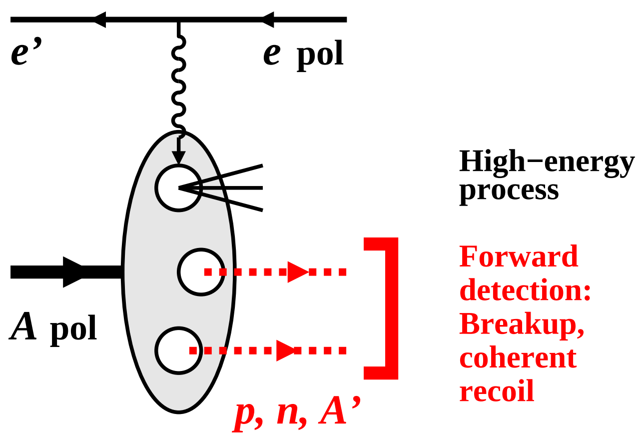
Physics with eA(light) scattering at EIC

C. Weiss (JLab), MCEGs for future ep and eA facilities, Vienna, 20-Nov-2019

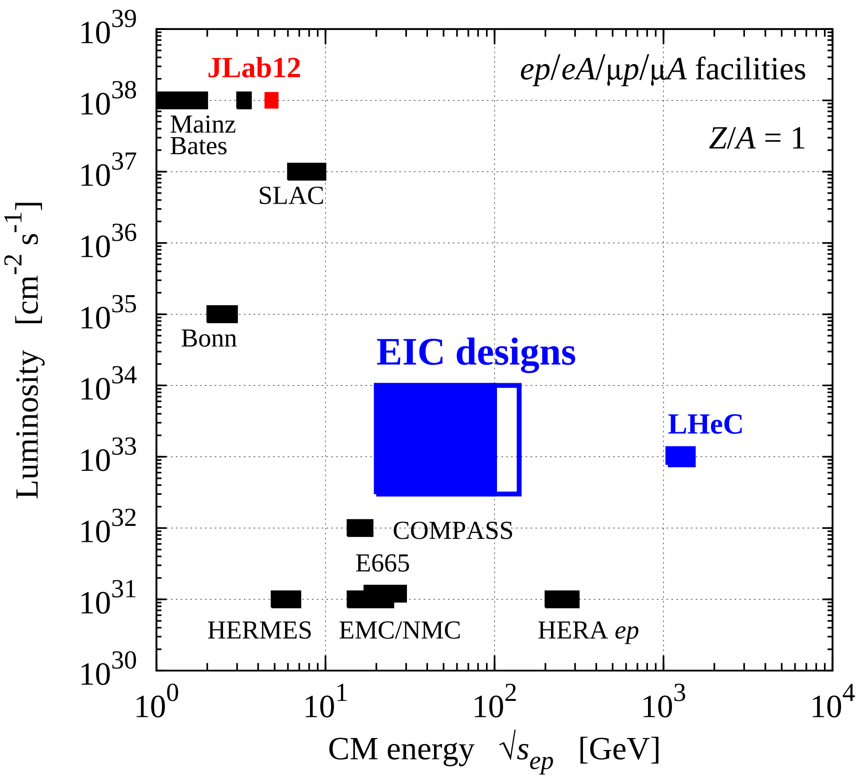


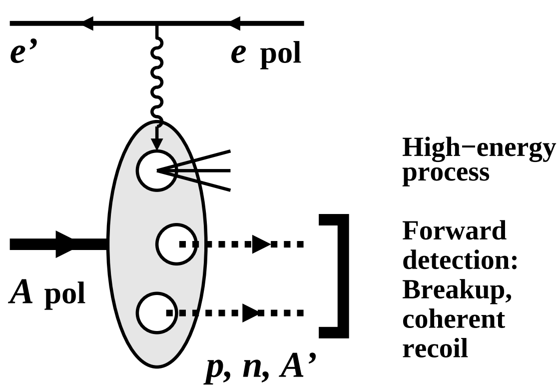
EIC simulations: JLab 2014/15 LDRD project
W. Cosyn, V. Guzey, D. Higinbotham, Ch. Hyde,
K. Park, P. Nadel-Turonski, M. Sargsian,
M. Strikman, C. Weiss [Webpage]
+ ongoing theoretical research

- Light-ion phyiscs at EIC
  - Energy, luminosity, polarization, detection
  - Objectives and challenges
- Nuclear breakup measurements
  - Deuteron and spectator tagging
  - High-energy process ↔ low-energy stucture
  - Applications: Free neutron, EMC effect, ...
  - Final-state interactions
- Coherent processes with light nuclei
  - Nuclear GPDs, quark/gluon imaging
  - Controled centrality, shadowing

[• MCEG role and status

Light ions: EIC capabilities





- CM energy $\sqrt{s_{ep}} \sim$ 20–100(140) GeV

  Factor $\sqrt{Z/A}$ for nuclei

  DIS at $x \gtrsim 10^{-3}$, $Q^2 \lesssim 10^2$ GeV^2

- Luminosity $\sim 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$

  Exceptional configurations in target
  Multi-variable final states
  Polarization observables

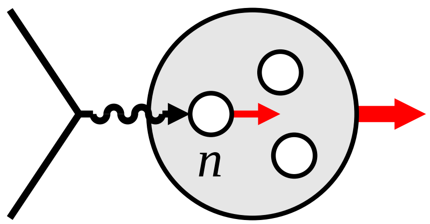
- Polarized protons and light ions

  Polarized deuteron, 3He, ...

- Forward detection of p, n, A

  Exclusive and diffractive processes
  Nuclear breakup and spectator tagging
  Coherent nuclear scattering

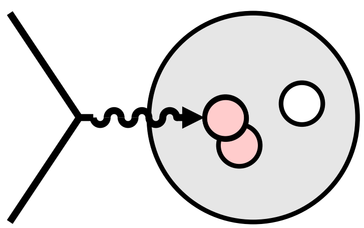
Light ions: Physics objectives



- Neutron structure

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

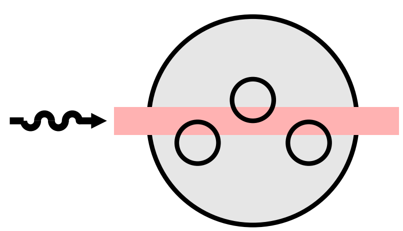
  Eliminate nuclear binding, non-nucleonic DOF!



- 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

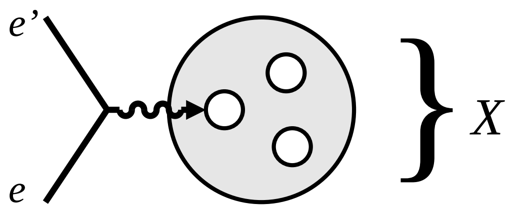
  Coherent interaction of high–energy probe
  with multiple nucleons, shadowing, saturation

  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: Measurements

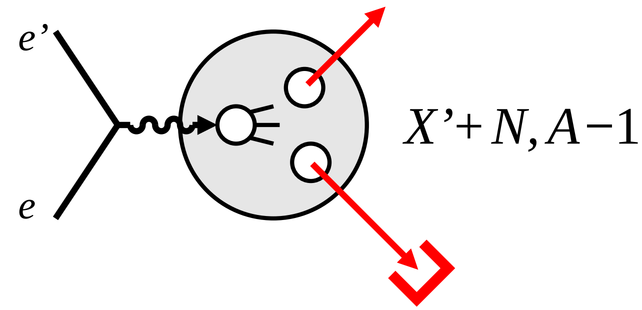


- Inclusive scattering

  No information on initial-state nuclear configuration

  Final-state interactions irrelevant, closure Σ_X

  Basic measurements at EIC
  D, 3He (unpol/pol), 4He, ...



- Nuclear breakup detection ("tagging")

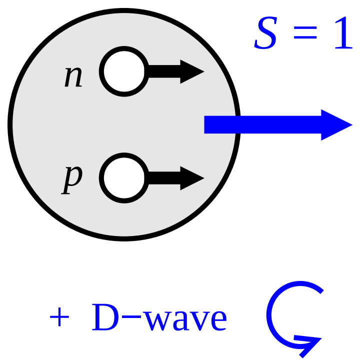
  Potential information on initial-state nuclear configuration

  Final-state interactions important, influence breakup amplitudes

  New opportunities with EIC!
  New challenges for theory and MCEG!

[• Coherent processes $\rightarrow$ following

Tagging: Deuteron and spectator tagging

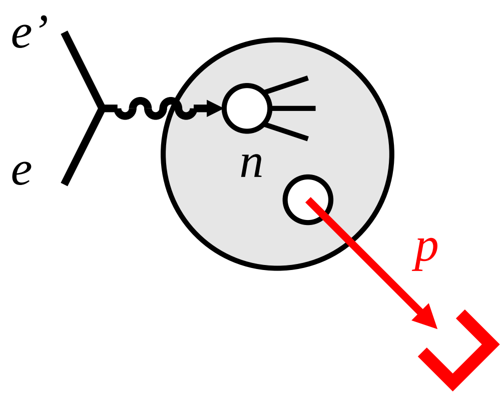


- Deuteron target unpol/pol

  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

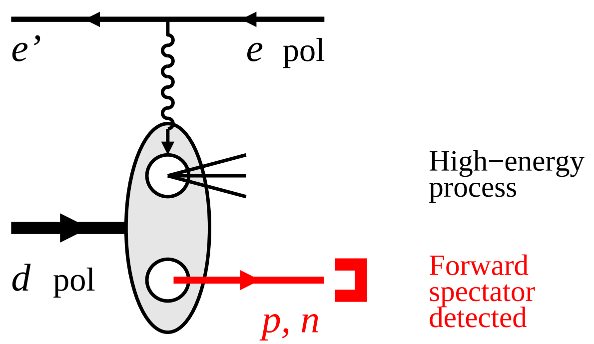
  Identifies active nucleon

  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

Tagging: Collider experiments



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

[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
  Expertise LHC, Tevatron, RHIC, HERA $\rightarrow$ EIC

- Advantages over fixed-target

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

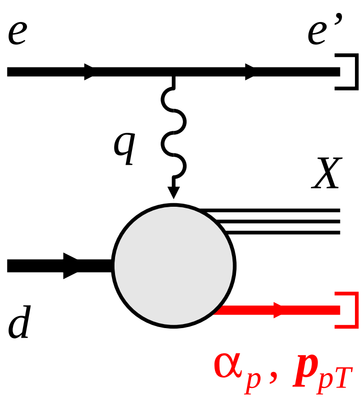
  Potentially good acceptance and resolution

  Deuteron polarization in beam,
  no holding magnets around target

  Forward neutron detection possible

  Unique physics potential!

Tagging: Cross section and observables



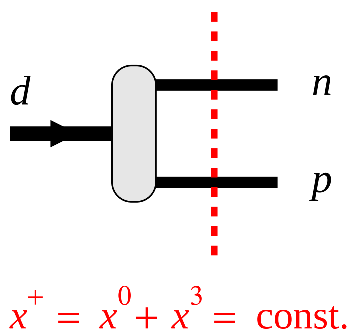
$$\frac{d\sigma}{dx\, dQ^2\, (d^3p_p/E_p)} = [\text{flux}] \Big[F_{Td}(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_{Ld}(..)$$

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

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

- Semi-inclusive DIS cross section $e + d \rightarrow e' + X + p$
- 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 Trentadue, Veneziano 93; Collins 97
- No assumptions re composite nuclear structure, $A = \sum N$, etc.

Tagging: Theoretical description



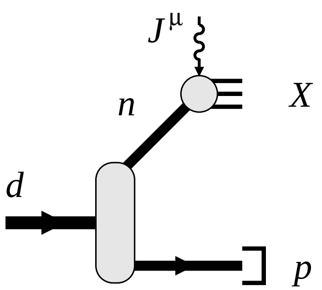
- Light-front quantization

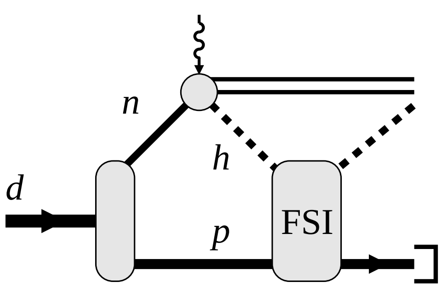
  High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 =$ const.

  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!





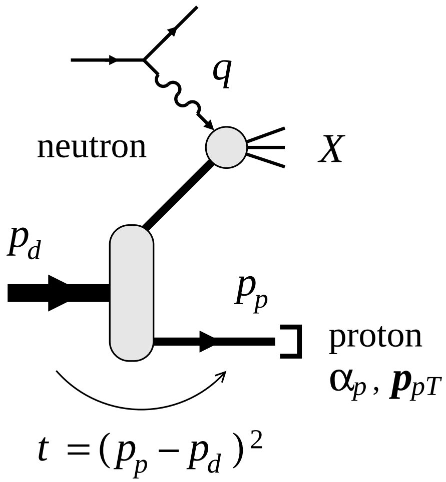
- Composite description

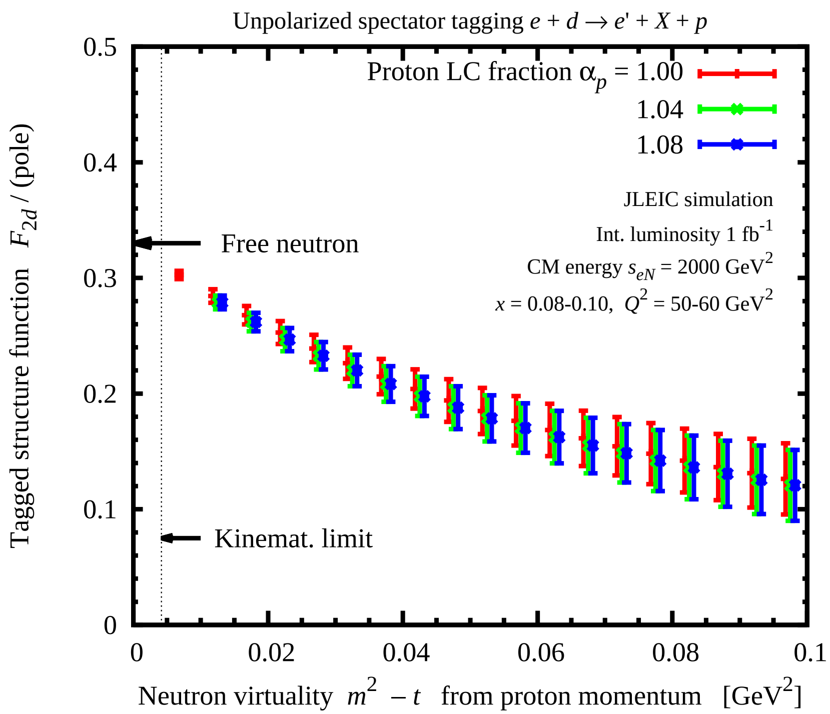
  Impulse approximation IA: DIS final state and spectator nucleon evolve independently

  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 $\rightarrow$ neutron off-shellness $t - m^2 = -2|\boldsymbol{p}_{pT}^2| + t'_{\rm min}$

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

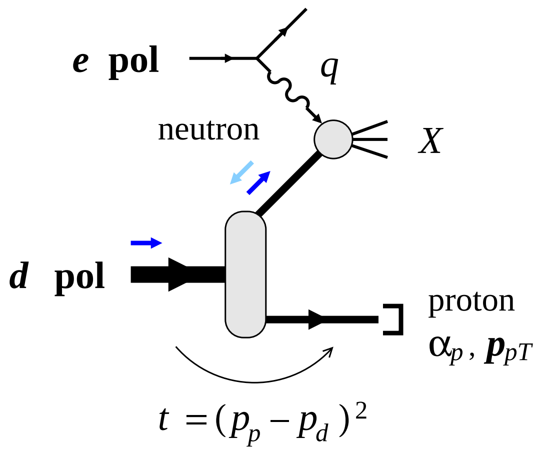
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 05

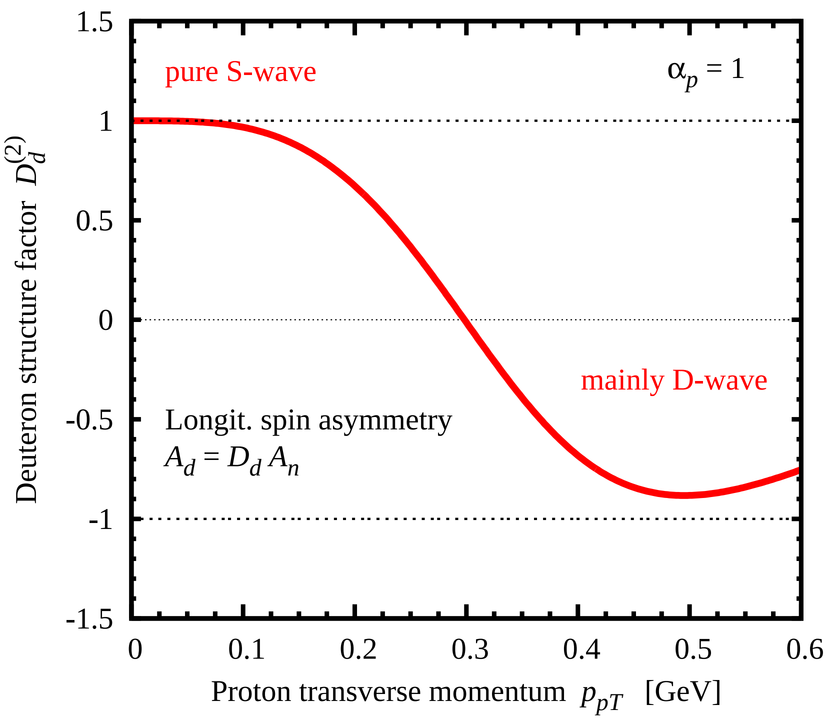
- EIC simulations

  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





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

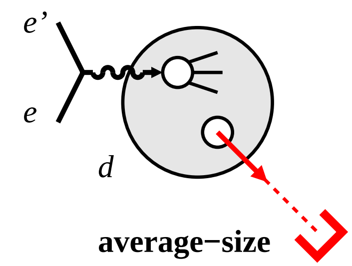
  Possible with int lumi $\sim$ few 10 fb^{-1}

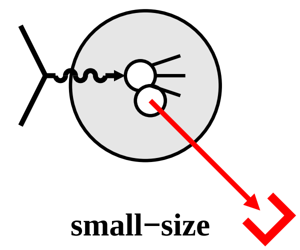
Tagging: EMC effect, non-nucleonic DoF

- Configuration dependence of nuclear partonic structure?

  What momenta/distances cause modifications?

  Connection EMC effect $\leftrightarrow$ NN short-range correlations?
  Quarks: Hen, Higinbotham, Piasetzky, Weinstein, et al.
  Gluonic structure: Miller, Sievert, Venugopalan 17



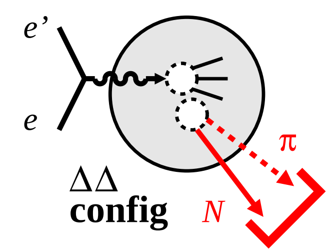


- Tagged nuclear structure functions

  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

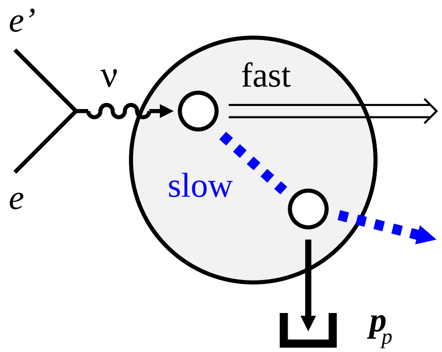


- Tagging $\Delta\Delta$ configurations

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

  Direct demonstration of non-nucleonic degrees of freedom

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

"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, cf. factorization

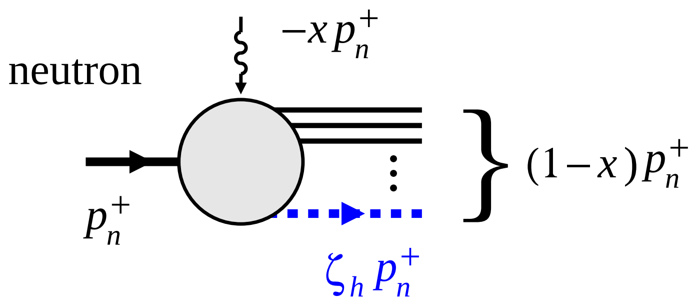
- FSI effects calculated $x \sim$ 0.1–0.5

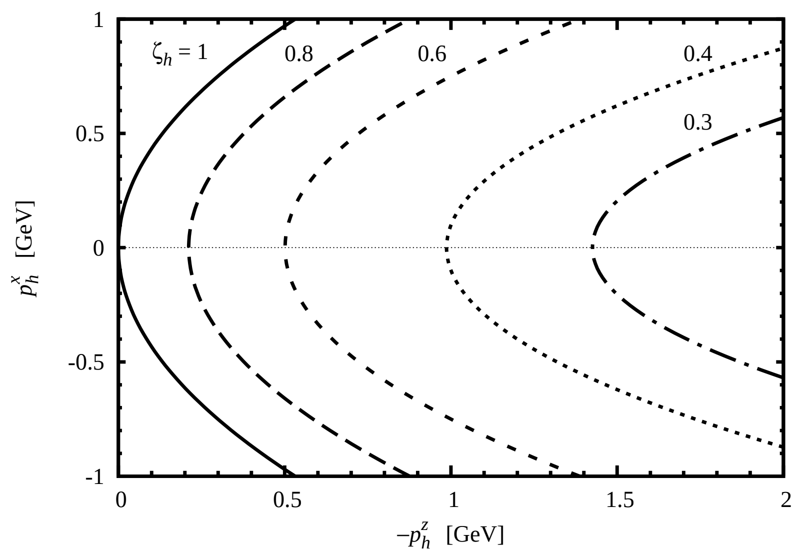
  Experimental data on nucleon fragmentation

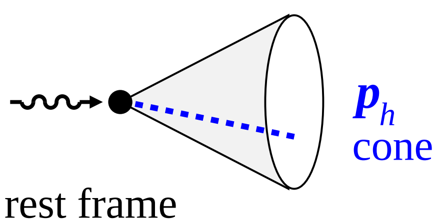
  Hadron-nucleon low-energy scattering amplitudes

  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

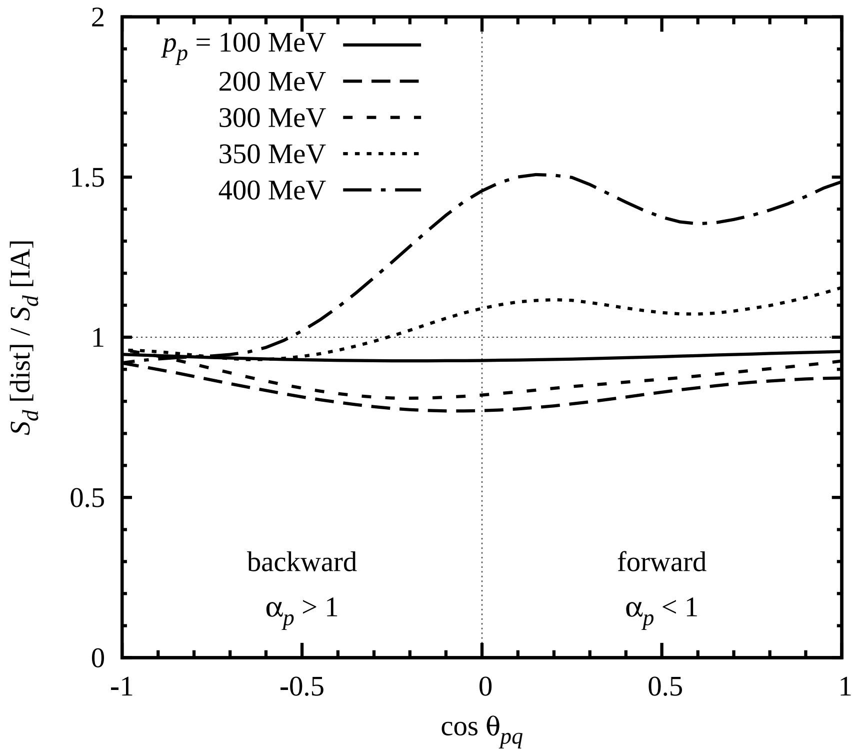
  No backward movers if $h =$ nucleon

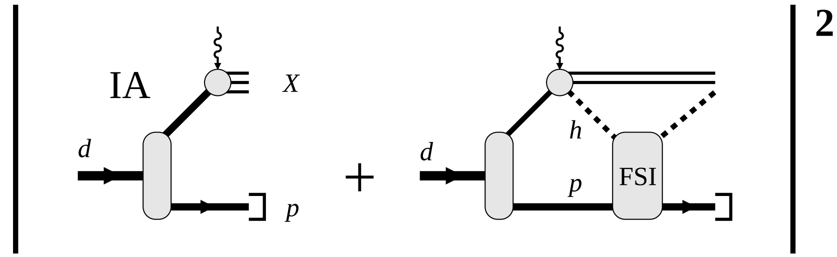
- Experimental data

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

  EIC should measure nucleon fragmentation!
  Nucleon structure physics + input for nuclear FSI

Tagging: FSI momentum and angle dependence





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

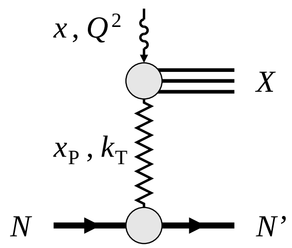
- Momentum and angle dependence in rest frame

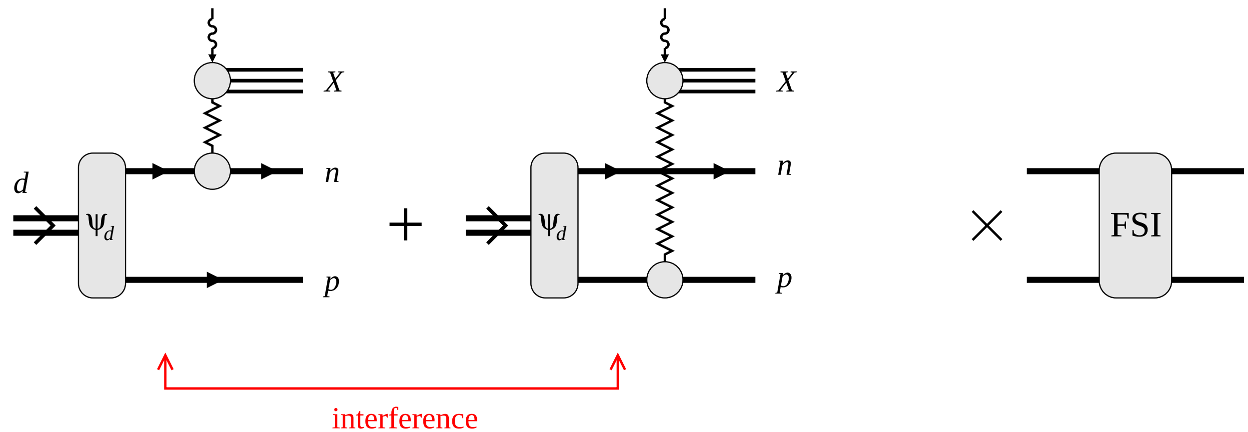
  $p_p < 300$ MeV   IA $\times$ FSI interference, absorptive, weak angular dependence

  $p_p > 300$ MeV $|\text{IA}|^2$, refractive, strong angular dependence

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

Tagging: Diffraction and shadowing at small x





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

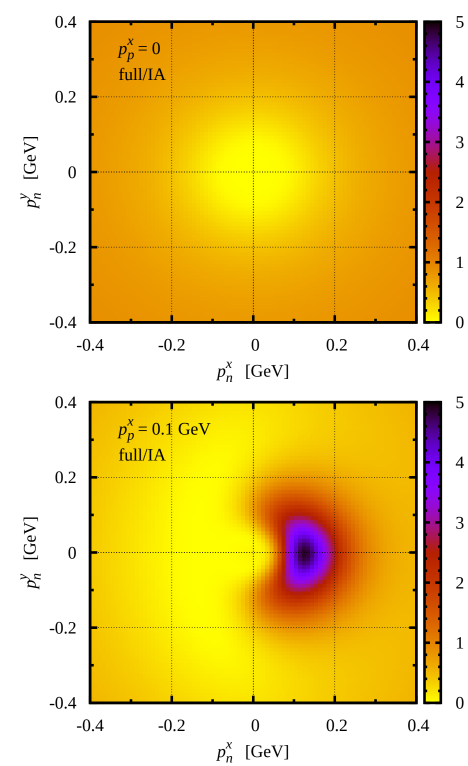
- Shadowing: QM interference of diffractive scattering on neutron or proton
  Observed in inclusive nuclear scattering

- Final-state interactions

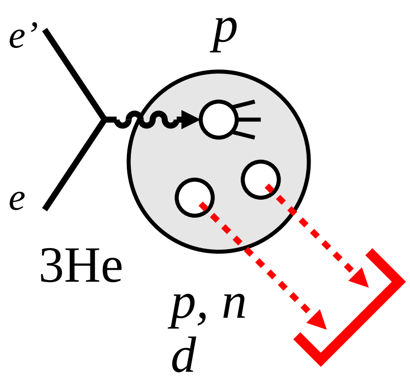
  Low-momentum pn system with $S = 1, I = 0$

  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 ↔ 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

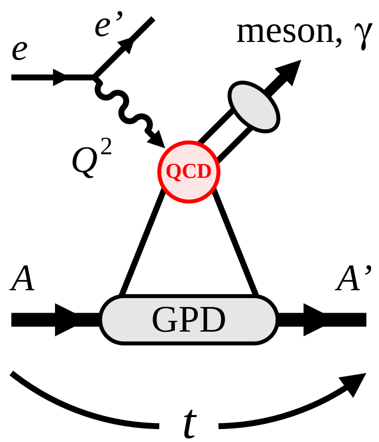
- Nuclear breakup much more complex than A=2

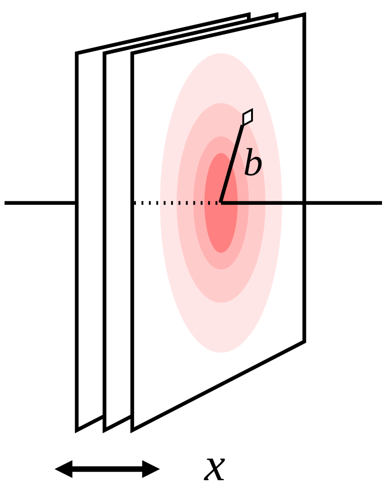
  IA: Wave function overlap, large amplitude factors
  Experience with quasielastic breakup: JLab Hall A

  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

Coherent processes: Nuclear quark-gluon imaging





- Hard exclusive processes

  QCD factorization theorem
  Collins, Frankfurt, Strikman 96

  Generalized parton distributions $\langle A' | \, \mathcal{O}(\text{twist-2}) \, | A \rangle$:
  Unify concepts of parton density and form factor
  Müller et al. 94; Ji 96, Radyushkin 96

- Transverse spatial distribution of quarks/gluons

  Transverse coordinate $\boldsymbol{b} \overset{\text{Fourier}}{\longleftrightarrow} \boldsymbol{\Delta}_T \qquad (t = -\boldsymbol{\Delta}_T^2)$

  Compare quark $\leftrightarrow$ gluon, charge $\leftrightarrow$ matter distributions

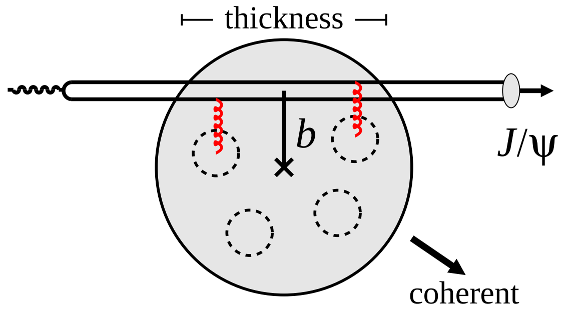
  Dynamics: Distributions change with x, polarization

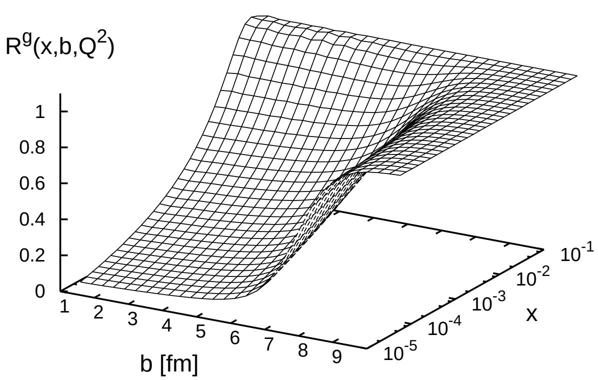
- EIC: Quark-gluon imaging of light nuclei

  Probe quarks: DVCS γ; π, K, ρ^+, K^*
  Probe gluons: $J/\psi, \phi$; DVCS γ NLO

  Nuclei: D spin-1, 3He spin-1/2, 4He spin-0

Coherent processes: Centrality, shadowing





- eA collision at defined centrality

  Basic question of high-energy nuclear collisions
  Empirical measures of centrality in heavy-ion collisions

  Can be used to study dynamics!

- Nuclear shadowing in coherent scattering

  Suppression of leading-twist gluon density at small x from interference of scattering on different nucleons
  Seen in ultraperipheral γA at LHC: ALICE, CMS. $\rightarrow$ Talk Guzey

  Impact parameter $\leftrightarrow$ thickness
  Theoretical models: Guzey et al 09

  Light ions: Test shadowing mechanism in simplest systems, positive detection of forward ions

  Heavy ions: Veto nuclear breakup
  Caldwell, Kowalski 09

Summary

- EIC will enable next-generation physics program in eA(light) scattering

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

  Free neutron from on-shell extrapolation, eliminates nuclear binding and D-wave

  Configuration dependence of nuclear modifications, EMC effect

  Theory well developed, separates high-energy process $\leftrightarrow$ low-energy structure

  Extension to $A > 2$ possible, requires substantial nuclear structure input

- Coherent processes in eA present new possibilities for structure and dynamics

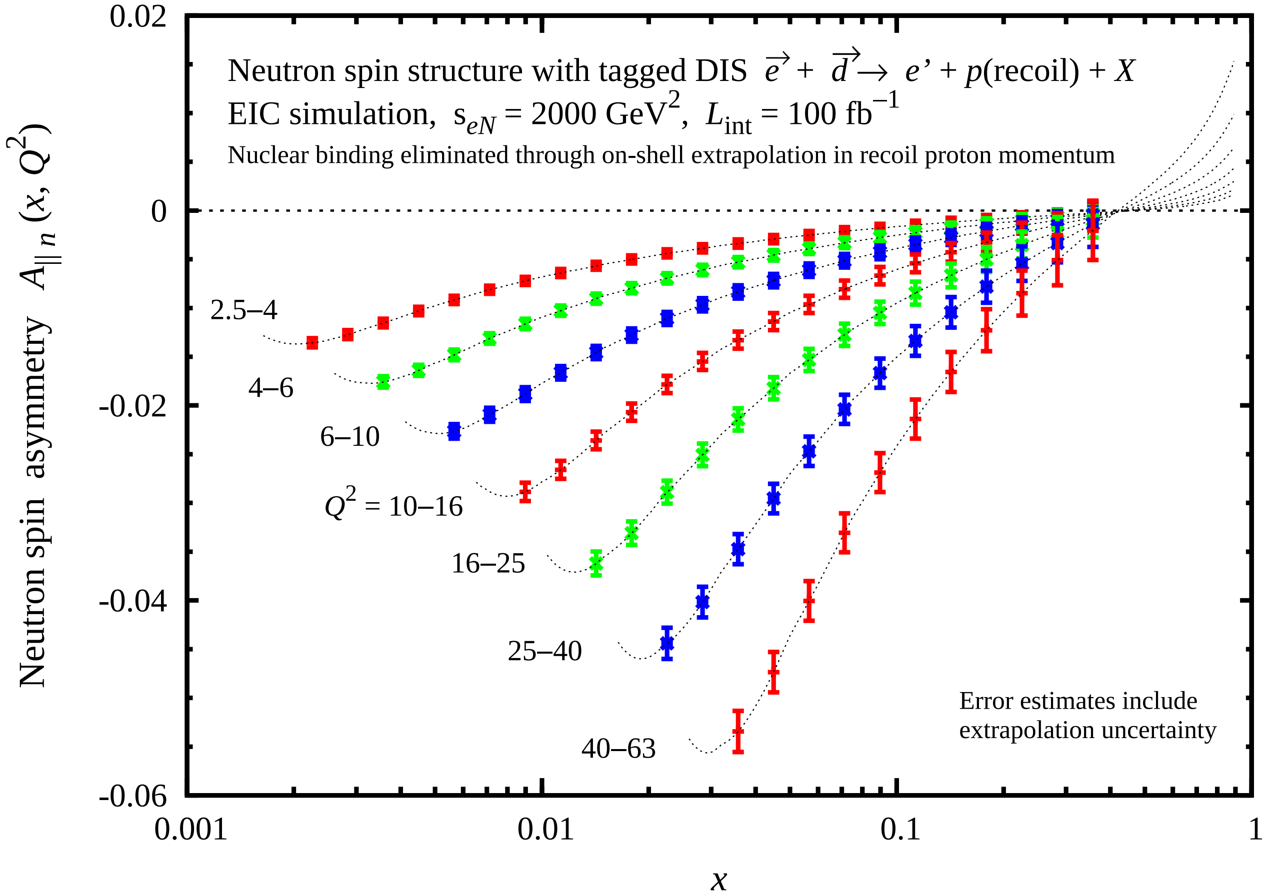
  Image nucleus in terms of quark/gluon degrees of freedom

  Nuclear shadowing as function of centrality/thickness

- Nuclear breakup and coherent recoil are essentially QM processes, need to be described by QM cross section models, not probabilistic MC
  $\rightarrow$ tomorrow

Supplementary material

Tagging: Neutron spin structure II



$$A_{\parallel n} = \frac{\sigma(+-) - \sigma(++)}{\sigma(+-) + \sigma(++)} = D\,\frac{g_{1n}}{F_{1n}} + \ldots$$

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

depolarization factor

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

- Precise measurement of neutron spin structure

  Wide kinematic range: Leading $\leftrightarrow$ higher twist, nonsinglet $\leftrightarrow$ 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