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

Tensor SIDIS Workshop and b1/Azz Collaboration Meeting

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Outline

- **Based on LoI submitted to JLab PAC 54 (LOI12-26-006)**
- Physics motivation
  - Gluon transversity in tensor-polarized deuteron
  - Measurement via inclusive DIS
  - Theoretical prediction using the spectator model
- Experimental setup
  - SHMS
  - Transverse polarized target
- Monte Carlo simulation
  - Spectrometer acceptance
  - Signal rate
- Anticipated run plan & future tasks
- Summary

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Deuteron PDFs

- More PDFs with tensor target polarization than proton's

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}, $h_{1LT}^\perp$

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}, $h_{1TT}^\perp$ $h_{1TT}^{\perp\perp}$

- $h^g_{1TT}(x)$ = "Gluon transversity"
  - Linearly polarized gluons *in* Transversely tensor-polarized deuteron
  - Gluonic degrees of freedom arising from the state of deuteron (not nucleon)
  - Experimentally challenging

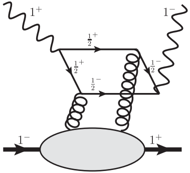
Measurements of Gluon Transversity TMD

- SIDIS
  - Full TMD information
  - Our long-term measurement

cf. Ishara's talk on Thursday

- DIS with ND_3 — This measurement
  - Integrated TMD information
  - High inclusive rates
    with simple spectrometer setup
  - Our first measurement

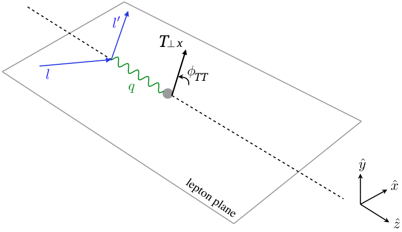
One leading contribution in DIS



(PRD 94, 014507)

- DIS with NH_3 — LoI for JLab PAC 44,
  "Search for Exotic Gluonic States in the Nucleus"
  - Tensor polarization of Nitrogen
  - Different experimental technique
  - Complementary observable

Inclusive Tensor-Polarized DIS



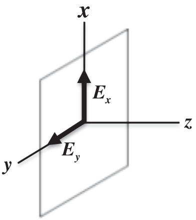
(Based on JHEP12, 067)

- Cross section

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

  - (i): Target polarization state (E_x or E_y)
  - Unpol. term: $\mathcal{U}(x, Q^2, y) = xy^2 F_1(x, Q^2) + (1-y)F_2(x, Q^2)$
  - Longitudinal term: $\mathcal{T}_{LL}(x, Q^2, y)$
  - Transverse term: $\mathcal{T}_{TT}(x, Q^2, y, \phi_{TT}) = -\frac{x(1-y)}{2}\,\Delta(x, Q^2)\cos 2\phi_{TT}$
    - $\Delta(x, Q^2)$ = Inclusive double-helicity-flip DIS structure function
    - ϕ_{TT}: Azimuthal angle between lepton plane and transverse tensor axis

- **Target polarization state**
  - E_x: Vertical orientation in the Hall-C convention ($S_{TT}^{xx} = -1$)
  - E_y: Horizontal orientation ($S_{TT}^{xx} = +1$)



- **Cross-section difference**

$$\frac{d\Delta\sigma_{xy}}{dx\,dy\,d\phi_{TT}} \equiv \frac{d\sigma^{Ex}}{dx\,dy\,d\phi_{TT}} - \frac{d\sigma^{Ey}}{dx\,dy\,d\phi_{TT}} = \mathcal{K}(x,Q^2,y)\,x(1-y)\,\Delta(x,Q^2)\cos 2\phi_{TT}$$

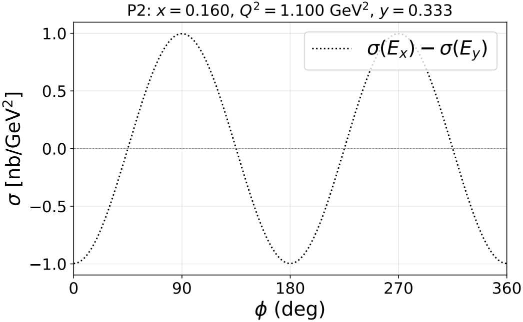
  - $\mathcal{U}(x,Q^2,y)$ and $\mathcal{T}_{LL}(x,Q^2,y)$ vanish
  - $\Delta(x,Q^2)$ accessible via $\mathcal{T}_{TT}(x,Q^2,y,\phi_{TT})$

- **Relation to gluon transversity at leading twist**

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

Theoretical Prediction

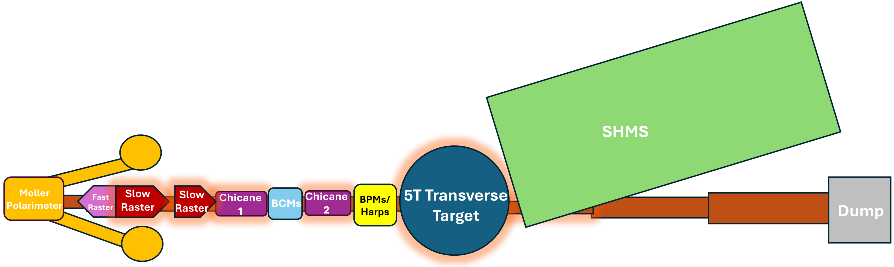
- Based on the spectator model — cf. Ishara's talk on Thursday



  - Max $\Delta\sigma_{xy} \approx 1$ nb/GeV^2

Experimental Setup — Overview

- Following the g2p2 experiment in design and run time

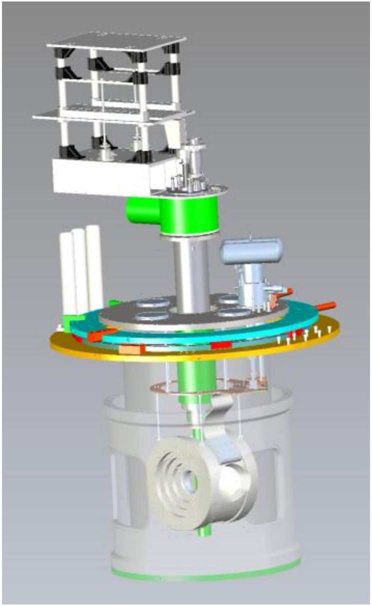


(Courtesy of David Ruth)

  - 5T transverse polarized magnet
  - Chicane magnet
  - Low current (85 nA) beam
  - Slow raster
  - SHMS

Polarized Target

- ND_3 material
- Tensor polarization enhanced via ssRF
- Two polarization orientations
  - Horizontal (E_y) — as pictured
  - Vertical (E_x)
- Required hardware changes
  - Remount the magnet to change the polarization orientation
  - Reconfigure the chicane magnet together



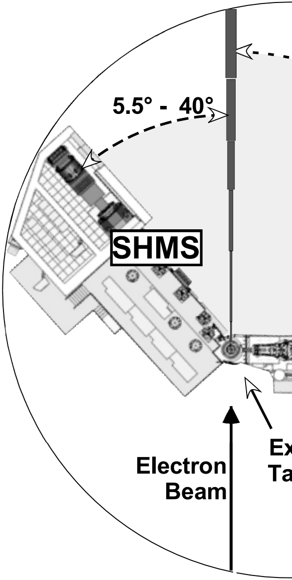
(Courtesy of David Ruth)

SHMS

- For inclusive electron measurement
- Spec — arXiv:2503.08706v1

Central momentum	2 to 11 GeV
Momentum acceptance	-10% to $+22\%$
Angle range	5.5 to 40 degrees
Horizontal angle acceptance	± 18 mrad
Vertical angle acceptance	± 45 mrad

- Coordinate
  - x = Pointing downwards
  - y = Pointing to the left
    when seen in the $+z$ direction
  - z = Pointing to the downstream
    along the beam or spectrometer axis



Monte Carlo Study

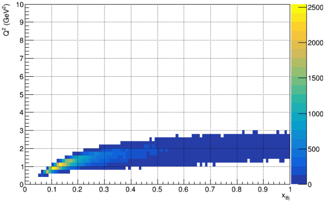
- Many thanks to David Ruth for providing instructions and field data
- Aim
  - Optimization of spectrometer configuration
  - Estimation of event rates (= statistical precision)
- Hall-C single arm MC — `https://github.com/gaskelld/mc-single-arm`
  - Branch "target-field"
  - Our modified version: `https://github.com/forhad-h2030/mc-single-arm`
- Basic settings
  - Beam energy = 11.0 GeV
  - Acceptance cut by `shsmSTOP_id==0`
  - Use of true (not reconstructed) momenta and angles

Target Magnetic Field in MC

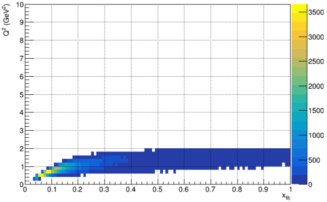
- Field map
  - trg_field_map.dat provided by David
  - Given in (r, z)
- Parameters in the MC input file (*.inp)
  - "target field angle"
    - To rotate the field in y-z
    - 0.0 = Longitudinal direction
    - 90.0 = Horizontally (y) transverse direction
  - "target field mode" — New parameter added by ourselves
    - 0 = The y-z mode
    - +1 = $+x$ direction (ignoring "target field angle")
    - −1 = $-x$ direction (ignoring "target field angle")
- For the E_x and E_y configurations
  - For E_y; Angle = 90.0
  - For E_x; Mode = +1 or −1

Acceptance in (x_{Bj}, Q^2)

- Spectrometer configuration
  - Central momentum: $p_0^{sp} = 7.5$ GeV
  - Central angle: $\theta_0^{sp} = 5.5^\circ$
- Cross-section-weighted MC yields
  - E_x



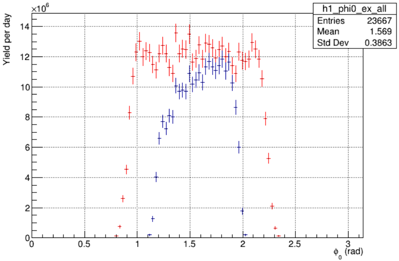
  - E_y



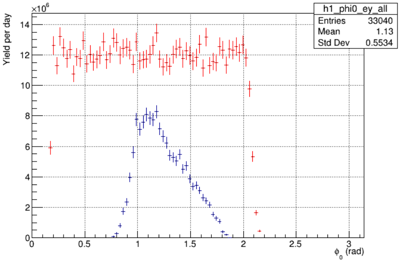
  - Different between E_x and E_y, due to the target magnet field
- Selection of common range
  - $0.12 \leq x_{Bj} \leq 0.20$
  - $1.0 \leq Q^2 \leq 1.2$ GeV^2

Acceptance in ϕ_0

- ϕ_0: Azimuthal angle of scattered electron in the Hall-C coordinate
  - $\phi_0 \sim \pi/2$ with SHMS $\Longrightarrow \phi_{TT} \sim \pi/2$ — *next page*
- Generated & Accepted MC yields
  - In $0.12 \leq x_{Bj} \leq 0.20$ & $1.0 \leq Q^2 \leq 1.2$ GeV^2
  - E_x



  - E_y

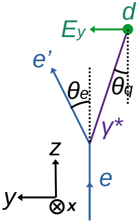


  - Different between E_x and E_y
- Selection of common range
  - $1.20 \leq \phi_0 \leq 1.50$

Projection of Tensor Axis to Virtual Photon

- Virtual-photon tilt angle

$$\tan\theta_q = \frac{E' \sin\theta_e}{E - E' \cos\theta_e}$$



  - $E = 11$ GeV, $E' = 5$ GeV, $\theta_e = 8^\circ$
    $\Longrightarrow Q^2 = 1\ \text{GeV}^2,\ x = 0.1,\ \theta_q = 7^\circ$
  - Coefficient in cross-section difference:

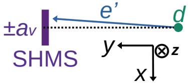
$$-\Delta S_{TT}^{xx} \equiv S_{TT}^{xx,(Ey)} - S_{TT}^{xx,(Ex)} = 1 + \cos^2\theta_q$$

$$\Delta\sigma_{xy} = \Delta S_{TT}^{xx} \mathcal{K} \frac{x(1-y)}{2} \Delta\ \cos 2\phi$$

  - Correction factor:

$$R_{central} \equiv \frac{\Delta S_{TT}^{xx}}{\Delta S_{TT}^{xx}\big|_{ideal}} = \frac{1+\cos^2\theta_q}{2} = 0.993$$

- Averaging in SHMS acceptance



  - Vertical acceptance: $a_v = 45$ mrad
  - Average of $\cos 2\phi_0$ modulation

$$\langle\cos 2\phi_0\rangle_{\pm a_v} \simeq -1 + \frac{2\theta_e}{a_v}\tan^{-1}\left(\frac{a_v}{\theta_e}\right) \simeq 0.94$$

  - Irrelevant in case of ϕ_0-binned measurement

Anticipated Production Times

- Luminosity: $L = 0.9 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Beam current: $I = 85$ nA
  - Target packing fraction: $p = 1$
- To achieve 3σ statistical significance

Set	p_0^{sp} (GeV)	θ_0^{sp} ($^\circ$)	x_{Bj}	Q^2 (GeV^2)	ϕ_0 (rad)	Crude R_U (kHz)	ΔR_{xy}^{raw} (Hz)	Production time (days)
S1	7.5	5.5	0.12-0.20	1.0-1.2	1.20-1.50	1.3	0.21	16
S2	7.5	8.0	0.17-0.20	1.4-1.6	1.40-1.70	0.46	0.060	55

  - Experimental effects
    - Dilution factor: $f = 6/20$
    - Polarization: $P_{TT} = 0.3$
    - Data-taking efficiency: $\epsilon = 0.5$
  - S1 is the current best set
  - S2 could explore larger Q^2 region but need too-many days

Preliminary Run Plan

Task	Days	Comment
E_x tensor-enhanced production	8.0	Focused on $x \sim 0.07$–0.15 settings
E_y tensor-enhanced production	8.0	Matched statistics to E_x
E_x zero-tensor vector controls	2.0	Helicity-difference normalization checks
E_y zero-tensor vector controls	2.0	Matched to E_x controls
Dummy/empty/carbon/dilution and repeated normalization setting	2.0	Material and long-term stability checks
Total production beam	22.0	85 nA, 11 GeV primary
Target anneals, TE/NMR calibrations, target material handling	4.0	Uses g_2^p target procedures
Magnet reconfiguration between E_x and E_y	4.0	No rapid flip assumed
Optics, sieve, BCM, Moller, detector calibrations	4.0	Reduced by running after g_2^p
Contingency and field-map validation	2.0	Especially for first E_x configuration
Total overhead	12.0	
Total preliminary request	**34.0**	PAC days

- Days (and manpower) will be estimated better

Near-Future Tasks (toward Proposal)

- Detailed planning on experimental settings
  - Target magnet rotation — Manpower and days needed?
  - Chicane magnet adjustment — Manpower and days needed?
  - Optimum beam current — Higher?
- Re-examination of spectrometer setting
  - More uniform acceptance in both E_x and E_y?
  - Measurement of ϕ_0 dependence
  - Consideration of spectrometer resolution
- Development on measurement+analysis methods for better systematic controls
  - Data taking with zero-tensor vector polarization
    - Control of vector-polarized effects
    - Control of acceptance difference
  - Data taking with no polarization
    - Control of acceptance difference

Summary

- We intend to measure the gluon transversity ($h^g_{1TT}(x, Q^2)$) via inclusive DIS off tensor-polarized deuteron
  - LoI submitted to JLab PAC 54 (LOI12-26-006)
  - Foreseeing the SIDIS measurement
- The cross-section difference between two tensor-pol. states (E_x and E_y)
  - Max $\Delta\sigma_{xy} \approx 1$ nb/GeV^2 based on the spectator model
- Measurement with SHMS at $I = 85$ nA
  - Tensor-polarized ND_3 material
  - 5T transverse polarized magnet with E_x and E_y
- The MC study
  - The spectrometer acceptance varies with E_x and E_y
  - The current best configuration: p_0^{sp} = 7.5 GeV, θ_0^{sp} = 5.5°
  - $0.12 \leq x_{Bj} \leq 0.20$, $1.0 \leq Q^2 \leq 1.2$ GeV^2, $1.20 \leq \phi_0 \leq 1.50$
  - 16 production days to achieve 3σ significance
- The measurement plan is being considered toward a PAC proposal