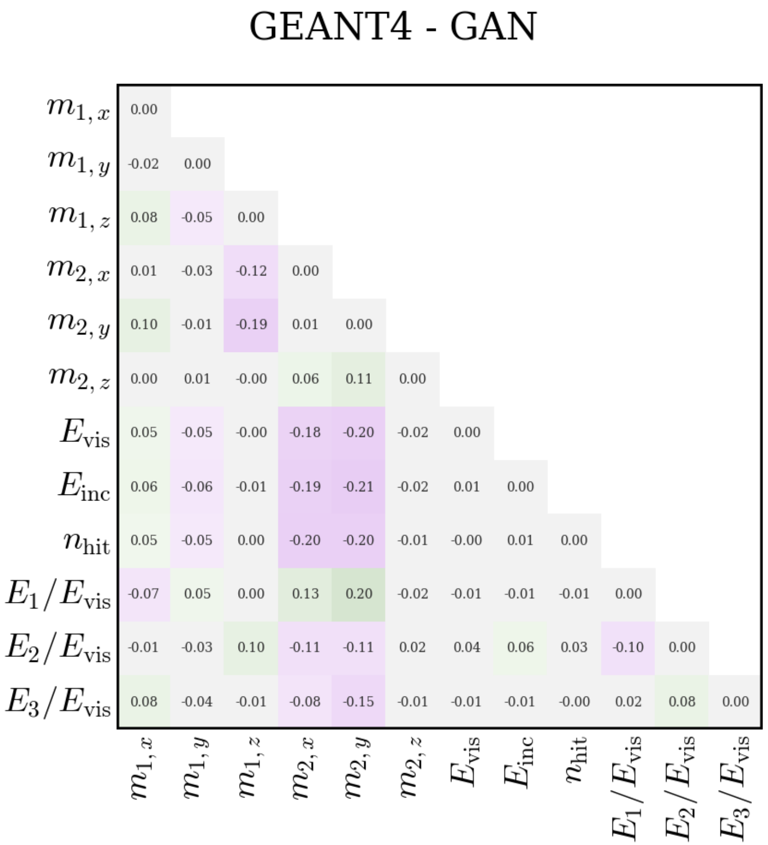
Application of generative networks to CMS HGCal has started in our group with **close collaboration** with experts in the field

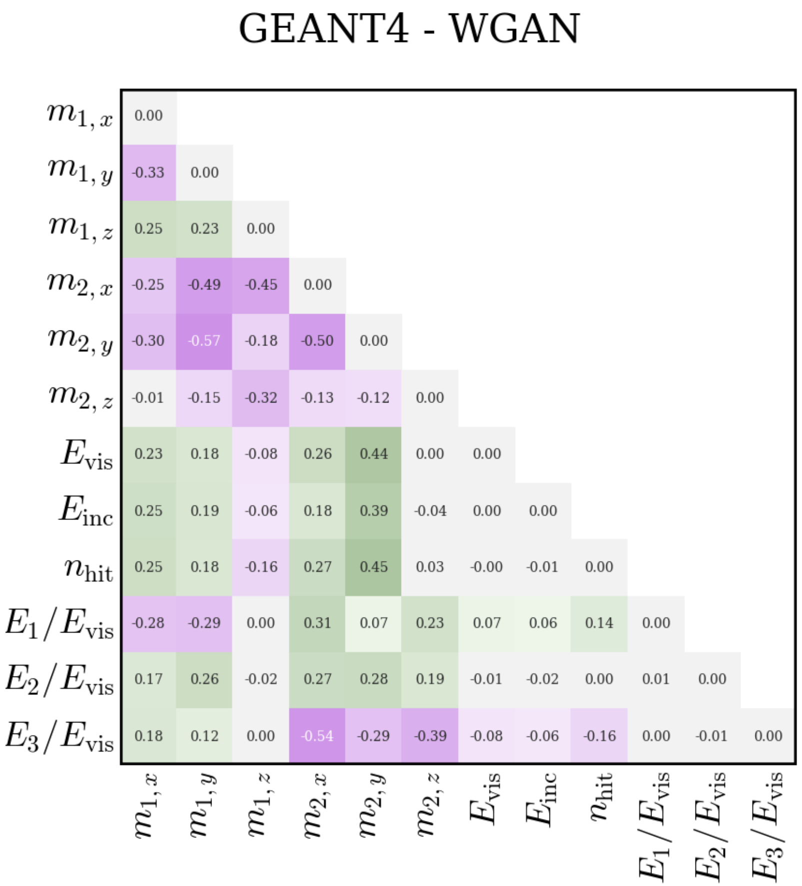
Stay tuned for our preliminary results!!



Correlations







✓ Correlations between individual shower properties present in GEANT4 are correctly reproduced by our generative models

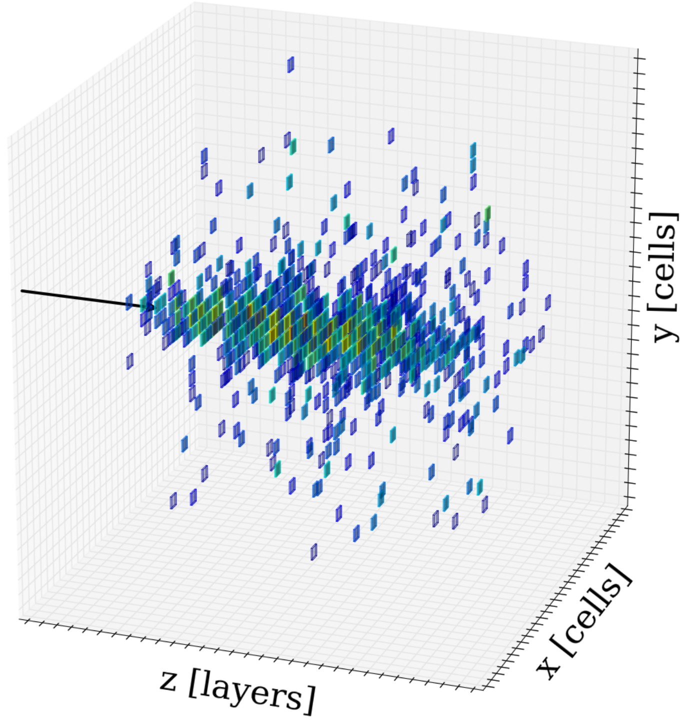
Challenges

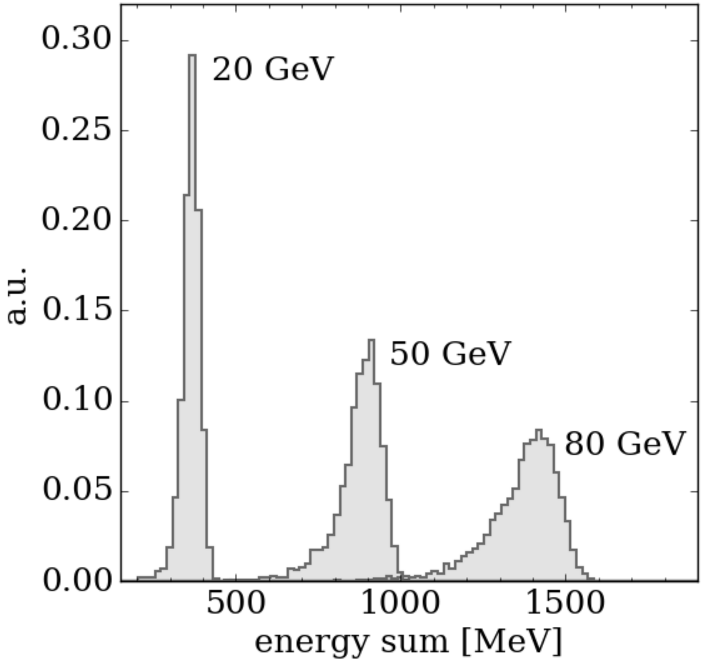
Quality measures:

- Reproduce Geant4 showers
- Shower shape variables have to be examined, especially:
    - ◉ Number of hits
    - ◉ Radial & longitudinal profile
- Differential energy distributions: shape & accuracy

Energy conditioning

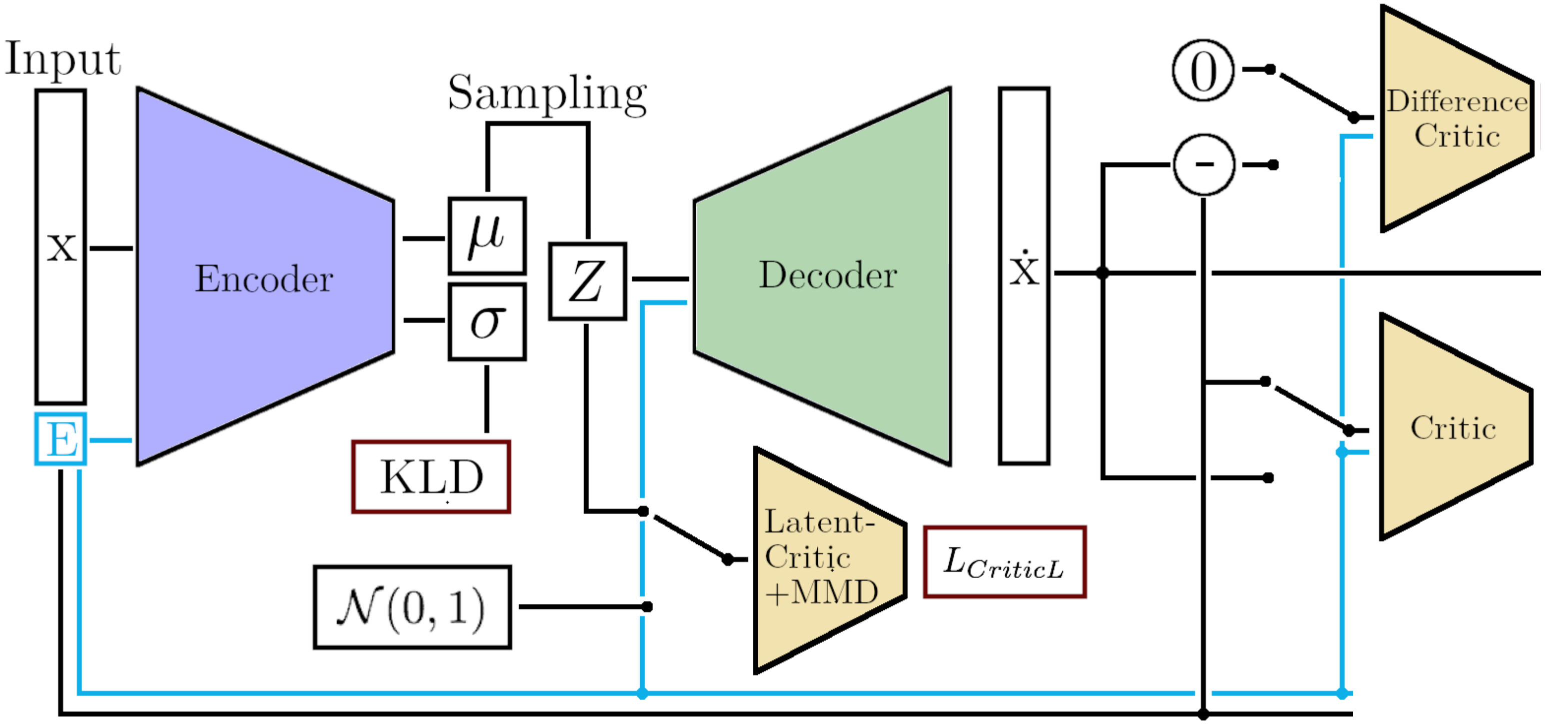
- Condition generator / decoder on incoming particle's energy
    - ◉ Not same as visible (or reconstructed) energy!





BiB-AE

arXiv:1912.00830

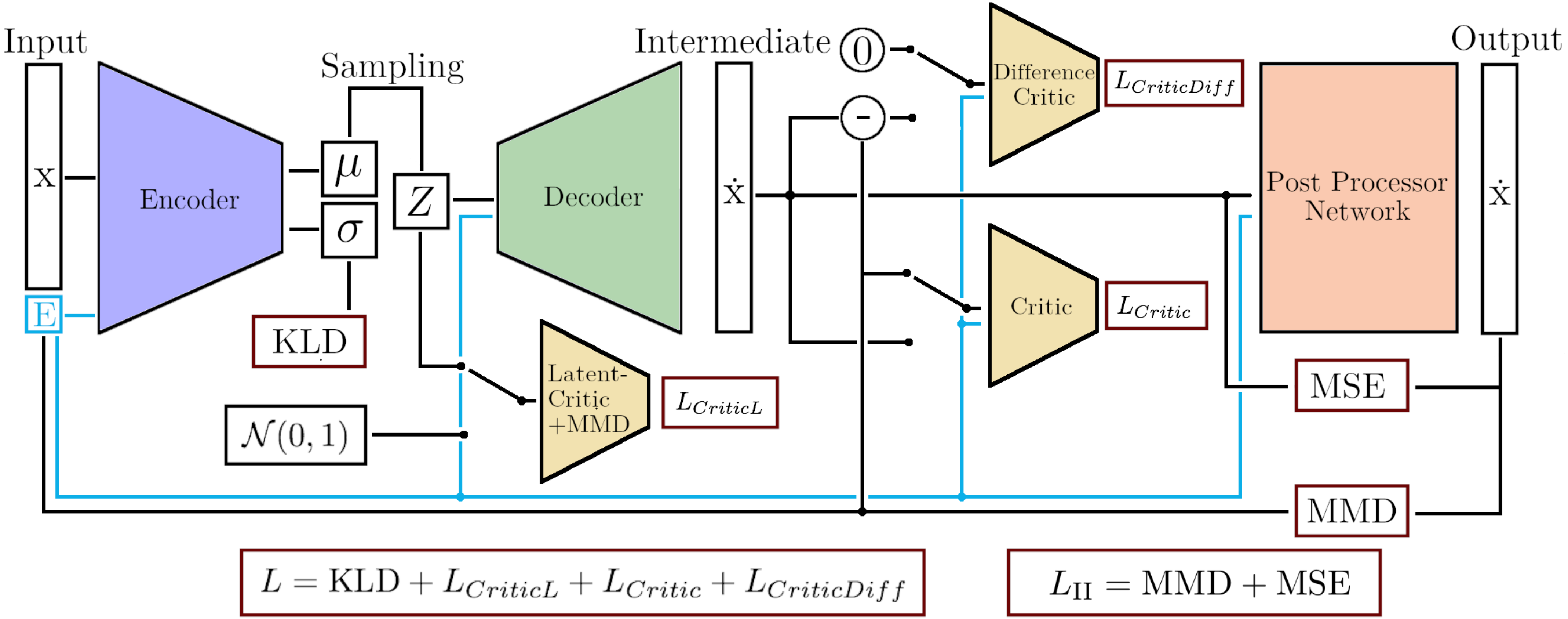


$$L = \mathrm{KLD} + L_{CriticL} + L_{Critic} + L_{CriticDiff}$$

Bounded Information Bottleneck AutoEncoder (BiB-AE)

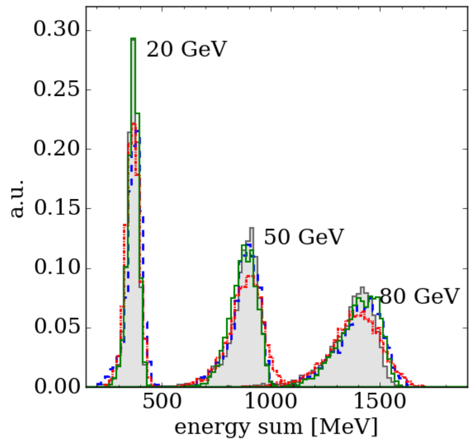
- It expands VAE structure
- Additional critics for
  - Latent space regularisation
  - Reconstruction
- Inspired by CS paper

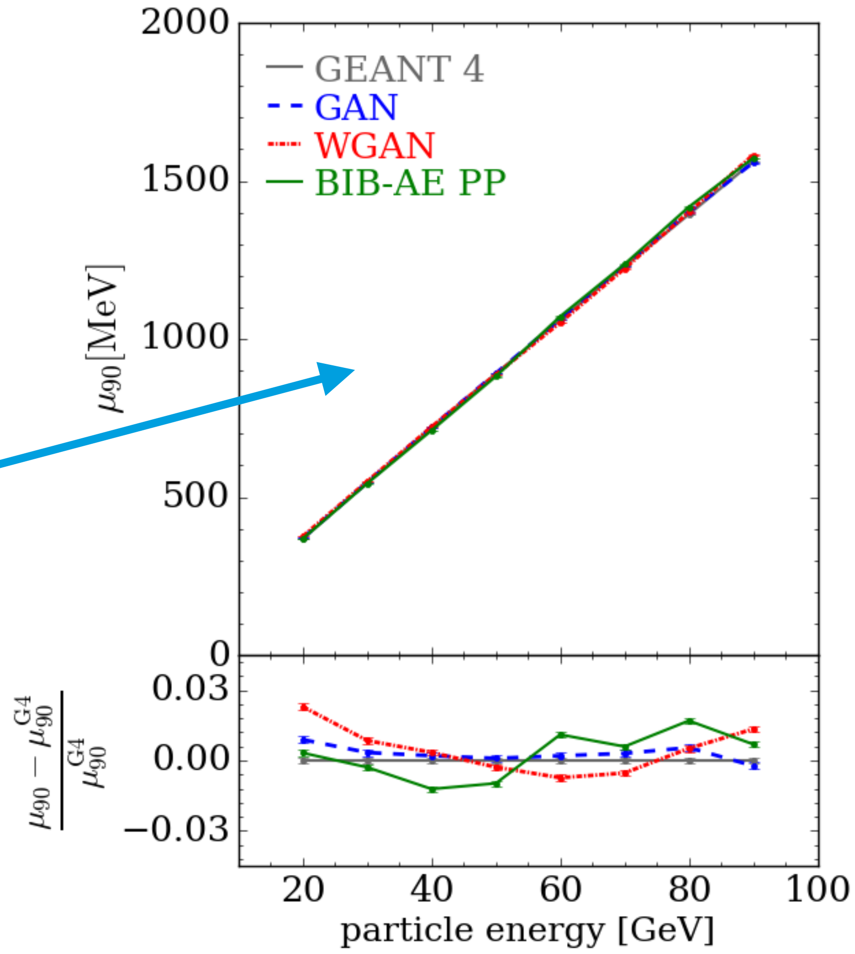
BiB-AE

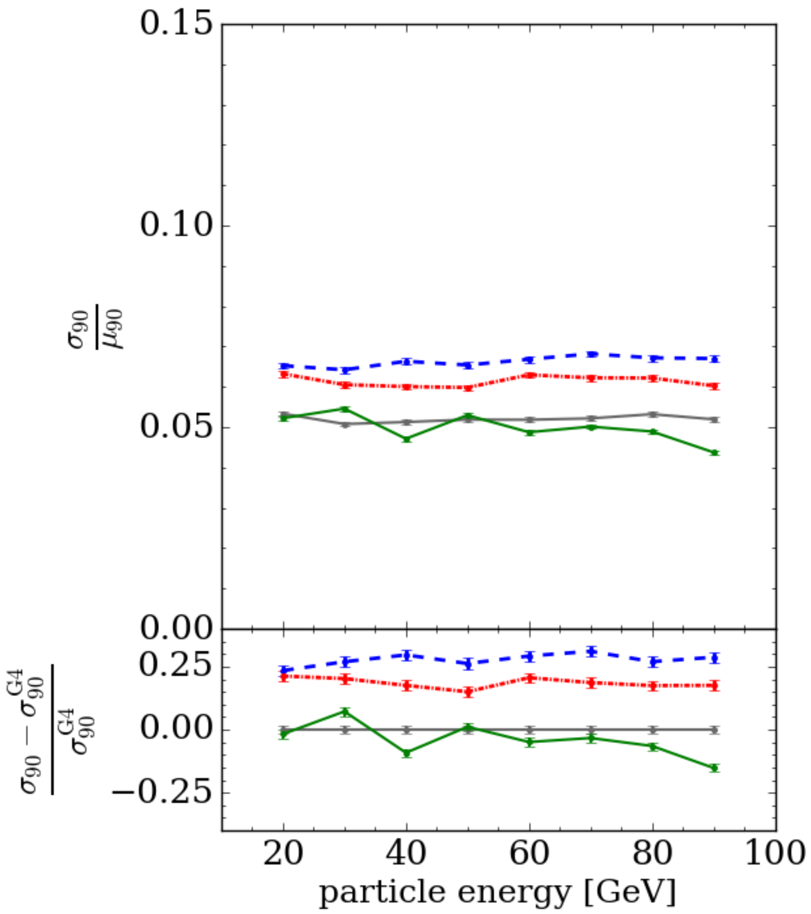


Post Processor Network for final cell-energy tuning!!

Results: Linearity and Width



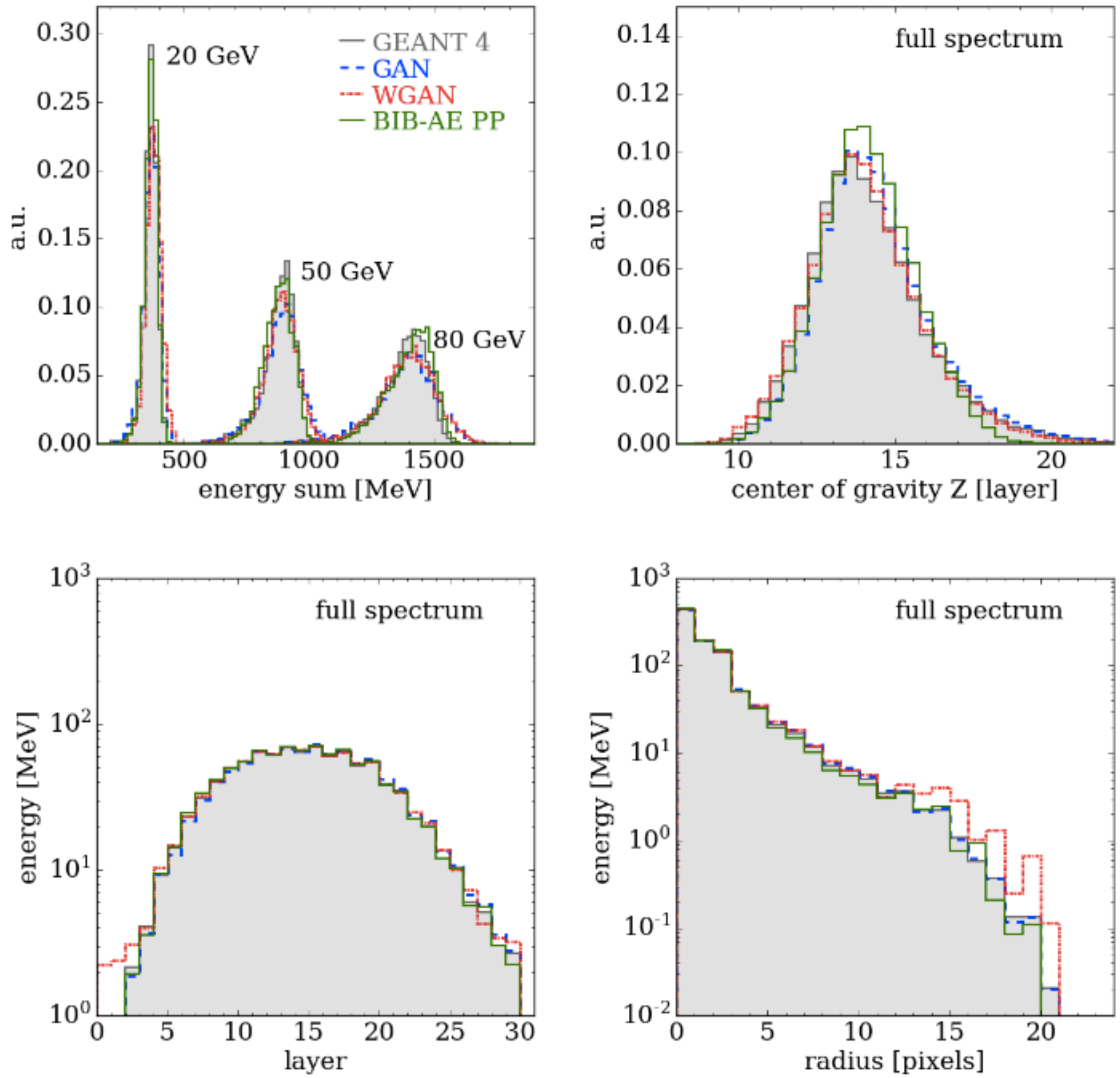




✓ Overall good modelled by all generative models. Deviations up to few percent

◉ Overestimated by GAN and WGAN

Distributions…



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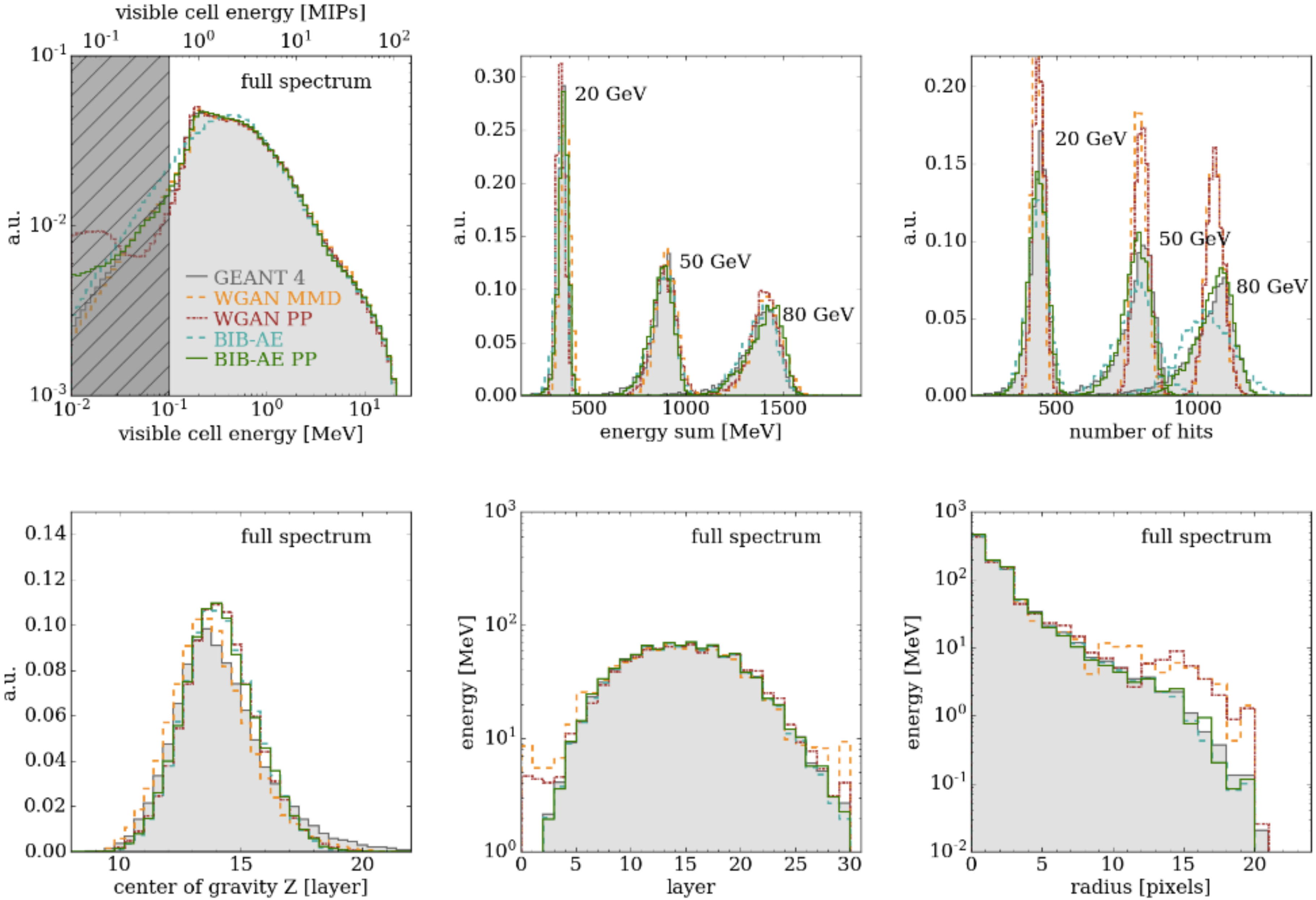
WGAN + PP



visible cell energy [MIPs]
full spectrum
GEANT 4
WGAN MMD
WGAN PP
BIB-AE
BIB-AE PP
a.u.
visible cell energy [MeV]
20 GeV
50 GeV
80 GeV
energy sum [MeV]
number of hits
full spectrum
center of gravity Z [layer]
energy [MeV]
layer
radius [pixels]