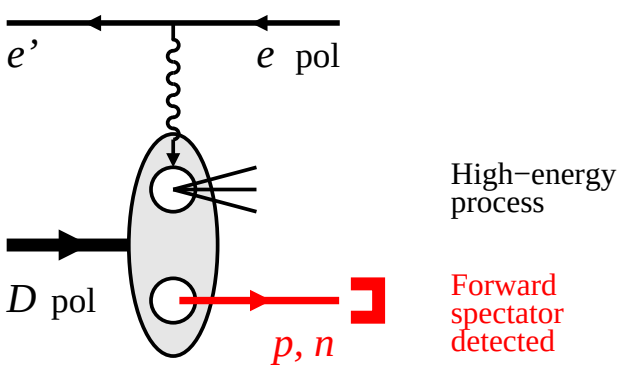
Spectator tagging with EIC: Physics and experimental requirements

C. Weiss (JLab), CFNS&RBRC Workshop on Physics and Detector Requirements at Zero Degree, 25-Sep-2019



- Light ion physics at EIC

  Physics objectives

- Deuteron and spectator tagging

  Observables and theoretical description

  Free neutron structure extraction

  Neutron spin structure, S $\leftrightarrow$ D waves

  Nucleon interactions: EMC/SRC at large x, diffraction and shadowing at small x

- Experimental requirements

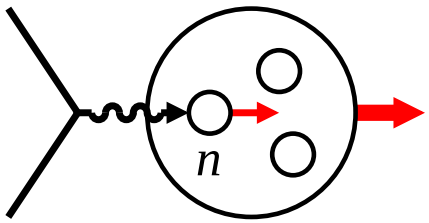
  Forward coverage and resolution

  Ion beam momentum spread

EIC simulations: JLab 2014/15 LDRD
W. Cosyn, V. Guzey, D. Higinbotham, Ch. Hyde, K. Park, P. Nadel-Turonski, M. Sargsian, M. Strikman, C. Weiss∗
[Webpage]

Theory: Continuing effort
Strikman, CW, PRC97 (2018) 035209 [INSPIRE]
Cosyn, CW, arXiv:1906.11119 [INSPIRE]
+ in preparation

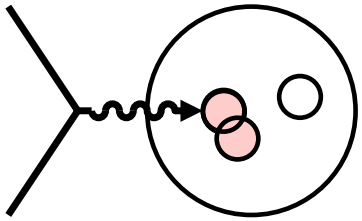
Light ions: Physics objectives



- Neutron structure

  Flavor decomposition of PDFs/GPDs/TMDs,
  singlet vs. non-singlet QCD evolution, polarized gluon

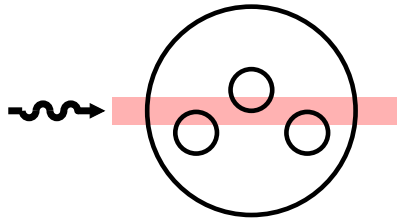
  Eliminate nuclear binding, non-nucleonic DOF!



- Nucleon interactions in QCD

  Nuclear modification of quark/gluon densities
  Short-range correlations, non-nucleonic DOF
  QCD origin of nuclear forces

  Associate modifications with interactions!



- Coherent phenomena in QCD

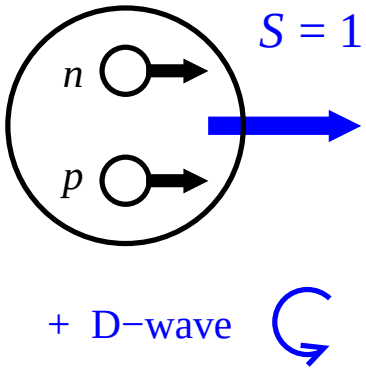
  Coherent interaction of high–energy probe
  with multiple nucleons, shadowing, saturation

  Identify coherent response!

[Nucleus rest frame view]

Common challenge: Effects depend on the nuclear configuration during the high-energy process.
Need to "control" the configurations!

Light ions: Deuteron, spectator tagging

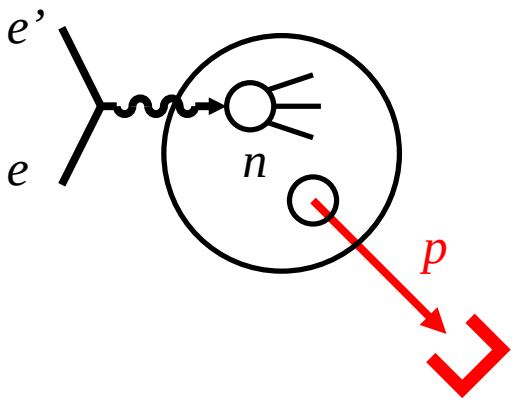


- Deuteron unpol/pol

  Nucleonic wave function simple, known well including light-front WF for high-energy processes

  Neutron spin-polarized, some D-wave depolarization

  Intrinsic Δ isobars suppressed by isospin $= 0$
  Large Δ component in 3He. Frankfurt etal 96; Bissey etal 02



[Nucleus rest frame view]

- Spectator nucleon tagging

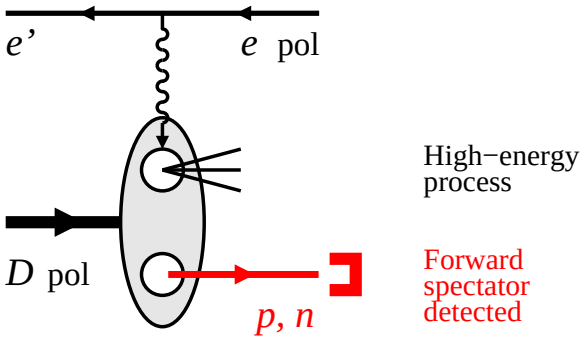
  Identifies active nucleon

  Controls configuration through recoil momentum:
  Spatial size, S $\leftrightarrow$ D wave

  Typical momenta $\sim$ few 10 – 100 MeV (rest frame)

  Tagging in fixed-target experiments
  CLAS6/12 BONUS, recoil momenta p = 70-150 MeV
  JLab12 ALERT, Hall A

Light ions: Deuteron and spectator tagging



$$p_{p\parallel} = \frac{1}{2}\left[1 + \mathcal{O}\left(\frac{p_p[\text{rest}]}{m}\right)\right]$$

[Collider frame view]

- Spectator tagging with colliding beams

  Spectator nucleon moves forward
  with approx. 1/2 ion beam momentum

  Detection with forward detectors integrated
  in interaction region and beams optics
  Expertise LHC, Tevatron, RHIC, HERA → this workshop

- Advantages over fixed-target

  No target material, $\boldsymbol{p}_p[\text{rest}] \to 0$ possible

  Potentially good acceptance and resolution

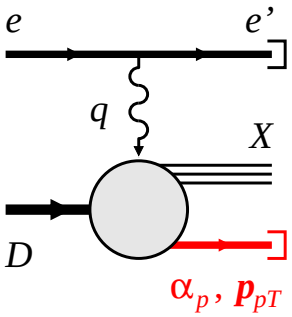
  Deuteron polarization in beam,
  no holding magnets around target

  Forward neutron detection possible

- Unique physics potential

Tagging: Observables and structures

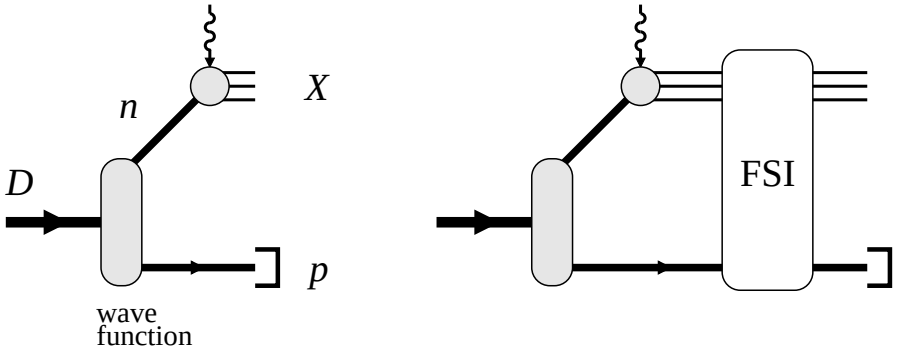
- Tagged DIS cross section $eD \to e' + X + N$



$$\frac{d\sigma}{dx dQ^2\, d^3p_p/E_p} = [\text{flux}] \Big[F_{TD}(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_{LD}(..) + \phi_p\text{-dependent} + \text{spin-dependent structures} \Big]$$

$\alpha_p = p_p^+/p_D^+$ longitudinal, $\boldsymbol{p}_{pT}$ transverse proton momentum ($\gamma^* D$ collinear)

- Theoretical description: Separate nuclear $\leftrightarrow$ nucleonic structure



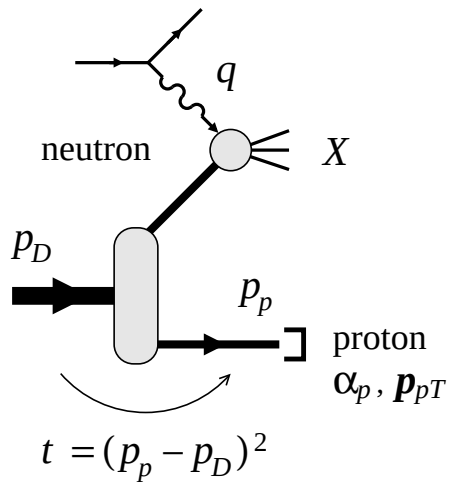
Deuteron wave function $\langle pn|D\rangle$ at fixed light-front time $x^+ = t + z$

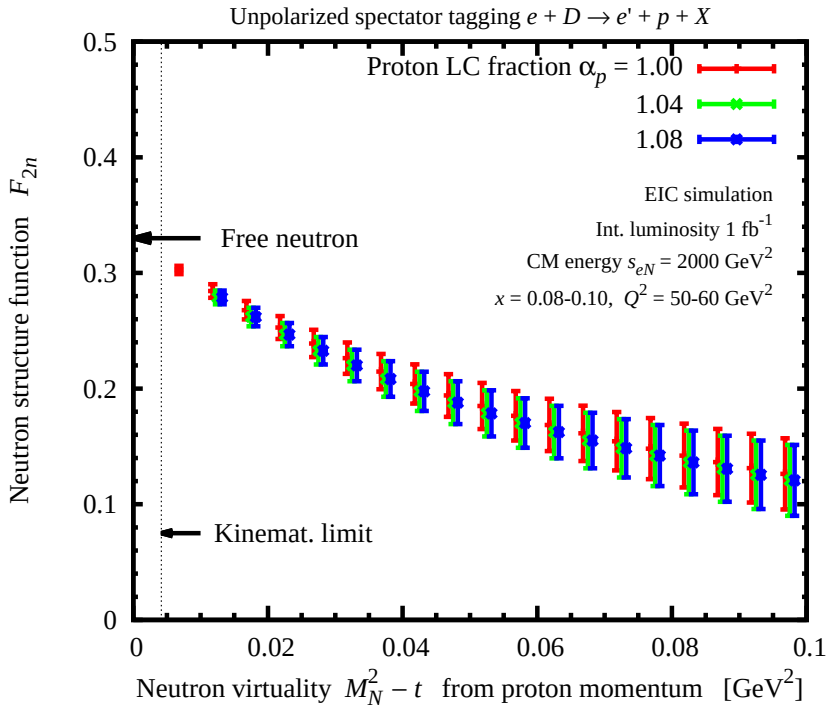
Impulse approximation

Final-state interactions

Use tagged momentum as variable: Control nuclear binding, minimize/maximize FSI

Tagging: Free neutron structure





- Nuclear binding: Motion, interaction

- Extract free neutron structure

  Measure tagged structure function dependence on proton momentum $\rightarrow$ neutron off-shellness $t - m^2 = -2|\boldsymbol{p}_{pT}^2| + t'_{\min}$

  Extrapolate to on-shell point $t - m^2 \rightarrow 0$

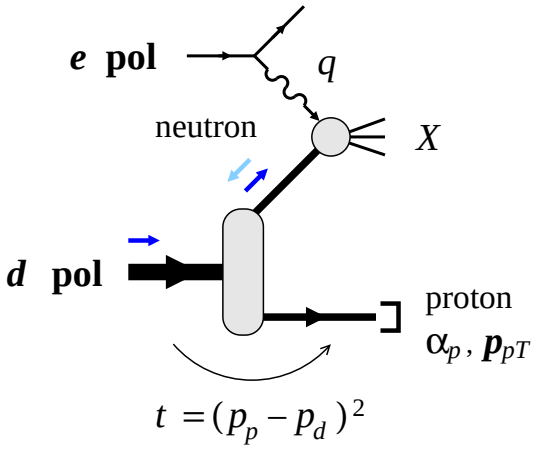
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 05

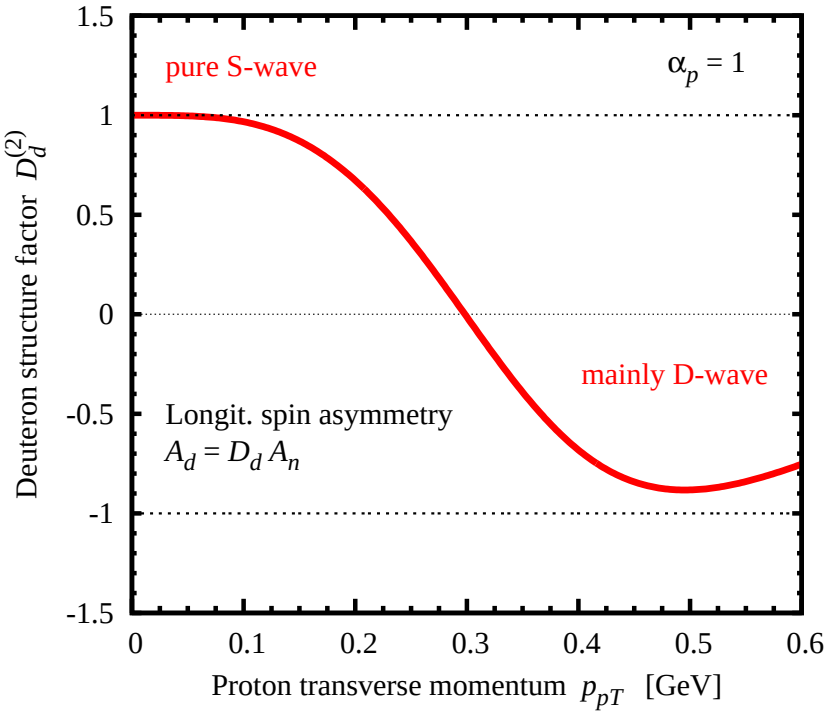
- EIC simulations

  Uncertainty mainly systematic: Proton momentum resolution/smearing
  2014/15 LDRD

  F_{2n} extracted with percent-level accuracy at $x \sim 0.1$, applications $\bar{d}/\bar{u}$

Tagging: Neutron spin structure





- Nuclear binding: Neutron polarization?

  S + D waves, depolarization

- Control neutron polarization

  Measure tagged spin asymmetries

  D-wave drops out at $\boldsymbol{p}_{pT} = 0$:
  Pure S-wave, neutron 100% polarized

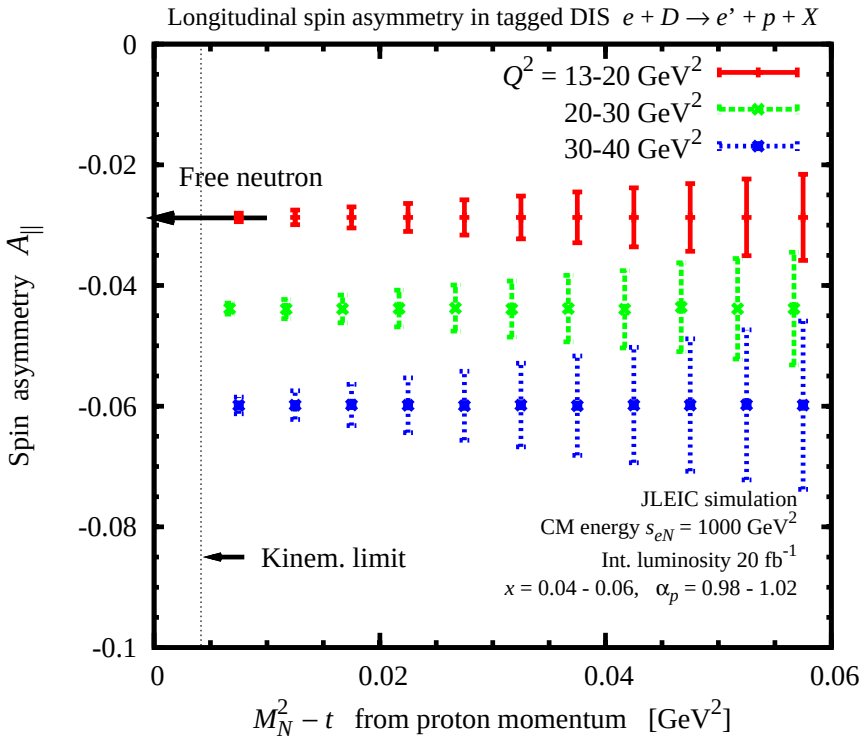
  [$|\boldsymbol{p}_{pT}| \approx 400$ MeV: D-wave dominates]

- Combine with on-shell extrapolation:
  Free neutron spin structure

  Asymmetry depends weakly on neutron off-shellness $t - m^2 \sim -2|\boldsymbol{p}_{pT}|^2$

Frankfurt, Strikman 83. Cosyn, CW arXiv:1902.03678

Tagging: Neutron spin structure II



- EIC simulations

  Measurement of tagged spin asymmetry with on-shell extrapolation
  2014/15 LDRD: Simplified deuteron model

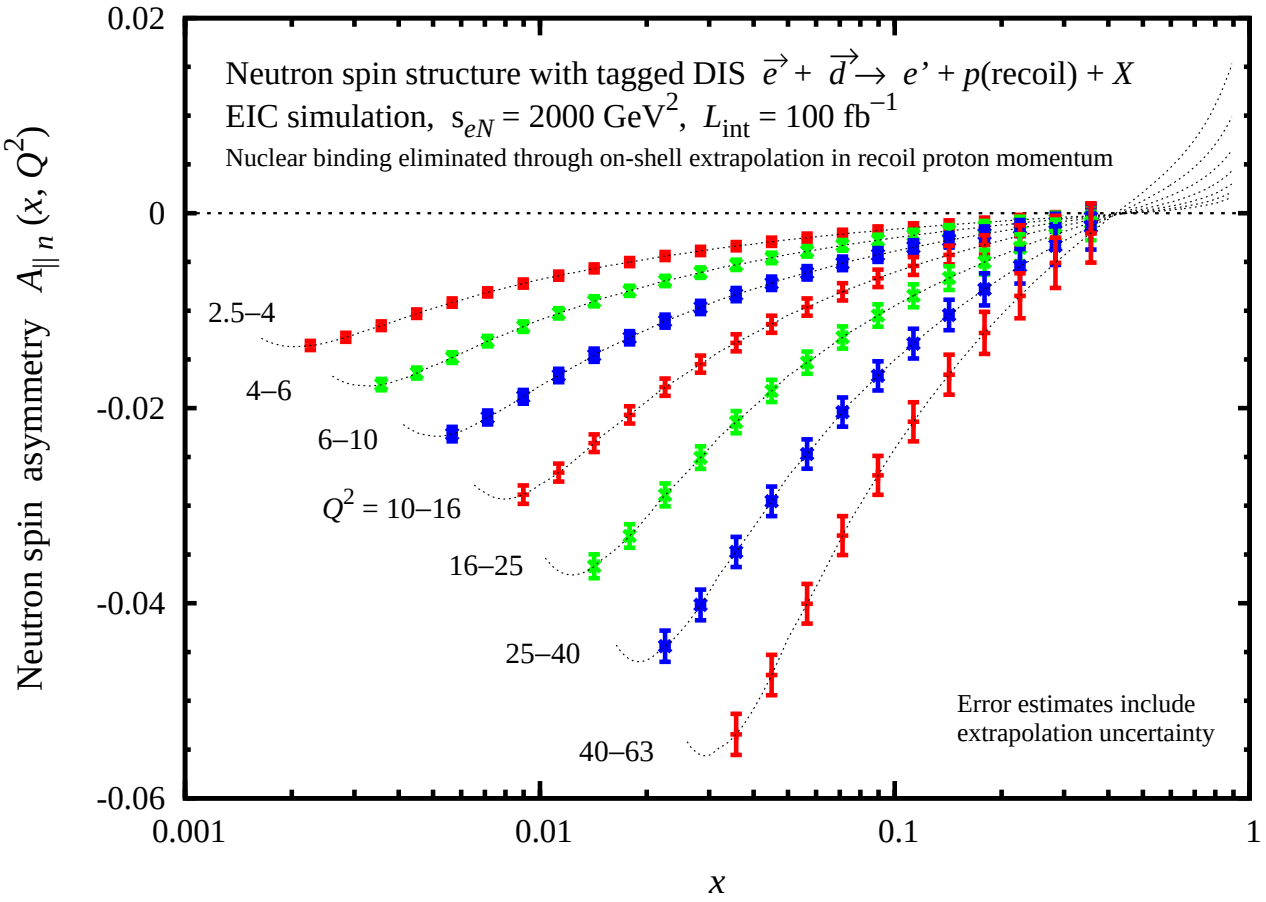
  Momentum smearing/resolution effects largely cancel in asymmetry

- Statistics requirements

  Physical asymmetries $\sim$ 0.05-0.1, actual polarizations $P_e P_D \sim 0.5$

  Requires int lumi $\sim$ few 10 fb^{-1}

Tagging: Neutron spin structure III



$$A_{\parallel n} = \frac{\sigma(+-) - \sigma(++)}{\sigma(+-) + \sigma(++)} = D\,\frac{g_1}{F_1} + \ldots$$

$$D = \frac{y(2-y)}{2 - 2y + y^2}$$

depolarization factor

$$y = \frac{Q^2}{x s_{eN}}$$

- Precise measurement of neutron spin structure

  Wide kinematic range: Leading ↔ higher twist, nonsinglet ↔ singlet QCD evolution

  Parton density fits: Flavor separation $\Delta u \leftrightarrow \Delta d$, gluon spin ΔG

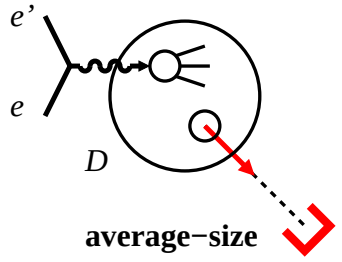
  Nonsinglet $g_{1p} - g_{1n}$ and Bjorken sum rule

Tagging: Nucleon interactions

- Configuration dependence of nuclear partonic structure?

  What momenta/distances cause modifications?

  Connection EMC effect $\leftrightarrow$ NN short-range correlations?

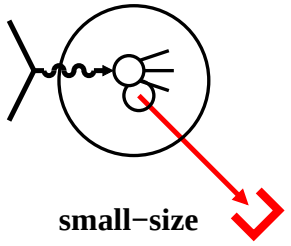


- Tagged nuclear structure functions

  Measure nucleon momentum dependence at $p_T \sim$ few 100 MeV

  Separate initial-state modifications $\leftrightarrow$ final-state interactions?
  Kinematic dependence: Strikman, CW, PRC97 (2018) 035209

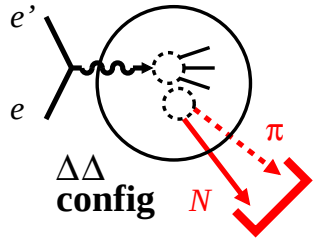
  Proton and neutron detection possible



- Tagging $\Delta\Delta$ configurations

  Measure $e + D \rightarrow e' + X + \pi + N$, reconstruct Δ from πN

  Direct demonstration of non-nucleonic degrees of freedom
  $\rightarrow$ Talk Strikman



Tagging: Nucleon interactions

- Tagged DIS on deuteron with current fragmentation analysis ("semi-inclusive DIS")

  Flavor structure of nuclear modifications with semi-inclusive $\pi^{\pm}$

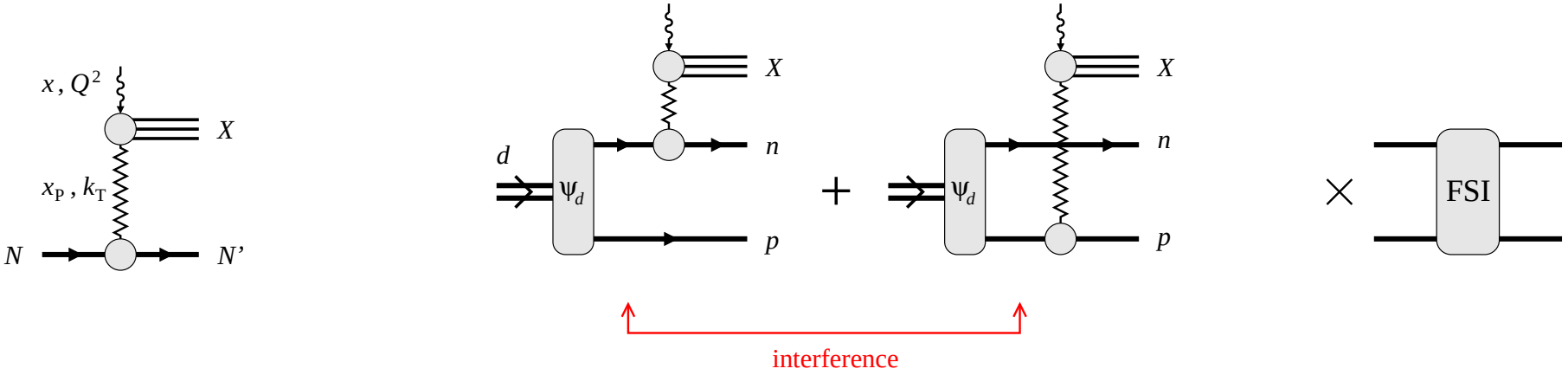
  Gluonic modifications with open charm production
  JLab LDRD 2016/17 Weiss et al.

- Tagged DIS on light nuclei $A > 2$

  Could test isospin dependence and/or universality of bound nucleon structure
  $(A-1)$ ground state recoil, e.g. 3He (e, e' d) X

  Theoretically challenging, cf. experience with quasielastic breakup

Tagging: Diffraction and shadowing



- Diffraction in nucleon DIS at $x \ll 0.1$

  Nucleon remains intact, recoils with $k \sim$ few 100 MeV (rest frame)

  10-15% of events diffractive. Detailed studies at HERA: QCD factorization, diffractive PDFs

- Shadowing in deuteron DIS

  Diffraction can happen on neutron or proton: QM interference

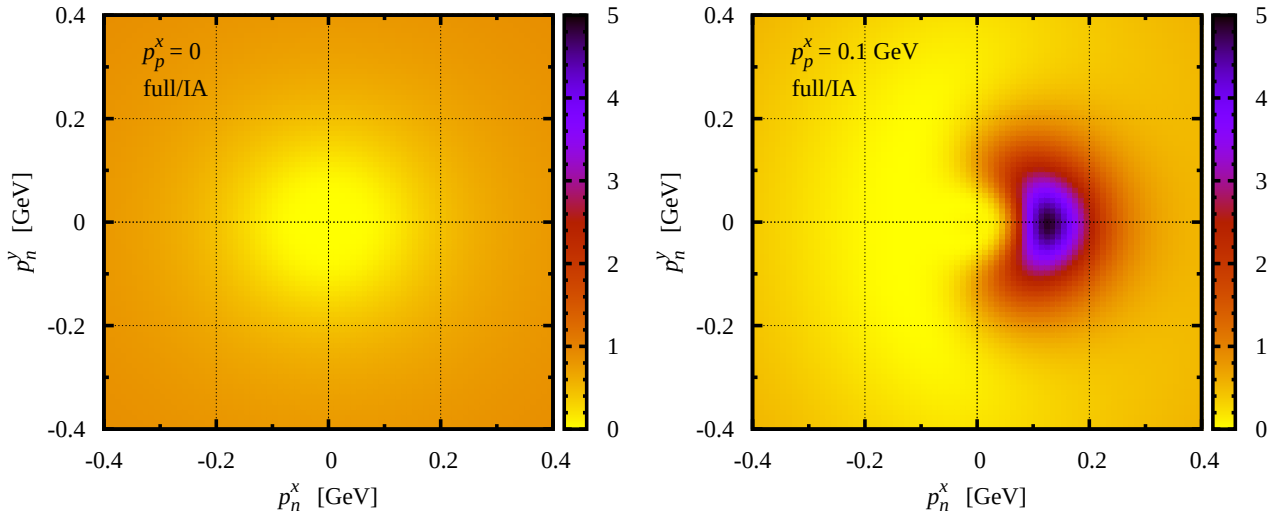
  Reduction of cross section compared to IA — shadowing. Leading-twist effect.
  Frankfurt, Strikman, Guzey 12. Hints seen in J/ψ production in UPCs at LHC ALICE.

- Diffraction and shadowing in tagged DIS

  Differential studies as function of recoil momentum!

  Large FSI effects. Outgoing pn scattering state must be orthogonal to D bound state
  Guzey, Strikman, CW, in preparation

Tagging: Diffraction and shadowing



$$R = \frac{d\sigma(\text{full})}{d\sigma(\text{IA})}$$ as function of neutron $\boldsymbol{p}_{nT}$ for fixed proton $\boldsymbol{p}_{pT}$

- Final-state interactions in diffractive tagged DIS $e + D \to e' + X + n + p$

  Large FSI effects due to orthogonality

  Shadowing effects calculated Guzey, Strikman, CW, in preparation

  Other application: High-p_T deuteron breakup and gluonic structure of small-size pn configuration Miller, Sievert, Venugopalan 17

Tagging: Detection requirements

Proton

$p_{p\perp}$ = 0...200 MeV neutron struct, diffraction
0...1 GeV SRC, interactions

$\Delta p_{p\perp}$ = 10–20 MeV

$p_{p\parallel} = (0.5\text{–}1.5) \times p_{D\parallel}$

$\Delta p_{p\parallel}/p_{p\parallel} \lesssim 0.01$

Neutron

$p_{n\perp}$ = 0...few 100 MeV

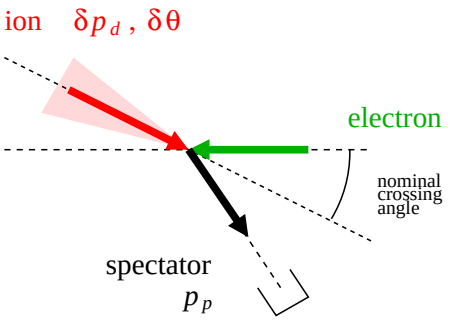
$\Delta p_{n\perp}$ = ?

$p_{n\parallel} = (0.5\text{–}1.5) \times p_{D\parallel}$

$\Delta p_{n\parallel}/p_{n\parallel}$ = ?

- Forward protons from deuteron breakup have 1/2 rigidity of deuteron beam
- Forward detector design → Talk tomorrow

Intrinsic momentum spread in ion beam



- Transverse momentum spread $\sigma \sim$ few 10 MeV
- Smearing effect $\boldsymbol{p}_{pT}(\text{vertex}) \neq \boldsymbol{p}_{pT}(\text{measured})$, can partly be corrected by convolution
- Significant systematic uncertainty in tagged neutron structure measurements. Correlated, x and Q^2-indpendent. JLab LDRD

Summary

- Spectator tagging with deuteron overcomes main limiting factor of nuclear DIS: Control of nuclear configurations during high-energy process

  Free neutron structure from on-shell extrapolation

  Controled neutron polarization, D-wave depolarization eliminated

  Nucleon interactions and modified partonic structure in defined configurations

- Theory progressing

  Final-state interactions, polarized deuteron, shadowing and diffraction

  Ready for next-generation process simulations

- Need EIC forward detector design to make it work – coverage, resolution

- EIC light-ion physics program is unique, has great potential