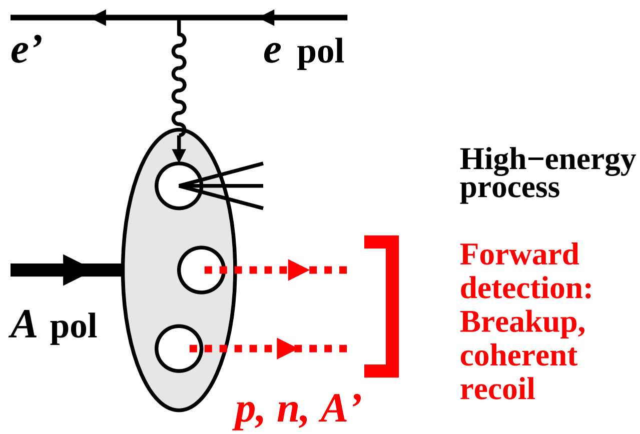
Nuclear breakup measurements in DIS: Motivation, theory, applications

C. Weiss (JLab), Exploring QCD with light nuclei at EIC, CFNS Stony Brook, 21-Jan-2020



- Special case of QCD target fragmentation
- Unique physics potential
- Evolving program JLab12 $\rightarrow$ EIC
- Deuteron simplest, A > 2 developing
- Impact on EIC forward detector design

- Motivation

  Control nuclear configuration in DIS process

- Theory

  Target fragmentation of nucleus

  Separating nuclear $\leftrightarrow$ nucleonic structure

  Impulse approximation, final state interactions

- Applications

  Free neutron structure and spin

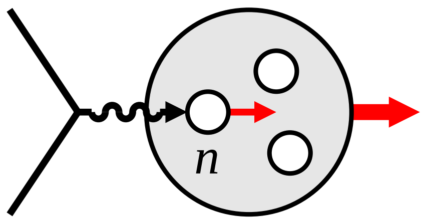
  Configuration dependence of EMC effect

  Non-nucleonic DoF, Δ

  Tagged diffraction and shadowing

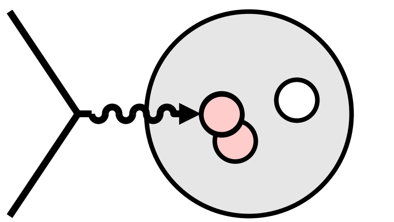
  $\rightarrow$ Talks Guzey, Cosyn, Scopetta, Dupre, Hauenstein, ...

Light ions: Objectives and challenges



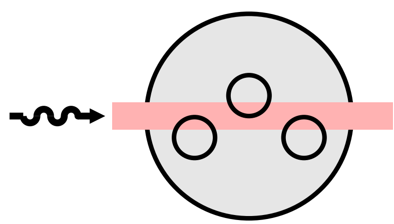
- Neutron spin structure

  Extract free neutron structure
  Eliminate nuclear binding: motion, interaction
  Account for effective polarization, dilution from proton



- Nucleon interactions: EMC effect, SRCs

  Associate modified partonic structure with particular
  NN interactions: quantum numbers, distances
  Identify non-nucleonic DoF



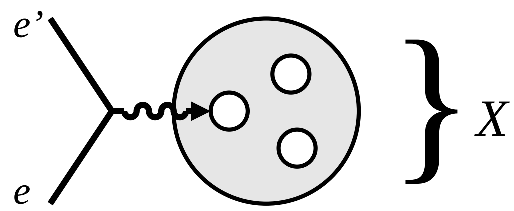
- Coherent phenomena in QCD

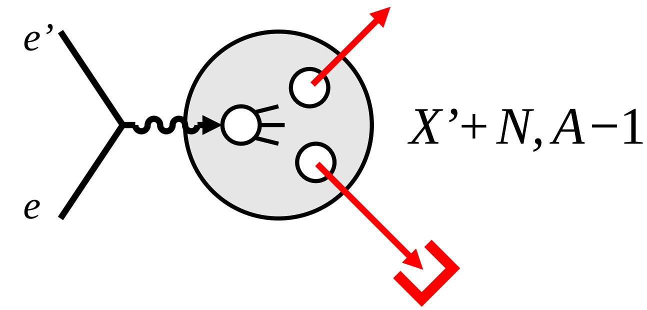
  Demonstrate onset of coherence
  Unravel contributions $N = 2, 3, \ldots$

[Nucleus rest frame view]

Common challenge: Effects depend on the nuclear configuration during the high-energy process.
Main "limiting factor!"

Light ions: Measurements





- Inclusive scattering

  No information on initial-state nuclear configuration

  Model effects in all configurations, average with nuclear wave fn $\psi^* \psi$

  Final-state interactions irrelevant, closure Σ_X

  Basic measurements
  D, 3He (unpol/pol), 4He, ...
  $\rightarrow$ Talk Maxwell

- Nuclear breakup detection – "tagging"

  Potential information on initial-state nuclear configuration

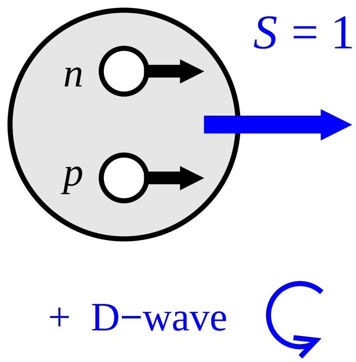
  Study effects in defined configurations

  Final-state interactions important, influence breakup amplitudes

  New opportunities with JLab12 and EIC!
  New challenges for theory and detection!

[• Coherent processes $\rightarrow$ Talks Scopetta, Joosten]

Light ions: Deuteron and spectator tagging

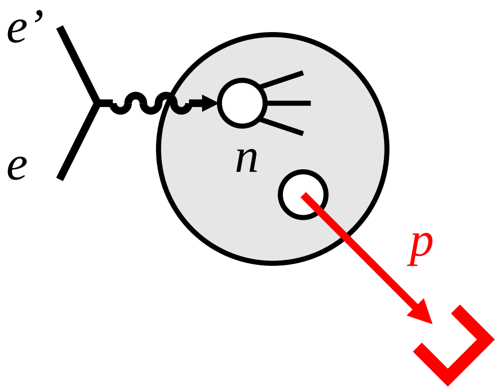


- Deuteron as simplest system

  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 $\rightarrow$ Talk Guzey



[Nucleus rest frame view]

- Spectator nucleon tagging

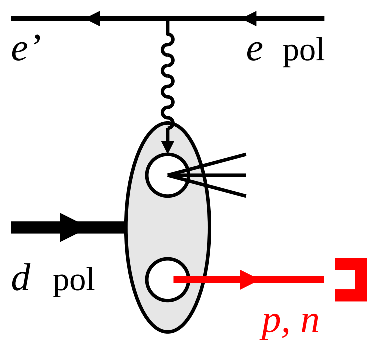
  Identifies active nucleon

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

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

  Proton tagging in fixed-target experiments
  CLAS6/12 BONUS, recoil momenta $p =$ 70-150 MeV
  JLab12 ALERT, Hall A TDIS $\rightarrow$ Talks Dupre, Keppel

Light ions: Tagging with EIC



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

[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
  → Talks Nadel-Turonski, Hyde, Jentsch

- Advantages over fixed-target

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

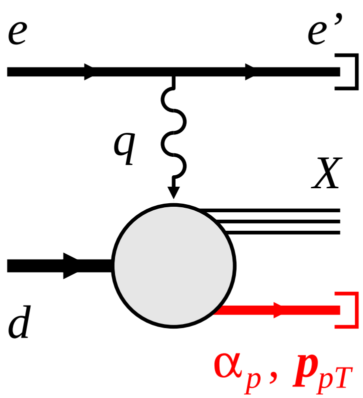
  Setup acts as magnetic spectrometer,
  potentially good acceptance and resolution

  Forward neutron detection possible

- This presentation

  Focus on deuteron as simplest system,
  discuss possible extensions to $A > 2$
  → Talks Dupre, Scopetta

Tagging: Cross section and observables



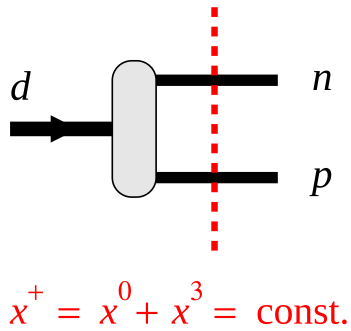
$$\frac{d\sigma}{dx\,dQ^2\,(d^3p_p/E_p)} = [\text{flux}]\Big[F_{Td}(x,Q^2;\alpha_p,p_{pT}) + \epsilon F_{Ld}(..)$$

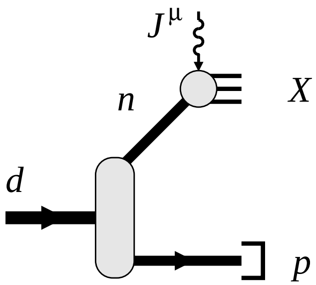
$$+\sqrt{2\epsilon(1+\epsilon)}\cos\phi_p F_{LT,d}(..) + \epsilon\cos(2\phi_p)F_{TT,d}(..)$$

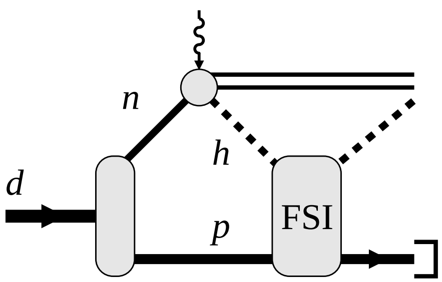
$$+ \text{ spin-dependent structures}\Big]$$

- Semi-inclusive DIS cross section $e + d \to e' + X + p$
- Proton recoil momentum described by LF components $p_p^+ = \alpha_p p_d^+/2$, $\boldsymbol{p}_{pT}$, simply related to $\boldsymbol{p}_p$(restframe)
- Special case of target fragmentation: QCD factorization, leading-twist
  Trentadue, Veneziano 93; Collins 97 $\longrightarrow$ Talk Ceccopieri
- No assumptions re composite nuclear structure, $A = \sum N$, etc.

Tagging: Theoretical description







- Light-front quantization

  High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 = \text{const.}$

  Deuteron LF wave function $\langle pn | d \rangle = \Psi(\alpha_p, \boldsymbol{p}_{pT})$

  Matching nuclear $\leftrightarrow$ nucleonic structure
  Frankfurt, Strikman 80's

  Low-energy nuclear structure, cf. non-relativistic theory!

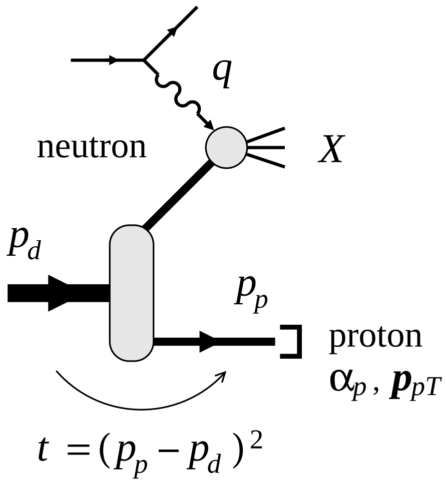
- Composite description

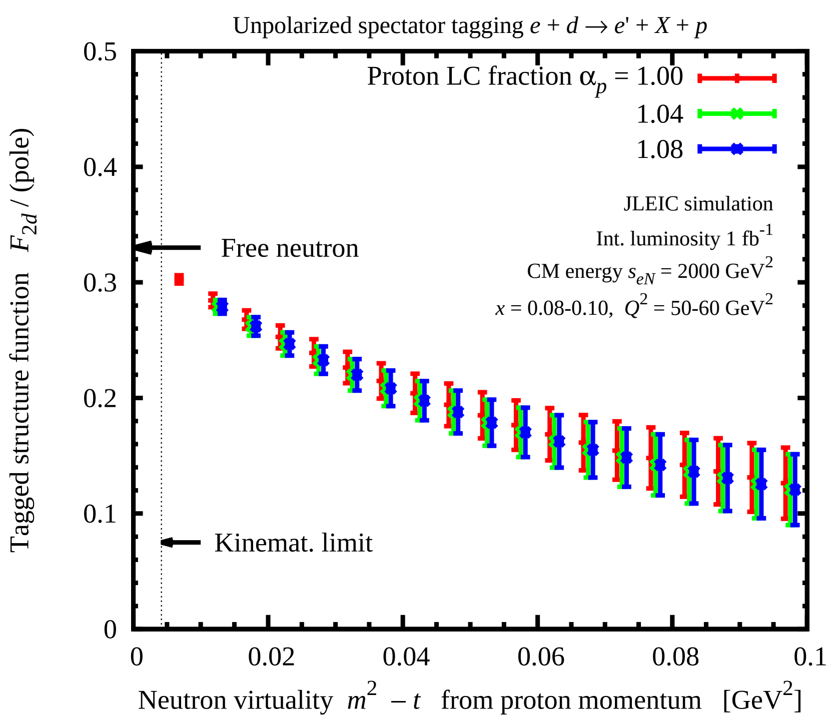
  Impulse approximation IA: DIS final state and spectator nucleon evolve independently

  Final-state interactions: Part of DIS final state interacts with spectator, transfers momentum

  Idea: Use tagged momentum as variable
  to 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 $\longrightarrow$ neutron off-shellness $t - m^2 = -2|\boldsymbol{p}_{pT}^2| + t'_{\min}$

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

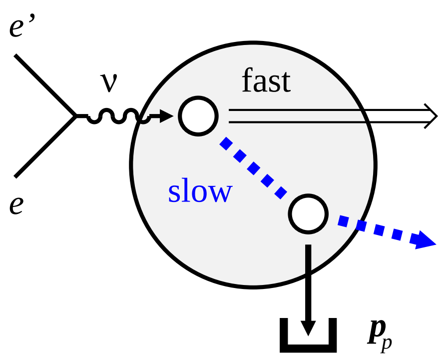
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 05

  EIC simulations
  2014/15 LDRD

- Extension to polarized DIS

  Tagged proton momentum controls S/D ratio, effective neutron polarization
  $\longrightarrow$ Talk Cosyn

Tagging: Final-state interactions



- DIS final state can interact with spectator

  Changes recoil momentum distributions in tagging

  No effect on total cross section – closure

- Nucleon DIS final state has two components [current and target jet]

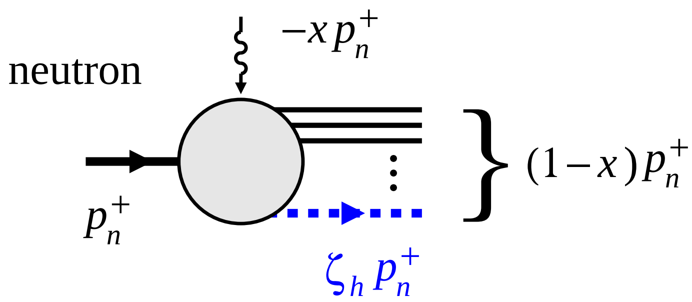
"Fast"	$E_h = O(\nu)$	hadrons formed outside nucleus interact weakly with spectators
"Slow"	$E_h = O(\mu_{\text{had}}) \sim 1$ GeV	formed inside nucleus interacts with hadronic cross section dominant source of FSI respects QCD factorization in target fragmentation $\rightarrow$ Talks Ceccopieri, Strikman

- FSI effects calculated $x \gtrsim 0.1$

  Exp. data on nucleon fragmentation + hadron-nucleon low-energy scattering amplitudes

  Light-front quantum mechanics: Deuteron pn wave function, rescattering process
  Strikman, CW, PRC97 (2018) 035209

Tagging: Hadrons from nucleon fragmentation

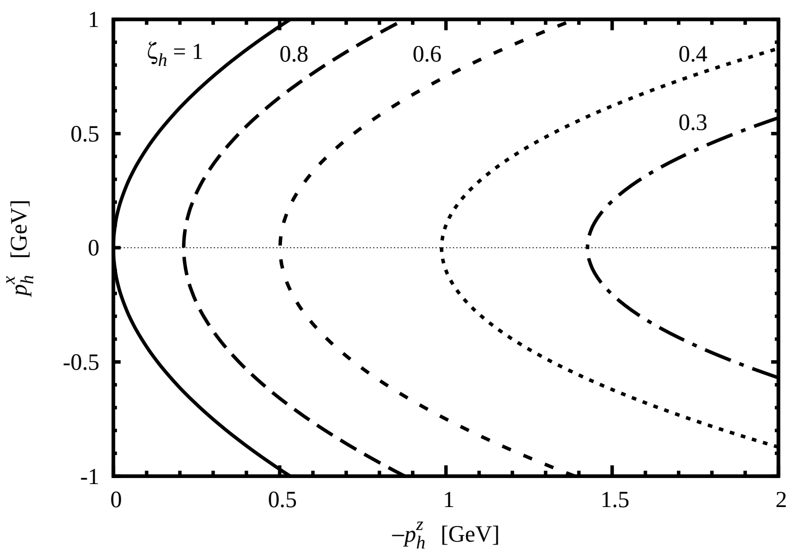


- Kinematic variables

  $\zeta_h, \boldsymbol{p}_{hT}$ hadron LC mom $\zeta_h \leftrightarrow x_{\mathrm{F}}$

  Slow hadrons in rest frame have $\zeta_h \sim 1$

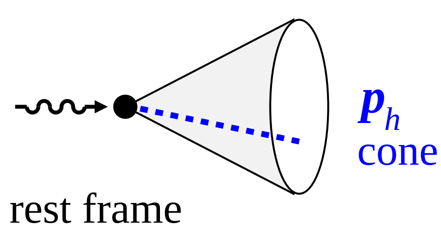
  $\zeta_h < 1 - x$ kinematic limit



- Momentum distribution in rest frame

  Cone opening in virtual photon direction

  No backward movers if $h =$ nucleon

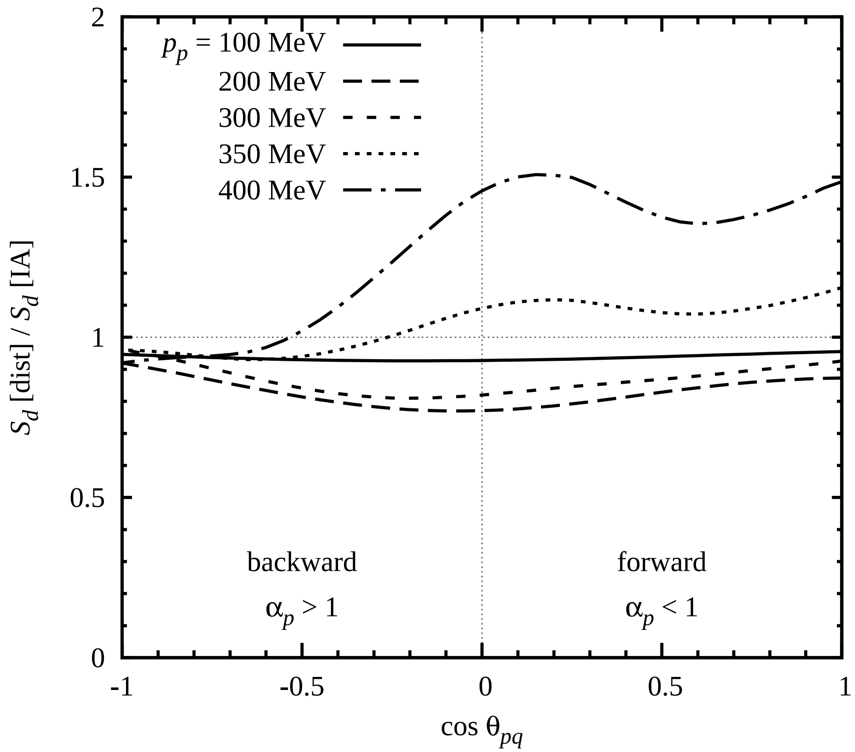


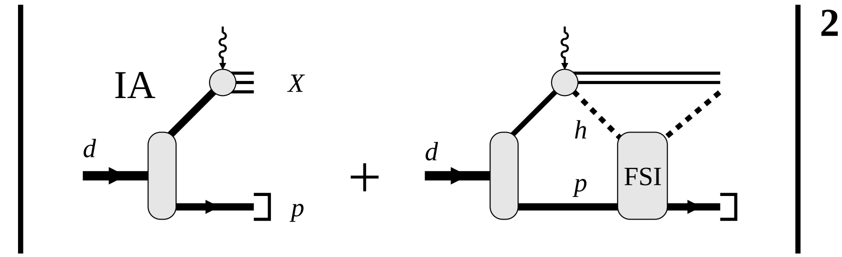
- Experimental data

  HERA $x < 0.01$: x_{F} distns of p, n, scaling
  Cornell $x > 0.1$: Momentum distns of p, π
  Neutrino DIS data $x \sim 0.1$ → Talk Strikman

  EIC should measure nucleon fragmentation!
  Spin/flavor dependence? Kinematic dependence?
  Nucleon structure physics + input for nuclear FSI

Tagging: FSI momentum and angle dependence





- Quantum-mechanical description: Interference, absoprtion
  Strikman, CW 18

- Momentum and angle dependence in rest frame

$p_p <$ 300 MeV	IA $\times$ FSI interference, absorptive, weak angular dependence
$p_p >$ 300 MeV	$\|\text{IA}\|^2$, refractive, strong angular dependence

- FSI vanishes at on-shell point $t - m^2 \to 0$; extrapolation possible

Tagging: Applications

- Tagged EMC effect

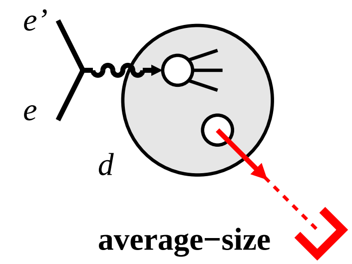
  What momenta/distances cause modifications?

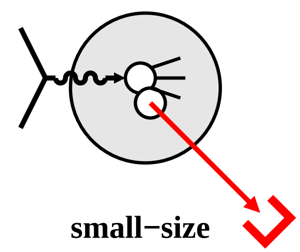
  Connection EMC effect $\leftrightarrow$ NN short-range correlations?
  Extensive studies $\rightarrow$ Talks Piasetzky, Segarra, Arrington

  Modified gluonic structure in heavy quarkonium production
  Miller, Sievert, Venugopalan 2017 $\rightarrow$ Talk Venugopalan

  Measure nucleon momentum dependence at $p_T \sim$ few 100 MeV
  Proton and neutron detection possible

  Separate initial-state modifications $\leftrightarrow$ final-state interactions?
  $\rightarrow$ Discussion

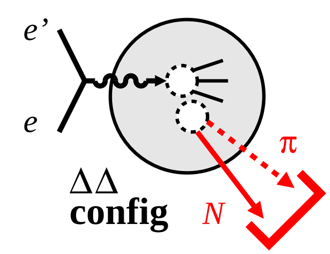




- Tagging $\Delta\Delta$ configurations

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

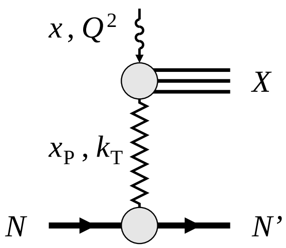
  Direct demonstration of non-nucleonic degrees of freedom

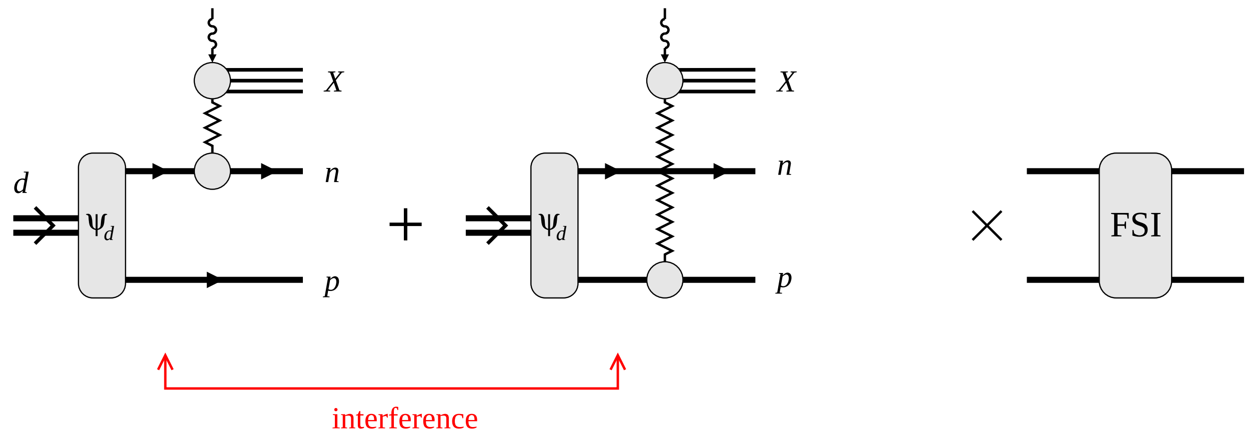


- Tagging with polarized deuteron

  Spin-orbit correlations, tensor polarized structures $\rightarrow$ Talk Cosyn

Tagging: Diffraction and shadowing at small x





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

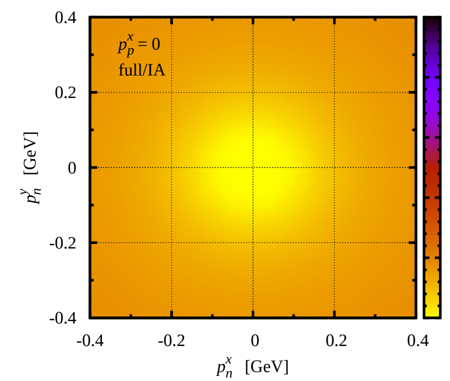
- Shadowing: QM interference of diffractive scattering on neutron or proton
  Observed in inclusive nuclear scattering

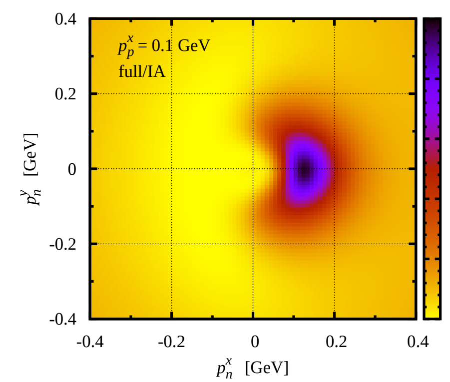
- Final-state interactions

  Low-momentum pn system with $S = 1, I = 0$

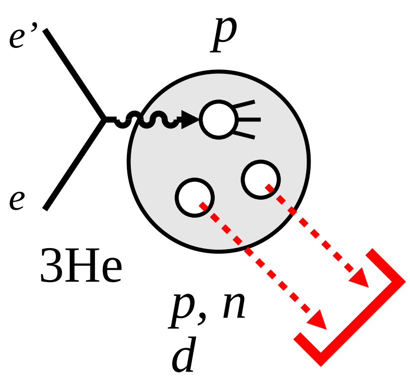
  pn breakup state must be orthogonal to d bound state

  Large distortion, deviations from IA
  Guzey, Strikman, CW; in progress





Tagging: Light nuclei $A > 2$



- Potential applications

  Isospin dependence neutron $\leftrightarrow$ proton

  Universality of bound nucleon structure

- Simplest example: A-1 ground state recoil

  3He (e, e' d) X, including polarization
  Ciofi, Kaptari, Scopetta 99; Kaptari et al. 2014; Milner et al. 2018

  Bound proton $\leftrightarrow$ free proton structure

- Nuclear breakup much more complex than A=2

  IA: Wave function overlap, large amplitude factors
  Experience with quasielastic breakup: JLab Hall A

  FSI: Multiple trajectories

  Requires new nuclear structure imput:
  Light-front spectral functions, decay functions, FSI
  Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent [Webpage].
  Emerging collaboration with low-energy nuclear structure community

Summary

- Detection of nuclear breakup expands physics reach of eA(light) DIS

  Control nuclear configuration in DIS process – main limiting factor

- Theory of nuclear breakup well developed

  Special case of target fragmentation: QCD factorization, twist-2 structures

  Composite description, separation of nuclear and nucleonic structure

  FSI from "slow" hadrons produced by nucleon fragmentation, respects QCD factorization

  Deuteron unique – simplest system

- Interesting applications with deuteron at EIC

  Free neutron structure from on-shell extrapolation

  Configuration dependence of nuclear modifications, EMC effect

  Diffraction and shadowing

- Developments needed

  Theory for $A > 2$ nuclei: Needs input from nuclear structure, FSI

  EIC forward detector for nuclear breakup