Fast Calorimeter Simulation With Machine Learning Techniques

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Sebastian Bieringer, Erik Buhmann, Sascha Diefenbacher, Engin Eren, Frank Gaede, Gregor Kasieczka, William Korcari, Katja Krüger, **Peter McKeown**[1], Lennart Rustige, Imahn Shekhzadeh

[1] **Deutsches Elektronen-Synchrotron**

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peter.mckeown@desy.de

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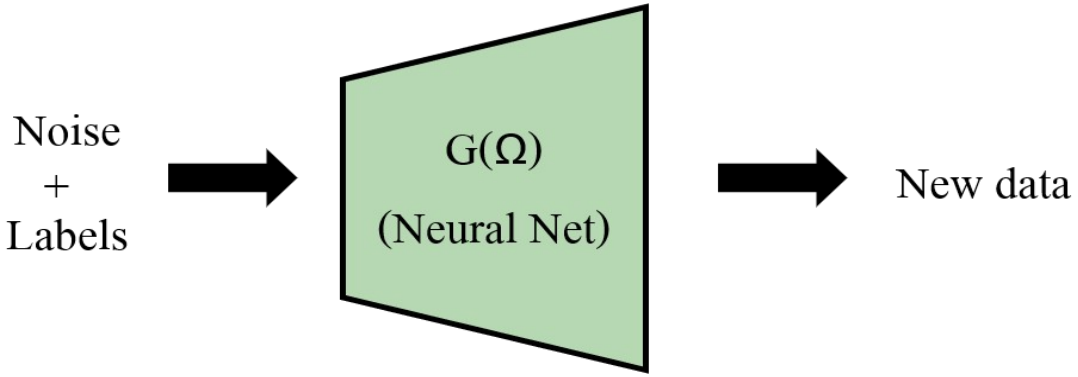
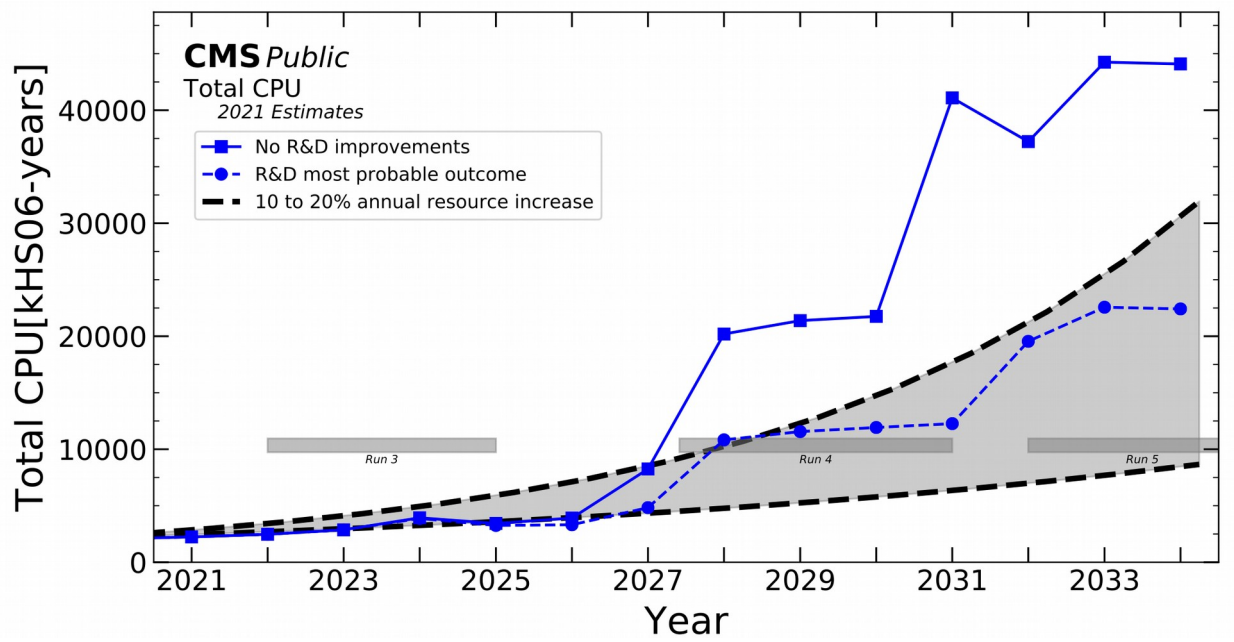
Reducing the Strain on HEP Computing Resources

- **MC simulation (Geant4)** is computationally **expensive**
  - **Calorimeters** most intensive part of detector simulation
- Major bottleneck e.g. **HL-LHC**
- **Generative models** potentially offer orders of magnitude speed up



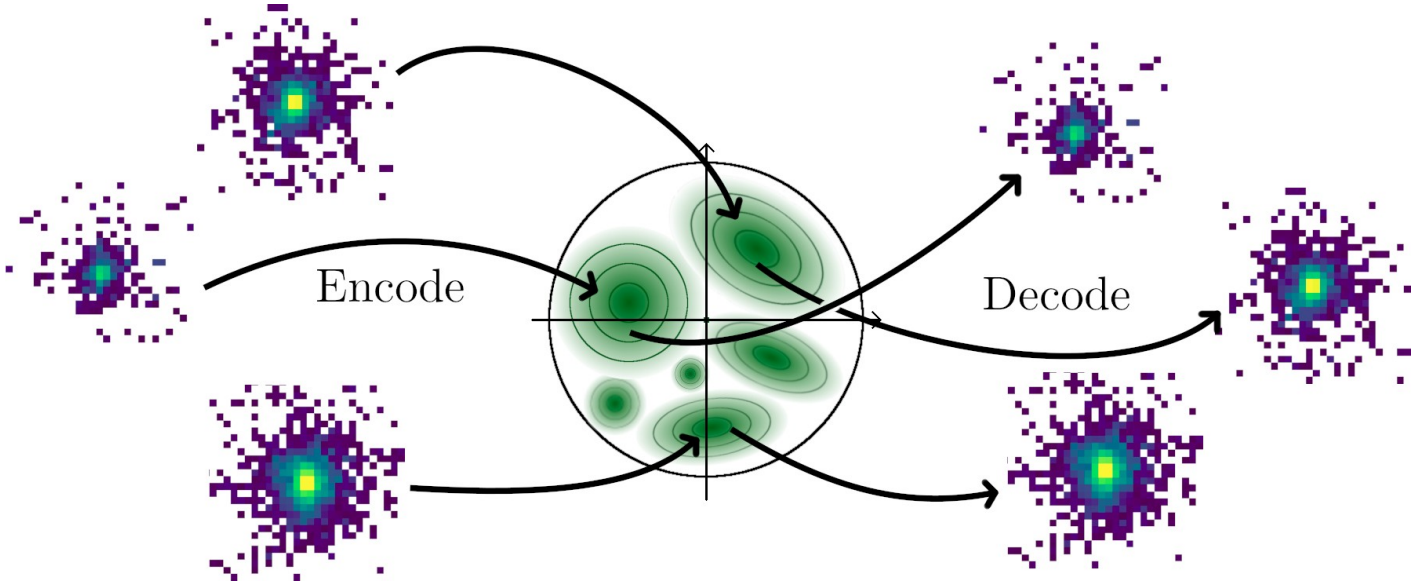


CMS Collaboration, Offline and Computing Public Results (2021), https://twiki.cern.ch/twiki/bin/view/CMSPublic/CMSOfflineComputingResults

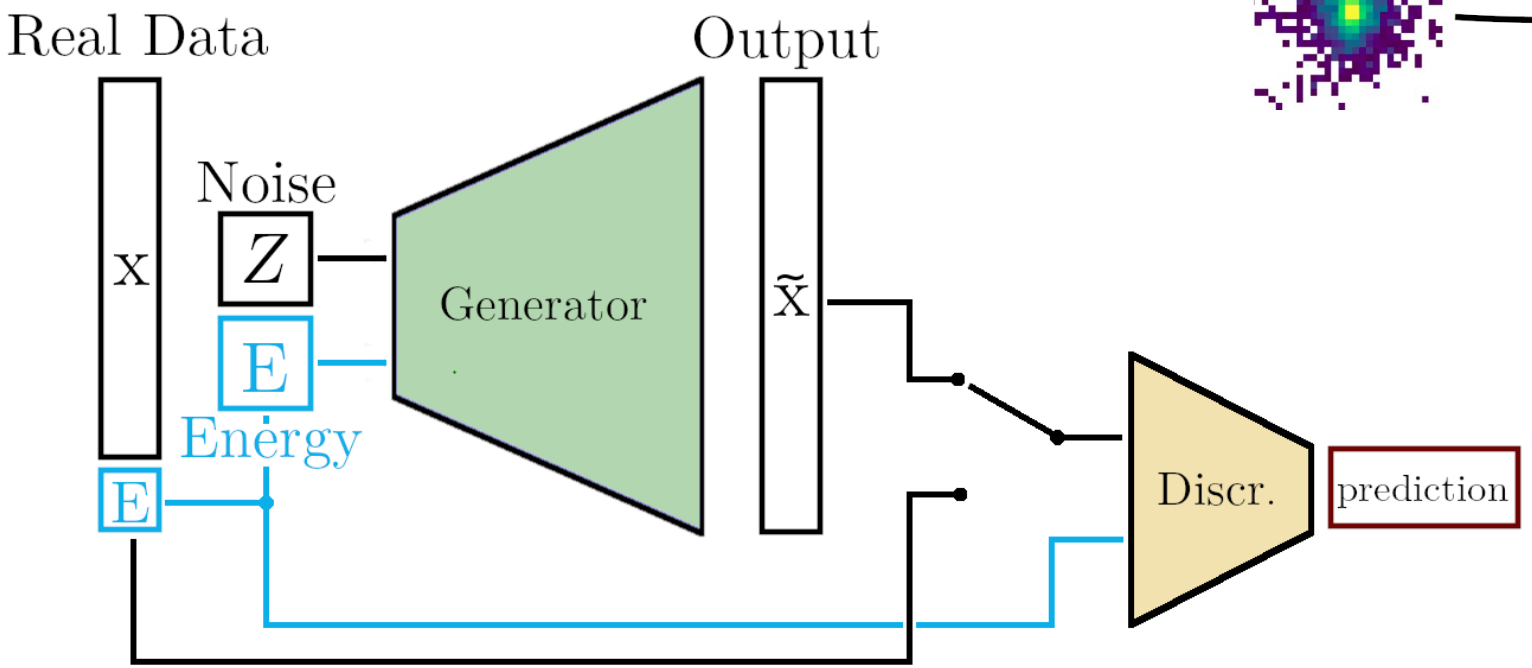
Common Generative Models

- **VAE**[1]**:** Encoder-decoder structure
- **GAN**[2]**:** Adversarial feedback from discriminator

Variational Autoencoder (**VAE**)



Generative Adversarial Network (**GAN**)

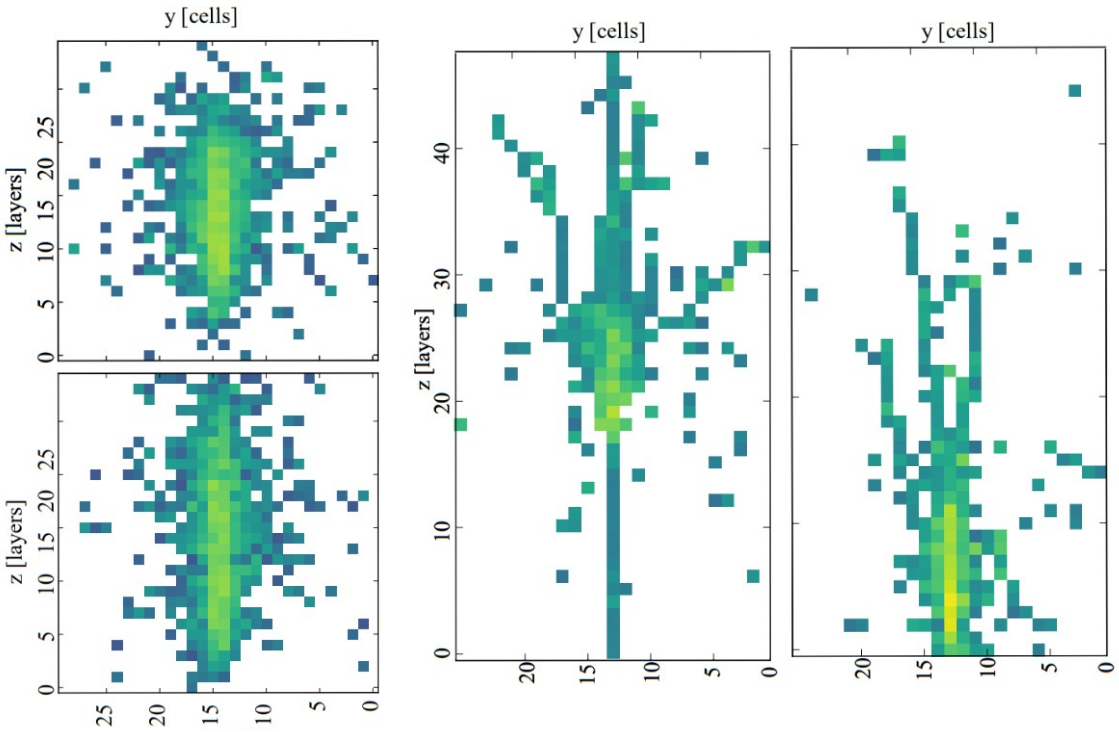


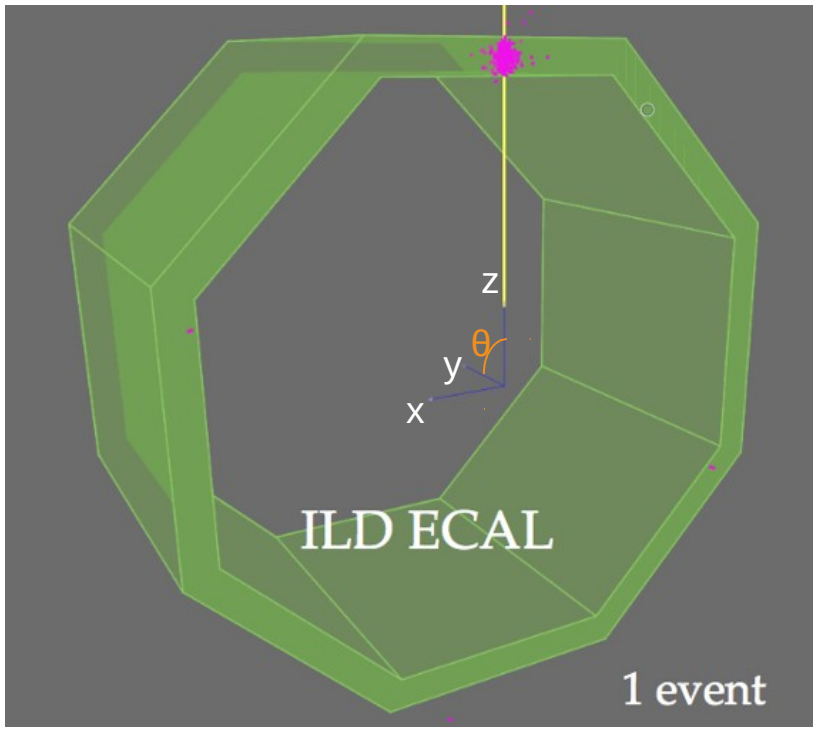
- Models studied:
  - Wasserstein GAN **(WGAN)**
  - Bounded Information Bottleneck Autoencoder **(BIB-AE)**

[1] D.P. Kingma, M. Welling. Auto-encoding Variational Bayes (2014), arXiv:1312.6114

[2] Ian Goodfellow et. al., Generative Adversarial Nets (2014), arXiv:1406.2661

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

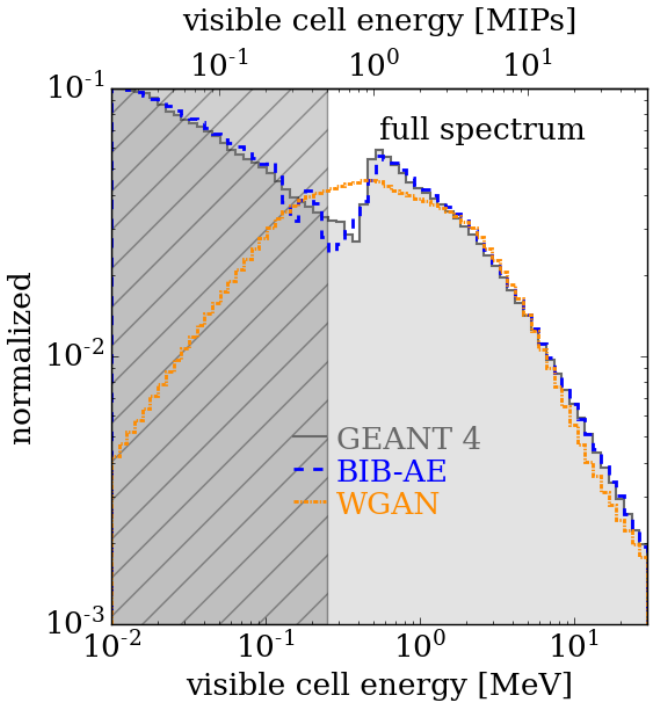
- **Simultaneous conditioning** on multiple parameters crucial for a general simulation tool
  - Start with **photons**
  - Vary incident **energy and angle**

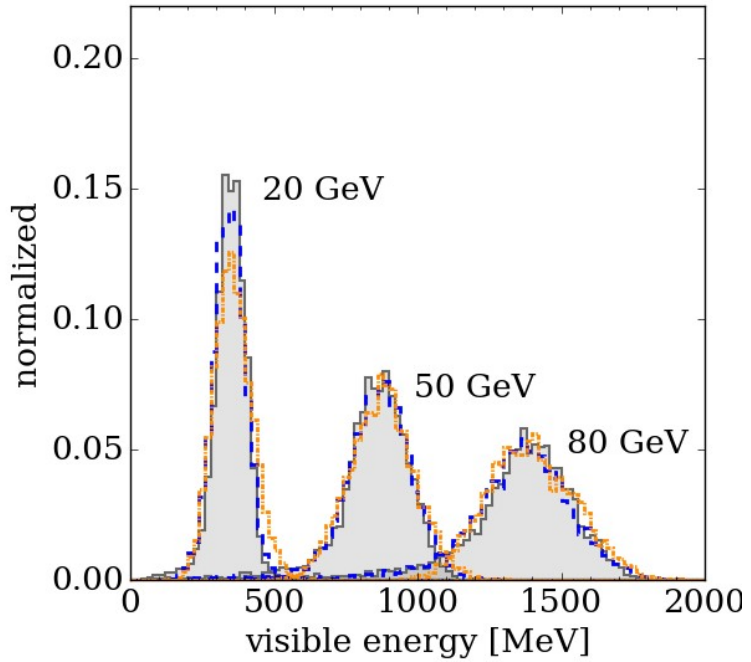
Latest Progress

Hadronic Calorimeter Showers

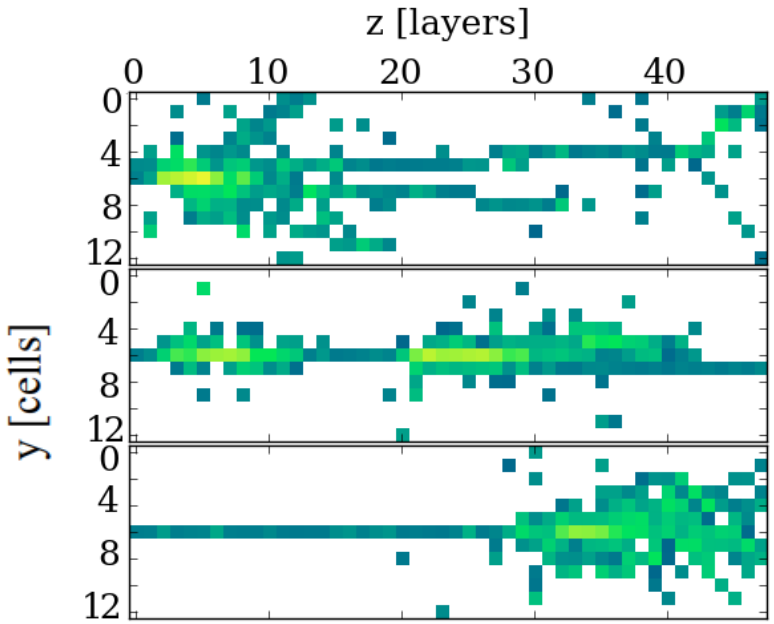
- Achieve **significant speedups** (CPU/GPU)
- Achieve **high degree of fidelity**

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





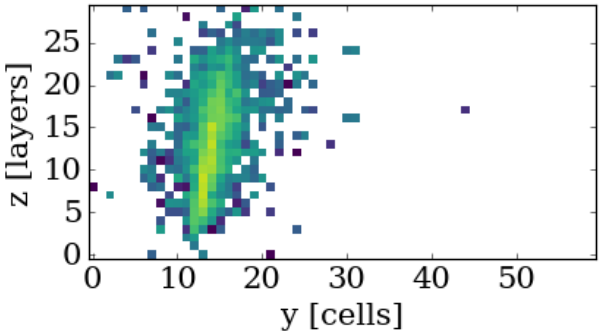
Hardware	Simulator	Time / Shower [ms]	Speed-up
CPU	GEANT4	2684 ± 125	$\times 1$
	WGAN	47.923 ± 0.089	$\times 56$
	BIB-AE	350.824 ± 0.574	$\times 8$
GPU	WGAN	0.264 ± 0.002	$\times 10167$
	BIB-AE	2.051 ± 0.005	$\times 1309$

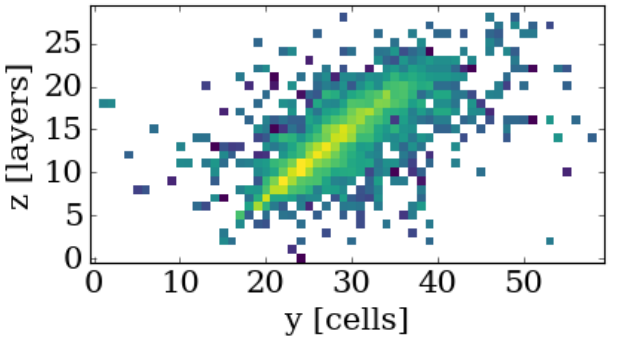


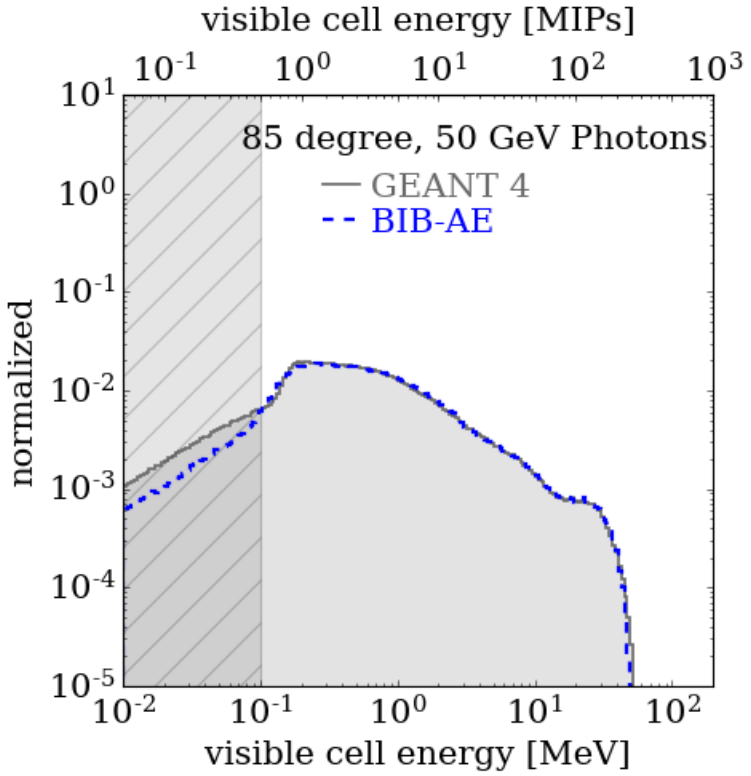
Latest Progress

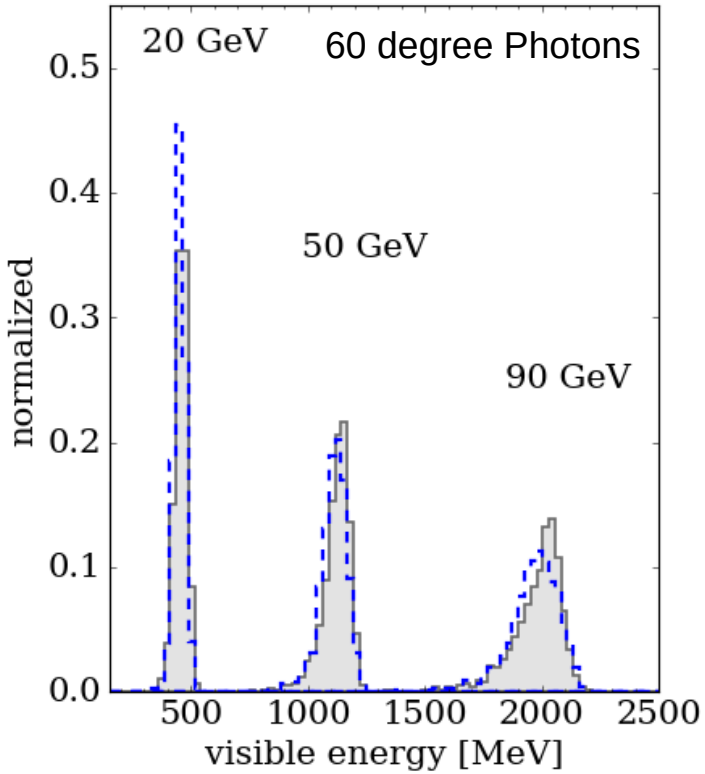
Angular Photon Showers

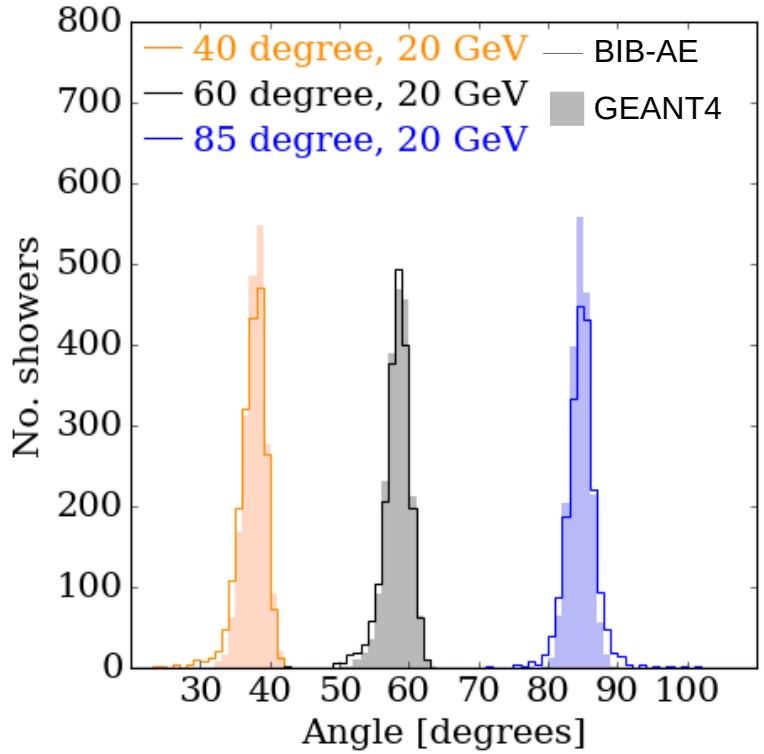
- Simultaneous **Energy and Angular conditioning** demonstrated while maintaining strong physics performance
  - Publication in preparation











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

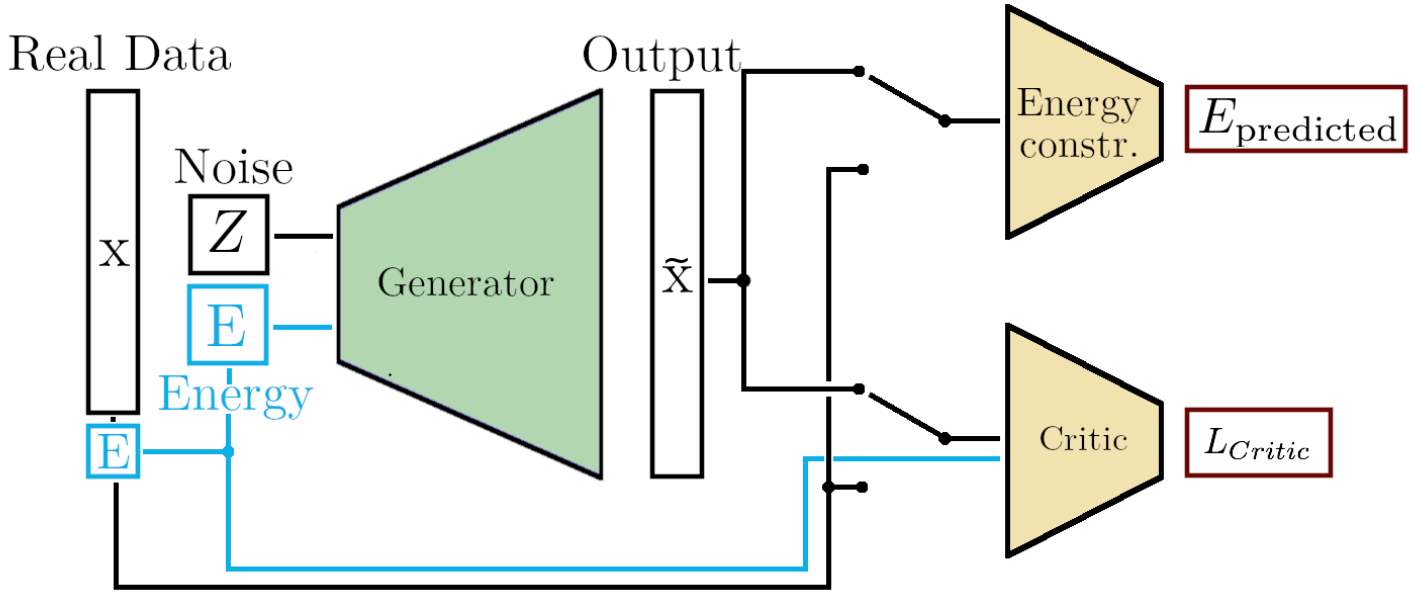
- Strategies for dealing with **complex** and **irregular geometries**
- **Integration** into the existing tools (Geant4)
- Full benchmark of **physics performance** after **reconstruction**

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**



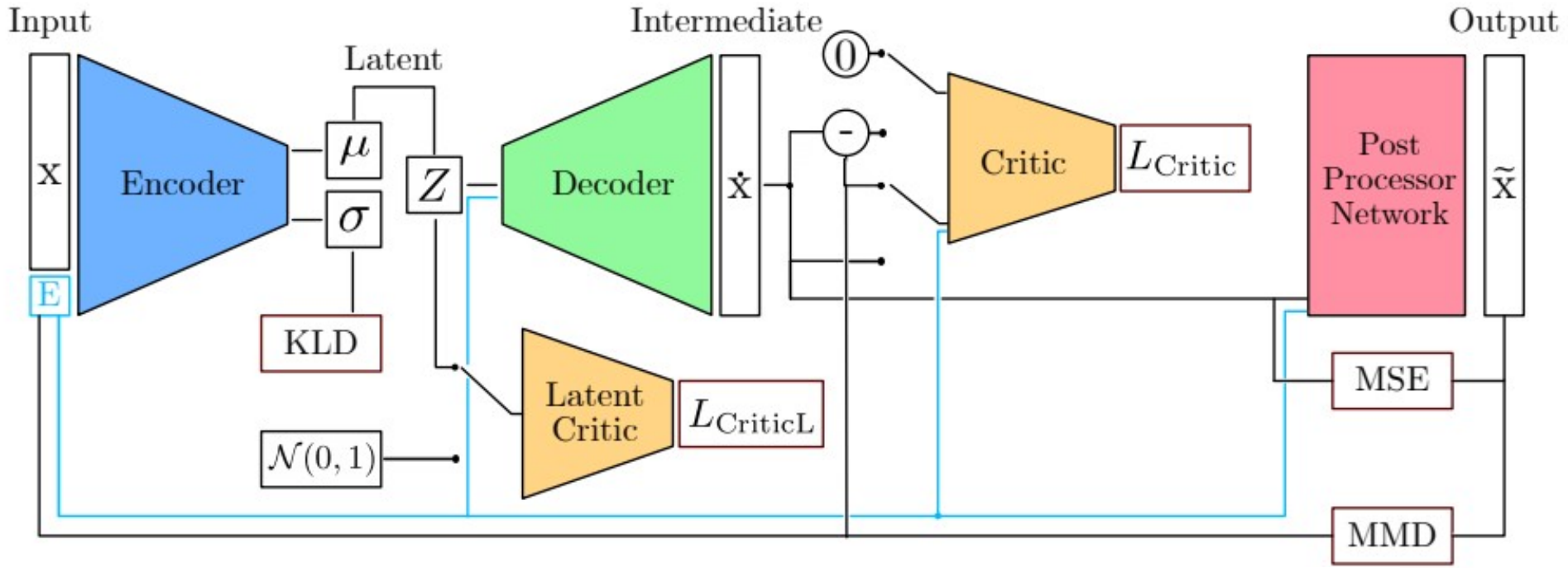
Architectures: BIB-AE

Bounded-Information Bottleneck Autoencoder (BIB-AE)

- **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

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

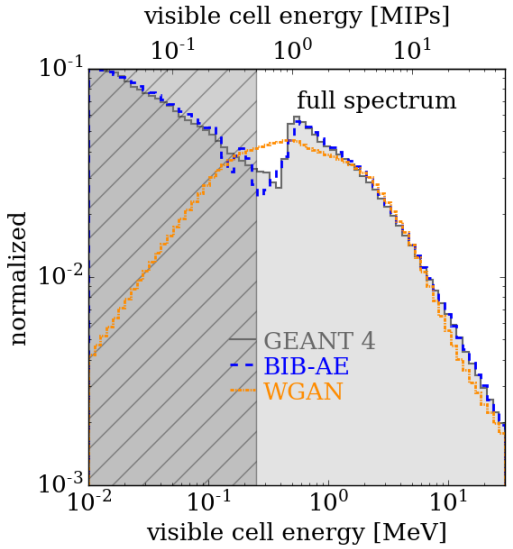
Buhmann et. al: **Getting High: High Fidelity Simulation of High Granularity Calorimeters with High Speed**, CSBS 5, 13 (2021)

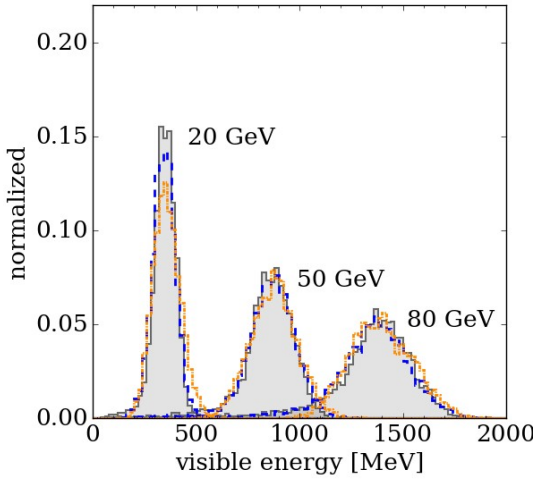


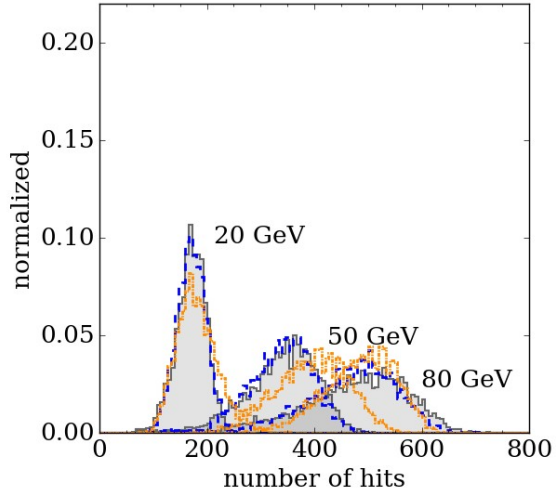
$$L_{\text{BIB-AE}} = \text{KLD} + L_{\text{CriticL}} + L_{\text{Critic}}$$

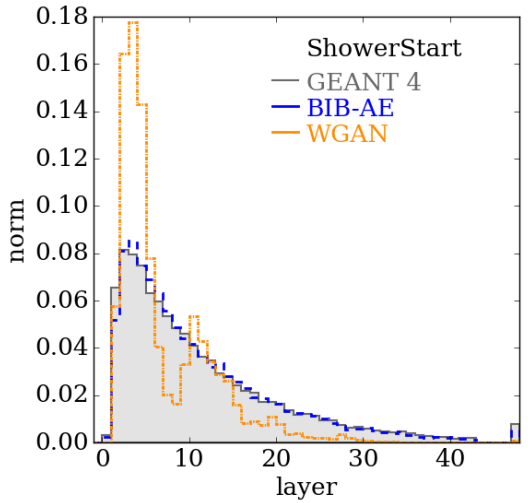
$$L_{\text{Post}} = \text{MMD} + \text{MSE}$$

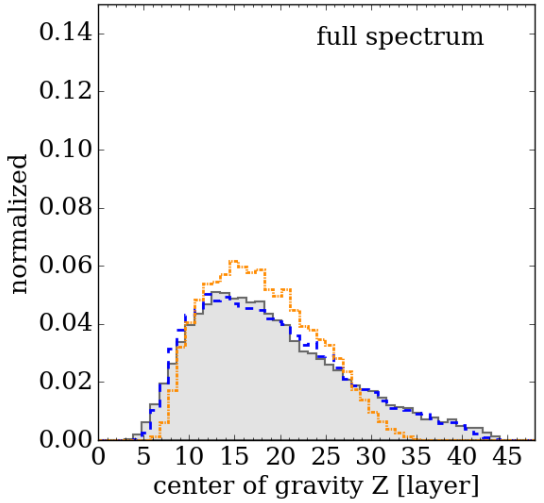
Pion Showers: Sim Level Results

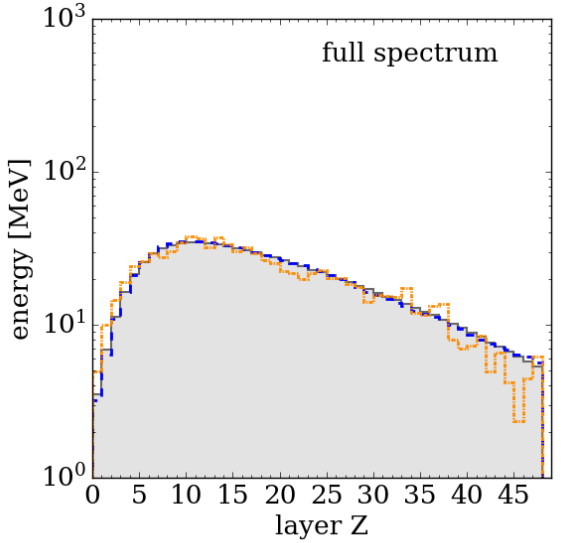








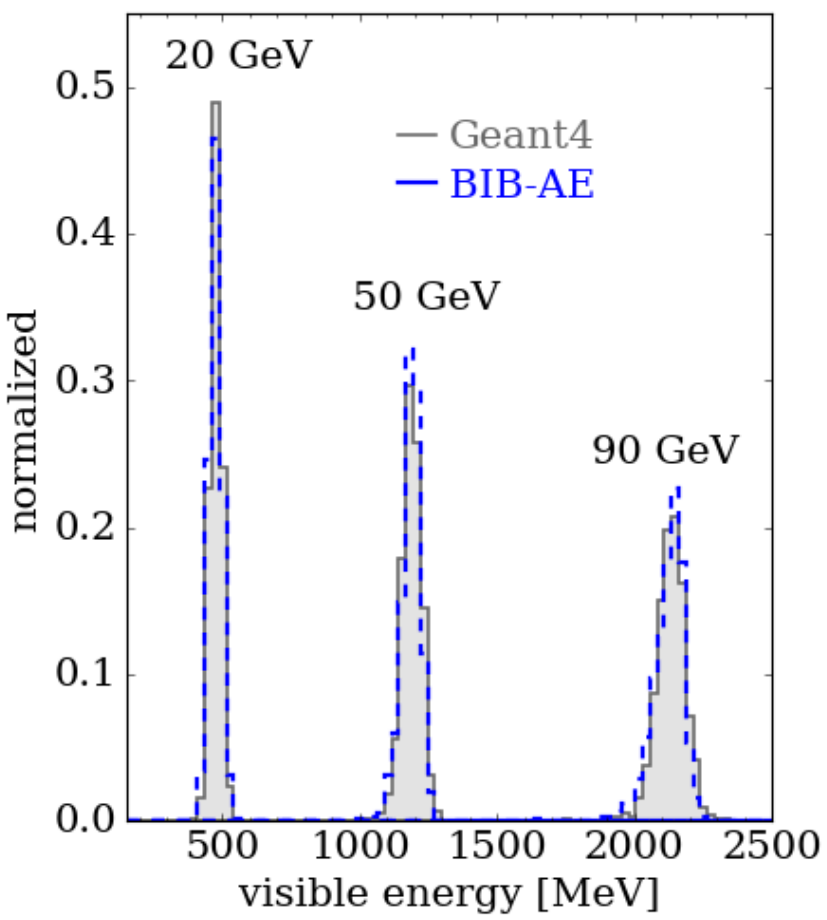




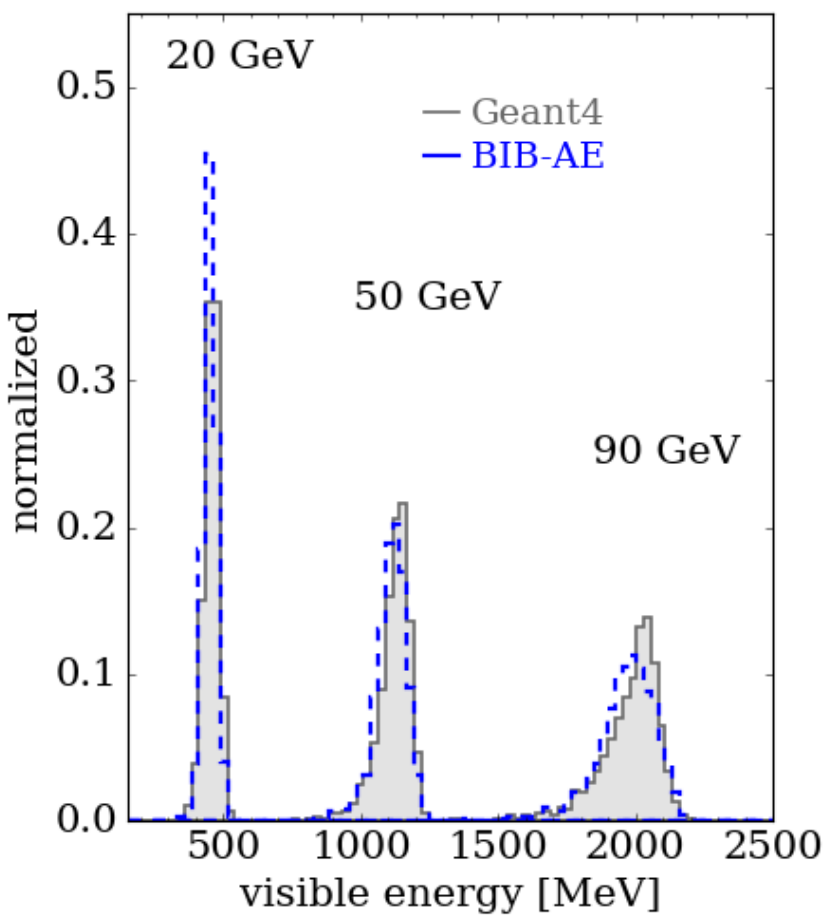
Results: Visible Energy Sum

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

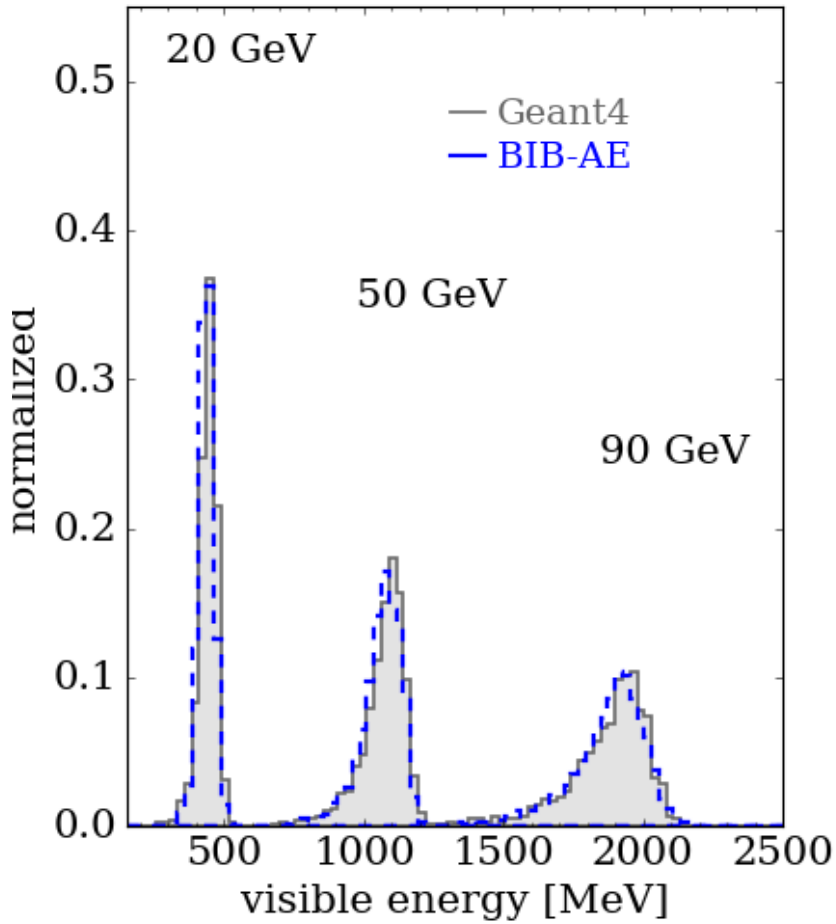
40 degree Photons



60 degree Photons

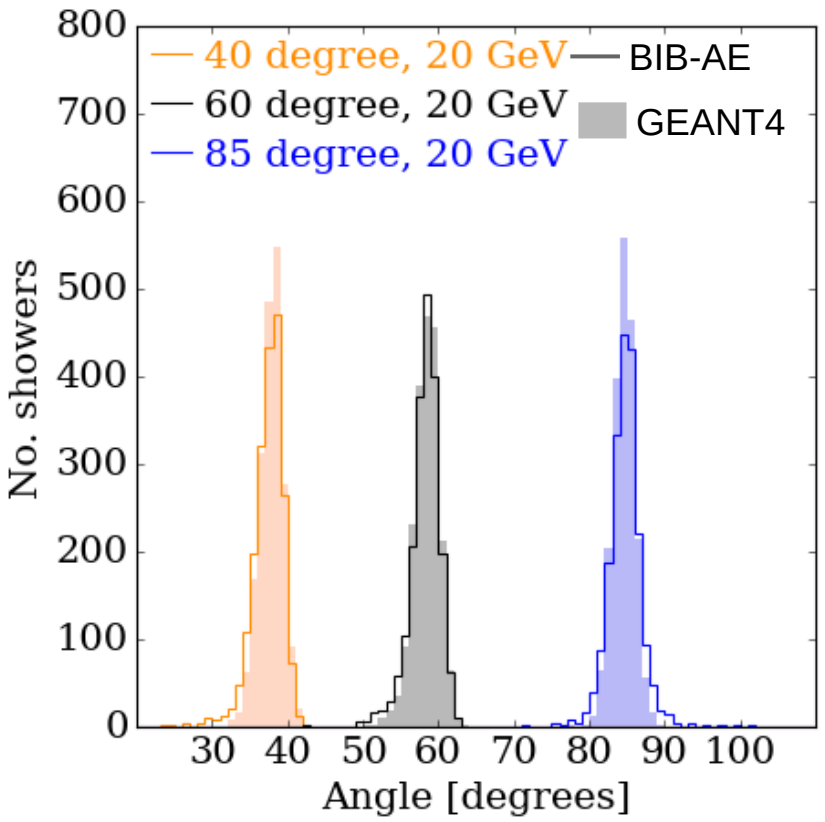


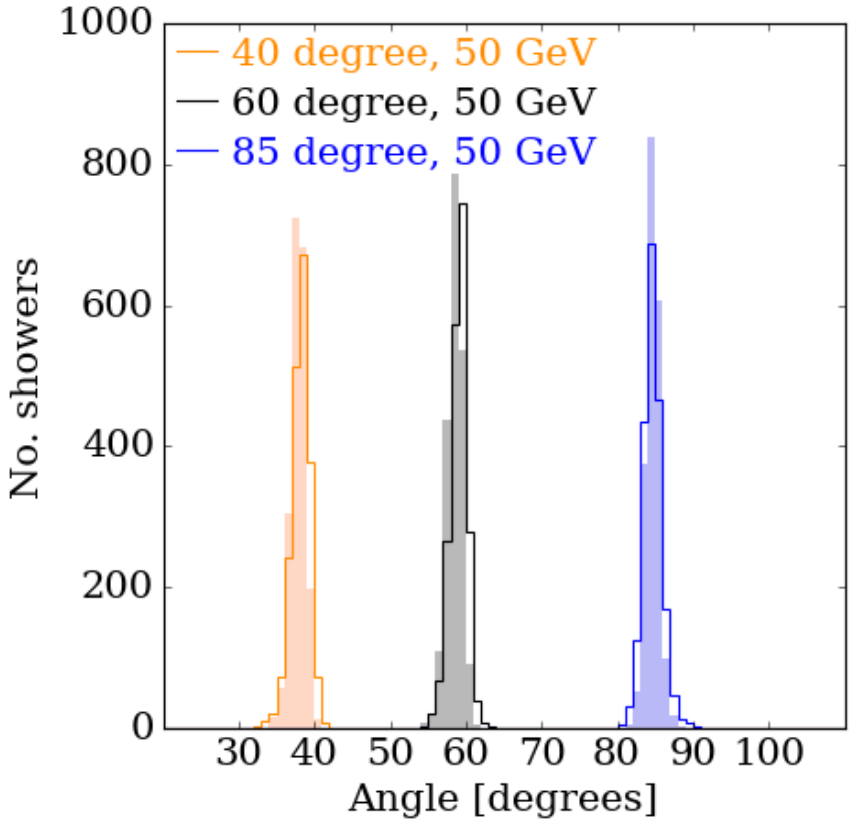
85 degree Photons

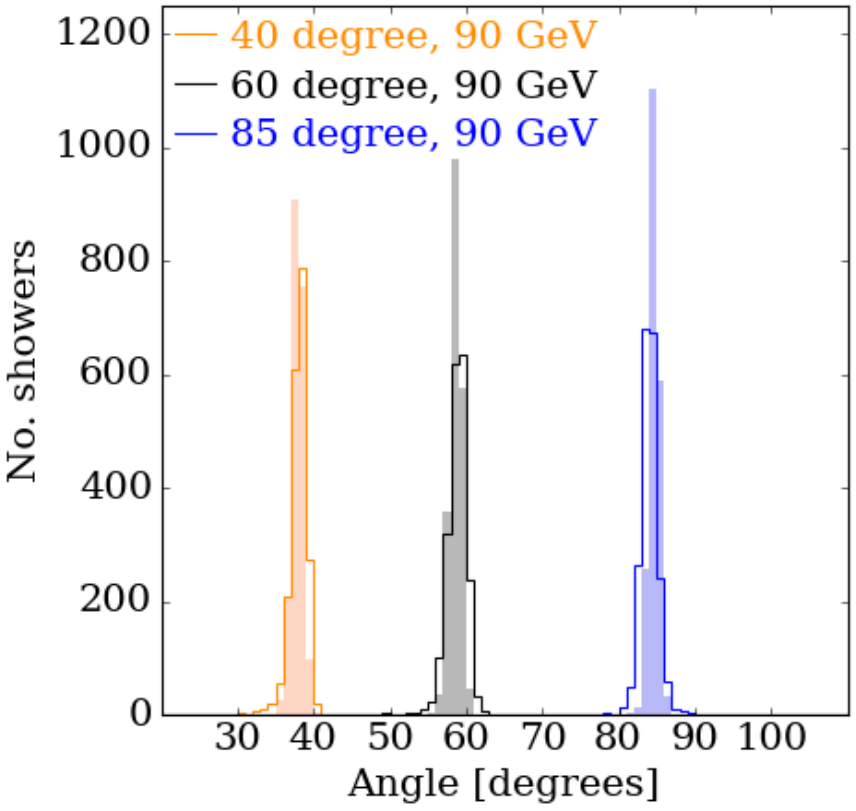


Results: Angular Reconstruction Distributions

- 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