TMDPDFs extractions with DNNs

Ishara Fernando & Dustin Keller

2025 EIC User Group Early Career Workshop

July 11-13, 2025
Jefferson Lab
Newport News, VA, US.

Based on : https://doi.org/10.1103/PhysRevD.108.054007

UVA - Spin
PHYSICS GROUP

University of Virginia

U.S. DEPARTMENT OF ENERGY | Office of Science

This work is supported by DOE contract DE-FG02-96ER40950

Outline

- Motivation
- A brief introduction to TMDs
- Sivers asymmetry from SIDIS
- DNN Approach for $SU(3)_{flavor}$
- DNN Method Testing
- DNN Fits & Results for Sivers function
- Unpolarized TMDs extraction
- 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?

Introducing this ‘novel’ method of extracting TMDs with Deep Neural Networks (DNNs)

First time in TMD extractions (published in 2023)

- 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

TMDPDFs

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

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	$\theta_{LL}(x, \mathbf{k_T^2})$ $\theta_{TT}(x, \mathbf{k_T^2})$ $\theta_{LT}(x, \mathbf{k_T^2})$	$g_{1TT}(x, \mathbf{k_T^2})$ $g_{1LT}(x, \mathbf{k_T^2})$	$h_{1LL}^\perp(x, \mathbf{k_T^2})$ $h_{1TT}(x, \mathbf{k_T^2}), h_{1TT}^\perp(x, \mathbf{k_T^2})$ $h_{1LT}(x, \mathbf{k_T^2}), h_{1LT}^\perp(x, \mathbf{k_T^2})$

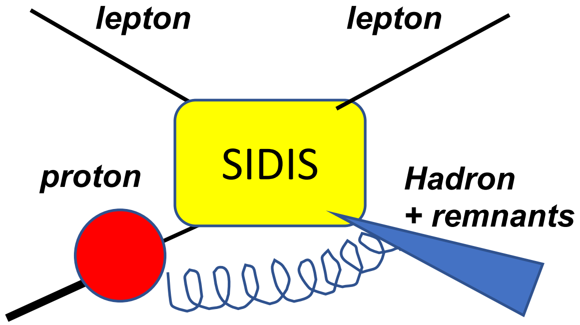
At leading-twist, the Quark correlator can be decomposed into 8 components (6 T - even and 2 T -odd terms)

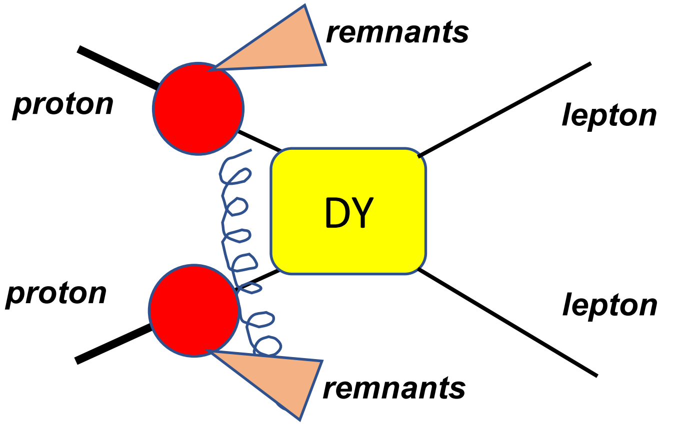
$$\Phi(x, k_T, P, S) = f_1(x, k_T^2)\frac{\not{P}}{2} + \frac{h_{1T}(x, k_T^2)}{4}\gamma_5[\not{S}_T, \not{P}] + \frac{S_L}{2} g_{1L}(x, k_T^2)\gamma_5 \not{P} + \frac{k_T.S_T}{2M} g_{1T}(x, k_T^2)\gamma_5 \not{P}$$
$$+ S_L h_{1L}^\perp(x, k_T^2)\gamma_5 \frac{[\not{k}_T, \not{P}]}{4M} + \frac{k_T.S_T}{2M}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

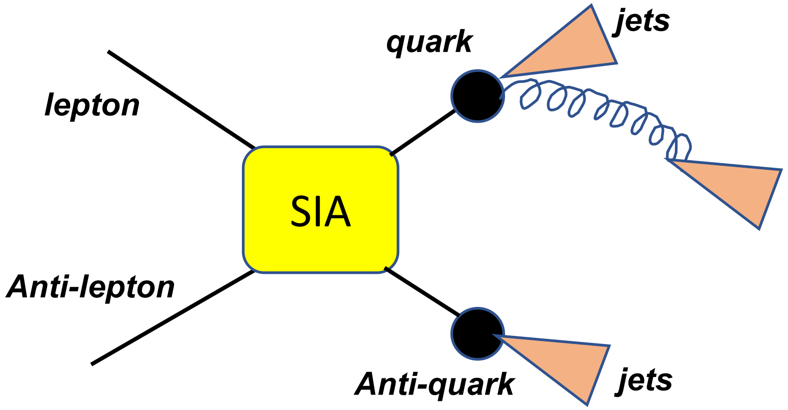
T-even

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

T-odd



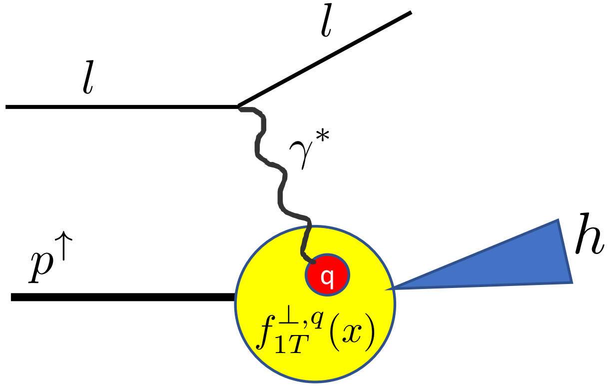




TMDPDFs

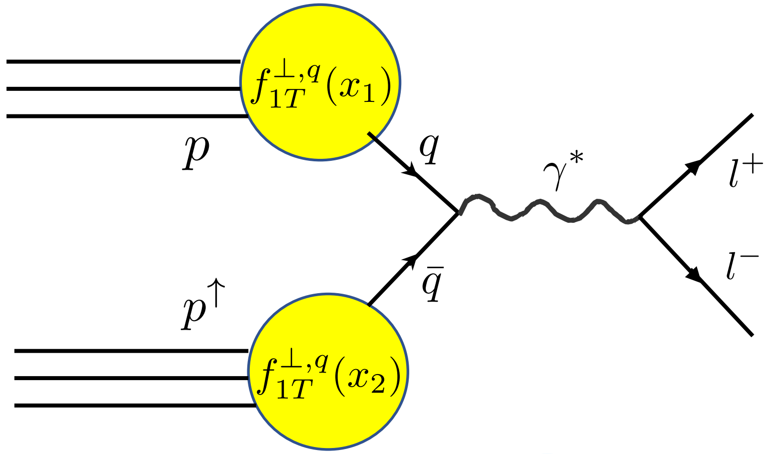
Leading Twist		Quark Polarization		
		Unpolarized [U]	Circular [L]	Linear [T]
Target Polarization	U	f_1 Unpolarized		$h_1^\perp$ Boer-Mulders
	L		g_1 Helicity	$h_{1L}^\perp$ Worm-gear 1
	T	$f_{1T}^\perp$ Sivers	g_{1T} Worm-gear 2	h_1 Transversity; $h_{1T}^\perp$ Pretzelosity
	TENSOR	$\theta_{LL}(x,\mathbf{k_T^2})$,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

Polarized Semi Inclusive DIS



* For these two processes TMD factorization is proven

Polarized DY



$$\frac{d\sigma_{SIDIS}^{LO}}{dxdydzdp_T^2d\phi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{y^2}{2x}\right)\right]$$
$$\times\left(F_{UU,T}+\epsilon F_{UU,L}\right)\left\{1+\cos 2\phi_h\left(\epsilon A_{UU}^{\cos 2\phi_h}\right)\right.$$
$$+S_T\left[\sin(\phi_h-\phi_s)\left(A_{UT}^{\sin(\phi_h-\phi_s)}\right)+\sin(\phi_h+\phi_s)\left(\epsilon A_{UT}^{\sin(\phi_h+\phi_s)}\right)\right.$$
$$\left.\left.+\sin(3\phi_h-\phi_s)\left(\epsilon A_{UT}^{\sin(3\phi_h-\phi_s)}\right)\right]\right\}$$

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

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq}F_v^1\left\{1+\cos^2\theta+sin^2\theta cos2\phi_{CS}A_U^{cos2\phi_{CS}}\right.$$
$$+S_T\left[(1+\cos^2\theta)\sin\phi_s A_T^{\sin\phi_s}+\sin^2\theta\left(\sin(2\phi_{CS}+\phi_s)A_T^{\sin(2\phi_{CS}+\phi_s)}\right.\right.$$
$$\left.\left.\left.+\sin(2\phi_{CS}-\phi_s)A_T^{\sin(2\phi_{CS}-\phi_s)}\right)\right]\right\}$$

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

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

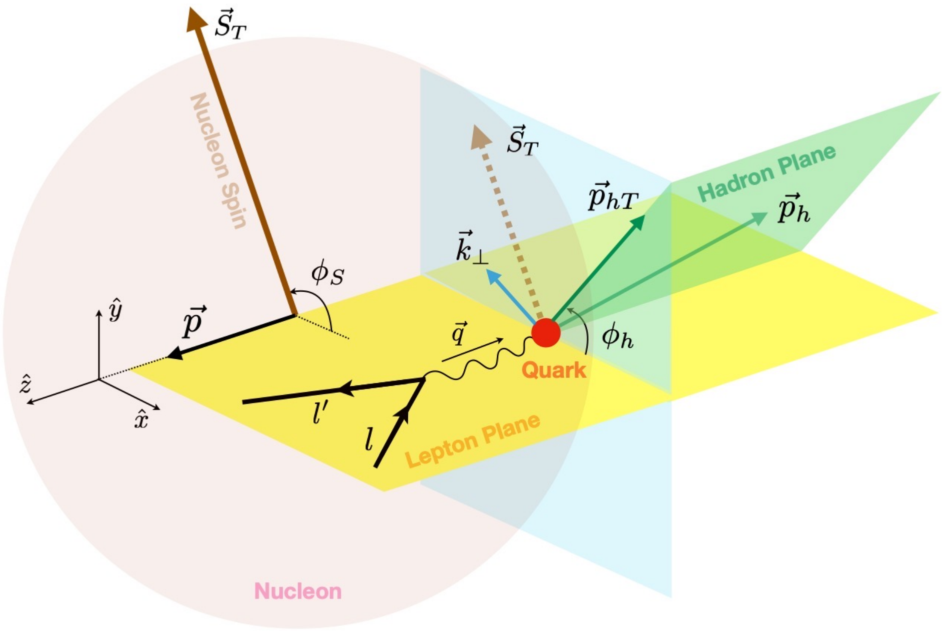
$f_{1T}^{\perp q}\big|_{SIDIS} = -f_{1T}^{\perp q}\big|_{DY}$

$h_1^{q}\big|_{SIDIS} = h_1^{q}\big|_{DY}$

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

Sivers Asymmetry from SIDIS

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



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

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

Anselmino et al. (2017)

Single Spin Asymmetry (Sivers Asymmetry)

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

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

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

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

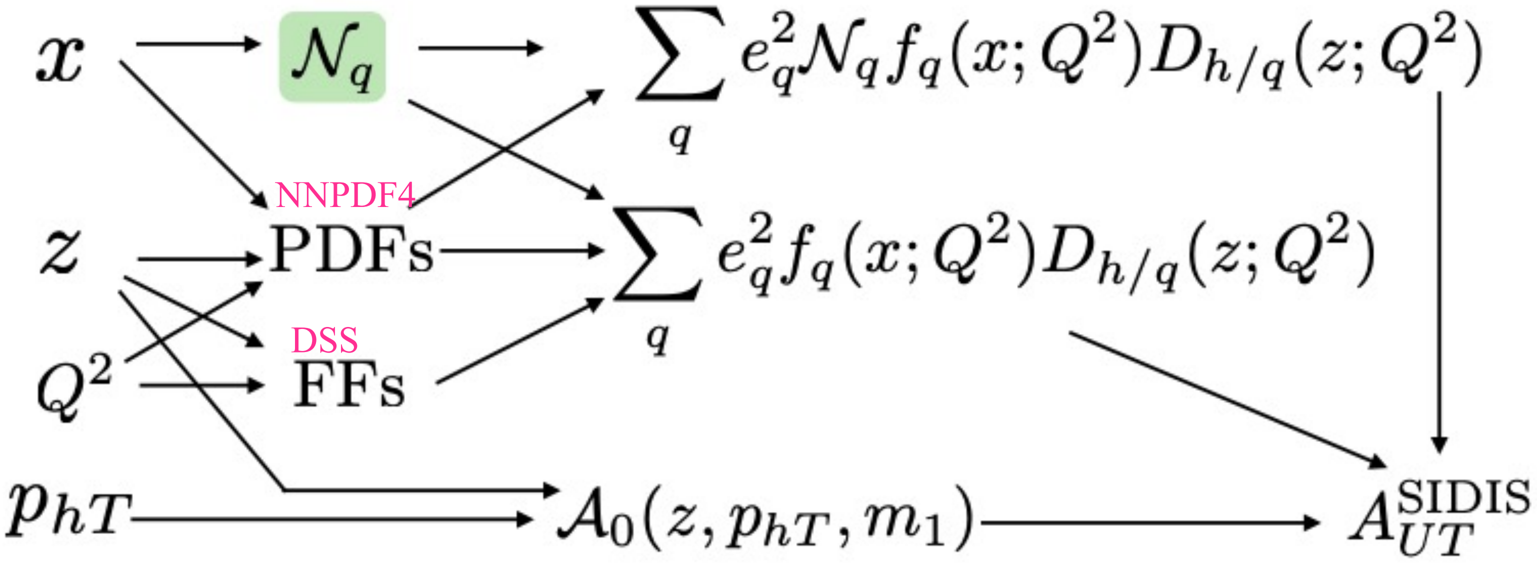
$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,z,p_{hT}) = \mathcal{A}_0(z,p_{hT},m_1)\left(\frac{\sum_q \mathcal{N}_q(x) e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}\right)$$

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

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

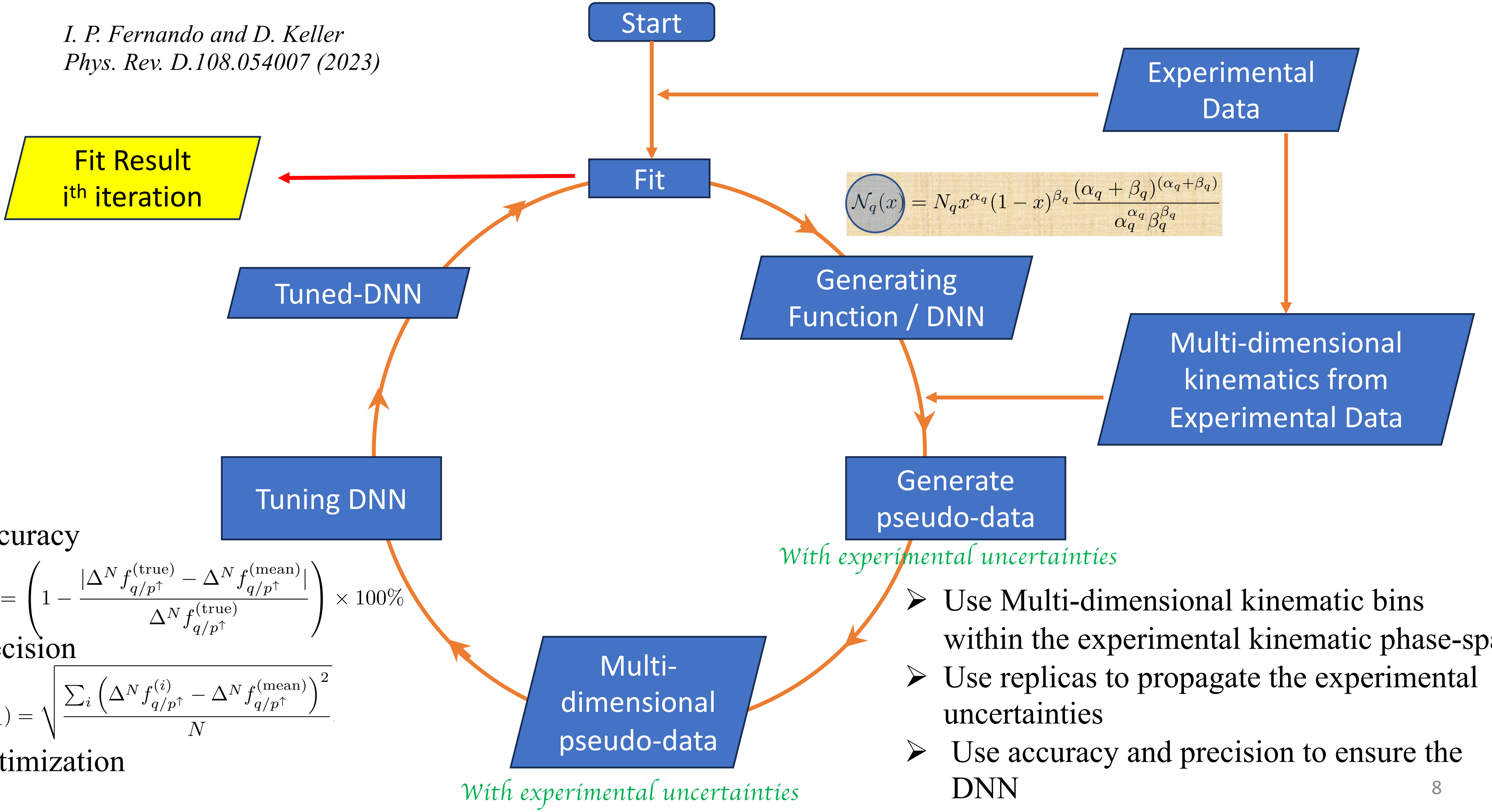
DNN Approach

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



The DNN Method for extracting Sivers function

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



- Accuracy

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

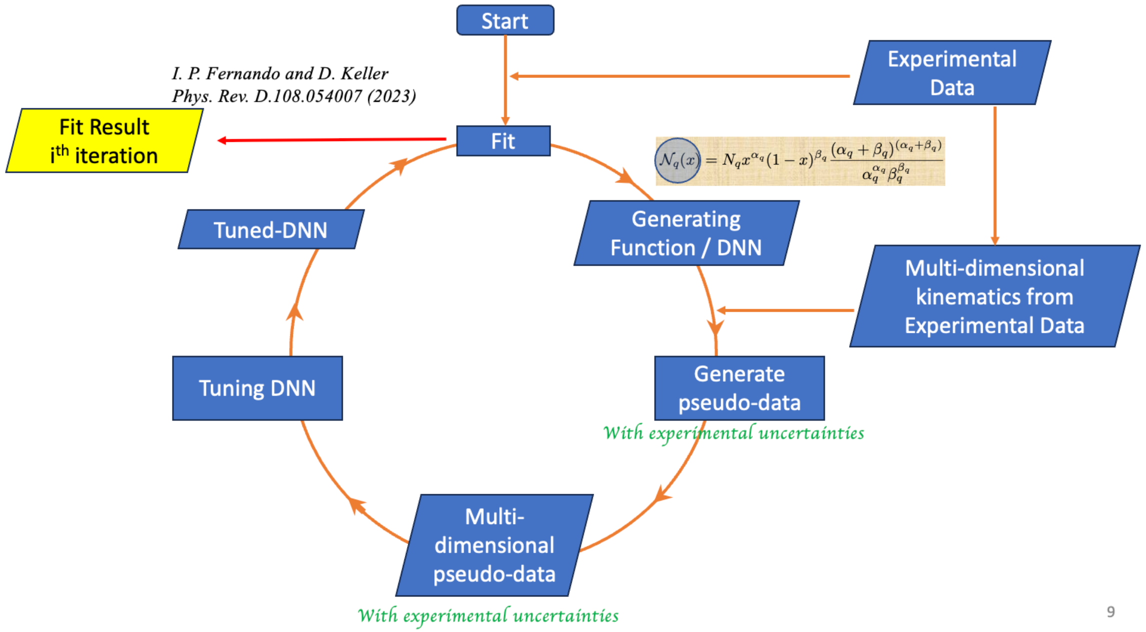
- Precision

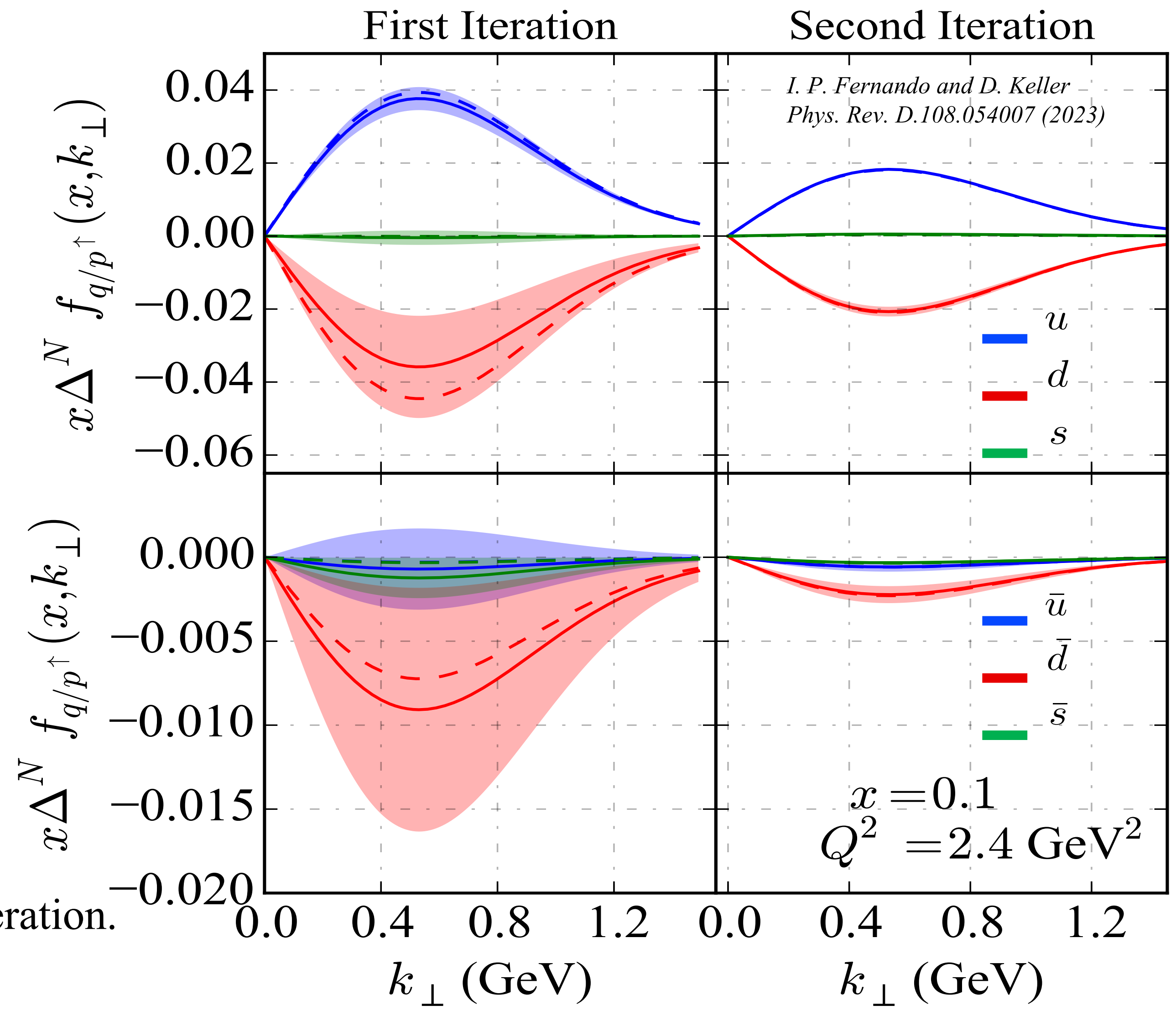
$$\sigma_q(x,k_\perp) = \sqrt{\frac{\sum_i \left(\Delta^N f_{q/p^\uparrow}^{(i)} - \Delta^N f_{q/p^\uparrow}^{(\text{mean})}\right)^2}{N}}$$

- Optimization

- 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

DNN Method testing





- Dashed lines represent the ***generating function*** in each iteration.
- A comparison: Improving the ***generating function***
  Fine-tuning the hyperparameters
- Solid-lines and the band represent the mean and 68% CL with 1000 replicas of the DNN model.

Data Selection

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
	$Q^2 > 1$ 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
	$Q^2 > 1$ 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
	$Q^2 > 1$ 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
	$Q^2 > 1$ 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]	$0.3 < x_{\pi} < 0.7$		
	$4.3 < Q_M < 8.5$		
	$0.6 < q_T < 1.9$		

Proton DNN model

Deuteron DNN model

HERMES2020 3D binned data

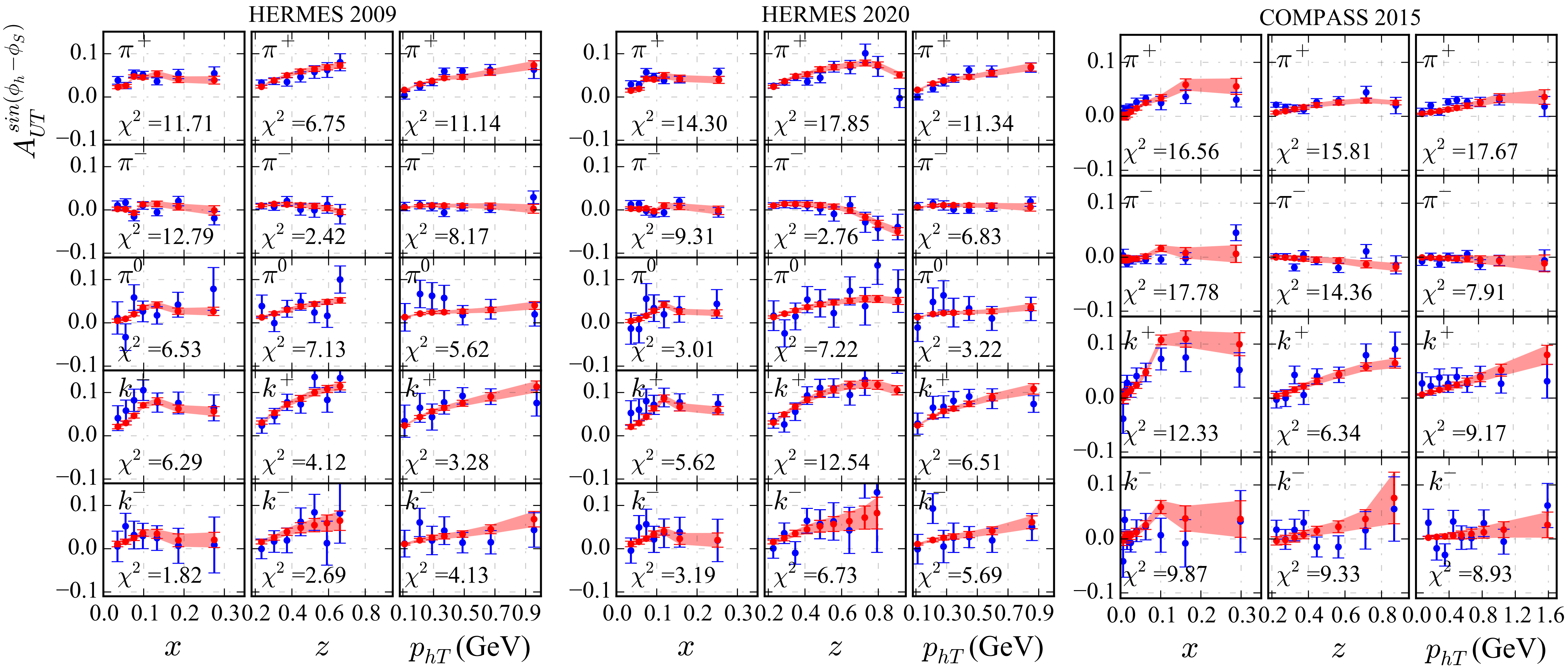
Projections from Proton DNN model

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

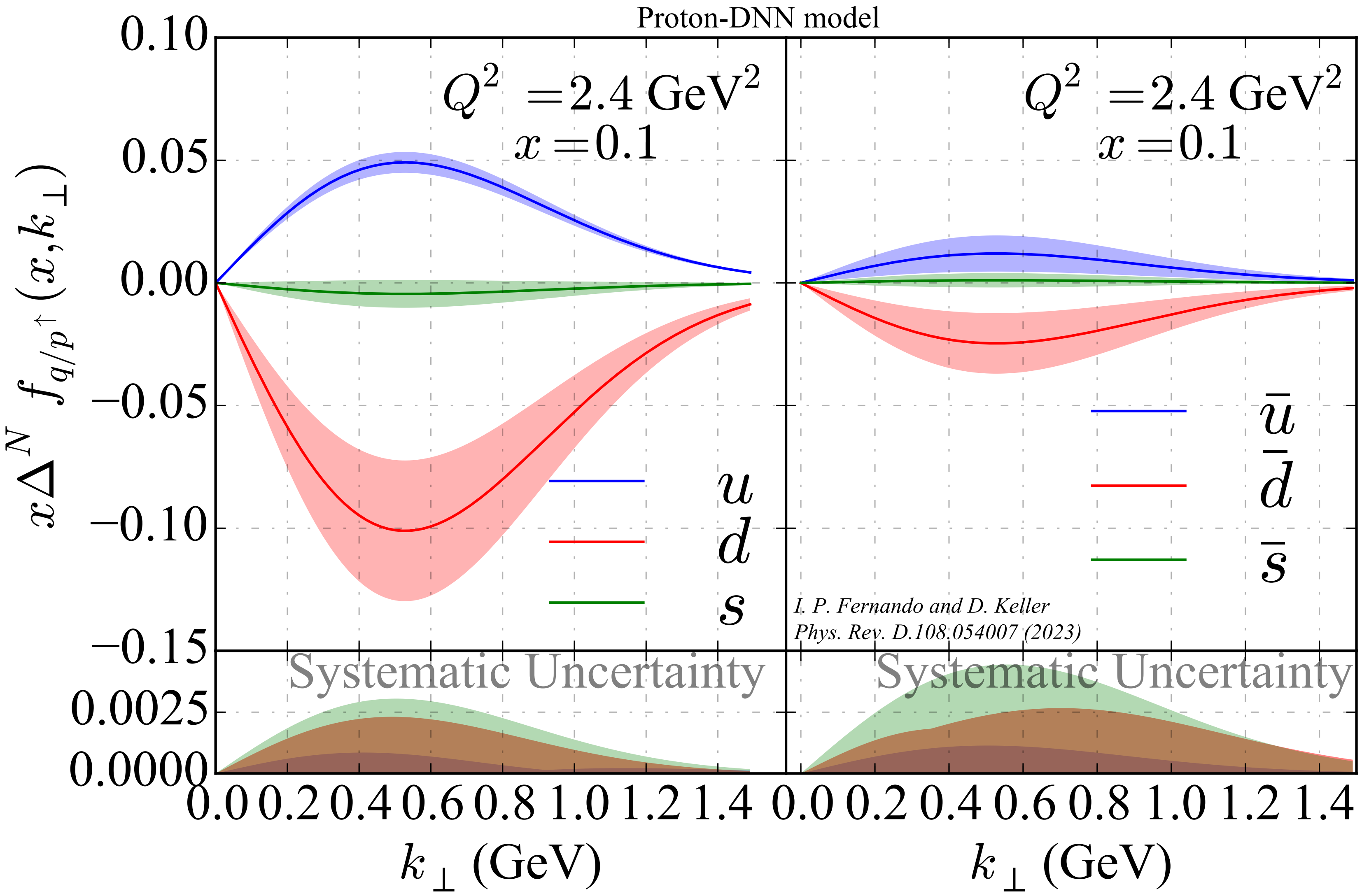
I. P. Fernando and D. Keller
Phys. Rev. D.108.054007 (2023)

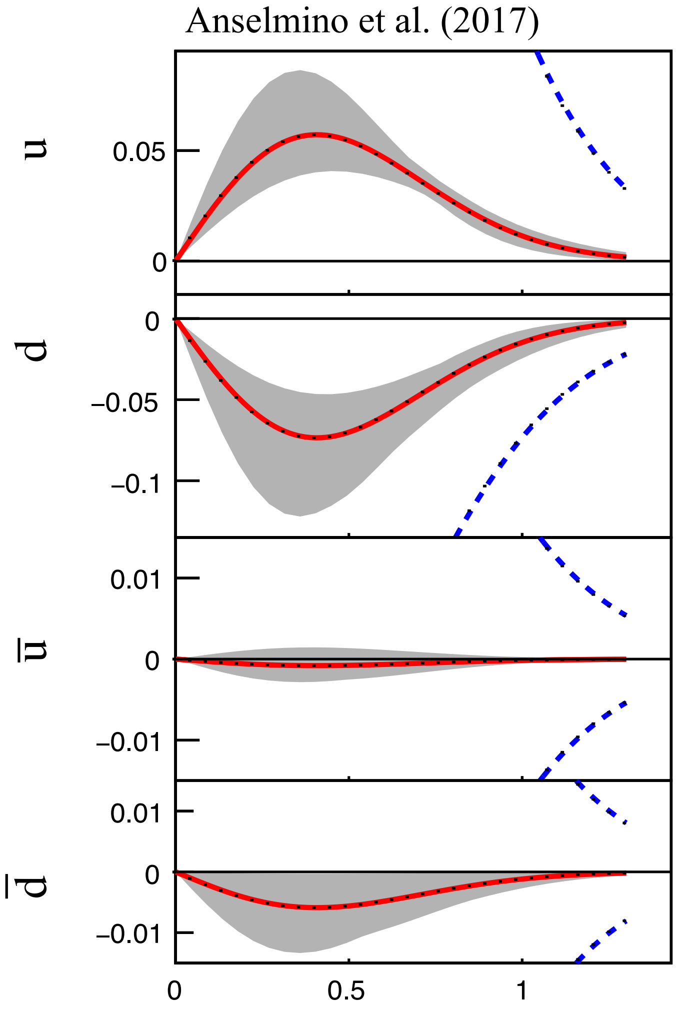


- ➢ All data points are well-described by the proton-DNN model.
- ➢ No kinematic cuts were implemented.

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

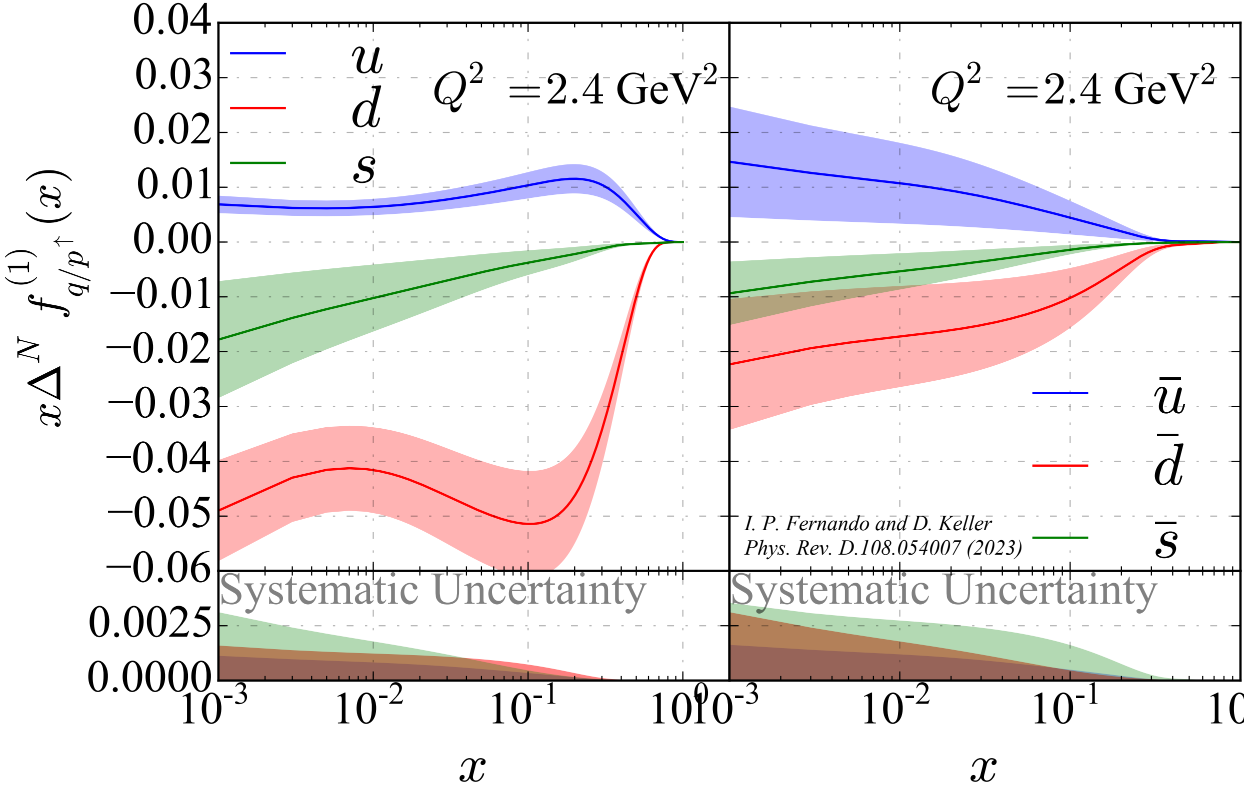
Sivers functions from the “Proton” DNN Model

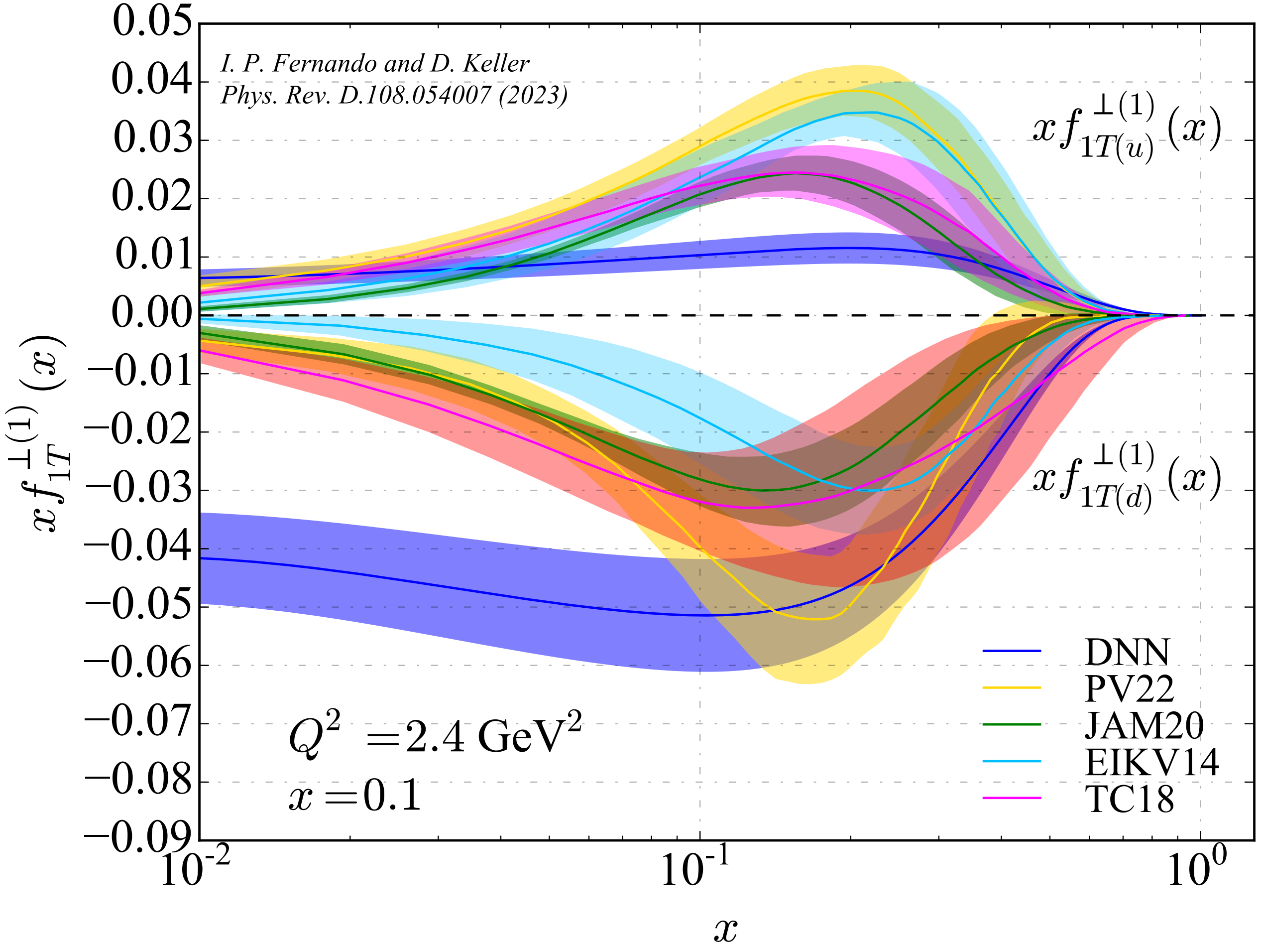




Sivers 1st moments from the "Proton" Model

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



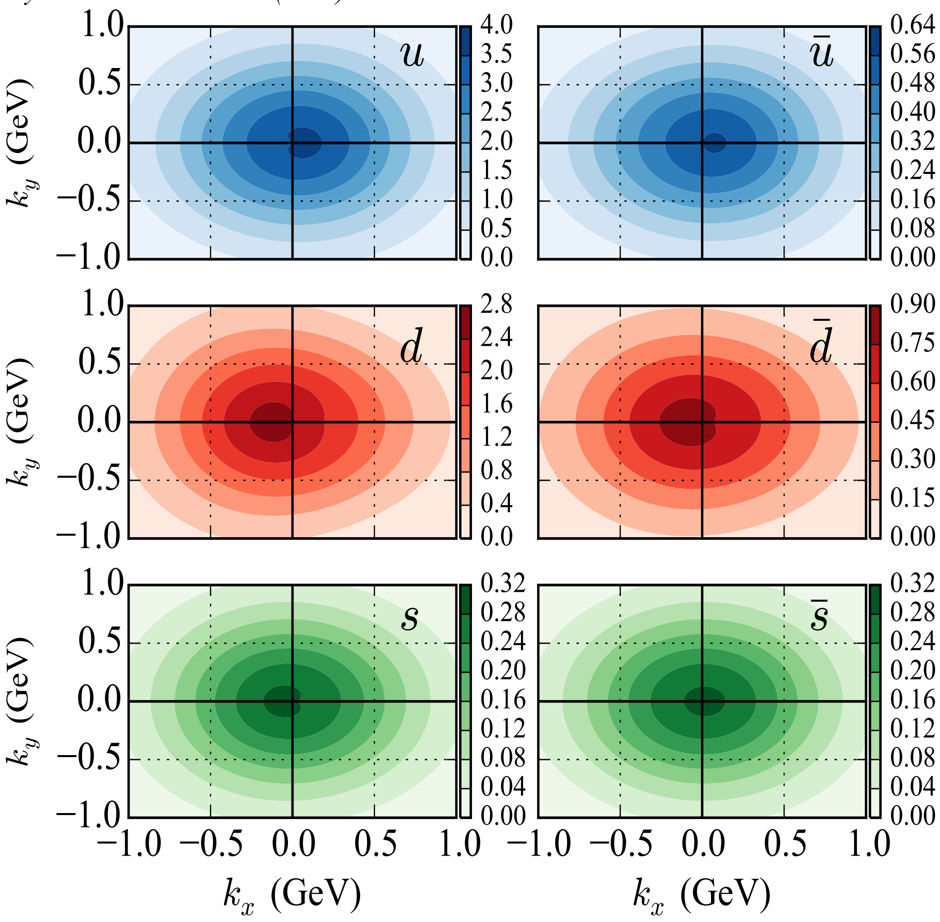


3D Tomography from the "Proton" DNN Model

$$\rho^a_{p\uparrow}(x, k_x, k_y; Q^2) = f^a_1(x, k^2_\perp; Q^2) - \frac{k_x}{m_p} f^{\perp a}_{1T}(x, k^2_\perp; Q^2)$$

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

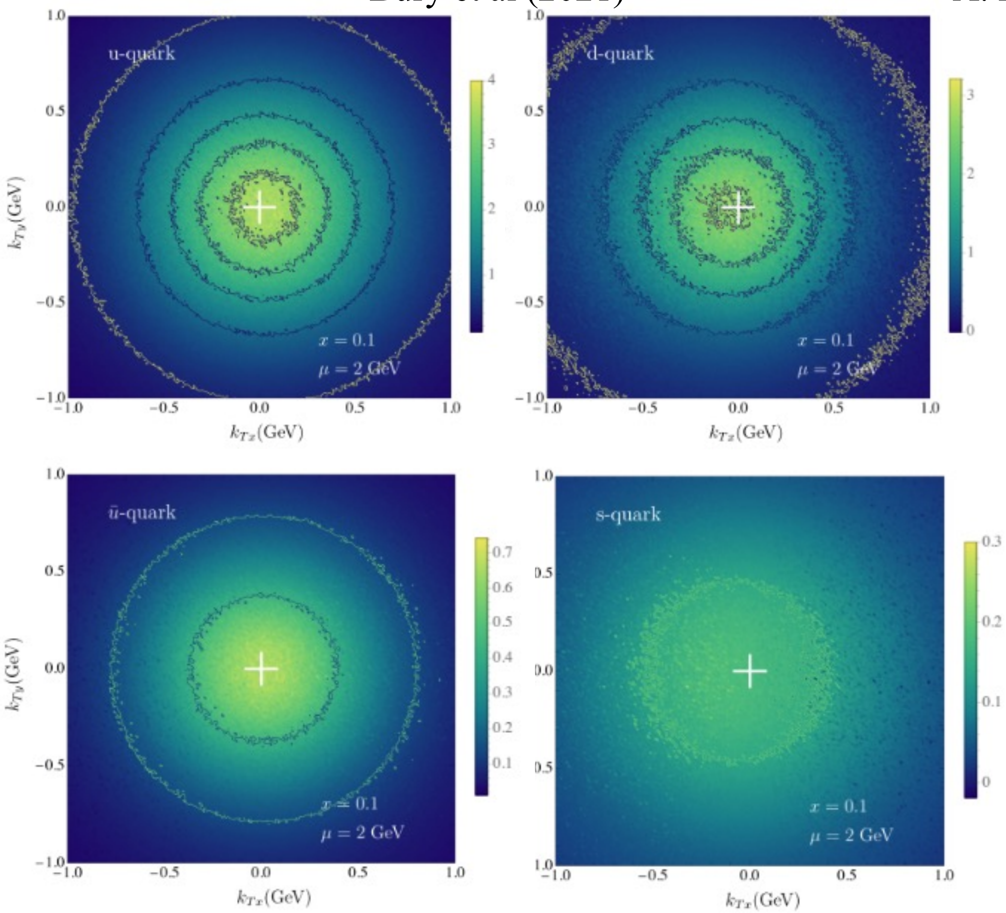
Proton-DNN model



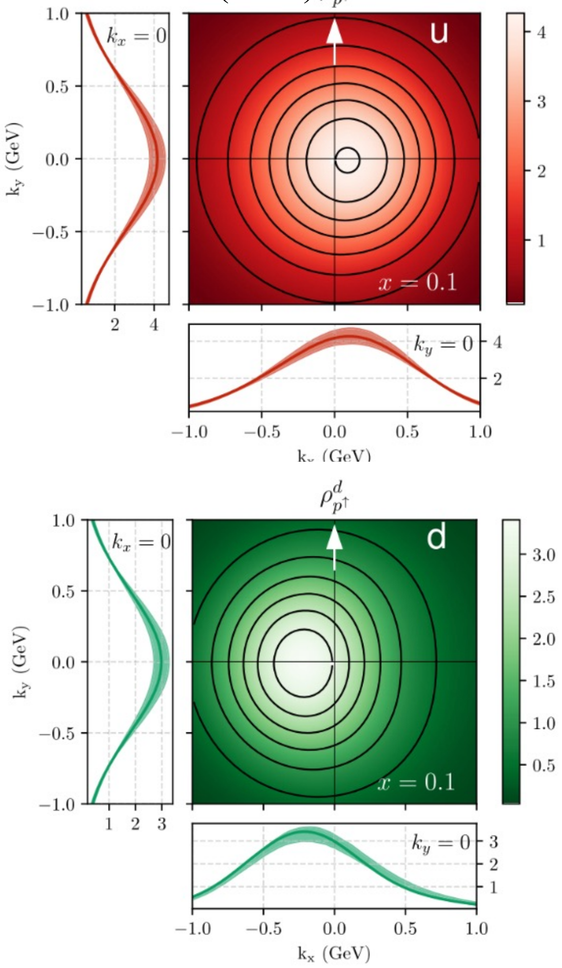
$Q^2 = 2.4\ \mathrm{GeV}^2$

$x = 0.1$

Bury et al (2021)



A. Bacchetta et al (2021)



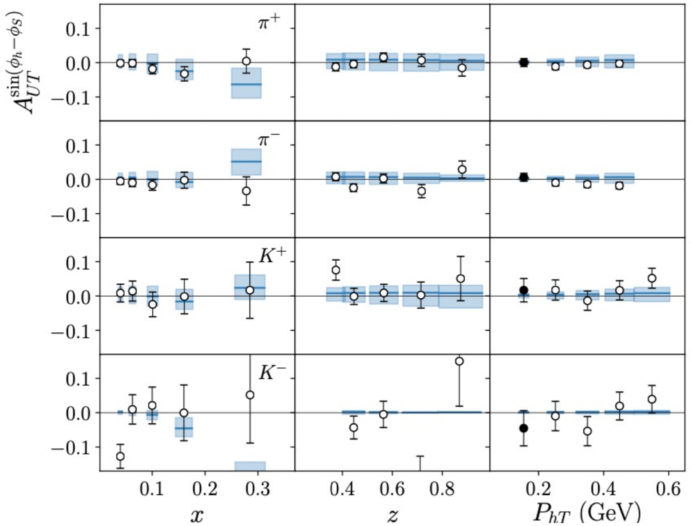
Deuteron DNN Fit Results

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

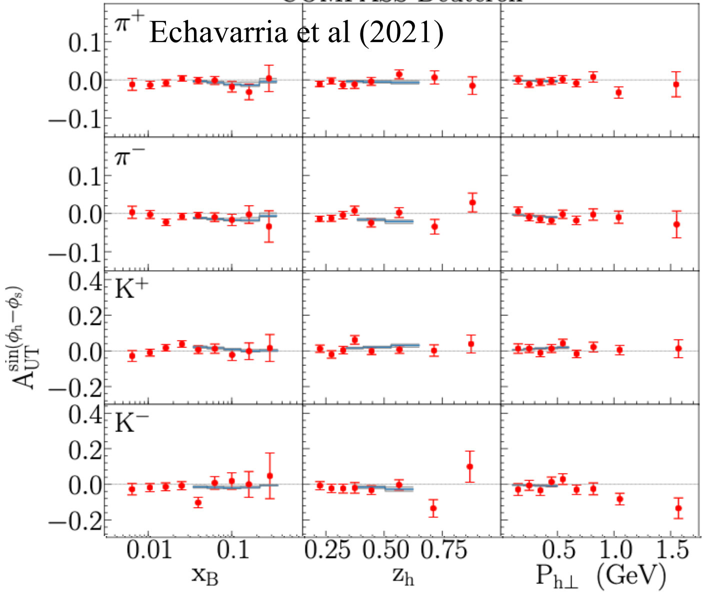
~~$f^{\perp}_{1T,u\leftarrow d} = f^{\perp}_{1T,d\leftarrow d} = \frac{f^{\perp}_{1T,u\leftarrow p} + f^{\perp}_{1T,d\leftarrow p}}{2}$~~

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

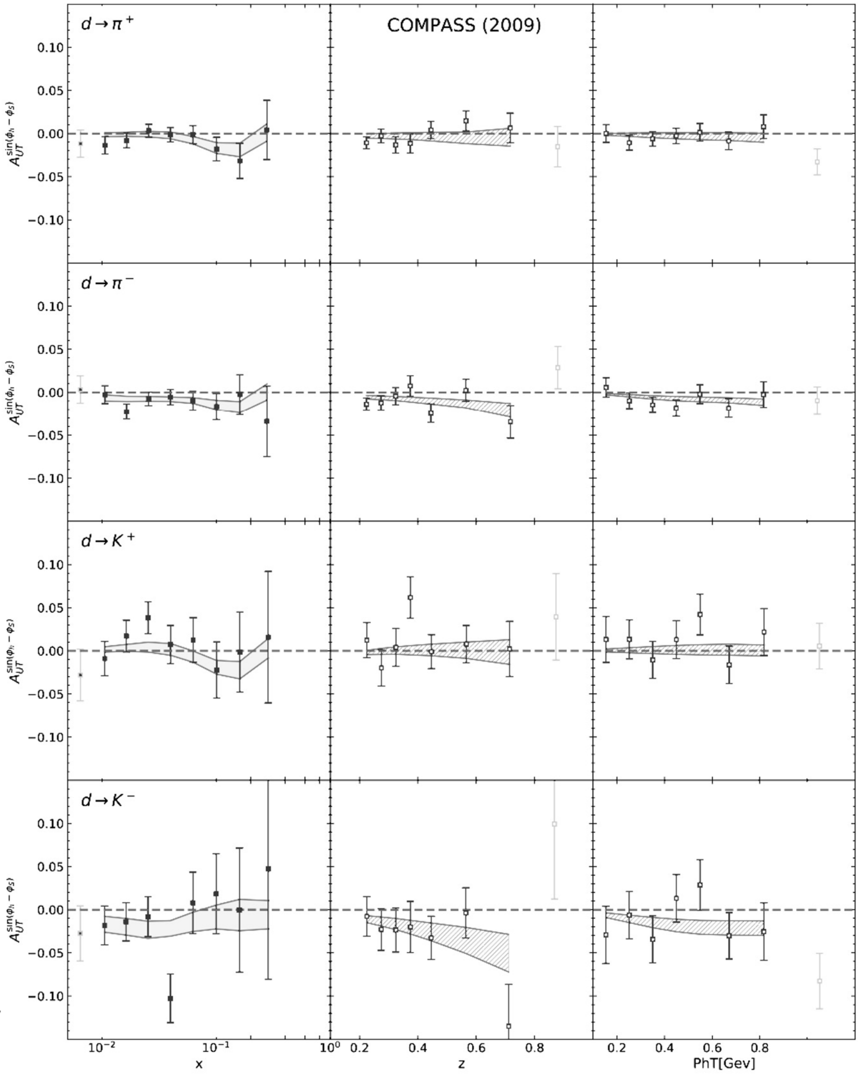
Bury et al (2021)



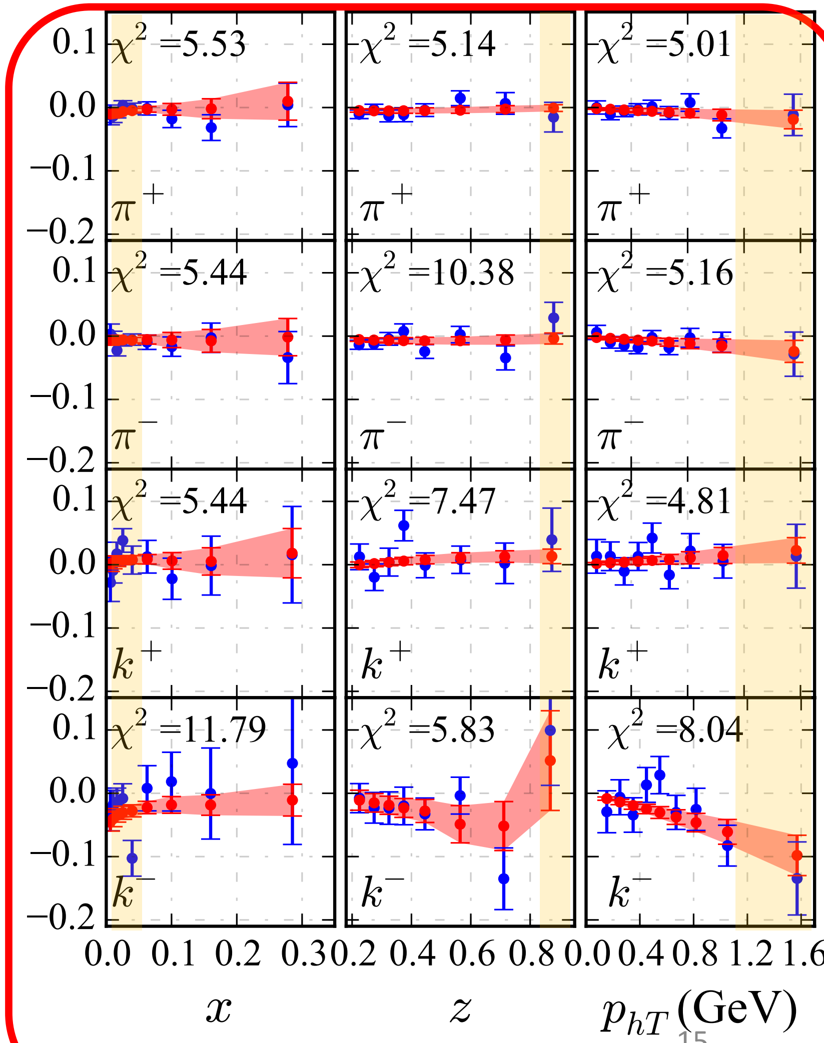
COMPASS Deuteron



Bacchetta et al (2022)

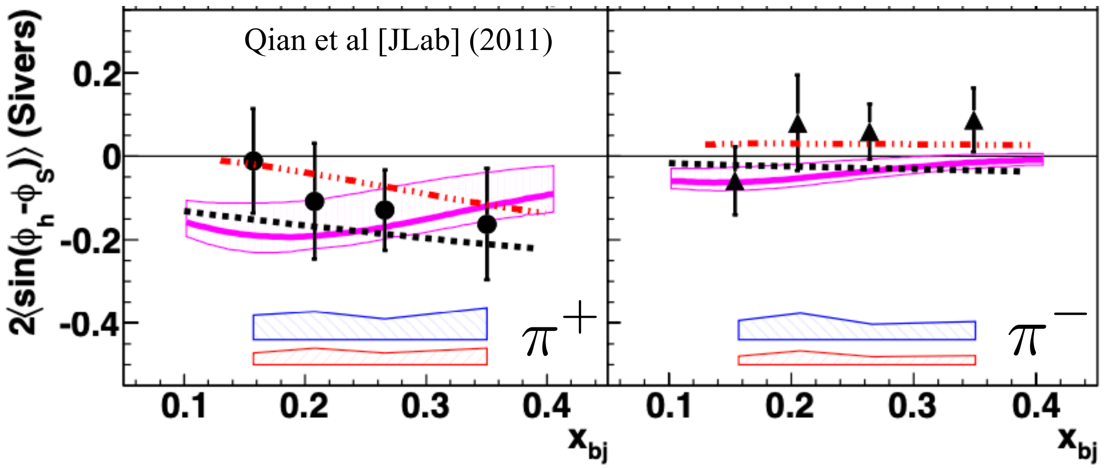


COMPASS 2009

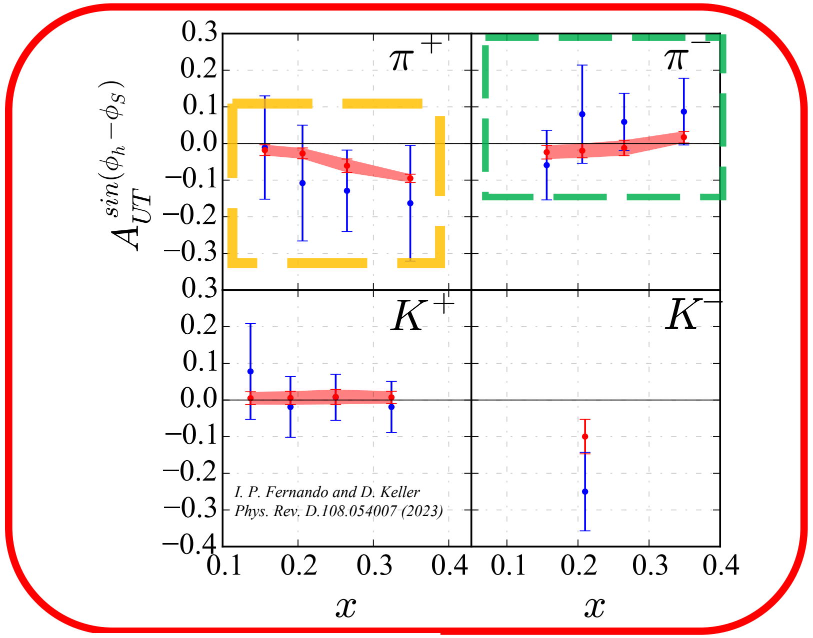


I. P. Fernando and D. Keller
Phys. Rev. D.108.054007 (2023)

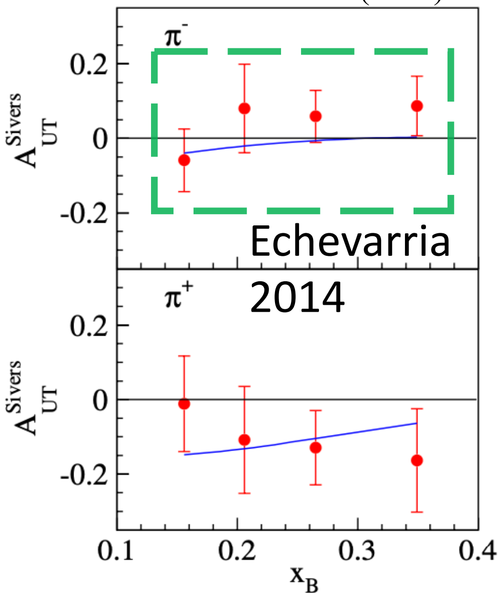
Deuteron DNN Projections for JLab Kinematics



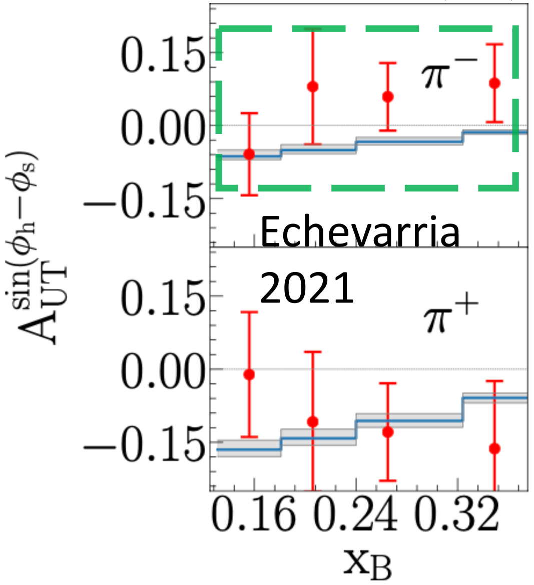
Deuteron-DNN

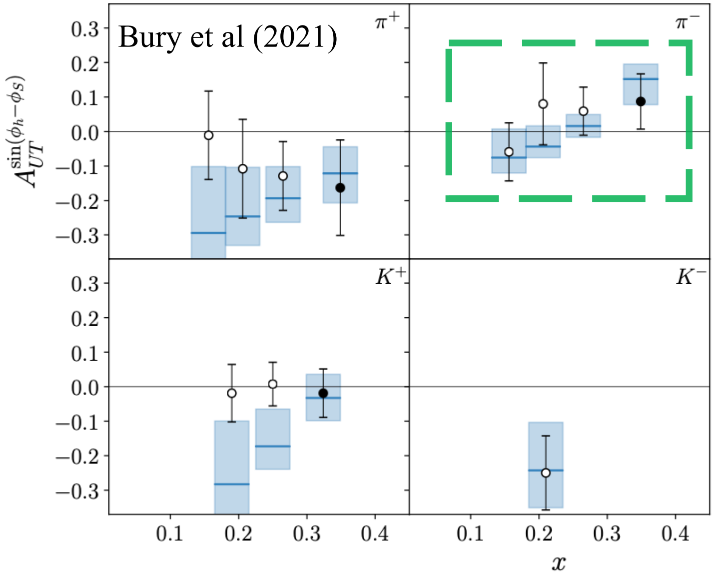


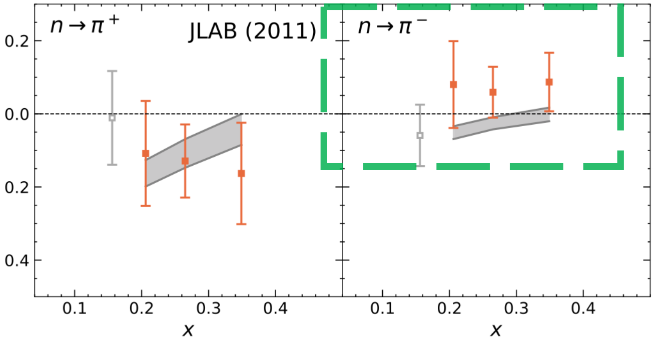
Echevarria et al (2014)



Echevarria et al (2021)

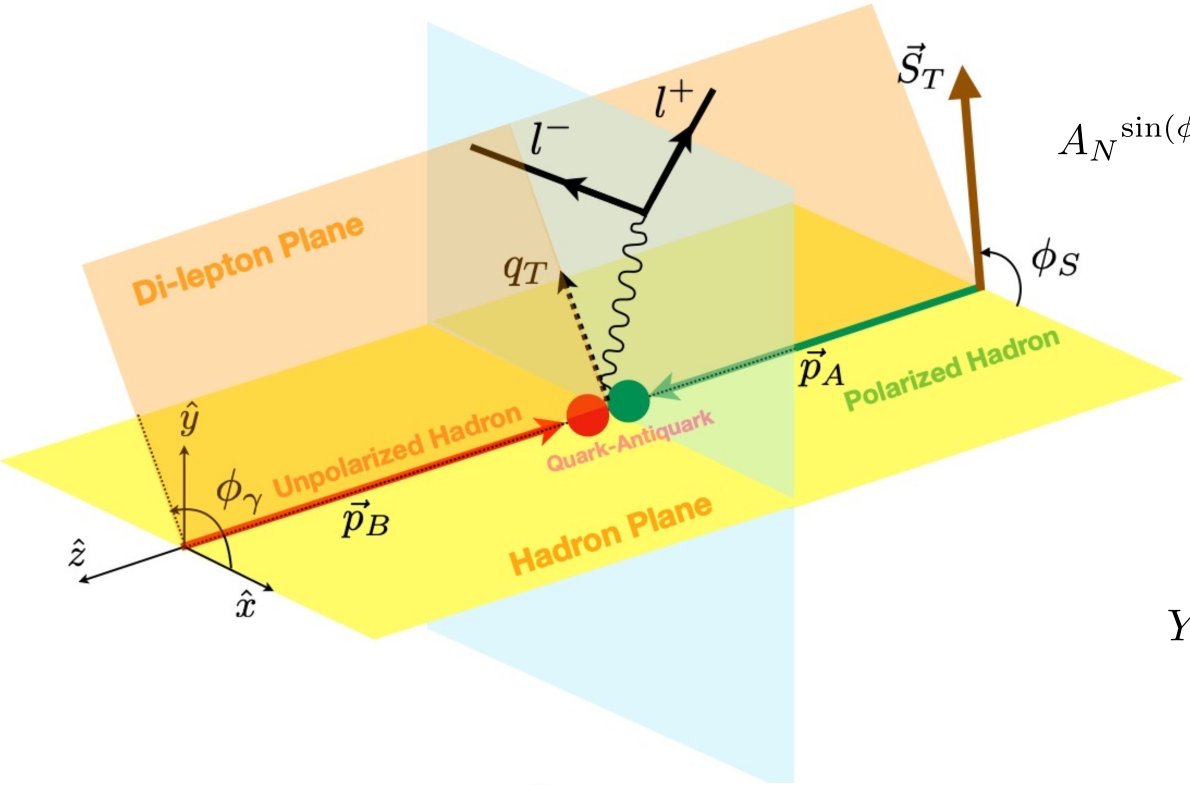


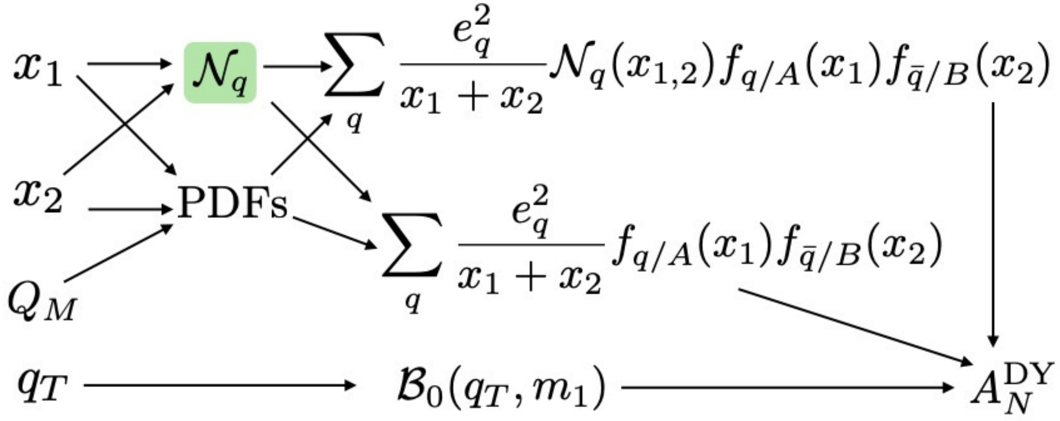




Bacchetta et al (2022)

DNN Model Projections: DY





Anselmino et al. (2017)

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

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

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

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

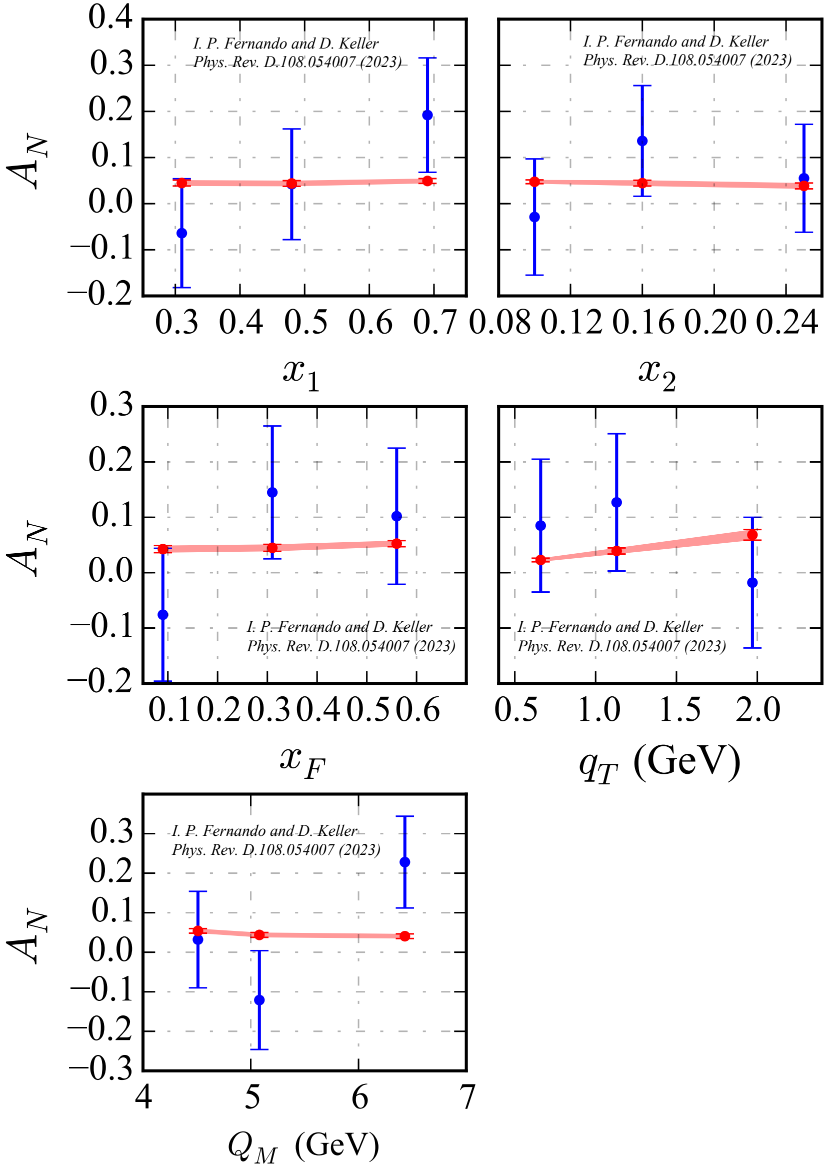
$$\frac{1}{\langle k_S^2\rangle} = \frac{1}{m_1^2} + \frac{1}{\langle k_{\perp 1}^2\rangle}$$

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

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

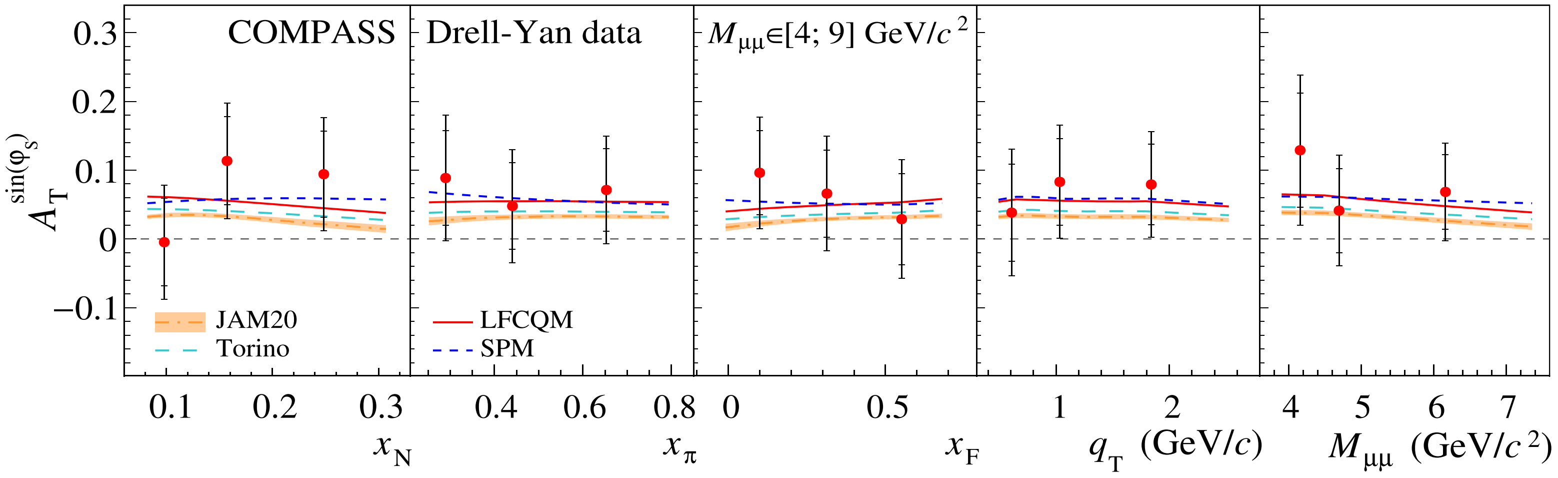
DNN (Proton) Model Projections: DY

COMPASS 2017 DY Projections



COMPASS 2024

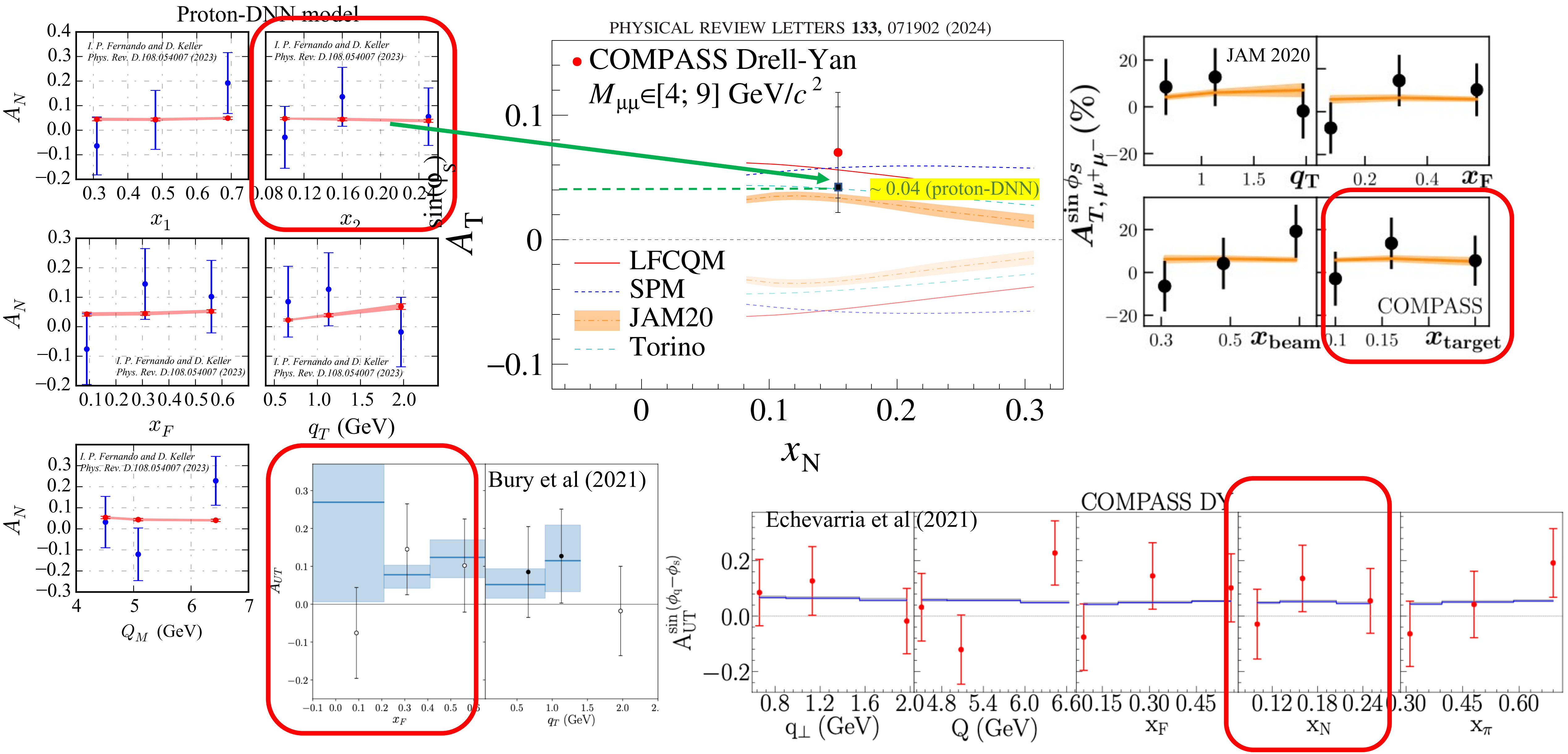
PHYSICAL REVIEW LETTERS **133,** 071902 (2024)



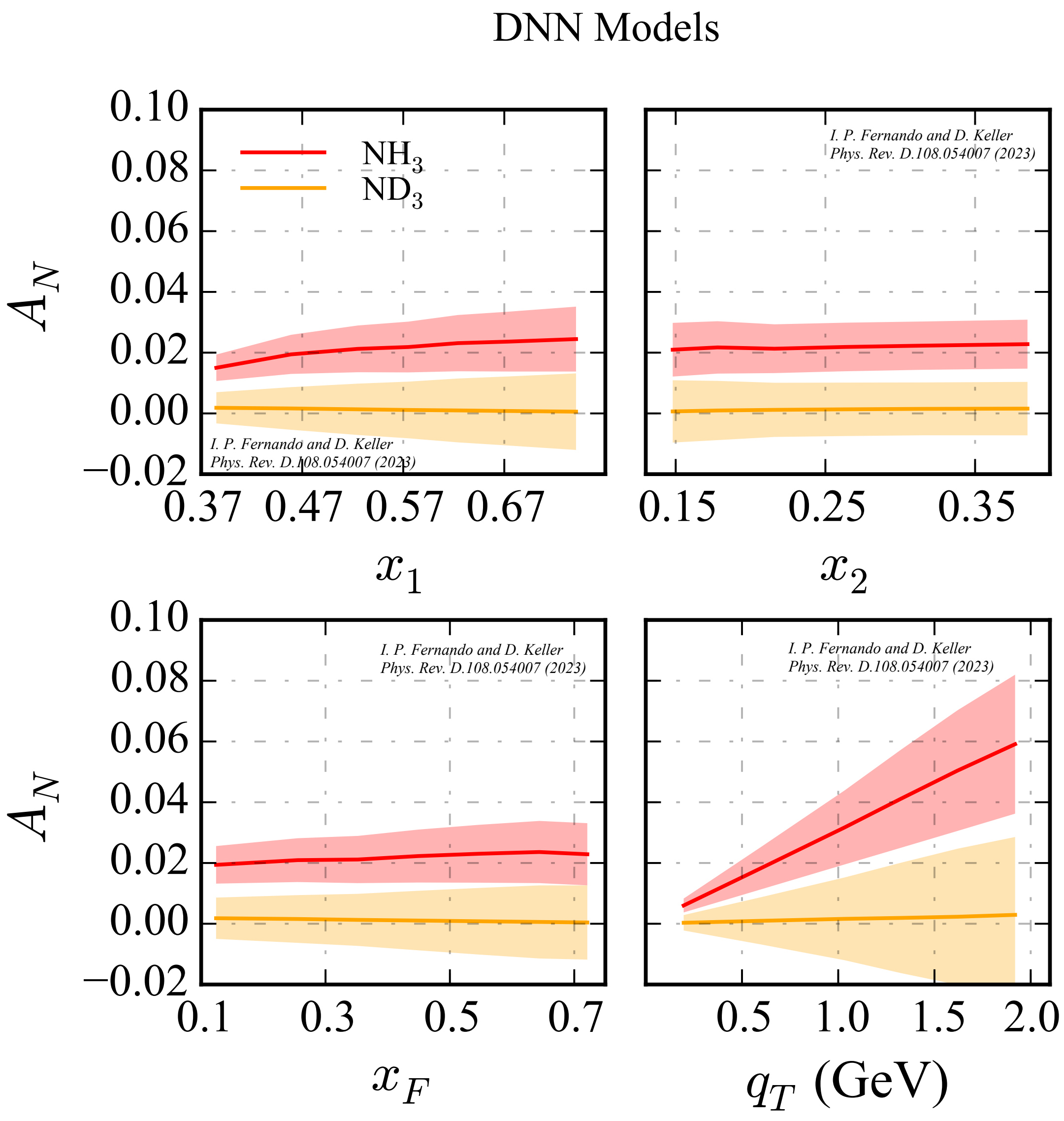
Note: These proton-DNN projections based on the assuming the sign-change of the Sivers functions

DNN Model Projections: DY

In Comparison with COMPASS 2024 Final



DNN Model Projections: DY @ SpinQuest



- 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.

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

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
   $Q^2 > 1.63\ \text{GeV}^2,\ \ 0.2 < z < 0.6,\ \ 0.2 < p_{hT} < 0.9$ GeV

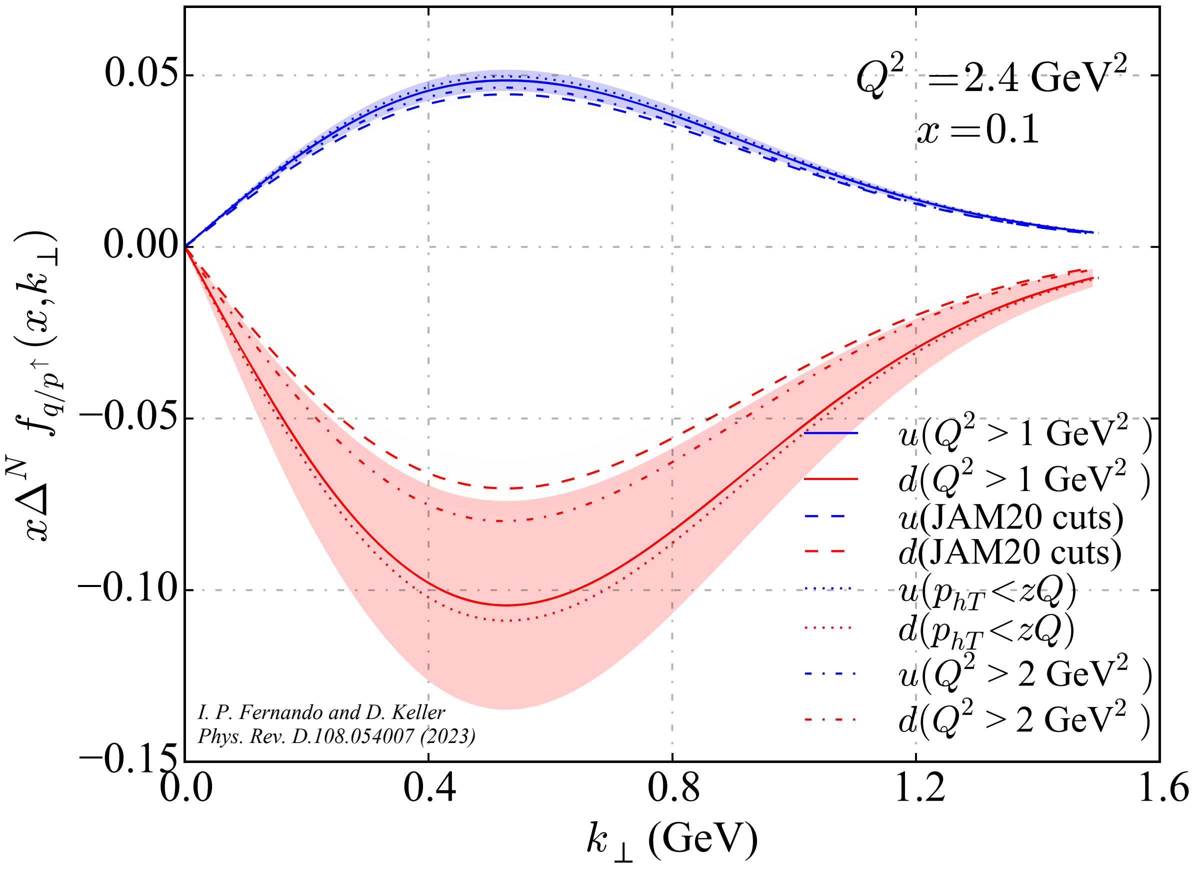
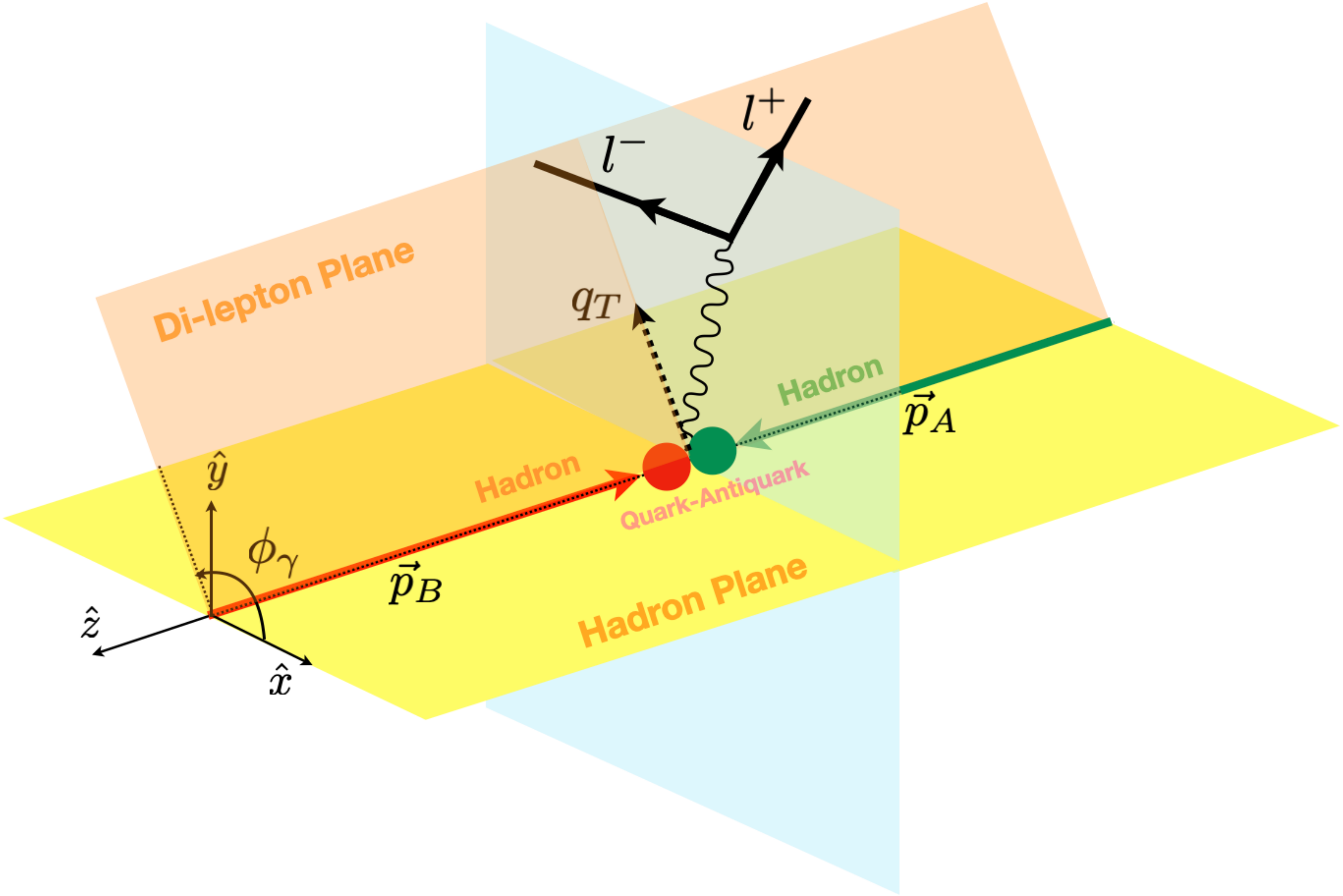


FIG. 17. Solid lines with light band represent the u (in blue), d (in red) Sivers functions using the cut $Q^2 > 1$ GeV^2. These resulting DNN models made from the cuts from all tests are also shown.

Unpolarized TMDs with fixed target DY data



Unpolarized TMDs: Motivation

- Can we obtain TMDs directly in k_T space instead of bT-space?
  We are interested in both. We think having a framework with k_T and complimentary to b_T space

$$\frac{d\sigma}{dq_T dQ_M dy} = \frac{16\pi^2\alpha^2}{9Q_M^3} q_T \sum_q e_q^2 \mathcal{H}^{DY} \int d^2\mathbf{k}_{aT} d^2\mathbf{k}_{bT} f_{q/a}(x_a, \mathbf{k}_{aT}; \mu_Q, Q^2) f_{\bar{q}/b}(x_b, \mathbf{k}_{bT}; \mu_Q, Q^2) \delta^{(2)}(\mathbf{q}_T - \mathbf{k}_{aT} - \mathbf{k}_{bT}) + (x_a \leftrightarrow x_b)$$

- Number of data points vs cuts:
  Our goal is to use as much data as available while TMD factorization is still valid.

- Different types of parameterizations attempted in the literature:
  So, we want to explore a purely numerical approach utilizing DNNs

Unpolarized TMDs: Setup

Introducing (exploration of) a separable form

$$f_q(x, k_\perp, Q_M) = f_q(x, Q_M)\, s(x, k_\perp)\, \mathcal{B}(Q_M)$$

Colinear-PDFs with DGLAP Evolution

Transvers Momentum Kernal (DNN)

Transvers Momentum Evolution Kernal (DNN)

$$\hat{f}_1^a(x, \boldsymbol{b}_T^2; \mu_f, \zeta_f) = \hat{f}_1^a(x, \boldsymbol{b}_T^2; \mu_i, \zeta_i) \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma(\mu, \zeta_f) \right\} \left(\frac{\zeta_f}{\zeta_i} \right)^{K(|\boldsymbol{b}_T|, \mu_i)/2}$$

$$\frac{d\sigma}{dq_T dQ_M dy} = \frac{16\pi^2\alpha^2}{9Q_M^3} q_T \sum_q e_q^2 \mathcal{H}^{DY} \int d^2\mathbf{k}_{aT} d^2\mathbf{k}_{bT} f_{q/a}(x_a, \mathbf{k}_{aT}; \mu_Q, Q^2) f_{\bar{q}/b}(x_b, \mathbf{k}_{bT}; \mu_Q, Q^2) \delta^{(2)}(\mathbf{q}_T - \mathbf{k}_{aT} - \mathbf{k}_{bT}) + (x_a \leftrightarrow x_b)$$

$$\frac{d\sigma}{dq_T dQ_M dy} = \frac{16\pi^2\alpha^2}{9Q_M^3} q_T \sum_q e_q^2 x_a f_q(x_a, Q_M) x_b f_{\bar{q}}(x_b, Q_M) \mathcal{S}(q_T, x_a, x_b) \mathcal{B}^2(Q_M) + (x_a \leftrightarrow x_b)$$

Unpolarized TMDs: Setup

Introducing (exploration of) a separable form

$$f_q(x, k_\perp, Q_M) = f_q(x, Q_M)s(x, k_\perp)\mathcal{B}(Q_M)$$

Colinear-PDFs with DGLAP Evolution

Transvers Momentum Kernal

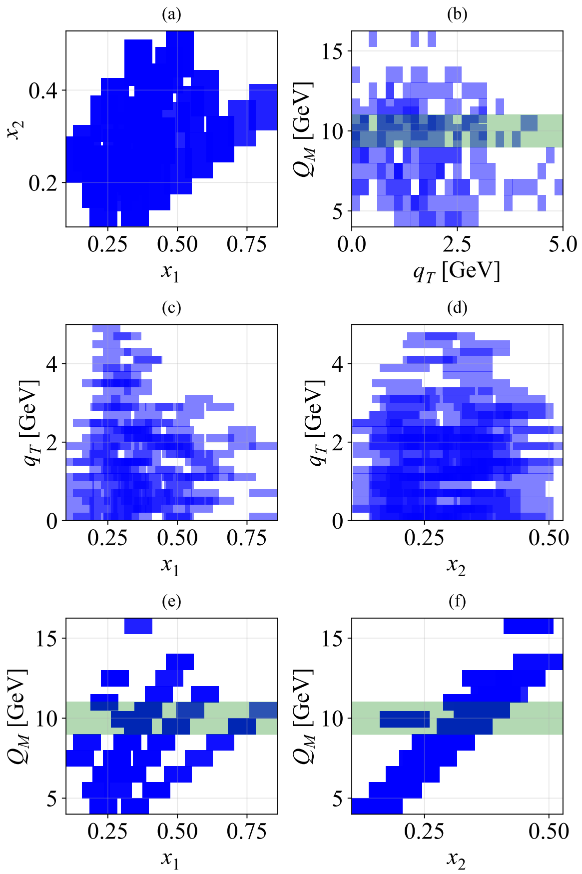
Transvers Momentum Evolution Kernal

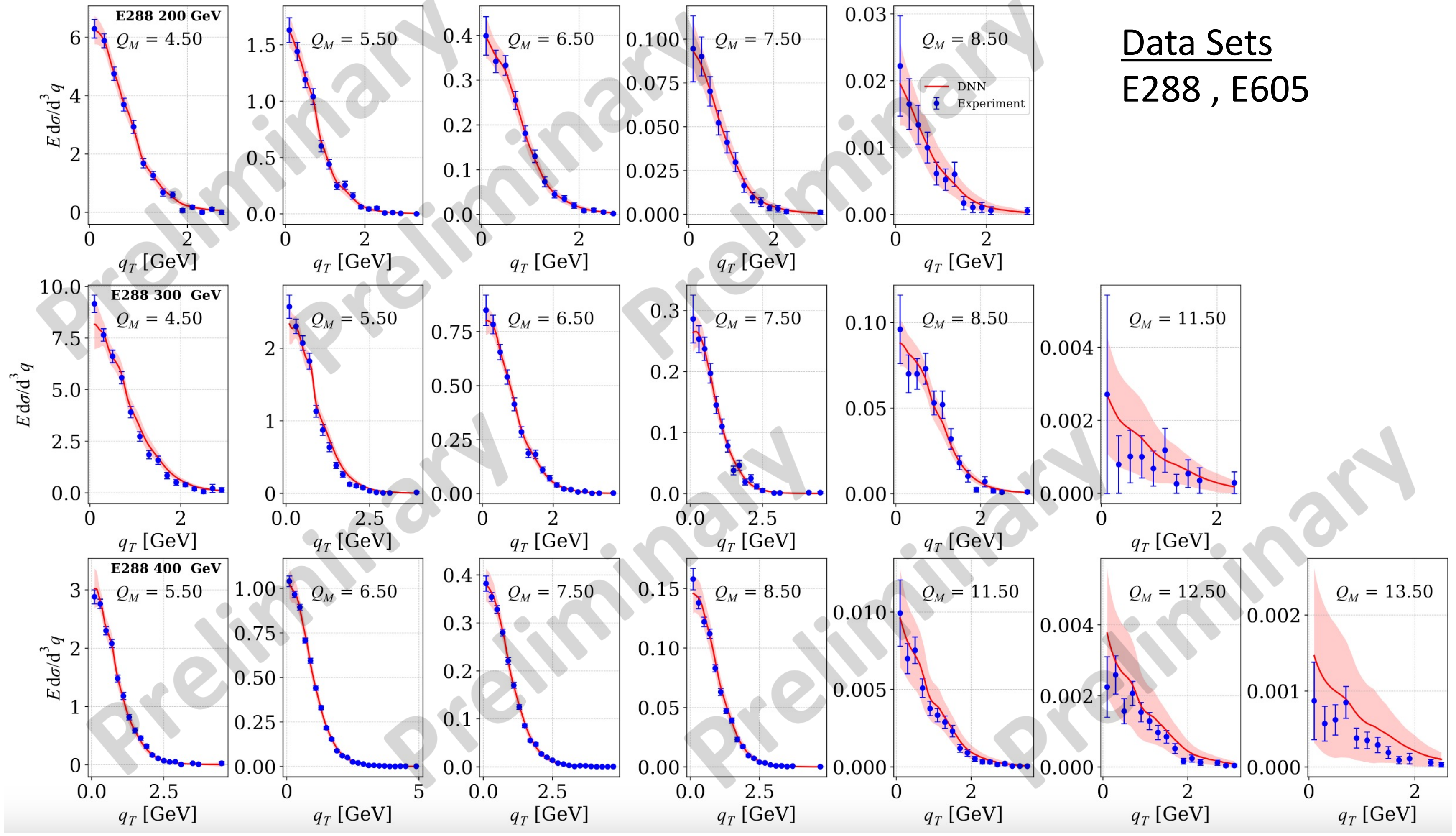
$$\frac{d\sigma}{dq_T dQ_M dy} = \frac{16\pi^2\alpha^2}{9Q_M^3} q_T \sum_q e_q^2 \mathcal{H}^{DY} \int d^2\mathbf{k}_{aT} d^2\mathbf{k}_{bT} f_{q/a}(x_a, \mathbf{k}_{aT}; \mu_Q, Q^2) f_{\bar{q}/b}(x_b, \mathbf{k}_{bT}; \mu_Q, Q^2) \delta^{(2)}(\mathbf{q}_T - \mathbf{k}_{aT} - \mathbf{k}_{bT}) + (x_a \leftrightarrow x_b)$$

$$\frac{d\sigma}{dq_T dQ_M dy} = \frac{16\pi^2\alpha^2}{9Q_M^3} q_T \sum_q e_q^2 x_a f_q(x_a, Q_M) x_b f_{\bar{q}}(x_b, Q_M) \mathcal{S}(q_T, x_a, x_b) \mathcal{B}^2(Q_M) + (x_a \leftrightarrow x_b)$$

$$S(q_T, x_a, x_b) = \int_0^\infty dk_\perp k_\perp \int_0^{2\pi} d\phi s(x_a, k_\perp) s\left(x_b, \sqrt{q_T^2 + k_\perp^2 - 2q_T k_\perp \cos\phi}\right)$$

Current Status





Data Sets
E288 , E605

$$S(q_T, x_a, x_b) = \int_0^\infty dk_\perp k_\perp \int_0^{2\pi} d\phi s(x_a, k_\perp) s\left(x_b, \sqrt{q_T^2 + k_\perp^2 - 2q_T k_\perp \cos\phi}\right)$$

$$f_q(x; Q) = \int d^2k_\perp f_q(x, k_\perp; Q)$$

Finalizing the simultaneous fits to obtain the TMDs (flavor dependent)

$$f_q(x, k_\perp, Q_M) = f_q(x, Q_M) s(x, k_\perp) \mathcal{B}(Q_M)$$

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
- We have successfully tested our method with pseudo-data, also a dedicated systematic study.
- 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…

Next:

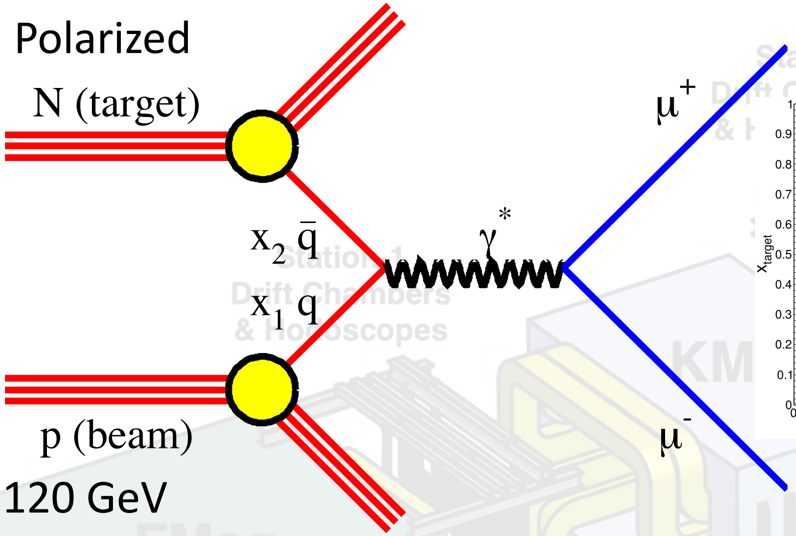
- Applying the "DNN method" to extract other TMDs such as Transversity, Boer-Mulders function, as well as Spin-1 TMDs.
- Make projections to EIC kinematics

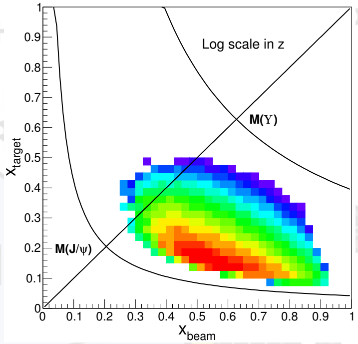
SpinQuest (E1039) Experiment at Fermilab

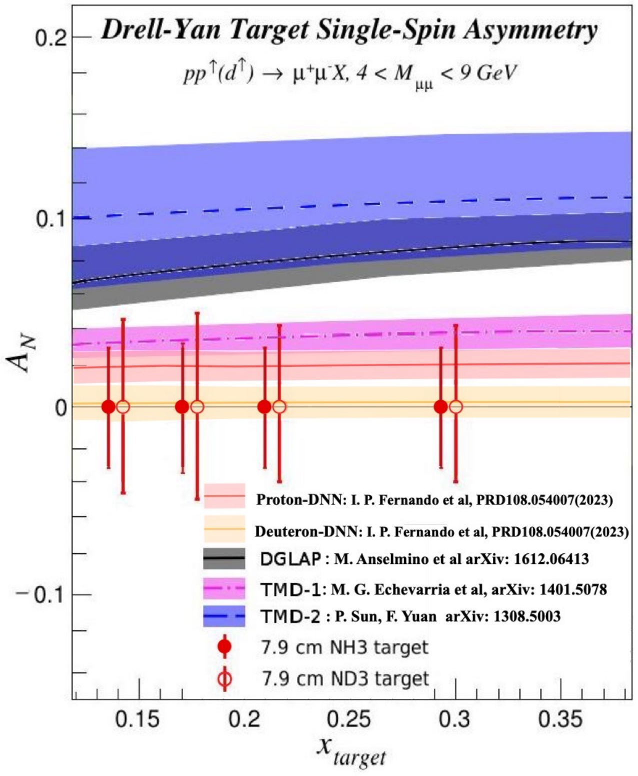
- Probing Sivers asymmetry from the (light) ‘sea’ quark contributions

Stay Tuned!

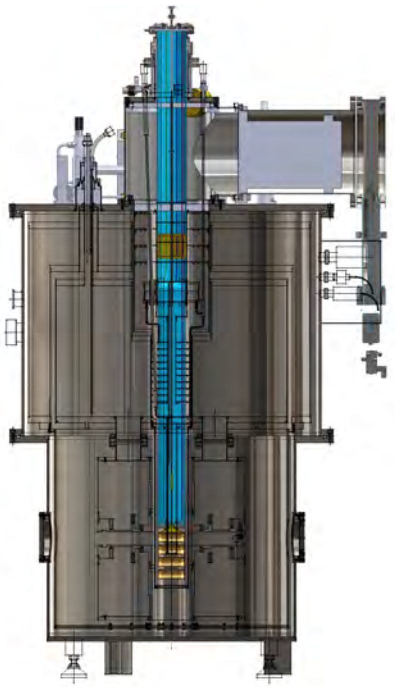
$$pp^{\uparrow}(d^{\uparrow}) \rightarrow \mu^+\mu^- X,\ 4 < M_{\mu\mu} < 9\ GeV$$







$$\frac{d\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_i e_i^2(q_i^B(x_1,Q^2)\bar{q}_i^T(x_2,Q^2) + \bar{q}_i^B(x_1,Q^2)q_i^T(x_2,Q^2))$$



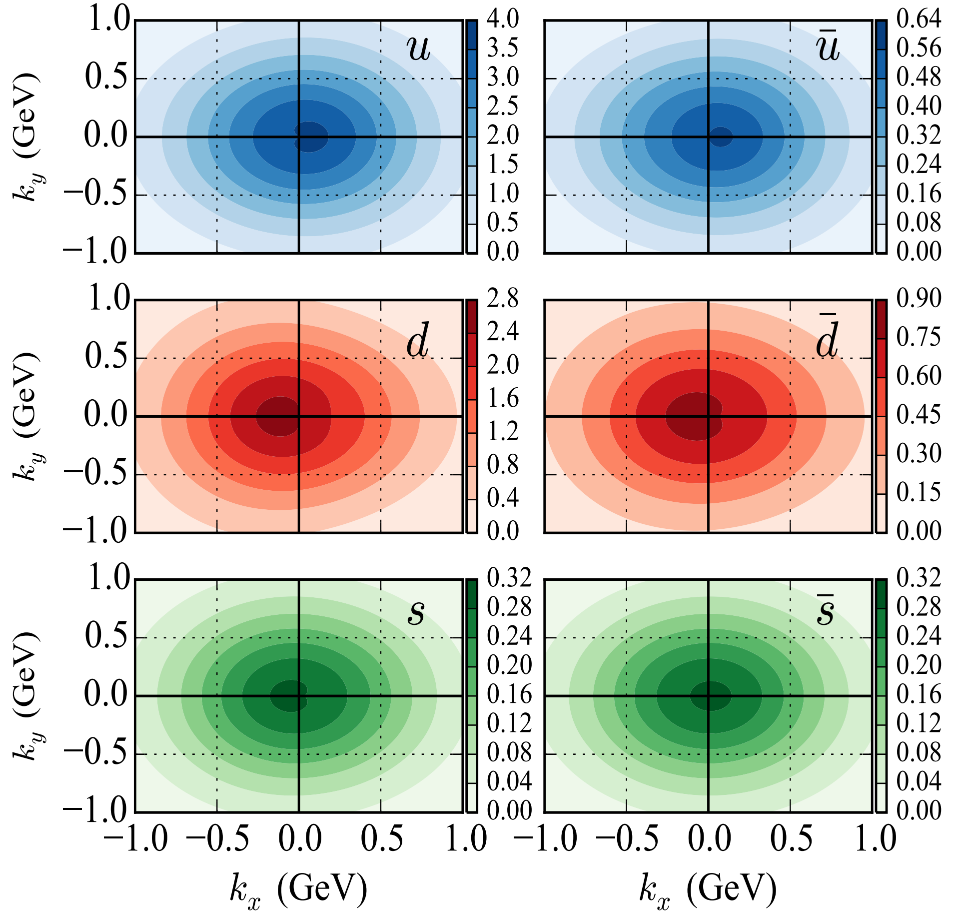
LANL-UVA
Polarized Target

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!



Thank you

UNIVERSITY of VIRGINIA

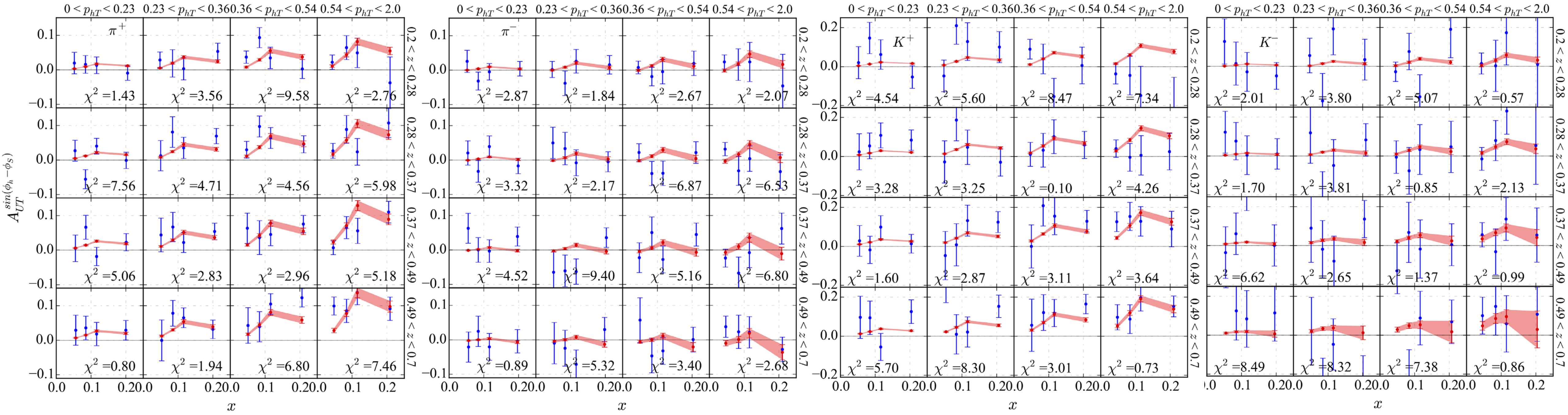
UVA - Spin
PHYSICS GROUP

U.S. DEPARTMENT OF ENERGY | Office of Science

This work is supported by DOE contract DE-FG02-96ER40950

Backup Slides

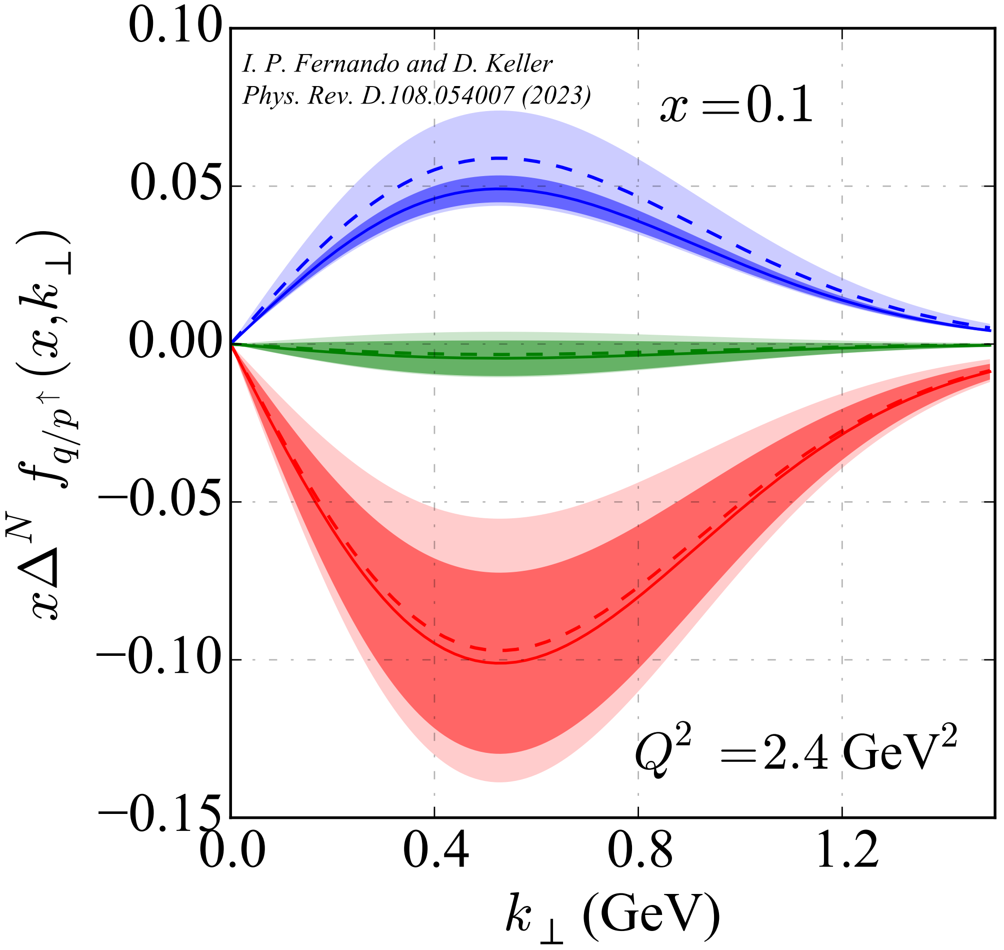
Projections from the “Proton” DNN Model



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: With Real data (Quality of the extraction)

Backup



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)

Systematic Studies: Choice of h(k)

Backup

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

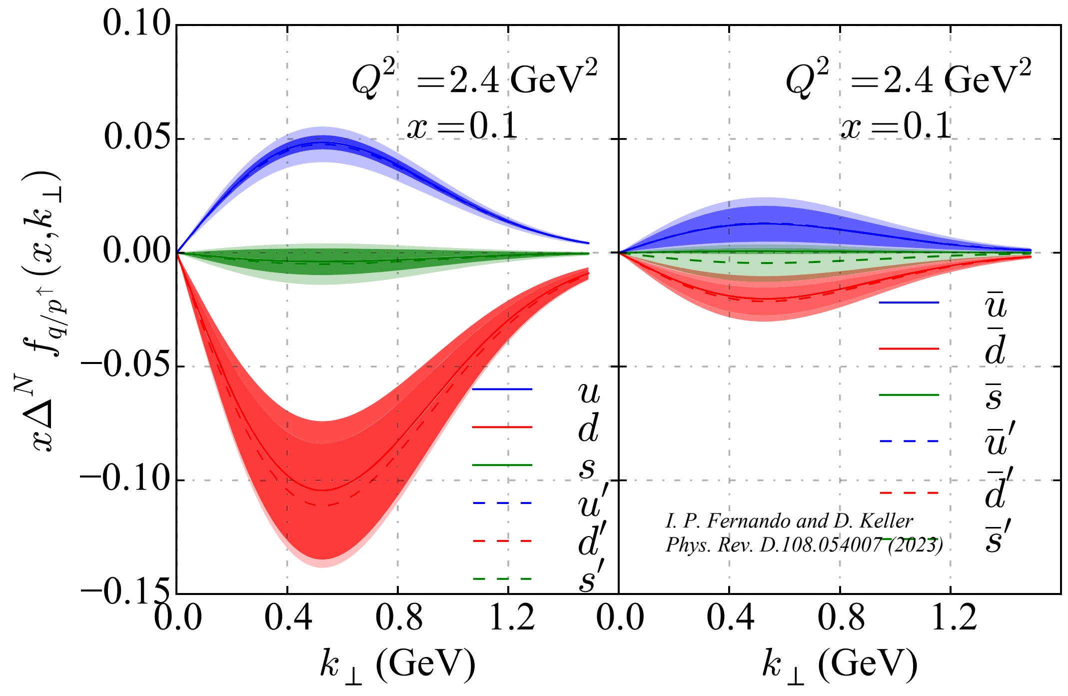


FIG. 19. Using two different $h(k_\perp)$. Solid line with dark band represents the Sivers functions with $h(k_\perp) = \sqrt{2e}\frac{k_\perp}{m_1}e^{-k_\perp^2/m_1^2}$, whereas the dashed line with light band represents the Sivers functions with $h(k_\perp) = \frac{2k_\perp m_1}{m_1^2+k_\perp^2}$.

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

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

- 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: data cuts

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

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.

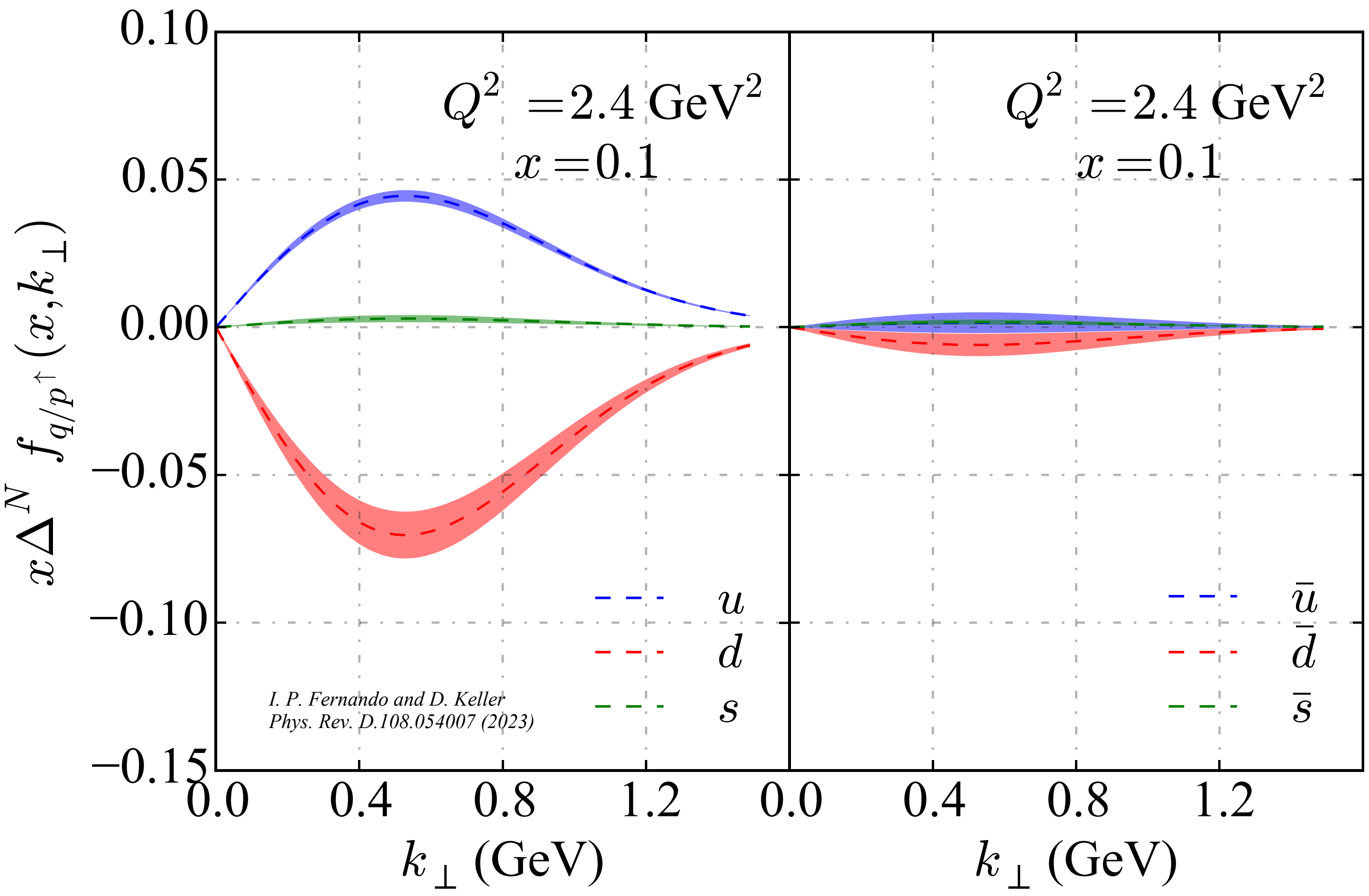


FIG. 18. Sivers functions from a retrained DNN model using the cuts [65] to the data demonstrating that being selective with the data can reduce the error bands of the fit but may also add an unintentional bias.

Systematic Studies : TMD Evolution

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

The solution of the TMD evolution equations

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

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

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

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

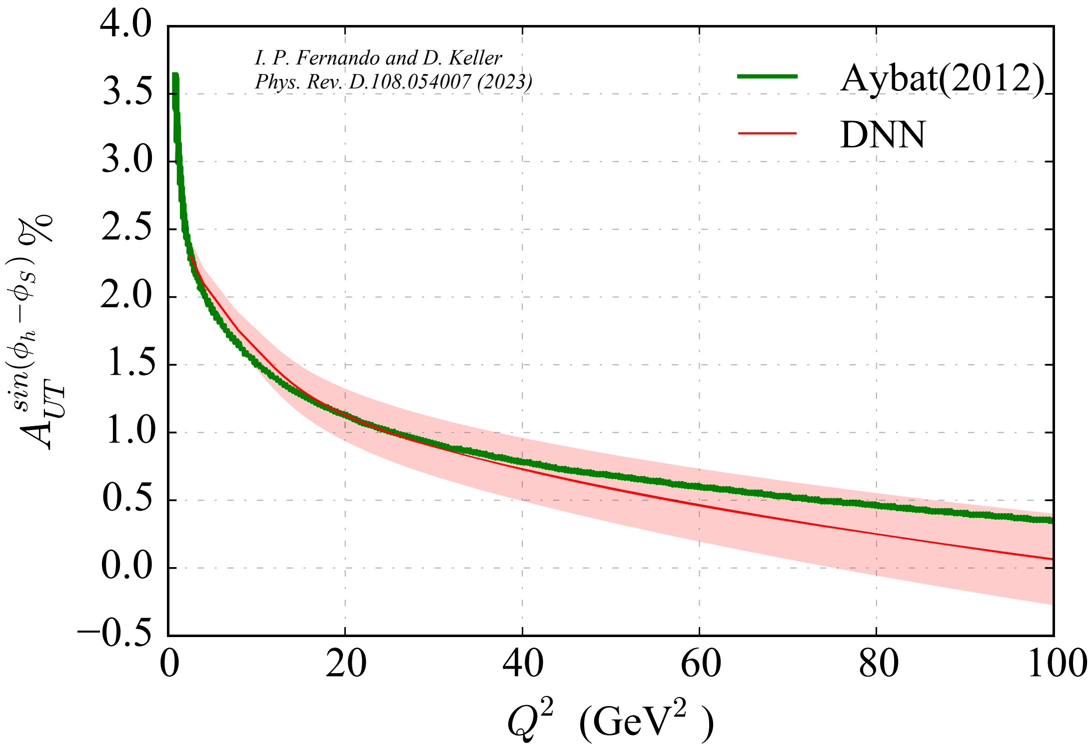


FIG. 21. The Sivers asymmetry evolution in Q^2 compared to the result from [6]. The red-colored solid line and the band represent the mean and standard deviation of the $A_{UT}^{\sin(\phi_h - \phi_S)}$ from 1000 replica models of the proton DNN at $x = 0.12$, $z = 0.32$, $p_{hT} = 0.14$ GeV.

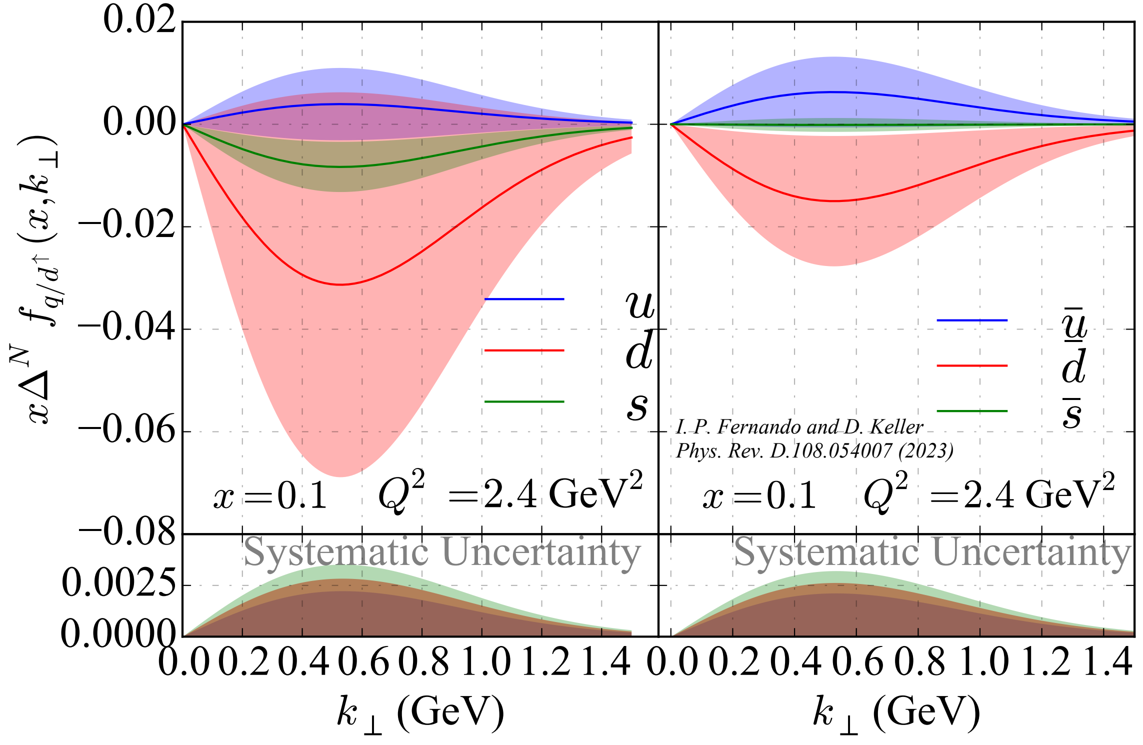
Backup

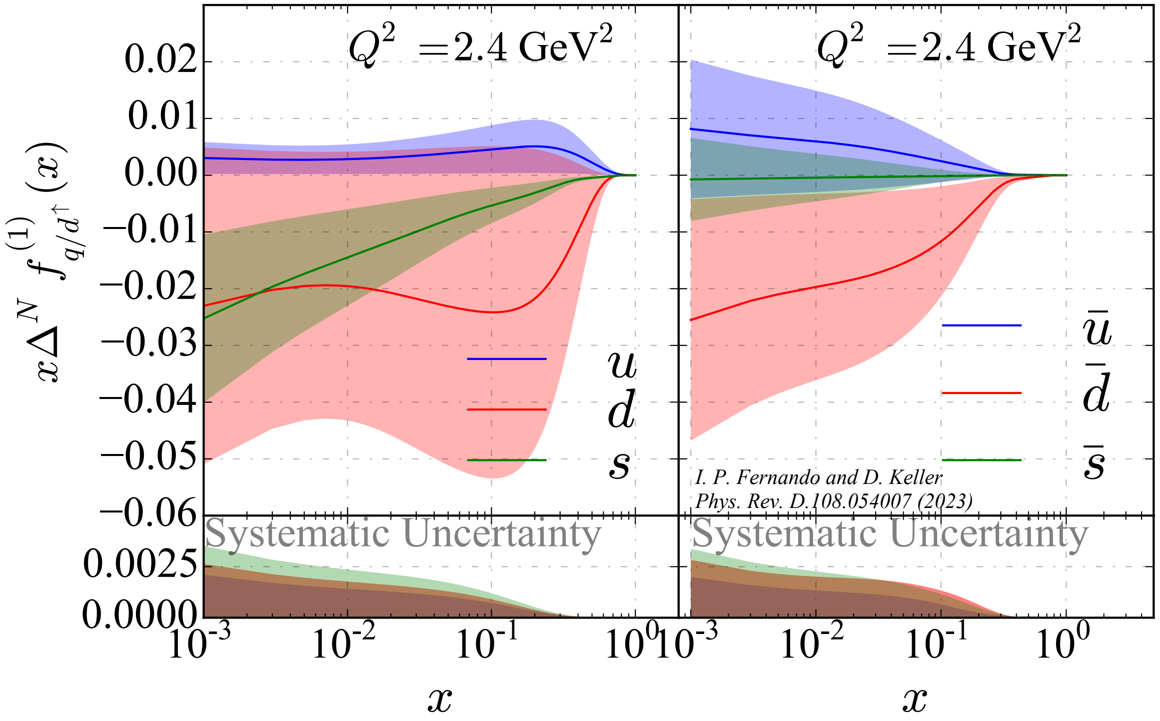
DNN Method: Results from the “Deuteron” Model

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

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

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



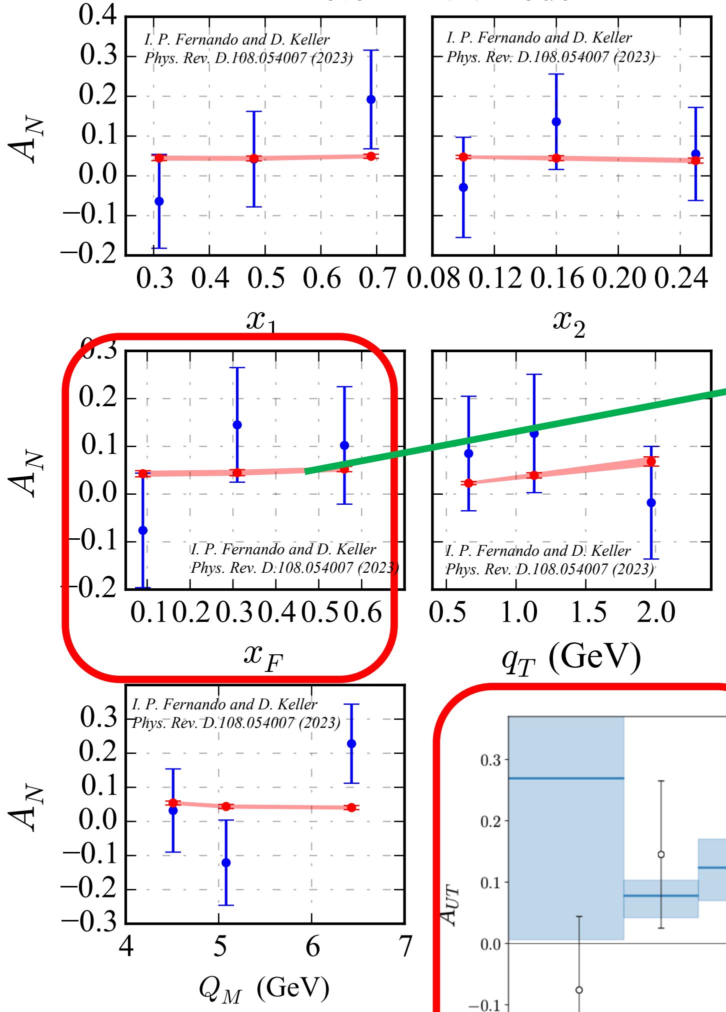


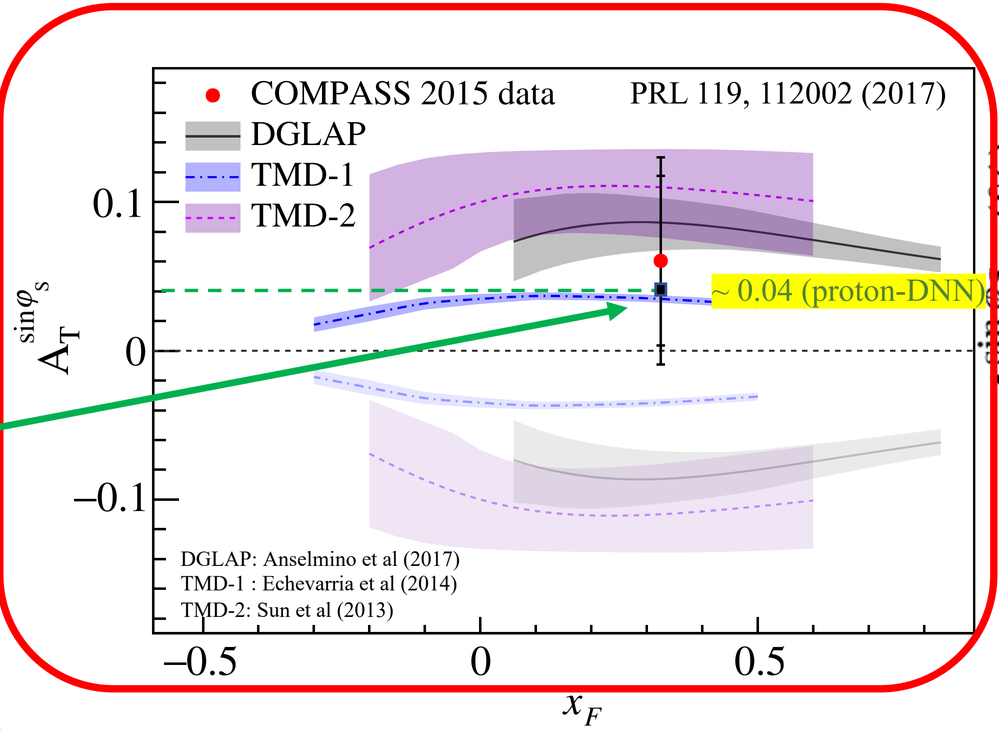
Backup

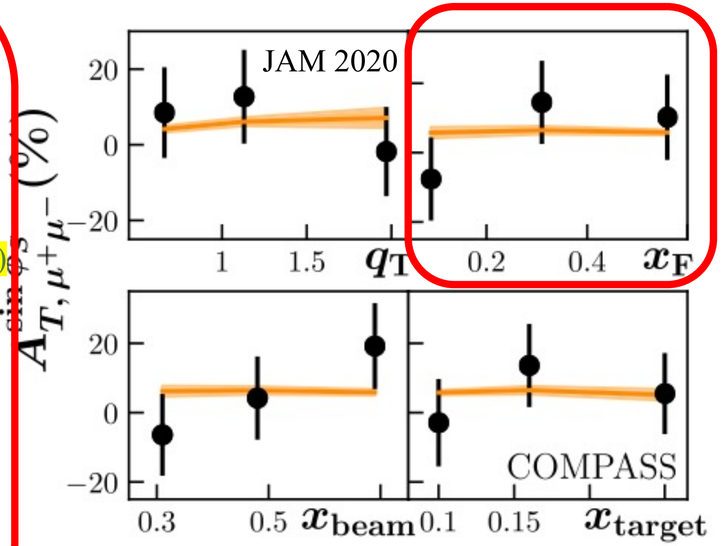
DNN Model Projections: DY

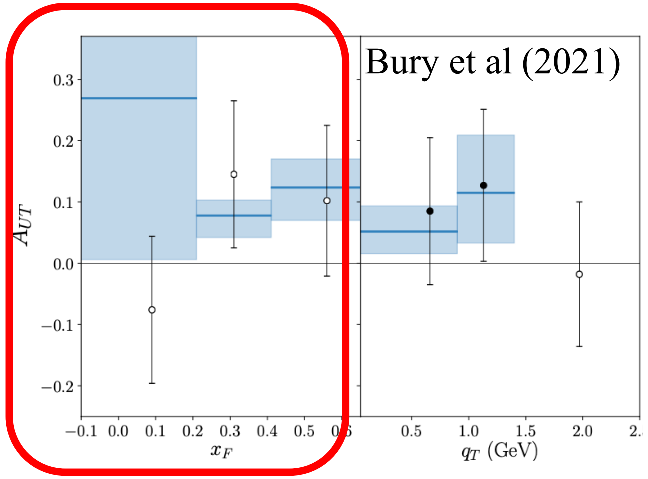
COMPASS 2017 DY Projections

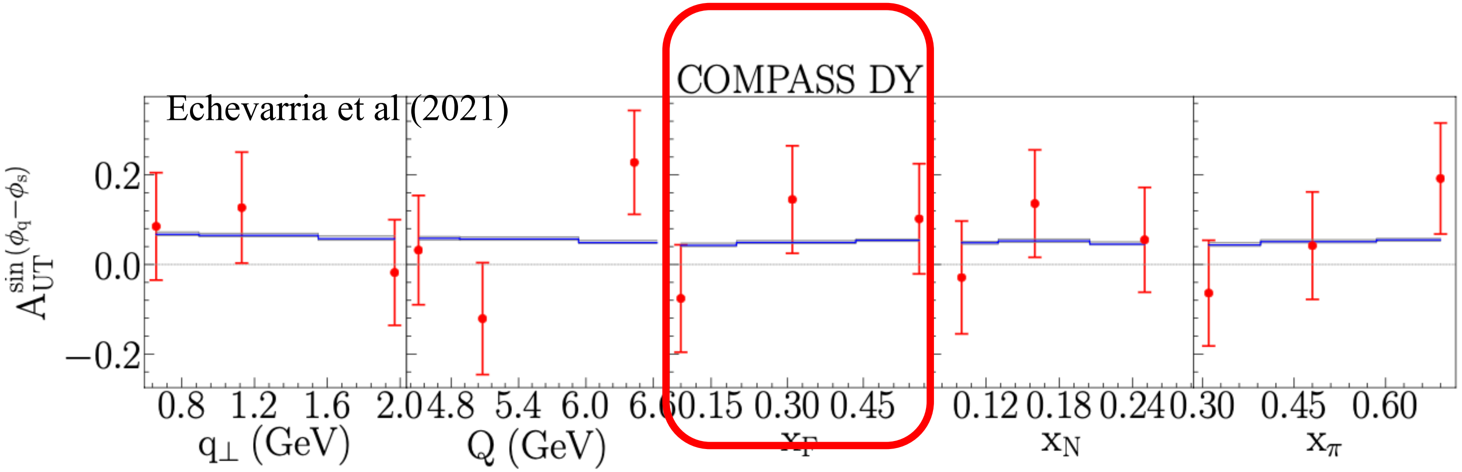
Proton-DNN model

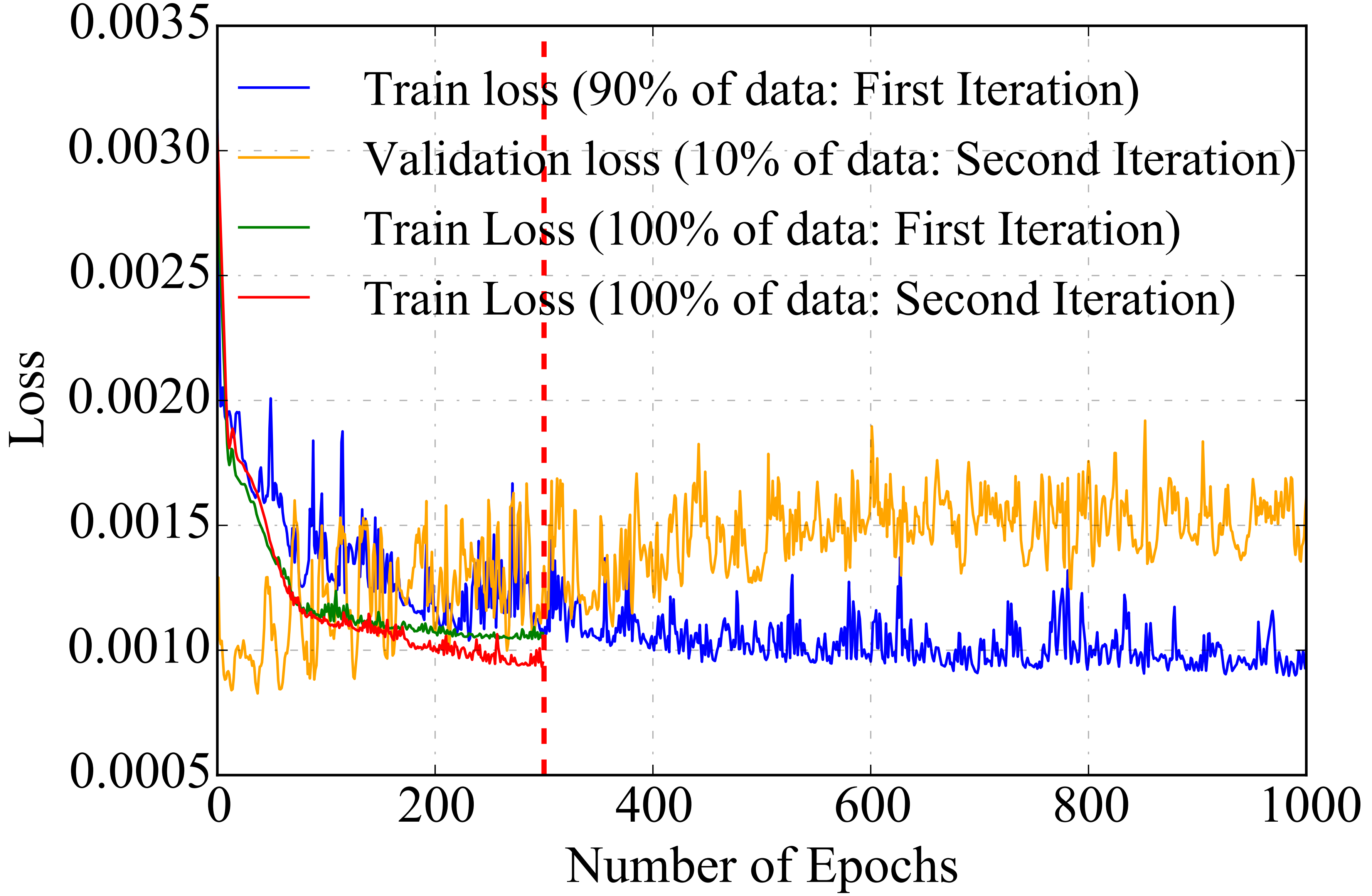











Train loss (90% of data: First Iteration)
Validation loss (10% of data: Second Iteration)
Train Loss (100% of data: First Iteration)
Train Loss (100% of data: Second Iteration)
Loss
0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0
200
400
600
800
1000
Number of Epochs

Backup

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