

Tagged DIS on polarized deuteron

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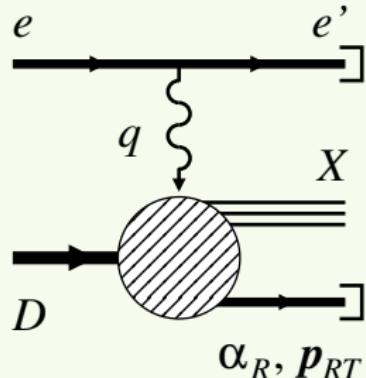
Ghent University, Belgium

Polarized light ion physics with EIC, Ghent

in collaboration with
Ch. Weiss, M. Sargsian
JLab LDRD project on spectator tagging



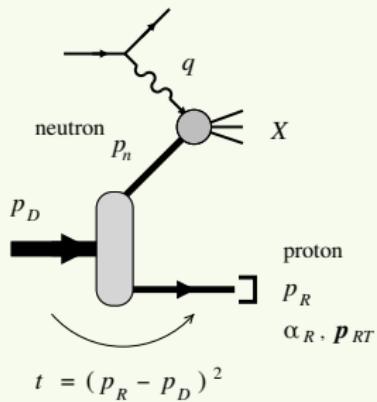
Tagged spectator DIS process with deuteron



- 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 ~ 70 MeV

Pole extrapolation for on-shell nucleon structure

- Allows to extract free neutron structure in a **model independent** way
 - ▶ Recoil momentum \mathbf{p}_R controls off-shellness of neutron $t' \equiv t - m_N^2$
 - ▶ 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 (spin) 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

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

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

- ▶ 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

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

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

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

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

- Split in longitudinal and transverse components

$$\rho_{\lambda\lambda'} = \frac{1}{3} \begin{bmatrix} 1 + \frac{3}{2} \mathbf{S}_L + \sqrt{\frac{3}{2}} \mathbf{T}_{LL} & \frac{3}{2\sqrt{2}} \mathbf{S}_T e^{-i(\phi_h - \phi_S)} & \sqrt{\frac{3}{2}} \mathbf{T}_{TT} e^{-i(2\phi_h - 2\phi_T)} \\ -\sqrt{3} \mathbf{T}_{LT} e^{-i(\phi_h - \phi_T)} & 1 - \sqrt{6} \mathbf{T}_{LL} & \frac{3}{2\sqrt{2}} \mathbf{S}_T e^{-i(\phi_h - \phi_S)} \\ -\sqrt{3} \mathbf{T}_{LT} e^{i(\phi_h - \phi_T)} & \frac{3}{2\sqrt{2}} \mathbf{S}_T e^{i(\phi_h - \phi_S)} & 1 - \frac{3}{2} \mathbf{S}_L + \sqrt{\frac{3}{2}} \mathbf{T}_{LL} \end{bmatrix}.$$

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)]

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

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

Spin 1 SIDIS: General structure of cross section

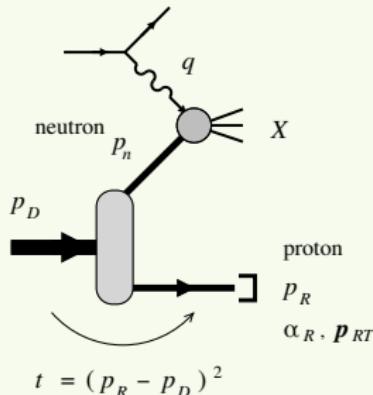
- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ($\mathbf{q}W = W\mathbf{q} = 0$)
- Cross section has 41 structure functions,

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

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

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

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

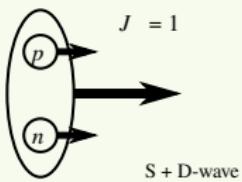
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda),$$

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

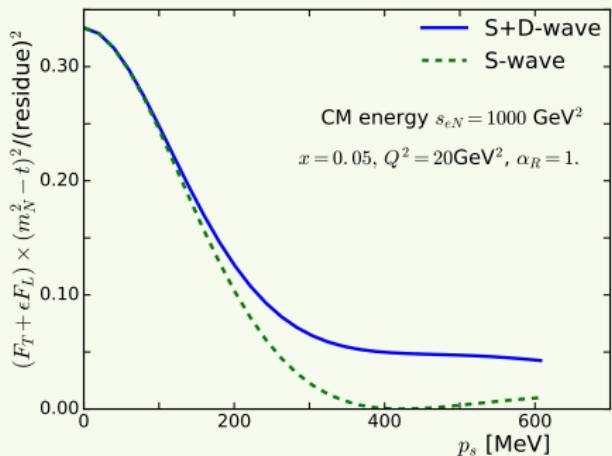


- Up to momenta of a few 100 MeV dominated by NN component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]
- One obtains a Schrödinger (non-rel) like eq. for the wave function components, rotational invariance recovered
-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

$$\Psi_{\lambda}^D(\mathbf{k}_f, \lambda_1, \lambda_2) = \sqrt{E_{k_f}} \sum_{\lambda'_1 \lambda'_2} \mathcal{D}_{\lambda_1 \lambda'_1}^{\frac{1}{2}} [\mathcal{R}_{fc}(k_{1_f}^{\mu}/m_N)] \mathcal{D}_{\lambda_2 \lambda'_2}^{\frac{1}{2}} [\mathcal{R}_{fc}(k_{2_f}^{\mu}/m_N)] \Phi_{\lambda}^D(\mathbf{k}_f, \lambda'_1, \lambda'_2)$$

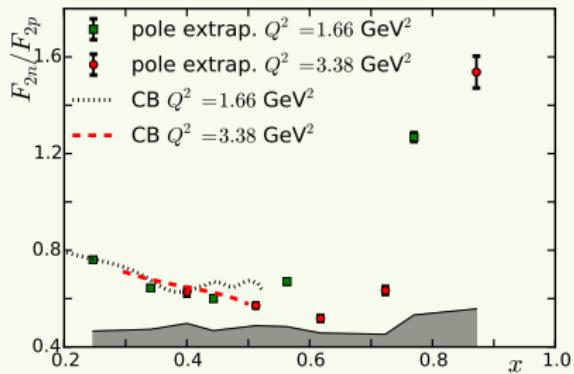
- Differences with non-rel wave function:
 - ▶ appearance of the **Melosh rotations** to account for light-front quantized nucleon states
 - ▶ \mathbf{k}_f is the relative 3-momentum of the nucleons in the light-front boosted rest frame of the free 2-nucleon state (so not a "true" kinematical variable)

Unpolarized structure function



- Extrapolation for $(m_N^2 - t) \rightarrow 0$ 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

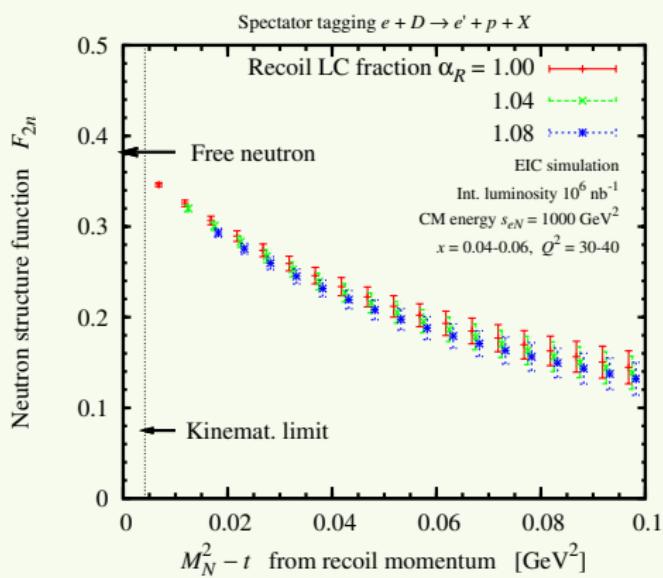
Use Bonus data: F_{2n}/F_{2p}



WC, M. Sargsian, PRC93 '16

- 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 , but **sub-DIS Q^2**
- Relevant for the dynamical generation of high-momentum quarks [imbalanced Fermi systems]

Tagging: free neutron structure



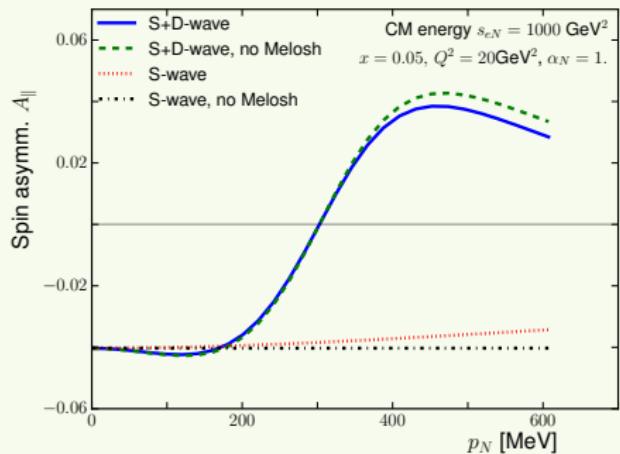
JLab LDRD arXiv:1407.3236, arXiv:1409.5768,
C. Hyde talk

- 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

$$A_{||} = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + -\sigma(--)}{\sigma(++) + \sigma(-+) + -\sigma(+-) + -\sigma(--)} [\phi h^{\text{avg}}]$$
$$= \frac{F_L S_L}{F_T + \epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$$

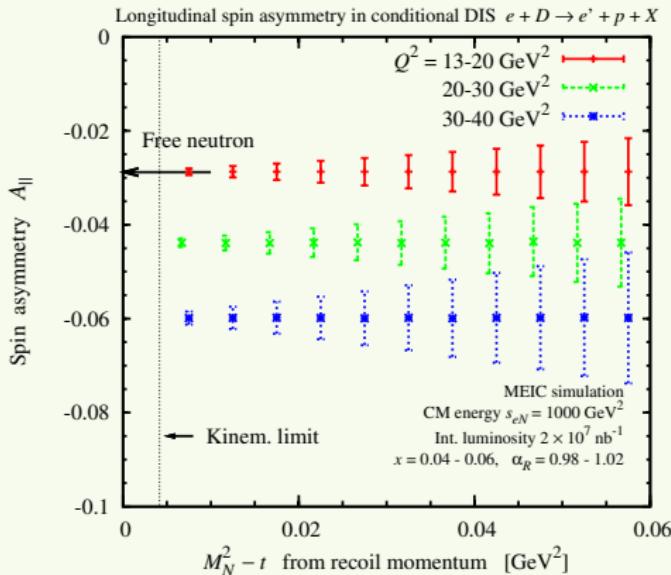


- Again clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

Tagging: polarized neutron structure

On-shell extrapolation of double spin asymm.

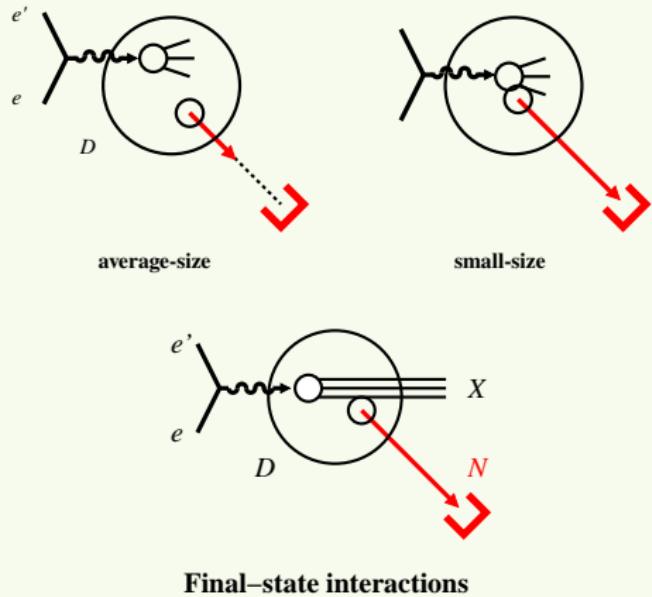
$$A_{||} = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + \sigma(--)}{\sigma(++) + \sigma(-+) + \sigma(+-) + \sigma(--)} [\phi_h \text{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L} = D \frac{g_{1n}}{F_{1n}} + \dots$$



JLab LDRD arXiv:1407.3236, arXiv:1409.5768

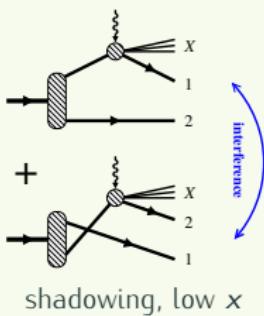
- Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)
- Statistics requirements
 - ▶ Physical asymmetries $\sim 0.05 - 0.1$
 - ▶ Effective polarization $P_e P_D \sim 0.5$
 - ▶ Luminosity required $\sim 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- Precise measurement of neutron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

Tagging: EMC effect

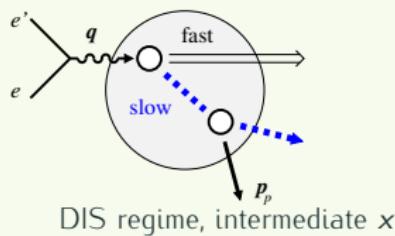


- Medium modification of nucleon structure embedded in nucleus (EMC effect)
 - ▶ dynamical origin?
 - ▶ caused by which momenta/distances in nuclear WF
 - ▶ spin-isospin dependence?
- tagged EMC effect
 - ▶ recoil momentum as extra handle on medium modification (off-shellness, size of nuclear configuration) 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}

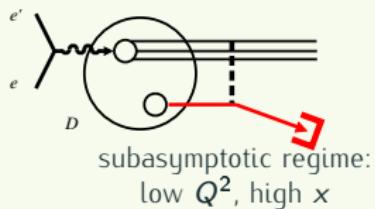
Final-state interactions: three regimes



shadowing, low x



DIS regime, intermediate x



subasymptotic regime:
low Q^2 , high x

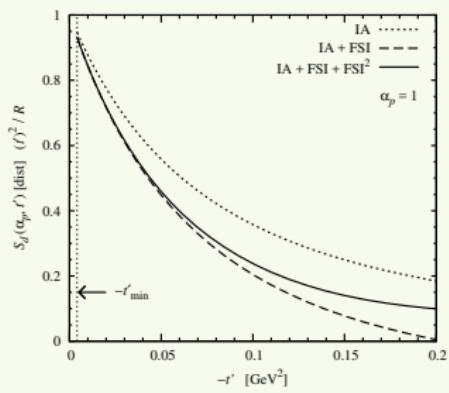
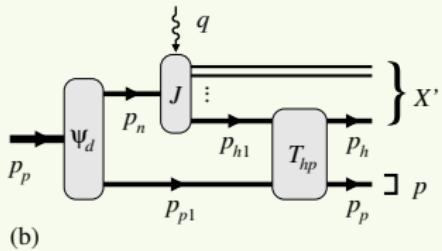
- (anti-)shadowing → Vadim Guzey's talk
- FSI between slow hadrons from the DIS products and spectator nucleon, fast hadrons hadronize after leaving the nucleus.
- Data show slow hadrons in the target fragmentation region are mainly nucleons.
- Input needed from nucleon target fragmentation data → **also possible at EIC**

M. Strikman, Ch. Weiss arXiv:1706.02244

- rescattering of resonance-like structure with spectator nucleon in eikonal approximation [Deeps,BONuS].

WC,M. Sargsian arXiv:1704.06117

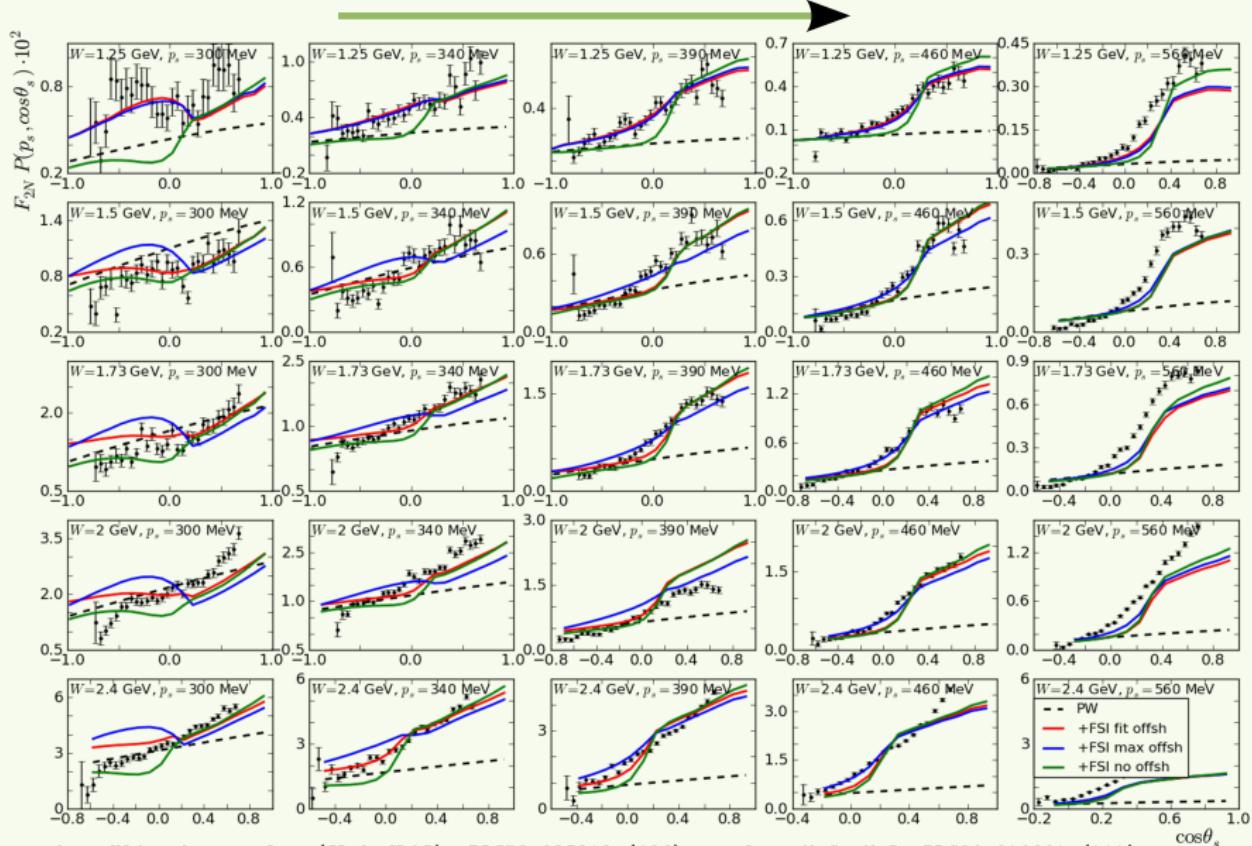
FSI 2: intermediate x model



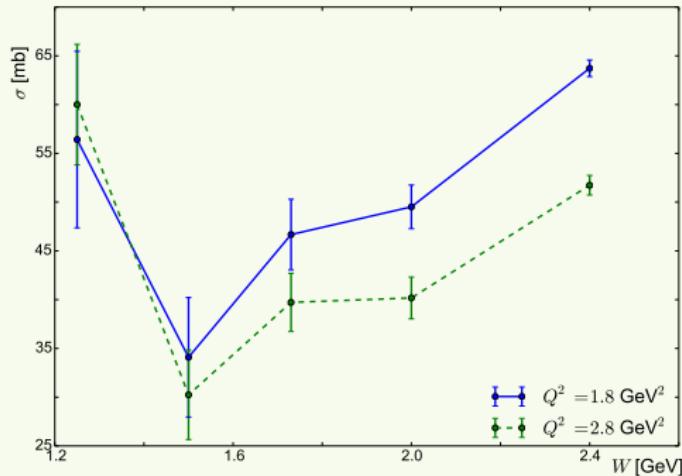
- Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.
- Inclusion FSI diagram adds two contributions: FSI term (\sim absorption, negative) and FSI^2 term (\sim refraction, positive)
- At low momenta ($p_r < 200$ MeV) FSI term dominates, 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 $|t'|$.

hi x FSI: Deeps, fitted calculation

increasing p_s



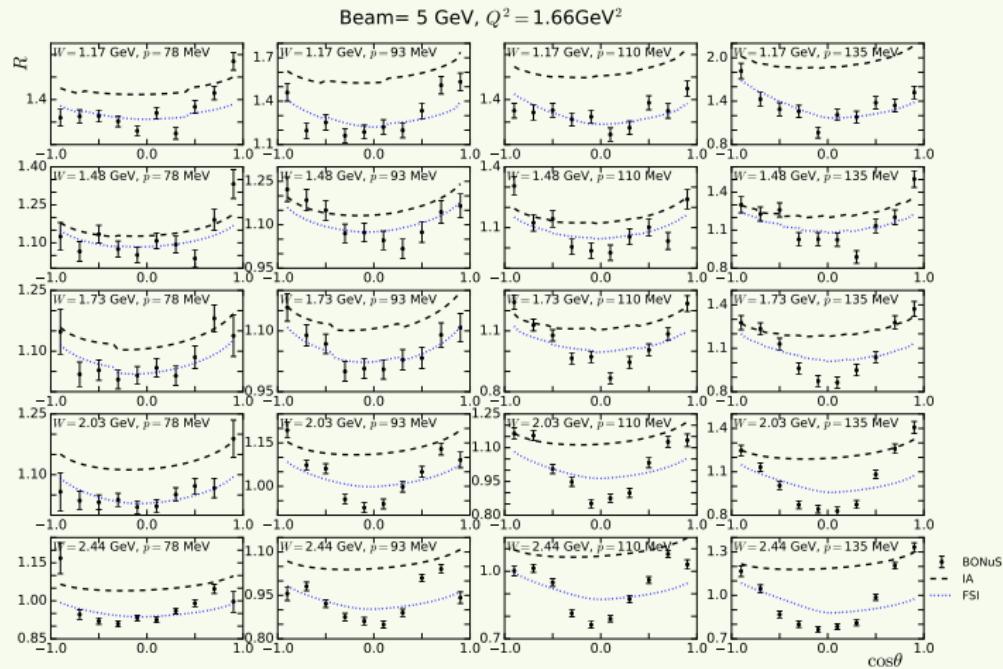
What can the σ_{XN} fit teach us?



- σ rises with invariant mass W , no sign of hadronisation plateau
- σ 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

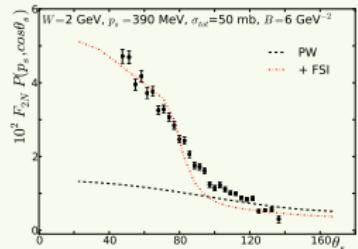
Comparison with BONuS ($p_s = 70 - 140$ MeV)



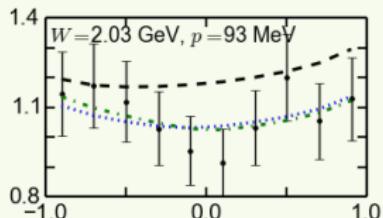
- Data were normalized to a plane-wave model (ratio R), FSI model used to redo normalization

Features of FSI in tagged DIS

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

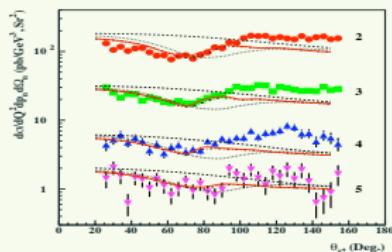
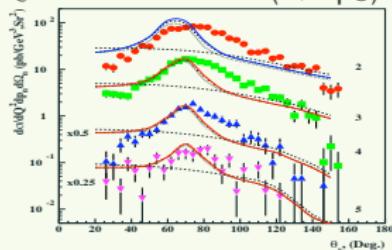


high recoil momentum



low recoil momentum

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



M. Sargsian PRC82 014612 ('10)

- 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

Tagging: developments and extensions

- Final-state interactions
 - ▶ in tagged $\vec{e} + \vec{D}$
 - ▶ maximized/minimized by choice of kinematics. Constrain FSI models.
 - ▶ azimuthal and spin observables non-zero through FSI
- Tagging with complex nuclei $A > 2$
 - ▶ isospin dependence, universality of bound nucleon structure
 - ▶ $A - 1$ ground state recoil
- Resolved final states: SIDIS on neutron, hard exclusive channels

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