Spin-1 Tensor Structure Functions

(CAA Proposal)

Jiwan Poudel

on behalf of

Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

CLAS12 Analysis Proposal

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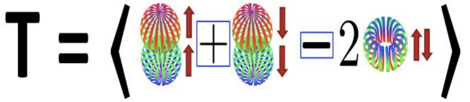
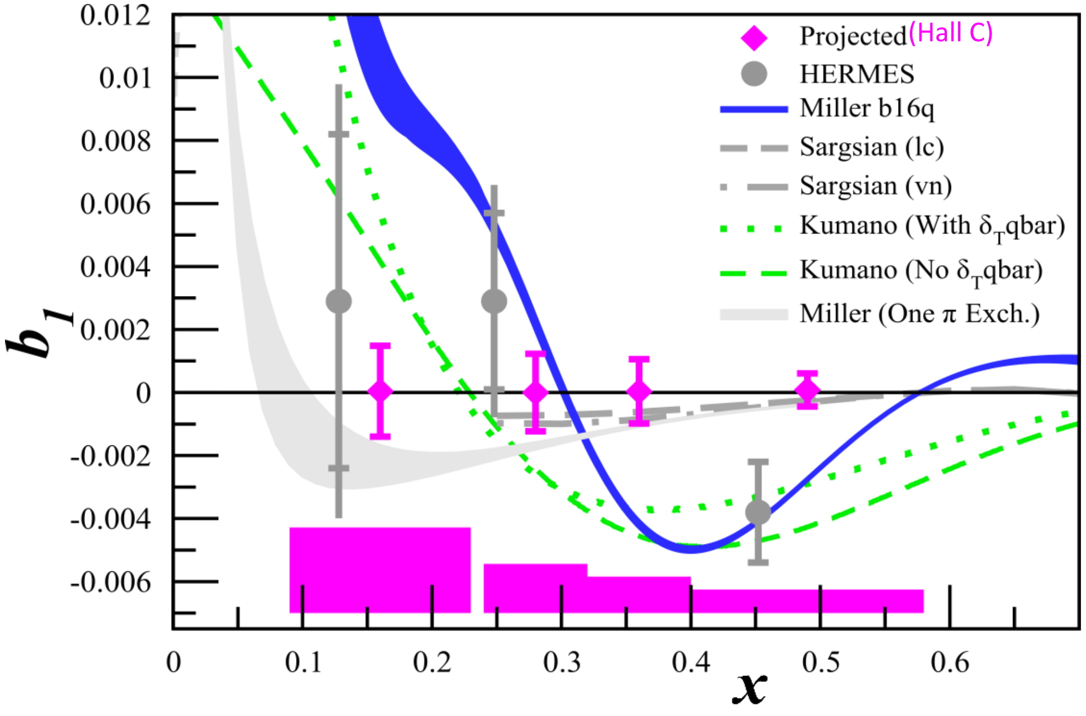
Outline

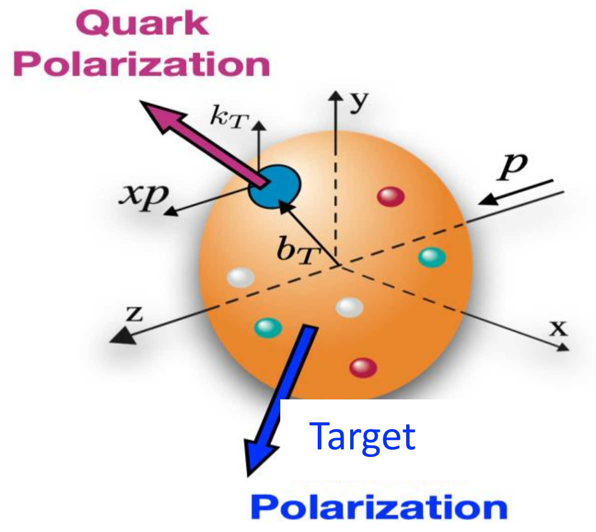
- Motivation of the study
- Tensor polarization in spin-1 target
- Tensor structure functions (Inclusive and SIDIS)
- CLAS12 data and analysis plan
- Analysis group
- Summary



Motivation of the Study

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

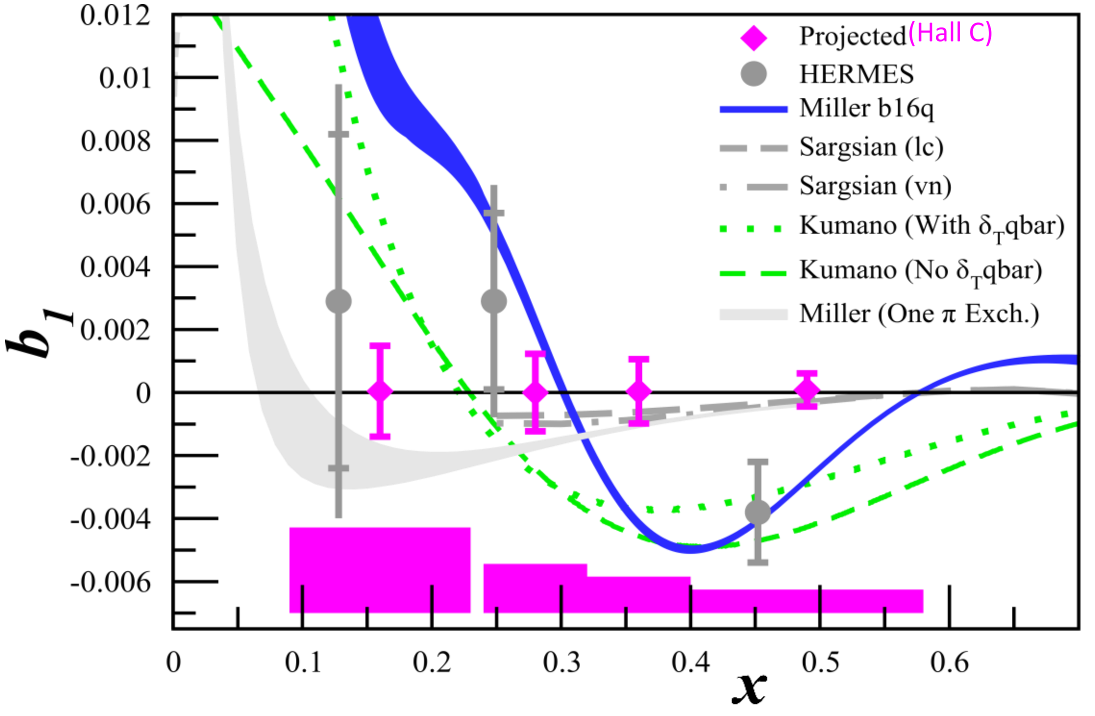


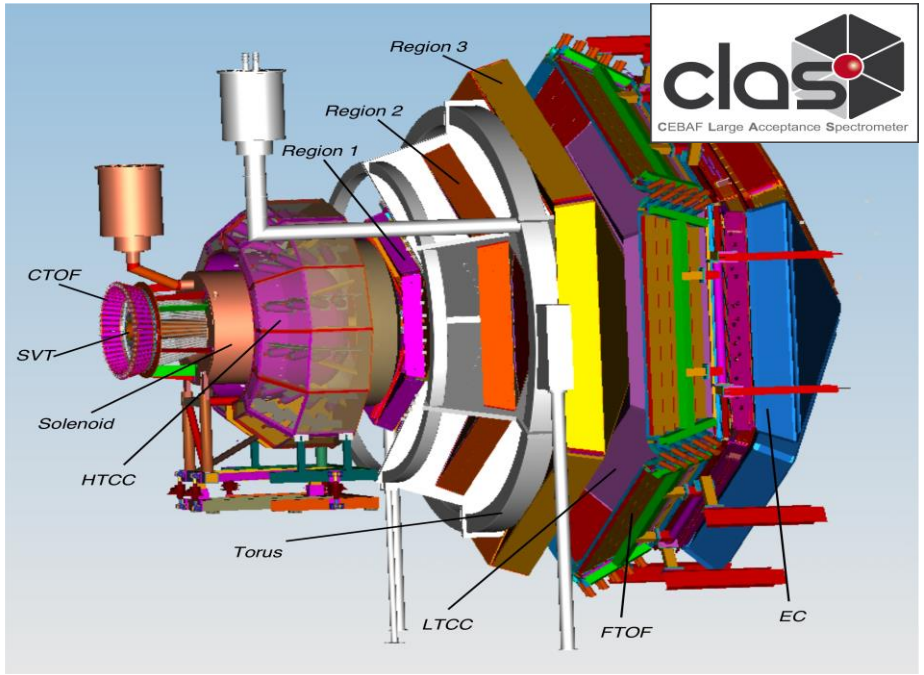


Experimental Programs

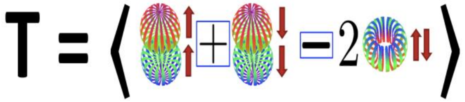
- HERMES experimental result for b_1 in 2005, but no additional experimental data
- Approved experiment for the precision measurement of b_1 in Hall C (enhanced tensor pol.)
- No experimental study/results on tensor TMDs yet

=> CLAS12 Run group C has longitudinally polarized deuteron data :: tensor polarization (following Boltzmann statistics at thermal equilibrium)





Tensor Polarization of Spin-1 System

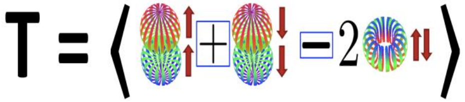


Tensor Polarization in Spin-1

- Spin-1/2 system splits into 2 energy levels in magnetic field (Zeeman effect)
  - m = +1/2 and -1/2 energy states with population n_+ and n_-
  - Vector polarization ($S_{||}$) = $(n_+ - n_-)/(n_+ + n_-)$ => $[-1 < S_{||} < 1]$

- 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 ($T_{||\,||}$) = $(n_+ + n_- - 2n_0)/(n_+ + n_0 + n_-)$ => $[-2 < T_{||\,||} < 1]$

Spin-1 Polarization

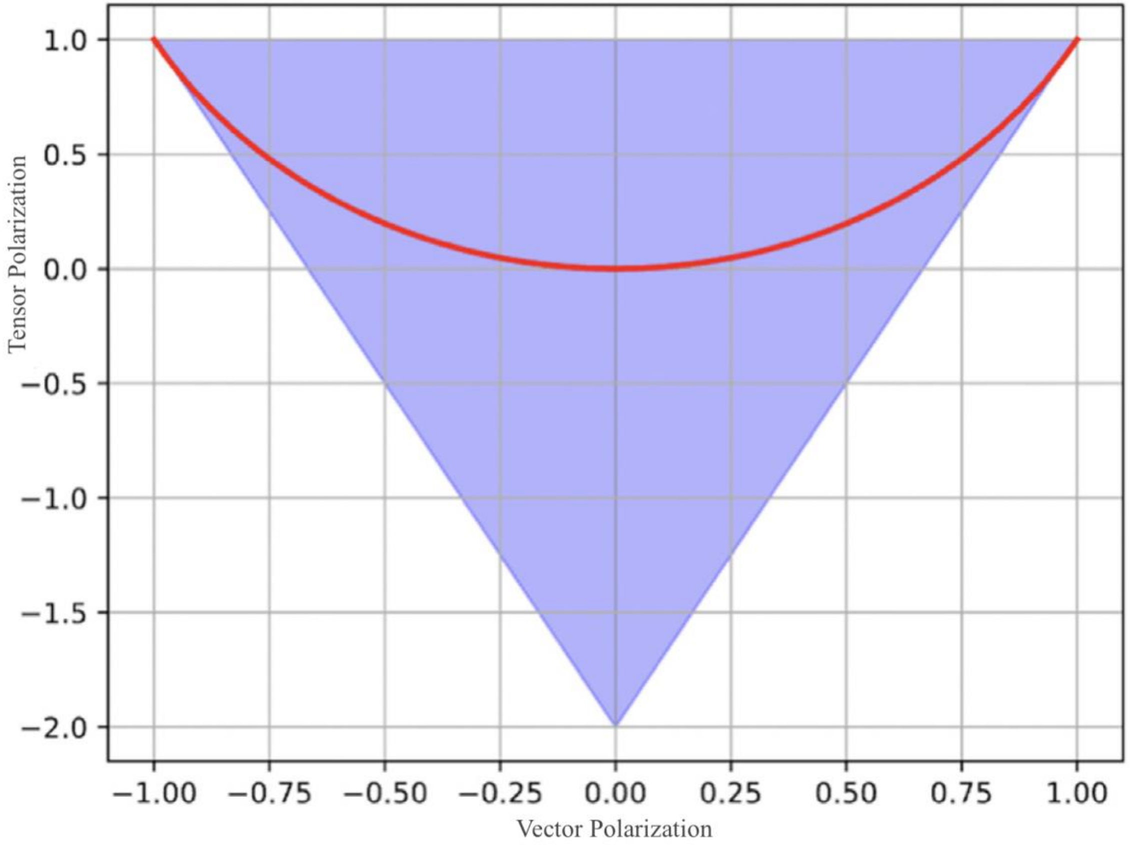


- The spin system follows the Boltzmann distribution at thermal equilibrium

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

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

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

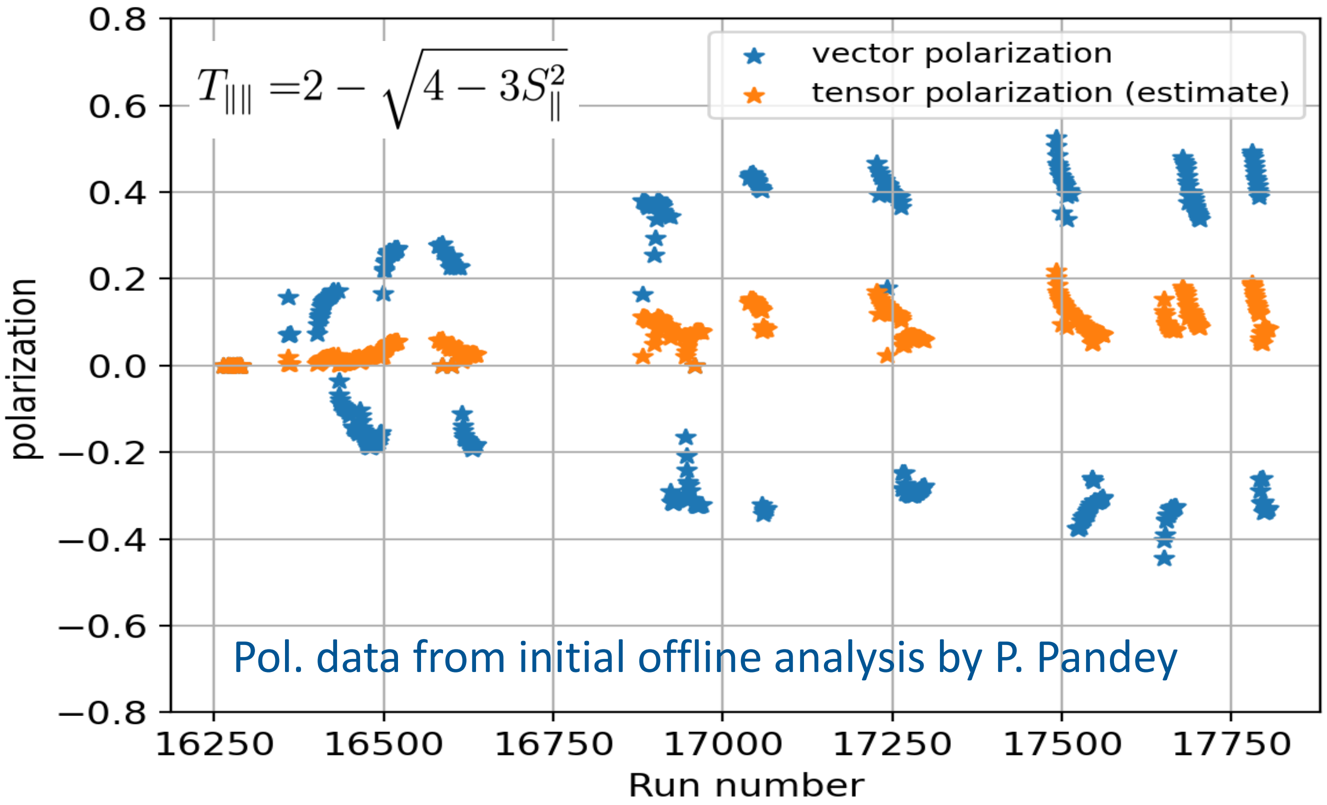


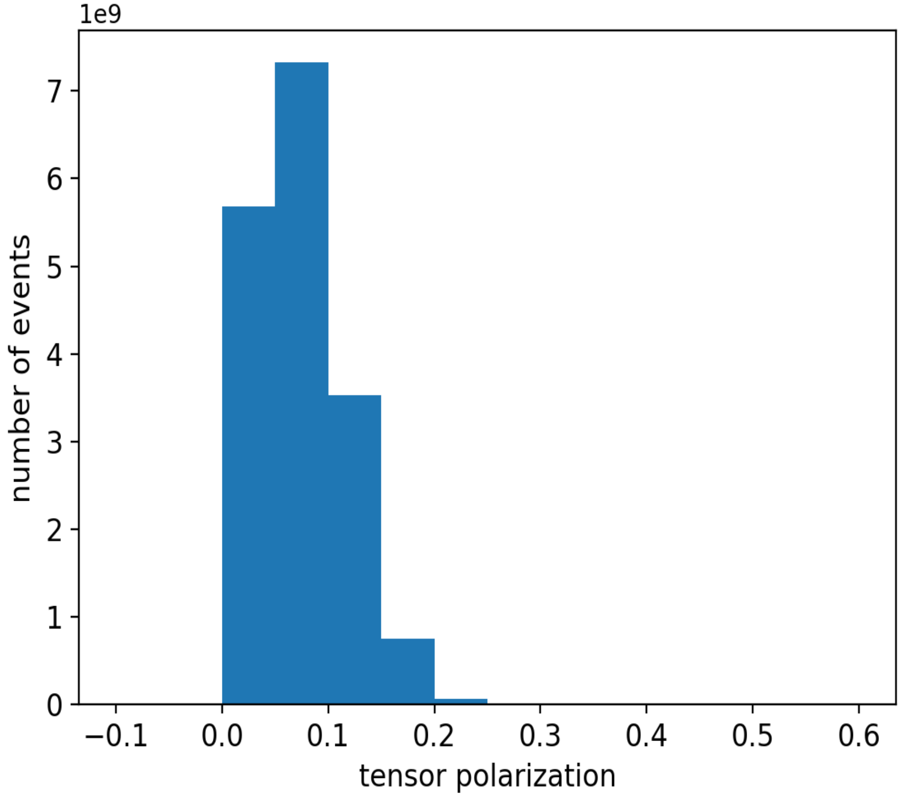
J. Clement and D. Keller, NIMA 1050 (2023)

CLAS12 RG-C Target

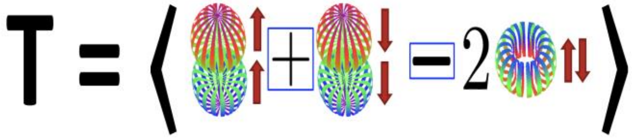
$T = \langle \ldots \rangle$

- 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

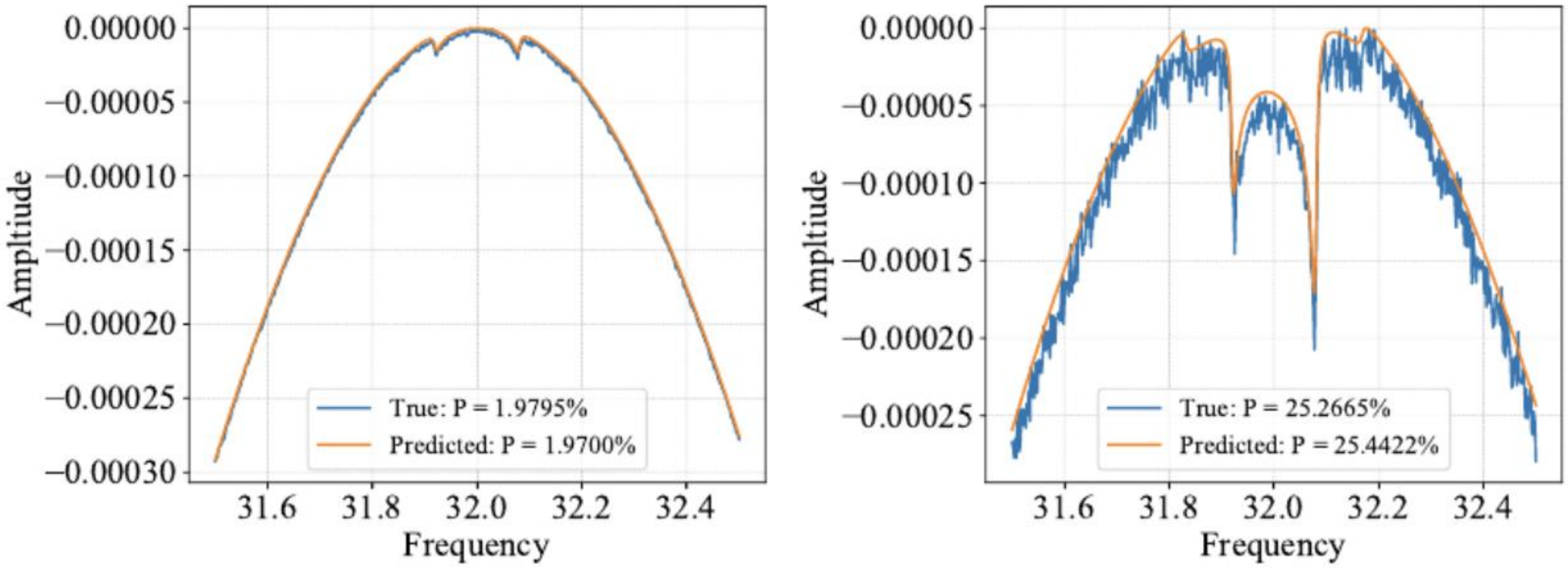




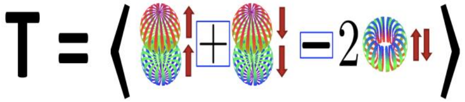
Spin-1 Polarization



- Two overlapping absorption lines in NMR spectra of deuteron
- Further work using Deep Neural Network (DNN) to extract tensor polarization directly from NMR spectra
- DNN method reduces the uncertainty in extracting the polarization significantly compared to the conventional method



DNN fitting model showing accuracy of predicted vector polarization above 99% on Monte-Carlo simulated data



Spin-1 Tensor Structure Functions

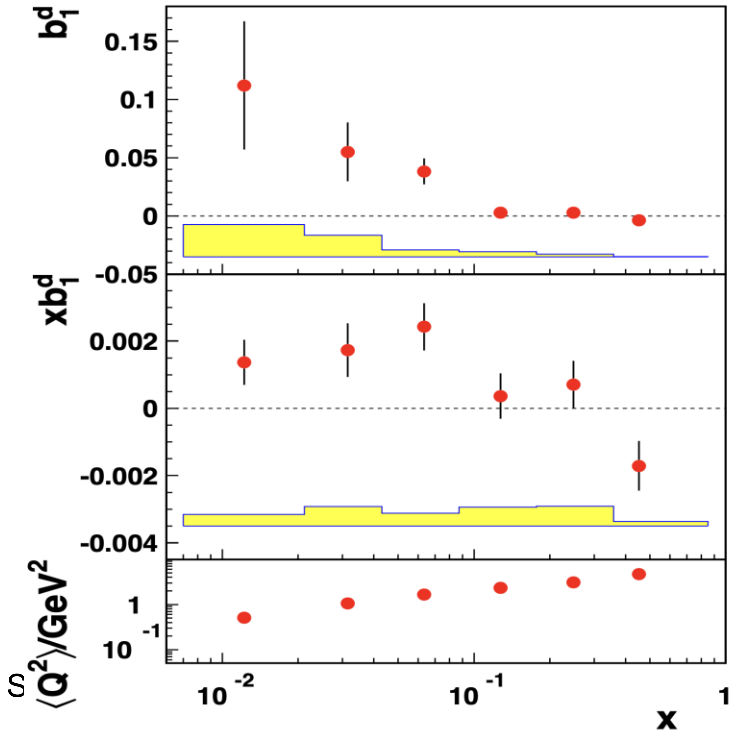
Spin-1 Structure Function: Inclusive

- 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)



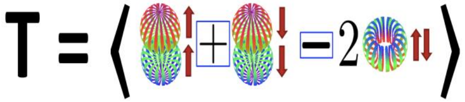
First measurement of b_1 by HERMES Collaboration (2005)

Naïve Partonic model:

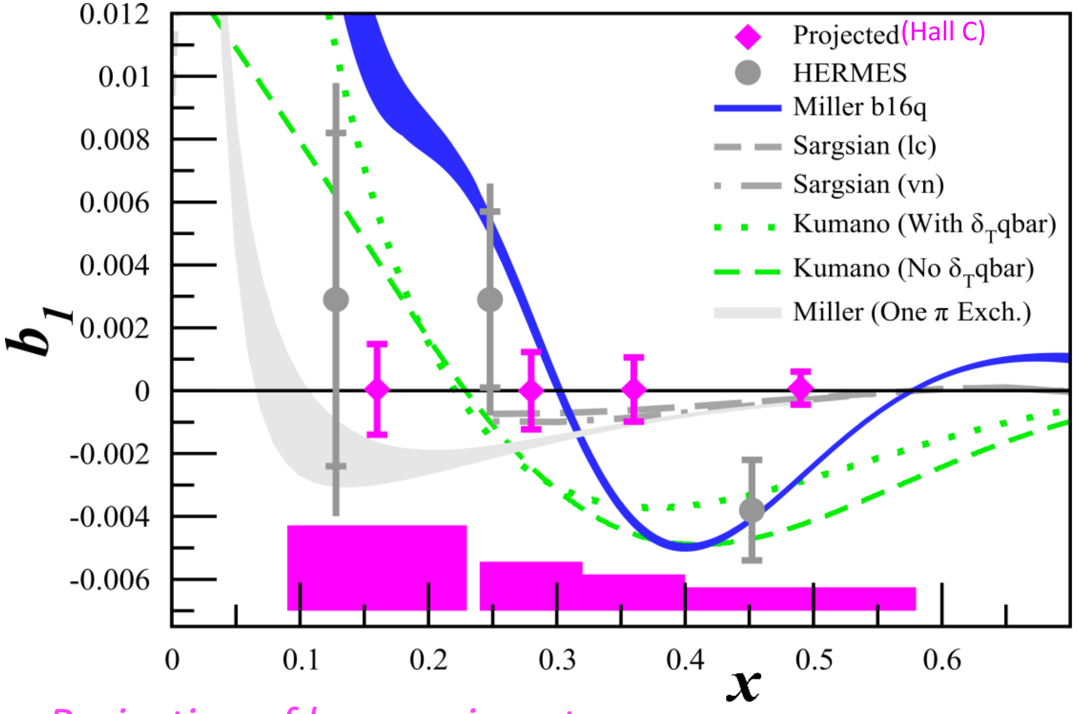
$$b_1(x) = \frac{1}{2}\left(2q_\uparrow^0(x) - q_\uparrow^1(x) - q_\downarrow^1(x)\right)$$
$$b_2(x) = 2x b_1(x)$$

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

Tensor Structure Function: Inclusive Process



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

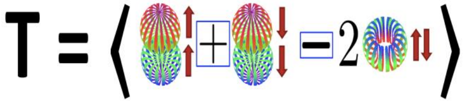


Projection of b_1 experiment approved for Hall C

Leading twist PDFs (1-D distributions)

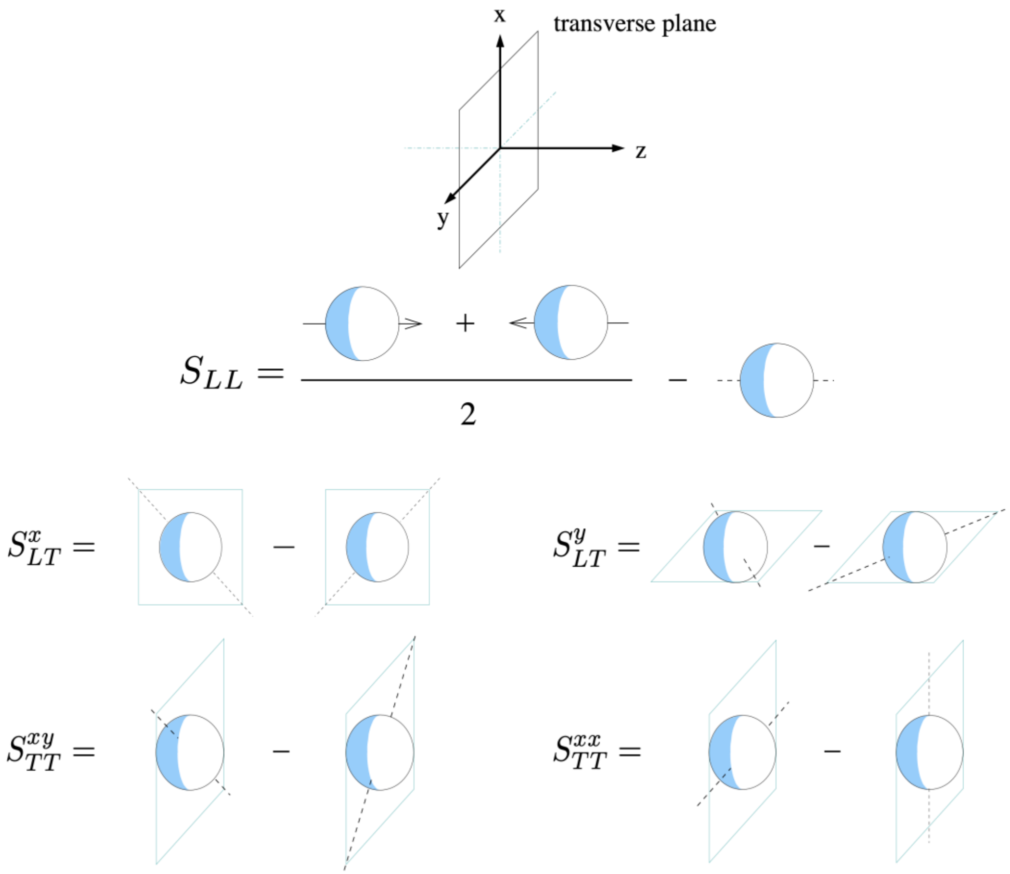
Quark / Hadron	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	T-even	T-odd	T-even	T-odd	T-even	T-odd
U	f_1					
L			$g_{1L}\,(g_1)$			
T					$[h_1]$	
LL	$f_{1LL}\,(b_1)$					
LT						*1 $[h_{1LT}]$
TT						

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



Spin-1 Tensor TMDs: SIDIS Process

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



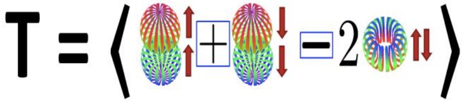
Leading twist TMDs (3-D distributions)

Hadron \ Quark	U (γ^+)		L ($\gamma^+\gamma_5$)		T ($i\sigma^{i+}\gamma_5 / \sigma^{i+}$)	
	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)

Spin-1 Tensor Structure Functions: SIDIS



- 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:

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

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

To be Published

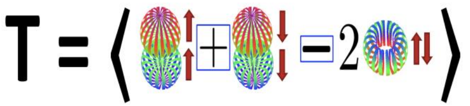
A. Bacchetta (2023)

Tensor Polarization:

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

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

Spin-1 Tensor Structure Functions: SIDIS



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

To be Published

A. Bacchetta (2023)

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

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

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

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

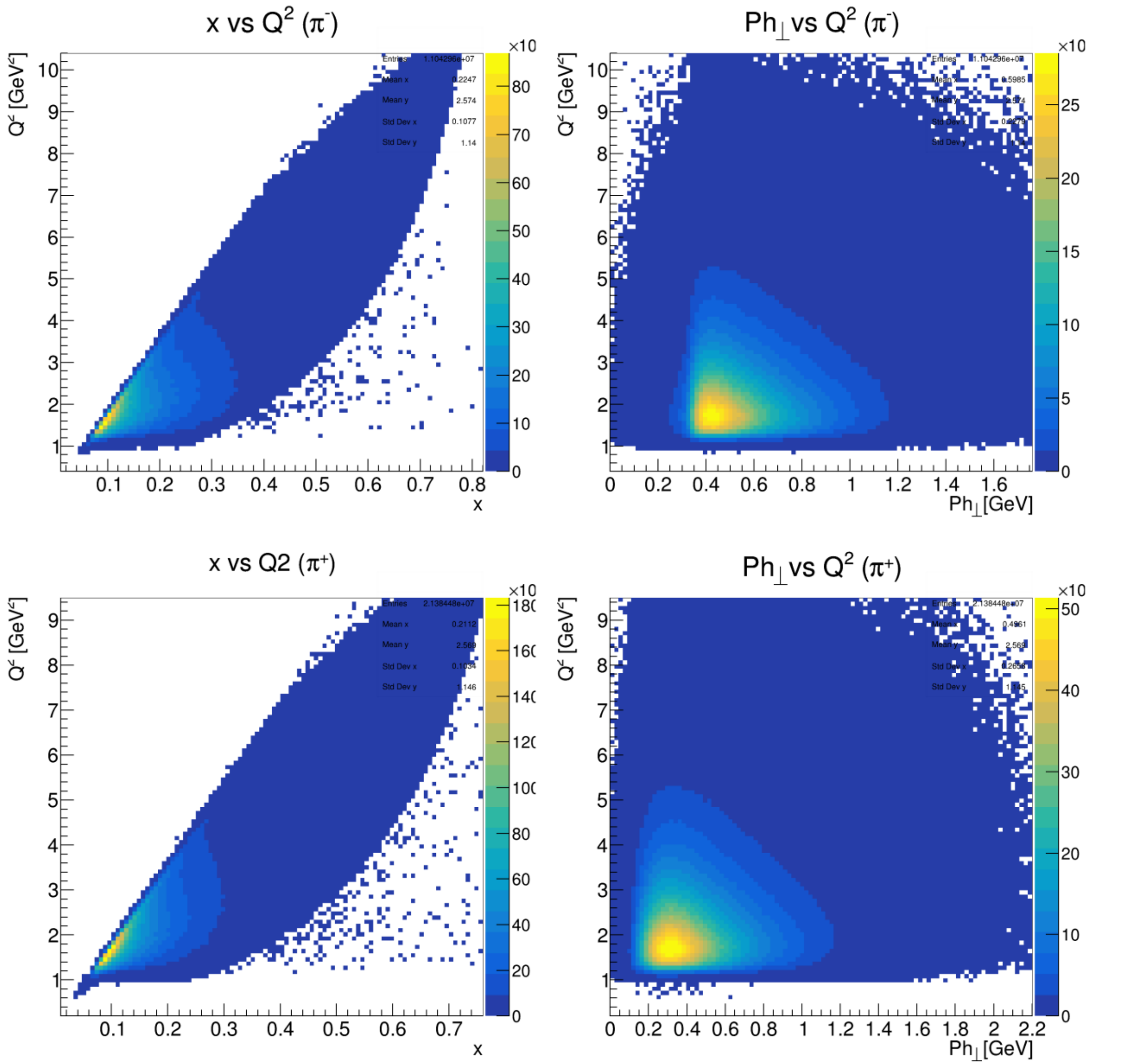
$$F_{L(LL)}^{\sin\phi_h} = \frac{2M}{Q} C\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(x e_{LL} H_1^{\perp} + \frac{M_h}{M} f_{1LL} \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(x g_{LL}^{\perp} D_1 + \frac{M_h}{M} h_{1LL}^{\perp} \frac{\tilde{E}}{z}\right)\right]$$

CLAS12 Data and Analysis Plans

CLAS12 Data

- 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

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

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

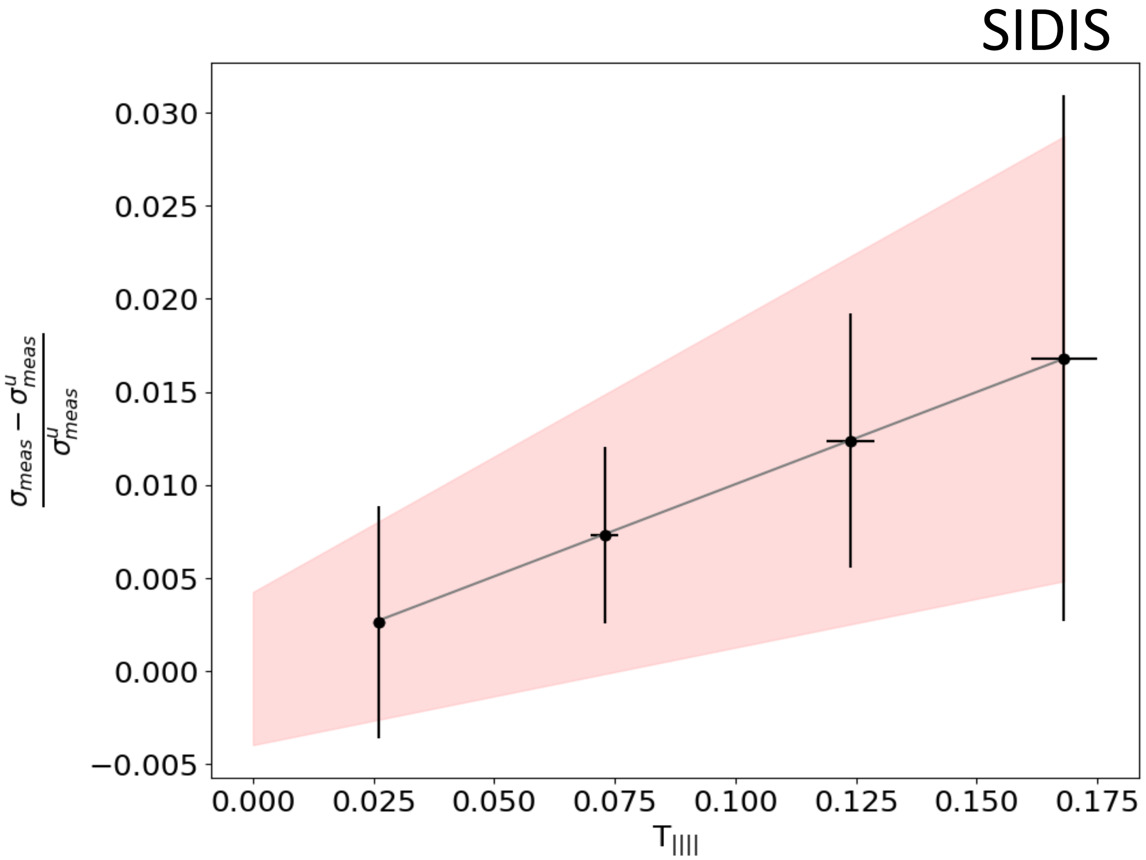
SIDIS

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

- Angular modulation to extract different tensor structure functions

Tensor Structure Function: Estimation

- 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



Active Group Members

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Ishara P. Fernando
(Target + CLAS12)

UNIVERSITY of VIRGINIA

Spin 1 Transverse Momentum Dependent Tensor Structure Functions in CLAS12

CLAS12 Analysis Proposal

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Elena Long
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(Target + Tensor exp.)

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(Theory)

UNIVERSITÀ DI PAVIA

+ graduate students

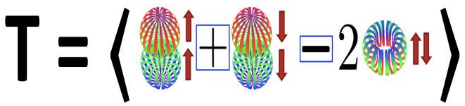
University of New Hampshire

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

Jefferson Lab

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.



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
- 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: our group is expanding

We would like to invite everybody interested in this tensor Physics to join us on this effort !!!

Spin-1 Tensor TMDs: SIDIS

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

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

- Kinematics

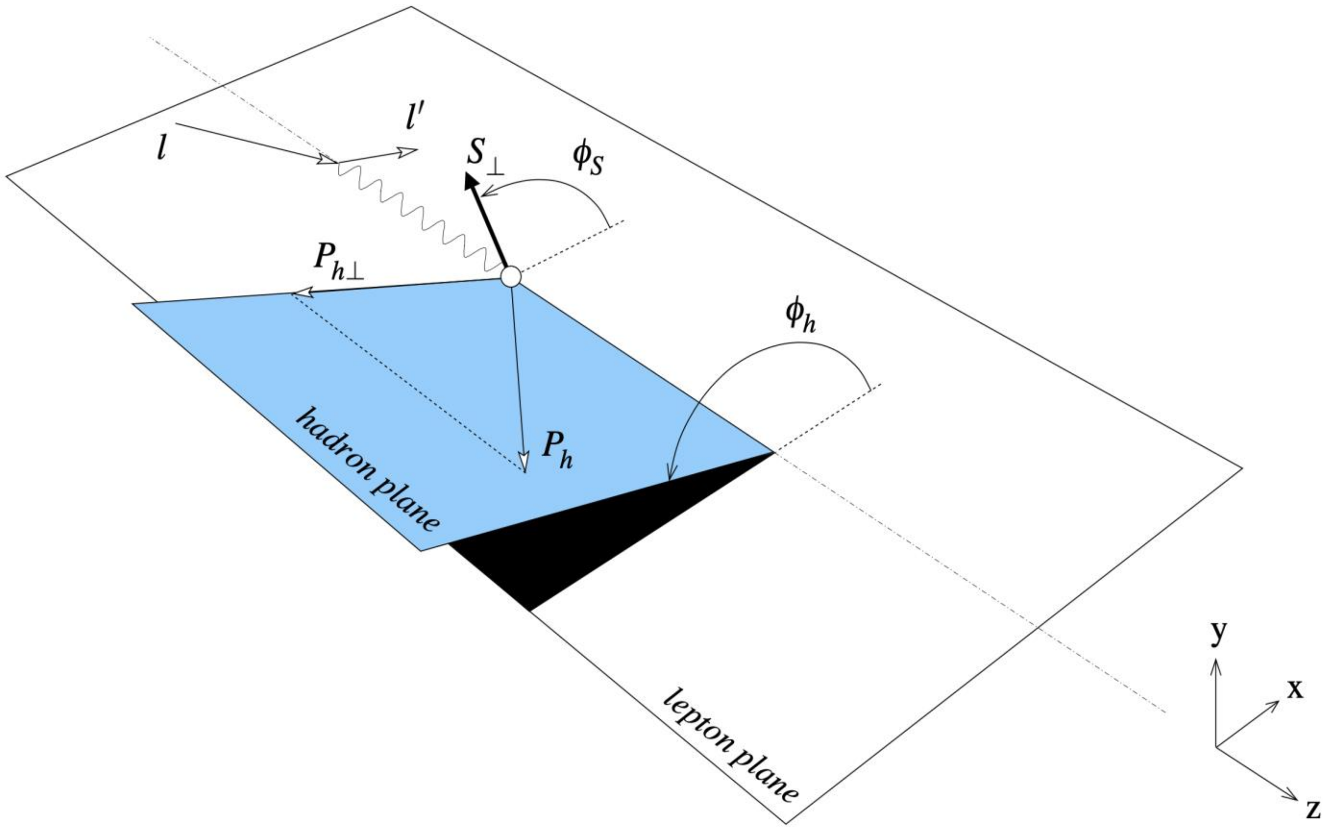
$$x_d = \frac{Q^2}{2P_d \cdot q} \qquad 0 < x_d < 1$$

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

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

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

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



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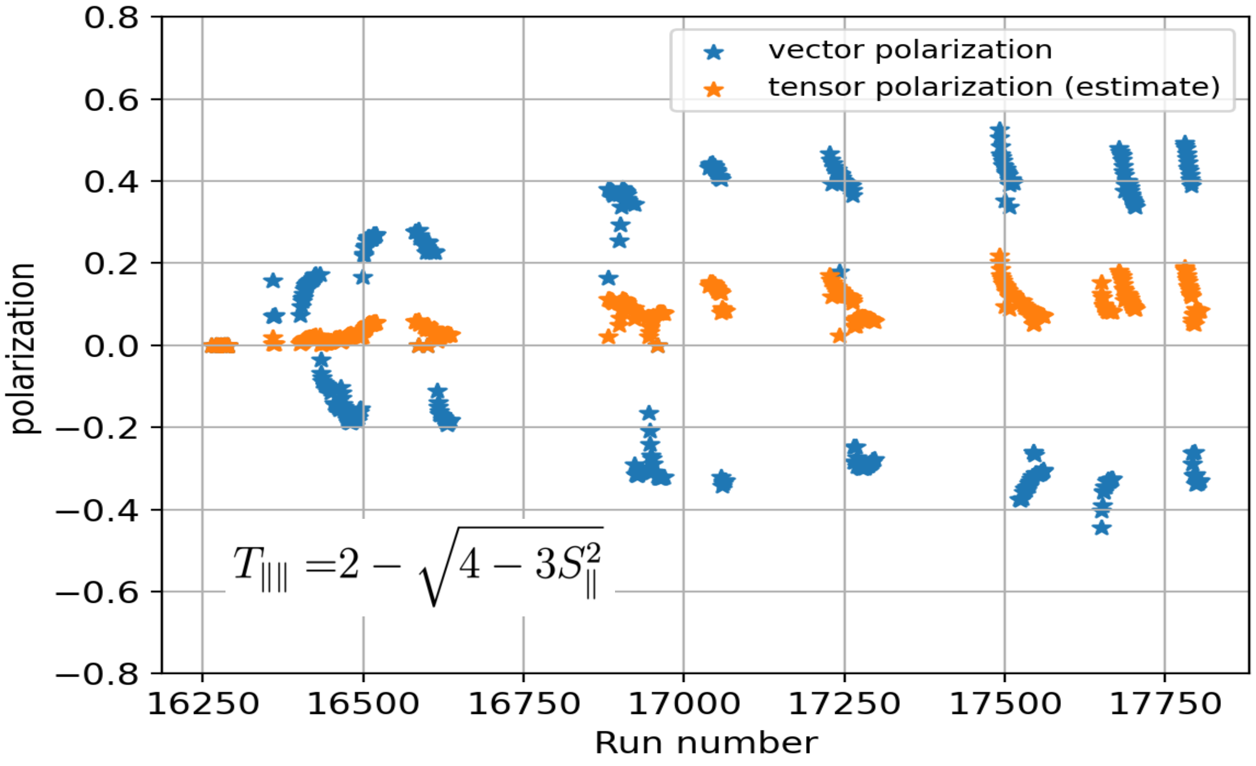

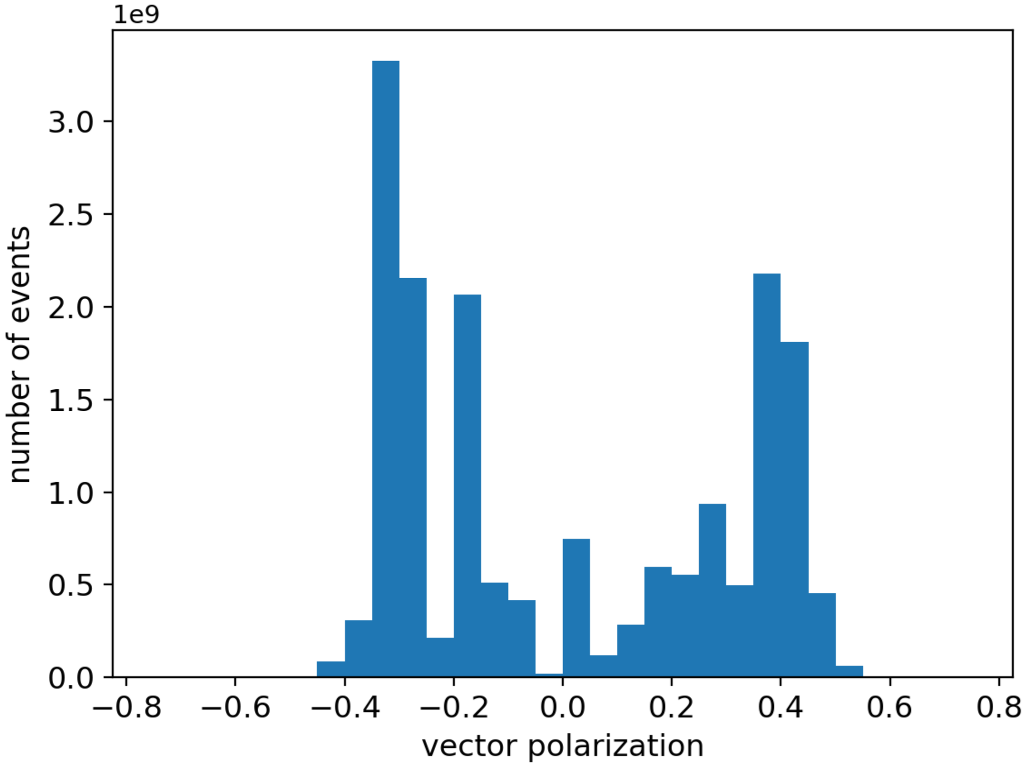

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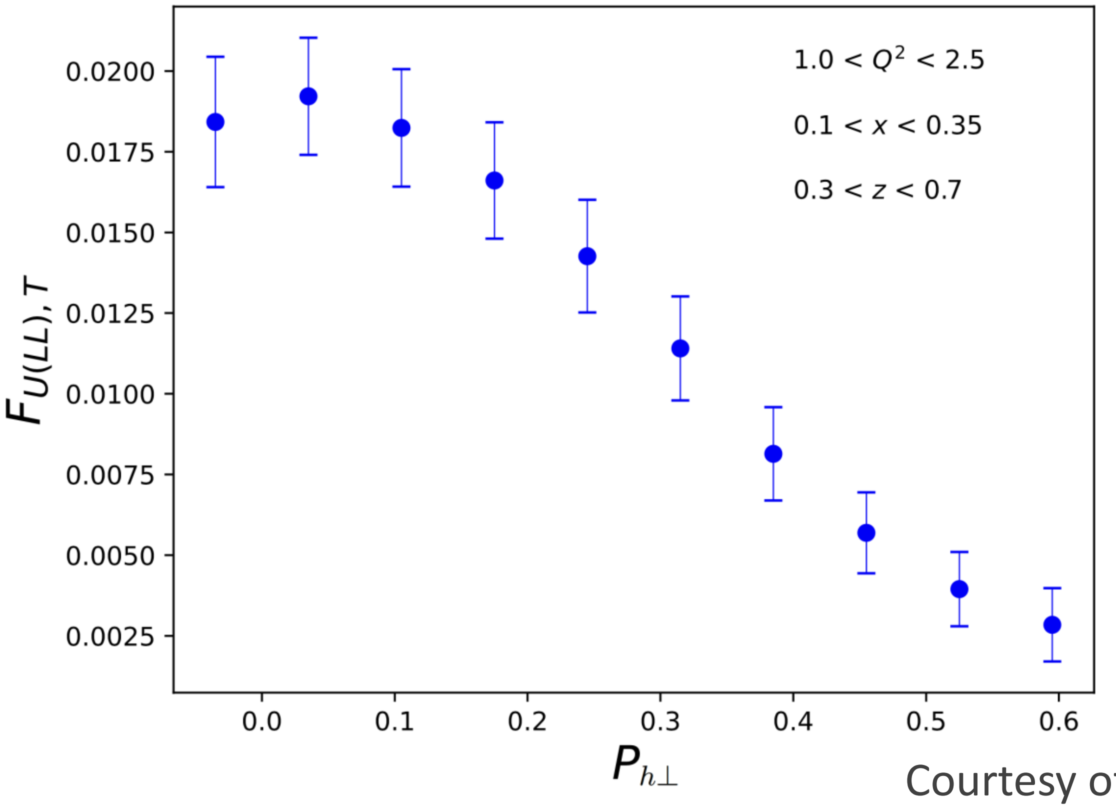
Backup

- 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 $F_{UU,T}$

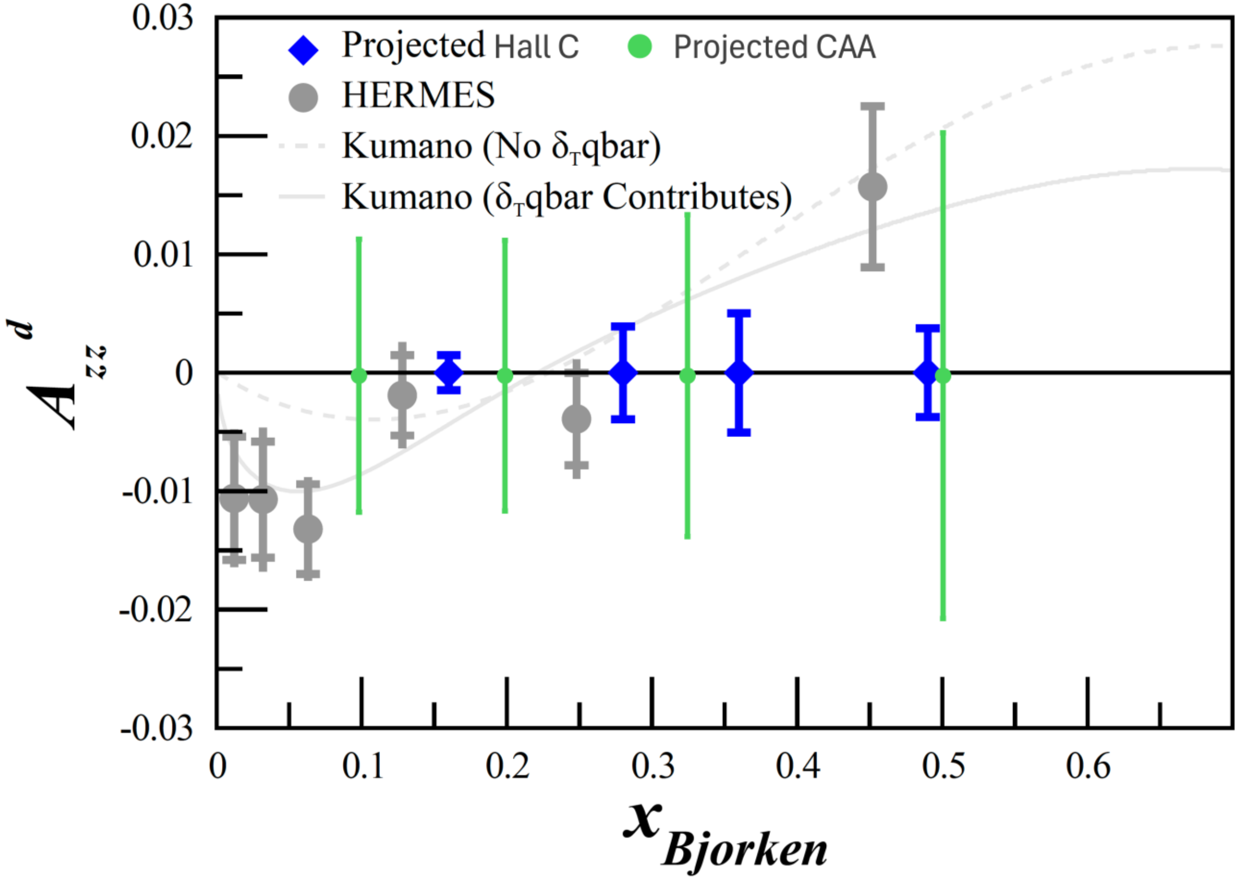


Courtesy of D. Ruth

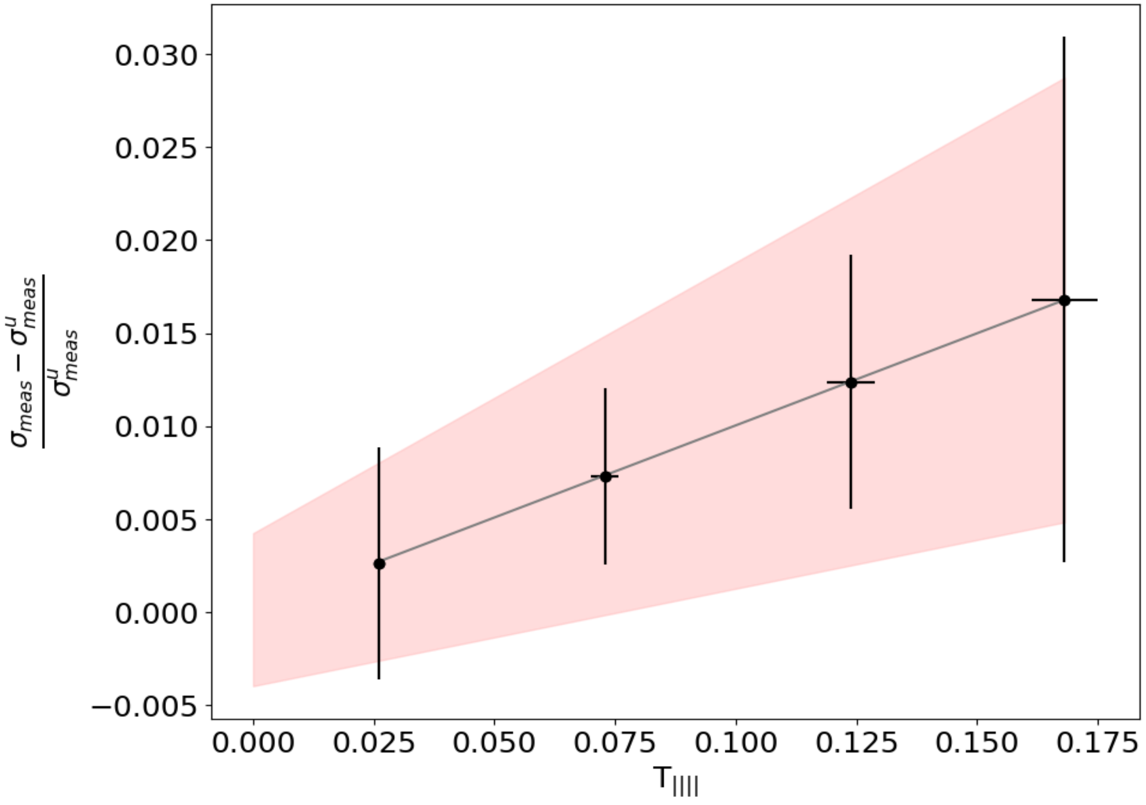
Backup

- Expected result from Inclusive and SIDIS analysis of CLAS12 RGC data

Inclusive



SIDIS



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