

# Utilizing Deep Neural Networks for the Extraction of Drell-Yan Angular Coefficients in $pp$ Collisions with a 120 GeV Beam Energy

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Representing the FermiLab SeaQuest/E906 Collaboration

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Science

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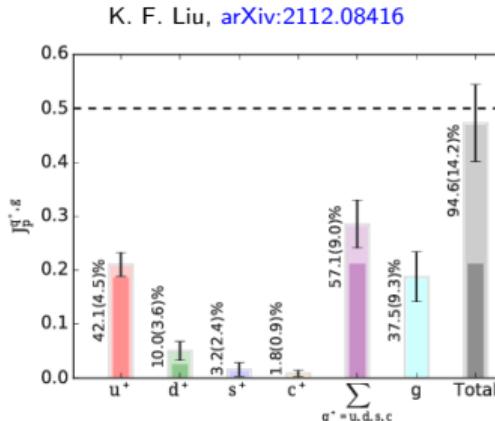
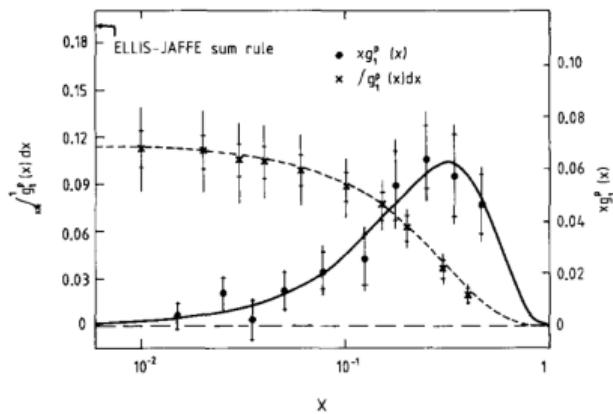
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## Summary

# Internal Structure of the Proton & Transverse Momentum

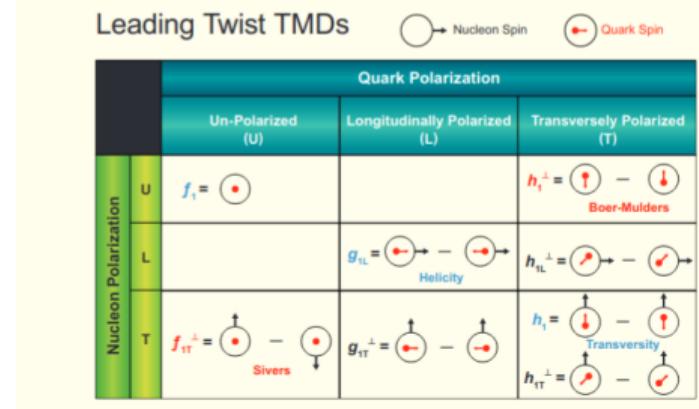
## Distributions

J. Ashman et al. , DOI:10.1016/0370-2693(88)91523-7



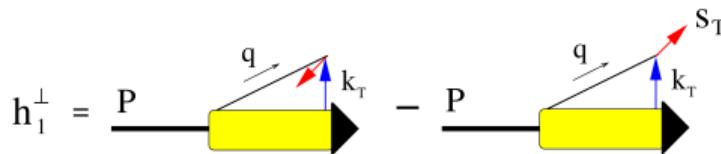
- ▶ Proton is a spin  $\frac{1}{2}$  fermion.
- ▶ Total spin of the proton → internal structure of proton.

A. Accardi et al, arXiv:1212.1701



- ▶ TMDs : distributions of the hadron's quark or gluon momenta that are perpendicular to the momentum transfer between the beam and the hadron.

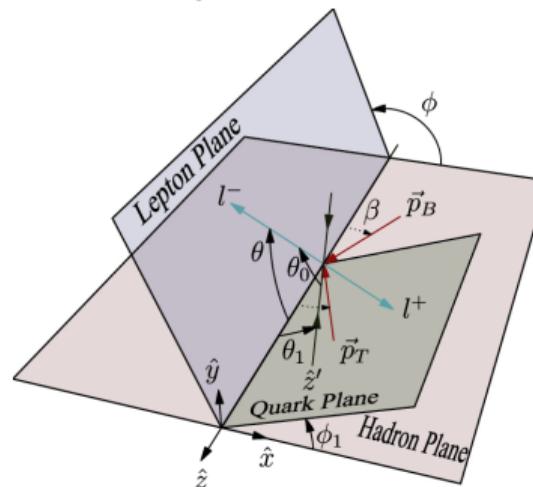
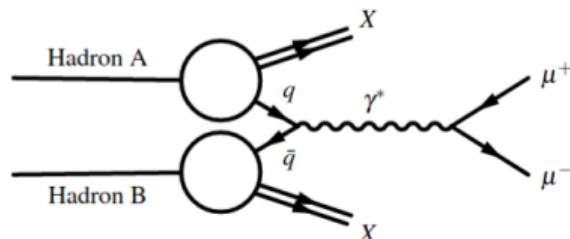
# Boer-Mulders Function & Drell-Yan Process



$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{1}{2} \nu \sin^2 \theta \cos 2\phi$$

J. C. Peng et al., [arXiv:1808.04398](https://arxiv.org/abs/1808.04398)

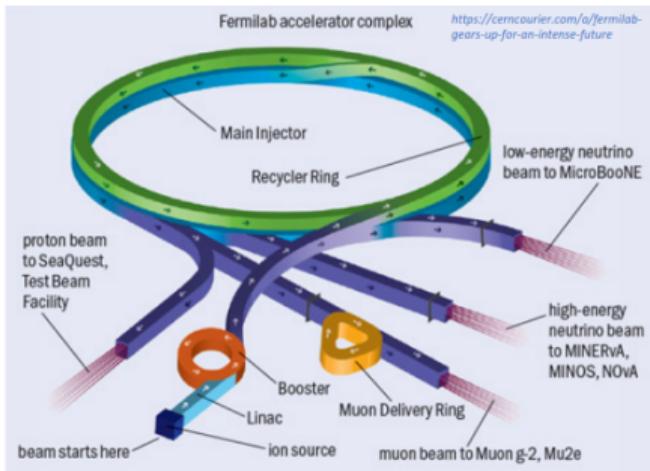
- ▶ BMF : Describes the net polarization of quarks inside an unpolarized proton.
- ▶  $h_1^\perp \rightarrow$  quark distribution that quantifies a particular spin-orbit correlation.



- ▶ Collins-Soper frame: rest frame of di-muons → using the beam proton direction to construct the azimuthal and polar angles.
- ▶ Extraction of the  $\nu$  parameter → BM function.

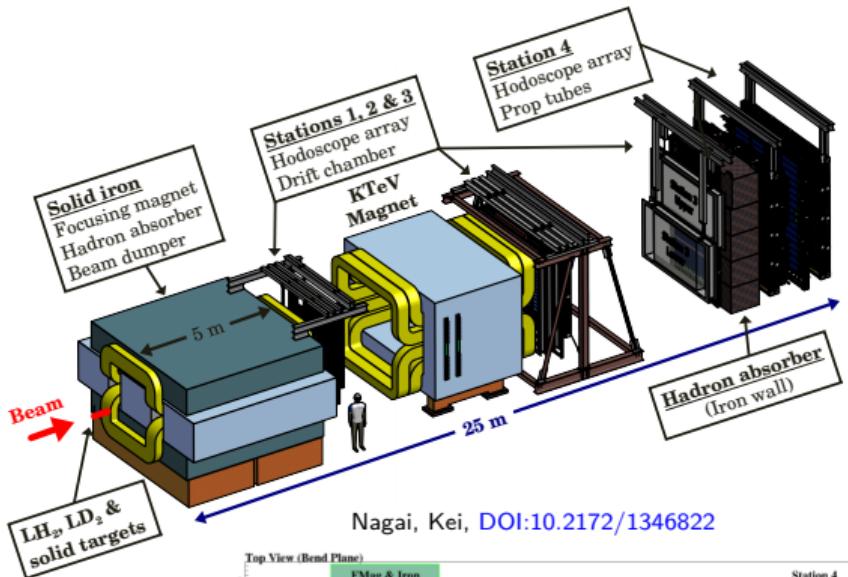
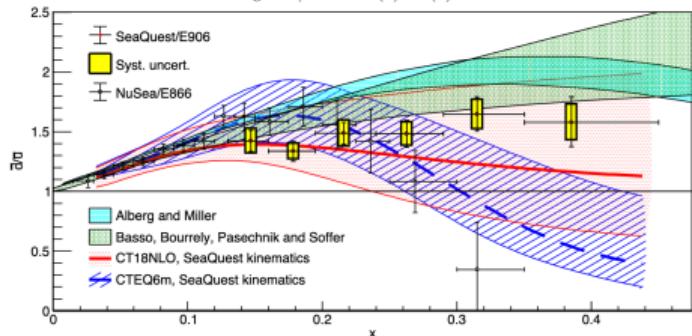
# FermiLab SeaQuest/E906 Experiment

C. A. Aidala et al., arXiv:1706.09990

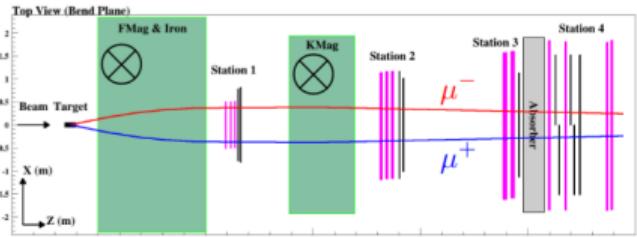


J. Dove et al., arXiv:2103.04024

Figure 2 | Ratios of  $\bar{d}(x)$  to  $\bar{u}(x)$ .

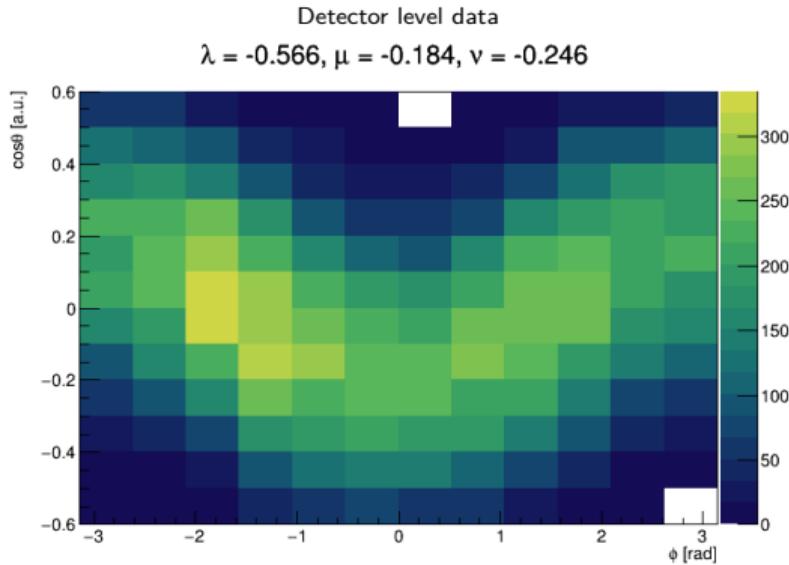
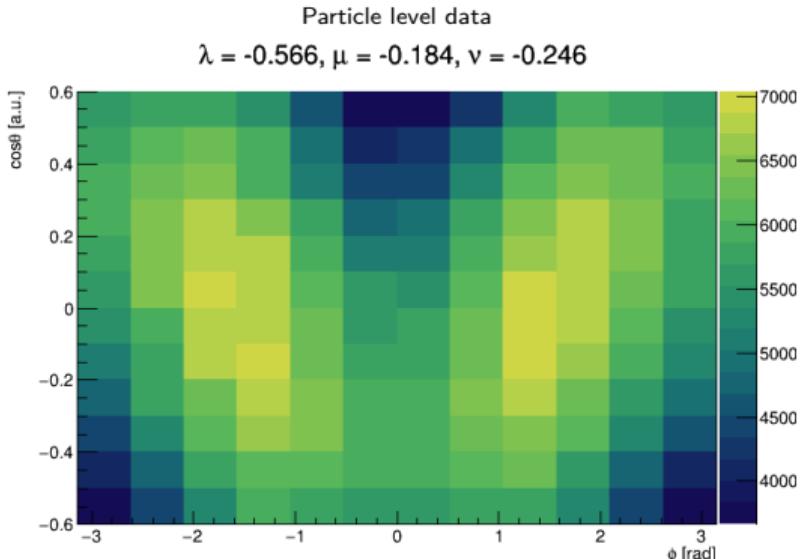


Nagai, Kei, DOI:10.2172/1346822



- ▶ Fixed target experiment at Fermilab.
- ▶ Use 120 GeV beam energy from main injector.

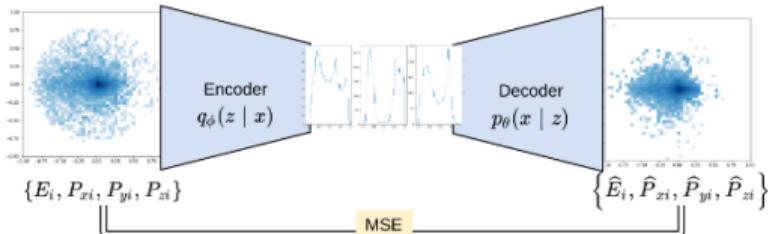
# Unfolding Detector Level Data



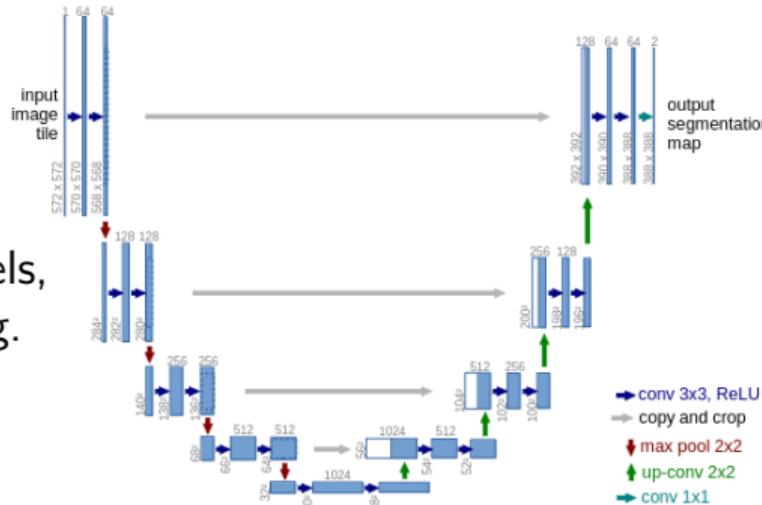
- ▶ Detector level data need to be corrected for acceptance, reconstruction inefficiencies, detector smearing, etc.
- ▶ Unfolding  $\rightarrow f: X_{\text{detector}} \rightarrow X_{\text{particle}}$
- ▶ Deep neural networks excel at approximating complex non-linear functions, making them ideal for mapping between detector level and particle level.

# Autoencoders and U-Nets

Taoli Cheng et al., arXiv:2007.01850



Olaf Ronneberger et al., arXiv:1505.04597



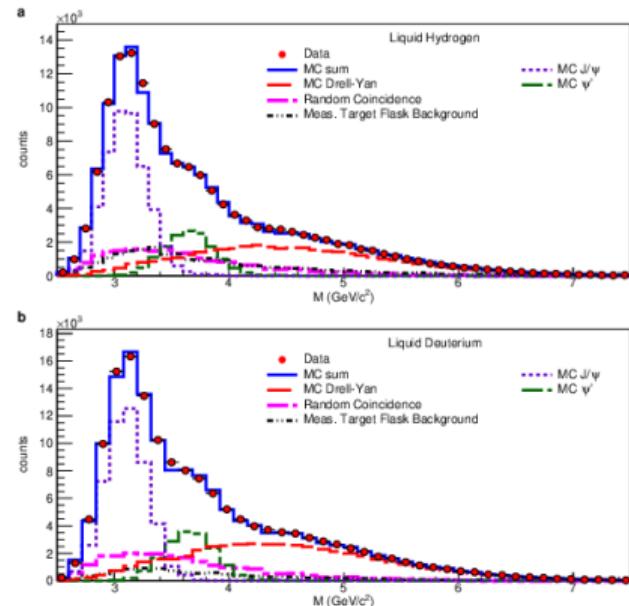
- ▶ Autoencoders(AE) are generative models, which are also used for image denoising.
- ▶ AEs encode input data to latent dimension ( $z$ ) and then decoder try to reconstruct input data.
- ▶ U-Nets are U-shaped AEs that made a major breakthrough in image segmentation.
- ▶ We use U-Nets to reconstruct particle-level data using detector-level data as inputs.

# Data Creation

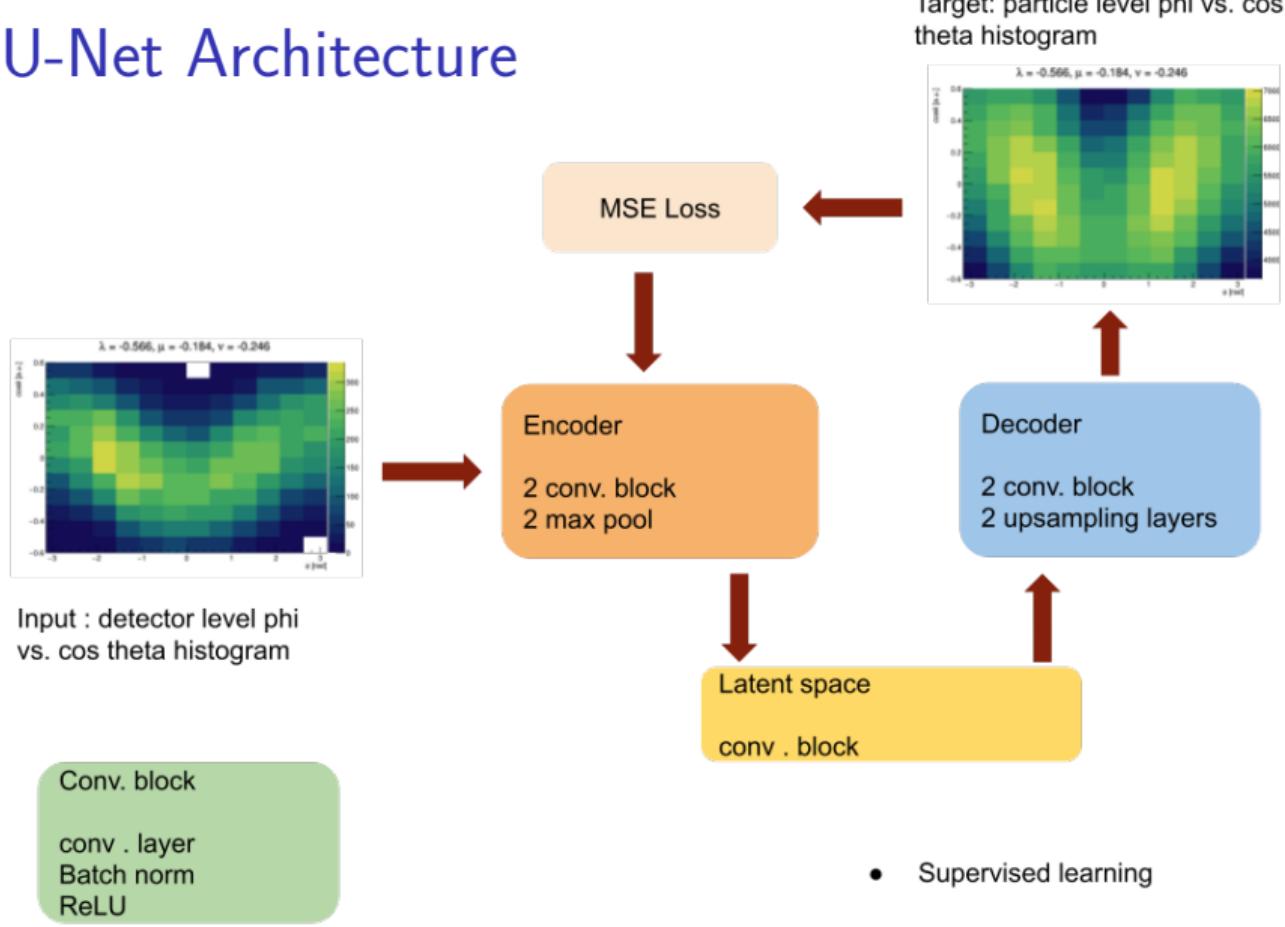
- ▶ Monte-Carlo data was generated using “PYTHIA” generator and events were passed through E906 detector simulation using “GEANT4”.
- ▶ Each histogram has specific  $\lambda$ ,  $\mu$ , and  $\nu$  values, which were sampled uniformly from the ranges  $[-1, 1]$ ,  $[-0.5, 0.5]$ , and  $[-0.5, 0.5]$  respectively.
- ▶ DY angular coefficients were injected to a histograms by weighting the events using;

$$w = \frac{1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{1}{2} \nu \sin^2 \theta \cos 2\phi}{1 + \cos^2 \theta}$$

J. Dove et al., arXiv:2103.04024

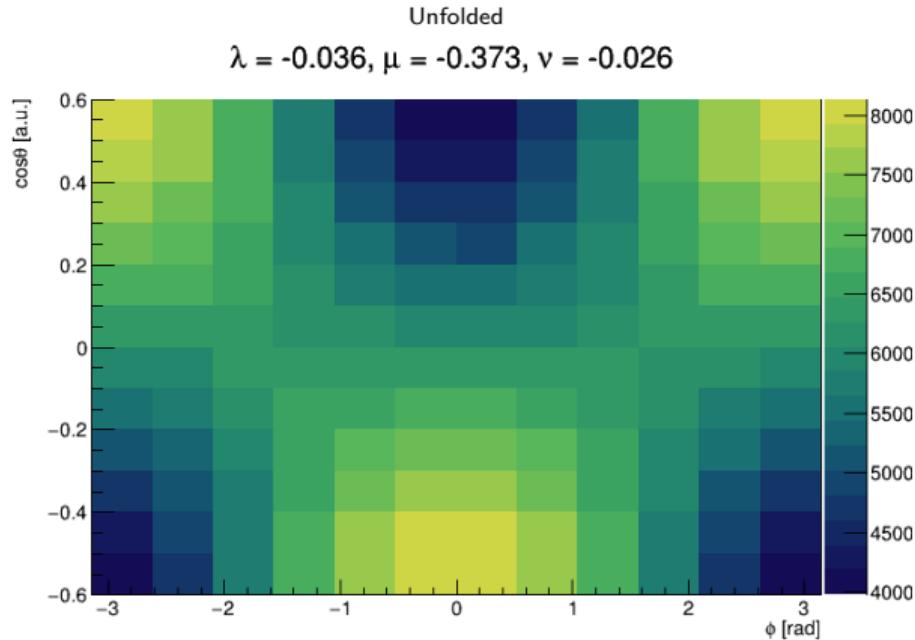
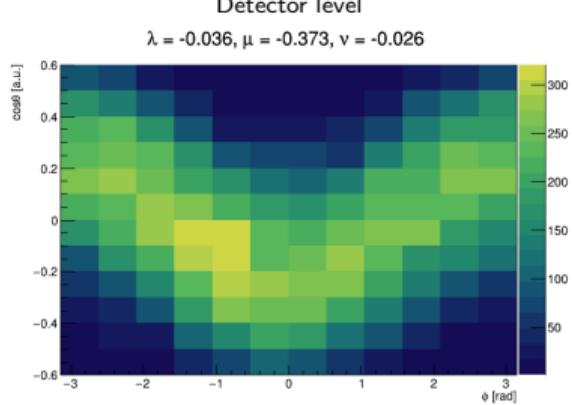
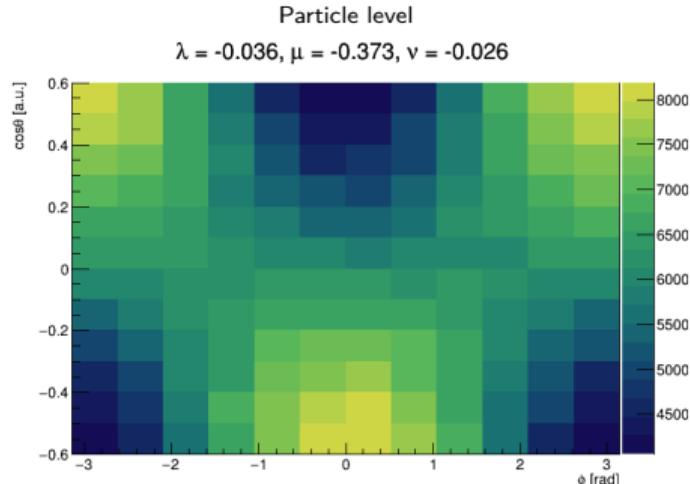


# U-Net Architecture



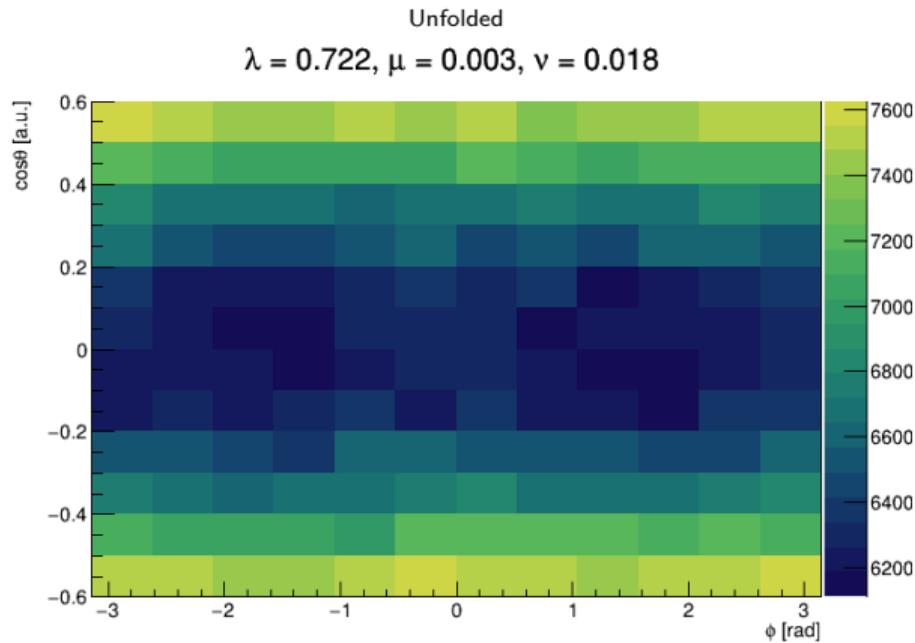
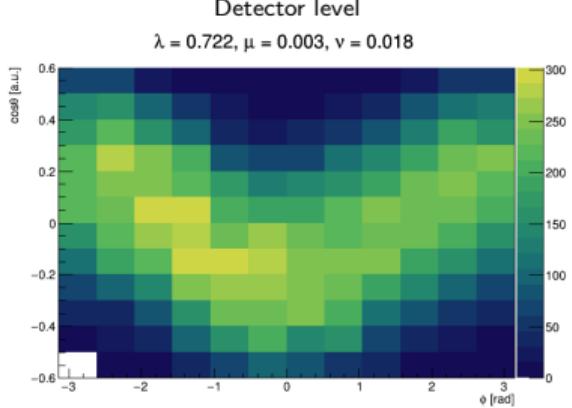
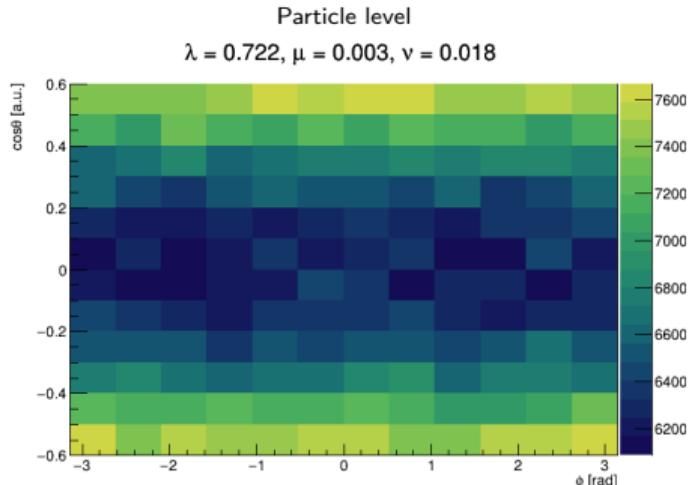
Model was trained in Fermilab Elastic Analysis Facility ([EAF](#)) using Nvidia A100 GPU.

# Few Unfolded Histograms

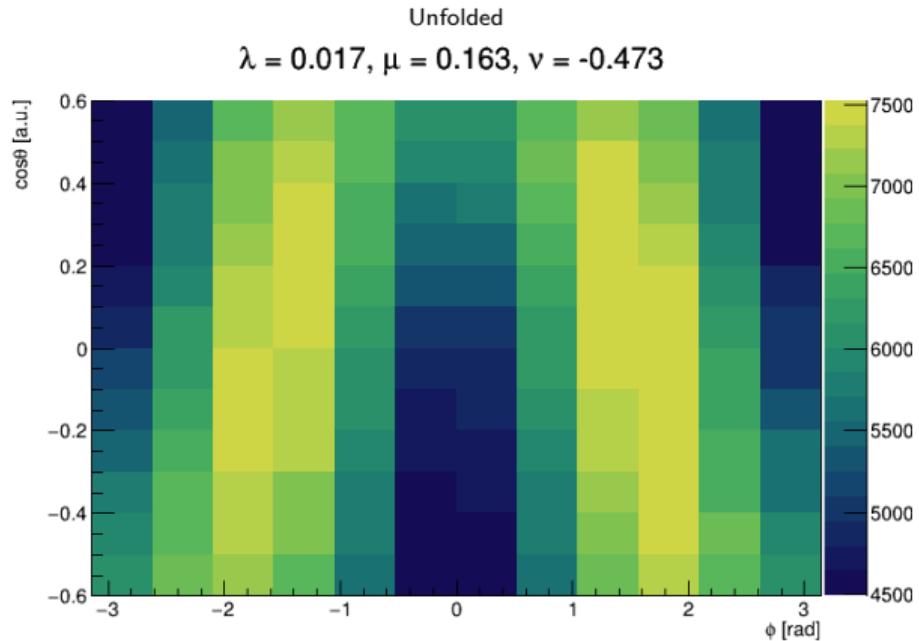
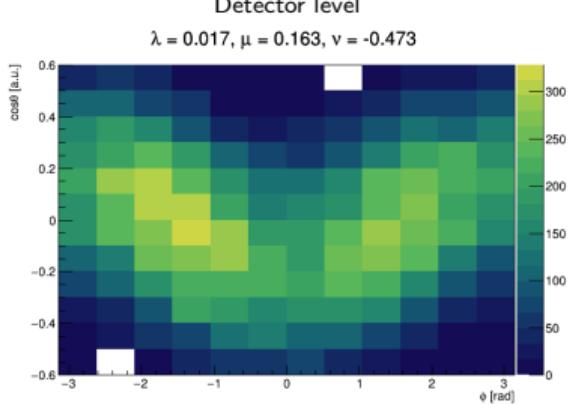
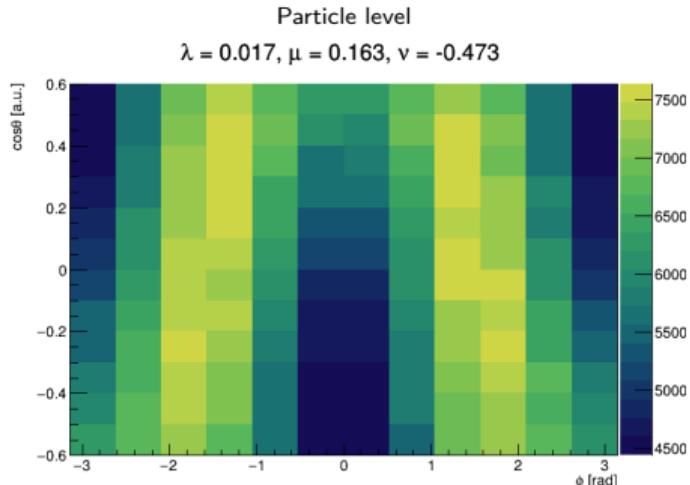


Note that particle level - generated truth info., detector level - reconstruct info., unfolded - U-Net output

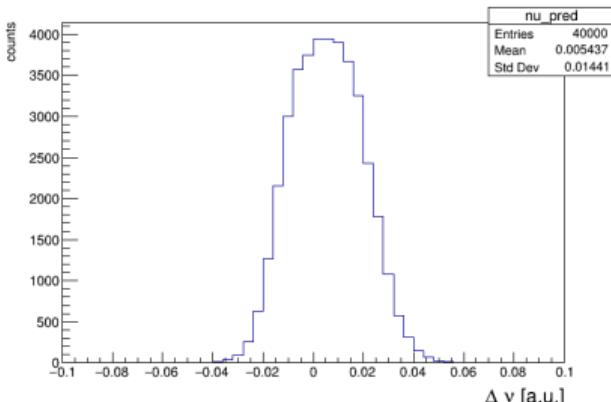
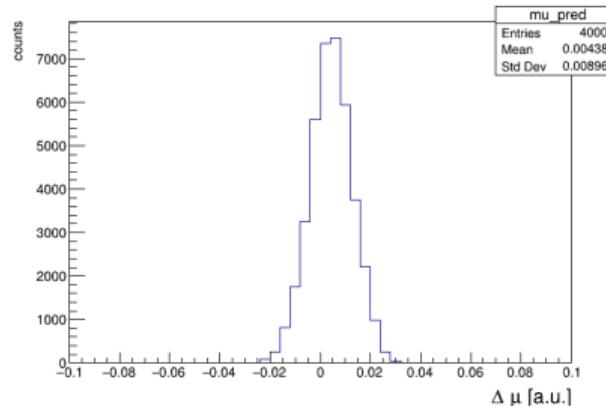
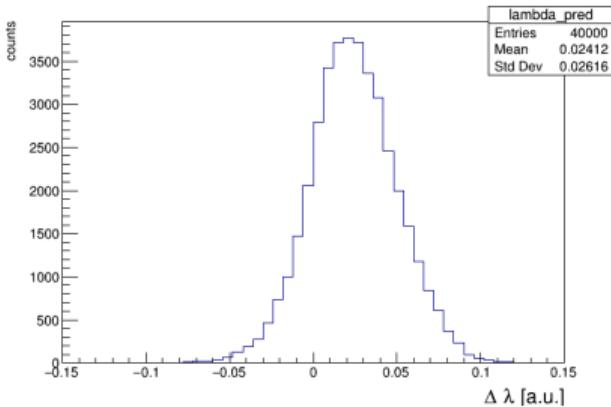
# Few Unfolded Histograms



# Few Unfolded Histograms



# Resolution of the Unfolded Fit Results



- Unfolded  $\phi$ -cos  $\theta$  histograms are fitted using;

$$f(\phi, \cos \theta) = A(1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{1}{2} \nu \sin^2 \theta \cos 2\phi) \quad (1)$$

- X axis;  $\Delta = \text{Injected} - \text{Unfolded}$

## Comparison of Few Unfolded Fit Results

	Particle level	Unfolded
$\lambda$	$-0.584 \pm 0.008$	$-0.579 \pm 0.007$
$\mu$	$-0.178 \pm 0.002$	$-0.177 \pm 0.002$
$\nu$	$-0.238 \pm 0.003$	$-0.241 \pm 0.003$
$\lambda$	$-0.037 \pm 0.009$	$-0.035 \pm 0.009$
$\mu$	$-0.367 \pm 0.002$	$-0.370 \pm 0.002$
$\nu$	$-0.021 \pm 0.003$	$-0.033 \pm 0.003$
$\lambda$	$0.701 \pm 0.011$	$0.689 \pm 0.011$
$\mu$	$0.006 \pm 0.002$	$-0.004 \pm 0.002$
$\nu$	$0.016 \pm 0.003$	$0.019 \pm 0.003$

- ▶ Note that these  $\lambda$ ,  $\mu$ , and  $\nu$  values does not represent any physics information.
- ▶ To extract the  $\lambda$ ,  $\mu$ , and  $\nu$  values, a fit was performed using equation 1 for both particle and detector levels.

## Summary

- ▶ The spin of the proton is an intrinsic property that can be used to understand the internal structure of the proton.
- ▶ A non-zero  $\cos 2\phi$  asymmetry in the Drell-Yan process will provide information about the transverse motion of the quarks inside the proton.
- ▶ U-Nets can be utilized as a method to unfold detector-level data to particle-level data. This approach is applicable in high-dimensional feature spaces.
- ▶ We plan to use this method to extract the Drell-Yan angular coefficients from the FermiLab E906/SeaQuest data with higher precision.
- ▶ We plan to correct any discrepancies between experimental data and Monte Carlo (MC) simulations by reweighting.
- ▶ We plan to use the “Bootstrapping” method to enhance the precision of the prediction.
- ▶ Acknowledgment: This work was funded by the DOE Office of Science, Medium-Energy Nuclear Physics Program.