

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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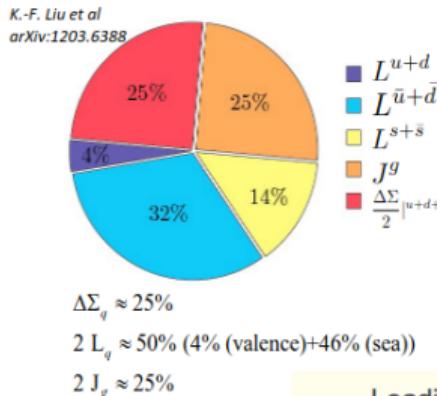
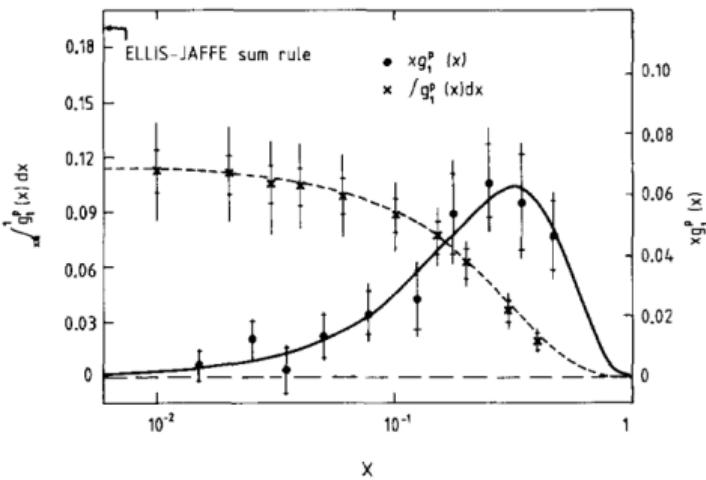
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Summary

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

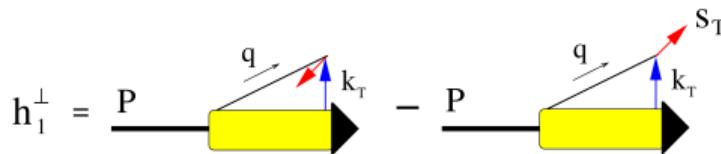
Leading Twist TMDs

Legend:
○ Nucleon Spin
● Quark Spin

Quark Polarization			
	Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	$f_1 = \bullet$		$h_i^\perp = \begin{array}{c} \uparrow \\ \bullet \end{array} - \begin{array}{c} \downarrow \\ \bullet \end{array}$ Boer-Mulders
		$g_{iL} = \bullet \rightarrow - \bullet$ Helicity	$h_{iL}^\perp = \begin{array}{c} \uparrow \\ \bullet \end{array} \rightarrow - \begin{array}{c} \downarrow \\ \bullet \end{array} \rightarrow$
	$f_{1T}^\perp = \begin{array}{c} \uparrow \\ \bullet \end{array} - \begin{array}{c} \downarrow \\ \bullet \end{array}$ Sivers	$g_{iT}^\perp = \begin{array}{c} \uparrow \\ \bullet \end{array} - \begin{array}{c} \downarrow \\ \bullet \end{array}$	$h_{iT}^\perp = \begin{array}{c} \uparrow \\ \bullet \end{array} - \begin{array}{c} \downarrow \\ \bullet \end{array}$ Transversity

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

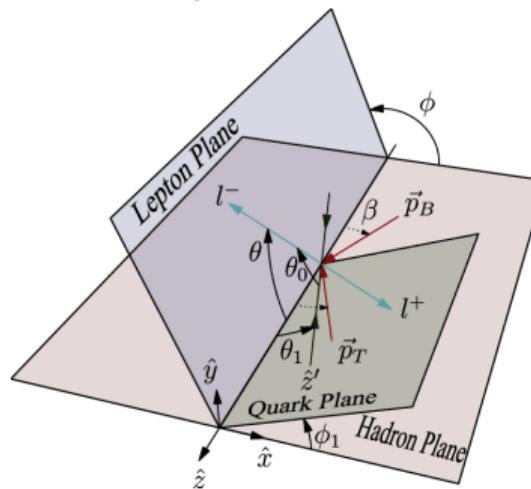
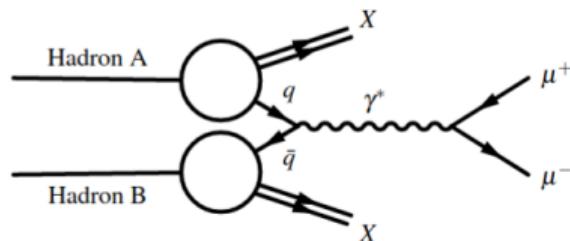
Boer-Mulders Function & Drell-Yan Process



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

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

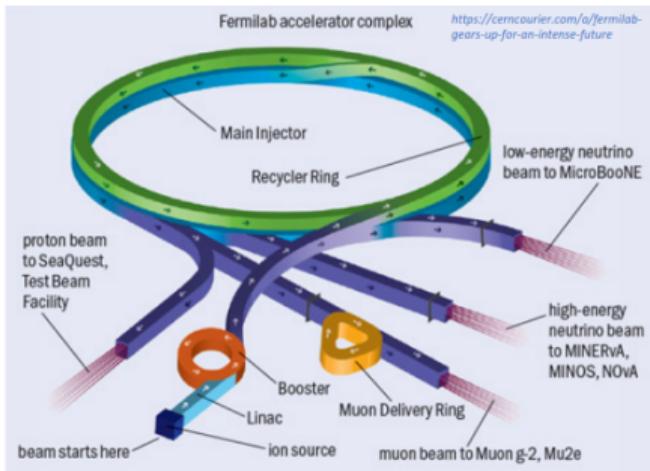
- ▶ BMF : Describes the net polarization of quarks inside an unpolarized proton.
- ▶ $h_1^\perp \rightarrow$ quark distribution that quantifies a particular spin-orbit correlation.



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

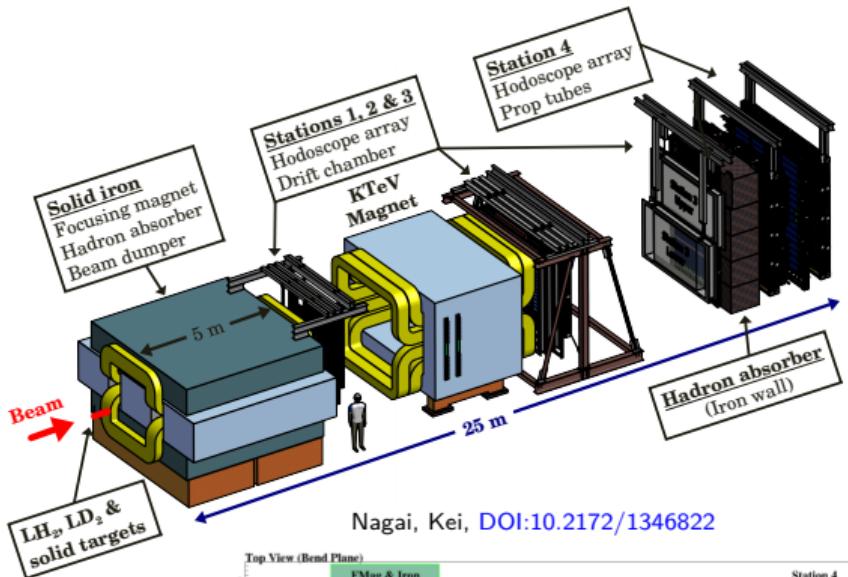
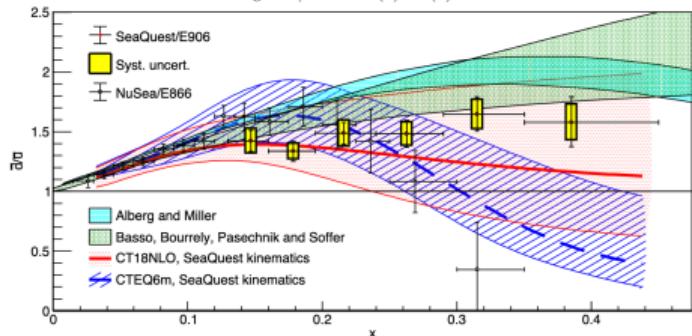
FermiLab SeaQuest/E906 Experiment

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

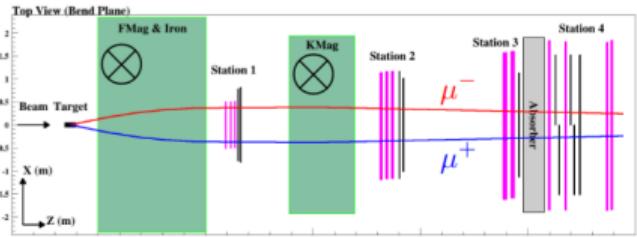


J. Dove et al., arXiv:2103.04024

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

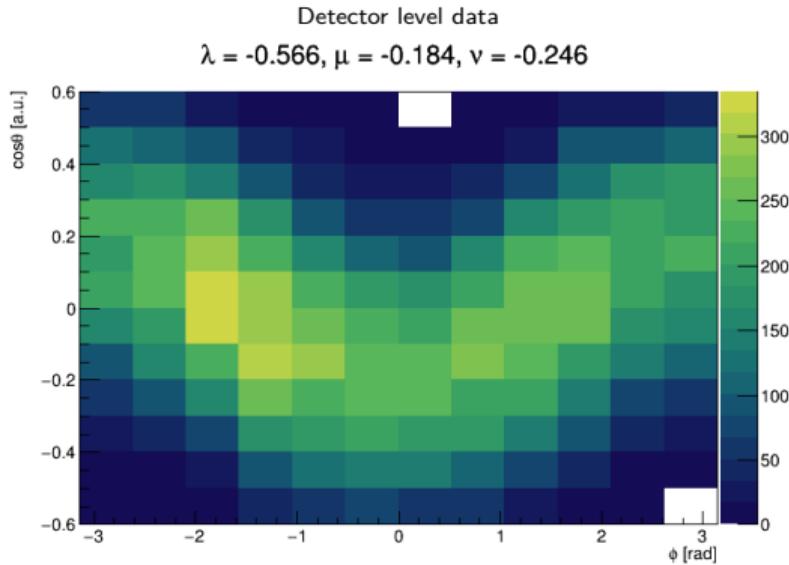
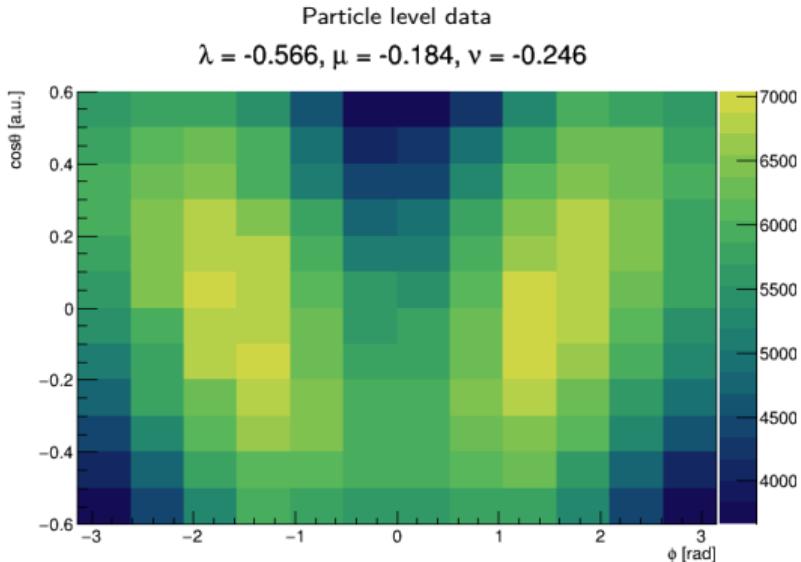


Nagai, Kei, DOI:10.2172/1346822



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

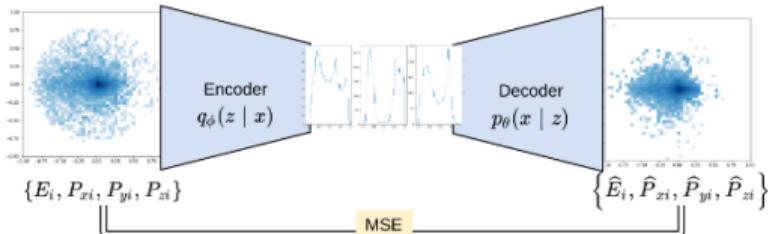
Unfolding Detector Level Data



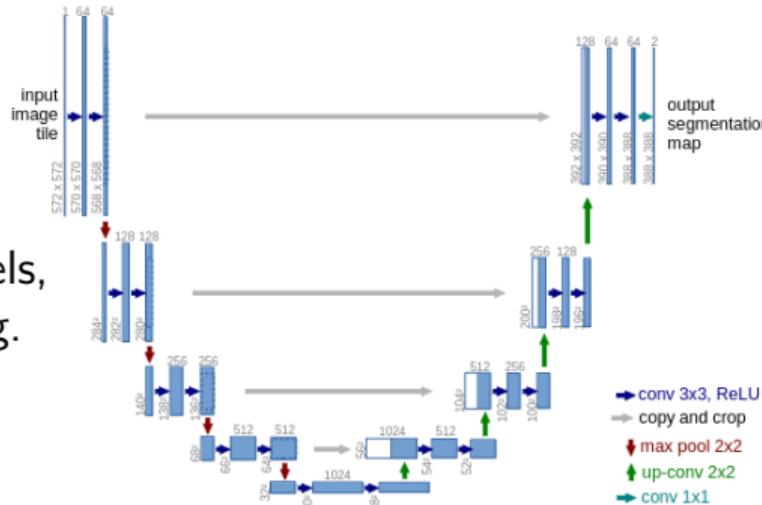
- ▶ Detector level data need to be corrected for acceptance, reconstruction inefficiencies, detector smearing, etc.
- ▶ Unfolding $\rightarrow f: X_{\text{detector}} \rightarrow X_{\text{particle}}$
- ▶ Deep neural networks excel at approximating complex non-linear functions, making them ideal for mapping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

Autoencoders and U-Nets

Taoli Cheng et al., arXiv:2007.01850



Olaf Ronneberger et al., arXiv:1505.04597



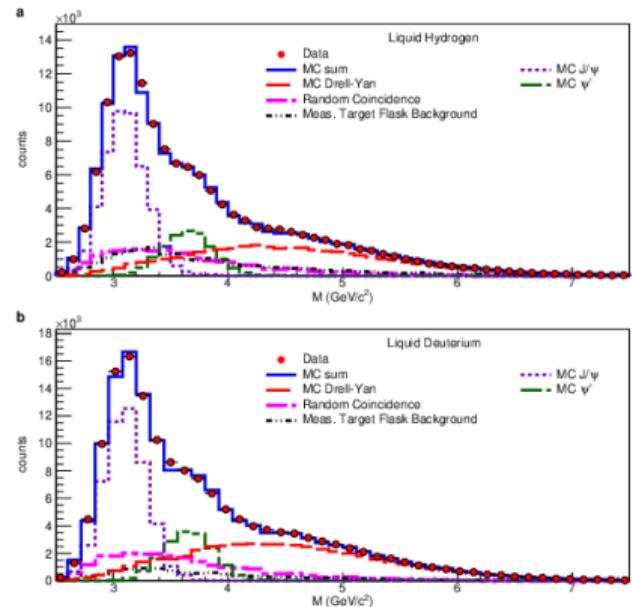
- ▶ Autoencoders(AE) are generative models, which are also used for image denoising.
- ▶ AEs encode input data to latent dimension (z) and then decoder try to reconstruct input data.
- ▶ U-Nets are U-shaped AEs that made a major breakthrough in image segmentation.
- ▶ We use U-Nets to reconstruct particle-level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

Data Creation

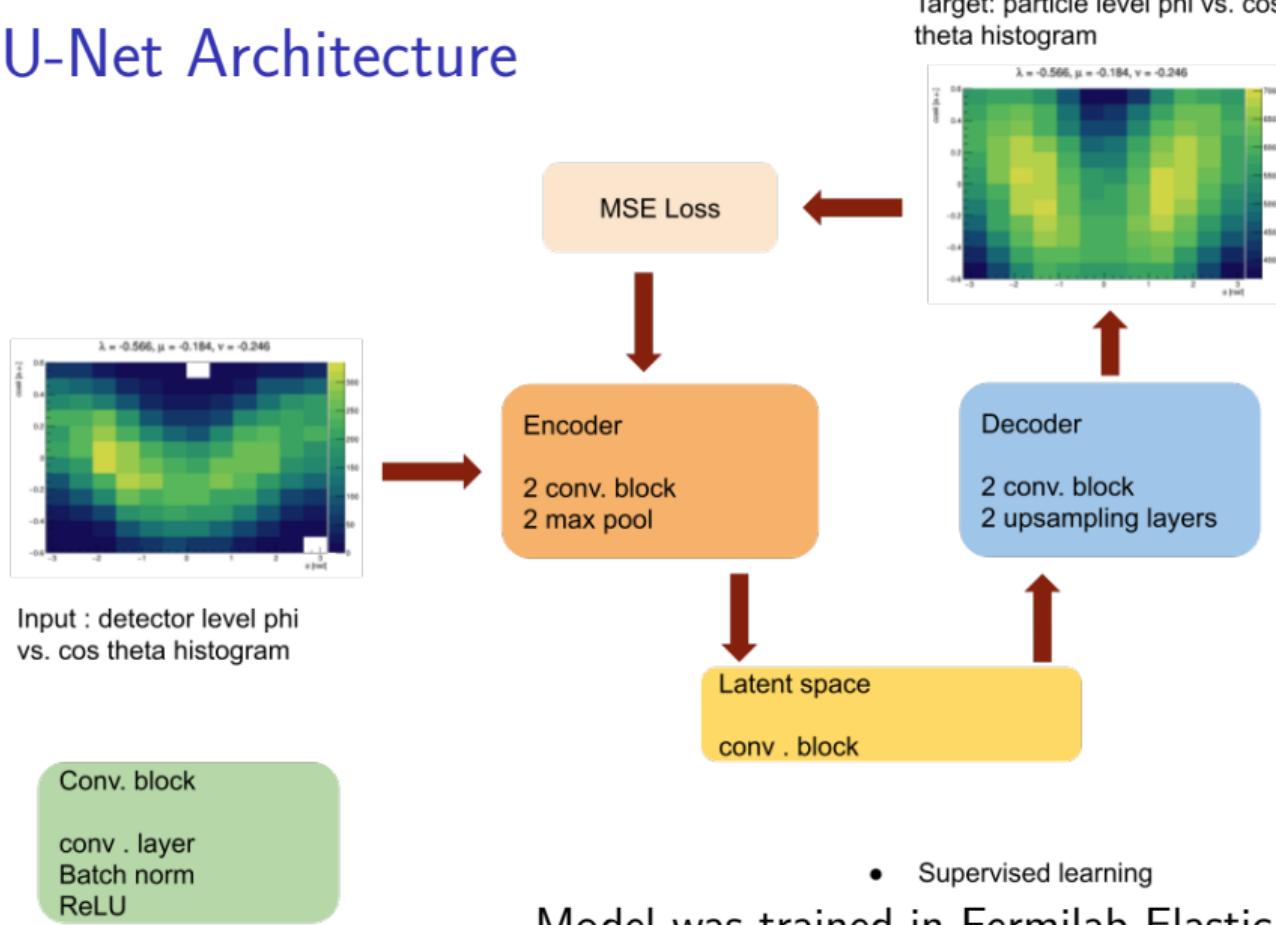
- ▶ Monte-Carlo data was generated using “PYTHIA” generator and events were passed through E906 detector simulation using “GEANT4”.
- ▶ λ , μ and ν values were sampled uniformly in the ranges $[-1, 1]$, $[-0.5, 0.5]$ and $[-0.5, 0.5]$ respectively.
- ▶ DY angular coefficients were injected to the histograms 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



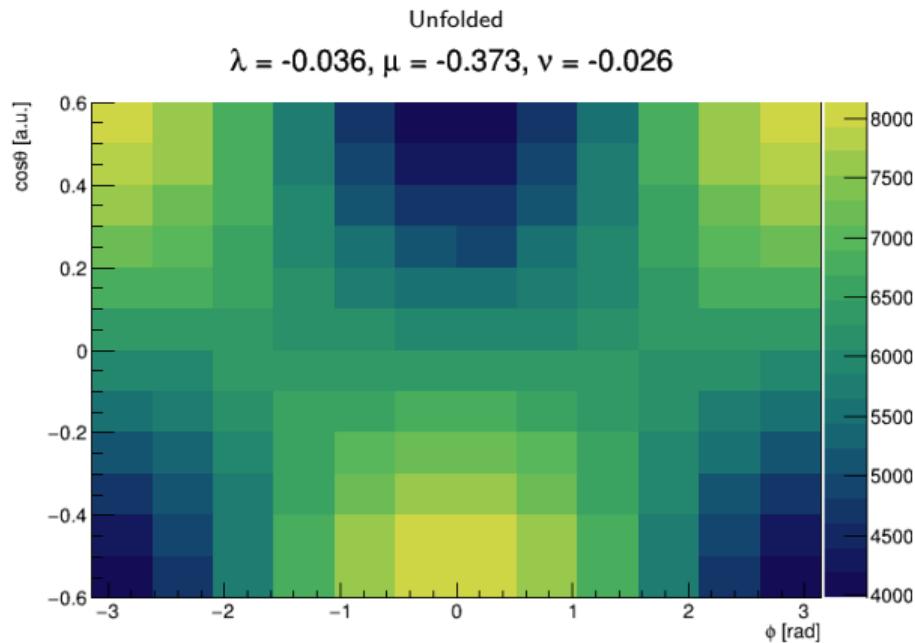
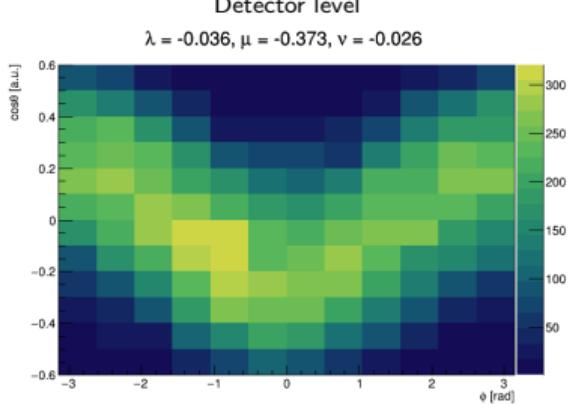
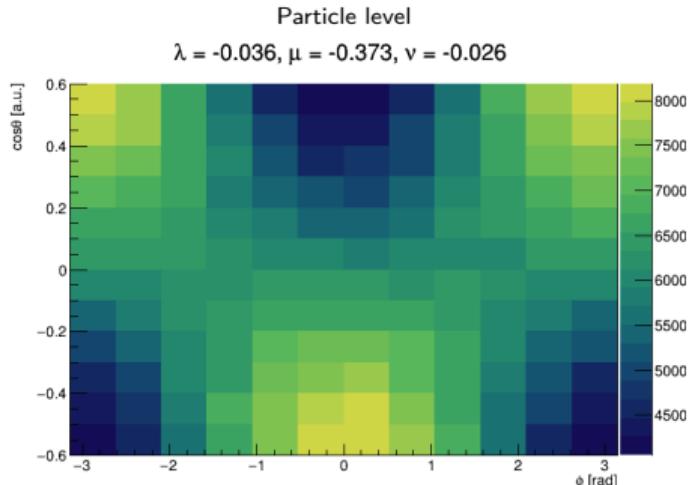
U-Net Architecture



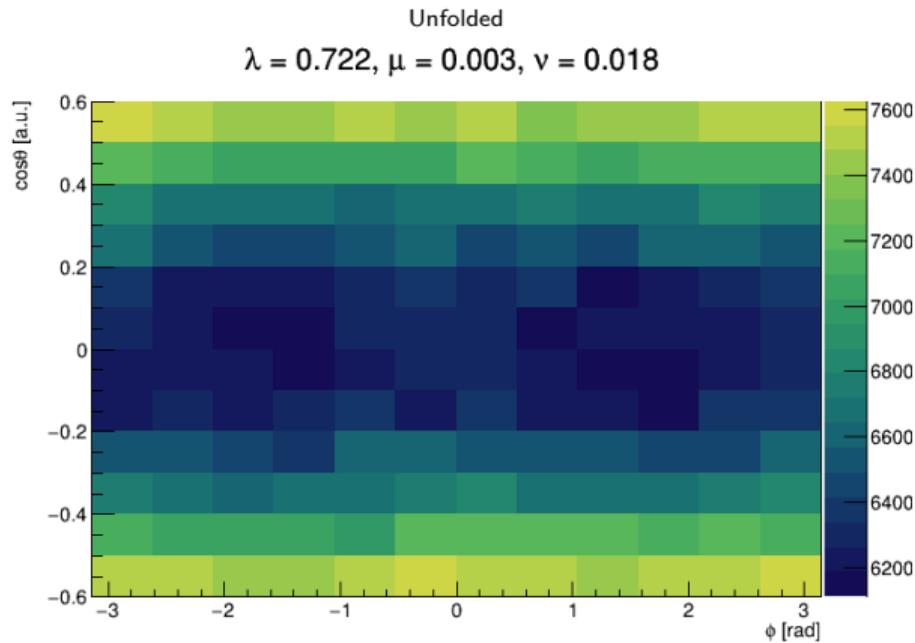
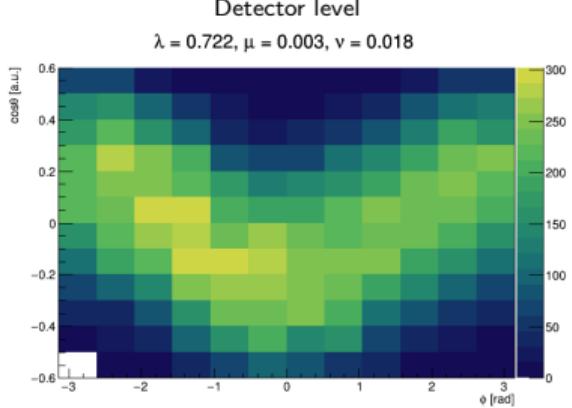
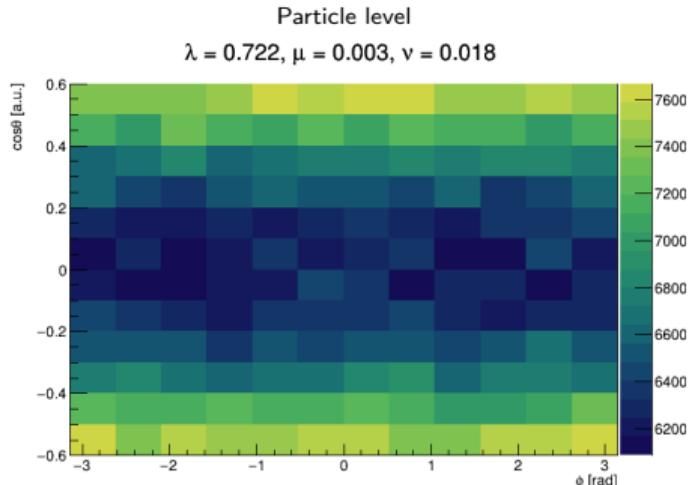
- Supervised learning

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

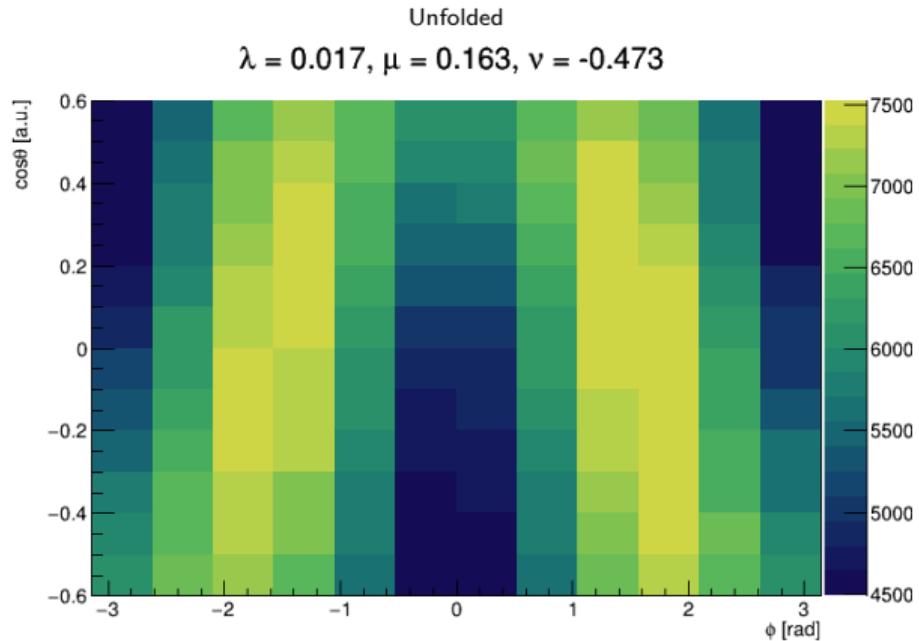
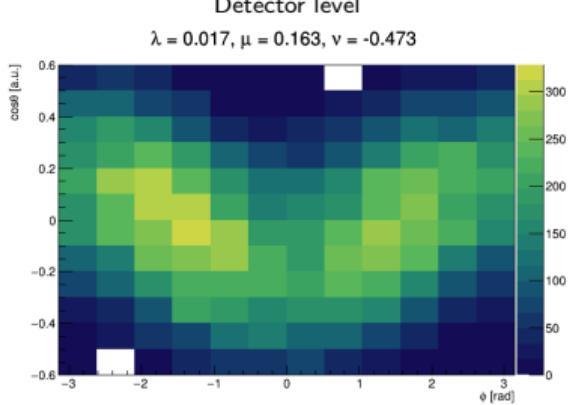
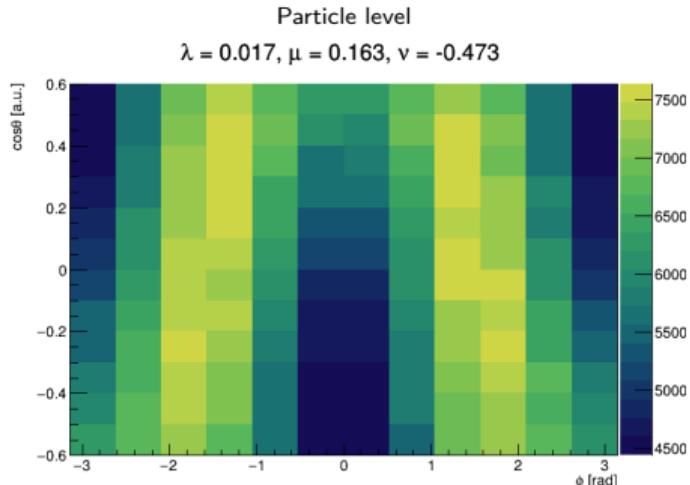
Few Unfolded Histograms



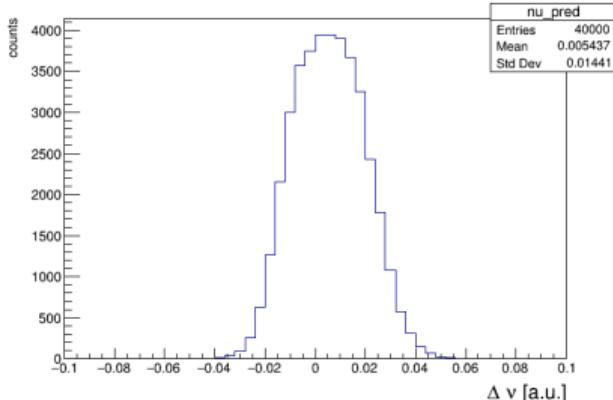
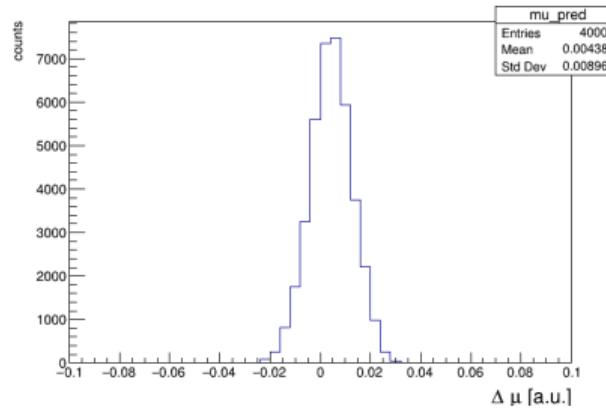
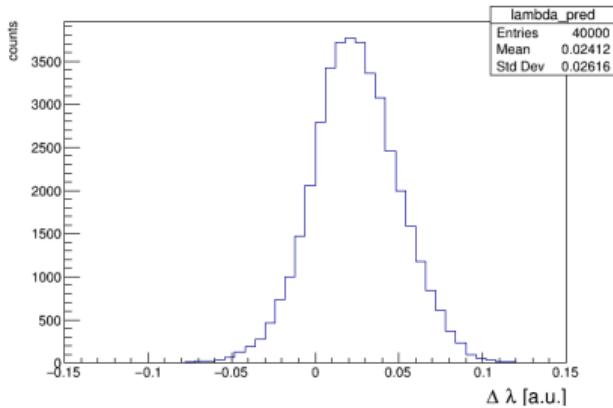
Few Unfolded Histograms



Few Unfolded Histograms



Resolution of the Unfolded Fit Results



- Unfolded ϕ -cos θ histograms are fitted using;

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

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

Comparison of Few Unfolded Fit Results

	Particle level	Unfolded
λ	-0.584 ± 0.008	-0.579 ± 0.007
μ	-0.178 ± 0.002	-0.177 ± 0.002
ν	-0.238 ± 0.003	-0.241 ± 0.003
λ	-0.037 ± 0.009	-0.035 ± 0.009
μ	-0.367 ± 0.002	-0.370 ± 0.002
ν	-0.021 ± 0.003	-0.033 ± 0.003
λ	0.701 ± 0.011	0.689 ± 0.011
μ	0.006 ± 0.002	-0.004 ± 0.002
ν	0.0156 ± 0.003	0.019 ± 0.003

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.