Polarized deuteron DIS with spectator tagging

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Exploring QCD with Light Nuclei at an EIC
Stony Brook
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in collaboration with Ch. Weiss
JLab LDRD project on spectator tagging

FLORIDA INTERNATIONAL UNIVERSITY

Outline

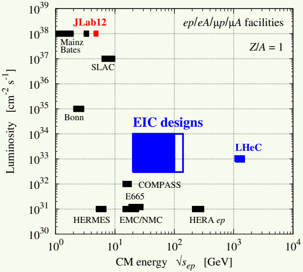
- Physics with light ions at EIC → spectator tagging
- Deuteron structure on the light front
- Longitudinal double spin asymmetry in electron-deuteron tagged proton DIS
  → neutron spin structure g_{1n}
- Extensions

Why focus on light ions at an EIC?

- Measurements with light ions address essential parts of the EIC physics program
  - neutron structure
  - nucleon interactions
  - coherent phenomena
- Light ions have unique features
  - polarized beams
  - breakup measurements & tagging
  - first principle theoretical calculations of initial state
- Intersection of two communities
  - high-energy scattering
  - low-energy nuclear structure

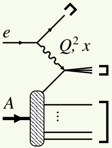
Use of light ions for high-energy scattering and QCD studies remains relatively unexplored

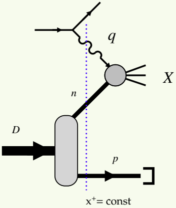
EIC design characteristics (for light ions)



- CM energy $\sqrt{s_{eA}} = \sqrt{Z/A}\ 20 - 100\text{GeV}$
  DIS at $x \sim 10^{-3} - 10^{-1}$, $Q^2 \leq 100\text{GeV}^2$
- High luminosity enables probing/measuring
  - exceptional configurations in target
  - multi-variable final states
  - polarization observables
- Forward detection of target beam remnants
  - diffractive and exclusive processes
  - coherent nuclear scattering
  - nuclear breakup and tagging
  - forward detectors integrated in designs
- Polarized light ions
  - ^{3}He, d @ eRHIC
  - spin structure, polarized EMC, tensor pol, ...

Theory: high-energy scattering with nuclei





- Interplay of two scales: high-energy scattering and low-energy nuclear structure. Virtual photon probes nucleus at fixed lightcone time $x^+ = x^0 + x^3$
- Scales can be separated using methods of light-front quantization and QCD factorization
- Tools for high-energy scattering known from *ep*
- Nuclear input: light-front momentum densities, spectral functions, overlaps with specific final states in breakup/tagging reactions
  - framework known for deuteron, can be extended to ^{3}He
  - still **low-energy** nuclear physics, just formulated differently

Neutron structure measurements

Needed for flavor separation, singlet vs non-singlet evolution etc.

- EIC will measure **inclusive** DIS on light nuclei [d, ^{3}He, ^{3}H(?)]
  - Simple, no FSI effects
  - Compare n from ^{3}He $\leftrightarrow$ p from ^{3}H
  - Comparison n from ^{3}He, d
    ^{3}He $\rightarrow$ talk Maxwell

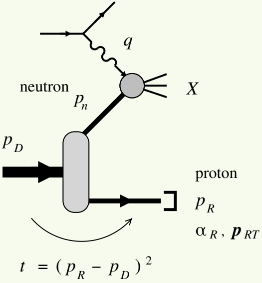
- **Uncertainties** limited by nuclear structure effects (binding, Fermi motion, non-nucleonic dof)

- ^{3}He is in particular affected because of intrinsic Δs $\rightarrow$ talk Guzey

If we want to aim for precision, use tools that avoid these complications

Neutron structure with tagging

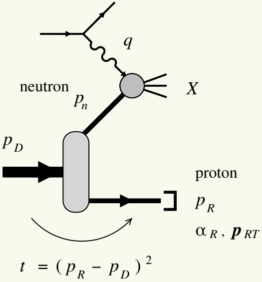
- Proton tagging offers a way of controlling the nuclear configuration



- Advantages for the deuteron
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable `Strikman, Weiss PRC '18` $\rightarrow$ talk Weiss

- Suited for colliders: no target material ($p_p \rightarrow 0$), forward detection, polarization.
  fixed target CLAS BONuS limited to recoil momenta ~ 70 MeV
  $\rightarrow$ talk Keppel

Pole extrapolation for on-shell nucleon structure



- Allows to extract free neutron structure
  - 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 (spin) structure at an EIC

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
  - Results for longitudinal spin asymmetries
  - FSI corrections (unpolarized [Strikman, Weiss PRC '18], $\rightarrow$ talk Weiss)

- 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

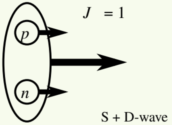
$$S^\mu = \langle \hat{W}^\mu \rangle , \qquad T^{\mu\nu} = \frac{1}{2}\sqrt{\frac{2}{3}}\langle \hat{W}^\mu \hat{W}^\nu + \hat{W}^\nu \hat{W}^\mu + \frac{4}{3}\left(g^{\mu\nu} - \frac{\hat{P}^\mu \hat{P}^\nu}{M^2} \right) \rangle$$

- Split in longitudinal and transverse components

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

- Can be formulated in **covariant** manner $\rightarrow \rho^{\mu\nu} = \sum_{\lambda\lambda'} \epsilon^{*\mu}(\lambda')\epsilon^\nu(\lambda)\rho_{\lambda\lambda'}$

Deuteron light-front wave function



- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Berestetsky, Terentev, Coester,Keister,Polyzou et al.]
  → Overlap with on-shell free two-nucleon state
- 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

$$\Psi_\lambda(\boldsymbol{k},\lambda_p,\lambda_n)=\sqrt{E_k}\sum_{\lambda'_p\lambda'_n}\mathcal{D}^{\frac{1}{2}}_{\lambda_p\lambda'_p}[R_{fc}(k_1^\mu/m)]\mathcal{D}^{\frac{1}{2}}_{\lambda_n\lambda'_n}[R_{fc}(k_2^\mu/m)]\Phi_\lambda(\boldsymbol{k},\lambda'_p,\lambda'_n)$$

- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - $\boldsymbol{k}$ 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)

Effective neutron spin density matrix

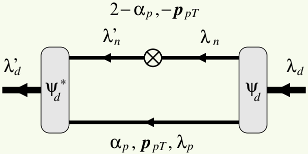
- Deuteron LF wavefunction:

$$\Psi_{\lambda_d}(\boldsymbol{k},\lambda_p,\lambda_n)=\sqrt{E_k}\sum_{\lambda'_p\lambda'_n}\mathcal{D}^{\frac{1}{2}}_{\lambda_p\lambda'_p}[R_{fc}(k_1^\mu/m)]\mathcal{D}^{\frac{1}{2}}_{\lambda_n\lambda'_n}[R_{fc}(k_2^\mu/m)]\Phi_\lambda(\boldsymbol{k},\lambda'_p,\lambda'_n)$$

- 4D covariant formulation: [Kondryatchuk, Strikman '83]

$$\Psi_{\lambda_d}(\alpha_p,\boldsymbol{p}_{pT},\lambda_p,\lambda_n)=\bar{u}_{\mathrm{LF}}(p_n\lambda_n)\Gamma_\alpha(p_p,p_n)v_{\mathrm{LF}}(p_p,\lambda_p)\epsilon^\alpha_{pn}(p_{pn},\lambda_d)$$

- Matrix elements of nucleon operators



$$\langle\hat{O}_n\rangle=\int\frac{d\alpha_p}{\alpha_p}d^2p_{pT}\frac{2\mathrm{tr}[\Pi_n\Gamma_n]}{(2-\alpha_p)}\qquad\qquad \alpha_p=2p_p^+/p_d^+$$

- Effective neutron spin density matrix (cfr. parton correlators in QCD)

$$\Pi_n=(\rho_{pn})^{\alpha\beta}(\not{p}_n+m)\Gamma_\alpha(\not{p}_p-m)\Gamma_\beta(\not{p}_n+m)$$

Nucleon LF momentum distributions

- Can be split into unpolarized, vector and tensor polarization terms:

$$\Pi_n[\text{unpol}] = \frac{1}{2}(\not{p}_n + m)(f_0^2 + f_2^2)\,,$$
$$\Pi_n[\text{vector}] = \frac{1}{2}(\not{p}_n + m)\not{s}_n(\boldsymbol{S}_d, \boldsymbol{k})\gamma_5\,,$$
$$\Pi_n[\text{tensor}] = -\frac{1}{2}(\not{p}_n + m)(\boldsymbol{k}\,T_d\,\boldsymbol{k})\frac{3}{k^2}\left(2f_0 + \frac{f_2}{\sqrt{2}}\right)\frac{f_2}{\sqrt{2}}\,.$$

- Allows for the definition of **nucleon** light-front momentum distributions

Helicity independent $$S_d(\alpha_p, \boldsymbol{p}_{pT}) = \frac{\text{tr}[\Pi_n \gamma^+]}{(2-\alpha_p)^2 p_d^+}\,,$$

Helicity dependent $$\Delta S_d(\alpha_p, \boldsymbol{p}_{pT}) = \frac{\text{tr}[\Pi_n(-\gamma^+\gamma_5)]}{(2-\alpha_p)^2 p_d^+}$$

- S_d receives contributions from $\Pi_n[\text{unpol}]$ and $\Pi_n[\text{tensor}]$
  ΔS_d receives contributions from $\Pi_n[\text{vector}]$
- Tensor polarization does not induce nucleon helicity dependence

Nucleon LF momentum distributions (II)

- LF momentum distributions obey sum rules
  - baryon

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{unpol}] = 1 \,,$$
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{tensor}] = 0 \,,$$

  - momentum

$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{unpol}] = 1 \,,$$
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} (2-\alpha_p) S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{tensor}] = 0$$

  - axial

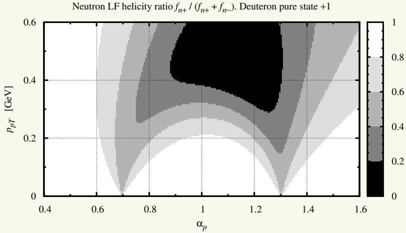
$$\int \frac{d\alpha_p}{\alpha_p} d^2 p_{pT} \Delta S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{vector}] = S_d^z \frac{g_{Ad}}{2g_A} \,,$$
$$1 - \frac{3}{2}\omega_2 = \frac{g_{Ad}}{2g_A} \,.$$

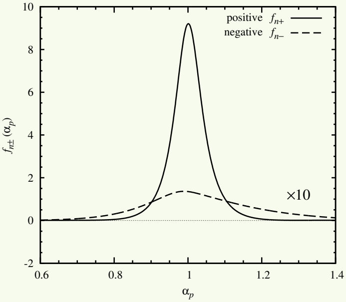
Polarized neutrons in polarized deuteron

- For a pure +1 deuteron state, we can introduce

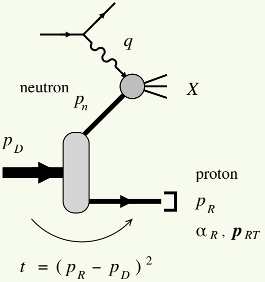
$$f_{n\pm}[\text{pure } +1] = \frac{1}{2}(S_d \pm \Delta S_d)[\text{pure } +1]$$

distributions of neutrons with LF helicity $\pm 1/2$





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

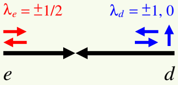
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda) \,,$$

All SF can be written as

$F_{ij}^k = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{or}\, g_{1,2}(\tilde{x}, Q^2)\} \times \{$bilinear forms in deuteron radial wave function $f_0(k)$ [S-wave], $f_2(k)$ [D-wave]$\}$

- 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]

Polarized structure function: longitudinal asymmetry



- On-shell extrapolation of double spin asymmetry
  - Nominator
    $d\sigma_{||} \;\equiv\; \frac{1}{4}\left[\mathrm{d}\sigma(+\tfrac{1}{2},+1) - \mathrm{d}\sigma(-\tfrac{1}{2},+1) - \mathrm{d}\sigma(+\tfrac{1}{2},-1) + \mathrm{d}\sigma(-\tfrac{1}{2},-1)\right]$
  - Two possible denominators: 3-state and 2-state

$$d\sigma_3 \equiv \frac{1}{6}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1) + \mathrm{d}\sigma(\Lambda_e,0)\right]$$
$$d\sigma_2 \equiv \frac{1}{4}\sum_{\Lambda_e}\left[\mathrm{d}\sigma(\Lambda_e,+1) + \mathrm{d}\sigma(\Lambda_e,-1)\right]$$

  - Asymmetries: **tensor polarization** enters in 2-state one

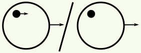
$$A_{||,3} = \frac{d\sigma_{||}}{d\sigma_3}[\phi_h\,\mathrm{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L}$$
$$A_{||,2} = \frac{d\sigma_{||}}{d\sigma_2}[\phi_h\,\mathrm{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}}(F_{T_{LL}T} + \epsilon F_{T_{LL}L})}$$

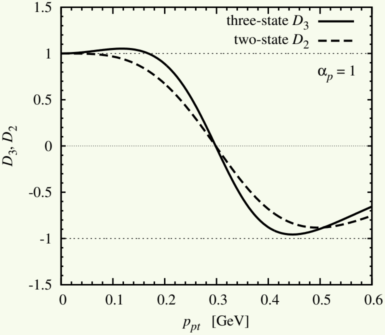
- Impulse approximation yields in the Bjorken limit $\left[\alpha_p = \frac{2p_p^+}{p_D^+}\right]$

$$A_{||,i} \approx \mathcal{D}_i(\alpha_p, |p_{pT}|)A_{||n} = \mathcal{D}_i(\alpha_p, |p_{pT}|)\frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1+\epsilon R_n)F_{1n}(\tilde{x}, Q^2)}$$

Nuclear structure factors $\mathcal{D}_2$, $\mathcal{D}_3$

- Quantifies neutron depolarization due to nuclear structure
- Depends on spectator kinematics α_p, p_{pT}
- $\mathcal{D}_2 = \Delta S_d[\text{pure } +1]/S_d[\text{pure } +1]$ has **probabilistic interpretation**
- $\mathcal{D}_3 = \Delta S_d[\text{pure } +1]/S_d[\text{unpol}]$ has no such interpretation.





WC, C. Weiss, PLB ('19); in preparation

- Bounds: $-1 \leq \mathcal{D}_2 \leq 1$
- Due to lack of OAM $\mathcal{D}_2 \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- $\mathcal{D}_3$ violates bounds due to lack of tensor pol. contribution
- $\mathcal{D}_3 \neq 0$ for $p_T = 0$
- $\mathcal{D}_2$ closer to unity at small recoil momenta
- 2-state asymmetry is also easier experimentally!!

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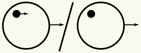
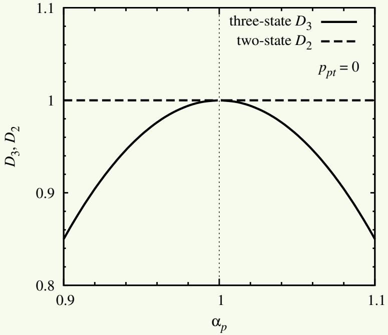


- $\mathcal{D}_3 = \Delta S_d[\text{pure } +1]/S_d[\text{unpol}]$ has no such interpretation.



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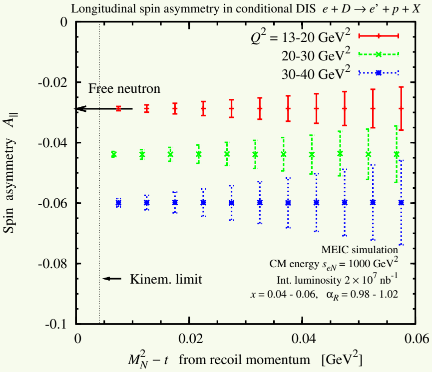
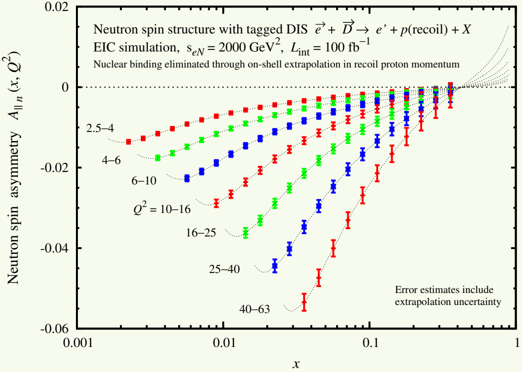
Tagging: simulations of $A_{||}$



JLab LDRD arXiv:1407.3236, arXiv:1409.5768
https://www.jlab.org/theory/tag/

- D-wave suppr. at on-shell point $\rightarrow$ neutron $\sim$ 100% polarized
- 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 $\sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

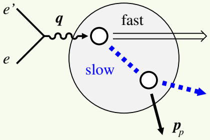
On-shell extrapolation of double spin asymm. $A_{||} = D\frac{g_{1n}}{F_{1n}} + \cdots$

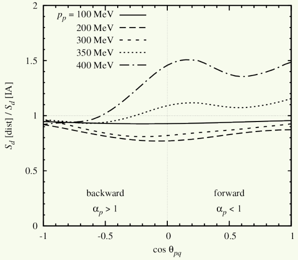


- As depolarization factor $D = \frac{y(2-y)}{2-2y+y^2}$ and $y \approx \frac{Q^2}{xs_{eN}}$, wide range of s_{eN} required!

- 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

Final-state interactions in tagging





Strikman, Weiss, PRC7 035209 ('18)

- **Issue** in tagging: DIS products can interact with spectator → rescattering, absorption
- Dominant contribution at intermediate $x \sim 0.1 - 0.5$ from "**slow**" hadrons that hadronize inside nucleus
- Measure fracture functions with EIC → talks Ceccopieri, Strikman
- Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.
- FSI vanish at the pole → pole extrapolation **still feasible**

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

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

Nuclear imaging: deuteron tensor polarization

→ Talks Slifer, Long, Kumano

- Tensor polarization in D probes **nuclear effects**
- Little explored in high-energy scattering
- Inclusive b_1 result from HERMES: no conventional nuclear calculation reproduces data
- Spin 1 targets admit gluon transversity
- Tagged cross section yields 23 additional structure functions with specific azimuthal dependences [`Cosyn,Sargsian,Weiss, in prep.`]
- T-odd SF [DSA] are zero in impulse approximation → sensitive to FSI

Extensions for $A > 2$?

→ talk Scopetta

- Construction of Poincaré covariant $A = 3$ states, operators becomes harder due to additional constraints of **cluster separability**
- Solution is known: Sokolov **packing operators** [Sokolov; Lev]
- For DIS free currents (cfr parton model; leading twist pdfs) obey Poincaré covariance constraints in collinear frames [Lev,Pace,Salmé]
  → angular conditions
- Add Sokolov packing operators to currents for $A > 2$ to obey cluster separability
- Formalism is known, non-trivial calculations need to be carried out

EIC Yellow Paper report

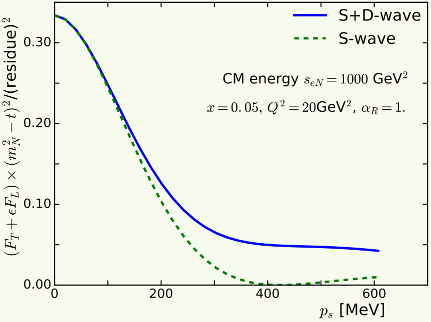
- Working group: tagging & diffraction
  - Cosyn (FIU), Hen (MIT), Higinbotham (JLab), Klein (LBL), Stasto (PSU)
- Detector requirements to study these processes, identify benchmark reaction channels
- Get in touch if you can and want to contribute!

Conclusions

- Light ions address important parts of the EIC physics program
- Tagging and nuclear breakup measurements overcome limitations due to nuclear uncertainties in inclusive DIS → **precision machine**
- Unique observables with **polarized deuteron**: free neutron spin structure, tensor polarization
- Extraction of nucleon spin structure in a wide kinematic range
- Lots of extensions to be explored!

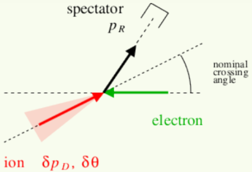
Backup Slides

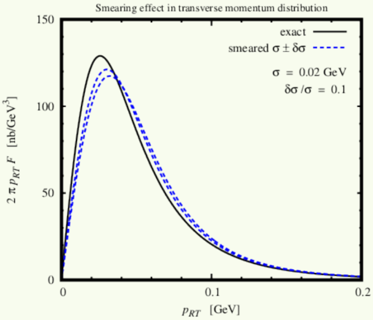
Unpolarized structure function



- 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

JLEIC: Momentum spread in beam

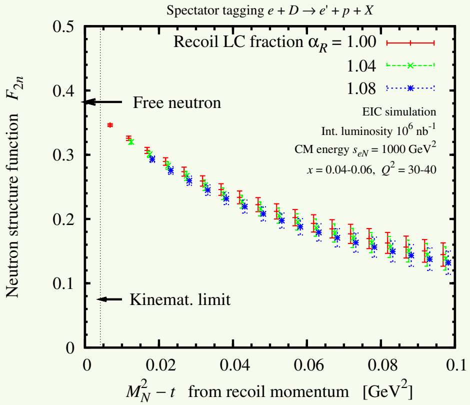




[Ch. Hyde, K. Park et al.]

- Intrinsic beam spread in ion beam "smears" recoil momentum
  - transverse momentum spread of $\sigma \approx 20$ MeV ($\delta\sigma/\sigma \sim 10\%$)
  - p_R(measured) $\neq$ p_R(vertex)
  - Systematic correlated uncertainty, x, Q^2 independent
- Dominant syst. uncertainty at JLEIC, detector resolution much higher than beam momentum spread (diff for eRHIC)
- On-shell extrapolation feasible!!

Tagging: unpolarized neutron structure

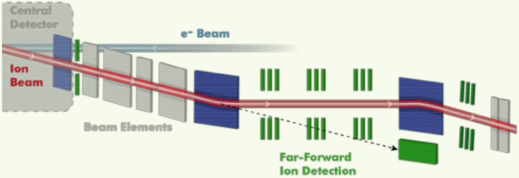


`JLab LDRD arXiv:1407.3236, arXiv:1409.5768,`
`https://www.jlab.org/theory/tag/`

$\alpha_R = 2p_R^+/p_D^+$

- 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 $\bar{d} - \bar{u}$

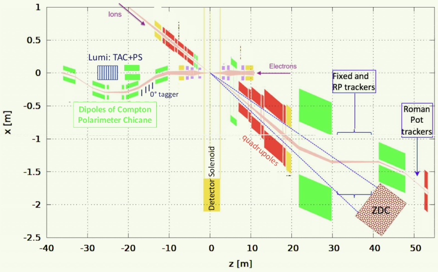
EIC: forward detection system

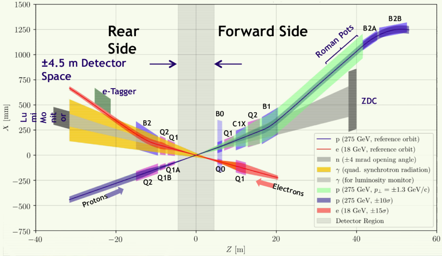


[not to scale]

- Large acceptance forward detector [concept: P. Nadel-Turonski, Ch. Hyde et al.]
  - beams collide at small crossing angle 25-50 mrad
  - forward p/n/ions travel through ion beam quadrupole magnets
  - dispersion generated by dipole magnets
  - detector systems:
    tracking in dipole magnets
    Roman pots for charged (p,ions) forward particles
    zero-degree calorimeters (ZDCs) for neutrals (neutron, photon)
- Major optimization and integration challenge
  - Forward particles with range of rigidities (momentum/charge), different from beam
  - Range in ion beam energy
  - Geometry of magnets and infrastructure
  - More complex than forward detectors at HE colliders [HERA, RHIC, LHC]

EIC: forward detection system





JLEIC IR design: V. Morozov et al 2019,
eRHIC IR design, Ch. Montag et al 2019

- IR designs
  - JLEIC and eRHIC design similar
  - Differences: crossing angle 50 [JLEIC] - 25 mrad [eRHIC]; JLEIC secondary focus at RP location
- Forward acceptance and resulotion
  - software framework developed
  - simulations on-going
- Momentum spread in ion beam
  - transverse momentum spread $\sim$ few 10 MeV
  - smearing effect: $p_T[\text{vertex}] \neq p_T[\text{measured}]$, systematic uncertainty