Generative Models for Fast Simulation of Electromagnetic and Hadronic Showers in Highly Granular Calorimeters

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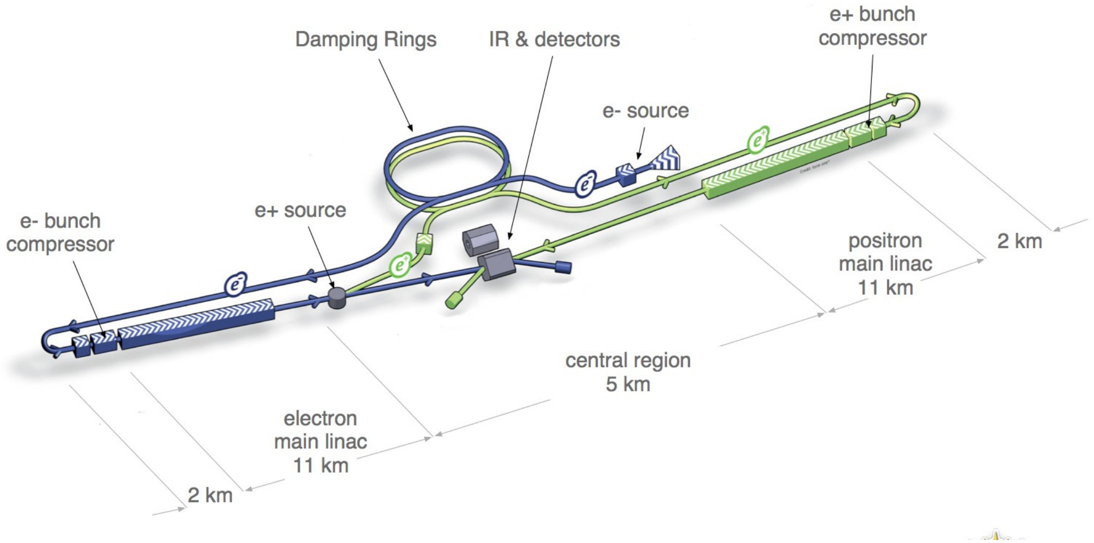
The ILD Concept

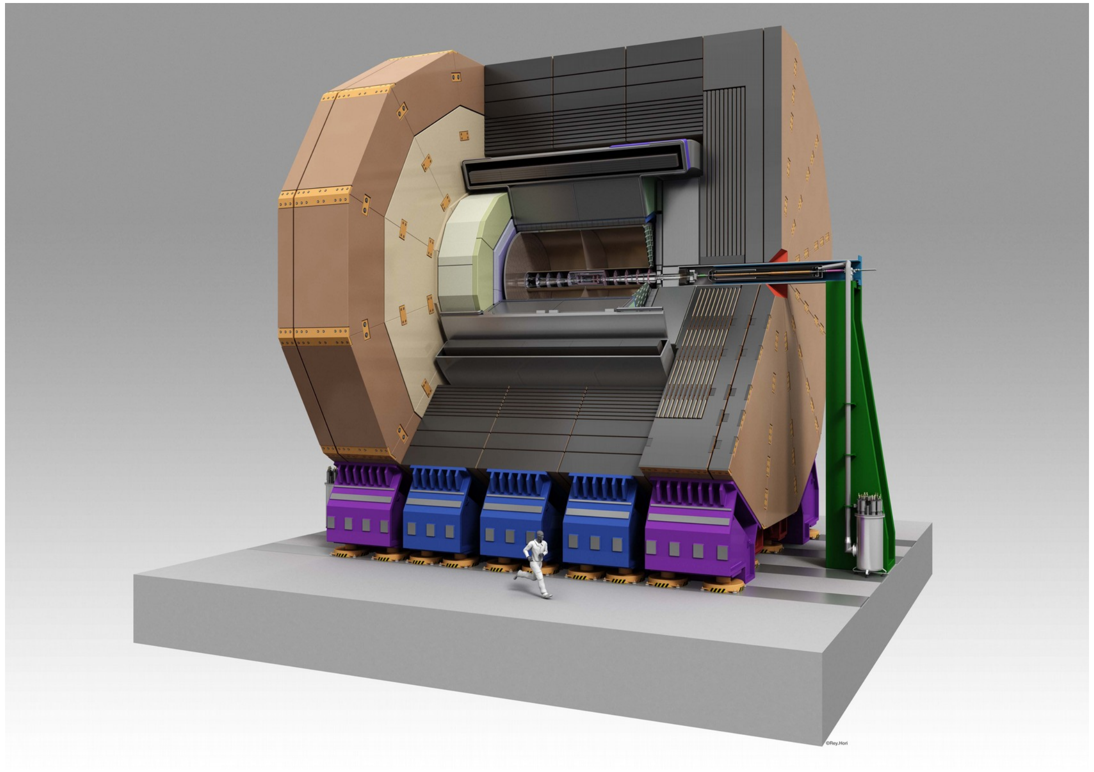


- Context: Future Higgs Factories

- Case Study: International Large Detector (**ILD**) concept for the International Linear Collider (ILC)

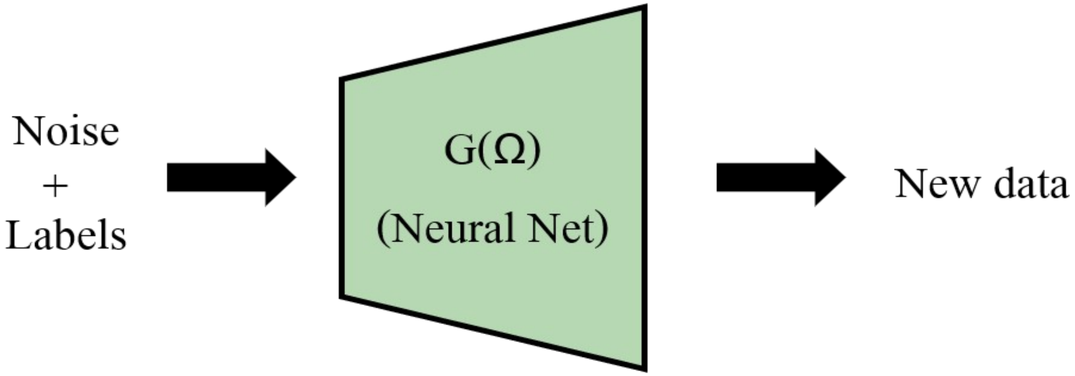
- Optimized for Particle Flow
  - Reconstruct each individual particle in subdetector
  - Obtain optimal detector resolution

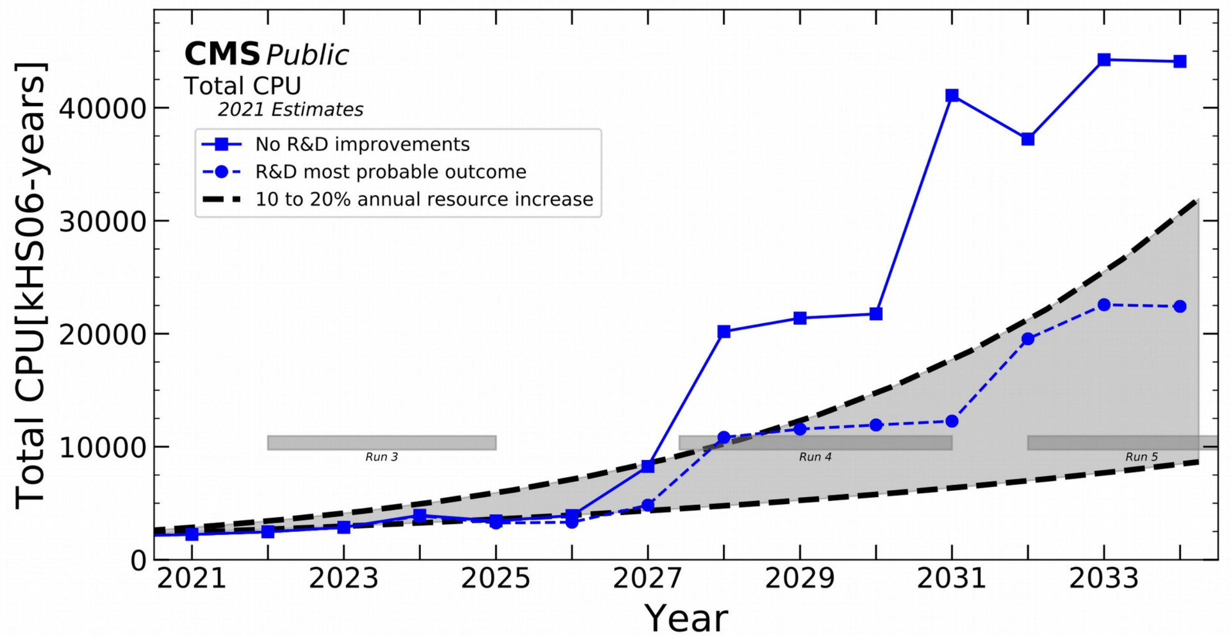
- High granularity calorimeters:
  - Sampling calorimeters
  - **SiW Ecal**: 30 layers, 5x5 mm^2, 2 sampling fractions
  - **FeSci Hcal**: 48 layers, 3x3 cm^2



Reducing the Strain on HEP Computing Resources

- **MC simulation (Geant4)** is computationally **expensive**
  - Calorimeters most intensive part of detector simulation
- **Generative models** potentially offer orders of magnitude speed up



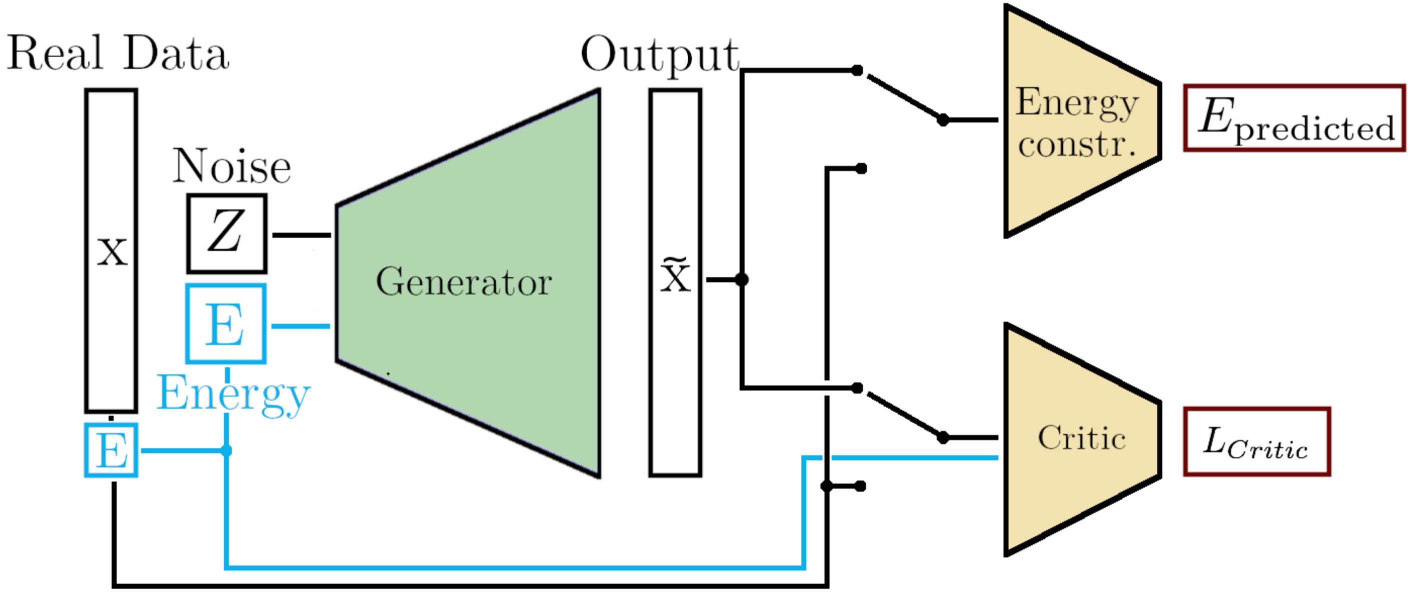


CMS Collaboration, Offline and Computing Public Results (2021), https://twiki.cern.ch/twiki/bin/view/CMSPublic/CMSOfflineComputingResults

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**



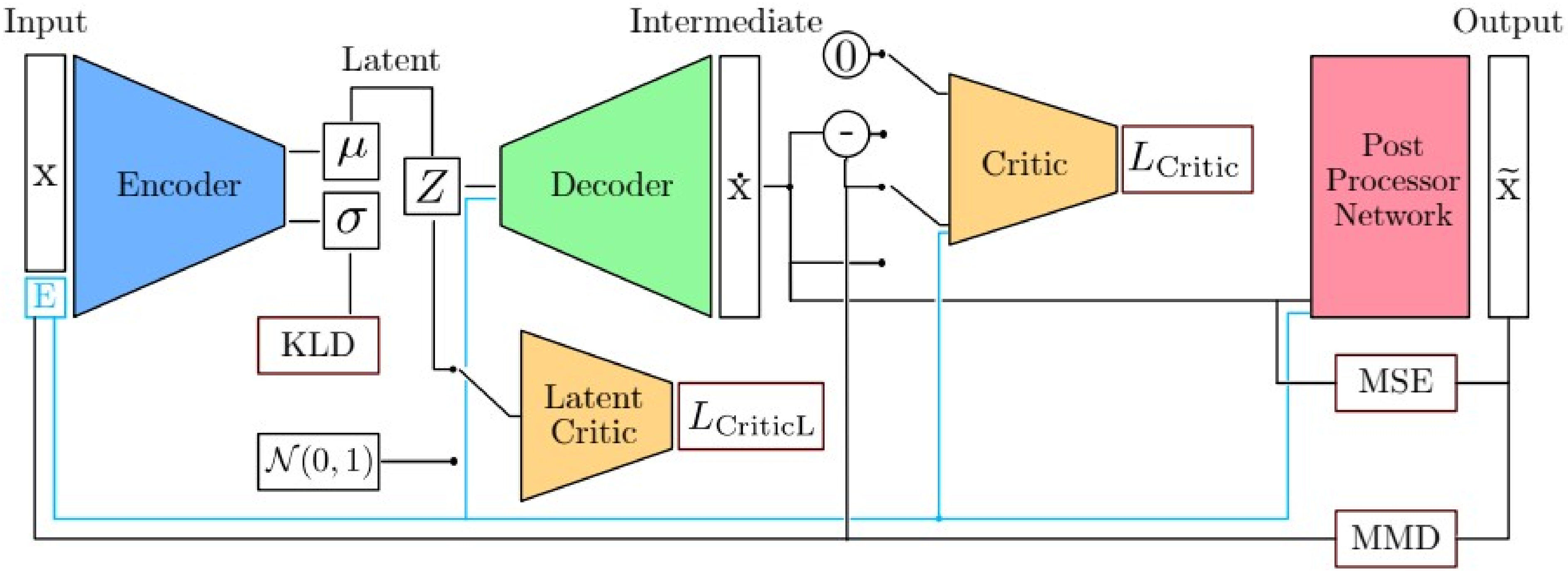
Architectures: BIB-AE

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)

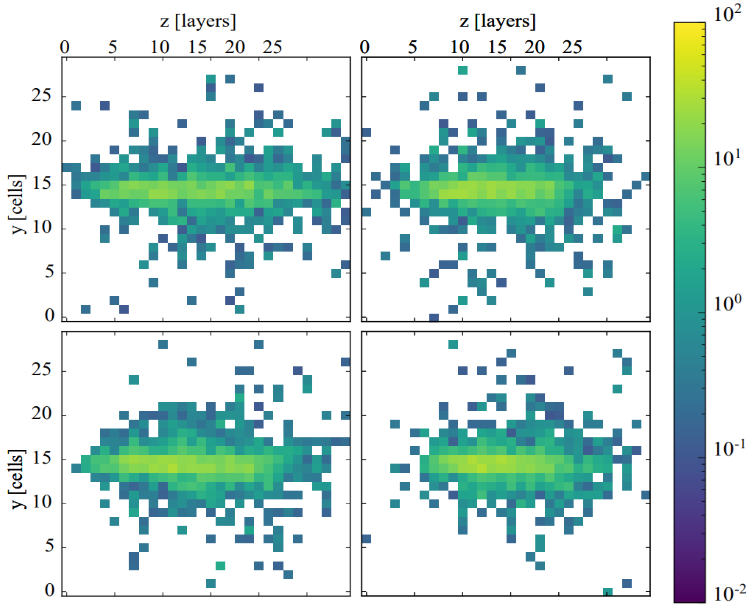
- **Unifies** features of both **GANs** and **VAEs**
- **Post-Processor** network: Improve per-pixel energies; second training
- Multi-dimensional KDE sampling: better modeling of latent space



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

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

From Photons to Pions

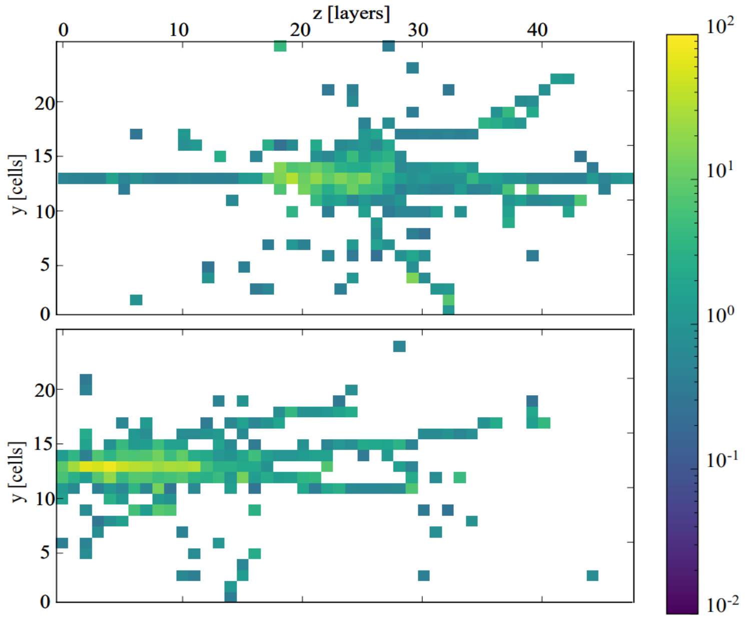


Photon showers

- Predominantly governed by EM interactions
- Compact structure

↓

Relatively easy to generalise



Pion showers

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

↓

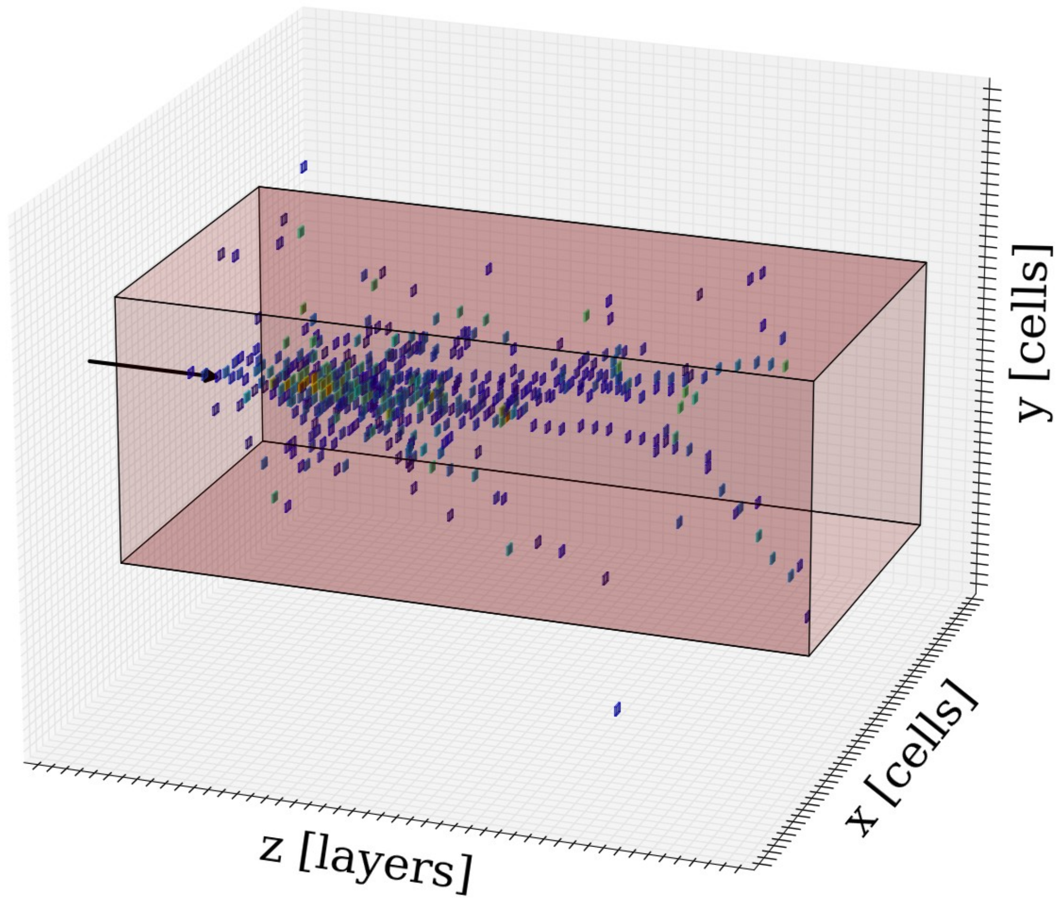
Hard to learn

	Energy	Angles θ, ϕ	ECAL +HCAL	Reco
Photon showers	✓	+	N/A	X
Pion showers	+	X	X	+

✓ = Achieved X = Yet to be done

\+ = Addressed here

Pion Dataset



- Remove ECal from geometry
- Training data generation with Geant4

- Irregular HCAL geometry projected into 25x25x48 regular grid
  - Significantly reduce sparsity
  - Barely lose any hits

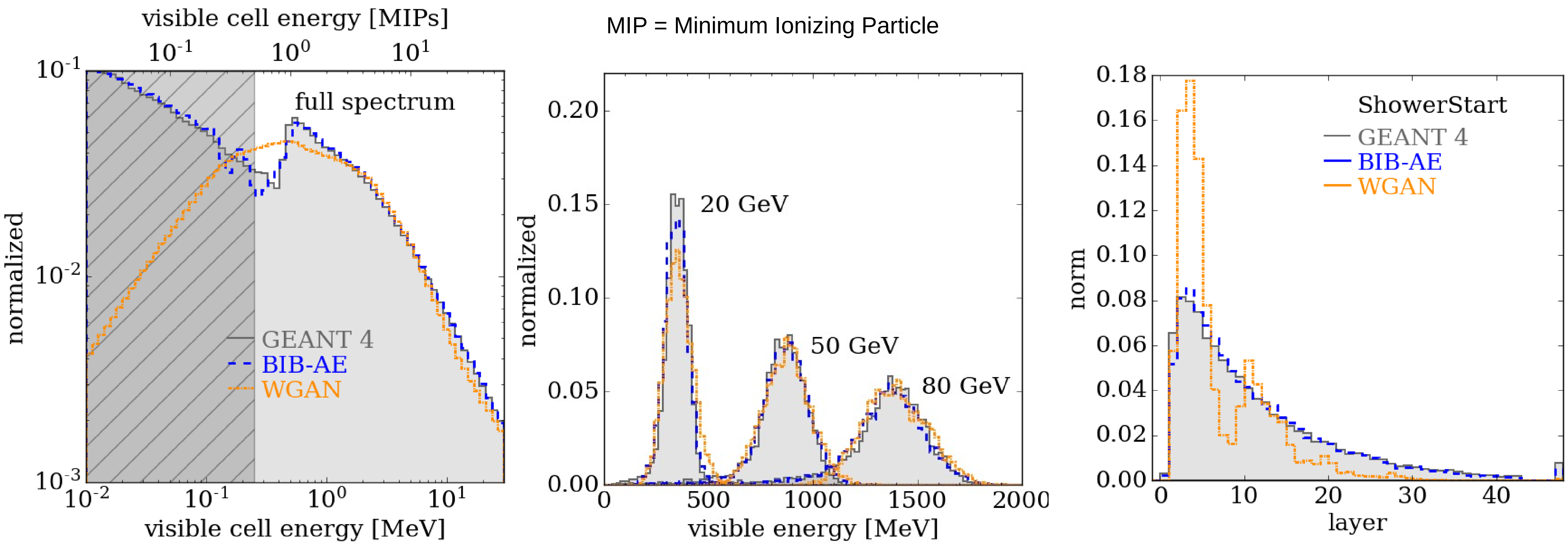
- 500k **pion** showers
- Fixed incident point and angle
- Uniform **energy**: **10-100 GeV**

Pion Showers: Sim Level Results

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

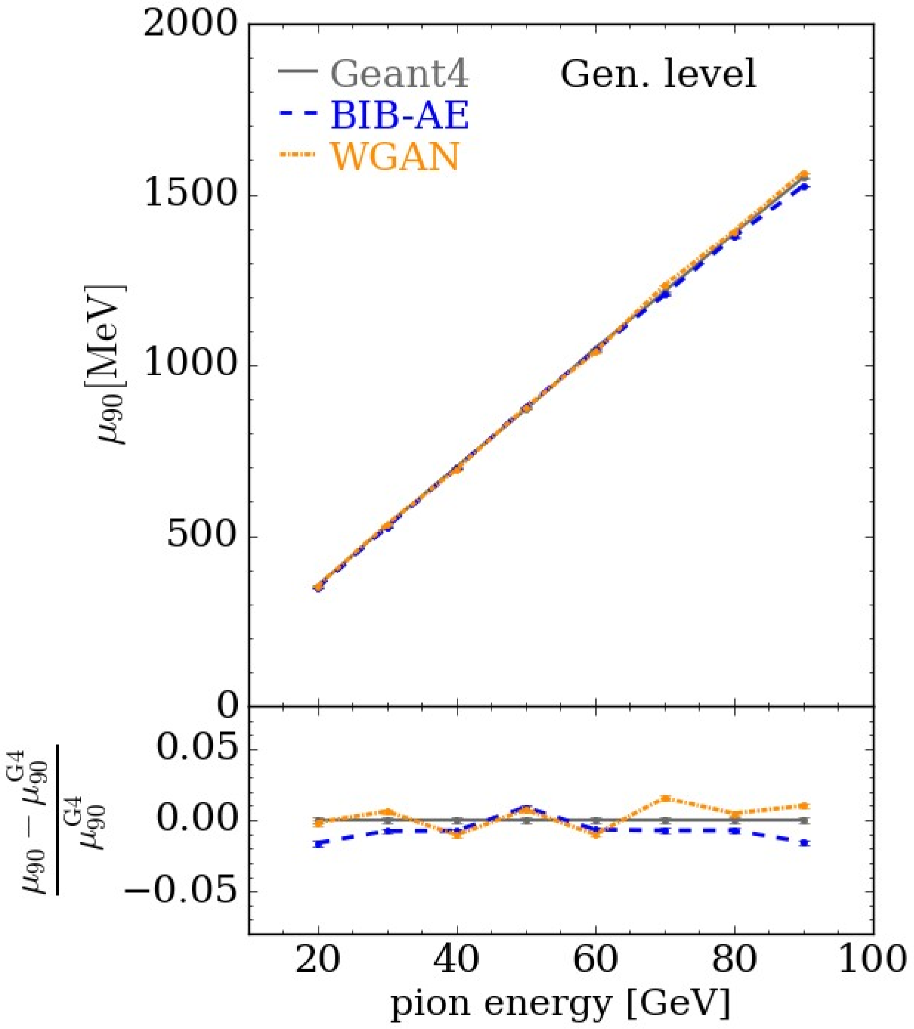
- BIB-AE shows consistently high performance; WGAN performance is mixed

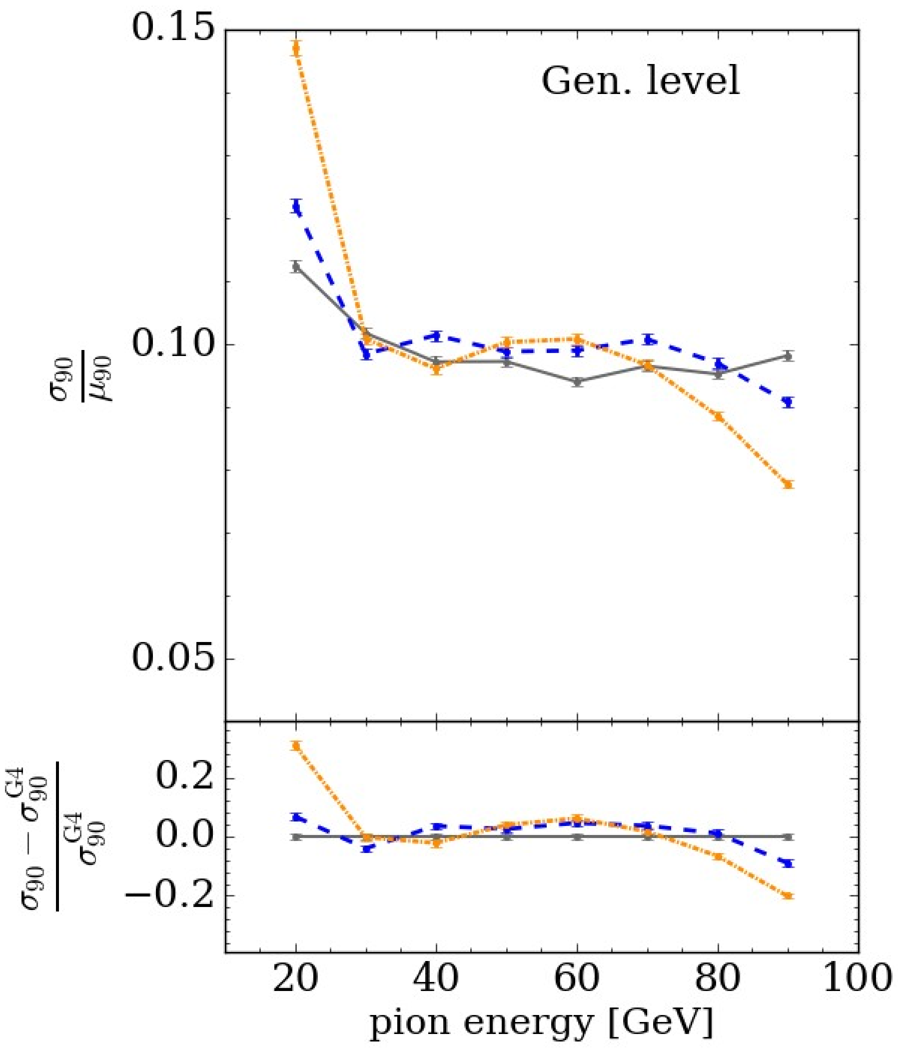
MIP = Minimum Ionizing Particle



Pion Showers: Linearity and Resolution at Sim Level

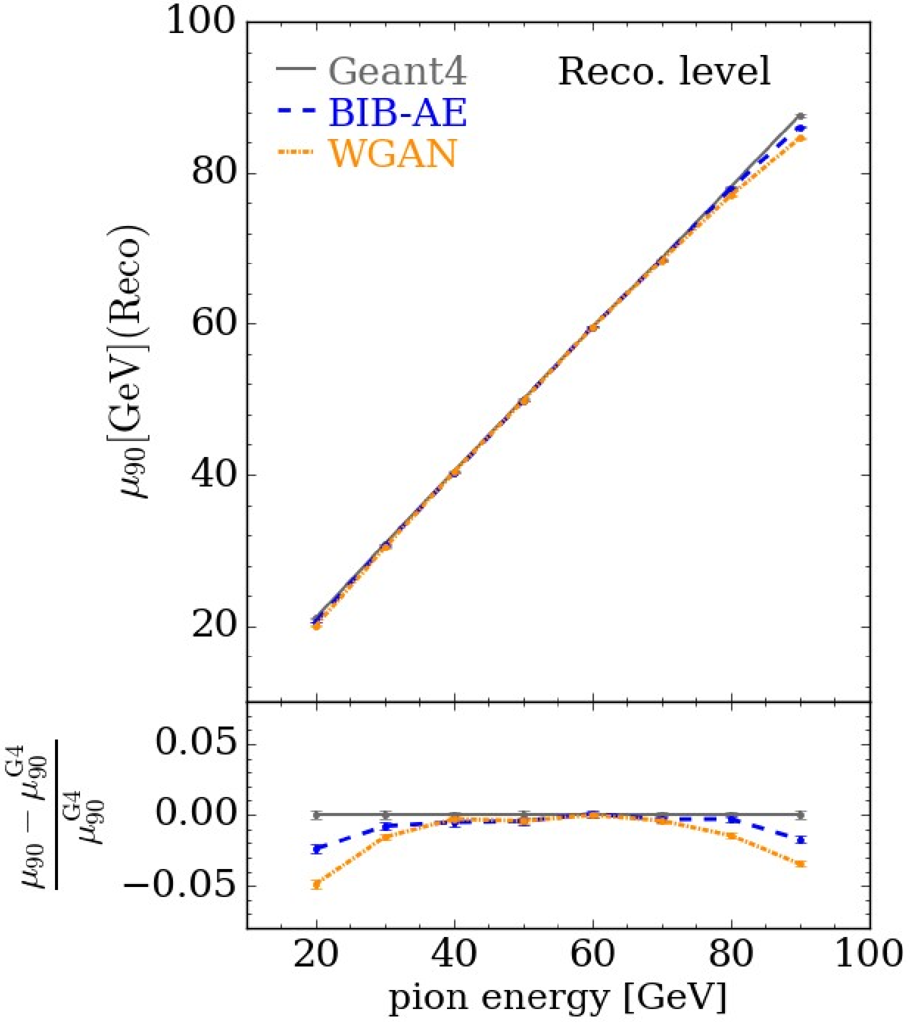
- BIB-AE is largely consistently; WGAN has worse resolution at the edges

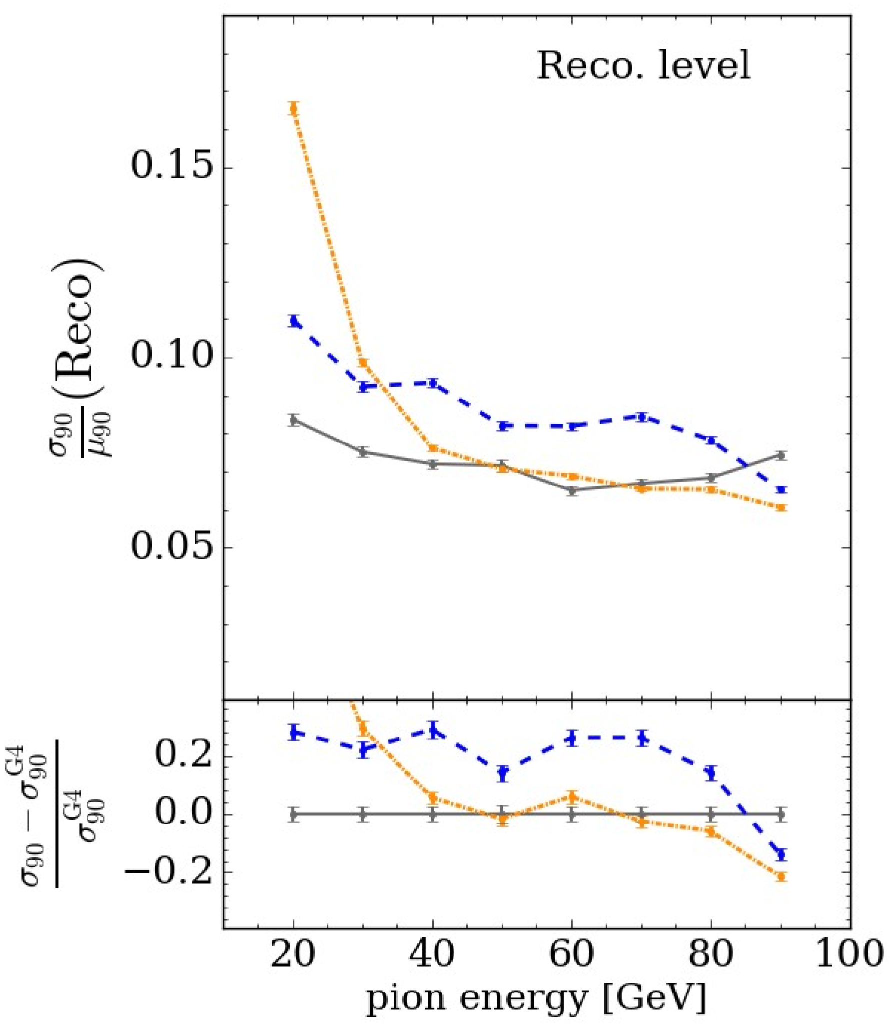




Pion Showers: Linearity and Resolution Post Reconstruction

- Interface with Pandora PFA; after reconstruction the picture changes





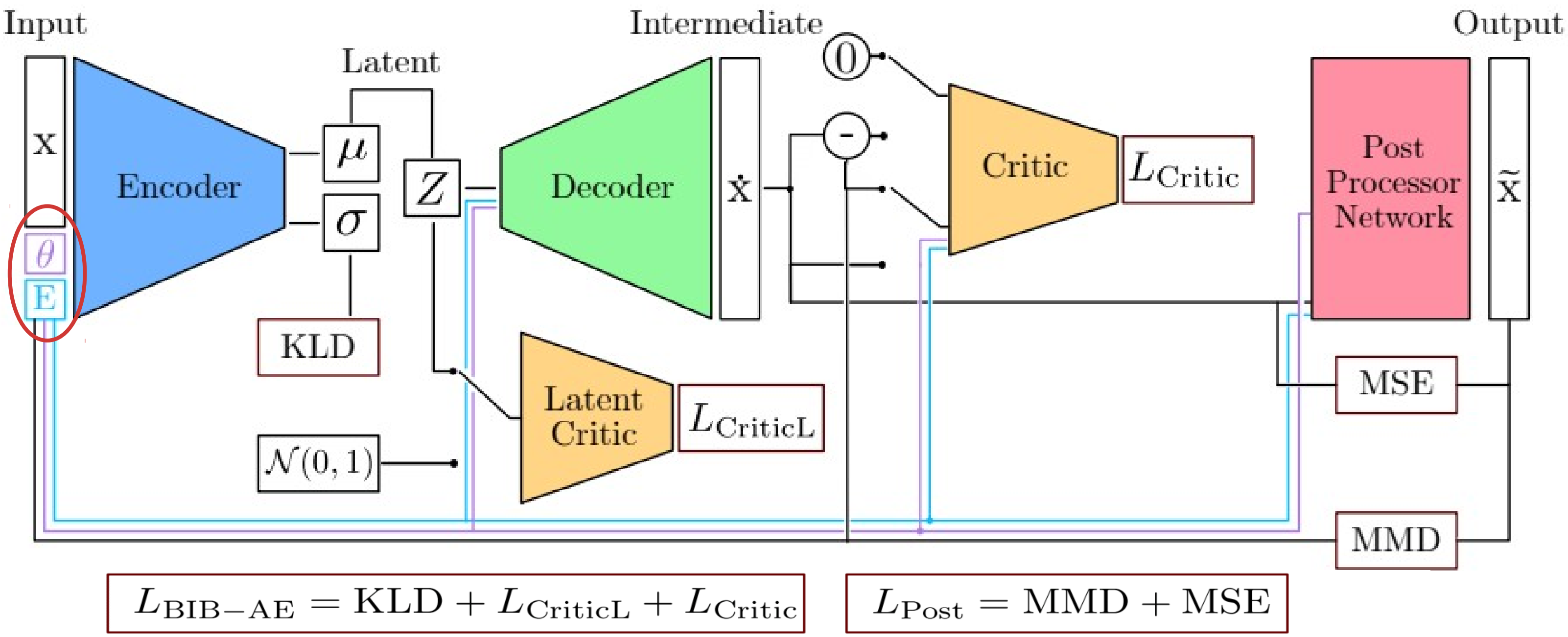
Pion Showers: Computing Time for Inference

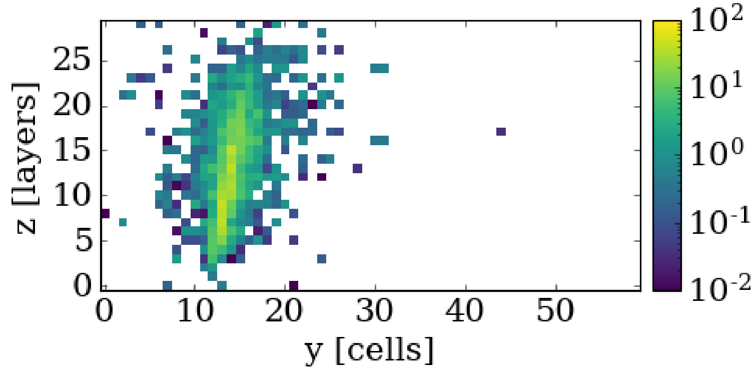
Hardware	Simulator	Time / Shower [ms]	Speed-up
CPU	GEANT4	2684 ± 125	$\times 1$
	WGAN	47.923 ± 0.089	$\times 56$
	BIB-AE	350.824 ± 0.574	$\times 8$
GPU	WGAN	0.264 ± 0.002	$\times 10167$
	BIB-AE	2.051 ± 0.005	$\times 1309$

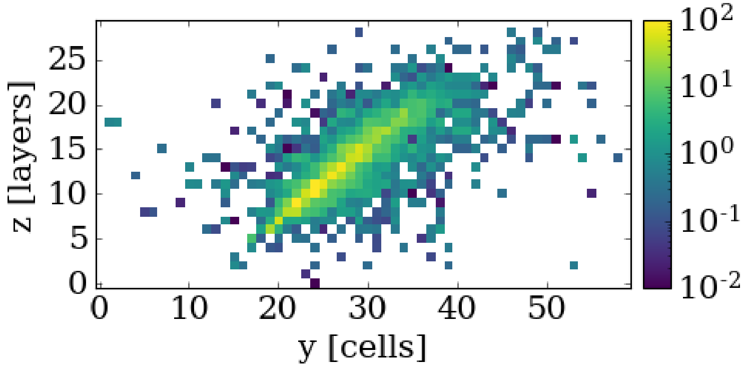
Speed-up of as much as four orders of magnitude on single core of Intel® Xeon® CPU E5-2640 v4 and NVIDIA® A100 for the best performing batch size

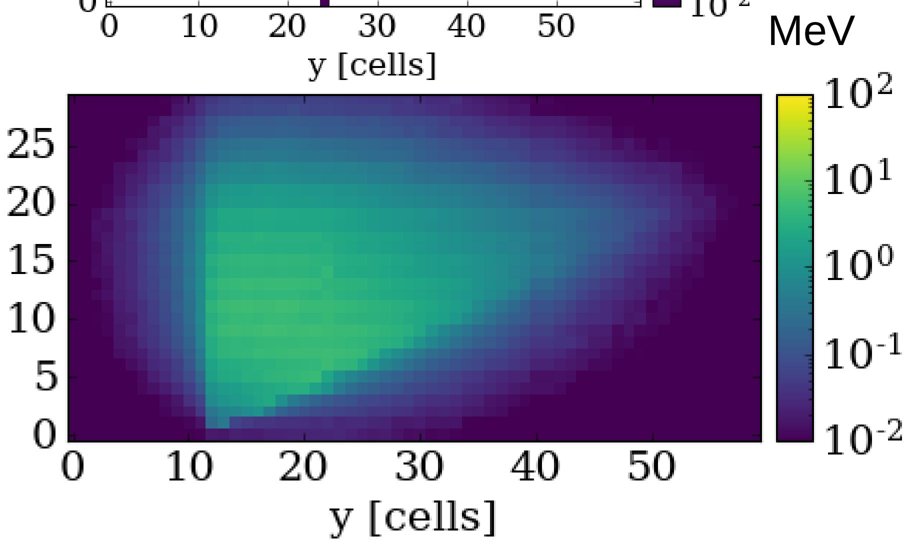
Angular and Energy conditioning- Training data

- 500,000 **photons** with fixed incident point
- Vary **energy**: **10-100 GeV**
- Vary **polar angle** in one direction: **90°-30°**
- Project to regular grid
  - Shape (30,60,30) (x,y,z)





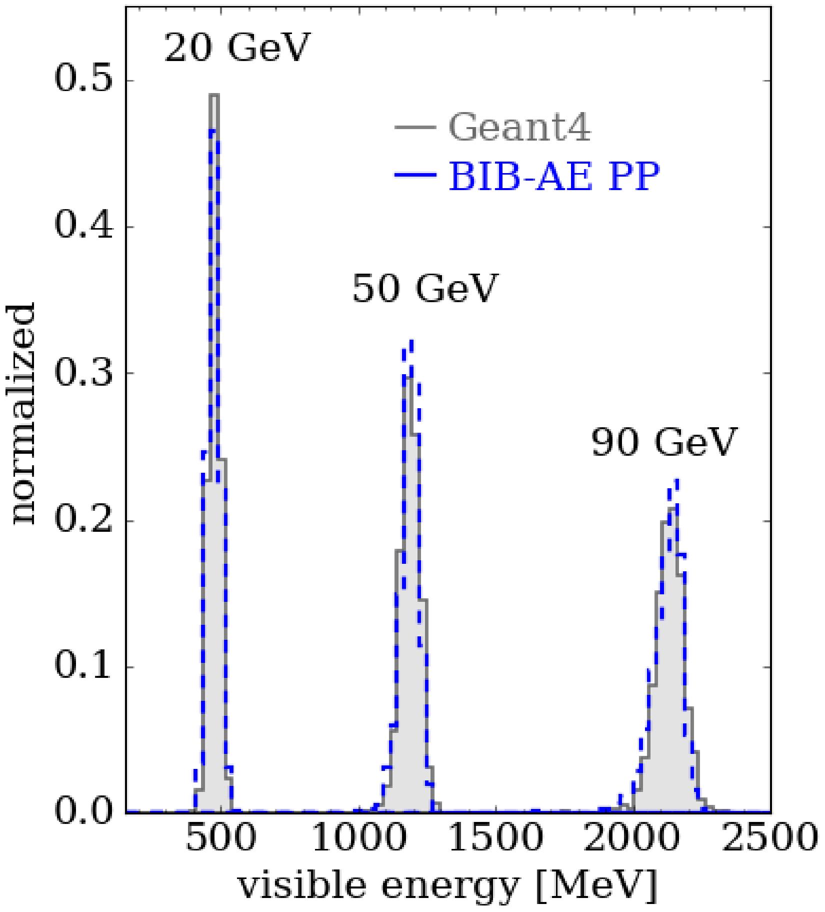




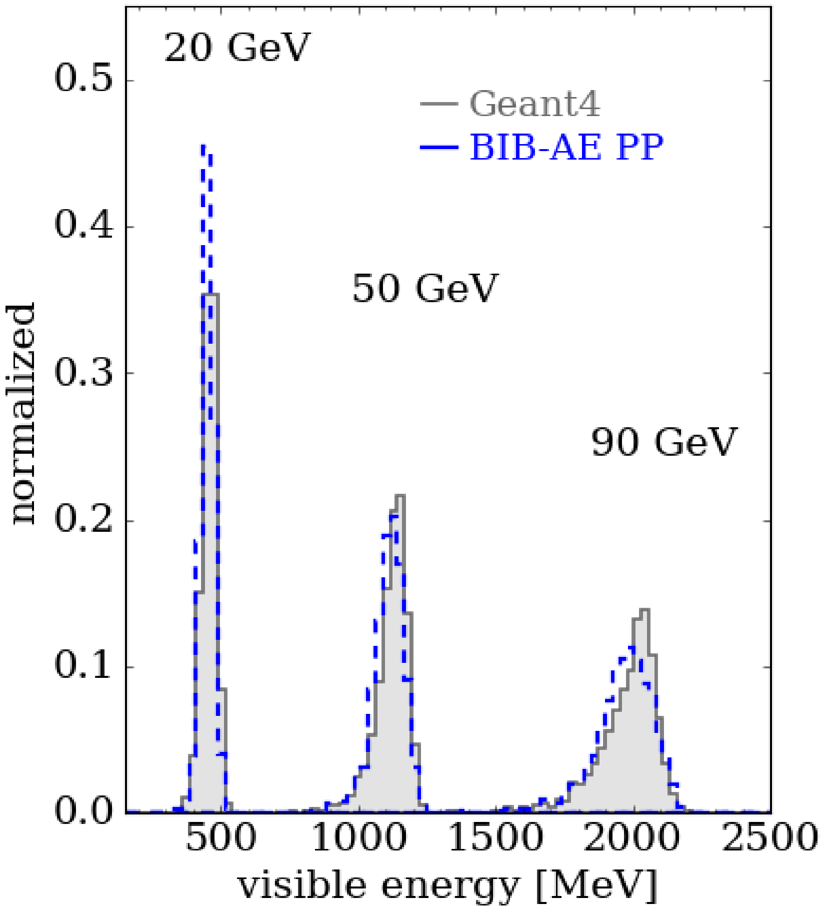
Results: Visible Energy Sum

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

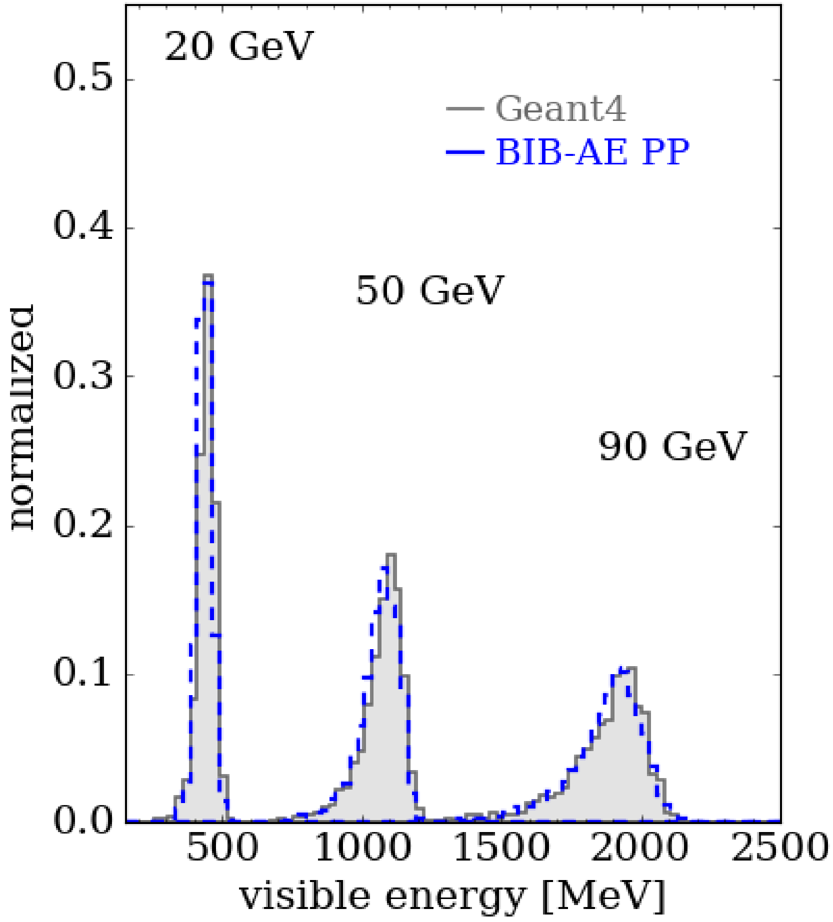
40 degree Photons



60 degree Photons

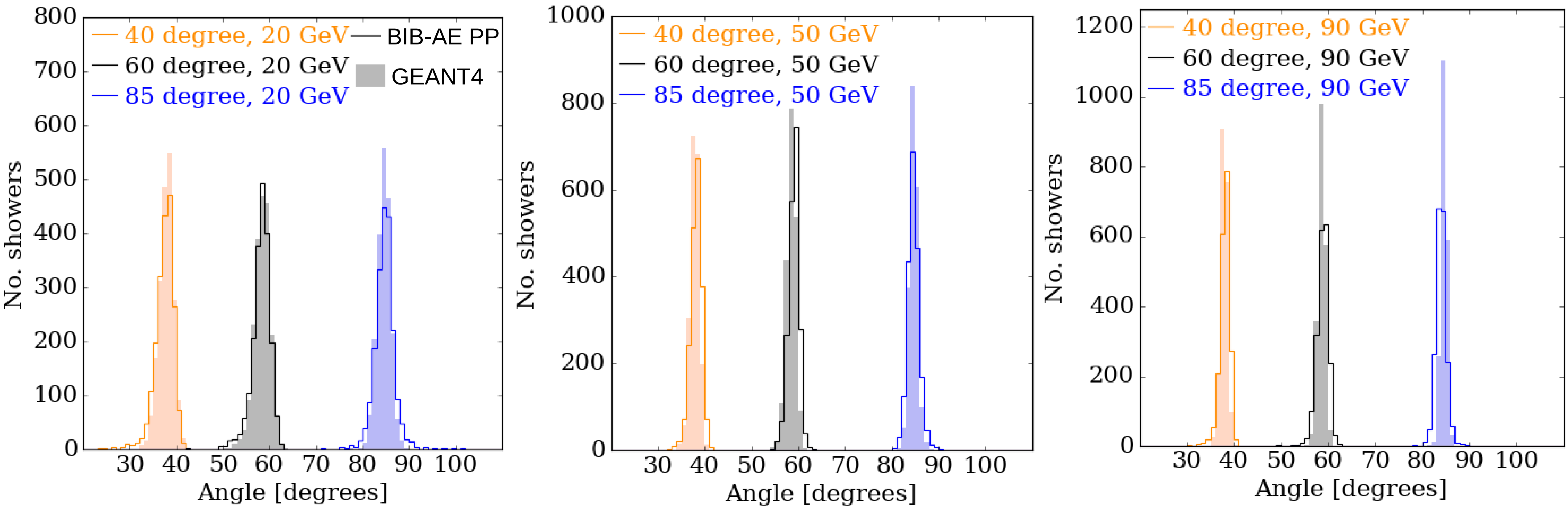


85 degree Photons



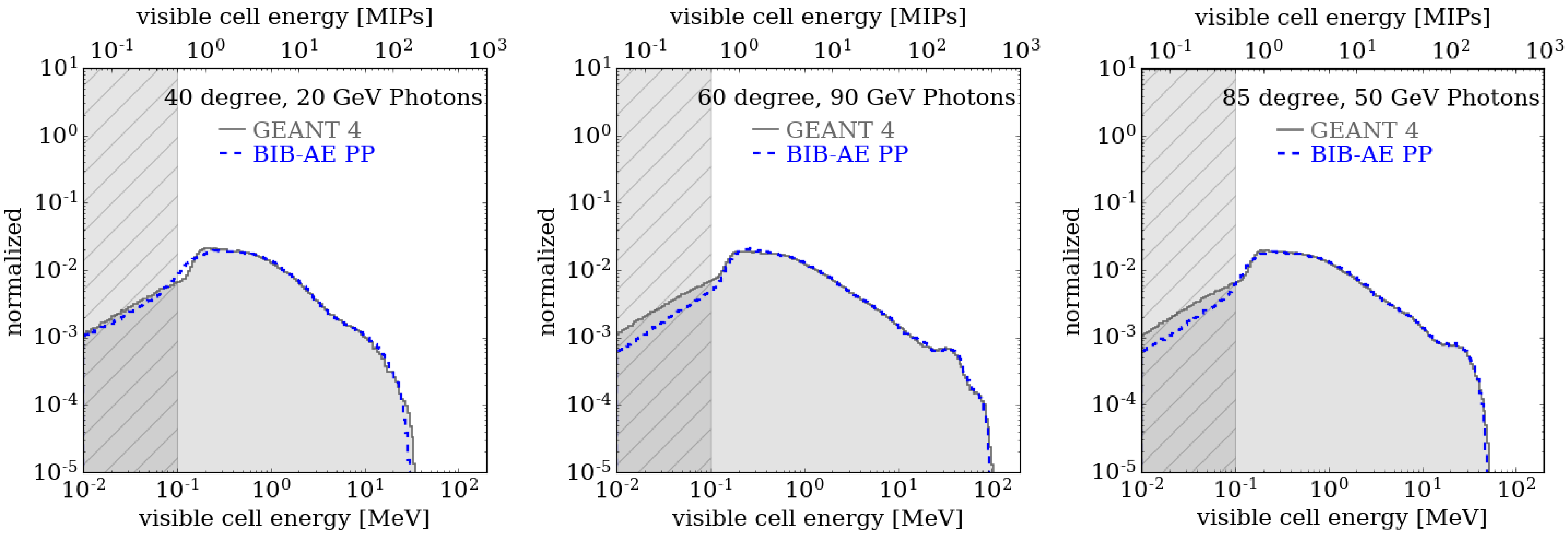
Results: Angular Reconstruction Distributions

- 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



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
- Demonstrated high fidelity simulation of **photon** showers with **angular and energy conditioning**
- Initial investigation into generative model performance after **reconstruction**

Next Steps

Hadron Shower Simulation

- Simulation of hadronic showers combining **ECAL and HCAL**

Photon Shower Simulation

- Benchmark performance after **reconstruction** and **timing**
- Develop strategy for dealing with **arbitrary incident positions**

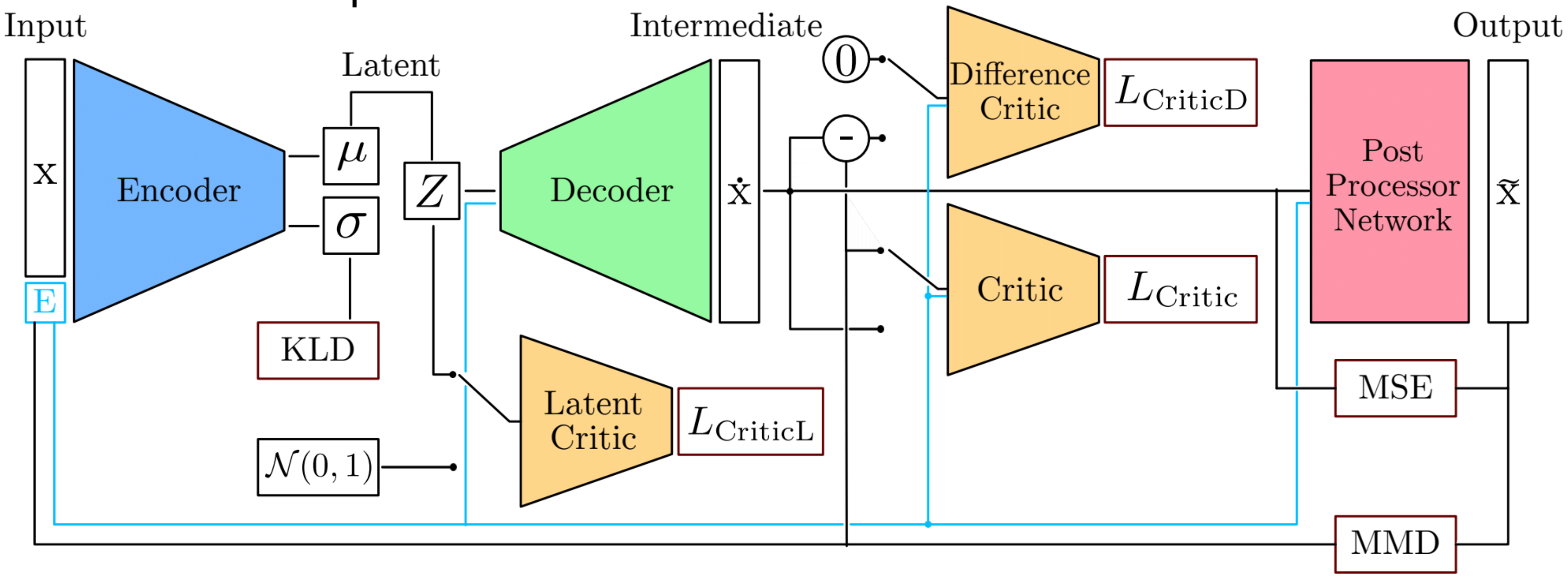
Backup

Architectures: BIB-AE

More Details

- Unifies features of both GANs and VAEs
- Adversarial critic networks rather than pixel-wise difference a la VAEs
- Improved latent regularisation: additional critic and MMD term
- Post-Processor network: Improve per-pixel energies; second training

- Updates and improvements:
  - Dual and resetting critics: prevent artifacts caused by sparsity
  - Batch Statistics: prevent outliers/ mode collapse
  - Multi-dimensional KDE sampling: better modeling of latent space



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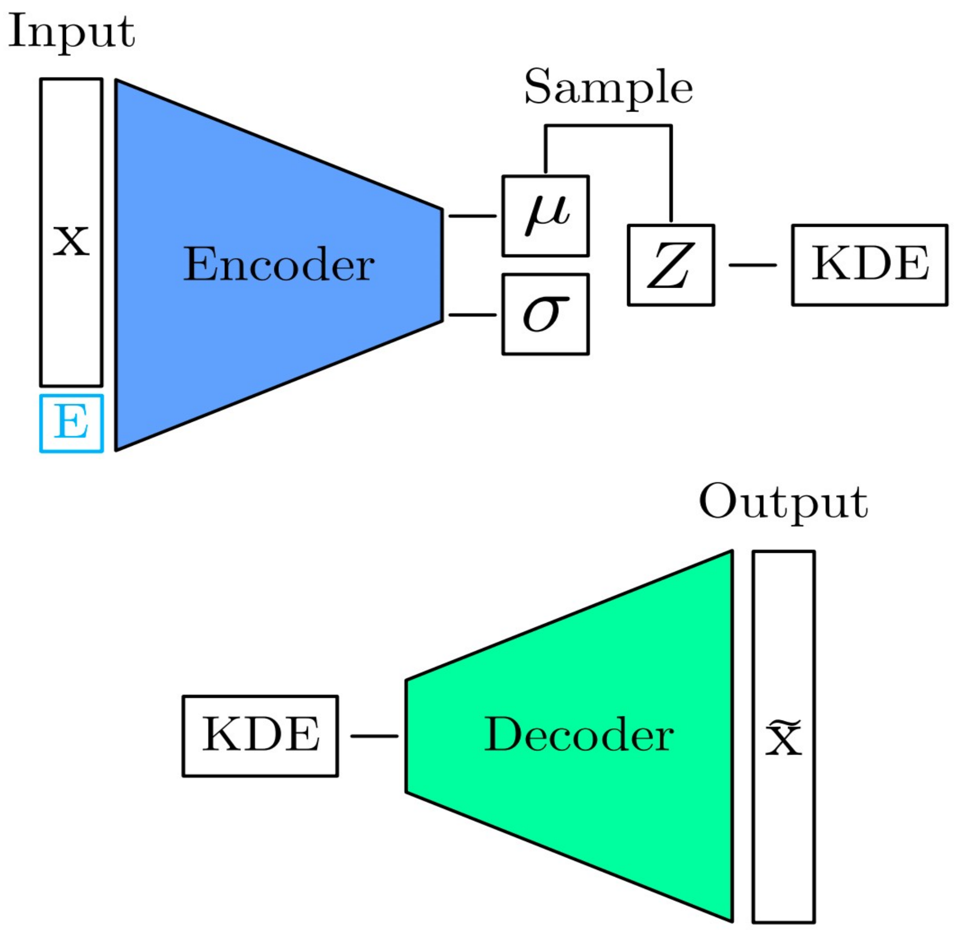
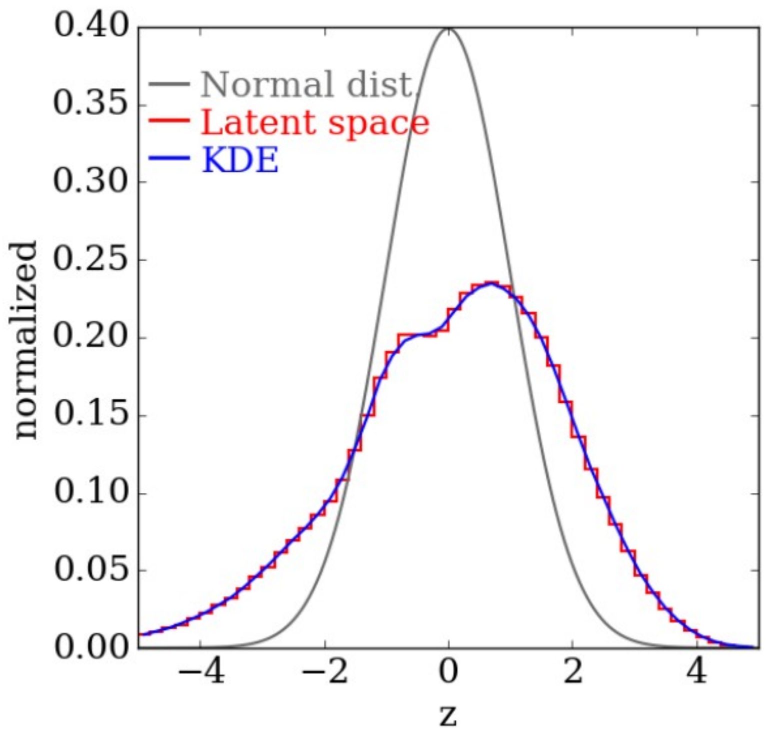
$$L_{\mathrm{Post}} = \mathrm{MMD} + \mathrm{MSE}$$

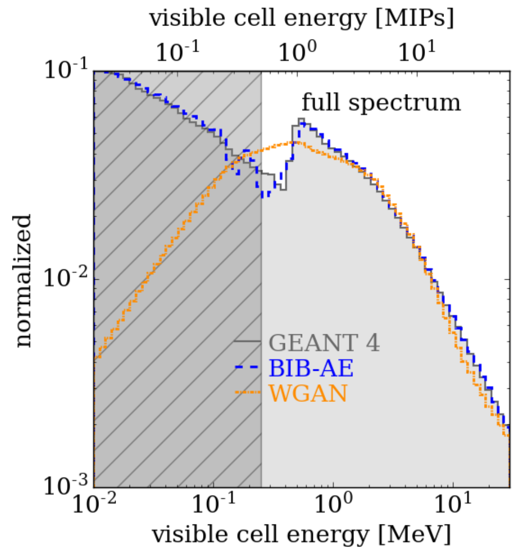
Kernel Density Estimation: BIB-AE

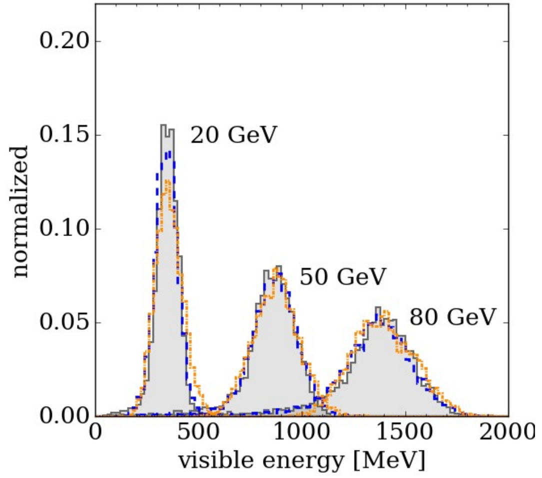


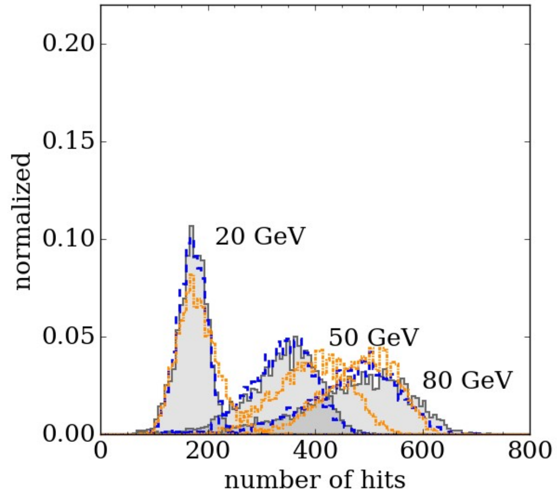


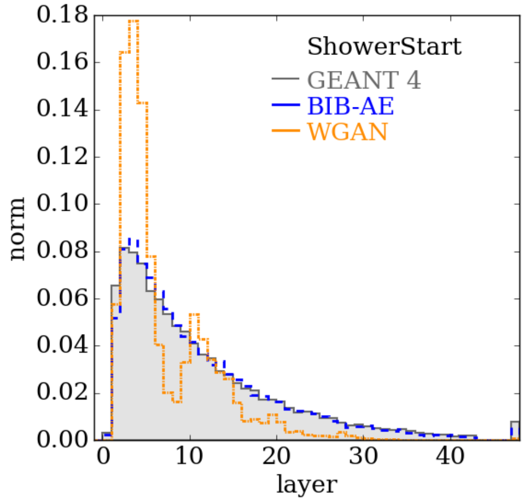
Buhmann et. al: **Decoding Photons: Physics in the Latent Space of a BIB-AE Generative Network**, EPJ Web of Conferences 251, 03003 (2021)

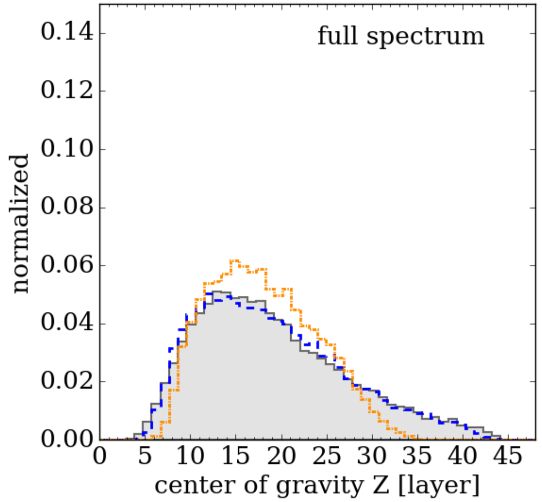
Pion Showers: Sim Level Results

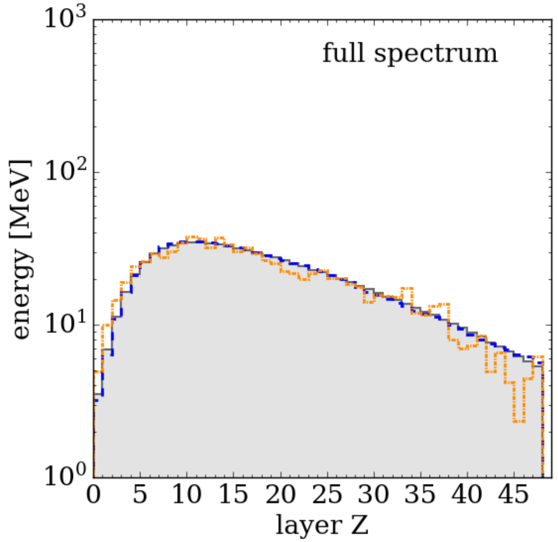




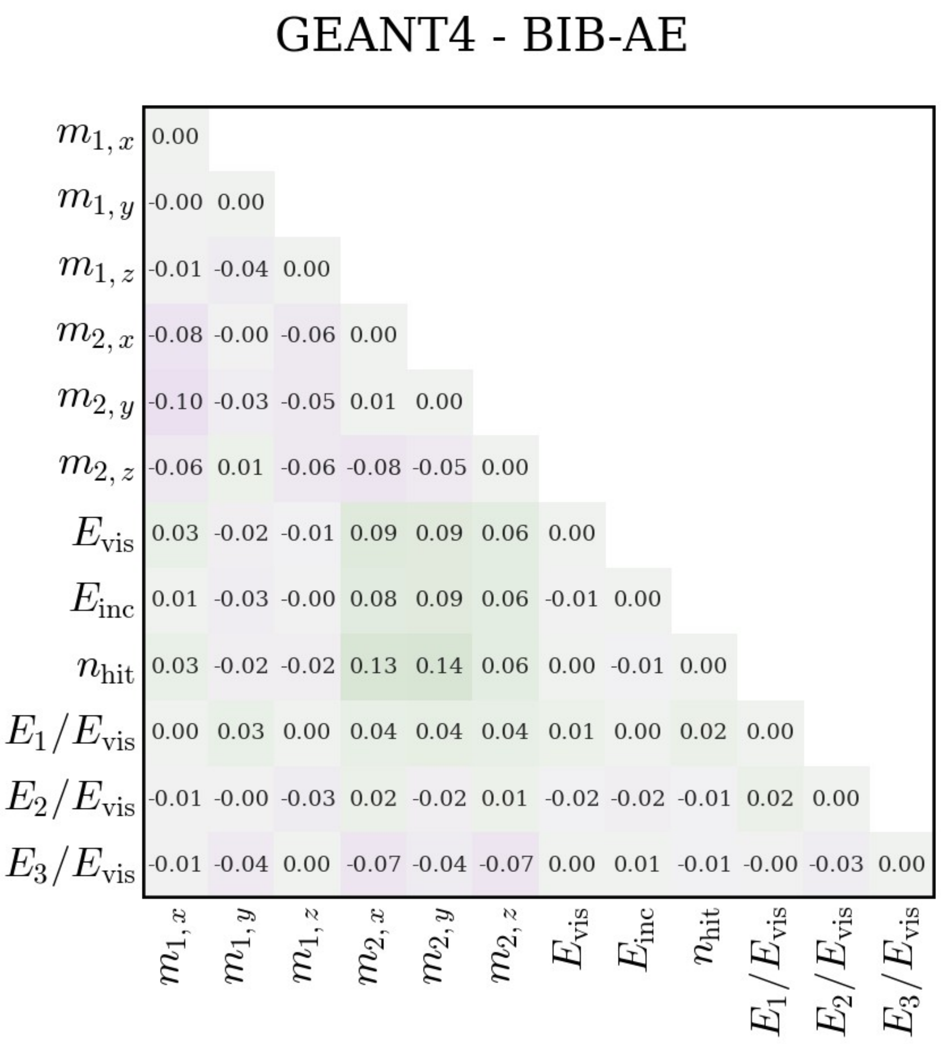


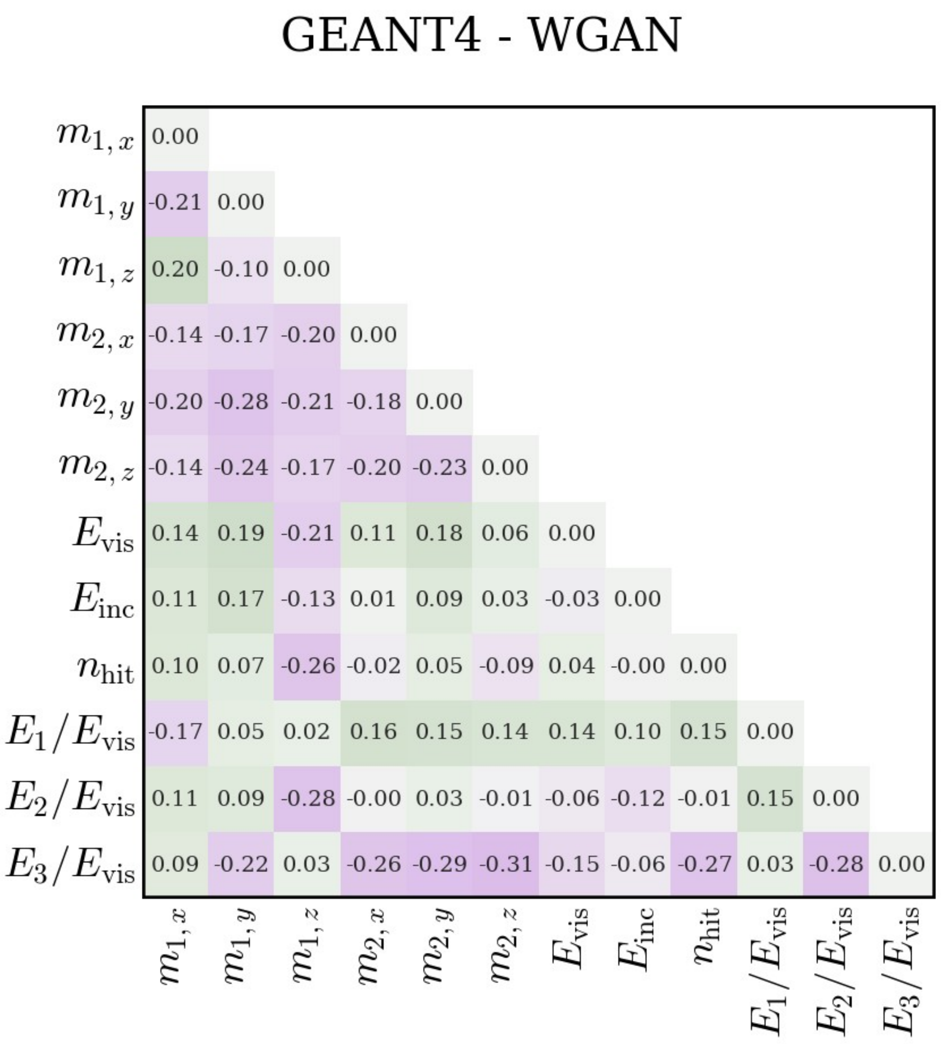




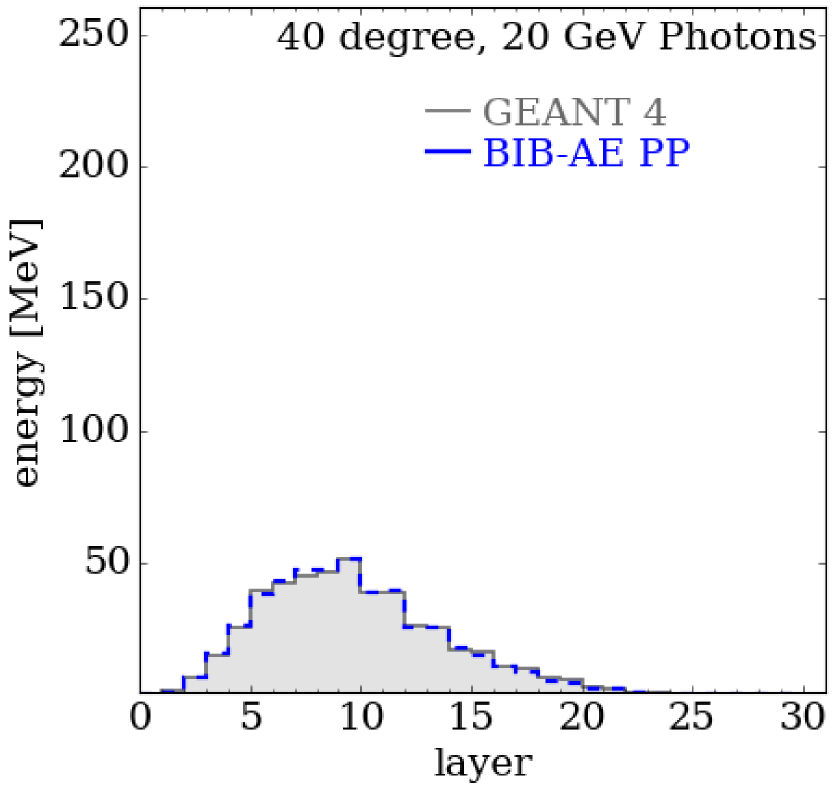


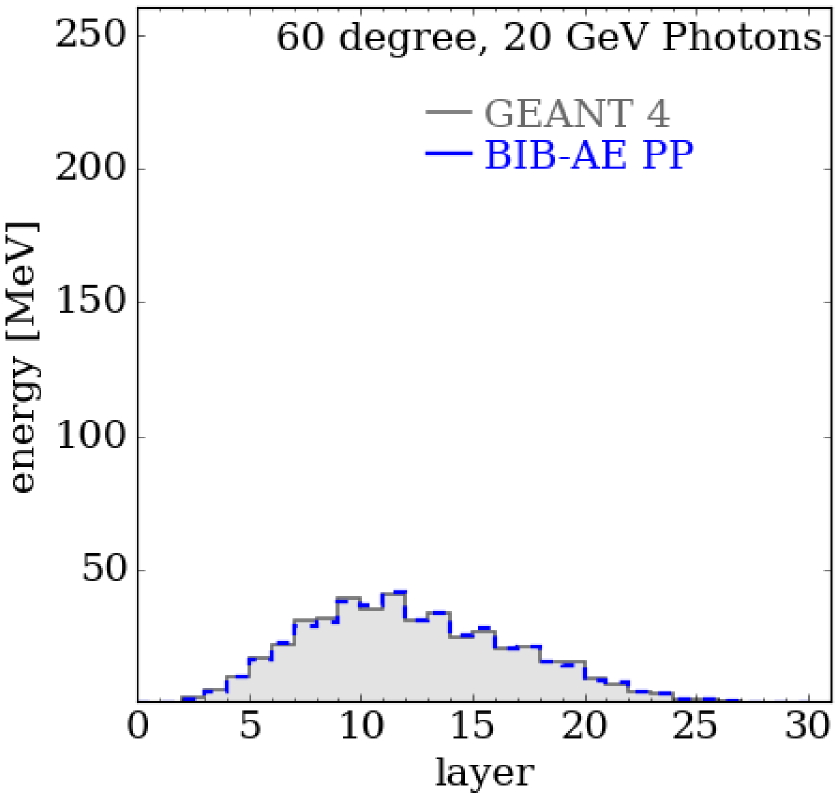
Pion correlations

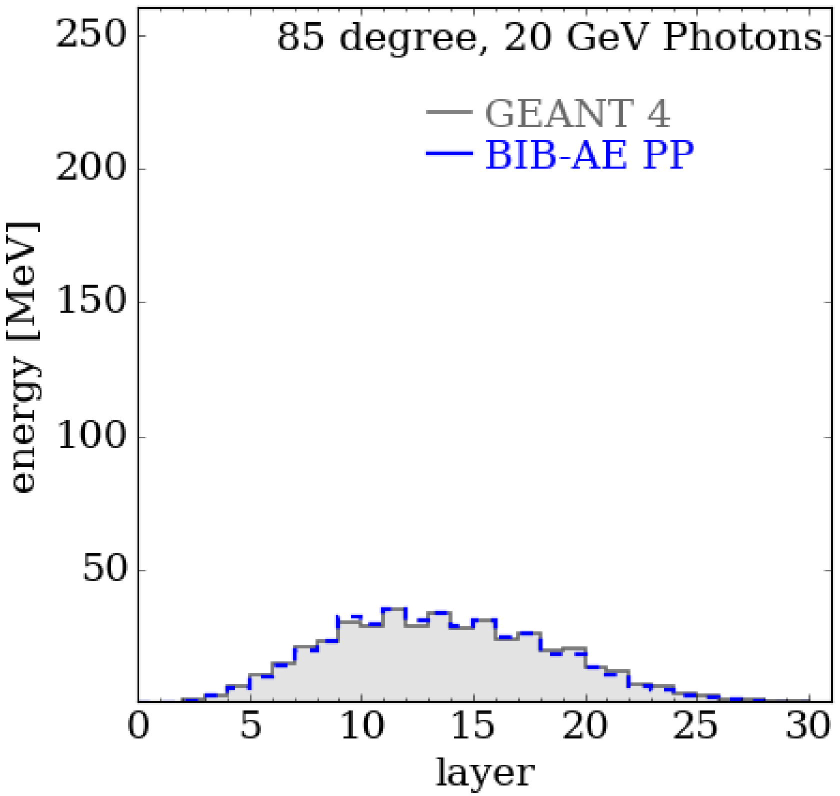




Results: Longitudinal Profile







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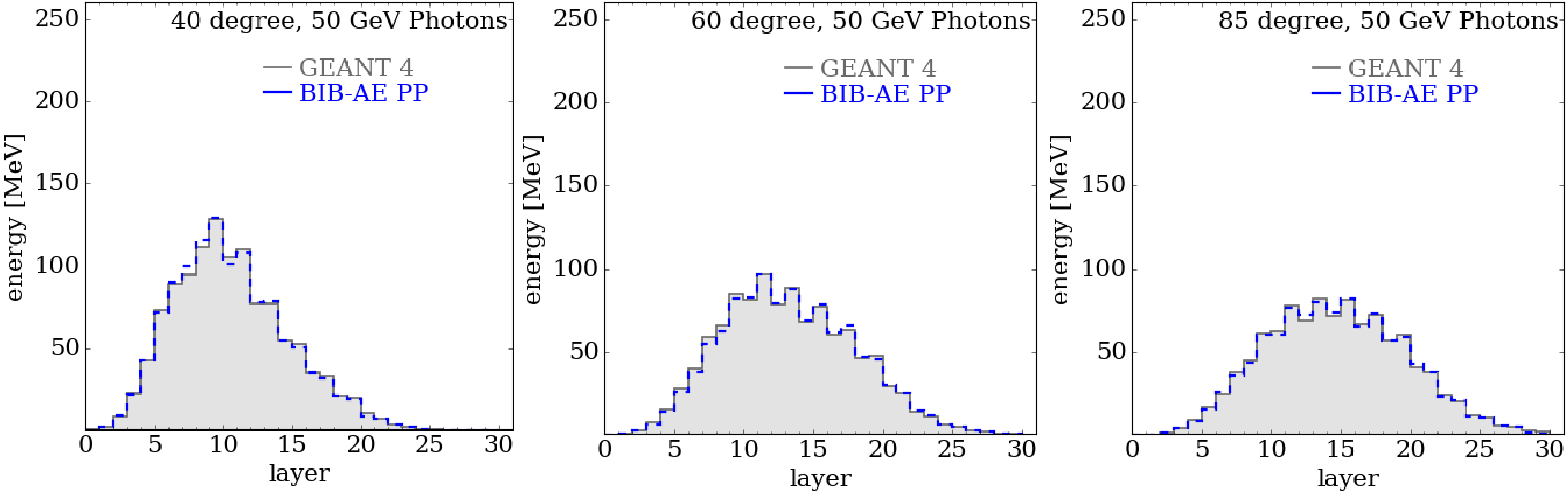

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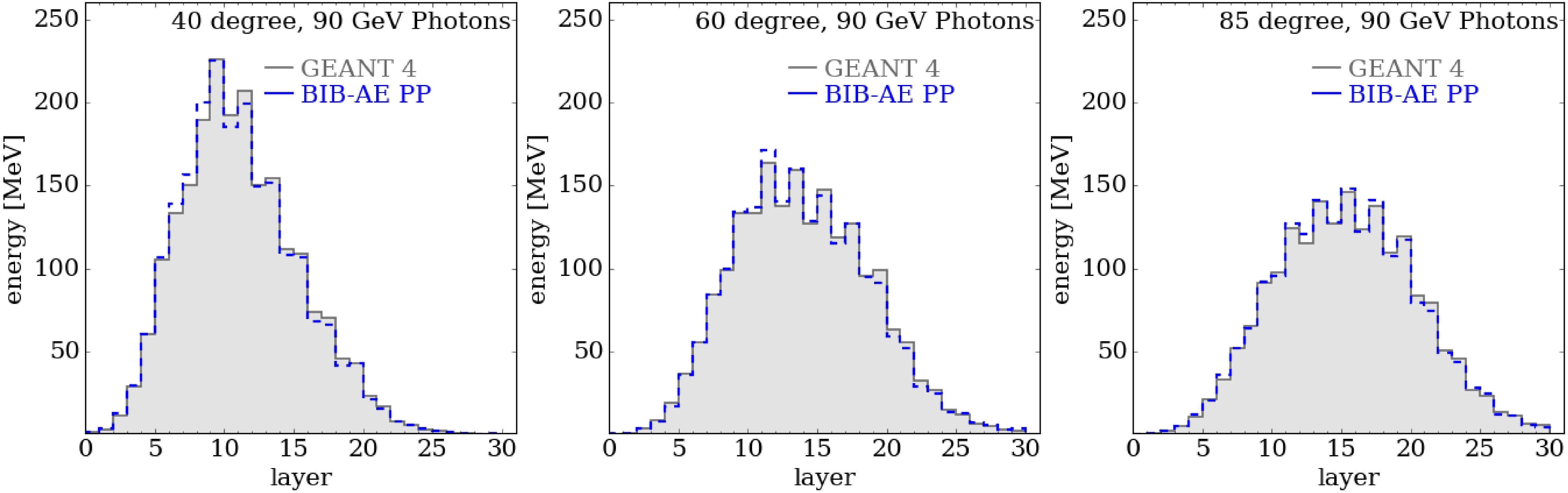
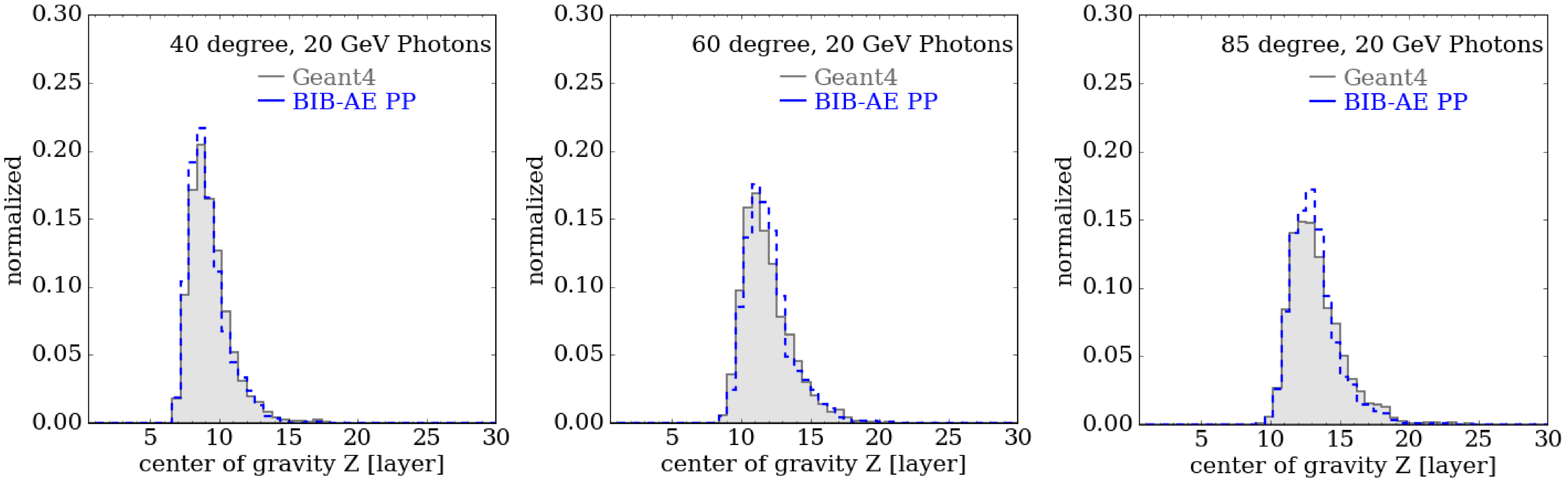


Results: Center of Gravity



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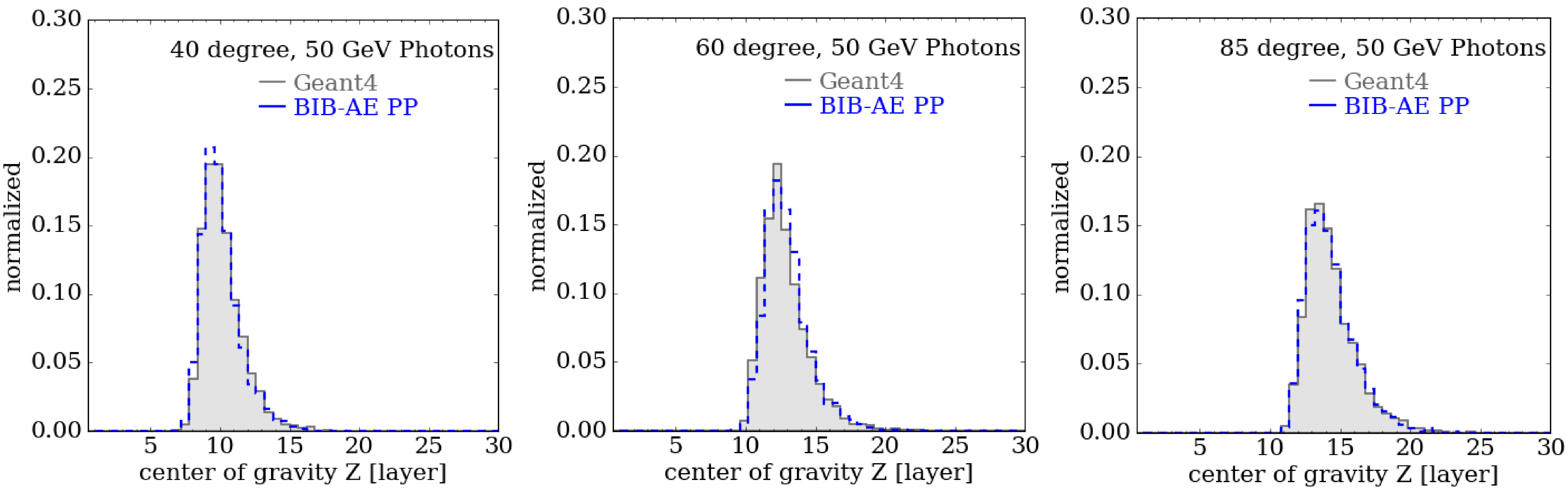

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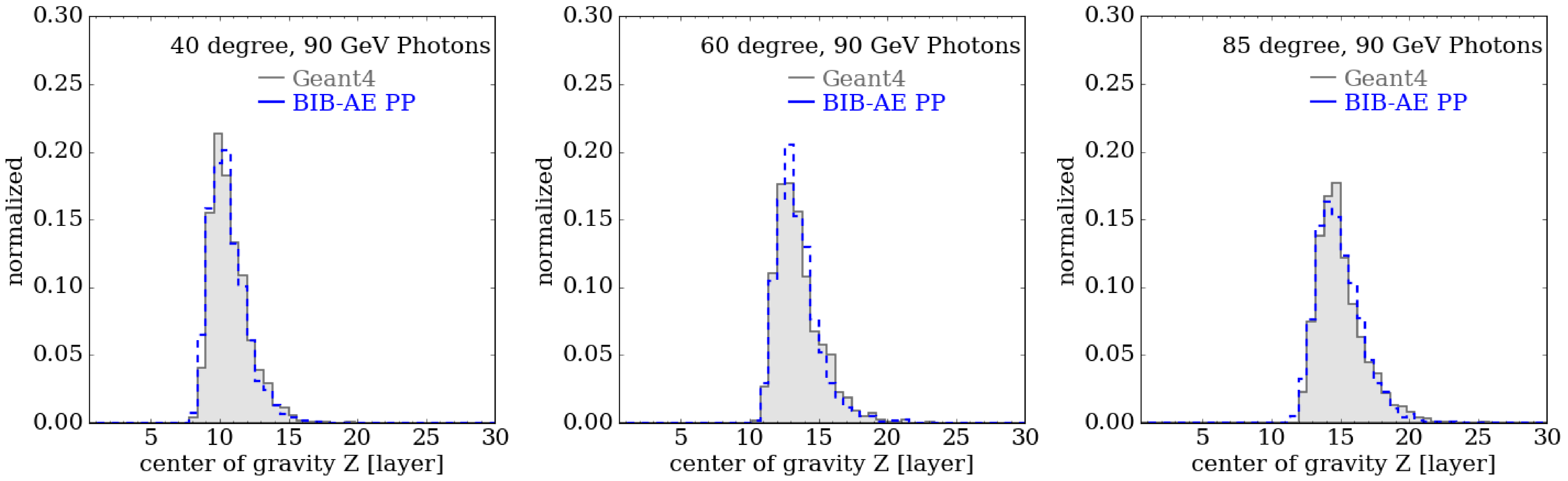
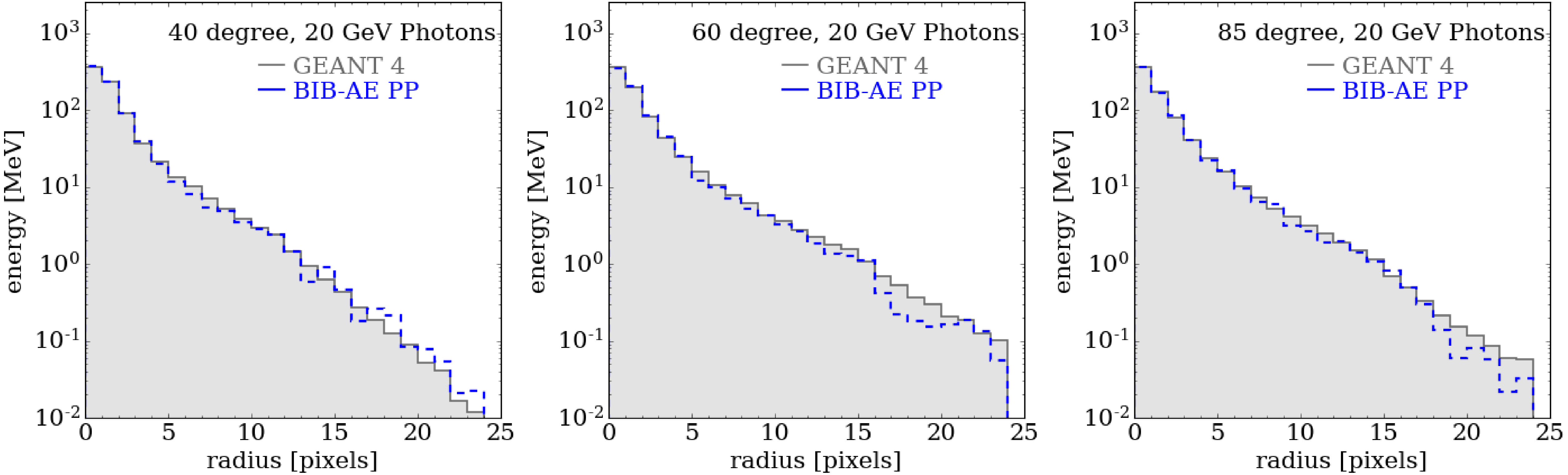


Results: Radial Profile



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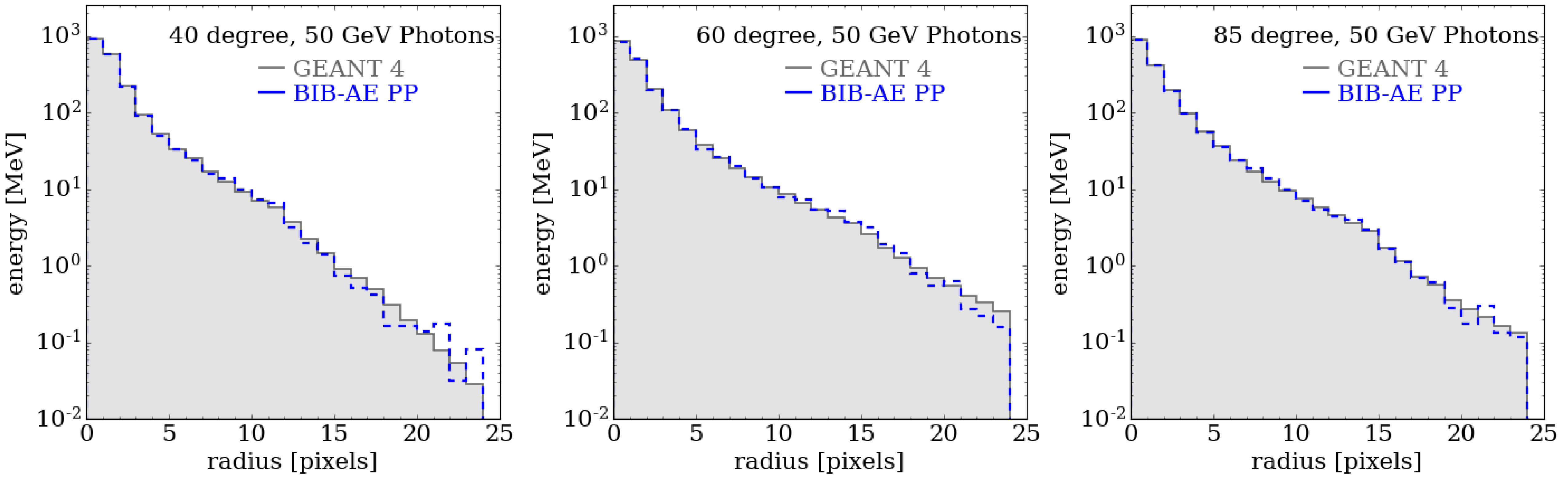

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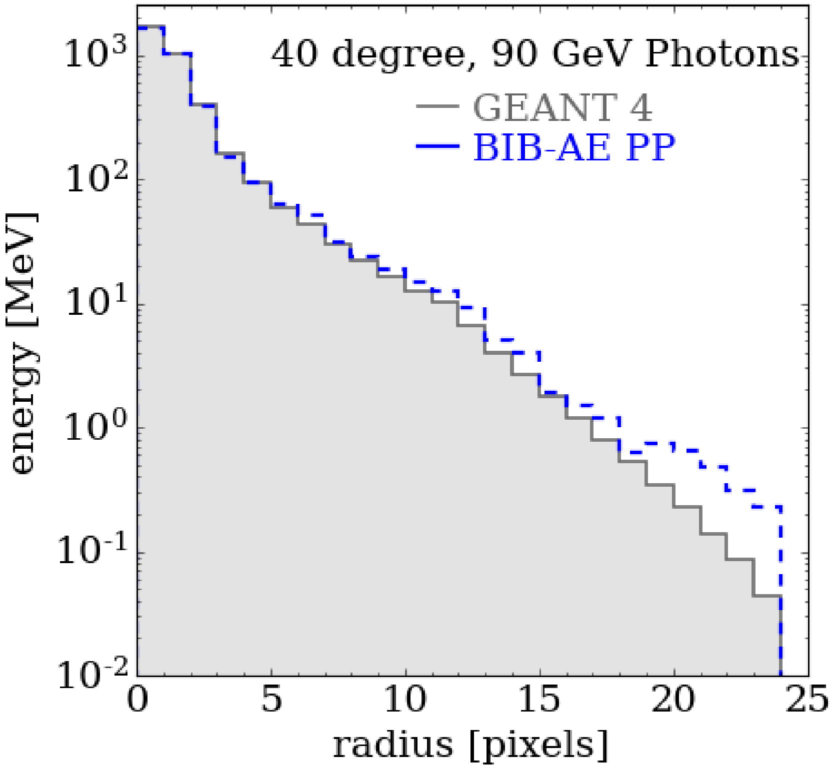
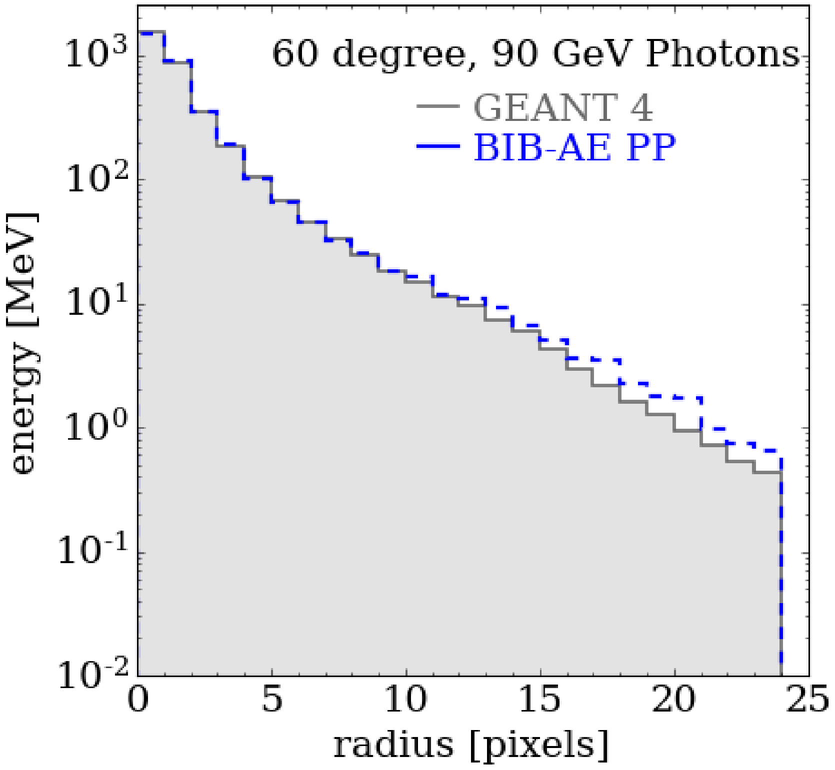
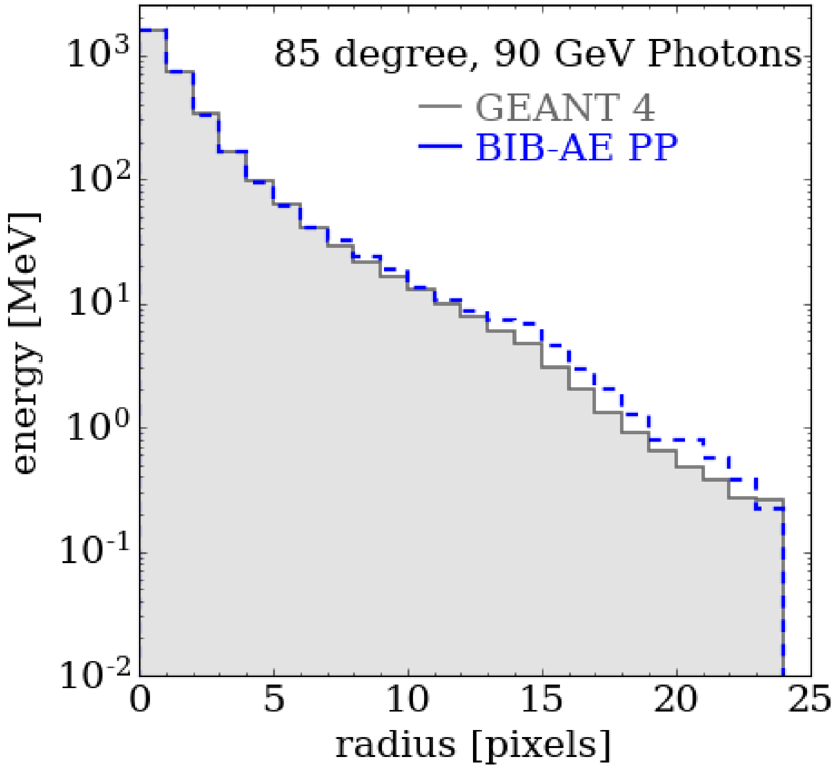
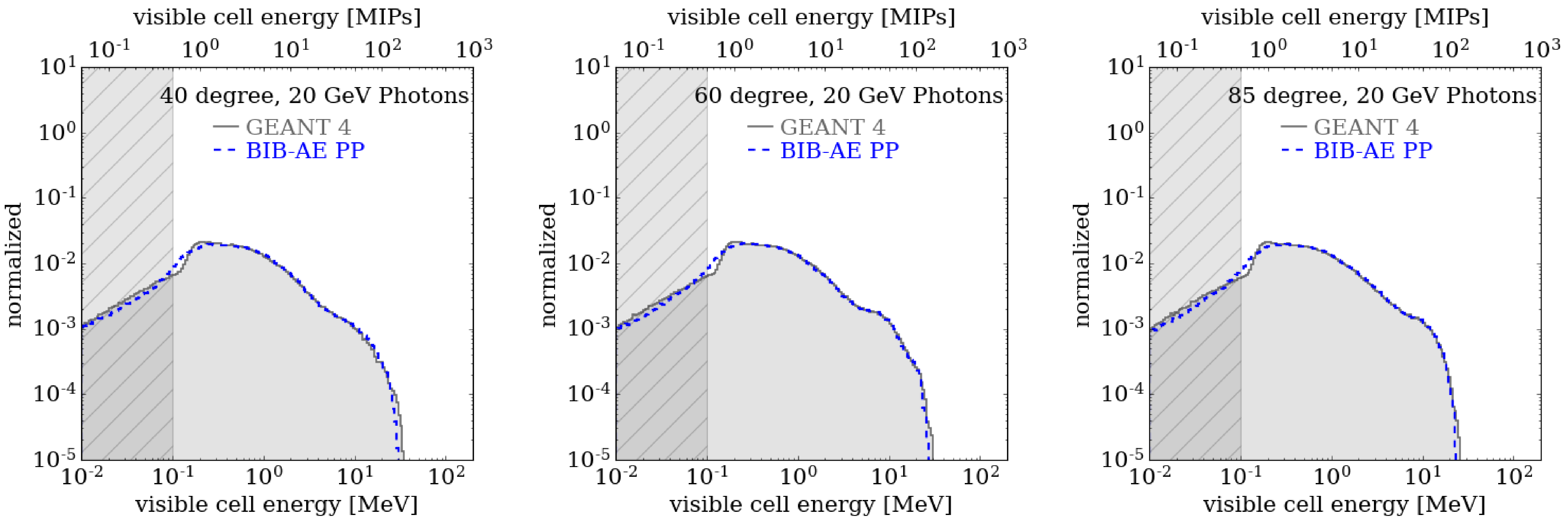






Results: Cell Energy Spectrum



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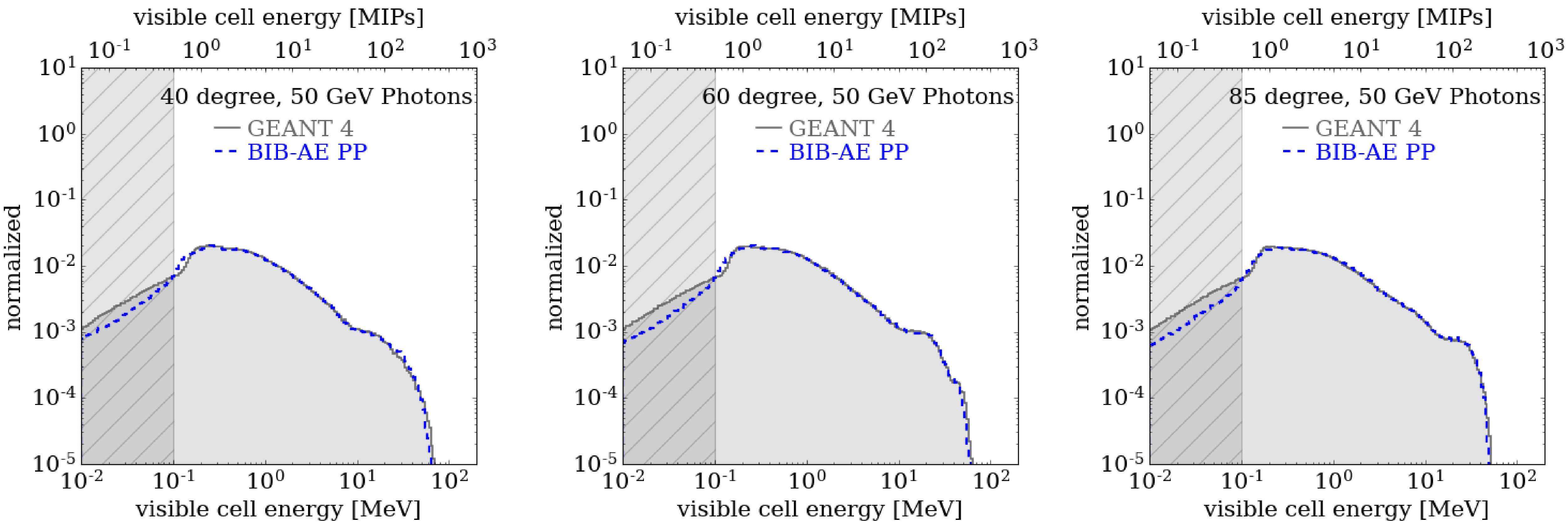

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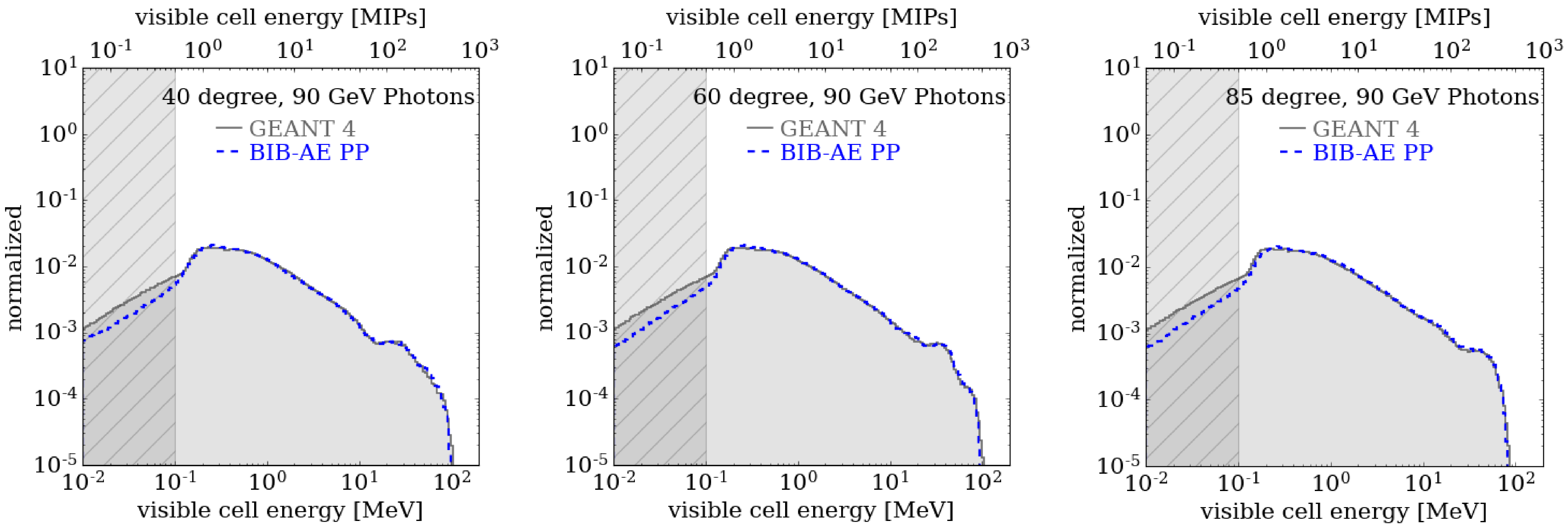

Results: Number of Hits