Tagged spectator DIS off a polarized spin-1 target

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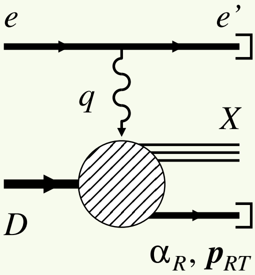
Tagged spectator DIS process with deuteron



- 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

$$\vec{e} + \vec{T} \to e' + X + h$$

- 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

$$W_D^{\mu\nu} = Tr[\rho_{\lambda\lambda'} W^{\mu\nu}(\lambda'\lambda)]$$

- Characterized by **3 vector** and **5 tensor** parameters

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

- Split in longitudinal and orthogonal components

$$\rho_{\lambda\lambda'} = \frac{1}{3}\begin{bmatrix} 1 - \frac{3}{2}S_L + \sqrt{\frac{3}{2}}T_{LL} & \begin{array}{c} \frac{3}{2\sqrt{2}}S_\perp e^{+i(\phi_h - \phi_S)} \\ + \sqrt{3}T_{L\perp}e^{+i(\phi_h - \phi_{T_L})} \end{array} & \sqrt{\frac{3}{2}}T_{\perp\perp}e^{+i(2\phi_h - 2\phi_{T_\perp})} \\ \begin{array}{c} \frac{3}{2\sqrt{2}}S_\perp e^{-i(\phi_h - \phi_S)} \\ + \sqrt{3}T_{L\perp}e^{-i(\phi_h - \phi_{T_L})} \end{array} & 1 - \sqrt{6}T_{LL} & \begin{array}{c} \frac{3}{2\sqrt{2}}S_\perp e^{i(\phi_h - \phi_S)} \\ - \sqrt{3}T_{L\perp}e^{i(\phi_h - \phi_{T_L})} \end{array} \\ \sqrt{\frac{3}{2}}T_{\perp\perp}e^{-i(2\phi_h - 2\phi_{T_\perp})} & \begin{array}{c} \frac{3}{2\sqrt{2}}S_\perp e^{-i(\phi_h - \phi_S)} \\ - \sqrt{3}T_{L\perp}e^{-i(\phi_h - \phi_{T_L})} \end{array} & 1 + \frac{3}{2}S_L + \sqrt{\frac{3}{2}}T_{LL} \end{bmatrix}$$

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,

$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2\alpha^2}{Q^4(1-\epsilon)}\left(F_U + F_S + F_T\right) d\Gamma_{P_h}\,,$$

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

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

$$\begin{aligned}
F_S = {} & S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{US_L}^{\sin\phi_h} + \epsilon\sin 2\phi_h F_{US_L}^{\sin 2\phi_h}\right] \\
& + S_L h\left[\sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LS_L}^{\cos\phi_h}\right] \\
& + S_\perp\left[\sin(\phi_h-\phi_S)\left(F_{US_T,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h-\phi_S)}\right) + \epsilon\sin(\phi_h+\phi_S) F_{US_T}^{\sin(\phi_h+\phi_S)}\right. \\
& \left. + \epsilon\sin(3\phi_h-\phi_S) F_{US_T}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{US_T}^{\sin\phi_S} + \sin(2\phi_h-\phi_S) F_{US_T}^{\sin(2\phi_h-\phi_S)}\right)\right] \\
& + S_\perp h\left[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S) F_{LS_T}^{\cos(\phi_h-\phi_S)} + \right. \\
& \left. \sqrt{2\epsilon(1-\epsilon)}\left(\cos\phi_S F_{LS_T}^{\cos\phi_S} + \cos(2\phi_h-\phi_S) F_{LS_T}^{\cos(2\phi_h-\phi_S)}\right)\right]\,,
\end{aligned}$$

Spin 1 SIDIS: General structure of cross section

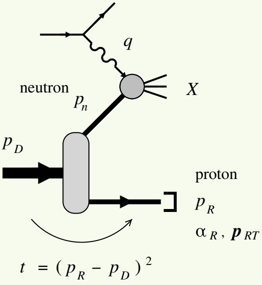
- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and QED Ward identity
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2\alpha^2}{Q^4(1-\epsilon)} \left(F_U + F_S + F_T\right) d\Gamma_{P_h},$$

  - 23 SF unique to the spin 1 case (tensor pol.)

$$\begin{aligned}
F_T = T_{LL} \Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \Big] \\
& + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\
& + T_{L\perp} [\cdots] + T_{L\perp} h [\cdots] \\
& + T_{\perp\perp} \Big[\cos(2\phi_h - 2\phi_{T_\perp}) \left(F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T_\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T_\perp})} \right) \\
& + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_\perp})} \\
& + \sqrt{2\epsilon(1+\epsilon)} \left(\cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_\perp})} \right) \Big] \\
& + T_{\perp\perp} h [\cdots]
\end{aligned}$$

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

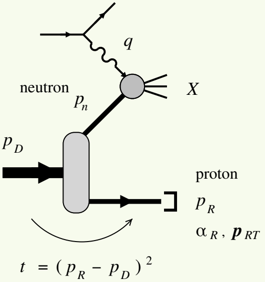
$$W_D^{\mu\nu}(\lambda',\lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda',\lambda),$$

- Nucleon hadr tensor has standard (un)polarized contributions
  - Effective Bjorken $\tilde{x}$ depends on recoil momentum $(\alpha_R, \boldsymbol{p}_{R\perp})$

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

- $\rho_D^U(\lambda',\lambda)$ related distribution of **unpolarized** nucleons in the deuteron
- $\rho_D^z(\lambda',\lambda)$ to **longitudinally** pol. nucleon distribution (deut. "helicity")
- $\rho_D^{x,y}(\lambda',\lambda)$ to **transversally** pol. nucleon distr. (deut. "transversity")

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

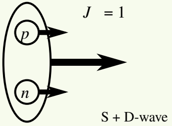
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda)\,,$$

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:

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

- In the IA the following structure functions are **zero**
  - lepton pol. SSA [$F_{LU}^{\sin\phi_h}$]
  - target vector pol. SSA [8 SFs]
  - target tensor pol. DSA [7 SFs]

Deuteron light-front wave function



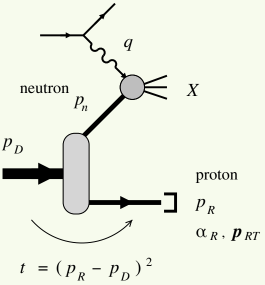
- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]

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

$$\Psi^D_\lambda(\mathbf{k}_f, \lambda_1, \lambda_2) = \sqrt{E_{k_f}} \sum_{\lambda_1'\lambda_2'} \mathcal{D}^{\frac{1}{2}}_{\lambda_1\lambda_1'}[R_{fc}(k^\mu_{1_f}/m_N)]\mathcal{D}^{\frac{1}{2}}_{\lambda_2\lambda_2'}[R_{fc}(k^\mu_{2_f}/m_N)]\Phi^D_\lambda(\mathbf{k}_f, \lambda_1', \lambda_2')$$

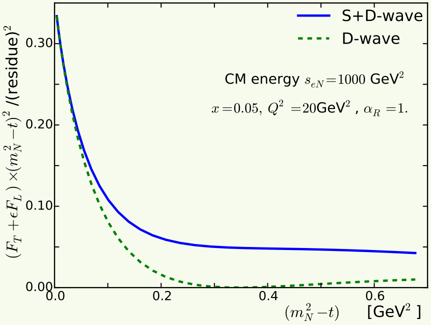
- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - 3-momentum $\mathbf{k}_f$ is the relative momentum of the nucleons in the light-front boosted rest-frame of the free 2-nucleon state (so not a "true" kinematical variable)

Pole extrapolation for on-shell nucleon structure



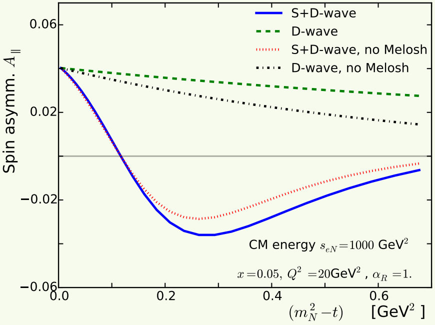
- Allows to extract free neutron structure
  - Recoil momentum p_R controls off-shellness of neutron $t - m_N^2$
  - Free neutron at pole $t - m_N^2 \to 0$: "on-shell extrapolation"
  - Small deuteron binding energy results in small extrapolation length
  - Eliminates nuclear binding and FSI effects `[Sargsian,Strikman PLB '05]`
- D-wave suppressed at on-shell point $\to$ neutron $\sim 100\%$ polarized
- Precise measurements of neutron structure at an EIC

Unpolarized structure function



- 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 $A_{||} = \frac{\sigma(++)-\sigma(-+)}{\sigma(++)+\sigma(-+)} = \frac{F_{LS_L}}{F_T+\epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$
- 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

Outlook

- 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)