

# Extracting the $\cos 2\phi$ Asymmetry in the Drell-Yan process using U-Nets

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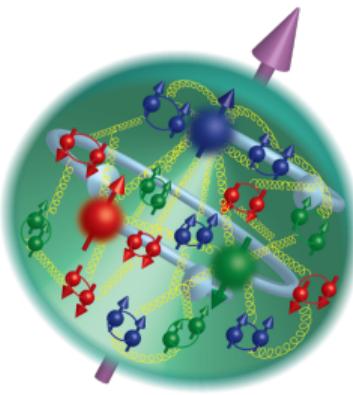
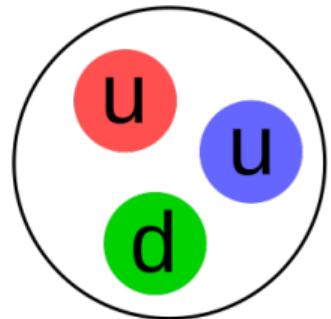
## FermiLab SeaQuest/E906 Experiment

## Analysis Motivation

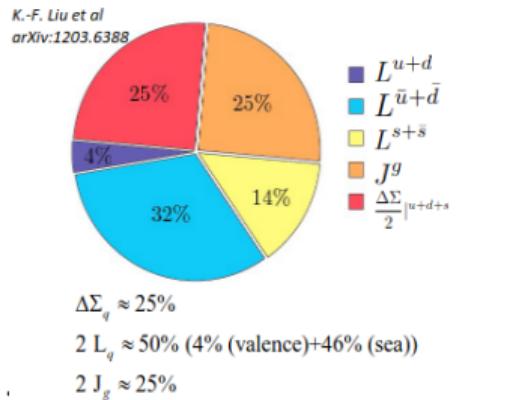
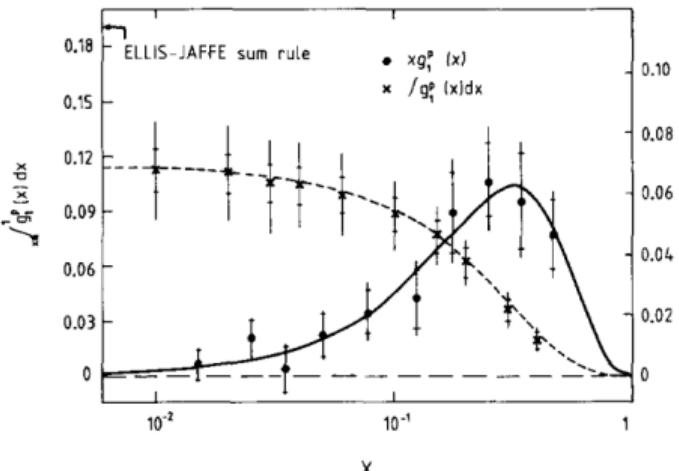
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## Summary

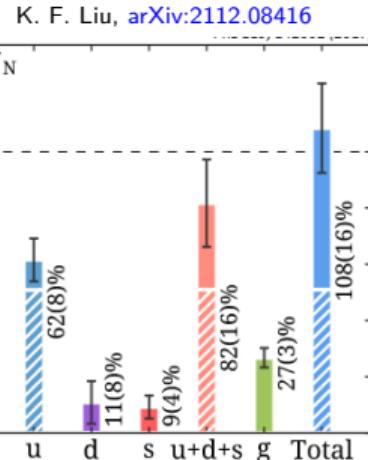
# Internal Structure of the Proton



J. Ashman et al., DOI:[10.1016/0370-2693\(88\)91523-7](https://doi.org/10.1016/0370-2693(88)91523-7)



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



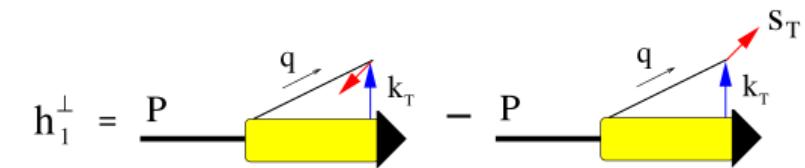
# Transverse Momentum Distributions (TMDs) and Boer-Mulders Function

A. Accardi et al, arXiv:1212.1701

Leading Twist TMDs



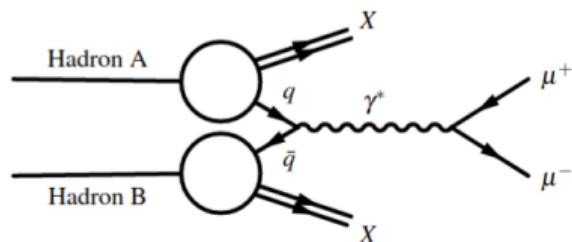
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		$h_1^\perp = \odot \uparrow - \odot \downarrow$ Boer-Mulders
	L		$g_{1L} = \odot \rightarrow - \odot \rightarrow$ Helicity	$h_{1L}^\perp = \odot \rightarrow - \odot \rightarrow$
	T	$f_{1T}^\perp = \odot \uparrow - \odot \downarrow$ Sivers	$g_{1T}^\perp = \odot \uparrow - \odot \uparrow$	$h_{1T}^\perp = \odot \uparrow - \odot \uparrow$ Transversity



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

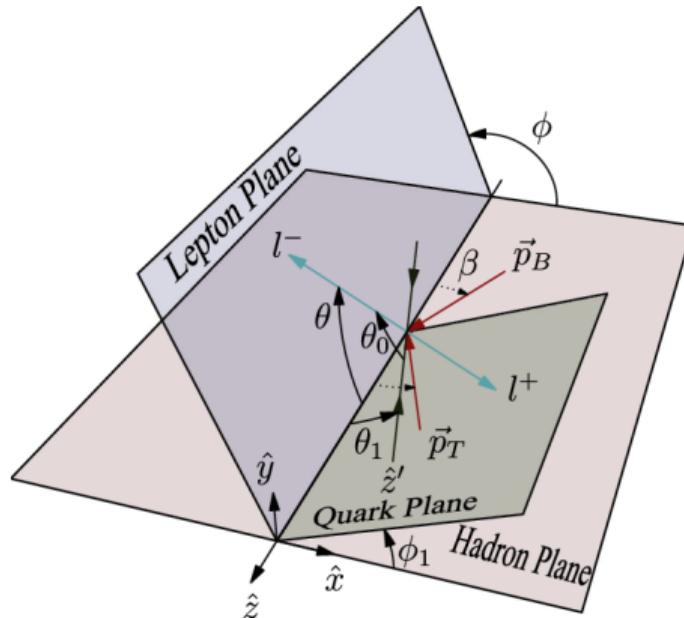
- ▶ TMDs : distributions of the hadron's quark or gluon momenta that are perpendicular to the momentum transfer between the beam and the hadron.
- ▶ Provide information on the confined motion of quarks and gluons inside the hadron and complement the information on the hadron structure.

# Drell-Yan Process



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

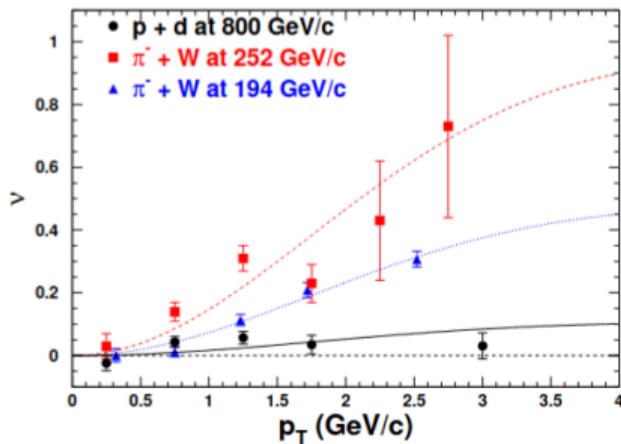
J. C. Peng et al., [arXiv:1808.04398](https://arxiv.org/abs/1808.04398)



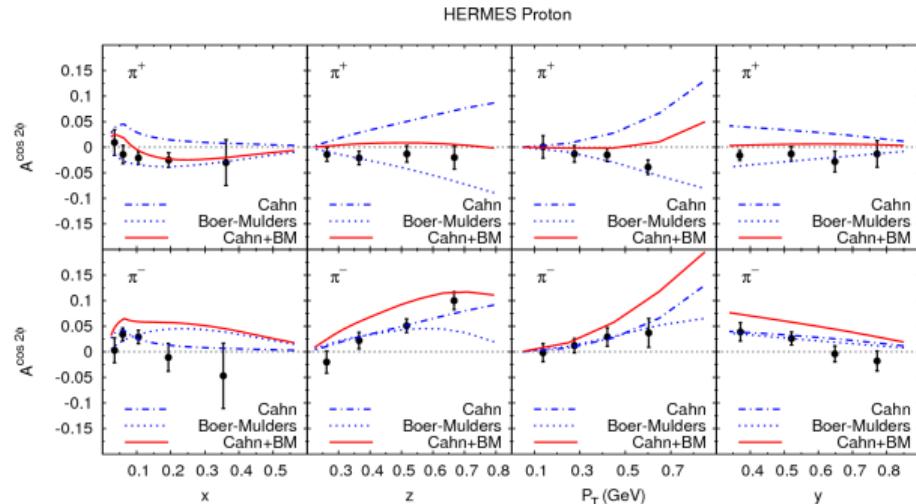
- ▶ Useful for probing the internal structure of the proton
- ▶ Collins-Soper frame: using the beam proton direction to construct the azimuthal and polar angles
- ▶ Extraction of the  $\nu$  parameter  $\rightarrow$  BM function

# Evidence for Non-zero BM Function

L.Y. Zhu et al., arXiv:hep-ex/0609005



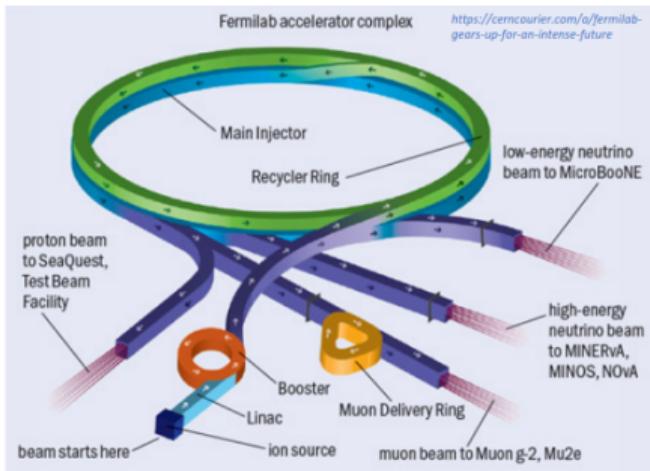
Vincenzo Barone et al., arXiv:0912.5194



- ▶ “NA10”, “E615” and “HERMES” experiments provide evidence for a non-zero BM function.

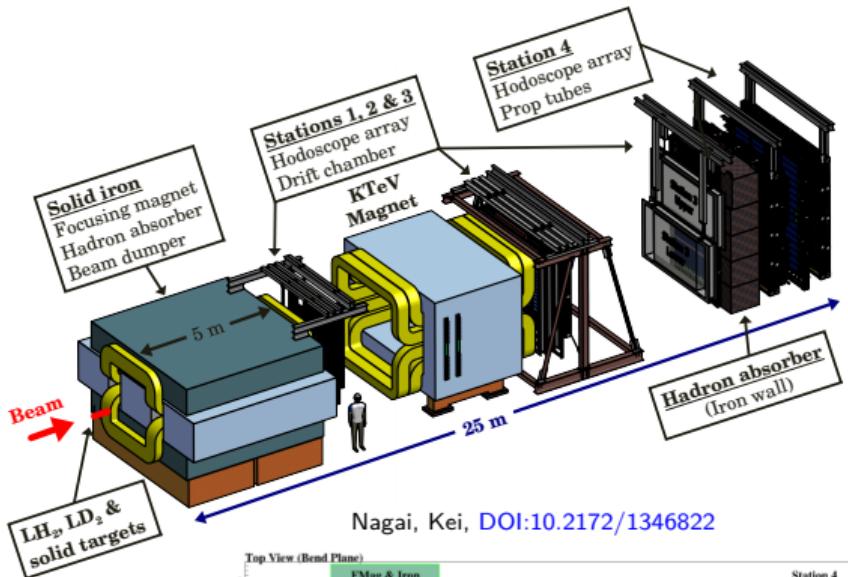
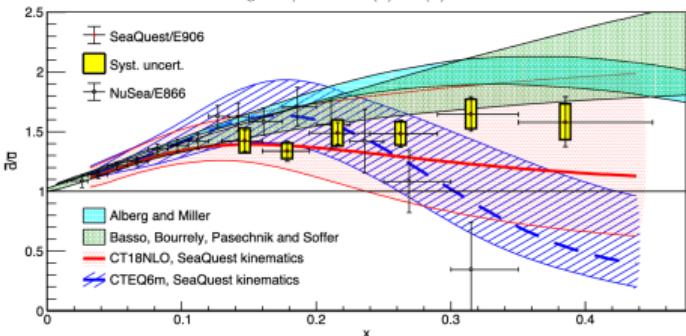
# FermiLab SeaQuest/E906 Experiment

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

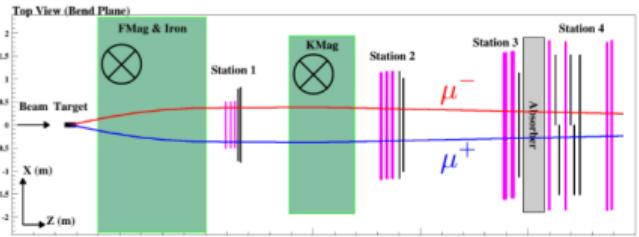


J. Dove et al., arXiv:2103.04024

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

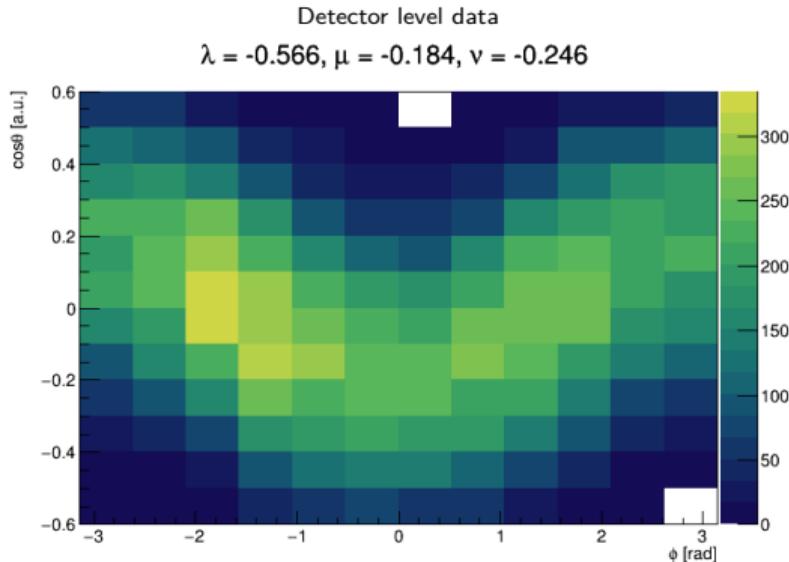
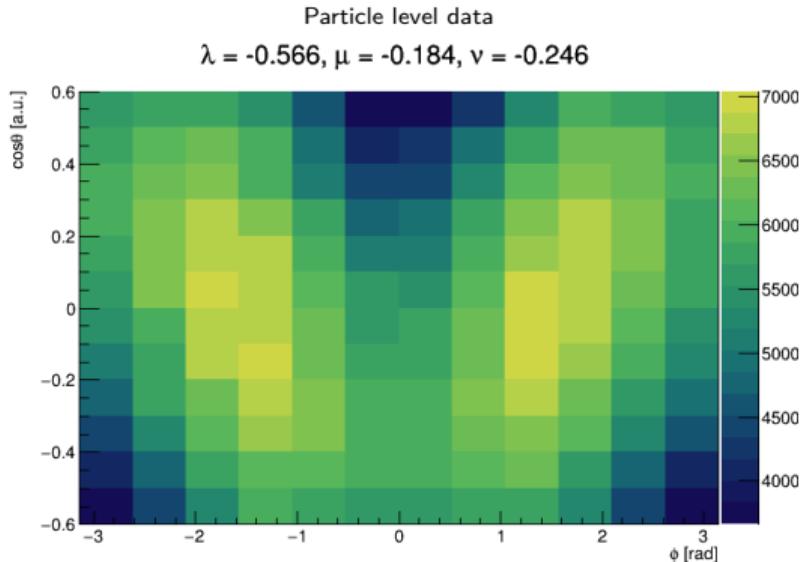


Nagai, Kei, DOI:10.2172/1346822



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

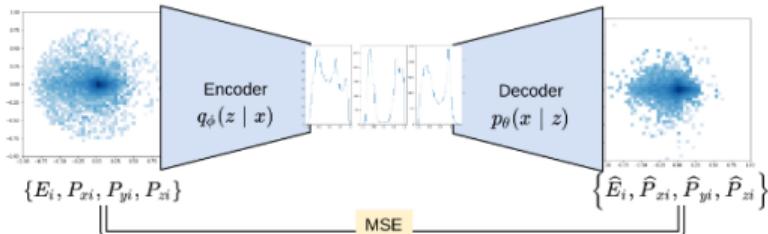
# Unfolding Detector Level Data



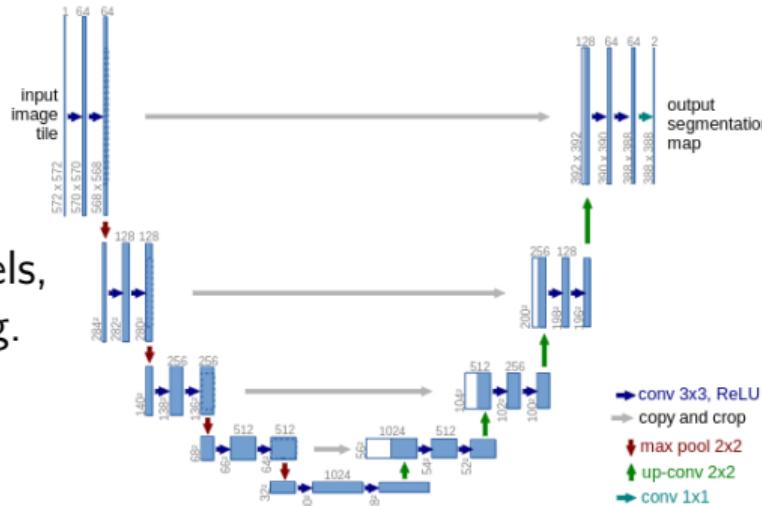
- ▶ Detector level data need to be corrected for acceptance, reconstruction inefficiencies, detector smearing, etc.
- ▶ Unfolding  $\rightarrow f: X_{\text{detector}} \rightarrow X_{\text{particle}}$
- ▶ Deep neural networks excel at approximating non-linear functions, making them ideal for mapping between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

# Autoencoders and U-Nets

Taoli Cheng et al., arXiv:2007.01850



Olaf Ronneberger et al., arXiv:1505.04597



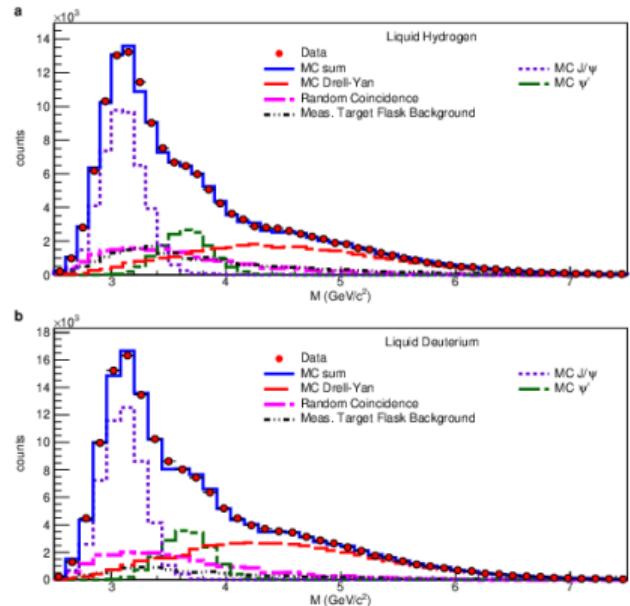
- ▶ Autoencoders(AE) are generative models, which are also used for image denoising.
- ▶ AEs encode input data to latent dimension ( $z$ ) and then decoder try to reconstruct input data.
- ▶ U-Nets are U-shaped AEs that made a major breakthrough in image segmentation.
- ▶ We use U-Nets to reconstruct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

# Data Creation

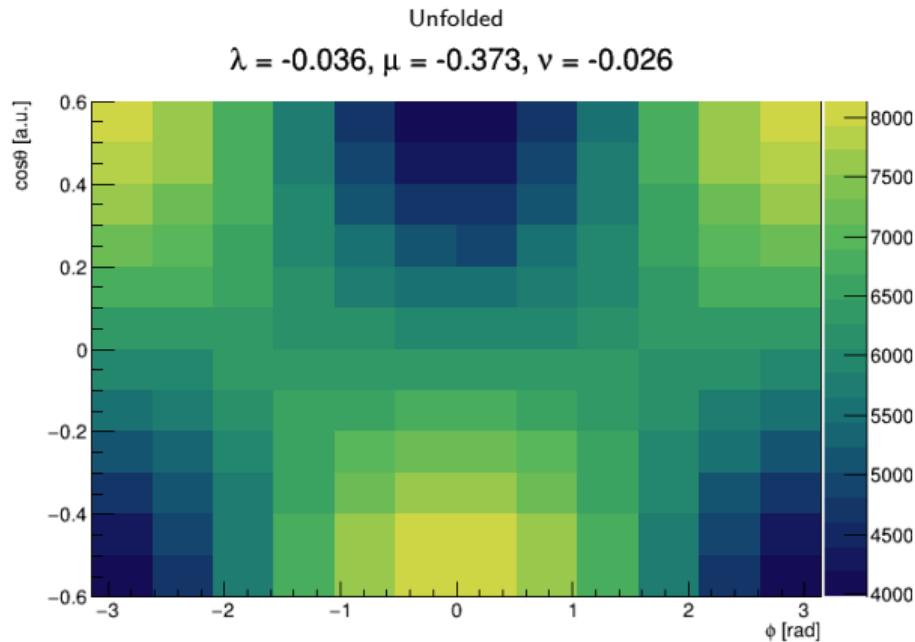
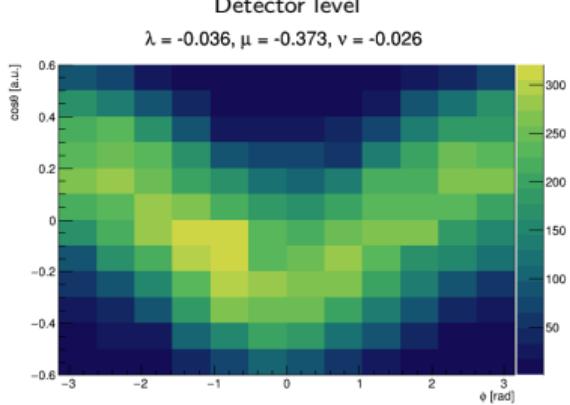
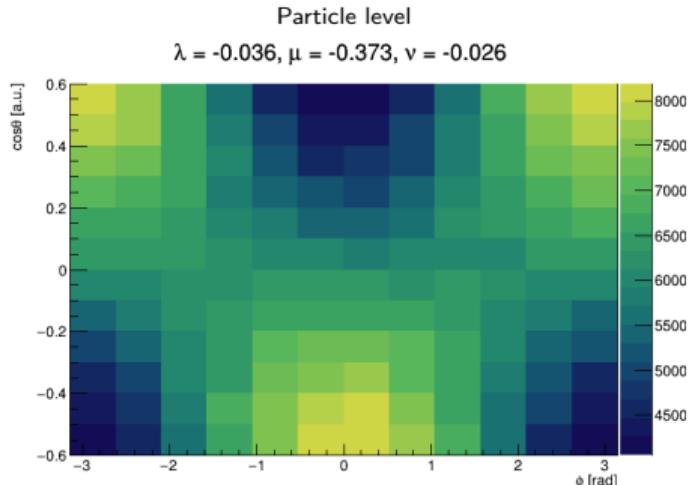
- ▶ Monte-Carlo data was generated using “PYTHIA” generator and events were passed through E906 detector simulation using “GEANT4”.
- ▶  $\lambda$ ,  $\mu$  and  $\nu$  values were sampled uniformly in the ranges  $[-1, 1]$ ,  $[-0.5, 0.5]$  and  $[-0.5, 0.5]$  respectively.
- ▶ DY angular coefficients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

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

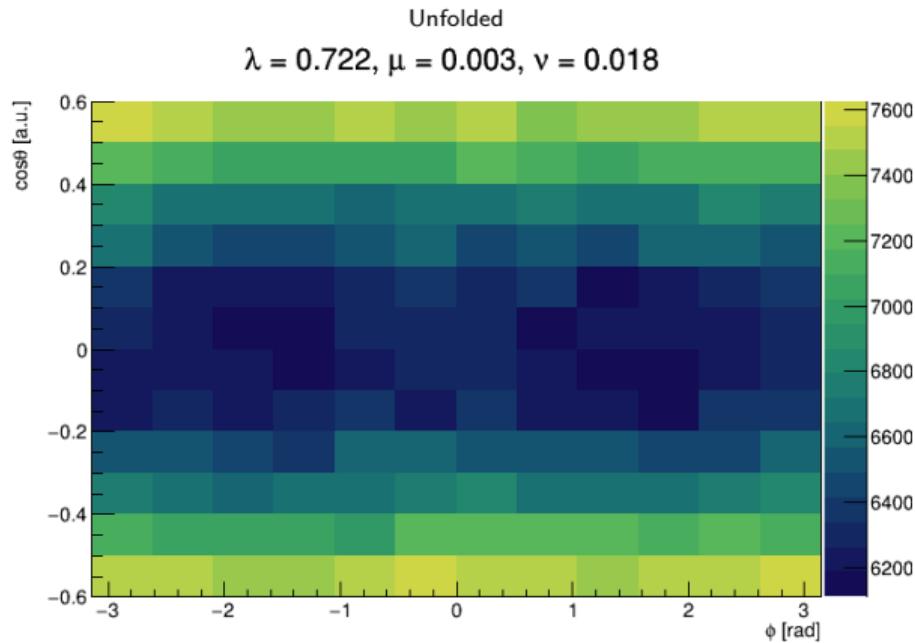
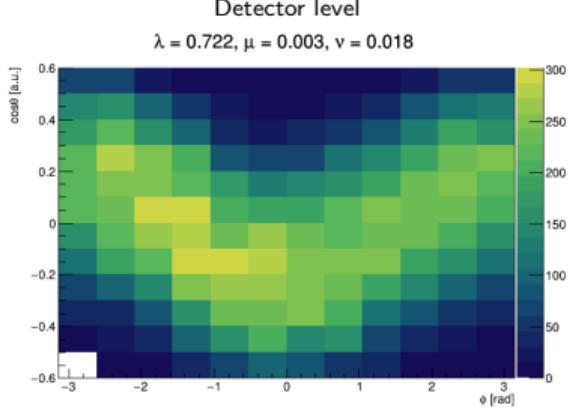
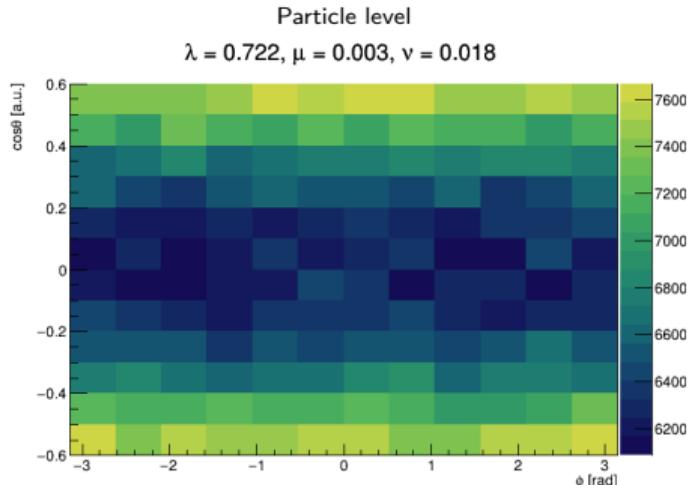
J. Dove et al., arXiv:2103.04024



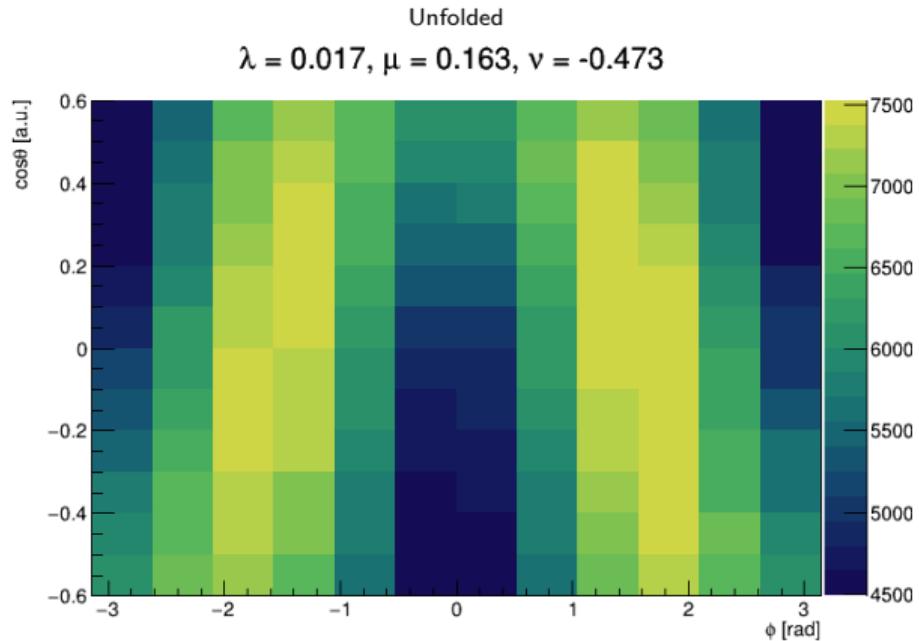
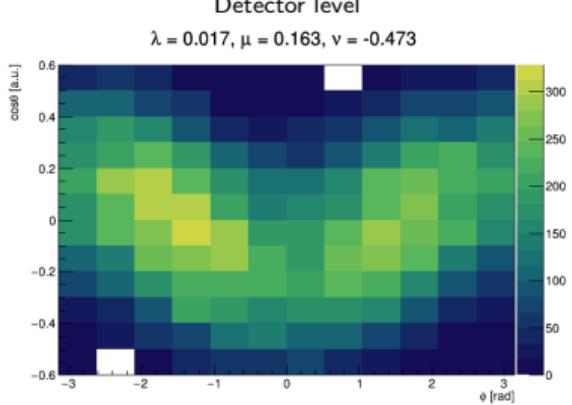
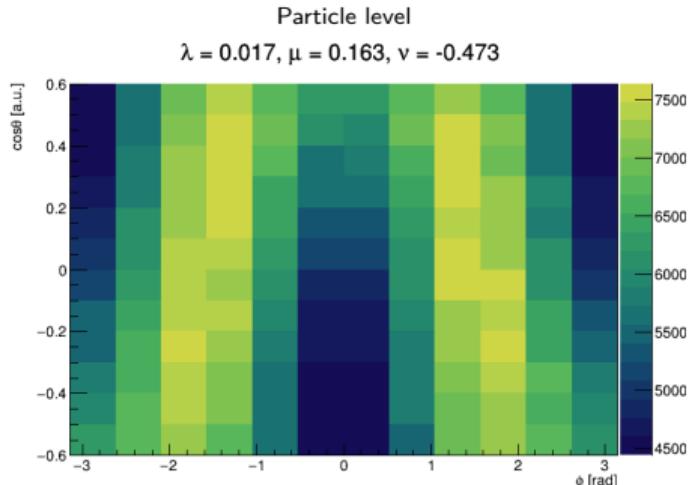
# Few Unfolded Histograms



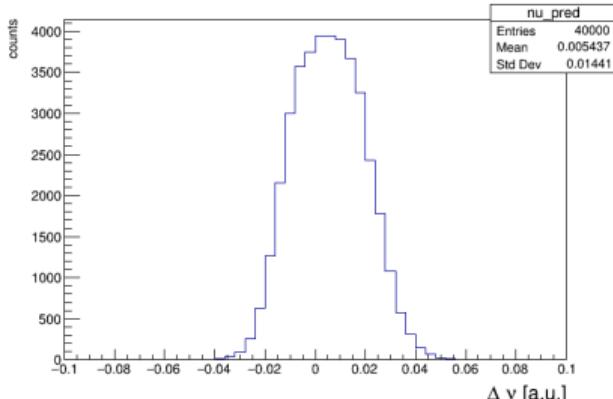
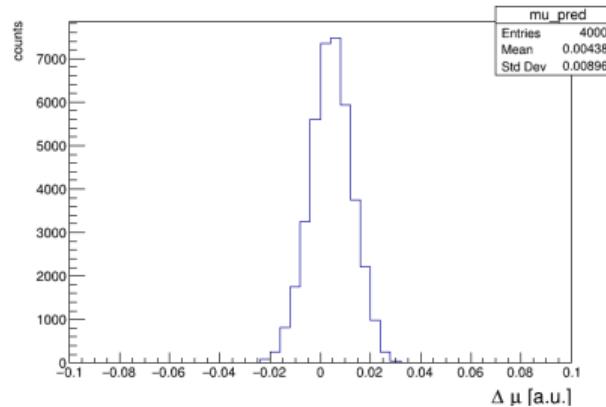
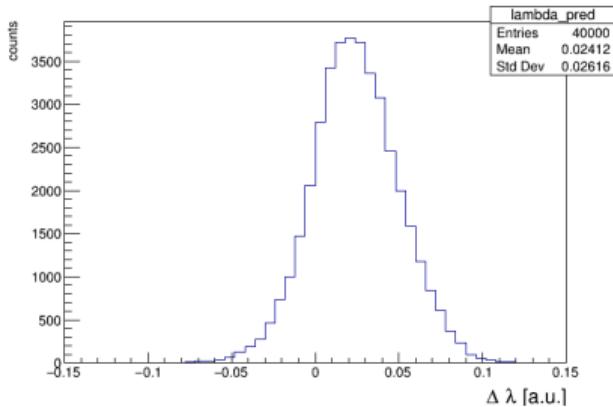
# Few Unfolded Histograms



# Few Unfolded Histograms



# Resolution of the Unfolded Fit Results



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

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

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

## Comparison of Few Unfolded Fit Results

	Particle level	Unfolded
$\lambda$	$-0.584 \pm 0.008$	$-0.579 \pm 0.007$
$\mu$	$-0.178 \pm 0.002$	$-0.177 \pm 0.002$
$\nu$	$-0.238 \pm 0.003$	$-0.241 \pm 0.003$
$\lambda$	$-0.037 \pm 0.009$	$-0.035 \pm 0.009$
$\mu$	$-0.367 \pm 0.002$	$-0.370 \pm 0.002$
$\nu$	$-0.021 \pm 0.003$	$-0.033 \pm 0.003$
$\lambda$	$0.701 \pm 0.011$	$0.689 \pm 0.011$
$\mu$	$0.006 \pm 0.002$	$-0.004 \pm 0.002$
$\nu$	$0.0156 \pm 0.003$	$0.019 \pm 0.003$

## 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.