Fast Calorimeter Simulation With Machine Learning Techniques

MU Days 2022, GSI

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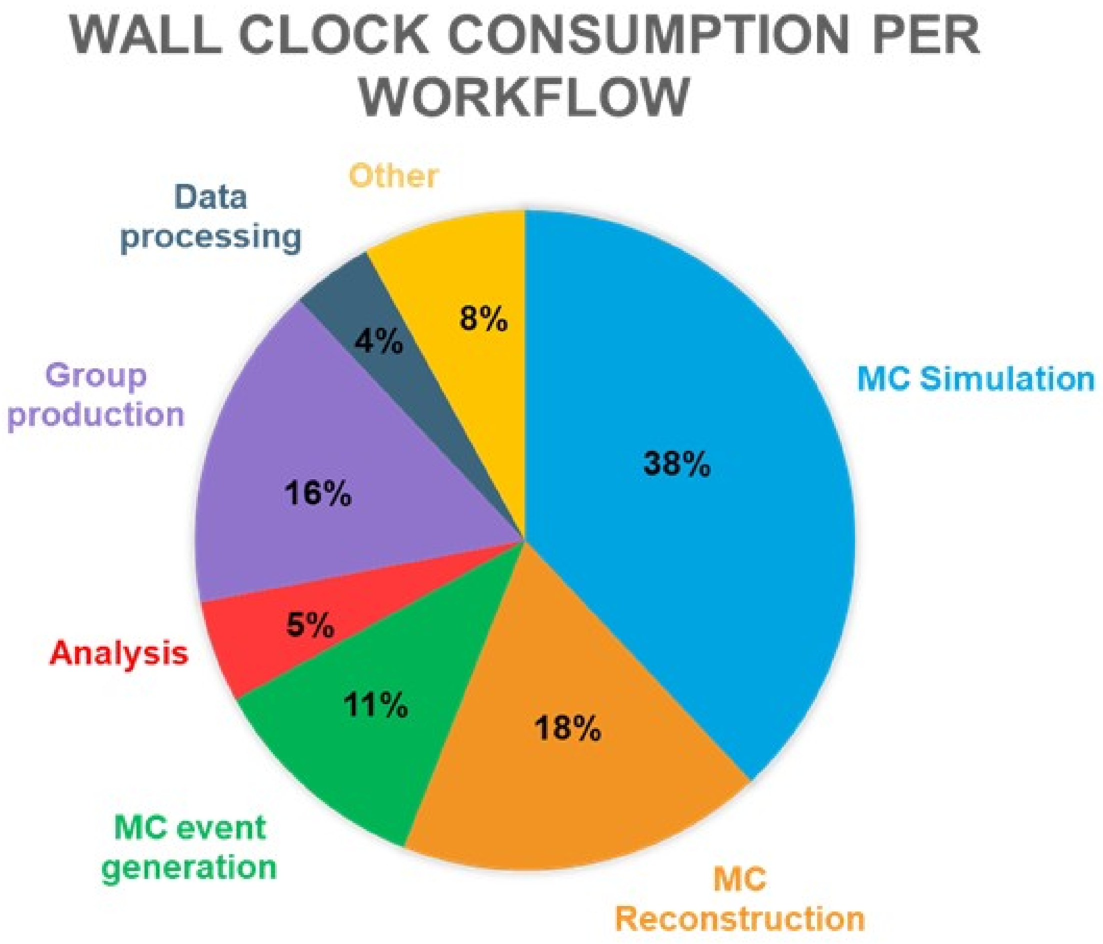
The Strain on HEP Computing Resources

- Ever **increasing demand** for computing resources
  - **MC simulation** largest fraction
  - **Calorimeters** most intensive part of detector simulation

- Projected computing resources required far outstrip what will be available
  - E.g HL-LHC

- **Generative ML models** potentially offer orders of magnitude speed up



D. Costanzo, J. Catmore, ATLAS Computing update, LHCC meeting , 2019

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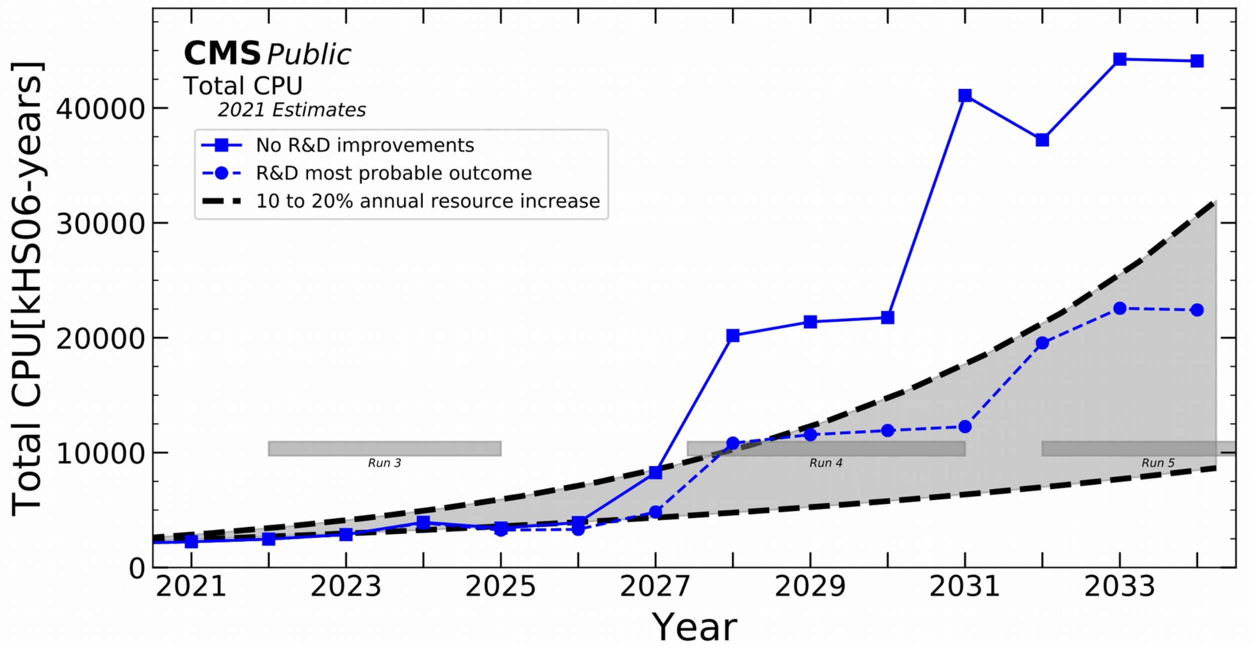
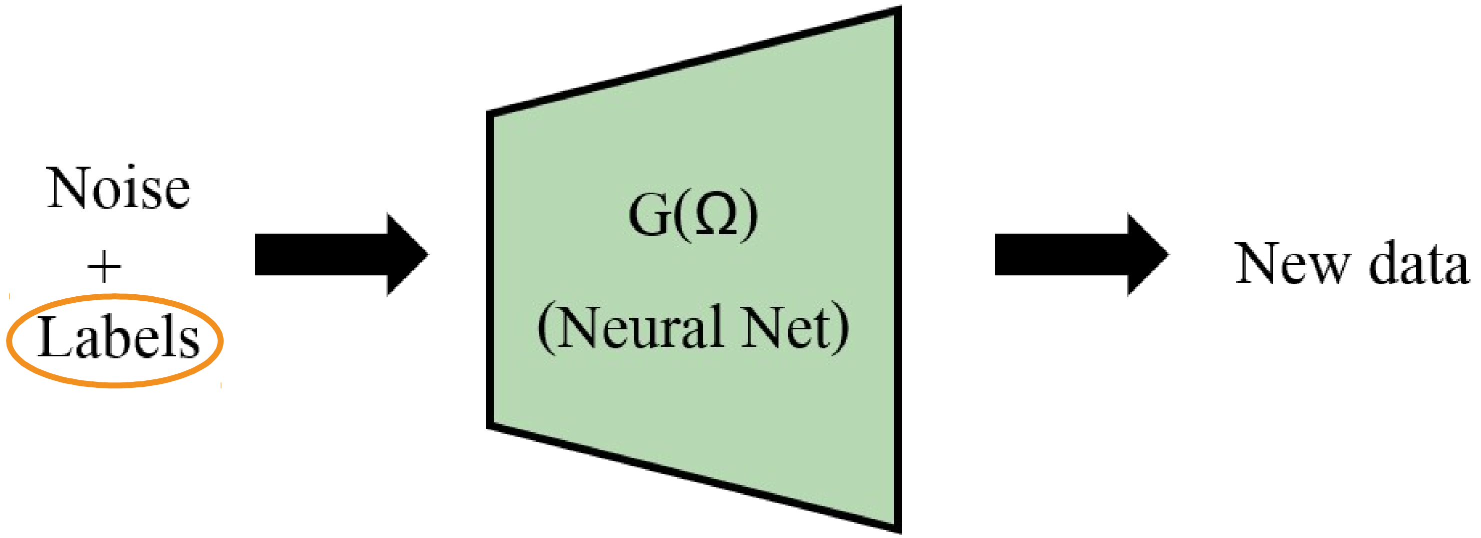


CMS Collaboration, Offline and Computing Public Results (2021), https://twiki.cern.ch/twiki/bin/view/CMSPublic/CMSOfflineComputingResults

Generative Models

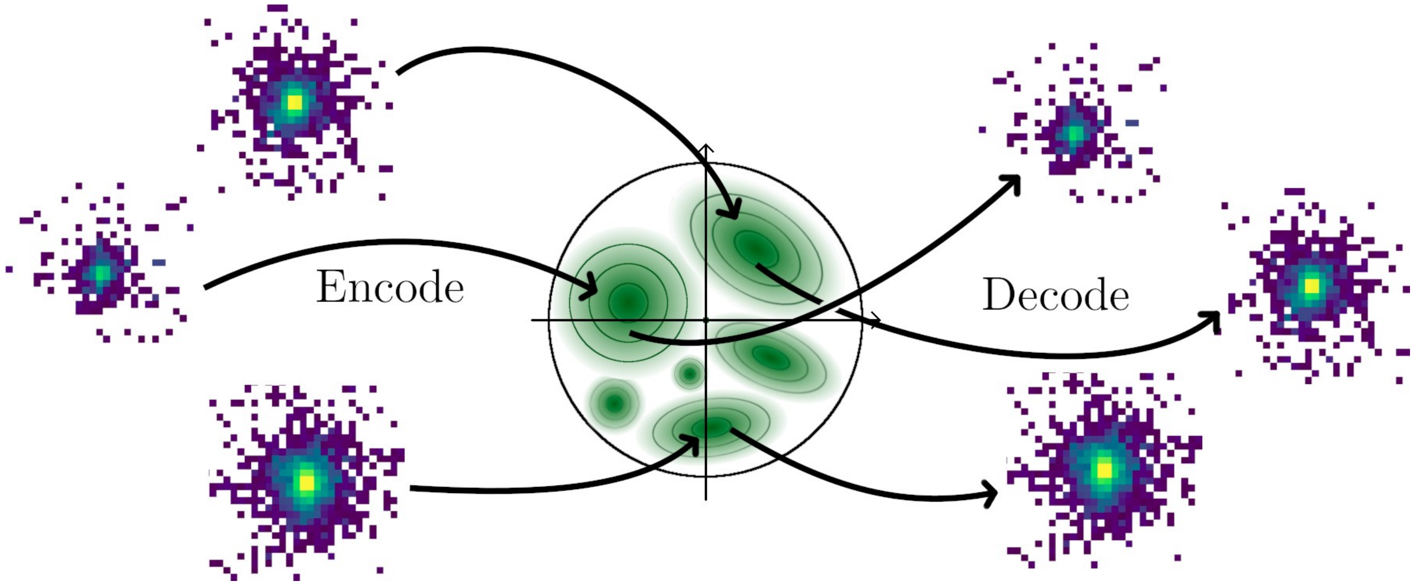
- Approach to fast simulation- **amplify statistics**
- Aim: **augment** full physics-based **GEANT4** simulation by learning a **transfer function**
- Promising solution: **generative models**
  - Generate **new samples** following the distribution of original data
  - Map random noise to data
  - Highly **parallelizable**
  - **Conditioning (E.g., E, θ, φ)**

Butter et. al, GANplifying event samples, SciPost Phys. 10, 139 (2021)

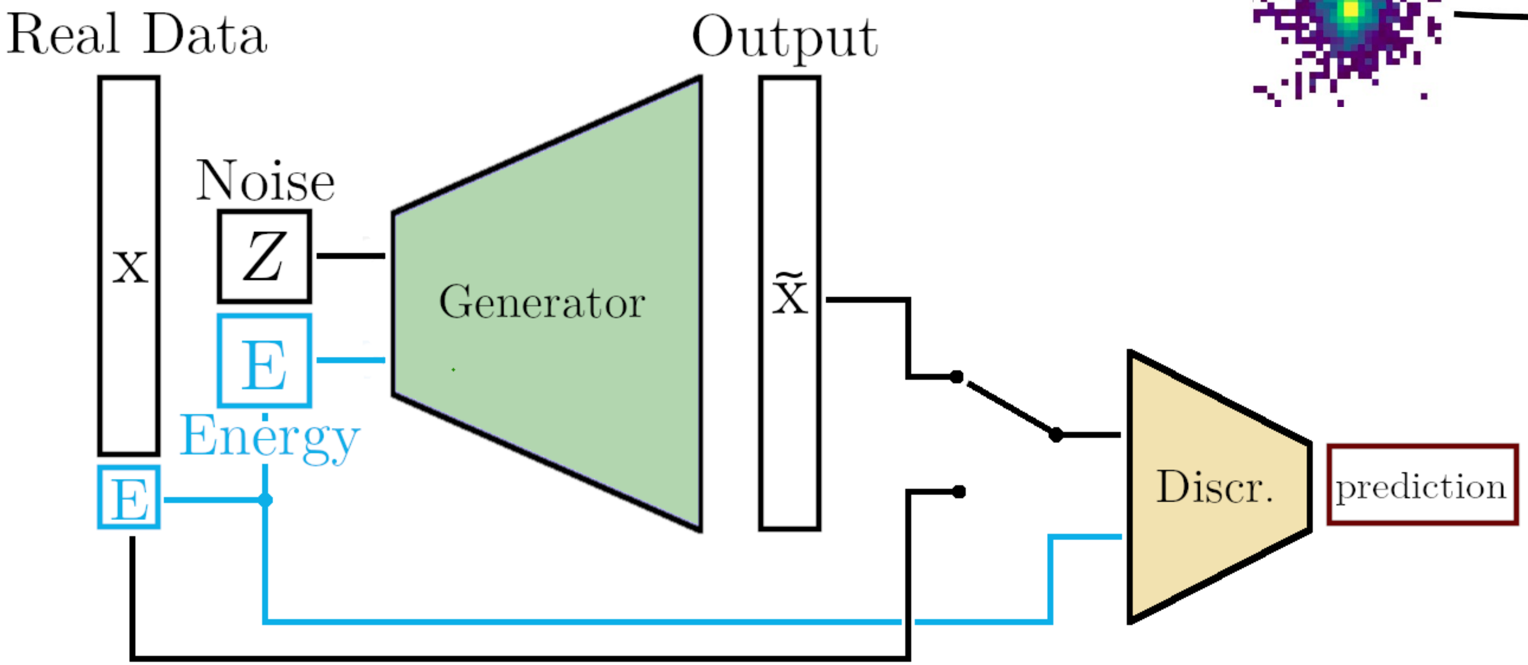


Common Generative Models

Variational Autoencoder (**VAE**)

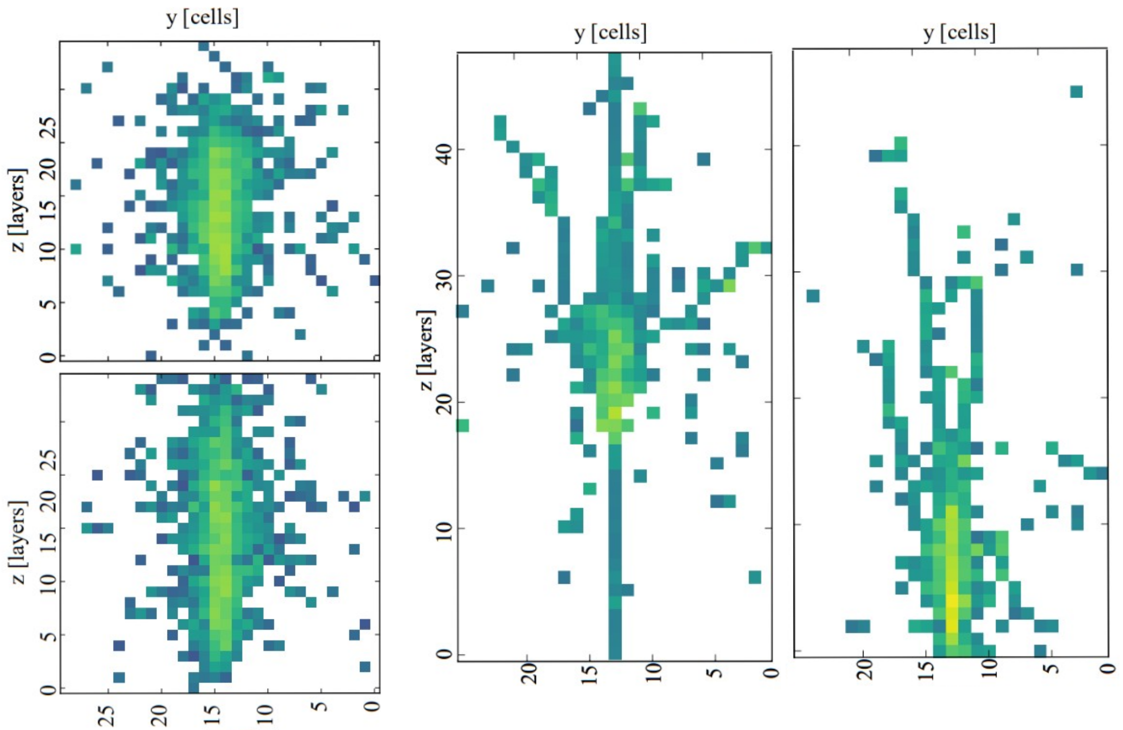


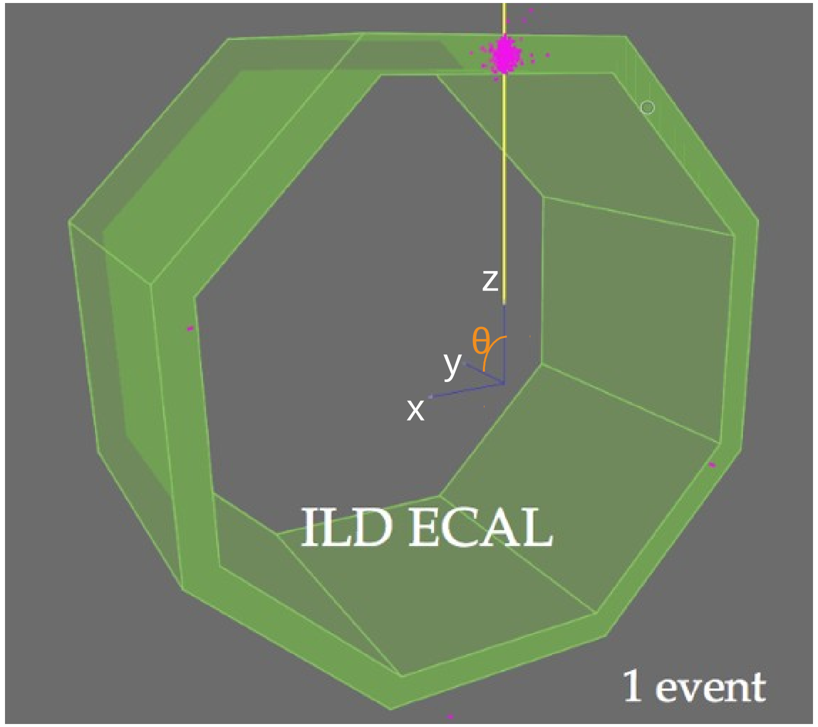
Generative Adversarial Network (**GAN**)



- Models studied:
  - Wasserstein GAN **(WGAN)**
  - Bounded Information Bottleneck Autoencoder **(BIB-AE)**

Challenges for Generative ML Calorimeter Simulations





From Photons to Pions

- **Hadronic** showers significantly harder to learn than electromagnetic showers
  - **Complex** topologies
  - Large event-to-event **fluctuations**

Multi-Parameter Conditioning

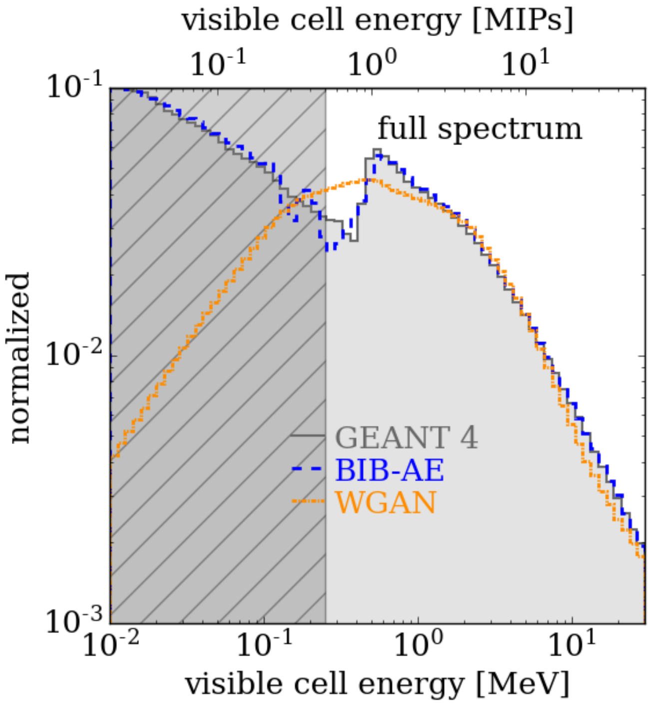
- **Simultaneous conditioning** on multiple parameters crucial for a general simulation tool
  - Start with **photons**
  - Vary incident **energy and angle**

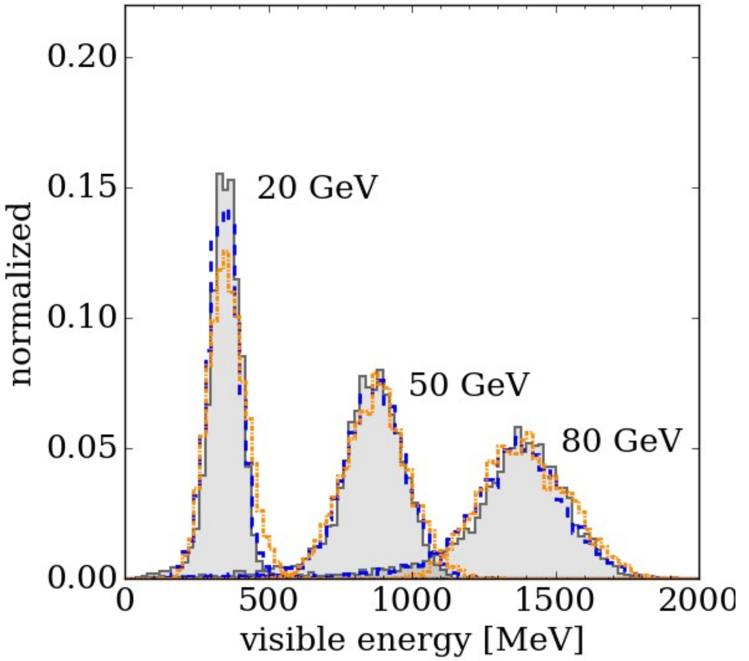
Latest Progress

Hadronic Calorimeter Showers

- Achieve **significant speedups** (CPU/GPU)
- Achieve **high degree of fidelity**

Hadrons, Better, Faster, Stronger,
E. Buhmann, et al.
[MLST 3 025014 (2022)]





Hardware	Simulator	Time / Shower [ms]	Speed-up
CPU	GEANT4	2684 ± 125	×1
	WGAN	47.923 ± 0.089	×56
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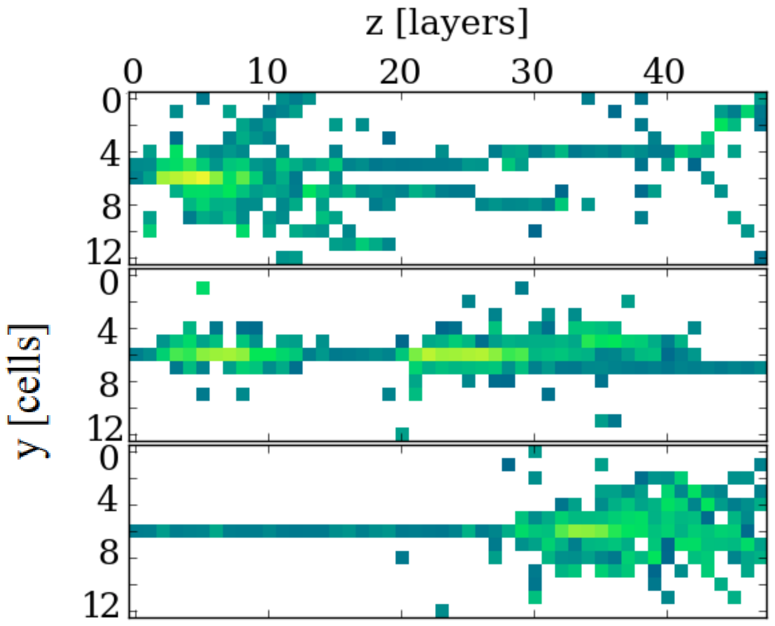
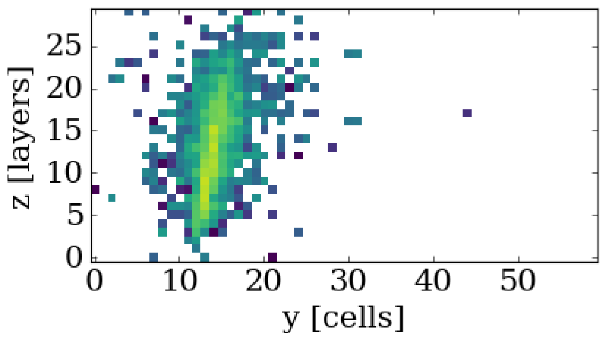
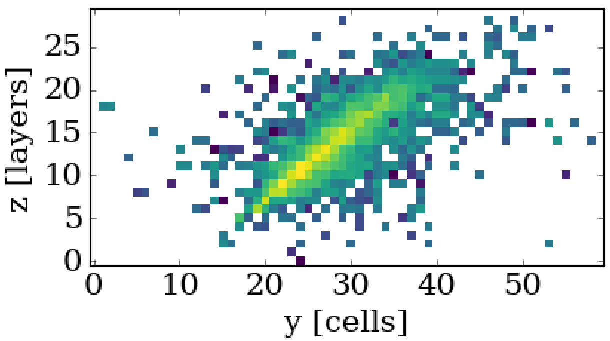


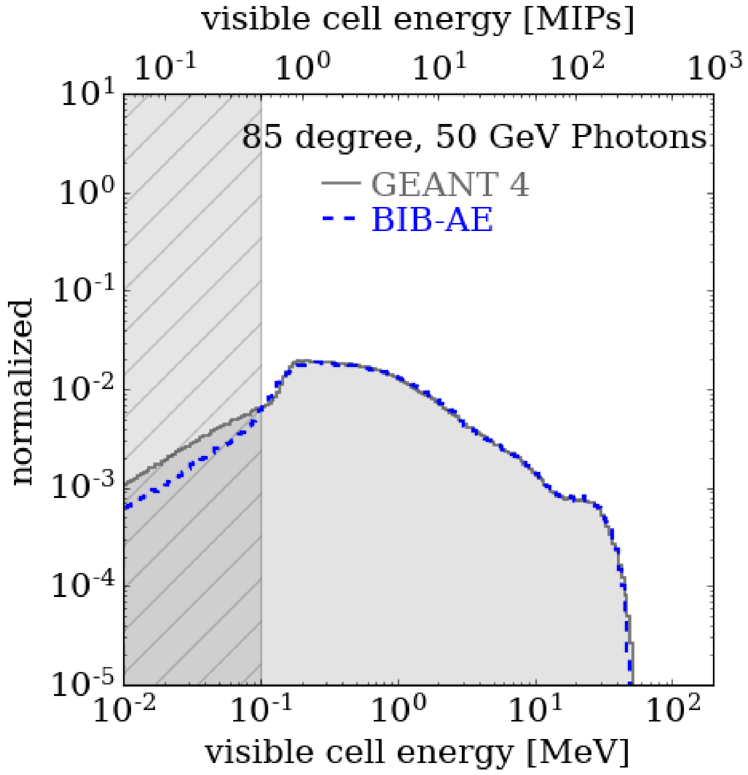
Latest Progress

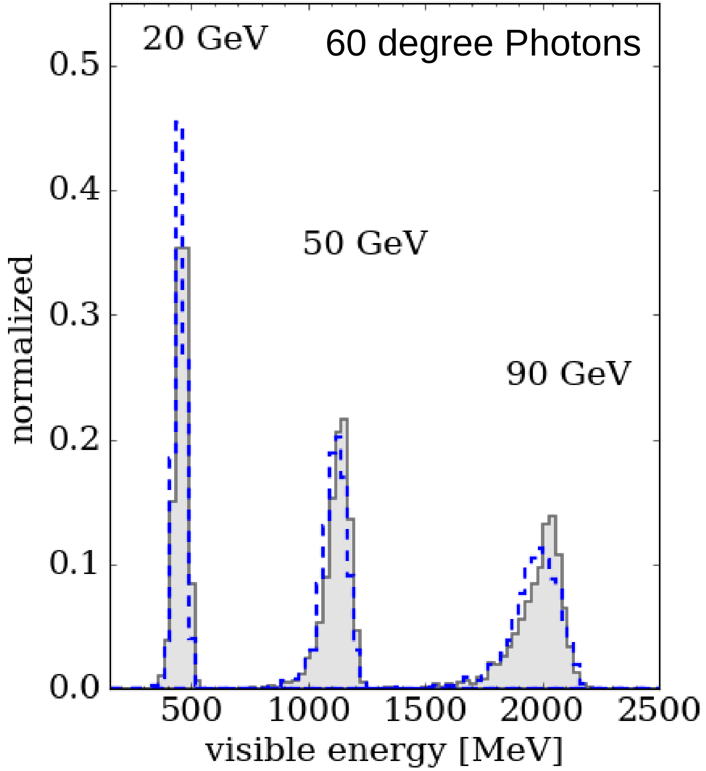
Angular Photon Showers

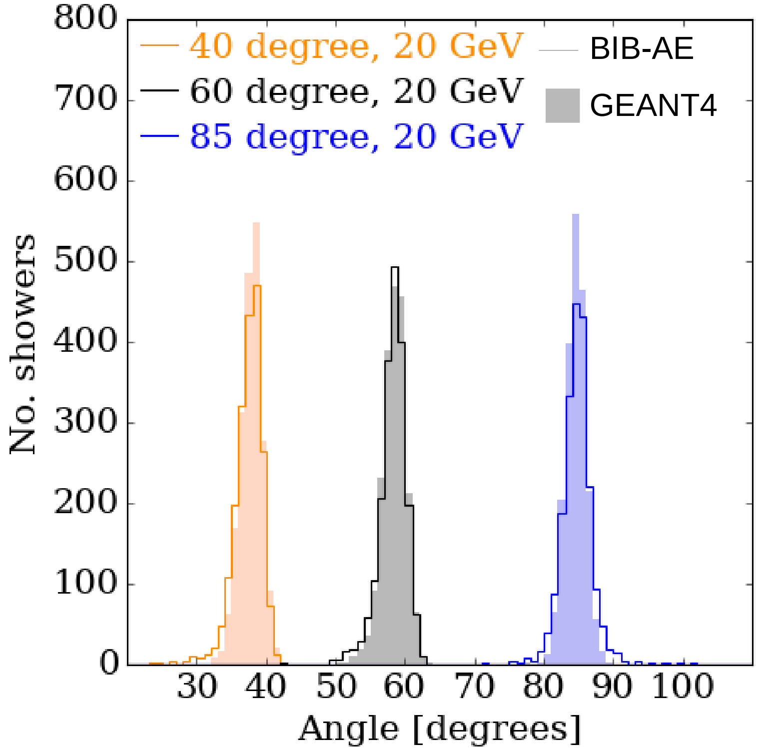
- Simultaneous **Energy and Angular conditioning** demonstrated with high physics performance
  - Publication in preparation











Summary

Achieved

- Generative models hold promise for **fast** simulation of calorimeter showers with **high fidelity**
- Demonstrated high fidelity simulation of **hadronic** showers with generative models
- Demonstrated high fidelity simulation of **photon** showers with **angular and energy conditioning**

Next Steps

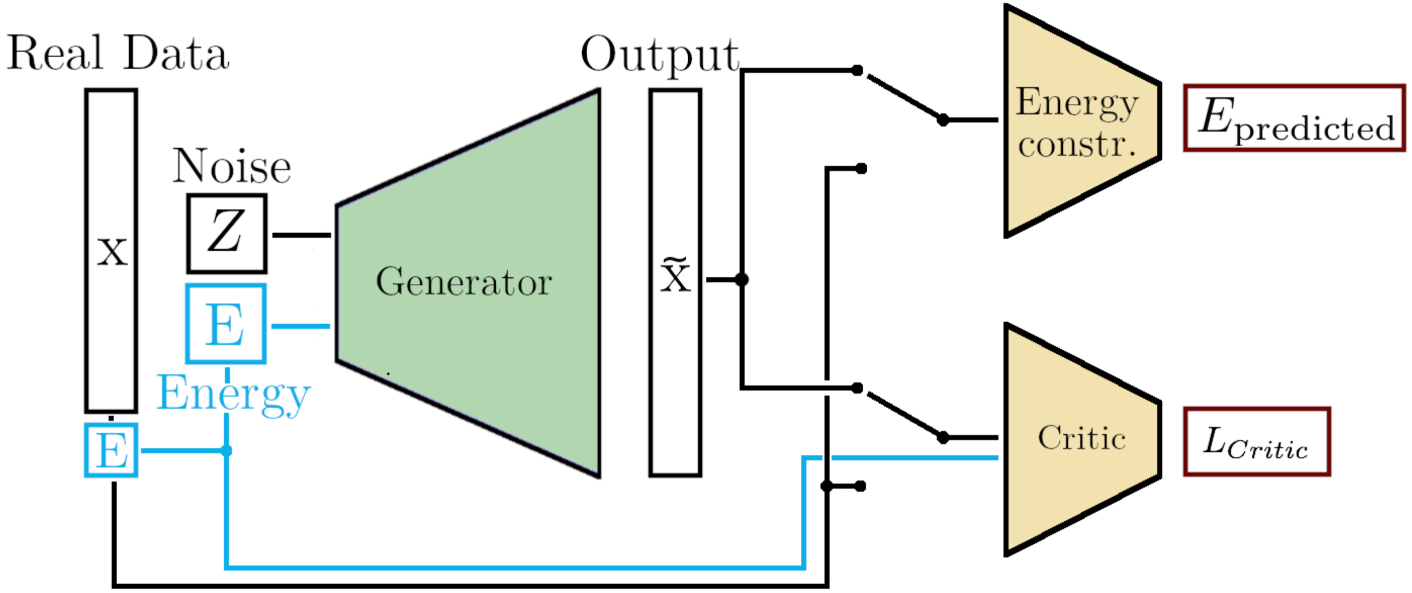
- Strategies for dealing with **complex** and **irregular geometries**
- **Integration** into the existing tools (Geant4)
- Full benchmark of **physics performance** after **reconstruction**

Backup

Architectures: WGAN

WGAN

- Alternative to classical GAN training; Generator and Critic Networks
- Wasserstein-1 distance as loss with gradient penalty: **improve stability**
- **Addition of auxiliary constrainer network for improved conditioning performance**



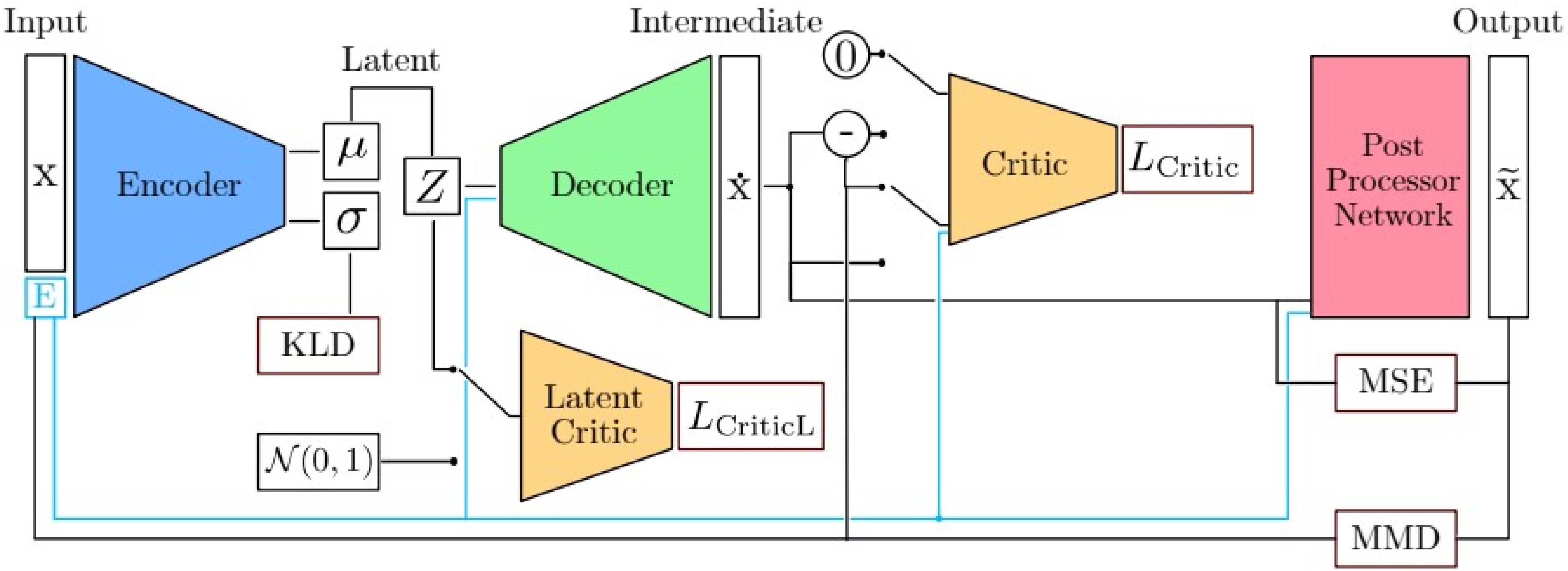
Architectures: BIB-AE

Bounded-Information Bottleneck Autoencoder (BIB-AE)

Voloshynovskiy et. al: Information bottleneck through variational glasses, arXiv:1912.00830 (2019)

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

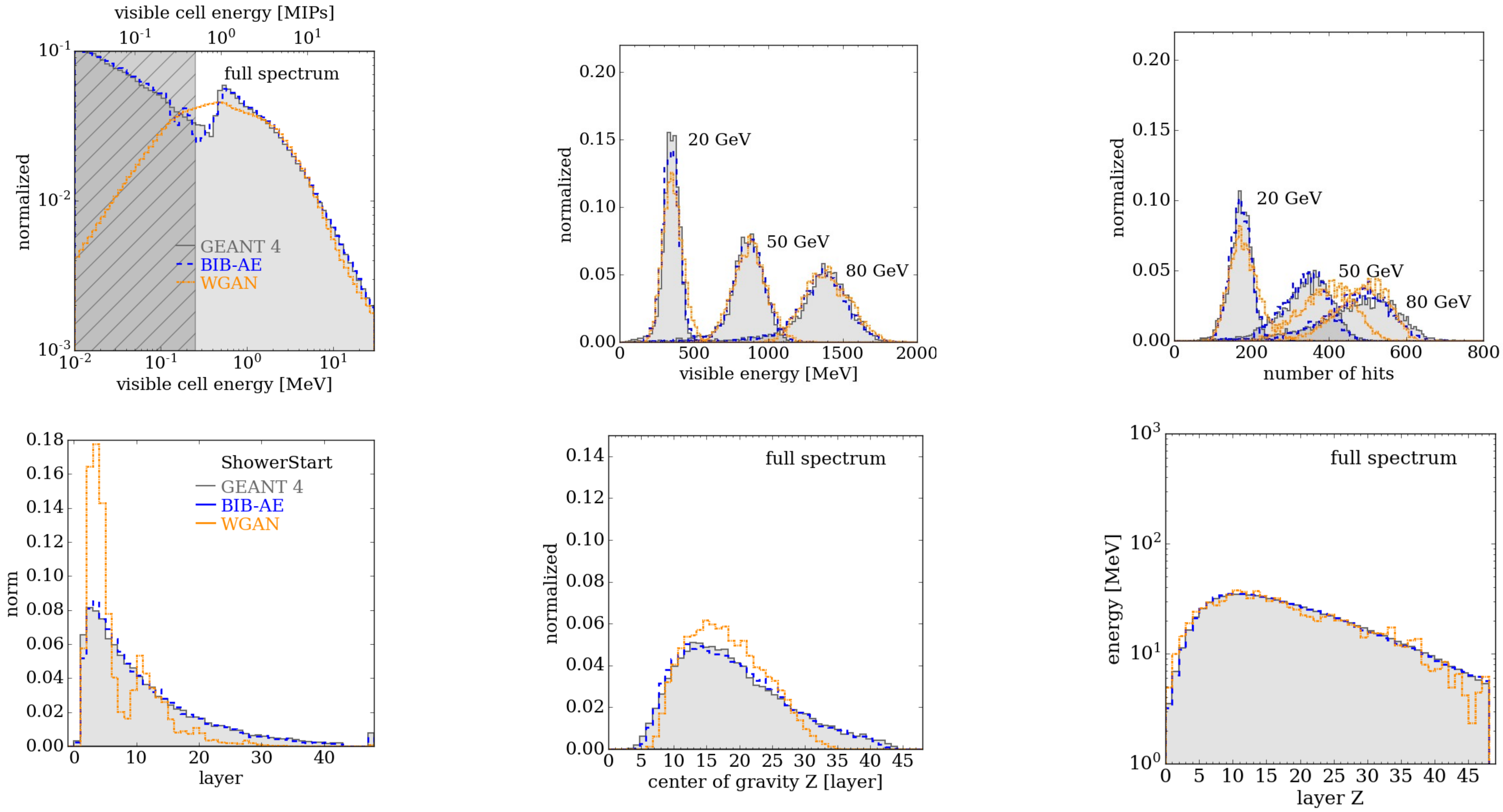
- **Unifies** features of both **GANs** and **VAEs**
- **Post-Processor** network: Improve per-pixel energies; second training
- Multi-dimensional KDE sampling: better modeling of latent space



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

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

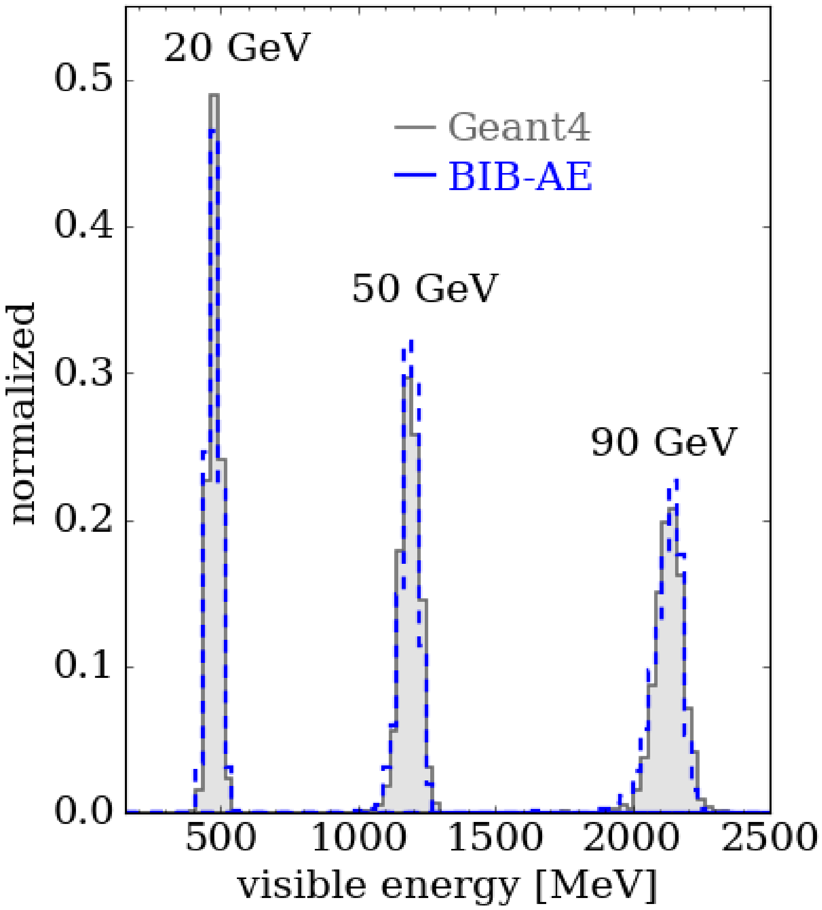
Pion Showers: Sim Level Results



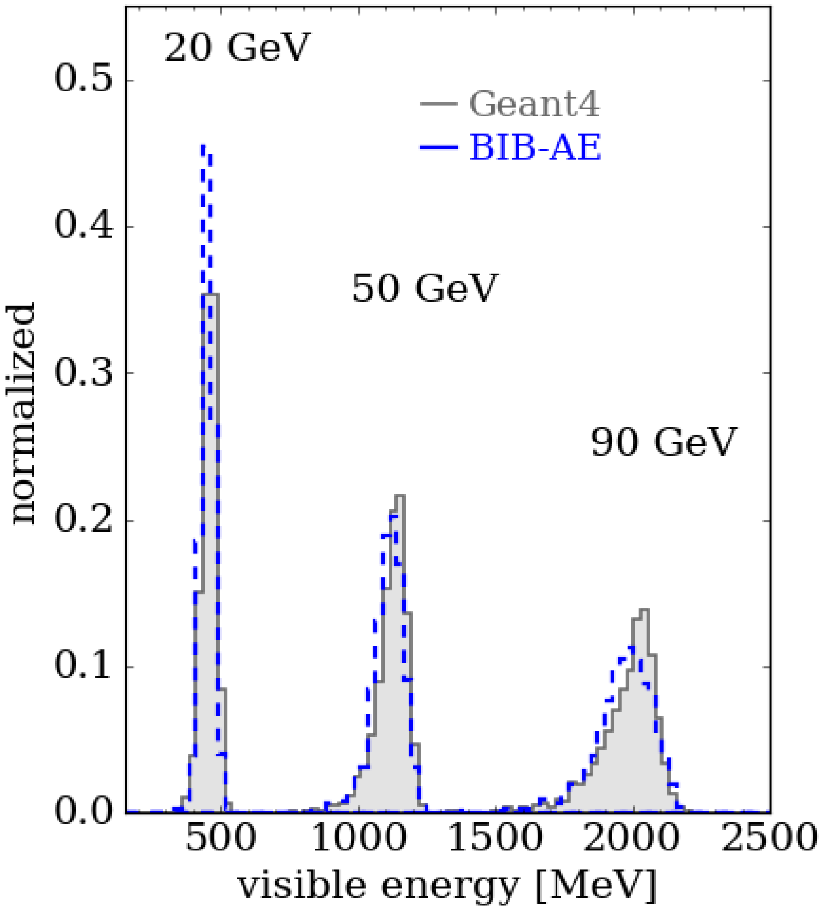
Results: Visible Energy Sum

- Visible energy is nicely described for different incident angles and energies

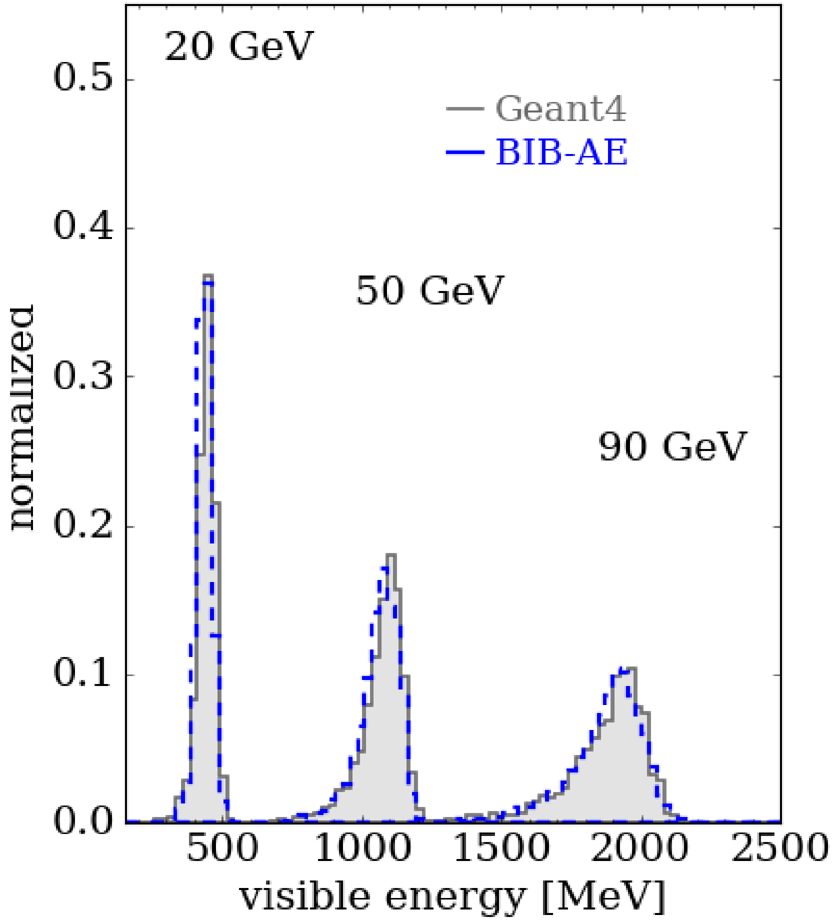
40 degree Photons



60 degree Photons

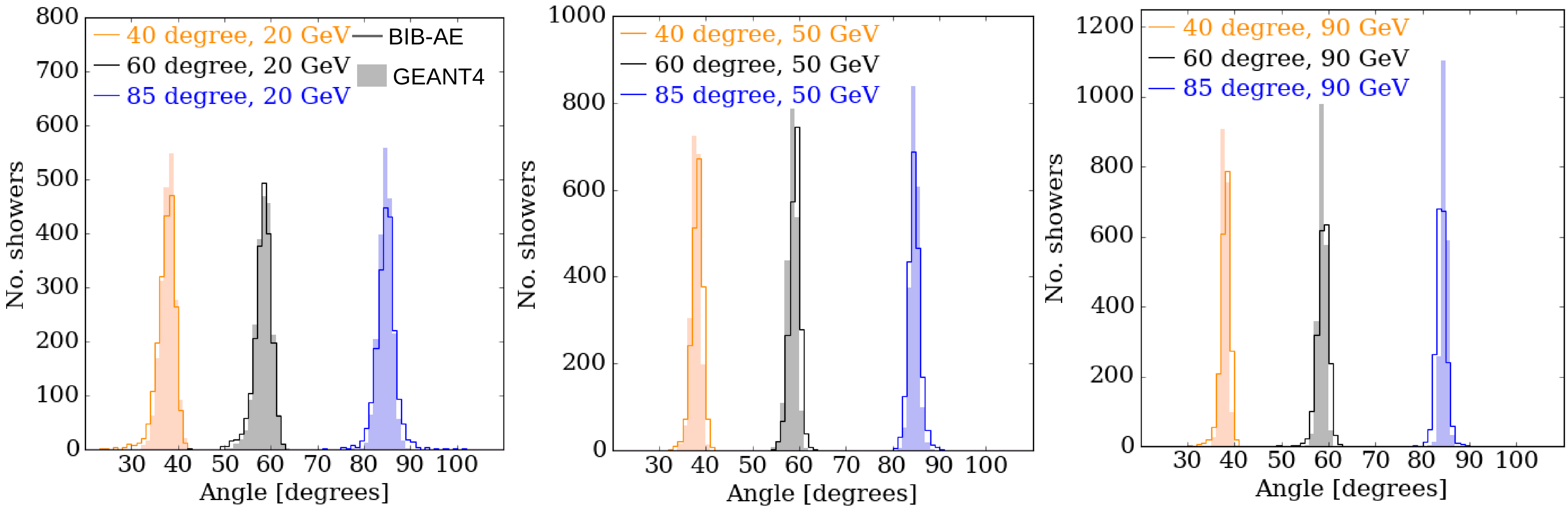


85 degree Photons



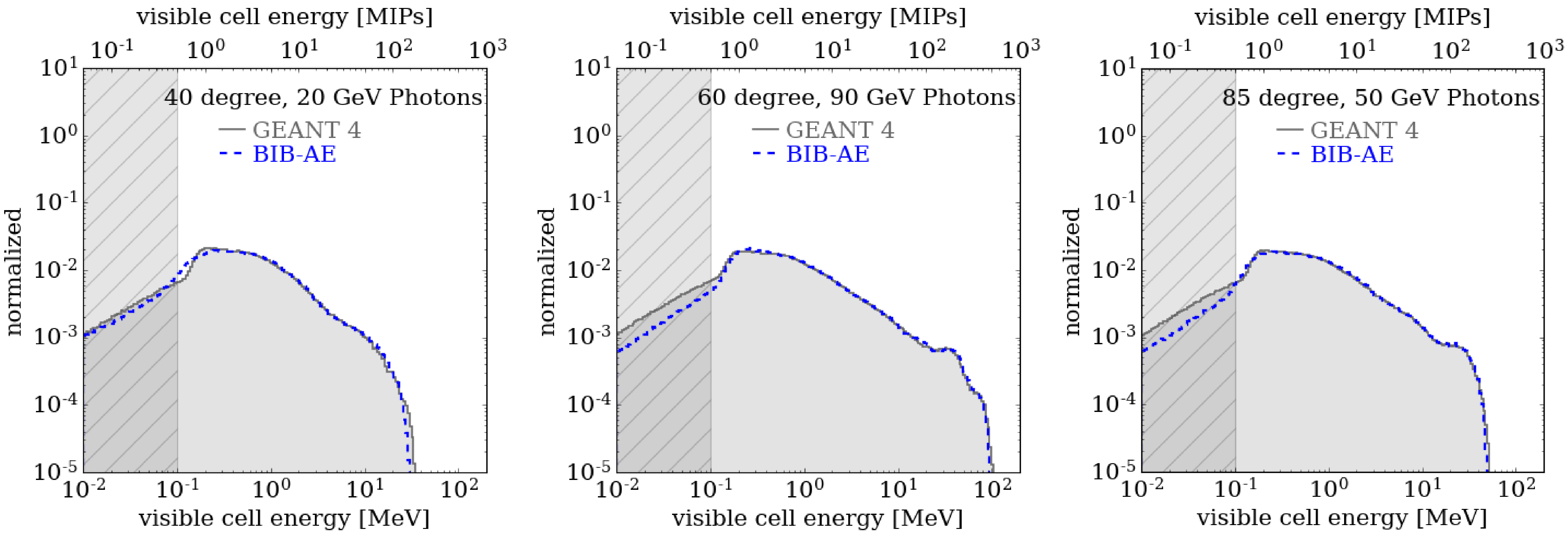
Results: Angular Reconstruction Distributions

- Angular distributions agree well for given incident energies after reconstruction with a PCA



Results: Cell Energy Spectrum

- Post Processor Network retains its ability to correctly describe the cell energy distribution



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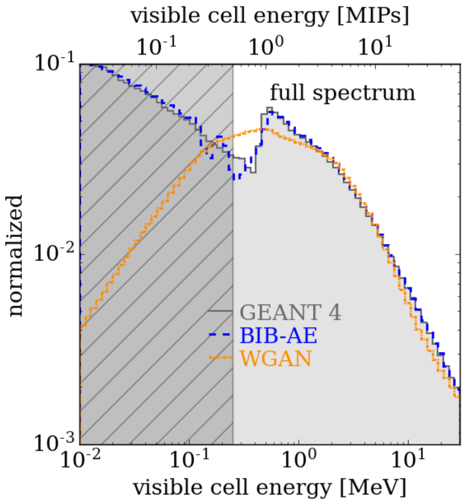

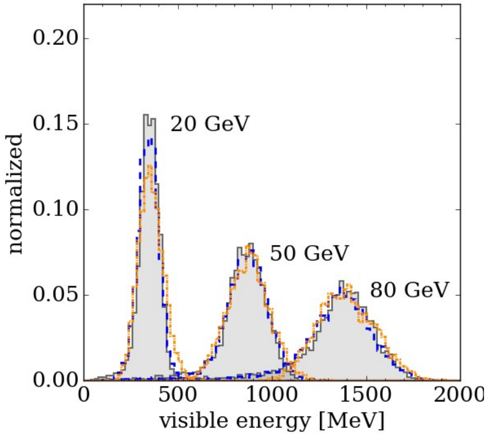

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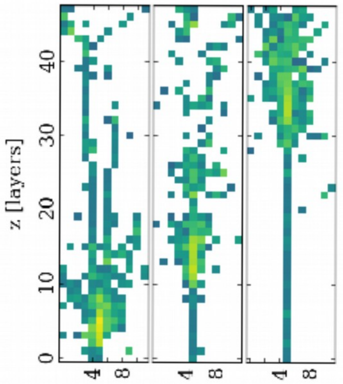

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