High Fidelity Simulation of High Granularity Calorimeters with High Speed

ILD Analysis and Software Meeting

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16.12.2020

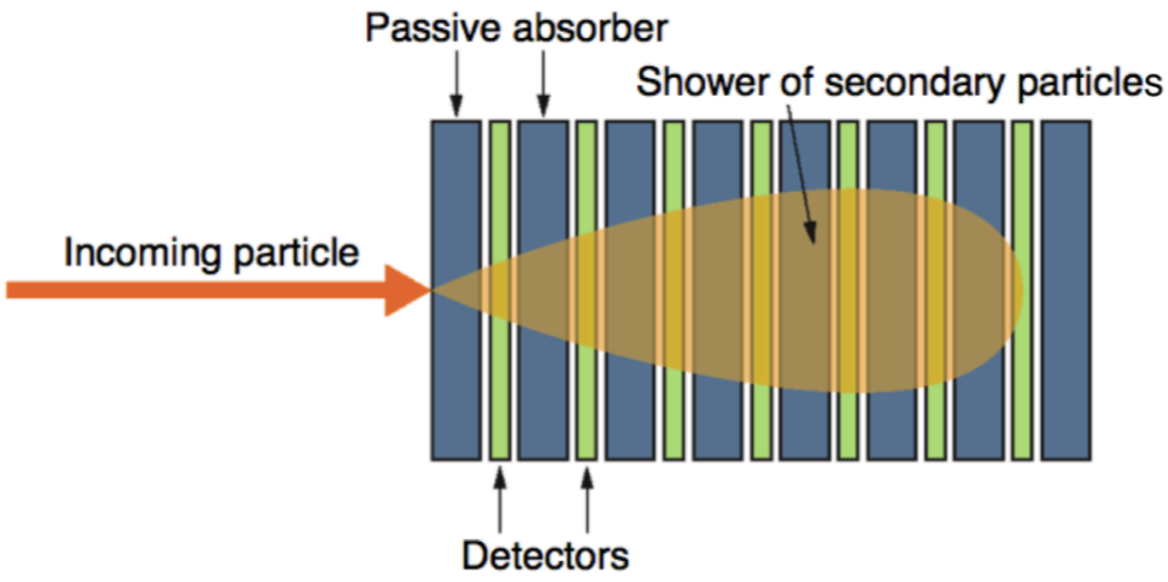
arxiv:2005.05334

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

Calorimeters in a HEP Experiment

- Incoming particle initiates the showers and secondary particles are produced
- These secondary particles further produce other particles until the full energy is absorbed



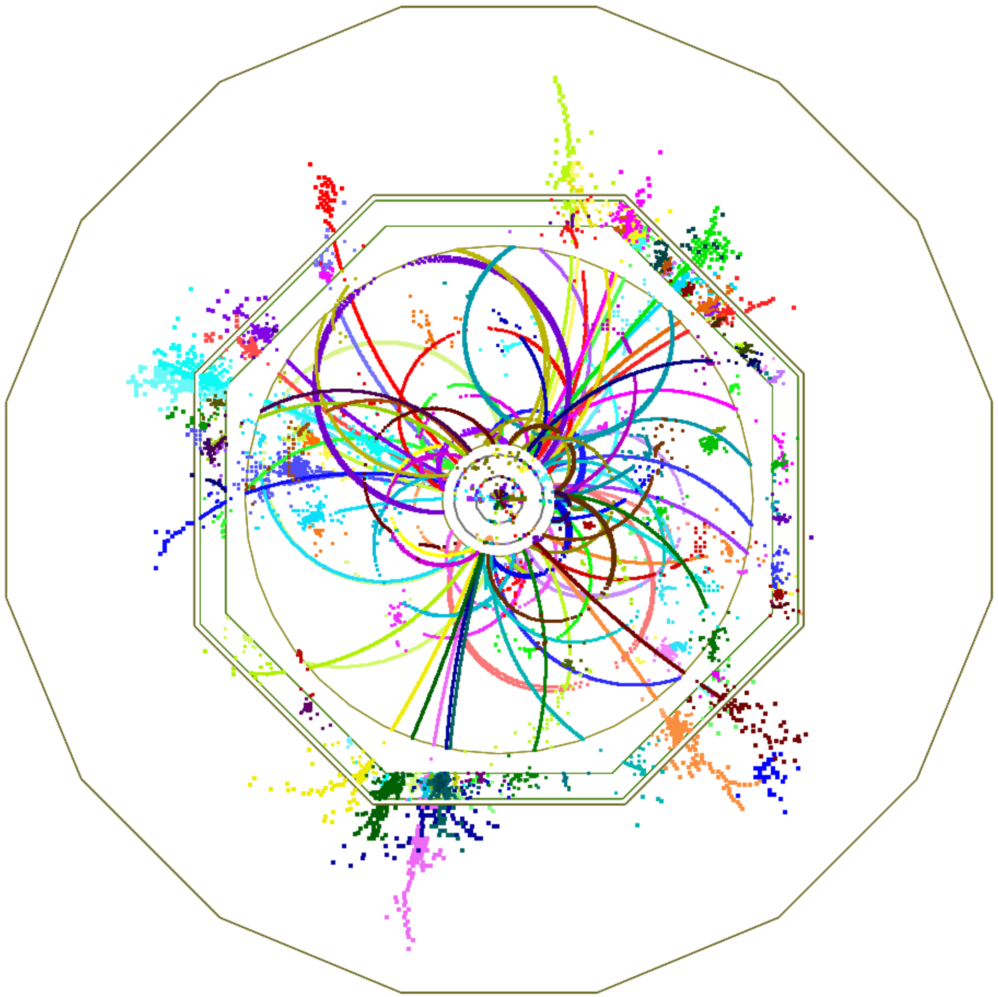
One type of EM calorimeter: sampling calorimeter

- Alternating layers of passive absorbers and active detectors
- Only **fraction** of particle energy is recorded (visible energy)

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

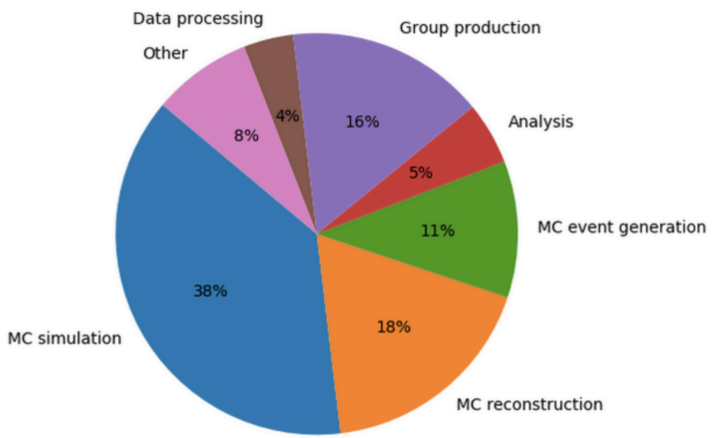


Figure from D.Costanzo, J.Catmore, LHCC meeting

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!

CALOGAN: Simulating 3D high energy particle showers in multilayer electromagnetic calorimeters with generative adversarial networks

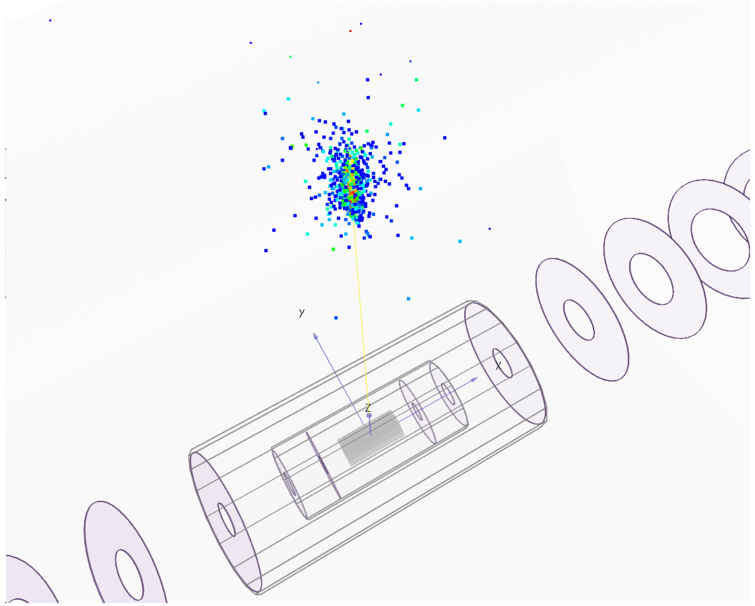
Michela Paganini, Luke de Oliveira, and Benjamin Nachman
Phys. Rev. D **97**, 014021 – Published 30 January 2018

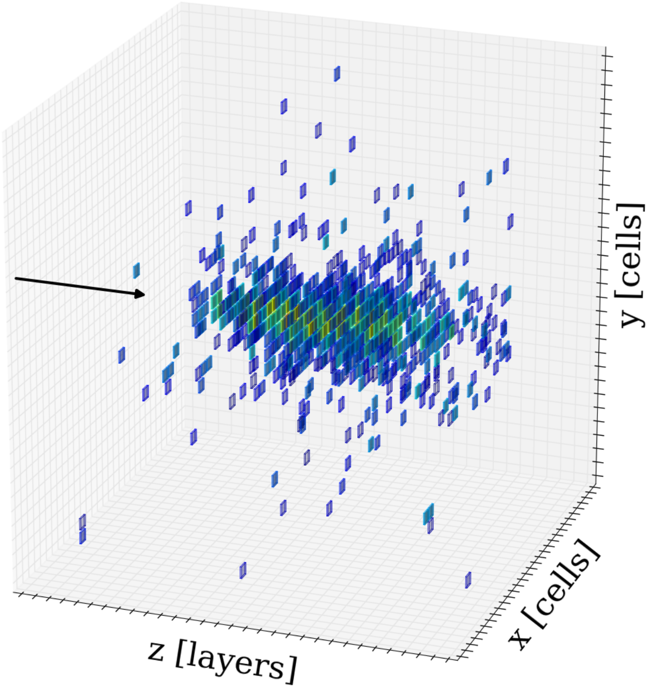
Simulator	Hardware	Batch size	ms/shower
GEANT4	CPU	N/A	1772
CALOGAN	CPU	1	13.1
		10	5.11
		128	2.19
		1024	2.03
	GPU	1	14.5
		4	3.68
		128	0.021
		512	0.014
		1024	0.012 ✓

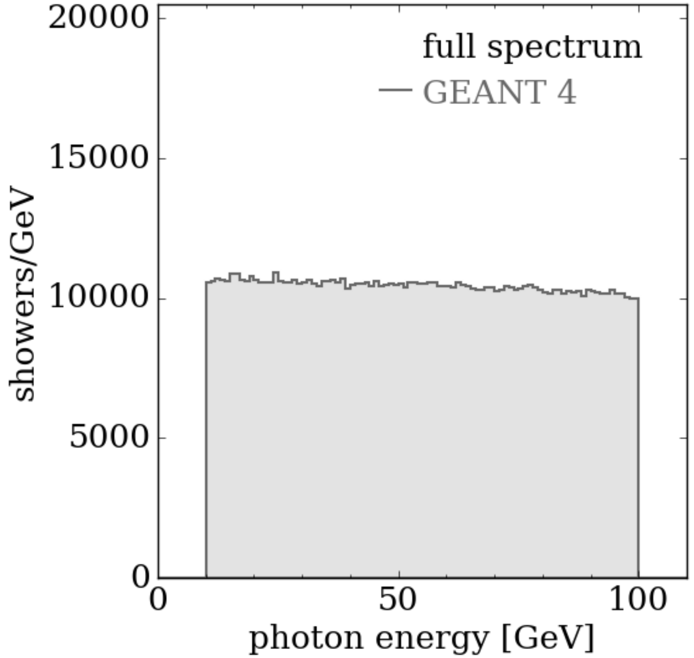
Training Data

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







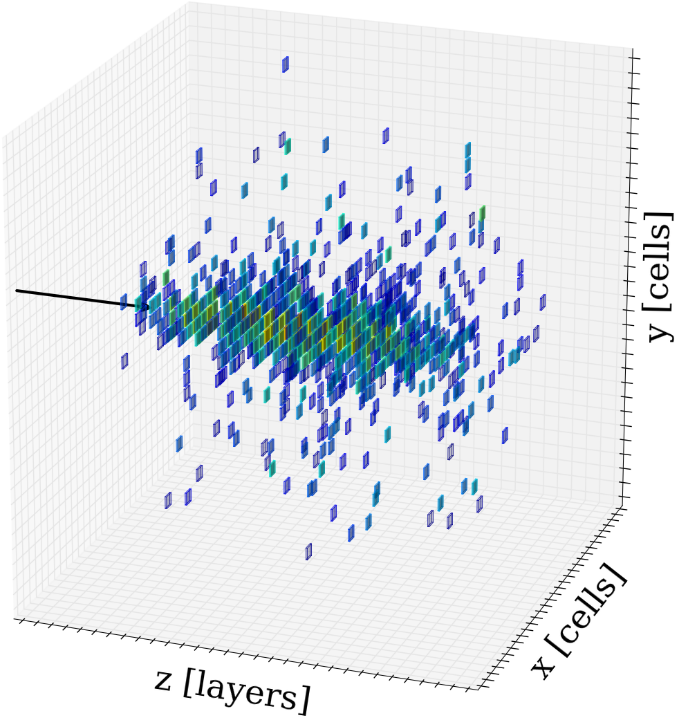
Challenges

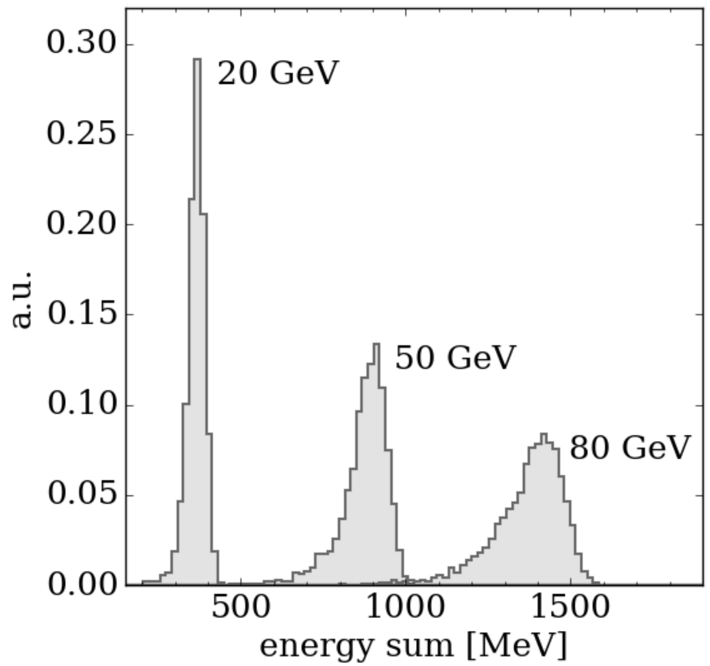
Quality measures:

- 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!

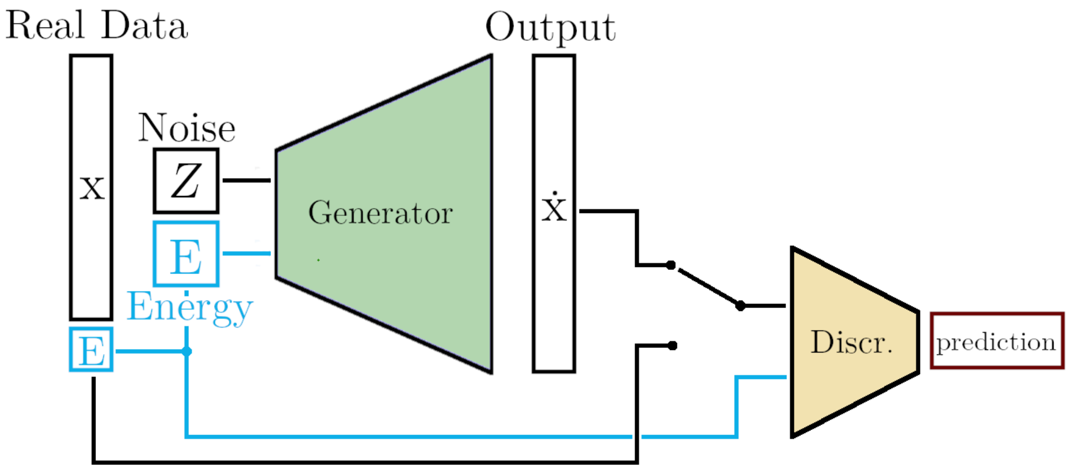




Generative Models
GAN and WGAN

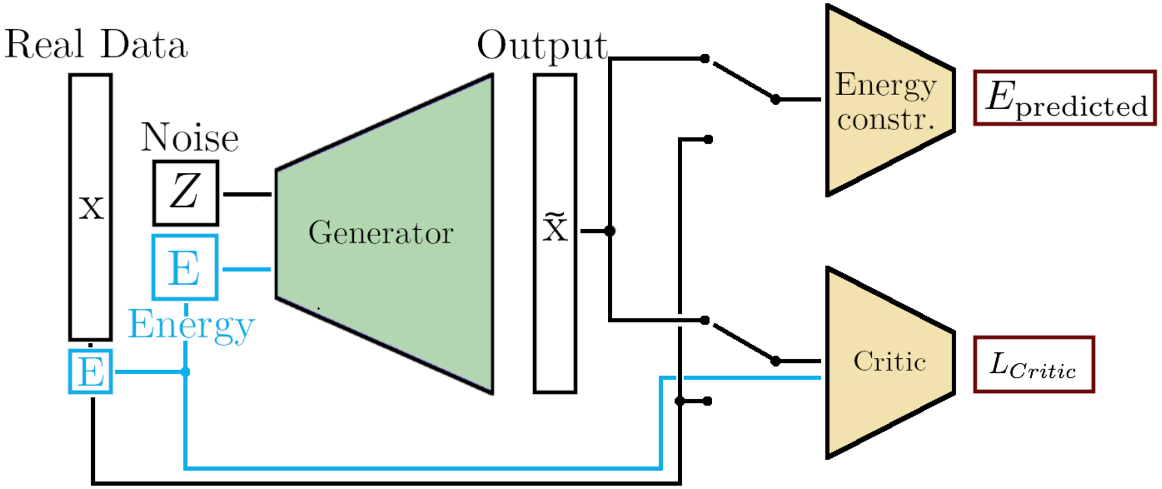
Generative Adversarial Network (GAN)

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

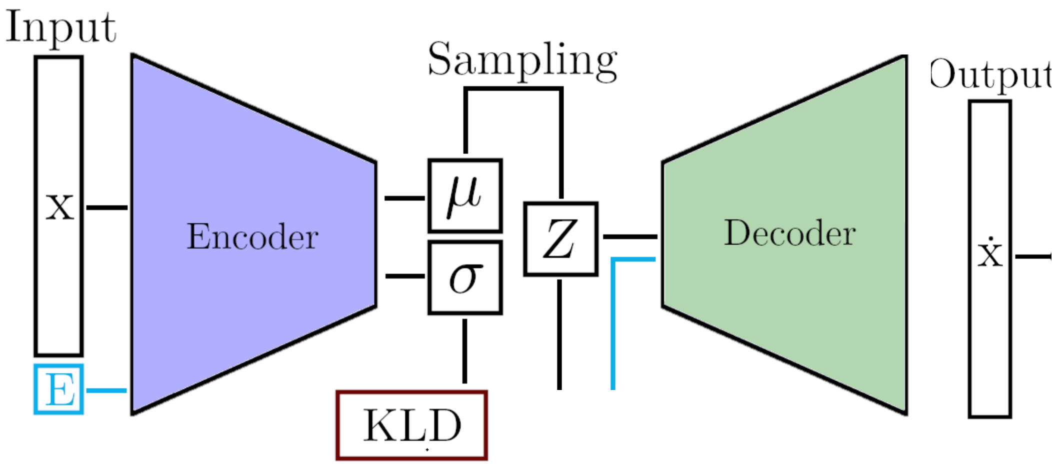


Wasserstein GAN (WGAN)

- 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



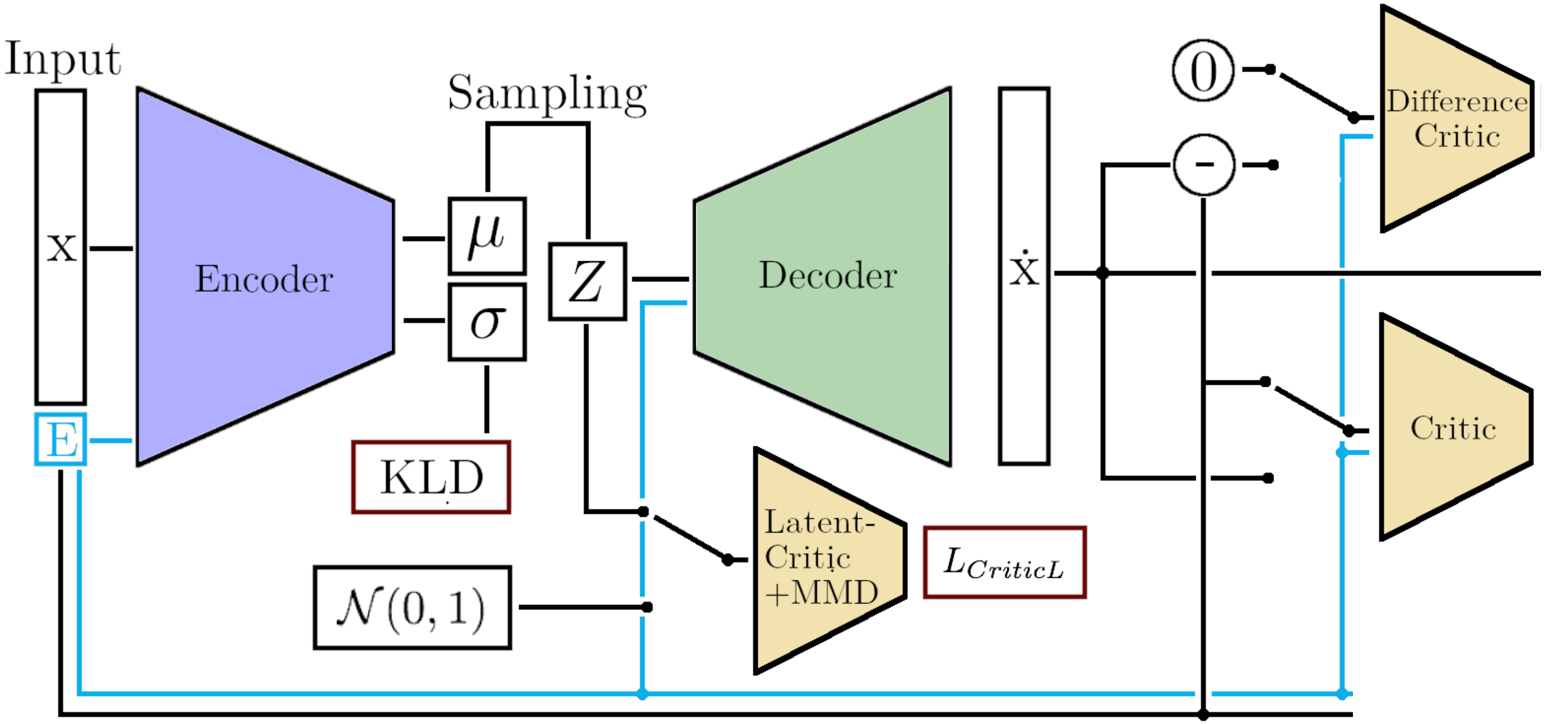
Variational Autoencoders (VAE)



- Encodes images to Gaussian latent space
- Reconstructs images from latent space information
  - ✴Loss function: Pixel wise difference between input and output
  - ✴KLD loss to regularise the latent space

BiB-AE

arXiv:1912.00830

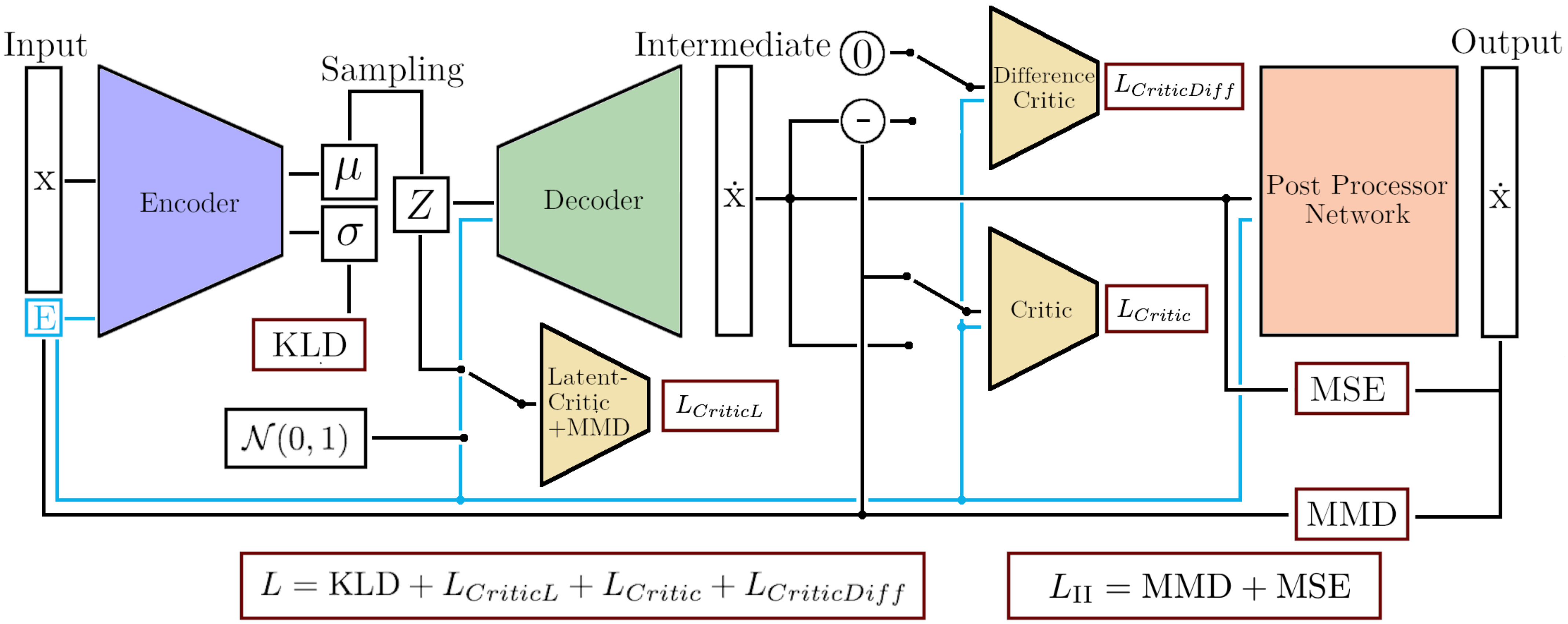


$$L = \mathrm{KLD} + L_{CriticL} + L_{Critic} + L_{CriticDiff}$$

Bounded Information Bottleneck AutoEncoder (BiB-AE)

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

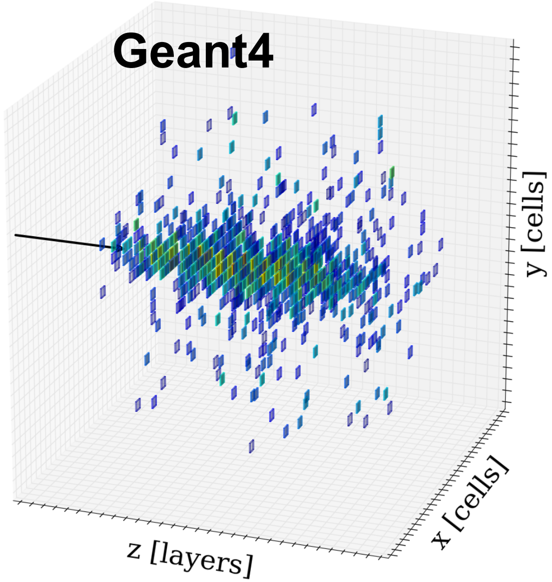
BiB-AE

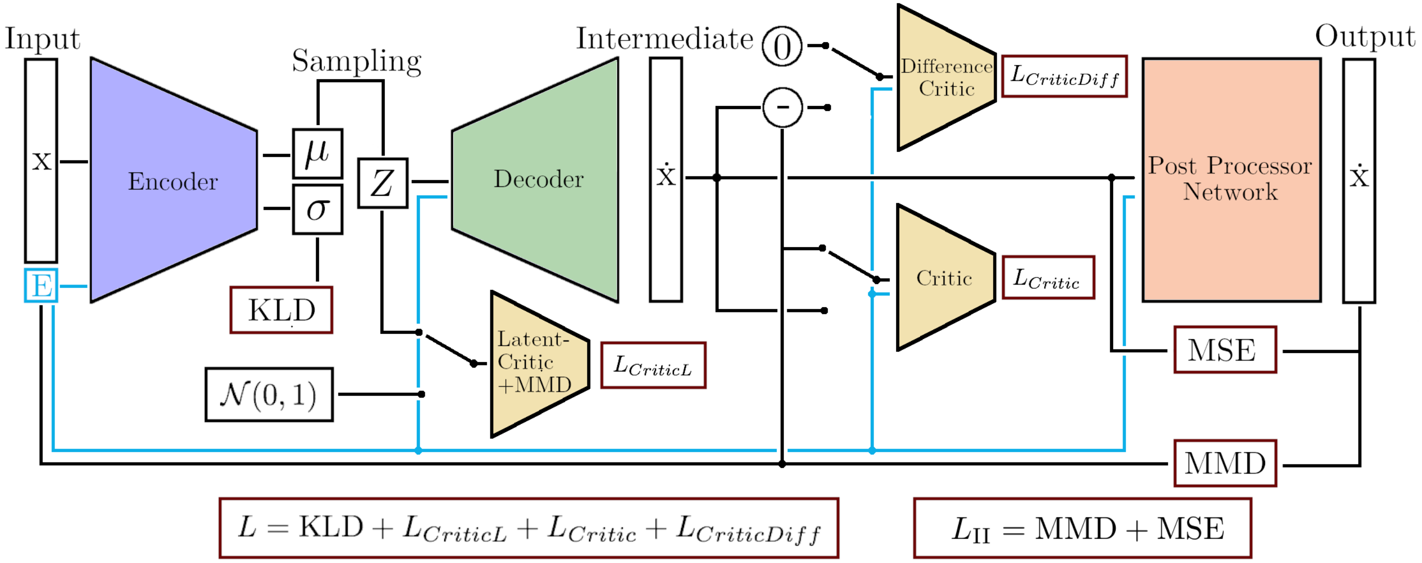


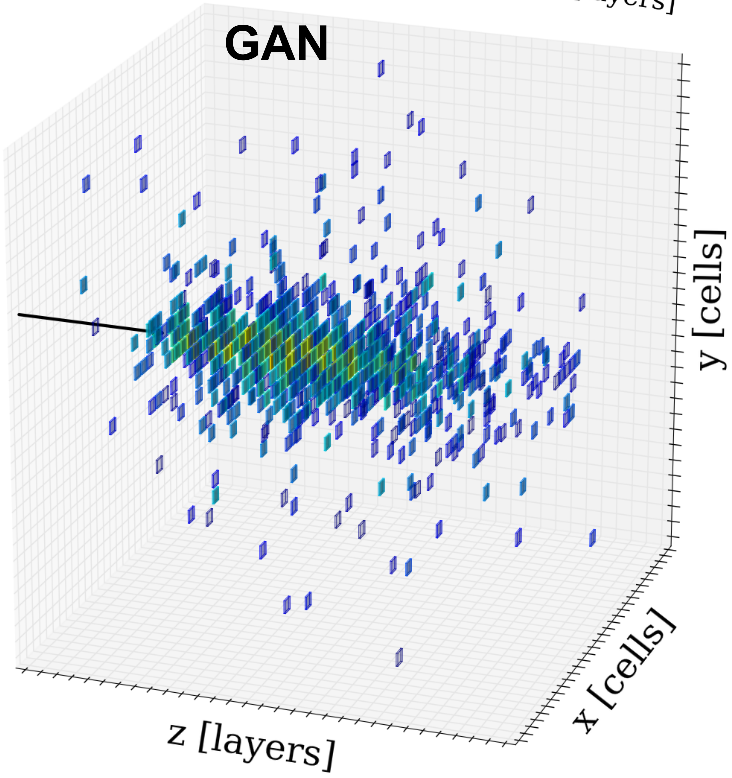
Post Processor Network for final cell-energy tuning!!

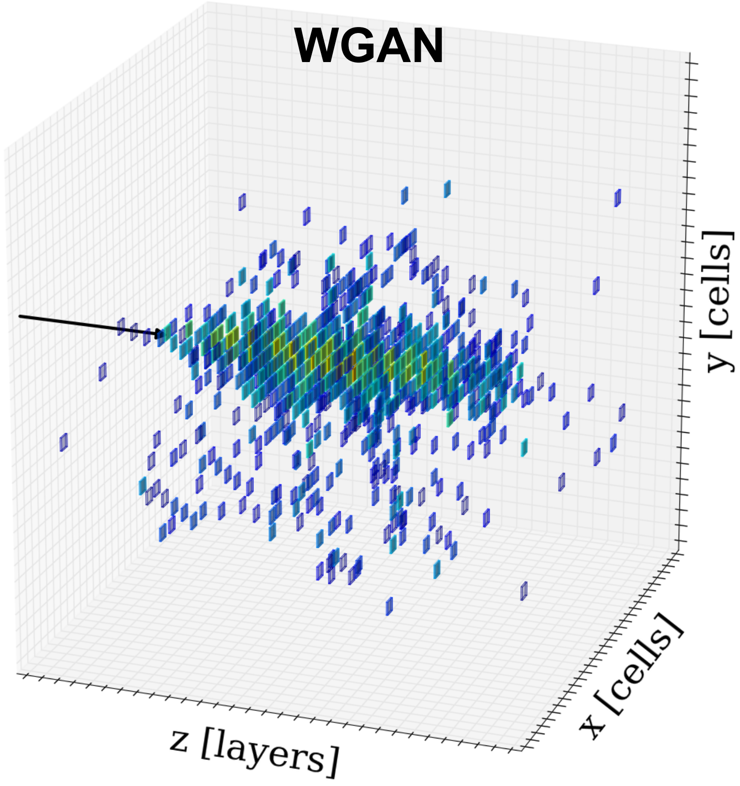
Results

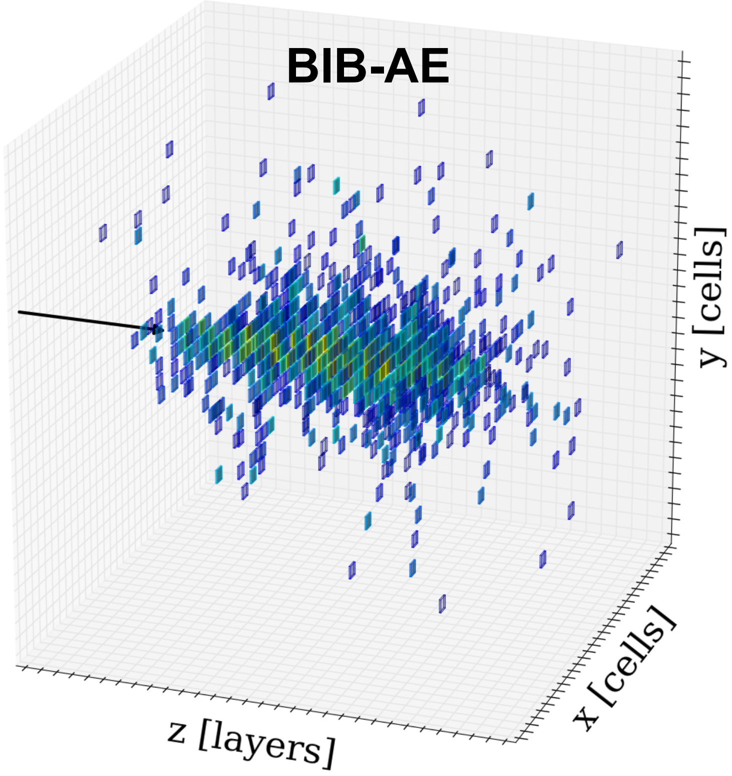
looks realistic???



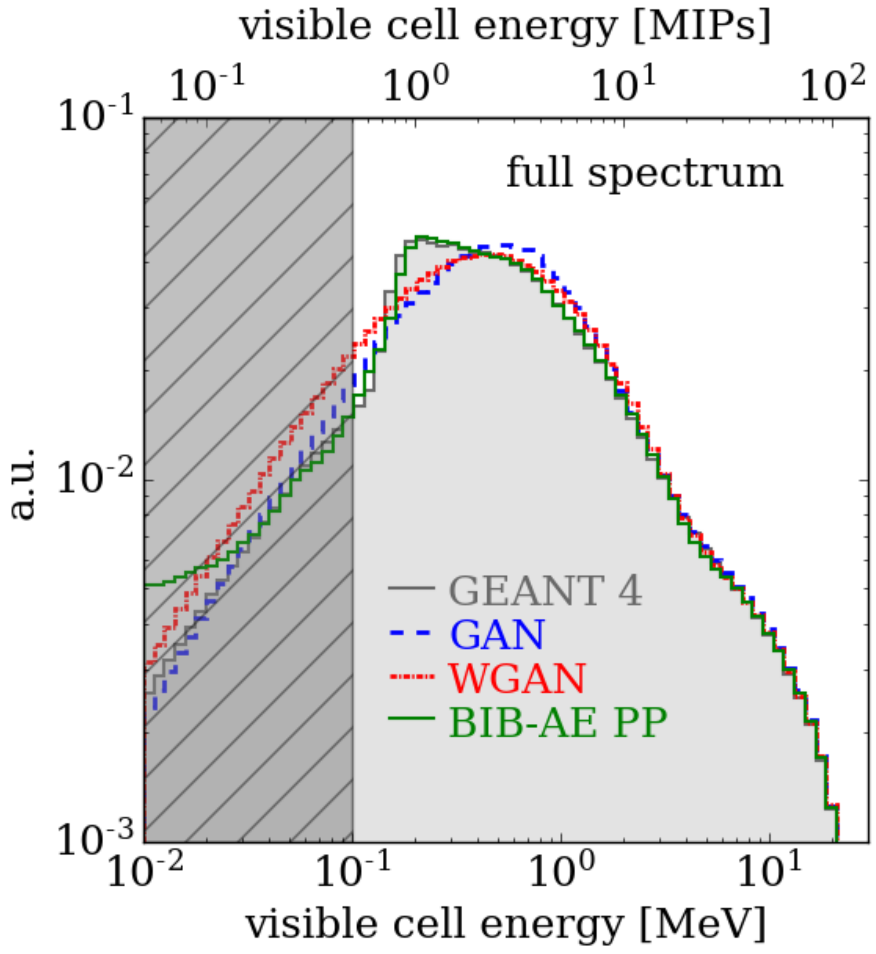


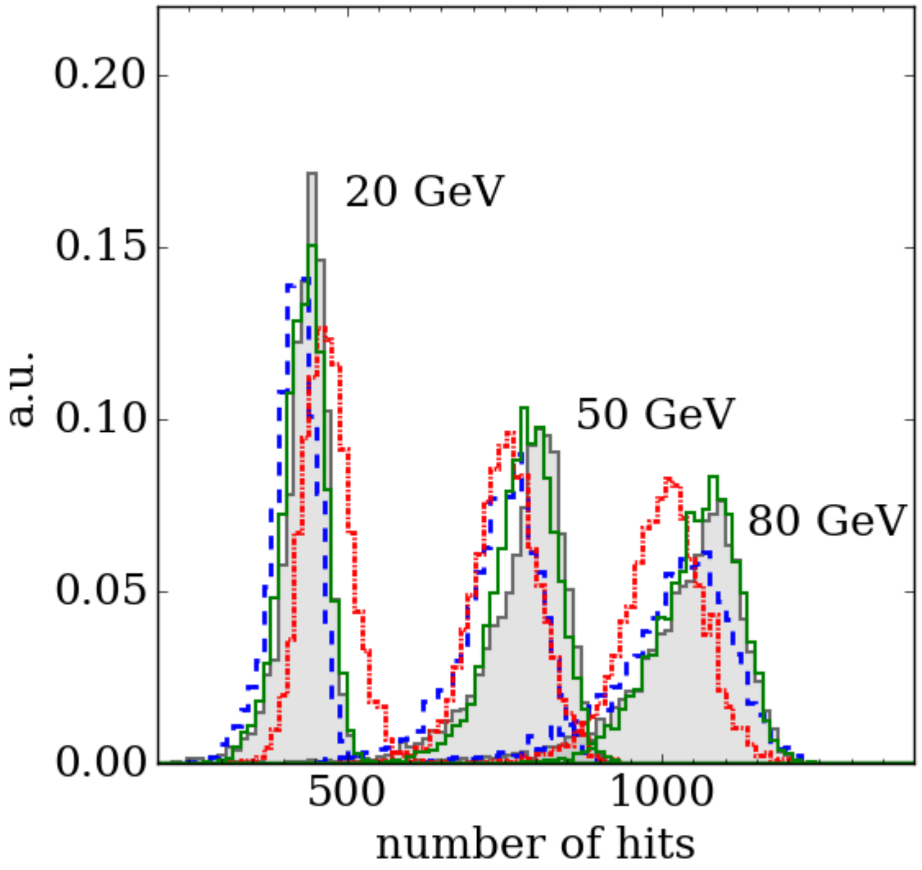






Results: Cell energy and Number of hits

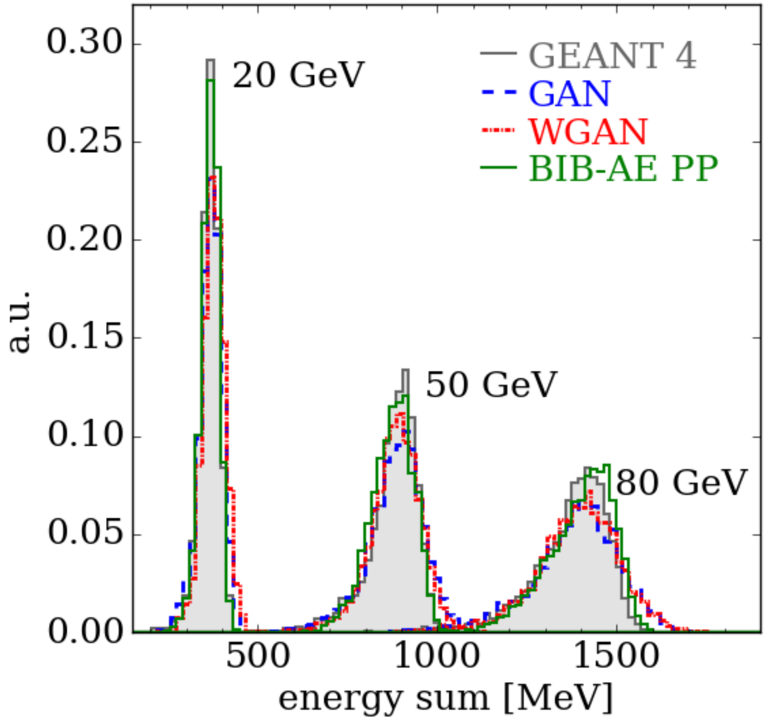


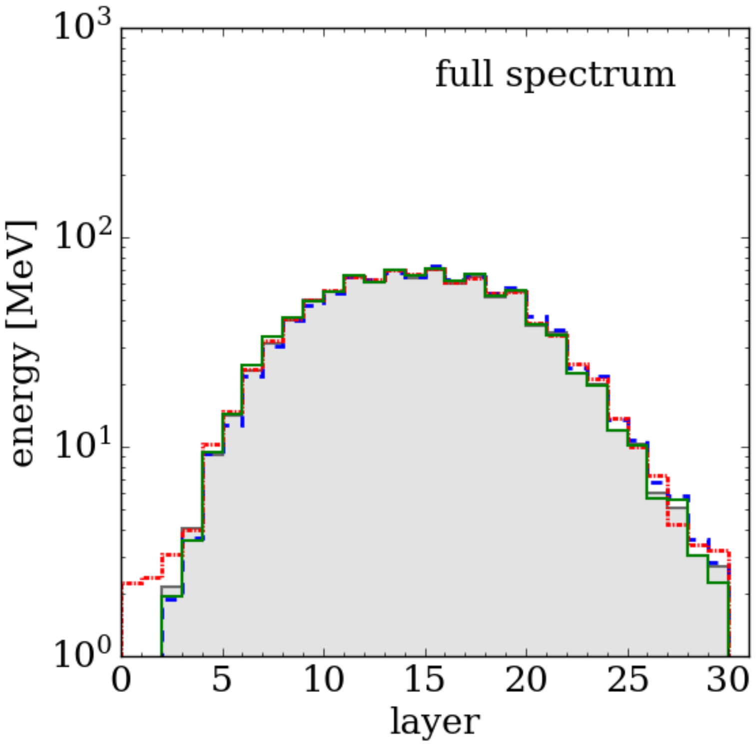


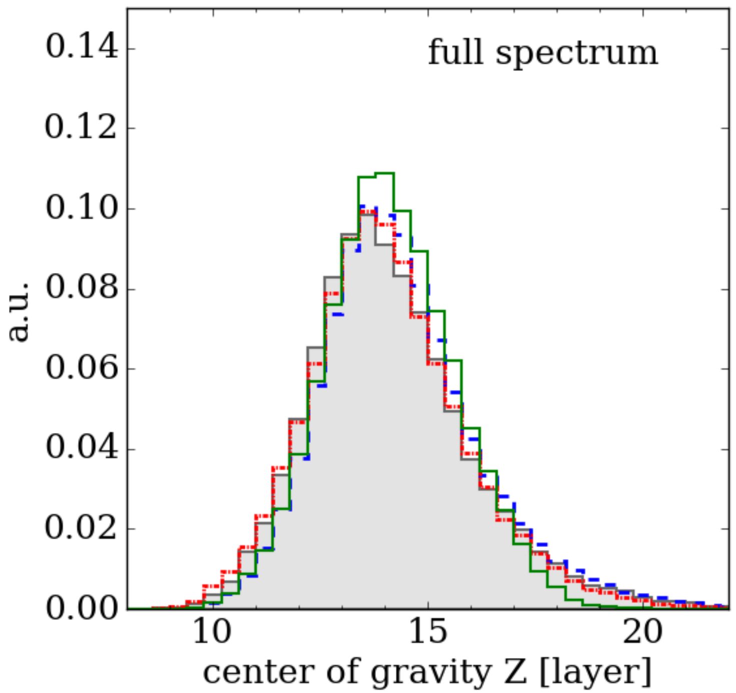
- Both GAN and WGAN <u>fail</u> to capture MIP bump around 0.2 MeV
- ✓ BiB-AE is able to produce this feature thanks to Post-Processing network

- GAN and WGAN slightly <u>underestimate</u> 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

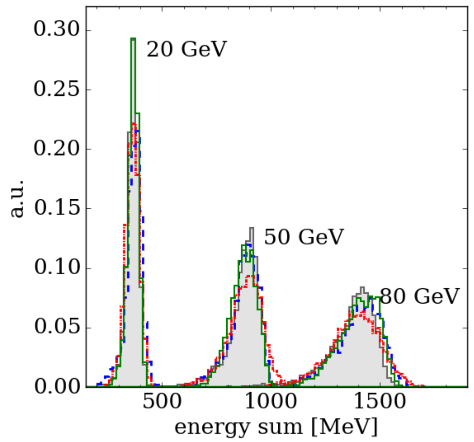
✓ reproduce the bulk of the distributions very well.

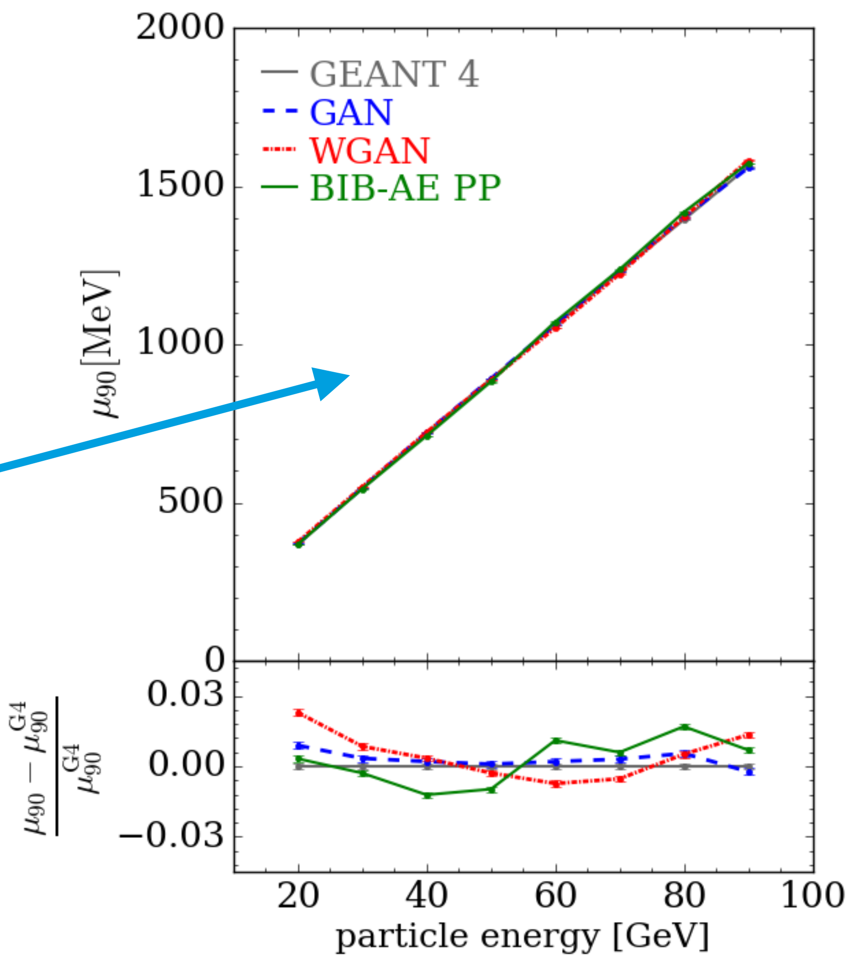
- slight deviations for the WGAN appear around the edges

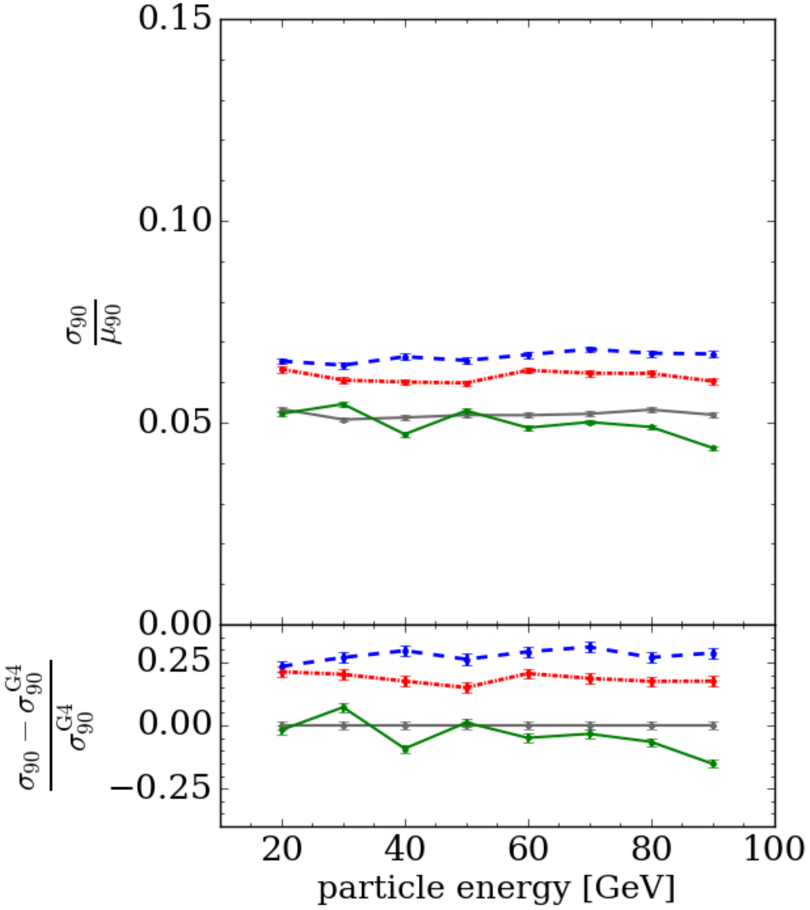
- Deviations for BiB-AE

  ✓ Explainable via latent space encoding

Results: Linearity and Width







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

◉ Overestimated by GAN and WGAN

Computation Time

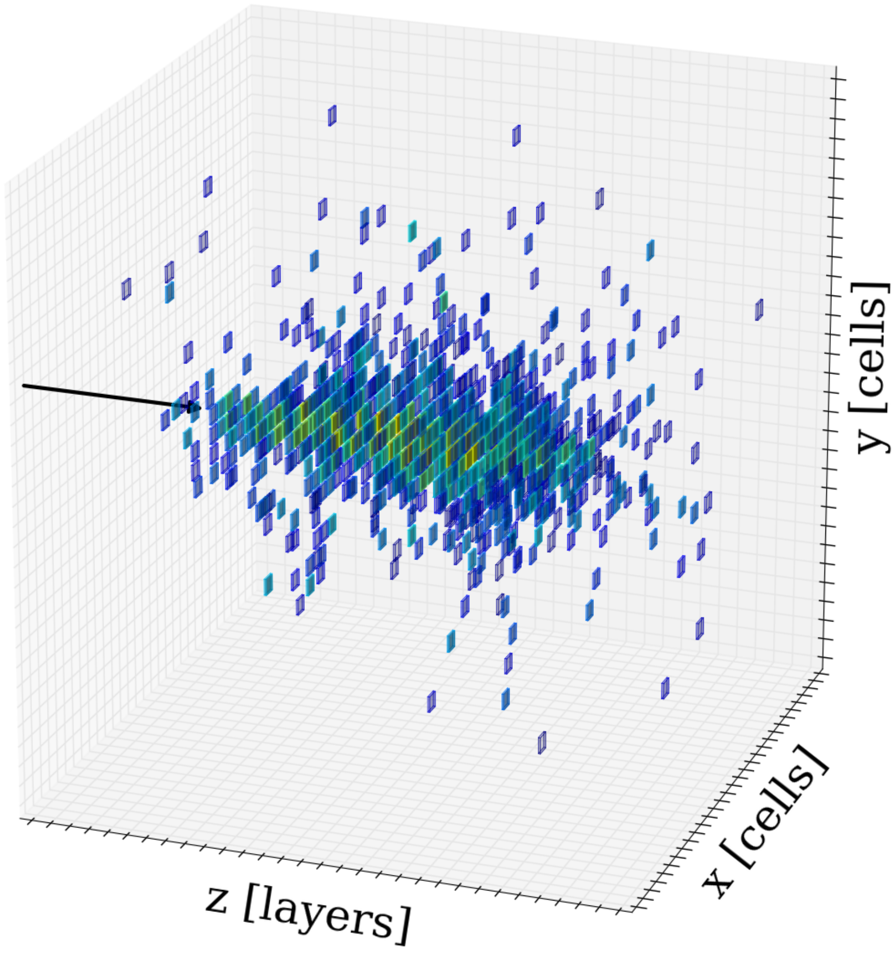
Simulator	Hardware	Batch Size	15 GeV	Speed-up	10-100 GeV Flat	Speed-up
GEANT4	CPU	N/A	1445.05 ± 19.34 ms	-	4081.53 ± 169.92 ms	-
WGAN	CPU	1	64.34 ± 0.58 ms	**x23**	63.14 ± 0.34 ms	**x65**
		10	59.53 ± 0.45 ms	**x24**	56.65 ± 0.33 ms	**x72**
		100	58.31 ± 0.93 ms	**x25**	58.11 ± 0.13 ms	**x70**
		1000	57.99 ± 0.97 ms	**x25**	57.99 ± 0.18 ms	**x70**
BIB-AE	CPU	1	426.60 ± 3.27 ms	**x3**	426.32 ± 3.62 ms	**x10**
		10	422.60 ± 0.26 ms	**x3**	424.71 ± 3.53 ms	**x10**
		100	419.64 ± 0.07 ms	**x3**	418.04 ± 0.20 ms	**x10**
WGAN	GPU	1	3.24 ± 0.01 ms	**x446**	3.25 ± 0.01 ms	**x1256**
		10	6.13 ± 0.02 ms	**x236**	6.13 ± 0.02 ms	**x666**
		100	5.43 ± 0.01 ms	**x266**	5.43 ± 0.01 ms	**x752**
		1000	5.43 ± 0.01 ms	**x266**	5.43 ± 0.01 ms	**x752**
BIB-AE	GPU	1	3.14 ± 0.01 ms	**x838**	3.19 ± 0.01 ms	**x1279**
		10	1.56 ± 0.01 ms	**x1287**	1.57 ± 0.01 ms	**x2600**
		100	1.42 ± 0.01 ms	**x1366**	1.42 ± 0.01 ms	**x2874**

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**

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
  - ◉ hadronic showers
  - ◉ integrate into existing tools / frameworks



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

Backup

Correlations

GEANT4 - BIB-AE PP

	$m_{1,x}$	$m_{1,y}$	$m_{1,z}$	$m_{2,x}$	$m_{2,y}$	$m_{2,z}$	E_{vis}	E_{inc}	n_{hit}	E_1/E_{vis}	E_2/E_{vis}	E_3/E_{vis}
$m_{1,x}$	0.00											
$m_{1,y}$	-0.26	0.00										
$m_{1,z}$	-0.02	-0.00	0.00									
$m_{2,x}$	0.16	0.02	-0.25	0.00								
$m_{2,y}$	-0.03	-0.20	-0.23	-0.12	0.00							
$m_{2,z}$	-0.01	0.00	-0.12	0.29	0.22	0.00						
E_{vis}	-0.27	-0.28	-0.08	0.13	0.06	-0.16	0.00					
E_{inc}	-0.26	-0.27	-0.04	0.09	0.03	-0.18	-0.01	0.00				
n_{hit}	-0.27	-0.30	-0.11	0.20	0.14	-0.08	-0.00	-0.01	0.00			
E_1/E_{vis}	0.05	0.03	0.02	0.27	0.22	0.01	0.00	-0.03	0.03	0.00		
E_2/E_{vis}	-0.08	-0.08	-0.33	-0.09	-0.04	0.36	0.12	0.07	0.12	0.23	0.00	
E_3/E_{vis}	0.03	0.04	0.01	-0.20	-0.20	-0.27	-0.16	-0.11	-0.18	0.01	-0.31	0.00

GEANT4 - GAN

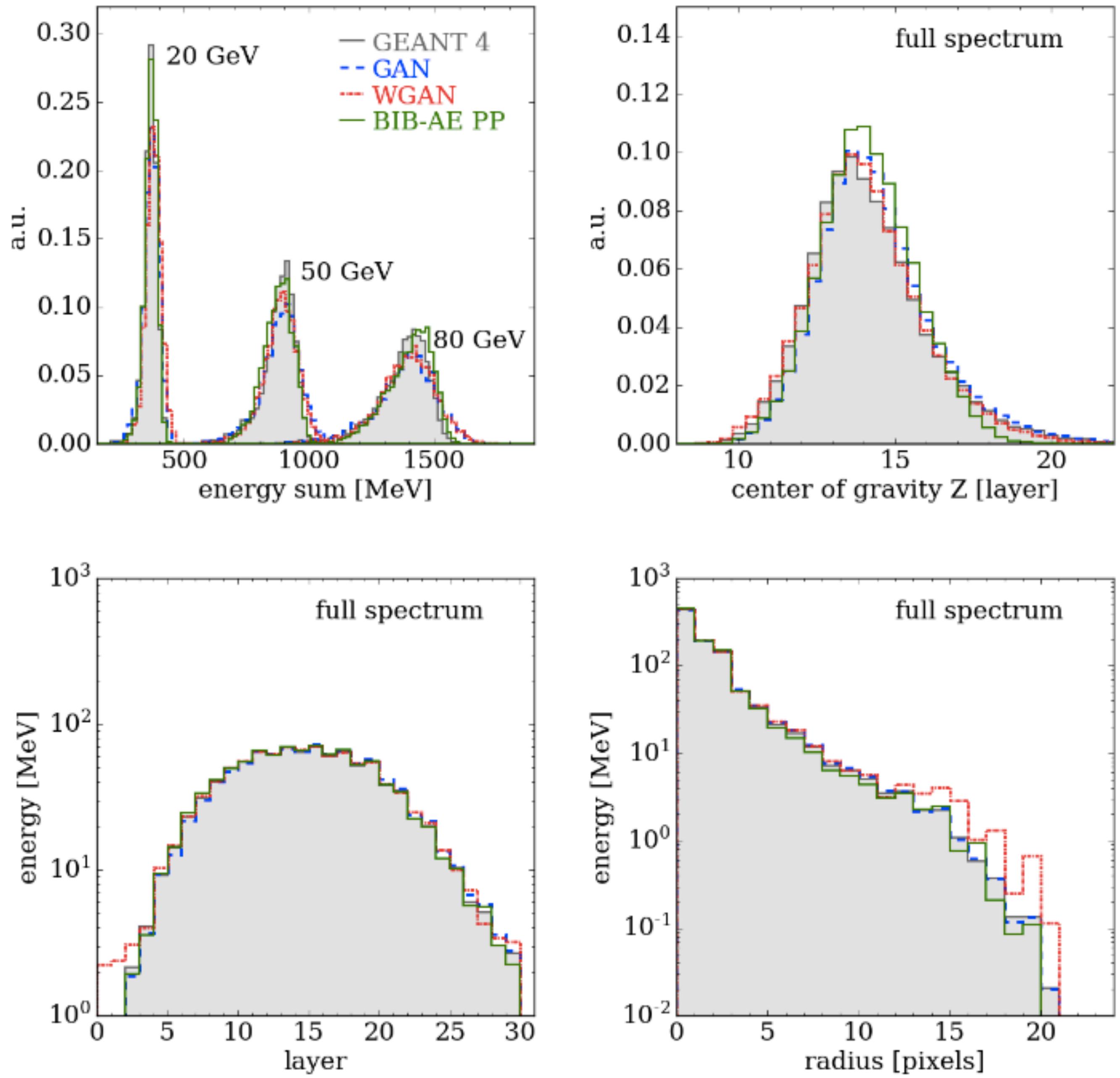
	$m_{1,x}$	$m_{1,y}$	$m_{1,z}$	$m_{2,x}$	$m_{2,y}$	$m_{2,z}$	E_{vis}	E_{inc}	n_{hit}	E_1/E_{vis}	E_2/E_{vis}	E_3/E_{vis}
$m_{1,x}$	0.00											
$m_{1,y}$	-0.02	0.00										
$m_{1,z}$	0.08	-0.05	0.00									
$m_{2,x}$	0.01	-0.03	-0.12	0.00								
$m_{2,y}$	0.10	-0.01	-0.19	0.01	0.00							
$m_{2,z}$	0.00	0.01	-0.00	0.06	0.11	0.00						
E_{vis}	0.05	-0.05	-0.00	-0.18	-0.20	-0.02	0.00					
E_{inc}	0.06	-0.06	-0.01	-0.19	-0.21	-0.02	0.01	0.00				
n_{hit}	0.05	-0.05	0.00	-0.20	-0.20	-0.01	-0.00	0.01	0.00			
E_1/E_{vis}	-0.07	0.05	0.00	0.13	0.20	-0.02	-0.01	-0.01	-0.01	0.00		
E_2/E_{vis}	-0.01	-0.03	0.10	-0.11	-0.11	0.02	0.04	0.06	0.03	-0.10	0.00	
E_3/E_{vis}	0.08	-0.04	-0.01	-0.08	-0.15	-0.01	-0.01	-0.01	-0.00	0.02	0.08	0.00

GEANT4 - WGAN

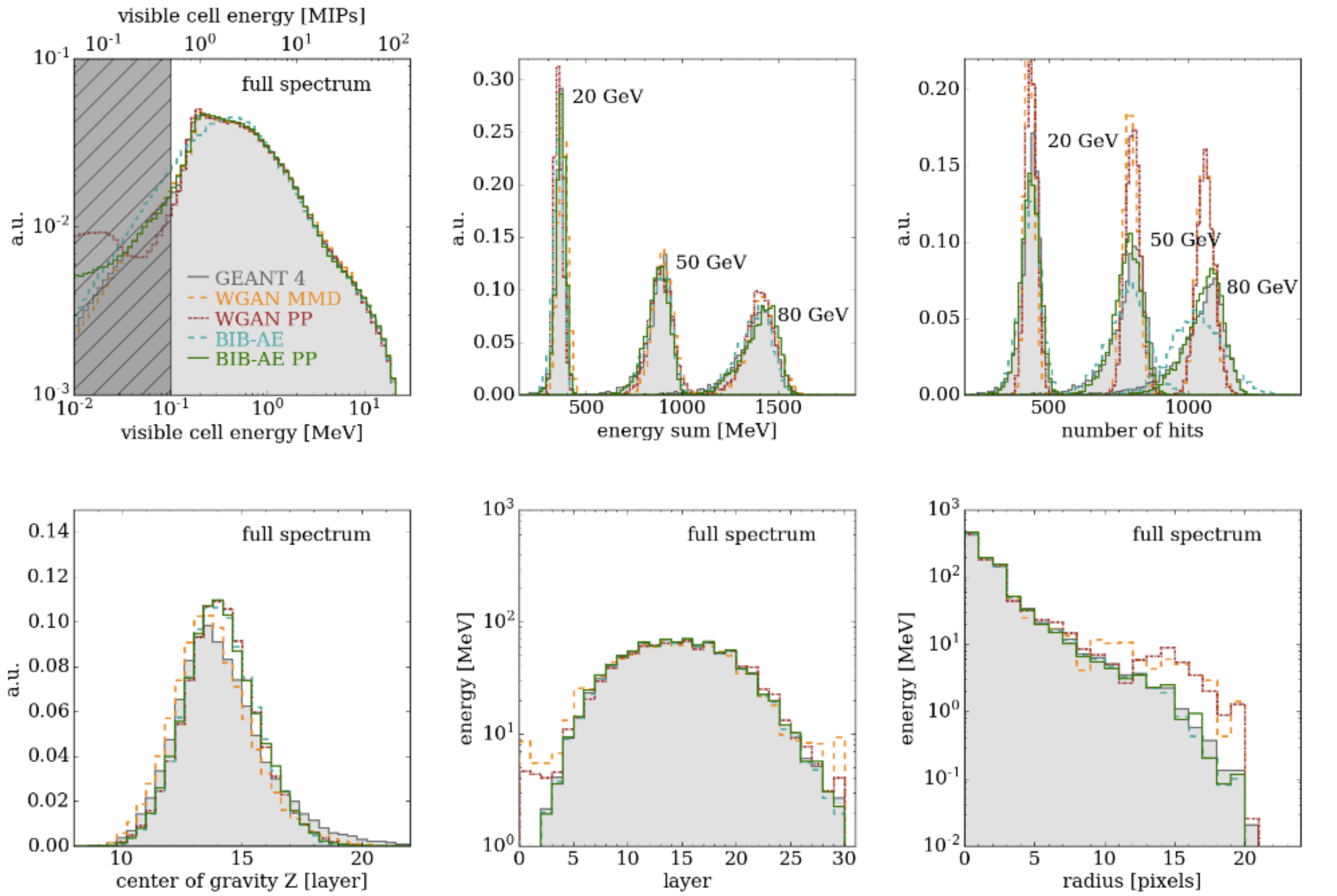
	$m_{1,x}$	$m_{1,y}$	$m_{1,z}$	$m_{2,x}$	$m_{2,y}$	$m_{2,z}$	E_{vis}	E_{inc}	n_{hit}	E_1/E_{vis}	E_2/E_{vis}	E_3/E_{vis}
$m_{1,x}$	0.00											
$m_{1,y}$	-0.33	0.00										
$m_{1,z}$	0.25	0.23	0.00									
$m_{2,x}$	-0.25	-0.49	-0.45	0.00								
$m_{2,y}$	-0.30	-0.57	-0.18	-0.50	0.00							
$m_{2,z}$	-0.01	-0.15	-0.32	-0.13	-0.12	0.00						
E_{vis}	0.23	0.18	-0.08	0.26	0.44	0.00	0.00					
E_{inc}	0.25	0.19	-0.06	0.18	0.39	-0.04	0.00	0.00				
n_{hit}	0.25	0.18	-0.16	0.27	0.45	0.03	-0.00	-0.01	0.00			
E_1/E_{vis}	-0.28	-0.29	0.00	0.31	0.07	0.23	0.07	0.06	0.14	0.00		
E_2/E_{vis}	0.17	0.26	-0.02	0.27	0.28	0.19	-0.01	-0.02	0.00	0.01	0.00	
E_3/E_{vis}	0.18	0.12	0.00	-0.54	-0.29	-0.39	-0.08	-0.06	-0.16	0.00	-0.01	0.00

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

Distributions…



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
center of gravity Z [layer]
energy [MeV]
layer
radius [pixels]