DIS on a polarized spin-1 target with spectator tagging

Wim Cosyn

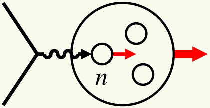
Ghent University, Belgium

JLab Theory Seminar

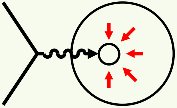
in collaboration with
Ch. Weiss, M. Sargsian
JLab LDRD project on spectator tagging

GHENT UNIVERSITY

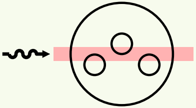
Light ions at EIC: physics objectives



- **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



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



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

Dedicated workshop at Ghent last month
https://www.jlab.org/indico/event/246/

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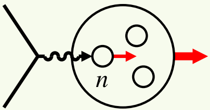

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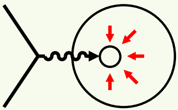

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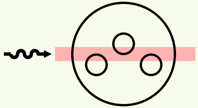

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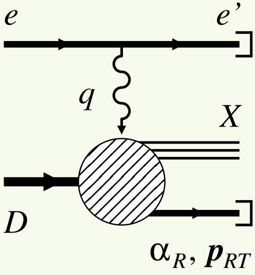
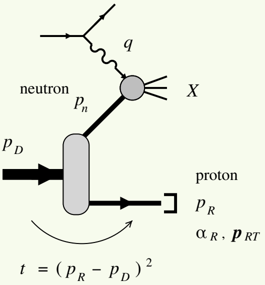
Tagged spectator DIS process with deuteron



- 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**)
- 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 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

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
- Experimental apparatus

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 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)]

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

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

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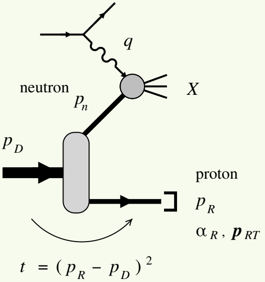
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dxdQ^2 d\phi_{l'}} = \frac{y^2\alpha^2}{Q^4(1-\epsilon)}\left(F_U + F_S + F_T\right) d\Gamma_{P_h}\,,$$

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

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



- Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

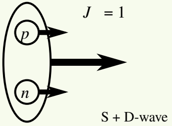
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2-\alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda),$$

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 $U(k), W(k)\}$

- 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



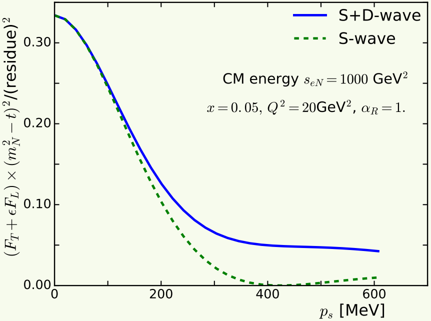
- Up to momenta of a few 100 MeV dominated by ***NN*** component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]

- 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

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

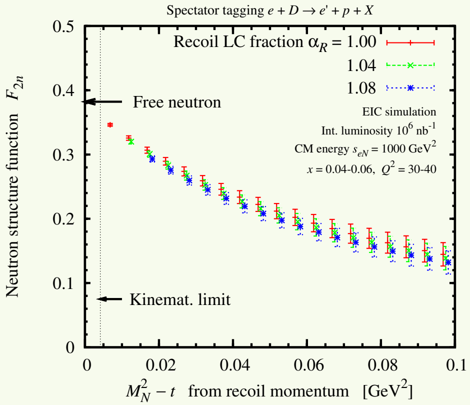
- Differences with non-rel wave function:
  - appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - $\boldsymbol{k}_f$ is the relative 3-momentum of the nucleons in the light-front boosted rest frame of the free 2-nucleon state (so not a "true" kinematical variable)

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

Tagging: free neutron structure

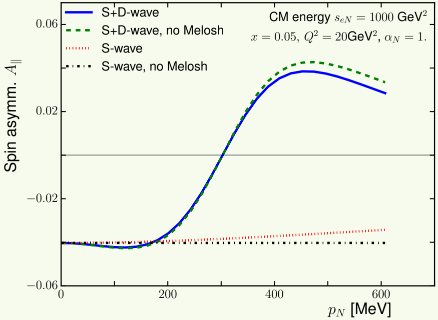


JLab LDRD arXiv:1407.3236, arXiv:1409.5768,
C. Hyde talk

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

On-shell extrapolation of double spin asymm.

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

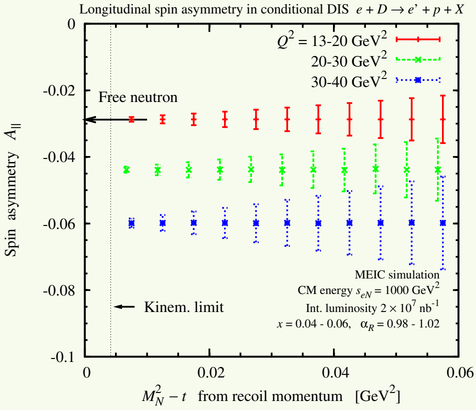


- Again clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

Tagging: polarized neutron structure

On-shell extrapolation of double spin asymm.

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

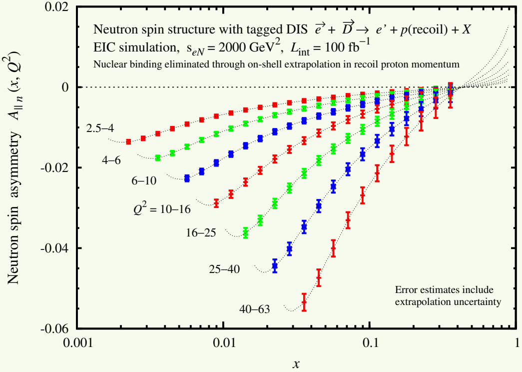


JLab LDRD arXiv:1407.3236, arXiv:1409.5768

- 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 $\sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- Precise measurement of neutron spin structure

Tagging: polarized neutron structure II

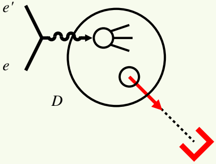
On-shell extrapolation of double spin asymm. $A_{||} = D\frac{g_{1n}}{F_{1n}} + \cdots$



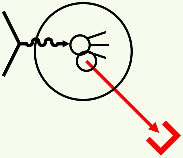
- As depolarization factor $D = \frac{y(2-y)}{2-2y+y^2}$ and $y \approx \frac{Q^2}{xs_{eN}}$, wide range of s_{eN} required!

- 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

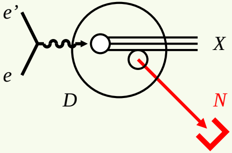
Tagging: EMC effect



average-size



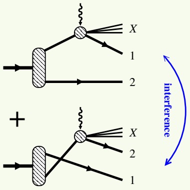
small-size



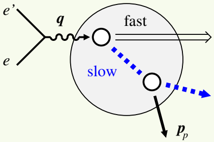
Final−state interactions

- 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 $\tilde{x}$

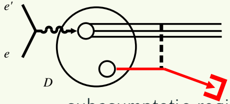
Final-state interactions: three regimes



shadowing, low x



DIS regime, intermediate x



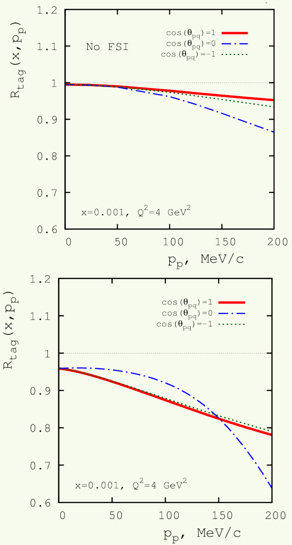
subasymptotic regime: low Q^2, high x

- 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+]
- 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

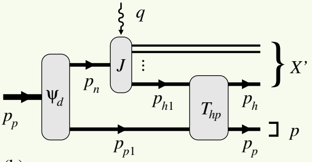
FSI 1: Shadowing at small x in tagged DIS

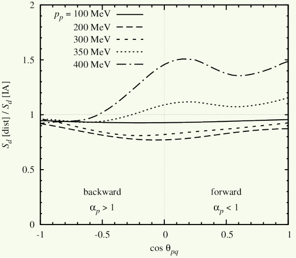


[Guzey,Strikman,Weiss; in preparation]

- Explore shadowing through recoil momentum dependence
- Shadowing enhanced in tagged DIS compared to inclusive
  - enhancement factor from AGK rules
  - shadowing term drops slower with p_R than IA
- FSI contributions between slow p and n in diffractive events
- Large FSI effects in diffractive amplitudes ($\sim$ 40%), also at zero spectator momenta due to orthogonality of np state to deuteron
- Effects smaller in tagged as diffractive are $\sim$ 10% of total events
- Possibilities to study diffractive events by double tagging

FSI 2: intermediate x model

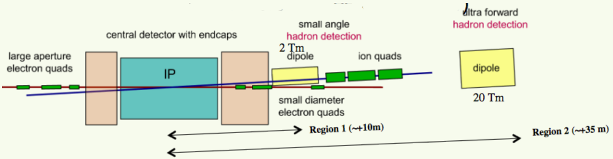




Strikman, Weiss, arXiv:1706.02244, PRC accepted

- 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, postive)
- 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**
- Calculation with realistic deuteron wf (AV18)

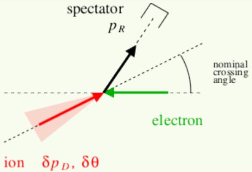
JLEIC full-acceptance detector

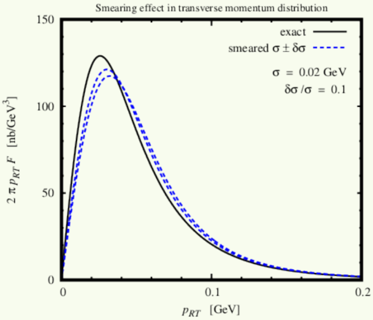


Nadel-Turonski, Ent, Hyde
R. Yoshida, talk at Ghent workshop

- Forward detector integrated in interaction region & beam optics
- Good acceptance for elastic recoil
  Rigidity same as beam. Large dispersion generated *after* IP
  Longitudinal momentum up to 99.5% of beam, angles down to 2 mrad (10 σ)
- Good acceptance for spectators and ion fragments
  Rigidity different from beam. Large magnet apertures, small gradients
- Good momentum and angular resolution
  Longitudinal $dp/p \sim 4 \times 10^{-4}$, angular $\delta\theta \sim 0.2$ mrad
  $p_{TR} \sim 15\,\mathrm{MeV}/c$ resolution for tagged 50 GeV/A deuterium beam

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: 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