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

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GHENT UNIVERSITY

Inclusive DIS on light nuclei

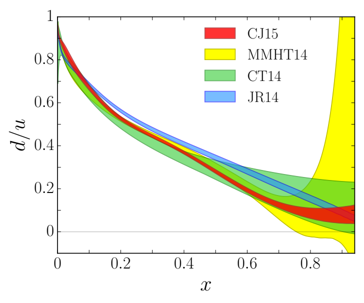
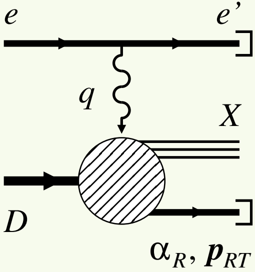


Fig. from Accardi et al. PRD93 ('16)

- 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

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 ~ 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

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

- 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

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

- 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 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)]

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

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

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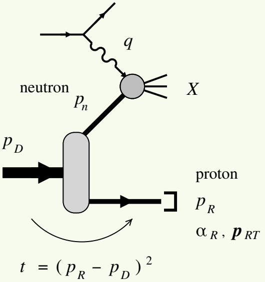
  - 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive (b_{1-4}) [Hoodbhoy, Jaffe, Manohar PLB'88]

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

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

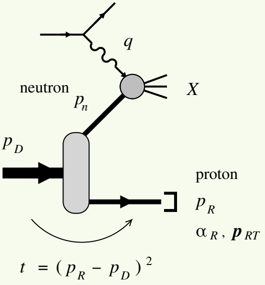
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda),$$

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

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

- $\rho_D^U(\lambda', \lambda)$ 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



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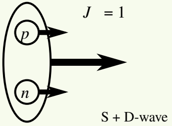
All SF can be written as

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

- 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



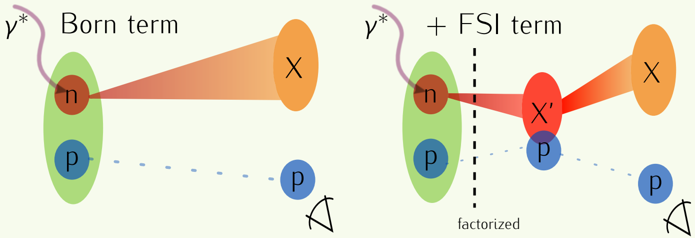
- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]

- 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

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

- 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)

FSI model at high x



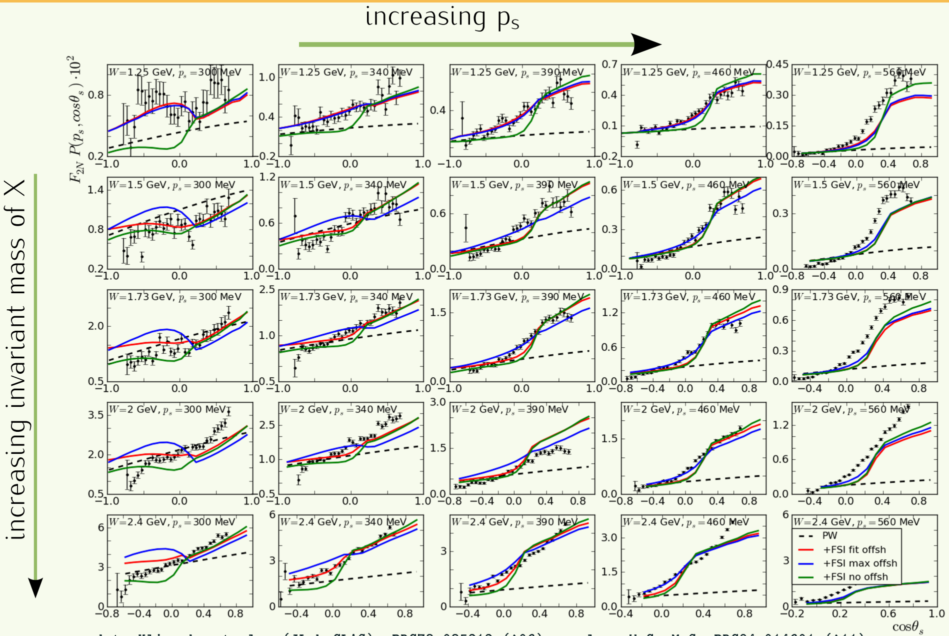
- X: details about composition and evolution unknown
- Use general properties of soft scattering theory, without specifying X
- Factorized approach

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

- Generalised Eikonal Approximation
  - takes spectator **recoil** into account
  - can use **realistic** nuclear wf
- Ideal for light nuclei! (D, ^{3}He, ...)

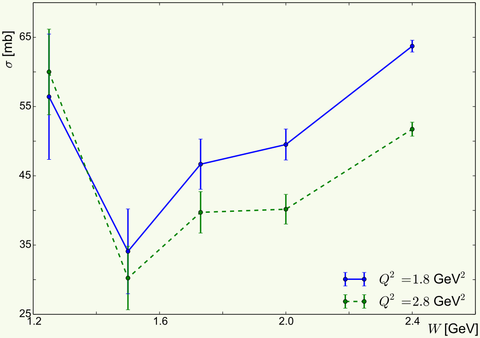
Diffractive amplitude: $f = \sigma_{tot}(W,Q^2)(1+i\epsilon(W,Q^2))exp^{\beta(W,Q^2)t/2}$

Deeps: FSI fitted calculation



data:Klimenko et al. (JLab CLAS), PRC73 035212 ('06) calc: W.C.,M.S. PRC84 014601 ('11)

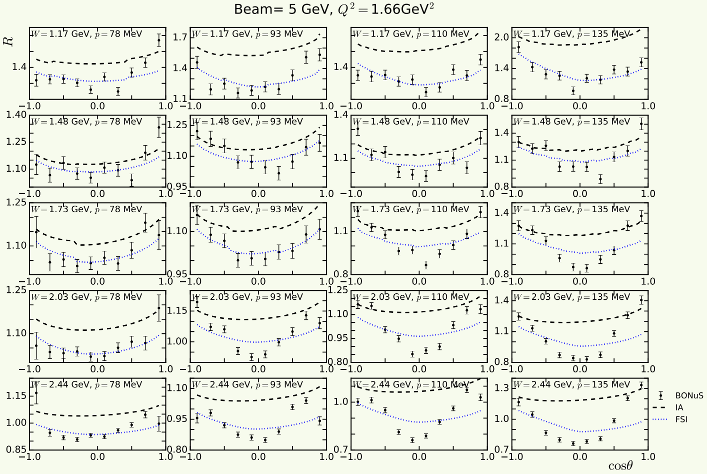
What can the σ_{XN} fit teach us?



- 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

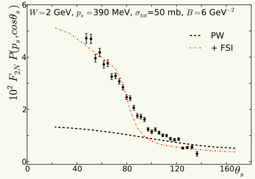
Comparison with BONuS ($p_s = 70 - 140$ MeV)

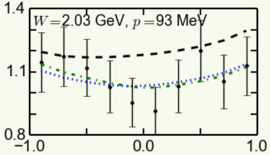


- Data were normalized to a plane-wave model (ratio R), FSI model used to redo normalization

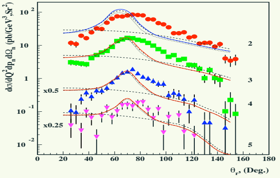
Features of FSI in tagged DIS

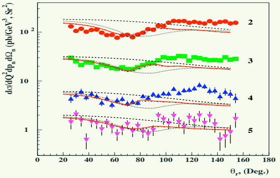
Tagged DIS $D(e,e'p_s)X$





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





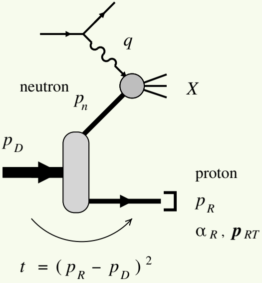
M. Sargsian PRC82 014612 ('10)

high recoil momentum

low recoil momentum

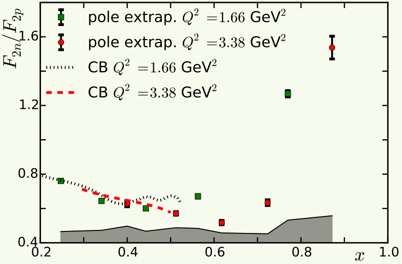
- FSI effects grow in forward direction at high p_r, different from quasi-elastic case, difference in possible phase-space
- FSI effects not zero in the backward region for lower p_s

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 $t - m_N^2 \to 0$: "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 → neutron ∼ 100% polarized
- Precise measurements of neutron structure at an EIC

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

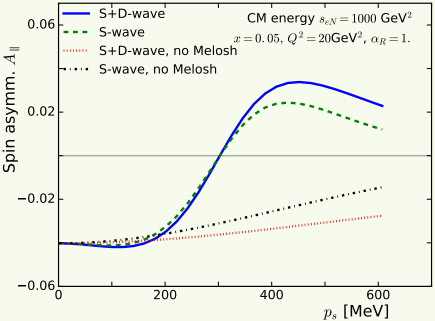


WC, M. Sargsian, PRC93 '16

- 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, 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]

Polarized structure function

Impulse approx calculation



JLAB LDRD project for EIC
`https://www.jlab.org/theory/tag/`
`arXiv:1407.3236, arXiv:1409.5768, arXiv:1601.066665`

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

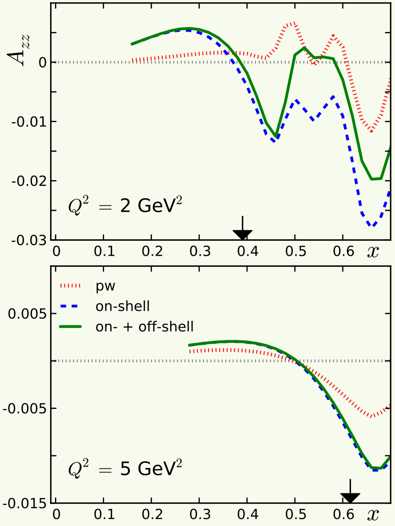
A_{zz} in inclusive DIS

- 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)

A_{zz} in inclusive DIS



WC, M. Sargsian, arXiv:1407.1653

WC,W. Melnitchouk, MS, PRC89 ('14)

- 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 → high spectator momenta) can pick up resonance contributions through the convolution
- Size of FSI effects decreases at higher Q^2 (phase-space effect)

Conclusion

- 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