DIS on the (polarized) deuteron: opportunities beyond inclusive scattering

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Inclusive DIS on light nuclei

- Needed to obtain neutron data, flavor separation of pdfs etc.
- Average over all possible nuclear configurations
- Fermi motion, non-nucleonic components, medium effects, off-shell effects
- Deuteron is very loosely bound (2.2 MeV)
- Dominant uncertainty at high $x$ in pdfs

Fig. from Accardi et al. PRD93 ('16)
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
- Measured for unpol. deuteron @ JLab: Deeps (high $p_r$) & BONuS (low $p_r$)
- Will be possible in a wide kinematic range @ EIC (polarized for JLEIC)
- Suited for colliders: no target material, forward detection.
  - fixed target CLAS BONuS limited to recoil momenta $\sim 70$ MeV
What is needed? What results will I show you?

- General expression of SIDIS for a polarized spin 1 target
  - Tagged spectator DIS is SIDIS in the target fragmentation region
    \[ e + \vec{T} \rightarrow e' + X + h \]

- Dynamical model to express structure functions of the reaction
  - First step: impulse approximation (IA) model
  - FSI: model for high \( x \) region (small \( W \), moderate \( Q^2 \))

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

WC, M. Sargsian, Ch. Weiss, to be published

- Comparison with Deeps and Bonus
- Neutron spin structure @ EIC
- Tensor polarized deuteron structure
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

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

- Split in longitudinal and transverse components

\[
\rho_{\lambda\lambda'} = \frac{1}{3} \begin{bmatrix}
1 + \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} & \frac{3}{2} S_T e^{-i(\phi_h - \phi_S)} & \frac{3}{2} S_T e^{-i(2\phi_h - 2\phi_{TT})} \\
\frac{3}{2} \sqrt{2} S_T e^{i(\phi_h - \phi_S)} & 1 - \sqrt{6} T_{LL} & \frac{3}{2} \sqrt{2} S_T e^{-i(\phi_h - \phi_S)} \\
\sqrt{\frac{3}{2}} T_{TT} e^{i(2\phi_h - 2\phi_{TT})} & \frac{3}{2} \sqrt{2} S_T e^{i(\phi_h - \phi_S)} & 1 - \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} \\
- \sqrt{3} T_{LT} e^{i(\phi_h - \phi_{TL})} & - \sqrt{3} T_{LT} e^{i(\phi_h - \phi_{TL})} & \frac{3}{2} \sqrt{2} S_T e^{-i(\phi_h - \phi_S)} + \sqrt{3} T_{LT} e^{-i(\phi_h - \phi_{TL})} \\
\end{bmatrix}
\]
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,

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

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

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

\[
F_S = S_L \left[ \sqrt{2\epsilon(1+\epsilon)} \sin\phi_h F_{US}^{\sin\phi_h} + \epsilon \sin 2\phi_h F_{US}^{\sin 2\phi_h} \right]
+ S_L h \left[ \sqrt{1 - \epsilon^2} F_{LS} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_h F_{LS}^{\cos\phi_h} \right]
+ S_\perp \left[ \sin(\phi_h - \phi_S) \left( F_{UST,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UST,L}^{\sin(\phi_h - \phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{UST}^{\sin(\phi_h + \phi_S)} \right]
+ \epsilon \sin(3\phi_h - \phi_S) F_{UST}^{\sin(3\phi_h - \phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left( \sin\phi_S F_{UST}^{\sin\phi_S} + \sin(2\phi_h - \phi_S) F_{UST}^{\sin(2\phi_h - \phi_S)} \right)
\]

\[
+ S_\perp h \left[ \sqrt{1 - \epsilon^2} \cos(\phi_h - \phi_S) F_{LS}^{\cos(\phi_h - \phi_S)} + \right.
\]

\[
\left. \sqrt{2\epsilon(1-\epsilon)} \left( \cos\phi_S F_{LS}^{\cos\phi_S} + \cos(2\phi_h - \phi_S) F_{LS}^{\cos(2\phi_h - \phi_S)} \right) \right],
\]
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,

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

- 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive \((b_{1-4})\) [Hoodbhoy, Jaffe, Manohar PLB’88]

\[
F_T = T_{LL} \left[ F_{UTLL,T} + \epsilon F_{UTLL,L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UTLL}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UTLL}^{\cos 2\phi_h} \right]
\]

\[
+ T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LTLL}^{\sin \phi_h}
\]

\[
+ T_{L\perp} \ldots + T_{L\perp} h \ldots
\]

\[
+ T_{\perp\perp} \left[ \cos(2\phi_h - 2\phi_{T\perp}) \left( F_{UTTT,T}^{\cos(2\phi_h - 2\phi_{T\perp})} + \epsilon F_{UTTT,L}^{\cos(2\phi_h - 2\phi_{T\perp})} \right) \\
+ \epsilon \cos 2\phi_{T\perp} F_{UTTT}^{\cos 2\phi_{T\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T\perp}) F_{UTTT}^{\cos(4\phi_h - 2\phi_{T\perp})} \\
+ \sqrt{2\epsilon(1+\epsilon)} \left( \cos(\phi_h - 2\phi_{T\perp}) F_{UTTT}^{\cos(\phi_h - 2\phi_{T\perp})} + \cos(3\phi_h - 2\phi_{T\perp}) F_{UTTT}^{\cos(3\phi_h - 2\phi_{T\perp})} \right) \right] \\
+ T_{\perp\perp} h \ldots
\]
Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

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

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

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

- \( \rho_D^U(\lambda', \lambda) \) related to distribution of unpolarized nucleons in the deuteron
- \( \rho_D^Z(\lambda', \lambda) \) to longitudinally pol. nucleon distribution
- \( \rho_D^{X,Y}(\lambda', \lambda) \) to transversally pol. nucleon distribution
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

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

All SF can be written as

\[
F_{ij}^k = \{\text{kin. factors and deuteron polarization}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{or } g_{1,2}(\tilde{x}, Q^2)\} \times \{\text{bilinear forms in deuteron radial wave function } U(k), W(k)\}
\]

In the IA the following structure functions are zero → sensitive to FSI
- 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]
- One obtains a Schrödinger (non-rel) like eq. for the wave function components, rotational invariance recovered
- Light-front WF obeys baryon and momentum sum rule

\[ \psi_D^{\lambda}(k_f, \lambda_1, \lambda_2) = \sqrt{E_{kf}} \sum_{\lambda'_1 \lambda'_2} D_{\lambda_1 \lambda'_1}^{\frac{1}{2}} [R_{fc}(k_{1f}^{\mu} / m_N)] D_{\lambda_2 \lambda'_2}^{\frac{1}{2}} [R_{fc}(k_{2f}^{\mu} / m_N)] \Phi_D^{\lambda}(k_f, \lambda'_1, \lambda'_2) \]

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

- $X$: details about composition and evolution unknown
- Use general properties of soft scattering theory, without specifying $X$
- Factorized approach

W.C., M. Sargsian, PRC84 014601 ('11)

- Generalised Eikonal Approximation
  - takes spectator recoil into account
  - can use realistic nuclear wf
- Ideal for light nuclei! ($^2$H, $^3$He, ...)

Diffractive amplitude: $f = \sigma_{tot}(W, Q^2)(1 + i\epsilon(W, Q^2))\exp^{\beta(W, Q^2)t/2}$
Deeps: FSI fitted calculation

Increasing $p_s$

data: Klimenko et al. (JLab CLAS), PRC73 035212 (’06)
calc: W.C., M.S. PRC84 014601 (’11)
What can the $\sigma_{\gamma N}$ fit teach us?

- $\sigma$ rises with invariant mass $W$, no sign of hadronisation plateau
- $\sigma$ drops with $Q^2$, sign of Color Transparency?

More measurements at higher $Q^2$ needed

Values can be used as input for FSI effects in other calculations
Data were normalized to a plane-wave model (ratio $R$), FSI model used to redo normalization.
Features of FSI in tagged DIS

Tagged DIS $D(e,e'p_s)X$

- **W = 2 GeV, $p_s = 390$ MeV, $\sigma_{tot} = 50$ mb, $B = 6$ GeV$^{-2}$**
- PW
- PW + FSI

- High recoil momentum
- Low recoil momentum

Quasi-elastic $D(e,e'p_s)n$

- FSI effects grow in forward direction at high $p_r$, different from quasi-elastic case, difference in possible phase-space
- FSI effects not zero in the backward region for lower $p_s$

M. Sargsian PRC82 014612 ('10)
Pole extrapolation for on-shell nucleon structure

- Allows to extract free neutron structure in a model independent way
  - Recoil momentum $p_R$ controls off-shellness of neutron $t - m_N^2$
  - Free neutron at pole $t - m_N^2 \rightarrow 0$: “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
Use Bonus data: \( F_{2n}/F_{2p} \)

- Robust results wrt deuteron wave function, fsi parameters, normalization of the data used in the extraction.
- Good agreement with Christy, Bosted parametrization at lower \( x \) values
- **Striking rise** of the ratio at high \( x \), would mean large \( d/u \) ratio at high \( x \) but sub-DIS \( Q^2 \)
- Sign of hard isosinglet quark-quark correlation, analogous to np pairing in nuclei? [imbalanced 2-component Fermi systems]

WC, M. Sargsian, PRC93 ’16
Polarized structure function

Impulse approx calculation

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

- 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

- Would enable precision measurements of neutron spin structure over a wide kinematic range @ EIC

JLAB LDRD project for EIC
https://www.jlab.org/theory/tag/
$A_{zz}$ in inclusive DIS

- Scattering from a tensor polarized deuteron target (unpolarized electron) $d\sigma = d\sigma_u(1 + \frac{1}{2} P_{zz} A_{zz})$, sensitive to 4 new structure functions compared to the spin 1/2 case.

$$A_{zz} = \frac{\sigma^+ + \sigma^- - 2\sigma^0}{\sigma^+ + \sigma^- + \sigma^0}$$

- Observable is identical 0 for a $S$-wave deuteron, very small when $D$-wave is included. Sensitive to non-nucleonic contributions such as hidden color (G. Miller, PRC89 (2014) 045203)

- Hermes measurement incompatible with simplest nuclear physics calculations

- Upcoming JLab12 experiment will improve our knowledge: E12-13-011

- Only nucleonic contributions in our model + FSI in resonance region

- Inclusive cross section through forward Compton amplitude (optical theorem)
Inclusive DIS

- Only resonance contributions considered in the FSI
- JLab 12 GeV kinematics considered
- Non-negligable contribution from FSI even at low $x$, but not enough to match Hermes data
- Convolution (D-wave dominance $\rightarrow$ high spectator momenta) can pick up resonance contributions through the convolution
- Size of FSI effects decreases at higher $Q^2$ (phase-space effect)
Wealth of possibilities with tagged spectator (polarized) DIS

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

Light-front IA model, FSI in the resonance region

Good agreement with JLab Deeps and BONuS data

Pole extrapolation of BONuS data shows striking rise of $F_{2n}/F_{2p}$ at high $x$

Recoil momentum dependence permits separation of nuclear and nucleon structure

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

- Spectator tagging in $eD$ scattering with EIC enables next-generation measurements with maximal control and unprecedented accuracy

$A_{zz}$ sensitive to FSI but still small