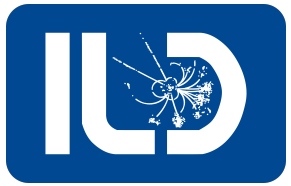
Generative Models Hadronic Shower Simulation

Erik Buhmann, Sascha Diefenbacher, **Engin Eren**, Frank Gaede, Daniel Hundhausen, Gregor Kasieczka, William Korcari, Anatolii Korol, Katja Krüger, Peter McKeown, Lennart Rustige

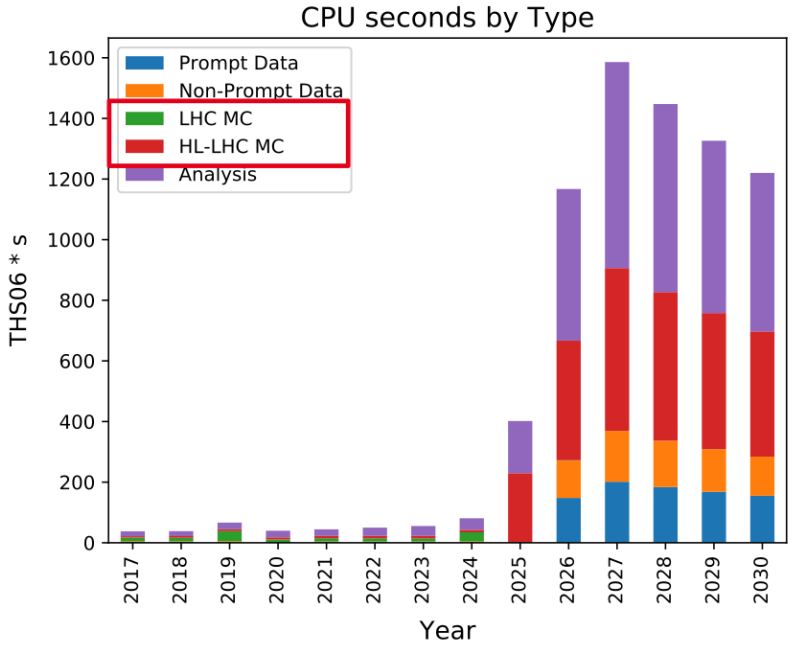
22.03.2022
DPG Spring Meeting



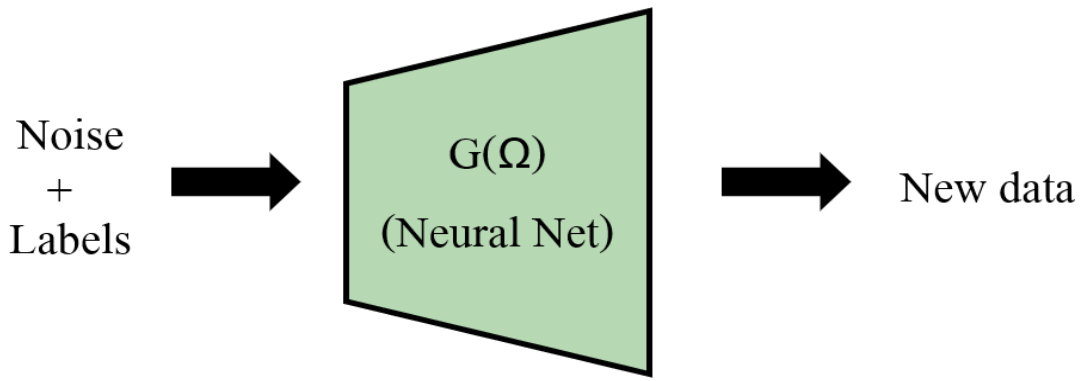
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

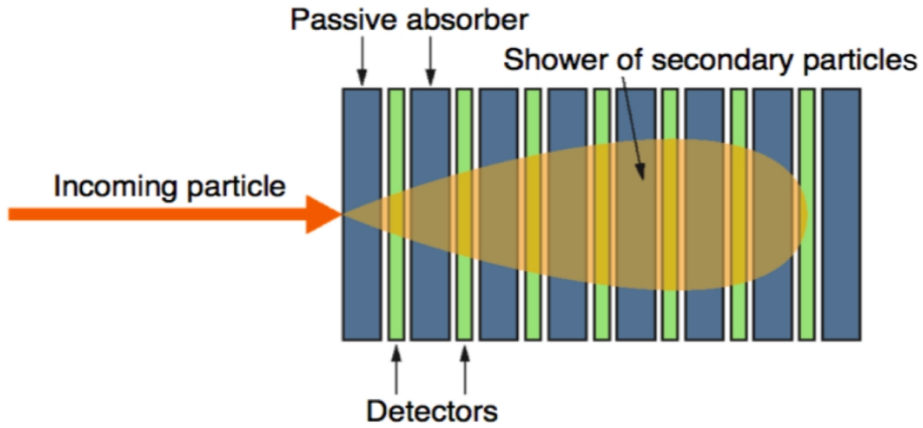
The bottleneck in HEP Computing Resources

- MC simulation is computationally expensive
  - Calorimeters most intensive part of detector simulation
- **Generative models** potentially offer orders of magnitude speed up
- Amplify statistics of original data set
  - Generate new samples following distribution of original data
  - Significant less time per shower

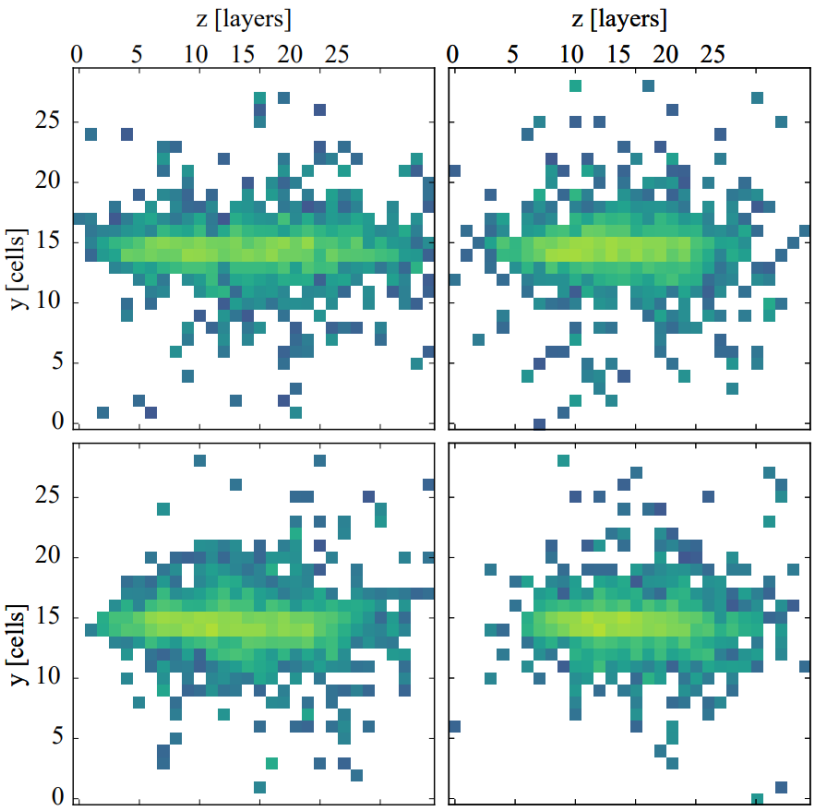


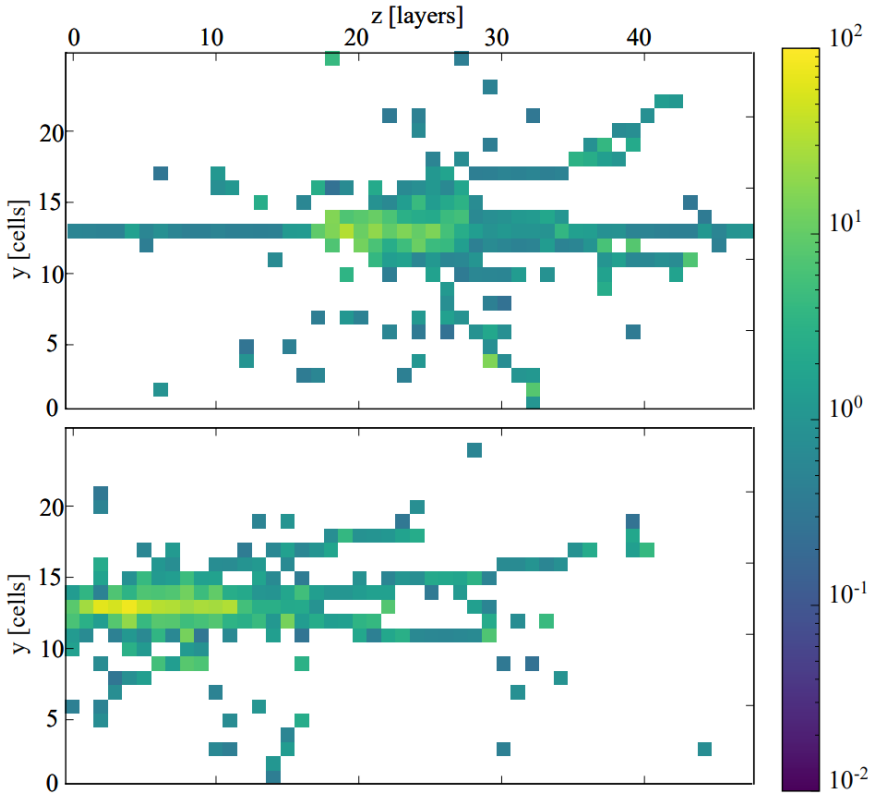
The HEP Software Foundation., Albrecht, J., Alves, A.A. et al. A Roadmap for HEP Software and Computing R&D for the 2020s. Comput Softw Big Sci 3, 7 (2019).





From Photons to Pions





Photon showers

- Predominantly governed by EM interactions
- Compact structure

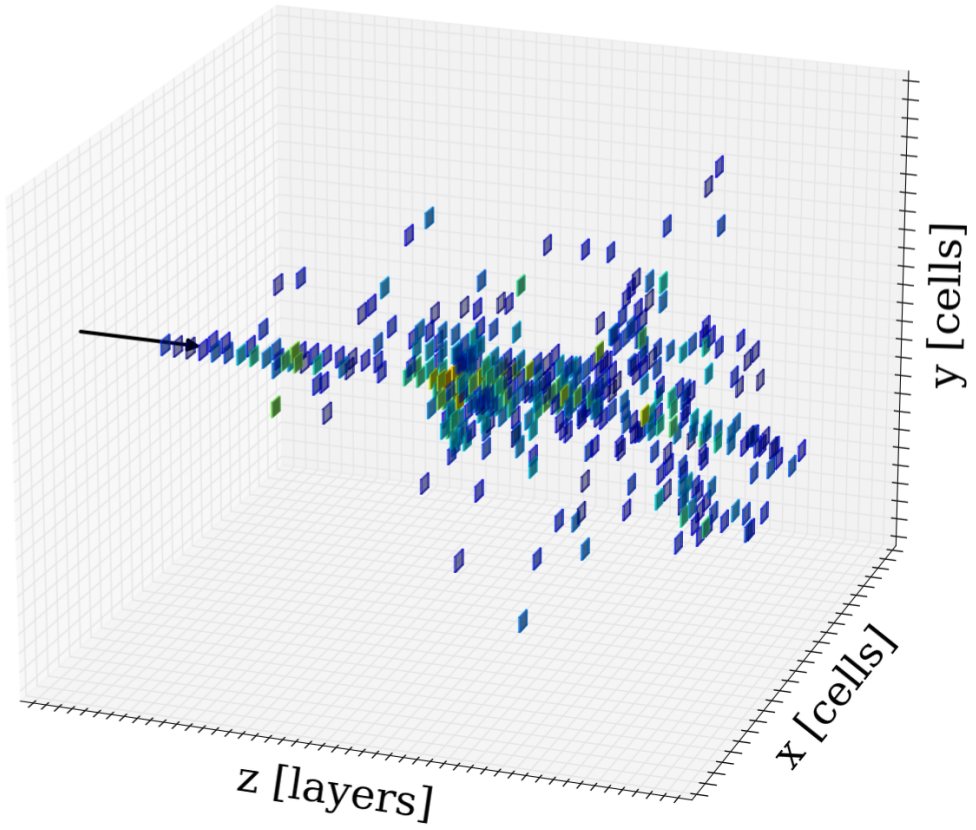
→ **Easy to generalise**

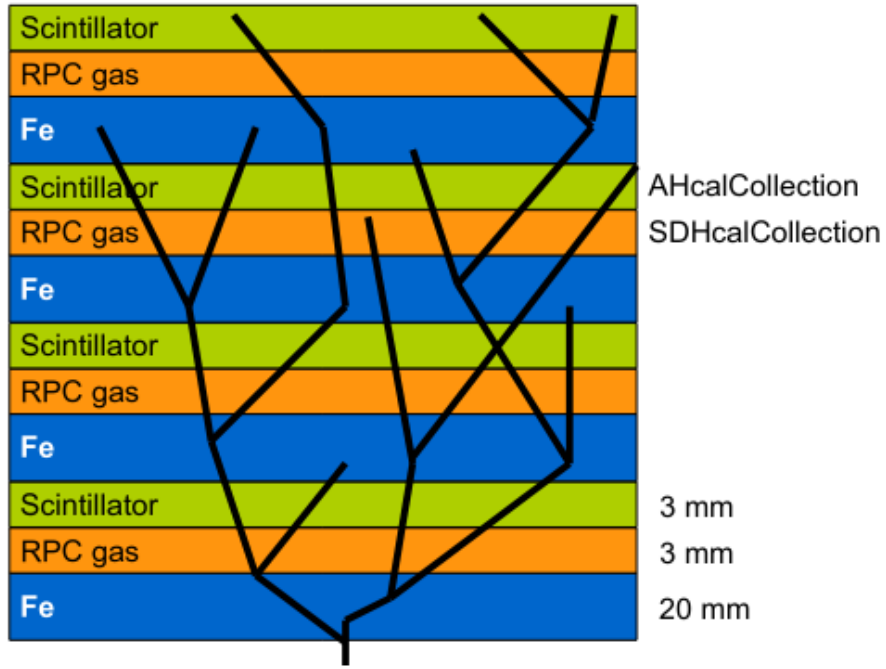
Pion showers

- Hadronic and EM interactions
- Complex structure
- Large event-to-event fluctuations

→ **Hard to learn**

Pion Dataset





- 500k showers
- Fixed incident point and angle
- Projected onto **48 x 25 x 25**
- Uniform energy: 10 GeV to 100 GeV

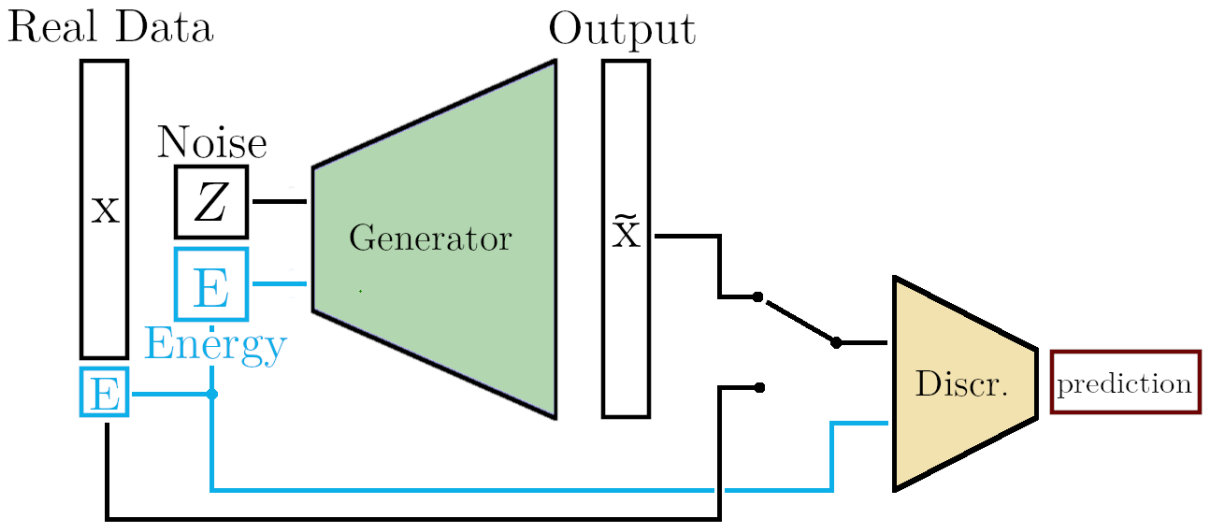
Hybrid simulation of ILD Hadron Calorimeter:

- Hits are recorded for scintillator and RPCs at the same time
- Here only scintillator (AHCal) is used

Architectures: GAN and WGAN

GAN

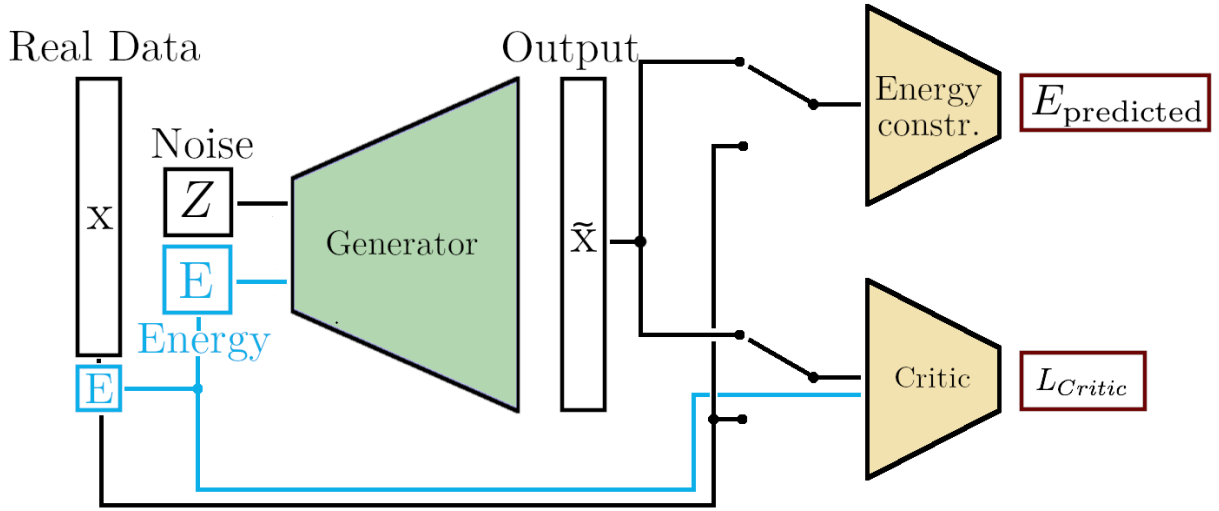
- Original Generative architecture applied for shower generation
- Discriminator and Generator play a min-max game



WGAN

- Alternative to classical GAN training
- Wasserstein-1 distance as loss with gradient penalty: **improve stability**

- **Addition of auxiliary constrainer networks for improved conditioning performance**

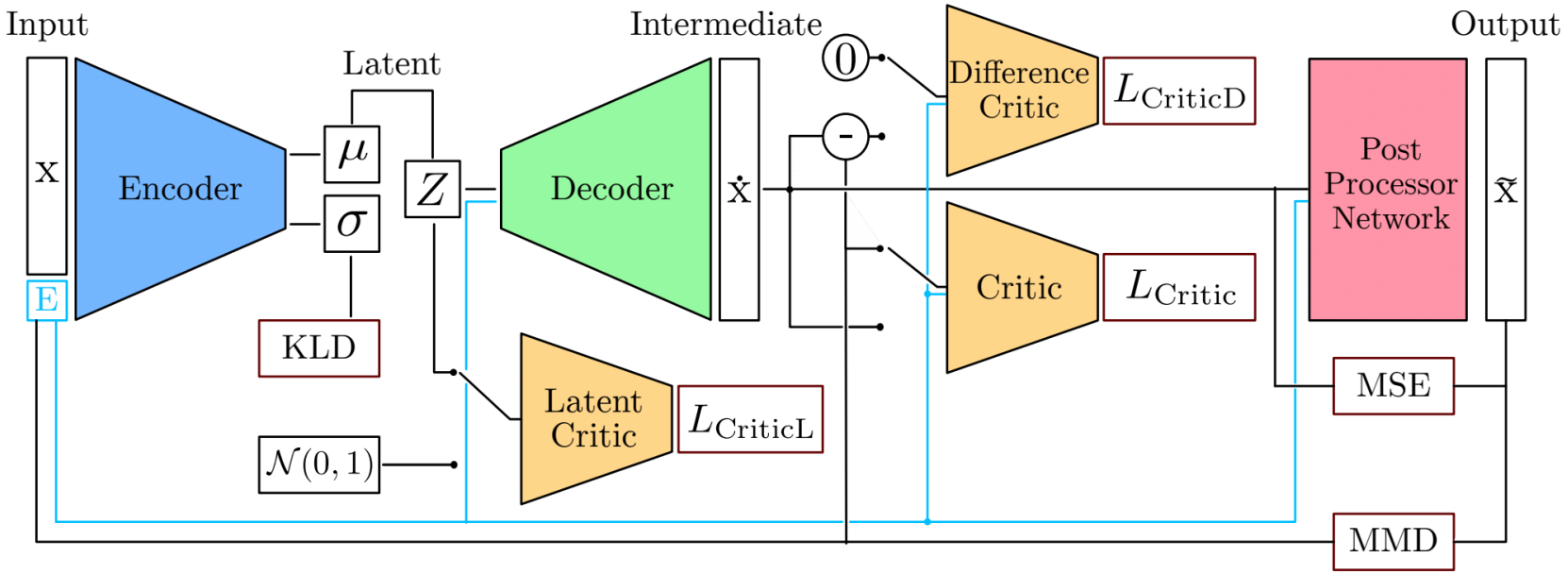


Architectures: BIB-AE

Bounded-Information Bottleneck Autoencoder (BIB-AE)

Voloshynovskiy et. al: **Information bottleneck through variational glasses**, arXiv:1912.00830

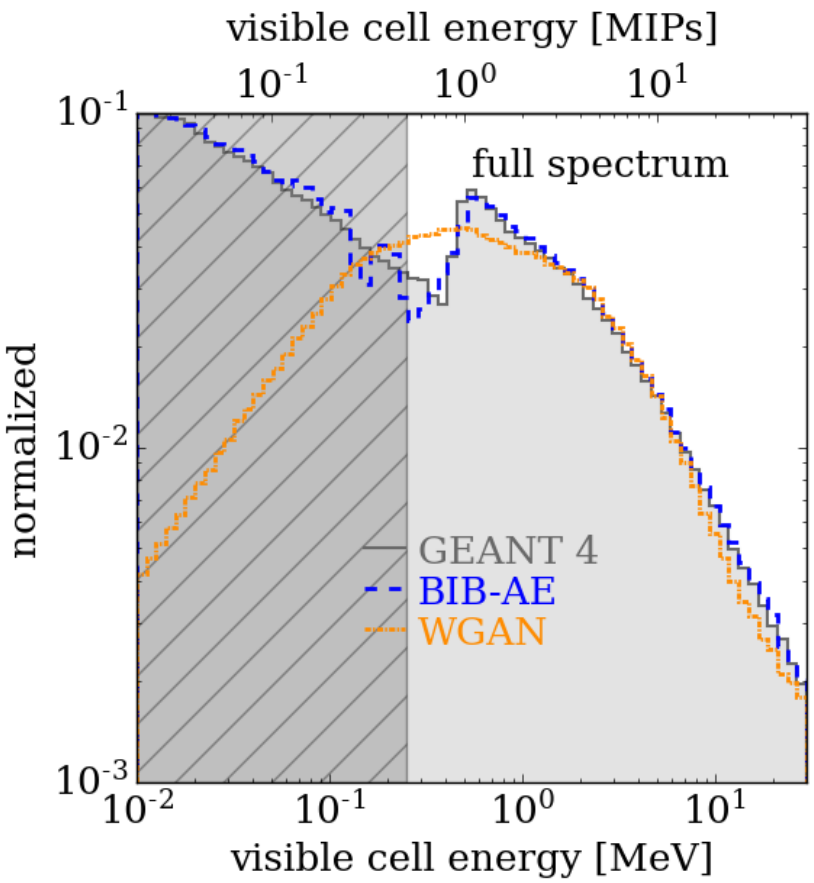
- Unifies features of both GANs and VAEs
- Post-Processor network: Improve per-pixel energies; second training
- Multi-dimensional KDE sampling: better modeling of latent space



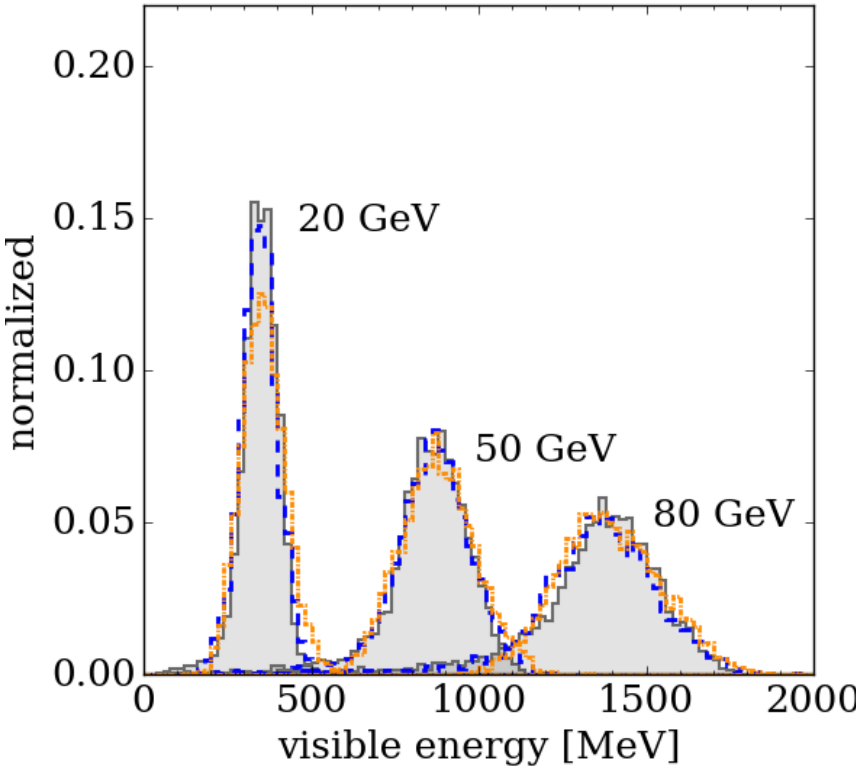
$$L_{\text{BIB-AE}} = \text{KLD} + L_{\text{CriticL}} + L_{\text{Critic}} + L_{\text{CriticD}}$$

$$L_{\text{Post}} = \text{MMD} + \text{MSE}$$

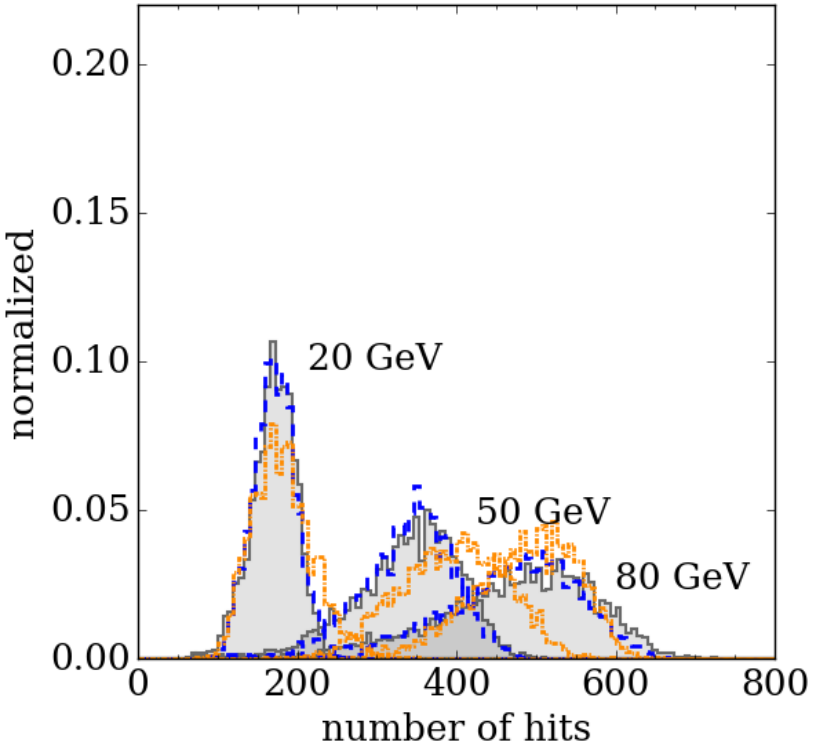
Pion Shower Results I



Very good agreement of MIP peak for **BIB-AE** with Post-Processing!

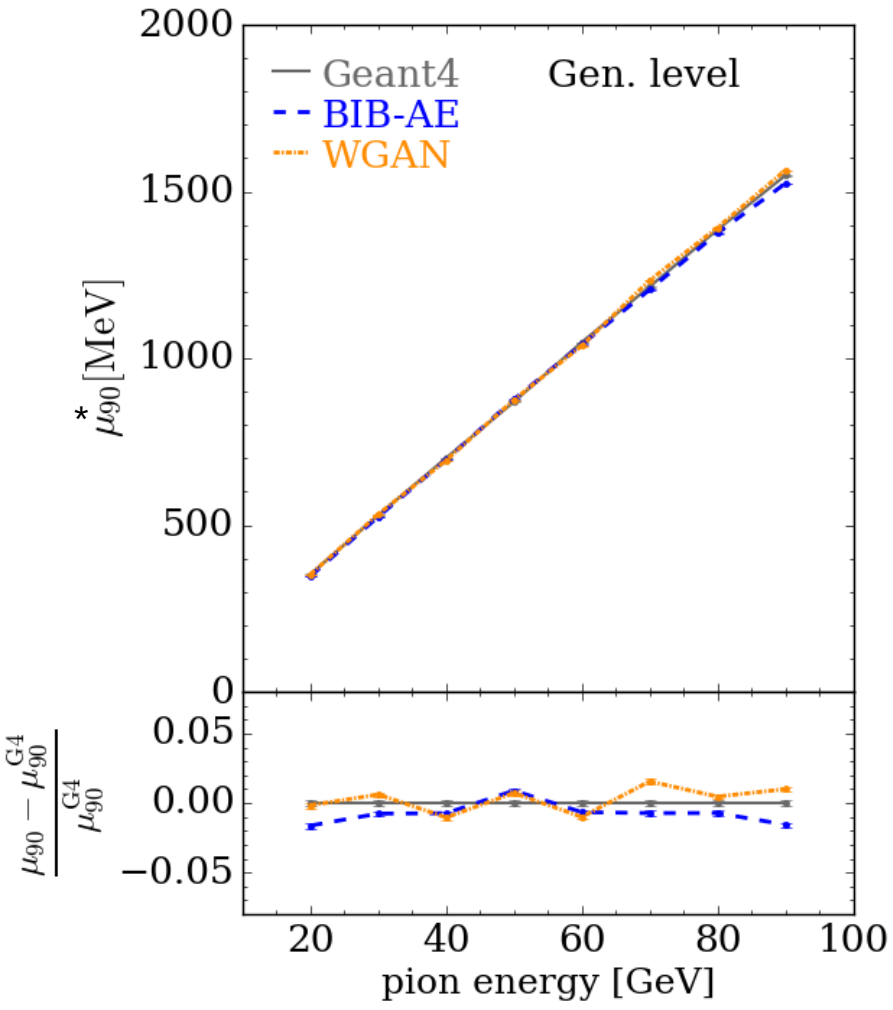


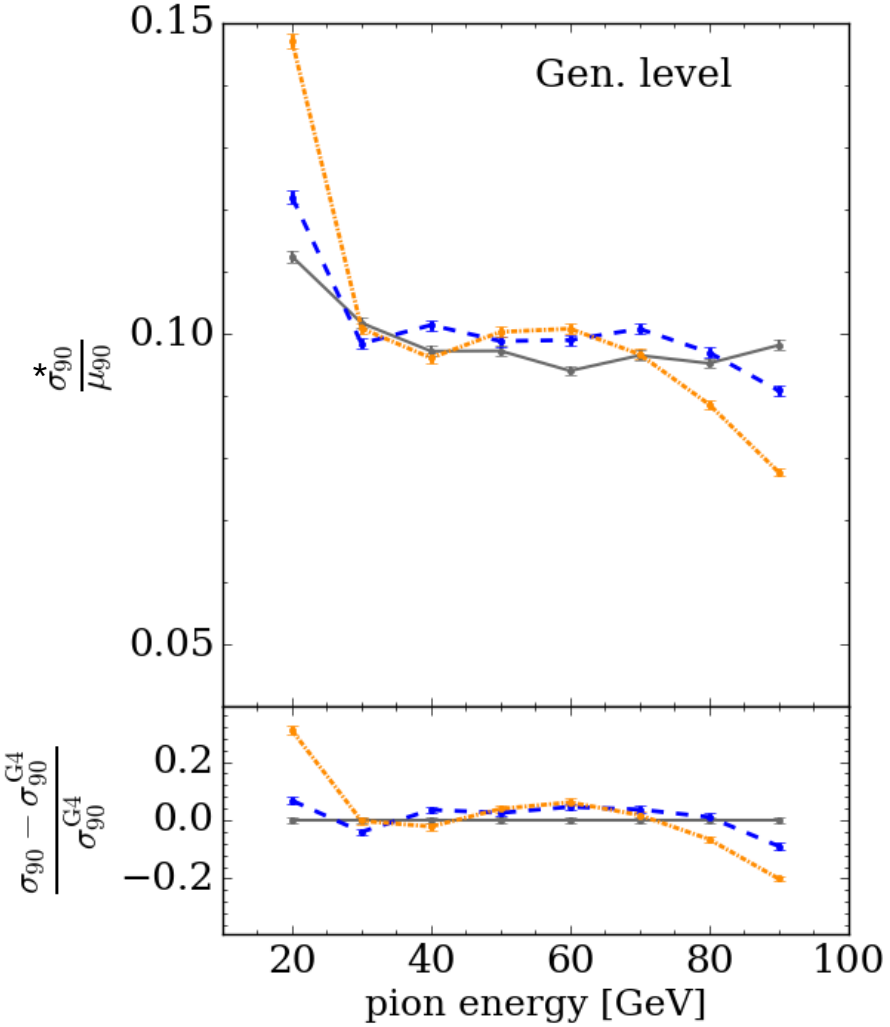
Great agreement with Geant4



Too much hits for **WGAN** ~50 GeV
BIB-AE is better

Pion Shower Results II

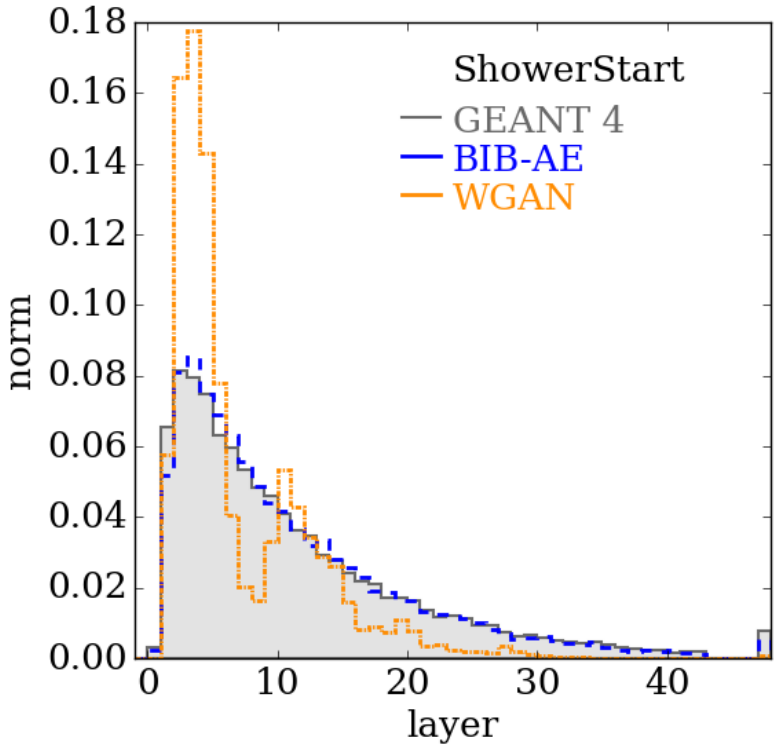


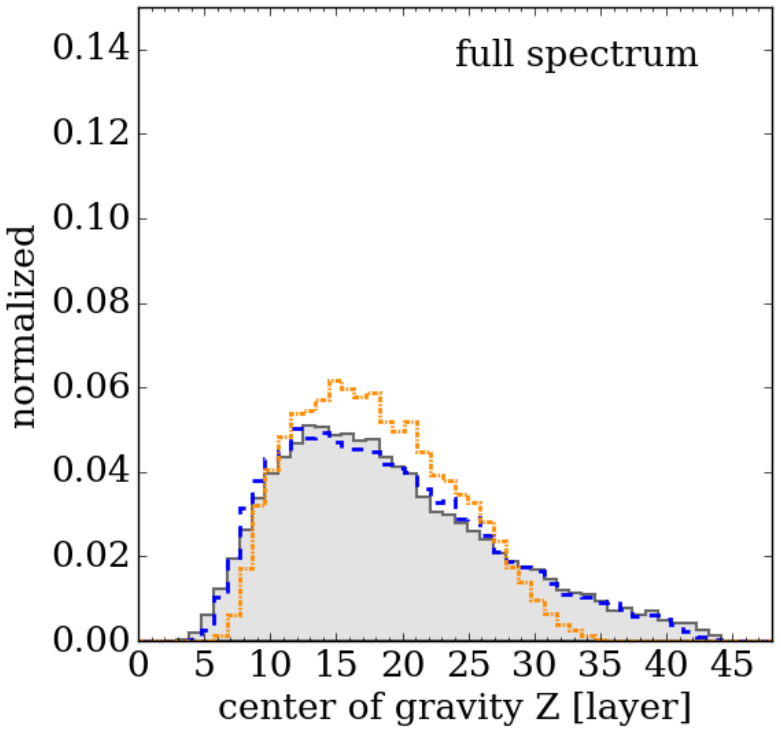


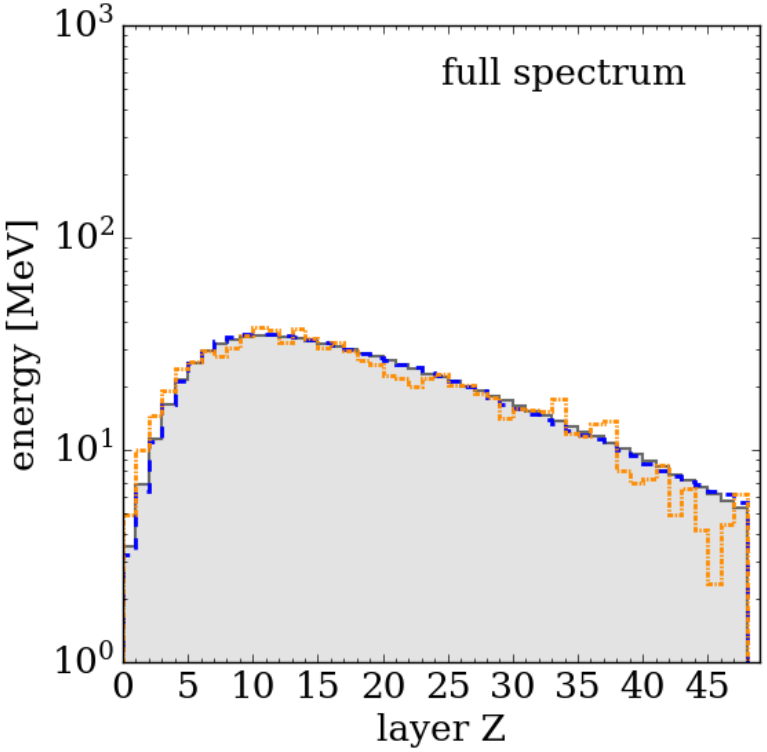
The most important quantity to get it right..

*the mean and root-mean-square of the 90% core of visible energy distributions

Pion Shower Results III



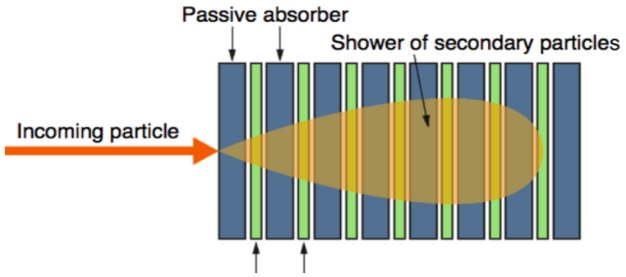




BIB-AE reproduces Geant4 distributions

WGAN performance is not as great...

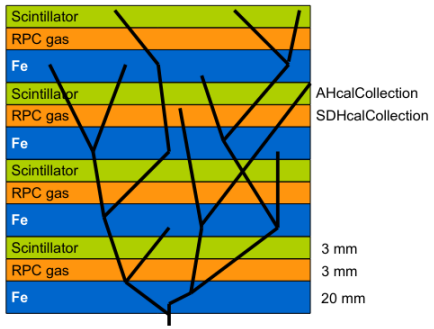
ILD Analysis Pipeline

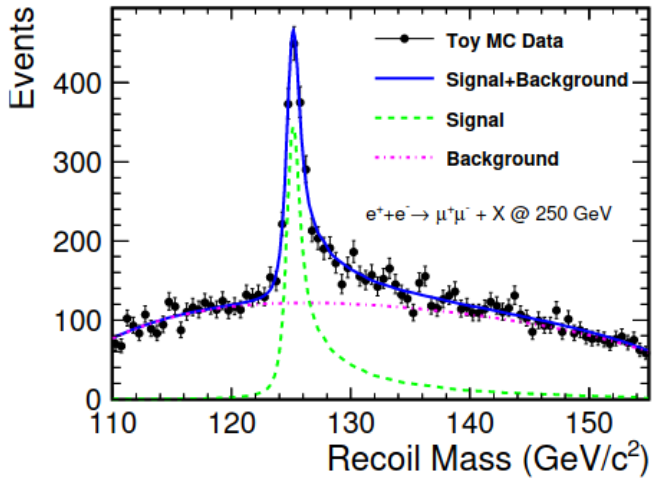


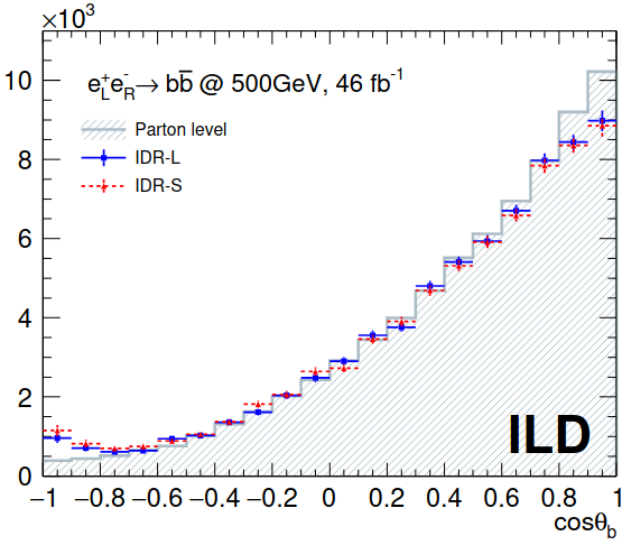
Geant4

Calibration & Digitization

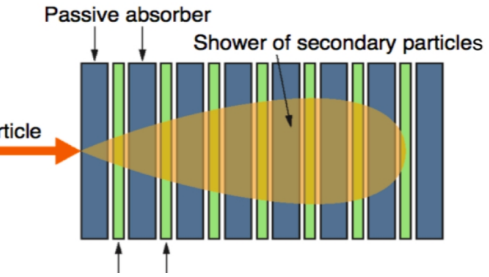
Particle Flow Reconsturction

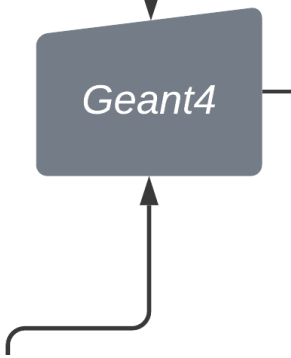


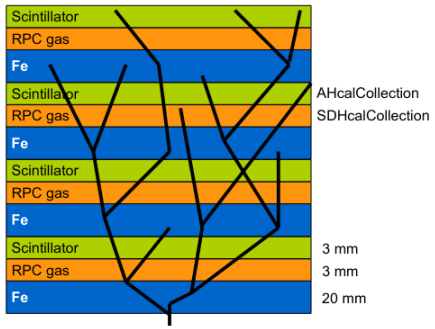


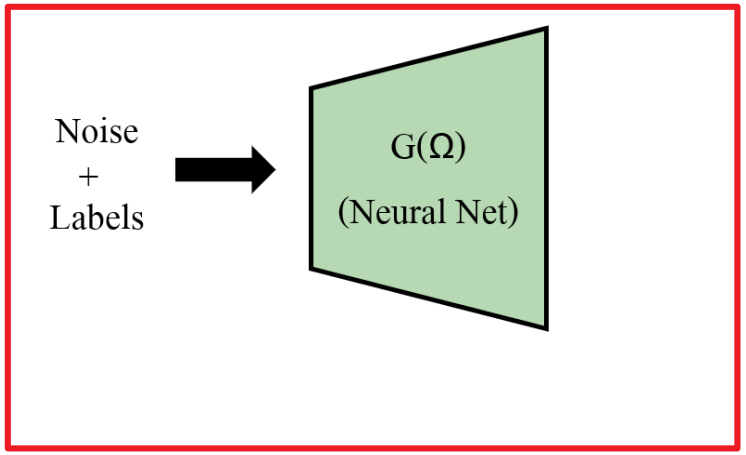


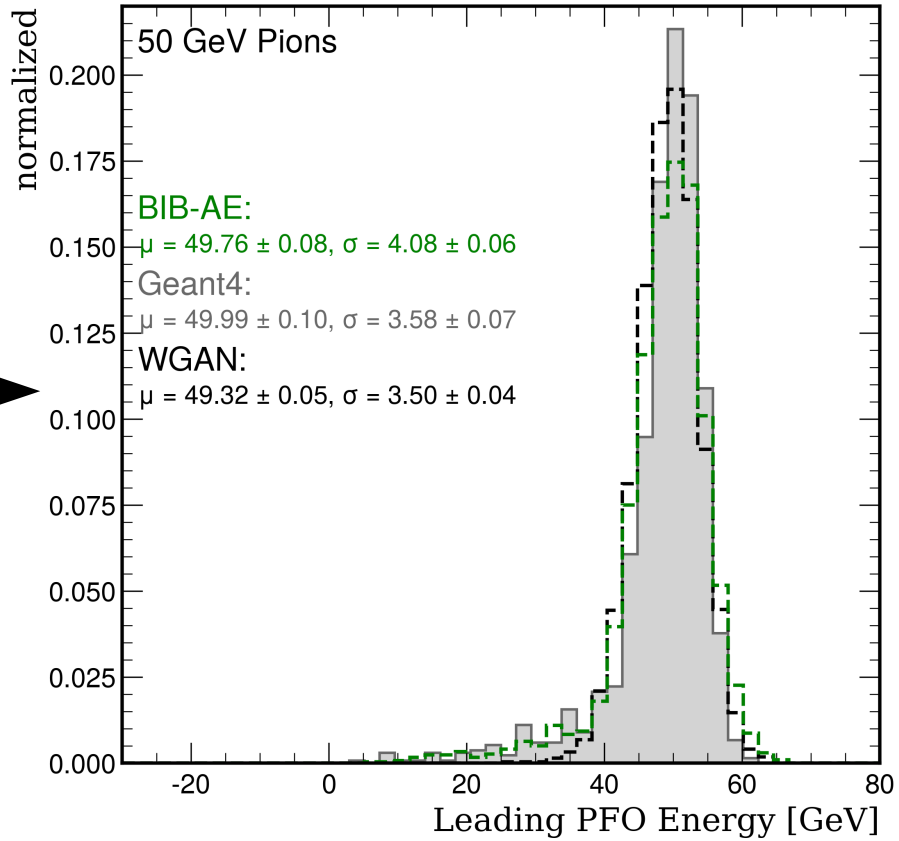
..with Generative Models





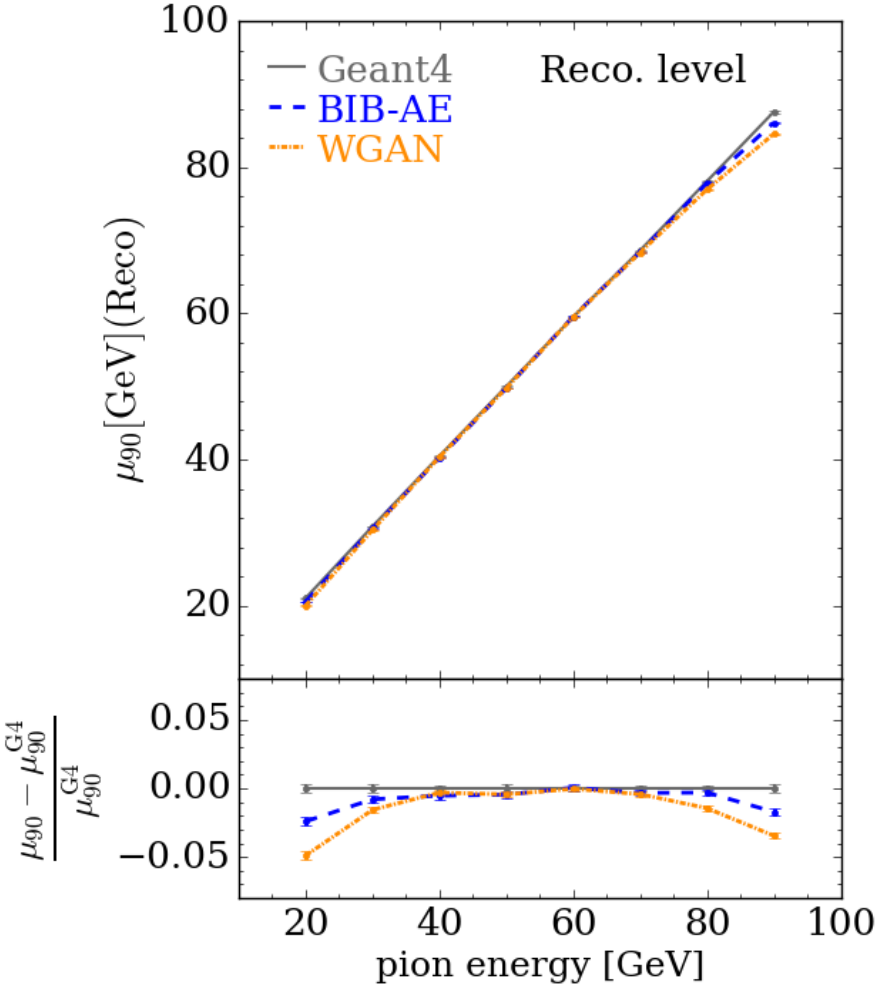




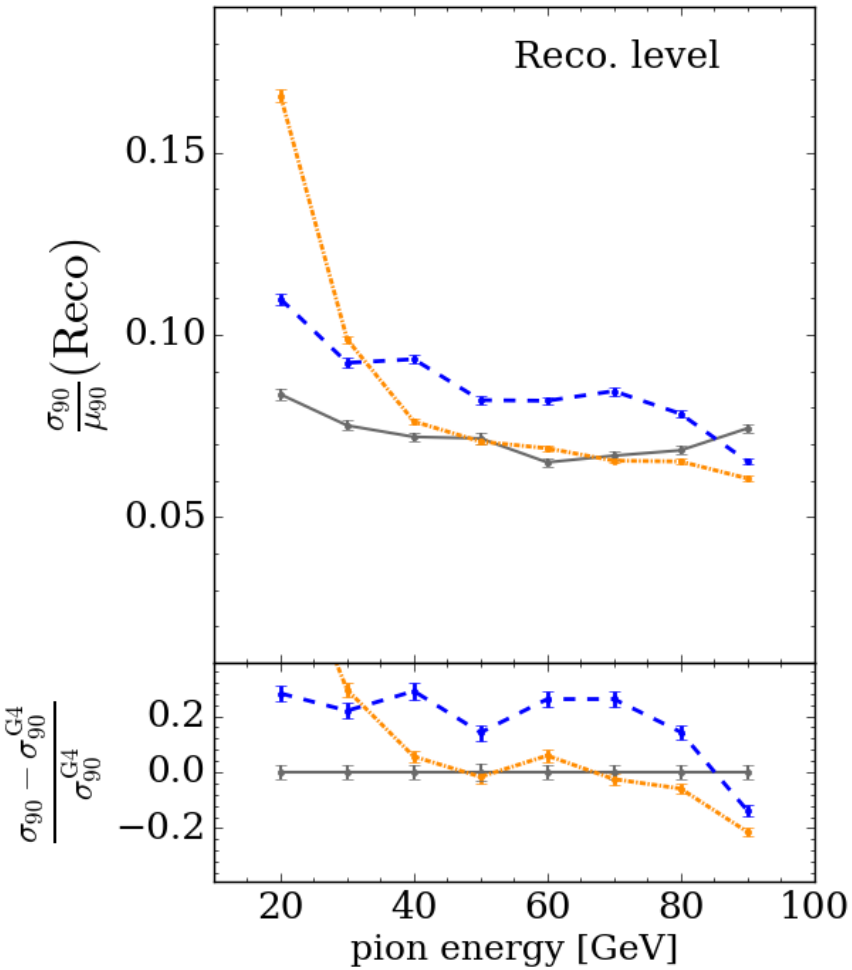


- First attempts to integrate generative ML models into the reconstruction workflow

Pion Showers after Reconstruction

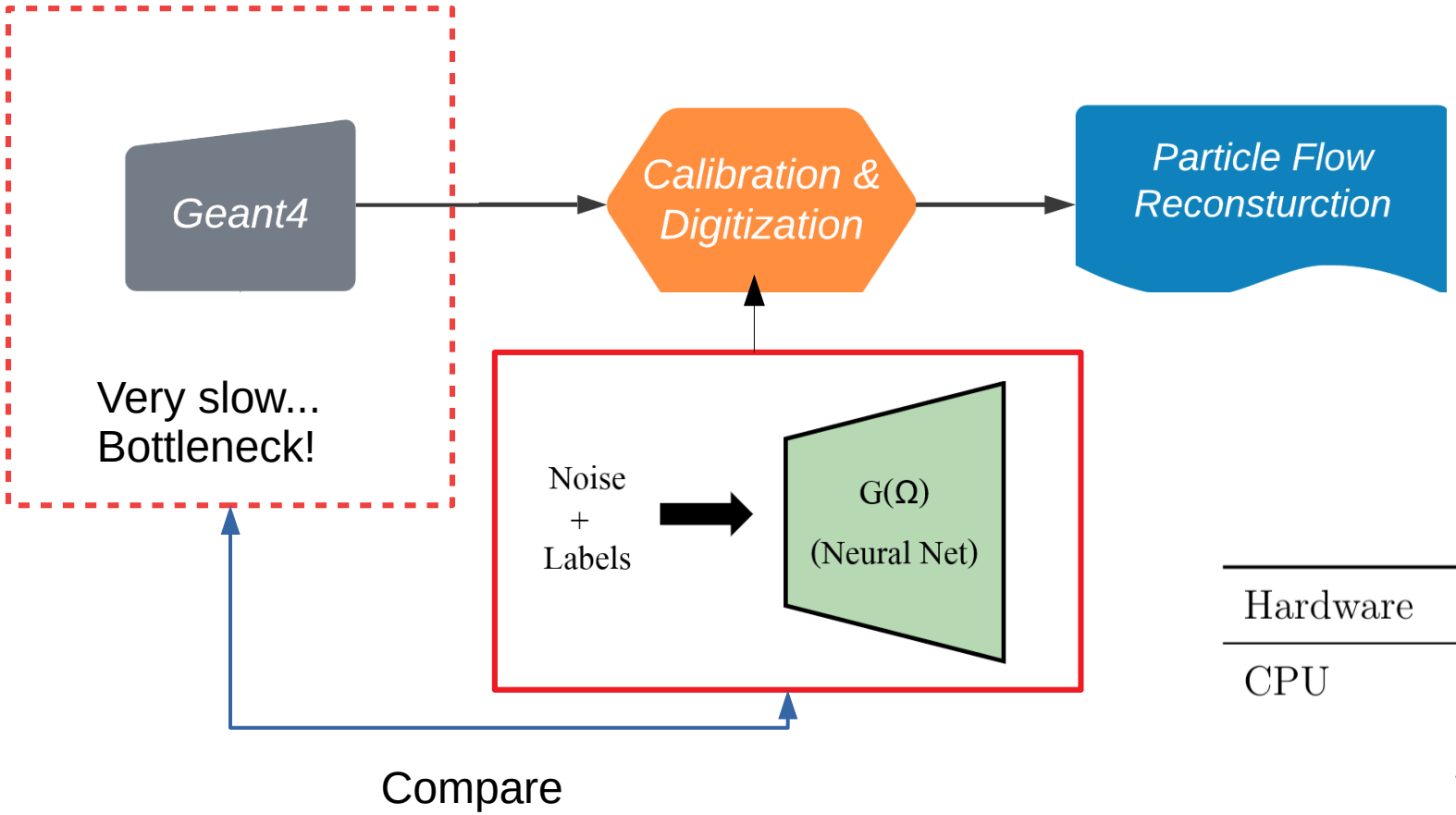


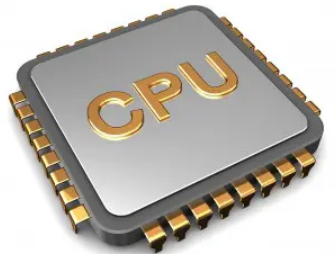
Both models show some discrepancy up to 3-5% at the edges.

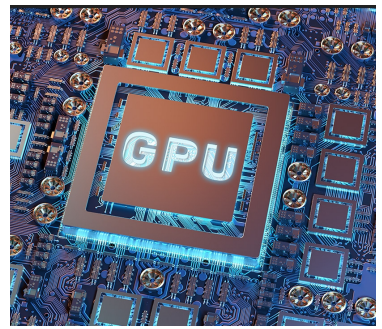


Very good agreement by **WGAN** in the middle incident energies.

Generation Time







Hardware	Simulator	Time / Shower [ms]	Speed-up
CPU	GEANT4	2684 ± 125	$\times 1$
	WGAN	47.923 ± 0.089	$\times 56$
	BIB-AE	350.824 ± 0.574	$\times 8$
GPU	WGAN	0.264 ± 0.002	$\times 10167$
	BIB-AE	2.051 ± 0.005	$\times 1309$

Both models offer significant speedups!

Conclusion

Achieved

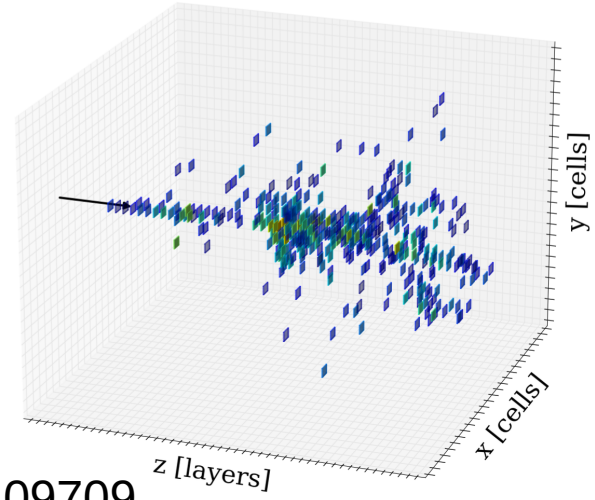
- Generative models hold promise for fast simulation of calorimeter showers with high fidelity
- Demonstrated high fidelity simulation of hadronic showers with generative models
  - Submitted to *Machine Learning: Science and Technology*

Ongoing Work

- Vary energy and angle simultaneously and study effect on performance
- Incorporate angular conditioning in more sophisticated architectures e.g. B

Next Steps

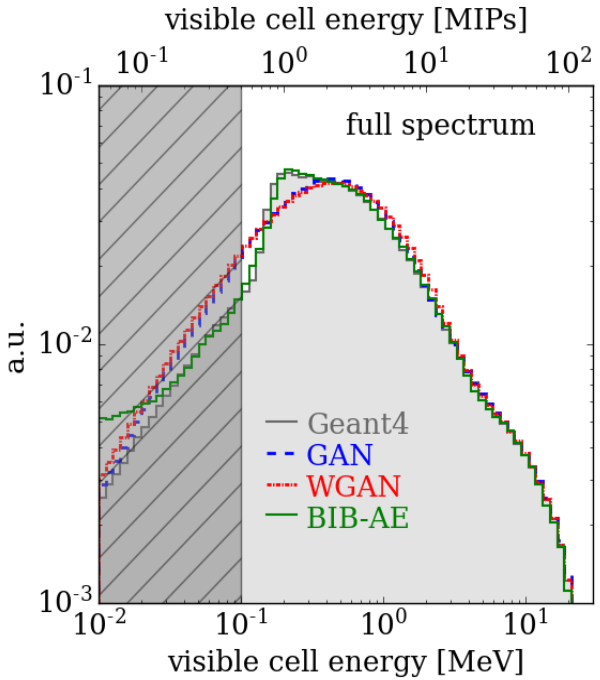
- Simulation of hadronic showers including HCAL and ECAL

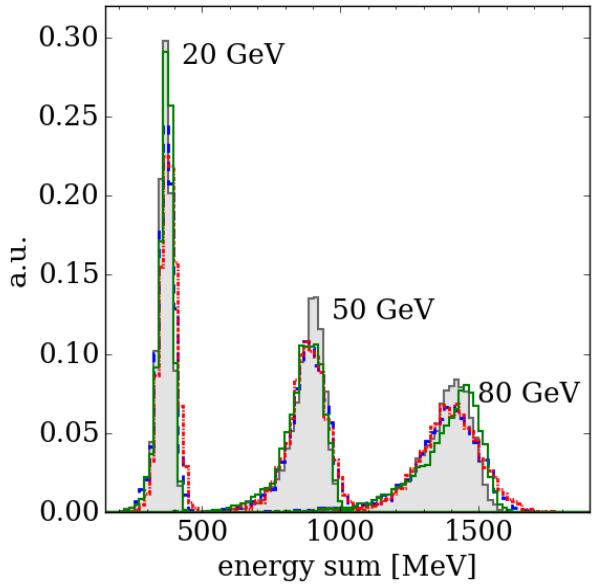


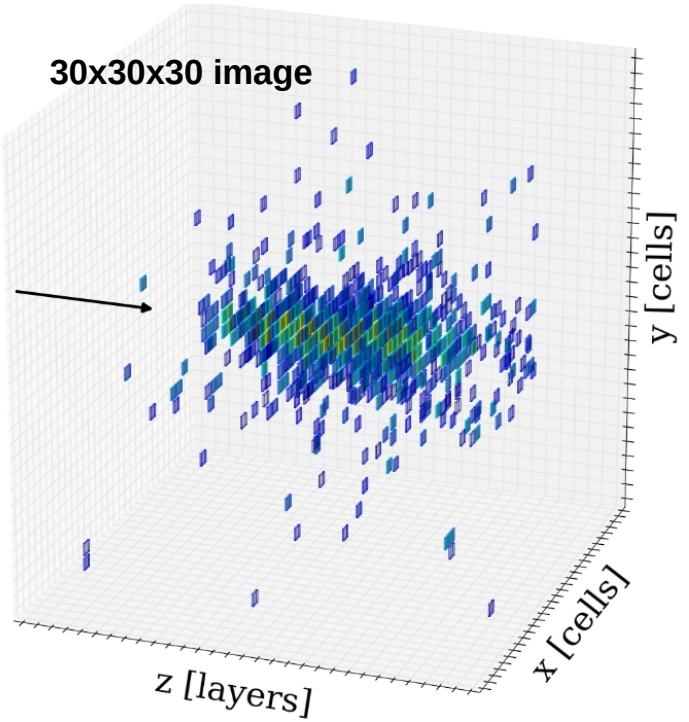
arXiv:2112.09709

Backup

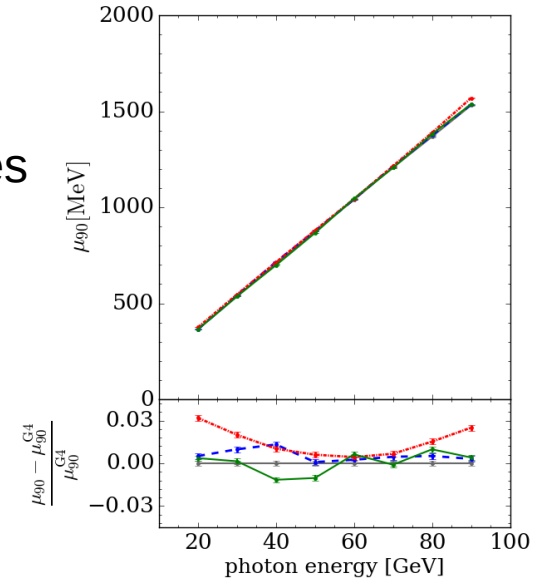
Photon Showers







High fidelity of shower properties are achieved



Hardware	Simulator	Photons	
		Time/shower[ms]	Speed-up
CPU	Geant4	4082±170	×1
	WGAN	61.44±0.03	×66
	BIB-AE	95.98±0.08	×43
GPU	WGAN	3.93±0.03	×1039
	BIB-AE	1.60±0.03	×2551

Significant speed ups

Buhmann, et al.: **Getting High: High Fidelity Simulation of High Granularity Calorimeters with High Speed.** Comput Softw Big Sci 5, 13 (2021)