Tensor TMDs and Structure Functions

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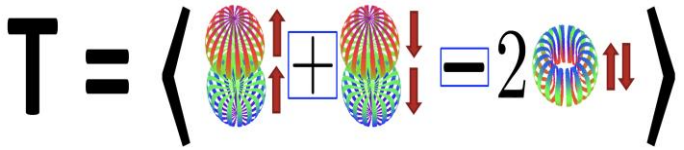
Outline

- Tensor polarization
- Tensor TMDs and Structure functions
- Planning and Preparation for tensor TMDs
- Summary

Tensor Polarization

- 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 $(S_{||}) = (n_+ - n_-)/(n_+ + n_-)$ => $[-1 < S_{||} < 1]$



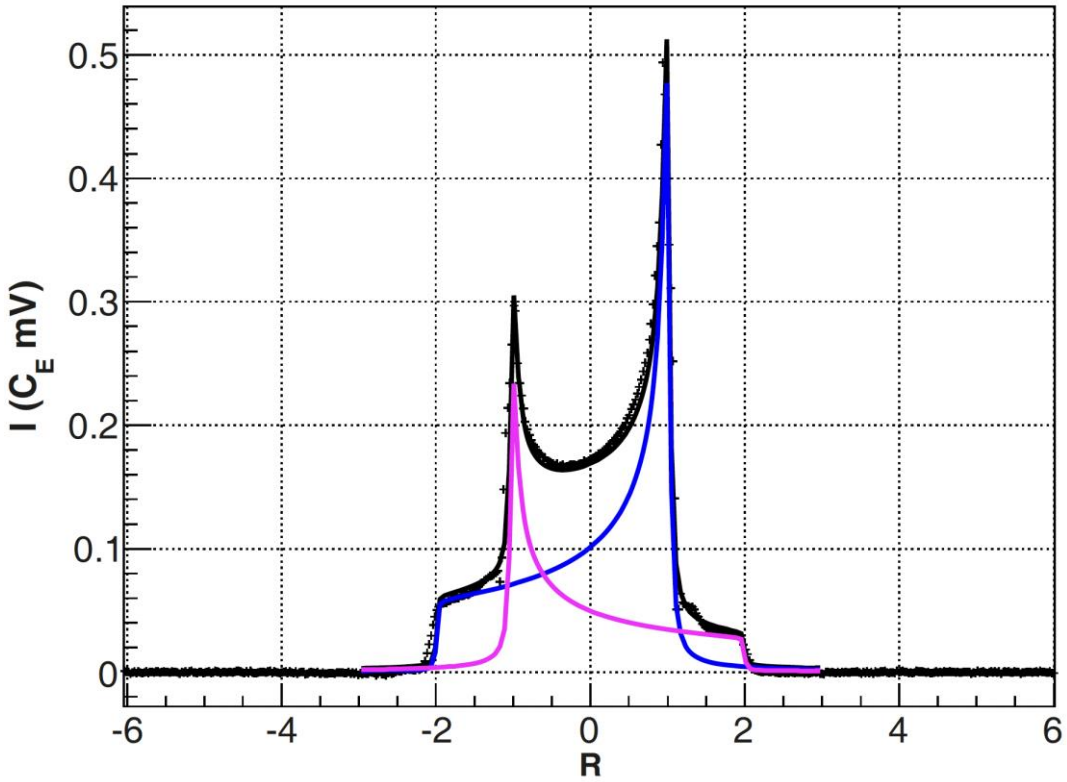
- Spin-1 system splits into 3 energy levels in magnetic field
  - m = +1 , 0 and -1 energy states with population n_+, n_0 and n_-
  - Vector polarization $(S_{||}) = (n_+ - n_-)/(n_+ + n_0 + n_-)$
  - Tensor polarization $(T_{|| ||}) = (n_+ + n_- - 2n_0)/(n_+ + n_0 + n_-)$ => $[-2 < T_{|| ||} < 1]$

Spin-1 Polarization

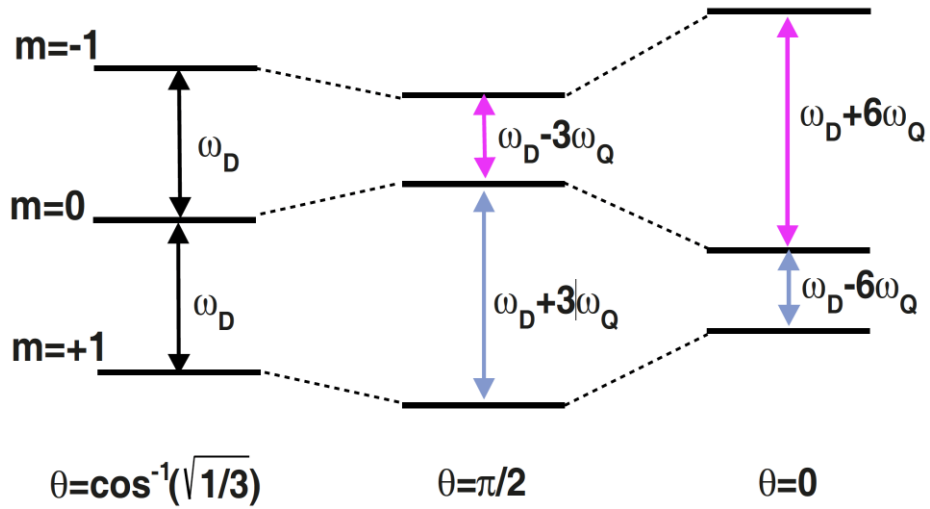
- Shift in energy level due to deuteron quadrupole moment ($\hbar\omega_D$: Zeeman and $\hbar\omega_Q$: quadrupole energy)

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

- Two overlapping absorption lines in NMR spectra



$$R=\frac{\omega - \omega_D}{3\omega_Q}$$



Polarization based on absorption line Intensity (I):

Vector Polarization ($S_{||}$) = $C_E(I_+ + I_-)$

Tensor Polarization ($T_{||\,||}$) = $C_E(I_+ - I_-)$

D. Keller, EPJA 53 (2017)
D. Keller, D. Crabb and D. Day, NIMA 981 (2020)
J. Clement and D. Keller, NIMA 1050 (2023)

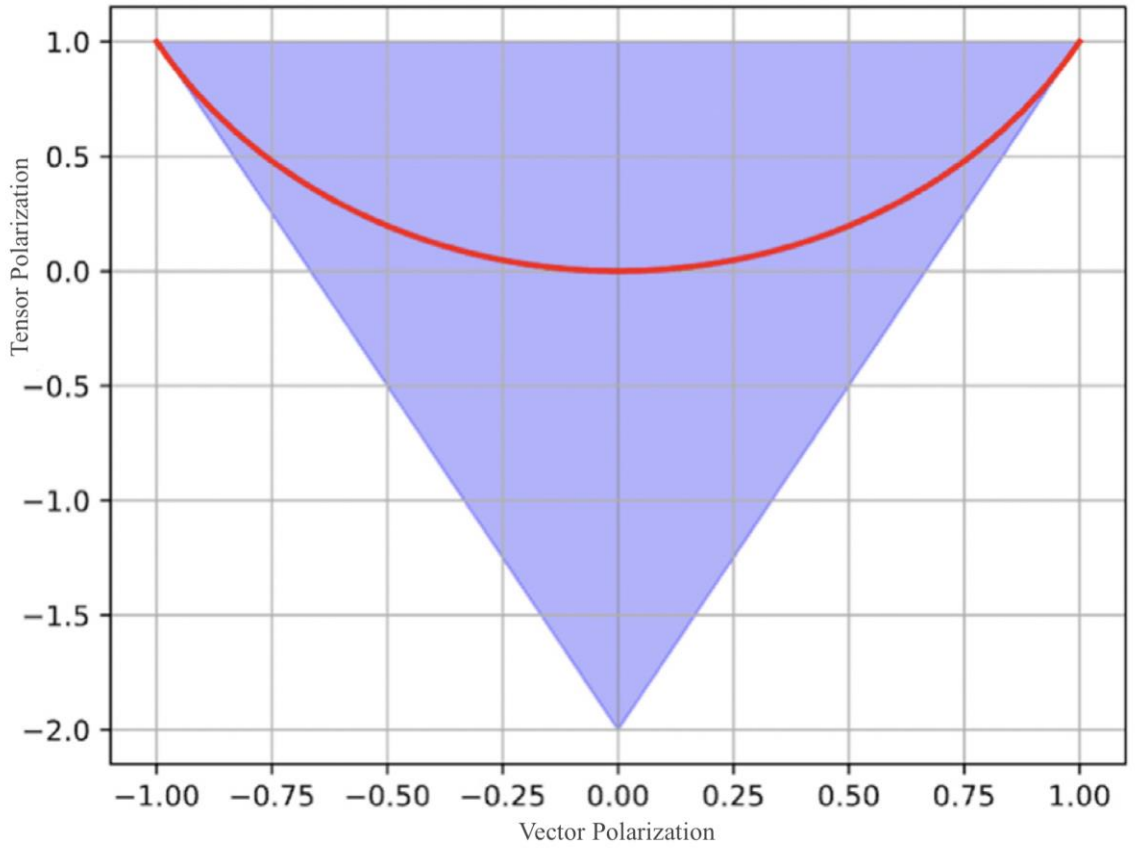
Spin-1 Polarization

- The spin system follows the Boltzmann distribution at thermal equilibrium

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

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

- Vector pol. of 50% corresponds to 19.7% of Tensor pol. with Dynamic Nuclear Polarization(DNP)



D. Keller, EPJA 53 (2017)
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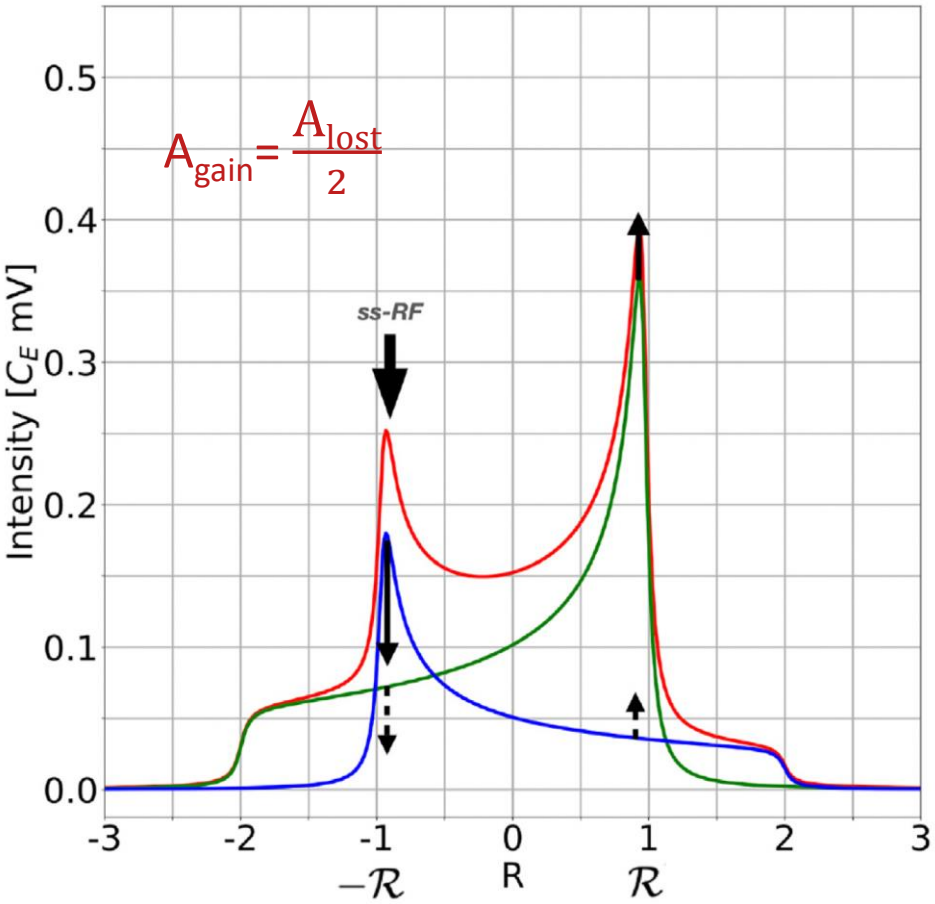
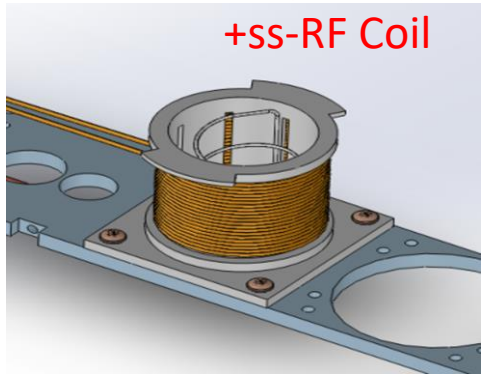
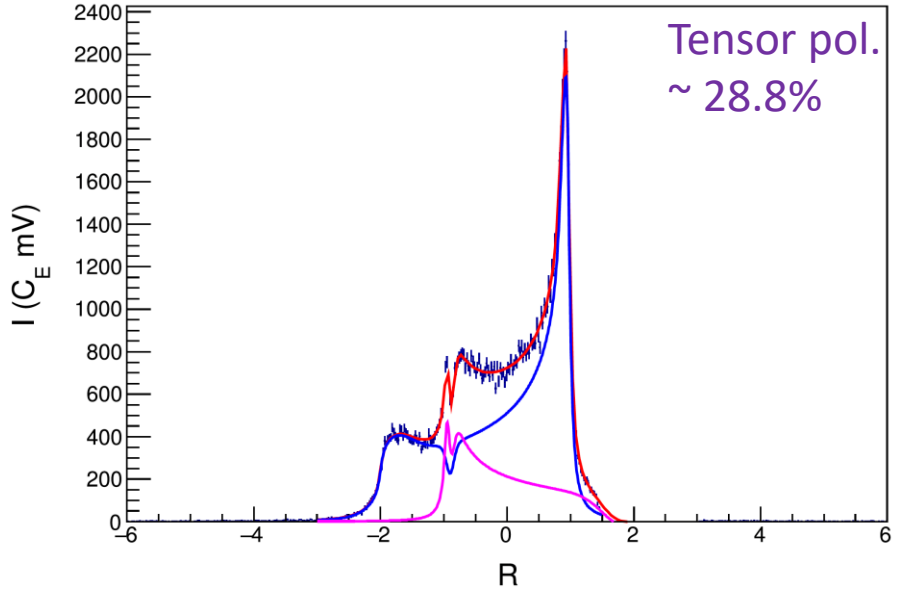
Tensor Polarization Enhancement

- Tensor enhancement via Dynamic Nuclear Polarization (DNP) + semi-saturating RF (ss-RF)

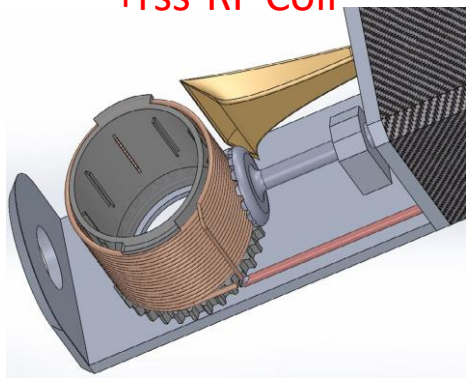


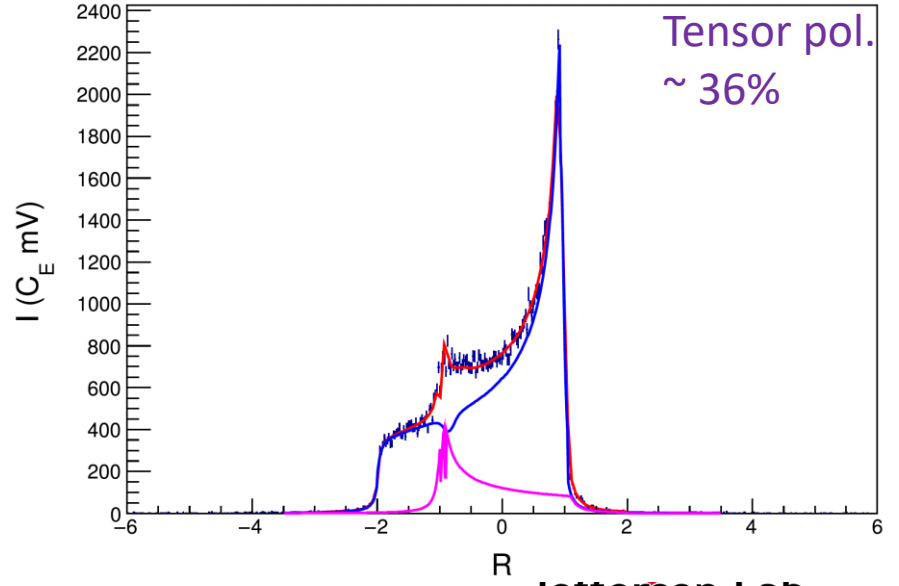
Target Cup
+ss-RF Coil





Target Cup
+rss-RF Coil





D. Keller, EPJA 53 (2017)
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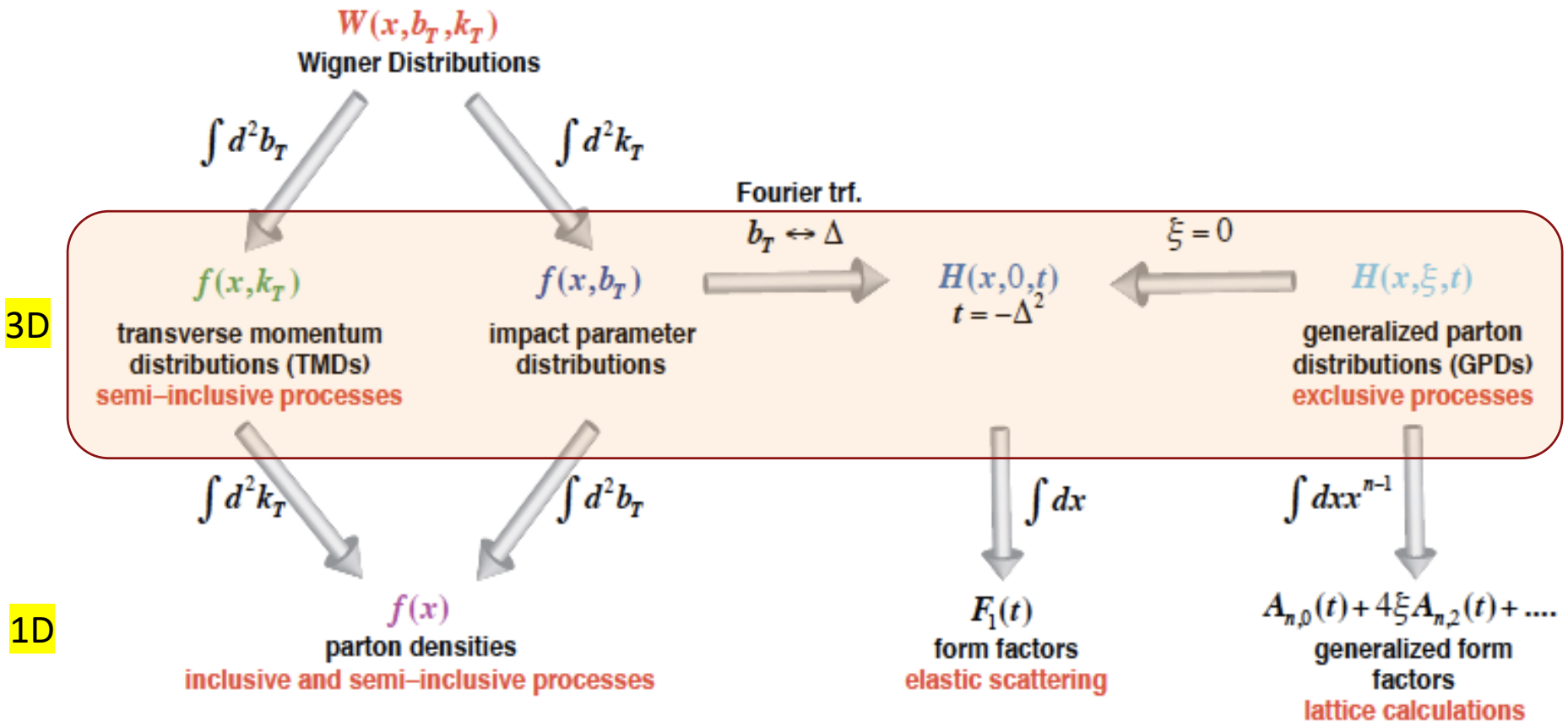
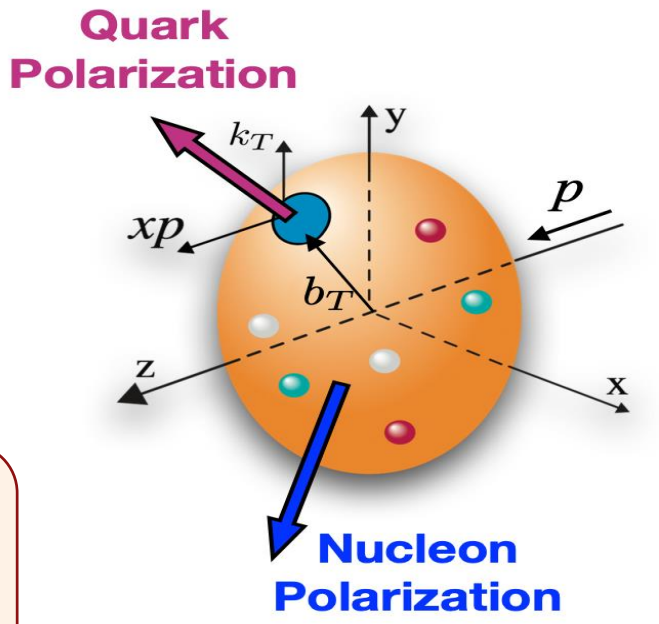
Tensor TMDs: Introduction

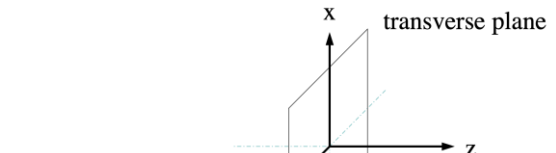
- Nucleon tomography





Spin-1 Tensor TMDs: distribution functions

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



$$S_{LL} = \frac{\rightarrow\ +\ \leftarrow}{2} - \quad S^{x}_{LT} = - \quad S^{y}_{LT} = -$$

$$S^{xy}_{TT} = - \quad S^{xx}_{TT} = -$$

Leading twist TMDs

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

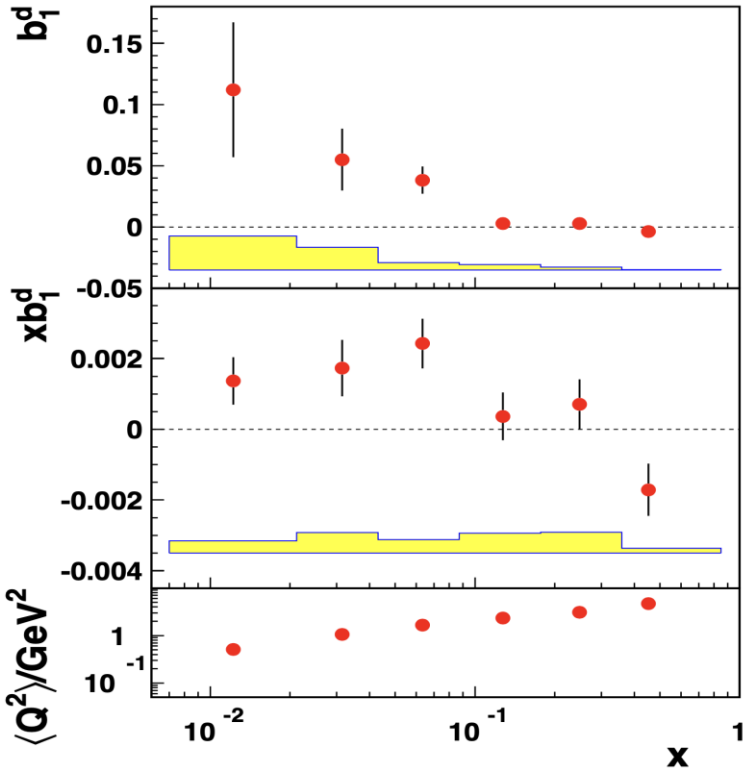
- These functions have never been experimentally studied
- Integral over transverse momenta provides PDFs

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

Tensor Structure Function: Inclusive process

- Inclusive process (tensor structure function):
  - ➢ b_1 structure function of deuteron studied experimentally in HERMES (non-vanishing b_1) -> admixture of S and D- state

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



First measurement of b_1 by HERMES Collaboration (2005)

Leading twist PDFs

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						

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

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

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

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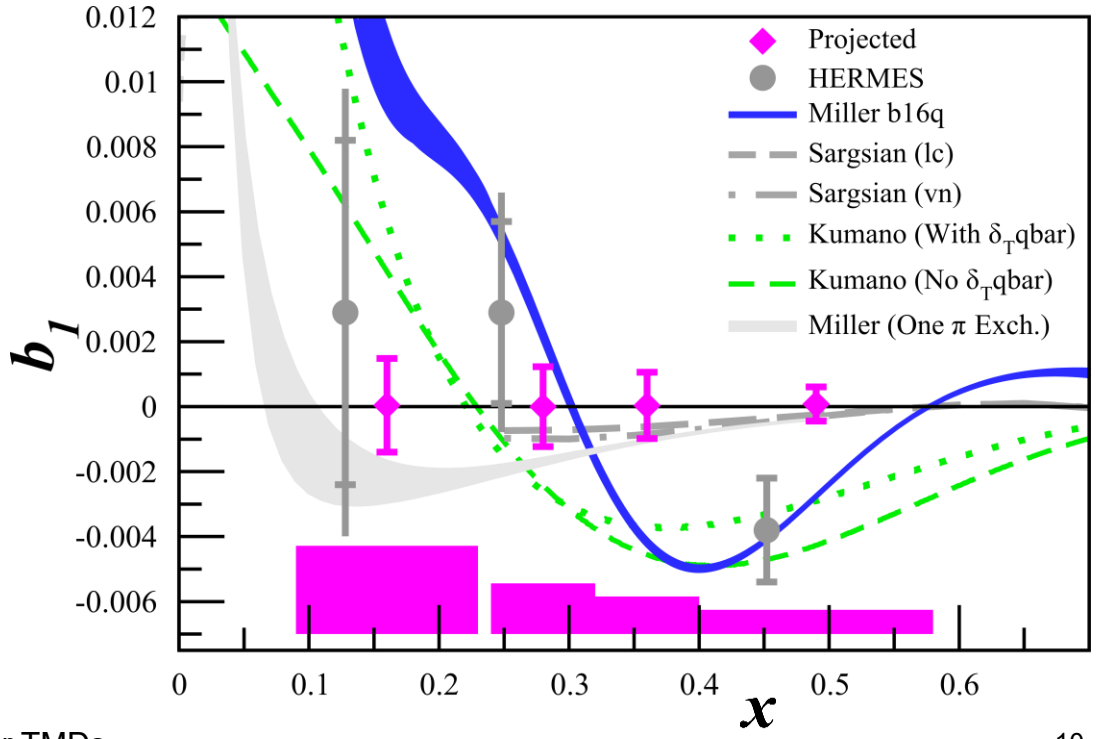
Tensor Structure Function: Inclusive process

- Inclusive process (tensor structure function):
  - ➢ New Tensor experiment approved in Hall-C
  - ➢ higher statistics around zero-crossing region
- $$b_1(x) = \frac{1}{2}\left(2q^0_\uparrow(x) - q^1_\uparrow(x) - q^1_\downarrow(x)\right)$$
  $$b_2(x) = 2x b_1(x)$$



Projection of New b_1 experiment in Hall C

Leading twist PDFs

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)

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Spin-1 Tensor TMDs: 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:

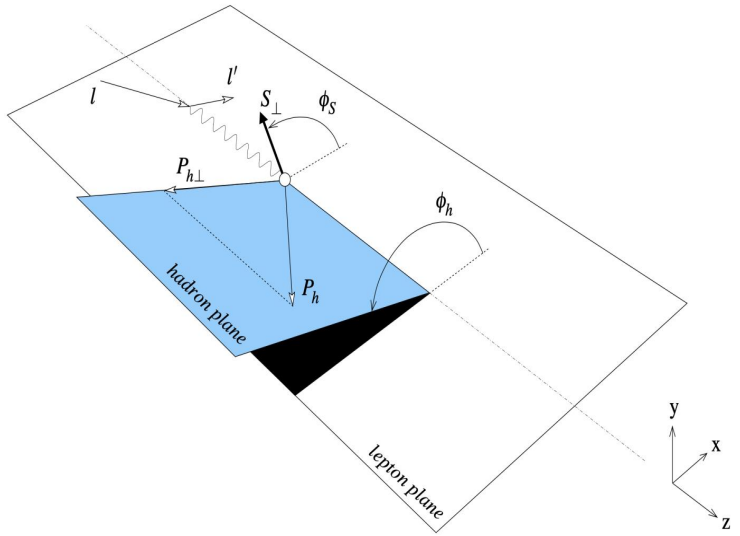
$$+ S_\parallel\left\{\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h\ F_{UL}^{\sin\phi_h} + \epsilon\sin(2\phi_h)\ F_{UL}^{\sin 2\phi_h}\right\}$$

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

Tensor Polarization:

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

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



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

A. Bacchetta (2023)

Spin-1 Tensor TMDs: SIDIS

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

TMDs are not experimental observables

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

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

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

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

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

A. Bacchetta (2023)

Extracting Observables

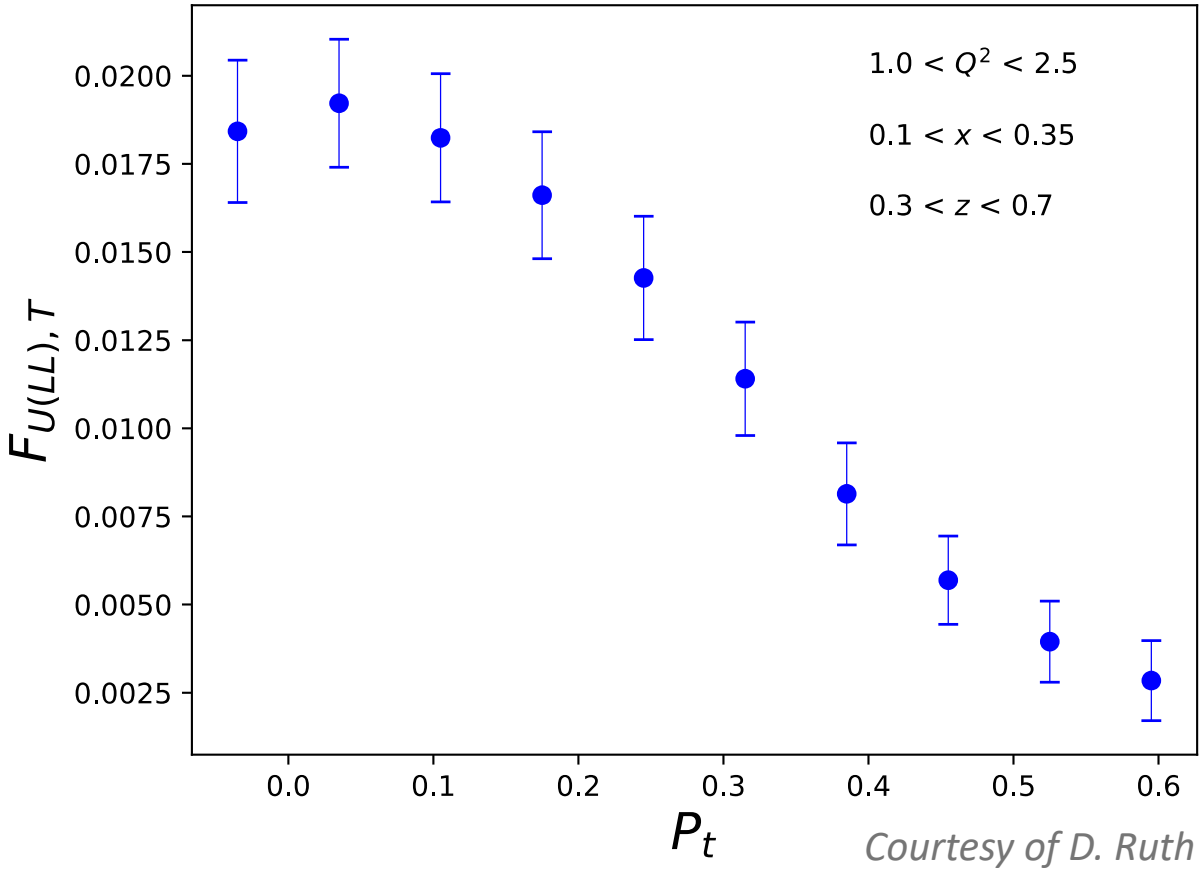
- Total cross section $\sigma = \sigma_{\text{Unpol}} + \sigma_{\text{Vect}} + \sigma_{\text{Tens}}$
- Vector polarization contribution suppressed with the data on both (+ve & -ve) vector polarity of target
- Unpolarized contribution removed with the data on unpolarized target.

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

- Further angular modulation to extract tensor structure functions

Observable: Simulation

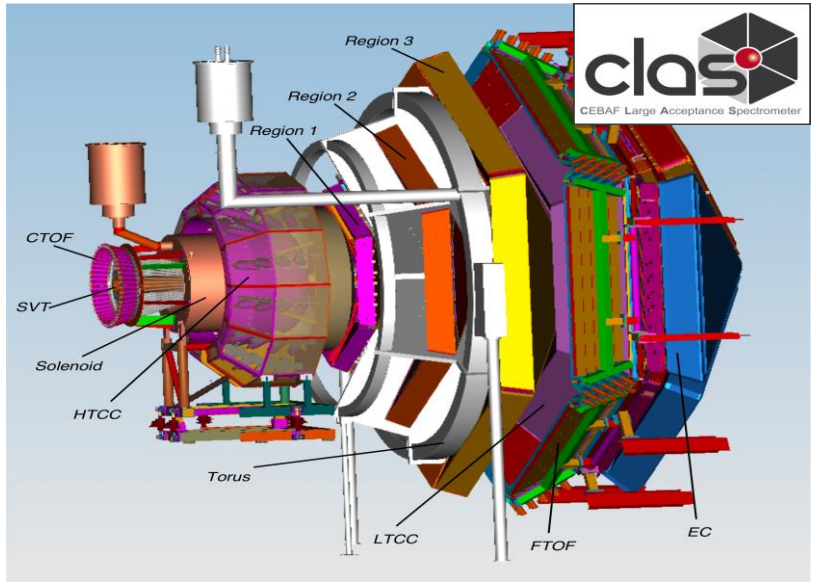
- Unpolarized structure function $(F_{UU,T})$ from simulation using PDF and FF information from LHAPDF
- Tensor structure function $(F_{U(LL),T})$ considering 10% of the unpolarized component $F_{UU,T}$

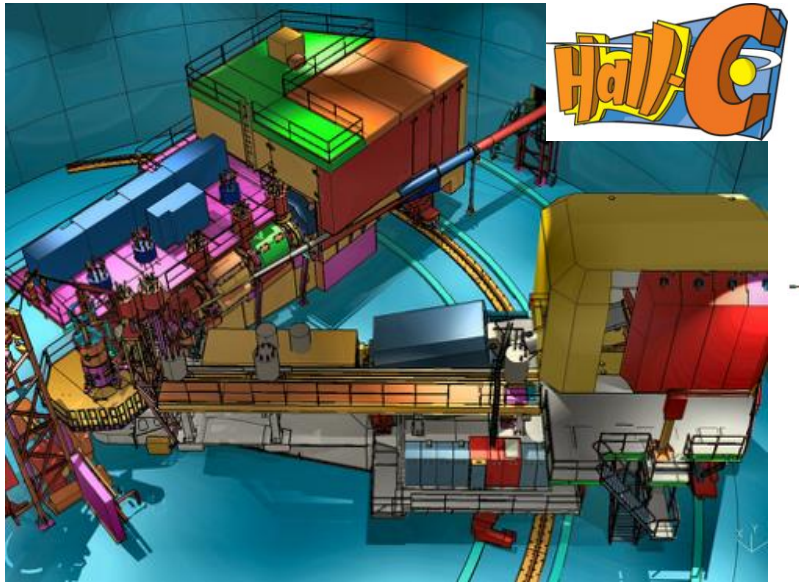


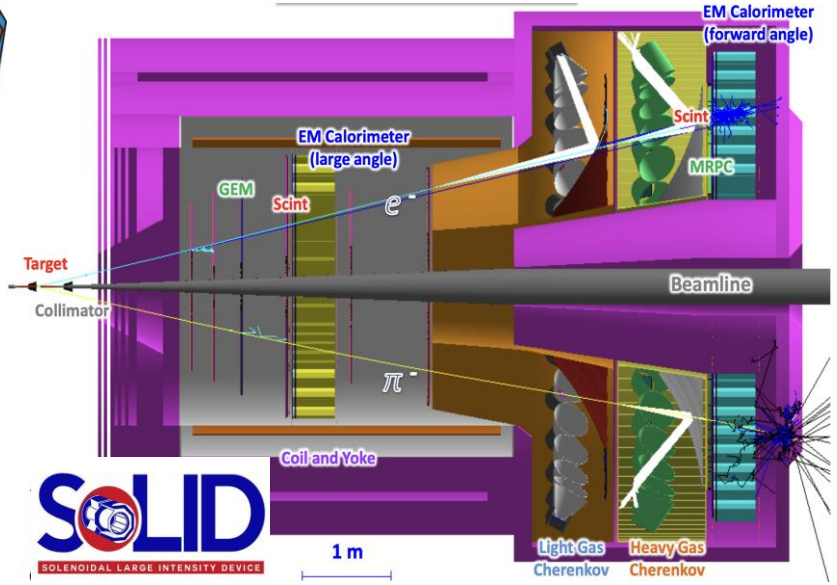
Courtesy of D. Ruth

Planning and Preparation for Tensor TMDs

- Analysis Proposal for using CLAS12 (Run Group - C) data to measure tensor structure functions (as a proof of principle)
- Letter of Intent (LOI) to PAC-52 for the future experiment in Hall C at JLab
- Collaboration with theorist
- Prospect to extend the measurement in SoLID + other facilities



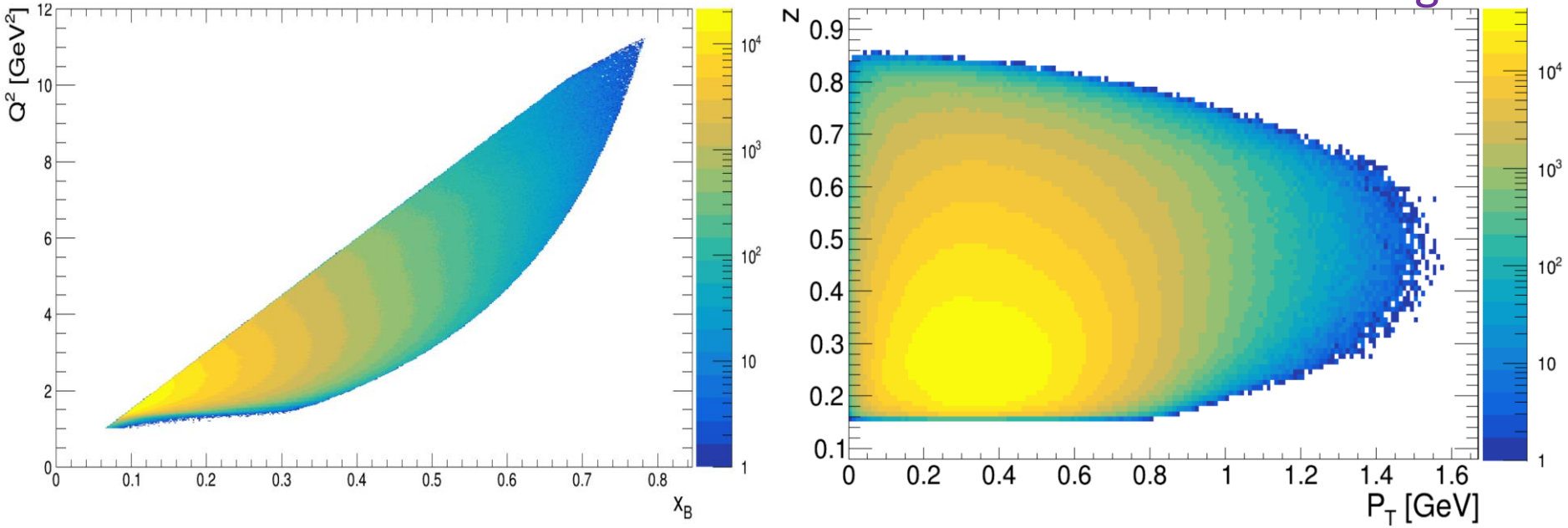


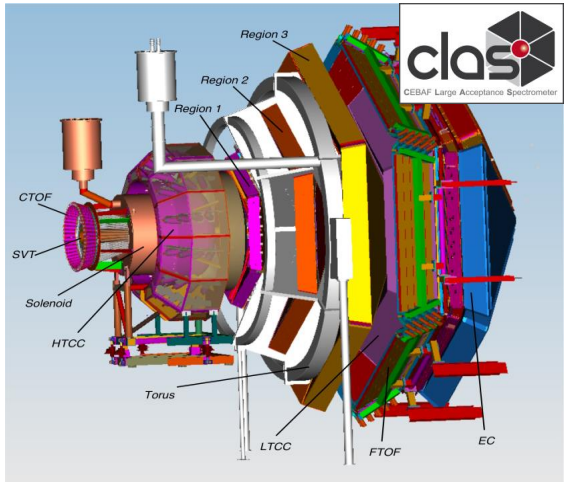


CLAS12 Analysis Proposal (CAA)

- First exploratory measurement of Tensor Structure Function via SIDIS
- Available RG-C data from longitudinally polarized deuterated ammonia target
- Tensor polarization via vector polarization in thermal equilibrium
- Large acceptance of CLAS12, but limited tensor statistics in RG-C data

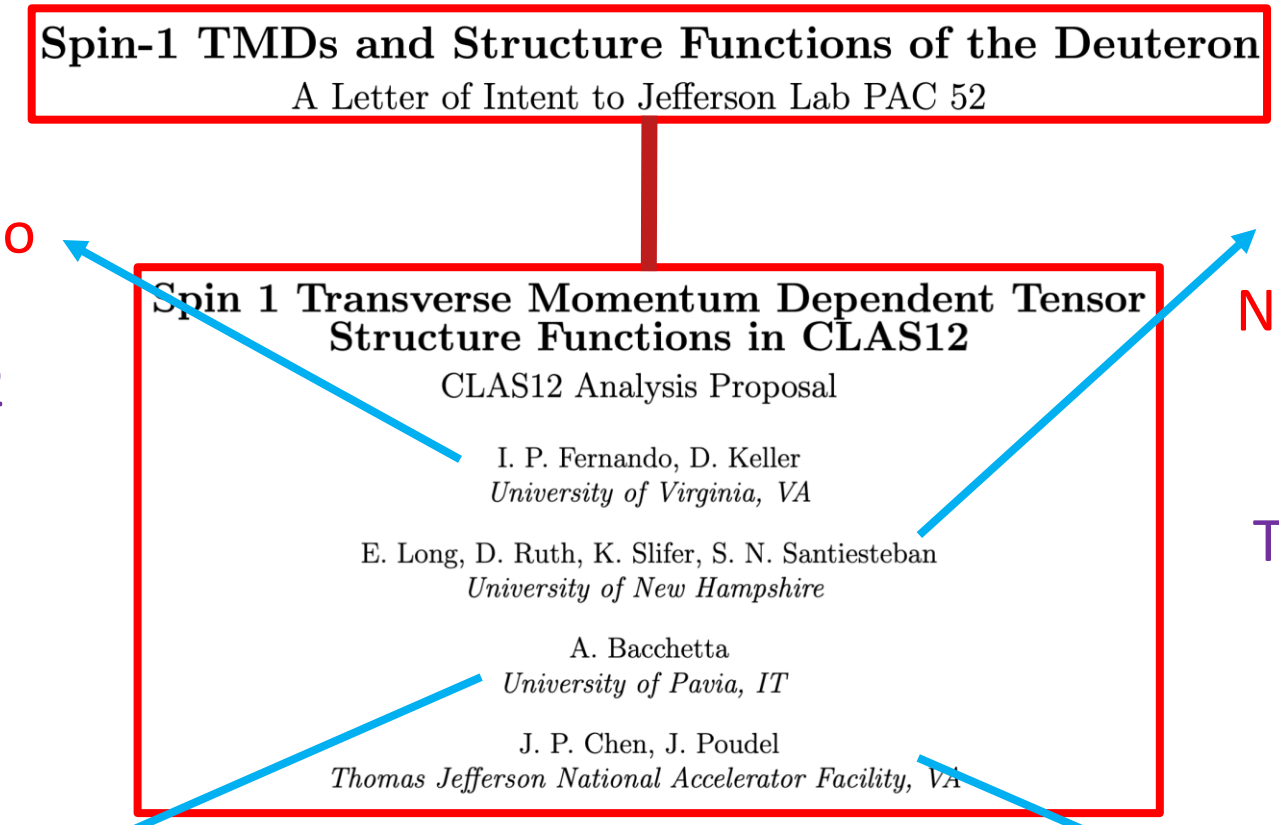
CLAS12 kinematic coverage





S. Diel et al. (CLAS12) PRL 128 (2022)

LOI to PAC52 and CAA: Active members



Dustin Keller
Ishara P. Fernando
UVA
Target + CLAS12

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

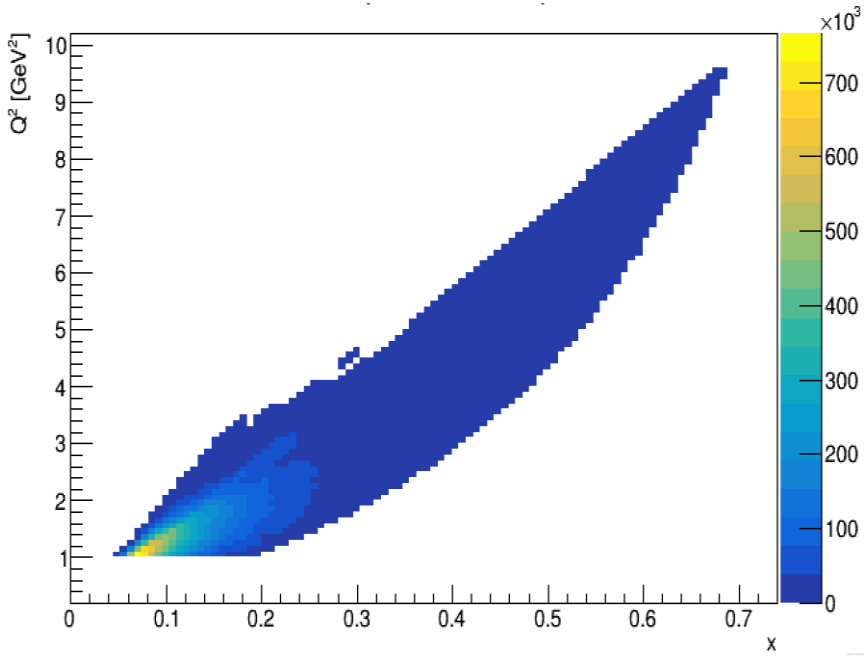
Alessandro Bacchetta
Univ. of Pavia
Theory

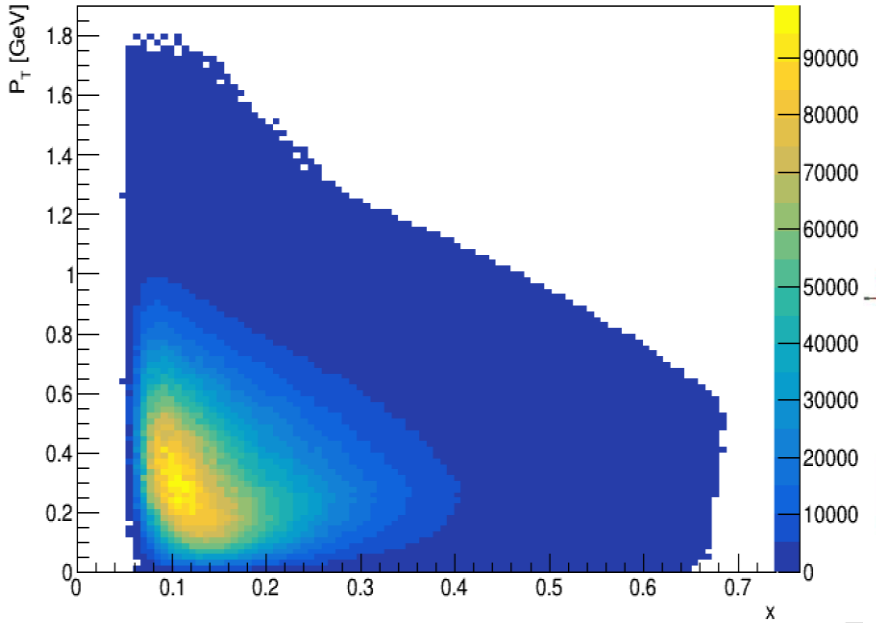
+ graduate students

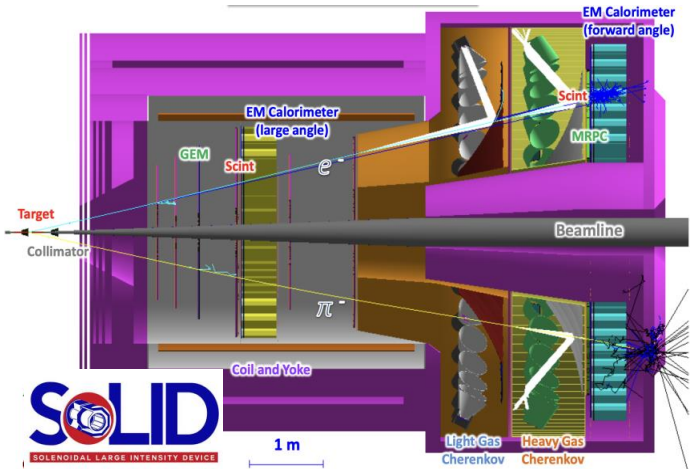
Jian-Ping Chen
Jiwan Poudel
JLab
Tensor exp. + CLAS12

SoLID: Luminosity Frontier

- Large acceptance of SoLID and higher luminosity
- Enhanced tensor polarized target
- Extension for the precision study of Tensor TMDs and Structure Function







Courtesy of N. Santiesteban

Summary

- Theoretical support from A. Bacchetta for tensor TMDs and structure functions
- Enhancement of tensor polarization ongoing via different techniques within our group
- Submission of LOI to PAC52 for a new tensor experiment in Hall C at JLab
- Preparation of CLAS12 CAA to look existing data from RG-C for the first exploratory study of tensor structure function via SIDIS
- Planning to extend the tensor TMD studies in SoLID
- Interesting physics to understand the partonic structure of light nuclei
- Novel information on deuteron, if experimentally successful, about the interplay between the QCD and the nuclear structure

Spin-1 Tensor TMDs: Backup

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

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

- Kinematics

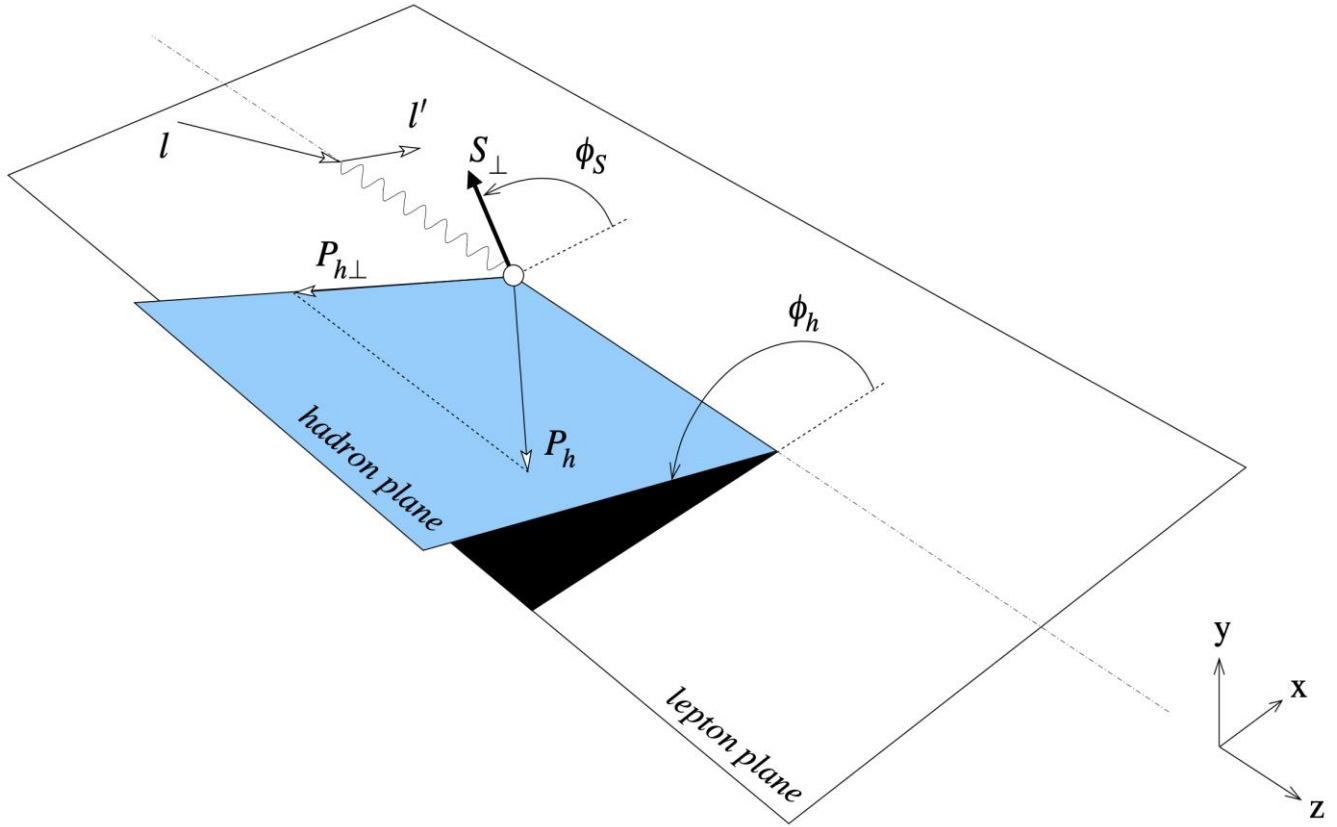
$$x_d = \frac{Q^2}{2P_d \cdot q} \qquad 0 < x_d < 1$$

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

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

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

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



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

Backup

- Inclusive process: