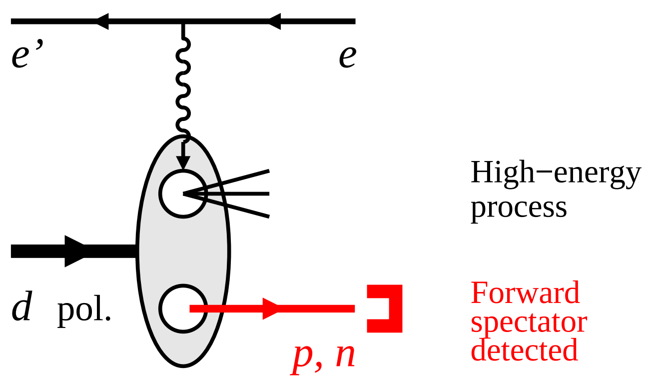
High-energy eA scattering with spectator tagging: Motivation, theory, applications

C. Weiss (JLab), 3rd SRC-EMC Workshop, MIT & JLab EIC Center, 22-26 Mar 2021



- Unique physics potential
- Evolving program JLab12 → EIC
- Deuteron simplest, A > 2 developing
- Close connection theory – experiment
- Impact on EIC forward detector design

- Motivation

  Control nuclear configuration in DIS process

- Theory

  Light-front quantization

  Matching nuclear ↔ nucleonic structure

  Impulse approximation, final state interactions

- Applications

  Free neutron structure

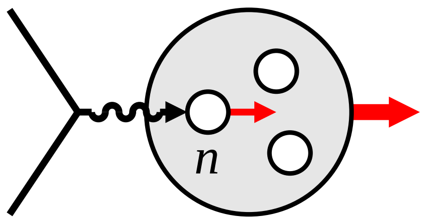
  Configuration dependence of EMC effect

  Polarized deuteron vector & tensor

  Tagging with 3He

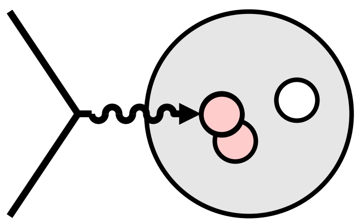
  → Talks Kuhn, Kutz, Cosyn, Baker, Tu, Nguyen, Hauenstein, ...

Light nuclei: Objectives and challenges



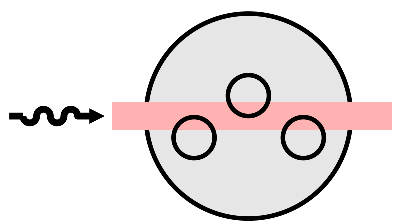
- Neutron spin structure

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



- Nuclear interactions: SRCs, EMC effect

  Identify correlated NN configurations
  Associate modified partonic structure with particular NN interactions: quantum numbers, distances



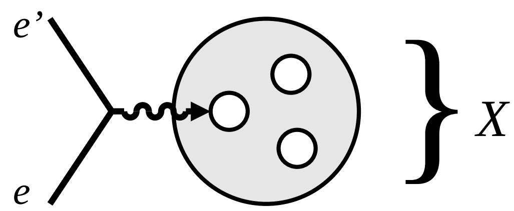
- Coherent phenomena in QCD at small x

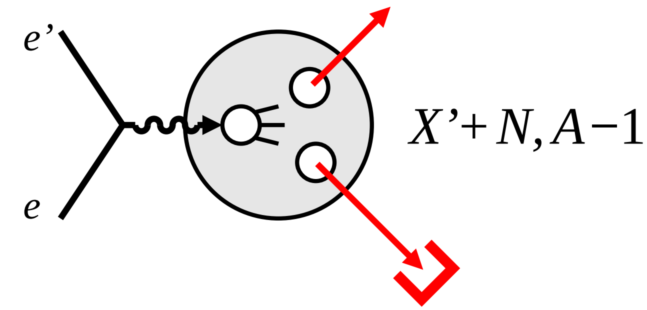
  Demonstrate onset of coherence
  Unravel contributions $N = 2, 3, \ldots$

[Nucleus rest frame view]

Common challenge: Effects depend on the nuclear configuration during the high-energy process.

Light nuclei: 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, ...
  $\rightarrow$ Talks Sirca, Ye

- Nuclear breakup detection – tagging

  Potential information on initial-state nuclear configuration

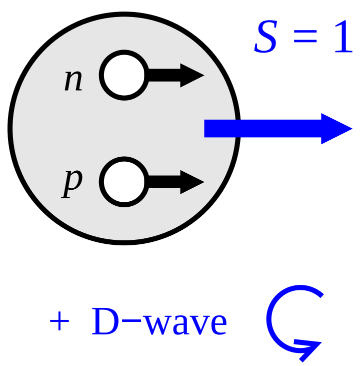
  Study effects in defined configurations

  Final-state interactions important, influence breakup amplitudes

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

[• Coherent processes]

Light nuclei: Deuteron and spectator tagging

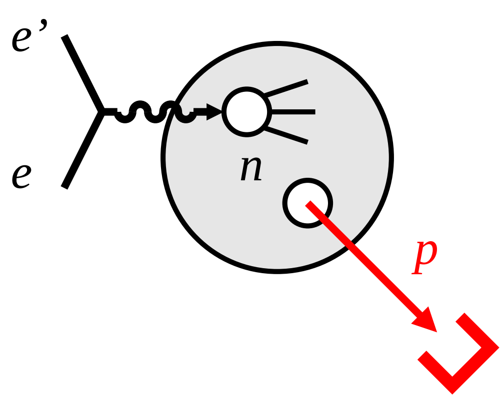


- Deuteron as simplest system

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

  p and n spin-polarized, some D-wave depolarization

  $|pn\rangle$ light-front description valid up to $k \sim 1$ GeV, intrinsic Δ isobars suppressed by isospin $= 0$
  $\rightarrow$ Talk Strikman



[Nucleus rest frame view]

- Spectator nucleon tagging

  Identifies active nucleon

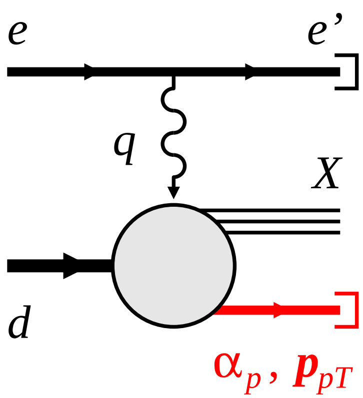
  Controls configuration through recoil momentum: Spatial size, S $\leftrightarrow$ D wave $\rightarrow$ Talk Cosyn

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

  Nucleon tagging in fixed-target experiments
  Protons: JLab6/12 BONUS $p =$ 70-150 MeV; ALERT, TDIS
  Neutrons: BAND

  Collider: Forward detection

Tagging: Cross section and observables



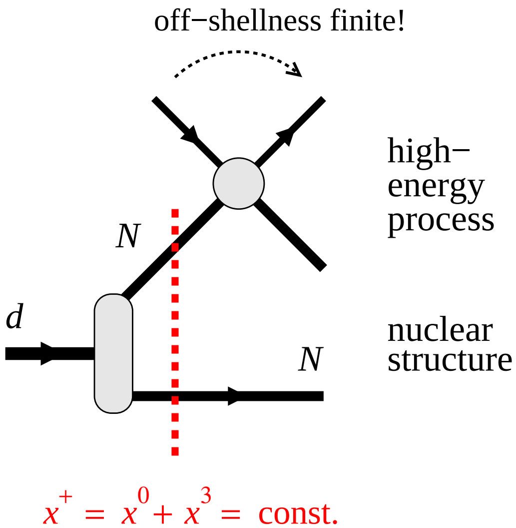
$$\frac{d\sigma}{dx\,dQ^2\,(d^3p_p/E_p)} = [\text{flux}] \Big[F_{Td}(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_{Ld}(..)$$

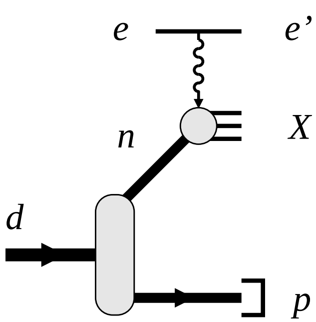
$$+ \sqrt{2\epsilon(1+\epsilon)}\,\cos\phi_p F_{LT,d}(..) \; + \; \epsilon\,\cos(2\phi_p) F_{TT,d}(..)$$

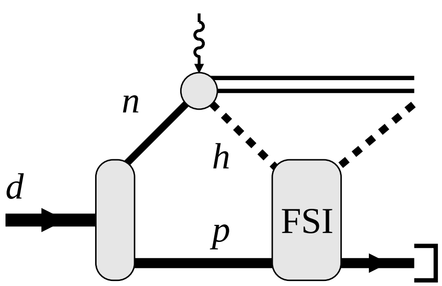
$$+ \;\text{spin-dependent structures} \Big]$$

- Semi-inclusive DIS cross section $e + d \to e' + X + p$
- Tagged proton 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
- No assumptions re composite nuclear structure, $A = \sum N$, etc.

Tagging: Theoretical description







- Light-front quantization

  Nuclear structure described at fixed light-front time $x^+ = x^0 + x^3 =$ const.

  Off-shellness of nucleon scattering process remains finite in high-energy limit, permits matching with on-shell nucleon amplitudes Frankfurt, Strikman 80's

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

  Low-energy nuclear structure $\leftrightarrow$ non-relativistic theory

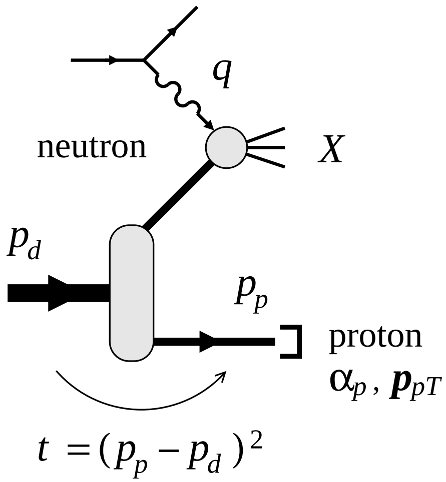
- Composite description

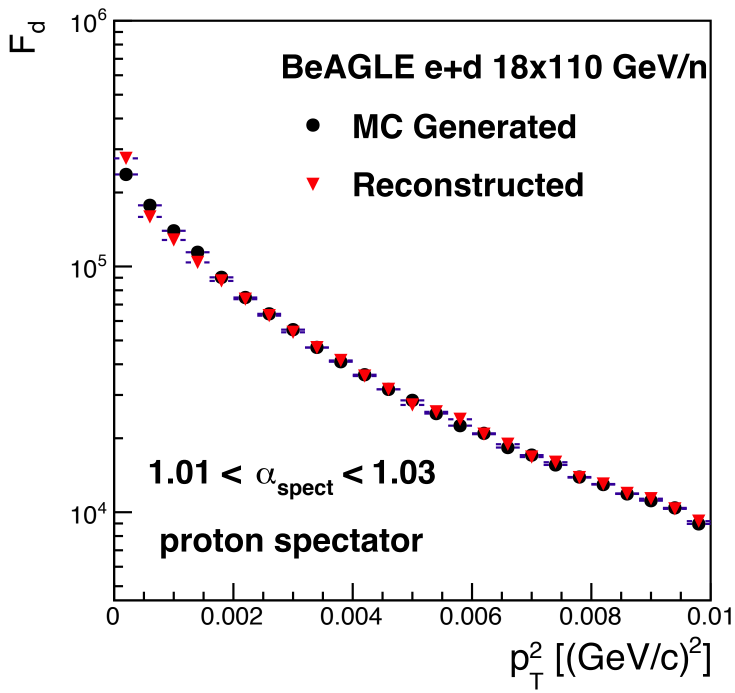
  Impulse approximation IA: DIS final state and spectator nucleon evolve independently

  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





Simulation EIC forward detector IR1 2021

- 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 $t - m^2 \rightarrow 0$

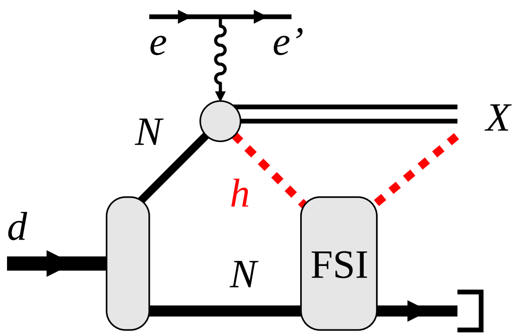
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 05

  EIC simulations
  JLab LDRD 2014/15; Jentsch, Tu, CW 2021

- Extension to polarized DIS

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

Tagging: Final-state interactions



- Final state of HE process can interact with spectator

  Changes momentum distributions in tagging

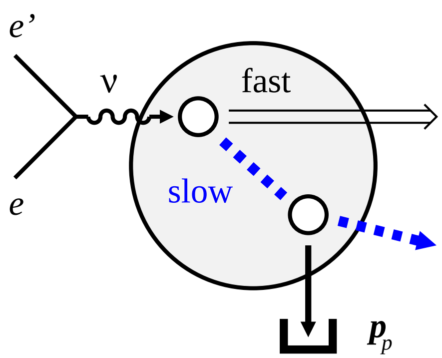
  No effect on total cross section – closure

  Depends on process and kinematics
  What states are produced in high-energy process?
  How do they interact with spectator?

- FSI in tagged ed $\rightarrow$ e'XN

DIS, $x \gtrsim 0.1$	$h =$ target fragmentation hadrons on-shell rescattering	Ciofi degli Atti, Kaptari, Kopeliovich 2004- Strikman CW 2018 ←
DIS, $x \ll 0.1$	$h =$ diffractive nucleons QM rescattering, orthogonality	Guzey, Strikman, CW; in progress
Finite W resonance region	$X = \sum N^*$	Sargsian, Strikman 2006 Cosyn, Sargsian, Melnitchouk 2011-

Tagging: FSI in tagged DIS x $\gtrsim$ 0.1



- Space-time picture in nuclear rest frame

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

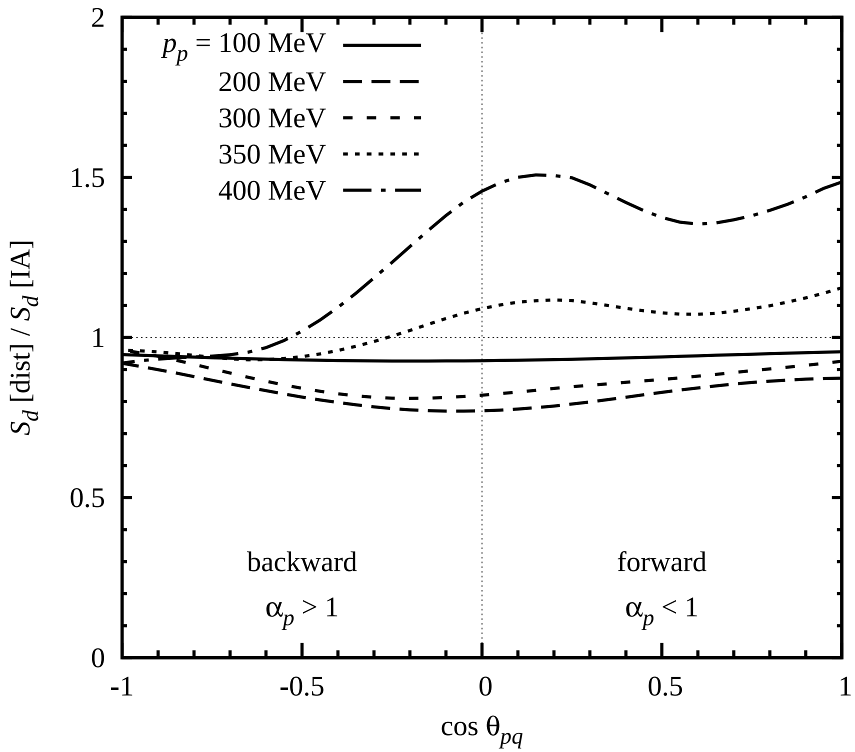
"Fast"	$E_h = O(\nu)$	hadrons formed outside nucleus interact weakly with spectators
"Slow"	$E_h = O(\mu_{\text{had}}) \sim 1$ GeV	formed inside nucleus interacts with hadronic cross section dominant source of FSI respects QCD factorization in target fragmentation

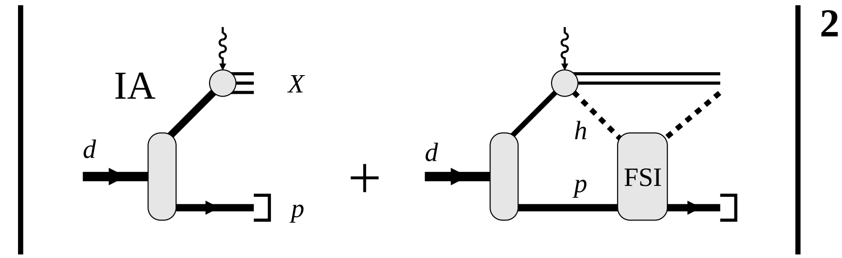
- FSI effects calculated

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: FSI in tagged DIS x $\gtrsim$ 0.1





- 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 — $|\text{FSI}|^2$, refractive, strong angular dependence

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

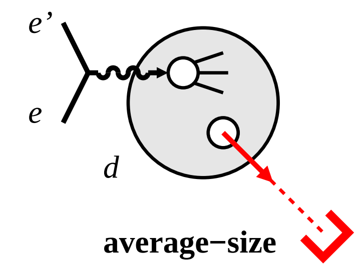
Tagging: Applications

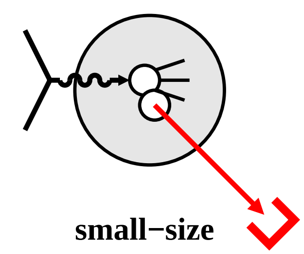
- Tagged EMC effect

  What momenta/distances cause modifications?
  Connection EMC effect $\leftrightarrow$ NN short-range correlations?

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

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

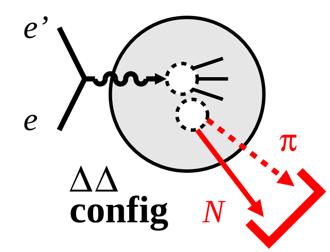




- Tagging $\Delta\Delta$ configurations

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

  Direct demonstration of non-nucleonic degrees of freedom



- Tagging with polarized deuteron

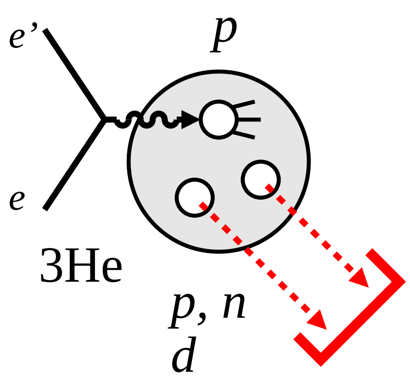
  Spin-orbit correlations, tensor polarized structures $\rightarrow$ Talk Cosyn

Tagging: Light nuclei A > 2

- Potential applications

  Isospin dependence neutron ↔ 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 ↔ 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

- Deuteron and spectator tagging overcome main limiting factor of nuclear DIS: Control of nuclear configuration during high-energy process

- Light-front quantization is unique method for high-energy scattering from composite systems, permits factorizing/matching of nuclear and nucleonic structure

- Free neutron structure can be extracted model-independently using pole extrapolation, not affected by FSI

- SRC/EMC studies at p(tagged) $\sim$ few 100 MeV require solid theory of FSI

  FSI generally large, depends on process and kinematics

  Essentially quantum-mechanical effects – interference, absorption, orthogonality

  Need experimental data to test/refine theoretical models

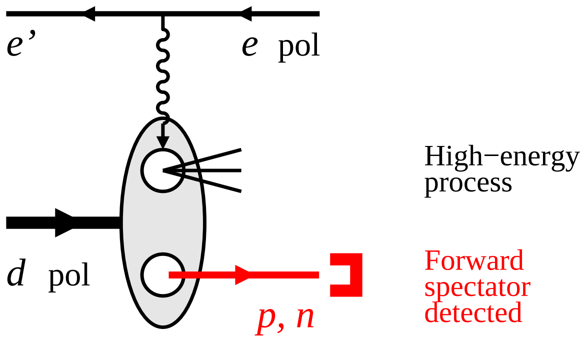
  Need strategies to separate initial-state modifications $\leftrightarrow$ final-state interactions

- Extensions of tagging to $A > 2$ require major theoretical development

- Exciting prospects for programs at JLab12 and EIC

Supplementary material

Light nuclei: Tagging with EIC



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

[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
  $\rightarrow$ Talks Baker, Tu, Nguyen, Hauenstein, Higinbotham

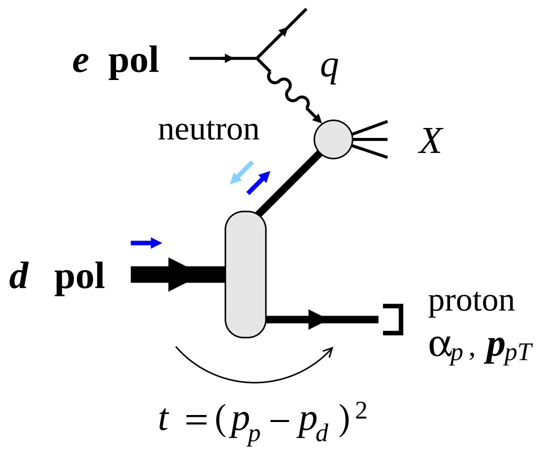
- Advantages over fixed-target

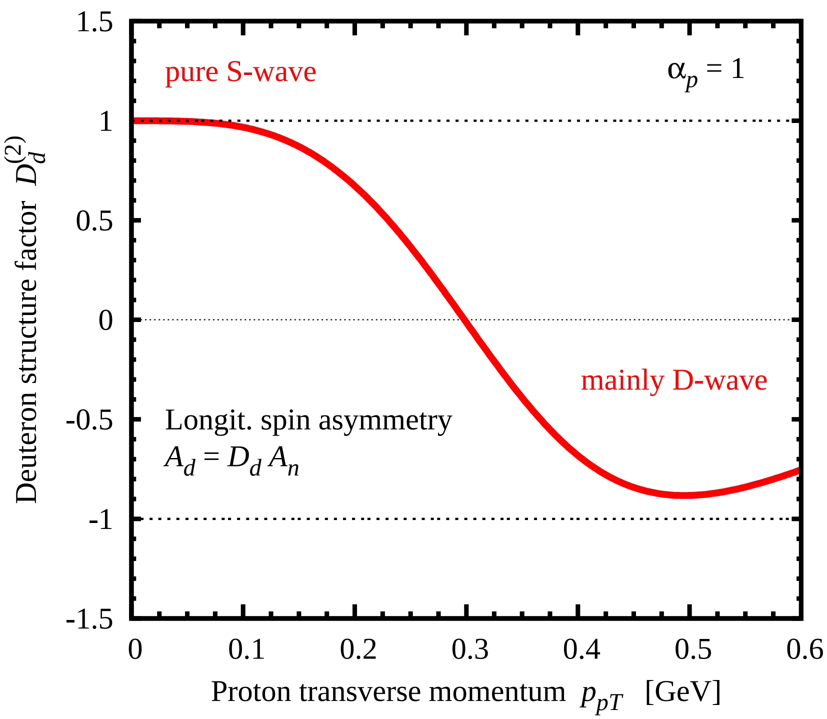
  No target material, $\boldsymbol{p}_p[\text{rest}] \rightarrow 0$ possible

  Protons: Setup acts as magnetic spectrometer,
  good acceptance and resolution

  Neutron: Zero-degree calorimeter

Tagging: Neutron spin structure





Cosyn, CW, PLB799 (2019) 135035

- 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]

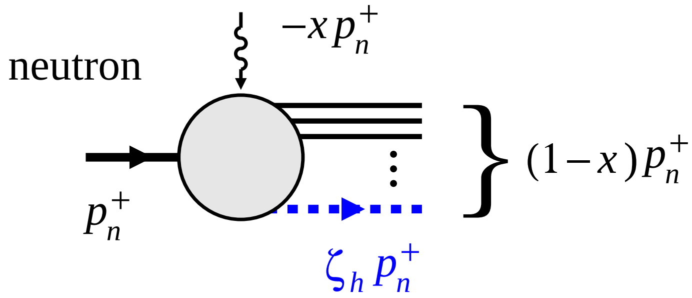
- Free neutron spin structure

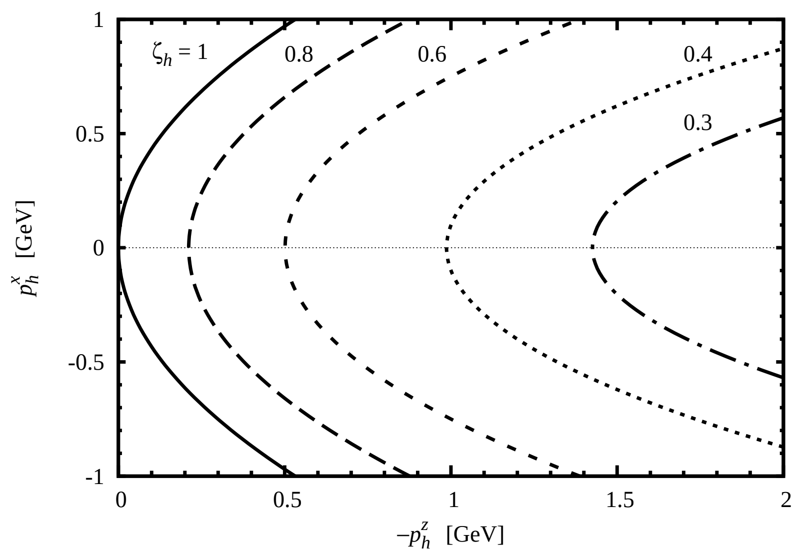
  On-shell extrapolation of asymmetry

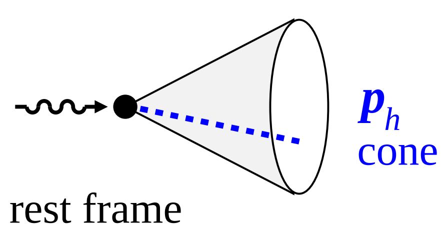
- EIC simulations

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

Tagging: Hadrons from nucleon fragmentation







- Kinematic variables

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

  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

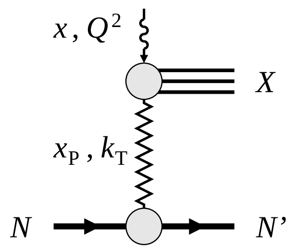
  No backward movers if $h =$ nucleon

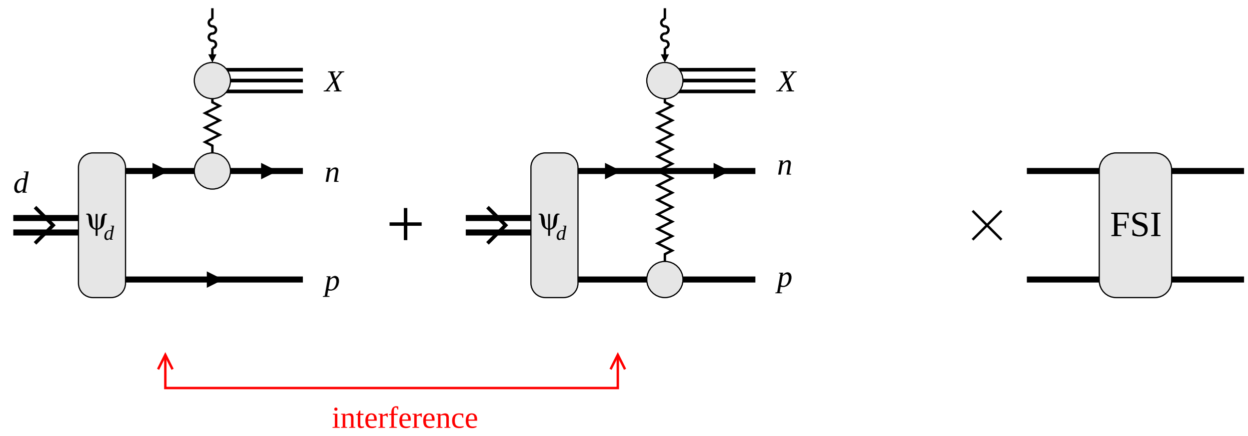
- Experimental data

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

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

Tagging: FSI in diffractive DIS 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