Tagged spectator DIS off a polarized spin-1 target

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QCD Evolution '16
Amsterdam

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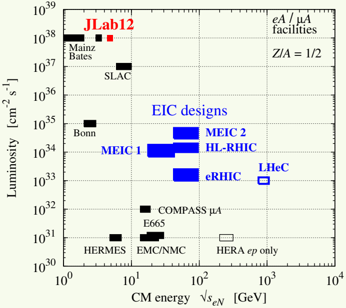
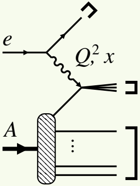
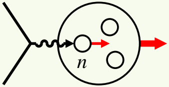
Light ions at an EIC





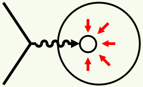
- Wide kinematic range: CM energy $\sqrt{s_{eN}} = 20 - 100$ GeV
  - $Q^2 \sim$ few 10 GeV^2 for DIS
  - $x \sim 10^{-1} - 10^{-3}$ for sea quarks & gluons
- High luminosity $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - detection of exception nuclear configurations feasible
  - multi-variable final states
  - polarization observables
- Polarized light ions
  - eRHIC: unpolarized D, polarized ^{3}He
  - JLEIC: polarized D and ^{3}He figure-8 ring layout

Light ions: physics objectives



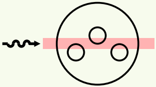
- **Neutron** structure
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects

  How to account for nuclear binding and non-nucl. dof?



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

  How to control nuclear environment?

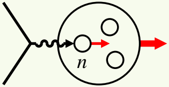


- **Coherence** and saturation
  - interaction of high-energy probe with coherent quark-gluon fields

  How to verify onset of coherence?

Challenges to be addressed by theory and new experimental techniques

Light ions: physics objectives



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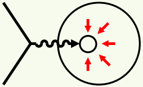

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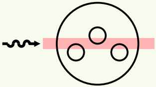

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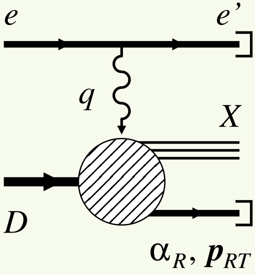
Tagged spectator DIS process with deuteron



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

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 perp components

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

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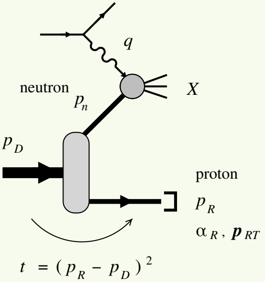
  - 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive (b_{1-4}) [Hoodbhoy, Jaffe, Manohar PLB'88]

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

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

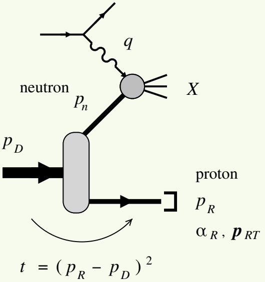
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda),$$

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

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

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

Tagged DIS with deuteron: model for the IA



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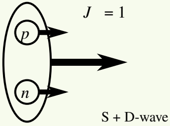
Allows us to write all of the 41 conditional structure functions as a product of a factor dep. on nucleon SF and a D spectral function dep. on the polarization state. One example:

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

- In the IA the following structure functions are **zero** $\rightarrow$ 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

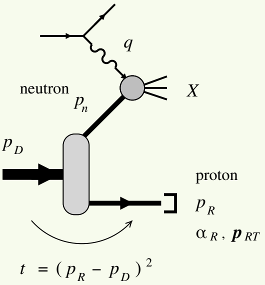


- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]
- One obtains a Schrödinger (non-rel) like eq. for the wave function components
- Light-front WF obeys baryon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

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

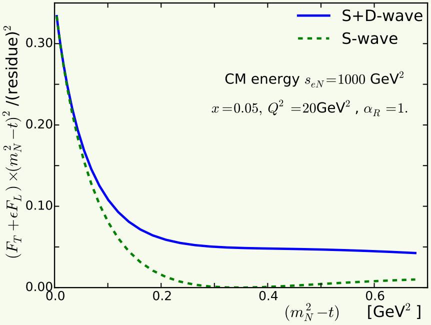
- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - 3-momentum $\boldsymbol{k}_f$ is the relative momentum of the nucleons in the light-front boosted rest-frame of the free 2-nucleon state (so not a “true” kinematical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

Pole extrapolation for on-shell nucleon structure



- Allows to extract free neutron structure 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 $\to$ neutron $\sim 100\%$ polarized
- Precise measurements of neutron structure at an EIC

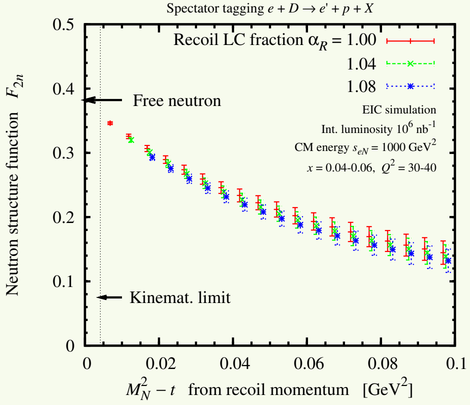
Unpolarized structure function



- 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

Tagging: free neutron structure

Precise measurements of F_{2n}



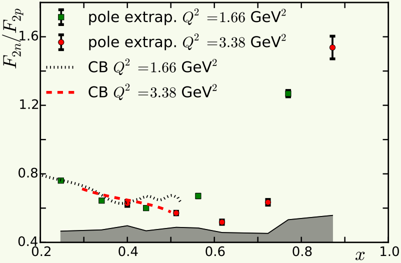
JLab LDRD arXiv:1407.3236, arXiv:1409.5768

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

Tagging: extrapolation of BONuS data

- BONuS experiment @JLab (CLAS) measured tagged spectator unpolarized cross section down to momenta 70 MeV [Baillie et al., PRL108 '12; Tkachenko et al. PRC89 '14]
- **Normalization issue** with BONuS data: detector efficiency varied with p_s. Cross sections normalized to plane-wave model in backward spectator region
- Model which includes **nuclear FSI in the high x region** through effective eikonal rescattering amplitudes of produced X with spectator [WC, Sargsian PRC84 '11; WC,W. Melnitchouk,MS PRC89 '14]
- FSI parameters (Q^2, W dependent) constrained by data at higher spectator momenta [Deeps @JLab, Klimenko et al., PRC73 '06]
- Refitted BONuS normalization of the data to the FSI model for the highest Q^2,W bins ($\rightarrow x \leq 0.5$), where F_{2n} is well established.
- Introduces some model dependence in this particular analysis. **Not** an issue in collider kinematics: no target material, forward detection, extrapolation distance is smaller...

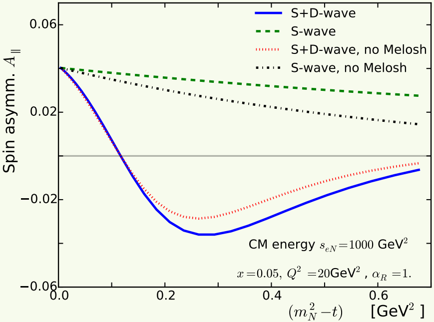
Use Bonus data: F_{2n}/F_{2p}



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**
- Ratio highest at largest Q^2 value ... Duality arguments??
- Sign of hard isosinglet quark-quark correlation, analogous to np pairing in nuclei? [imbalanced 2-component Fermi systems]

Polarized structure function

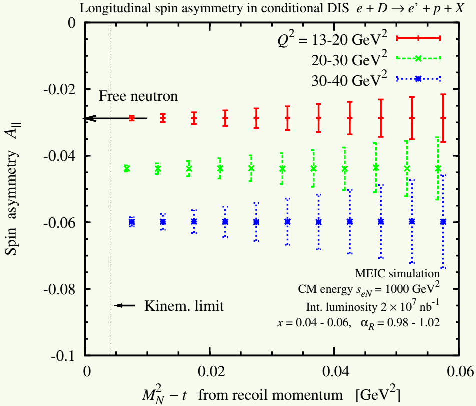


- Spin asymmetry $A_{||} = \frac{\sigma(++)-\sigma(-+)}{\sigma(++)+\sigma(-+)} = \frac{F_{LS_L}}{F_T+\epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$
- Again clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

Tagging: polarized neutron structure

On-shell extrapolation of double spin asymm.

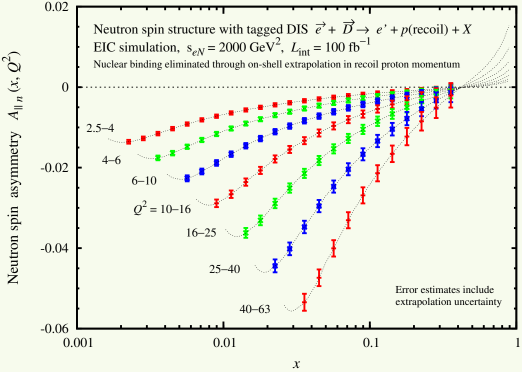
$$A_{||} = \frac{\sigma(++)-\sigma(-+)}{\sigma(++)+\sigma(-+)} = \frac{F_{LS_L}}{F_T+\epsilon F_L} = D\frac{g_{1n}}{F_{1n}} + \cdots$$



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 $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

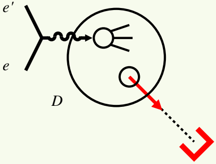
On-shell extrapolation of double spin asymm. $A_{||} = D\frac{g_{1n}}{F_{1n}} + \cdots$



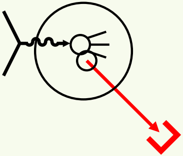
- As depolarization factor $D = \frac{y(2-y)}{2-2y+y^2}$ and $y \approx \frac{Q^2}{x s_{eN}}$, wide range of s_{eN} required!

- Precise measurement of neutron spin structure
  - separate leading- /higher-twist
  - non-singlet/singlet QCD evolution
  - pdf flavor separation $\Delta u, \Delta d$. ΔG through singlet evolution
  - non-singlet $g_{1p} - g_{1n}$ and Bjorken sum rule

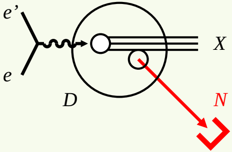
Tagging: EMC effect



average-size



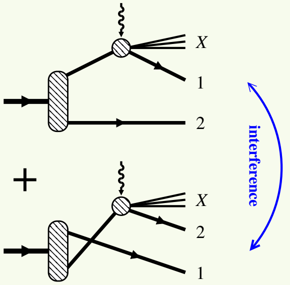
small-size

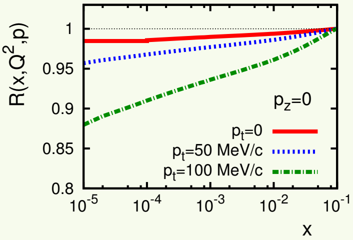


Final−state interactions

- 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 $\tilde{x}$

Tagging: Coherence and 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 $A \gg 1$
  - Quantify approach to saturation at small x
- Coherent scattering $e + D \rightarrow e + M + D$
  Exclusive meson production, DVCS, nuclear GPDs

Tagging: developments and extensions

- Final-state interactions in tagged $e + D$
  - distorts recoil momentum dependence away from the on-shell pole $t \neq m_N^2$
  - broad momentum distribution, interactions of spectator with slow debris `[Cosyn,Sargsian,Strikman,Weiss;in progress.  Ciofi, Kopeliovich 02]`
  - 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

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.
- Recoil momentum dependence permits separation of nuclear and nucleon structure
- 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
  - Coherence and shadowing
- Pole extrapolation of BONuS data shows striking rise of F_{2n}/F_{2p} at high x

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
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- **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`