Neutron structure from deuteron deep inelastic scattering with spectator tagging

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JLab seminar

in collaboration with Ch. Weiss
JLab LDRD project on spectator tagging
Outline

- Physics with light ions at EIC
- Deuteron structure on the light front
- Longitudinal double spin asymmetry in electron–deuteron tagged proton DIS
  $\rightarrow$ 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 – 100GeV
  DIS at $x \sim 10^{-3} – 10^{-1}$, $Q^2 \leq 100$GeV$^2$

- High luminosity enables probing/measuring
  - exceptional configurations in target
  - multi-variable final states
  - polarization observables

- Polarized light ions
  - $^3$He, other @ eRHIC
  - d, $^3$He, other @ JLEIC (figure 8)
  - spin structure, polarized EMC, tensor pol, ...

- Forward detection of target beam remnants
  - diffractive and exclusive processes
  - coherent nuclear scattering
  - nuclear breakup and tagging
  - forward detectors integrated in designs
Light ions at EIC: 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

- **Nucleon interactions in QCD**
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation

- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

Need to control nuclear configurations that play a role in these processes
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 $^3\text{He}$
  - 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\text{He}, ^3\text{H}(?)])
  - Simple, no FSI effects
  - Compare \(n\) from \(^3\text{He}\) ↔ \(p\) from \(^3\text{H}\)
  - Comparison \(n\) from \(^3\text{He}\), \(d\)

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

- \(^3\text{He}\) is in particular affected because of intrinsic \(\Delta s\)

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

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

- D-wave suppressed at on-shell point → neutron $\sim 100\%$ polarized

- Precise measurements of neutron (spin) structure at an EIC
General expression of SIDIS for a polarized spin 1 target

- Tagged spectator DIS is SIDIS in the target fragmentation region

\[ e^+ + T \rightarrow e' + X + h \]

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])

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 3x3 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

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

- Split in longitudinal and transverse components

\[
\rho_{\lambda \lambda'} = \frac{1}{3} \begin{bmatrix}
1 + \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} & \frac{3}{2} \sqrt{2} S_T e^{-i(\phi_h - \phi_S)} & \frac{3}{2} \sqrt{2} S_T e^{-i(2\phi_h - 2\phi_T)} \\
\frac{3}{2} S_T e^{i(\phi_h - \phi_S)} & 1 - \sqrt{6} T_{LL} & \frac{3}{2} S_T e^{-i(\phi_h - \phi_S)} \\
- \sqrt{3} T_{LT} e^{i(\phi_h - \phi_T)} & \frac{3}{2} \sqrt{2} S_T e^{i(\phi_h - \phi_S)} & 1 - \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL}
\end{bmatrix}
\]

- Can be formulated in **covariant** manner → \( \rho^{\mu \nu} = \sum_{\lambda \lambda'} \varepsilon^{\mu}_{\lambda'}(\lambda') \varepsilon^{\nu}(\lambda) \rho_{\lambda \lambda'} \)
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.]
  \[\rightarrow\] 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

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

- Differences with non-rel wave function:
  - appearance of the Melosh rotations to account for light-front quantized nucleon states
  - $k$ 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:

\[ \Psi_{\lambda_d}(k, \lambda_p, \lambda_n) = \sqrt{E_k} \sum_{\lambda'_p, \lambda'_n} D_{\lambda_p \lambda'_p}^{1/2} [R_{fc}(k_1^u/m)] D_{\lambda_n \lambda'_n}^{1/2} [R_{fc}(k_2^u/m)] \phi_{\lambda}(k, \lambda'_p, \lambda'_n) \]

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

\[ \Psi_{\lambda_d}(\alpha_p, p_{pT}, \lambda_p, \lambda_n) = \bar{u}_{LF}(p_n \lambda_n) \Gamma_{\alpha}(p_p, p_n) v_{LF}(p_p, \lambda_p) \epsilon_{\alpha p}(p_{pn}, \lambda_d) \]

- Matrix elements of nucleon operators

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

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

\[ \Pi_n = (\rho_{pn})^{\alpha \beta} (p_n + m) \Gamma_{\alpha}(p_p - m) \Gamma_{\beta}(p_n + m) \]
Nucleon LF momentum distributions

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

\[
\Pi_n[\text{unpol}] = \frac{1}{2}(p_n + m)(f_0^2 + f_2^2),
\]

\[
\Pi_n[\text{vector}] = \frac{1}{2}(p_n + m)s_n(S_d, k)\gamma_5,
\]

\[
\Pi_n[\text{tensor}] = -\frac{1}{2}(p_n + m)(k T_d k) \frac{3}{k^2} \left(2f_0 + \frac{f_2}{\sqrt{2}}\right) \frac{f_2}{\sqrt{2}}.
\]

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

\[
S_d(\alpha_p, p_{pT}) = \frac{\text{tr}[\Pi_n \gamma^+]}{(2 - \alpha_p)^2 p_d^+},
\]

\[
\Delta S_d(\alpha_p, p_{pT}) = \frac{\text{tr}[\Pi_n(-\gamma^+ \gamma_5)]}{(2 - \alpha_p)^2 p_d^+}
\]

- \(S_d\) receives contributions from \(\Pi_n[\text{unpol}]\) and \(\Pi_n[\text{tensor}]\)
- \(\Delta S_d\) receives contributions from \(\Pi_n[\text{vector}]\)
- Deuteron tensor polarization does not induce nucleon helicity dependence
Nucleon LF momentum distributions (II)

- LF momentum distributions obey sum rules
  - baryon
  \[
  \int \frac{d\alpha_p}{\alpha_p} d^2 p_T S_d(\alpha_p, p_{pT})[\text{unpol}] = 1 ,
  \]
  \[
  \int \frac{d\alpha_p}{\alpha_p} d^2 p_T S_d(\alpha_p, p_{pT})[\text{tensor}] = 0 ,
  \]

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

  - axial
  \[
  \int \frac{d\alpha_p}{\alpha_p} d^2 p_T \Delta S_d(\alpha_p, p_{pT})[\text{vector}] = S_d^2 \frac{g_{Ad}}{2g_A} ,
  \]
  \[
  1 - \frac{3}{2} \omega_2 = \frac{g_{Ad}}{2g_A} .
  \]
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 ±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

\[
F_{ij}^{k} = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2)\text{or } g_{1,2}(\tilde{x}, Q^2)\} \times \{\text{bilinear forms in deuteron radial wave function } f_{0}(k) [S\text{-wave}], f_{2}(k) [D\text{-wave}]\}
\]

- 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]
On-shell extrapolation of double spin asymmetry

- Nominator
  \[ d\sigma_{||} = \frac{1}{4} \left[ d\sigma(+\frac{1}{2}, +1) - d\sigma(-\frac{1}{2}, +1) - d\sigma(+\frac{1}{2}, -1) + d\sigma(-\frac{1}{2}, -1) \right] \]

- Two possible denominators: 3-state and 2-state
  \[ d\sigma_3 = \frac{1}{6} \sum_{\Lambda_e} [d\sigma(\Lambda_e, +1) + d\sigma(\Lambda_e, -1) + d\sigma(\Lambda_e, 0)] \]
  \[ d\sigma_2 = \frac{1}{4} \sum_{\Lambda_e} [d\sigma(\Lambda_e, +1) + d\sigma(\Lambda_e, -1)] \]

- Asymmetries: tensor polarization enters in 2-state one
  \[ A_{||,3} = \frac{d\sigma_{||}[\phi_{h \text{ avg}}]}{d\sigma_3} = \frac{F_{LS_L}}{F_T + \epsilon F_L} \]
  \[ A_{||,2} = \frac{d\sigma_{||}[\phi_{h \text{ avg}}]}{d\sigma_2} = \frac{F_{LS_L}}{F_T + \epsilon F_L + \frac{1}{\sqrt{6}}(F_{T_{LL}T} + \epsilon F_{T_{LL}L})} \]

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

- Asymmetries in the Bjorken limit
  \[ A_{||,i} \approx D_i(\alpha_p, |p_pT|) A_{||,n} = D_i(\alpha_p, |p_pT|) \frac{D_{||}g_{1n}(\tilde{x}, Q^2)}{2(1 + \epsilon R_n) F_{1n}(\tilde{x}, Q^2)} \]
Nuclear structure factors $D_2, D_3$

- Quantifies neutron depolarization due to nuclear structure
- Depends on spectator kinematics $\alpha_p, p_{pT}$
- $D_2 = \Delta S_d[\text{pure } +1]/S_d[\text{pure } +1]$ has **probabilistic interpretation**
- $D_3 = \Delta S_d[\text{pure } +1]/S_d[\text{unpol}]$ has no such interpretation.

**Bounds:** $-1 \leq D_2 \leq 1$

- Due to lack of OAM $D_2 \equiv 1$ for $p_T = 0$
- Clear contribution from D-wave at finite recoil momenta
- $D_3$ violates bounds due to lack of tensor pol. contribution
- $D_3 \not= 0$ for $p_T = 0$
- $D_2$ closer to unity at small recoil momenta
- 2-state asymmetry is also easier experimentally!!

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WC, C. Weiss, PLB ('19); in preparation
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Tagging: simulations of $A_{||}$

- **D-wave suppr. at on-shell point** → 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 $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$

Longitudinal spin asymmetry in conditional DIS $e + D \rightarrow e' + p + X$

$Q^2 = 13-20 \text{GeV}^2$

$20-30 \text{GeV}^2$

$30-40 \text{GeV}^2$

Free neutron

Kinem. limit

$M_N^2 - t$ from recoil momentum [GeV$^2$]

https://www.jlab.org/theory/tag/
Tagging: simulations of $A_{||}$

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

Neutron spin asymmetry $A_{|| n}(x, Q^2)$

Neutron spin structure with tagged DIS $\bar{e} + D \rightarrow e' + p(\text{recoil}) + X$

EIC simulation, $s_{eN} = 2000 \text{ GeV}^2$, $L_{\text{int}} = 100 \text{ fb}^{-1}$

Nuclear binding eliminated through on-shell extrapolation in recoil proton momentum $Q^2 = 10^{-16} 6^{-10} 4^{-6} 2.5^{-4} 16^{-25} 25^{-40} 40^{-63}$

Error estimates include extrapolation uncertainty

- 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 $\Delta u, \Delta d$. $\Delta G$ through singlet evolution
  - non-singlet $g_{1p} - g_{1n}$ and Bjorken sum rule
Final-state interactions in tagging

- **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

- 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**

*Strikman, Weiss, PRC7 035209 (’18)*
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,

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

\( U + S \) part identical to spin 1/2 case [Bacchetta et al. JHEP ('07)]

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

\[
F_S = S_L \left[ \sqrt{2\epsilon(1 + \epsilon)} \sin \phi_h F_{USL}^{\sin \phi_h} + \epsilon \sin 2\phi_h F_{USL}^{2 \phi_h} \right] + S_L h \left[ \sqrt{1 - \epsilon^2} F_{LSL} + \sqrt{2\epsilon(1 - \epsilon)} \cos \phi_h F_{LSL}^{\cos \phi_h} \right] + S_\perp \left[ \sin(\phi_h - \phi_S) \left( F_{UST,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UST,L}^{\sin(\phi_h - \phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{UST}^{\sin(\phi_h + \phi_S)} + \epsilon \sin(3\phi_h - \phi_S) F_{UST}^{3\phi_h - \phi_S} + \sqrt{2\epsilon(1 + \epsilon)} \left( \sin \phi_S F_{UST}^{\sin \phi_S} + \sin(2\phi_h - \phi_S) F_{UST}^{2 \phi_h - \phi_S} \right) \right] + S_\perp h \left[ \sqrt{1 - \epsilon^2} \cos(\phi_h - \phi_S) F_{LSL}^{\cos(\phi_h - \phi_S)} + \sqrt{2\epsilon(1 - \epsilon)} \left( \cos \phi_S F_{LSL}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LSL}^{2 \phi_h - \phi_S} \right) \right],
\]
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- 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]

$$F_T = T_{LL} \left[ F_{UT_{LL}, T} + \epsilon F_{UT_{LL}, L} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi_h F_{UT_{LL}}^{\cos \phi_h} + \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \right]$$

$$+ T_{LL} h \sqrt{2\epsilon(1 - \epsilon)} \sin \phi_h F_{LT_{LL}}^{\sin \phi_h}$$

$$+ T_{L\perp} \left[ \cdots \right] + T_{L\perp} h \left[ \cdots \right]$$

$$+ T_{\perp\perp} \left[ \cos(2\phi_h - 2\phi_{T\perp}) \left( F_{UT_{TT}, T}^{\cos(2\phi_h - 2\phi_{T\perp})} + \epsilon F_{UT_{TT}, L}^{\cos(2\phi_h - 2\phi_{T\perp})} \right) \right]$$

$$+ \epsilon \cos 2\phi_{T\perp} F_{UT_{TT}}^{\cos 2\phi_{T\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T\perp})}$$

$$+ \sqrt{2\epsilon(1 + \epsilon)} \left( \cos(\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T\perp})} + \cos(3\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T\perp})} \right)$$

$$+ T_{\perp\perp} h \left[ \cdots \right]$$
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 $\rightarrow$ sensitive to FSI
Extensions for $A > 2$?

- Construction of Poincaré covariant $A = 3$ is states 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]

- Add Sokolov packing operators to currents for $A > 2$ to obey cluster separability.

- Formalism is known, non-trivial calculations need to be carried out.
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 \((m^2_N - t) \rightarrow 0\) 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
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!!

[Ch. Hyde, K. Park et al.]
Tagging: unpolarized neutron structure

- $F_{2n}$ 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 $\bar{d} - \bar{u}$

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$\alpha_R = 2p_R^+/p_D^+$
**EIC: forward detection system**

- **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

- **IR designs**
  - JLEIC and eRHIC design similar
  - Differences: crossing angle 50 [JLEIC] - 25 mrad [eRHIC]; JLEIC secondary focus at RP location

- **Forward acceptance and resolution**
  - software framework developed
  - simulations on-going

- **Momentum spread in ion beam**
  - transverse momentum spread ~ few 10 MeV
  - smearing effect: $p_T[\text{vertex}] \neq p_T[\text{measured}]$, systematic uncertainty

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