DIS on a polarized deuteron with spectator tagging

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EICUG '17

in collaboration with
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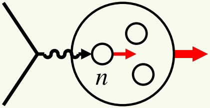
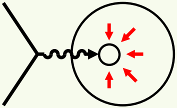
JLab LDRD project on spectator tagging

GHENT UNIVERSITY

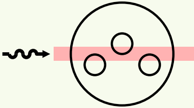
Light ions: physics objectives



- **Neutron** structure
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects

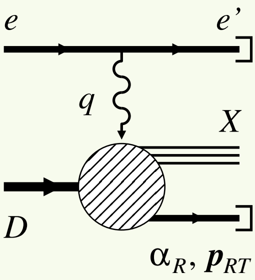


- **Bound** nucleons in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force



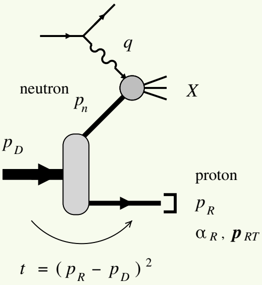
- **Coherence** and saturation
  - interaction of high-energy probe with coherent quark-gluon fields

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)
- suited for colliders: no target material, forward detection, transverse pol.
  fixed target CLAS BONuS limited to recoil momenta $\sim$ 70 MeV

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 $t' \equiv t - m_N^2$
  - 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

Outline

- Theoretical Formalism
  - 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
    - FSI corrections
  - Light-front structure of the deuteron
    - Natural for high-energy reactions as **off-shellness of nucleons** in LF quantization remains **finite**
- Neutron structure with pole extrapolation for EIC
- Experimental apparatus

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 transverse components

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

Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ($qW = Wq = 0$)
- 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)]

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

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

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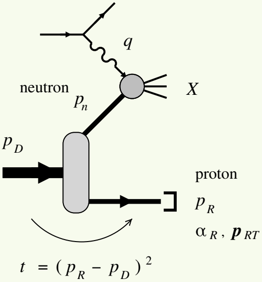
- Cross section has 41 structure functions,

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

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

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

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

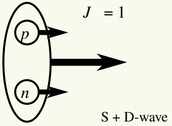
$$W_D^{\mu\nu}(\lambda',\lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda',\lambda)\,,$$

All SF can be written as

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

- In the IA the following structure functions are **zero** → sensitive to FSI
  - beam 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

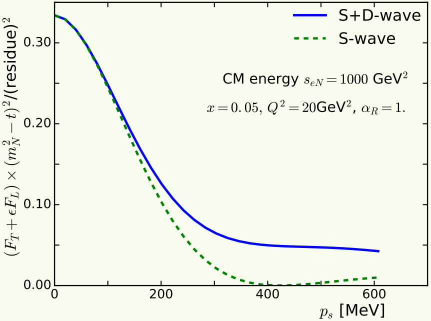


- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]
- One obtains a Schrödinger (non-rel) like eq. for the wave function components, rotational invariance recovered
- Light-front WF obeys baryon and momentum sum rule

$$\Psi^D_\lambda(\boldsymbol{k}_f,\lambda_1,\lambda_2)=\sqrt{E_{k_f}}\sum_{\lambda'_1\lambda'_2}\mathcal{D}^{\frac{1}{2}}_{\lambda_1\lambda'_1}[R_{fc}(k^\mu_{1_f}/m_N)]\mathcal{D}^{\frac{1}{2}}_{\lambda_2\lambda'_2}[R_{fc}(k^\mu_{2_f}/m_N)]\Phi^D_\lambda(\boldsymbol{k}_f,\lambda'_1,\lambda'_2)$$

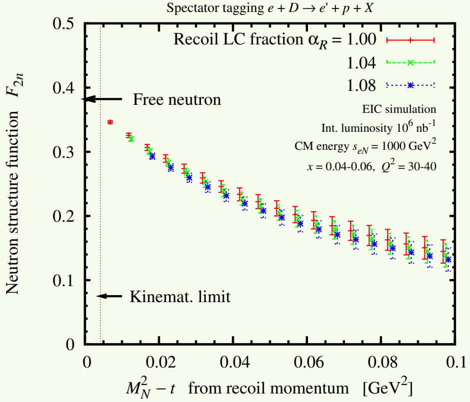
- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - $\boldsymbol{k}_f$ is the relative 3-momentum of the nucleons in the light-front boosted rest frame of the free 2-nucleon state (so not a “true” kinematical variable)

Unpolarized structure function



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

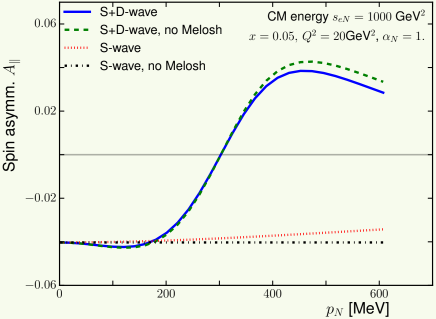
Tagging: free neutron structure



JLab LDRD arXiv:1407.3236, arXiv:1409.5768

- F_{2n} extracted with percent-level accuracy at $x < 0.1$
- Uncertainty mainly systematic due to intrinsic momentum spread in beam (JLab LDRD project: detailed estimates)
- In combination with proton data non-singlet $F_{2p} - F_{2n}$, sea quark flavor asymmetry $\bar{d} - \bar{u}$

Polarized structure function



- Spin asymmetry

$$A_{||} = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + -\sigma(--)}{\sigma(++) + \sigma(-+) + -\sigma(+-) + -\sigma(--)}[\phi_h \text{avg}]$$

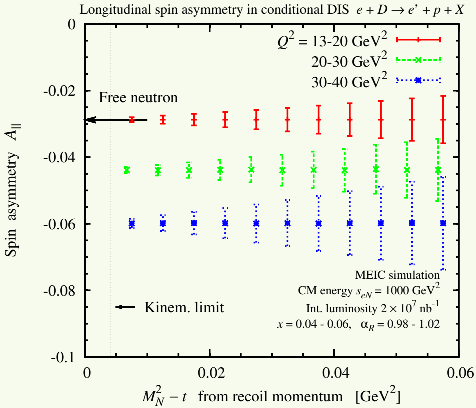
$$= \frac{F_{LS_L}}{F_T + \epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$$

- 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

Tagging: polarized neutron structure

On-shell extrapolation of double spin asymm.

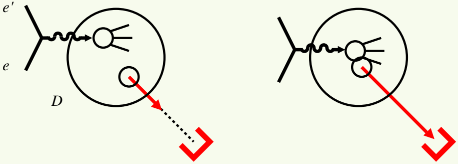
$$A_{||} = \frac{\sigma(++)-\sigma(-+)-\sigma(+-)+-\sigma(--)}{\sigma(++)+\sigma(-+)+-\sigma(+-)+-\sigma(--)}[\phi_h \mathrm{avg}] = \frac{F_{LS_L}}{F_T+\epsilon F_L} = D\frac{g_{1n}}{F_{1n}} + \cdots$$



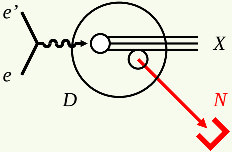
JLab LDRD arXiv:1407.3236, arXiv:1409.5768

- Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)
- Statistics requirements
  - Physical asymmetries $\sim 0.05 - 0.1$
  - Effective polarization $P_e P_D \sim 0.5$
  - Luminosity required $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Precise measurement of neutron spin structure

Tagging: EMC effect



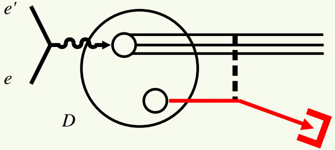
average-size **small-size**



Final−state interactions

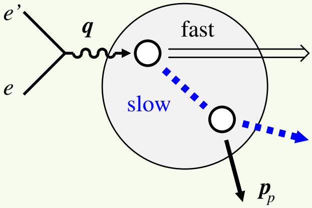
- Medium modification of nucleon structure embedded in nucleus (EMC effect)
  - dynamical origin?
  - caused by which momenta/distances in nuclear WF
  - spin-isospin dependence?
- tagged EMC effect
  - recoil momentum as extra handle on medium modification (off-shellness, size of nuclear configuration) away from the on-shell pole
  - EIC: Q^2 evolution, gluons, spin dependence!
- Interplay with final-state interactions!
  - use $\tilde{x} = 0.2$ to constrain FSI
  - constrain medium modification at higher $\tilde{x}$

Final-state interactions: three regimes



subasymptotic regime: low Q^2, high x

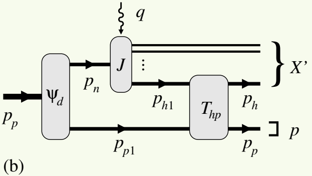
- rescattering of resonance-like structure with spectator nucleon [Deeps,BONuS].
  WC,M. Sargsian arXiv:1704.06117

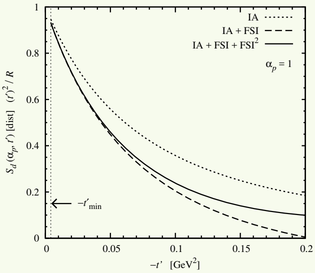


DIS regime, intermediate x

- FSI between slow hadrons from the DIS products and spectator nucleon, fast hadrons hadronize after leaving the nucleus.
- Data show slow hadrons in the target fragmentation region are mainly nucleons.
- Input needed from nucleon target fragmentation data → also possible at EIC

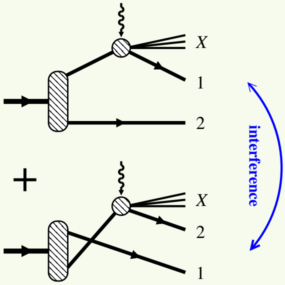
FSI 2: intermediate x model

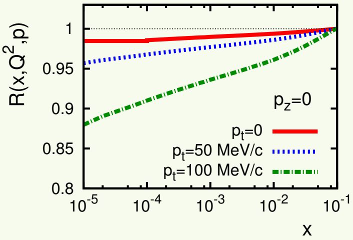




- Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.
- Inclusion FSI diagram adds two contributions: FSI term ($\sim$ absorption, negative) and FSI^2 term ($\sim$ refraction, postive)
- At low momenta ($p_r < 200$ MeV) FSI term dominates, at larger momenta FSI^2 dominates.
- Both contributions vanish at the pole $\rightarrow$ pole extrapolation **still feasible**
- FSI correction 1/2 of IA at $p_r \approx 200$ MeV, decreases linearly with $|t'|$.

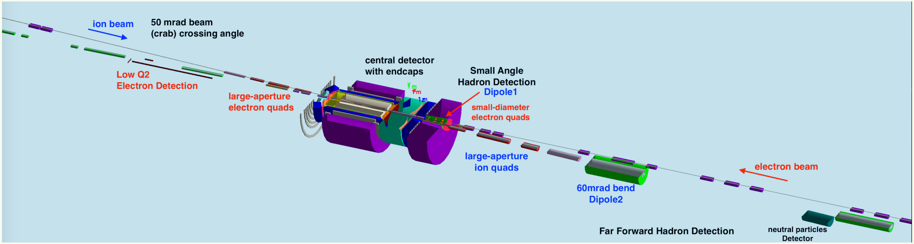
FSI 3: shadowing at small x





- Shadowing in inclusive DIS $x \ll 10^{-1}$
  - Diffractive DIS on single nucleon (leading twist, HERA)
  - Interference of DIS on nucleon 1 and 2
  - Calculable in terms of nucleon diffractive structure functions [Gribov 70s, Frankfurt,Guzey,Strikman '02+]
- Shadowing in tagged DIS
  - Explore shadowing through recoil momentum dependence [Guzey,Strikman,Weiss; in progress]
  - Reveal nuclear momentum components building op coherent fields at small x
  - Study coherence in $A = 2$, complimentary to $A \gg 1$

JLEIC full-acceptance detector



P. Nadel-Turonski et al.

- Forward detector integrated in interaction region & beam optics
- Good acceptance for elastic recoil
  Rigidity same as beam. Large dispersion generated *after* IP
  Longitudinal momentum up to 99.5% of beam, angles down to 2 mrad (10 σ)
- Good acceptance for spectators and ion fragments
  Rigidity different from beam. Large magnet apertures, small gradients
- Good momentum and angular resolution
  Longitudinal $dp/p \sim 4 \times 10^{-4}$, angular $\delta\theta \sim 0.2$ mrad
  $p_{TR} \sim 15\,\text{MeV}/c$ resolution for tagged 50 GeV/A deuterium beam

R&D project at JLAB

- Develop simulation tools (physics models, event generators, analysis tools) for DIS on light ions with spectator tagging at MEIC and study physics impact.
- ran FY14-15
  D. Higinbotham, W. Melnitchouk, P. Nadel-Turonski, K. Park, C. Weiss (JLab), Ch. Hyde (ODU), M. Sargsian (FIU), V. Guzey (PNPI), with collaborators W. Cosyn (Ghent), S. Kuhn (ODU), M. Strikman (PSU), Zh. Zhao (JLab)
- **Tools, documentation, results publicly available. Open for collaboration!**
- More info:
  `https://www.jlab.org/theory/tag/`
  `arXiv:1407.3236`, `arXiv:1409.5768v1`, `arXiv:1601.066665`, `arXiv:1609.01970`

Conclusions

- 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, relativistic nuclear spin effects contribute.
- FSI/shadowing effects calculable
- Spectator tagging in eD scattering with EIC enables next-generation measurements with maximal control and unprecedented accuracy
  - Neutron structure functions, including spin
  - Nuclear modifications of quark/gluon structure
- Extensions:
  - Tagging with $A > 2$: isospin dependence, universality of bound nucleon structure ; $A - 1$ recoil
  - Coherent processes: nuclear GPDs
  - Resolved final states: SIDIS on neutron, hard exclusive channels