Convolutional Neural Network For Ultra-High-Energy Cosmic Rays Reconstruction at Telescope Array x4

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Department of Physics, NTU
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What Are Convolutional Neural Networks?

Deep Learning

Deep learning (DL) approximates a function by using a deep neural network (DNN) to learn suitable parameters (D. Ivanov et al., 2020)

CNN recognizes spatial adjacency information:
image recognition

D. Ivanov et al. (2020). Using Deep Learning to Enhance Event Geometry Reconstruction for the Telescope Array Surface Detector

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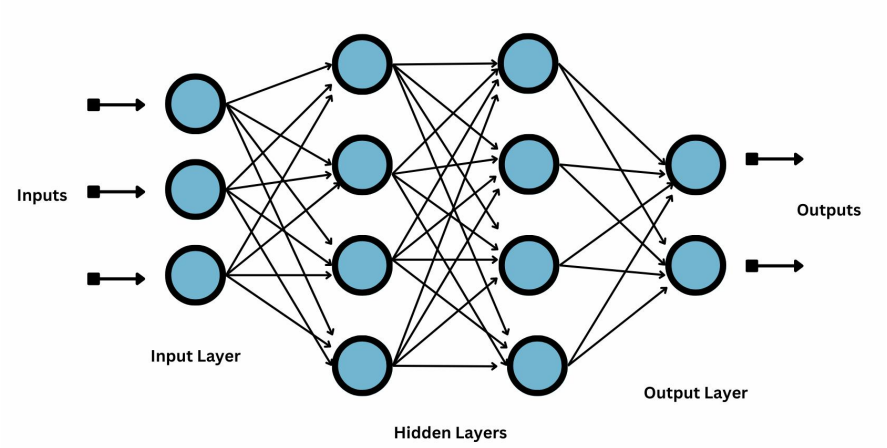
$$CNN \subseteq DNN \subseteq ML \subseteq AI$$



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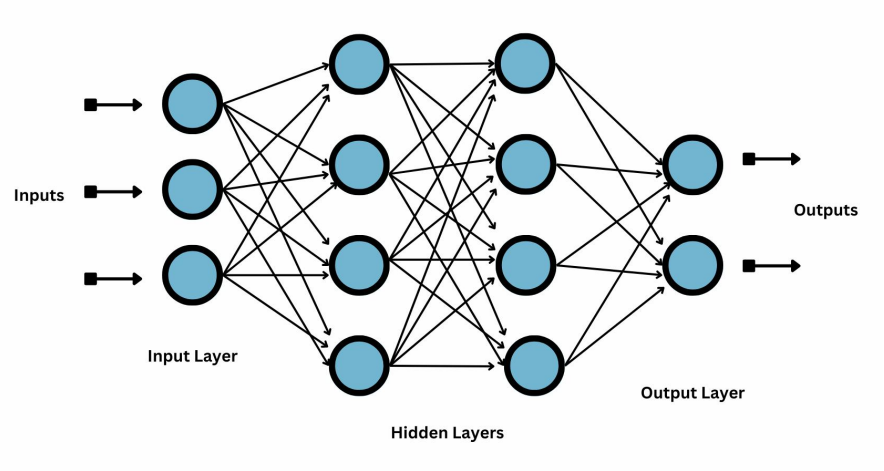
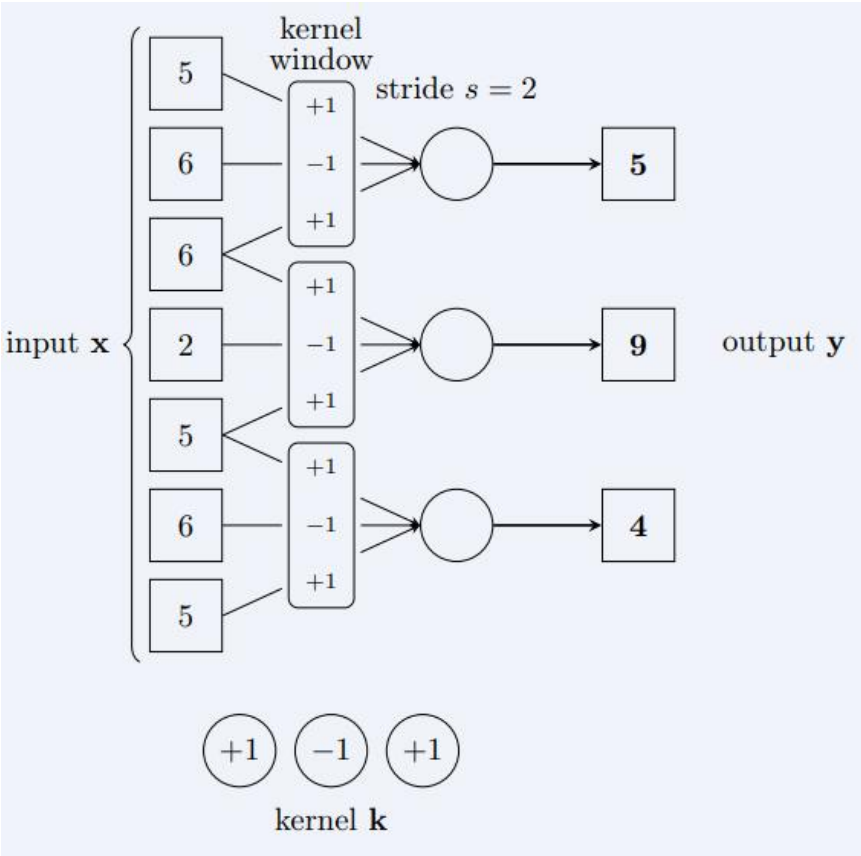


Quick Example



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Data Preparation (1/2)

The Highest-Energy Cosmic Rays

James J. Beatty[1] and Stefan Westerhoff[2]

[1]Center for Cosmology and Astroparticle Physics, Departments of Physics and Astronomy, The Ohio State University, Columbus, Ohio 43210; email: beatty@mps.ohio-state.edu

[2]Department of Physics and IceCube Research Center, University of Wisconsin-Madison, Madison, Wisconsin 53706; email: westerhoff@wisc.edu

Standard Reconstruction

For short: STD

Event: time-dependent signals (WF) from both layers of each triggered station.

J. J. Beatty and S. Westerhoff, Annu. Rev. Nucl. Part. Sci., vol. 59, no. 1

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Event: time-dependent signals (WF) from both layers of each triggered station.

- **7** free fitting parameters are used / **14** parameters are estimated for each event
- Ensure reconstruction quality:
  #(event trigger) / zenith angle / core position / geometry & lateral distribution profile (LDF) χ^2 / arrival direction / uncertainty of shower LDF

J. J. Beatty and S. Westerhoff, Annu. Rev. Nucl. Part. Sci., vol. 59, no. 1

Data Preparation (2/2)

Monte Carlo simulation

Produce TAx4 training data with **CORSIKA (QGSJET II-04) Monte Carlo**

- Zenith angle follows $\sin\theta\cos\theta$
- Use *dstparser* to convert to *.h5* format
- Main constituents are protons, other nuclei (Fe, Ni,...) are not discussed.

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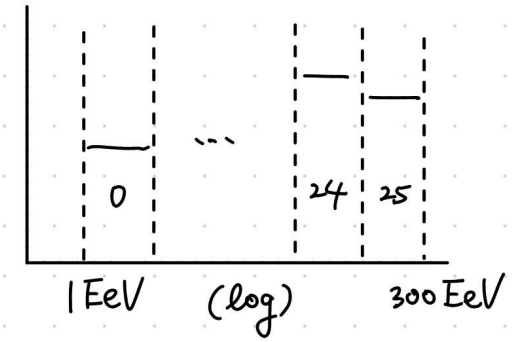
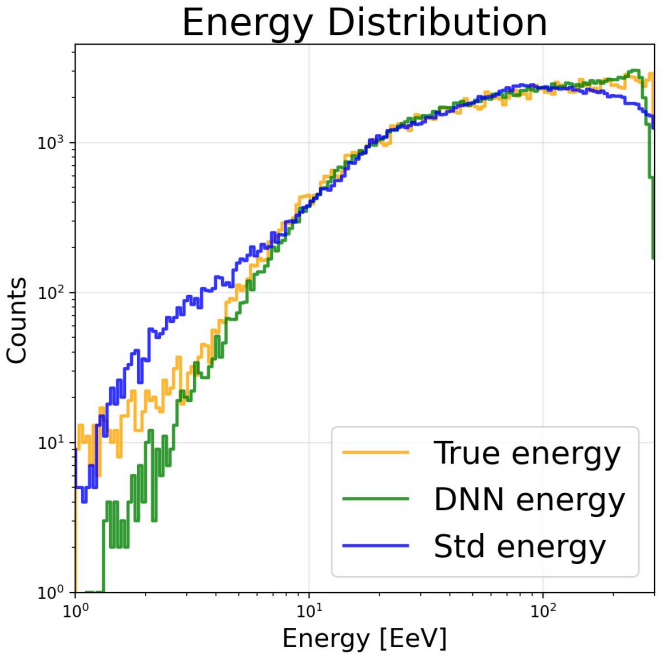
- Main constituents are protons, other nuclei (Fe, Ni,...) are not discussed.
- Data are binned for **training:**

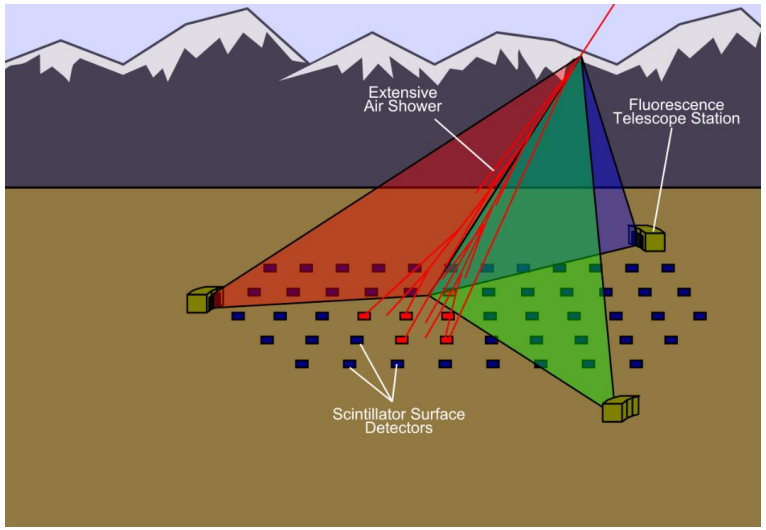
26 bins × 1000 orientations × 1000 showers = 2.6×10^7 events

1000 *h5* files

50 final (*h5)* files







Training Model

Architecture of CNN

Developed as a model for UHECR reconstruction, based on a DL model for another observatory

Shown to improve upon STD

A. Prosekin et al., Proc. Sci., ICRC2021, 2025, p. 308

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Other Info

- Adaptive kernel setup
- CNN reconstruction is trained on ~90% of data and tested on ~10% of data.

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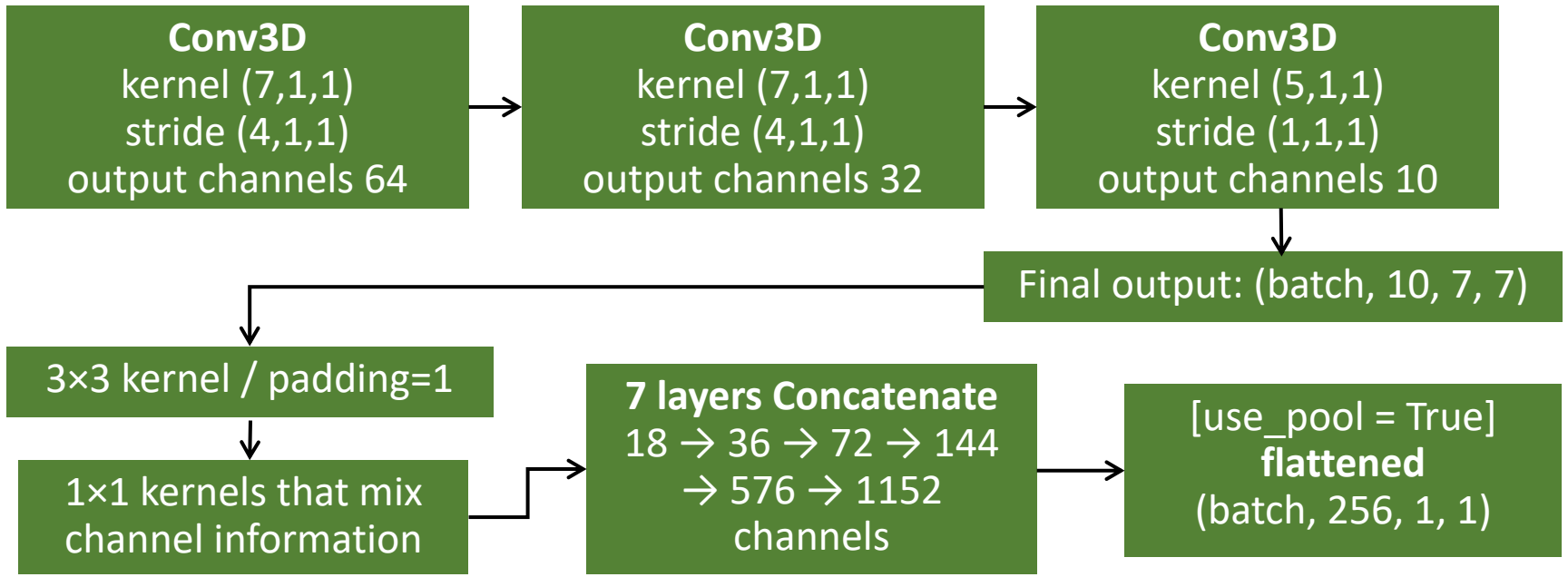

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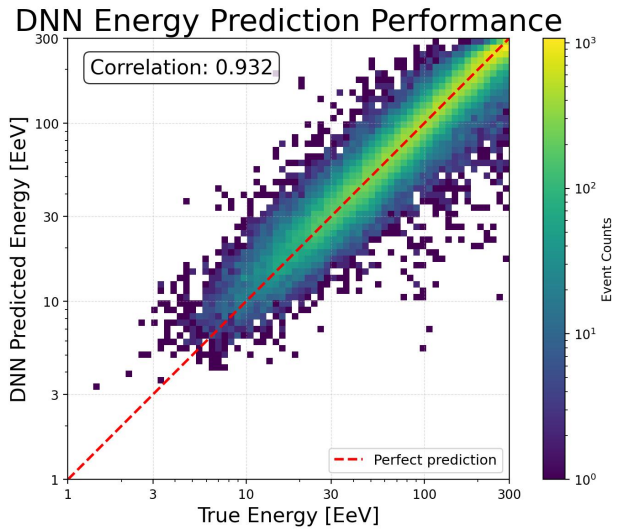
Energy Reconstruction Results

Bias and resolution
Reconstruction by zenith angle
Energy reconstruction improves upon result of the Standard Reconstruction (STD)



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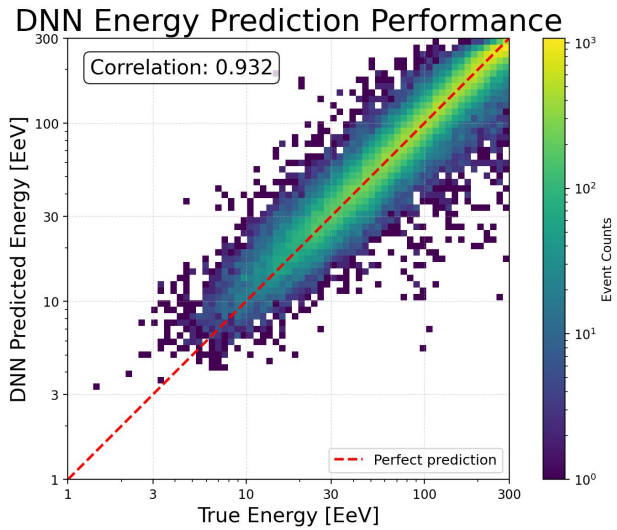

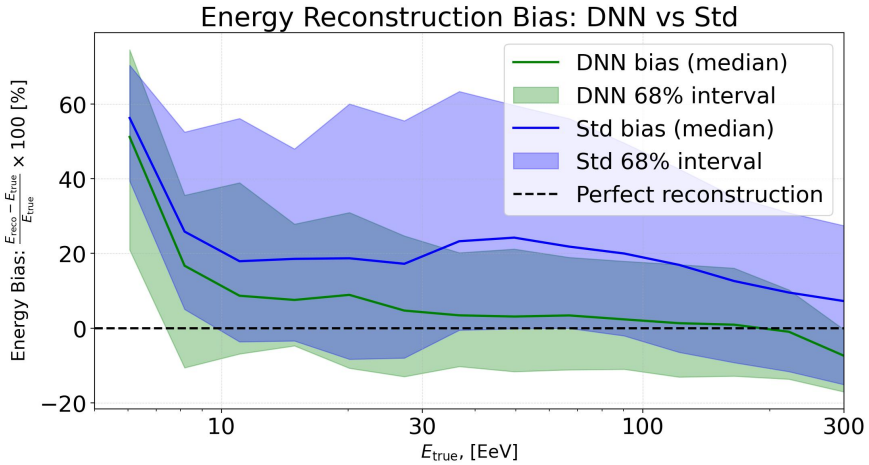

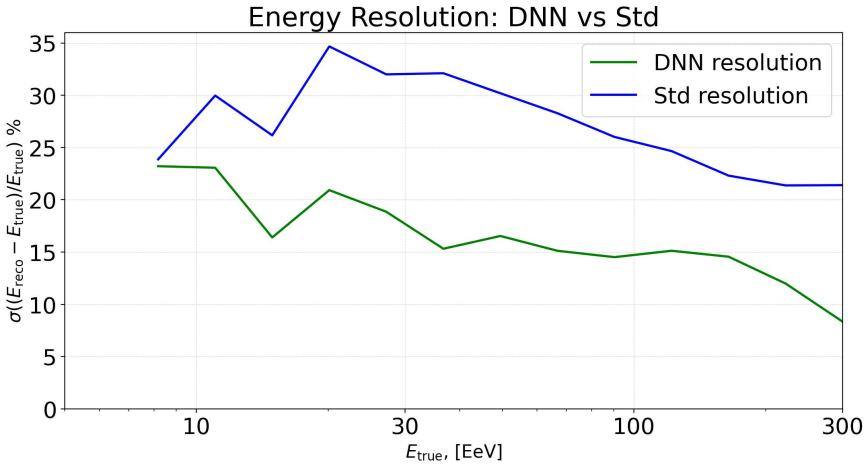

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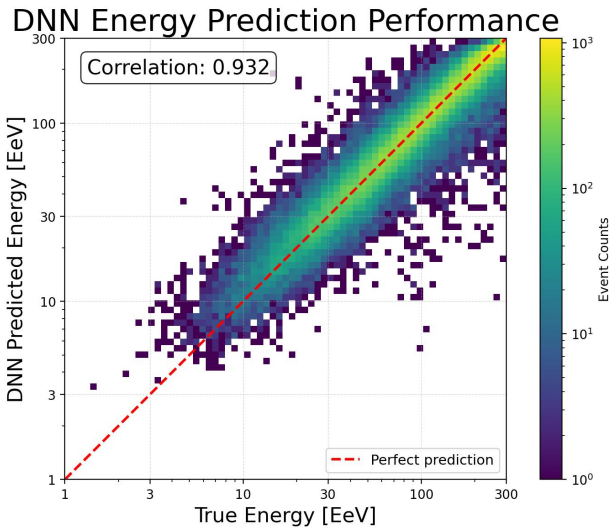
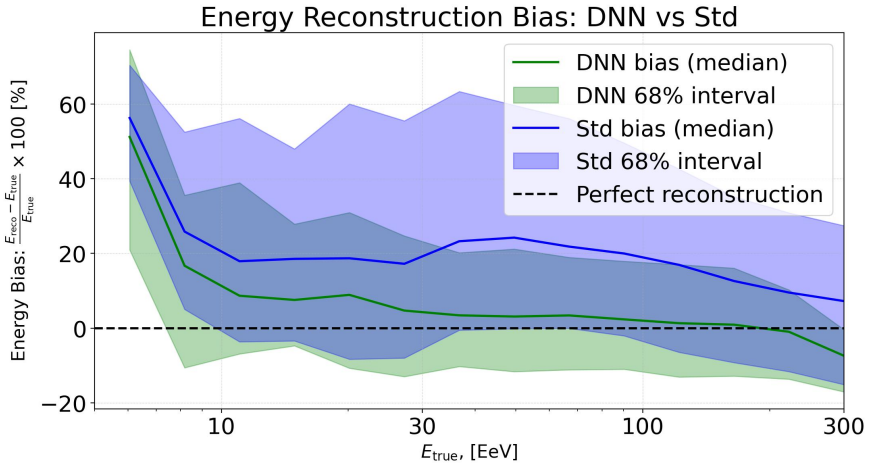
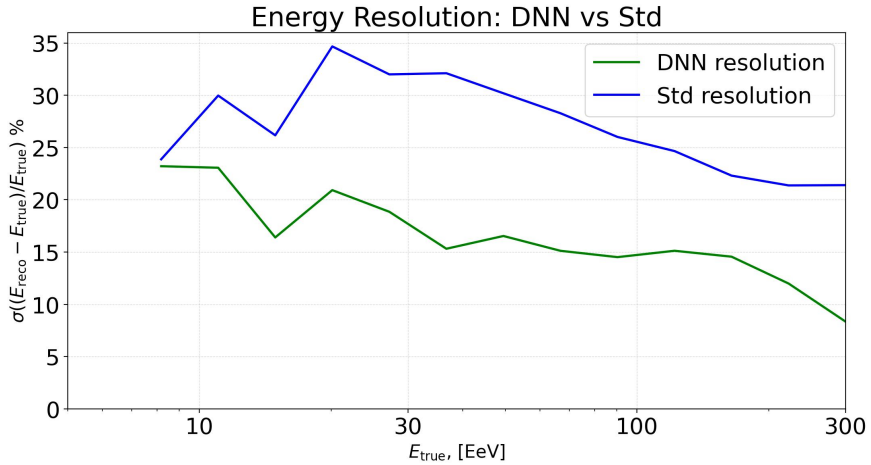
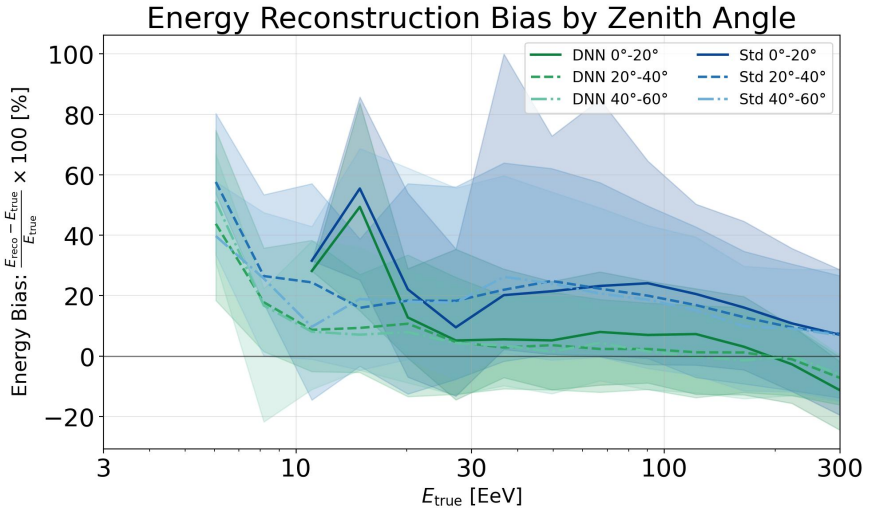
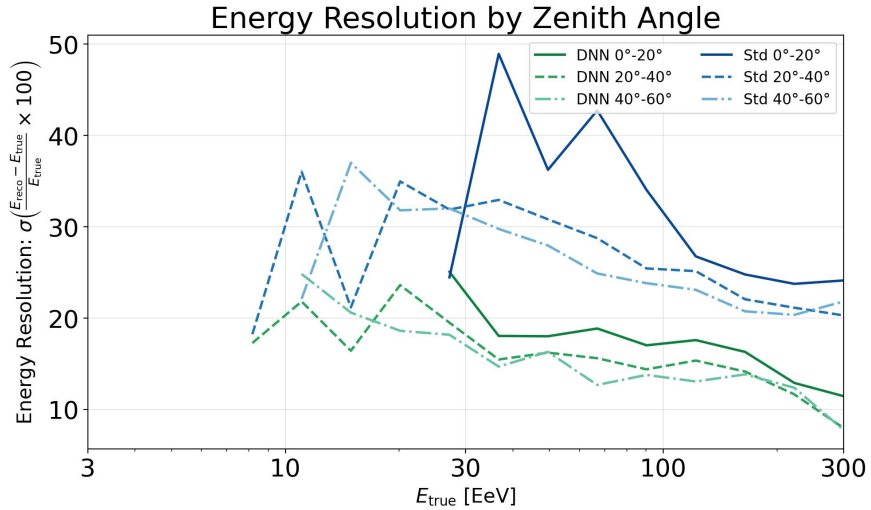






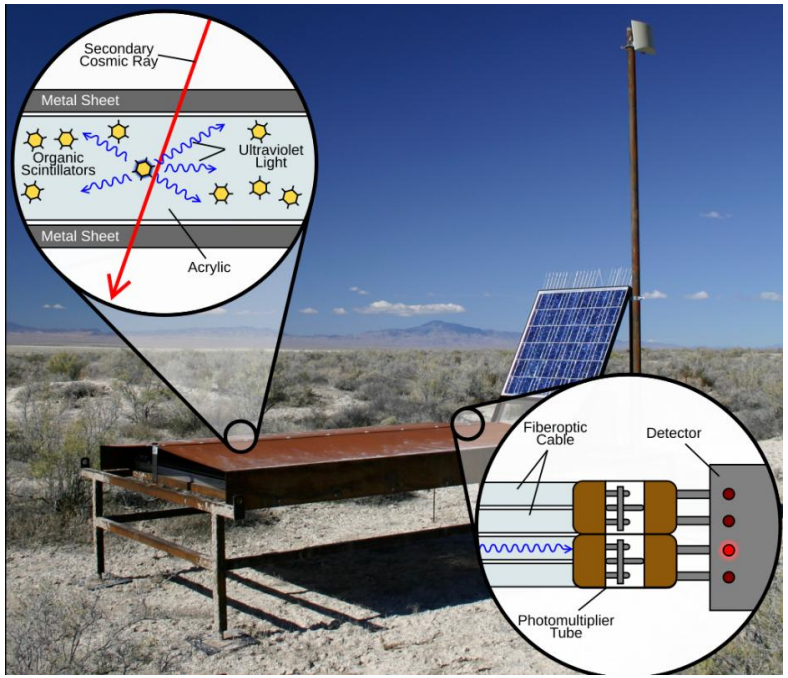




Angular Reconstruction Results

Angular Reconstruction

Angular resolution is the shower incident on surface detector (SD) azimuthal angle
CNN improves on STD at all energy levels



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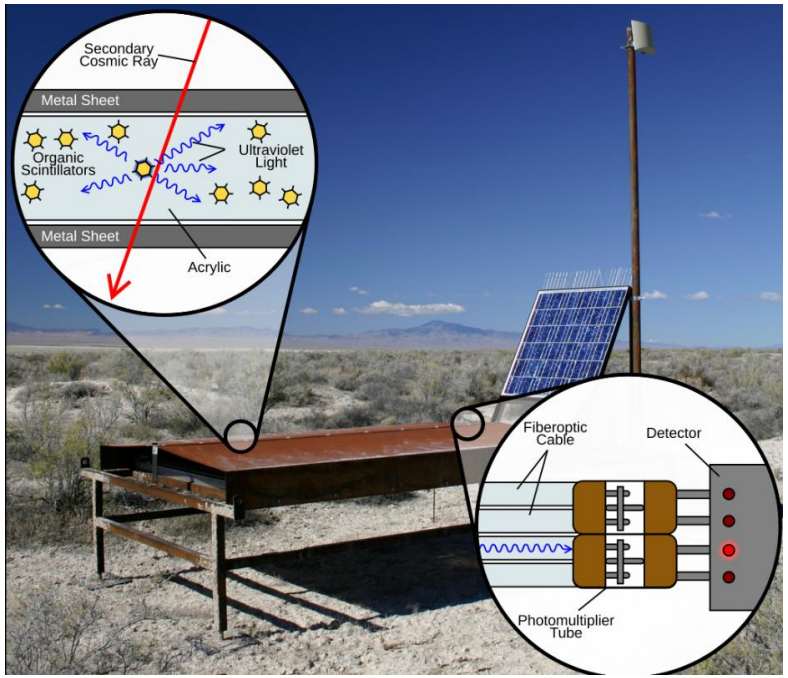

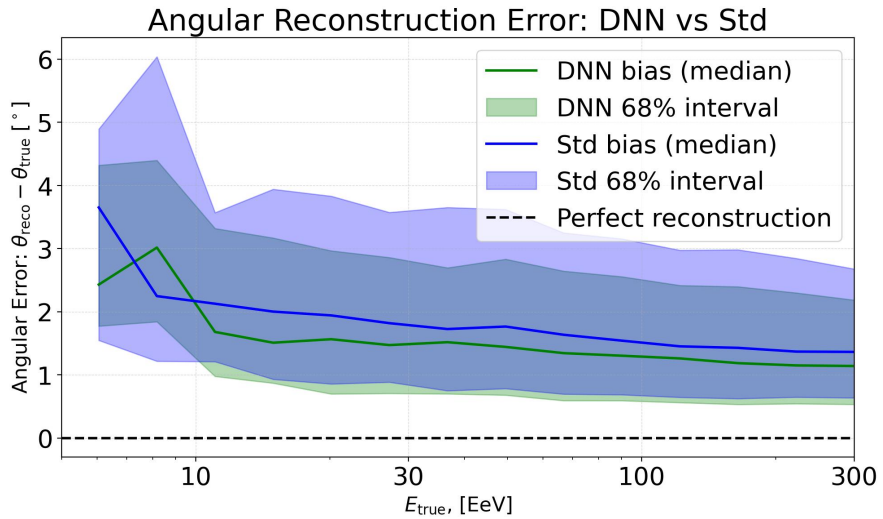

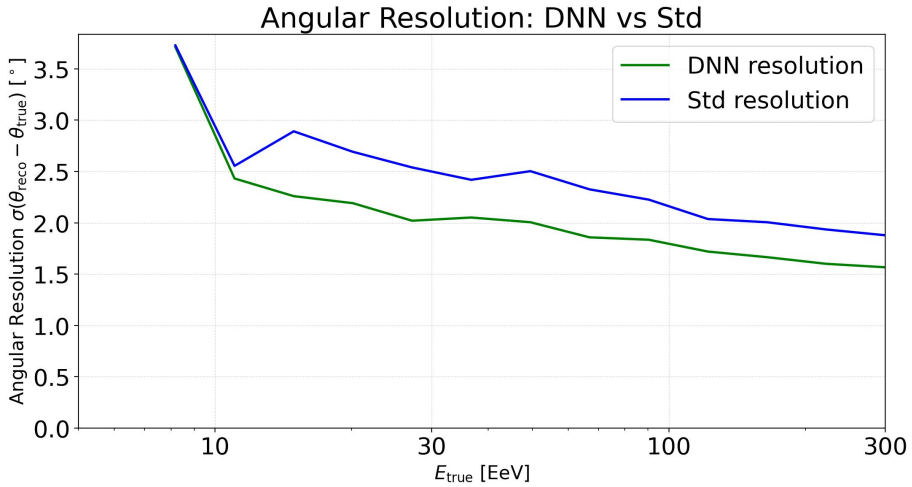

Other Reconstruction Results

Parameters

Xmax: atmospheric depth of shower event creation

Shower core position: position of detector at event center

STD does not predict Xmax

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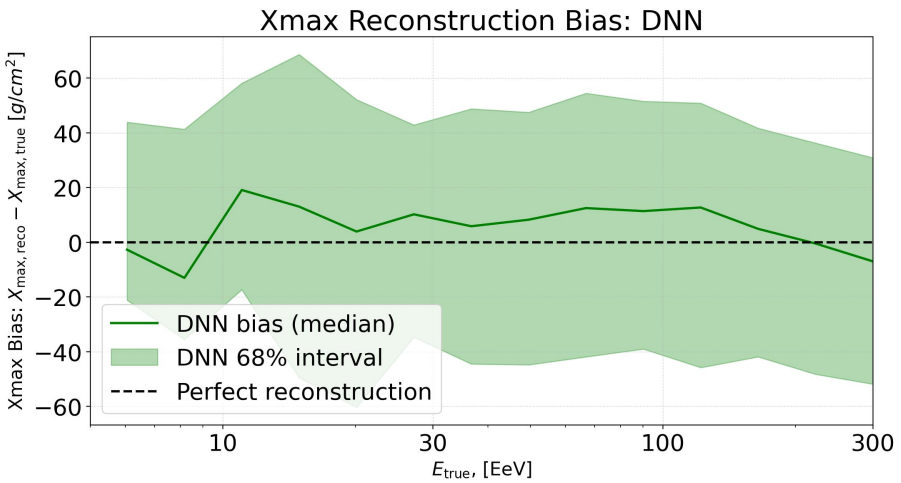
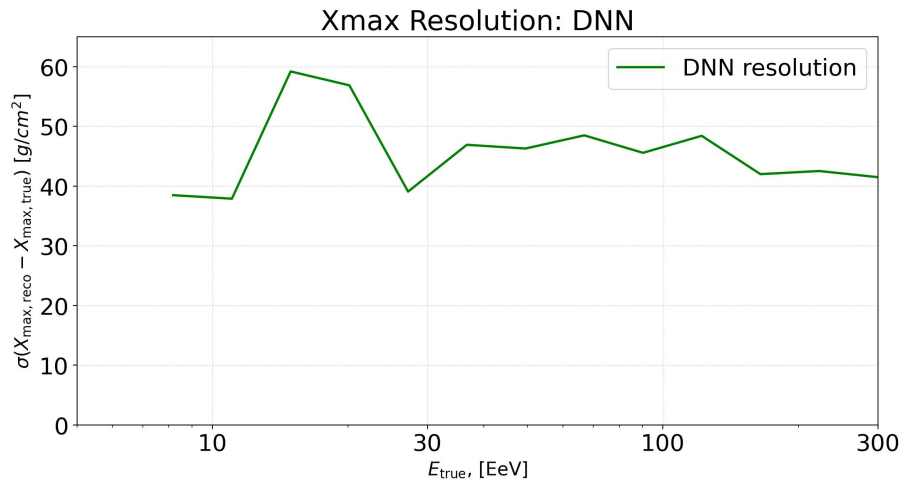
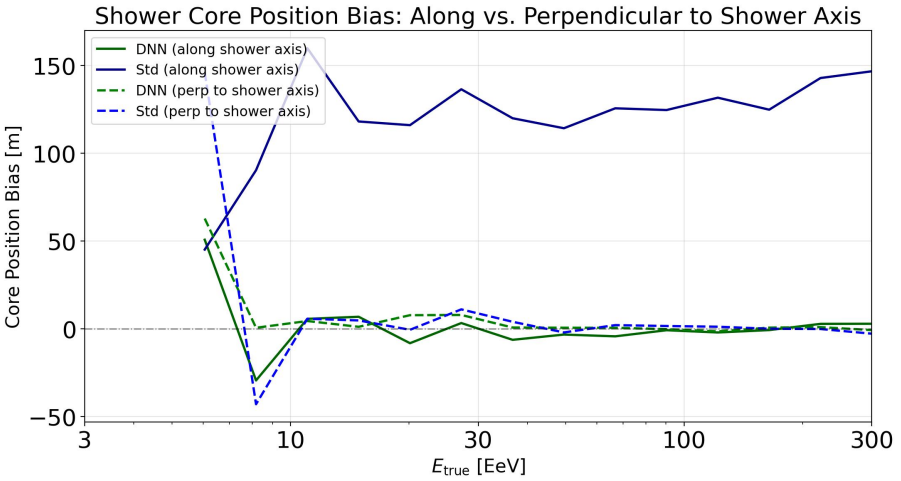
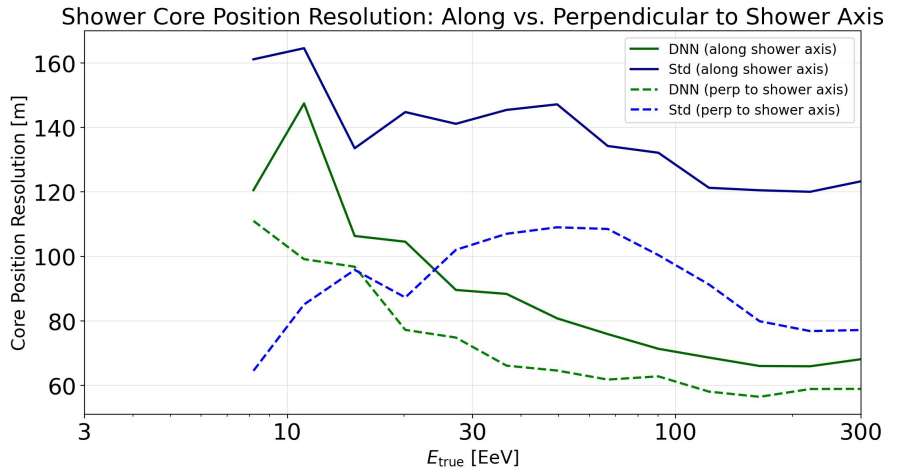


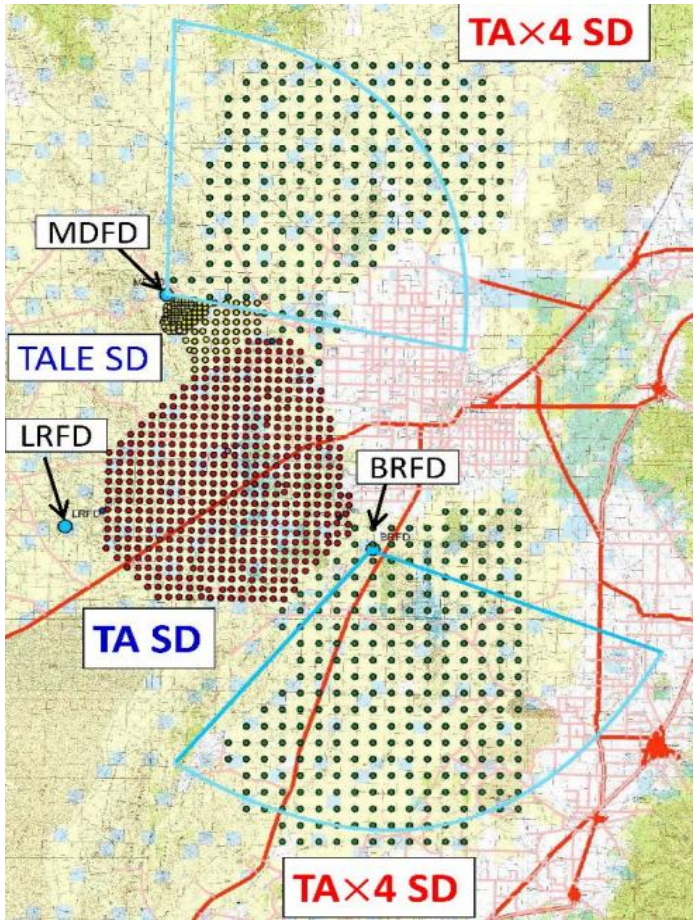






Summary

- CNN is trained on TAx4 Monte Carlo data for protons generated with a hadronic interaction model, using ASGC DiCOS resources.
- CNN improves on the bias and resolution of compared to STD.
- Prediction of CNN on real/hybrid TAx4 data would shed light on physics and possibly resolve discrepancy between TA and TAx4 data.



Acknowledgement

Thanks to Dr. Anatoli Fedynitch, Dr. Anton Prosekin, and the SATORI group

Presenter: Jonathan Huang