Tagged spectator DIS off a polarized spin-1 target

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Tagged spectator DIS process with deuteron

- DIS off a nuclear target with a slow (relative to nucleus c.m.) nucleon detected in the final state
- Control nuclear configuration
- Advantages for the deuteron
  - simple $NN$ system, non-nucleonic ($\Delta\Delta$) dof suppressed
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable
- Wealth of possibilities to study (nuclear) QCD dynamics
- Will be possible in a wide kinematic range @ EIC (polarized for JLEIC)
  - dedicated talk Wed. in WG7
What is needed?

- General expression of SIDIS for a polarized spin 1 target
  - Tagged spectator DIS is SIDIS in the target fragmentation region
    \[ e^+ + T \rightarrow e^0 + X + h \]

- Dynamical model to express structure functions of the reaction
  - First step: impulse approximation (IA) model

- Light-front structure of the deuteron
  - Natural for high-energy reactions as off-shellness of nucleons in LF quantization remains finite
Polarized spin 1 particle

- Spin state described by a 3*3 density matrix in a basis of spin 1 states polarized along the collinear virtual photon-target axis

\[ W_{D}^{\mu\nu} = \text{Tr}[\rho_{\lambda\lambda'} W_{\lambda\lambda'}^{\mu\nu}(\lambda'\lambda)] \]

- Characterized by 3 vector and 5 tensor parameters

\[ S^\mu = \langle \hat{W}^\mu \rangle, \quad T^{\mu\nu} = \frac{1}{2} \sqrt{\frac{2}{3}} \langle \hat{W}^\mu \hat{W}^\nu + \hat{W}^\nu \hat{W}^\mu + \frac{4}{3} \left( g^{\mu\nu} - \frac{\hat{P}^\mu \hat{P}^\nu}{M^2} \right) \rangle \]

- Split in longitudinal and orthogonal components

\[
\rho_{\lambda\lambda'} = \frac{1}{3} \begin{bmatrix}
1 - \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} & \frac{3}{2\sqrt{2}} S_\perp e^{i(\phi_h - \phi_S)} + \sqrt{3} T_{L\perp} e^{i(\phi_h - \phi_T)} & \sqrt{\frac{3}{2}} T_{\perp\perp} e^{i(2\phi_h - 2\phi_{T\perp})} \\
\frac{3}{2\sqrt{2}} S_\perp e^{-i(\phi_h - \phi_S)} + \sqrt{3} T_{L\perp} e^{-i(\phi_h - \phi_T)} & 1 - \sqrt{6} T_{LL} & \frac{3}{2\sqrt{2}} S_\perp e^{i(\phi_h - \phi_S)} - \sqrt{3} T_{L\perp} e^{i(\phi_h - \phi_T)} \\
\sqrt{\frac{3}{2}} T_{\perp\perp} e^{-i(2\phi_h - 2\phi_{T\perp})} & \frac{3}{2\sqrt{2}} S_\perp e^{-i(\phi_h - \phi_S)} - \sqrt{3} T_{L\perp} e^{-i(\phi_h - \phi_T)} & 1 + \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL}
\end{bmatrix}
\]
Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and QED Ward identity
- Cross section has 41 structure functions,

\[
\frac{d\sigma}{dx dQ^2 d\phi_y} = \frac{y^2 \alpha^2}{Q^4 (1 - \epsilon)} (F_U + F_S + F_T) d\Gamma_{P_h},
\]

- U + S part identical to spin 1/2 case [Bacchetta et al. JHEP ('07)]

\[
F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{2\phi_h} + \hbar \sqrt{2\epsilon(1 - \epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h}
\]

\[
F_S = S_L \left[ \sqrt{2\epsilon(1 + \epsilon)} \sin \phi_h F_{US_L}^{\sin \phi_h} + \epsilon \sin 2\phi_h F_{US_L}^{2\phi_h} \right]

+ \frac{S_L \hbar \left[ \sqrt{1 - \epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1 - \epsilon)} \cos \phi_h F_{LS_L}^{\cos \phi_h} \right]}{\sqrt{1 - \epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1 - \epsilon)} \cos \phi_h F_{LS_L}^{\cos \phi_h}}

+ S_\perp \left[ \sin(\phi_h - \phi_S) \left( F_{US_T,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h - \phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{US_T}^{\sin(\phi_h + \phi_S)} \right]

+ \sqrt{2\epsilon(1 + \epsilon)} \left( \sin \phi_S F_{US_T}^{\sin \phi_S} + \sin(2\phi_h - \phi_S) F_{US_T}^{\sin(2\phi_h - \phi_S)} \right)

+ \frac{S_\perp \hbar \left[ \sqrt{1 - \epsilon^2} \cos(\phi_h - \phi_S) F_{LS_T}^{\cos(\phi_h - \phi_S)} + \sqrt{2\epsilon(1 - \epsilon)} \left( \cos \phi_S F_{LS_T}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h - \phi_S)} \right) \right]}{\sqrt{1 - \epsilon^2} F_{LS_T}^{\cos(\phi_h - \phi_S)} + \sqrt{2\epsilon(1 - \epsilon)} \left( \cos \phi_S F_{LS_T}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h - \phi_S)} \right)},
\]
Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and QED Ward identity
- Cross section has 41 structure functions,

\[
\frac{d\sigma}{dx dQ^2 d\phi'} = \frac{y^2 \alpha^2}{Q^4(1 - \epsilon)} (F_U + F_S + F_T) d\Gamma_{\Phi_h}
\]

- **23 SF** unique to the spin 1 case (tensor pol.), 4 survive in inclusive \((b_1-4)\)

\[
F_T = T_{LL} \left[ F_{UTLL,T} + \epsilon F_{UTLL,L} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi_h F_{UTLL}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UTLL}^{\cos 2\phi_h} \right] \\
+ T_{LL} h \sqrt{2\epsilon(1 - \epsilon)} \sin \phi_h F_{LTLL}^{\sin \phi_h} \\
+ T_{L \perp} [\ldots] + T_{L \perp} h [\ldots] \\
+ T_{\perp \perp} \left[ \cos(2\phi_h - 2\phi_T) \left( F_{UTT,T}^{\cos(2\phi-h-2\phi_T)} + \epsilon F_{UTT,L}^{\cos(2\phi-h-2\phi_T)} \right) \right] \\
+ \epsilon \cos 2\phi_T F_{UTT}^{\cos 2\phi_T} + \epsilon \cos(4\phi_h - 2\phi_T) F_{UTT}^{\cos(4\phi_h-2\phi_T)} \\
+ \sqrt{2\epsilon(1 + \epsilon)} \left( \cos(\phi_h - 2\phi_T) F_{UTT}^{\cos(\phi_h-2\phi_T)} + \cos(3\phi_h - 2\phi_T) F_{UTT}^{\cos(3\phi_h-2\phi_T)} \right) \\
+ T_{\perp \perp} h [\ldots]
\]
Tagged DIS with deuteron: model for the IA

- Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

\[ W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_N^{\mu\nu} \rho^j_D(\lambda', \lambda) , \]

- Nucleon hadron tensor has standard (un)polarized contributions
  - Effective Bjorken \( \tilde{x} \) depends on recoil momentum \( (\alpha_R, p_{R\perp}) \)

\[ W_N^{\mu\nu} = -F_{1N}(g^{\mu\nu} + e_q^\mu e_q^\nu) + F_{2N} \frac{L_n^\mu L_n^\nu}{(p_n q)} \quad W_{N,i}^{\mu\nu} = -i \epsilon^{\mu\nu\rho\sigma} \frac{m_N q_\rho}{(p_i q)} \left[ s_{i,\sigma}(g_{1N} + g_{2N}) - \frac{(q s_i)}{(p_n q)} p_{n,\sigma} g_{2N} \right] \]

- \( \rho^U_D(\lambda', \lambda) \) related distribution of unpolarized nucleons in the deuteron
- \( \rho^Z_D(\lambda', \lambda) \) to longitudinally pol. nucleon distribution (deut. “helicity”)
- \( \rho^X_D(\lambda', \lambda) \) to transversally pol. nucleon distribution (deut. “transversity”)
Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

\[
W_{D}^{\mu \nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu \nu} \rho_D^j(\lambda', \lambda),
\]

Allows us to write all of the 41 conditional structure functions as a product of a factor dep. on nucleon SF and a D spectral function dep. on the polarization state. One example:

\[
F_{UU}^{\cos 2\phi_h} = \frac{|p_{R\perp}|}{(p_n q)} F_{2N}(x, \alpha_R, p_{R\perp}) \times \left[ U(k)^2 + W(k)^2 \right] \frac{(2\pi)^3 E_k}{\pi (2 - \alpha_R)^2}.
\]

In the IA the following structure functions are zero

- lepton polarized single-spin asymmetry \( F_{LU}^{\sin \phi_h} \)
- target vector polarized single-spin asymmetry [8 SFs]
- target tensor polarized double-spin asymmetry [7 SFs]
Deuteron light-front wave function

- Up to momenta of a few 100 MeV dominated by $NN$ component
- Can be evaluated in LFQM [Coester, Keister, Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt, Sargsian, Strikman]

![Diagram of J = 1 deuteron wave function]

- One obtains a Schrödinger (non-rel) like eq. for the wave function components
- Light-front WF obeys baryon and momentum sum rule

\[ \psi^D_{\lambda}(k_f, \lambda_1, \lambda_2) = \sqrt{E_{k_f}} \sum_{\lambda'_1 \lambda'_2} D_{\lambda 1 \lambda'_1}^{1/2} [R_{fc}(k^\mu_{1f} / m_N)] D_{\lambda 2 \lambda'_2}^{1/2} [R_{fc}(k^\mu_{2f} / m_N)] \Phi^D_{\lambda}(k_f, \lambda'_1, \lambda'_2) \]

- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - 3-momentum $k_f$ is the relative momentum of the nucleons in the light-front boosted rest-frame of the free 2-nucleon state (so not a “true” kinematical variable)
Pole extrapolation for on-shell nucleon structure

- Allows to extract free neutron structure
  - Recoil momentum $p_R$ controls off-shellness of neutron $t - m_N^2$
  - Free neutron at pole $t - m_N^2 \to 0$: "on-shell extrapolation"
  - Small deuteron binding energy results in small extrapolation length
  - Eliminates nuclear binding and FSI effects [Sargsian, Strikman PLB '05]

- D-wave suppressed at on-shell point $\rightarrow$ neutron $\sim 100\%$ polarized

- Precise measurements of neutron structure at an EIC
Unpolarized structure function

\[ (F_T + \epsilon F_L) \times (m_N^2 - t)^2 / \text{residue}^2 \]

CM energy \( s_{eN} = 1000 \text{ GeV}^2 \)
\[ x = 0.05, \; Q^2 = 20 \text{ GeV}^2, \; \alpha_R = 1. \]

- Extrapolation for \((m_N^2 - t) \to 0\) corresponds to on-shell neutron \(F_{2N}(x, Q^2)\)

- Clear effect of deuteron D-wave, largest in the region dominated by the tensor part of the \(NN\)-interaction

- D-wave drops out at the on-shell point
Polarized structure function

Spin asymmetry $A_{||} = \frac{\sigma(++) - \sigma(--)}{\sigma(++) + \sigma(--)}$

$$\propto \frac{F_{LSL}}{F_T + \epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$$

Again clear contribution from D-wave at finite recoil momenta

Relativistic nuclear effects through Melosh rotations, grow with recoil momenta

Both effects drop out near the on-shell extrapolation point
Study of tensor polarized observables

Final-state interactions, shadowing corrections

Medium modifications at higher nucleon momenta

More exclusive final-states (SIDIS in neutron current fragmentation region)
Conclusion

- General form of SIDIS with a spin 1 target, 23 tensor polarized structure functions unique to spin 1

- Results for the impulse approximation using deuteron light-front structure

- Important contributions from deuteron $D$-wave, Melosh rotations at larger spectator momenta. Become small if one does pole extrapolation of observables.

- Range of applications at an EIC (with polarized deuterons)