TMDPDFs extractions employing AI

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UVA - Spin
PHYSICS GROUP

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Outline

- Motivation
- A brief introduction to TMDs
- Sivers asymmetry from SIDIS
- DNN Approach for $SU(3)_{\text{flavor}}$
- DNN Method Testing
- DNN Fits & Results for Sivers function
- Summary and Outlook

Motivation

- TMDs: so far, model-dependent extractions → assumptions, limitations and biases
- Information from data: Has the full potential of the data been taken into account?

Motivation

- TMDs: so far, model-dependent extractions → assumptions, limitations and biases
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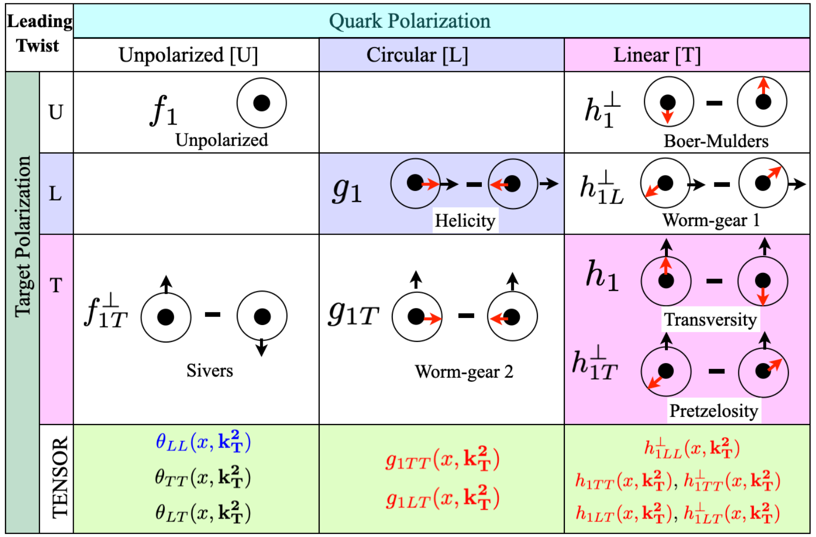
Introducing this <u>‘novel’ method</u> with Deep Neural Network (DNN) First time in TMD extractions

- Capacity to handle complex patterns, relationships in data with multi-D dependence.
- Data-driven
- Minimally biased → un-biased
- Uncertainty propagation (from data) using bootstrap method by generating ‘replicas’
  (Statistical & Systematic uncertainties from the experimental data are combined in quadrature)
- Recursive improvements to the DNN
- Systematic component can be quantified by a dedicated analysis

Intended to be
Exploratory & Instructional

TMD PDFs



Leading Twist		Quark Polarization		
		Unpolarized [U]	Circular [L]	Linear [T]
Target Polarization	U	f_1 Unpolarized		$h_1^\perp$ Boer-Mulders
	L		g_1 Helicity	$h_{1L}^\perp$ Worm-gear 1
	T	$f_{1T}^\perp$ Sivers	g_{1T} Worm-gear 2	h_1 Transversity $h_{1T}^\perp$ Pretzelosity
	TENSOR	$\theta_{LL}(x, \mathbf{k_T^2})$ $\theta_{TT}(x, \mathbf{k_T^2})$ $\theta_{LT}(x, \mathbf{k_T^2})$	$g_{1TT}(x, \mathbf{k_T^2})$ $g_{1LT}(x, \mathbf{k_T^2})$	$h_{1LL}^\perp(x, \mathbf{k_T^2})$ $h_{1TT}(x, \mathbf{k_T^2})$, $h_{1TT}^\perp(x, \mathbf{k_T^2})$ $h_{1LT}(x, \mathbf{k_T^2})$, $h_{1LT}^\perp(x, \mathbf{k_T^2})$

$$\Phi(x, k_T; S) = \int \frac{d\xi^- d\xi_T}{(2\pi)^3} e^{ik.\xi} \langle P, S | \bar{\psi}(0)\, \mathcal{U}_{[0,\xi]}\ \psi(\xi) | P, S \rangle |_{\xi^+=0}$$

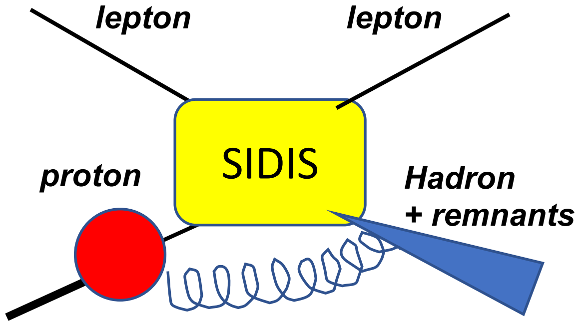
At leading-twist, the Quark correlator can be decomposed into 8 components (6 T - even and 2 T -odd terms)

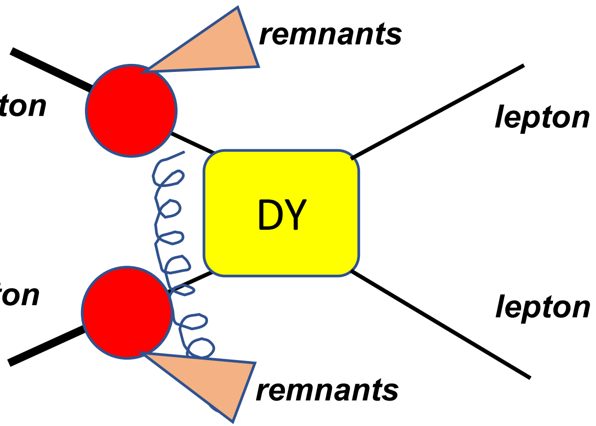
$$\Phi(x, k_T, P, S) = \boxed{f_1(x, k_T^2)\frac{\not{P}}{2} + \frac{h_{1T}(x, k_T^2)}{4}\gamma_5[\not{S}_T, \not{P}] + \frac{S_L}{2} g_{1L}(x, k_T^2)\gamma_5 \not{P} + \frac{k_T.S_T}{2M} g_{1T}(x, k_T^2)\gamma_5 \not{P} + S_L h_{1L}^\perp(x, k_T^2)\gamma_5 \frac{[\not{k}_T, \not{P}]}{4M} + \frac{k_T.S_T}{2M} h_{1T}^\perp(x, k_T^2)\gamma_5 \frac{[\not{k}_T, \not{P}]}{4M}}$$

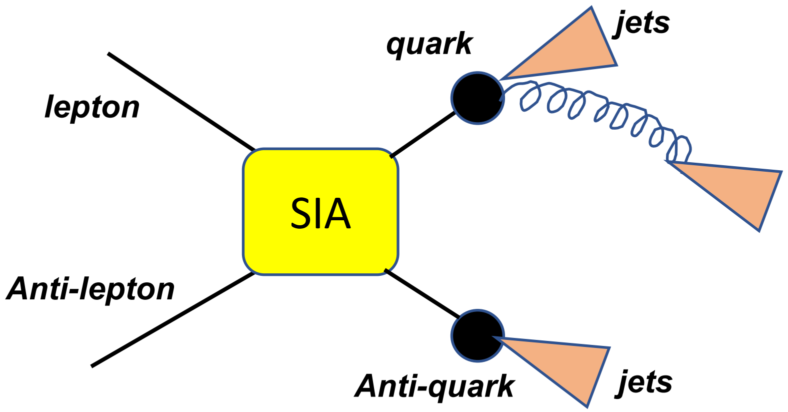
T-even

$$+ \boxed{i h_1^\perp(x, k_T^2) \frac{[\not{k}_T, \not{P}]}{4M} - \frac{\epsilon_T^{k_T S_T}}{4M} f_{1T}^\perp(x, k_T^2) \not{P}}$$

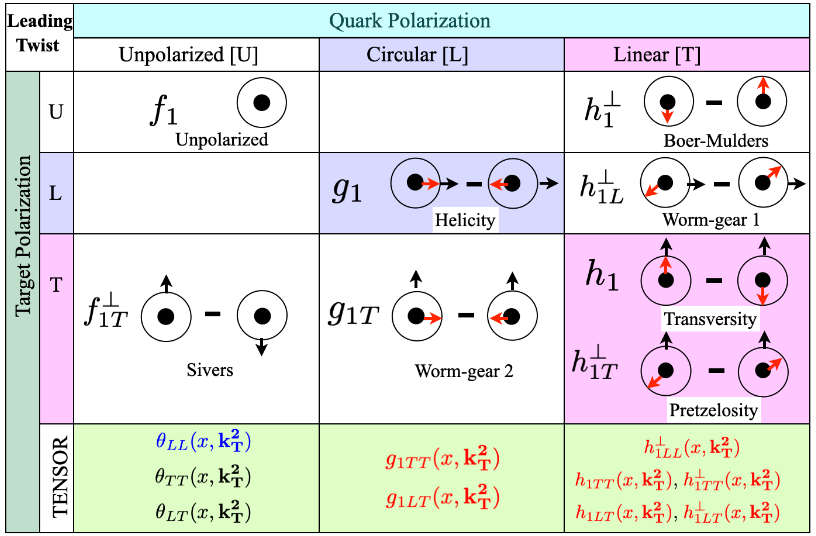
T-odd







TMD PDFs



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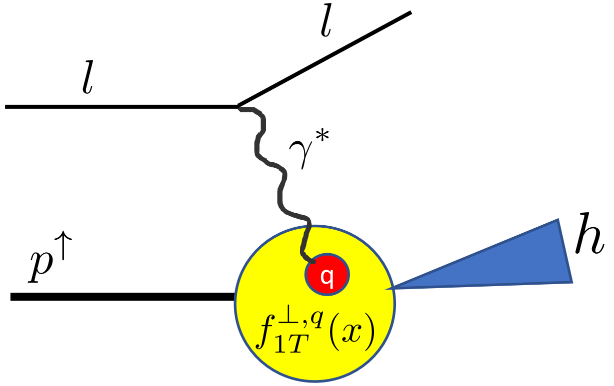
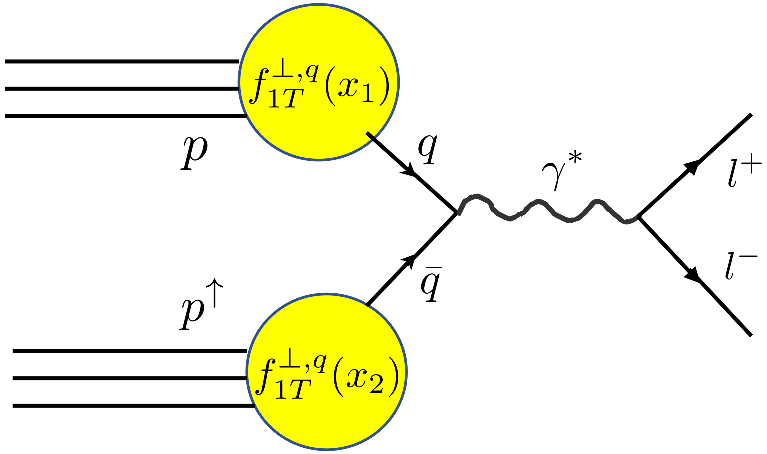
Polarized Semi Inclusive DIS



Polarized DY



* For these two processes TMD factorization is proven

$$\frac{d\sigma^{LO}_{SIDIS}}{dxdydzdp_T^2d\phi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{y^2}{2x}\right)\right]$$

$$\times (F_{UU,T}+\epsilon F_{UU,L})\{1+\cos 2\phi_h\left(\epsilon A_{UU}^{\cos 2\phi_h}\right)$$

$$+S_T\left[\sin(\phi_h-\phi_s)\left(A_{UT}^{\sin(\phi_h-\phi_s)}\right)+\sin(\phi_h+\phi_s)\left(\epsilon A_{UT}^{\sin(\phi_h+\phi_s)}\right)\right.$$

$$\left.+\sin(3\phi_h-\phi_s)\left(\epsilon A_{UT}^{\sin(3\phi_h-\phi_s)}\right)\right]$$

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq}F_v^1\{1+\cos^2\theta + sin^2\theta cos2\phi_{CS}A_U^{cos2\phi_{CS}}$$

$$+S_T\left[(1+\cos^2\theta)\sin\phi_s A_T^{\sin\phi_s}+\sin^2\theta\left(\sin(2\phi_{CS}+\phi_s)A_T^{\sin(2\phi_{CS}+\phi_s)}\right.\right.$$

$$\left.\left.+\sin(2\phi_{CS}-\phi_s)A_T^{\sin(2\phi_{CS}-\phi_s)}\right)\right]$$

$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \circledast H_{1q}^{\perp h}$ BM ⊛ CF

$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \circledast D_{1q}^{h}$ Sivers ⊛ FF

$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^{q} \circledast H_{1q}^{\perp h}$ Transv ⊛ CF

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \circledast H_{1q}^{\perp h}$ Pretz ⊛ CF

$A_T^{\cos 2\phi_{CS}} \propto h_1^{\perp q} \circledast h_1^{\perp q}$ BM ⊛ BM

$A_T^{\sin\phi_s} \propto f_1^{q} \circledast f_{1T}^{\perp q}$ PDF ⊛ Sivers

$A_T^{\sin(2\phi_{CS}-\phi_S)} \propto h_1^{\perp q} \circledast h_1^{q}$ BM ⊛ Transv

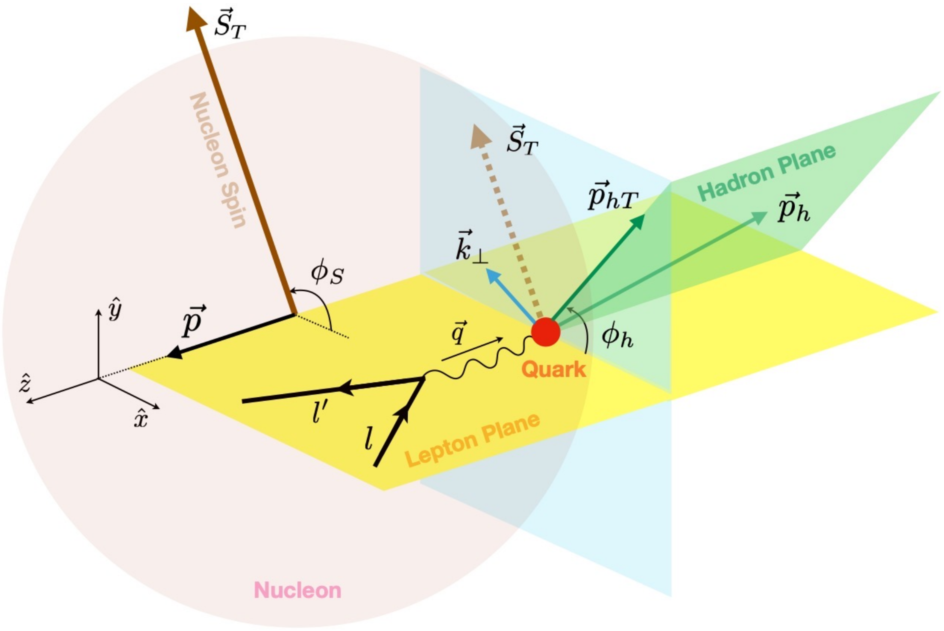
$A_T^{\sin(2\phi_{CS}+\phi_S)} \propto h_1^{\perp q} \circledast h_{1T}^{\perp q}$ BM ⊛ Pretz

$$h_1^{\perp q}\big|_{SIDIS} = -h_1^{\perp q}\big|_{DY}$$
$$f_{1T}^{\perp q}\big|_{SIDIS} = -f_{1T}^{\perp q}\big|_{DY}$$

$$h_1^{q}\big|_{SIDIS} = h_1^{q}\big|_{DY}$$
$$h_{1T}^{\perp q}\big|_{SIDIS} = h_{1T}^{\perp q}\big|_{DY}$$

Sivers Asymmetry from SIDIS

$$\frac{d^5\sigma^{lp\to lhX}}{dx\,dQ^2\,dz\,d^2p_\perp} = \sum_q e_q^2 \int d^2\mathbf{k}_\perp \left(\frac{2\pi\alpha^2}{x^2 s^2}\frac{\hat{s}^2+\hat{u}^2}{Q^4}\right)$$
$$\times \hat{f}_{q/p^\uparrow}(x,k_\perp) D_{h/q}(z,p_\perp) + \mathcal{O}(k_\perp/Q)$$



$$\hat{f}_{q/p^\uparrow}(x,k_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\boxed{\Delta^N f_{q/p^\uparrow}(x,k_\perp)}\vec{S}_T\cdot(\hat{p}\times\hat{k}_\perp)$$

$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\mathcal{N}_q(x) h(k_\perp) f_{q/p}(x,k_\perp)$$

Anselmino et al. (2017)

Single Spin Asymmetry (Sivers Asymmetry)

$$\langle p_\perp^2\rangle = 0.12 \pm 0.01\ \mathrm{GeV}^2$$
$$\langle k_\perp^2\rangle = 0.57 \pm 0.08\ \mathrm{GeV}^2$$

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,y,z,p_{hT}) = \frac{d\sigma^{l\uparrow p\to hlX} - d\sigma^{l\downarrow p\to lhX}}{d\sigma^{l\uparrow p\to hlX} + d\sigma^{l\downarrow p\to hlX}} \equiv \frac{d\sigma\uparrow - d\sigma\downarrow}{d\sigma\uparrow + d\sigma\downarrow}$$

$$\mathcal{A}_0(z,p_{hT},m_1) = \frac{\sqrt{2e}zp_{hT}}{m_1}\frac{[z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle]\langle k_S^2\rangle^2}{[z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle]^2\langle k_\perp^2\rangle} \times \exp\left[-\frac{p_{hT}^2 z^2\left(\langle k_S^2\rangle - \langle k_\perp^2\rangle\right)}{\left(z^2\langle k_S^2\rangle + \langle p_\perp^2\rangle\right)\left(z^2\langle k_\perp^2\rangle + \langle p_\perp^2\rangle\right)}\right]$$

$$\langle k_S^2\rangle = \frac{m_1\langle k_\perp^2\rangle}{m_1^2 + \langle k_\perp^2\rangle}$$

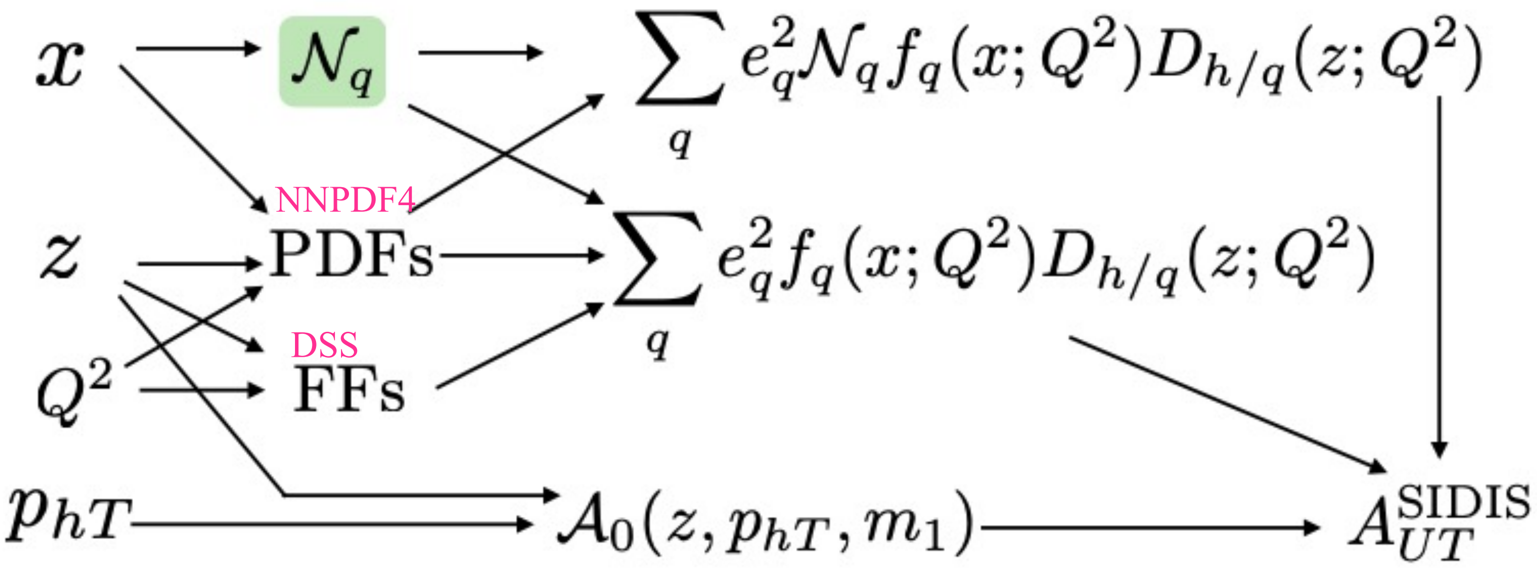
$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,z,p_{hT}) = \mathcal{A}_0(z,p_{hT},m_1)\left(\frac{\sum_q \mathcal{N}_q(x) e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}\right)$$

$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}}$$

$$\mathcal{N}_{\bar{q}}(x) = N_{\bar{q}}$$

DNN Approach

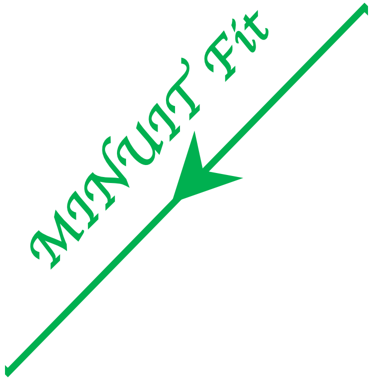
$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,z,p_{hT}) = \mathcal{A}_0(z,p_{hT},m_1)\left(\frac{\sum_q \mathcal{N}_q(x) e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}\right)$$



The DNN Method for extracting TMDs

I. P. Fernando and D. Keller
Phys. Rev. D.108.054007 (2023)

Experimental-data



generating function

$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}}$$

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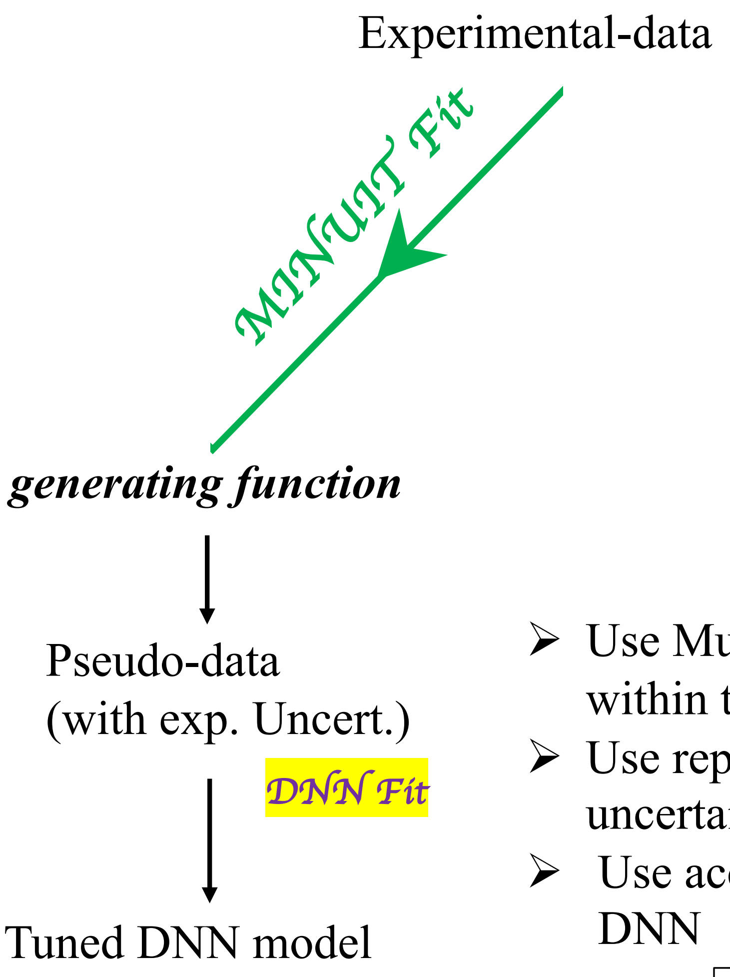

Experimental-data

MINUIT Fit

generating function

Pseudo-data
(with exp. Uncert.)

DNN Fit

Tuned DNN model

$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}}$$

- Use Multi-dimensional kinematic bins within the experimental kinematic phase-space
- Use replicas to propagate the experimental uncertainties
- Use accuracy and precision to ensure the DNN

$$\epsilon_q(x,k_\perp) = \left(1 - \frac{|\Delta^N f_{q/p^\uparrow}^{(\text{true})} - \Delta^N f_{q/p^\uparrow}^{(\text{mean})}|}{\Delta^N f_{q/p^\uparrow}^{(\text{true})}}\right) \times 100\%$$

$$\sigma_q(x,k_\perp) = \sqrt{\frac{\sum_i \left(\Delta^N f_{q/p^\uparrow}^{(i)} - \Delta^N f_{q/p^\uparrow}^{(\text{mean})}\right)^2}{N}}$$

The DNN Method for extracting TMDs

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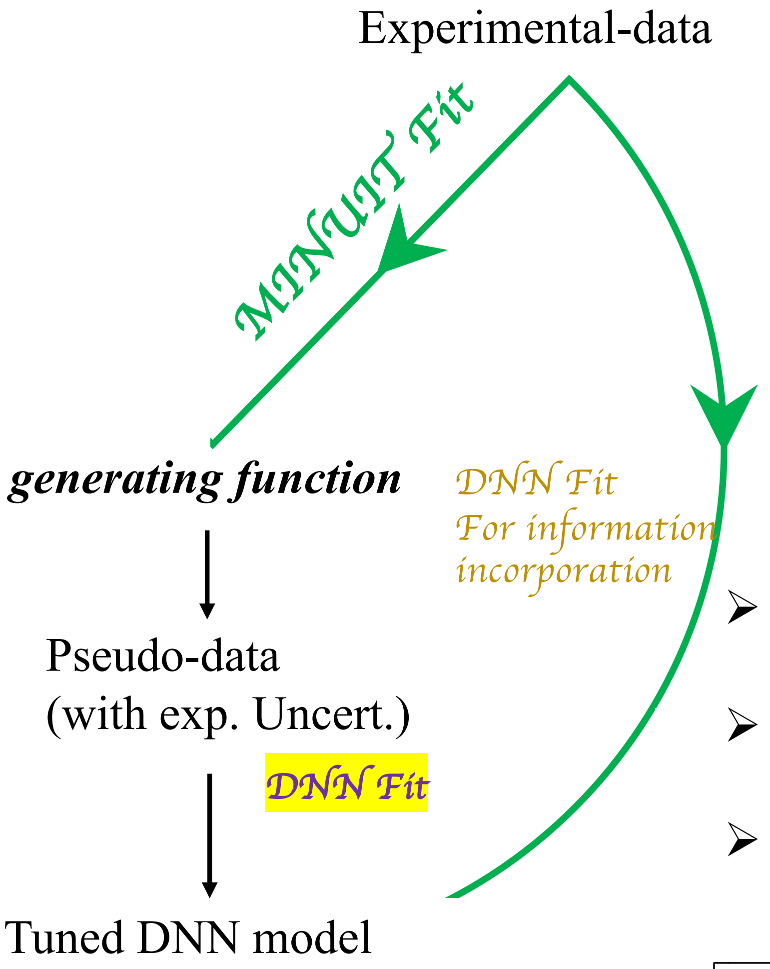
$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}}$$



Experimental-data

MINUIT Fit

generating function

Pseudo-data
(with exp. Uncert.)

DNN Fit

Tuned DNN model

DNN Fit
For information
incorporation

- Use the tuned DNN to fit with experimental data
- Use replicas to propagate the experimental uncertainties
- "Information incorporation phase"

$$\epsilon_q(x,k_\perp) = \left(1 - \frac{|\Delta^N f_{q/p^\uparrow}^{(\text{true})} - \Delta^N f_{q/p^\uparrow}^{(\text{mean})}|}{\Delta^N f_{q/p^\uparrow}^{(\text{true})}}\right) \times 100\%$$

$$\sigma_q(x,k_\perp) = \sqrt{\frac{\sum_i \left(\Delta^N f_{q/p^\uparrow}^{(i)} - \Delta^N f_{q/p^\uparrow}^{(\text{mean})}\right)^2}{N}}$$

The DNN Method for extracting TMDs

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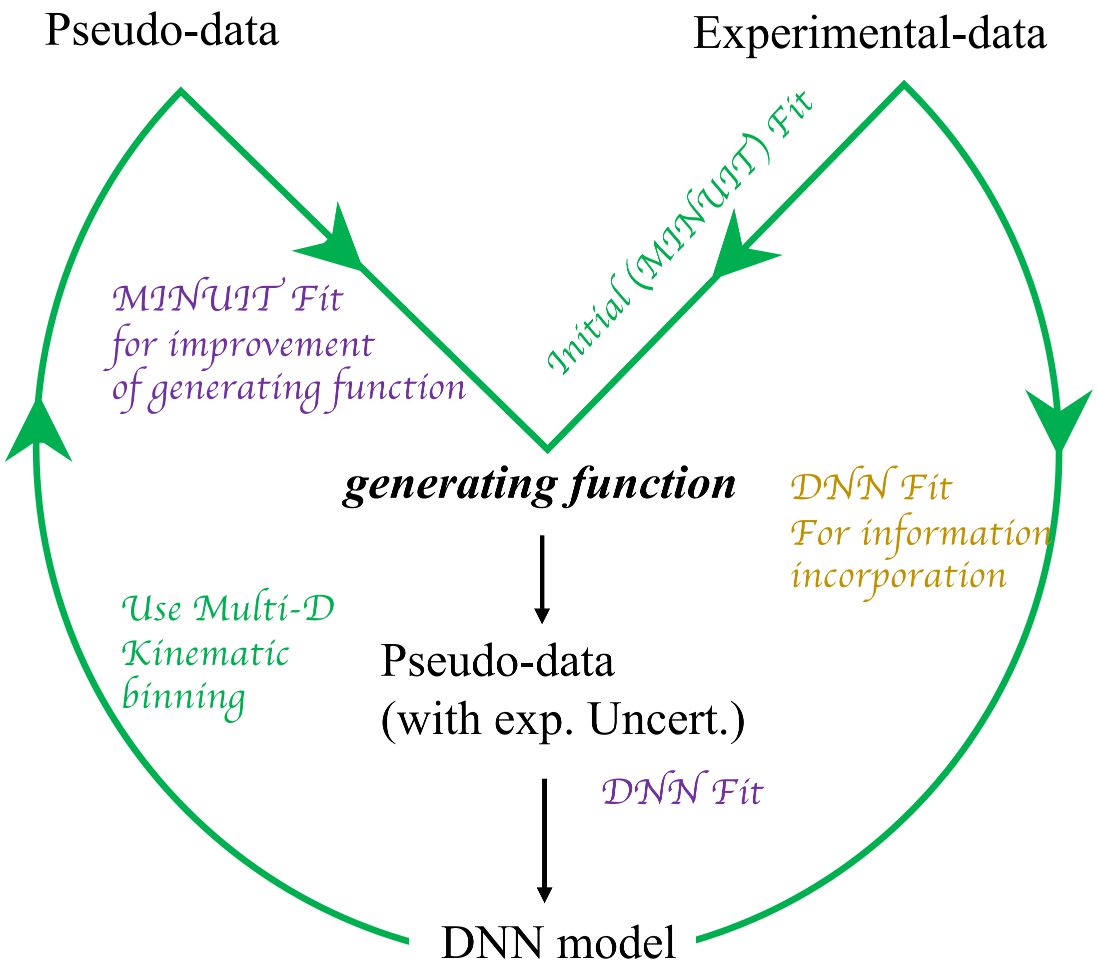
Iterations!
"Recursively Improving the DNN with multi-dimensional kinematic phase-space, and simultaneous information incorporation from experimental data (Nature)"



Pseudo-data

Experimental-data

MINUIT Fit
for improvement
of generating function

Initial (MINUIT) Fit

generating function

DNN Fit
For information
incorporation

Use Multi-D
Kinematic
binning

Pseudo-data
(with exp. Uncert.)

DNN Fit

DNN model

- We trained two separate models for "proton" and "neutron" (deuteron)
- To take full advantage of the information provided by the model testing in the previous slide, the steps from method testing with pseudo-data are performed again separately for proton and deuteron SIDIS data.

$$\epsilon_q(x,k_\perp) = \left(1 - \frac{|\Delta^N f^{(\mathrm{true})}_{q/p^\uparrow} - \Delta^N f^{(\mathrm{mean})}_{q/p^\uparrow}|}{\Delta^N f^{(\mathrm{true})}_{q/p^\uparrow}}\right) \times 100\%$$

$$\sigma_q(x,k_\perp) = \sqrt{\frac{\sum_i \left(\Delta^N f^{(i)}_{q/p^\uparrow} - \Delta^N f^{(\mathrm{mean})}_{q/p^\uparrow}\right)^2}{N}}$$

The DNN Method for extracting TMDs

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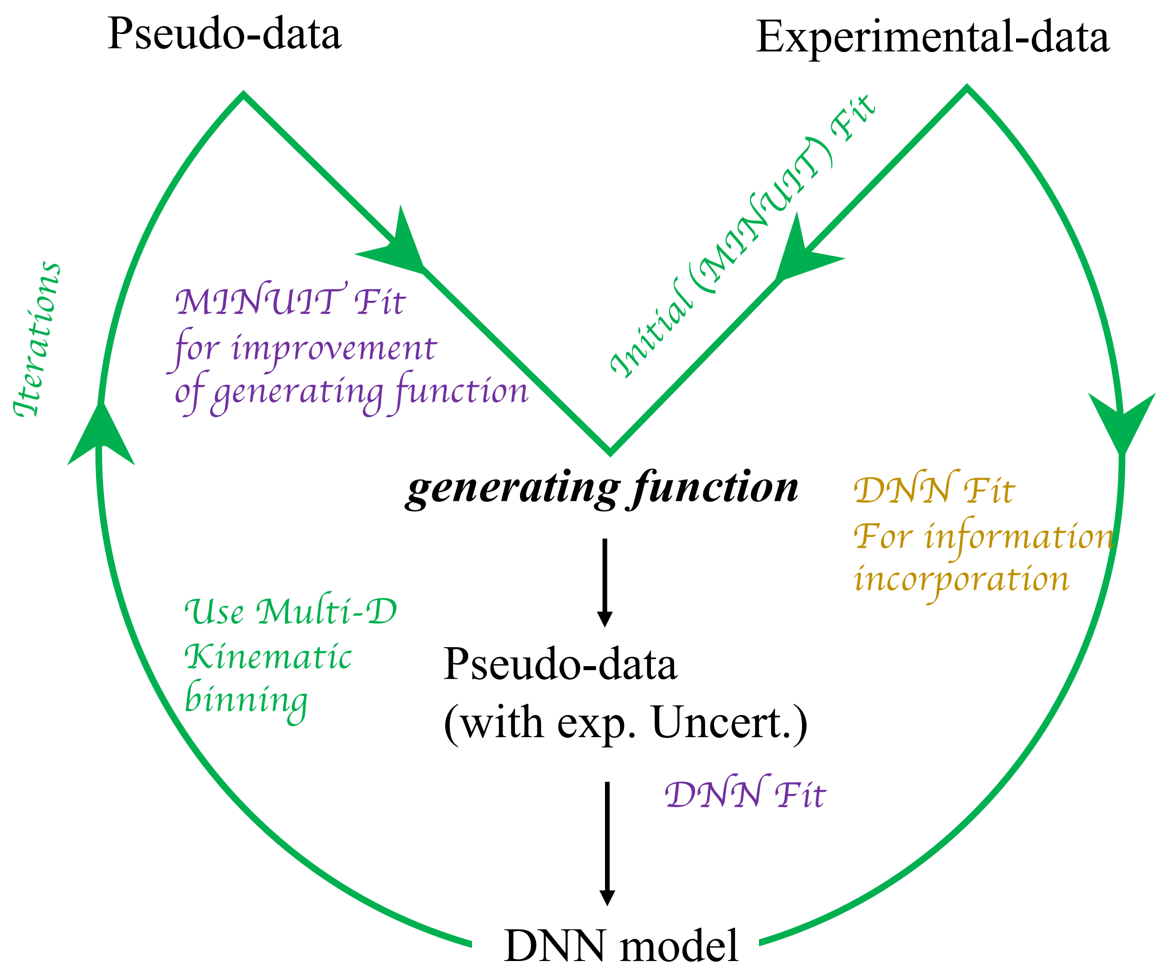

Pseudo-data

Experimental-data

Iterations

MINUIT Fit
for improvement
of generating function

Initial (MINUIT) Fit

generating function

DNN Fit
For information incorporation

Use Multi-D
Kinematic
binning

Pseudo-data
(with exp. Uncert.)

DNN Fit

DNN model

- Systematic study for both DNN models were performed separately using various generating functions.

- We trained two separate models for "proton" and "neutron" (deuteron)
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$$\epsilon_q(x, k_\perp) = \left(1 - \frac{|\Delta^N f^{(\text{true})}_{q/p^\uparrow} - \Delta^N f^{(\text{mean})}_{q/p^\uparrow}|}{\Delta^N f^{(\text{true})}_{q/p^\uparrow}}\right) \times 100\%$$

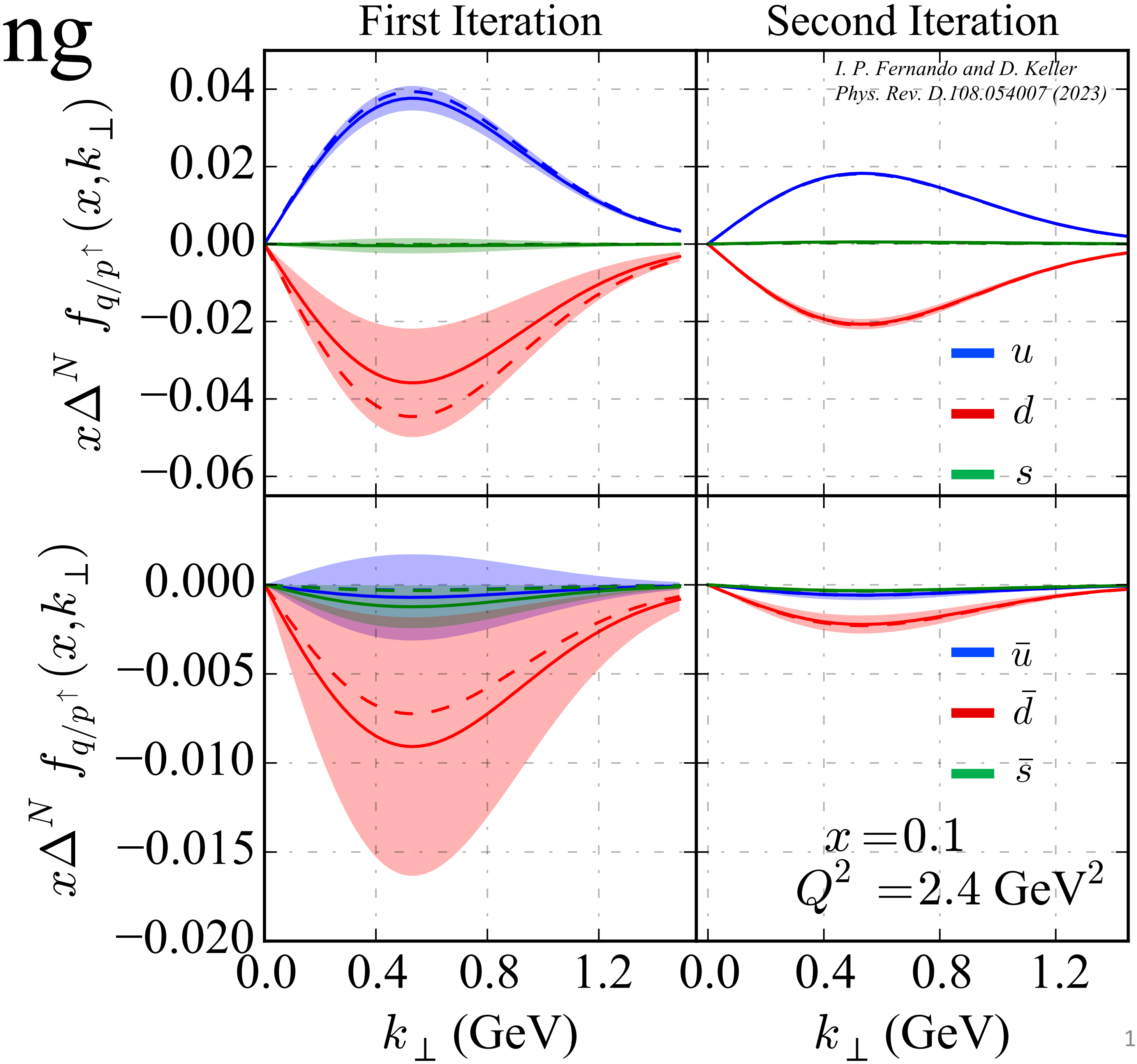
$$\sigma_q(x, k_\perp) = \sqrt{\frac{\sum_i \left(\Delta^N f^{(i)}_{q/p^\uparrow} - \Delta^N f^{(\text{mean})}_{q/p^\uparrow}\right)^2}{N}}$$

DNN Method testing

- Dashed lines represent the ***generating function*** in each iteration.

- A comparison:
  Improving the ***generating functio***n
  Fine-tuning the hyperparameters

- Solid-lines and the band represent the mean and 68% CL with 1000 replicas of the DNN model.



Data Selection

Proton DNN model

Deuteron DNN model

Dataset	Kinematic coverage	Reaction	Data points
HERMES2009	$0.023 < x < 0.4$	$p^\uparrow + \gamma^* \to \pi^+$	21
(SIDIS)	$0.2 < z < 0.7$	$p^\uparrow + \gamma^* \to \pi^-$	21
[53]	$0.1 < p_{hT} < 0.9$	$p^\uparrow + \gamma^* \to \pi^0$	21
	$Q^2 > 1\ \text{GeV}^2$	$p^\uparrow + \gamma^* \to K^+$	21
		$p^\uparrow + \gamma^* \to K^-$	21
HERMES2020	$0.023 < x < 0.6$	$p^\uparrow + \gamma^* \to \pi^+$	27, **64**
(SIDIS)	$0.2 < z < 0.7$	$p^\uparrow + \gamma^* \to \pi^-$	27, **64**
[55]	$0.1 < p_{hT} < 0.9$	$p^\uparrow + \gamma^* \to \pi^0$	27
	$Q^2 > 1\ \text{GeV}^2$	$p^\uparrow + \gamma^* \to K^+$	27, **64**
		$p^\uparrow + \gamma^* \to K^-$	27, **64**
COMPASS2015	$0.006 < x < 0.28$	$p^\uparrow + \gamma^* \to \pi^+$	26
(SIDIS)	$0.2 < z < 0.8$	$p^\uparrow + \gamma^* \to \pi^-$	26
[54]	$0.15 < p_{hT} < 1.5$	$p^\uparrow + \gamma^* \to K^+$	26
	$Q^2 > 1\ \text{GeV}^2$	$p^\uparrow + \gamma^* \to K^-$	26
COMPASS2009	$0.006 < x < 0.28$	$d^\uparrow + \gamma^* \to \pi^+$	26
(SIDIS)	$0.2 < z < 0.8$	$d^\uparrow + \gamma^* \to \pi^-$	26
[49]	$0.15 < p_{hT} < 1.5$	$d^\uparrow + \gamma^* \to K^+$	26
	$Q^2 > 1\ \text{GeV}^2$	$d^\uparrow + \gamma^* \to K^-$	26
JLAB2011	$0.156 < x < 0.396$	${}^3He^\uparrow + \gamma^* \to \pi^+$	4
(SIDIS) [52]	$0.50 < z < 0.58$	${}^3He^\uparrow + \gamma^* \to \pi^-$	4
	$0.24 < p_{hT} < 0.43$		
	$1.3 < Q^2 < 2.7$		
COMPASS2017	$0.1 < x_N < 0.25$	$p^\uparrow + \pi^- \to l^+ l^- X$	15
(DY) [50]	$0.3 < x_\pi < 0.7$		
	$4.3 < Q_M < 8.5$		
	$0.6 < q_T < 1.9$		

HERMES2020
3D binned data

Projections from
Proton DNN model

Projections from
Deuteron DNN model

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp)\big|_{\text{SIDIS}} = -\,\Delta^N f_{q/p^\uparrow}(x, k_\perp)\big|_{\text{DY}}$$

Proton DNN Fit Results

I. P. Fernando and D. Keller
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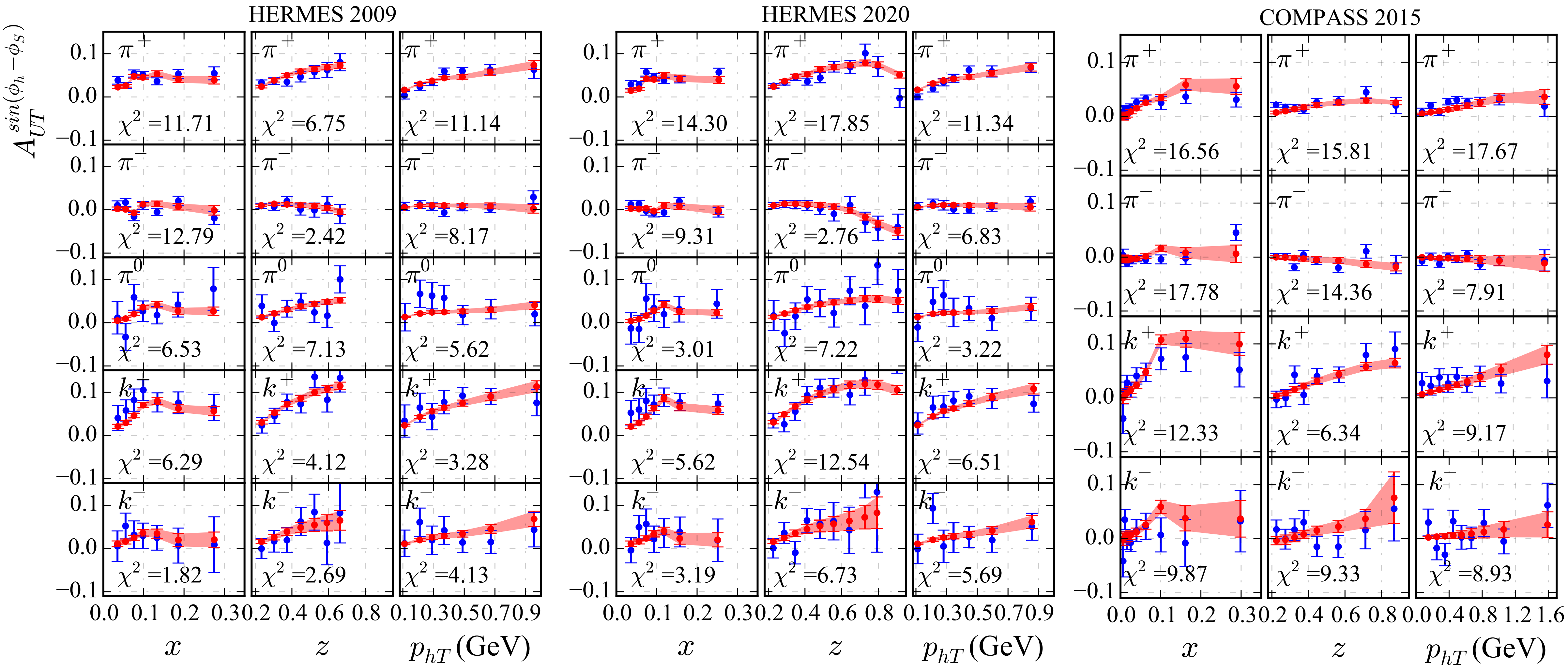
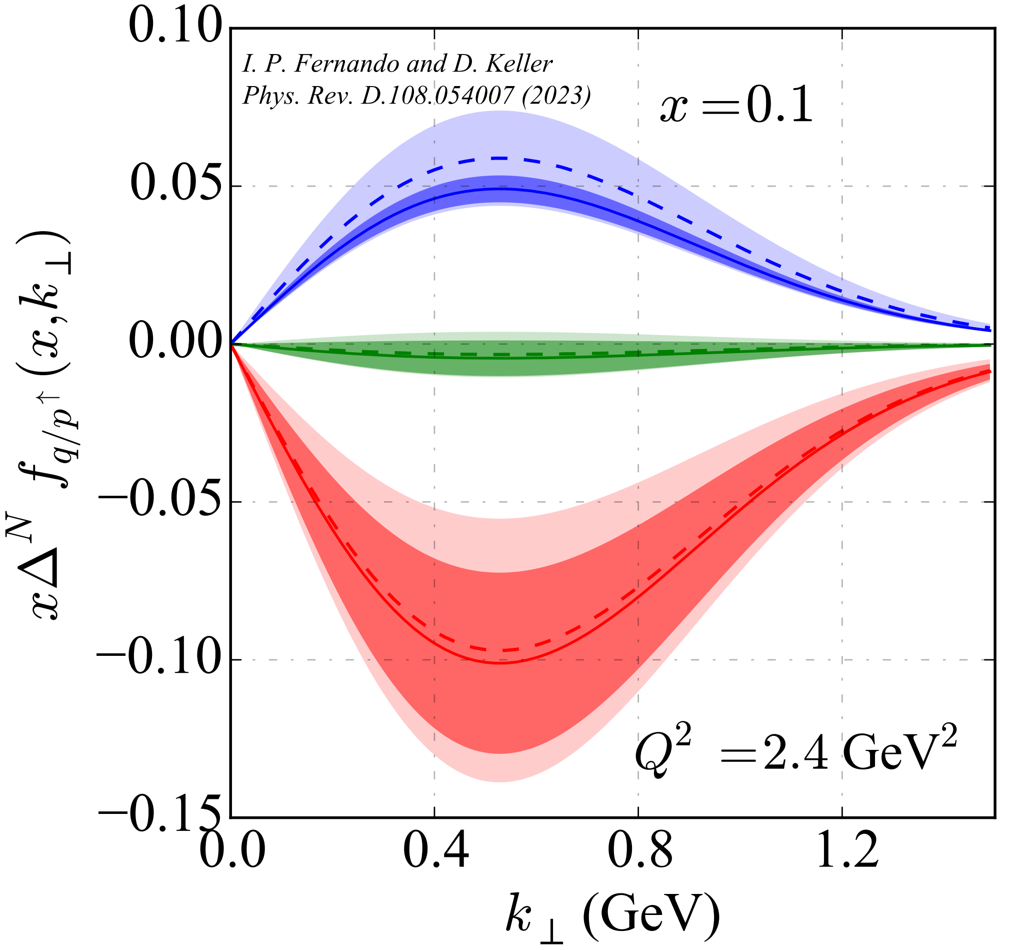


- ➢ All data points are well-described by the proton-DNN model.
- ➢ No kinematic cuts were implemented.

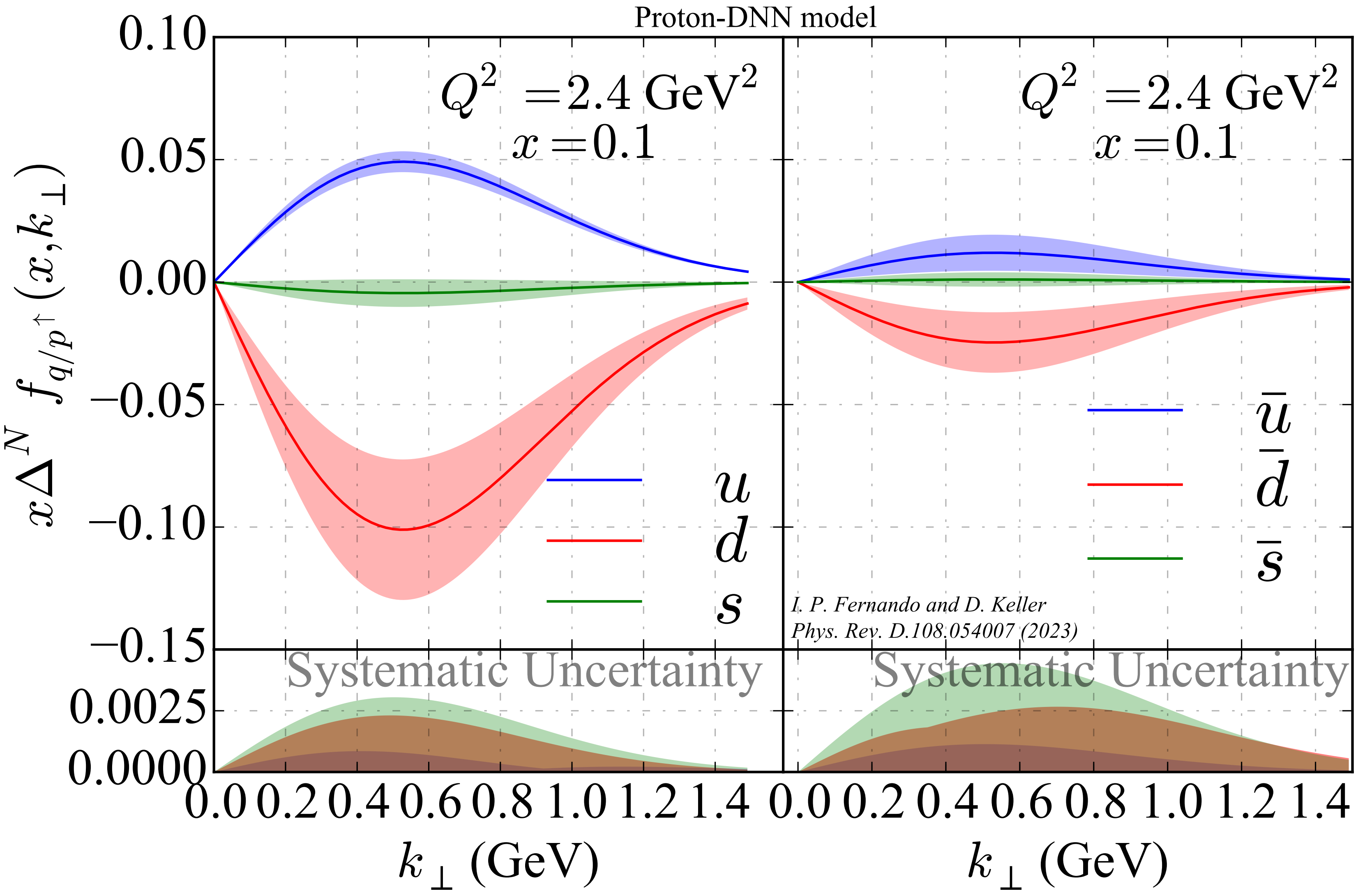
Calculated $\chi_{\text{total}}^2/N_{\text{pt}} = 1.04$

DNN Method: With Real data (Quality of the extraction)



The qualitative improvement of the extracted Sivers functions for u (blue), d (red), and s (green) quarks at x = 0.1 and Q^2=2.4 GeV^2 using the optimized proton-DNN model at the Second Iteration (solid-lines with dark-colored error bands with 68% CL), compared to the First Iteration (dashed-lines with light-colored error bands with 68% CL)

Sivers functions from the “Proton” DNN Model



Proton-DNN model

I. P. Fernando and D. Keller
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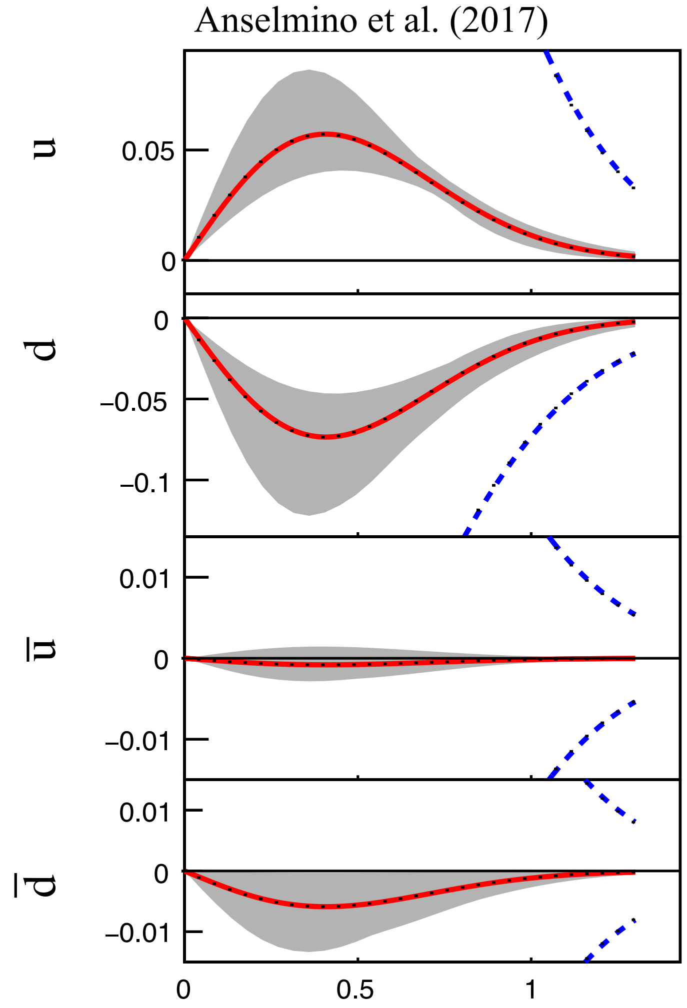
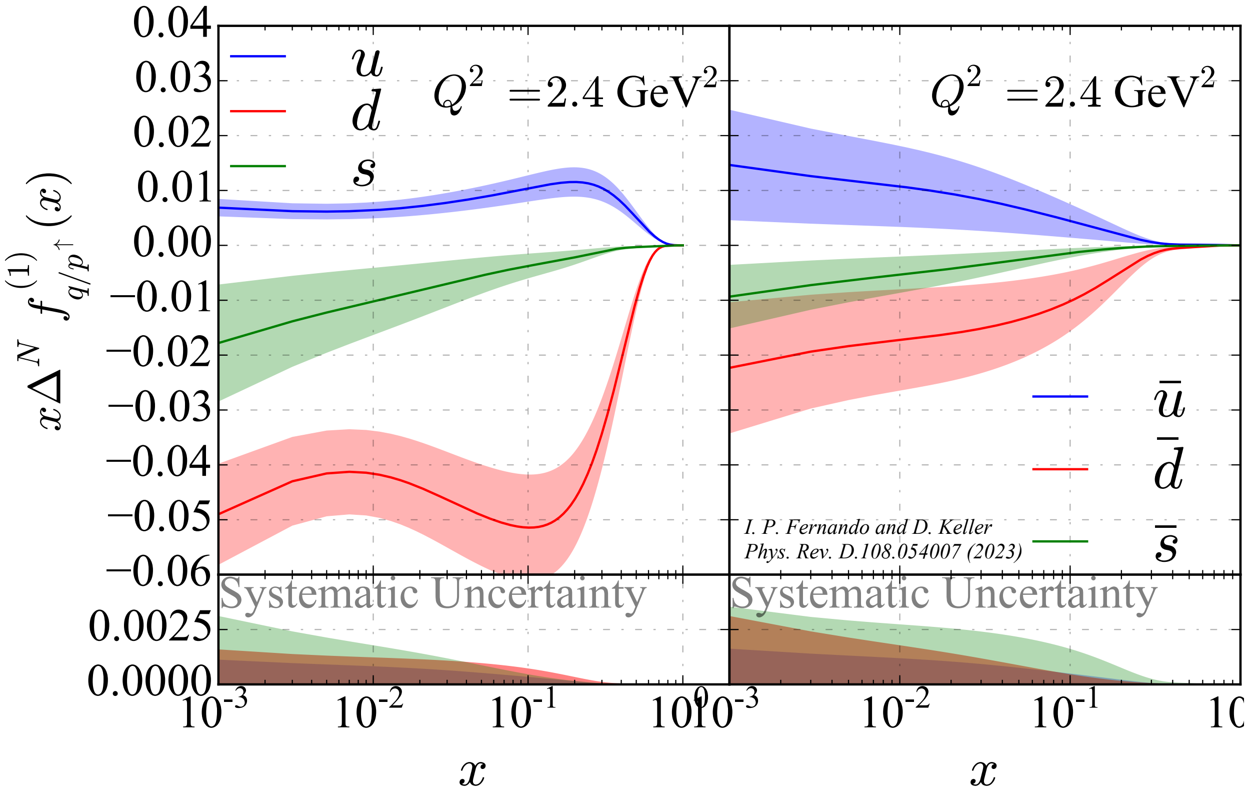


Anselmino et al. (2017)

Sivers 1st moments from the "Proton" Model

$$\Delta^N f^{(1)}_{q/p^\uparrow}(x) = \int d^2k_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f^{\perp(1)q}_{1T}(x)$$



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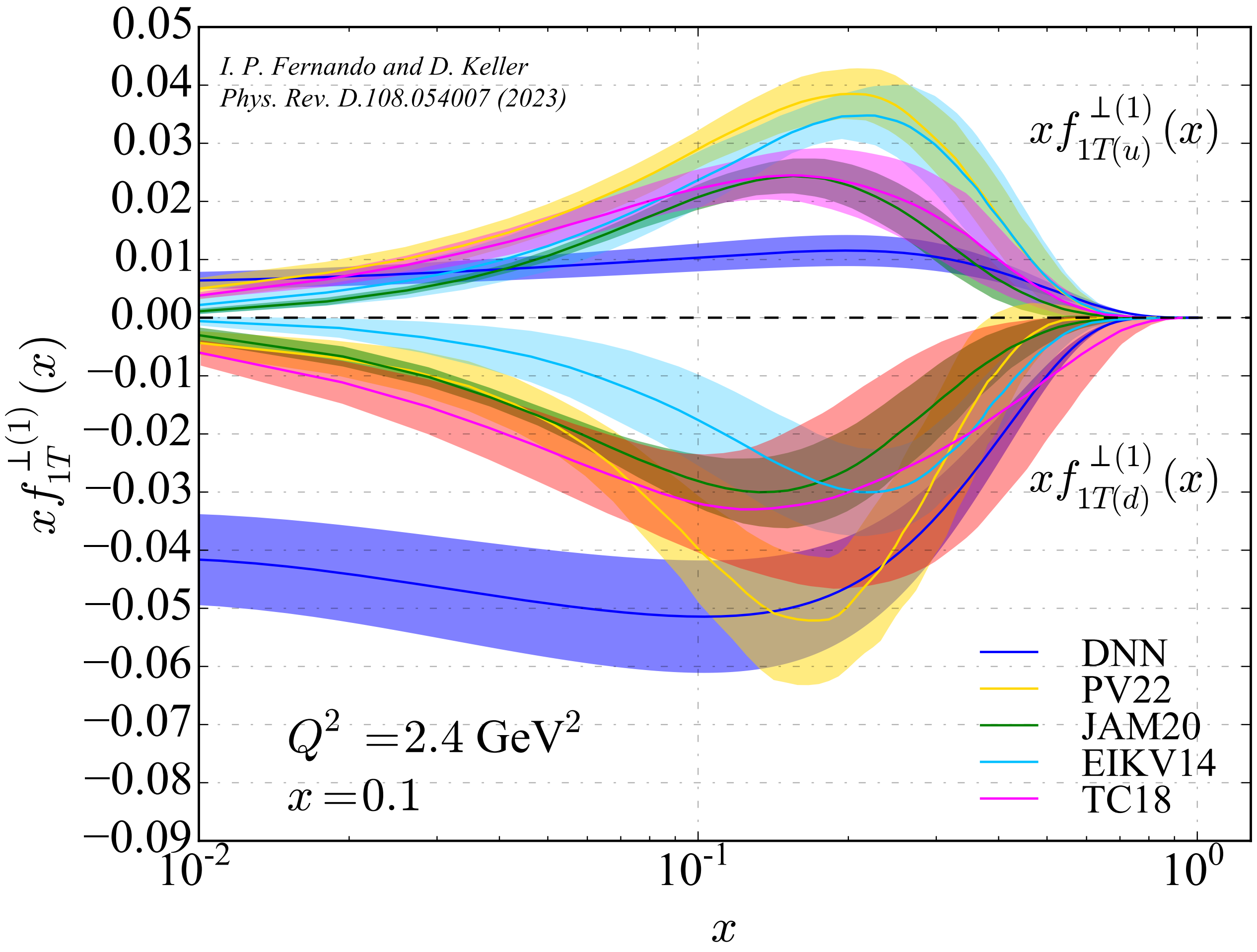

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3D Tomography from the "Proton" DNN Model

$$\rho^a_{p\uparrow}(x,k_x,k_y;Q^2) = f_1^a(x,k_\perp^2;Q^2) - \frac{k_x}{m_p} f_{1T}^{\perp a}(x,k_\perp^2;Q^2)$$

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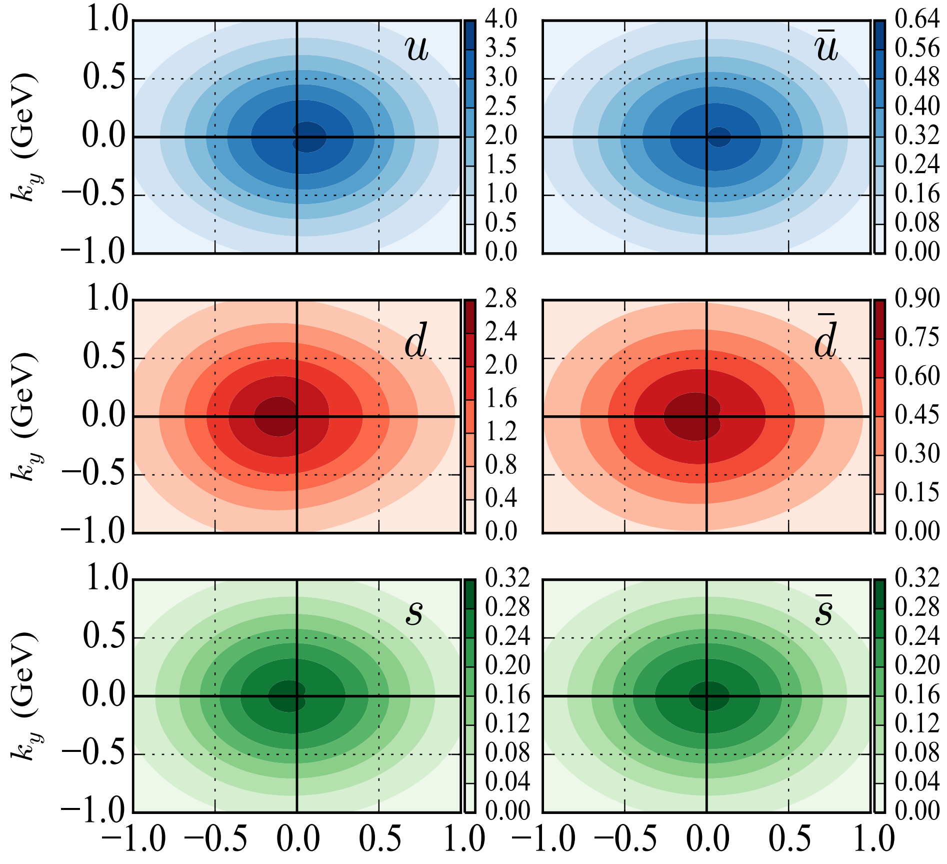
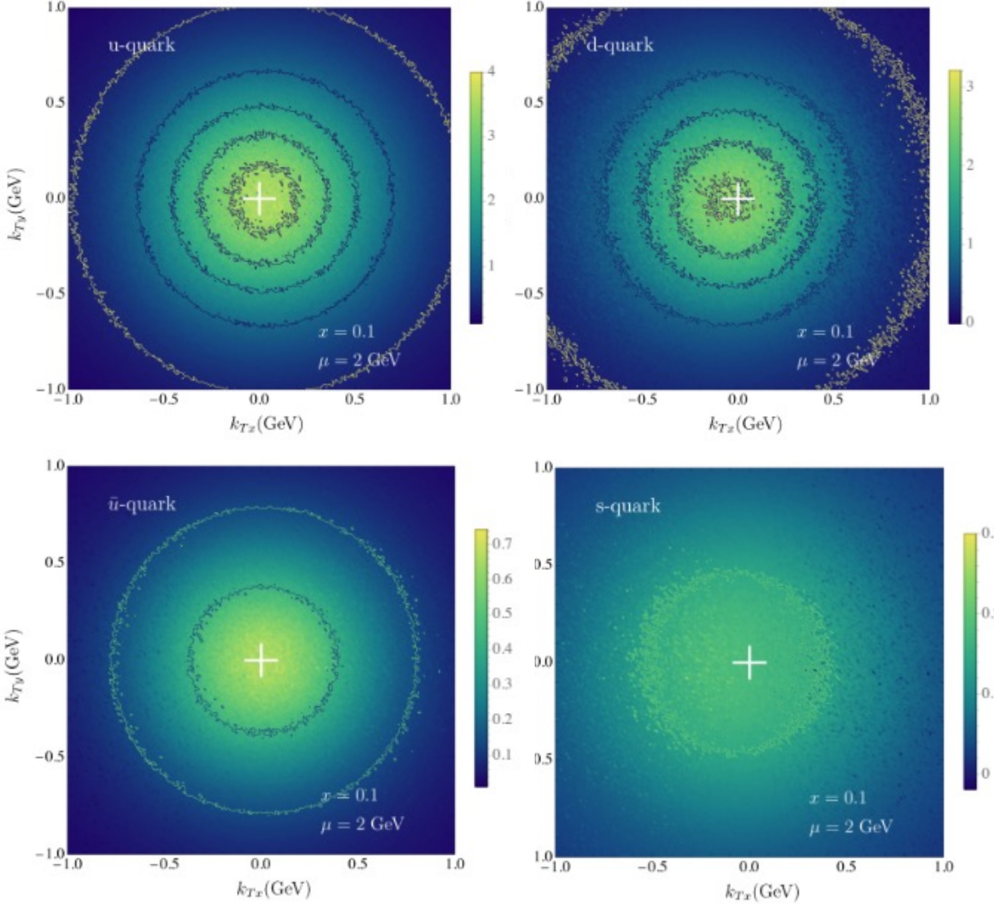
Proton-DNN model



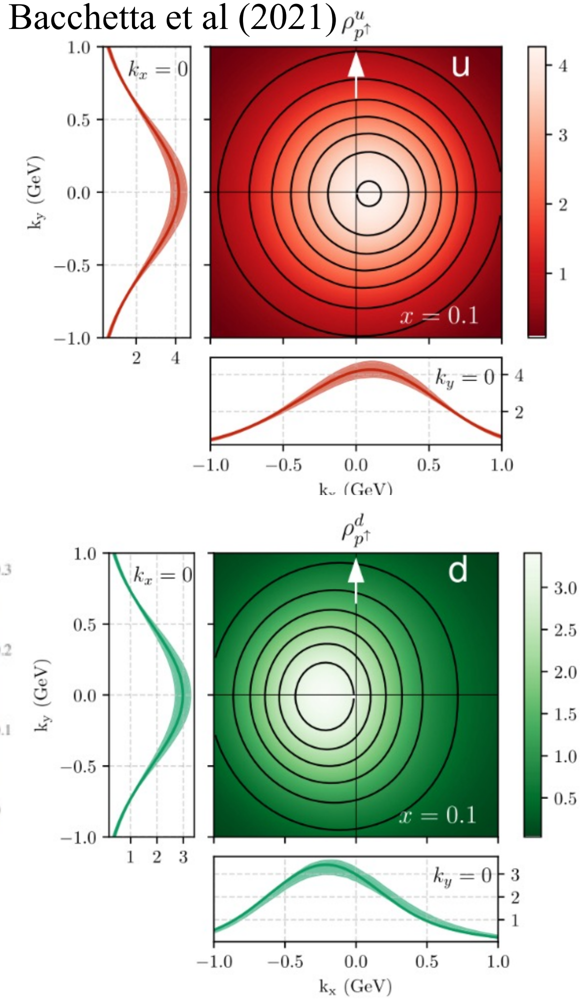
$Q^2 = 2.4$ GeV^2

$x = 0.1$

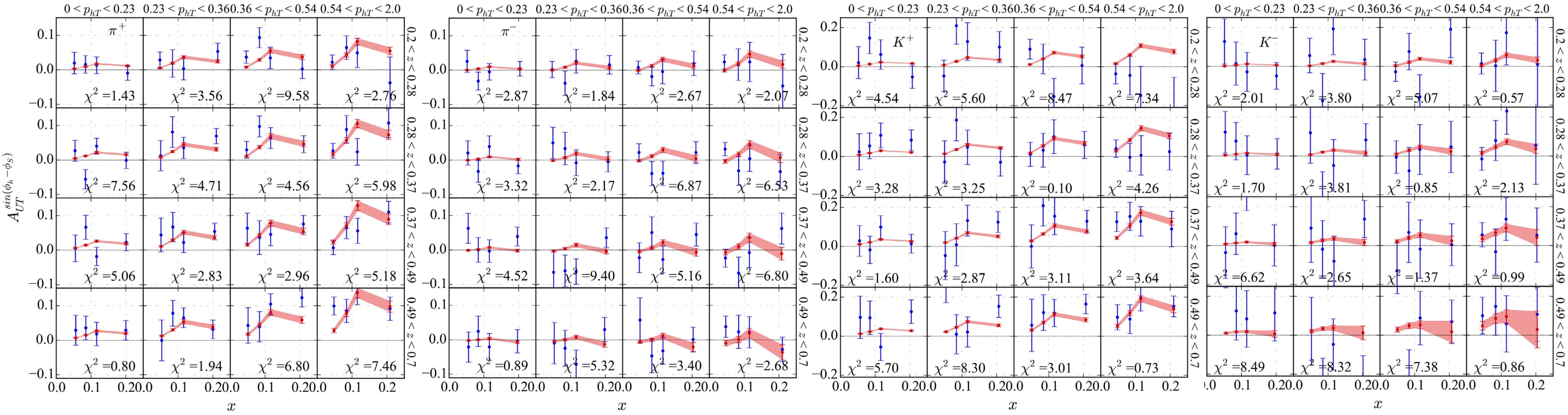
Bury et al (2021)



A. Bacchetta et al (2021)



Projections from the "Proton" DNN Model



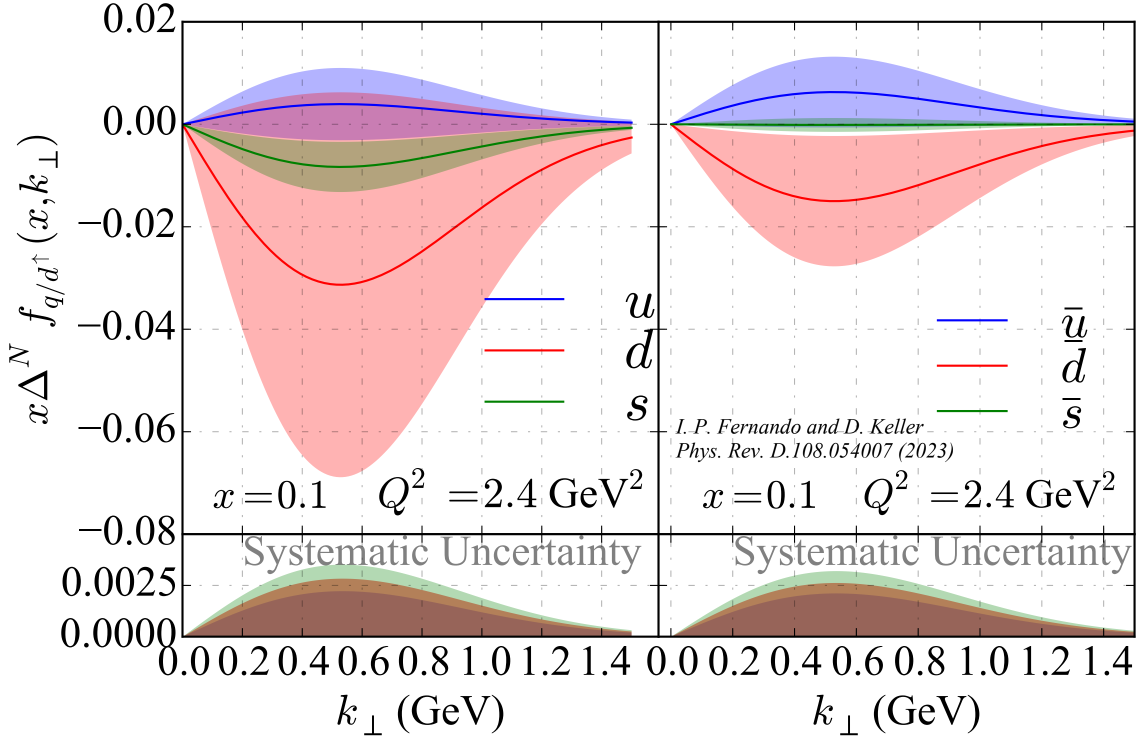
Projections of the of HERMES 2020 data for 3D kinematic bins, using the proton-DNN model including 68% C.L. error bands (in red) in comparison with the actual data points (in blue).

DNN Method: Results from the “Deuteron” Model

- ➢ Trained on COMPASS 2009 SIDIS data with Deuteron target.
- ➢ Did not imposed iso-spin symmetric conditions, or data cuts.

$$\cancel{f_{1T,u\leftarrow d}^{\perp} = f_{1T,d\leftarrow d}^{\perp} = \frac{f_{1T,u\leftarrow p}^{\perp} + f_{1T,d\leftarrow p}^{\perp}}{2}}$$

$$\Delta^N f_{q/p^\uparrow}^{(1)}(x) = \int d^2k_\perp \frac{k_\perp}{4m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) = -f_{1T}^{\perp(1)q}(x)$$



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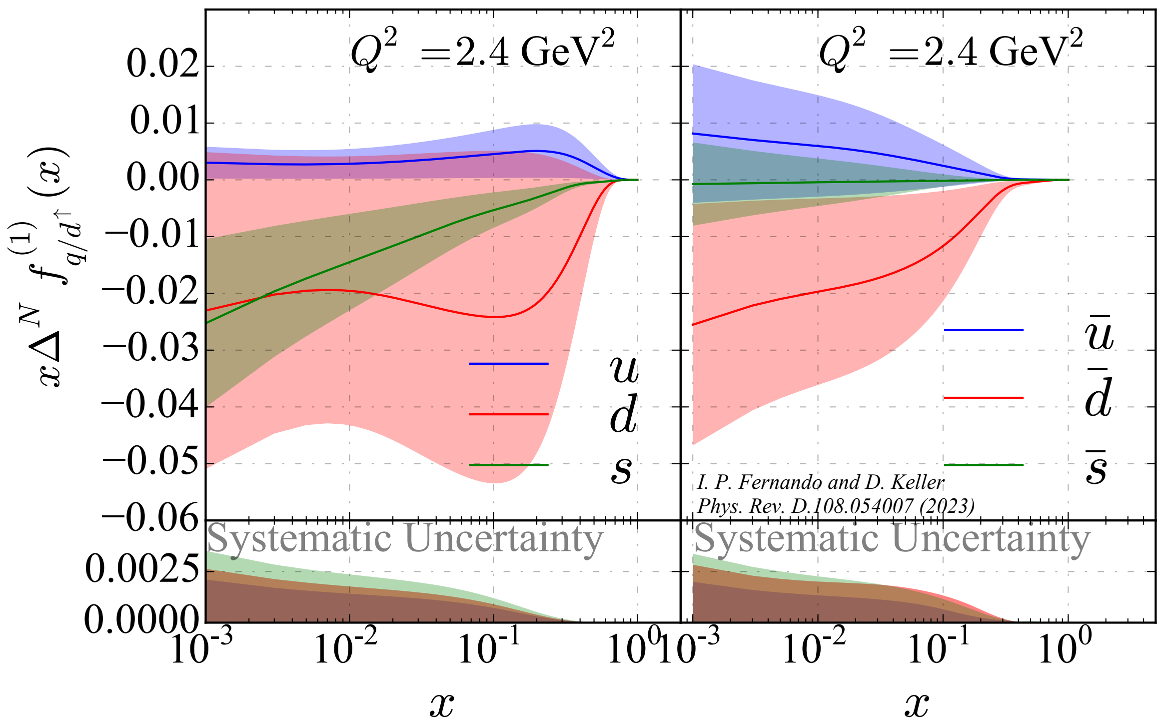

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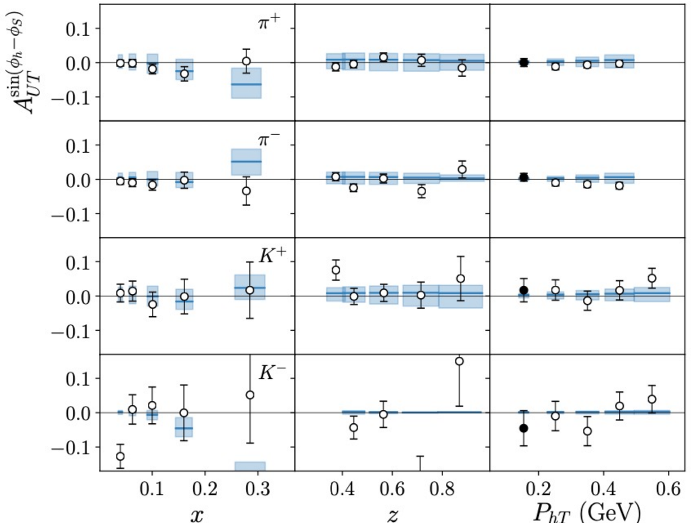
Deuteron DNN Fit Results

- No kinematic cuts are applied
  Deuteron-DNN model can describe data reasonably well
- No iso-spin symmetry conditions are applied

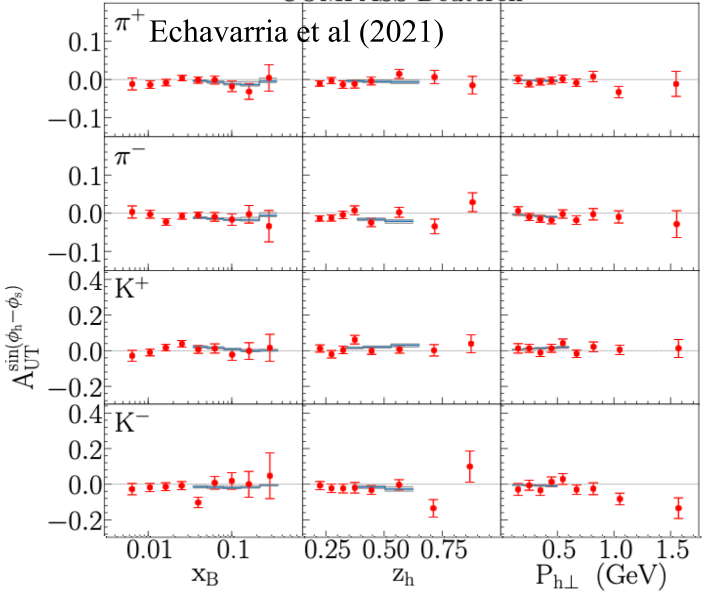
~~$f^{\perp}_{1T,u\leftarrow d} = f^{\perp}_{1T,d\leftarrow d} = \frac{f^{\perp}_{1T,u\leftarrow p} + f^{\perp}_{1T,d\leftarrow p}}{2}$~~

$\chi^2/N_{pt} = 0.81$

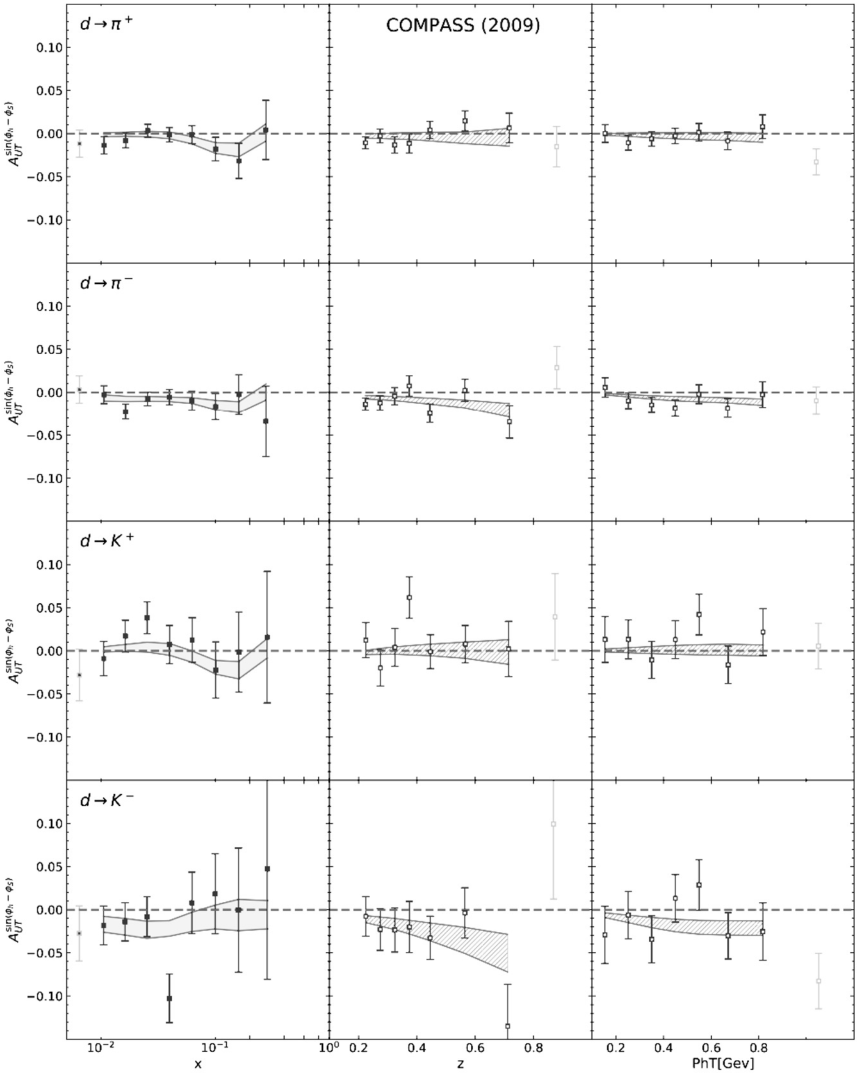
Bury et al (2021)



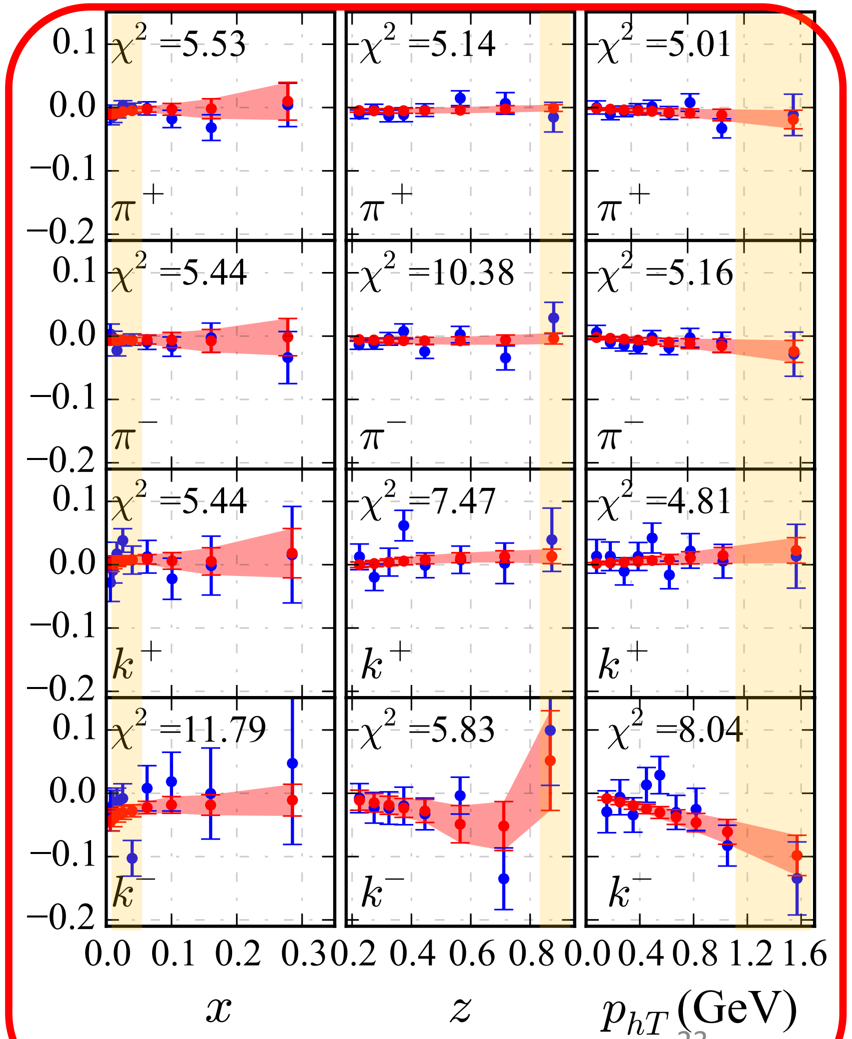
COMPASS Deuteron



Bacchetta et al (2022)



COMPASS 2009



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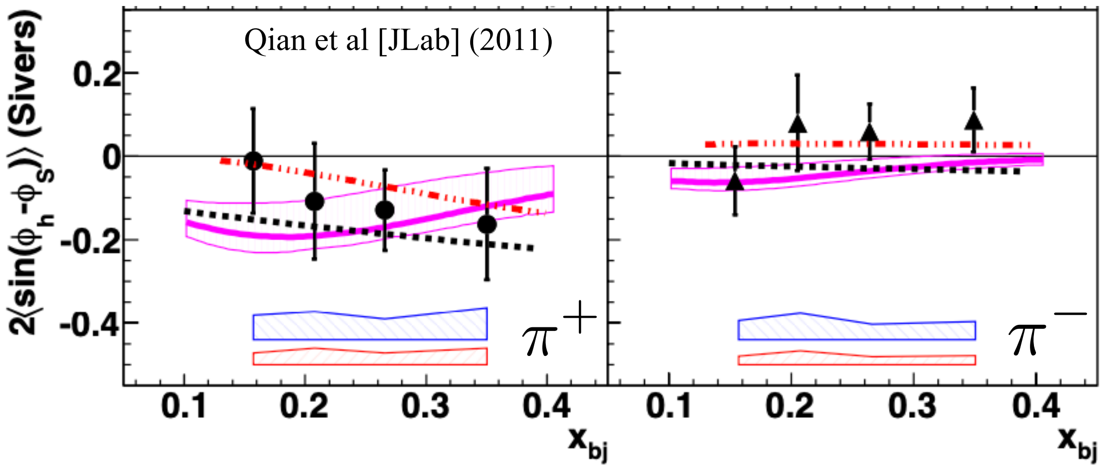
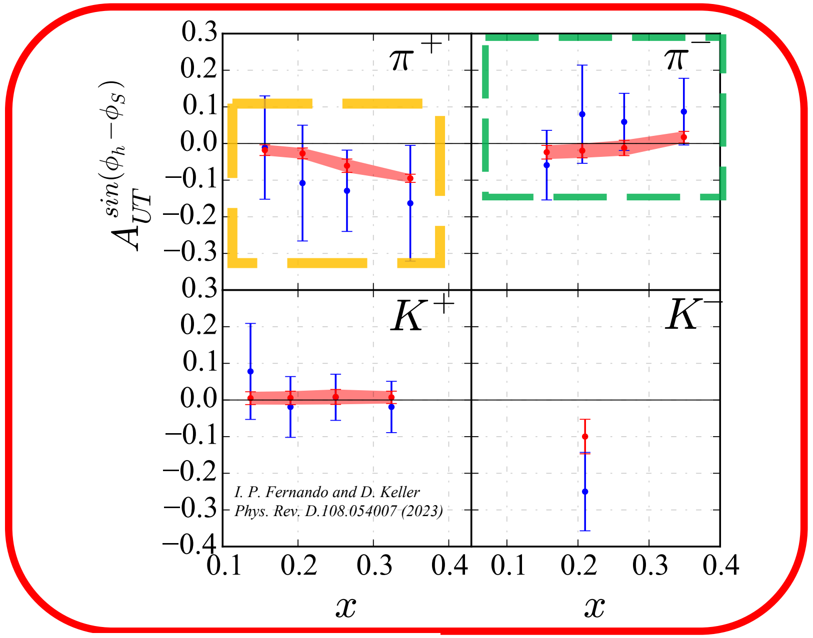
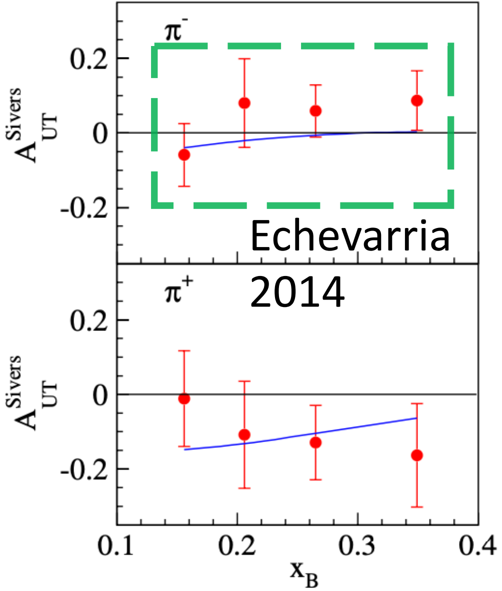
Deuteron DNN Projections for JLab Kinematics


Qian et al [JLab] (2011)

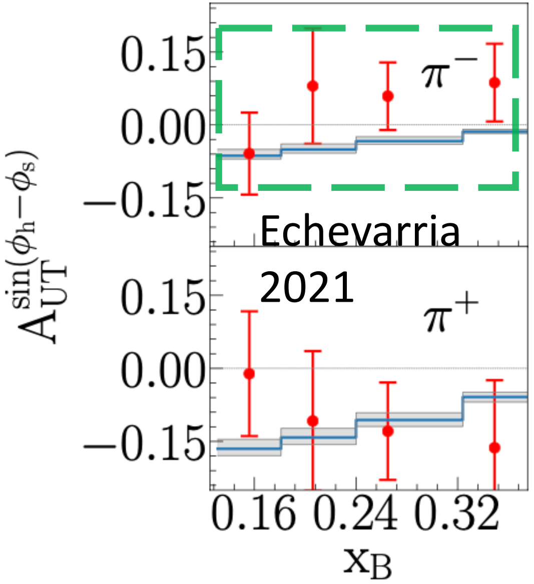
Deuteron-DNN

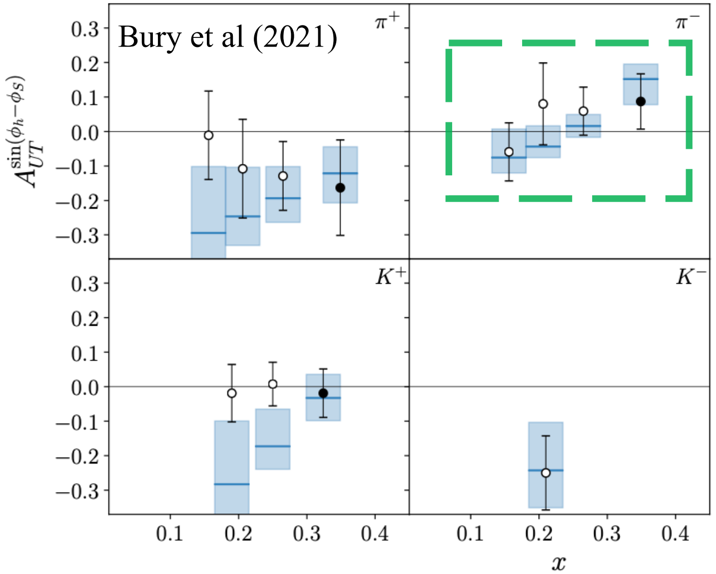


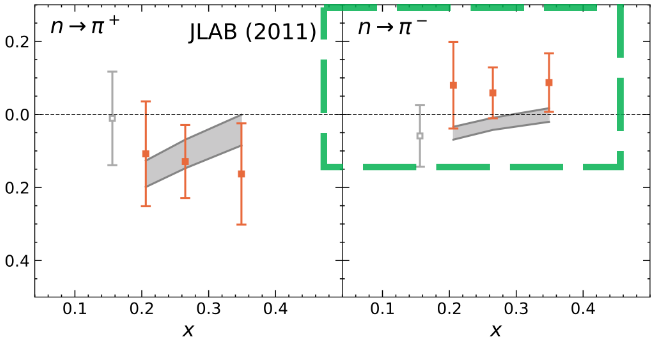
Echevarria et al (2014)



Echevarria et al (2021)



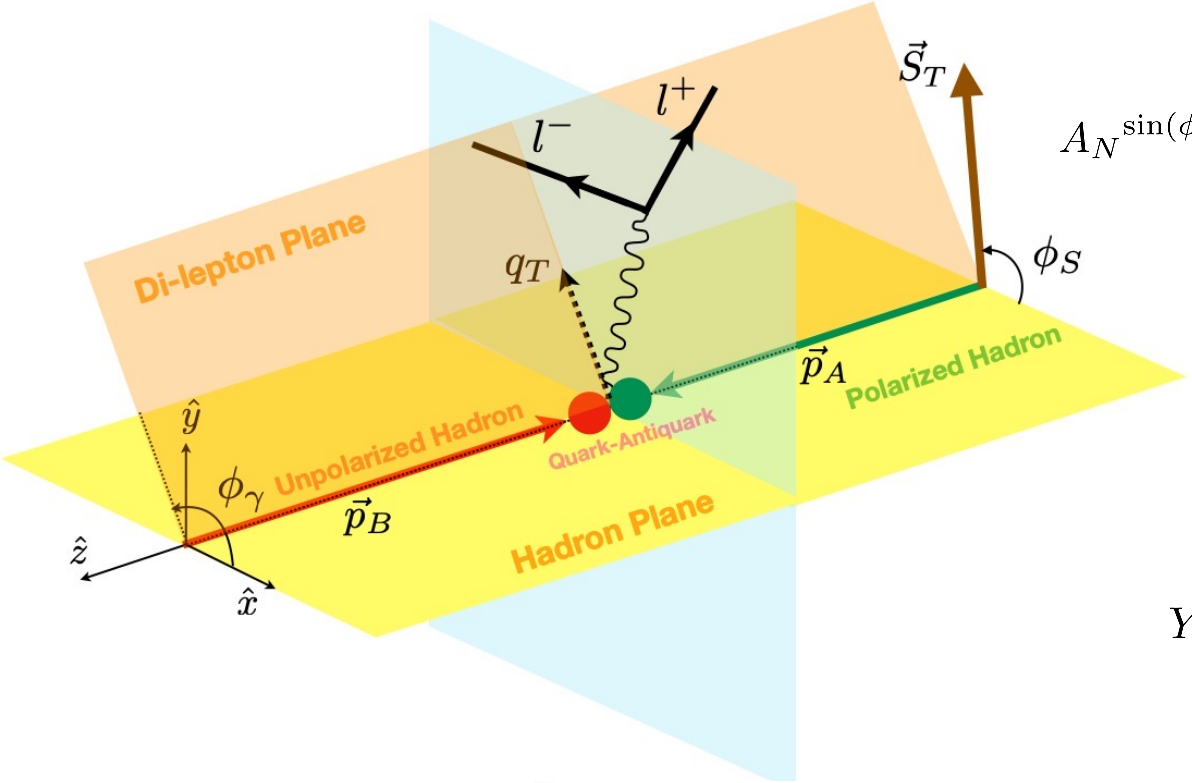

Bury et al (2021)



Bacchetta et al (2022)

DNN Model Projections: DY

Based on Anselmino et al. (2017)



$$A_N{}^{\sin(\phi_\gamma-\phi_S)}(x_F, M, q_T) \quad = \mathcal{B}_0(q_T, m_1)\frac{\sum_q \frac{e_q^2}{x_1+x_2}\mathcal{N}_q(x_1)f_{q/A}(x_1)f_{\bar{q}/B}(x_2)}{\sum_q \frac{e_q^2}{x_1+x_2}f_{q/A}(x_1)f_{\bar{q}/B}(x_2)}$$

$$\mathcal{B}_0(q_T, m_1) = \frac{q_T\sqrt{2e}}{m_1}\frac{Y_1(q_T, k_S, k_{\perp 2})}{Y_2(q_T, k_{\perp 1}, k_{\perp 2})}$$

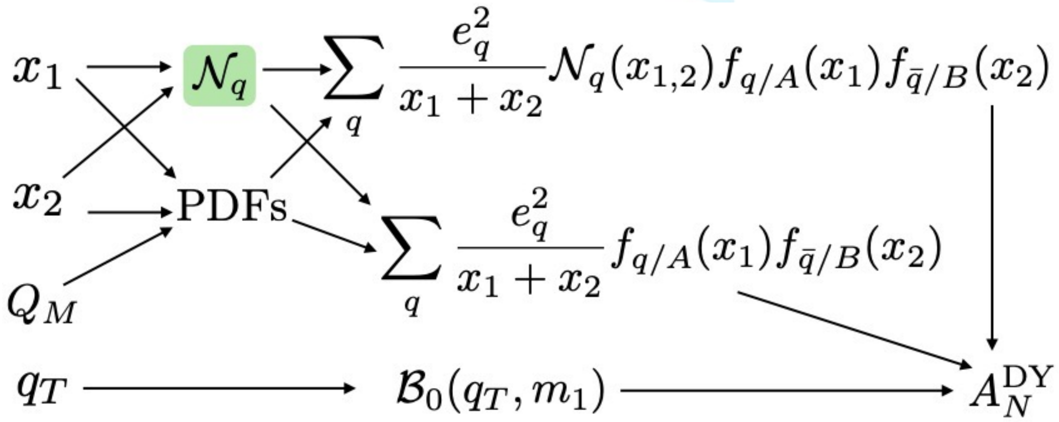
$$Y_1(q_T, k_S, k_{\perp 2}) = \left(\frac{\langle k_S^2\rangle^2}{\langle k_{\perp 2}^2\rangle\left(\langle k_S^2\rangle + \langle k_{\perp 2}^2\rangle\right)^2}\right) \times \exp\left(\frac{-q_T^2}{\langle k_S^2\rangle + \langle k_{\perp 2}^2\rangle}\right)$$

$$Y_2(q_T, k_{\perp 1}, k_{\perp 2}) = \left(\frac{1}{\langle k_{\perp 1}^2\rangle + \langle k_{\perp 2}^2\rangle}\right) \times \exp\left(\frac{-q_T^2}{\langle k_{\perp 1}^2\rangle + \langle k_{\perp 2}^2\rangle}\right)$$

$$\frac{1}{\langle k_S^2\rangle} = \frac{1}{m_1^2} + \frac{1}{\langle k_{\perp 1}^2\rangle}$$

$$\langle k_{\perp 1}^2\rangle = \langle k_{\perp 2}^2\rangle = \langle k_\perp^2\rangle = 0.25\ \mathrm{GeV}^2$$

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp)\big|_{\mathrm{SIDIS}} = -\,\Delta^N f_{q/p^\uparrow}(x, k_\perp)\big|_{\mathrm{DY}}$$



x_1

x_2

Q_M

q_T

$\mathcal{N}_q$

PDFs

$$\sum_q \frac{e_q^2}{x_1+x_2}\mathcal{N}_q(x_{1,2})f_{q/A}(x_1)f_{\bar{q}/B}(x_2)$$

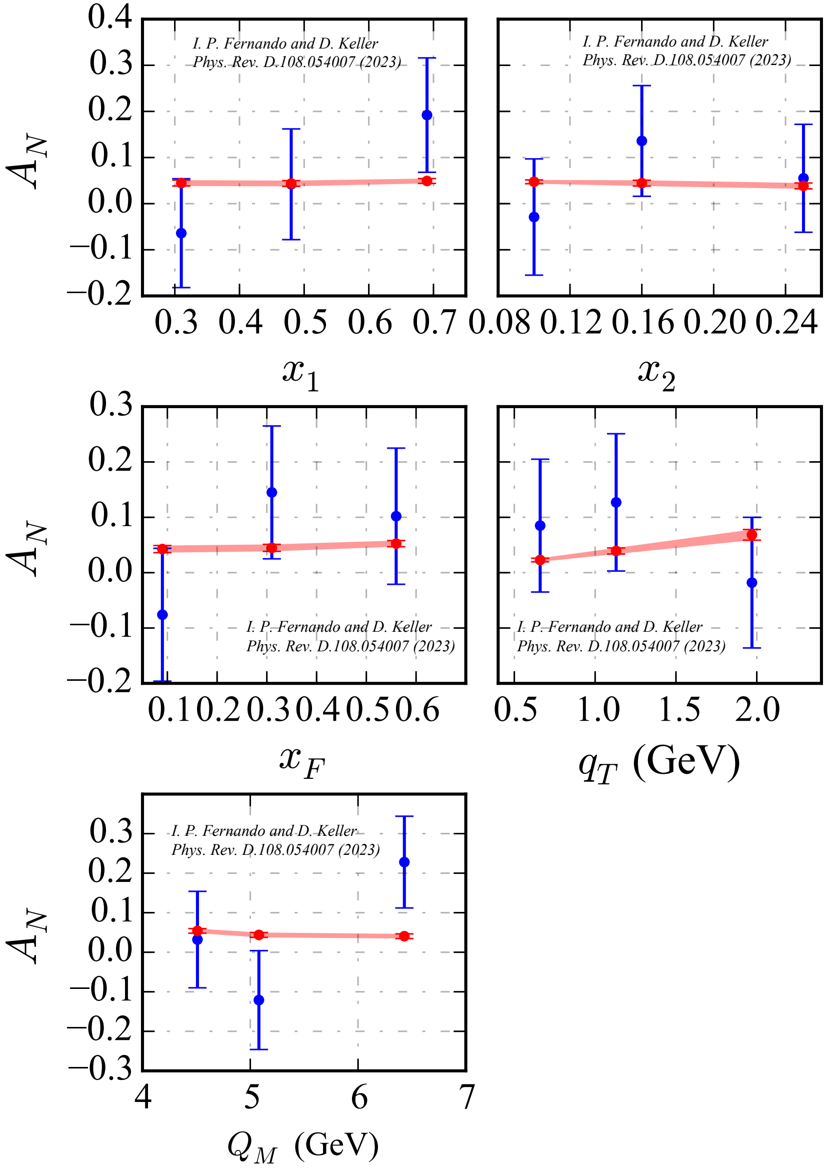
$$\sum_q \frac{e_q^2}{x_1+x_2}f_{q/A}(x_1)f_{\bar{q}/B}(x_2)$$

$$\mathcal{B}_0(q_T, m_1)$$

$$A_N^{\mathrm{DY}}$$

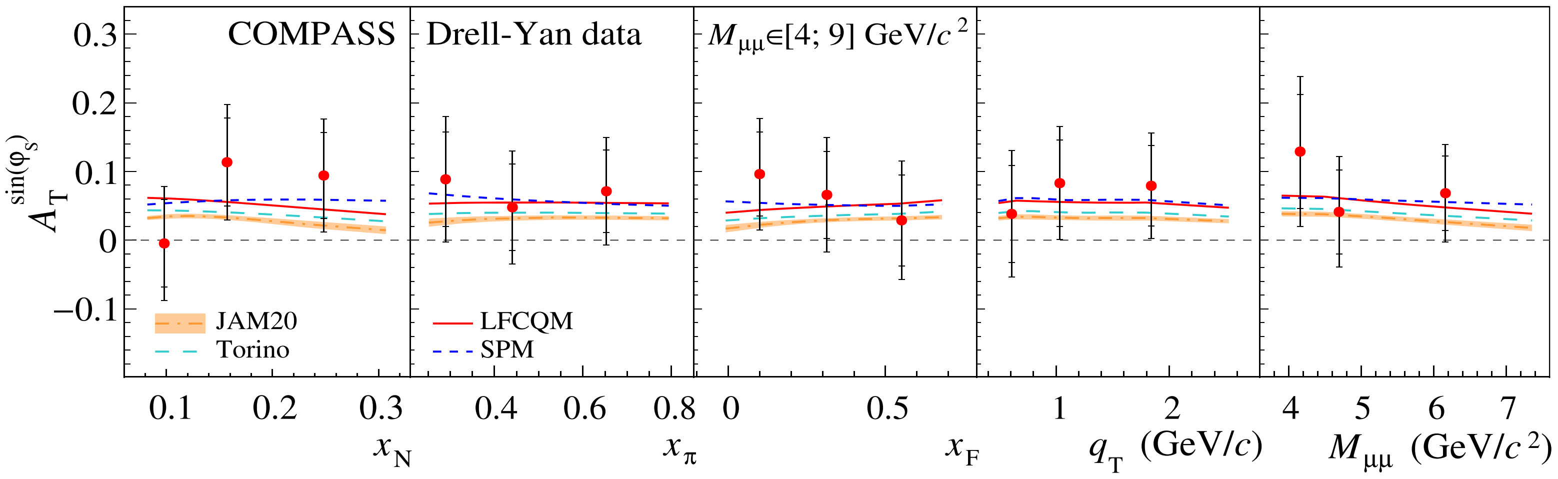
DNN (Proton) Model Projections: DY

COMPASS 2017 DY Projections



COMPASS 2024

PHYSICAL REVIEW LETTERS **133,** 071902 (2024)

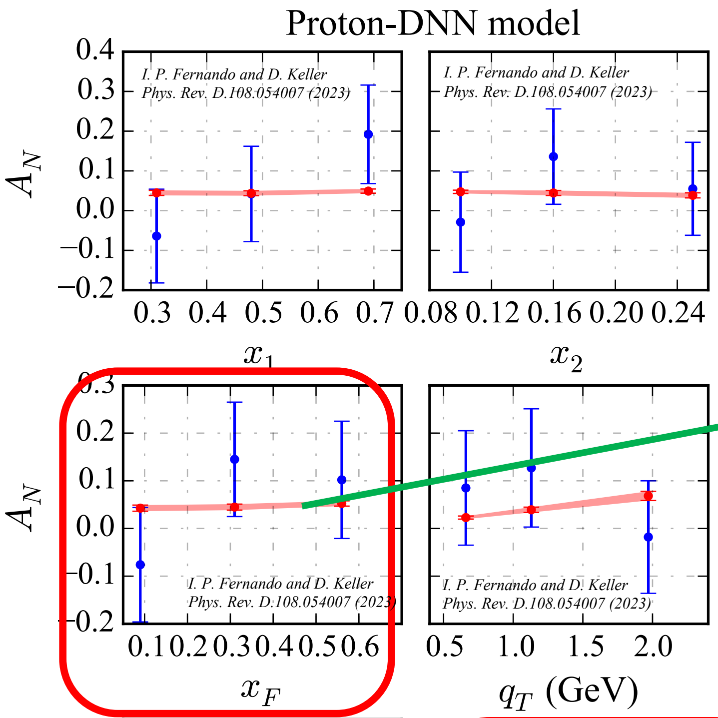


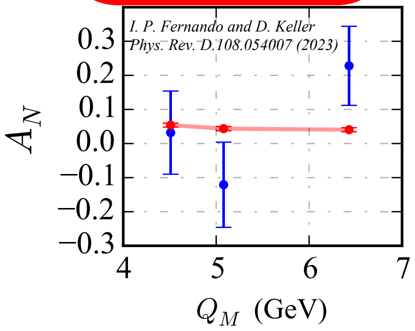
Note: These proton-DNN projections based on the assuming the sign-change of the Sivers functions

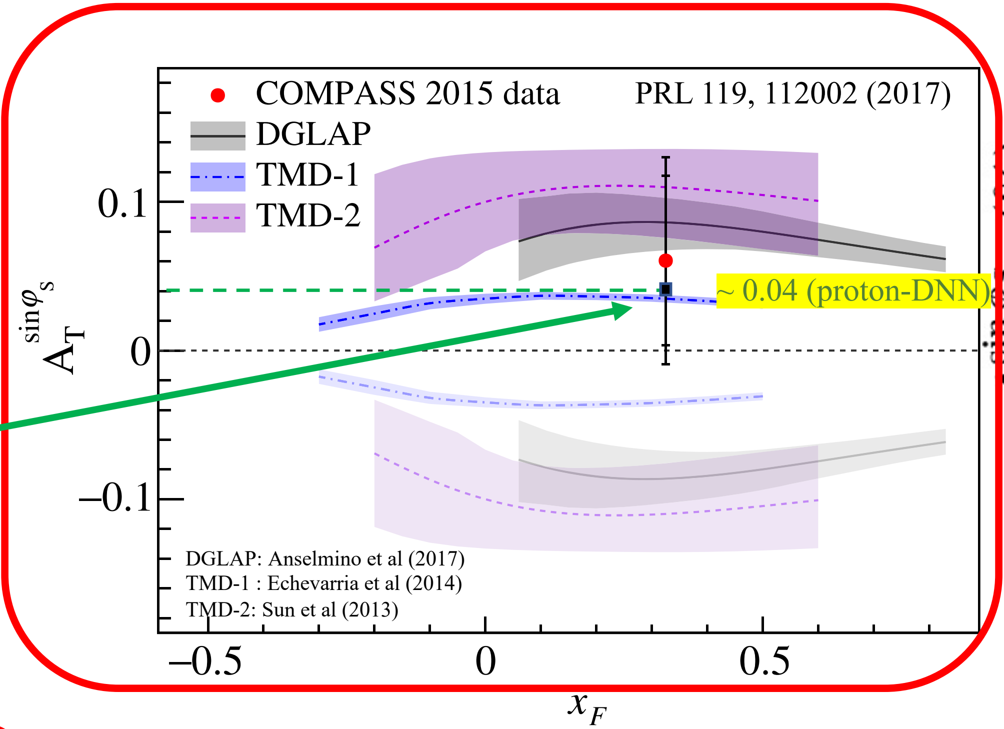
DNN Model Projections: DY

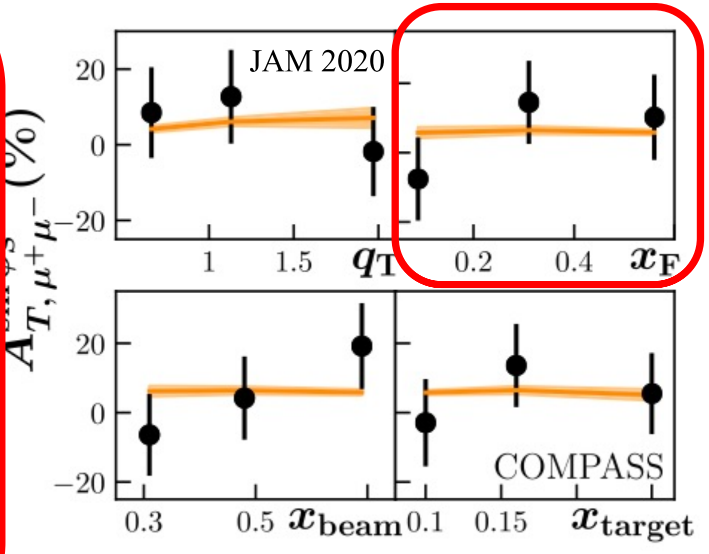
COMPASS 2017 DY Projections

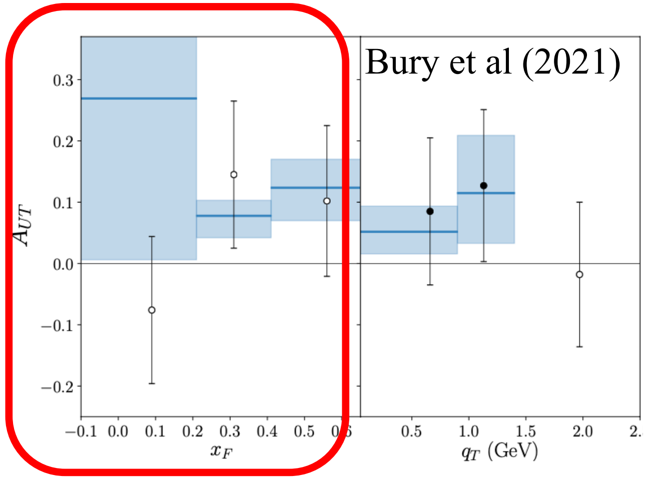
Proton-DNN model

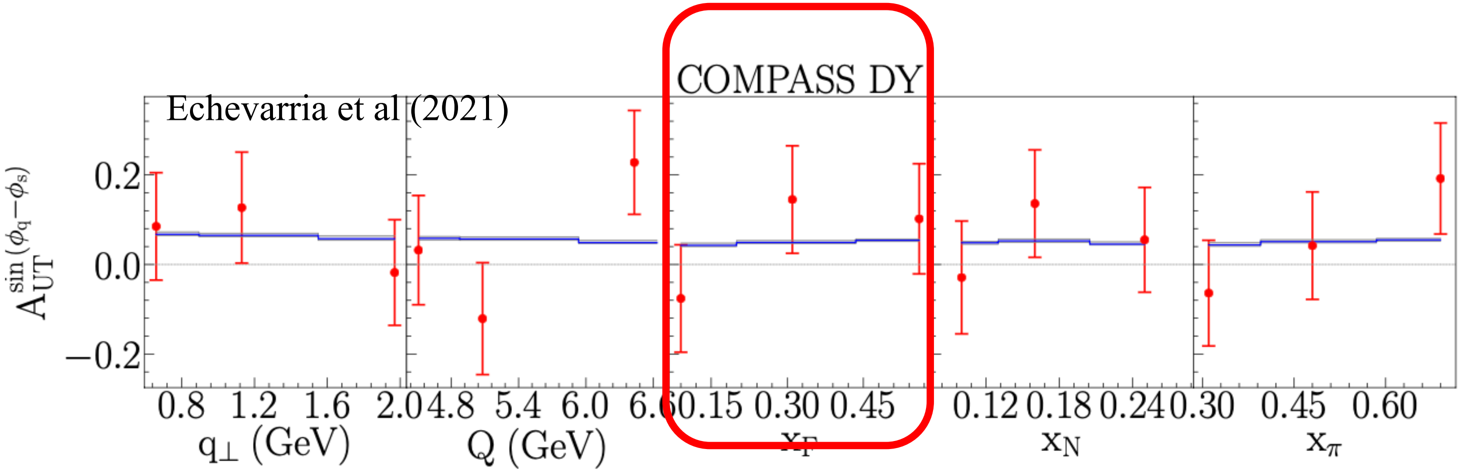






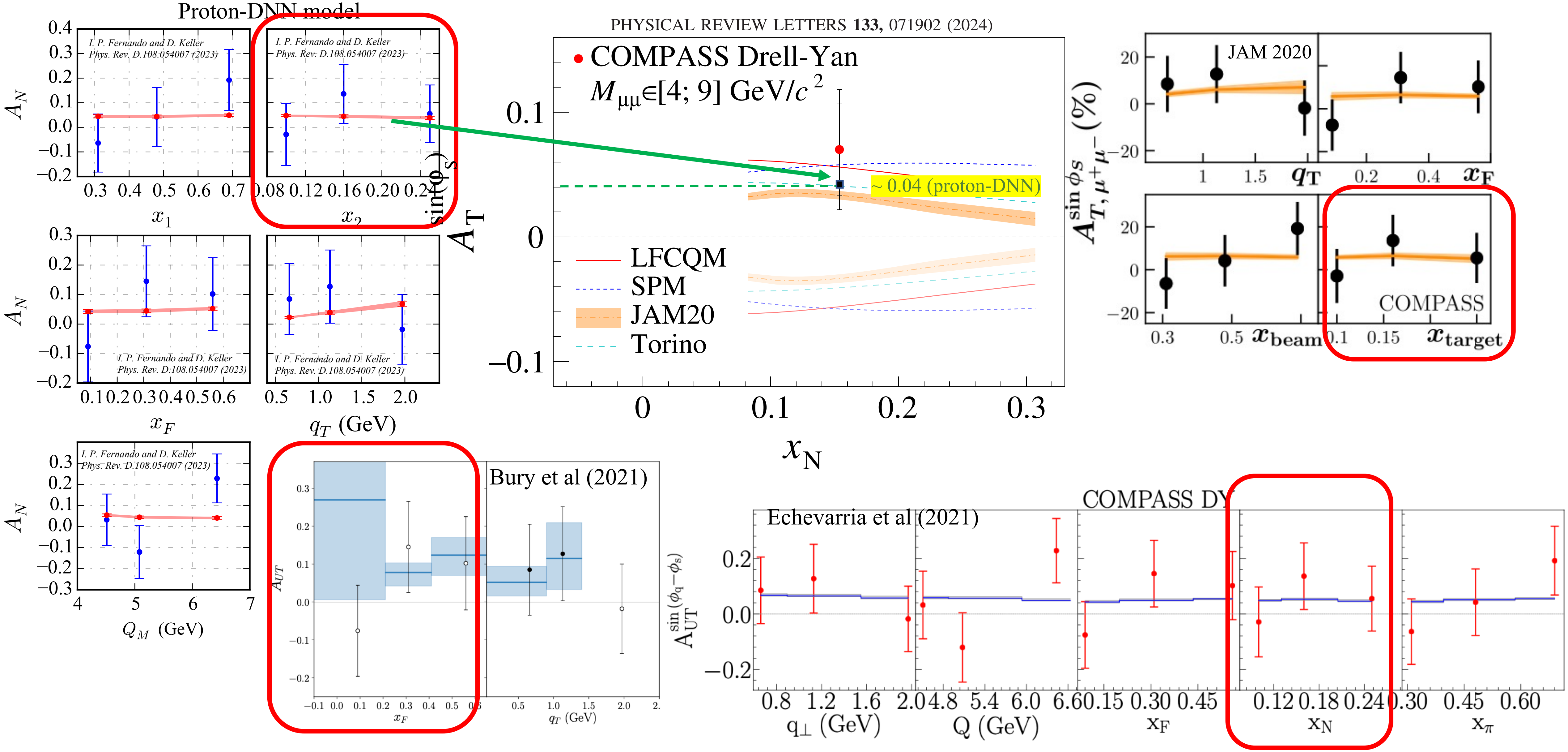




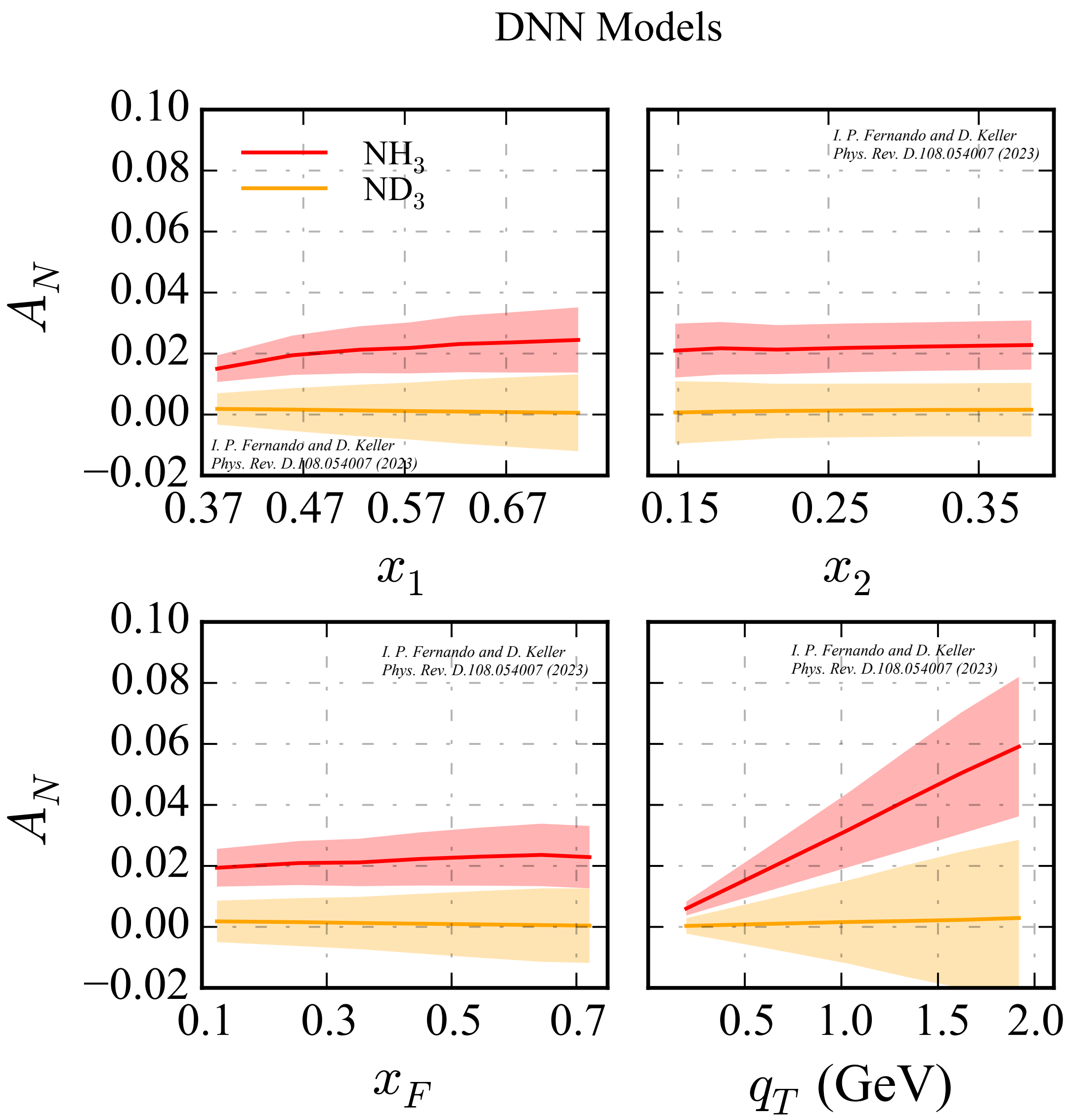


DNN Model Projections: DY

In Comparison with COMPASS 2024 Final



DNN Model Projections: DY @ SpinQuest



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- SpinQuest (E1039) experiment at Fermilab is aiming to extract the Sivers function for the light-sea quarks.
- Unpolarized 120 GeV proton beam with polarized proton and deuteron targets (separately).
- Proton-DNN model predictions (Red)
  Deuteron-DNN model predictions (Orange)

Systematic Studies: data cuts

So far, the applicability of TMD factorization was ensured by applying cuts to SIDIS data based on various criteria in the literature.

$$
\begin{aligned}
W^{\mu\nu} = & \sum_f |\mathcal{H}_f(Q^2,\mu)|^{\mu\nu} \\
& \times \int d^2k_\perp d^2p_\perp \delta^{(2)}(z_h k_\perp + p_\perp - p_{hT}) \\
& \times F_{f/N^\uparrow}(x, z_h k_\perp, S; \mu, \zeta_F) D_{h/f}(z_h, p_\perp; \mu, \zeta_D) \\
& + Y(p_{hT}, Q^2),
\end{aligned}
$$

Examples:

1. Bury et al JHEP 05 (2021) 151
   $Q > 2$ GeV
   $\delta = p_{hT}/zQ \leq 0.3$
2. Echevarria et al JHEP 01 (2021) 126
   $q_T/Q < 0.75$
3. JAM2020
   $Q^2 > 1.63\ \mathrm{GeV}^2,\ \ 0.2 < z < 0.6,\ \ 0.2 < p_{hT} < 0.9$ GeV

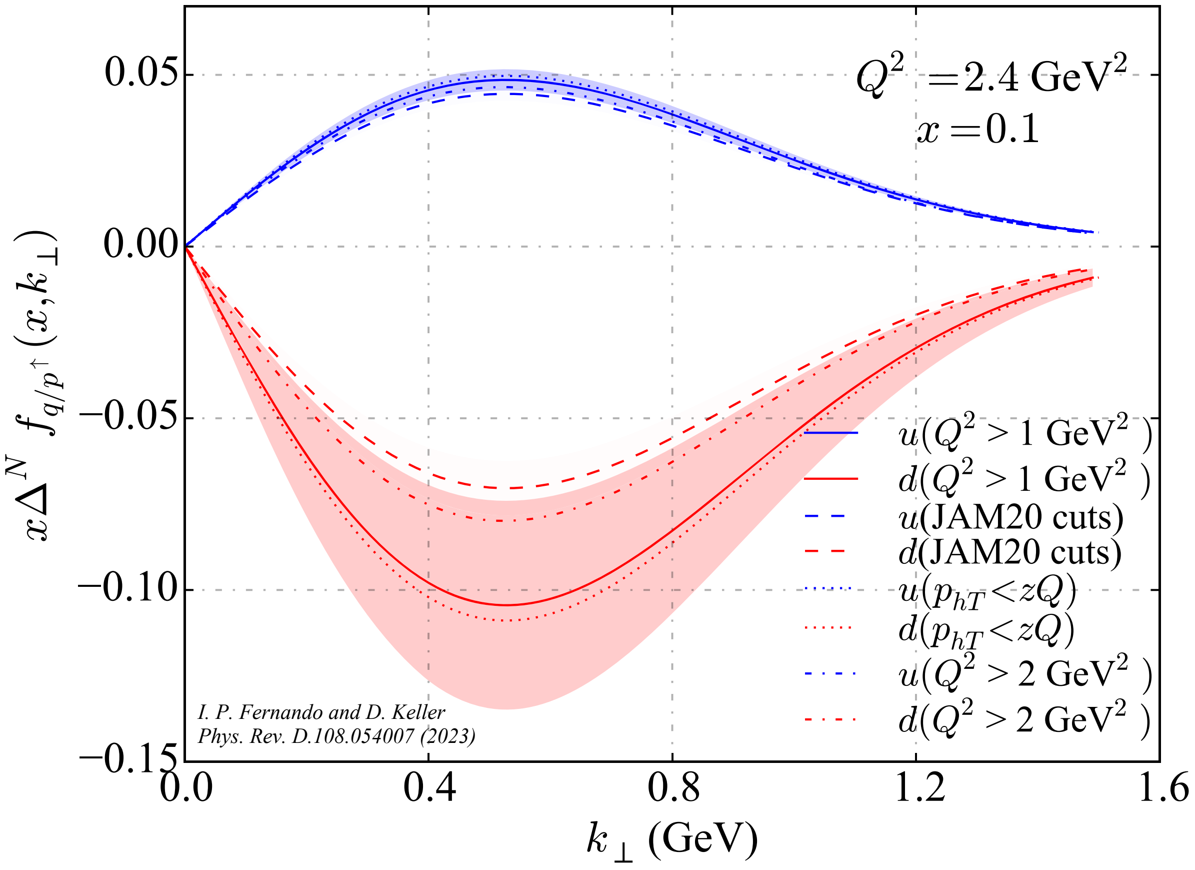

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FIG. 17. Solid lines with light band represent the *u* (in blue), *d* (in red) Sivers functions using the cut $Q^2 > 1$ GeV^2. These resulting DNN models made from the cuts from all tests are also shown.

Systematic Studies: data cuts

$$
\begin{aligned}
W^{\mu\nu} = & \sum_f |\mathcal{H}_f(Q^2,\mu)|^{\mu\nu} \\
& \times \int d^2k_\perp d^2p_\perp \delta^{(2)}(z_h k_\perp + p_\perp - p_{hT}) \\
& \times F_{f/N^\uparrow}(x, z_h k_\perp, S; \mu, \zeta_F) D_{h/f}(z_h, p_\perp; \mu, \zeta_D) \\
& + Y(p_{hT}, Q^2),
\end{aligned}
$$

In addition to the basic data cut $Q^2 > 1$ GeV^2 we performed $Q^2 > 2$ GeV^2 and, $p_{hT} < zQ$ cuts separately with the proton-DNN model to understand the impact on the extracted Sivers functions.

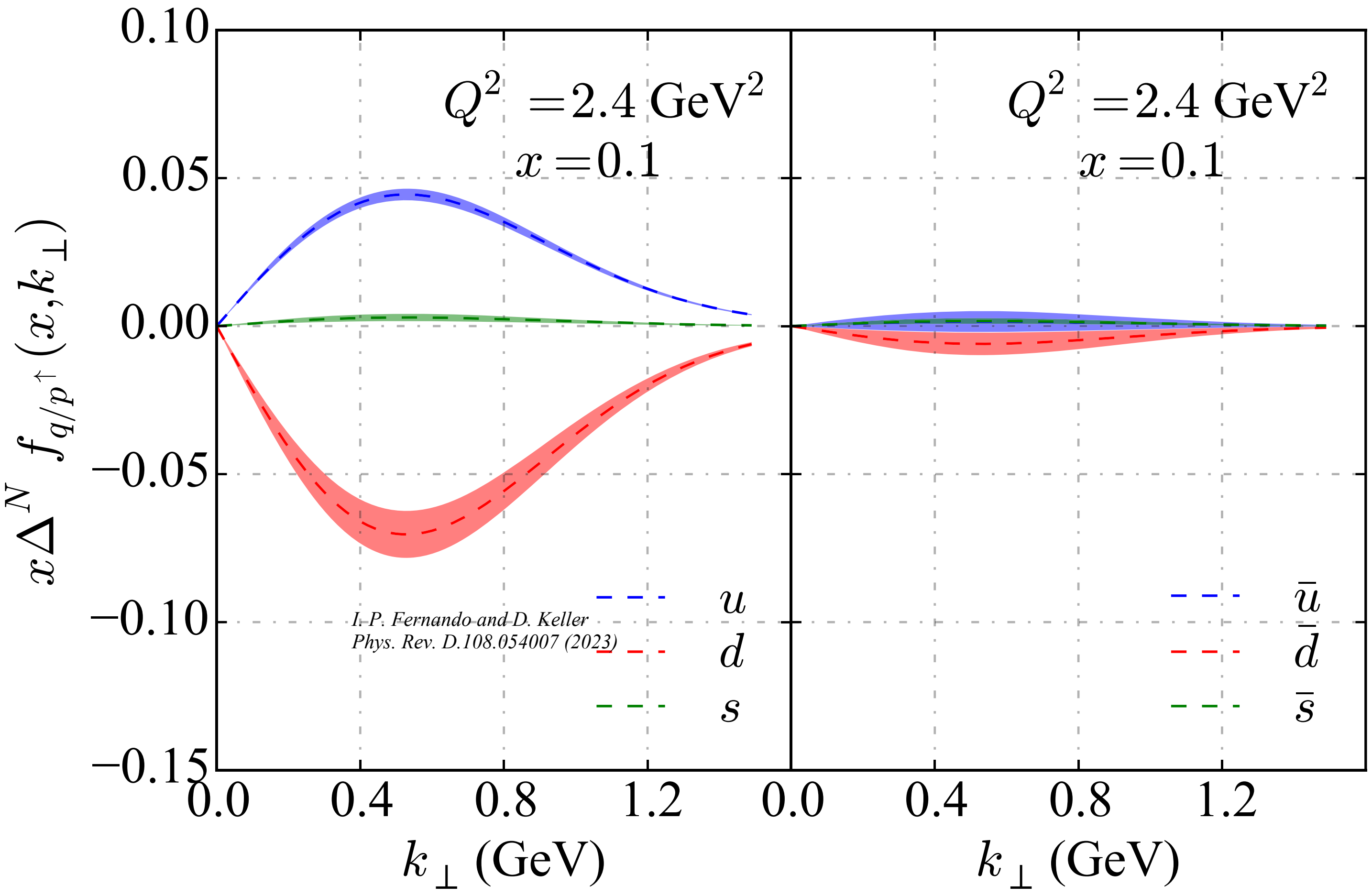

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FIG. 18. Sivers functions from a retrained DNN model using the cuts [65] to the data demonstrating that being selective with the data can reduce the error bands of the fit but may also add an unintentional bias.

Systematic Studies: Choice of h(k)

$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\mathcal{N}_q(x)h(k_\perp)f_{q/p}(x,k_\perp)$$

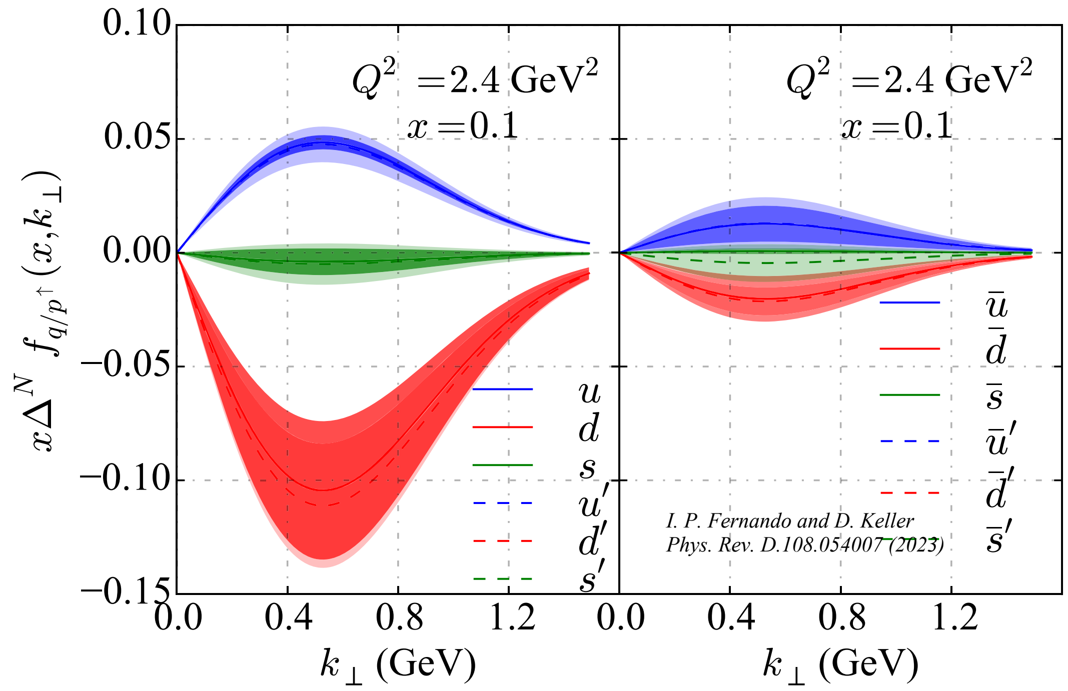

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FIG. 19. Using two different $h(k_\perp)$. Solid line with dark band represents the Sivers functions with $h(k_\perp) = \sqrt{2e}\frac{k_\perp}{m_1}e^{-k_\perp^2/m_1^2}$, whereas the dashed line with light band represents the Sivers functions with $h(k_\perp) = \frac{2k_\perp m_1}{m_1^2+k_\perp^2}$.

$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{m_1}\,e^{-k_\perp^2/m_1^2}$$

$$h(k_\perp) = \frac{2k_\perp m_1}{m_1^2 + k_\perp^2}$$

- ➢ It is clear that the DNN is capable of incorporating both types of h(k) without affecting the Sivers functions in the final model as well as the asymmetries (with deviation less than 1%).
- ➢ This is because DNN demonstrates that it maps to the h(k) such that the Sivers function is nearly unchanged.

Systematic Studies : TMD Evolution

$$\mathcal{N}_q(x) \longrightarrow \mathcal{N}_q(x, Q^2)$$

The solution of the TMD evolution equations

$$\mu^2 \frac{dF(x,b;\mu,\zeta)}{d\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2} F(x,b;\mu,\zeta)$$

$$\zeta \frac{F(x,b;\mu,\zeta)}{d\zeta} = -\mathcal{D}(b,\mu) F(x,b;\mu,\zeta),$$

$$F(x,b;\mu,\zeta) = \left(\frac{\zeta}{\zeta_\mu(b)}\right)^{-\mathcal{D}(b,\mu)} F(x,b)$$

$$\mu \sim Q, \qquad \zeta_F \zeta_D \sim Q^4, \qquad \mu^2 = \zeta^2 = Q^2$$

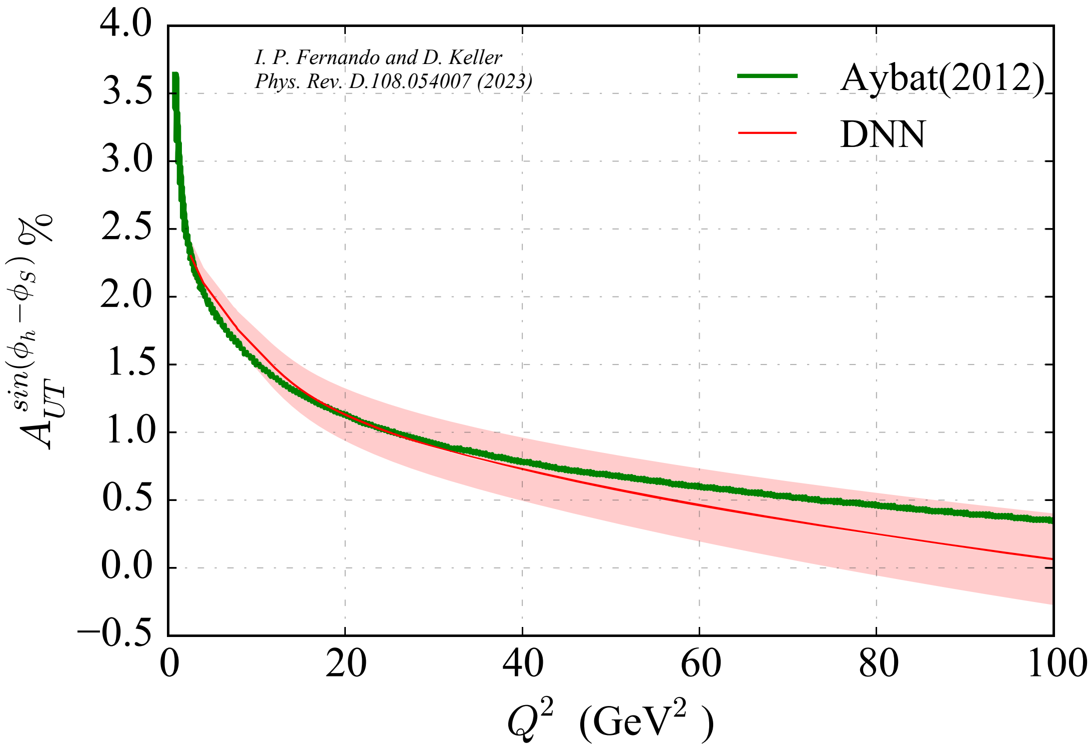

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FIG. 21. The Sivers asymmetry evolution in Q^2 compared to the result from [6]. The red-colored solid line and the band represent the mean and standard deviation of the $A_{UT}^{\sin(\phi_h-\phi_S)}$ from 1000 replica models of the proton DNN at $x = 0.12$, $z = 0.32$, $p_{hT} = 0.14$ GeV.

Summary & Outlook

- We proposed a method for performing global fits to extract TMDs employing DNNs (first-ever application of DNNs in extracting TMDs).
- Extracting Sivers function was performed as an example of this method based on utilizing DNNs and the use of generating function to ensure the accuracy and precision.
- We have successfully tested our method with pseudo-data, also a dedicated systematic study.
- We chose Deep Neural Net (DNN) method to incorporate all x-dependent features of $\mathcal{N}_q(x)$.
- We have already made a step-forward to consider incorporating TMD-evolution (needs more work)
- We performed global fit with experimental data: Separately on polarized SIDIS with Proton target and Deuteron target and obtained reasonably well description and extracted the Sivers functions for all light quark flavors in SU(3).
- We projected SIDIS and DY Sivers asymmetries: for already completed experiments (as a validation check: COMPASS) and upcoming experiments (such as SpinQuest).
- Currently working on Unpolarized TMDPDF extraction…

"Recursively Improving the DNN with multi-dimensional kinematic phase-space, and simultaneous information incorporation from experimental data (Nature)"

Next:

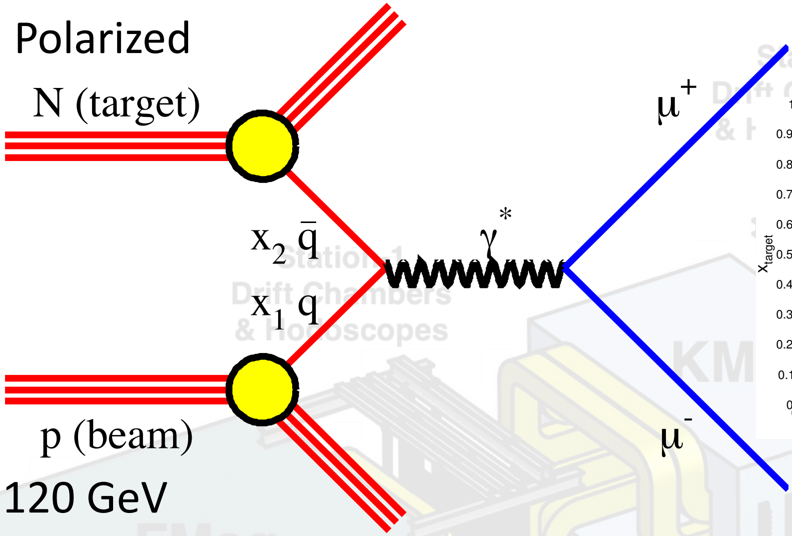
- Applying the "DNN method" to extract other TMDs such as Transversity, Boer-Mulders function, as well as Spin-1 TMDs.

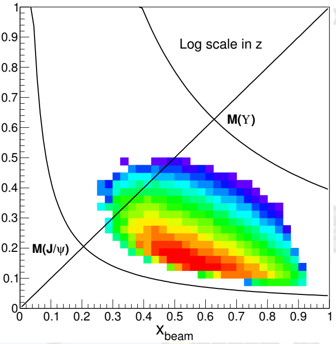
SpinQuest (E1039) Experiment at Fermilab

- Probing Sivers asymmetry from the (light) ‘sea’ quark contributions

Stay Tuned!

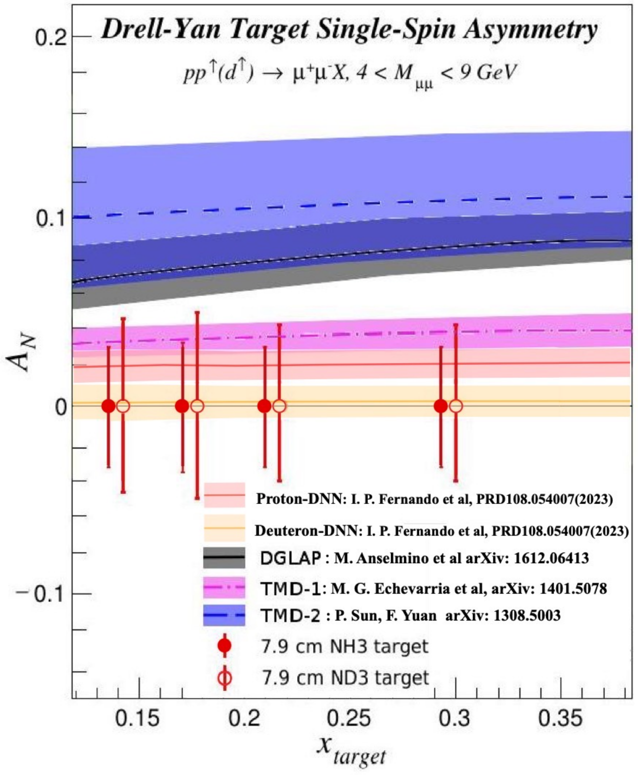
$$pp^{\uparrow}(d^{\uparrow}) \rightarrow \mu^+\mu^- X,\ 4 < M_{\mu\mu} < 9\ GeV$$

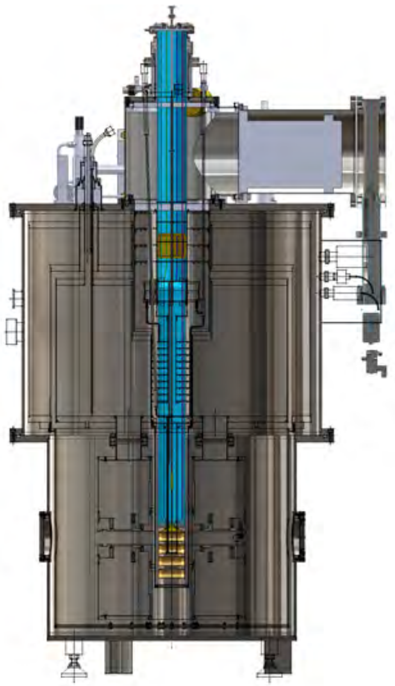




120 GeV
proton beam

$$\frac{d\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_i e_i^2 (q_i^B(x_1,Q^2)\bar{q}_i^T(x_2,Q^2) + \cancel{\bar{q}_i^B(x_1,Q^2) q_i^T(x_2,Q^2)})$$





LANL-UVA
Polarized Target

https://spinquest.fnal.gov/
http://twist.phys.virginia.edu/E1039/

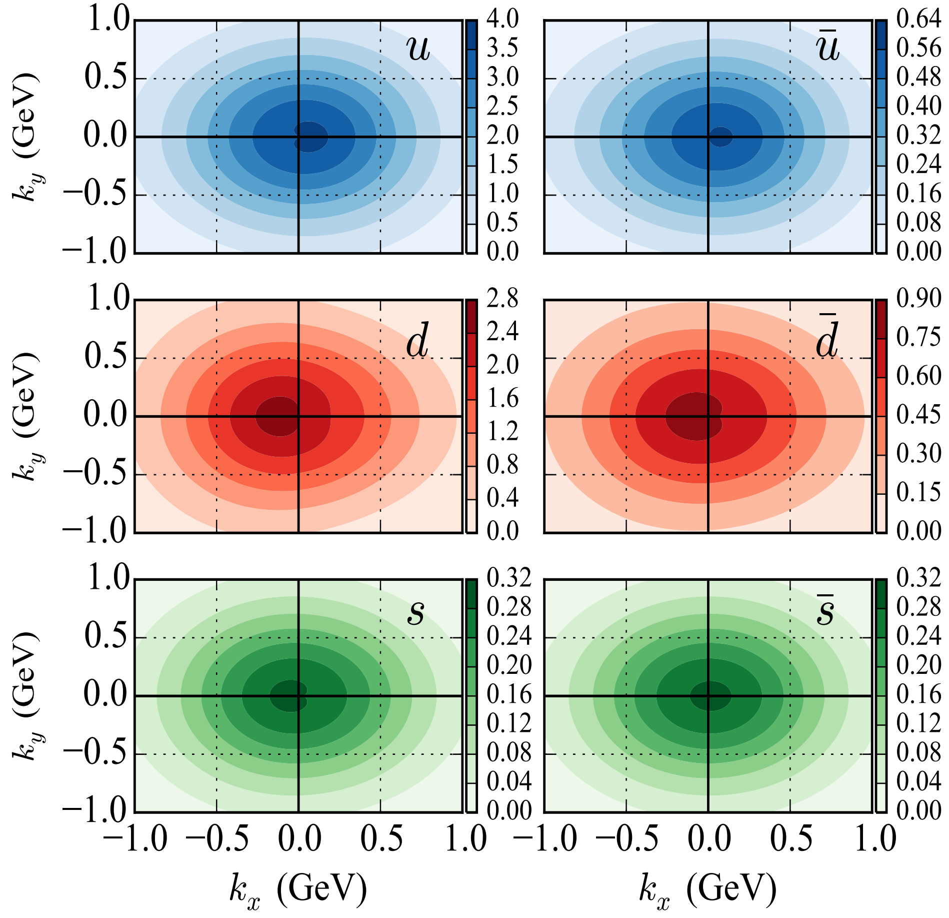
Please Join The Effort

Dustin Keller (dustin@virginia.edu)[Spokesperson]
Kun Liu (liuk@lanl.gov)[Spokesperson])

Highest beam intensity on a polarized target ever!

See Liliet’s talk

Thank you



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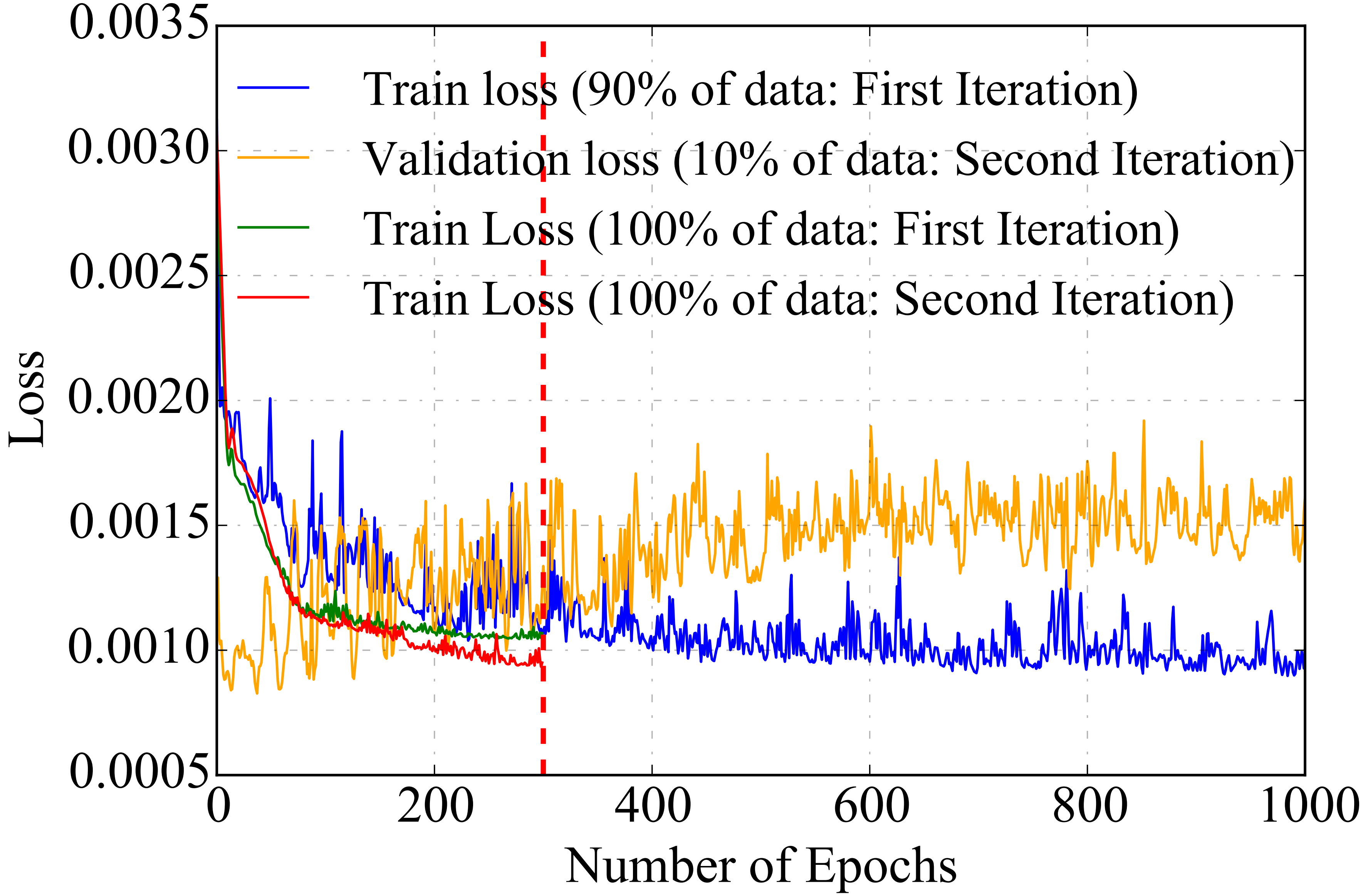
Backup Slides

Backup


Train loss (90% of data: First Iteration)
Validation loss (10% of data: Second Iteration)
Train Loss (100% of data: First Iteration)
Train Loss (100% of data: Second Iteration)
Loss
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0
200
400
600
800
1000
Number of Epochs

Backup

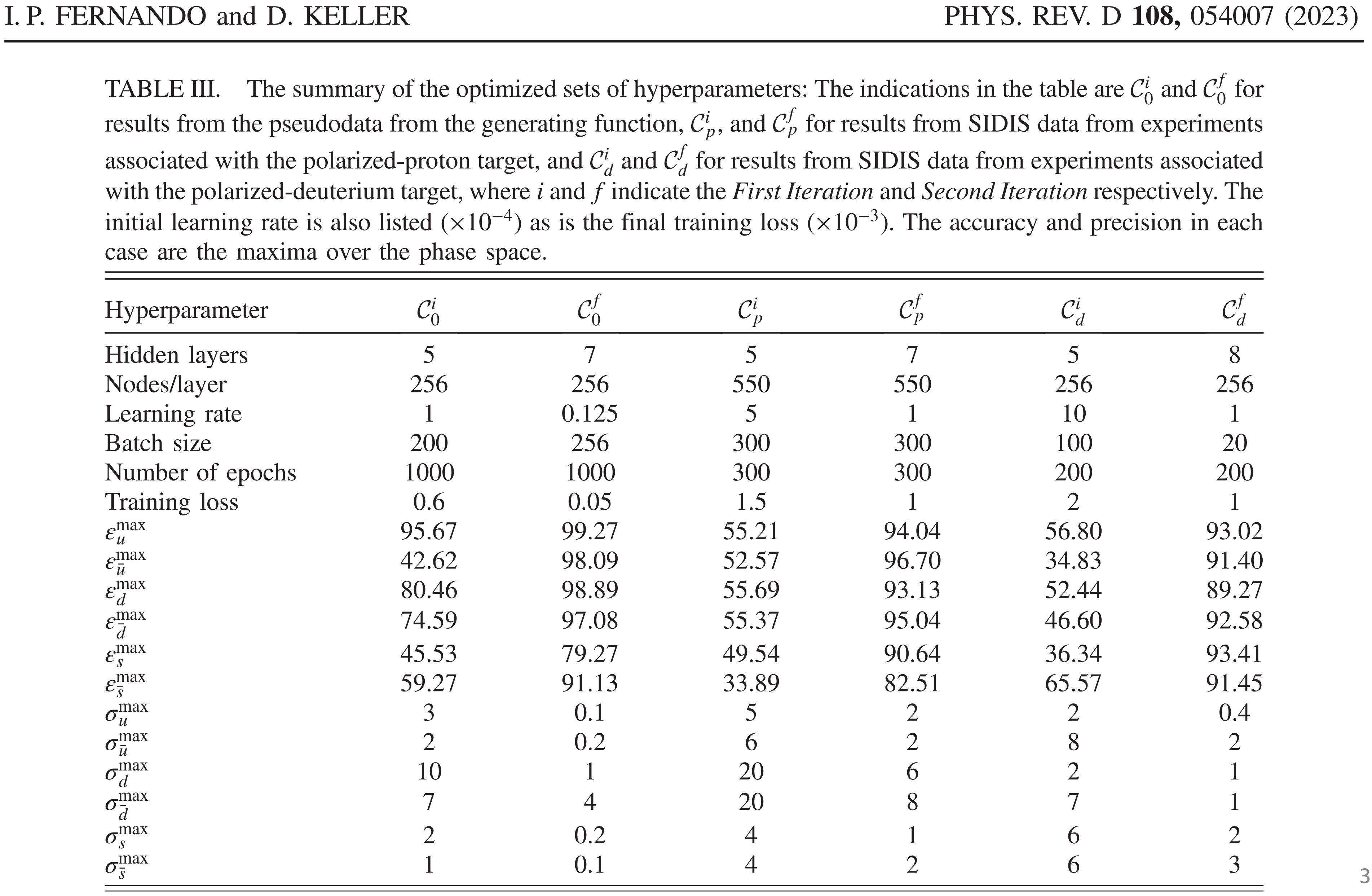


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TABLE III. The summary of the optimized sets of hyperparameters: The indications in the table are $\mathcal{C}_0^i$ and $\mathcal{C}_0^f$ for results from the pseudodata from the generating function, $\mathcal{C}_p^i$, and $\mathcal{C}_p^f$ for results from SIDIS data from experiments associated with the polarized-proton target, and $\mathcal{C}_d^i$ and $\mathcal{C}_d^f$ for results from SIDIS data from experiments associated with the polarized-deuterium target, where i and f indicate the *First Iteration* and *Second Iteration* respectively. The initial learning rate is also listed ($\times 10^{-4}$) as is the final training loss ($\times 10^{-3}$). The accuracy and precision in each case are the maxima over the phase space.

Hyperparameter	$\mathcal{C}_0^i$	$\mathcal{C}_0^f$	$\mathcal{C}_p^i$	$\mathcal{C}_p^f$	$\mathcal{C}_d^i$	$\mathcal{C}_d^f$
Hidden layers	5	7	5	7	5	8
Nodes/layer	256	256	550	550	256	256
Learning rate	1	0.125	5	1	10	1
Batch size	200	256	300	300	100	20
Number of epochs	1000	1000	300	300	200	200
Training loss	0.6	0.05	1.5	1	2	1
$\varepsilon_u^{\max}$	95.67	99.27	55.21	94.04	56.80	93.02
$\varepsilon_{\bar{u}}^{\max}$	42.62	98.09	52.57	96.70	34.83	91.40
$\varepsilon_d^{\max}$	80.46	98.89	55.69	93.13	52.44	89.27
$\varepsilon_{\bar{d}}^{\max}$	74.59	97.08	55.37	95.04	46.60	92.58
$\varepsilon_s^{\max}$	45.53	79.27	49.54	90.64	36.34	93.41
$\varepsilon_{\bar{s}}^{\max}$	59.27	91.13	33.89	82.51	65.57	91.45
$\sigma_u^{\max}$	3	0.1	5	2	2	0.4
$\sigma_{\bar{u}}^{\max}$	2	0.2	6	2	8	2
$\sigma_d^{\max}$	10	1	20	6	2	1
$\sigma_{\bar{d}}^{\max}$	7	4	20	8	7	1
$\sigma_s^{\max}$	2	0.2	4	1	6	2
$\sigma_{\bar{s}}^{\max}$	1	0.1	4	2	6	3