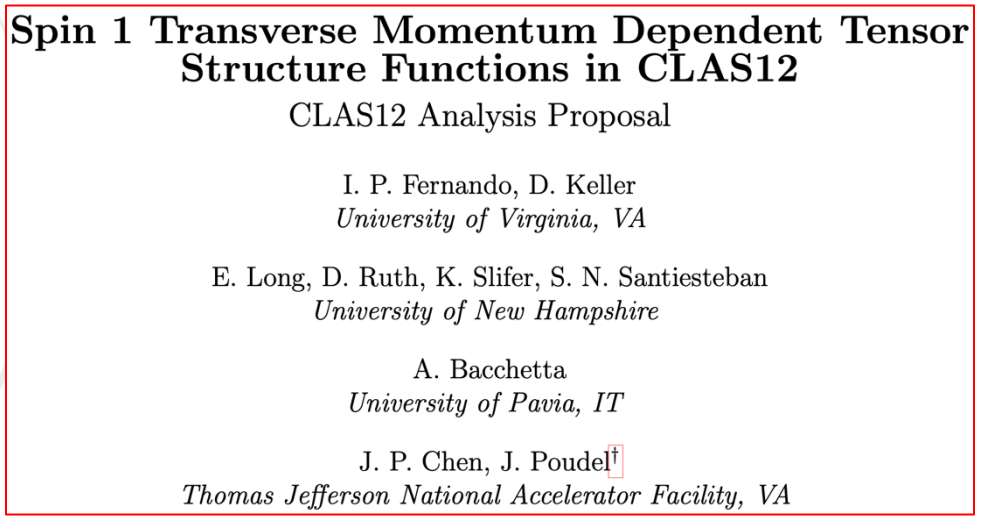
CLAS12 Approved Analysis (CAA): Spin-1 Tensor Structure Functions

Jiwan Poudel

Jefferson Lab



Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

CLAS12 Analysis Proposal

I. P. Fernando, D. Keller
University of Virginia, VA

E. Long, D. Ruth, K. Slifer, S. N. Santiesteban
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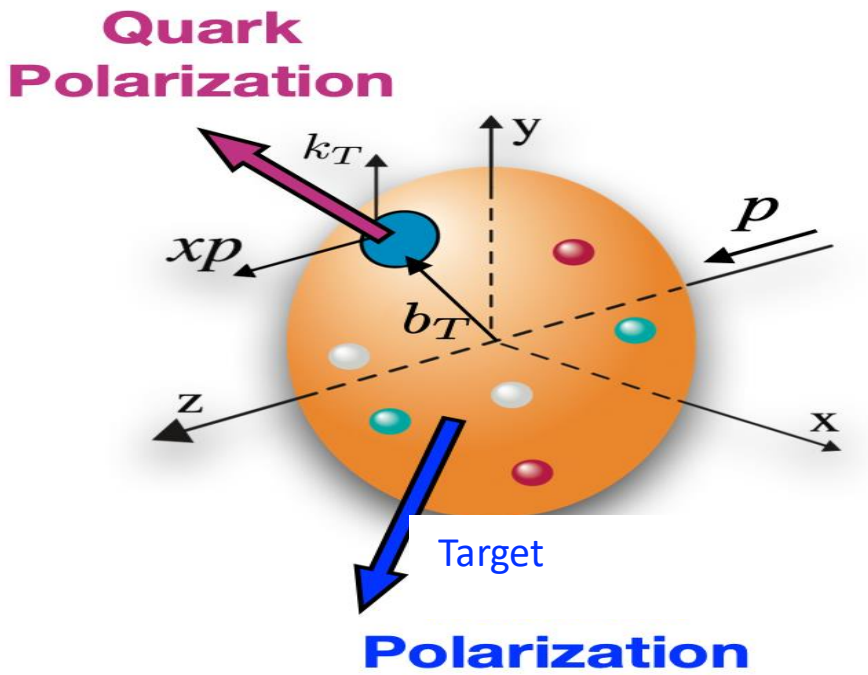
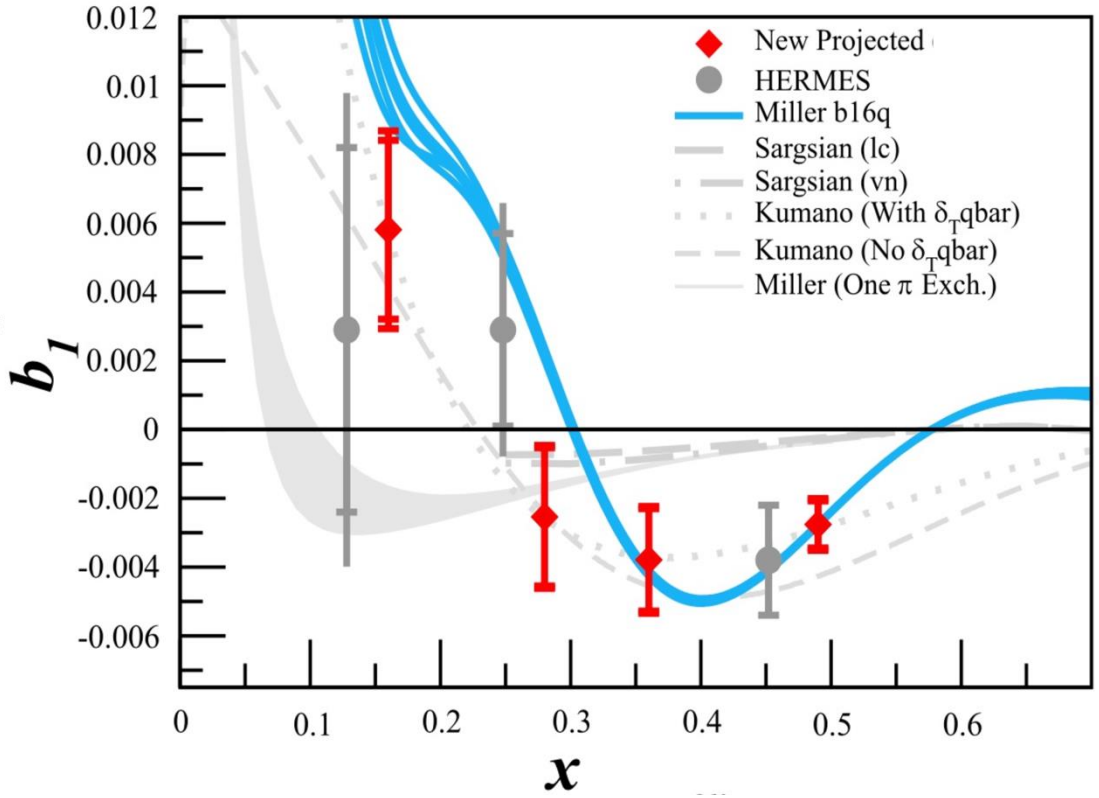
Motivation

- Explore the transverse momentum dependent tensor structure functions of Spin-1 system
- Constrain different theoretical models to describe the light nuclei
- Understand the exotic state of deuteron that cannot be naively constructed combining proton and neutron structure



Tensor Polarized Experiments

- HERMES experimental result for b_1 in 2005, but no additional experimental data
- Approved experiment for b_1/Azz in Hall C (enhanced tensor pol.): scheduled for 2030/31
- No experimental study/results on tensor TMDs yet



=> CLAS12 Run group C used longitudinally polarized deuteron target [Details of RG-C in Sebastian Kuhn's talk yesterday] :: tensor polarization (Boltzmann statistics at thermal equilibrium)

Polarization in Spin-1

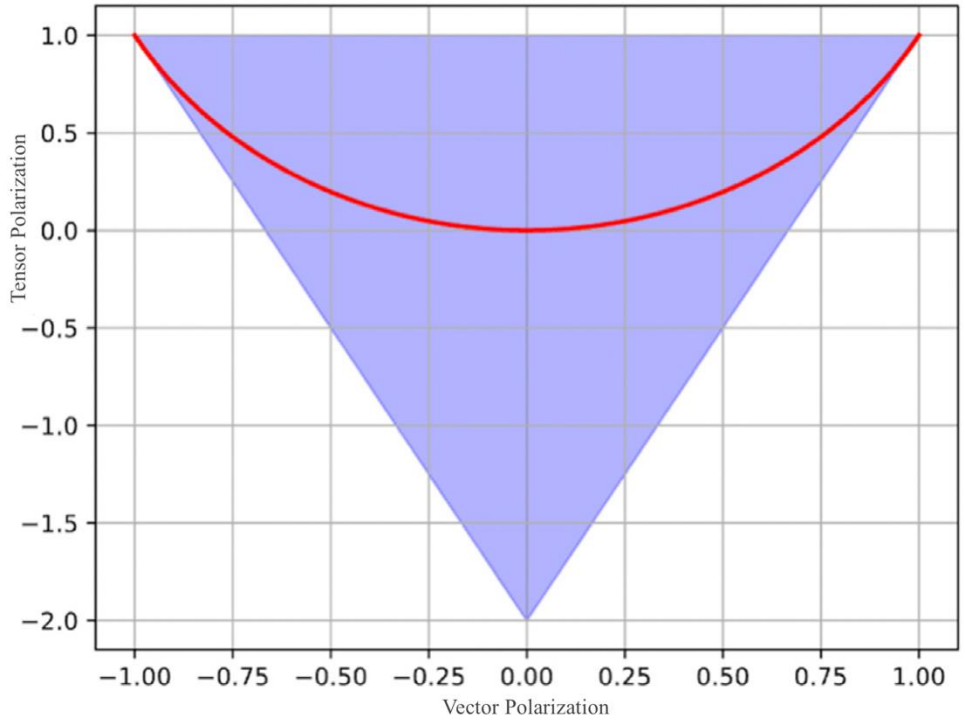
- Spin-1 system splits into 3 energy levels in magnetic field
  - m = +1 , 0 and -1 energy states with population n_+, n_0 and n_-
  - Vector polarization ($S_{||}$) = $(n_+ - n_-)/(n_+ + n_0 + n_-)$
  - Tensor polarization ($T_{||\,||}$) = $(n_+ + n_- - 2n_0)/(n_+ + n_0 + n_-)$ => $[-2 < T_{||\,||} < 1]$

- The spin system follows the Boltzmann distribution at thermal equilibrium

- => $$T_{|||} = 2 - \sqrt{4 - 3S_{||}^2}$$

  $[0 < T_{||\,||} < 1]$

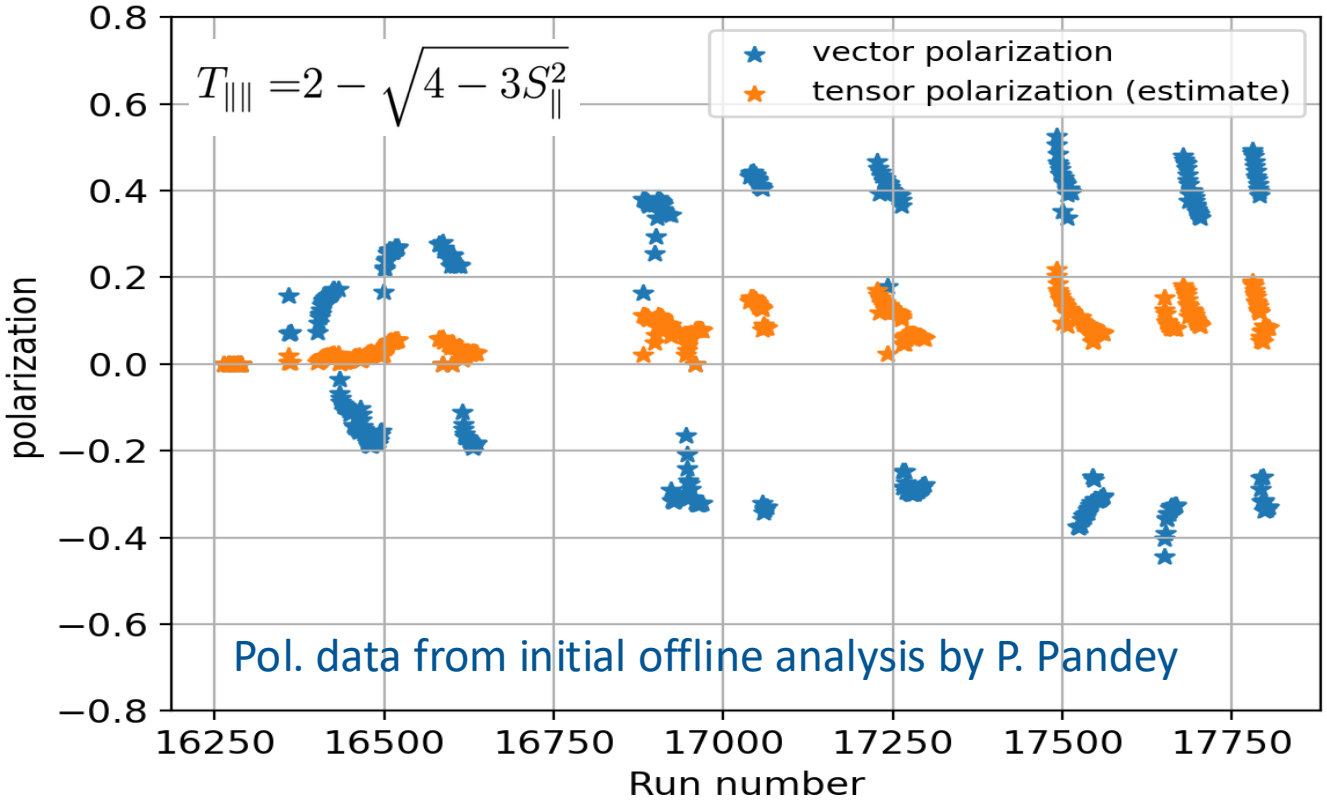
- Average vector pol. of 30% Corresponds to ~ 7% of Tensor pol with Dynamic Nuclear Polarization(DNP)

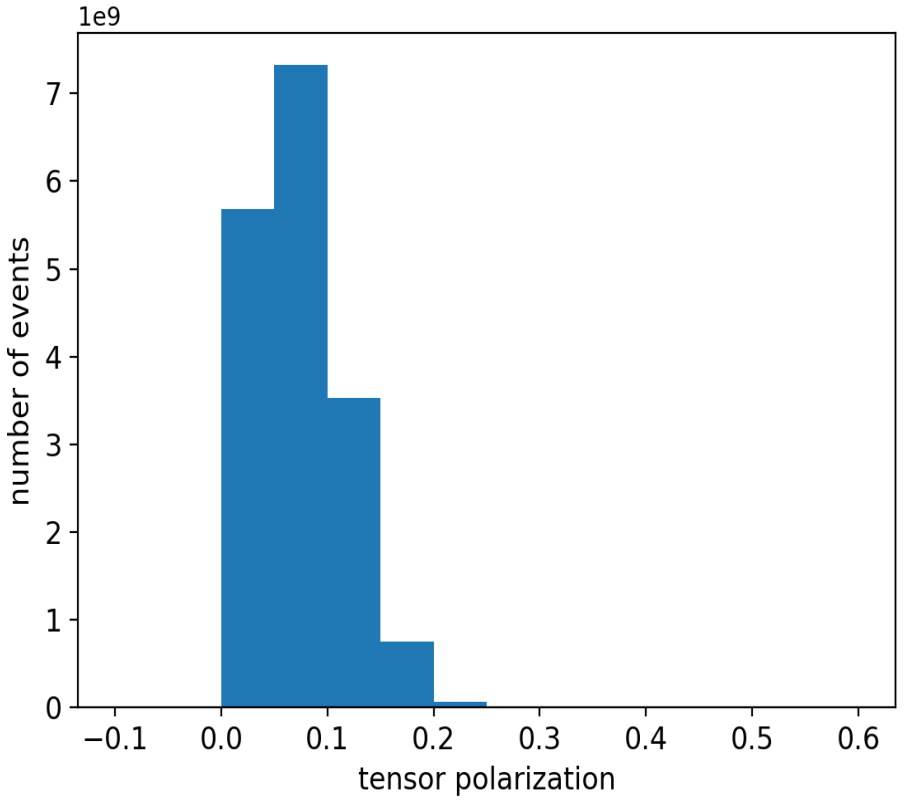


J. Clement and D. Keller, NIMA 1050 (2023)

CLAS12 RG-C Spin-1 Target

- CLAS12 Run Group–C data on longitudinal polarized ND_3 target (summer 2022– winter 2023)
- Average vector polarization of ND_3 target: 31% (along beam direction) and 26% (opposite dir.)
- Average tensor polarization ~ 7% (no tensor enhancement during RG-C)
- Approx. 1800 M events on polarized of ND_3 target





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CAA Proposal

- CLAS12 Approved Analysis (CAA) proposal for the analysis of existing experimental data
  1) Study for b_1 near the cross-over region via inclusive analysis
  2) Exploratory study of tensor TMD structure functions via SIDIS
  3) Understanding of in-beam target polarization with RG-C data
- Started discussion in 2023 with Alessandro Bacchetta for theoretical support
- Submitted proposal in July 2024 to CLAS12, review feedback in September 2024, and officially approved by CLAS12 Collaboration meeting in November 2024.

Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

CLAS12 Analysis Proposal

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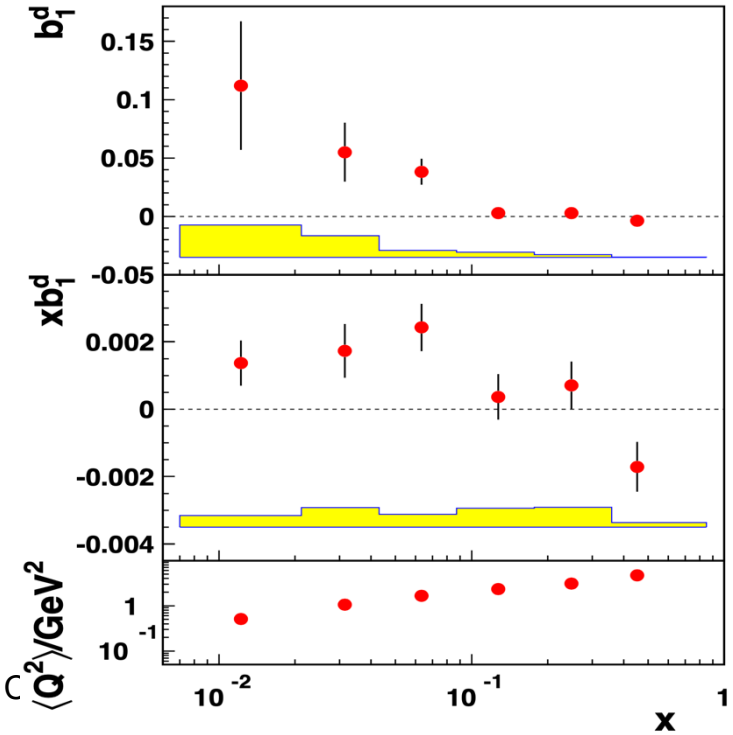
1) Inclusive: Spin-1 Structure Function

- Hadronic part of cross-section:

$$W_{\mu\nu}^{\lambda_f\lambda_i} = -F_1\hat{g}_{\mu\nu} + \frac{F_2}{M\nu}\hat{p}_\mu\hat{p}_\nu + \frac{ig_1}{\nu}\epsilon_{\mu\nu\lambda\sigma}q^\lambda s^\sigma + \frac{ig_2}{M\nu^2}\epsilon_{\mu\nu\lambda\sigma}q^\lambda(p\cdot q s^\sigma - s\cdot q p^\sigma)$$
$$- b_1 r_{\mu\nu} + \frac{1}{6}b_2(s_{\mu\nu}+t_{\mu\nu}+u_{\mu\nu}) + \frac{1}{2}b_3(s_{\mu\nu}-u_{\mu\nu}) + \frac{1}{2}b_4(s_{\mu\nu}-t_{\mu\nu}),$$

Tensor structure function b_1, b_2, b_3, b_4 (x-dependent):

- b_1 structure function of deuteron studied experimentally in HERMES (non-vanishing b_1)



First measurement of b_1 by HERMES Collaboration (2005)

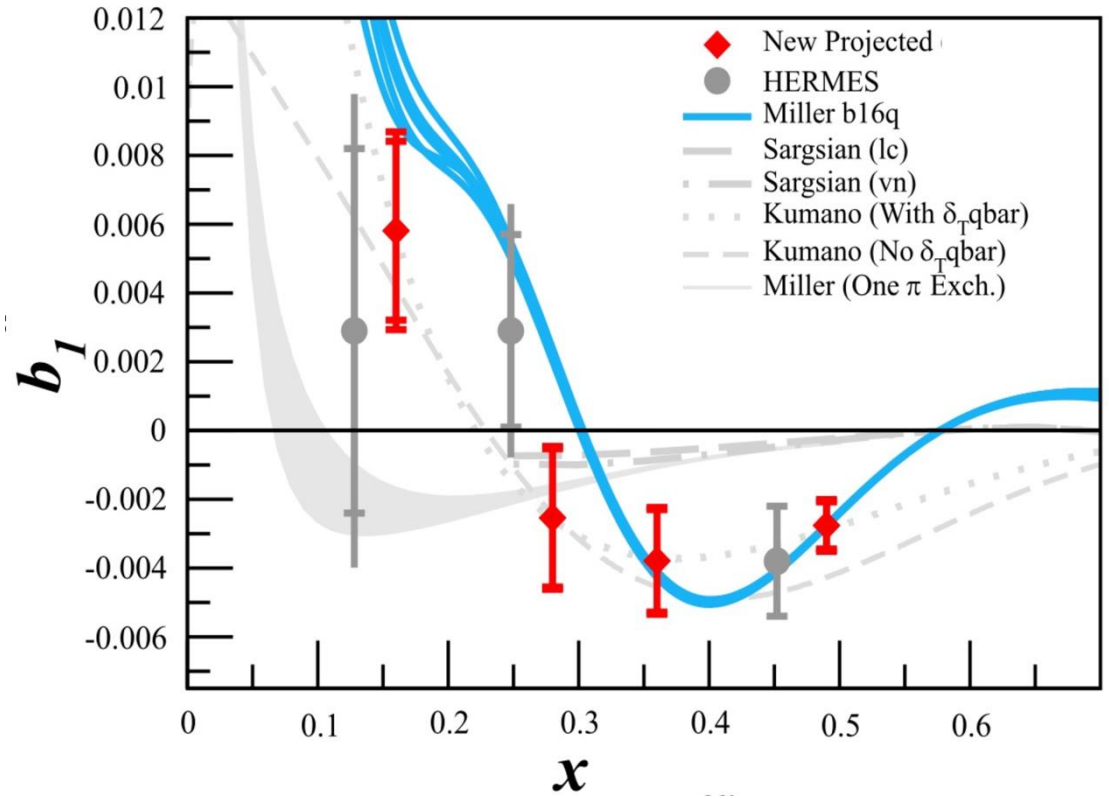
Naïve Partonic model:

$$b_1(x) = \frac{1}{2}\left(2q_\uparrow^0(x) - q_\uparrow^1(x) - q_\downarrow^1(x)\right)$$
$$b_2(x) = 2xb_1(x)$$

Pioneer study by P. Hoodbhoy, R.L. Jaffe and A. Manohar (1989)

1) Inclusive: Spin-1 Structure Function

- Inclusive process (tensor structure function):
  - CLAS12 coverage around zero-crossing region



Projection of b_1 experiment approved for Hall C

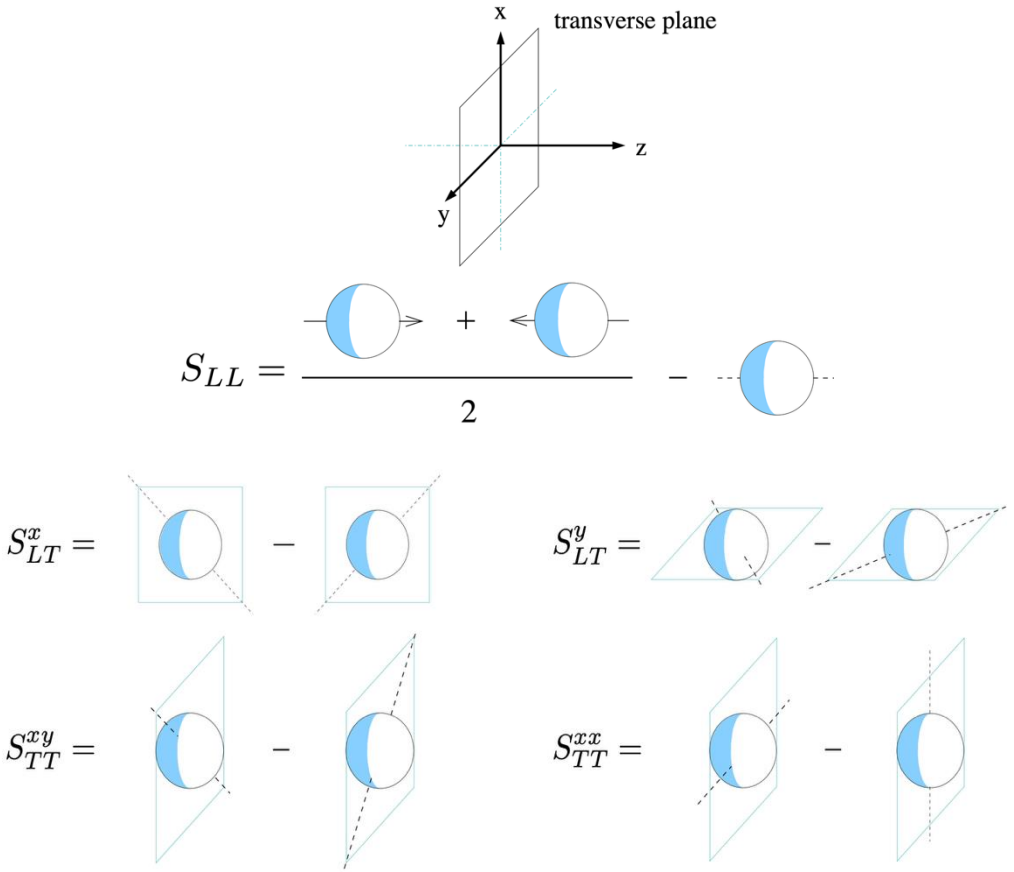
Leading twist PDFs (1-D distributions)

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5$ / σ^{i+})	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			g_{1L} (g_1)			
T					[h_1]	
LL	f_{1LL} (b_1)					
LT						*1 [h_{1LT}]
TT						

A. Bacchetta and P.J. Mulders, PRD 62 (2000)
S. Kumano and Q. Song, PRD 103 (2021)

2) SIDIS: Spin-1 Structure Function

- Semi-Inclusive DIS (SIDIS) process and Spin-1 TMDs [tensor: LL, LT, TT { LL≈ || || }]



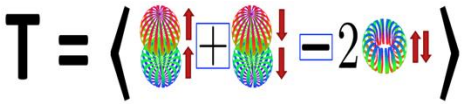
Leading twist TMDs (3-D distributions)

Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5$ / σ^{i+})	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					$[h_1^\perp]$
L			g_{1L}		$[h_{1L}^\perp]$	
T		$f_{1T}^\perp$	g_{1T}		$[h_1]$, $[h_{1T}^\perp]$	
LL	f_{1LL}					$[h_{1LL}^\perp]$
LT	f_{1LT}			g_{1LT}		$[h_{1LT}]$, $[h_{1LT}^\perp]$
TT	f_{1TT}			g_{1TT}		$[h_{1TT}]$, $[h_{1TT}^\perp]$

➢ Integral over the transverse momenta provides 1-D PDFs

A. Bacchetta and P.J. Mulders, PRD 62 (2000)
S. Kumano and Q. Song, PRD 103 (2021)

2) SIDIS: Spin-1 Structure Function



- Cross-section considering longitudinal polarization of target (SIDIS process in leading twist)

$$\frac{d\sigma}{dx\ dy\ d\psi\ dz\ d\phi_h\ dP_{h\perp}^2} = \frac{y^2\alpha^2}{2(1-\epsilon)xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\Bigg[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\ F_{UU}^{\cos\phi_h}$$

$$+ \epsilon\cos(2\phi_h)\ F_{UU}^{\cos(2\phi_h)} + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h\ F_{LU}^{\sin\phi_h}$$

Vector polarization:

$$+ S_\parallel\left\{\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h\ F_{UL}^{\sin\phi_h} + \epsilon\sin(2\phi_h)\ F_{UL}^{\sin 2\phi_h}\right\}$$

$$+ S_\parallel\lambda_e\left\{\sqrt{1-\epsilon^2}\ F_{LL} + \sqrt{2\epsilon(1-\epsilon}\cos\phi_h\ F_{LL}^{\cos\phi_h}\right\}$$

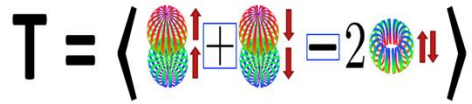
A. Bacchetta (2023)

Tensor Polarization:

$$+ T_{\parallel\parallel}\Bigg\{F_{U(LL),T} + \epsilon\ F_{U(LL),L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\ F_{U(LL)}^{\cos\phi_h}$$

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

2) SIDIS: Spin-1 Structure Function



- Tensor Structure Functions (*F*) of deuteron in terms of TMDs (f,g,h) convoluted with fragmentation functions (D, E, H)

A. Bacchetta (2023)

$$F_{U(LL),T} = C[f_{1LL} D_1]$$

$$F_{U(LL),L} = 0$$

$$F_{U(LL)}^{\cos\phi_h} = \frac{2M}{Q} C\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(x h_{LL} H_1^\perp + \frac{M_h}{M} f_{1LL}\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(x f_{LL}^\perp D_1 + \frac{M_h}{M} h_{1LL}^\perp \frac{\tilde{H}}{z}\right)\right]$$

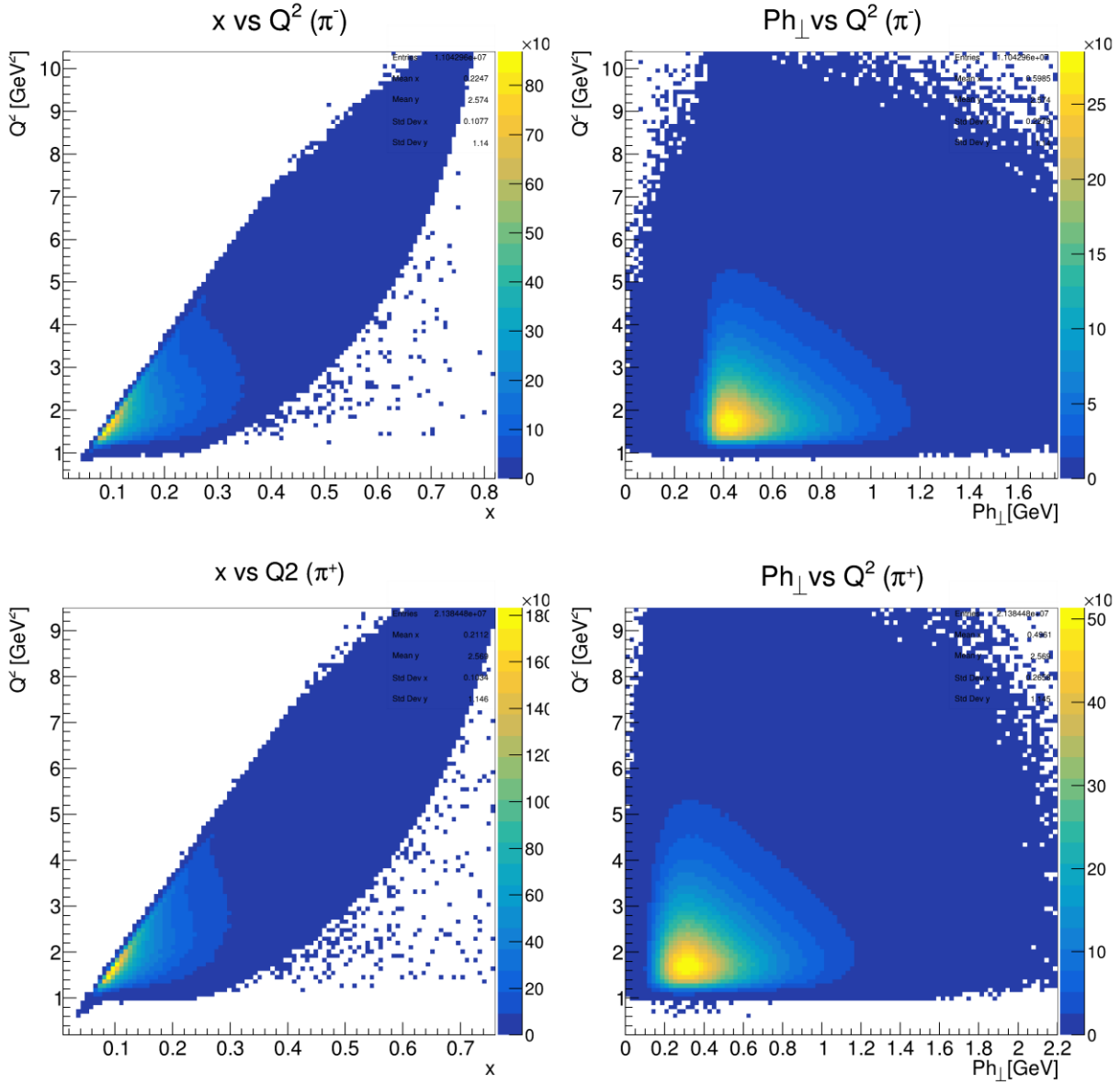
$$F_{U(LL)}^{\cos 2\phi_h} = C\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k_T})(\hat{\mathbf{h}}\cdot\mathbf{p_T}) - \mathbf{k_T}\cdot\mathbf{p_T}}{M M_h} h_{1LL}^\perp H_1^\perp\right]$$

$$F_{L(LL)}^{\sin\phi_h} = \frac{2M}{Q} C\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(x e_{LL} H_1^\perp + \frac{M_h}{M} f_{1LL}\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(x g_{LL}^\perp D_1 + \frac{M_h}{M} h_{1LL}^\perp \frac{\tilde{E}}{z}\right)\right]$$

CLAS12 Acceptance

- Analyze events with pion in the final state for the SIDIS analysis
- Planning to have 3 to 4 bins in $x_B < 0.8$
- All data will be combined in $Q^2 > 1$ GeV^2, $0.2 < z < 0.7$ and $P_T < 0.8$ GeV for this exploratory study

CLAS12 SIDIS Kinematics



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Data Analysis

- Total cross section $\sigma = \sigma_U + S_{||}\,\sigma_V + T_{||||}\,\sigma_T$
- Vector polarization contribution suppressed with the data on both (+ve & -ve) vector polarity of target
- Tensor part extracted from the linear fit of unpolarized + tensor polarized cross-section

$$\sigma^* = \left(\sigma(h_e = 0, S_{||}, T_{|||}) + \sigma(h_e = 0, -S_{||}, T_{|||}) - 2\sigma_U\right)$$

Inclusive

$A_{zz} = \sigma^*/(2T_{||||}\,\sigma_U)$

$A_{zz} \approx -b_1/3F_1^d$

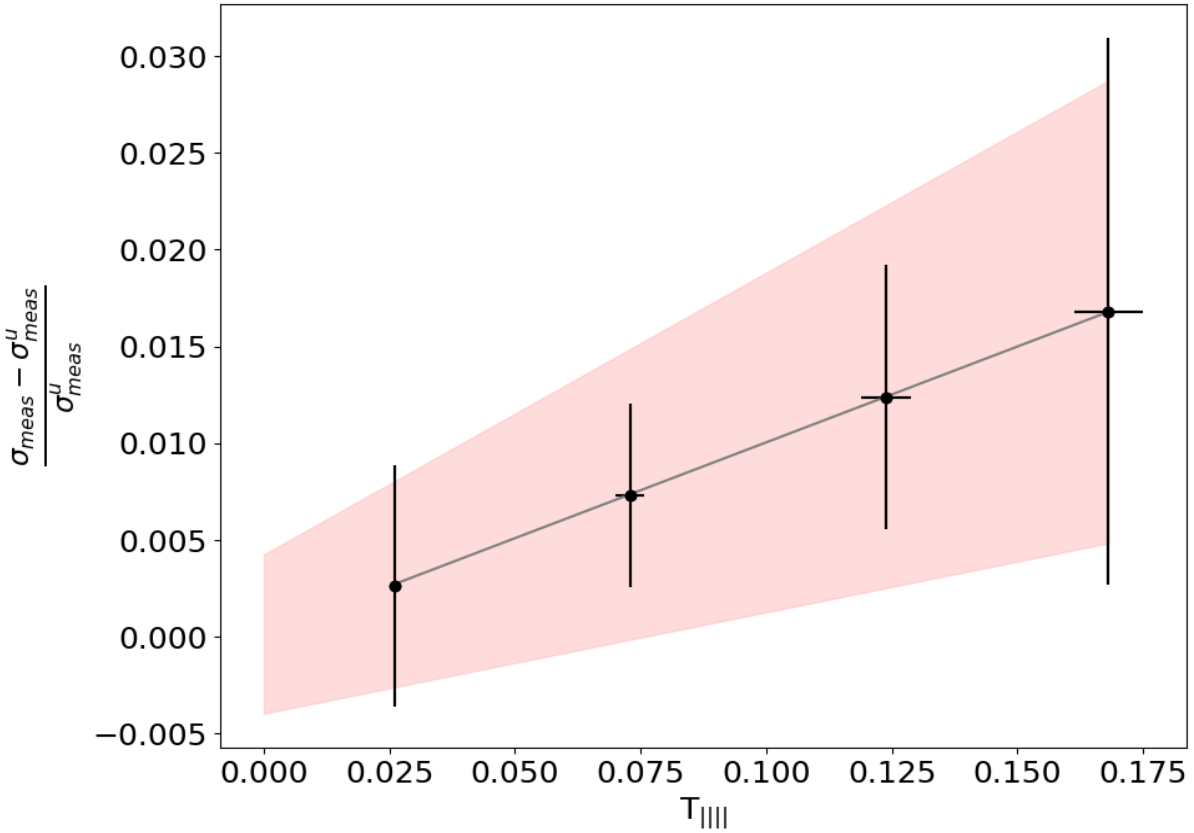
SIDIS

$$\frac{d\sigma^*}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{y^2\alpha^2}{2(1-\epsilon)xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)T_{|||}$$
$$\left\{F_{U(LL),T} + \epsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + +\sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\;F_{U(LL)}^{\cos\phi_h}\right\}$$

- Angular modulation to extract different tensor structure functions

Data Analysis: Tensor Contribution

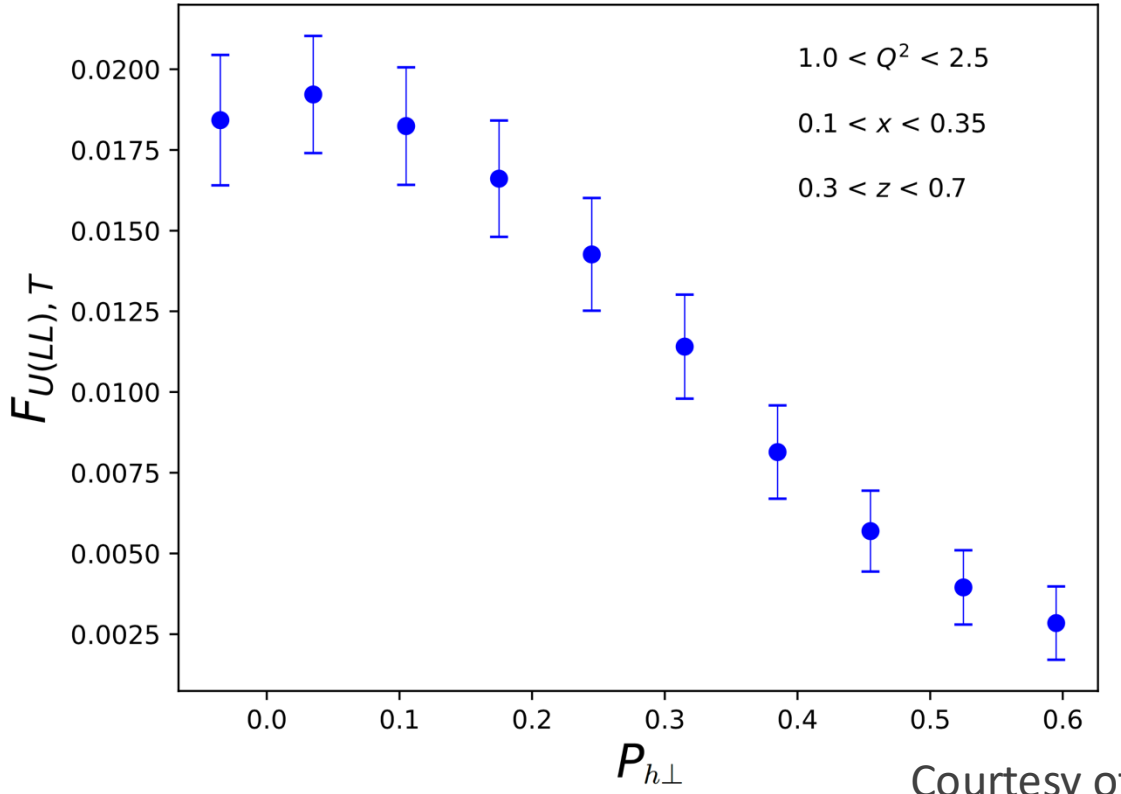
- Estimation of the tensor contribution from the CLAS12 RGC data
- Considered 1.7% of total events as pi+ SIDIS events (preliminary analysis)
- Slope of linear fit provides the tensor contribution



SIDIS

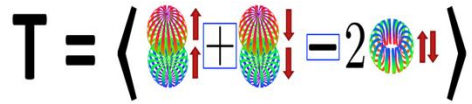
Tensor Structure Function: Simulation

- Unpolarized structure function $(F_{UU,T})$ generated using PDF and FF information from LHAPDF over the kinematic region of interest
- Tensor structure function $(F_{U(LL),T})$ is estimated considering 10% of the unpolarized component $F_{UU,T}$



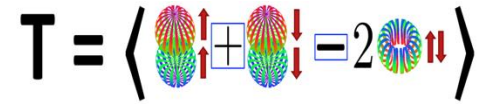
Courtesy of D. Ruth

Students on CAA



- Anchit Aurora (UNH): Resonance
- Chetra Lama (UNH): target polarization + quasi-elastic
- Hector ChinChay (UNH): SIDIS + dilution factor
- Muhammad Farooq (UNH): Inclusive DIS + target polarization
- Kehinde Ogunremi (NMSU): Recently joined the group (SIDIS)

Summary

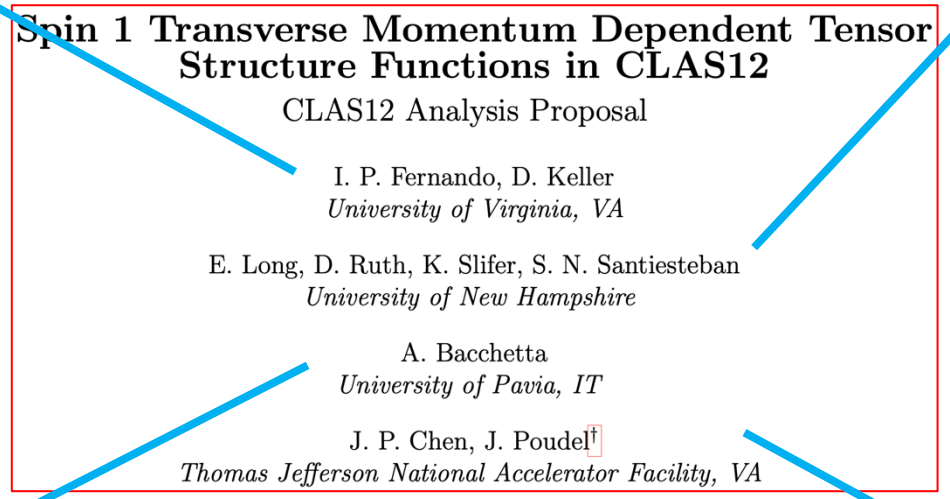


- Analyze the CLAS12 RG-C data for Spin-1 tensor structure functions (approved CAA)
  - Exploratory study of tensor TMD structure functions via SIDIS
  - Additional result for b_1 near the cross-over region via inclusive analysis
  - Understanding of in-beam target polarization with RG-C data
- Crucial preliminary measurement for the future dedicated experiments
- Unique mechanism to study hadron tomography in momentum space and QCD dynamics
- Interesting physics to understand the light nuclei: expanding group !!

We would like to invite you all to join us on these efforts !!!

Group Members

Dustin Keller
Ishara P. Fernando
(Target + CLAS12)



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Karl Slifer
Elena Long
Nathaly Santiesteban
David Ruth
(Target + Tensor exp.)

Alessandro Bacchetta
(Theory)

Postdoc + graduate students

Jian-Ping Chen
Jiwan Poudel
(Tensor exp. + CLAS12)

Spin-1 Tensor TMDs: SIDIS

- Semi-Inclusive DIS (SIDIS) process to study spin-1 TMDs

$$e(l) + d(P_d) \to e(l') + h(P_h) + X$$

- Kinematics

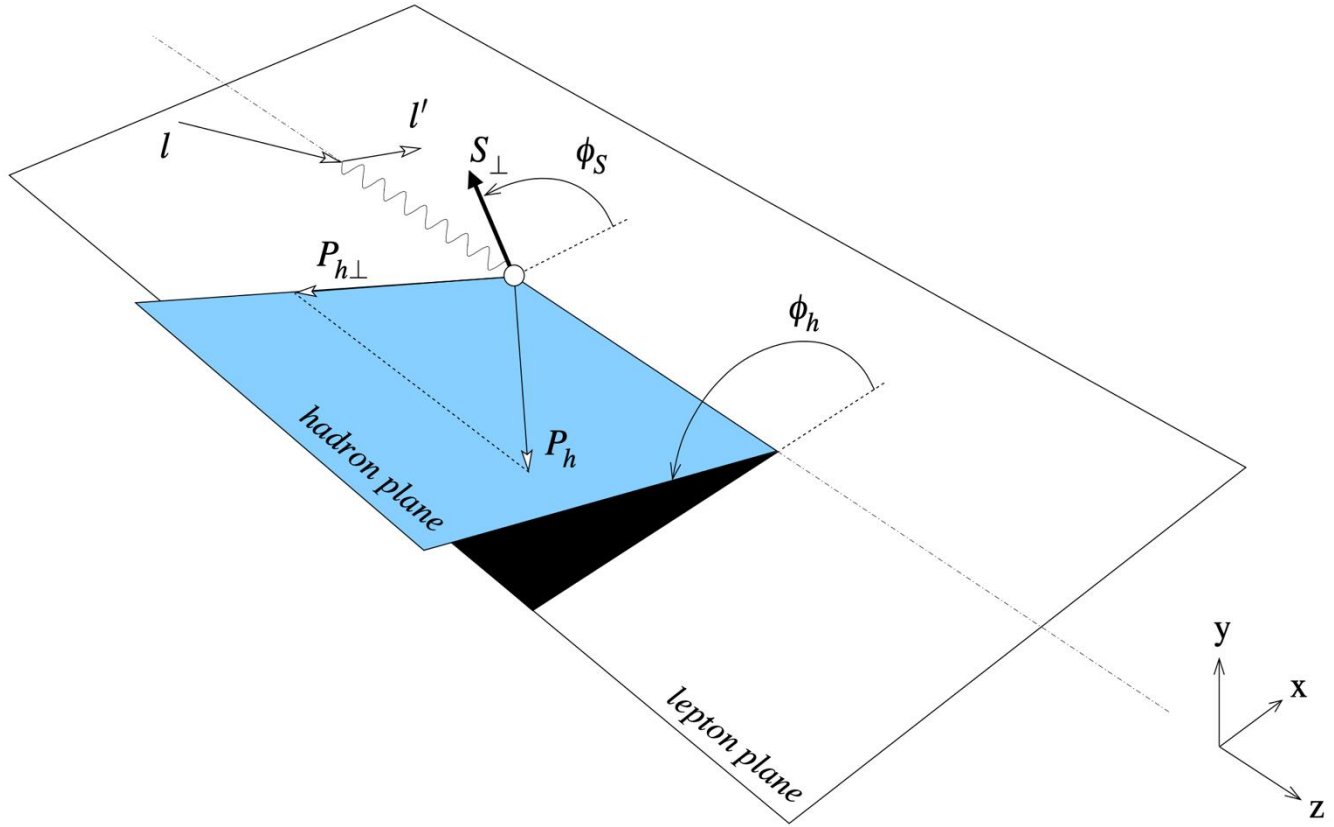
$$x_d = \frac{Q^2}{2P_d \cdot q} \qquad 0 < x_d < 1$$

$$y = \frac{P_d \cdot q}{P_d \cdot l}$$

$$z = \frac{P_d \cdot P_h}{P_d \cdot q}$$

$$\gamma = \frac{2M_d x}{Q}$$

$$x = 2x_d \qquad 0 < x < 2$$



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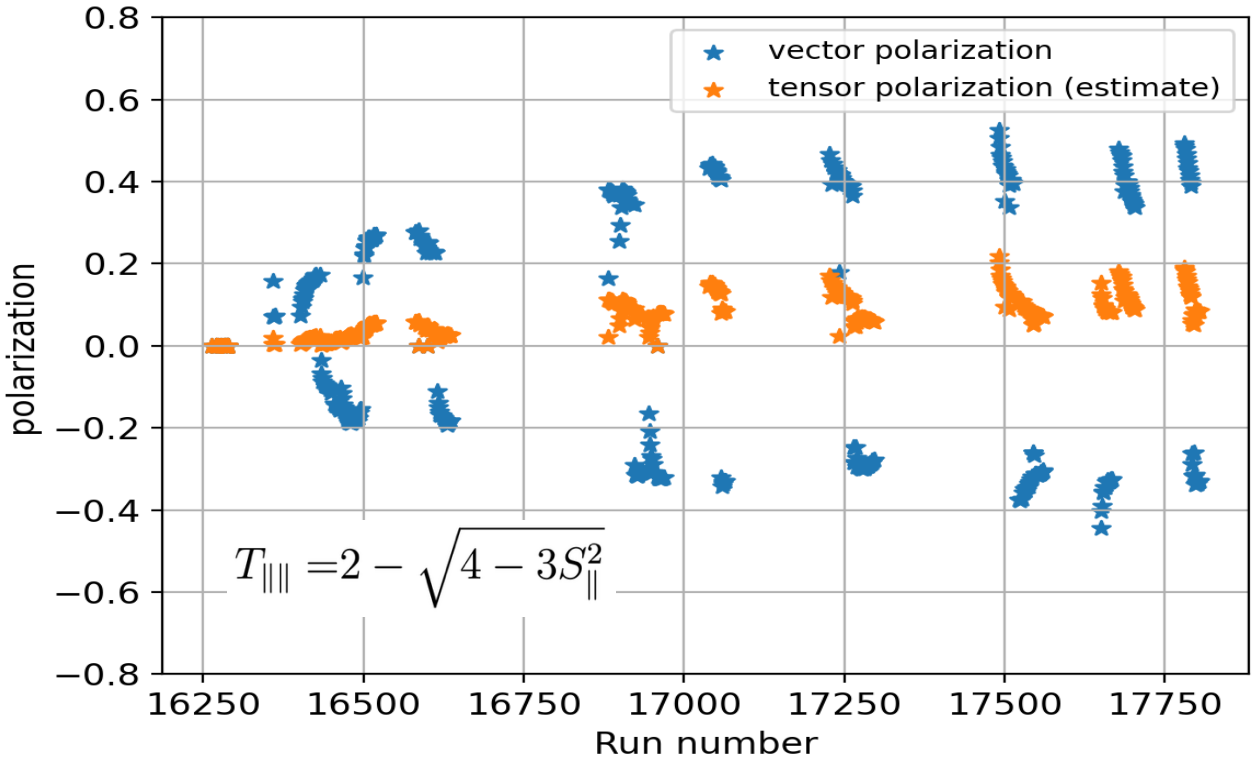

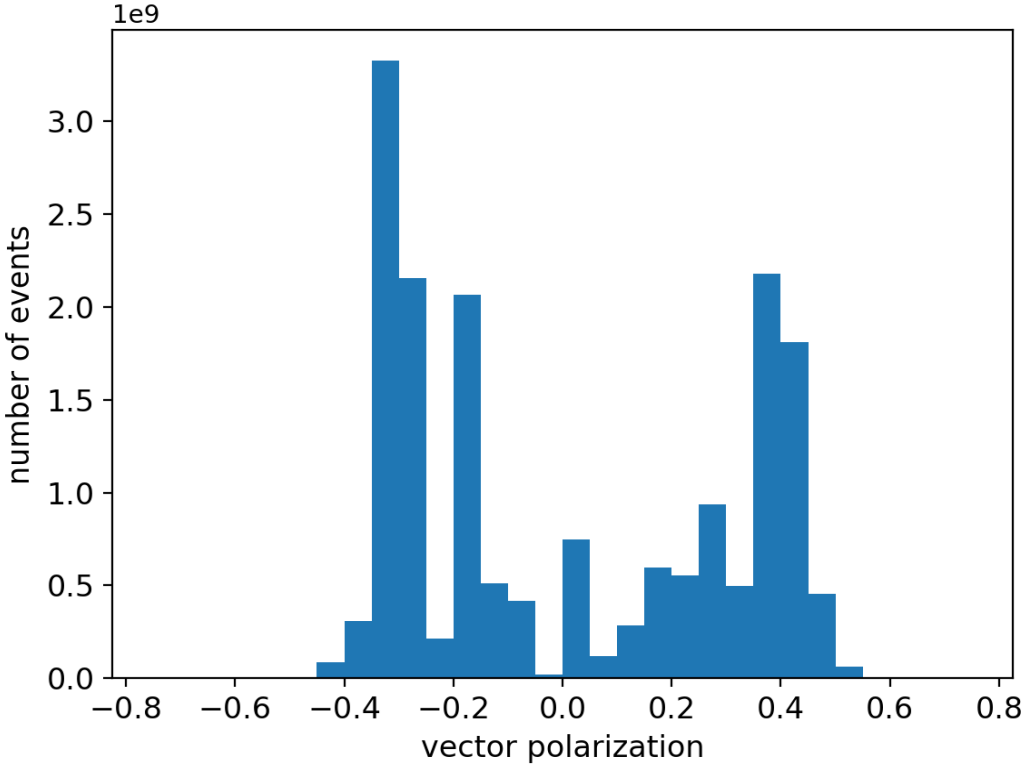

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CAA Review Report from CLAS12

Overall: The note is well written, putting forward the relevance and feasibility of the proposed analysis. The objectives, dataset and analysis strategy are well defined and realistic. The main limitation identified in this note are the large statistical and systematical uncertainties. However, the results will provide an initial guide for the rates and kinematics needed for future measurements of the structure functions in Hall C. We see no show stopper for this analysis and recommend the CAA to be approved.