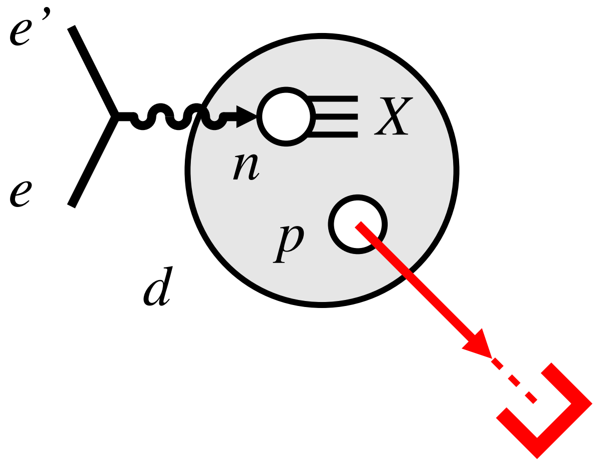
Spectator tagging: Inclusive measurements in controlled nuclear configurations

C. Weiss, Symposium Inclusive Measurements, 20-21 June 2023

Jefferson Lab



Basic idea: Use spectator momentum to control nuclear configurations during high-energy process

→ relative momentum, spatial size
→ interactions, non-nucleonic DoF
→ effective polarization

JLab 6/12 GeV: BONuS, ALERT, TDIS p tagging, BAND n tagging

EIC: Far-forward detectors, p and n tagging, good coverage + resolution, simulations.
Physics program: JLab LDRD, EIC Yellow Report

High-energy scattering on light nuclei

- Physics objectives
- Nuclear effects

Spectator tagging

- Control nuclear configurations
- High-energy process ↔ low-energy structure
- Final-state interactions

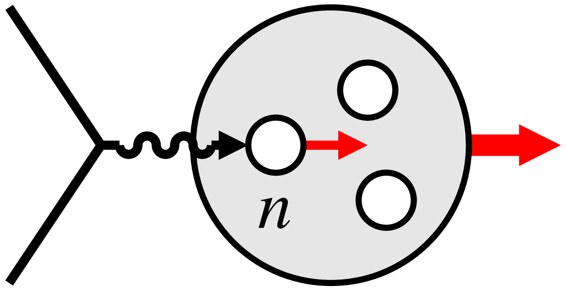
Applications

- Free neutron from on-shell extrapolation
- Effective neutron polarization
- Tensor-polarized deuteron
- Nuclear modifications (EMC effect)

Extensions

- A > 2, exclusive procs, improved theory…

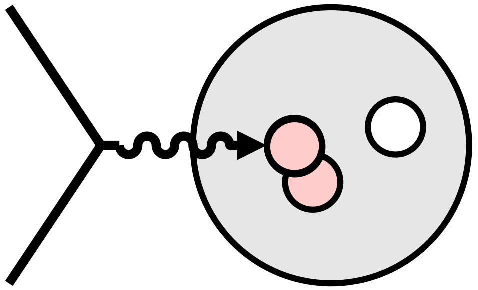
Light nuclei: Physics objectives



Neutron structure

Flavor decomposition of quark PDFs/spin, GPDs, TMDs

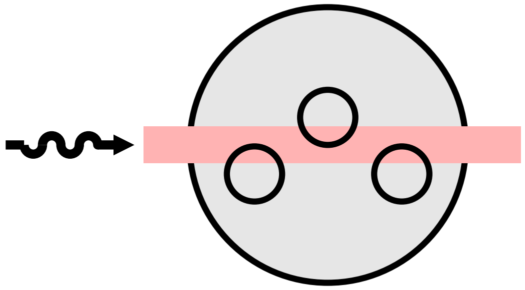
Singlet-nonsinglet separation in QCD evolution for ΔG



Nuclear interactions

Hadronic: Short-range correlations, NN core, non-nucleonic DoF

Partonic: Nuclear modification of partonic structure
EMC effect $x > 0.3$, antishadowing $x \sim 0.1$
Quarks/antiquarks/gluons? Spin, flavor? Dynamical mechanism?



Coherent phenomena

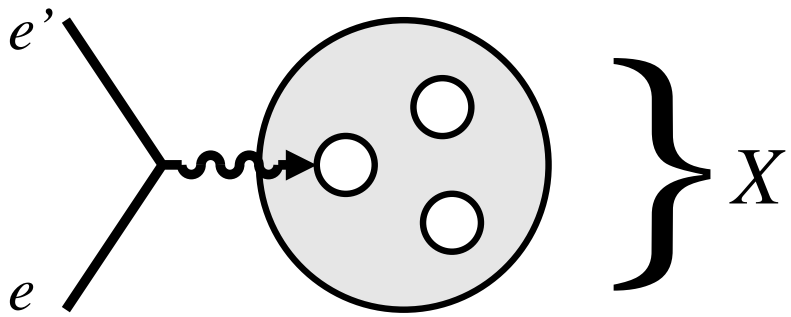
Nuclear shadowing $x \ll 0.1$

Buildup of coherence, interaction with 2, 3, 4… nucleons?
↔ Shadowing and saturation in heavy nuclei

[Nucleus rest frame view]

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

Light nuclei: Measurements



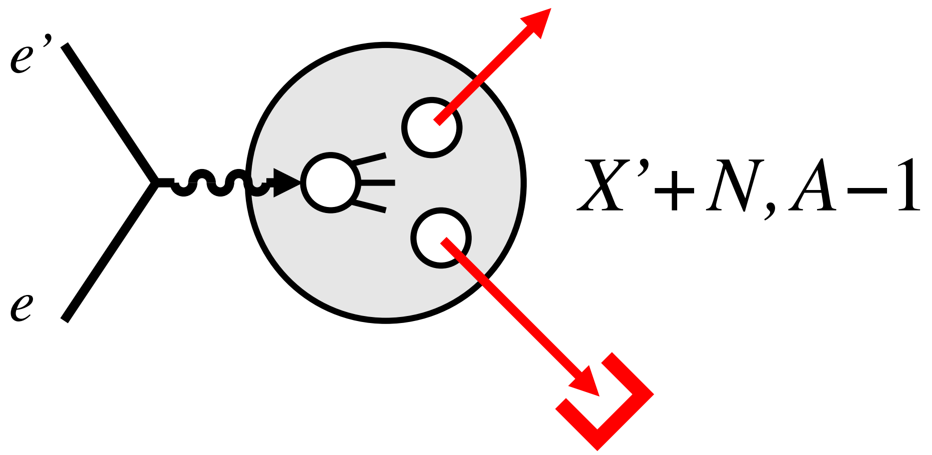
Inclusive measurements

No information on initial-state nuclear configuration

Model effects in all configurations, average with nuclear wave function $\Psi^* \ldots \Psi$

Final-state interactions irrelevant, closure Σ_X

Basic measurements: D, 3He (pol), 4He, …



Nuclear breakup detection - tagging

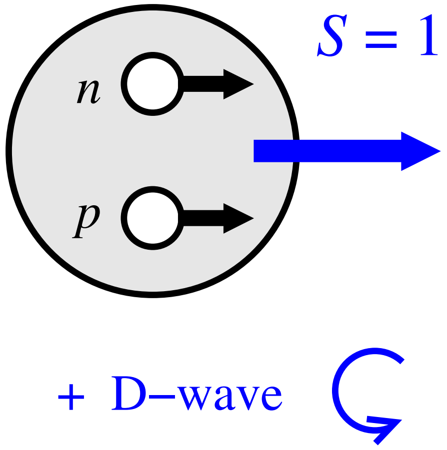
Potential information on initial-state nuclear configuration

Study effects in defined configurations, much simpler

Final-state interactions important, influence breakup amplitudes

New opportunities!
New challenges for detection and theory!

Light nuclei: Deuteron and spectator tagging



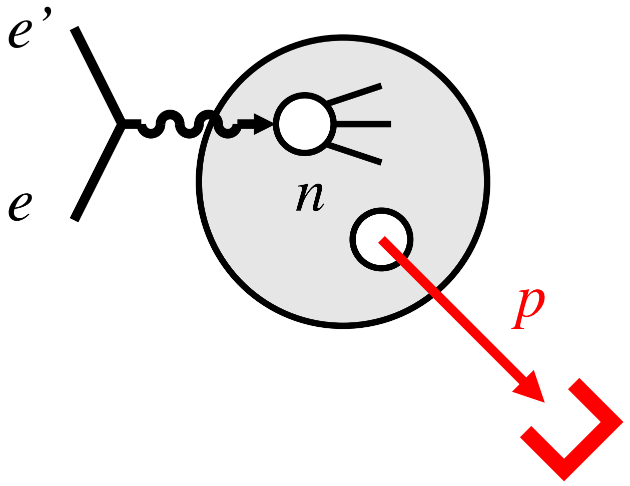
Deuteron as simplest system

Nucleonic wave function simple, well known (p ~< 400 MeV)

Nucleons spin-polarized, some D-wave depolarization

Intrinsic Δ isobars suppressed by isospin = 0

[cf. large Δ component in 3He Bissey, Guzey, Strikman, Thomas 2002]



[Nucleus rest frame view]

Spectator nucleon tagging

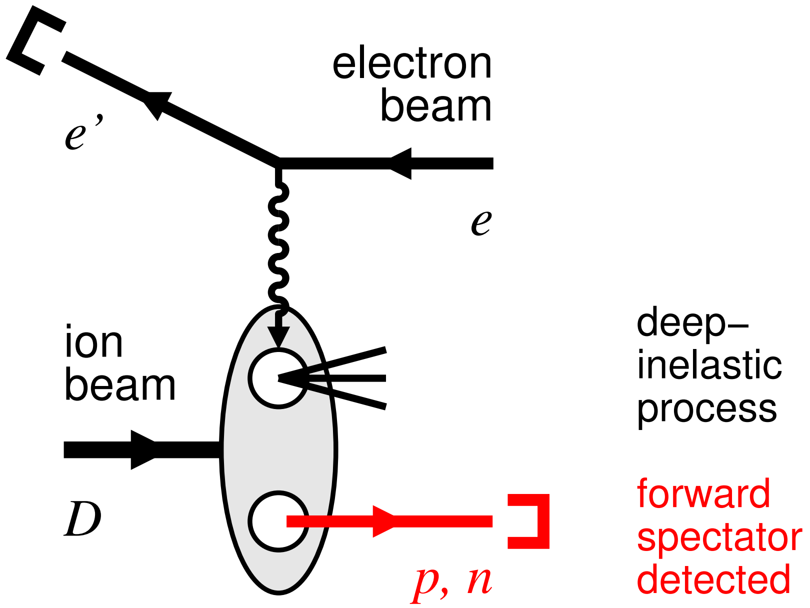
Identifies active nucleon

Controls configuration through recoil momentum:
spatial size → interactions, S/D wave

Typical momenta ~ few 10 — 100 MeV

Proton tagging in fixed-target experiments at JLab:
CLAS BONuS 6/12 GeV: p = 70-150 MeV
ALERT, HALL A TDIS
Neutron tagging: CLAS12 BAND
→ Talks Bueltmann, Tadepalli

Light nuclei: Spectator tagging with EIC



[Collider frame view]

Spectator tagging with colliding beams

Spectator moves forward in ion beam direction

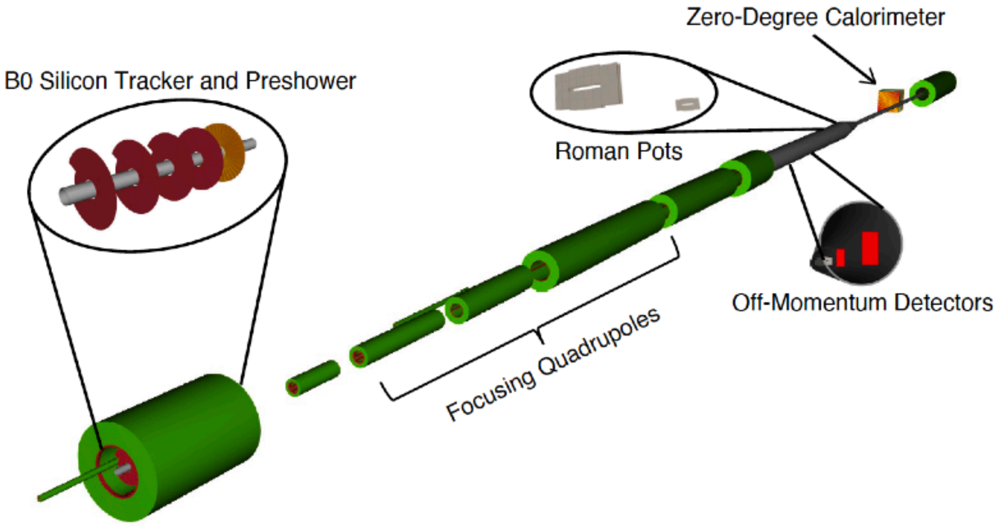
Longitudinal momentum controlled by light-cone fraction:

Given in deuteron rest frame by $$\frac{E_p + p_p^z}{M_D} \approx \frac{1}{2}\left(1 + \frac{p_p^z}{m}\right)$$

Conserved under boosts

Longitudinal momentum in detector $$P_{\|p} \approx \frac{P_D}{2}\left(1 + \frac{p_p^z}{m}\right)$$

Far-forward detectors



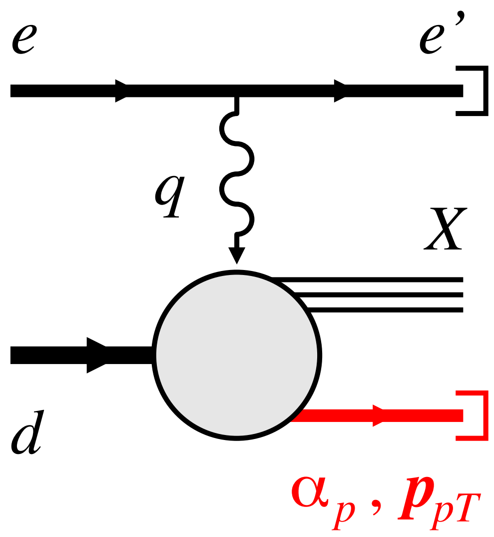
Magnetic spectrometer for protons, integrated in beam line, several subsystems: good acceptance and resolution

Zero-Degree Calorimeter for neutron

Advantage over fixed target: No target material, can detect spectators with rest frame momenta down to ~zero

Further information on EIC forward detectors and physics simulations:
EIC Yellow Report 2021 [INSPIRE]

Theory: Tagged DIS cross section



$$\frac{d\sigma}{dx\,dQ^2\,(d^3p_p/E_p)} = [\text{flux}]\Big[F_{Td}(x,Q^2;\alpha_p,p_{pT}) + \epsilon F_{Ld}(\,..\,)$$
$$+\sqrt{2\epsilon(1+\epsilon)}\,\cos\phi_p F_{LT,d}(\,..\,) + \epsilon\,\cos(2\phi_p) F_{TT,d}(\,..\,)$$
$$+ \text{spin-dep structures}\Big]$$

Semi-inclusive cross section $e + d \rightarrow e' + X + p$ (or n)

Collinear frame: Virtual photon and deuteron momenta collinear $\mathbf{q} \parallel \mathbf{p}_d$, along z-axis

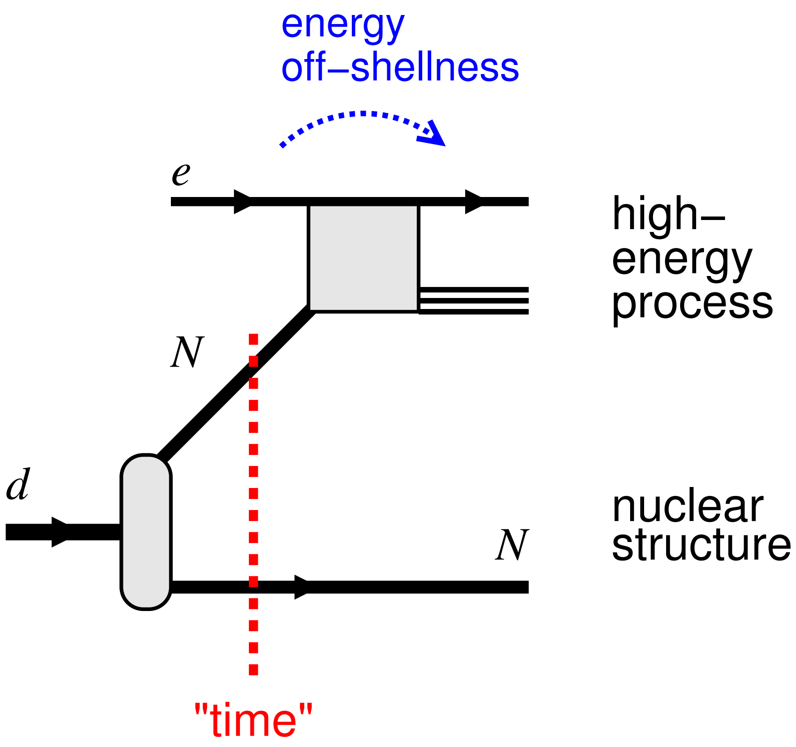
Proton recoil momentum described by light-cone components: $p_p^+ = \alpha_p p_d^+, \quad \mathbf{p}_{pT}$
Related in simple way to rest-frame 3-momentum

No assumption re composite nuclear structure, $A = \sum N$, or similar!

Special case of target fragmentation: Fracture function

[Trentadue, Veneziano 93; Collins 97]

Theory: Nucleus and nucleon structure



Light-front quantization

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

Off-shellness of electron-nucleon scattering amplitude remains finite in high-energy limit

Permits matching with on-shell nucleon scattering amplitude and structure functions

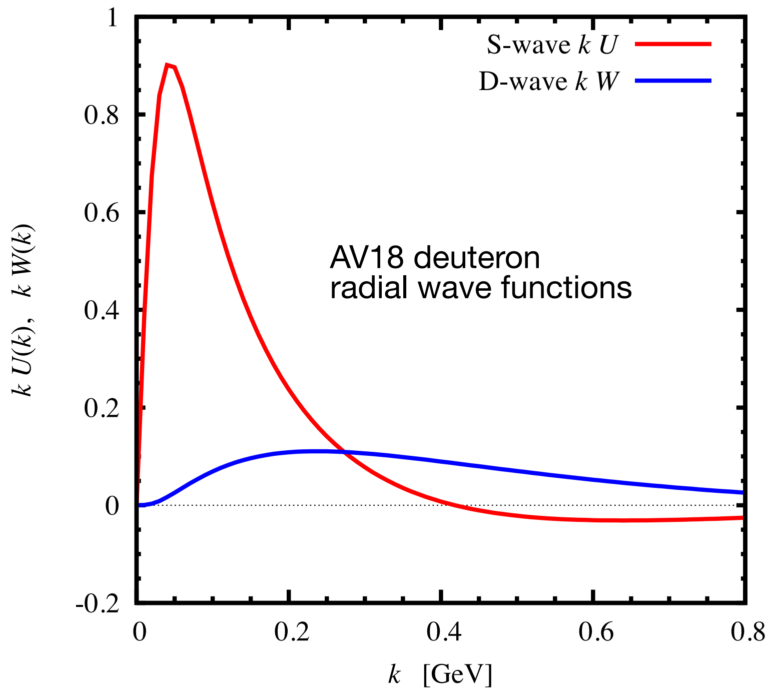
[Frankfurt, Strikman 80s]

Nuclear structure in nucleon degrees of freedom

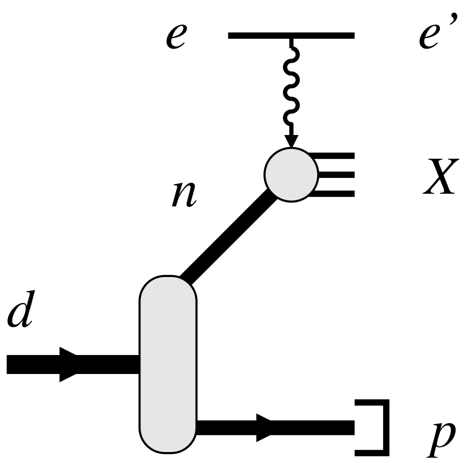
Nucleus described by wave function at fixed light-front time ${}_{x^+}\langle pn \,|\, d \rangle = \Psi(\alpha_p, p_{pT})$

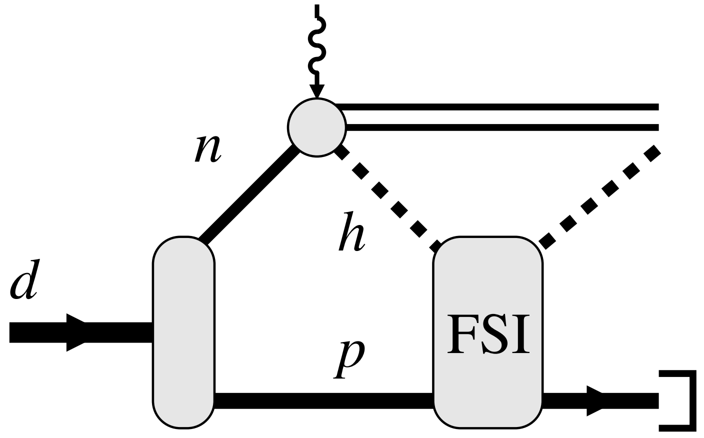
Contains low-energy nuclear structure, just “organized” in manner suitable for high-energy processes

Can be computed from microscopic NN interactions, or constructed approx. from nonrelativistic wave function



Theory: Nucleus and nucleon structure





For DIS in scaling regime $\nu, Q^2 \to \infty$: These approximations are consistent with leading twist factorization of $\sigma[eN]$, partonic sum rules, etc.

Impulse approximation

Spectator and DIS final state evolve independently

$$d\sigma[ed \to e'Xp] \;=\; S_d(\alpha_p, p_{pT})\, d\Gamma_p \times d\sigma[en \to e'X]$$

$$S_d(\alpha_p, p_{pT}) \;=\; \text{Flux} \times |\Psi_{\text{LF}}(\alpha_p, p_{pT})|^2$$ spectral function

Final-state interactions

Part of DIS final state interacts with spectator, transfers momentum

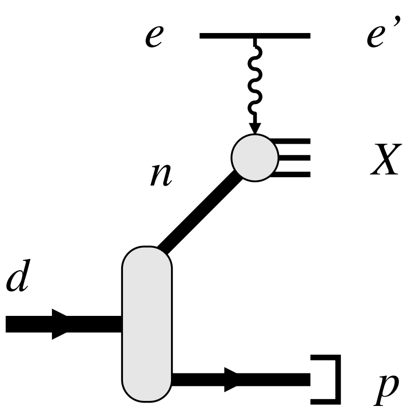
Requires theoretical modeling

Strategy

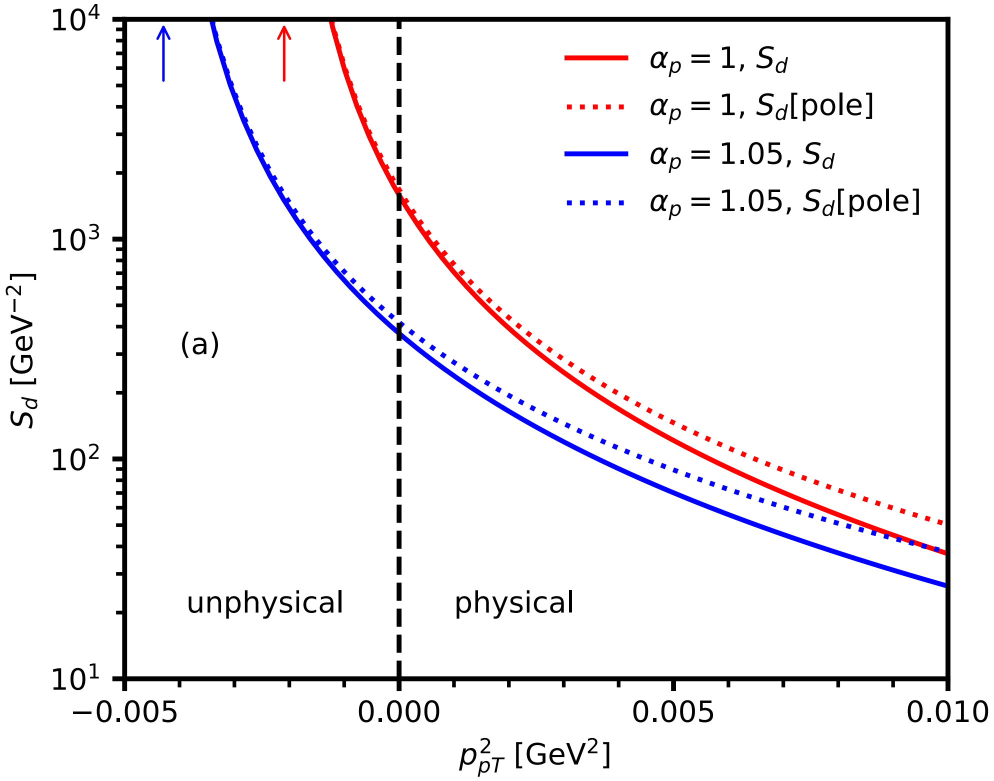
Use measured spectator momentum to control nuclear binding in initial state, interactions in final state

“Select configurations” in nucleus

Applications: Free neutron structure



$$S_d(\alpha_p, p_{pT}) \;=\; \frac{C}{(p_{pT}^2 + a_T^2)^2} \;+\; \text{(less sing.)}$$



Reaching free nucleons

Physical spectator momenta $p_{pT}^2 > 0$:
configs have finite size, nucleons interact

Analytic continuation to unphysical momenta $p_{pT}^2 < 0$
can reach configs with “infinite” size, nucleons free!

Light-front wave function: Pole at $p_{pT}^2 < 0$

[Feynman diagram: Neutron on mass shell
if 4-momentum $p_n^2 = (p_d - p_p)^2 = m^2$]

Extraction procedure

[Sargsian, Strikman 2005]

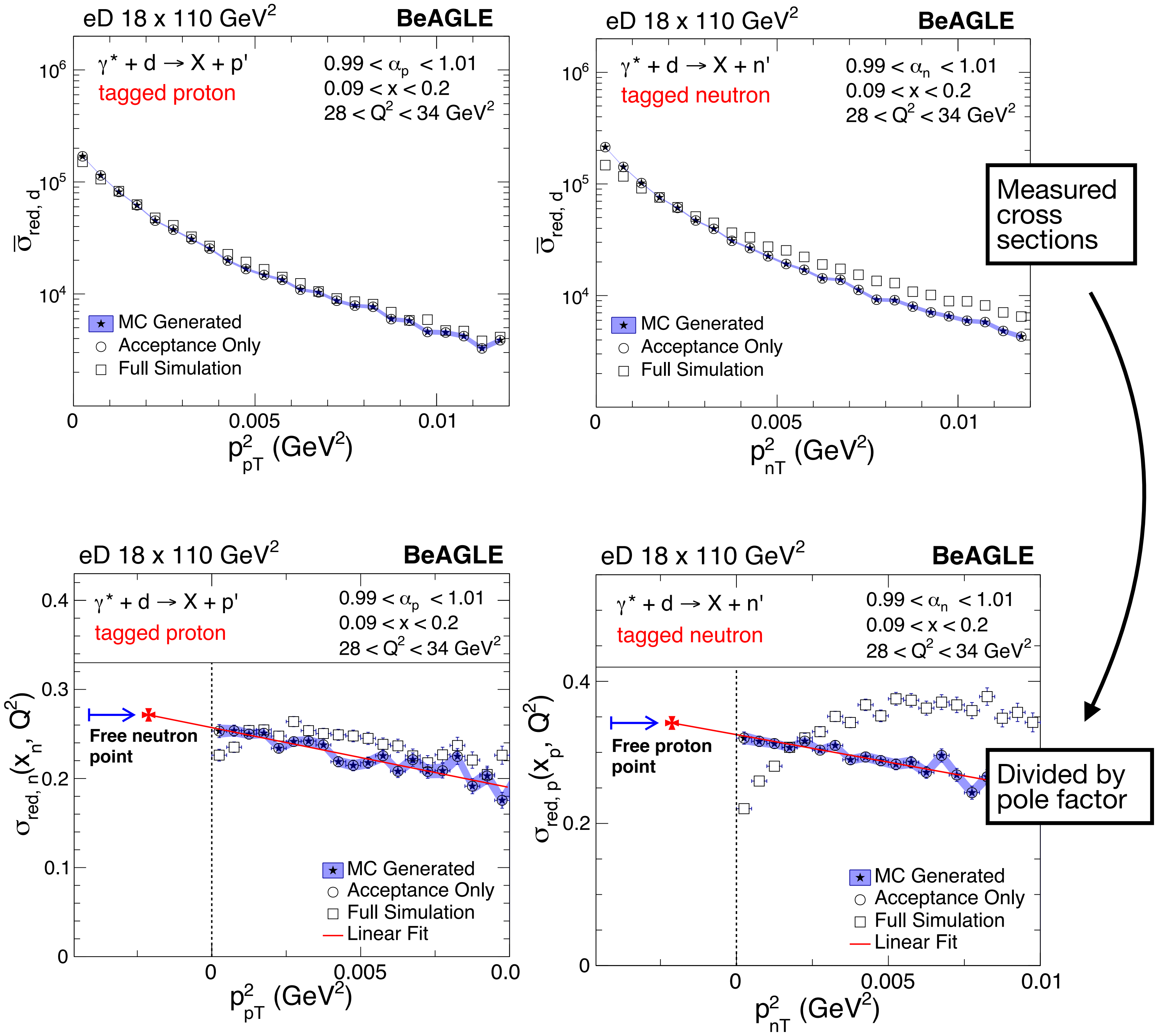
Measure proton-tagged cross section at fixed α_p
as function of $p_{pT}^2 > 0$

Divide data by pole term of spectral function

Extrapolate to pole position $p_{pT}^2 \to -a_T^2 < 0$

Experimentally challenging: Functions depend strongly
on p_{pT} — resolution!

Applications: Free neutron structure



EIC simulations: p and n tagging, pole extrapolation, uncertainty analysis, validation

Tagged cross section measured with excellent coverage

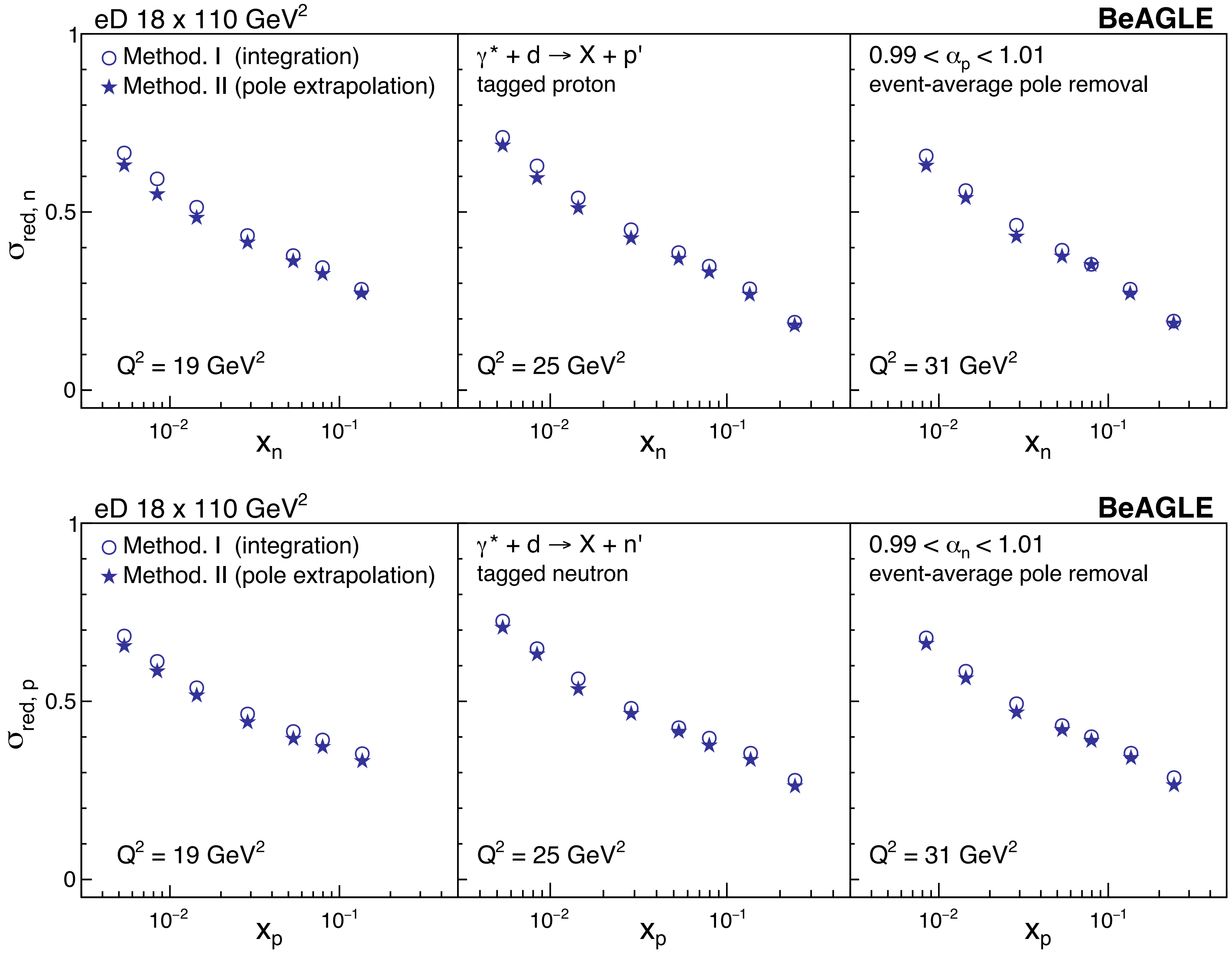
Significant uncertainties in division by pole factor $(p_{pT}^2 + a_T^2)^2$ due to experimental p_{pT} resolution

Pole extrapolation realistic for proton spectator, exploratory for neutron

Jentsch, Tu, Weiss, PRC 104, 065205 (2021)

EIC Yellow Report 2021

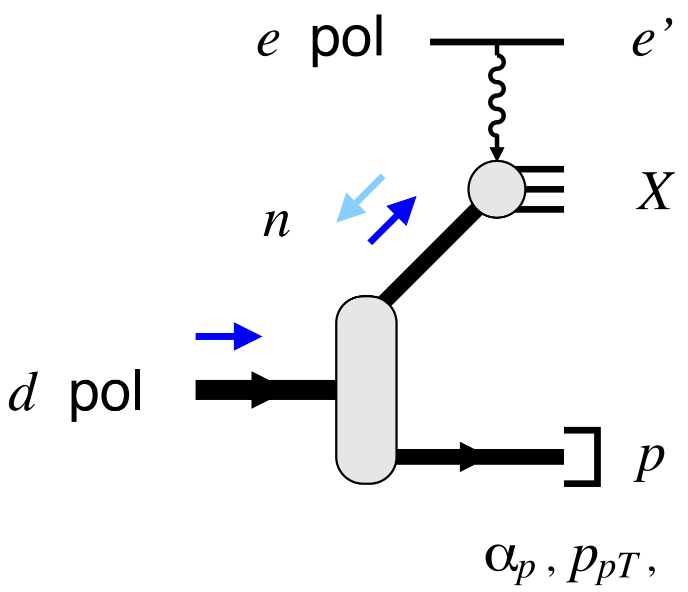
Applications: Free neutron structure

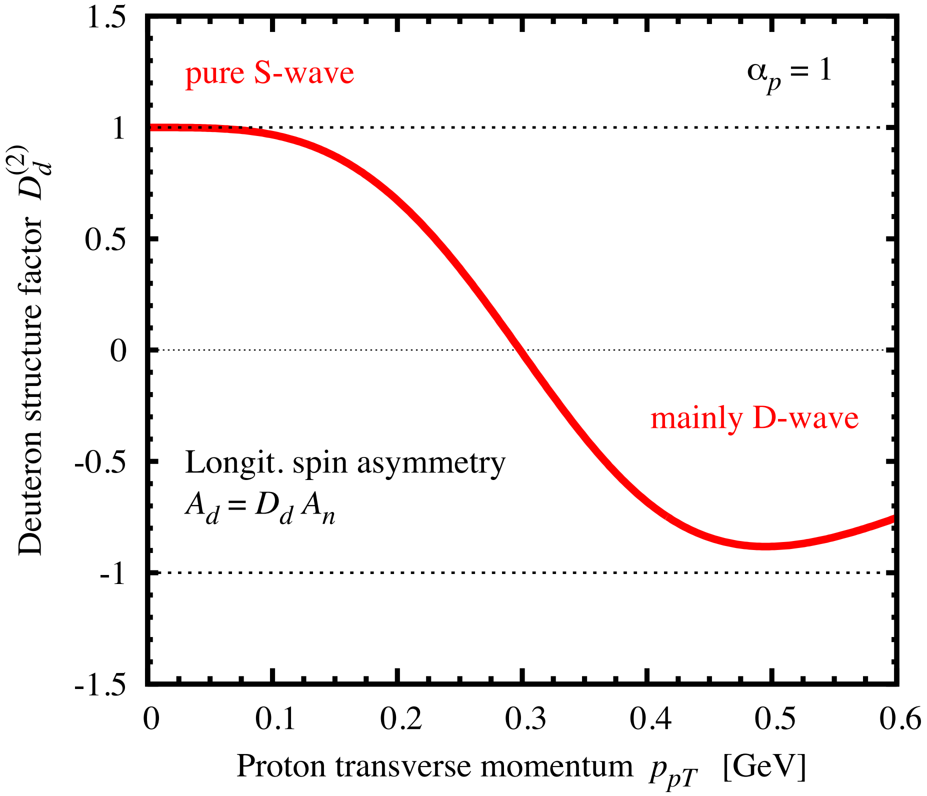


Jentsch, Tu, CW, PRC 104, 065205 (2021)

Validation of pole extrapolation results by comparison with input model

Applications: Polarized neutron structure





Cosyn, Weiss PLB799 (2019) 135035; PRC102 (2020) 065204

Neutron polarization in polarized deuteron

S + D wave, depolarization

Depends on momentum of pn configuration

Control neutron polarization with tagging

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

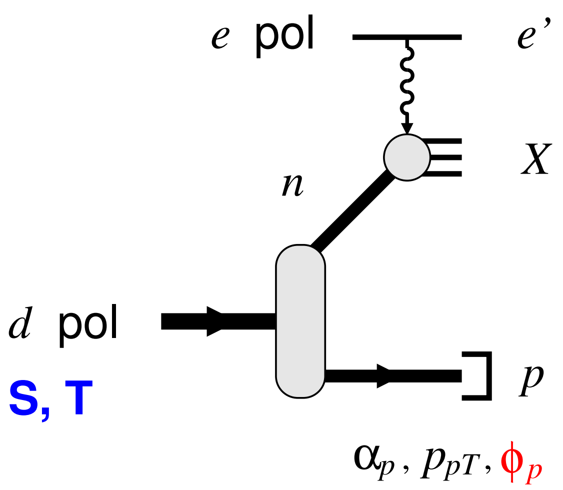
D wave dominates at $\mathbf{p}_{pT} \sim$ 400 MeV:
Neutron polarized opposite to deuteron spin!

Effects require proper light-front spin structure:
Light-front helicity states, Melosh rotations
[Frankfurt, Strikman 1983]

EIC prospects

Physics simulations: 2014-15 JLab LDRD

Applications: Polarized deuteron observables



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

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

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

Cosyn, Weiss, PRC102 (2020) 065204 + in preparation (2023)

Vector and tensor polarization

Spin-1 density matrix $\rho_{\lambda'\lambda}(\mathrm{S},\mathrm{T})$

3 vector, 5 tensor parameters

Spin observables

U + S + T cross section

ϕ_p-dependent structures

U + S cross section same as for spin-1/2
Bacchetta et al 2007

T cross section has 23 new structures, some with ϕ_p-dep unique to T polarization

Time-reversal odd structures: Zero in impulse approximation, serve as tests of FSI

Applications: More deuteron studies with EIC

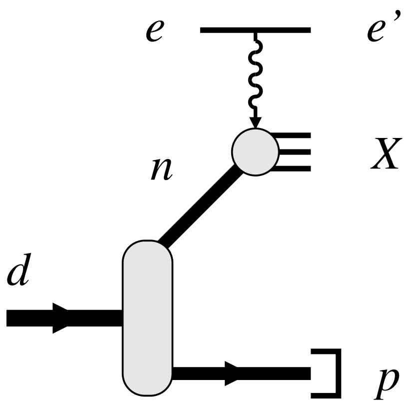
Tagged tensor-polarized DIS

Use spectator momentum to fix D/S ratio and maximize tensor polarization

Achieve tensor-polarized asymmetry $A_{zz} = \mathscr{O}(1)$ as opposed to $\ll 1$ without tagging

Cosyn, Weiss, in progress

Tagged EMC effect in deuteron $x > 0.3$



Use spectator momentum to fix momentum/size of pn configuration

Explore configuration dependence of EMC effect → Talk Accardi

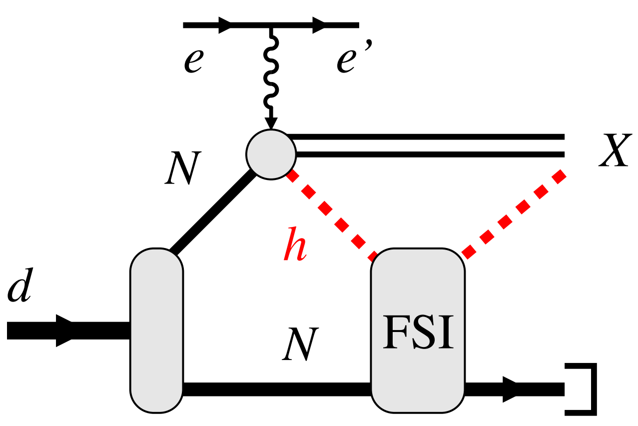
EIC simulations: Jentsch, Tu, Weiss, in progress

[Tagged diffractive DIS at $x \ll 0.1$

Configuration dependence of nuclear shadowing

Guzey, Strikman, Weiss, in progress

Final-state interactions: Basics



Part of final state of high-energy process interacts with spectator

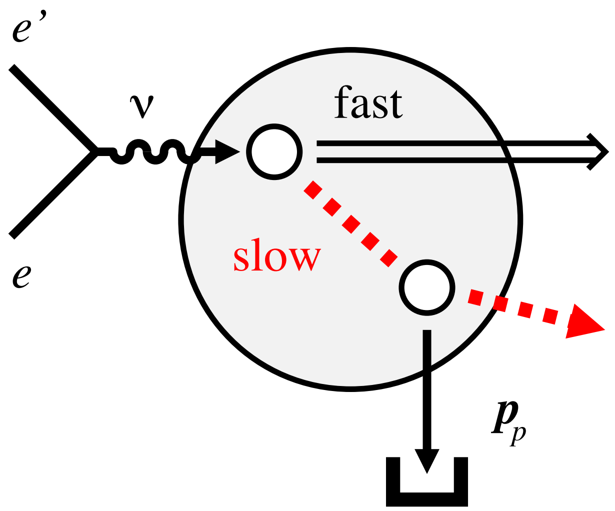
Changes spectator momentum distribution,
no effect on total cross section (closure)

What final states are produced? How do they interact?
Depends on specifics of high-energy process

Kinematic regimes and mechanisms

DIS, $x \gtrsim 0.1$	$h =$ target fragmentation hadrons on-shell rescattering	Ciofi degli Atti, Kaptari, Kopeliovich 2004+ Strikman, Weiss 2018
DIS, $x \ll 0.1$	$h =$ diffractive nucleons QM rescattering, interplay of coherent and incoherent channels	Guzey, Strikman, Weiss, in progress
Finite W, Q^2 (JLab 6/12 GeV)	$X = \sum N^*$ resonances challenge to implement coherence, color transparency	Cosyn, Sargsian, Melnitchouk 2011/14 Cosyn, Sargsian 2017

Final-state interactions: DIS at x >~ 0.1



[Deuteron rest frame view]

Space-time picture in deuteron rest frame

Strikman, Weiss PRC97 (2018) 035209

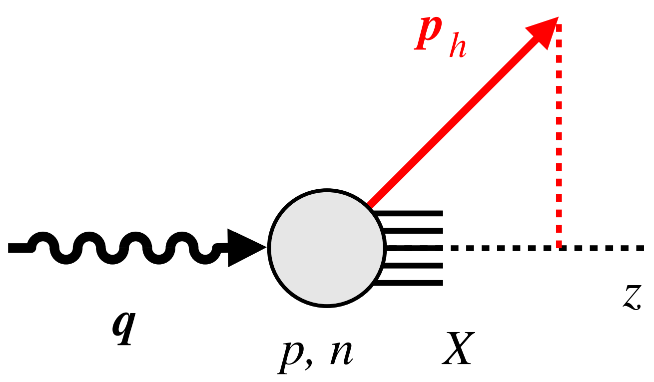
$\nu \gg$ hadronic scale: Large phase space for hadron production

"Fast" hadrons $E_h = \mathcal{O}(\nu)$ — current fragmentation region:
Formed outside nucleus, interaction with spectator suppressed

"Slow" hadrons $E_h = \mathcal{O}(1\text{ GeV}) \ll \nu$ — target fragmentation region:
Formed inside nucleus, interact with hadronic cross sections
Source of FSI in tagged DIS!

Picture respects QCD factorization of target fragmentation:
FSI only modifies soft breakup of target, does not cause long-range rapidity correlations

Final-state interactions: DIS at x >~ 0.1

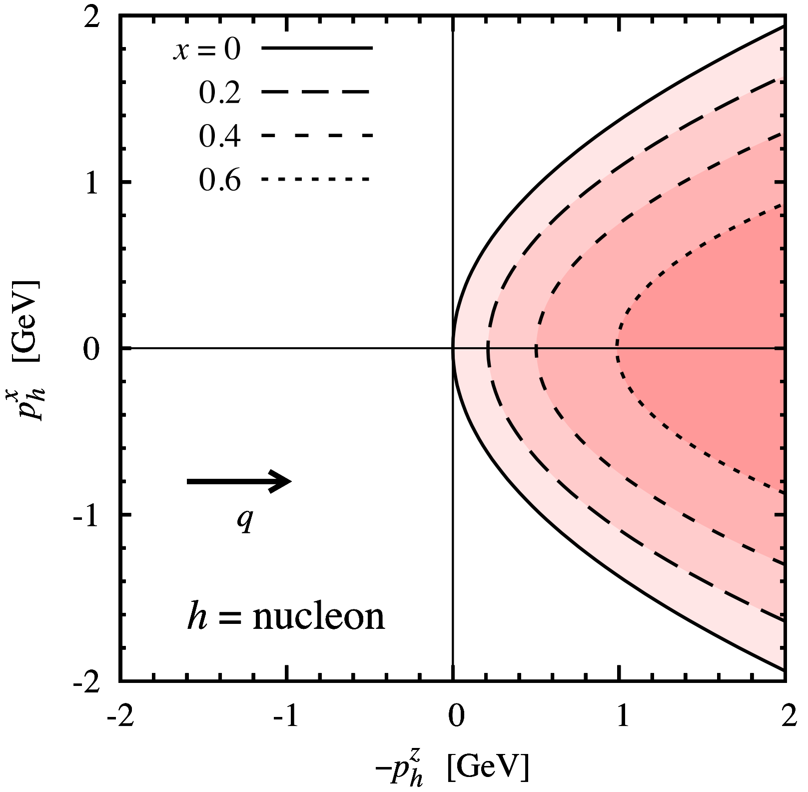


Studied distributions of slow hadrons in DIS on nucleon — target fragmentation

Described by light-cone variables
Constrained by light-cone momentum conservation

Used experimental distributions: HERA, EMC, neutrino DIS

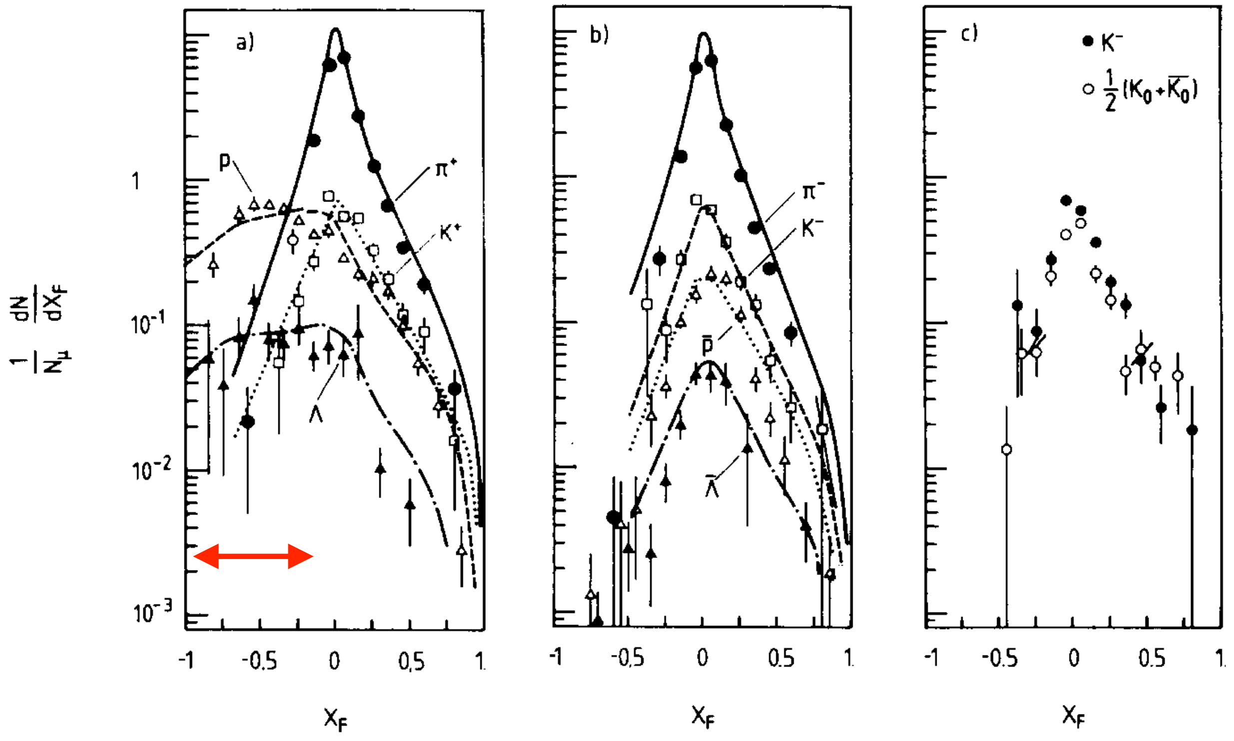
Need better data on target fragmentation: JLab12, EIC!



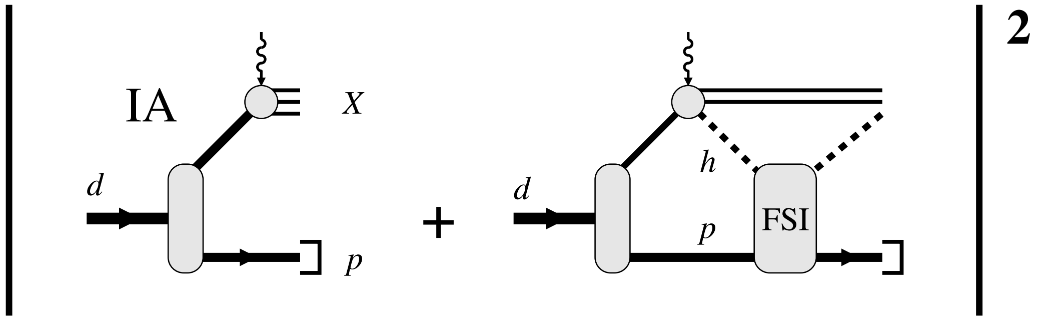
Momentum distribution of slow hadrons in nucleon rest frame: Cone in virtual photon direction

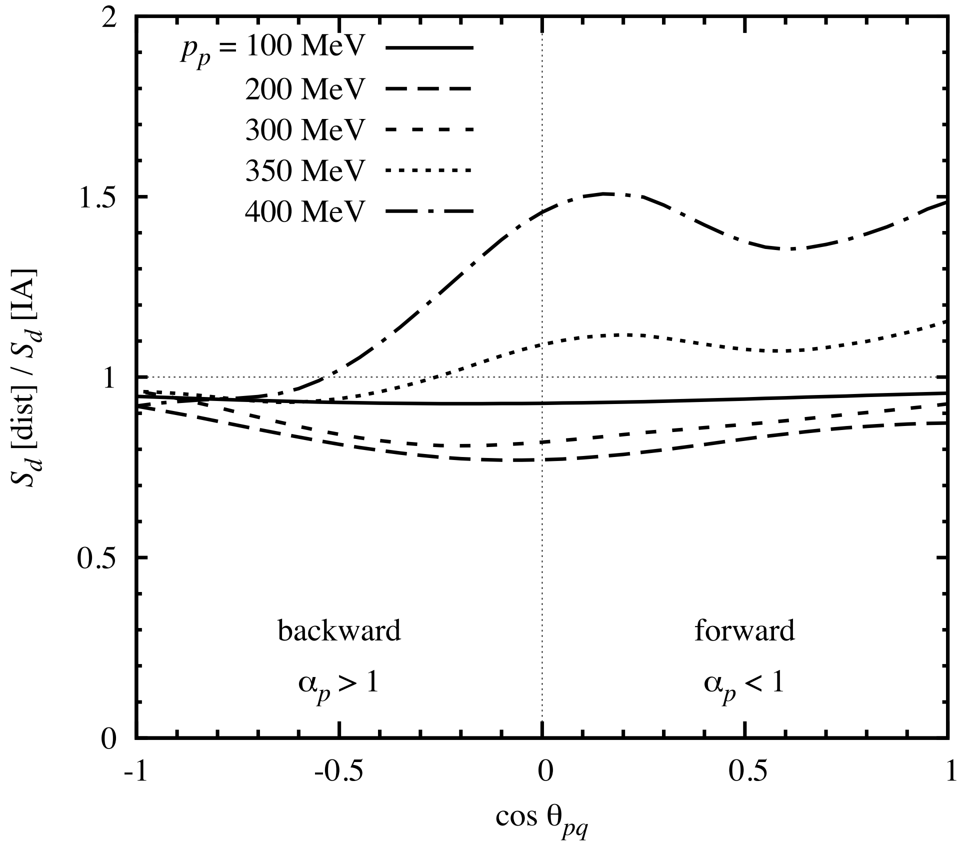
Strikman, Weiss PRC97 (2018) 035209

Hadron xF distributions EMC 1986



Final-state interactions: DIS at x >~ 0.1





FSI angular dependence in deuteron rest frame

Strikman, Weiss PRC97 (2018) 035209

FSI calculation

Evaluated scattering of slow hadrons from spectator

QM description: IA + FSI amplitudes, interference

FSI amplitude has imaginary and real part:
Absorption and refraction

Momentum and angular dependence

$p_p \lesssim$ 300 MeV: IA x FSI interference, absorptive,
weak angular dependence

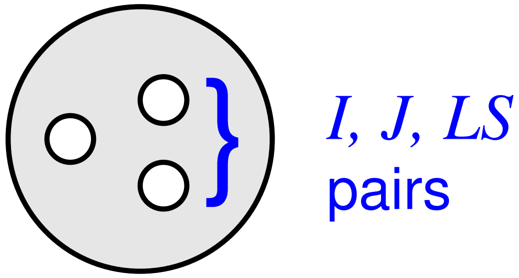
$p_p \gtrsim$ 300 MeV: $|\mathrm{FSI}|^2$, refractive,
strong angular dependence

Results used in EIC simulations,
analysis of JLab12 BAND experiment

Future: A > 2 nuclei

Will be available at EIC, esp. 3He(pol)

Contain NN pairs with various I, J, LS quantum numbers:
Study nuclear interaction effects in different configurations

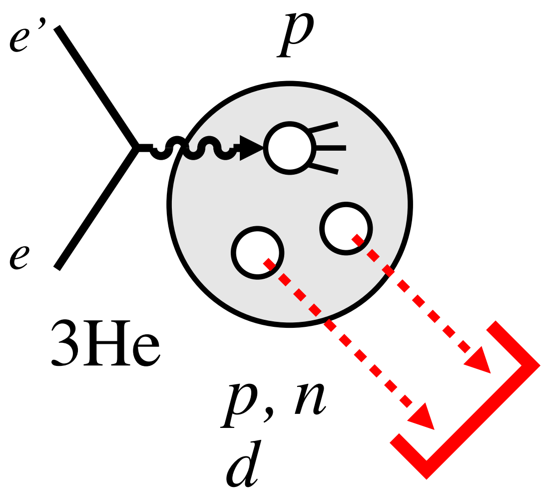


Light-front structure more complex:
Angular momentum coupling, LF ↔ nonrelativistic correspondence
Lev 1990s; Salme et al. 2000s

Nuclear breakup processes A > 2

2-body: e + 3He → e’ + X + d

3-body: e + 3He → e’ + X + pn, pp



Breakup more complex: Nuclear interactions in final state, distorted waves, wave function overlap factors

Needs extensive nuclear structure input!

3He: Ciofi, Kaptari, Scopetta e al 2000+

Summary

Spectator tagging with deuteron permits control of nuclear configuration in high-energy process and differential analysis of nuclear effects — new opportunities, new challenges for theory

Spectator tagging can access free neutron through pole extrapolation; control effective neutron polarization; maximize tensor polarization; control strength of interactions in EMC effect

Spectator tagging programs at JLab12/22 and EIC complementary:

JLab12/22: High luminosity for $x \gtrsim 0.5$, spectator momenta $p \sim$ 300-500 MeV, rare processes

EIC: Full DIS kinematics, $x < 0.1$, far-forward detector coverage and resolution, deuteron polarization?

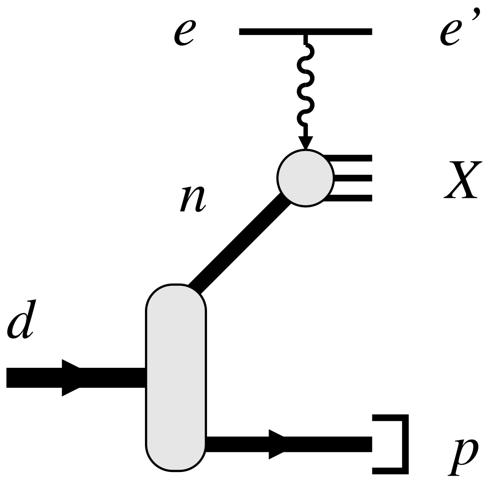
FSI essential for most applications of tagging, requires investment in theory, dedicated theory/modeling in different kinematic regions

Extension of breakup measurements to A > 2 require substantial nuclear structure input: Spectral functions, decay amplitudes for specific final states, final-state interactions

Rising program — many opportunities, long-term prospects

Supplemental material

Applications: Bound nucleon structure (EMC effect)



Basic assumption: Initial-state modification proportional to 4-dim virtuality of active nucleon = function of spectator momentum in tagged DIS [Frankfurt, Strikman 1988]

→ Talk Accardi

$$p_n^2 - m^2 \;=\; (p_d - p_p)^2 - m^2 \;=\; \text{function}(\alpha_p, p_{pT}) \;\equiv\; V(\alpha_p, p_{pT})$$

$$F_{2n}(x, Q^2; \alpha_p, p_{pT})[\text{bound}] \;=\; \left[1 + \frac{V(\alpha_p, p_{pT})}{\langle V \rangle} f(x) \right] F_{2n}(x, Q^2)[\text{free}]$$

[same for $p \leftrightarrow n$]

Model parameters fixed by inclusive EMC effect data $(0.3 < x < 0.7)$ and "average virtuality" $\langle V \rangle_A$ from nuclear structure calculations
[Ciofi degli Atti, Frankfurt, Kaptari, Strikman 2007]

Minimal model. Includes possibility that EMC effect generated by SRCs, but not limited to it. Alternative to GCF

Challenge: Separate initial-state modifications from final-state interactions in tagged DIS measurements

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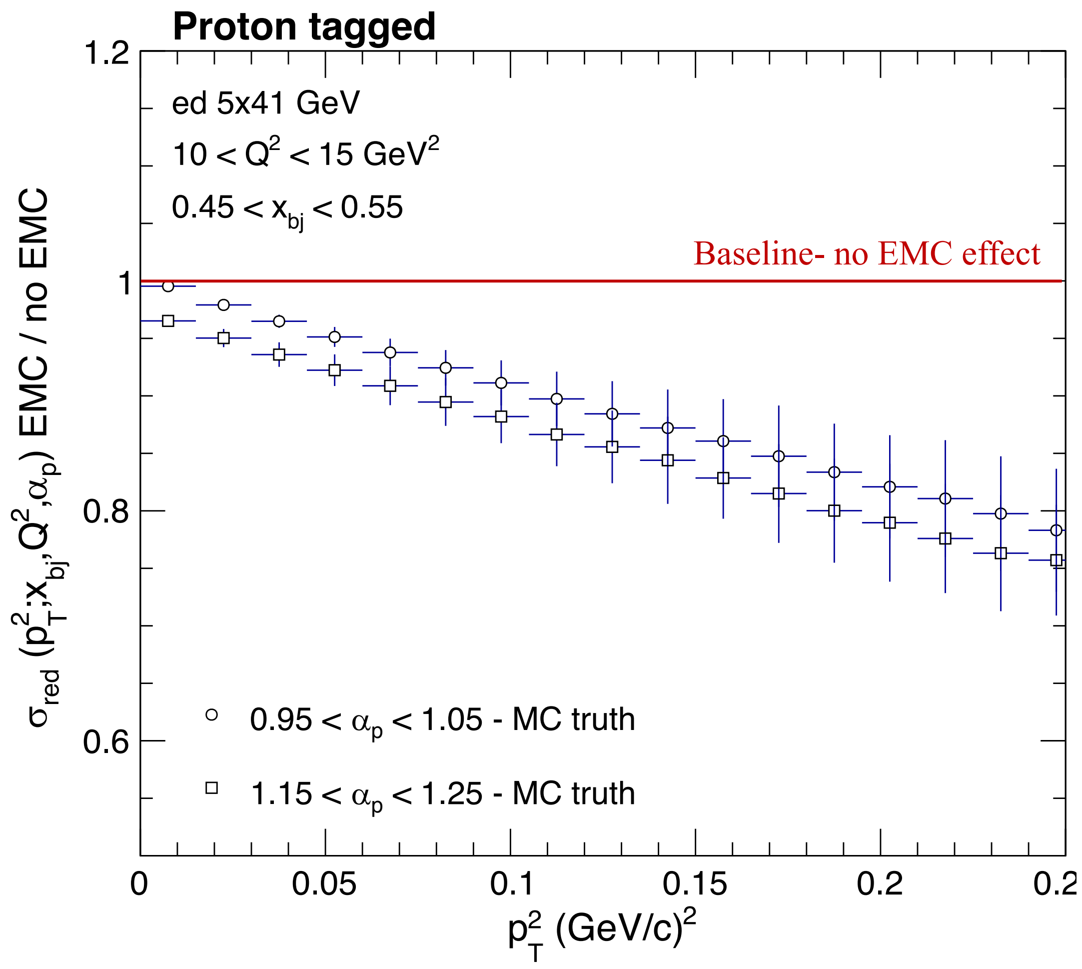

BeAGLE simulation, 10^9 events ~ 25 fb^{-1}
ed 5x41 GeV

Jentsch, Strikman, Tu, CW, DIS2022

Comparison of reduced cross section measurement with/without EMC effect

Baseline for expected modification

Statistical errors visible: Large x, exceptional configurations in deuteron

Here: Physics model does not include FSI.
Need strategy that accounts for FSI

Full simulation results: In progress