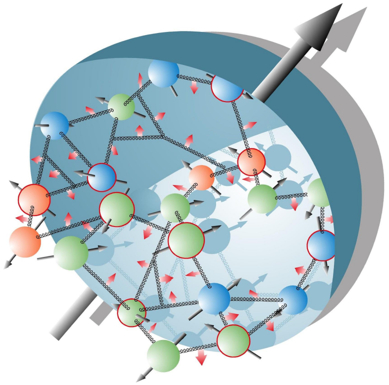
TMD measurements at Fermilab (for Spin ½ and Spin 1 targets)



Ishara Fernando & Dustin Keller

July 10-14, 2023

Tensor Spin Observables (@ ECT)*

Trento, Italy

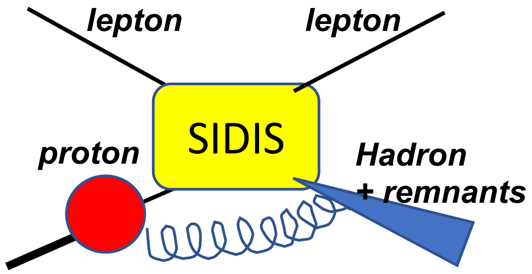
Based on: arxiv2205.01249 , arxiv.2304.14328

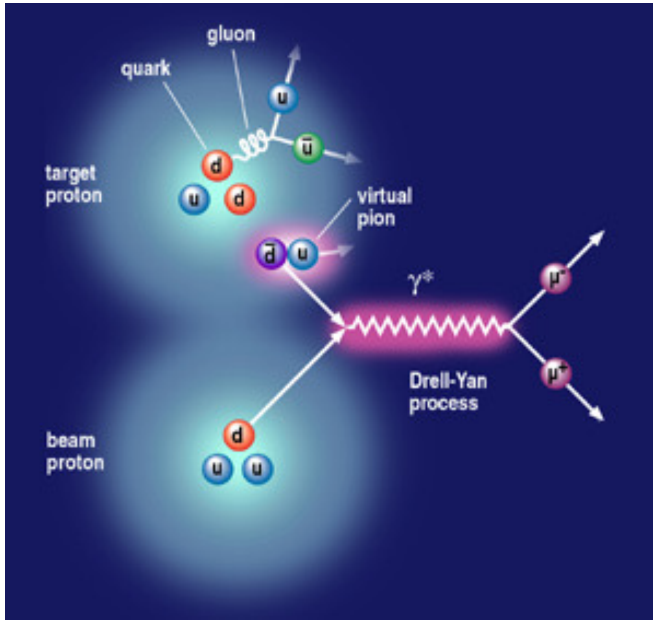
This work is supported by DOE contract DE-FG02-96ER40950

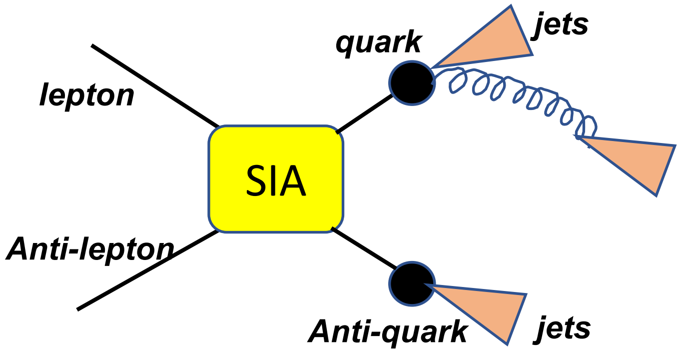
Outline

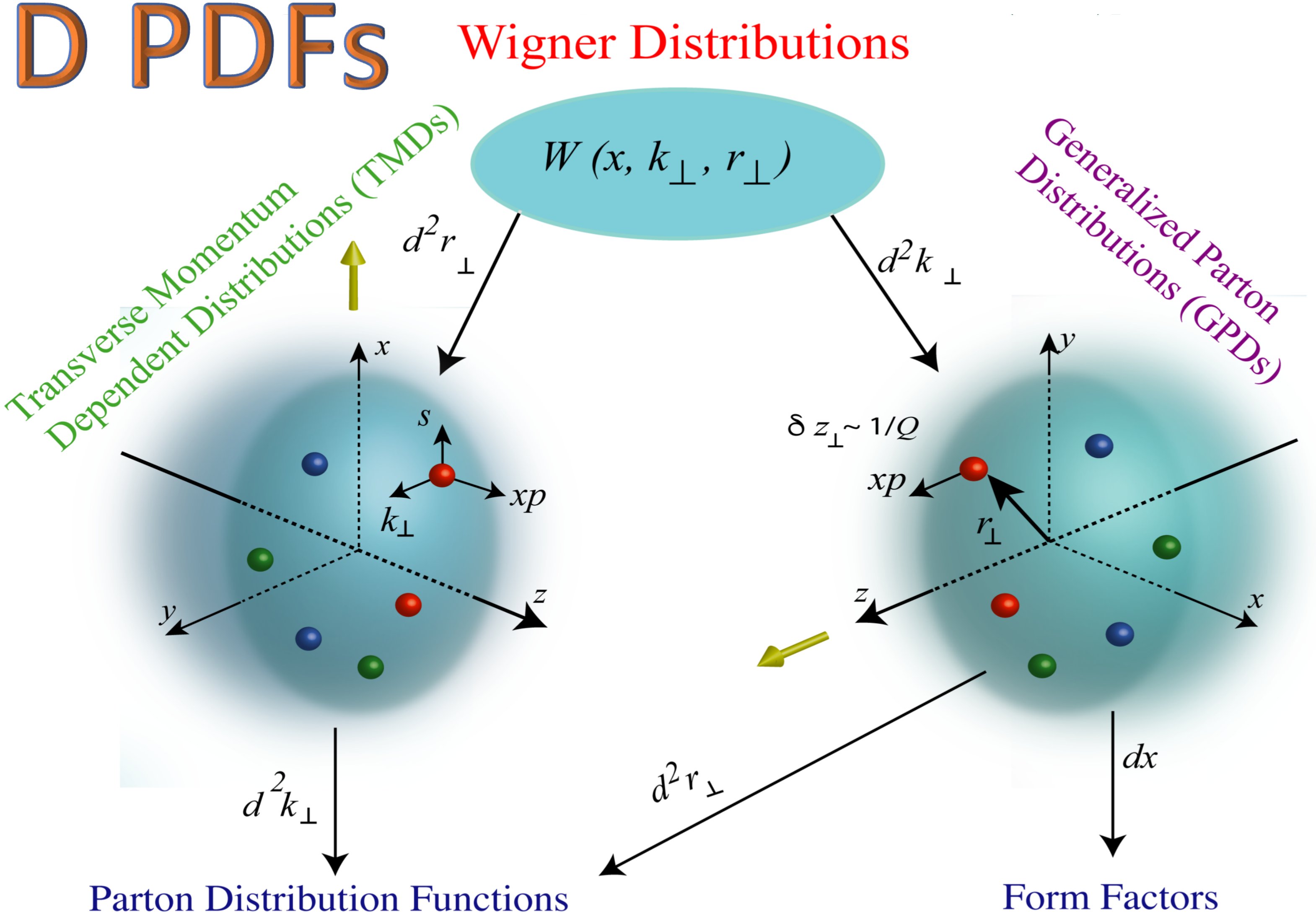
- A brief introduction to TMDs
- Sea-quark orbital angular momentum for the proton spin
- Sea-quark Sivers functions and the SpinQuest experiment
- An application of DNNs to extract TMDs: Sivers functions
- Spin 1 TMDs
  > Transversity
  > $f_{1LL}(x)$

TMD PDFs



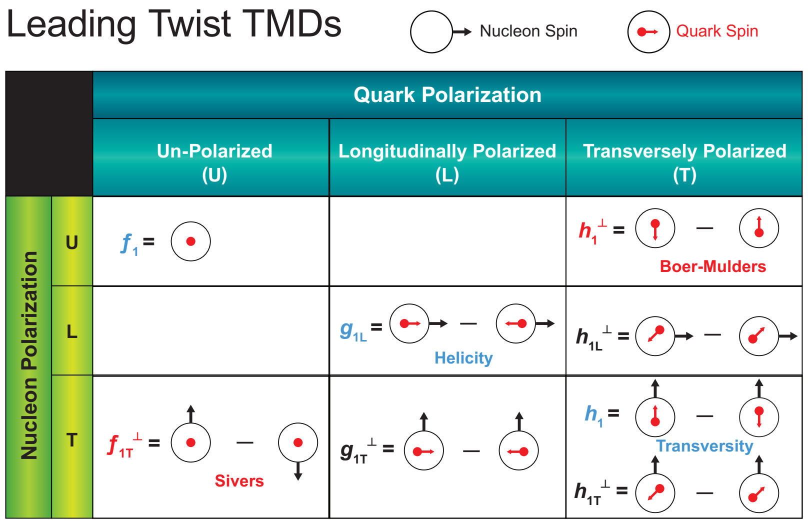






$$\Phi(x, k_T; S) = \int \frac{d\xi^- d\xi_T}{(2\pi)^3} e^{ik.\xi} \langle P, S | \bar{\psi}(0)\, \mathcal{U}_{[0,\xi]}\, \psi(\xi) | P, S \rangle |_{\xi^+=0}$$

TMD PDFs



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

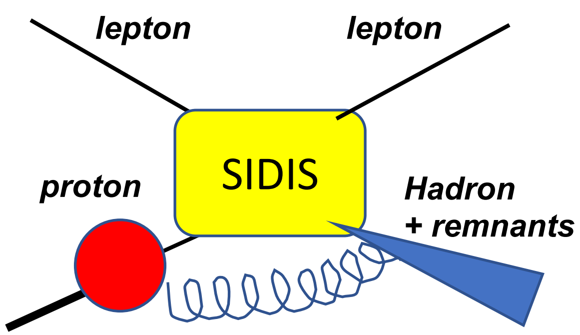
At leading-twist, the Quark correlator can be decomposed into 8 components (6 T - even and 2 T -odd terms)

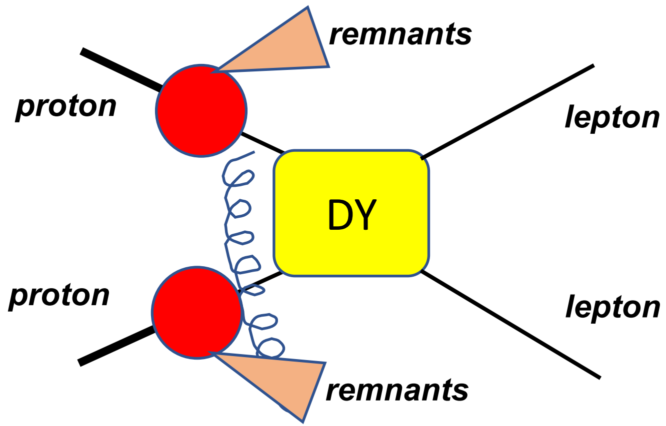
$$\Phi(x,k_T,P,S) = f_1(x,k_T^2)\frac{\not P}{2} + \frac{h_{1T}(x,k_T^2)}{4}\gamma_5[\not S_T,\not P] + \frac{S_L}{2}g_{1L}(x,k_T^2)\gamma_5\not P + \frac{k_T.S_T}{2M}g_{1T}(x,k_T^2)\gamma_5\not P$$
$$+ S_L h_{1L}^\perp(x,k_T^2)\gamma_5\frac{[\not k_T,\not P]}{4M} + \frac{k_T.S_T}{2M}h_{1T}^\perp(x,k_T^2)\gamma_5\frac{[\not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

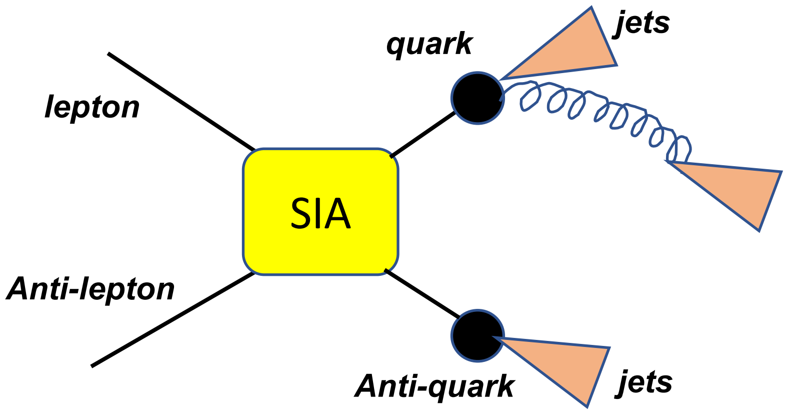
T-even

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

T-odd

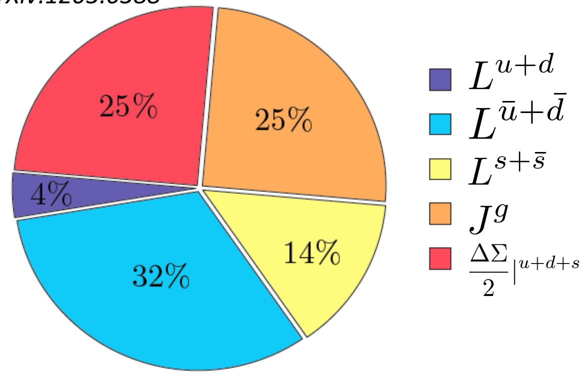






Possible missing spin contributions

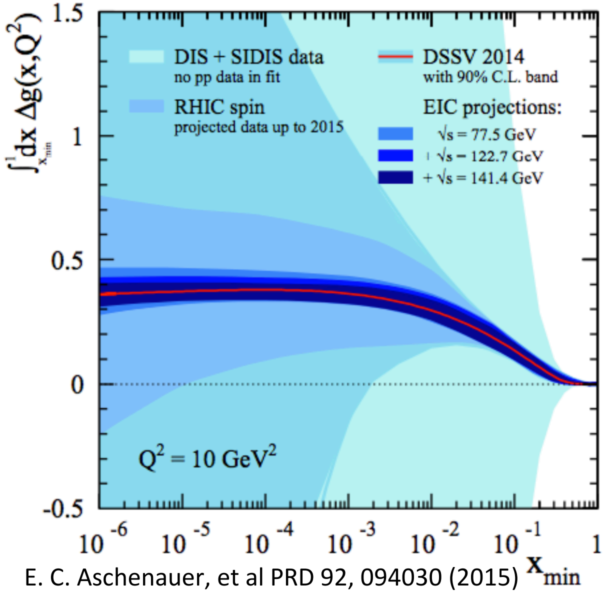
K.-F. Liu et al
arXiv:1203.6388



$\Delta\Sigma_q \approx 25\%$

$2\ L_q \approx 50\%$ (4% (valence)+46% (sea))

$2\ J_g \approx 25\%$



E. C. Aschenauer, et al PRD 92, 094030 (2015)

Ji's decomposition

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \sum_q L_q^z + J_g^z$$

Valence + Sea quarks' OAM

Jaffe-Manohar decomposition

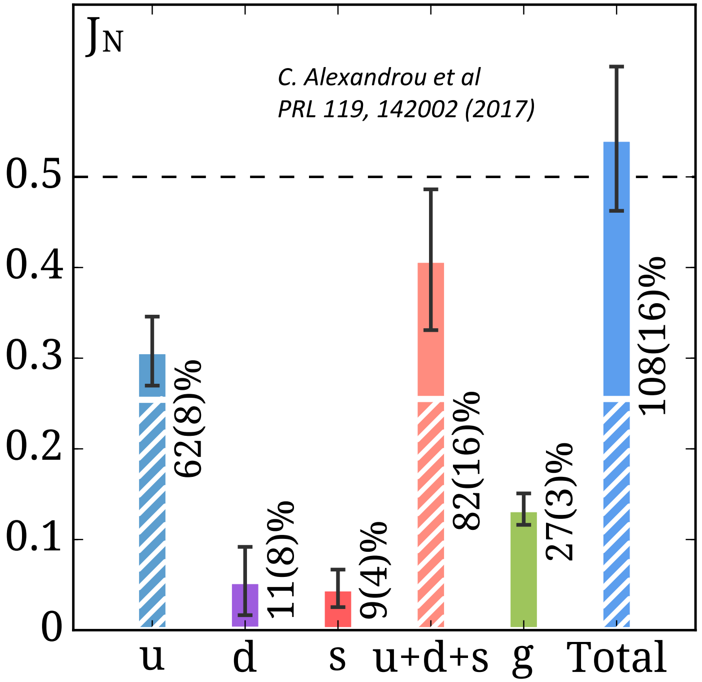
$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \sum_q \mathcal{L}^q + \Delta G + \mathcal{L}^g$$

Gluon total angular momentum

- Sea quark OAM could be a major contribution
  (J. Ellis and M. Karliner, Phys. I,ett. B213 (1988) 73)
- Separation of gluon intrinsic spin and OAM is constrained by gauge invariance

	$\frac{1}{2}\Delta\Sigma$	J	L	$\langle x\rangle$
u	0.415(13)(2)	0.308(30)(24)	-0.107(32)(24)	0.453(57)(48)
d	-0.193(8)(3)	0.054(29)(24)	0.247(30)(24)	0.259(57)(47)
s	-0.021(5)(1)	0.046(21)(0)	0.067(21)(1)	0.092(41)(0)
g	-	0.133(11)(14)	-	0.267(22)(27)
tot.	0.201(17)(5)	0.541(62)(49)	0.207(64)(45)	1.07(12)(10)

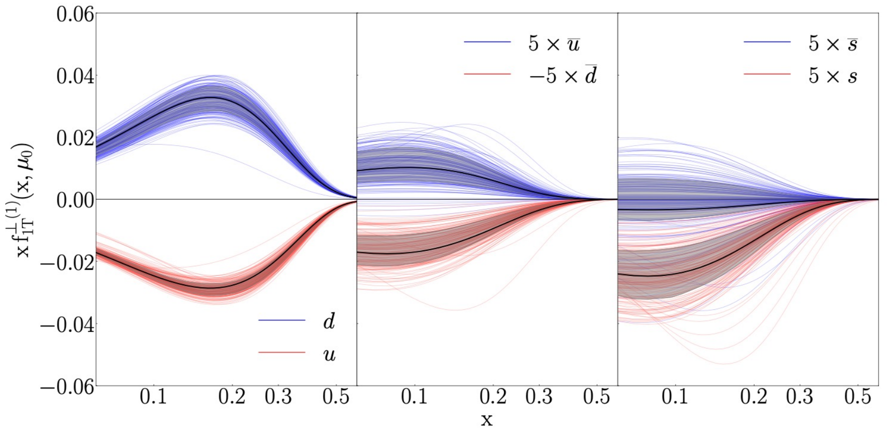
Data from 'sea'?



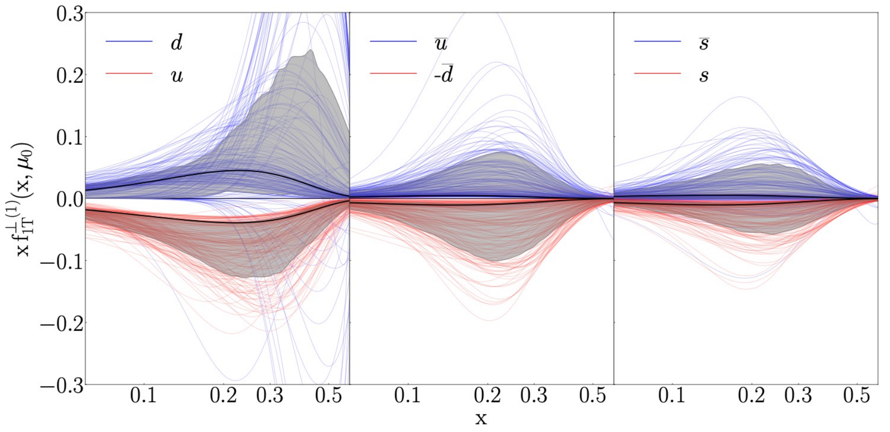
Global analyses of Sivers functions

- Lack of information on the ‘sea’ quarks is remaining.
- Assumptions were made on ‘sea’ in global fits

SIDIS only

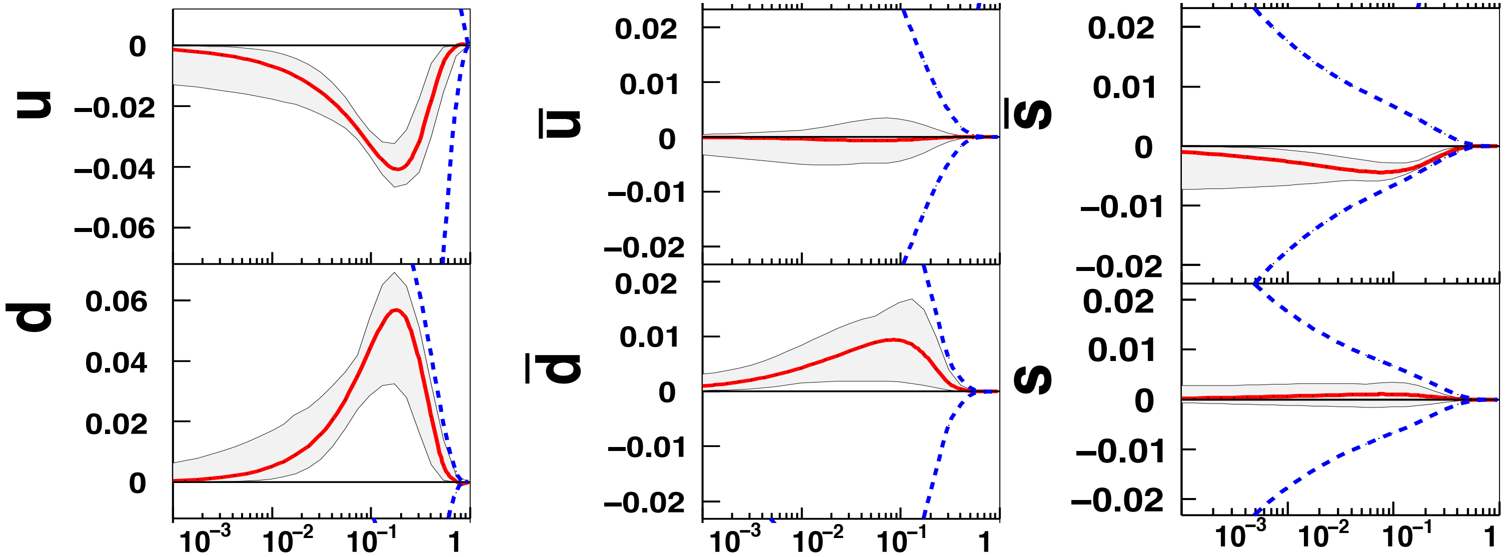


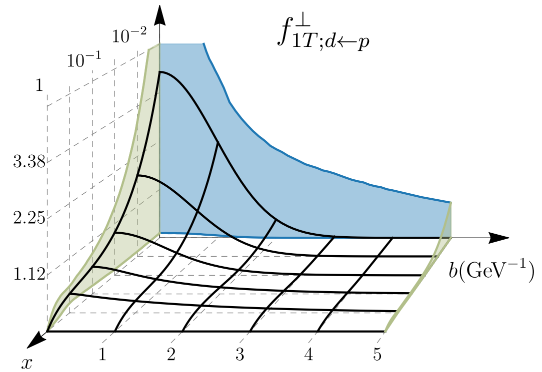
SIDIS + DY



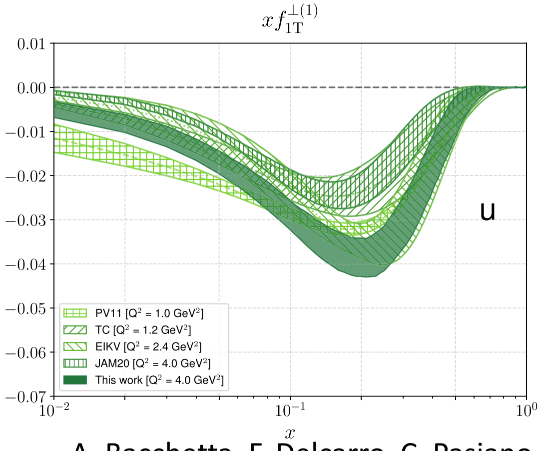
M. Echevarria, Z. Kang, J. Terry_JHEP_01_126_(2021)

M. Anselmino, M. Boglion, U. D’Alesio, S. Melis, F. Murgia, A. Prokudin_PRD_79_54010_(2009)





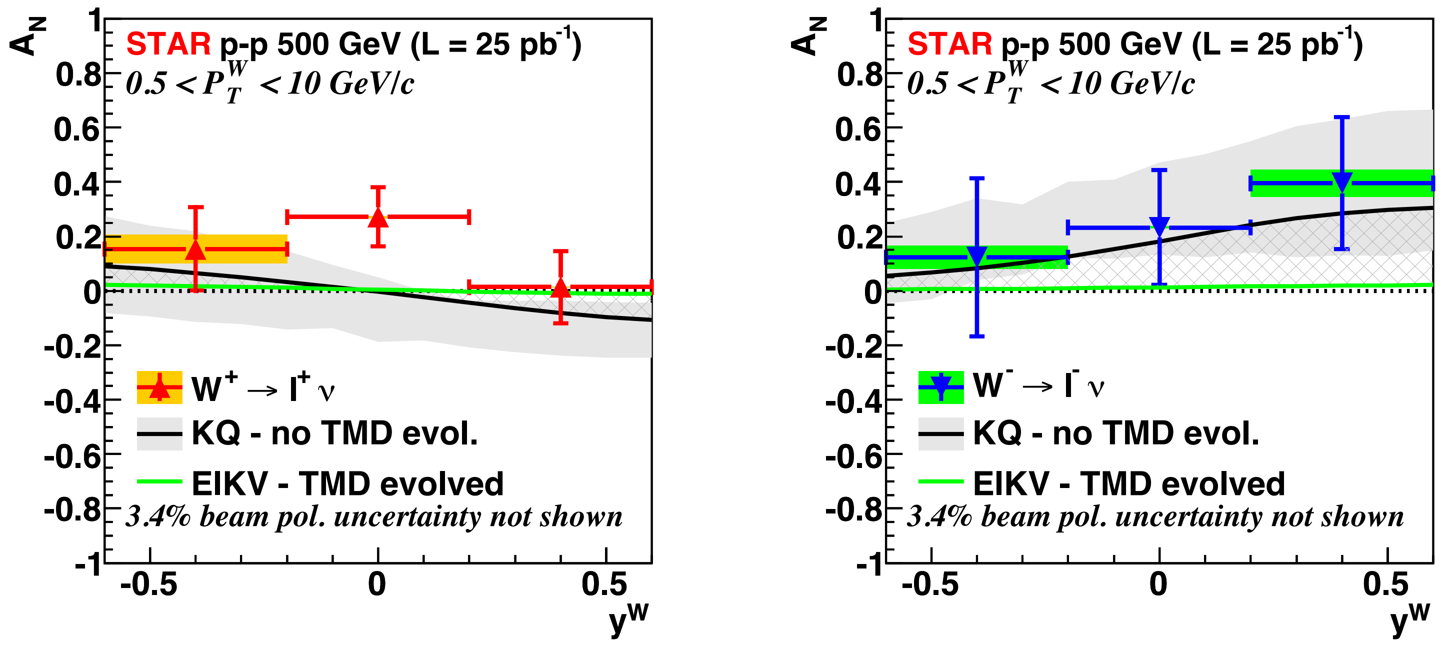
M. Bury, A. Prokudin , A. Vladimirov,, JHEP_05_151 (2021)



A. Bacchetta, F. Delcarro, C. Pasiano, M. Radici PLB 827 (2022) 136961

Sea-quarks Sivers functions

STAR Collaboration (PRL 116 132301 (2016))



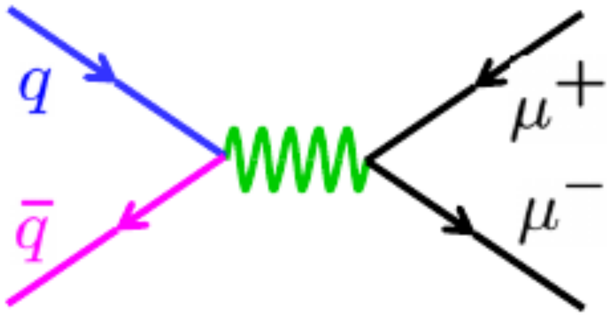
The solid gray bands represent the uncertainty due to the unknown sea quark Sivers functions estimated by saturating the sea quark Sivers function to their positivity limit in the KQ (**Z.-B. Kang and J. -W. Qiu PRL 103,172001 (2009)**)calculation

- Initial attempts to measure the Sivers asymmetry for sea quark Sivers have been reported by the STAR collaboration at RHIC using W/Z boson production. Their data is statistically limited and favor a sign-change only if TMD evolutions effects are significantly smaller than expected.
- Recent COMPASS DY experiment was also focusing on valence quarks Sivers functions through pion induced DY.
- **SpinQuest** will perform the first measurement of the Sivers asymmetry in proton-proton Drell-Yan process from the sea quarks with high statistics!
  Moreover, will provide an insight on the ***conditional universality*** for the (light) sea-quark Sivers functions.

Polarized fixed target Drell-Yan : Sensitivity to sea-quarks

beam: valence quarks at high x

target: sea quarks at low/intermediate x

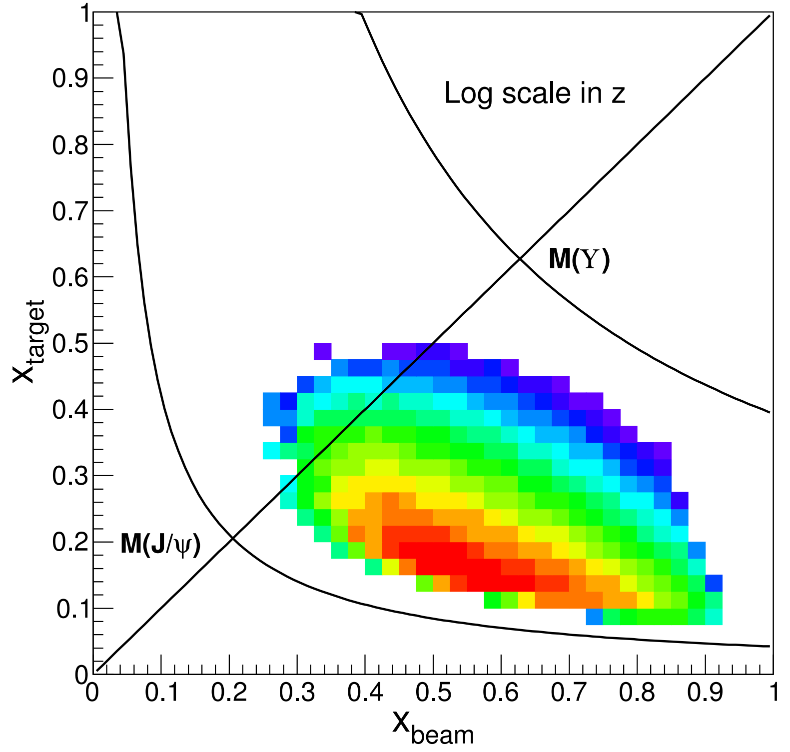


$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,...\}} e_q^2 [\bar{q}_t(x_t) q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)]$$

acceptance limited (Fixed Target, Hadron Beam)

Sea-quarks dominance

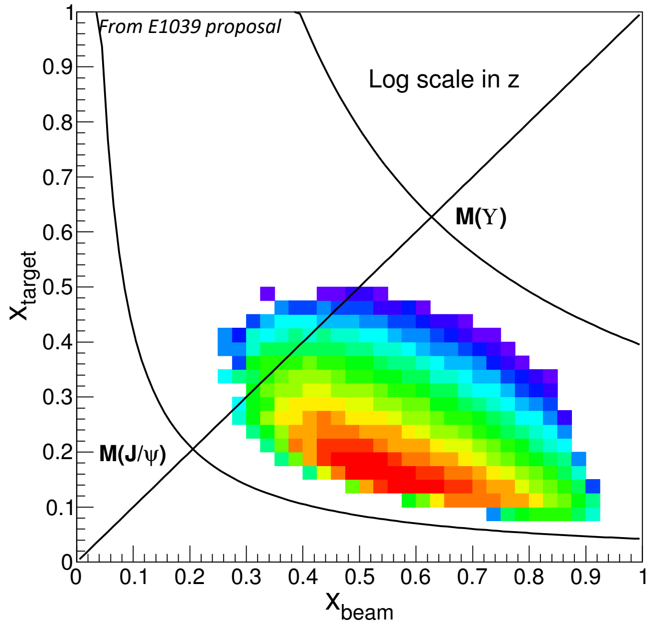
From E1039 proposal



Valence-quarks dominance

Polarized fixed target DY & J/ψ @ SpinQuest / E1039 experiment

$$A = \frac{\sigma(p_b^{un} p_t^{\uparrow}) - \sigma(p_b^{un} p_t^{\downarrow})}{\sigma(p_b^{un} p_t^{\uparrow}) + \sigma(p_b^{un} p_t^{\downarrow})}$$



Drell-Yan $\sigma(p + p^{\uparrow(\downarrow)} \rightarrow \gamma + X)$

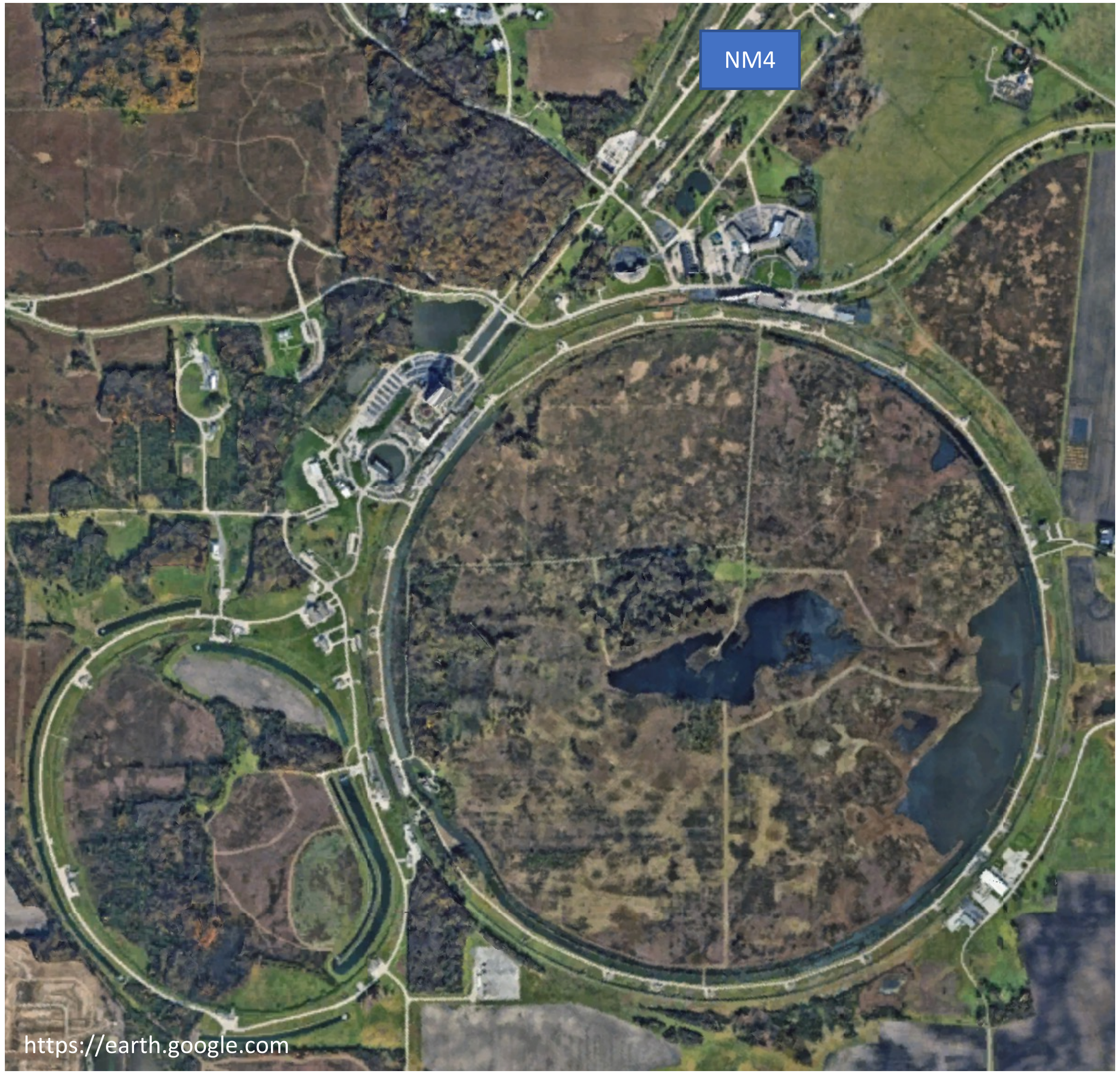
$$f_{q/p^\uparrow}(x, \mathbf{k_T}, \mathbf{S_T}; Q) = f_{q/p}(x, \mathbf{k_T}; Q) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x, \mathbf{k_T}, \mathbf{S_T}; Q)$$

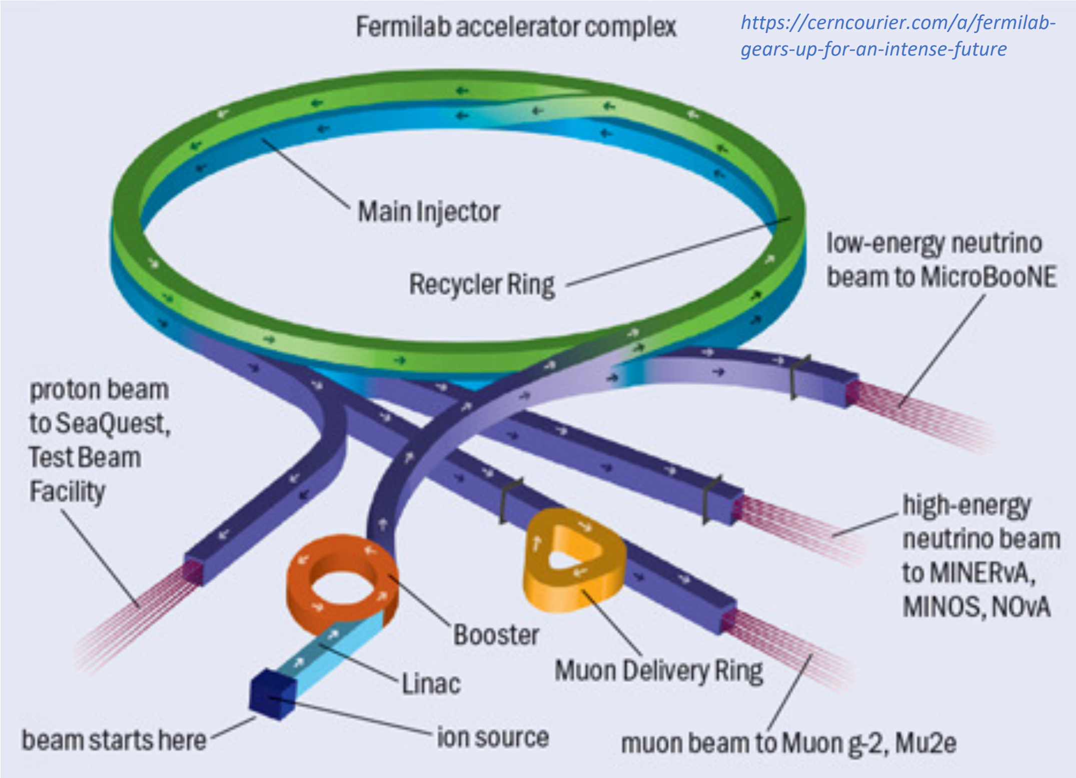
J/ψ $\sigma(p + p^{\uparrow(\downarrow)} \rightarrow J/\psi + X)$

$$f_{g/p^\uparrow}(x, \mathbf{k_T}, \mathbf{S_T}; Q) = f_{g/p}(x, \mathbf{k_T}; Q) + \frac{1}{2}\Delta^N f_{g/p^\uparrow}(x, \mathbf{k_T}, \mathbf{S_T}; Q)$$

- SpinQuest will be able to explore a new region of kinematics for J/ψ compare to the PHENIX measurements
- J/ψ production:
  - PHENIX → gg fusion at $\sqrt{s}$ =200 GeV
  - SpinQuest → $q\bar{q}$ annihilation + gg fusion at $\sqrt{s} = 15.5$ GeV

Fermilab proton beam main injector





- 120 GeV/c proton beam
- $\sqrt{s} = 15.5$ GeV
- Projected beam
  - $5{\times}10^{12} protons/spill$ Where $spill \approx 4.4\ s/min$
  - Bunches of $1ns$ with $19ns$ intervals ~ 53 MHz
  - $7{\times}10^{17} protons/year$ on target!

Fermilab proton beam main injector

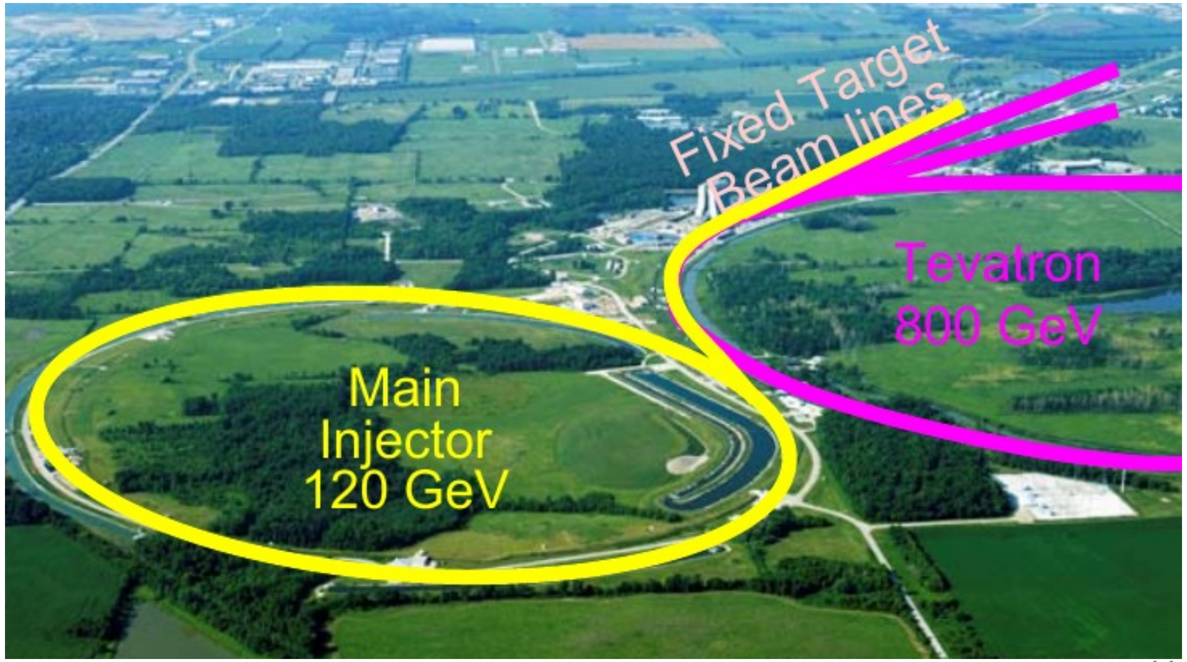
$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9x_1 x_2} \frac{1}{s} \times \sum_i e_i^2 [q_{ti}(x_t)\bar{q}_{bi}(x_b) + \bar{q}_{ti}(x_t)q_{bi}(x_b)]$$

Fermilab E866/NuSea

Data in 1996-1997
^{1}H, ^{2}H and nuclear targets
800 GeV proton beam

Fermilab E906/E1039

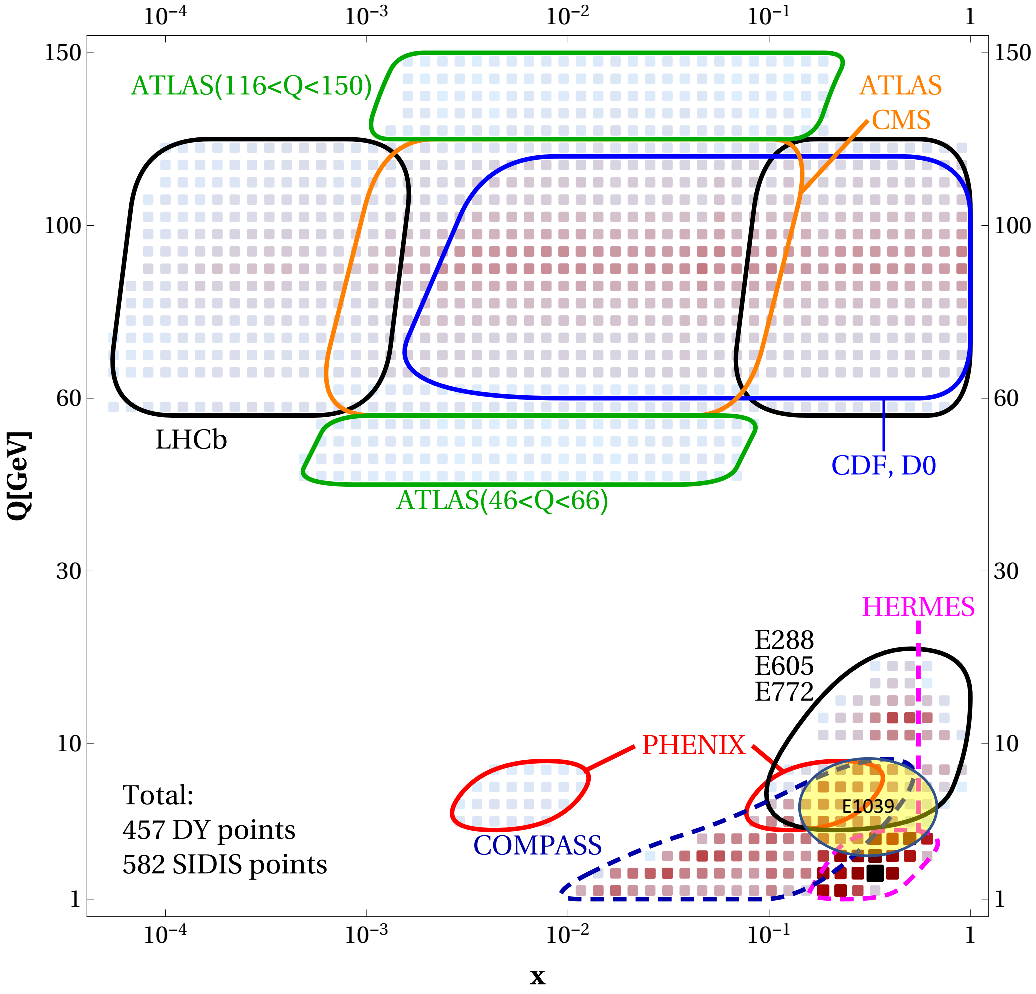
Data in > 2010
^{1}H, ^{2}H and nuclear targets
120 GeV proton beam



Therefore, the SpinQuest/E1039 experiment will get,

- Cross-Section scales as ~7 times compare to that with 800 GeV beam
- Luminosity is ~7 times compare to that with 800 GeV beam
- ~49 x Statistics with 800 GeV beam

Fermilab's uniqueness in kinematics and statistics for exploring TMDs



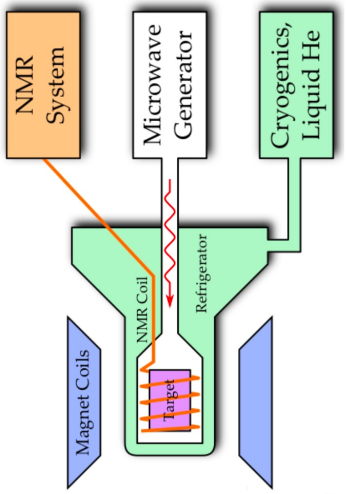
- SpinQuest (E1039) is attempting to push the proton beam intensity frontier on a solid polarized target.

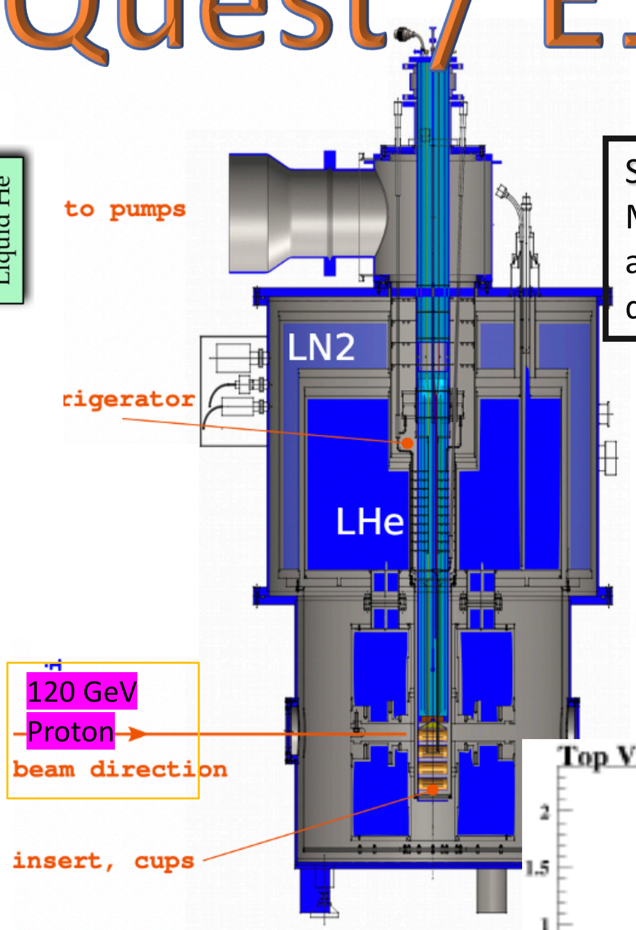
- The combination of high luminosity, large x-coverage, and a high-intensity beam with significant time between proton spills makes Fermilab the best place for this novel approach to measuring polarized target asymmetries in Drell-Yan scattering with high precision.

- With the current setting,
  $5\times10^{12} protons/spill$ Where $spill \approx 4.4\ s/min$
  Bunches of $1ns$ with $19ns$ intervals ~ $53\ MHz$

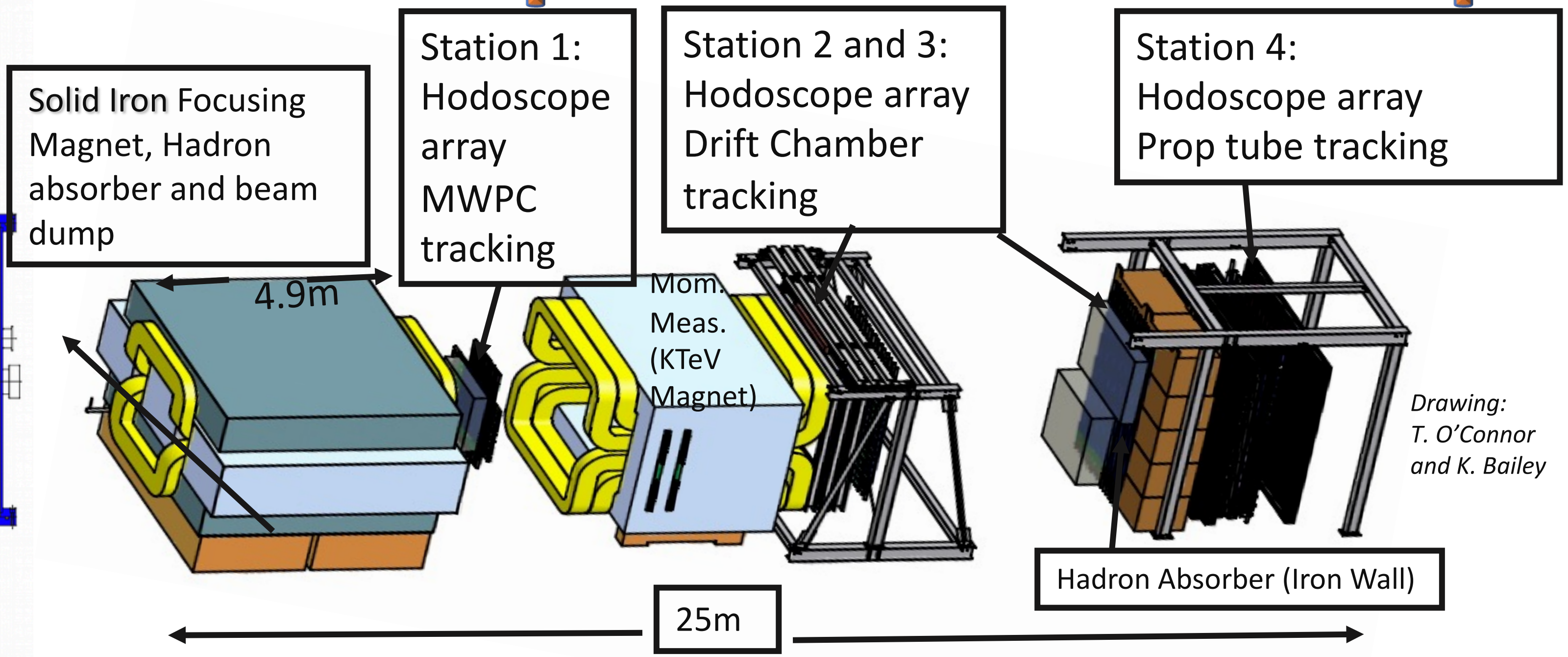
- Future plans at Fermilab (https://indico.fnal.gov/event/59663)
  More frequent spills with the flexibility of adjusting the time between spills → Higher Statistics!!!

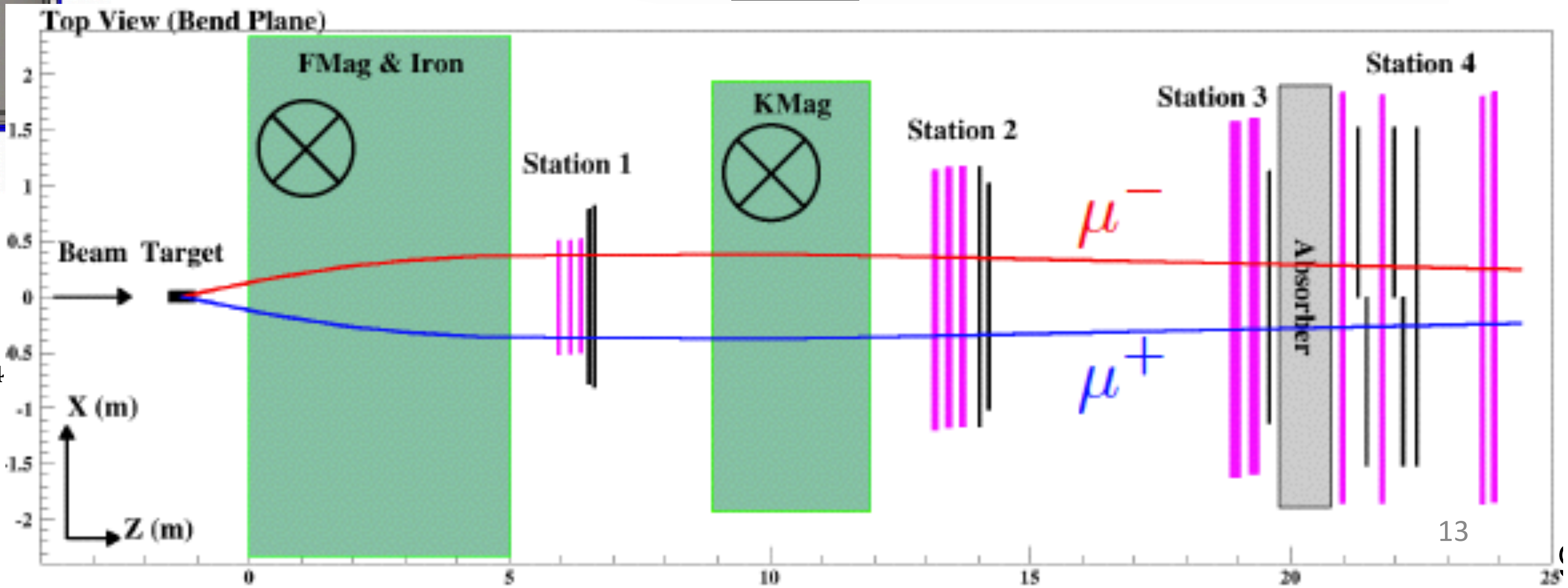
SpinQuest / E1039 Experiment Setup





Polarized solid NH3 & ND3 target setup

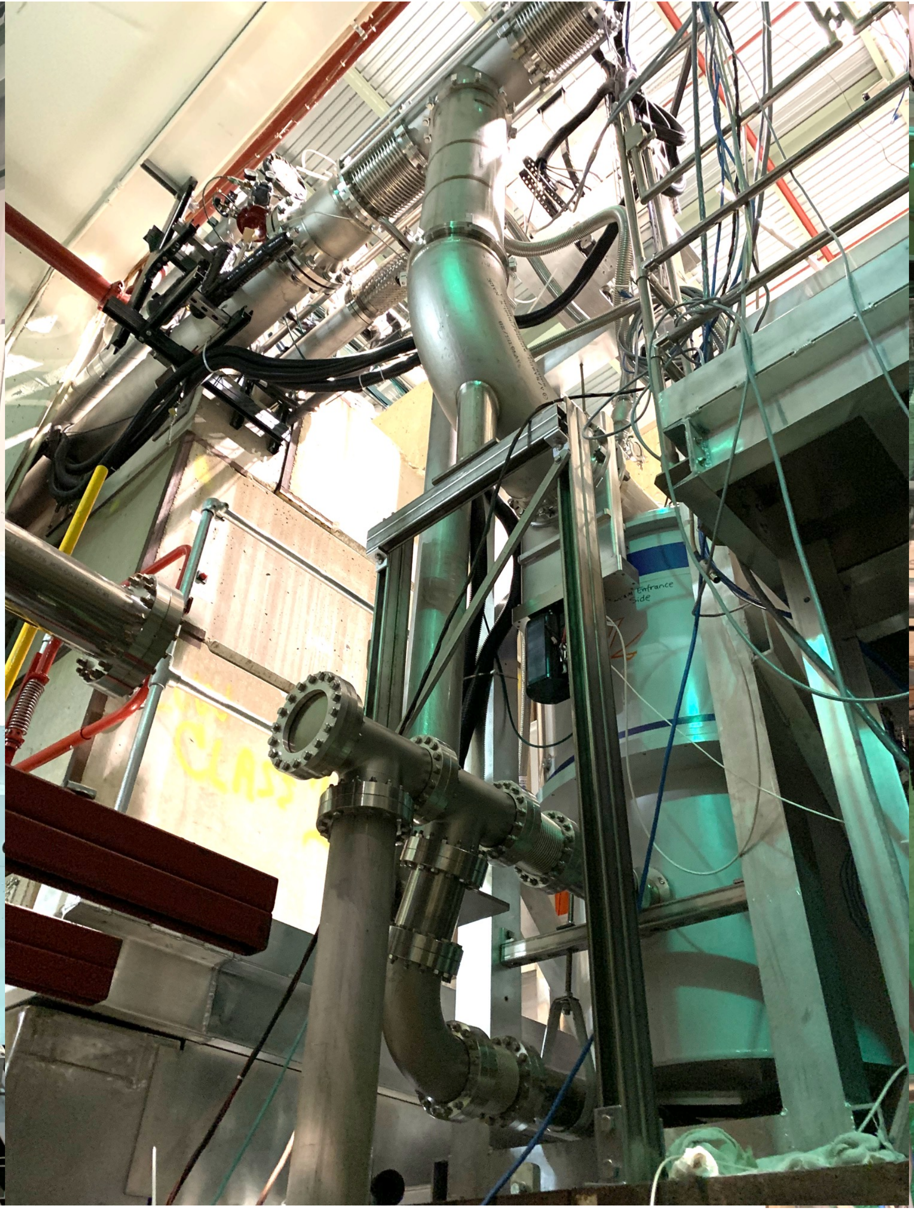




- Designed for high intensity proton beam (5×10^{12} $protons/spill$ with 4.4s spill) by **LANL-UVA group**
- 8 cm long solid NH_3 and ND_3 target cells
- Magnetic Field: B = 5 T with uniformity $dB/B < 10^{-4}$ over 8 cm
- ^{4}He evaporation refrigerator (3 W of maximum cooling power) keeping the target at 1.1 K.
- 140 GHz microwave source (with DNP technique)

SpinQuest / E1039 Experiment Setup

From beam down-stream



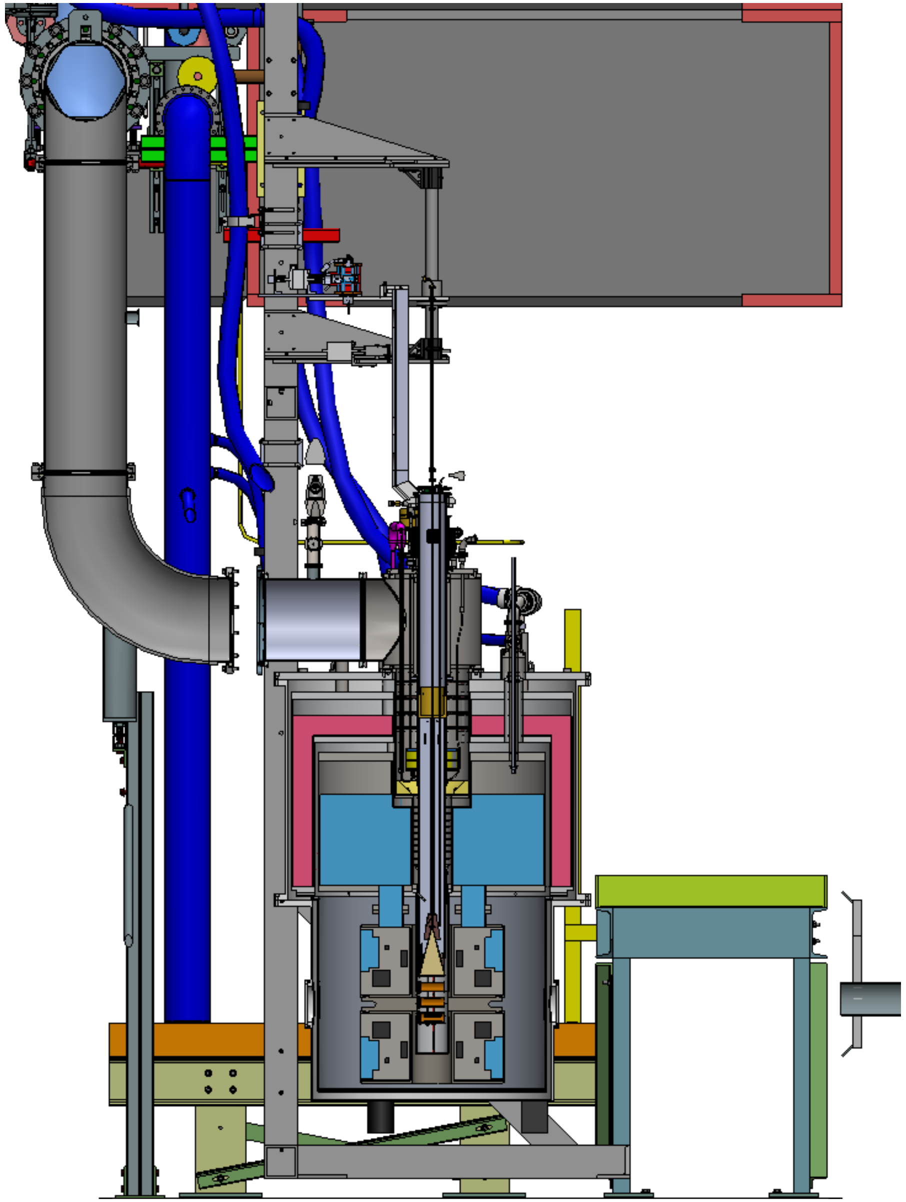
Beam-window and superconducting magnet

From target cave to beam-upstream

The Polarized Target

- ✓ The SpinQuest superconducting magnet
- ✓ ^{4}He evaporating refrigerator
- ✓ 140 GHz microwave source
- ✓ A large 17,000 m^3/hr pumping system
- ✓ NMR systems (UVA & LANL)

The Polarized Target



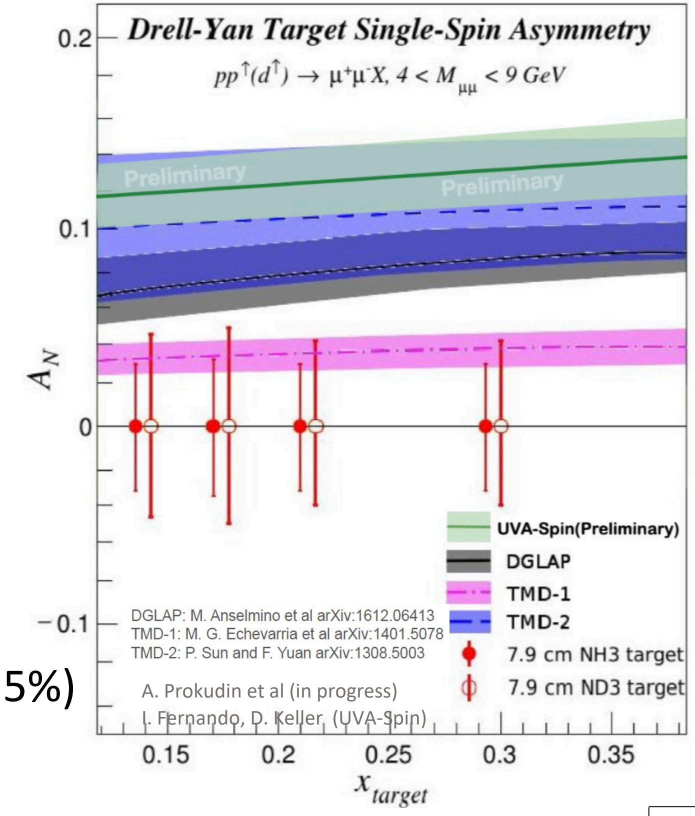
Predicted Uncertainties

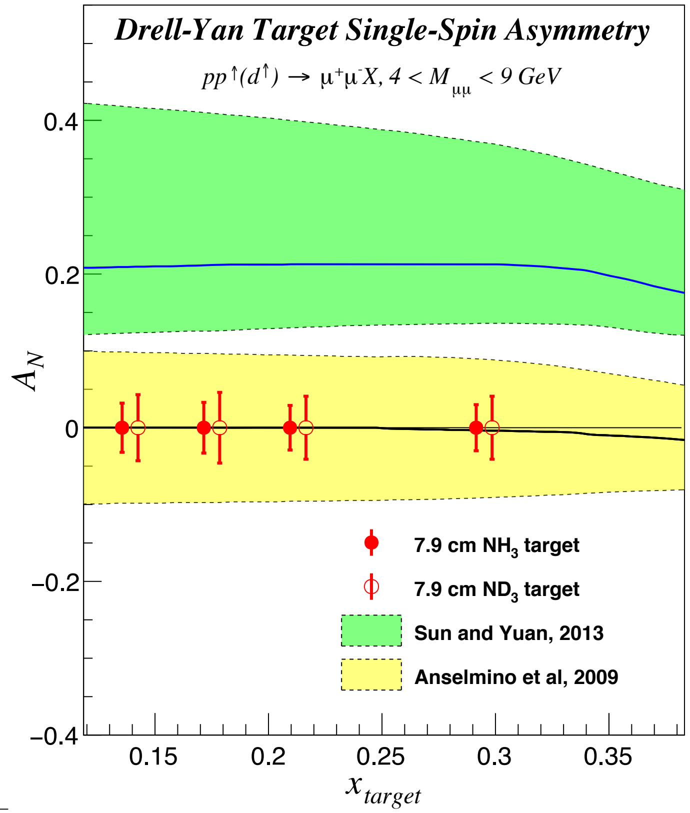
- Beam (∽ 2.5%)
  - Relative luminosity (∽ 1%)
  - Drifts (< 2%)
  - Scraping (∽ 1%)

- Analysis sources (∽ 3.5%)
  - Tracking efficiency (∽ 1.5%)
  - Trigger & geometrical acceptance (<2%)
  - Mixed background (∽ 3%)
  - Shape of DY (∽ 1%)

- Target (∽ 6-7 %)
  - TE calibration (proton ∽ 2.5%; deuteron ∽ 4.5%)
  - Polarization inhomogeneity (∽ 2%)
  - Density of target ($NH_{3(s)}$) (∽ 1%)
  - Uneven radiation damage (∽ 3%)
  - Beam-Target misalignment (∽ 0.5%)
  - Packing fraction (∽ 2%)
  - Dilution factor (∽ 3%)

- Projections from existing frameworks are limited by available data
also, separation of proton and neutron





x_2 bin	$< x_2 >$	NH_3 ($p^{\uparrow}$)		ND_3 ($d^{\uparrow}$)	
		N	ΔA (%)	N	ΔA (%)
0.10 - 0.16	0.139	5.0×10^4	3.2	5.8×10^4	4.3
0.16 - 0.19	0.175	4.5×10^4	3.3	5.2×10^4	4.6
0.19 - 0.24	0.213	5.7×10^4	2.9	6.6×10^4	4.1
0.24 - 0.60	0.295	5.5×10^4	3.0	6.4×10^4	4.1

$$A = \frac{2}{f|S_T|} \frac{\int d\phi_S d\phi \frac{dN(x_b, x_t, \phi_S, \phi)}{d\phi_S d\phi} sin(\phi_S)}{N(x_b, x_t)}$$

Material	Density	Dilution factor	Packing fraction	Polarization	Interaction length
NH_3	0.867 g/cm^3	0.176	0.60	80%	5.3%
ND_3	1.007 g/cm^3	0.300	0.60	32%	5.7%

SpinQuest / E1039 Timeline

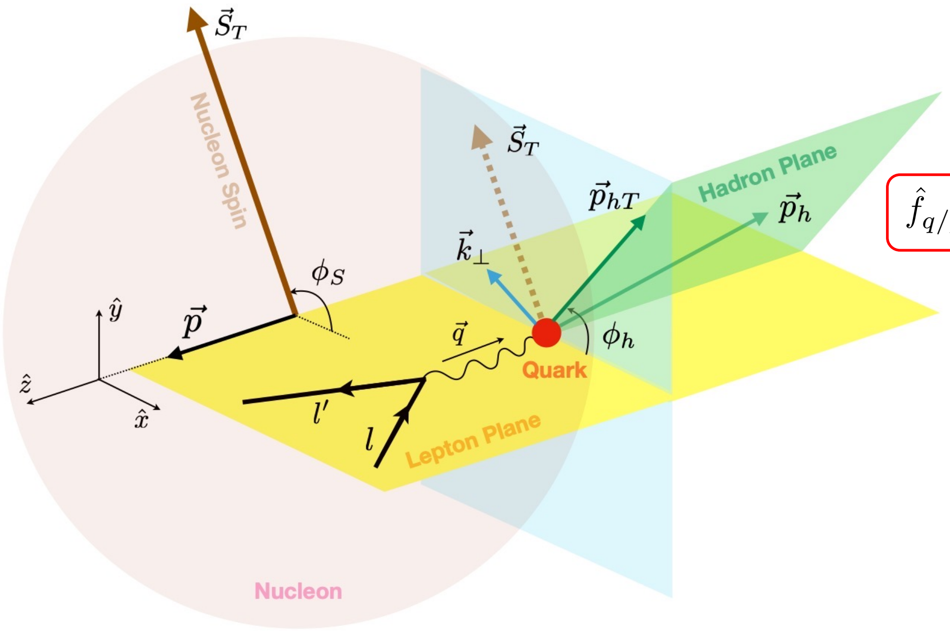
- 2018, March: DOE approval
- 2018, May: Fermilab stage-2 approval
- 2018, June: E906 decommissioned
- 2019, May: Transferred the polarized target from UVA to Fermilab
- Now: commission all components using cosmic rays
- Phase 1 of Polarized target commissioning is completed [January 2023]
- Phase 2 (with NH3, ND3): September 2023
- E1039 beam commissioning starts in this Fall 2023
  [Run for 2+ years, 2023-2025+]

Motivation for using DNNs as a tool

- Profound limitation in other phenomenological fits:
  The DY Sivers Asymmetry projections for SpinQuest has large uncertainties, and those projections are only for proton target.
- A complete SU(3) flavor dependent Sivers functions have been not extracted yet.
- The impact from the Sivers asymmetries with polarized proton target and neutron (deuteron) target was not explored yet.
  (mostly iso-spin symmetry condition was used with combined proton and deuteron data in global fits)

Sivers Asymmetry from SIDIS

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



Unpol. quark-dist. Sivers function

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

$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{m_p} f_{1T}^{\perp q}(x,k_\perp)\vec{S}_T\cdot(\hat{p}\times\hat{k}_\perp)$$

$$D_{h/q}(z,p_\perp) = D_{h/q}(z)\frac{1}{\pi\langle p_\perp^2\rangle}\exp^{-p_\perp^2/\langle p_\perp^2\rangle}$$

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

Anselmino et al. (2017)

Single Spin Asymmetry (Sivers Asymmetry)

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

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

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

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

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

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

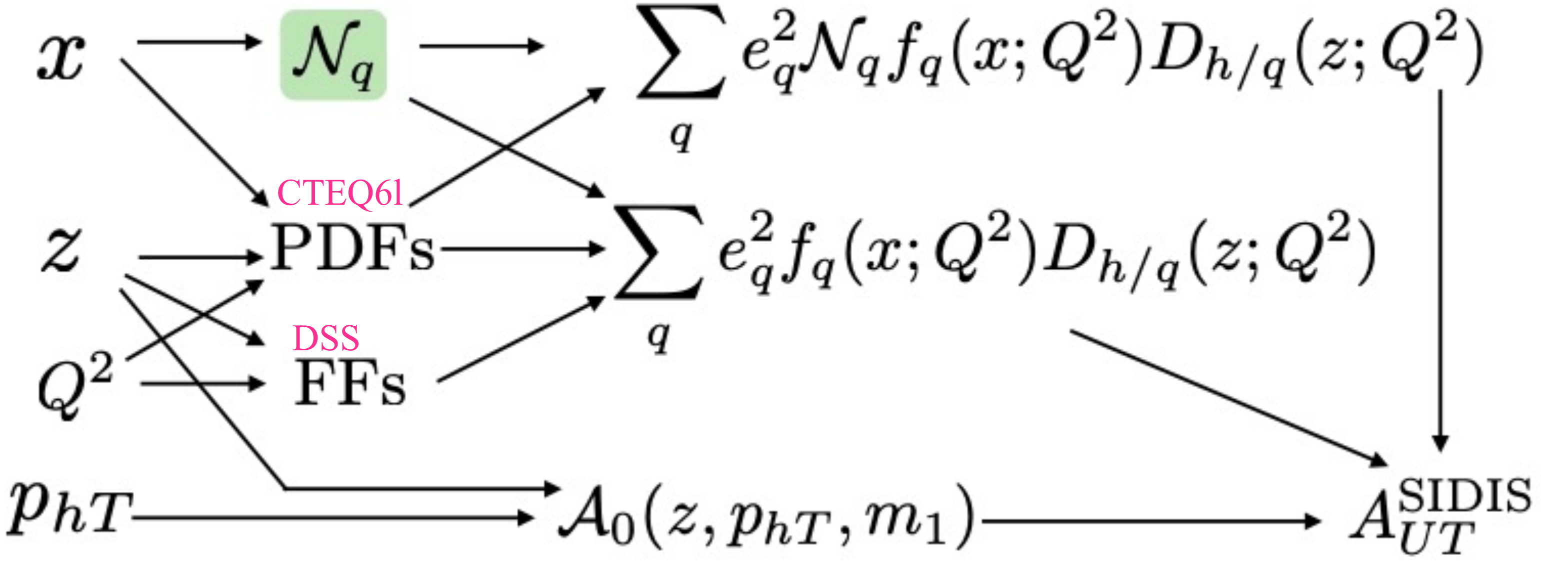
$\langle p_\perp^2\rangle = 0.12 \pm 0.01\ \mathrm{GeV}^2$

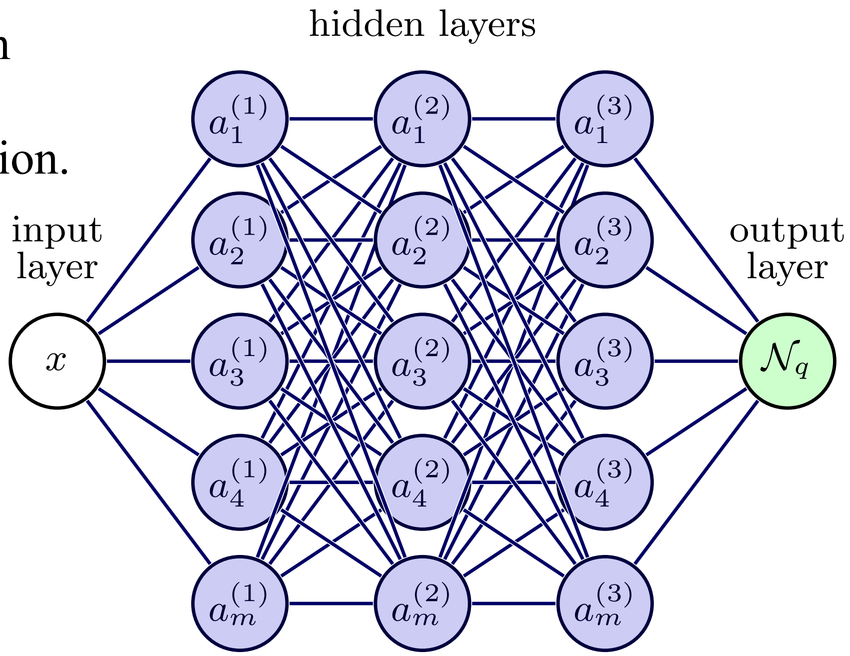
$\langle k_\perp^2\rangle = 0.57 \pm 0.08\ \mathrm{GeV}^2$

DNN Approach

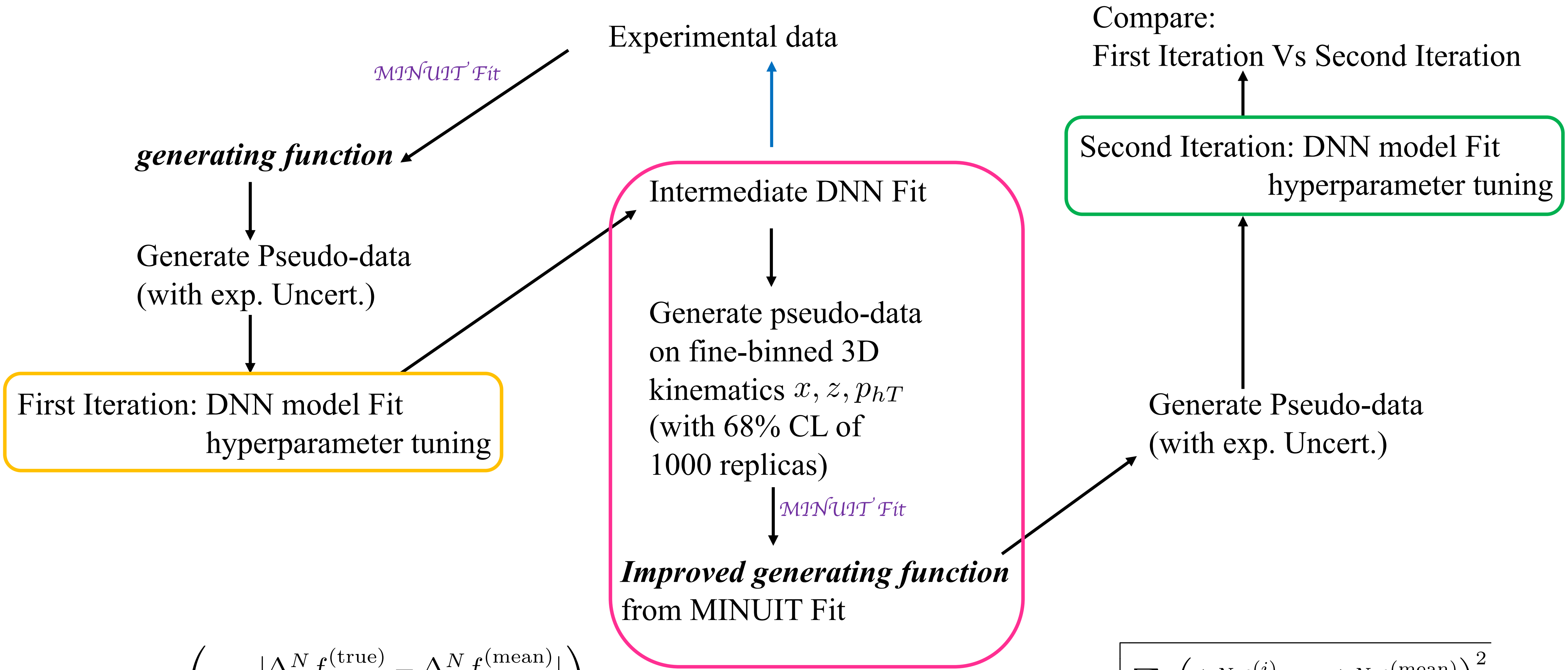
$$A_{UT}^{\sin(\phi_h-\phi_S)}(x,z,p_{hT}) = \mathcal{A}_0(z,p_{hT},m_1)\left(\frac{\sum_q \mathcal{N}_q(x) e_q^2 f_q(x) D_{h/q}(z)}{\sum_q e_q^2 f_q(x) D_{h/q}(z)}\right)$$

- The exceptional capacity of DNN to be ideal for function approximation (Universal Approximation Theorem).
- Each quark flavor q is independently handled by a separate $\mathcal{N}_q(x)$.
- The only input to to each $\mathcal{N}_q(x)$ is x.
- Statistical & Systematic uncertainties from the experimental data are combined in quadrature; then propagated using bootstrap method by generating replicas.
- Systematic uncertainty in method is evaluated with variations in generating function.





DNN Method Testing with pseudo-data

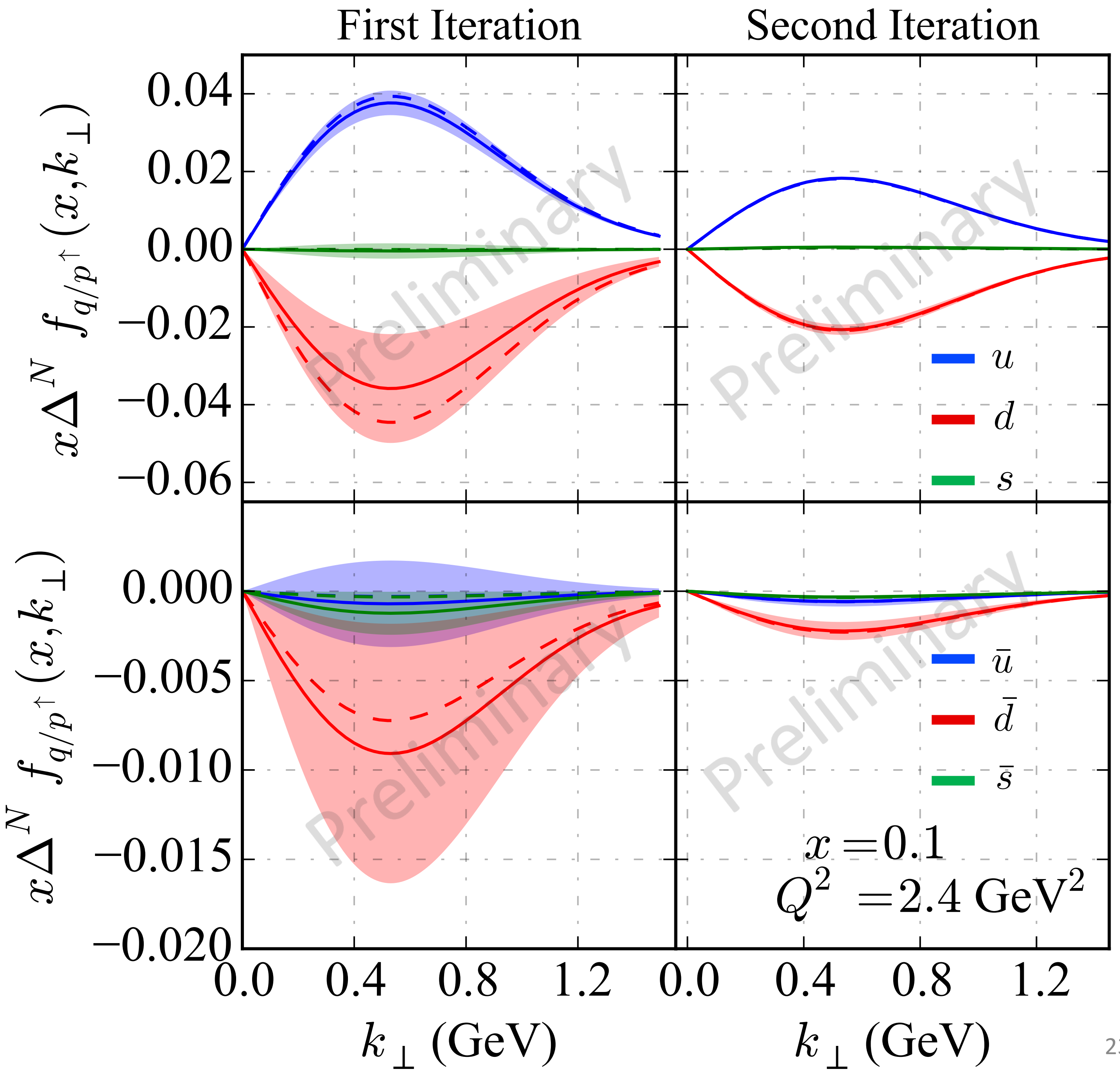


$$\epsilon_q(x, k_\perp) = \left(1 - \frac{|\Delta^N f_{q/p^\uparrow}^{(\mathrm{true})} - \Delta^N f_{q/p^\uparrow}^{(\mathrm{mean})}|}{\Delta^N f_{q/p^\uparrow}^{(\mathrm{true})}}\right) \times 100\%$$

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

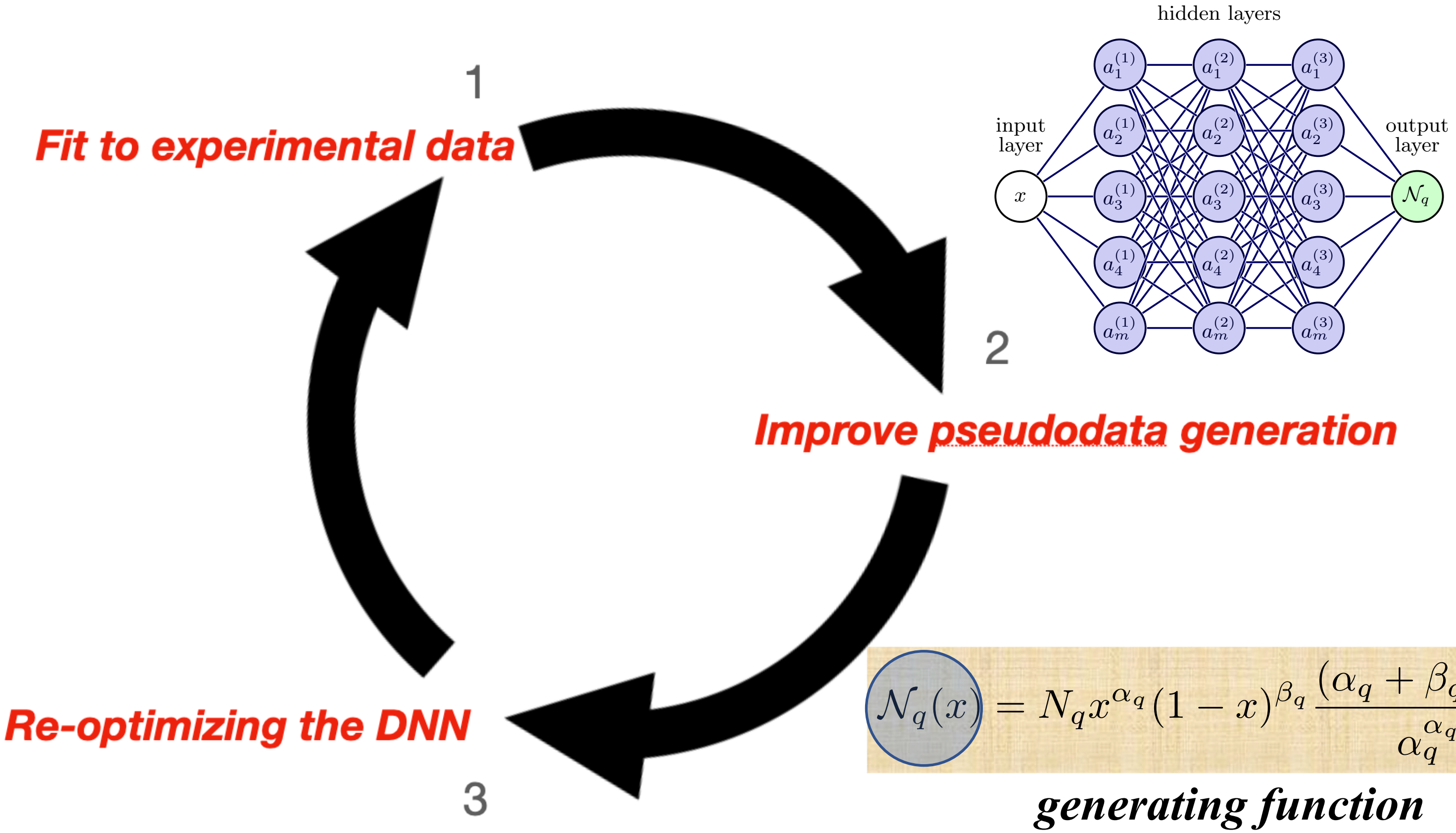
DNN Method testing with Pseudo data

- Dashed lines represent the ***generating function*** in each iteration.
- Solid-lines and the band represent the mean and 68% CL with 1000 replicas of the DNN model.



DNN Method: With Real data

- 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.



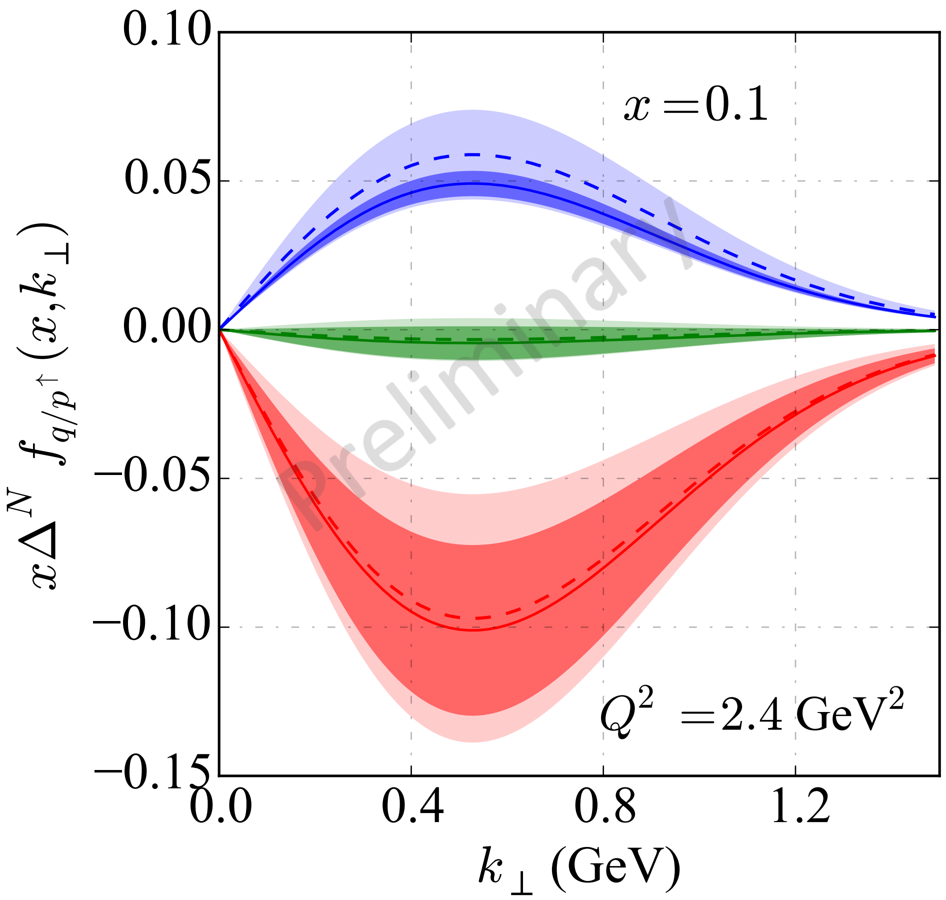
Generate pseudo-data on fine-binned 3D kinematics (with 68% CL of 1000 replicas)

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

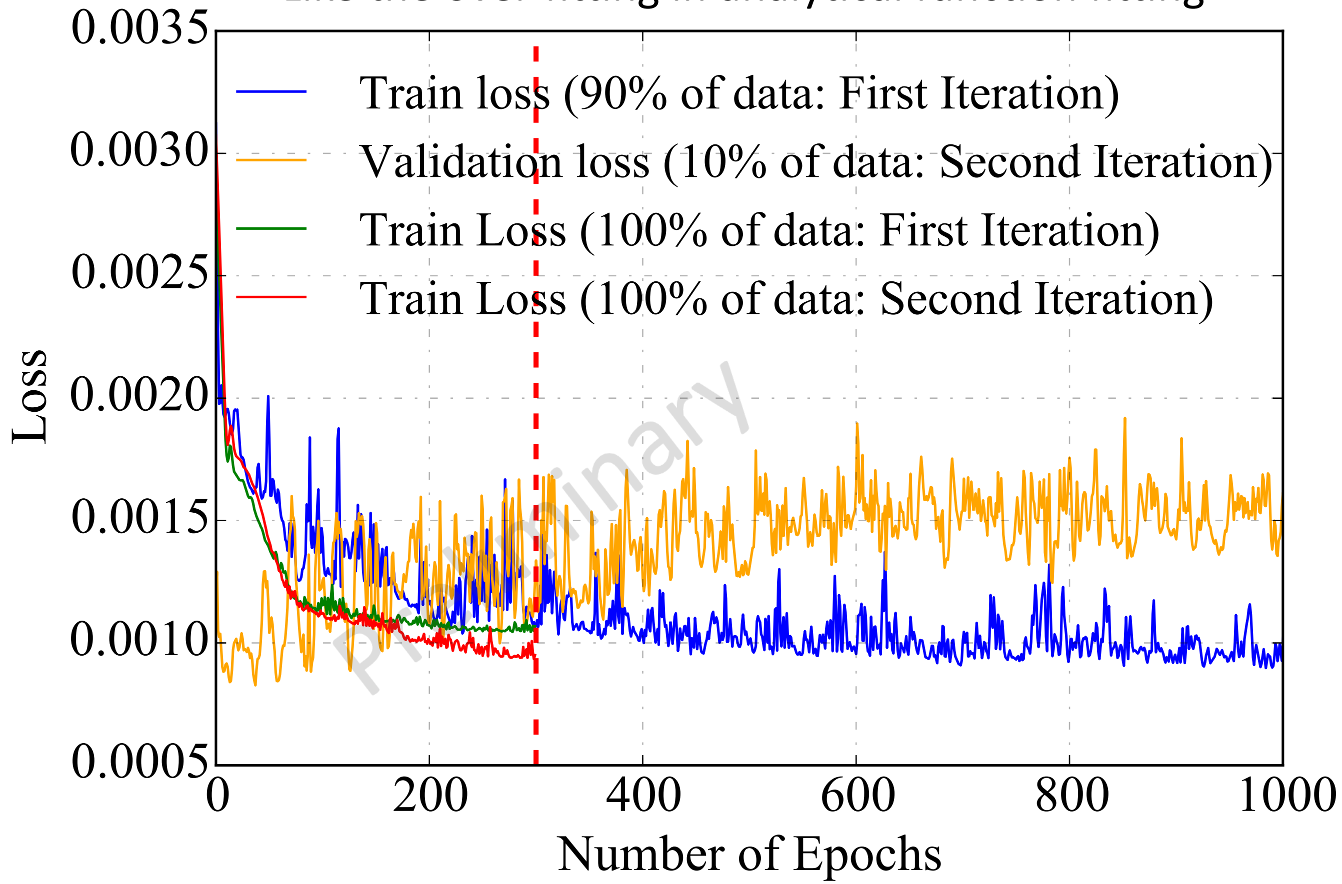
generating function

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

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



Optimum # of epochs to avoid over-training
Like the over-fitting in analytical function fitting



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)

Data Selection

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

Proton DNN model

Deuteron DNN model

HERMES2020 3D binned data

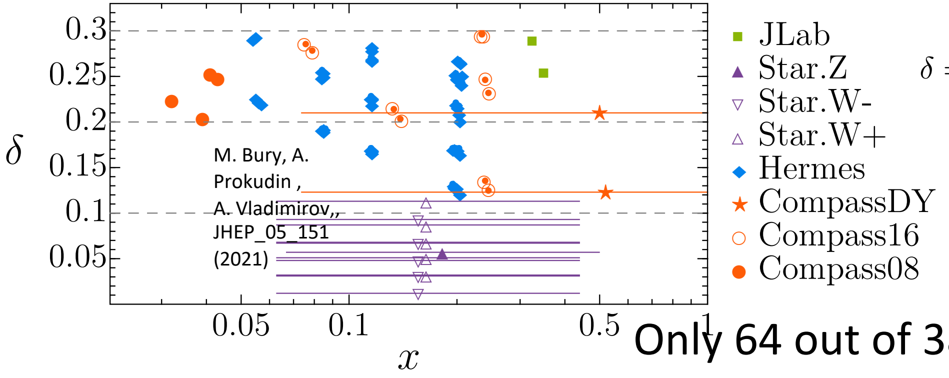
Projections from Proton DNN model

Projections from Deuteron DNN model

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

Data Selection

In the global fits to the date in the literature, a few distinct treatments have been followed regarding the preservation of the TMD Factorization Theorem.



$$\delta = \frac{|P_{hT}|}{zQ} \text{(in SIDIS)}, \qquad \delta = \frac{|q_T|}{Q} \text{(in DY)}$$

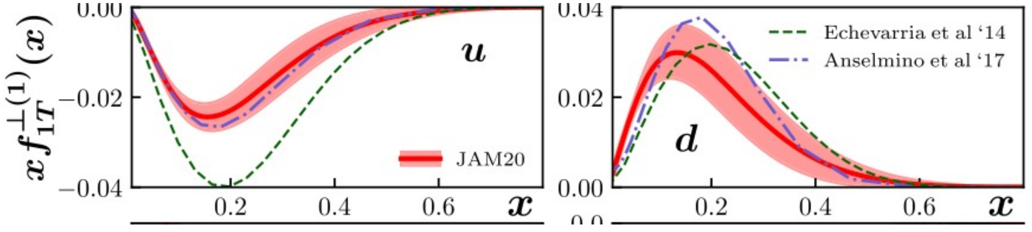
Only 64 out of 388 data points survived

$$0.2 < z_h < 0.6, \; Q^2 > 1.63\,\text{GeV}^2, \text{ and } 0.2 < P_{hT} < 0.9 \text{ (GeV)}. \qquad (5.9)$$

Notice that from the point of view of power counting the conditions $q_T \ll Q$, where $\mathbf{q}_T$ is the transverse momentum of the virtual photon in a frame in which both the target particle and the final-state hadron have no transverse momentum, and $P_{hT} \ll Q$, where P_{hT} is the transverse momentum of the produced hadron in $\gamma^* P$ frame, are equivalent since $q_T \simeq P_{hT}/z_h$. However, depending on the numerical value for z_h, data which satisfy $P_{hT} \ll Q$ may not satisfy $q_T \ll Q$ and therefore be difficult to describe in a TMD approach. Examples of description of HERMES multiplicities from Ref. [322] are shown in Fig. 5.2.

~ TMD Handbook (pg153)

" We now perform our simultaneous QCD global analysis of the SSA data summarized in Table I. The standard cuts of $0.2 < z < 0.6$, $Q^2 > 1.63$ GeV^2, and $0.2 < P_{hT} < 0.9$ GeV have been applied to all SIDIS datasets [97], "



J. Cammarota et al (JAM) PRD 102, 054002 (2020)

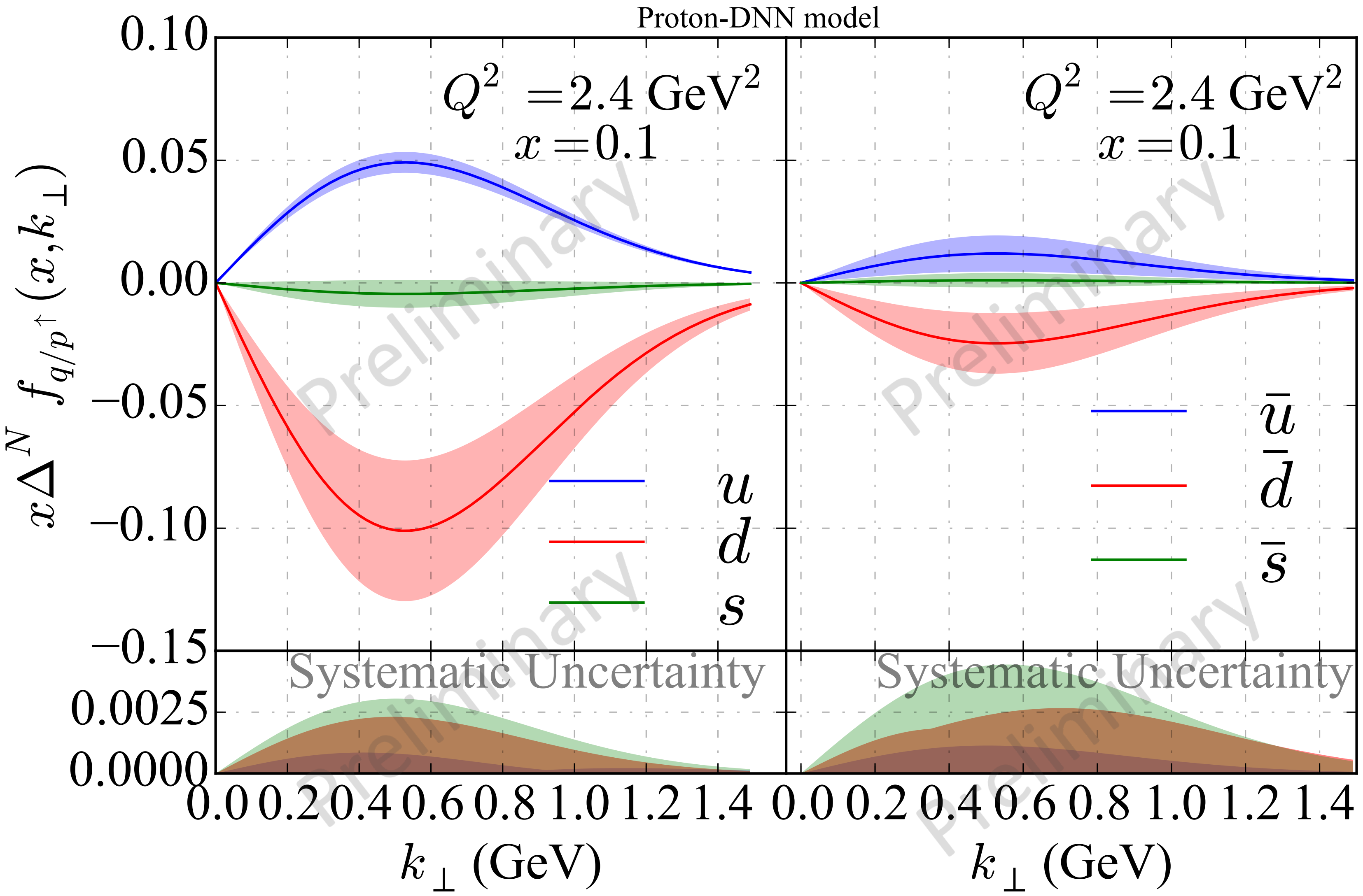
Only 126 out of 314 data points survived

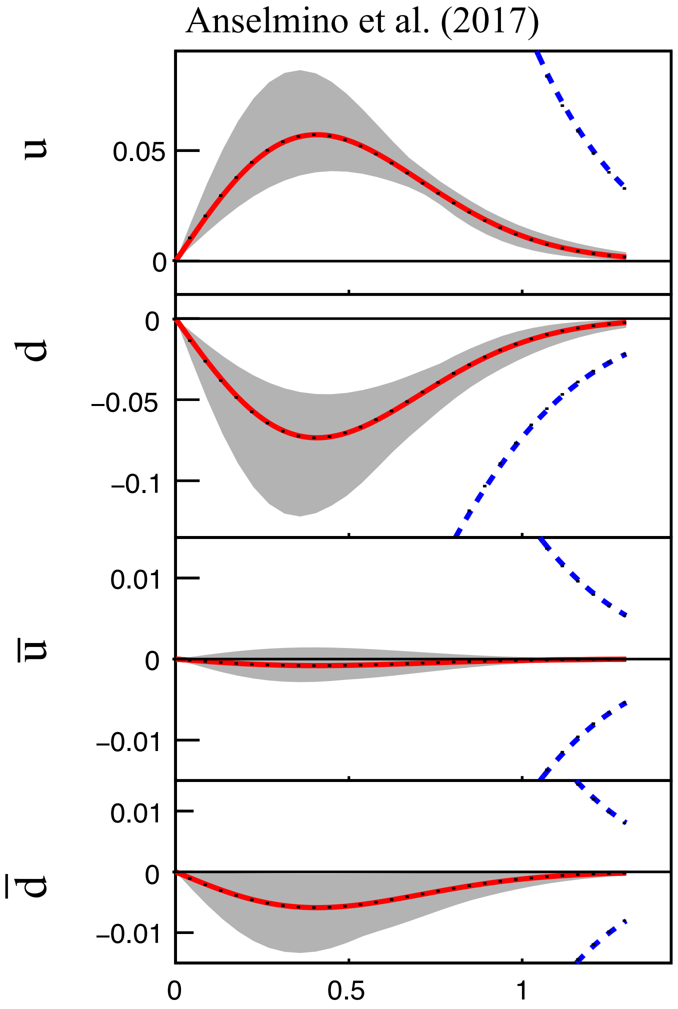
" While typical kinematic cuts from unpolarized SIDIS fits for instance in [23] select only data which has $q_\perp/Q < 0.25$, we find that this selection process leaves very few data points for the available Sivers data. In figure 6 we plot a histogram of the selected data SIDIS data as a function of $q_\perp$ and Q. We find that the cut $q_\perp/Q < 0.25$ leaves only 12 SIDIS data points, while the cut $q_\perp/Q < 0.5$ leaves 97 data points. In fact, we find that the majority of the data has $q_\perp/Q > 0.5$. In order to retain a large enough data set to perform a meaningful fit we perform the cut $q_\perp/Q < 0.75$. Furthermore to restrict the selected data set to the TMD region, we also enforce that the SIDIS data must have $P_{h\perp} < 1$ GeV. "

~ M. Echevarria, Z. Kang, J. Terry_JHEP_01_126_(2021)

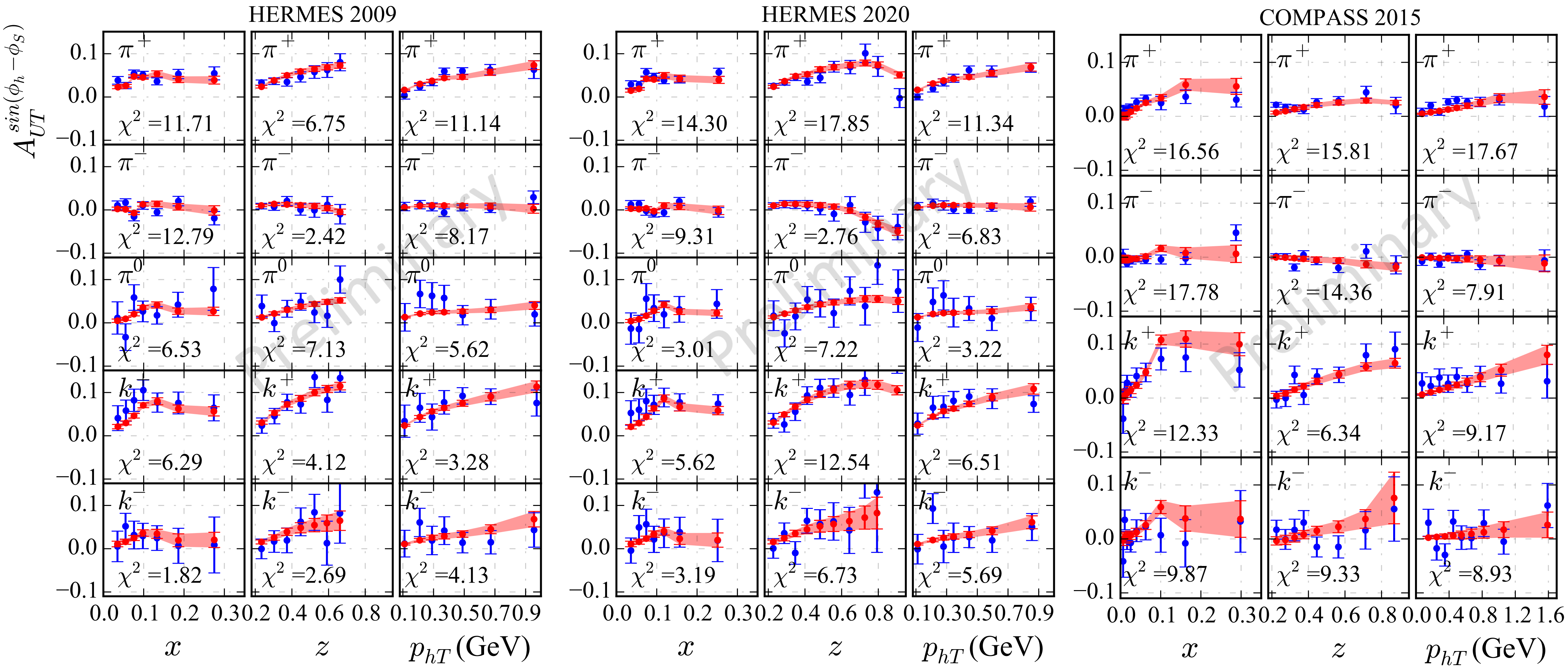
- TMD factorization loses accuracy at large qhT, with fractional errors characterized as $(qhT/Q)^\alpha$.
- The Collins and Soper (1982a) approach gives (m/Q) errors for the full range of qhT which treats the TMD term as a first approximation to the cross-section and allows for the application of a correction by applying an additive approximation (Y- Term) from the ordinary collinear factorization.
- Such corrections can be implicitly captured when training a DNN model over the full range of phT.

Sivers functions from the "Proton" DNN Model





Proton DNN Fit Results



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

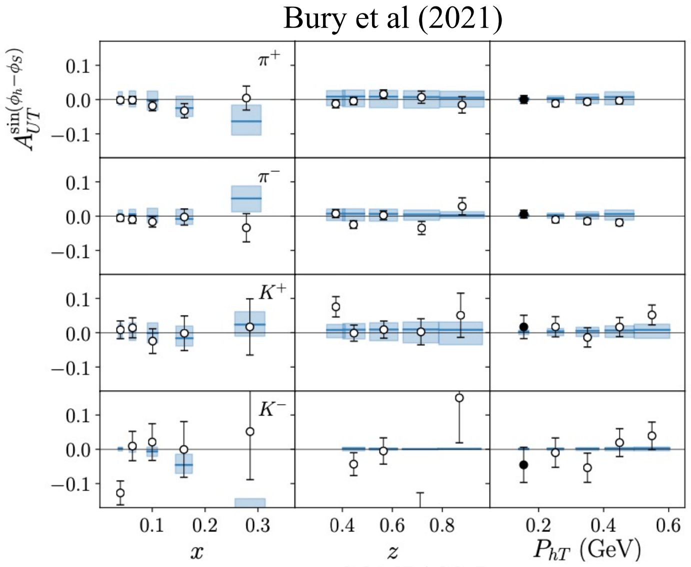
Calculated $\chi_{total}^2/N_{pt} = 1.04$

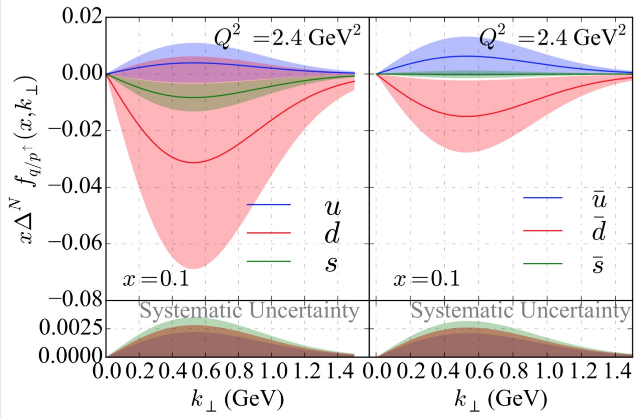
Deuteron DNN Fit Results

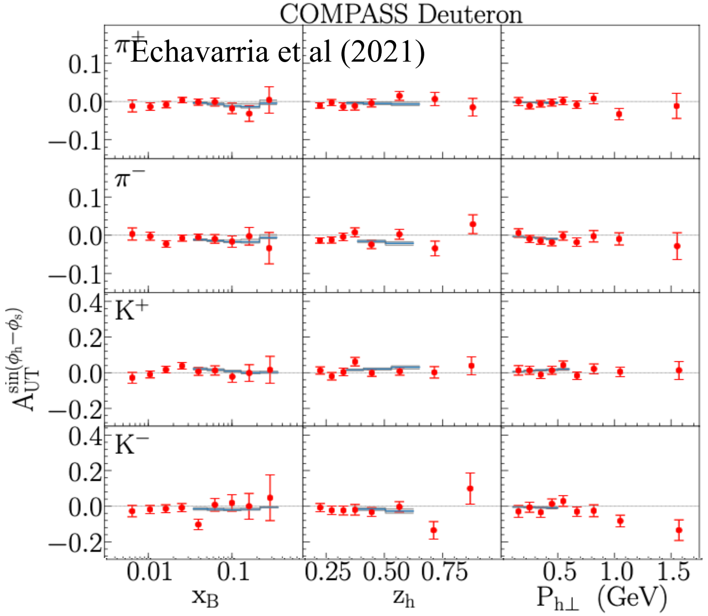
- No kinematic cuts are applied
  Deuteron-DNN model can describe data reasonably well
- No iso-spin symmetry conditions are applied

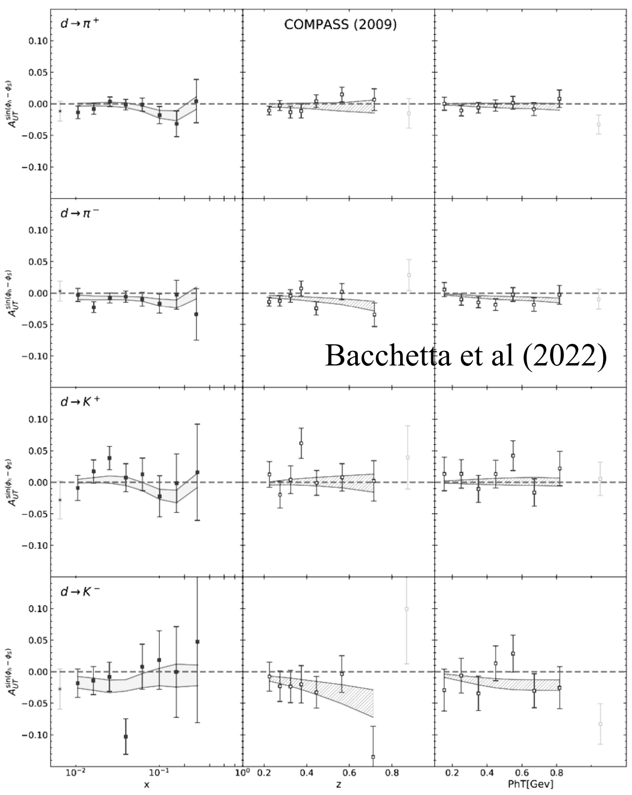
~~$f^{\perp}_{1T,u\leftarrow d} = f^{\perp}_{1T,d\leftarrow d} = \frac{f^{\perp}_{1T,u\leftarrow p} + f^{\perp}_{1T,d\leftarrow p}}{2}$~~

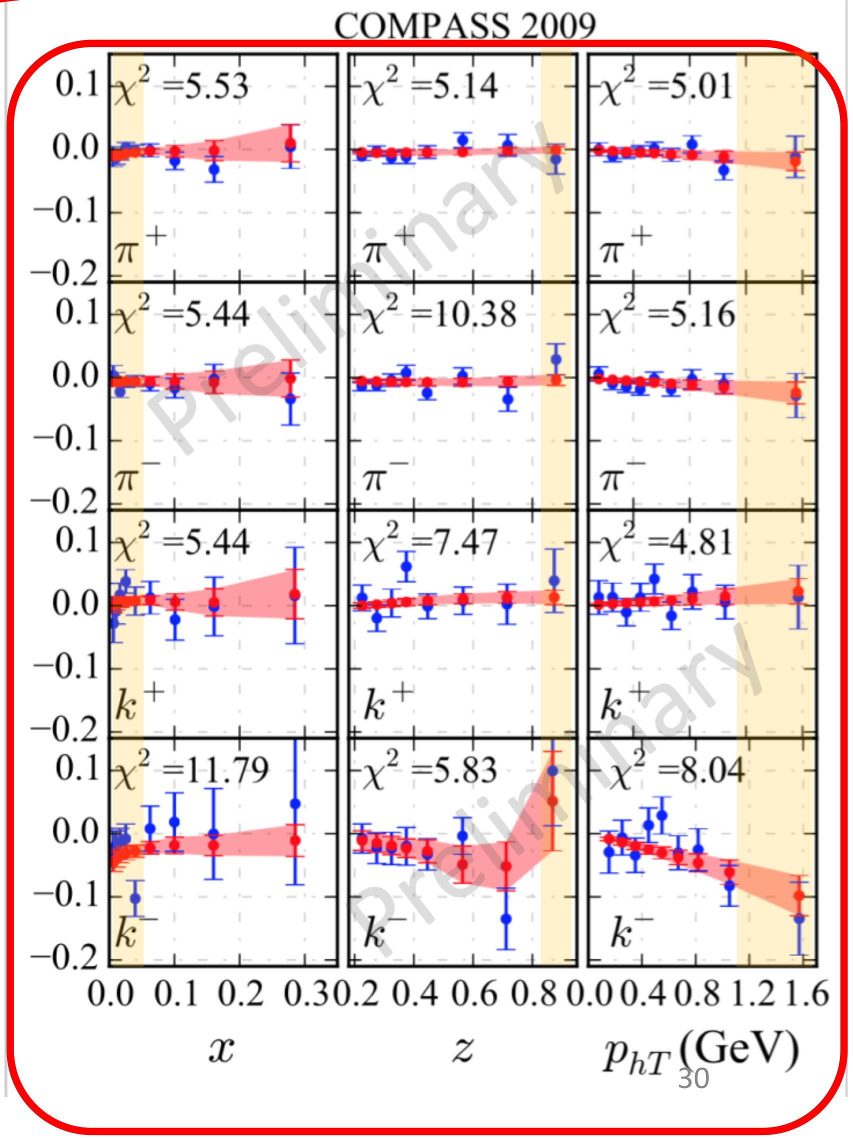
$\chi^2/N_{pt} = 0.76$





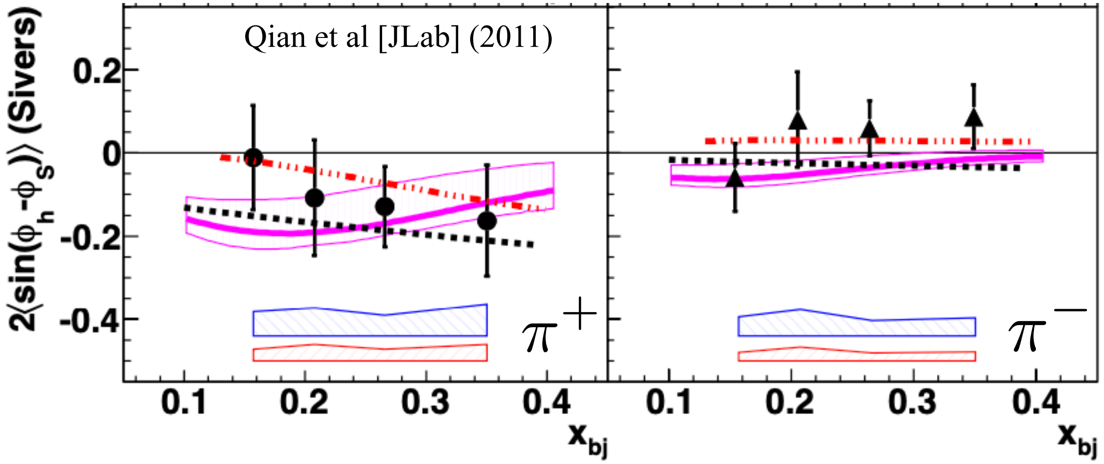


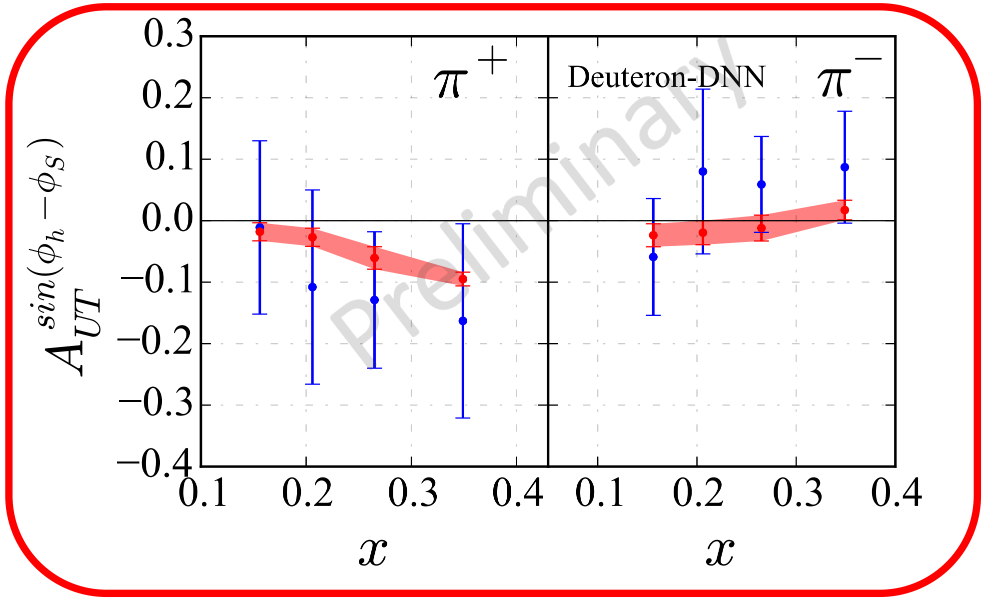


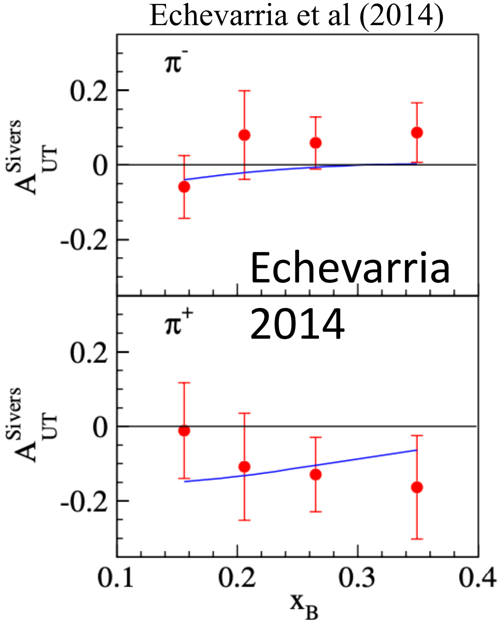


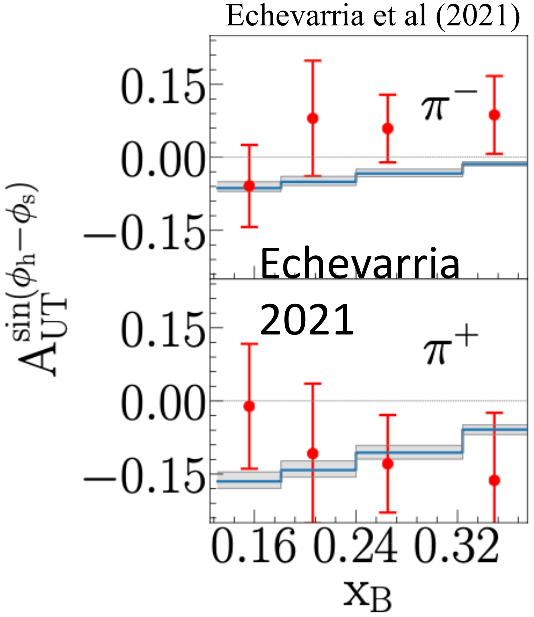
DNN Projections for JLab Kinematics

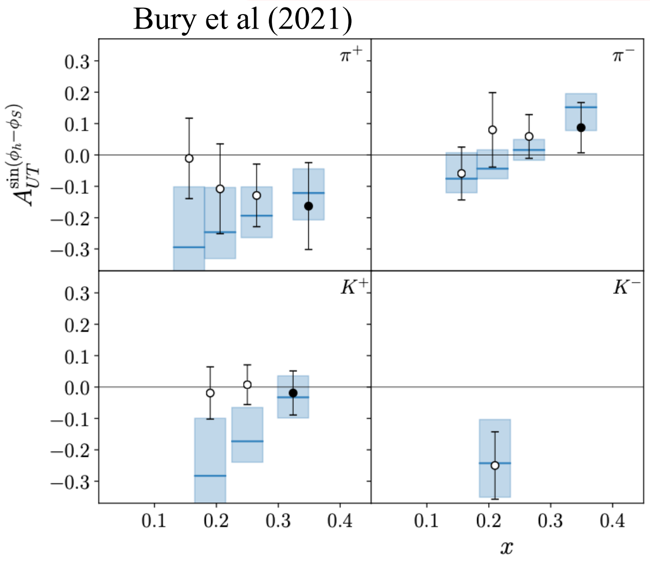
We can make unique projections for Helium3 and Deuteron for upcoming proposals at JLab!

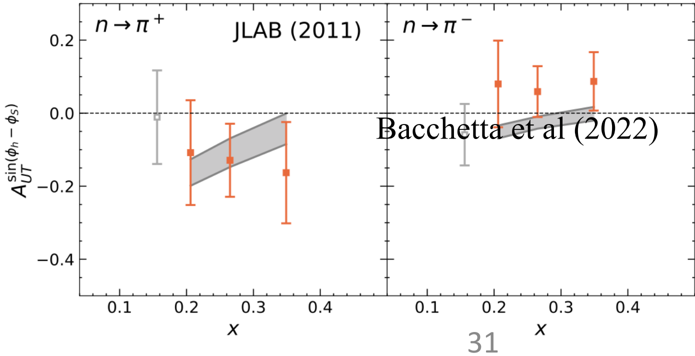






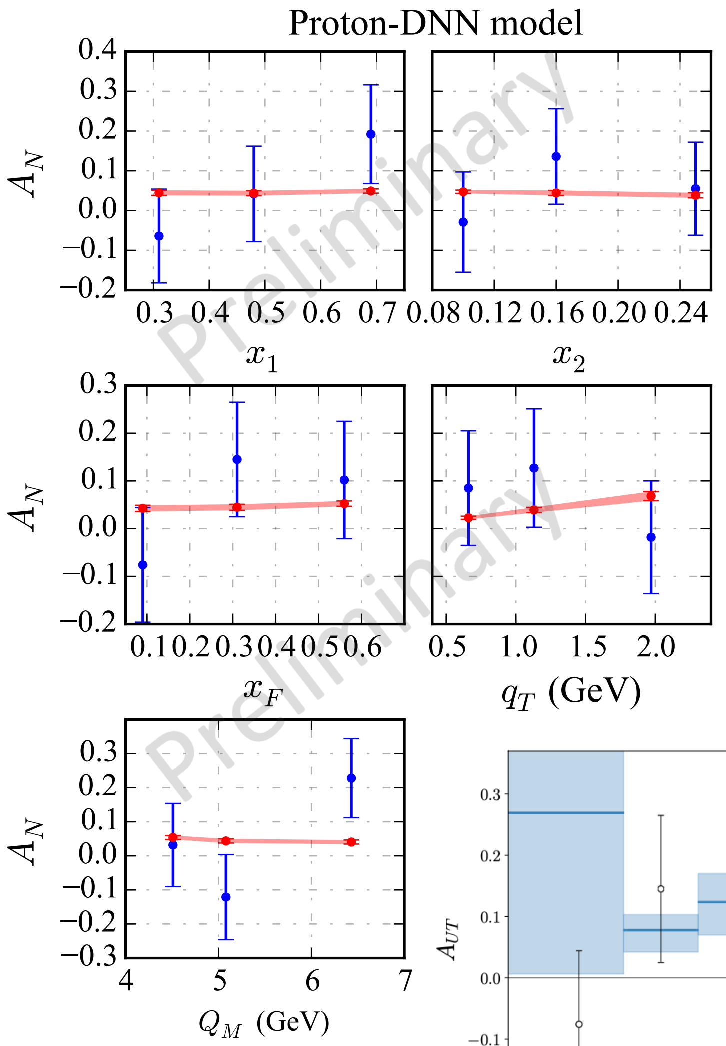


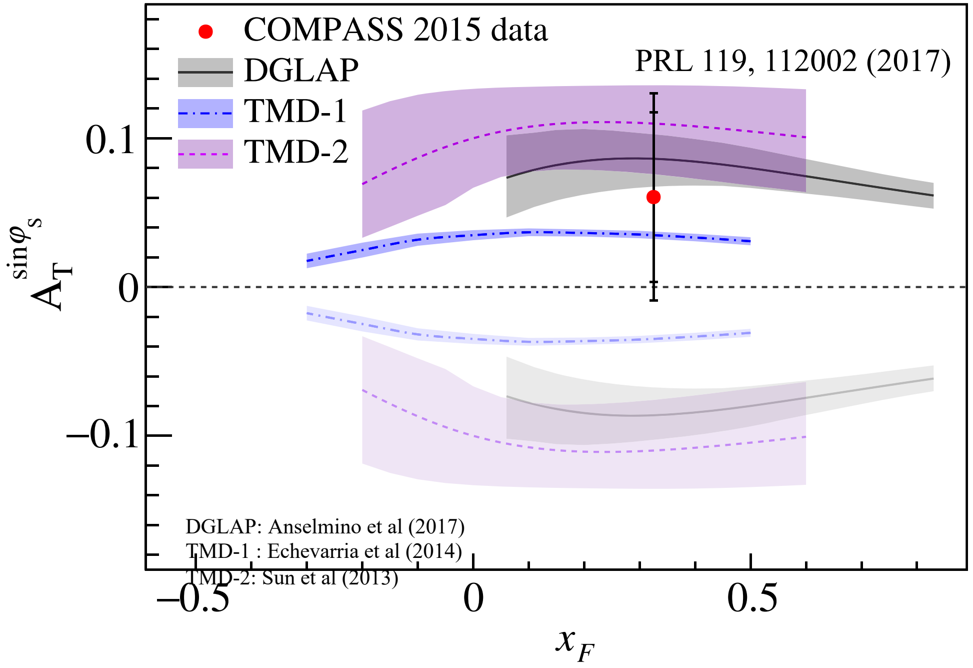


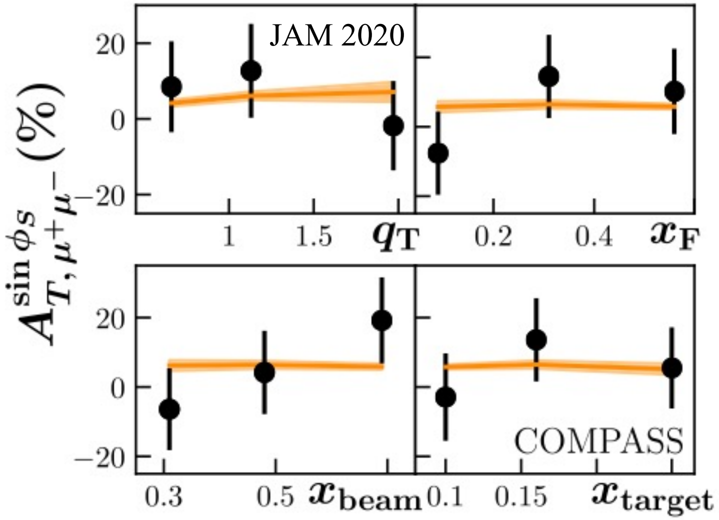


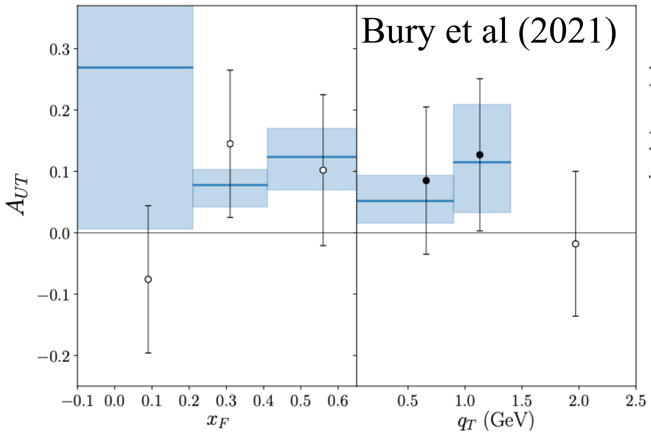
DNN Model Projections: DY

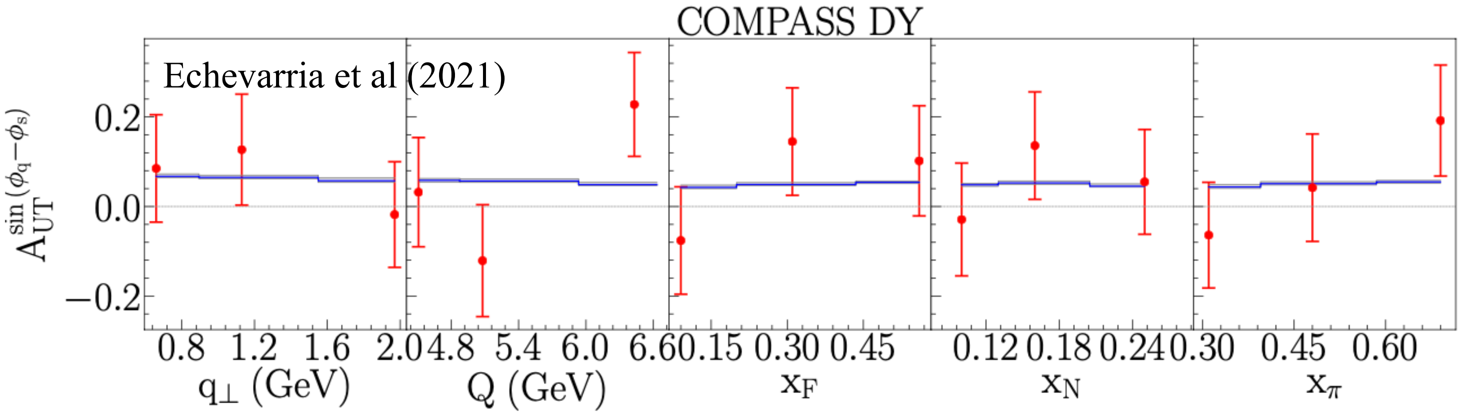
COMPASS 2017 DY Projections



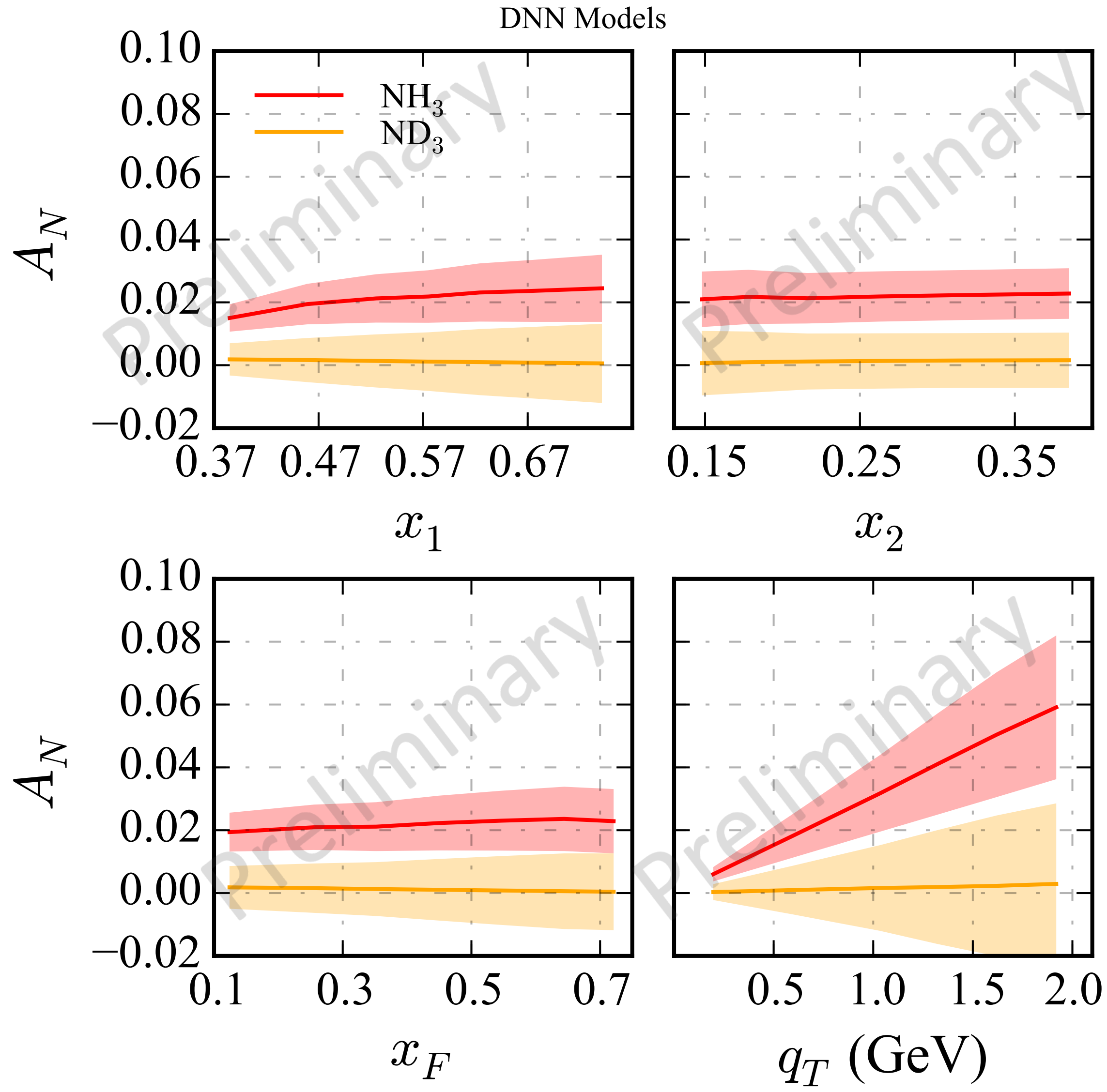








DNN Model Projections: DY @ SpinQuest

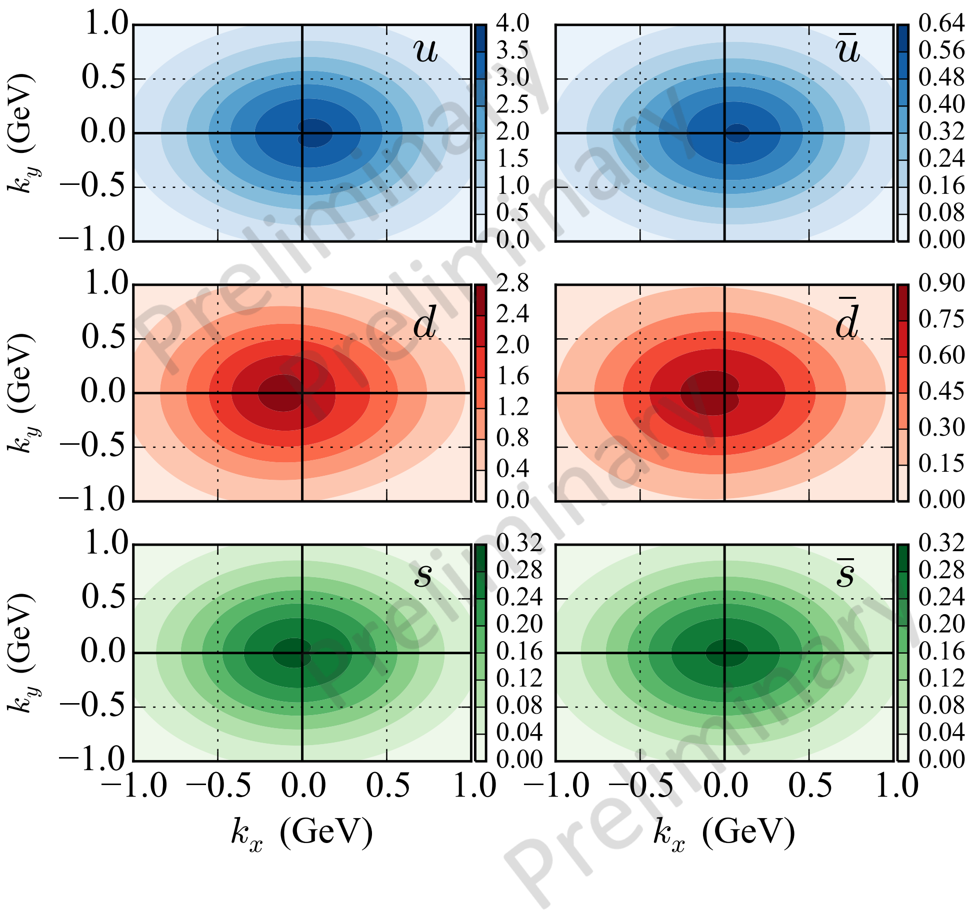


- SpinQuest (E1039) experiment at Fermilab is aiming to extract the Sivers function for the light-sea quarks.
- Unpolarized 120 GeV proton beam with polarized proton and deuteron targets (separately).
- Proton-DNN model predictions (Red) Deuteron-DNN model predictions (Orange)

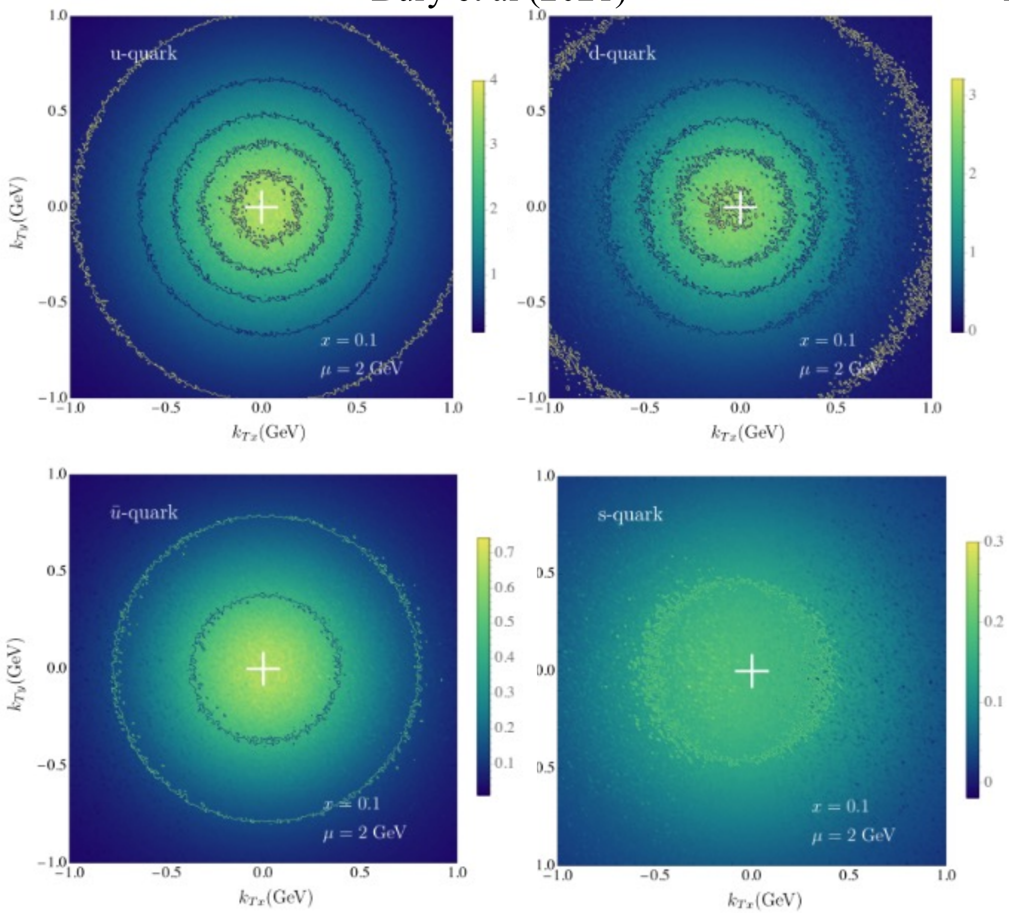
3D Tomography from the "Proton" DNN Model

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

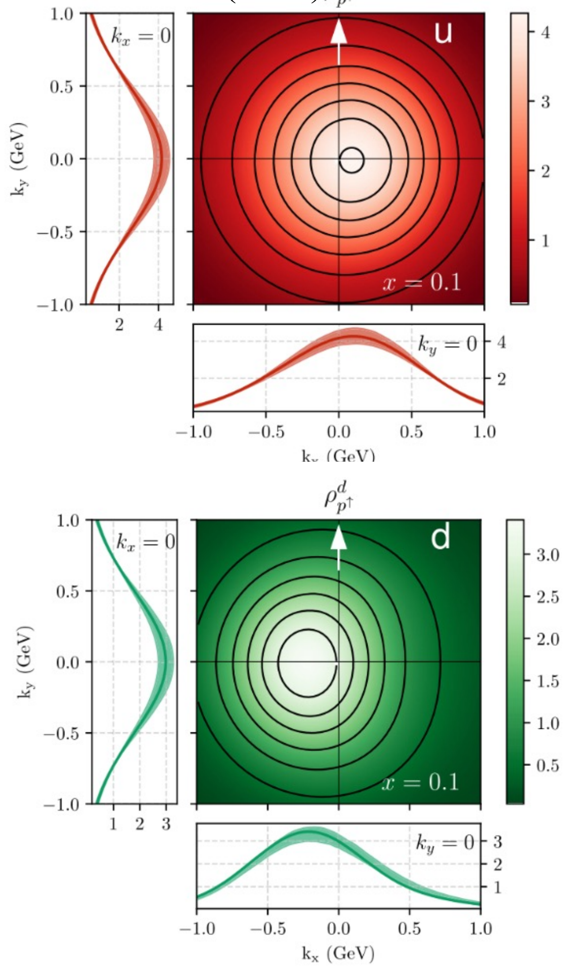
Proton-DNN model



Bury et al (2021)



Bacchetta et al (2021) $\rho^u_{p\uparrow}$



TMDs relationships between SIDIS and DY

SIDIS

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

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

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

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

DY

$$A_{T}^{\cos 2\phi_{CS}} \propto h_1^{\perp q} \circledast h_1^{\perp q} \quad \text{BM} \circledast \text{BM}$$

$$A_{T}^{\sin \phi_s} \propto f_1^{q} \circledast f_{1T}^{\perp q} \quad \text{PDF} \circledast \text{Sivers}$$

$$A_{T}^{\sin(2\phi_{CS}-\phi_S)} \propto h_1^{\perp q} \circledast h_1^{q} \quad \text{BM} \circledast \text{Transv}$$

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

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

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

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

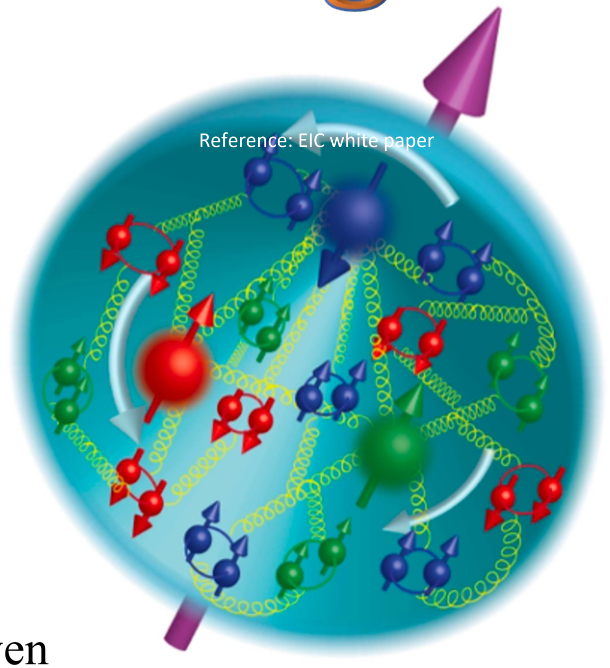
$$f_{1T}^{\perp q}\Big|_{SIDIS} = -\, f_{1T}^{\perp q}\Big|_{DY}\,.$$

There is a SpinQuest effort to extract BM from SeaQuest (E906) data, therefore DNN approach will allow us to extract all the leading twist TMDs.

TMDPDFs for Spin ½ and Spin 1 targets

leading twist		quark operator		
		unpolarized [U]	longitudinal [L]	transverse [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	$f_{1LL}(x, \boldsymbol{k}_T^2)$ $f_{1LT}(x, \boldsymbol{k}_T^2)$ $f_{1TT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^\perp(x, \boldsymbol{k}_T^2)$ h_{1TT}, $h_{1TT}^\perp$ h_{1LT}, $h_{1LT}^\perp$

At leading twist



- For Spin 1, There are 3 T-even and 7 T-odd additional TMDs appear for quarks.
- Similarly for the gluon TMDs, with polarized nuclear targets.

The use of the Transverse Momentum Distribution functions (TMDs) of polarizable nuclei offers the necessary connective bridge, allowing us to explore how these geometric properties emerge from quark and gluon dynamics.

Spin 1 TMDs for quarks and gluons

leading twist		quark operator		
		unpolarized [U]	longitudinal [L]	transverse [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	$f_{1LL}(x, \boldsymbol{k}_T^2)$ $f_{1LT}(x, \boldsymbol{k}_T^2)$ $f_{1TT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^{\perp}(x, \boldsymbol{k}_T^2)$ $h_{1TT}, \quad h_{1TT}^{\perp}$ $h_{1LT}, \quad h_{1LT}^{\perp}$

Gluon Operator

Target Polarization	Leading Twist	Unpolarized	Circular	Linear
Vector Polarized	U	f_1		$h_1^{\perp}$
	L		g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$
Tensor Polarized	LL	f_{1LL}		$h_{1LL}^{\perp}$
	LT	f_{1LT}	g_{1LT}	$h_{1LT}, h_{1LT}^{\perp}$
	TT	f_{1TT}	g_{1TT}	$h_{1TT}, \quad h_{1TT}^{\perp}$ $h_{1TT}^{\perp\perp}$

$$\Phi = \Phi_U + \Phi_L + \Phi_T + \Phi_{LL} + \Phi_{LT} + \Phi_{TT}$$

$$\Gamma^{ij} = \Gamma_U^{ij} + \Gamma_L^{ij} + \Gamma_T^{ij} + \Gamma_{LL}^{ij} + \Gamma_{LT}^{ij} + \Gamma_{TT}^{ij}$$

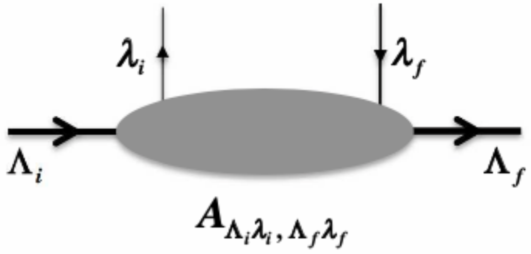
The collinear correlators after integrating over the momentum,

$$\Phi(x; P, S, T) = \frac{1}{2}\left[\not{P} f_1(x) + S_L \gamma_5 P g_1(x) + \frac{[\not{B}_T, \not{P}]\,\gamma_5}{2} h_1(x) + S_{LL} P f_{1LL}(x) + \frac{[\not{B}_{LT}, P]}{2} i h_{1LT}\left(x, k_T^2\right)\right].$$

$$\Gamma^{ij}(x) = \frac{x}{2}\left[-g_T^{ij} f_1(x) + i\epsilon_T^{ij} S_L g_1(x) - g_T^{ij} S_{LL} f_{1LL}(x) + S_{TT}^{ij} h_{1TT}(x)\right]$$

Transversity distributions: Quarks

$$\Delta_T q(x) = q_\uparrow(x) - q_\downarrow(x) \sim \mathrm{Im}\left(A_{\uparrow\uparrow,\uparrow\uparrow} - A_{\uparrow\downarrow,\uparrow\downarrow}\right)$$



- The SpinQuest polarized target configuration can be used to probe the sea-quark transversity distributions and help determine the tensor charge in the nucleon.
- The already proposed experiment E1039 will take data on both transversely polarized protons and neutrons.
- However, without additional data to separate the vector and tensor polarization contributions, the neutron transversity will be very difficult to decipher.
- The nucleon tensor charge is a fundamental nuclear property, and its determination is among the main goals of several experiments
- In terms of the partonic structure of the neutron, the tensor charge, for a particular quark type q, is constructed from the quark transversity distribution
- The neutron EDM is expressed by integrals of the transversity distributions to obtain the tensor charge

$$d_n = \sum_q d_q \delta q(Q^2) \qquad \delta q\left(Q^2\right) \equiv \int_0^1 dx\left(h_1^q\left(x, Q^2\right) - h_1^{\bar{q}}\left(x, Q^2\right)\right)$$

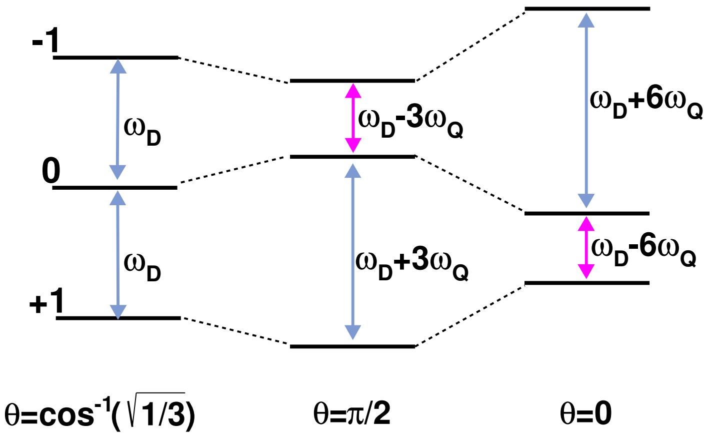
- The neutron polarization is always over 90% of the vector polarization of the deuteron.

That means: the deuteron target is a very good source of neutron polarized TMDs when the tensor polarization of the deuteron is mitigated.

Deuteron Polarization

- The deuterons have nonzero quadrupole moments
- The structural arrangement of the nuclei in the solid generate electric field gradients (EFG) which couple to the quadrupole moment.

This results in an additional degree of freedom in polarization that the spin-1/2 nucleons do not possess.



$$r = I_+/I_-$$

Vector Polarization

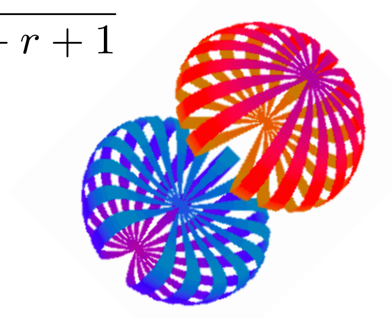
$$P_n = \frac{n_{+1} - n_{-1}}{n}$$

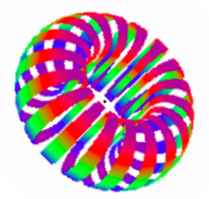
$$n = n_{+1} + n_0 + n_{-1}$$

Tensor Polarization

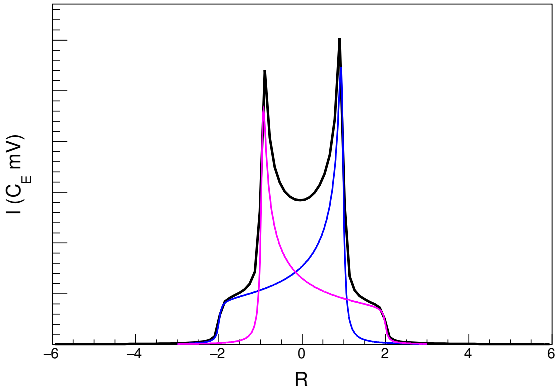
$$Q_n = \frac{n - 3n_0}{n}$$

$$P = \frac{r^2 - 1}{r^2 + r + 1}$$





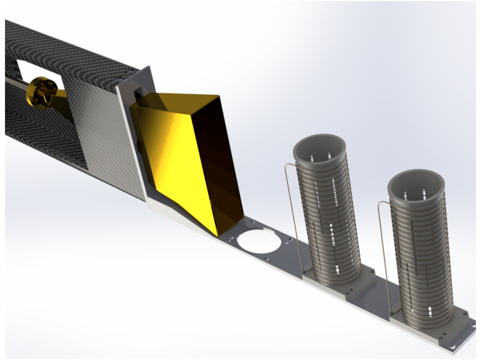
$$P_{zz} = \frac{r^2 - 2r + 1}{r^2 + r + 1}$$



$$E_m = -\hbar\omega_D m + \hbar\omega_Q(3\cos^2\theta - 1 + \eta\sin^2\theta\cos 2\phi)(3m^2 - 2)$$

$$\frac{P_{zz}}{P} = \frac{r - 1}{r + 1}.$$

Tensor Polarization Enhancement



- ✓ DNP microwaves
- ✓ Additional RF: Semi-Saturating RF (ss-RF) irradiation → to maximize Tensor polarization
- ✓ Continuous Wave NMR (CW-NMR)
- ✓ The rate depends on the intensity level and the applied magnetic field strength of the RF power.

J. Clement and D. Keller (2023) [https://doi.org/10.1016/j.nima.2023.168177]

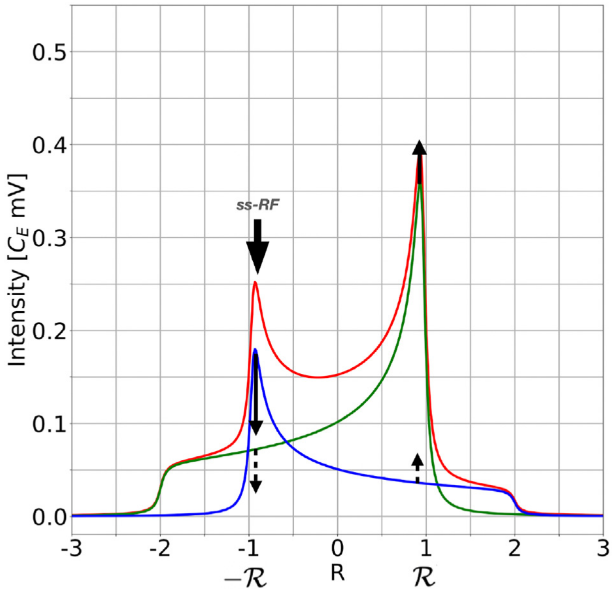
Under normal DNP-enhancement, conditions, the system is in Boltzmann equilibrium and Q_n can be calculated directly from P_n

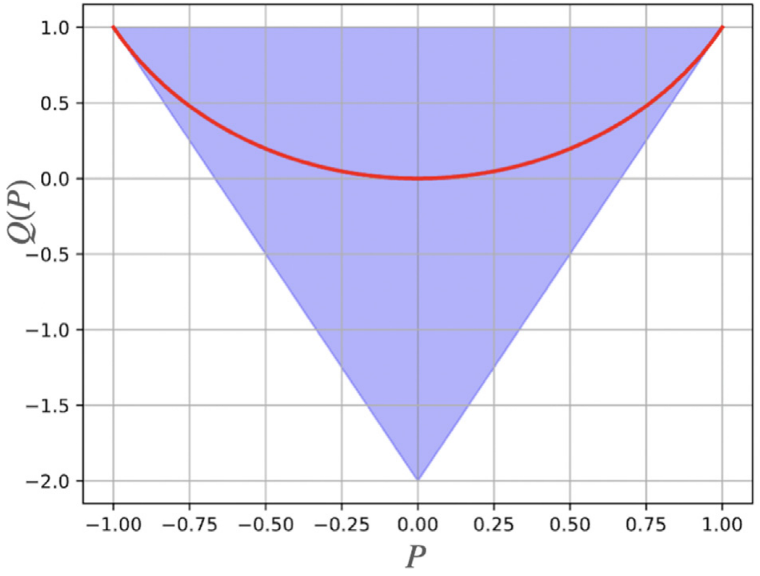
$$Q_n = 2 - \sqrt{4 - 3P_n^2}$$

Three Principles for Enhanced Tensor Polarization

- ❖ Differential Binning
- ❖ Spin Temperature Consistency
- ❖ Rate Response

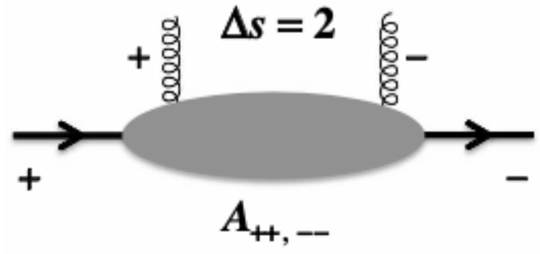
See Dustin's Talk
for more details





Transversity distributions: Gluons

The gluon transversity cannot exist in the nucleon where the spin flip Δs = 2 is not possible.



$$h_{1TT}^{g}(x) \sim \mathrm{Im}\, A_{++,--}$$

The spin flip of $\Delta s = 2(|\lambda_f - \lambda_i| = |\Lambda_f - \Lambda_i| = 2)$ is necessary for gluon transversity.

$$\Phi_{g/B}^{\alpha\beta}(x_b) \equiv \int d^2 p_{bT} \Phi_{g/B}^{\alpha\beta}(x, \vec{p}_{bT})$$
$$= \frac{1}{2}\left[-g_T^{\alpha\beta} f_{1,B}^{g}(x_b) + i\epsilon_T^{\alpha\beta} S_L g_{1,B}^{g}(x_b) - g_T^{g\,\alpha\beta} S_{LL} f_{1LL,B}^{g}(x_b) + S_{TT}^{\alpha\beta} h_{1TT,B}^{g}(x_b) \right]$$

Unpolarized distribution

Longitudinally-Polarized distribution

Longitudinally-Tensor-Polarized distribution — $f_{1LL}(x)$

Transversely-Tensor-Polarized distribution — Gluon Transversity

$$\boldsymbol{S} = (S_T^x, S_T^y, S_L)$$

$$\boldsymbol{T} = \frac{1}{2}\begin{pmatrix} -\frac{2}{3}S_{LL} + S_{\mathrm{TT}}^{xx} & S_{\mathrm{TT}}^{xy} & S_{LT}^{x} \\ S_{\mathrm{TT}}^{xy} & -\frac{2}{3}S_{LL} - S_{\mathrm{TT}}^{xx} & S_{LT}^{y} \\ S_{LT}^{x} & S_{LT}^{y} & \frac{4}{3}S_{LL} \end{pmatrix}$$

$$\vec{E}_0 = (0,0,1)$$
$$\vec{E}_\pm = \frac{1}{\sqrt{2}}(\mp 1, -i, 0)$$
$$\vec{E}_x = \frac{1}{\sqrt{2}}\left(\vec{E}_- - \vec{E}_+\right) = (1,0,0)$$
$$\vec{E}_y = \frac{i}{\sqrt{2}}\left(\vec{E}_- + \vec{E}_+\right) = (0,1,0)$$

The spin vector and tensor are written in terms of the polarization vector of the deuteron

$$\vec{S} = \mathrm{Im}\left(\vec{E}^* \times \vec{E}\right), \quad T_{ij} = \frac{1}{3}\delta_{ij} - \mathrm{Re}\left(E_i^* E_j\right)$$

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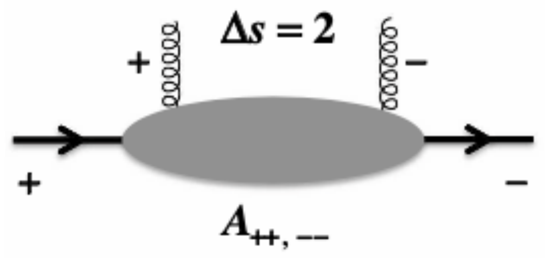

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Unpolarized distribution

Longitudinally-Polarized distribution

Longitudinally-Tensor-Polarized distribution

Transversely-Tensor-Polarized distribution

$f_{1LL}(x)$

Gluon Transversity

$\vec{E}_x$ a vector polarization

$\vec{E}_y$, a vector polarization

$\vec{E}_0$, a vector polarization

$S_T^x = S_T^y = S_L = 0$

$S_{TT}^{xy} = S_{LT}^x = S_{LT}^y = 0$

$S_{LL} = 1/2$

$S_{LL} = 1/2$

$S_{LL} = -1$

$S_T^{xx} = -1$

$S_{TT}^{xx} = +1$

$S_{TT}^{xx} = 0$

$\vec{E}_x - \vec{E}_y$

$2\vec{E}_x - \vec{E}_0$

$S_T^{xx} = -2$

With either of these configurations, the longitudinal tensor polarization is zero as well as any vector polarization contributions, and the critical term S_{TT}^{xx} is maximized.

Transversity distributions: Gluons

$$\Phi^{\alpha\beta}_{g/B}(x_b) \equiv \int d^2p_{bT}\Phi^{\alpha\beta}_{g/B}(x,\vec{p}_{bT})$$
$$= \frac{1}{2}\left[-g_T^{\alpha\beta} f^g_{1,B}(x_b) + i\epsilon_T^{\alpha\beta} S_L g^g_{1,B}(x_b) \; -g_T^{g\,\alpha\beta} S_{LL} f^g_{1LL,B}(x_b) + S^{\alpha\beta}_{TT} h^g_{1TT,B}(x_b)\right]$$

$$A_{E_{xy}} = \frac{d\sigma_{pd\to\mu^+\mu^-X}(E_x - E_y)/\left(d\tau dq_T^2 d\phi dy\right)}{d\sigma_{pd\to\mu^+\mu^-X}(E_x + E_y)/\left(d\tau dq_T^2 d\phi dy\right)}$$

$$\vec{E}_x - \vec{E}_y \equiv 2\vec{E}_x + \vec{E}_0 - U \qquad\qquad \vec{E}_x + \vec{E}_y \equiv U - \vec{E}_0$$

If the differential cross-section from the longitudinal tensor polarized part is small compared to the transverse tensor polarized part $f^g_{1LL} \approx 0$

$$A_{E_{xy}} = \frac{d\sigma_{pd\to\mu^+\mu^-X}(E_x - E_y)/\left(d\tau dq_T^2 d\phi dy\right)}{d\sigma_{pd\to\mu^+\mu^-X}(E_x + E_y)/\left(d\tau dq_T^2 d\phi dy\right)} = \frac{d\sigma_{pd\to\mu^+\mu^-X}(2E_x - U)/\left(d\tau dq_T^2 d\phi dy\right)}{d\sigma_{pd\to\mu^+\mu^-X}(U)/\left(d\tau dq_T^2 d\phi dy\right).}$$

The generalized experimental gluon transversity asymmetry can then be written as

$$A_{E_{xy}} = \frac{2\sigma^{E_x}_{pd\to\mu^+\mu^-X} - \sigma^U_{pd\to\mu^+\mu^-X}}{\sigma^U_{pd\to\mu^+\mu^-X}} = \frac{1}{fP_{zz}}\frac{2N^{E_x}_{pd\to\mu^+\mu^-X} - N^U_{pd\to\mu^+\mu^-X}}{N^U_{pd\to\mu^+\mu^-X}}$$

Transversity distributions: Gluons

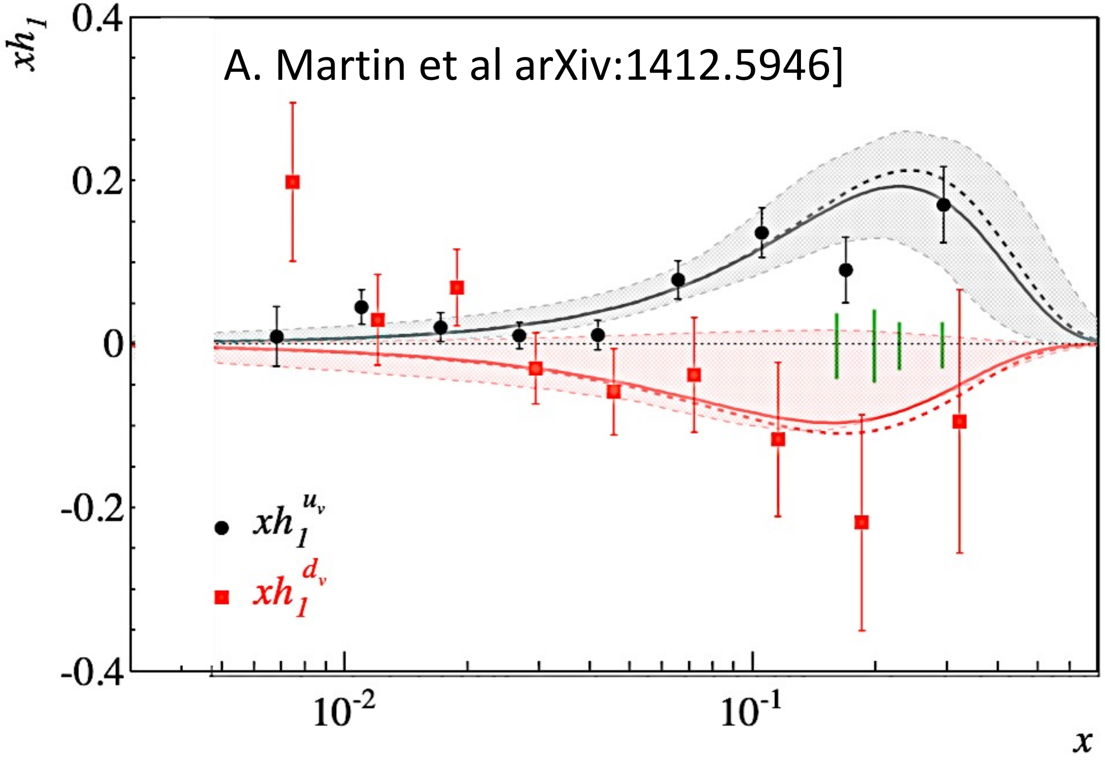
$$A_{E_{xy}} = \frac{2\sigma^{E_x}_{pd\to\mu^+\mu^- X} - \sigma^{U}_{pd\to\mu^+\mu^- X}}{\sigma^{U}_{pd\to\mu^+\mu^- X}} = \frac{1}{fP_{zz}}\frac{2N^{E_x}_{pd\to\mu^+\mu^- X} - N^{U}_{pd\to\mu^+\mu^- X}}{N^{U}_{pd\to\mu^+\mu^- X}}$$

where P_{zz} is the target ensemble tensor polarization pertaining to the tensor polarized cross-section events N^{E_x}

- There are several ways to build a gluon transversity asymmetry using different quantization axes and polarized target configurations
- But this equivalence provides a way to compare directly with predictions and requires the same polarized target magnet and orientation already in place in the SpinQuest experimental hall.
- σ^{E_x} can be measured with either a purely tensor polarized target or as the difference between a enhanced tensor polarized target with high tensor polarization and some vector polarization subtracted from a purely vector polarized target.
- A purely vector polarized target is significantly easier to make compared to a purely tensor polarized target, so this is our preferred method. This term in the asymmetry then becomes

Transversity projection: sea-quarks

https://arxiv.org/abs/2205.01249

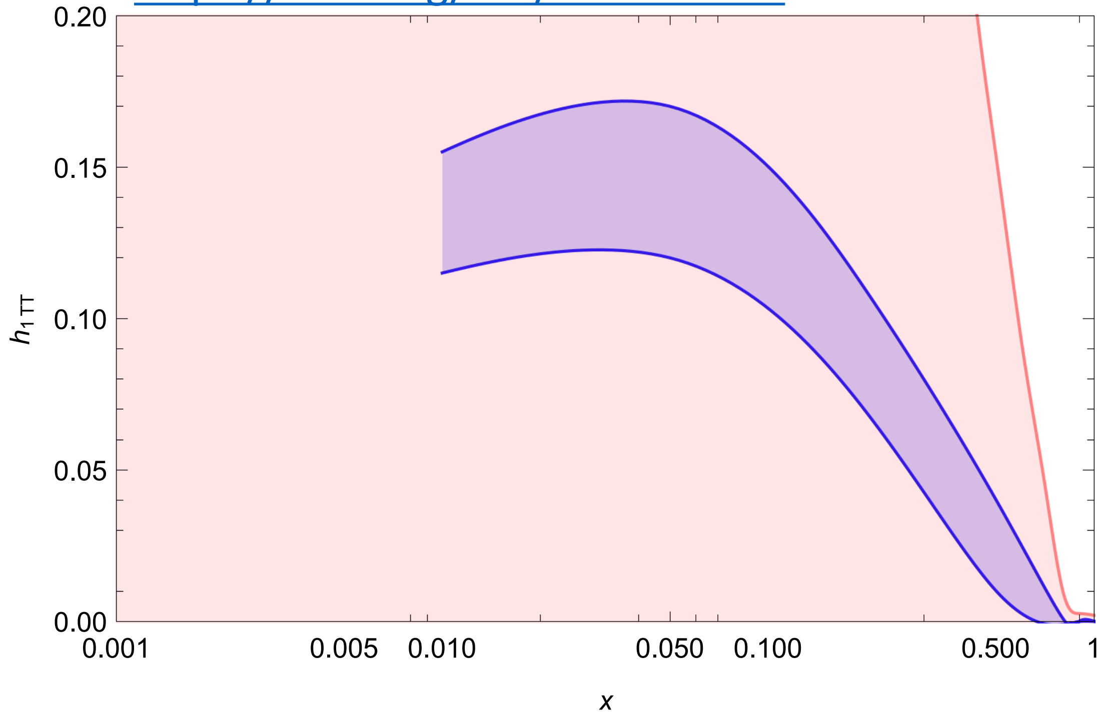


Only valence quark transversity of u and d were studied so far. Transversity distributions for sea-quark d-bar transversity for our range of kinematics is in progress (D. Keller & S. Kumano)

The (preliminary) projections are based on SIDIS data which is insensitive to sea-quark contributions by D. Keller using A. Martin et al framework.

Transversity projection: gluons

https://arxiv.org/abs/2205.01249



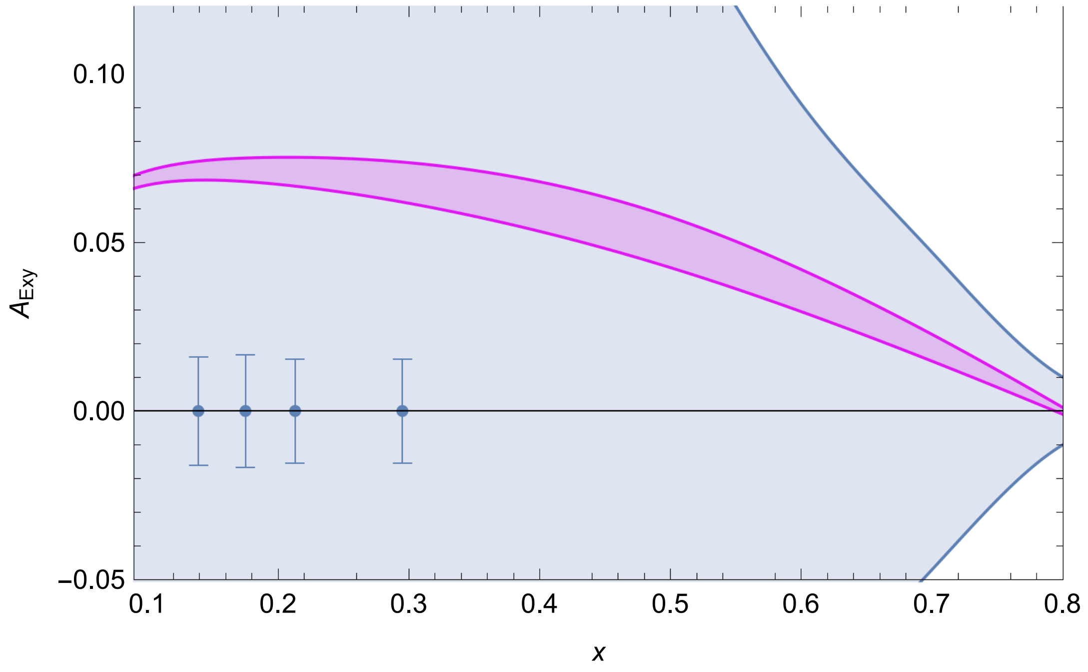
The model for h^g_{1TT} suggested by Kumano and Song (2020) for our range of kinematics is shown in purple.

The Soffer positivity bound is also shown in the same x region.

$$|h^g_{1TT}| \leq \frac{1}{2}\left(f^g_1 + \frac{f^g_{1LL}}{2} - g^g_1\right)$$

Linear Polarized Gluon Asymmetry Projections

https://arxiv.org/abs/2205.01249



- Projections of the linear polarized gluon asymmetry with expected errors from our proposed measurements.
- We are assuming an additional 0.05% absolute error as a conservative estimate in addition to the expected statistical and relative systematic contributions.
- An average over our range in qT and y is used
- The Soffer-like positivity bound is also shown in grey and used for the upper limit, which provides a scale for demonstrating the information gained from the proposed measurement.

Transversity proposal at Fermilab

- Formal proposal was presented to the FNAL PAC in January 2023 and was well received.
- But there will be no formal approval until the target material (NH3/ND3) can be approved to use at the lab.
- We expect that at the next PAC meeting in January 2024, all of this will be resolved.

Possible Future Programs at Fermilab

Quark/Gluon Transversity
Spin-dependent flavor asymmetry
Polarized EMC studies
Nuclei TMDs and Spin

Transversely Polarized Target

Helicity
Spin-dependent flavor asymmetry
Tensor polarized structure functions

Longitudinally Polarized Target

Possible Gluon Transversity from SIDIS at JLab

$$\frac{2\pi d\sigma\left(lH^{\uparrow}\to l'hX\right)}{d\phi dx_B dz_h dy}(E_x - E_y) = \frac{2\alpha^2(1-y)}{Q^2 y}\cos(2\phi_h) h^g_{1TT}(x_B, Q^2) H_1^{\perp}(z_h)$$

The cross section sum of these same two polarization directions provides the necessary numerator to construct a gluon transversity asymmetry which can be written as,

$$A_{E_{xy}} = \frac{d\sigma\left(E_x - E_y\right)/\left(d\phi dx_B dz_h dy\right)}{d\sigma\left(E_x + E_y\right)/\left(d\phi dx_B dz_h dy\right)}.$$

The generalized experimental gluon transversity asymmetry can then be written as,

$$A_{E_{xy}} = \frac{1}{fP_{zz}}\frac{\sigma^{E_x}_{ed\to e'\pi X} - \sigma^{E_y}_{ed\to e'\pi X}}{\sigma^{E_x}_{ed\to e'\pi X} + \sigma^{E_y}_{ed\to e'\pi X}},$$

We are working on an effort to propose SIDIS Transversity at JLab Hall A with the SoLID detector.
I'm going to be working this and anyone who is interested in will be welcomed!

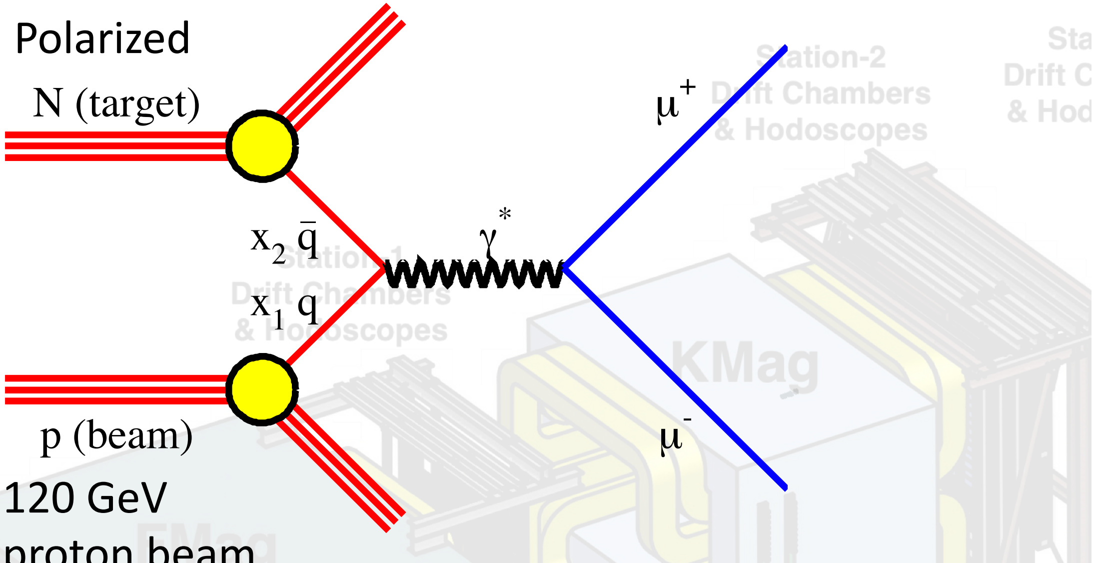
SpinQuest (E1039) Experiment at Fermilab

- Measurement of ‘sea’ quark Sivers function

Stay Tuned!

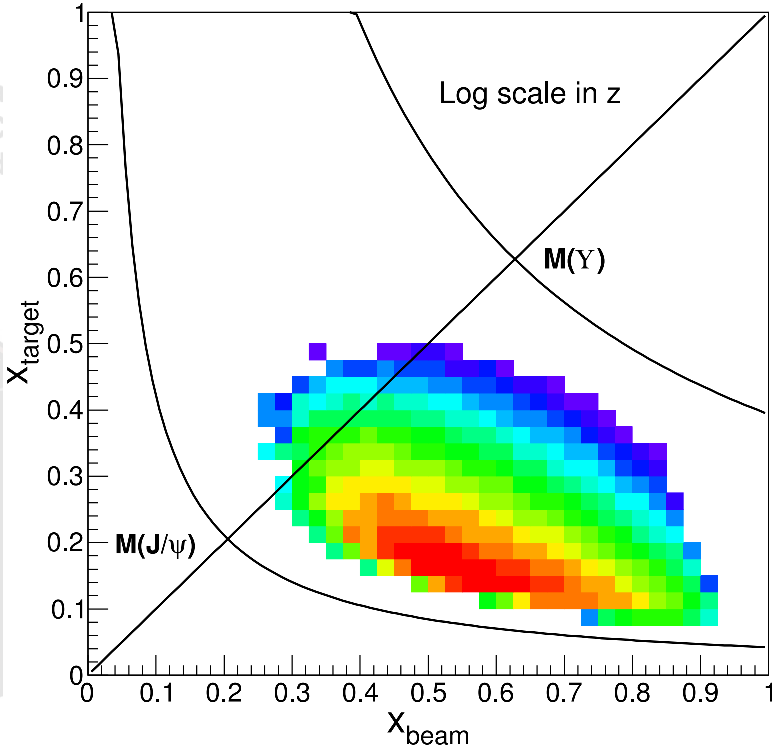
$pp^{\uparrow}(d^{\uparrow}) \rightarrow \mu^+\mu^- X,\ 4 < M_{\mu\mu} < 9\ GeV$

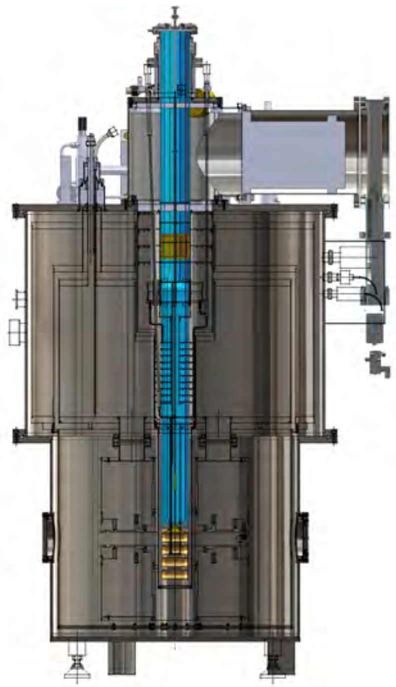
Polarized



120 GeV proton beam

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





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

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