Spin 1 SIDIS experiments with Transversely Tensor Polarized Targets

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for the UVA Spin Physics Team

b1/Azz Collaboration Meeting
&
Tensor SIDIS Workshop

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Jefferson Lab, Virginia

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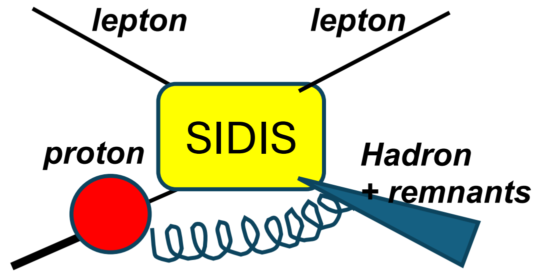
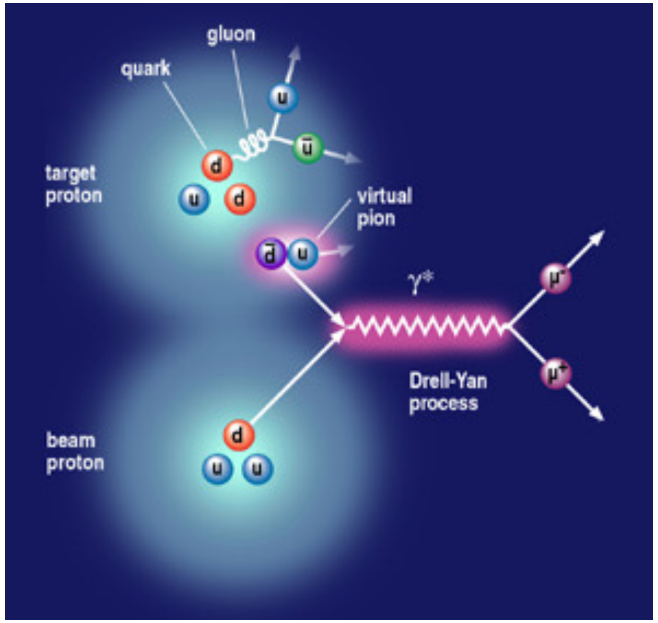
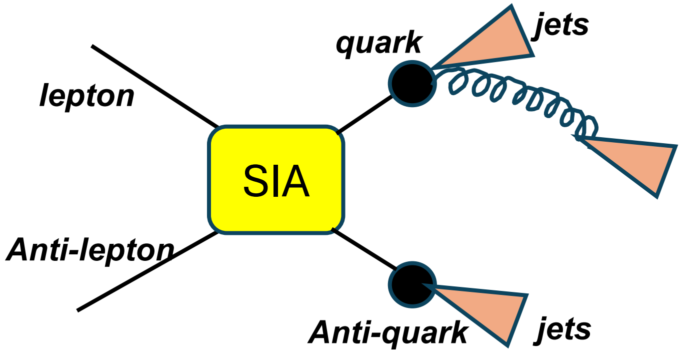
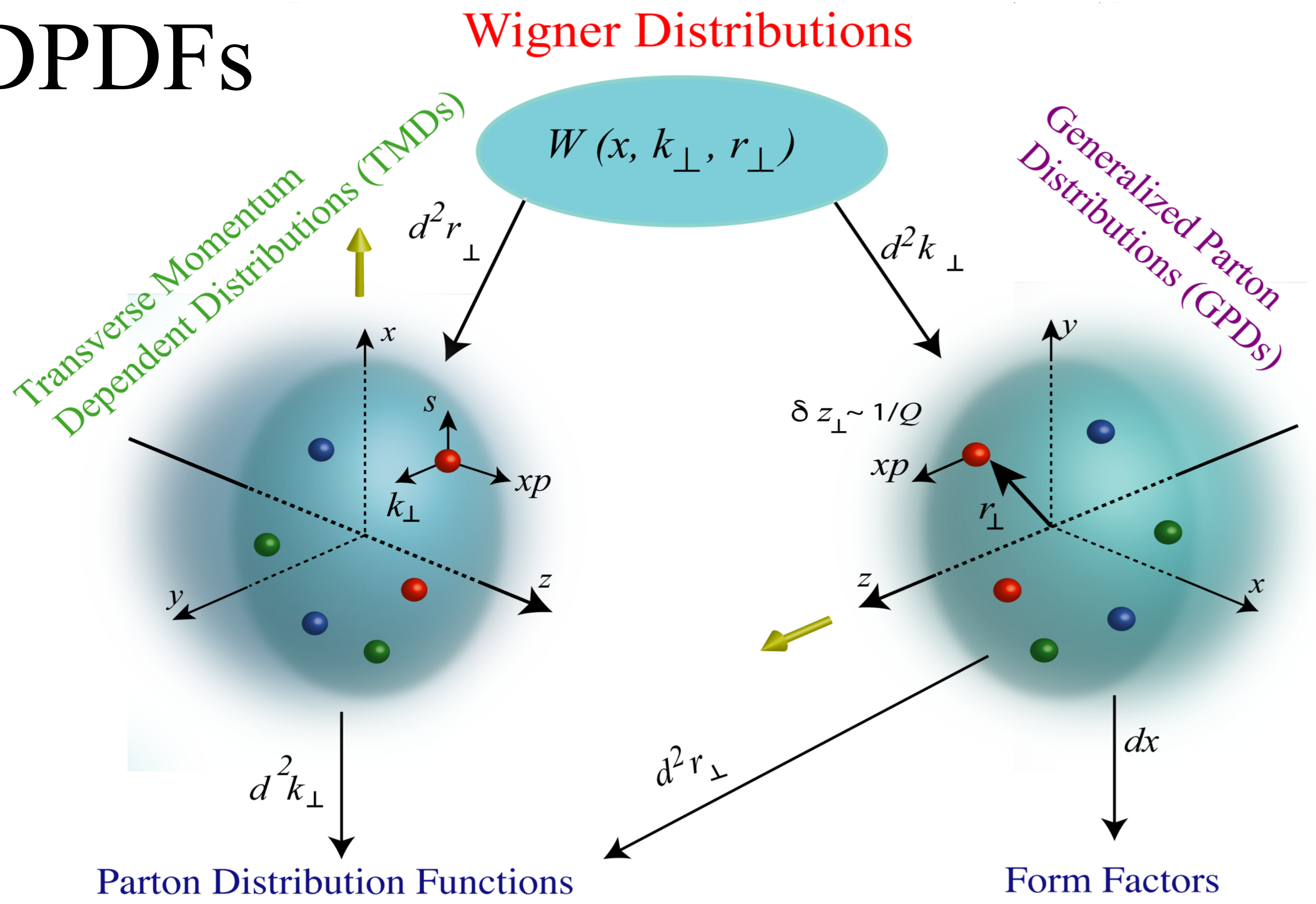
TMDPDFs



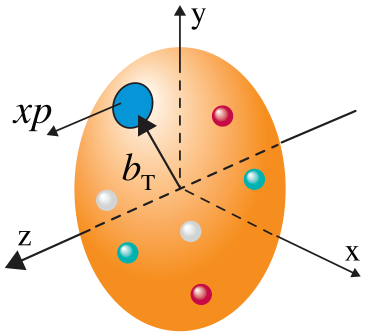






$$\Phi(x, k_T; S) = \int \frac{d\xi^- d\xi_T}{(2\pi)^3} e^{ik.\xi} \langle P, S|\bar{\psi}(0)\, \mathcal{U}_{[0,\xi]}\, \psi(\xi)|P, S\rangle|_{\xi^+=0}$$

TMDPDFs for Spin 1 & Beyond …



Leading Twist		Quark Polarization		
		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	$f_{1LL}(x, \boldsymbol{k}_T^2)$ $f_{1TT}(x, \boldsymbol{k}_T^2)$ $f_{1LT}(x, \boldsymbol{k}_T^2)$	$g_{1TT}(x, \boldsymbol{k}_T^2)$ $g_{1LT}(x, \boldsymbol{k}_T^2)$	$h_{1LL}^{\perp}(x, \boldsymbol{k}_T^2)$ $h_{1TT}(x, \boldsymbol{k}_T^2)$ $h_{1TT}^{\perp}(x, \boldsymbol{k}_T^2)$ $h_{1LT}(x, \boldsymbol{k}_T^2)$ $h_{1LT}^{\perp}(x, \boldsymbol{k}_T^2)$

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

Kumano et al (2020)

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

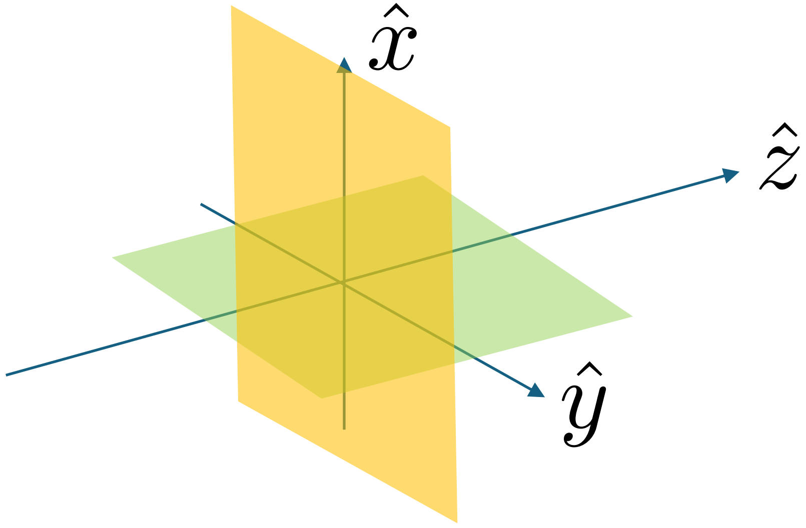
$$\Gamma^{ij} = \Gamma^{ij}_U + \Gamma^{ij}_L + \Gamma^{ij}_T + \Gamma^{ij}_{LL} + \Gamma^{ij}_{LT} + \Gamma^{ij}_{TT}$$

The collinear correlators after integrating over the momentum,

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

An ongoing UVA project: Leading-twist quark and gluon TMDs, GPDs, Structure Functions for polarized spin-3/2 targets as an exploratory first step (in progress).

Deuteron Polarizations



The deuteron polarization density matrix

$$\rho(S,T) = \frac{1}{3}\left(I + \frac{3}{2}S^i\Sigma^i + 3T^{ij}\Sigma^{ij}\right)$$

$\boldsymbol{\Sigma_i}$ are 3×3 spin matrices for the deuteron

$$\boldsymbol{\Sigma_x} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \boldsymbol{\Sigma_y} = \frac{i}{\sqrt{2}}\begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix} \quad \boldsymbol{\Sigma_z} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$\boldsymbol{\Sigma}_{ij}$ are spin tensors

$$\boldsymbol{\Sigma}_{ij} = \frac{1}{2}\left(\boldsymbol{\Sigma_i}\boldsymbol{\Sigma_j} + \boldsymbol{\Sigma_j}\boldsymbol{\Sigma_i}\right) - \frac{2}{3}\boldsymbol{I}\delta_{ij}$$

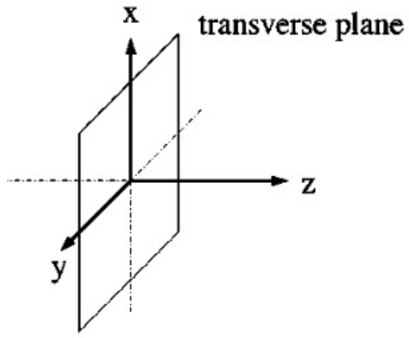
$$\boldsymbol{S} = (S_T^x, S_T^y, S_L)$$

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

$$\rho(S,T) = \begin{pmatrix} \frac{1}{3} + \frac{S_L}{2} + \frac{S_{LL}}{3} & \frac{S_T^x - iS_T^y}{2\sqrt{2}} + \frac{S_{LT}^x - iS_{LT}^y}{2\sqrt{2}} & \frac{S_{TT}^{xx} - iS_{TT}^{xy}}{2} \\ \frac{S_T^{x+iS_T^y}}{2\sqrt{2}} + \frac{S_{LT}^x + iS_{LT}^y}{2\sqrt{2}} & \frac{1}{3} - \frac{2S_{LL}}{3} & \frac{S_T^x - iS_T^y}{2\sqrt{2}} - \frac{S_{LT}^x - iS_{LT}^y}{2\sqrt{2}} \\ \frac{S_{TT}^{xx} + iS_{TT}^{xy}}{2} & \frac{S_T^x + iS_T^y}{2\sqrt{2}} - \frac{S_{LT}^x + iS_{LT}^y}{2\sqrt{2}} & \frac{1}{3} - \frac{S_L}{2} + \frac{S_{LL}}{3} \end{pmatrix}$$

https://arxiv.org/abs/hep-ph/0007120

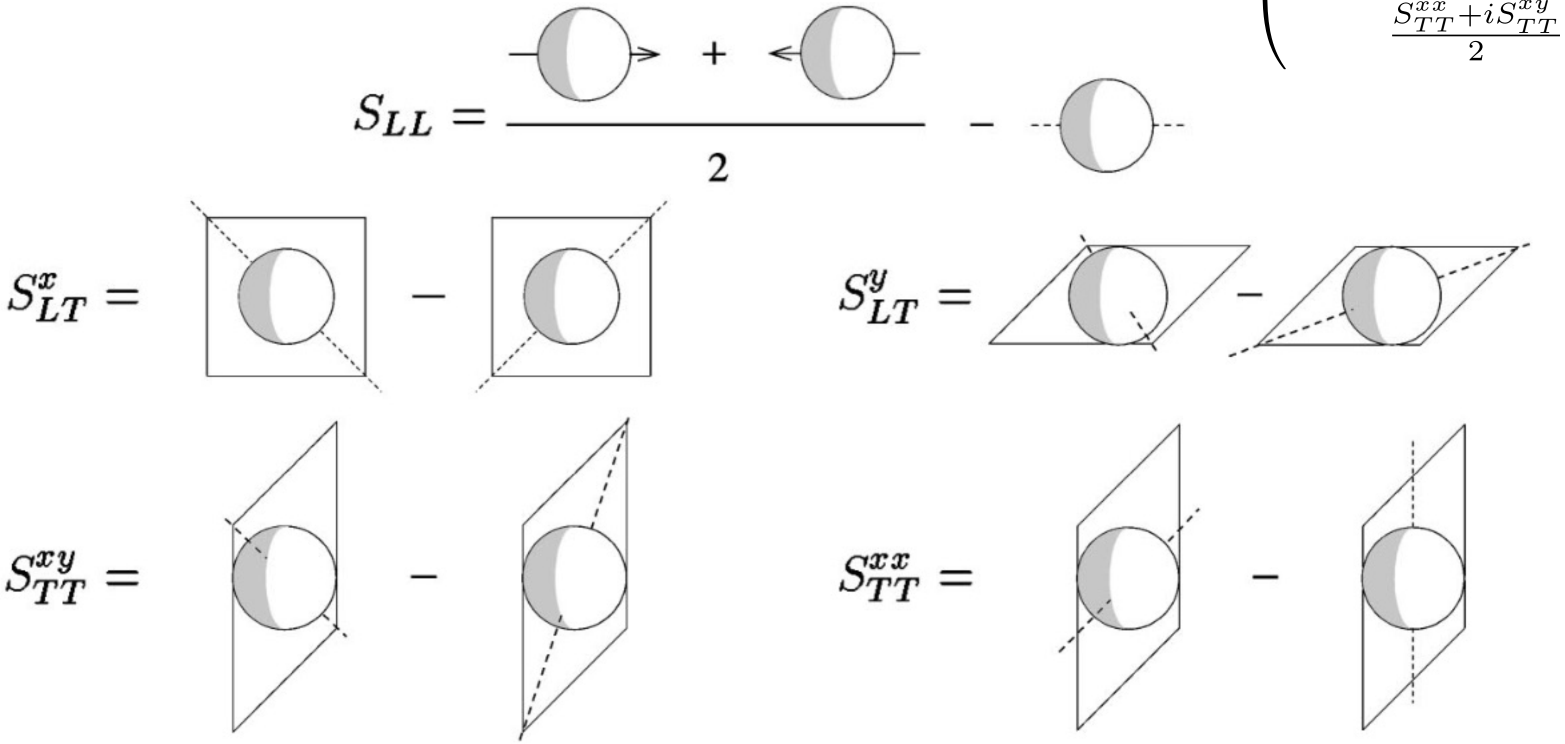
Deuteron Polarization Orientations



$$\boldsymbol{\Sigma}^i \hat{n}_i = \boldsymbol{\Sigma}_x \cos\theta \cos\varphi + \boldsymbol{\Sigma}_y \cos\theta \sin\varphi + \boldsymbol{\Sigma}_z \sin\theta.$$

$$P\left(m_{(\theta,\varphi)}\right) = \mathrm{Tr}\ \left\{\boldsymbol{\rho}\,|m_{(\theta,\varphi)}\rangle\langle m_{(\theta,\varphi)}|\right\}$$

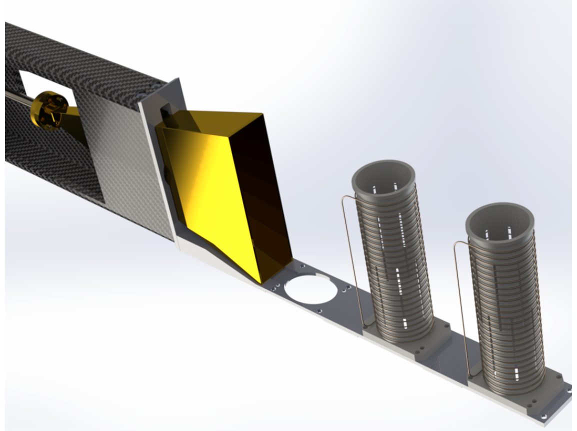
$$\rho(S,T) = \begin{pmatrix} \frac{1}{3} + \frac{S_L}{2} + \frac{S_{LL}}{3} & \frac{S_T^x - iS_T^y}{2\sqrt{2}} + \frac{S_{LT}^x - iS_{LT}^y}{2\sqrt{2}} & \frac{S_{TT}^{xx} - iS_{TT}^{xy}}{2} \\ \frac{S_T^{x+iS_T^y}}{2\sqrt{2}} + \frac{S_{LT}^x + iS_{LT}^y}{2\sqrt{2}} & \frac{1}{3} - \frac{2S_{LL}}{3} & \frac{S_T^x - iS_T^y}{2\sqrt{2}} - \frac{S_{LT}^x - iS_{LT}^y}{2\sqrt{2}} \\ \frac{S_{TT}^{xx} + iS_{TT}^{xy}}{2} & \frac{S_T^x + iS_T^y}{2\sqrt{2}} - \frac{S_{LT}^x + iS_{LT}^y}{2\sqrt{2}} & \frac{1}{3} - \frac{S_L}{2} + \frac{S_{LL}}{3} \end{pmatrix}$$



$$S_{LL} = \frac{1}{2}P\left(1_{(0,0)}\right) + \frac{1}{2}P\left(-1_{(0,0)}\right) - P\left(0_{(0,0)}\right),$$
$$S_{LT}^x = P\left(0_{(-\frac{\pi}{4},0)}\right) - P\left(0_{(\frac{\pi}{4},0)}\right),$$
$$S_{LT}^y = P\left(0_{(-\frac{\pi}{4},\frac{\pi}{2})}\right) - P\left(0_{(\frac{\pi}{4},\frac{\pi}{2})}\right),$$
$$S_{TT}^{xx} = P\left(0_{(\frac{\pi}{2},-\frac{\pi}{4})}\right) - P\left(0_{(\frac{\pi}{2},\frac{\pi}{4})}\right),$$
$$S_{TT}^{xy} = P\left(0_{(\frac{\pi}{2},\frac{\pi}{2})}\right) - P\left(0_{(\frac{\pi}{2},0)}\right).$$

A. BACCHETTA AND P. J. MULDERS PHYSICAL REVIEW D **62** 114004
https://arxiv.org/abs/hep-ph/0007120

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]

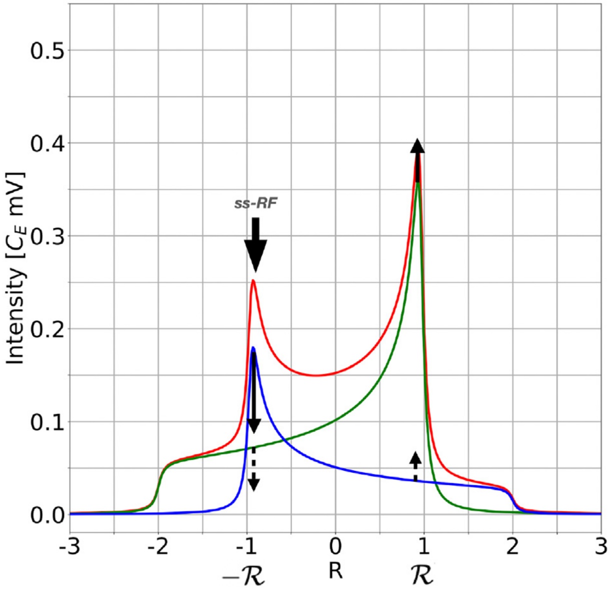
Under normal DNP-enhancement, conditions, the system is in Boltzmann equilibrium and Q_n can be calculated directly from P_n

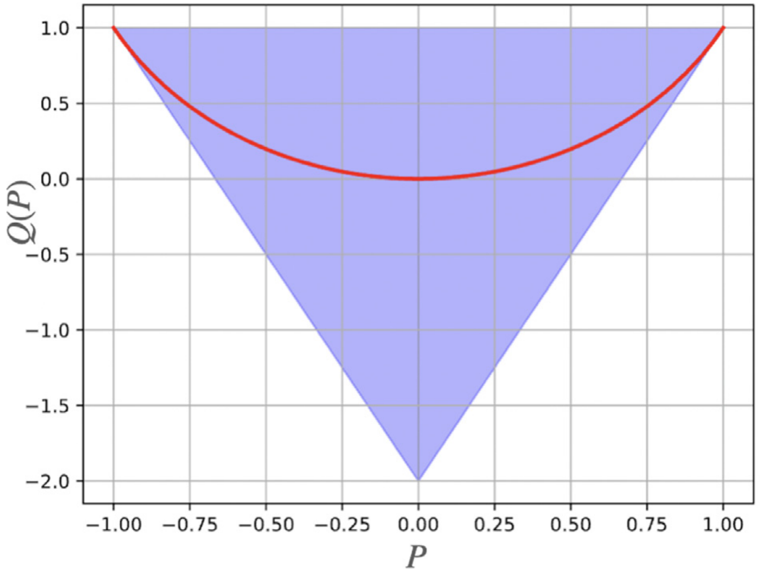
$$Q_n = 2 - \sqrt{4 - 3P_n^2}$$

Three Principles for Enhanced Tensor Polarization

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

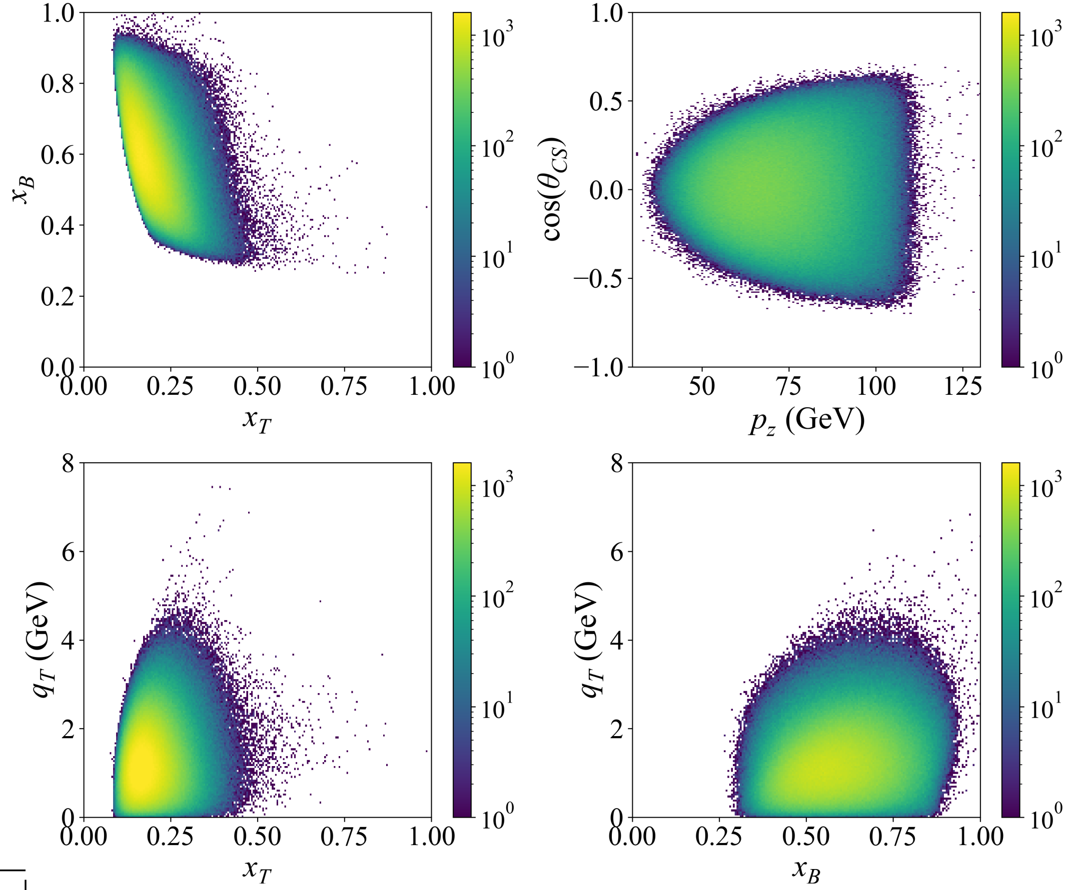
A recent article on advanced ss-RF measurement
D. Keller (2026)
https://doi.org/10.1140/epja/s10050-026-01790-y
See Devin's talk for updates on measuring and manipulating ss-RF





Transversity (SpinQuest +) program

- ❖ Formal proposal was presented to the FNAL PAC in January 2023 and was well received.
- ❖ Stage 1 approval at FNAL PAC in March 2025 https://pac.fnal.gov/wp-content/uploads/2025/04/PAC_Report_March_2025_Public.pdf
- ❖ DOE funding limitations in FNAL operations budget for this year (2026)
- ❖ Long shutdown stops in 2029, and SpinQuest resumes in 2030 with Proton Target with
- ❖ Transversity run expected to start in 2031with Deuteron Target



x_2-bin	$< x_2 >$	Vector-ND_3 ($d^{\uparrow}$)		Tensor-ND_3 ($d^{\uparrow}$)		$n^{\uparrow}$
		N	$\delta A_{E_{\pm}}$	N	$\delta A_{E_{xy}}$	δA_{UT}
0.10 - 0.16	0.139	2.1×10^4	7.1	2.2×10^4	15.8	7.4
0.16 - 0.19	0.175	1.9×10^4	7.5	2.0×10^4	16.7	7.8
0.19 - 0.24	0.213	2.4×10^4	6.7	2.5×10^4	14.9	7.1
0.24 - 0.60	0.295	2.4×10^4	6.7	2.5×10^4	14.9	7.1

- https://arxiv.org/abs/2205.01249
- Sea-Quark and Gluon Transversity TMDs of the Deuteron with Drell–Yan at SpinQuest, EPJA (in-progress)

SIDIS Cross-Section for Deuteron Target

$$\frac{d\sigma_{\text{Tens}}}{dx_d dy dz d\phi_h d\psi dP_{h\perp}^2} = \frac{\alpha^2}{x_d y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_d}\right) \Big\{ S_{LL} \Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{U(LL)}^{\cos\phi_h}$$

$$+ \varepsilon \cos(2\phi_h)\, F_{U(LL)}^{\cos 2\phi_h} + \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{L(LL)}^{\sin\phi_h} \Big]$$

$$+ |S_{LT}| \Big[\cos(\phi_h - \phi_{LT}) \Big(F_{U(LT),T}^{\cos(\phi_h-\phi_{LT})} + \varepsilon F_{U(LT),L}^{\cos(\phi_h-\phi_{LT})} \Big)$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} \Big(\cos\phi_{LT} F_{U(LT)}^{\cos\phi_{LT}} + \cos(2\phi_h - \phi_{LT}) F_{U(LT)}^{\cos(2\phi_h-\phi_{LT})} \Big)$$

$$+ \varepsilon \Big(\cos(\phi_h + \phi_{LT}) F_{U(LT)}^{\cos(\phi_h+\phi_{LT})} + \cos(3\phi_h - \phi_{LT}) F_{U(LT)}^{\cos(3\phi_h-\phi_{LT})} \Big)$$

$$+ \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \Big(\sin\phi_{LT} F_{L(LT)}^{\sin\phi_{LT}} + \sin(2\phi_h - \phi_{LT}) F_{L(LT)}^{\sin(2\phi_h-\phi_{LT})} \Big)$$

$$+ \lambda_e \sqrt{1-\varepsilon^2}\, \sin(\phi_h - \phi_{LT}) F_{L(LT)}^{\sin(\phi_h-\phi_{LT})} \Big]$$

With Transversely Tensor Polarized Target

$$+ |S_{TT}| \Big[\cos(2\phi_h - 2\phi_{TT}) \Big(F_{U(TT),T}^{\cos(2\phi_h-2\phi_{TT})} + \varepsilon F_{U(TT),L}^{\cos(2\phi_h-2\phi_{TT})} \Big)$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} \Big(\cos(\phi_h - 2\phi_{TT}) F_{U(TT)}^{\cos(\phi_h-2\phi_{TT})} + \cos(3\phi_h - 2\phi_{TT}) F_{U(TT)}^{\cos(3\phi_h-2\phi_{TT})} \Big)$$

$$+ \varepsilon \Big(\cos(2\phi_{TT}) F_{U(TT)}^{\cos(2\phi_{TT})} + \cos(4\phi_h - 2\phi_{TT}) F_{U(TT)}^{\cos(4\phi_h-2\phi_{TT})} \Big)$$

$$+ \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \Big(\sin(\phi_h - 2\phi_{TT}) F_{L(TT)}^{\sin(\phi_h-2\phi_{TT})} + \sin(3\phi_h - 2\phi_{TT}) F_{L(TT)}^{\sin(3\phi_h-2\phi_{TT})} \Big)$$

$$+ \lambda_e \sqrt{1-\varepsilon^2}\, \sin(2\phi_h - 2\phi_{TT}) F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})} \Big] \Big\},$$

J. Zhao, A. Bacchetta, S. Kumano, T. Liu, Y.-J. Zhuo, arXiv: 2058.06134

Structure functions related to Transversely Tensor Polarized Targets

With Unpolarized Beam

$$F_{U(TT),T}^{\cos(2\phi_h-2\phi_{LT})} = \mathcal{C}\Big[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2} f_{1TT} D_1\Big],$$

$$F_{U(TT),L}^{\cos(2\phi_h-2\phi_{LT})} = 0,$$

$$F_{U(TT)}^{\cos(\phi_h-2\phi_{TT})} = \frac{2M}{Q}\mathcal{C}\Big\{\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\big(x f_{TT} D_1 - \frac{M_h}{M} h_{1TT}\frac{\tilde{H}}{z}\big) + \frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\boldsymbol{p}_T^2 - 2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)(\boldsymbol{k}_T\cdot\boldsymbol{p}_T)}{2M^2 M_h}\Big[\Big(x h_{TT} H_1^\perp - \frac{M_h}{M} g_{1TT}\frac{\tilde{G}^\perp}{z}\Big) + \Big(x h_{TT}^\perp H_1^\perp - \frac{M_h}{M} f_{1TT}\frac{\tilde{D}^\perp}{z}\Big)\Big]\Big\},$$

$$F_{U(TT)}^{\cos(3\phi_h-2\phi_{TT})} = \frac{2M}{Q}\mathcal{C}\Big\{\frac{3(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)\big(2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2\big)}{2M^3}\Big(x f_{TT}^\perp D_1 + \frac{M_h}{M} h_{1TT}^\perp\frac{\tilde{H}^\perp}{z}\Big) + \frac{4(\boldsymbol{h}\cdot\boldsymbol{k}_T)(\boldsymbol{h}\cdot\boldsymbol{p}_T)^2 - 2(\boldsymbol{h}\cdot\boldsymbol{p}_T)(\boldsymbol{k}_T\cdot\boldsymbol{p}_T) - (\boldsymbol{h}\cdot\boldsymbol{k}_T)\boldsymbol{p}_T^2}{2M^2 M_h} \times\Big[\Big(x h_{TT}^\perp H_1^\perp + \frac{M_h}{M} f_{1TT}\frac{\tilde{D}^\perp}{z}\Big) - \Big(x h_{TT} H_1^\perp + \frac{M_h}{M} g_{1TT}\frac{\tilde{G}^\perp}{z}\Big)\Big]\Big\}$$

$$F_{U(TT)}^{\cos(2\phi_{TT})} = \mathcal{C}\Big[\frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1TT} H_1^\perp\Big],$$

$$F_{U(TT)}^{\cos(4\phi_h-2\phi_{TT})} = \mathcal{C}\Big[-\Big(\frac{4(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)\boldsymbol{p}_T^2 - 8(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^3}{2M^3 M_h} + \frac{4(\boldsymbol{k}_T\cdot\boldsymbol{p}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2 - (\boldsymbol{k}_T\cdot\boldsymbol{p}_T)\boldsymbol{p}_T^2}{2M^3 M_h}\Big) h_{1TT}^\perp H_1^\perp\Big],$$

With Longitudinally Polarized Beam

$$F_{L(TT)}^{\sin(\phi_h-2\phi_{TT})} = \frac{2M}{Q}\mathcal{C}\Big\{\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(x g_{TT} D_1 + \frac{M_h}{M} h_{1TT}\frac{\tilde{E}}{z}\Big) - \frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\boldsymbol{p}_T^2 - 2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)(\boldsymbol{k}_T\cdot\boldsymbol{p}_T)}{2M^2 M_h}\Big[\Big(x e_{TT} H_1^\perp - \frac{M_h}{M} f_{1TT}\frac{\tilde{G}^\perp}{z}\Big) - \Big(x e_{TT}^\perp H_1^\perp - \frac{M_h}{M} g_{1TT}\frac{\tilde{D}^\perp}{z}\Big)\Big]\Big\},$$

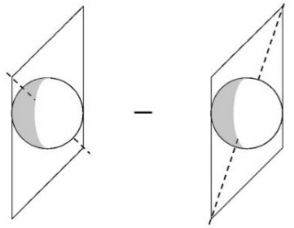
$$F_{L(TT)}^{\sin(3\phi_h-2\phi_{TT})} = \frac{2M}{Q}\mathcal{C}\Big\{-\frac{3(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)\big(2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2\big)}{2M^3}\Big(x g_{TT}^\perp D_1 + \frac{M_h}{M} h_{1TT}^\perp\frac{\tilde{E}}{z}\Big) + \frac{4(\boldsymbol{h}\cdot\boldsymbol{k}_T)(\boldsymbol{h}\cdot\boldsymbol{p}_T)^2 - 2(\boldsymbol{h}\cdot\boldsymbol{p}_T)(\boldsymbol{k}_T\cdot\boldsymbol{p}_T) - (\boldsymbol{h}\cdot\boldsymbol{k}_T)\boldsymbol{p}_T^2}{2M^2 M_h} \times\Big[\Big(x e_{TT} H_1^\perp + \frac{M_h}{M} f_{1TT}\frac{\tilde{G}^\perp}{z}\Big) + \Big(x e_{TT}^\perp H_1^\perp + \frac{M_h}{M} g_{1TT}\frac{\tilde{D}^\perp}{z}\Big)\Big]\Big\},$$

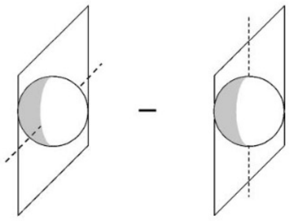
$$F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})} = \mathcal{C}\Big[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2} g_{1TT} D_1\Big],$$

J. Zhao, A. Bacchetta, S. Kumano, T. Liu, Y.-J. Zhuo, arXiv: 2058.06134

The phase-1 measurements with **transversely** tensor polarized ND_3 target

$$\frac{d\sigma_{(TT)}(l+d\to l'+h+X)}{dx\,dy\,d\phi_h\,d^2\mathbf{P}_{h\perp}} = \frac{y\alpha^2}{2(1-\epsilon)xQ^2}\left(1+\frac{\gamma^2}{2x}\right)$$

$S_{TT}^{xy} =$ 

$S_{TT}^{xx} =$ 

$$\times\Bigg[\underbrace{\left(F_{U(TT)}^{\cos(2\phi_h-2\phi_{TT})} + F_{U(TT)}^{\cos(\phi_h-2\phi_{TT})} + F_{U(TT)}^{\cos(3\phi_h-2\phi_{TT})} + F_{U(TT)}^{\cos(2\phi_{TT})} + F_{U(TT)}^{\cos(4\phi_h-2\phi_{TT})}\right)}_{\text{with unpolarized lepton beam}}$$

$$+\underbrace{\left(F_{L(TT)}^{\sin(\phi_h-2\phi_{TT})} + F_{L(TT)}^{\sin(3\phi_h-2\phi_{TT})} + F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})}\right)}_{\text{with longitudinally polarized lepton beam}}\Bigg]$$

The dominant/leading contribution
Will be from this Structure function
Whereas the other terms suppressed
By the higher twist and order $1/M_n$

$$F_{U(TT),T}^{\cos(2\phi_h-2\phi_{TT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2}f_{1TT}D_1\right]$$

Tensor-Cahn like quadrupole

$$F_{U(TT)}^{\cos(2\phi_{TT})} = \mathcal{C}\left[\frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h}h_{1TT}H_1^{\perp}\right]$$

Tensor Transversity

$$F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2}g_{1TT}D_1\right]$$

Worm gear type / helicity counter-part

Gluon Transversity TMD

$$\frac{d\sigma_{\text{Tens}}}{dx_d dy dz d\phi_h d\psi dP_{h\perp}^2} = \frac{\alpha^2}{x_d y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_d}\right)\Big\{S_{LL}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{U(LL)}^{\cos\phi_h}$$
$$+\,\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]$$
$$+\,|S_{LT}|\Big[\cos(\phi_h-\phi_{LT})\Big(F_{U(LT),T}^{\cos(\phi_h-\phi_{LT})} + \varepsilon F_{U(LT),L}^{\cos(\phi_h-\phi_{LT})}\Big)$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\Big(\cos\phi_{LT}F_{U(LT)}^{\cos\phi_{LT}} + \cos(2\phi_h-\phi_{LT})F_{U(LT)}^{\cos(2\phi_h-\phi_{LT})}\Big)$$
$$+\,\varepsilon\Big(\cos(\phi_h+\phi_{LT})F_{U(LT)}^{\cos(\phi_h+\phi_{LT})} + \cos(3\phi_h-\phi_{LT})F_{U(LT)}^{\cos(3\phi_h-\phi_{LT})}\Big)$$
$$+\,\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\Big(\sin\phi_{LT}F_{L(LT)}^{\sin\phi_{LT}} + \sin(2\phi_h-\phi_{LT})F_{L(LT)}^{\sin(2\phi_h-\phi_{LT})}\Big)$$
$$+\,\lambda_e\sqrt{1-\varepsilon^2}\sin(\phi_h-\phi_{LT})F_{L(LT)}^{\sin(\phi_h-\phi_{LT})}\Big]$$

$$F_{U(TT)}^{\cos(2\phi_{TT})} = \mathcal{C}\left[\frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h}h_{1TT}H_1^{\perp}\right]$$

$$+\,|S_{TT}|\Big[\cos(2\phi_h-2\phi_{TT})\Big(F_{U(TT),T}^{\cos(2\phi_h-2\phi_{TT})} + \varepsilon F_{U(TT),L}^{\cos(2\phi_h-2\phi_{TT})}\Big)$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\Big(\cos(\phi_h-2\phi_{TT})F_{U(TT)}^{\cos(\phi_h-2\phi_{TT})} + \cos(3\phi_h-2\phi_{TT})F_{U(TT)}^{\cos(3\phi_h-2\phi_{TT})}\Big)$$
$$+\,\varepsilon\Big(\cos(2\phi_{TT})F_{U(TT)}^{\cos(2\phi_{TT})} + \cos(4\phi_h-2\phi_{TT})F_{U(TT)}^{\cos(4\phi_h-2\phi_{TT})}\Big)$$
$$+\,\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\Big(\sin(\phi_h-2\phi_{TT})F_{L(TT)}^{\sin(\phi_h-2\phi_{TT})} + \sin(3\phi_h-2\phi_{TT})F_{L(TT)}^{\sin(3\phi_h-2\phi_{TT})}\Big)$$
$$+\,\lambda_e\sqrt{1-\varepsilon^2}\sin(2\phi_h-2\phi_{TT})F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})}\Big]\Big\},$$

With Transversely Tensor Polarized Target

J. Zhao, A. Bacchetta, S. Kumano, T. Liu, Y.-J. Zhuo, https://arxiv.org/abs/2508.06134 (2025)

Tensor-Cahn like quadrupole TMD

$$
\begin{aligned}
\frac{d\sigma_{\text{Tens}}}{dx_d dy dz d\phi_h d\psi dP_{h\perp}^2} = \frac{\alpha^2}{x_d y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_d}\right)\Big\{ S_{LL}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{U(LL)}^{\cos\phi_h} \\
+ \varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{L(LL)}^{\sin\phi_h}\Big] \\
+ |S_{LT}|\Big[\cos(\phi_h-\phi_{LT})\Big(F_{U(LT),T}^{\cos(\phi_h-\phi_{LT})} + \varepsilon F_{U(LT),L}^{\cos(\phi_h-\phi_{LT})}\Big) \\
+ \sqrt{2\varepsilon(1+\varepsilon)}\Big(\cos\phi_{LT} F_{U(LT)}^{\cos\phi_{LT}} + \cos(2\phi_h-\phi_{LT}) F_{U(LT)}^{\cos(2\phi_h-\phi_{LT})}\Big) \\
+ \varepsilon\Big(\cos(\phi_h+\phi_{LT}) F_{U(LT)}^{\cos(\phi_h+\phi_{LT})} + \cos(3\phi_h-\phi_{LT}) F_{U(LT)}^{\cos(3\phi_h-\phi_{LT})}\Big) \\
+ \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\Big(\sin\phi_{LT} F_{L(LT)}^{\sin\phi_{LT}} + \sin(2\phi_h-\phi_{LT}) F_{L(LT)}^{\sin(2\phi_h-\phi_{LT})}\Big) \\
+ \lambda_e\sqrt{1-\varepsilon^2}\sin(\phi_h-\phi_{LT}) F_{L(LT)}^{\sin(\phi_h-\phi_{LT})}\Big] \\
+ |S_{TT}|\Big[\cos(2\phi_h-2\phi_{TT})\Big(F_{U(TT),T}^{\cos(2\phi_h-2\phi_{TT})} + \varepsilon F_{U(TT),L}^{\cos(2\phi_h-2\phi_{TT})}\Big) \\
+ \sqrt{2\varepsilon(1+\varepsilon)}\Big(\cos(\phi_h-2\phi_{TT}) F_{U(TT)}^{\cos(\phi_h-2\phi_{TT})} + \cos(3\phi_h-2\phi_{TT}) F_{U(TT)}^{\cos(3\phi_h-2\phi_{TT})}\Big) \\
+ \varepsilon\Big(\cos(2\phi_{TT}) F_{U(TT)}^{\cos(2\phi_{TT})} + \cos(4\phi_h-2\phi_{TT}) F_{U(TT)}^{\cos(4\phi_h-2\phi_{TT})}\Big) \\
+ \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\Big(\sin(\phi_h-2\phi_{TT}) F_{L(TT)}^{\sin(\phi_h-2\phi_{TT})} + \sin(3\phi_h-2\phi_{TT}) F_{L(TT)}^{\sin(3\phi_h-2\phi_{TT})}\Big) \\
+ \lambda_e\sqrt{1-\varepsilon^2}\sin(2\phi_h-2\phi_{TT}) F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})}\Big]\Big\},
\end{aligned}
$$

With Transversely Tensor Polarized Target

A minor typo in the original paper

ϕ_{TT}

$$F_{U(TT),T}^{\cos(2\phi_h-2\phi_{LT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{M^2} f_{1TT} D_1\right]$$

J. Zhao, A. Bacchetta, S. Kumano, T. Liu, Y.-J. Zhuo, https://arxiv.org/abs/2508.06134 (2025)

Tensor-Cahn like quadrupole TMD

$$\frac{d\sigma_{\text{Tens}}}{dx_d dy dz d\phi_h d\psi dP_{h\perp}^2} = \frac{\alpha^2}{x_d y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_d}\right) \Big\{ S_{LL} \Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{U(LL)}^{\cos\phi_h}$$

$$+ \varepsilon \cos(2\phi_h)\, F_{U(LL)}^{\cos 2\phi_h} + \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{L(LL)}^{\sin\phi_h} \Big]$$

$$+ |S_{LT}| \Big[\cos(\phi_h - \phi_{LT}) \Big(F_{U(LT),T}^{\cos(\phi_h-\phi_{LT})} + \varepsilon F_{U(LT),L}^{\cos(\phi_h-\phi_{LT})} \Big)$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} \Big(\cos\phi_{LT} F_{U(LT)}^{\cos\phi_{LT}} + \cos(2\phi_h - \phi_{LT}) F_{U(LT)}^{\cos(2\phi_h-\phi_{LT})} \Big)$$

$$+ \varepsilon \Big(\cos(\phi_h + \phi_{LT}) F_{U(LT)}^{\cos(\phi_h+\phi_{LT})} + \cos(3\phi_h - \phi_{LT}) F_{U(LT)}^{\cos(3\phi_h-\phi_{LT})} \Big)$$

$$+ \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \Big(\sin\phi_{LT} F_{L(LT)}^{\sin\phi_{LT}} + \sin(2\phi_h - \phi_{LT}) F_{L(LT)}^{\sin(2\phi_h-\phi_{LT})} \Big)$$

$$+ \lambda_e \sqrt{1-\varepsilon^2}\, \sin(\phi_h - \phi_{LT}) F_{L(LT)}^{\sin(\phi_h-\phi_{LT})} \Big]$$

$$+ |S_{TT}| \Big[\cos(2\phi_h - 2\phi_{TT}) \Big(F_{U(TT),T}^{\cos(2\phi_h-2\phi_{TT})} + \varepsilon F_{U(TT),L}^{\cos(2\phi_h-2\phi_{TT})} \Big)$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} \Big(\cos(\phi_h - 2\phi_{TT}) F_{U(TT)}^{\cos(\phi_h-2\phi_{TT})} + \cos(3\phi_h - 2\phi_{TT}) F_{U(TT)}^{\cos(3\phi_h-2\phi_{TT})} \Big)$$

$$+ \varepsilon \Big(\cos(2\phi_{TT}) F_{U(TT)}^{\cos(2\phi_{TT})} + \cos(4\phi_h - 2\phi_{TT}) F_{U(TT)}^{\cos(4\phi_h-2\phi_{TT})} \Big)$$

$$+ \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \Big(\sin(\phi_h - 2\phi_{TT}) F_{L(TT)}^{\sin(\phi_h-2\phi_{TT})} + \sin(3\phi_h - 2\phi_{TT}) F_{L(TT)}^{\sin(3\phi_h-2\phi_{TT})} \Big)$$

$$+ \lambda_e \sqrt{1-\varepsilon^2}\, \sin(2\phi_h - 2\phi_{TT}) F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})} \Big\},$$

$$F_{L(TT)}^{\sin(2\phi_h-2\phi_{TT})} = \mathcal{C}\Big[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{M^2} g_{1TT} D_1 \Big]$$

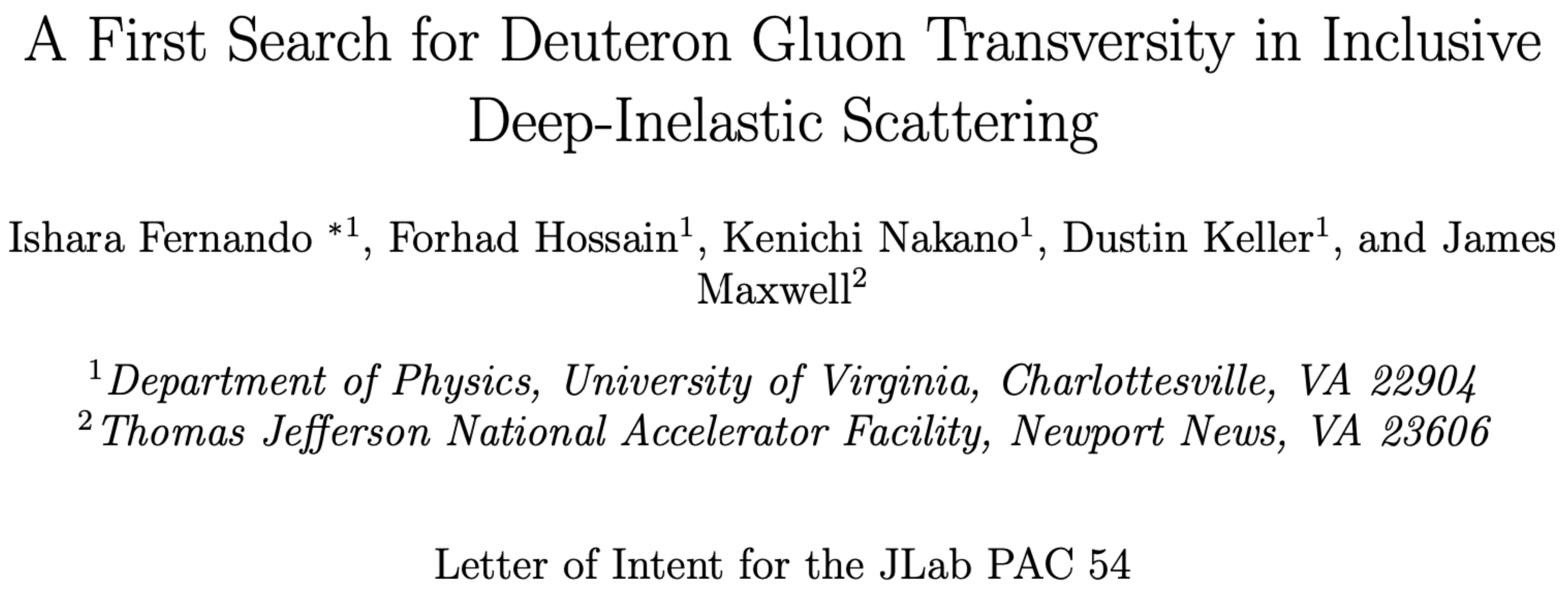
With Transversely Tensor Polarized Target

J. Zhao, A. Bacchetta, S. Kumano, T. Liu, Y.-J. Zhuo, https://arxiv.org/abs/2508.06134 (2025)

Current plan (maybe revised if needed)

- We selected the “Gluon Transversity” to start with the series of Tensor SIDIS experiments with “Transversely Tensor Polarized Target”
- As we we going through the planning, we realized that the “Gluon Transversity PDF” with DIS is a lower hanging fruit.
- A first step toward measuring Δ(x,Q2) experimentally was already outlined in a Letter of Intent using a transversely tensor-polarized NH3 target at Jefferson Lab (J. Maxwell et al), representing the pioneering effort to access this quantity in a nitrogen spin-1 nucleus.
- On the other hand, g2p2 experiment’s setup is relatively closer: additions are the “magnetic field transverse-side-way” orientation with the corresponding chicane adjustment (rotation)
- While using SHMS for the DIS events, we could utilize the HMS spectrometer to collect data for the SIDIS proposal

Gluon Transversity PDF


A First Search for Deuteron Gluon Transversity in Inclusive Deep-Inelastic Scattering

Ishara Fernando *[1], Forhad Hossain[1], Kenichi Nakano[1], Dustin Keller[1], and James Maxwell[2]

[1] *Department of Physics, University of Virginia, Charlottesville, VA 22904*
[2] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606*

Letter of Intent for the JLab PAC 54

https://www.jlab.org/exp_prog/proposals/26/LOI12-26-006.pdf

With the limited time, we were able to submit a LOI this time with the anticipation of a full proposal next year!

Gluon Transversity PDF

$$\frac{\mathrm{d}\sigma_i}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi} = \mathcal{K}(x,Q^2,y)\left[\mathcal{U}(x,Q^2,y) + S_{LL}^{(i)}\mathcal{T}_{LL}(x,Q^2,y) + S_{TT}^{xx,(i)}\mathcal{T}_{TT}(x,Q^2,y,\phi)\right]$$

$$\mathcal{U}(x,Q^2,y) = xy^2F_1(x,Q^2) + (1-y)F_2(x,Q^2) \qquad \mathcal{T}_{TT}(x,Q^2,y,\phi) = -\frac{x(1-y)}{2}\,\Delta(x,Q^2)\cos 2\phi$$

- The central experimental idea is to form the difference of two orthogonal tensor polarized target cross-sections

$$\frac{\mathrm{d}\Delta\sigma_{xy}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi} \equiv \frac{\mathrm{d}\sigma(E_x)}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi} - \frac{\mathrm{d}\sigma(E_y)}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi}$$

$$\frac{\mathrm{d}\Delta\sigma_{xy}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi} \equiv \frac{\mathrm{d}\sigma(E_x)}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi} - \frac{\mathrm{d}\sigma(E_y)}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi} = \mathcal{K}(x,Q^2,y)\,x(1-y)\,\Delta(x,Q^2)\cos 2\phi$$

$$\frac{\mathrm{d}\Delta\sigma_{xy}^{\mathrm{raw}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi} = f\,P_{TT}^{\mathrm{eff}}\,\mathcal{K}(x,Q^2,y)\,x(1-y)\,\Delta(x,Q^2)\cos 2\phi$$

Gluon Transversity PDF

The cross-section difference is the primary observable. In each accepted kinematic bin, or for each SHMS setting after acceptance correction, the measured difference will be fit to

$$\Delta\sigma_{xy}(\phi) = C_0 + C_2 \cos 2\phi + S_2 \sin 2\phi$$

The gluon-transversity signal is C_2. The nuisance coefficients C_0 and S_2 are diagnostic: a nonzero C_0 indicates an imperfect relative normalization or residual common tensor term, while a nonzero S_2 indicates angular misalignment, field-map leakage, or acceptance effects. For a narrow bin,

$$\Delta(x, Q^2) = \frac{C_2}{f P_{TT}^{\mathrm{eff}}\, \mathcal{K}(x, Q^2, y) x(1-y)}$$

For the finite SHMS acceptance, the extracted coefficient is the acceptance-weighted quantity

$$C_2^{\mathrm{bin}} = f P_{TT}^{\mathrm{eff}} \left\langle \mathcal{K}(x, Q^2, y) x(1-y) \Delta(x, Q^2) \right\rangle_{\mathrm{SHMS}}$$

The angular coverage of a single-arm Hall C spectrometer is limited compared with a solenoidal detector. Nevertheless, the vertical and horizontal target-field configurations, the SHMS vertical angular acceptance, and possible repeated settings can provide effective angle information.

$$\Delta(x, Q^2) = -\frac{\alpha_s(Q^2)}{2\pi}\, \mathrm{Tr}\, Q^2\, x^2 \int_x^1 \frac{\mathrm{d}y}{y^3}\, \delta G_d(y, Q^2)$$

Here we used the Spectator model for the “Gluon Transversity” [X. Xie et al 2603.15224] to estimate the rates

Spectator Model

Reference: Xiupeng Xie, Dian-Yong Chen, Zhun Lu https://arxiv.org/abs/2603.15224

In the spectator model, the deuteron state $|P, S, T\rangle$

- momentum: P
- Spin Vector: S
- Spin Tensor: T

Emitted gluon with momentum 'k'

On-shell spectator particle of spin-1, denoted by |P – k⟩, with momentum 'P – k' and mass 'M_s'.

The tree-level gluon-gluon correlator,

$$\Phi^{ij}(x, \boldsymbol{k}_T; S, T) = \frac{1}{xP^+}\frac{1}{(2\pi)^3}\frac{1}{2(1-x)P^+} \times \left[\overline{\mathcal{M}}^i_{0a}(x, \boldsymbol{k}_T; S, T)\,\mathcal{M}^j_{0a}(x, \boldsymbol{k}_T; S, T)\right]$$

$$\begin{aligned} &\mathcal{M}^j_{0a}(x, \boldsymbol{k}_T; S, T) \\ &= \langle P-k \,|F_a^{+j}|\, P, S, T\rangle \\ &= \epsilon_c^{*\nu}(P-k, \lambda_S)\, G_{ab}^{j\alpha}(k,k)\, \mathcal{Y}_{\mu\nu\alpha,bc}\epsilon^{\mu}(P,\lambda) \end{aligned}$$

polarization vector of the spectator — deuteron polarization vector

Inside the spectator loop the struck nucleon is off its mass shell. Its virtuality is

$$k^2_{\text{off}}(x, k_\perp^2, M_s) = -\frac{k_\perp^2}{1-x} - \frac{x\,M_s^2}{1-x} + x\,M^2,$$

Three deuteron-gluon spectator couplings (exponential → regularize divergences)

$$g_i(x, k_\perp^2, M_s) = \kappa_i \exp\left[\frac{k^2_{\text{off}}(x, k_\perp^2, M_s)}{\Lambda_S^2}\right], \quad i = 1, 2, 3,$$

→ tensor polarized TMDs $F_{(T)}^{(g_{1,3})}$

Since $k^2_{\text{off}} < 0$ for physical kinematics, the exponential ensures power-law suppression at large $k_\perp$ and large M_s.

Spectator Model

The spectator mass is weighted by a spectral function,

$$\rho(M_S) = \mu^{2a} \left[\frac{A}{B + \mu^{2b}} + \frac{C}{\pi\sigma} \exp\left(-\frac{(M_S - D)^2}{\sigma^2} \right) \right]$$

$$\mu^2 = M_S^2 - M^2$$

So that a TMD F is obtained from

$$F\left(x, \boldsymbol{k}_T^2\right) = \int_M^\infty dM_S \;\rho\left(M_S\right) F\left(x, \boldsymbol{k}_T^2; M_S\right)$$

Free (fit) parameters

Parameter	Mean	Replica 60
κ_1	0.713±0.604	0.350
κ_2	0.334±0.303	0.149
κ_3	15.56±6.06	12.88
Λ_S	1.34±0.18	1.36
a	1.564±1.442	1.529
b	10.14±5.66	5.93
A	138±141	221
B	5.86±6.65	6.42
C	305±164	359
D	1.19±0.55	1.31
σ	0.683±0.226	0.674

To determine these parameters, performed fit to the integrated unpolarized 'gluon' TMD

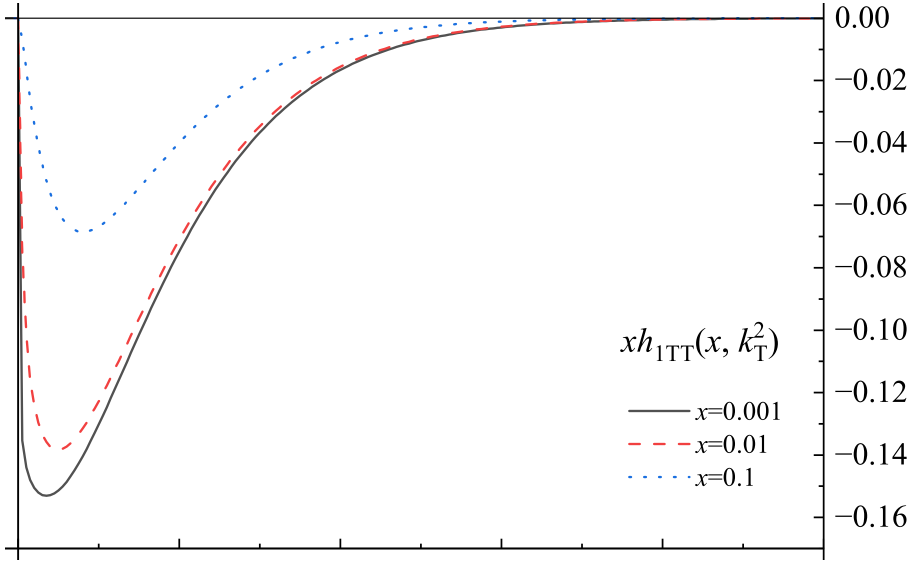
$$f_1\left(x\right) = \int d\boldsymbol{k}_T^2 \;f_1\left(x, \boldsymbol{k}_T^2\right)$$

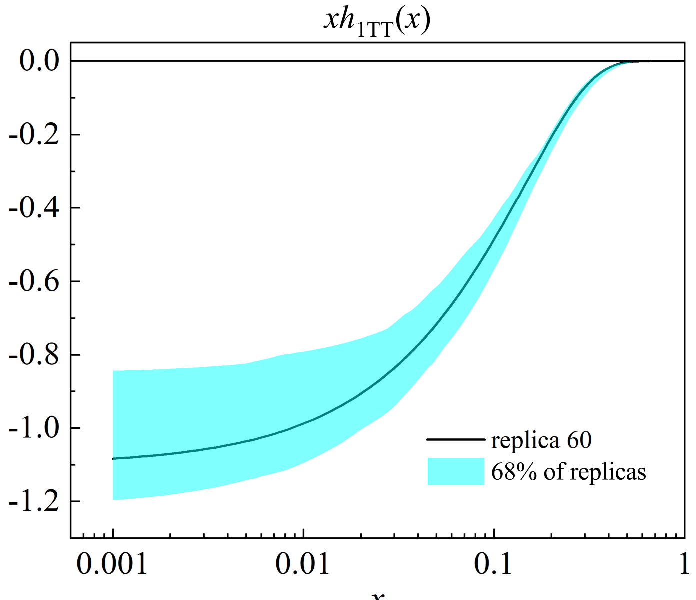
Assumptions

- Used nNNPDF1.0 at fixed hard scale 2 GeV
- Used the range 0.001 < x < 1
- Employed bootstrap method with Gaussian noise (with 100 replicas)

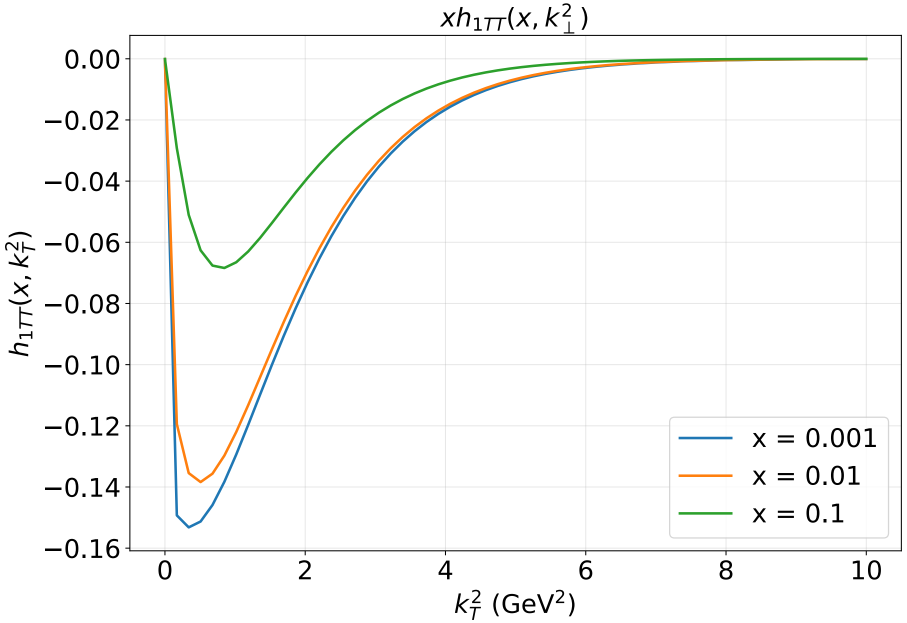
Reference: Xiupeng Xie, Dian-Yong Chen, Zhun Lu https://arxiv.org/abs/2603.15224

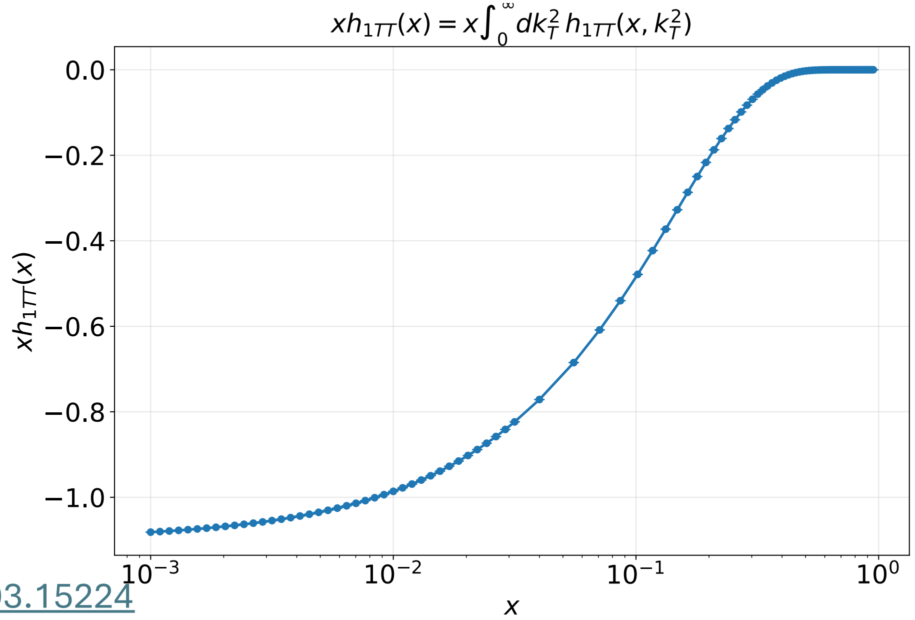
Spectator Model





Reproduced Plots





Reference: Xiupeng Xie, Dian-Yong Chen, Zhun Lu https://arxiv.org/abs/2603.15224

Spectator Model

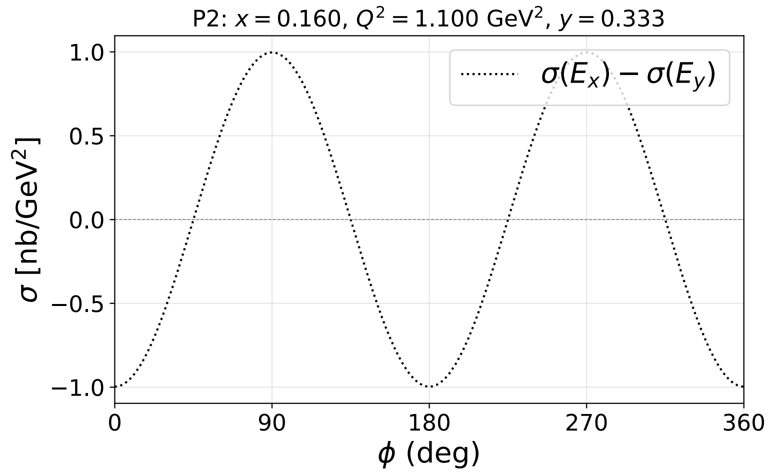
$$
\begin{aligned}
& h_{1TT}\left(x, \boldsymbol{k}_T^2\right) \\
=& \left(\frac{2k_T^{ij}}{S_{TT}^{\alpha\beta} k_{T\alpha\beta}} - \frac{\boldsymbol{k}_T^4 S_{TT}^{\alpha\beta} S_{TT\alpha\beta}}{2S_{TT}^{\alpha\beta} k_{T\alpha\beta} - \boldsymbol{k}_T^4 S_{TT}^{\alpha\beta} S_{TT\alpha\beta}} \left(\frac{S_{TT}^{ij}}{S_{TT}^{\alpha\beta} S_{TT\alpha\beta}} + \frac{2k_T^{ij\alpha} k_{T\alpha}}{\boldsymbol{k}_T^2 S_{TT}^{\alpha\beta} k_{T\alpha\beta}} \right) \right) \Phi_{TT}^{ij}\left(x, \boldsymbol{k}_T\right) \\
=& \Big\{ 4g_2 M^2 \boldsymbol{k}_T^2 \Big[g_3 \Big(\boldsymbol{k}_T^2 \left(M^2(3x-1)(x-1)^2 + (x(2x-1)+1) M_S^2 \right) + (2x-1)\boldsymbol{k}_T^4 + x\left(M_S^2 - M^2(x-1)^2 \right)^2 \Big) \\
& - 4g_1 M^2 (x-1) \left((2x-1)\left(\boldsymbol{k}_T^2 + x M_S^2 \right) + M^2 x (x-1)^2 \right) \Big] + \boldsymbol{k}_T^4 \Big[-2g_3 M_S^2 \left(M^2(x-1)\left(g_3(x-1) + 4g_1 \right) - g_3 \boldsymbol{k}_T^2 \right) \\
& + \left(M^2(x-1)\left(4g_1 - g_3(x-1) \right) - g_3 \boldsymbol{k}_T^2 \right)^2 + g_3^2 M_S^4 \Big] + 4g_2^2 M^4 \Big[2x M_S^2 \left((2(x-1)x+1)\boldsymbol{k}_T^2 - M^2(x-1)^2 x \right) \\
& + \left((2x-1)\boldsymbol{k}_T^2 + M^2 x (x-1)^2 \right)^2 + x^2 M_S^4 \Big] \Big\} \times \left\{ 256\pi^3 M^4 (x-1) x M_S^2 \left(\boldsymbol{k}_T^2 + x\left(M^2(x-1) + M_S^2 \right) \right)^2 \right\}^{-1}
\end{aligned}
$$

$$h_{1TT}(x)$$

$$\Delta(x, Q^2) = -\frac{\alpha_s(Q^2)}{2\pi} \, \mathrm{Tr}\, Q^2 x^2 \int_x^1 \frac{\mathrm{d}y}{y^3} \, \delta G_d(y, Q^2)$$

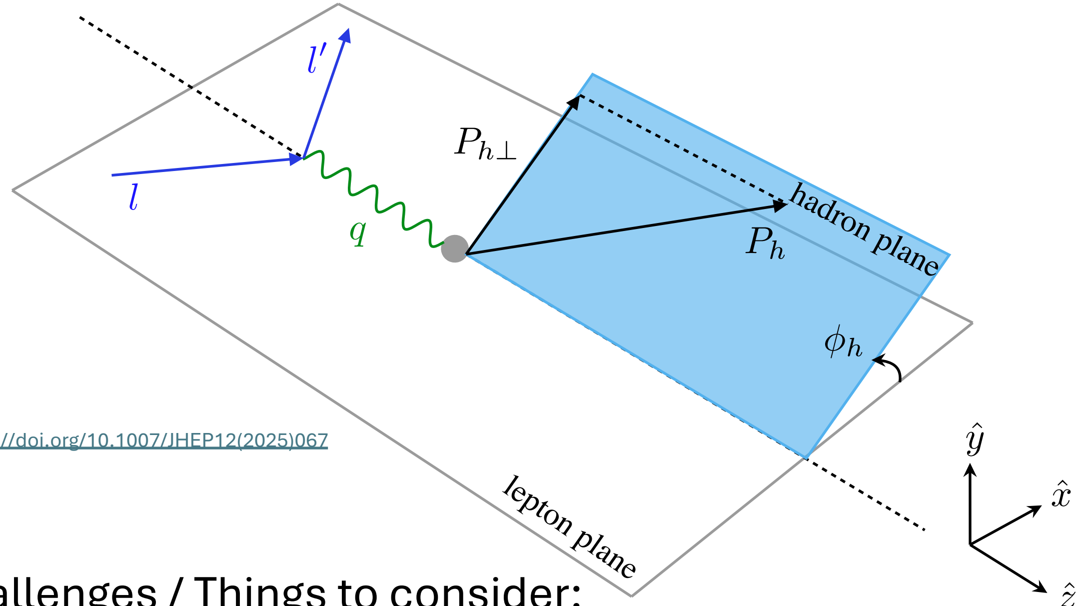
$$\frac{\mathrm{d}\Delta\sigma_{xy}^{\mathrm{raw}}}{\mathrm{d}x\, \mathrm{d}y\, \mathrm{d}\phi} = f P_{TT}^{\mathrm{eff}} \, \mathcal{K}(x, Q^2, y)\, x(1-y)\, \Delta(x, Q^2) \cos 2\phi$$

See Kenichi Nakano's talk for More details!



Gluon Transversity TMD

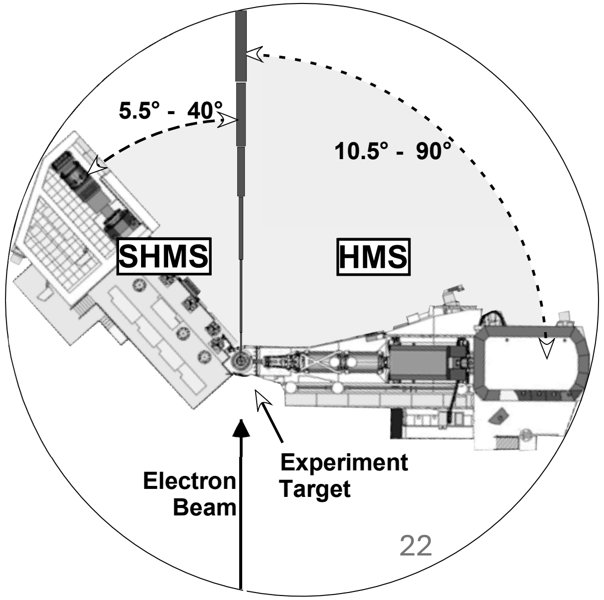
$$F_{U(TT)}^{\cos(2\phi_{TT})} = \mathcal{C}\left[\frac{\boldsymbol{k}_T \cdot \boldsymbol{p}_T}{M M_h} h_{1TT} H_1^{\perp}\right]$$



https://doi.org/10.1007/JHEP12(2025)067

Parameter	*HMS Performance*	*SHMS Specification*
Range of Central Momentum	0.4 to 7.4 GeV/c	2 to 11 GeV/c
Momentum Acceptance	±10%	-10% to +22%
Momentum Resolution	0.1% – 0.15%	0.03% – 0.08%
Scattering Angle Range	10.5° to 90°	5.5° to 40°
Target Length Accepted at 90°(HMS)/45° (SHMS)	10 cm	25 cm
Horizontal Angle Acceptance	±32 mrad	±18 mrad
Vertical Angle Acceptance	±85 mrad	±45 mrad
Solid Angle Acceptance	8.1 msr	4 msr
Horizontal Angle Resolution	0.8 mrad	0.5 – 1.2 mrad
Vertical Angle Resolution	1.0 mrad	0.3 – 1.1 mrad
Target resolution (y_{tar})	0.3 cm	0.1 - 0.3 cm
Maximum Event Rate	4–5 kHz	4–5 kHz
Max. Flux within Acceptance	~ 5 MHz	~ 5 MHz
e/h Discrimination	>1000:1 at 98% efficiency	>1000:1 at 98% efficiency
π/K Discrimination	100:1 at 95% efficiency	100:1 at 95% efficiency

https://arxiv.org/abs/2503.08706

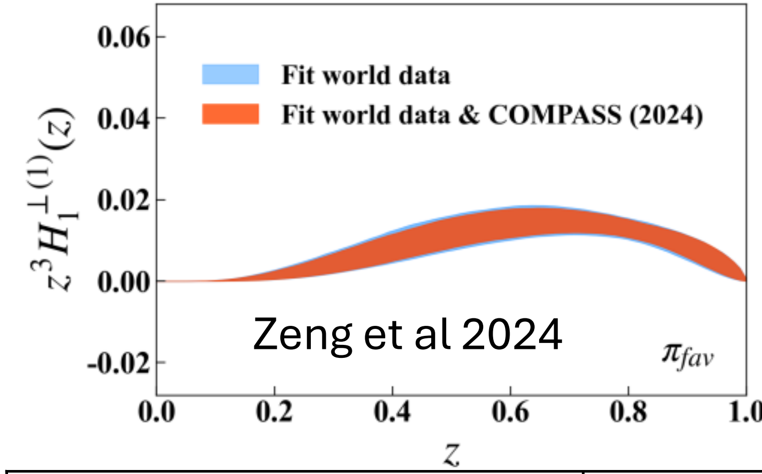


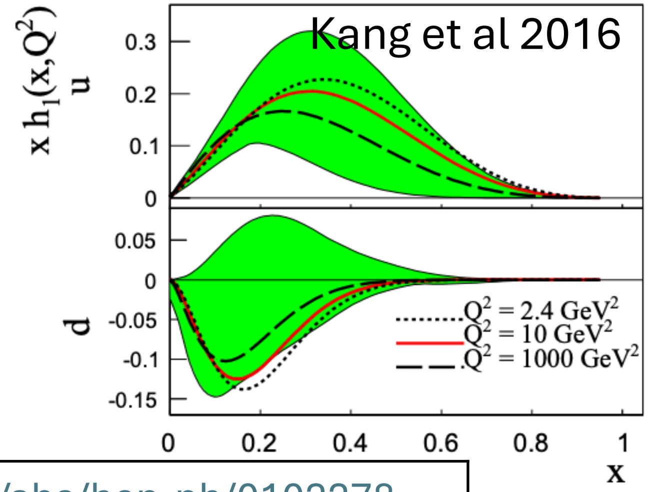
Challenges / Things to consider:

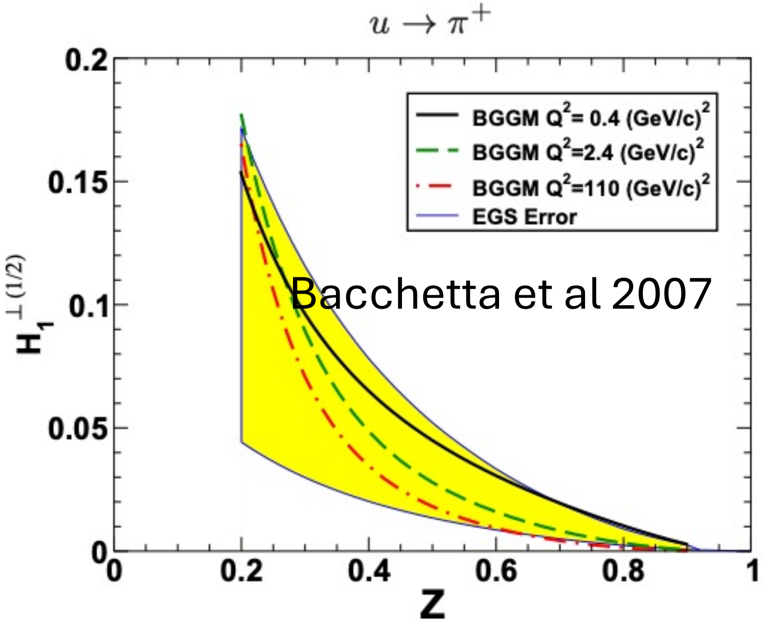
- We will need to take data with two orthogonal target orientations
- Chicane magnet will be installed for g2p2 but we will need it to be rotated by 90-deg (got some feedback from Jay Benesch)
- Currently HMS can be used, but there maybe a possibility of having SBS
- Explore other target orientations (orthogonal) to utilize the use of HMS
- Use an easily movable hadron detector (similar to Neutral Particle Detector)
- The other option is to build a detector that can be moved around

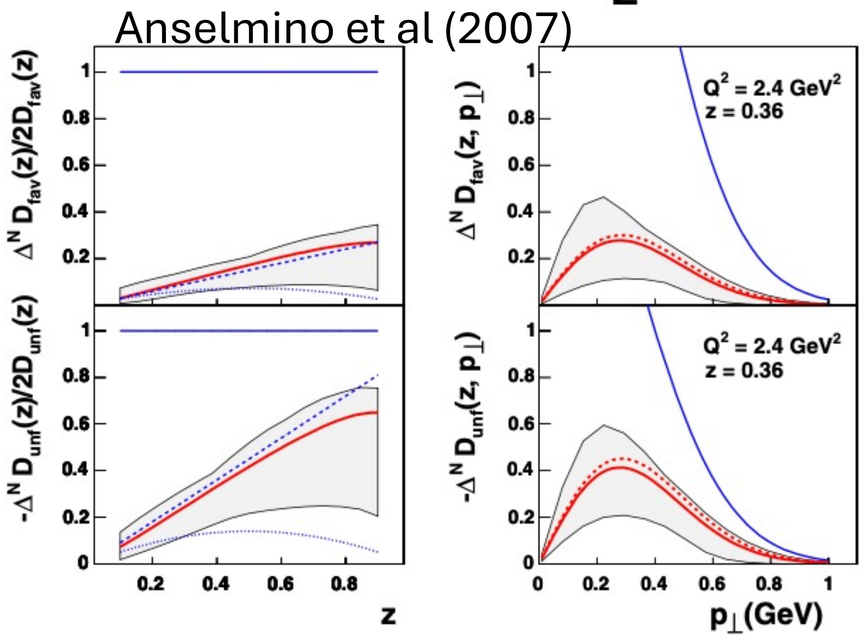
$$F_{U(TT)}^{\cos(2\phi_{TT})} = \mathcal{C}\left[\frac{\boldsymbol{k}_T \cdot \boldsymbol{p}_T}{M M_h} h_{1TT} H_1^{\perp}\right]$$

Collin’s function extractions to date…









Bacchetta et al 2001	https://arxiv.org/abs/hep-ph/0102278
Bacchetta et al 2002	https://arxiv.org/abs/hep-ph/0201091
Bacchetta et al 2003	https://arxiv.org/abs/hep-ph/0307282
Amrath et al 2005	https://arxiv.org/abs/hep-ph/0504124
Bacchetta et al 2007	https://arxiv.org/abs/0707.3372
Anselmino et al 2007	https://arxiv.org/abs/hep-ph/0701006
Kang et al 2016	https://arxiv.org/abs/1505.05589
Zeng et al 2022	https://arxiv.org/abs/2208.14620
Zeng et al 2024	https://arxiv.org/abs/2412.18324

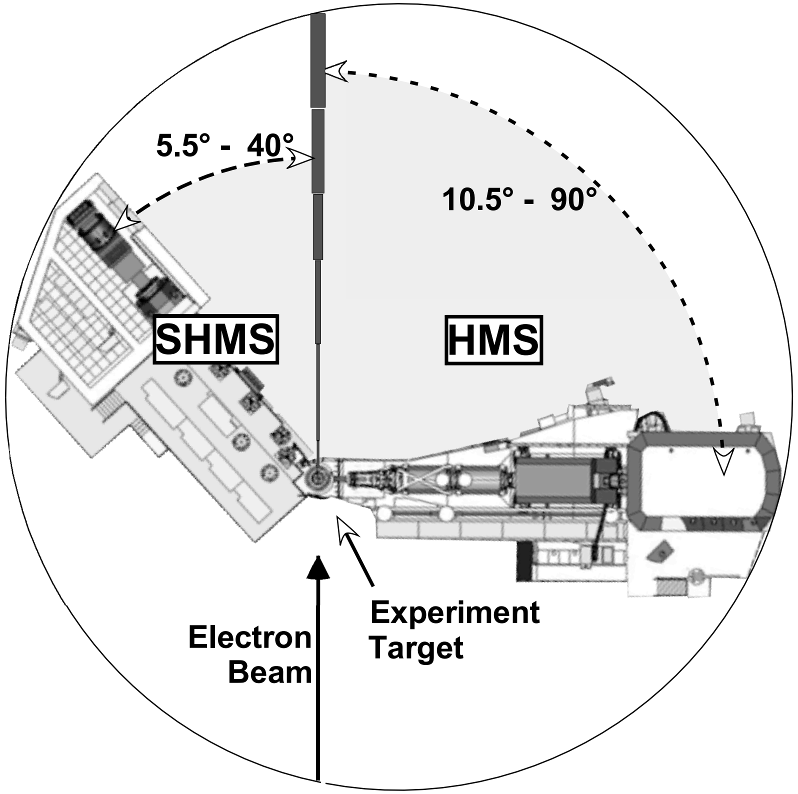
More TMDs to be probed…

Tensor-Cahn like quadrupole

$$F_{L(TT)}^{\sin(2\phi_h - 2\phi_{TT})} = \mathcal{C}\left[- \frac{2(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{M^2} g_{1TT} D_1 \right]$$

Worm gear type / helicity counter-part

$$F_{U(TT),T}^{\cos(2\phi_h - 2\phi_{TT})} = \mathcal{C}\left[- \frac{2(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{M^2} f_{1TT} D_1 \right]$$

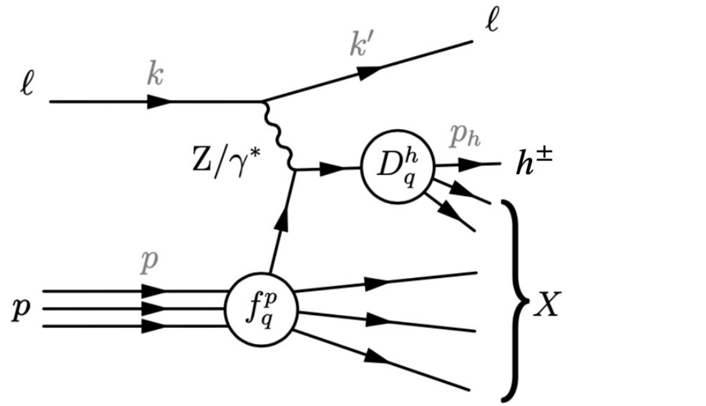


<u>Things to consider</u>

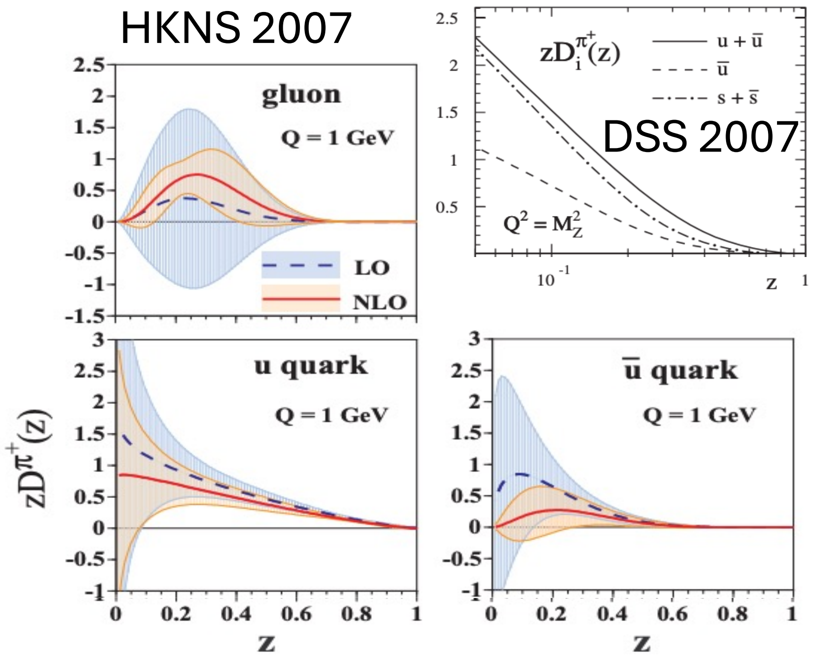
- It is possible to propose an experiment to measure both structure functions
- One requires ‘longitudinally polarized’ electron beam, while the other one
- The other one requires an ‘unpolarized’ electron beam (which can be constructed with two opposite helicity configurations of the beam)
- Faces the same challenges mentioned on the previous slide

Collinear Fragmentation function (D_1) extractions to date…

DSS (de Florian, Sassot,Stratmann) 2007	https://arxiv.org/abs/hep-ph/0703242
HKNS (Hirai, Kumano, Nagai, Sudoh) 2007	https://arxiv.org/abs/hep-ph/0702250
AKK08 2008	https://arxiv.org/abs/0807.2214
DSS 2014	https://arxiv.org/abs/1410.6027
NNFF 2017 and 2018	https://arxiv.org/abs/1706.07049 https://arxiv.org/abs/1807.03310
MAPFF	https://arxiv.org/abs/2105.08725
JAM19/JAM20/JAM22	https://arxiv.org/abs/1905.03788 https://arxiv.org/abs/2101.04664 https://arxiv.org/abs/2202.03372
NPC 2025	https://arxiv.org/abs/2503.21311 https://arxiv.org/abs/2502.17837 https://arxiv.org/abs/2407.04422
Borsa et al 2024	https://arxiv.org/abs/2110.14015



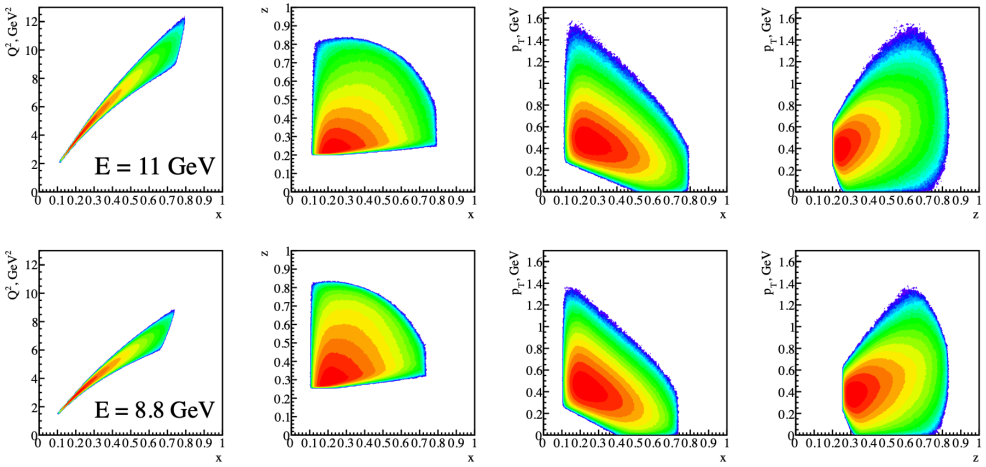
https://indico.jlab.org/event/498/contributions/9474/attachments/7655/10681/090322_CPHI22_FF.pdf



The prospective (tentative) plan with transversely tensor polarized targets

by Ishara Fernando, Forhad Hossain, Kenichi Nakano & Dustin Keller
(for the UVA Spin-Physics Group)

Pic credits G. Cates (UVA)



First Generation Tensor Experiments @ Hall C

Using standard DNP temps and intensity: 1K, 5T and 100nA

★ Gluon Transversity PDF with DIS (LOI submitted): Proposal for 2027

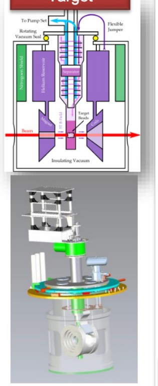
★ $$F_{U(TT)}^{\cos(2\phi_{TT})} = \mathcal{C}\left[\frac{\boldsymbol{k}_T \cdot \boldsymbol{p}_T}{M M_h} h_{1TT} H_1^{\perp}\right]$$

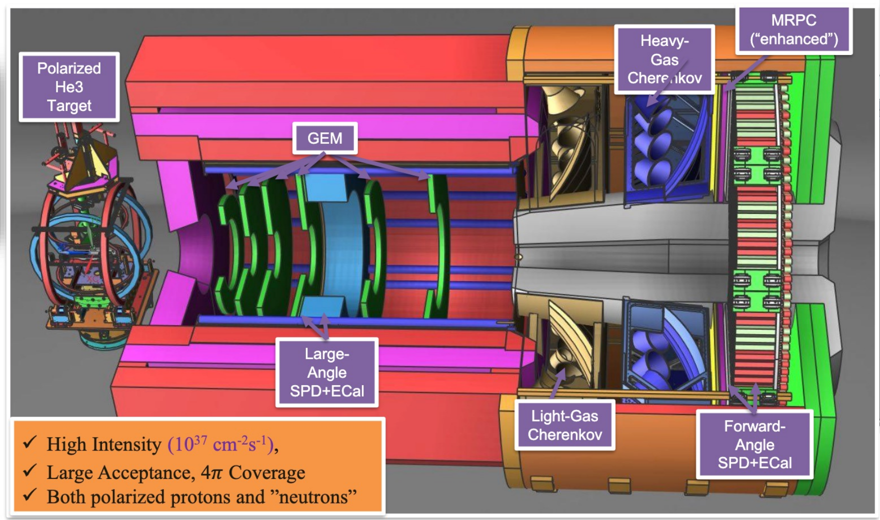
To run sequentially after the data taking for $F_{U,(LL)}$

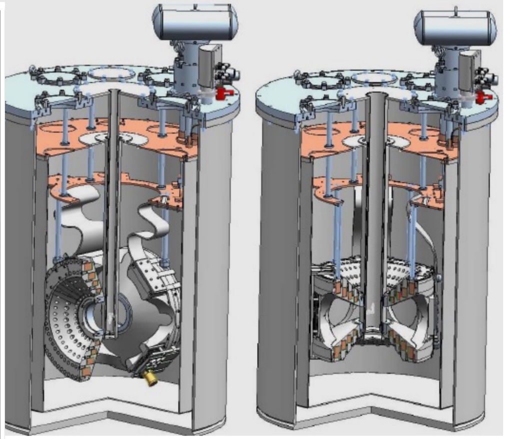
★ $$F_{U(TT),T}^{\cos(2\phi_h - 2\phi_{TT'})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{M^2} f_{1TT} D_1\right]$$

★ $$F_{L(TT)}^{\sin(2\phi_h - 2\phi_{TT})} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{M^2} g_{1TT} D_1\right]$$

Polarized NH3 (DNP) Target







Pic credits C. Keith (JLab)

Second Generation Tensor Experiments

Using lower DNP temps, higher field, and lower intensity: 0.5 K, B > 6.5 T, and 30nA

See Dustin's Talk

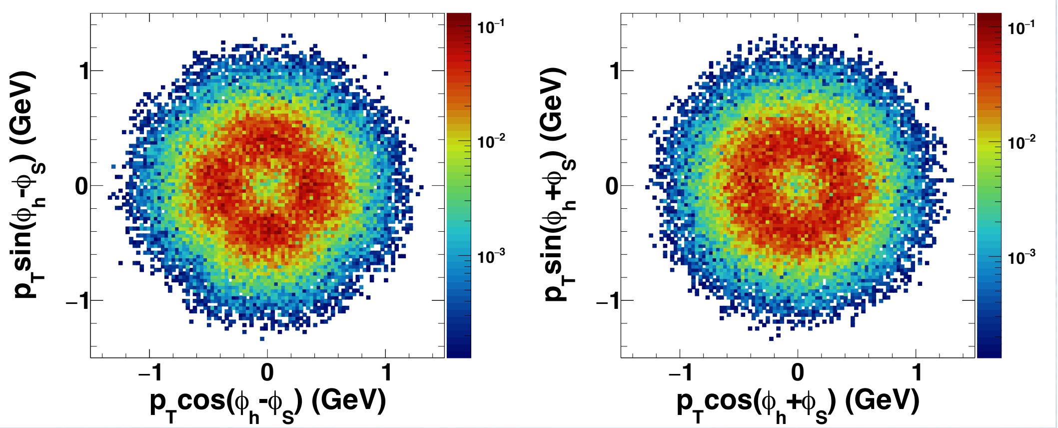
Potentially:
@ Hall A (with SoLID),
and @ Hall B (coordinating with CLAS Colaboration)

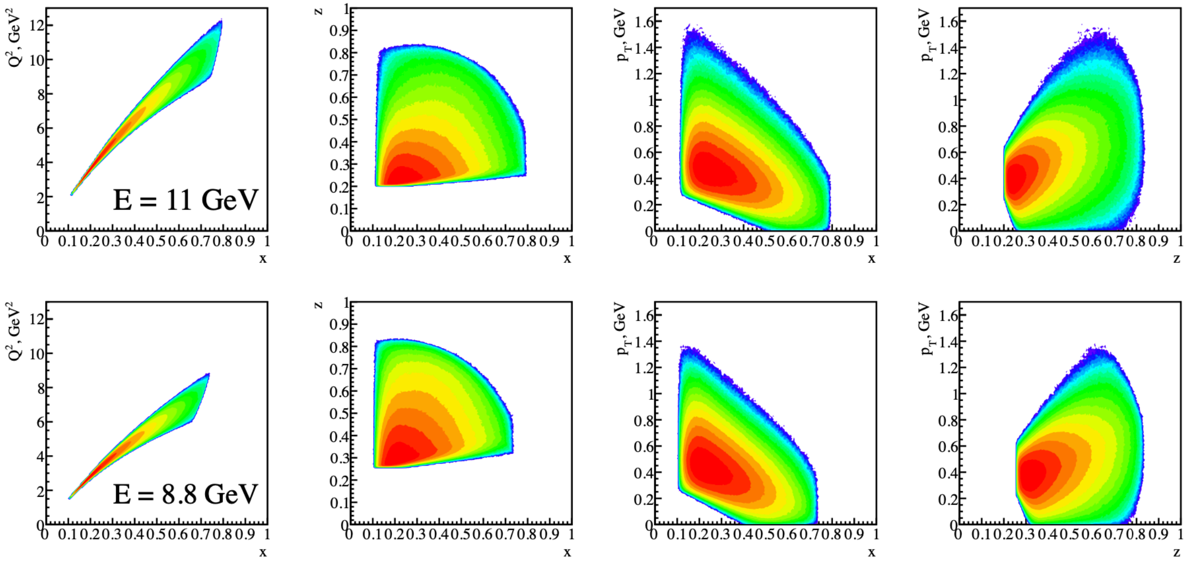
Thank you

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

Backup Slides

SBS SIDIS Kinematic Coverage





Pic credits G. Cates (UVA)

https://indico.jlab.org/event/450/contributions/8688/attachments/7234/9981/cates_sbs_sidis_jeopardy_pac49.pdf

RGH Status

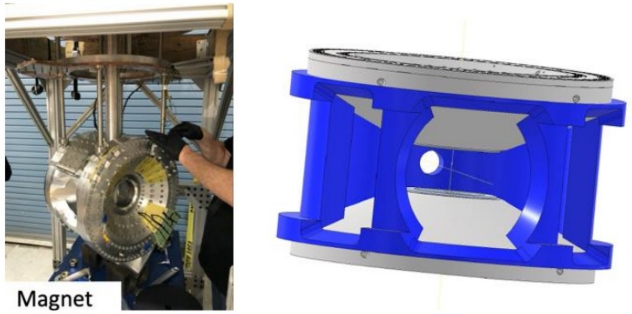
RGH Target & Magnet

Most viable solution to prioritize physics

Consolidated dynamically polarized NH_3 technology

Designed based on already successful realizations

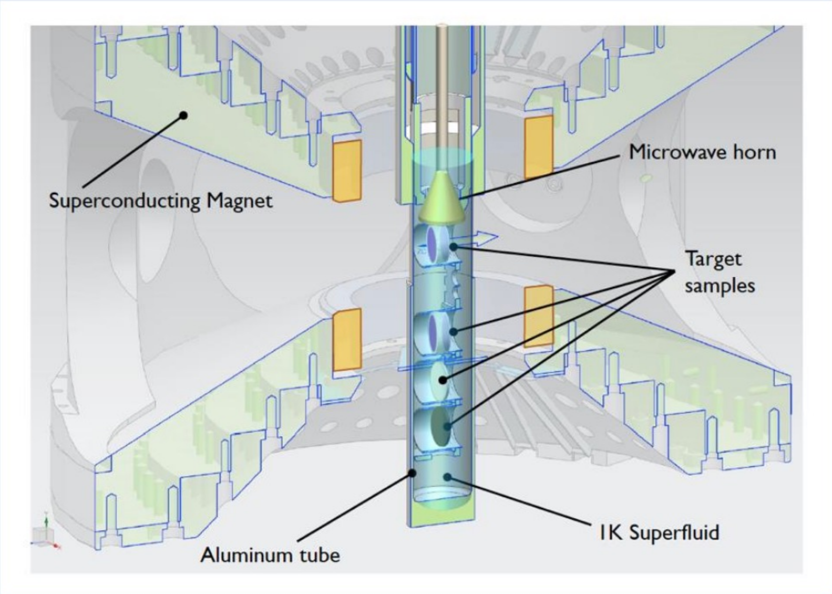
Hall-A G2p-Gep target (replica optimized for HTCC)
Hall-C E12-15-005 magnet (replica optimized for recoil detection)

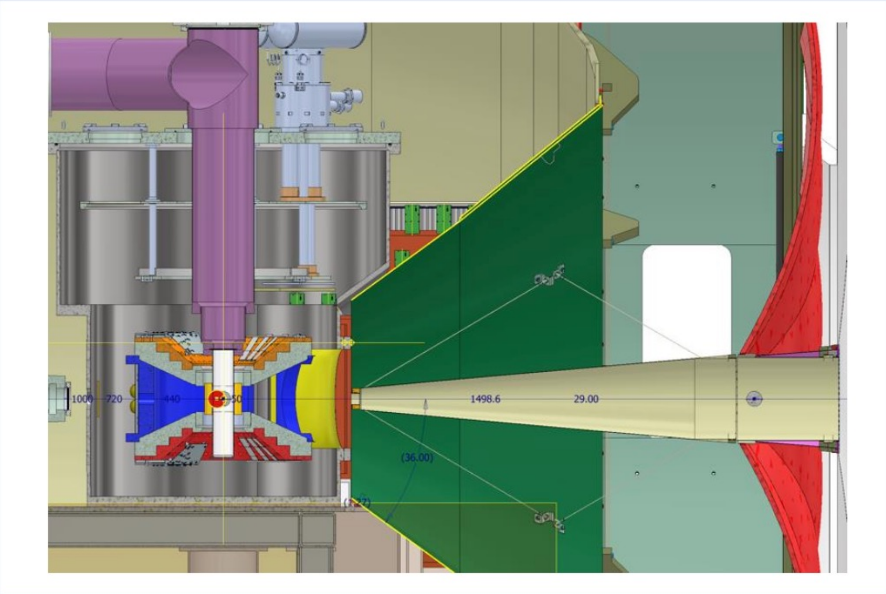


5T dipole acceptance:

$\pm$ 25° vertical

$\pm$ 65° horizontal





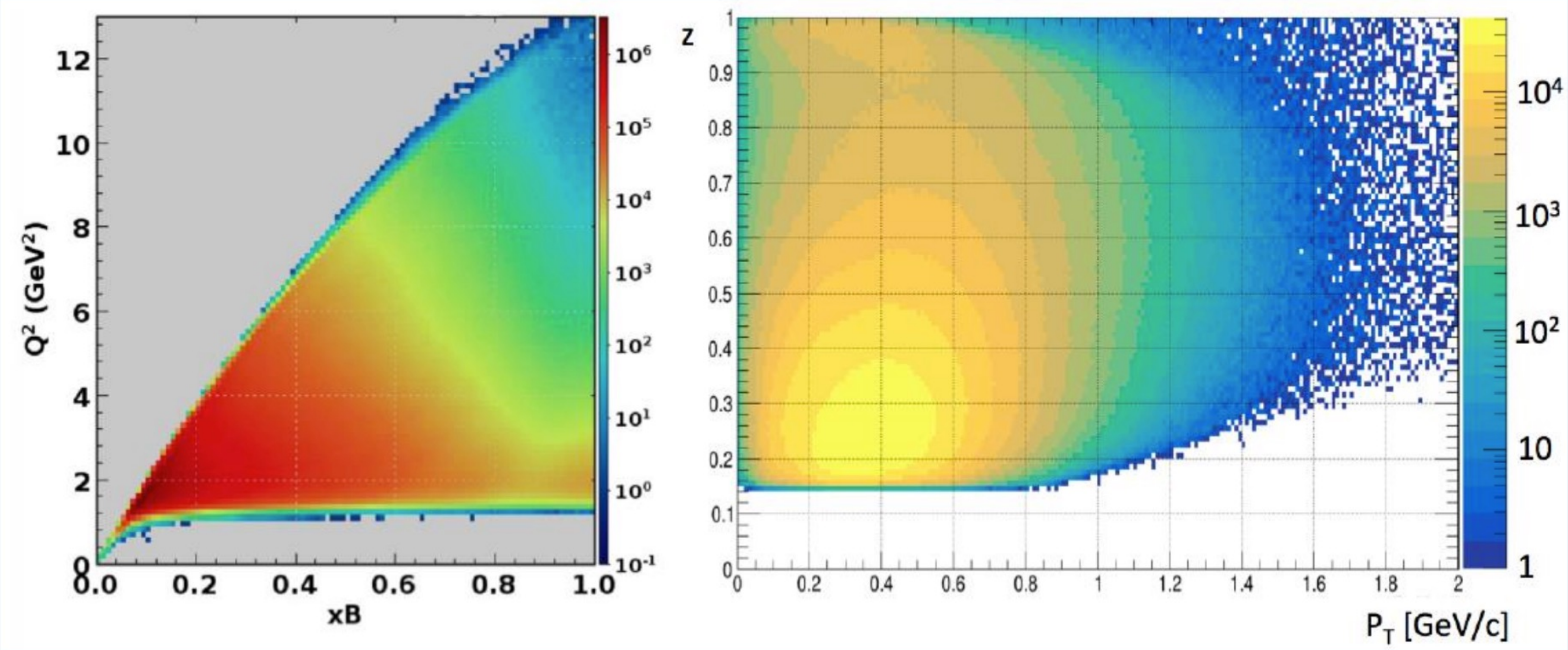
From Marco's slides:
https://www.fe.infn.it/~mcontalb/JLAB12/TALKs/PAC53/rgh_250723.pdf

RGH Status

CLAS12 Kinematic Reach

Features: wide phase space cover, excellent PID and statistics optimized for a multi-D analysis

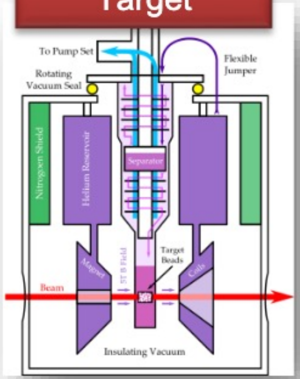
- disentangle kinematical correlations
- verify expected dependences (e.g. in Q^2) and isolate peculiar regimes (e.g. in z)
- study transition regions (e.g. in P_T)

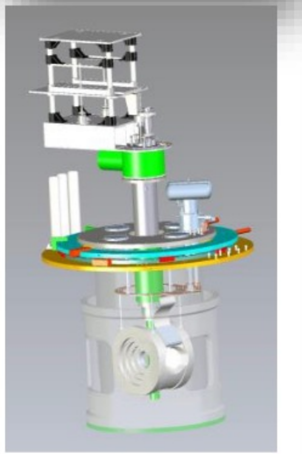


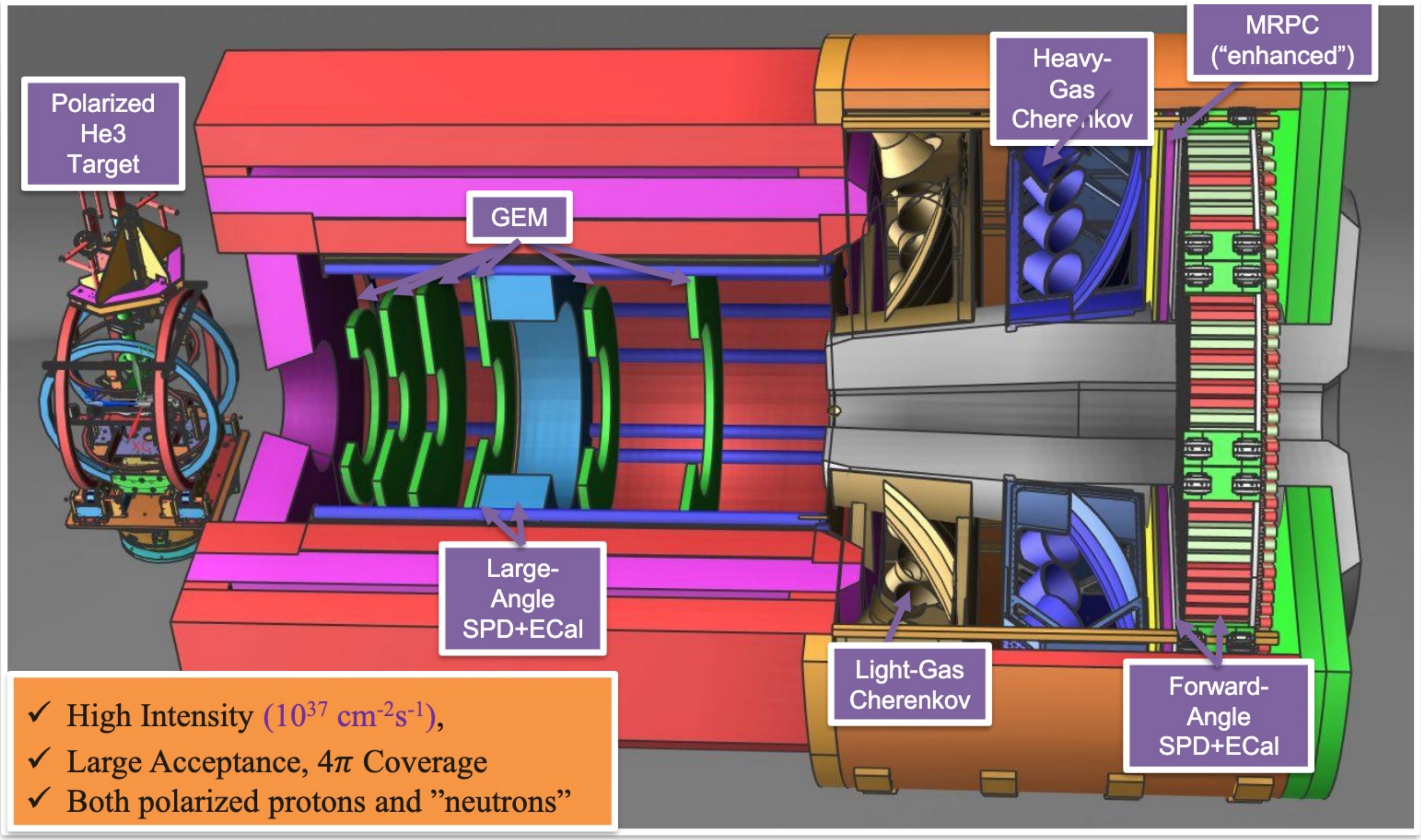
From Marco's slides:
https://www.fe.infn.it/~mcontalb/JLAB12/TALKs/PAC53/rgh_250723.pdf

Prospective Plans with SoLID (Hall A)

Polarized NH3 (DNP) Target



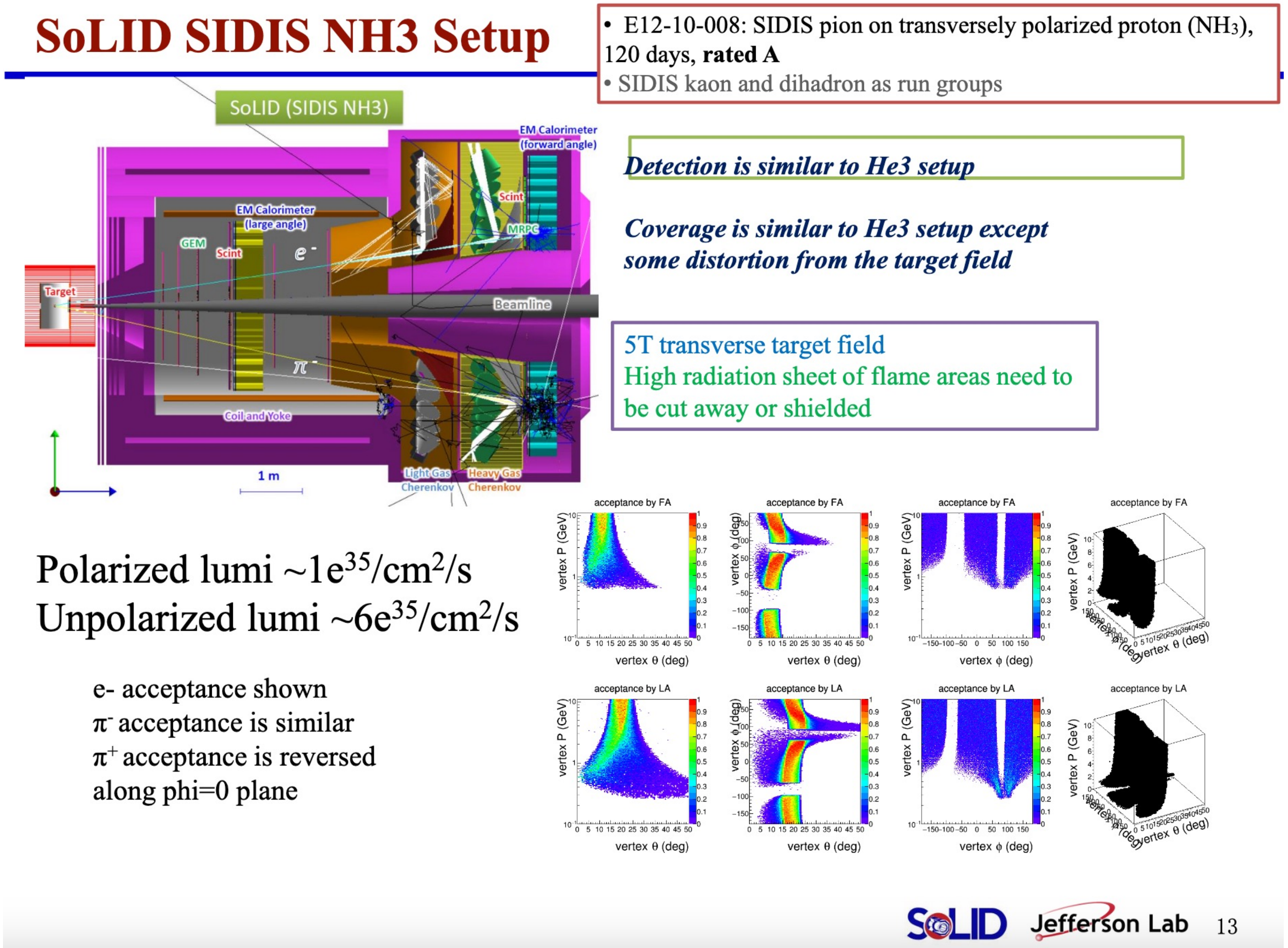




From the slides by Haiyan Gao and Zhiwen Zhao:
https://indico.phy.anl.gov/event/51/sessions/89/#20240619

+ Tensor Polarized ND3

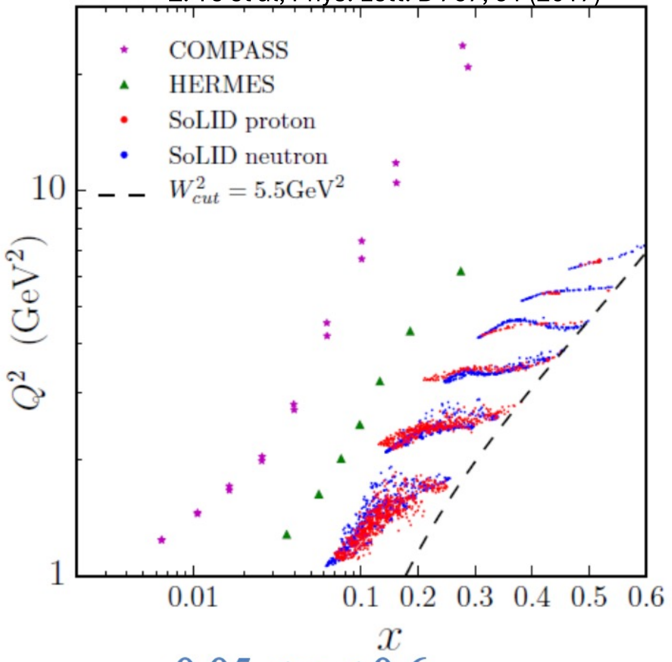
Prospective Plans with SoLID (Hall A)



+ ND3 Setup

Kinematic Coverage

Z. Ye et al, Phys. Lett. B 767, 91 (2017)



$0.05 < x < 0.6$

$1\text{GeV}^2 < Q^2 < 8\text{GeV}^2$

$0.3 < z < 0.7$

$0 < P_T < 1.6\text{GeV}$

From the slides by Haiyan Gao and Zhiwen Zhao: https://indico.phy.anl.gov/event/51/sessions/89/#20240619