Deuteron physics with spectator tagging in the early phase of EIC

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Jefferson Lab

Question: What physics could be pursued with spectator tagging in deuteron run in early phase of EIC?

Physics measurements considered here

Shadowing dynamics in tagged diffractive DIS	$x \sim 10^{-3} - 10^{-2}$	$L_{\text{int}} \sim$ few $\times\, 1$ fb^{-1}
Free neutron and proton structure from tagging with on-shell extrapolation	$x \sim 0.01 - 0.3$	$L_{\text{int}} \sim$ few $\times\, 1$ fb^{-1}
Bound neutron and proton structure and tagged EMC effect	$x \sim 0.3 - 0.6$	$L_{\text{int}} \sim$ few $\times\, 10$ fb^{-1}

Explanations and comments

Suggestions based on theoretical research and some physics simulations

Definite physics interest and impact

Estimates luminosity requirements are based on simulations or extrapolation from similar measurements

Intended to stimulate discussion and detector simulations

Early science program at EIC

Running conditions in first 5-7 years will be set by installation & commissioning schedule, esp. for electron polarization and hadron spin rotation

Staged science program, using early running conditions for maximum physics output

2024 EIC User Group Meeting: E. Aschenauer, R. Ent

Deuteron run planned for Year 2

10 GeV e x 130 GeV/u D $\sqrt{s} = 72$ GeV

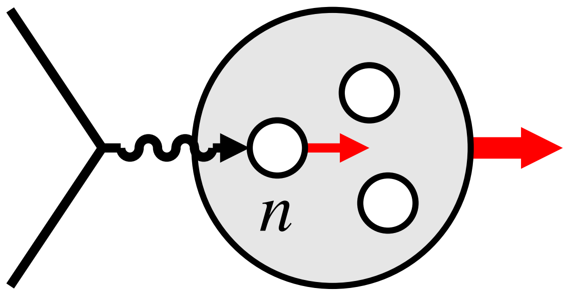
$L_{\text{int}} = 11\ \text{fb}^{-1}$ (per nucleon) estimated integrated luminosity per year

Far-forward detectors available for spectator tagging

3He run planned for Year 6

Includes polarization. Can be used for unpolarized tagged measurements complementary to deuteron: Light-ion physics program

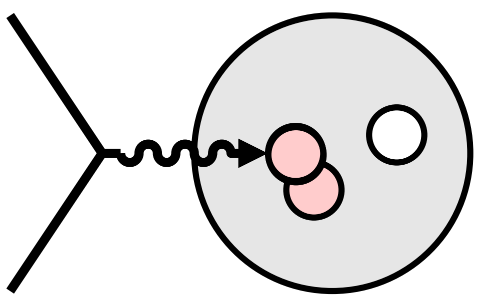
Light ions: Physics objectives



Neutron structure

Flavor decomposition of quark distributions and spin

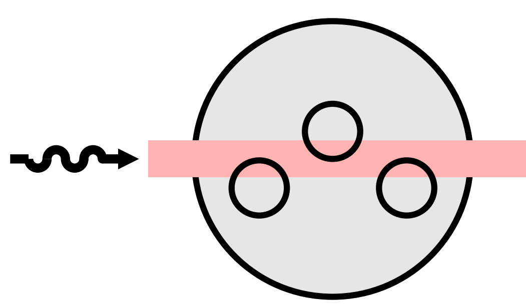
Singlet-nonsinglet separation in QCD evolution (ΔG, GPDs)



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

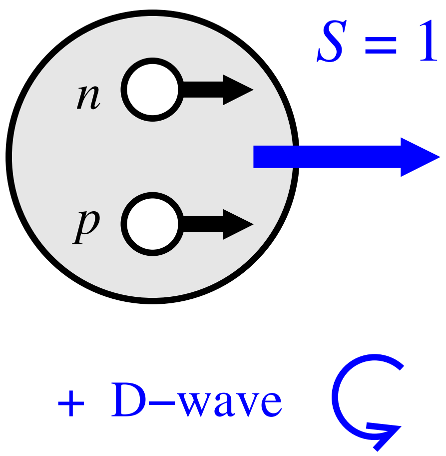
Nuclear shadowing $x \lesssim 0.01$

Buildup of coherence, interaction with 2, 3, 4… nucleons?
$\leftrightarrow$ 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 ions: Deuteron and spectator tagging

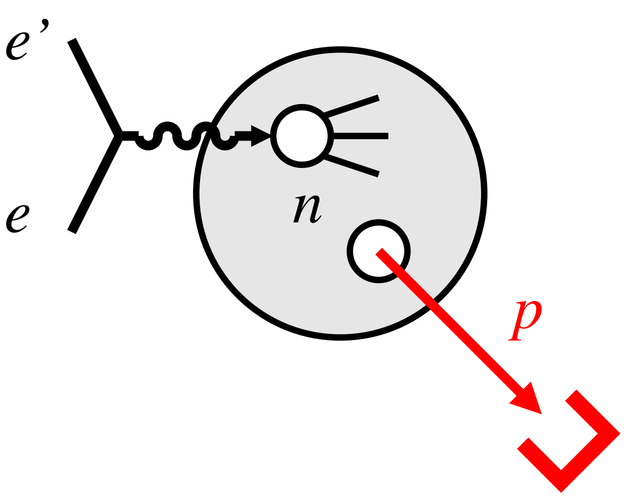


Deuteron as simplest system

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

NN interactions in known partial waves: Mostly S, some D-wave

Clean NN system: 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

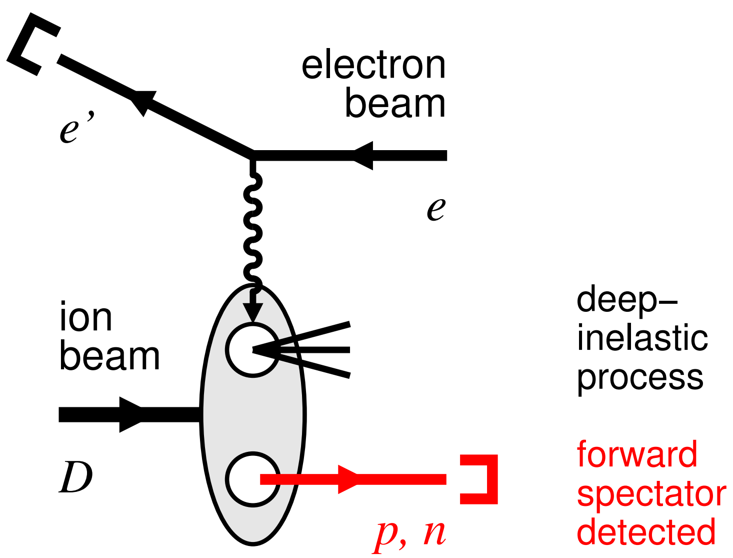
Identifies active nucleon

Controls configuration through measured spectator 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

Light ions: Spectator tagging with EIC



[Collider frame view]

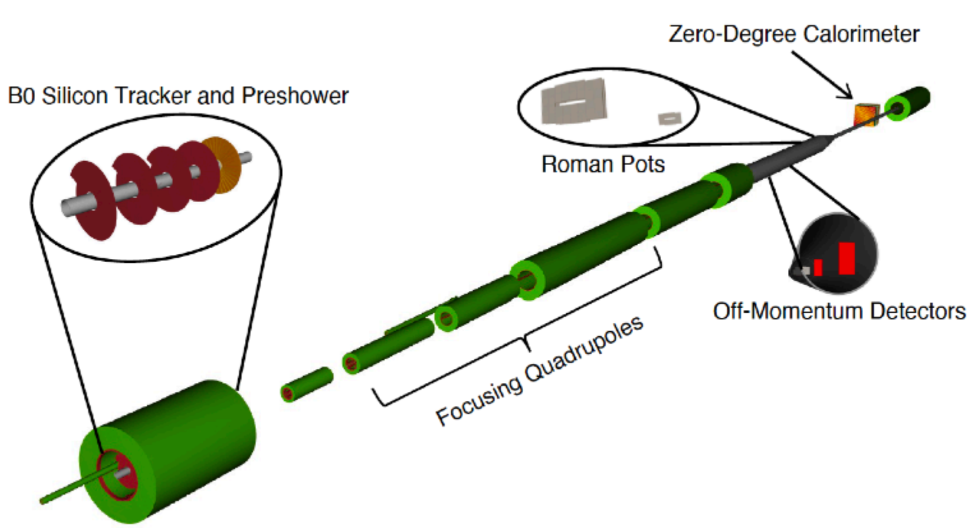
Spectator moves forward in ion beam direction

Spectator longitudinal momentum in detector controlled by light-cone fraction in deuteron rest frame:

$$p_{\parallel p}[\text{det}] \approx \frac{P_D}{2}\left(1 + \frac{p_{p\parallel}[\text{rest}]}{m}\right)$$

large offset, can be detected

Far-forward detection



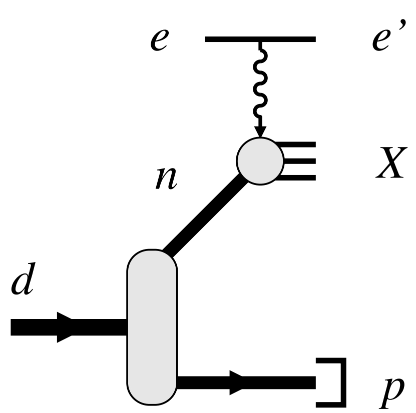
Proton: Rigidity(proton) $\neq$ Rigidity(deuteron), different subsystems used depending on $p_{\parallel p}, p_{Tp}$

Neutron: Zero-Degree Calorimeter

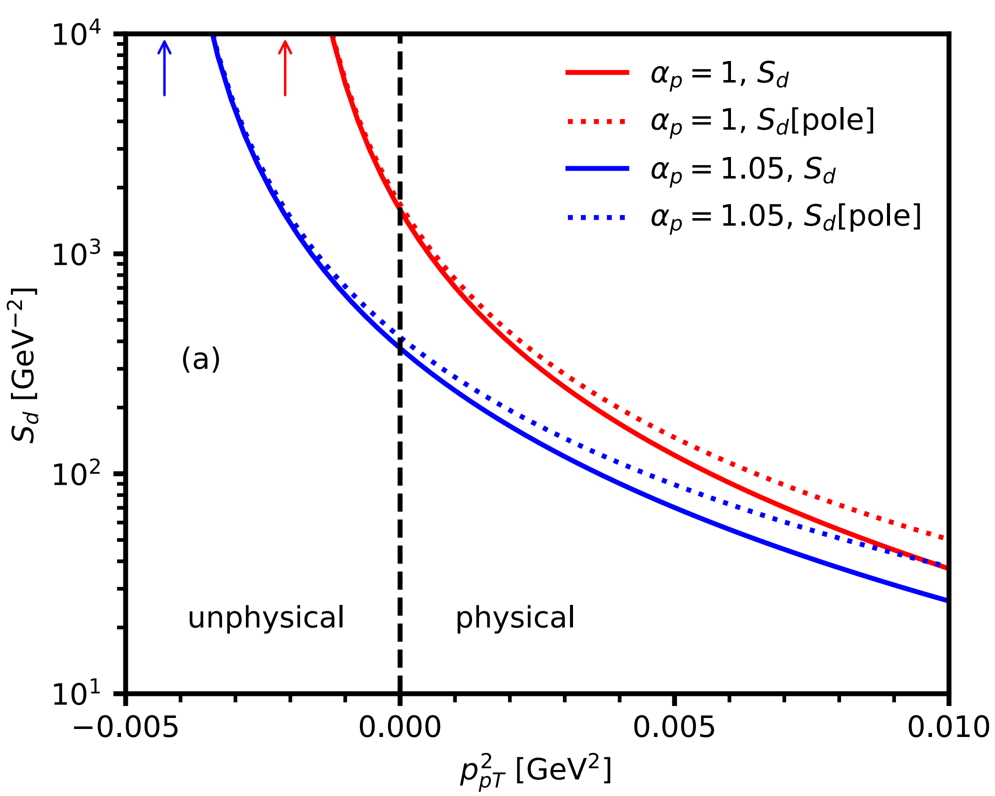
Advantage over fixed target: No target material, can detect spectators with rest frame momenta down to ~zero.

Physics-Detector simulations: Jentsch, Tu, Weiss, PRC 104, 065205 (2021)
EIC Yellow Report 2021 [INSPIRE]

Free neutron and proton structure



$$\sigma_{d,\text{tag}}(\alpha_p, p_{pT;...}) = \frac{C\,\sigma_n[\text{free}]}{(p_{pT}^2 + a_T^2)^2} + \text{(less sing.)}$$



Physics

Physical spectator momenta: NN configs in deuteron have finite size, nucleons interact

Analytic continuation to unphysical momenta can reach configs with “infinite” size, nucleons free!
Fundamental property: Bethe-Peierls pole in momentum, asymptotic S-wave

Tagged cross section: Pole at $p_{pT}^2 = -a_T^2 < 0$

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

Interest: Free neutron structure. Baseline for nuclear modifications. Free proton structure from neutron tagging

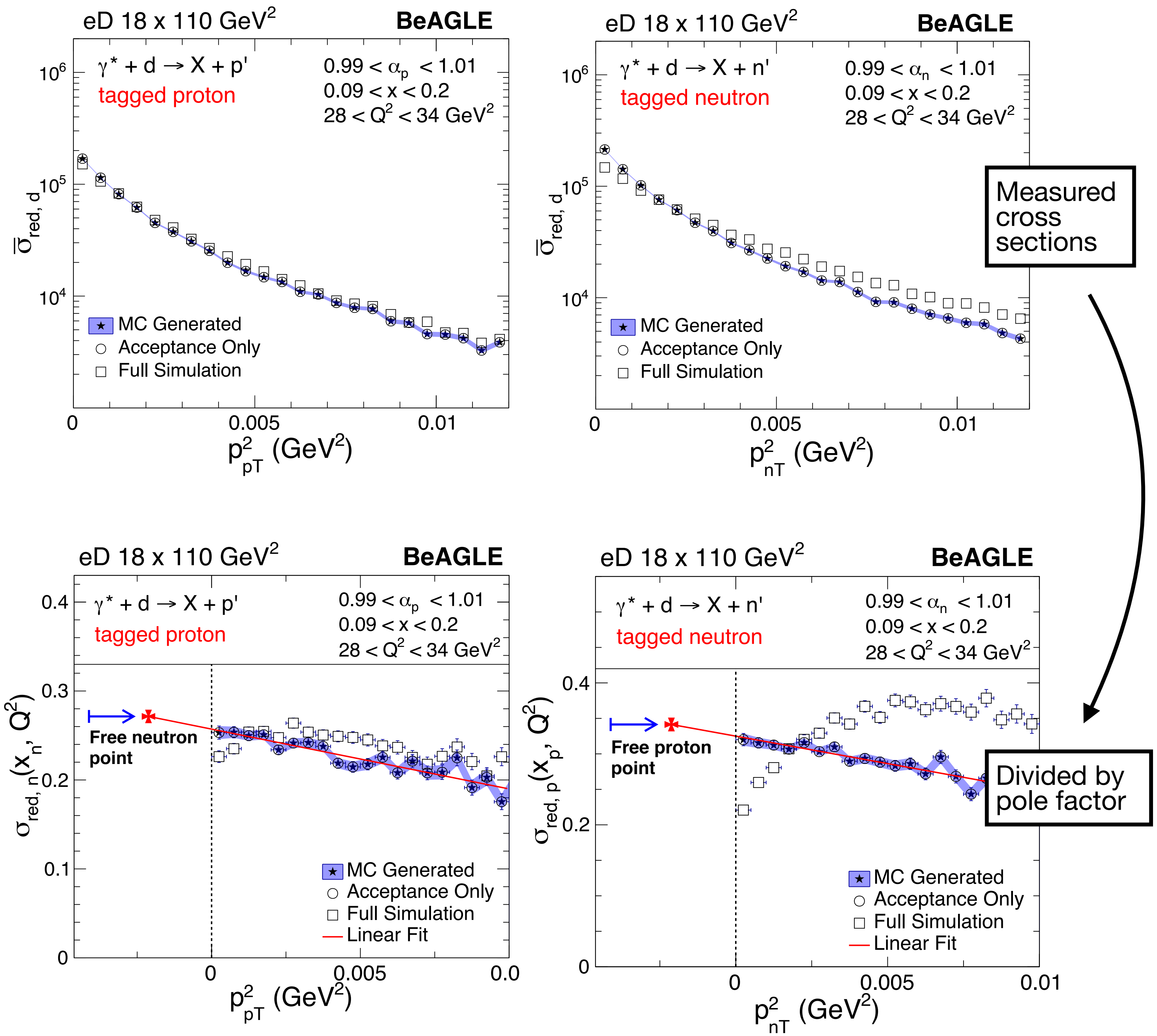
Measurement

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

Divide data by pole term of cross section

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

Free neutron and proton structure



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

EIC Yellow Report 2021

EIC simulations

p and n tagging, pole extrapolation, uncertainty analysis, validation

Tagged cross section measured with excellent coverage

Significant uncertainties in evaluation of pole factor due to p_T resolution

Pole extrapolation realistic for proton spectator, exploratory for neutron sp.

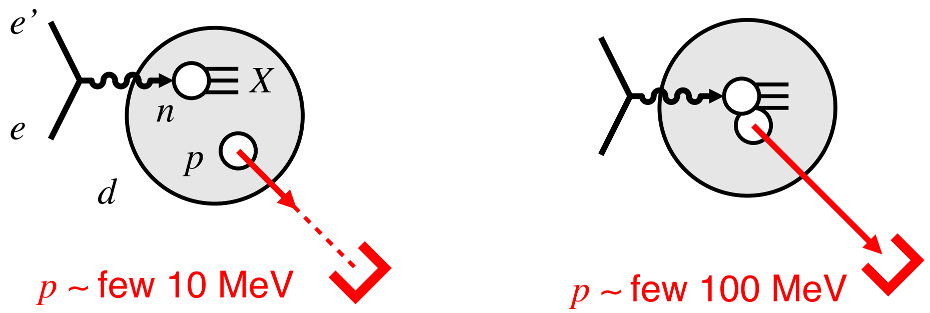
Assessment

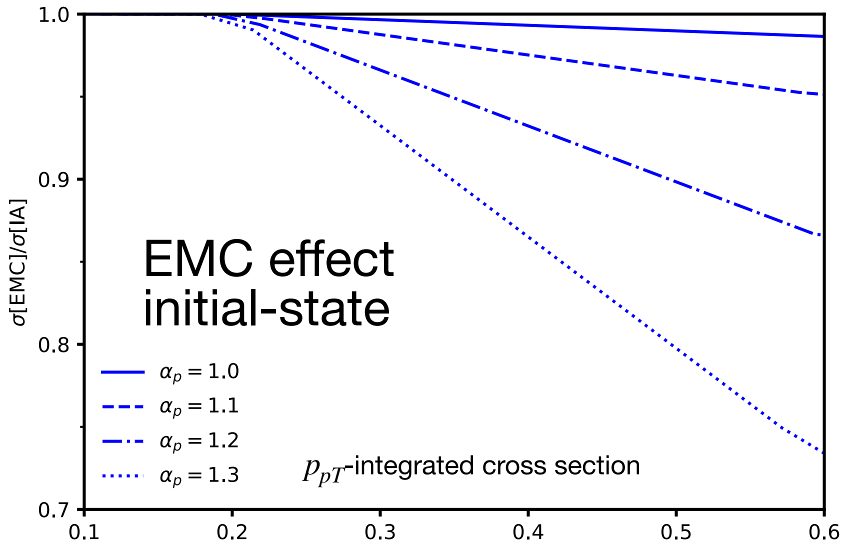
Systematics-limited, main uncertainty from p_T resolution

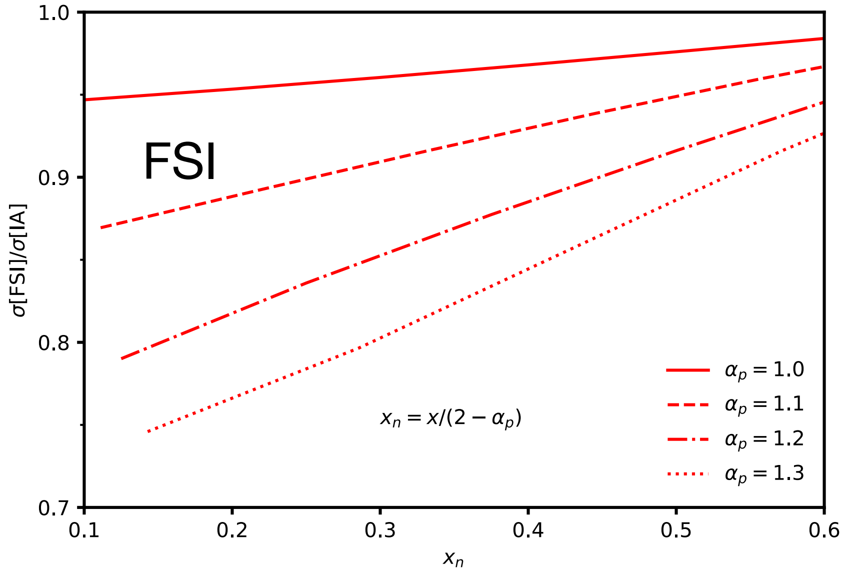
Possible with $L_{\text{int}} = \text{few} \times 1\ \text{fb}^{-1}$: Mainstream DIS kinematics, non-exceptional spectator momenta

Validate method for applications at higher luminosity: SIDIS, GPDs

Bound nucleon structure and tagged EMC effect







Physics

Suppression of nuclear quark density at $0.3 < x < 0.7$ observed in inclusive DIS

What NN distances/momenta cause modification?
$\leftrightarrow$ QCD origin of NN interactions

Deuteron: Control configurations with tagging!

Measurements

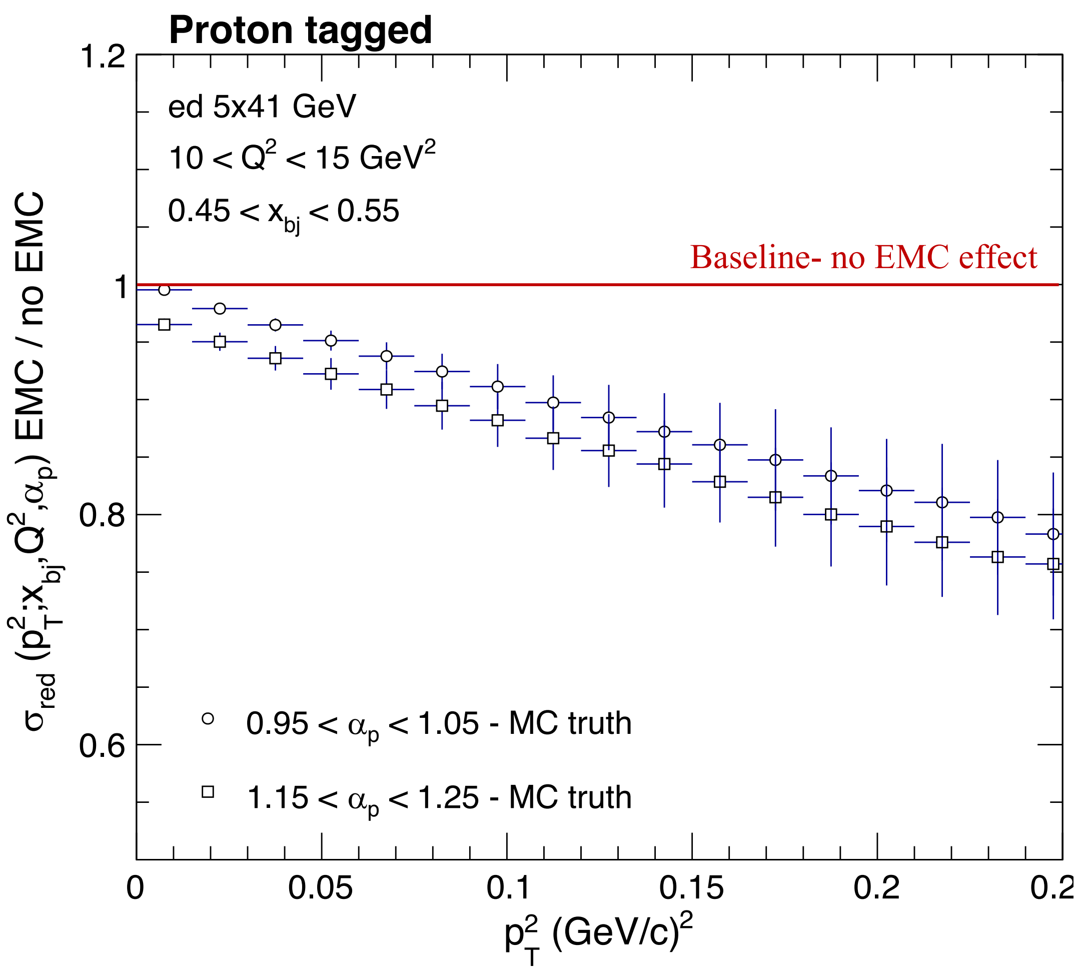
Use proton and neutron tagging with $\alpha_{p,n} > 1$, $p_T \sim$ few 100 MeV

Large EMC effect ~20-30% achievable

Final-state interaction effects are of same order as initial-state EMC effect, need strategy for separation

Strikman, Weiss PRC97 (2018) 035209; theory development in progress

Bound nucleon structure and tagged EMC effect



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

Jentsch, Strikman, Tu, CW, DIS2022

EIC simulations

Comparison of reduced cross section measurement with/without EMC effect

Baseline for expected modification

Statistical errors visible

Assessment

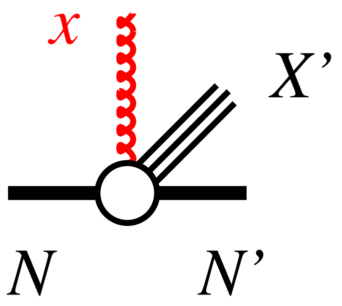
Statistics-limited: Large $x > 0.3$, exceptional configurations in deuteron

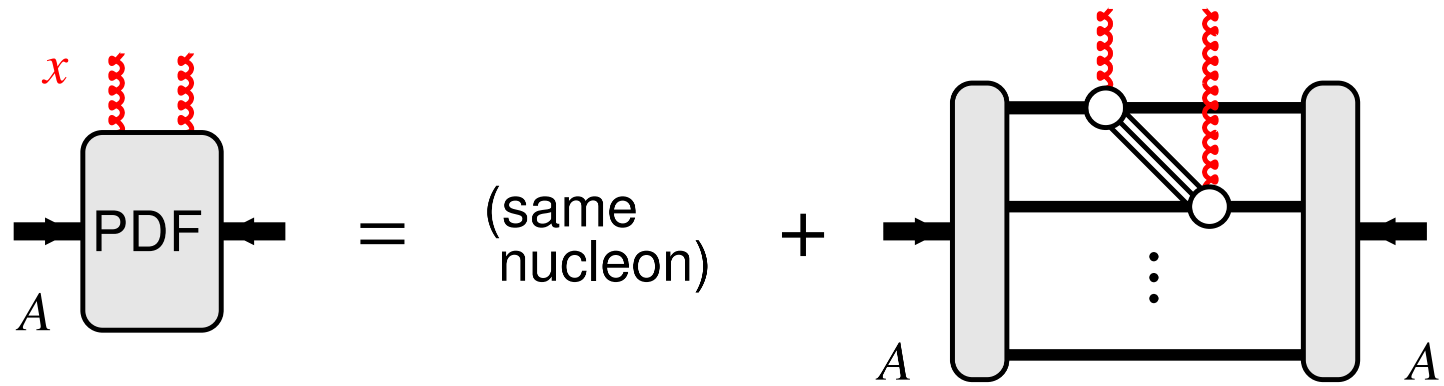
Some impact possible with $L_{\text{int}} \sim 10 - 20\,\text{fb}^{-1}$, should be simulated and optimized

Comment

Tagged DIS at $x \sim 0.2$ can probe antishadowing region.
Rates higher, but physics impact less clear → Discussion

Shadowing: Heavy nuclei



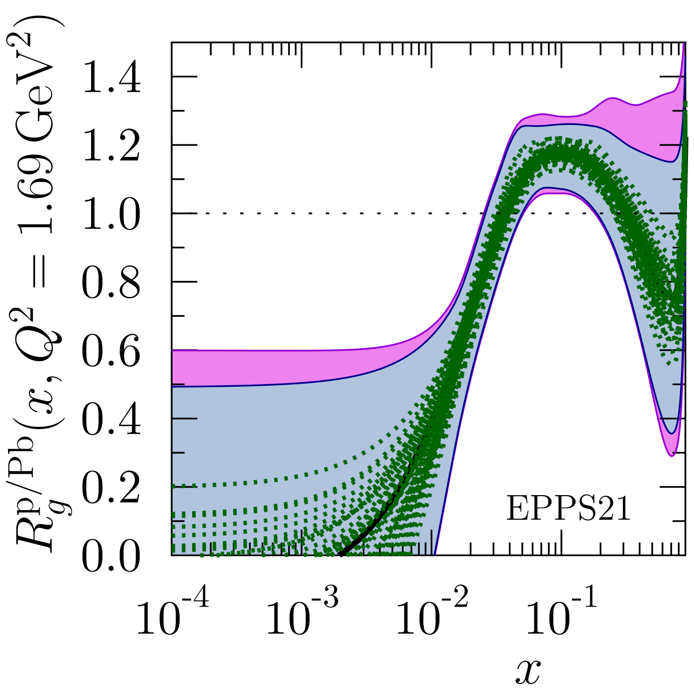


Nucleon: Removal of gluon with $x \ll 0.1$ can leave nucleon intact.
"Diffraction", observed in DIS at HERA

Nucleus: Interference of gluon removal from different nucleons causes correction to sum over nucleon gluon densities: "Shadowing"

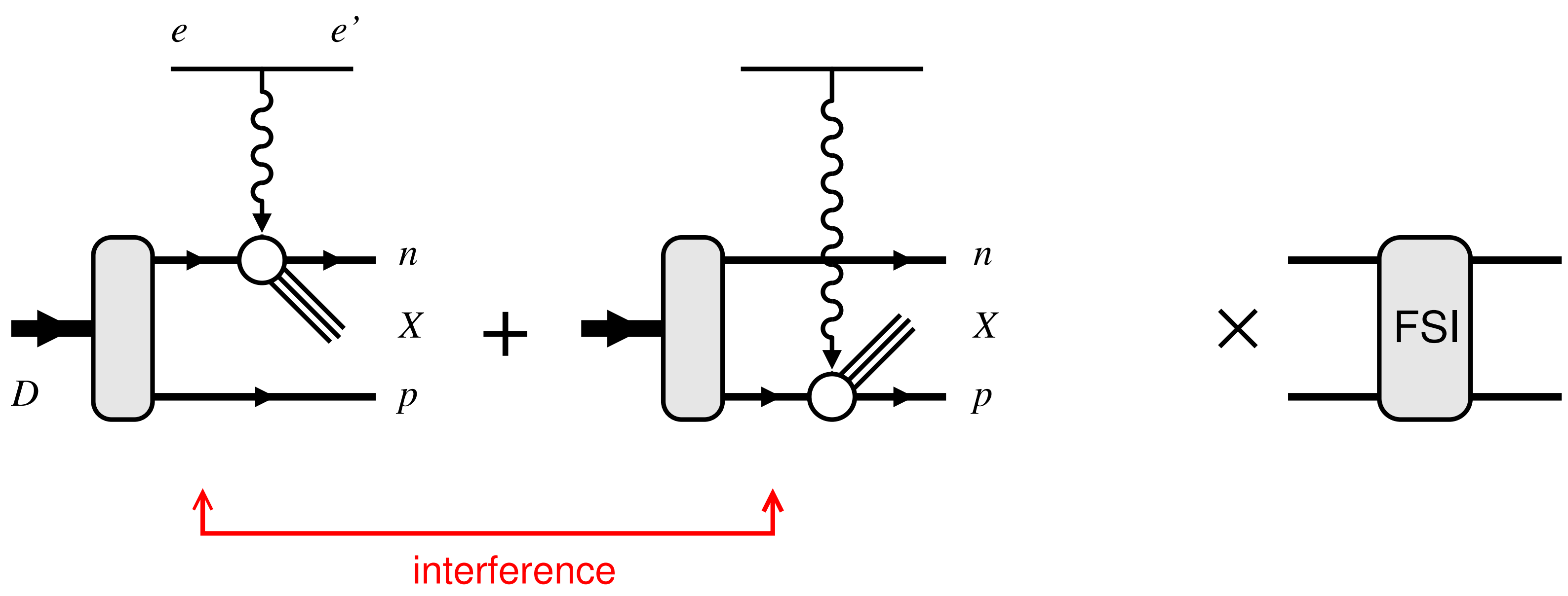
Reduction of nuclear gluon density at $x \lesssim 10^{-2}$.
Leading-twist effect. Observed in UPC at LHC

Governs approach to saturation $Q_s \sim A^{1/3}$.
Need to explore mechanism



Eskola, Paakkinen, Paukkunen, Salgado 2021

Shadowing: Deuteron and tagging



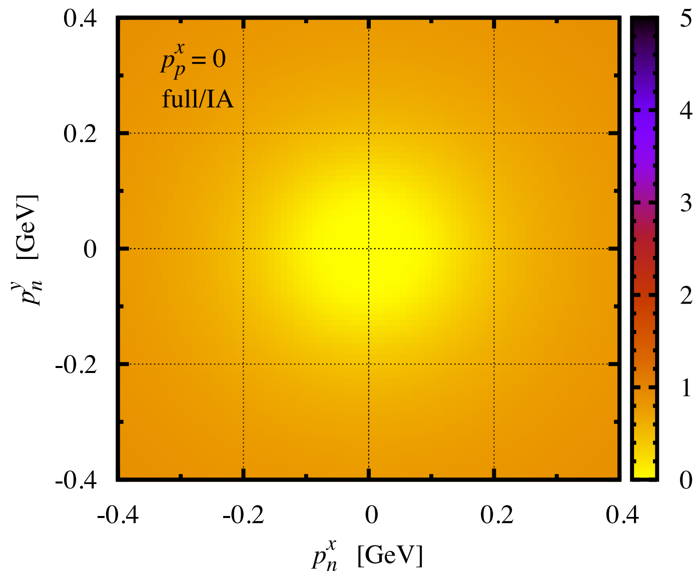
Tagged diffractive DIS $e + D \to e' + X + p + n$

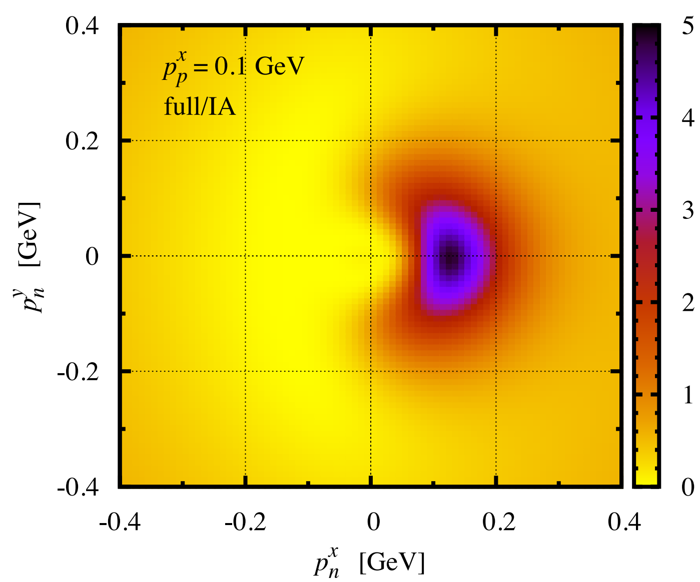
Explore interference mechanism of shadowing:
Configuration dependence, differential analysis

Large shadowing effect $\mathcal{O}(1)$ predicted for favored configurations (p and n aligned along photon direction)

Guzey, Strikman, CW; in preparation

Interplay of shadowing and low-energy FSI in pn system.
Measure both incoherent (pn) and coherent (D) final states





Shadowing: Deuteron and tagging

Assessment

Measurements should be feasible with few $\times\ 1$ fb^{-1}:
Inclusive diffraction $\sim 10 - 15\,\%$ of DIS cross section
Non-exceptional deuteron configurations

High-energy EIC kinematics favorable, $x \sim 10^{-3} - 10^{-2}$

Impact on small-x physics

Summary

Interesting physics measurements with spectator tagging possible under early running conditions

Shadowing dynamics in tagged diffractive DIS	$x \sim 10^{-3} - 10^{-2}$	$L_{\text{int}} \sim$ few $\times$ 1 fb^{-1}	←
Free neutron and proton structure from tagging with on-shell extrapolation	$x \sim 0.01 - 0.3$	$L_{\text{int}} \sim$ few $\times$ 1 fb^{-1}	←
Bound neutron and proton structure and tagged EMC effect	$x \sim 0.3 - 0.6$	$L_{\text{int}} \sim$ few $\times$ 10 fb^{-1}	

Inclusive tagged measurements could be extended to semi-inclusive/exclusive measurements as more luminosity becomes available

Tagged exclusive J/ψ production for gluon shadowing

Tagged free neutron with semi-inclusive π/K for flavor decomposition
Tagged free neutron DVCS or DVMP

[Discussion]