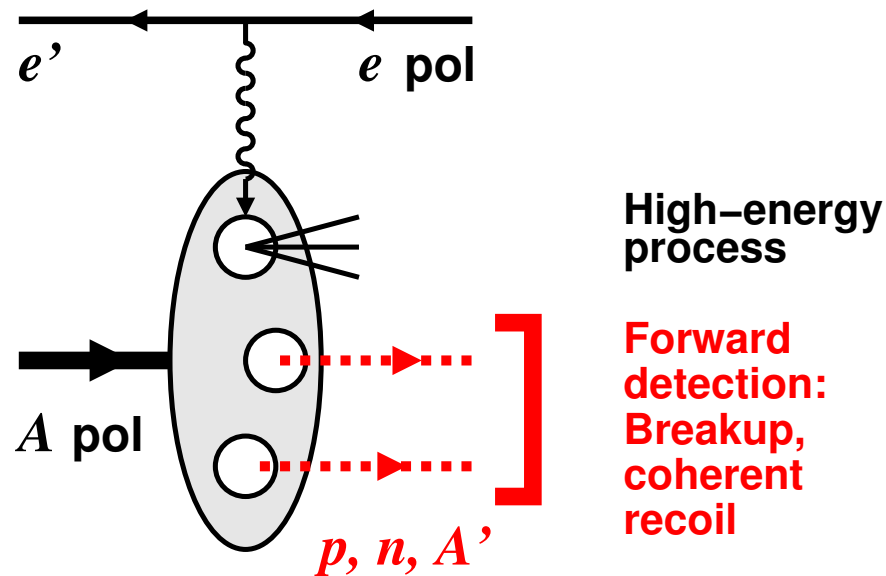# Next-generation light-ion physics with EIC

C. Weiss (JLab), Stony Brook U. Nuclear Theory-Experiment Seminar, 17 Jan 2024

Jefferson Lab

e' e **pol**

High–energy process

Forward detection: Breakup, coherent recoil

A **pol**

p, n, A'

Physics: Control nuclear configuration during high-energy process… new measurements

Theory: Interplay of high-energy process and low-energy nuclear structure… new methods

Detection: Forward detection of charged and neutral fragments… new solutions

With: W. Cosyn, V. Guzey, Ch. Hyde, A. Jentsch, P. Nadel-Turonski, M. Strikman, Zh. Tu, F. Vera…

Light-ion physics with EIC

Energy, luminosity, polarization, detection

Objectives and challenges

Spectator nucleon tagging with deuteron

High-energy process ↔ low-energy structure

Free neutron structure extraction

Polarization vector/tensor

NN interactions, EMC effect

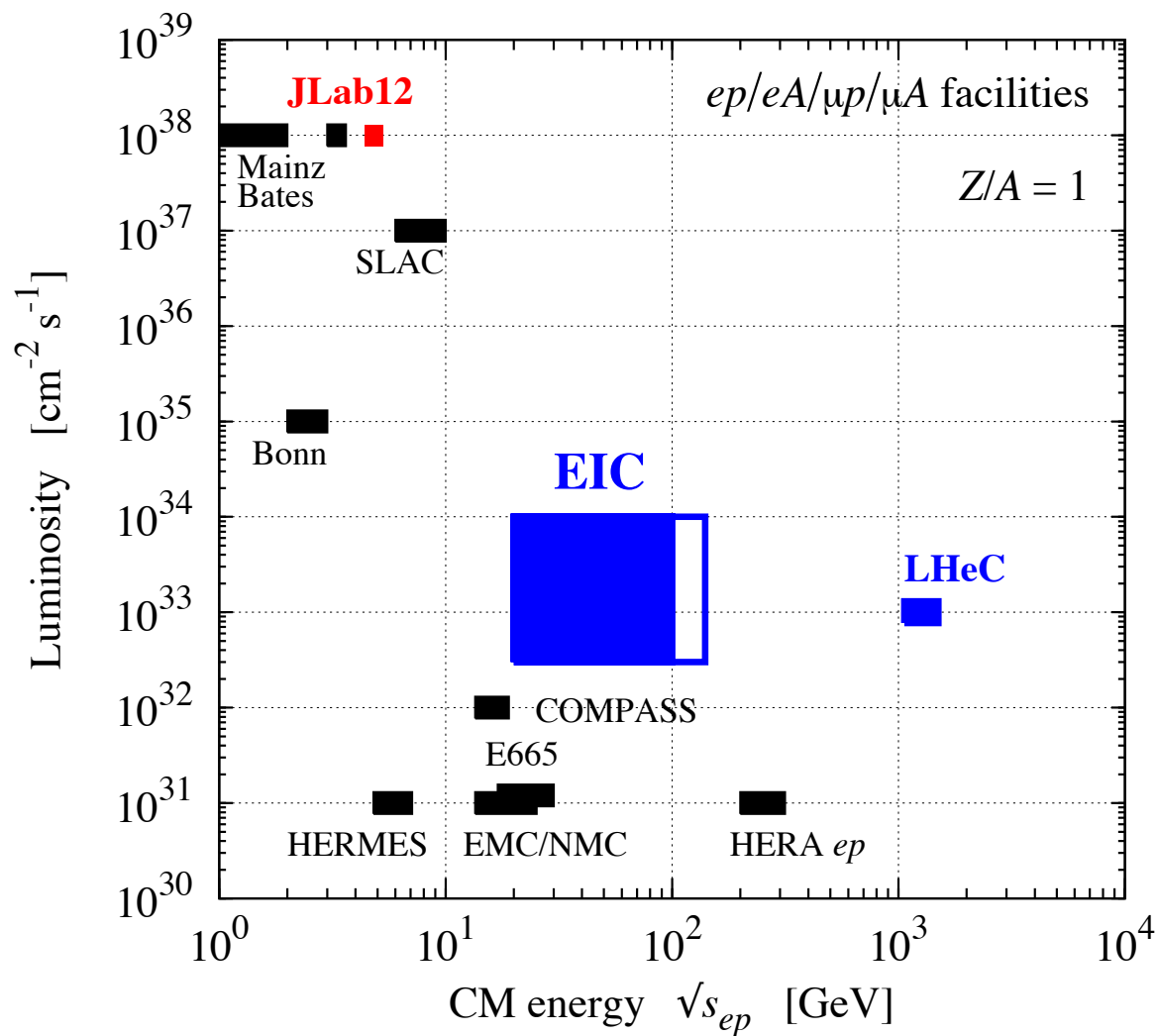Future: A > 2 nuclei, EFT methods, …

Coherent processes with light nuclei

Nuclear GPDs, shadowing dynamics

Future program

CM energy

$$\sqrt{s}_{ep} = 20 - 100 \ (140) \ \text{GeV}$$

Lower by $\sqrt{Z/A}$ for nuclei

High-energy processes: DIS, diffraction

Luminosity

Up to $\sim 10^{34}$ cm^{-2} s^{-1} (per nucleon)

Rare processes, exceptional configurations

Multivariable final states, polarization observables

Polarized ion beams
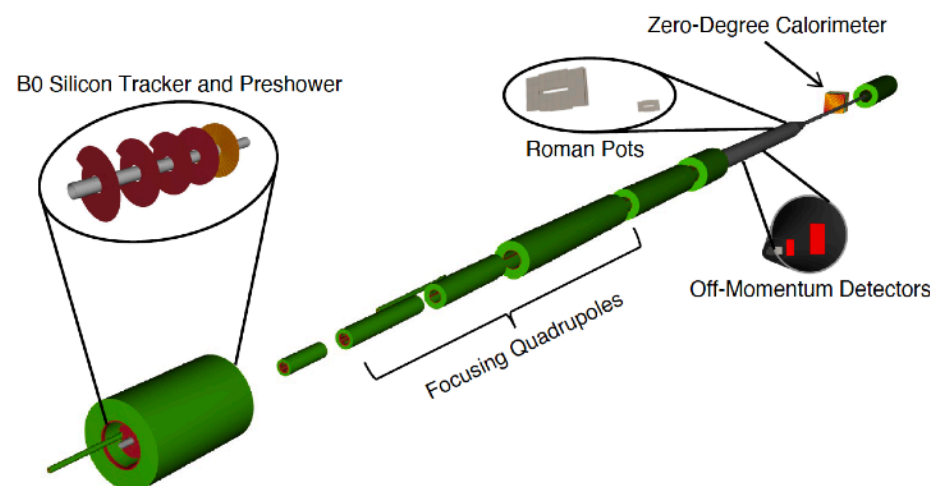
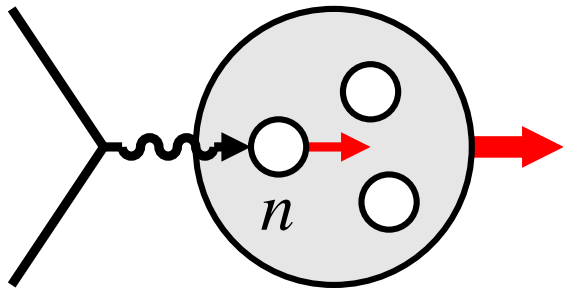Polarized proton and 3He + possibly 7Li, 9Be

Deuteron polarization as facility upgrade

Far-forward detection of p, n, A'

Nuclear breakup, spectator tagging

Exclusive and diffractive processes
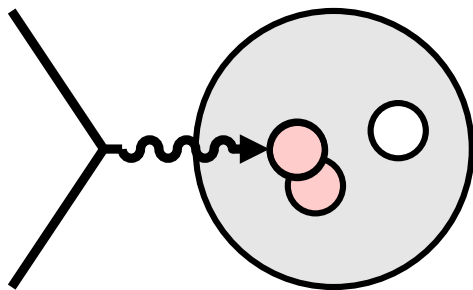
Coherent nuclear processes A→A

Neutron structure

Flavor decomposition of quark distributions and spin

Singlet-nonsinglet separation in QCD evolution for ΔG
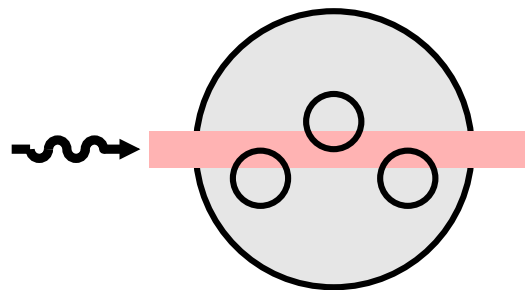
Nuclear interactions

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

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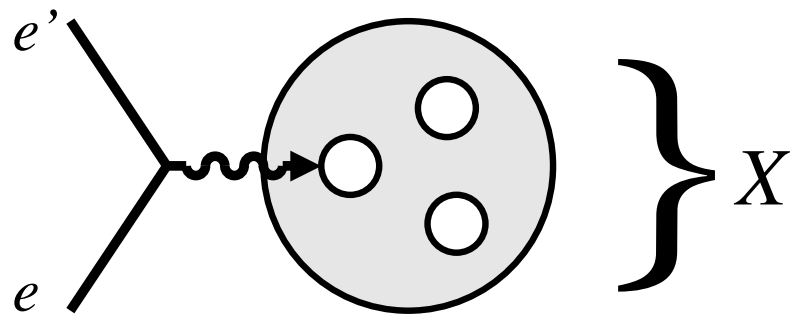Quarks/antiquarks/gluons? Spin, flavor? Dynamical mechanism?

Coherent phenomena

Nuclear shadowing $x \ll 0.1$

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

[Nucleus rest frame view]

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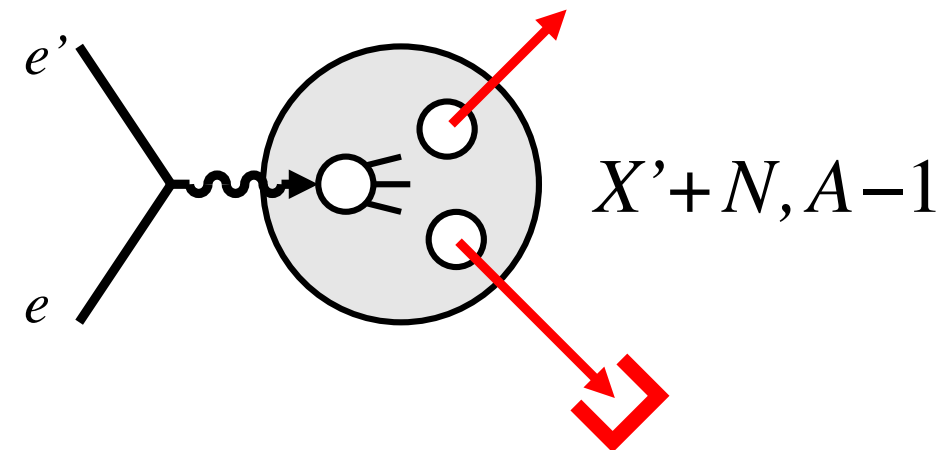during high-energy process. Main limiting factor.

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, …
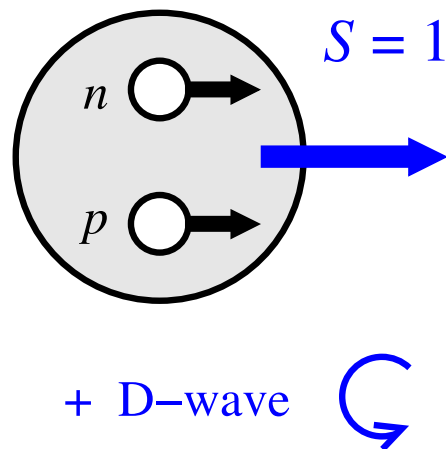
Nuclear breakup detection - tagging

Potential information on initial-state
nuclear configuration

Study effects in defined configurations,
much simpler

Final-state interactions important,
influence breakup amplitudes

New opportunities with EIC!
New challenges for detection and theory!
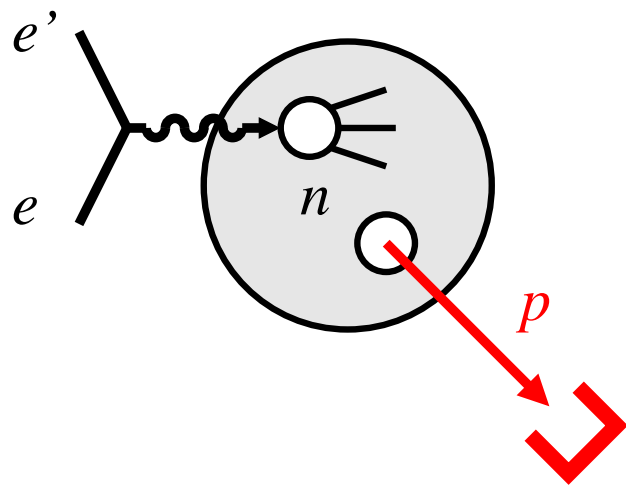
Deuteron as simplest system

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]

$S = 1$

n

p

+ D−wave

Spectator nucleon tagging

Identifies active nucleon

Controls configuration through recoil momentum:
spatial size → interactions, S/D wave
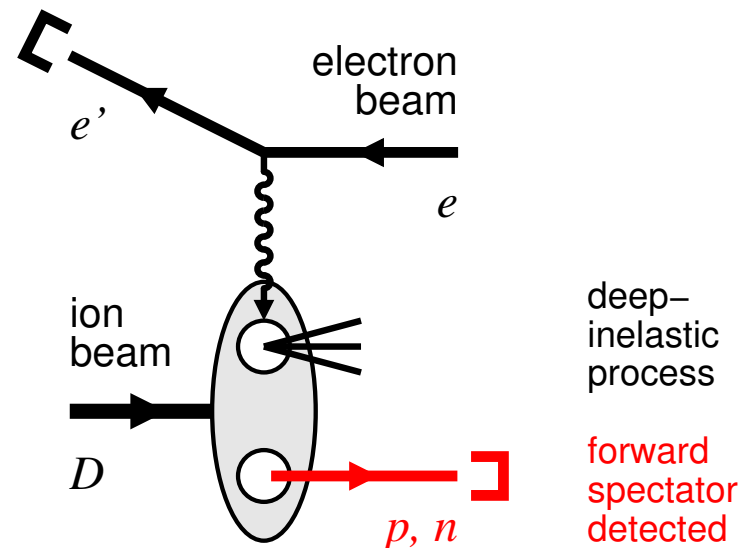
Typical momenta ~ few 10 — 100 MeV

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

e'

e

n

p

[Nucleus rest frame view]
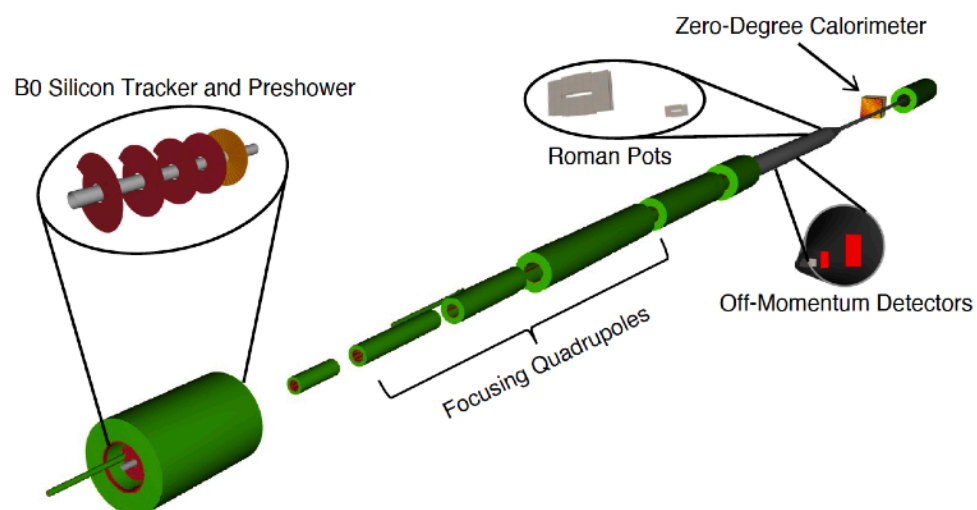
[Collider frame view]

Spectator moves forward in ion beam direction

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

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

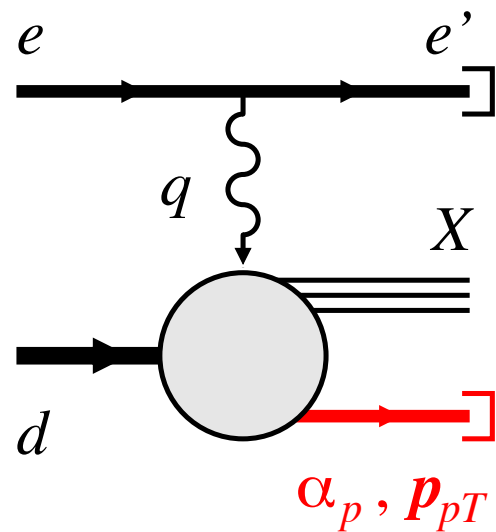large offset, can be detected

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

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

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

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

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: $p_p^+ = \alpha_p p_d^+$, $\mathbf{p}_{pT}$
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 in DIS

[Trentadue, Veneziano 93; Collins 97]

energy
off−shellness

e

high−
energy
process

N

d

N

nuclear
structure
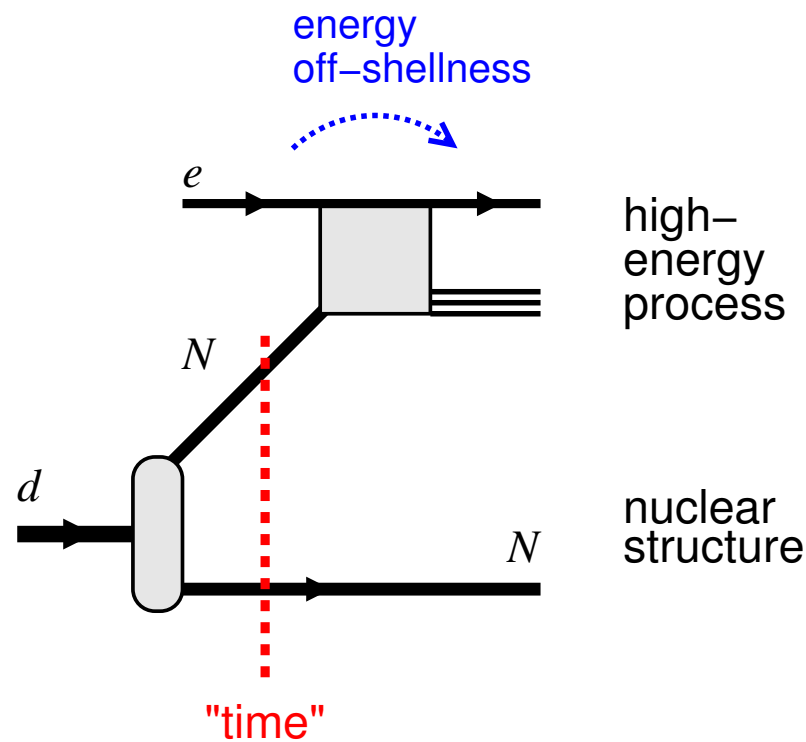
"time"

QM description

Nucleon states, nuclear wave function

Nucleons are on mass shell $p^2 = m^2$,
energy not conserved in intermediate states

eN scattering subprocess has initial $\neq$ final energy

Choice of "time" variable

Usual time x^0: Energy off-shellness grows with incident energy

Light-front time $x^+ = x^0 + x^3$: Off-shellness remains finite! $\leftarrow$

Light-front quantization

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

Enables composite description of high-energy scattering on nucleus: [Frankfurt, Strikman 80s]
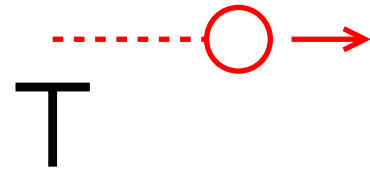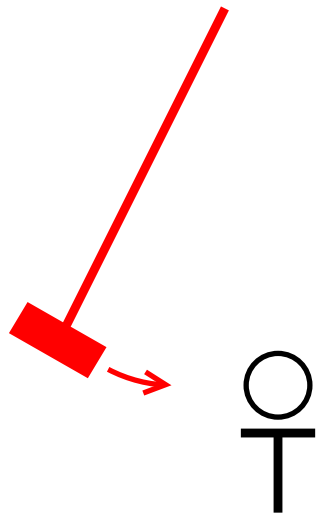Separation of nucleus and nucleon structure
Use of on-shell nucleon amplitudes/cross sections, measured in eN scattering
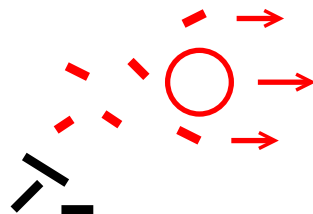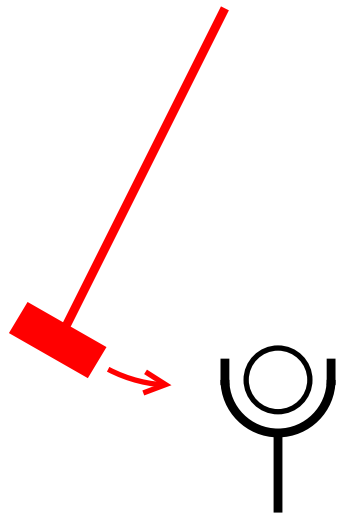Limited role of non-nucleonic DoF

Analogue: Teeing up a golf ball

Light-front quantization:
Low-energy structure aligned with
direction of high-energy process

Other quantization schemes:
Low-energy structure not aligned with
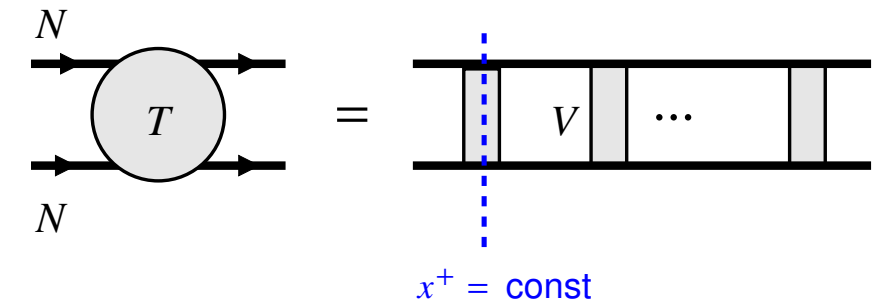direction of high-energy process

LF bound state equation

Construct NN interaction at fixed LF time x^+

Schrödinger (V) or Lippmann-Schwinger (T) type equations

Technical challenges: Rotational invariance, Fock truncation, A > 2

[Frankfurt, Strikman 1980s. Models/empirical interactions: Miller Cooke et al 2000s, Vary et al. 2010s. Future project: EFT interactions]

$$N \qquad \quad T \quad = \quad V \quad \cdots$$

$$N$$

$$x^+ = const$$

Approximation constructed from nonrelativistic wave function (A = 2)

Rotationally symmetric representation of LF variables:
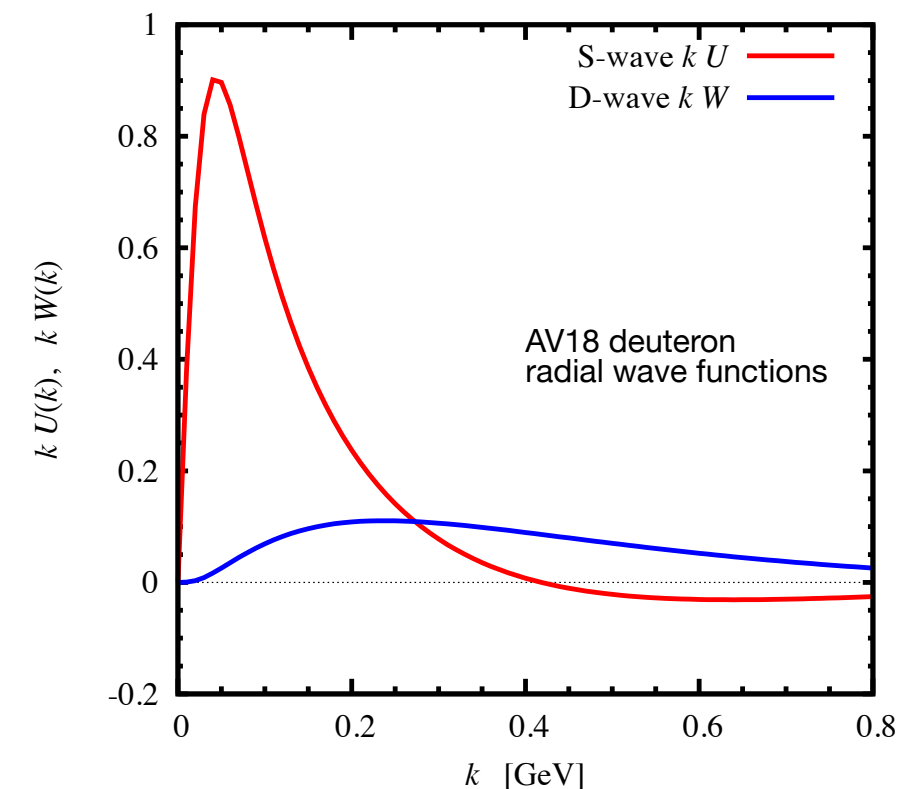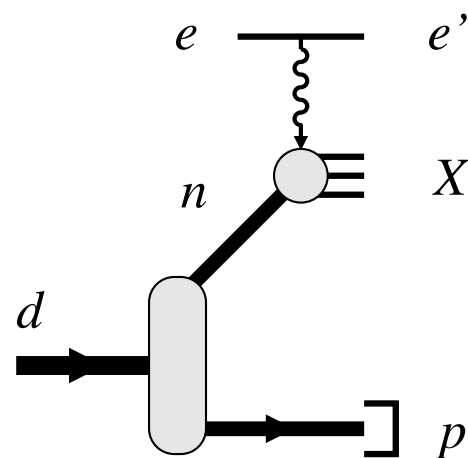$\mathbf{k}(\alpha_p, p_{pT})$ = 3-momentum in pn CM frame   [Terentev 1976]

Match LF and nonrelativistic wave functions:
$$\Psi_{\text{LF}}(\alpha_p, p_{pT}) \; = \; N \, \Psi_{\text{nonrel}}(\mathbf{k})$$

Imports knowledge of NN interactions in non-relativistic NMBT

AV18 deuteron radial wave functions

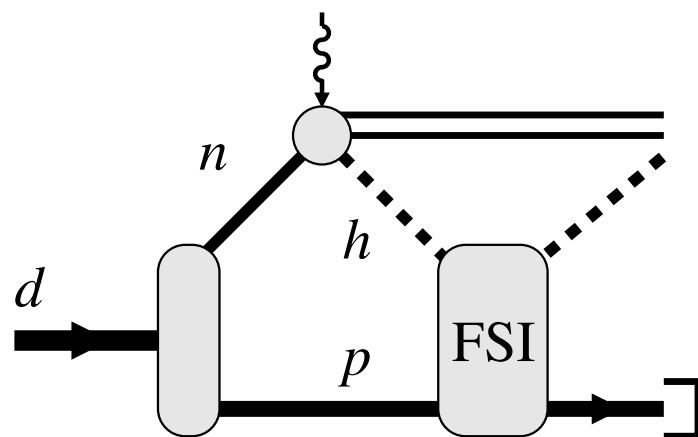S-wave $k\,U$
D-wave $k\,W$

$k\,U(k),\; k\,W(k)$

k [GeV]

Impulse approximation

Spectator and DIS final state evolve independently

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

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

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

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.

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

(a)
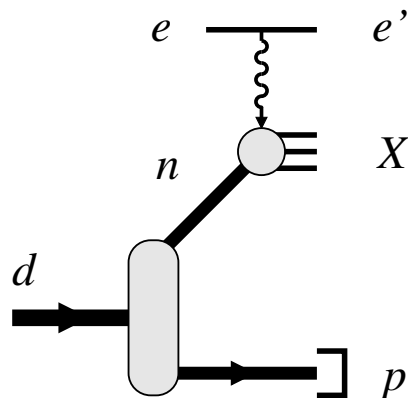
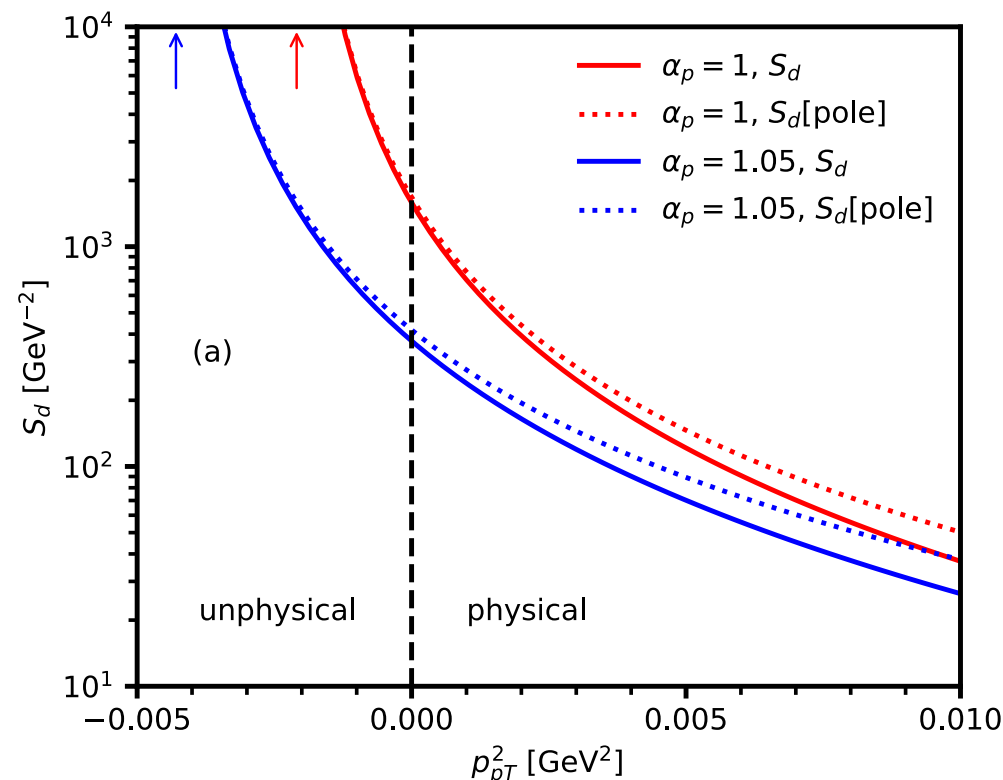Deuteron wave function has pole in unphysical region describing pn configurations of size $\to \infty$

Universal feature: Bethe-Peierls radius, asymptotic S-wave normalization

At pole nucleons are free, no interactions

Can be reached by analytic continuation in momentum

Light-front: Pole in transverse momentum p_{pT}^2
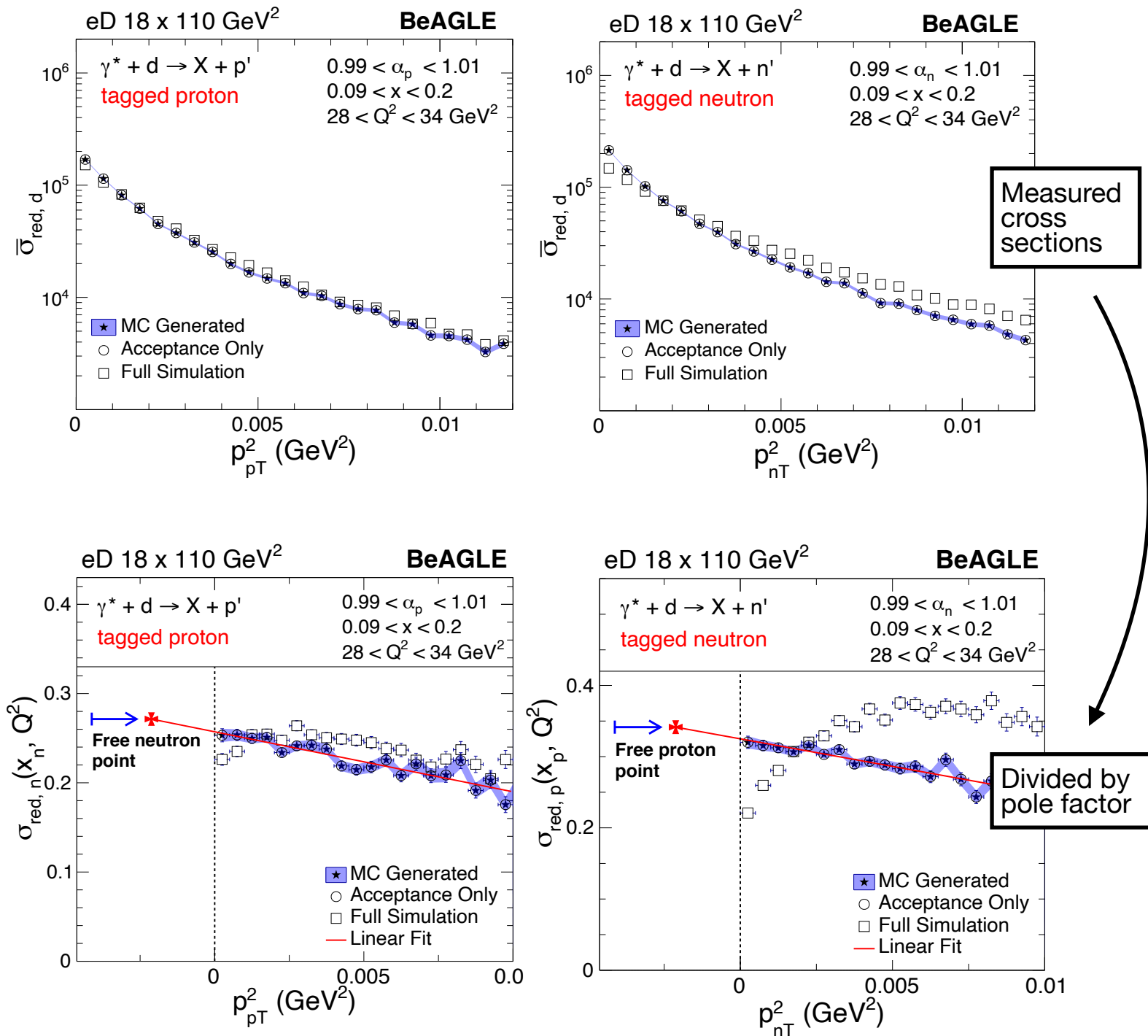
Extraction procedure [Sargsian, Strikman 2005]

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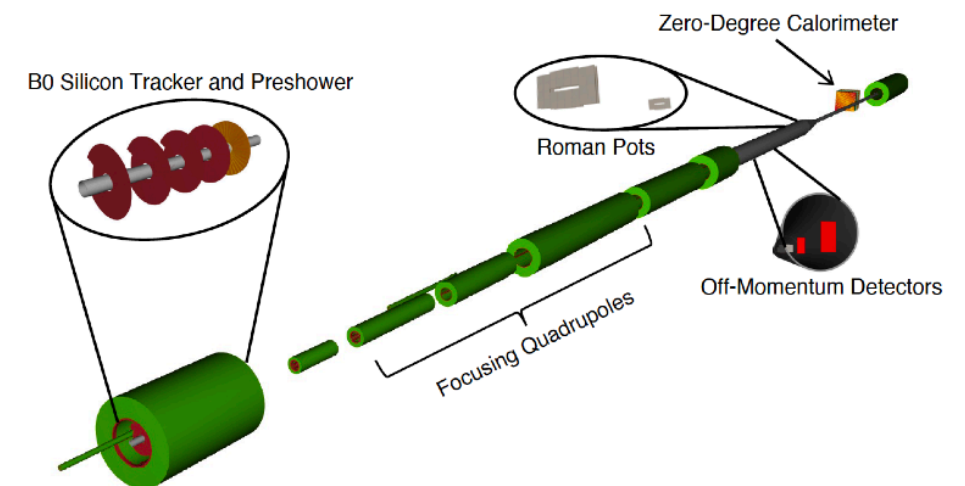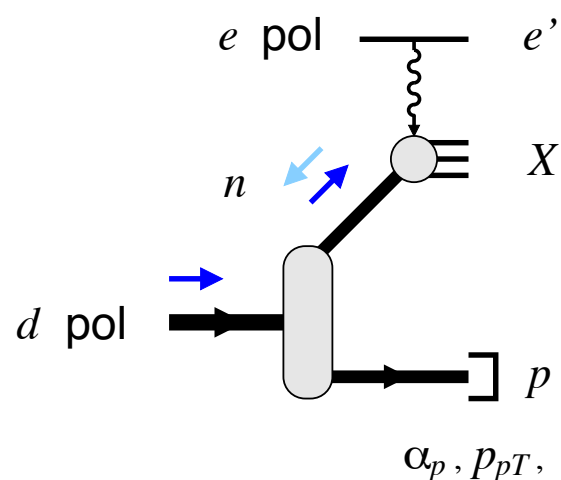
EIC simulations: p and n tagging, pole extrapolation, uncertainty analysis, validation

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.

Jentsch, Tu, Weiss, PRC104, 065205 (2021)
EIC Yellow Report 2021

$$A_{\|,d}(x, Q^2; \alpha_p, p_{pt}) \qquad \text{longitudinal double spin asymmetry}$$

$$= \frac{d\sigma_\|(+\tfrac{1}{2}, +1) - d\sigma_\|(-\tfrac{1}{2}, +1) - d\sigma_\|(+\tfrac{1}{2}, -1) + d\sigma_\|(-\tfrac{1}{2}, -1)}{d\sigma_\|(+\tfrac{1}{2}, +1) + d\sigma_\|(-\tfrac{1}{2}, +1) + d\sigma_\|(+\tfrac{1}{2}, -1) + d\sigma_\|(-\tfrac{1}{2}, -1)}$$

$$= \frac{S_d(\alpha_p, p_{pT})[S]}{S_d(\alpha_p, p_{pT})[U + T]} \, A_{\|,n}(x_n, Q^2)$$

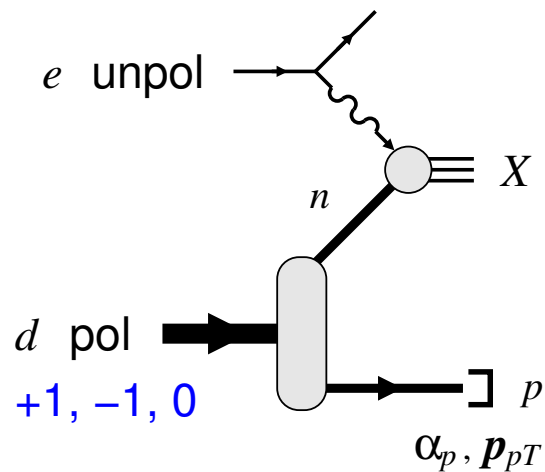$$D_d(\alpha_p, p_{pT}) \qquad \text{effective neutron polarization, depends on tagged proton momentum}$$
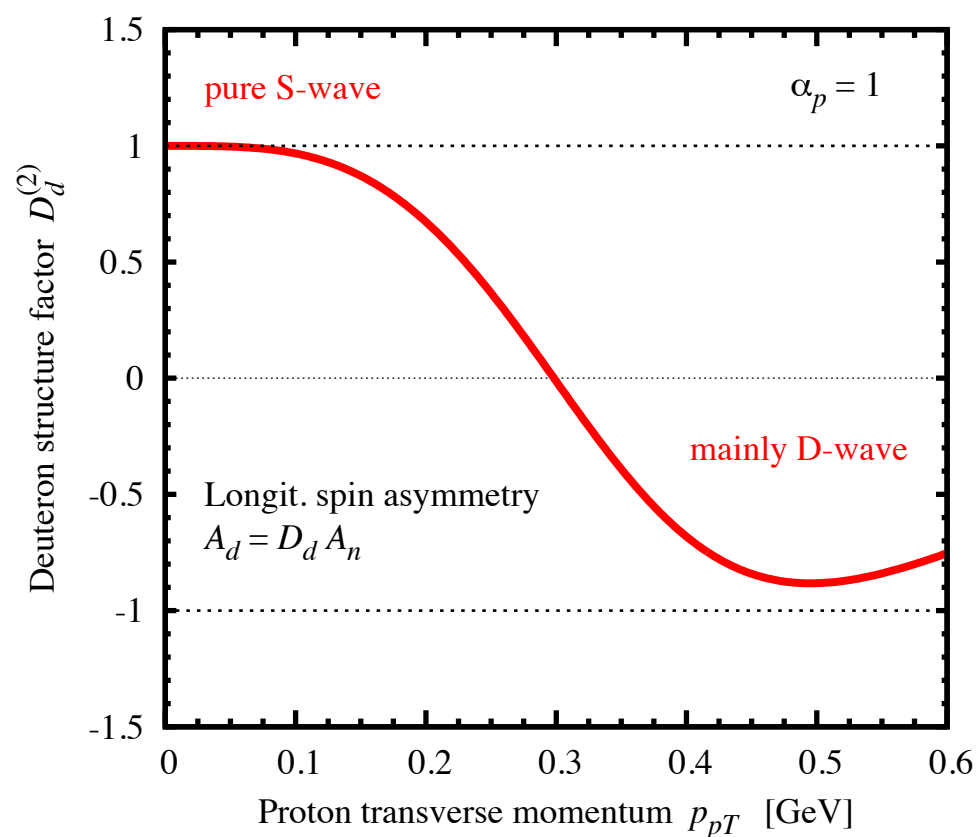
Control effective neutron polarization

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

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

EIC simulations: JLab LDRD 2014/15

Frankfurt, Strikman 1983

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

e unpol

n ≡ X

d pol

+1, −1, 0

α_p, $\boldsymbol{p}_{pT}$

p

$A_{zz,d}(x, Q^2; \alpha_p, \mathbf{p}_{pt})$ tensor polarized asymmetry

$$= \frac{d\sigma(+1) + d\sigma(-1) - 2d\sigma(0)}{d\sigma(+1) + d\sigma(-1) + d\sigma(0)}$$

$$-2 < A_{zz,d} < 1$$

$$= \frac{S_d(\alpha_p, p_{pT})[T_{LL}]}{S_d(\alpha_p, p_{pT})[U]}$$

effective tensor polarization, depends on tagged momentum

proportional to D-wave
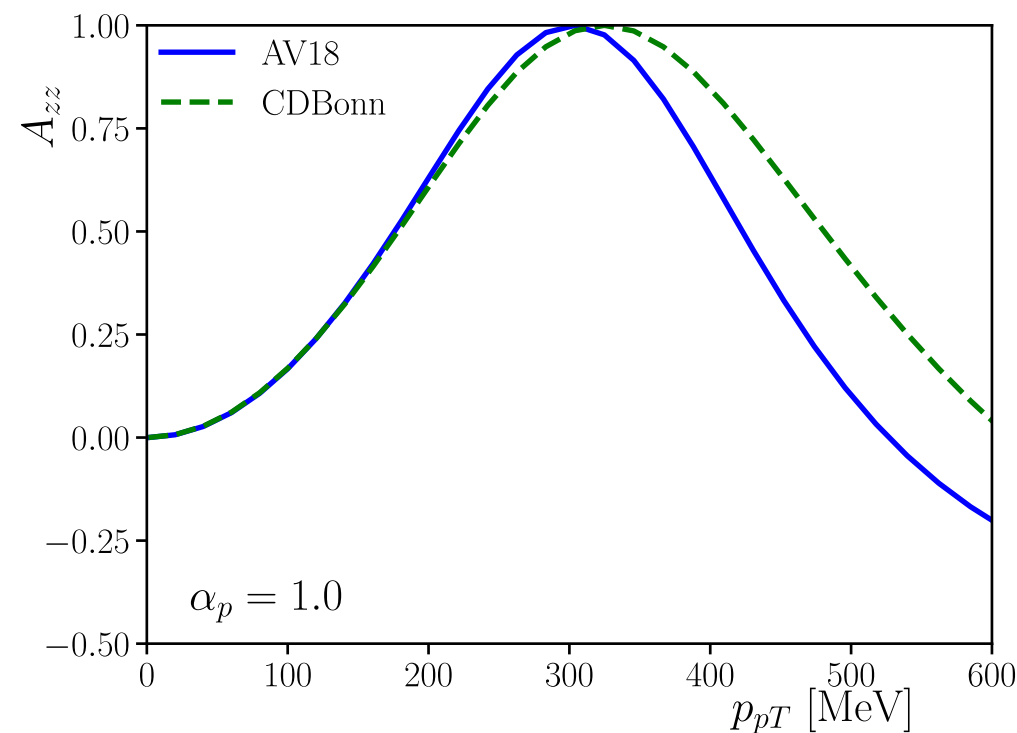
Maximize tensor polarized asymmetry

Maximal tensor polarization $A_{zz} = 1$
can be achieved at $p_{pT} \approx 300$ MeV and $\alpha_p = 1$

Much larger tensor asymmetry than in untagged scattering where most events come from nucleon momenta ~ few 10 MeV and D-wave is small

Frankfurt, Strikman 1983

Cosyn, Weiss, in progress

$p \sim$ few 10 MeV

$p \sim$ few 100 MeV
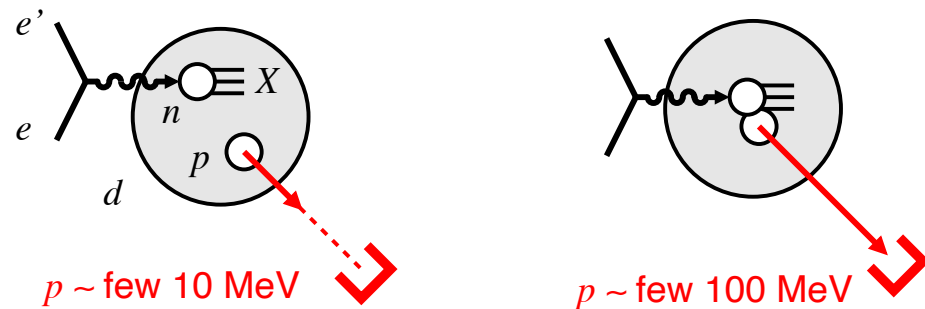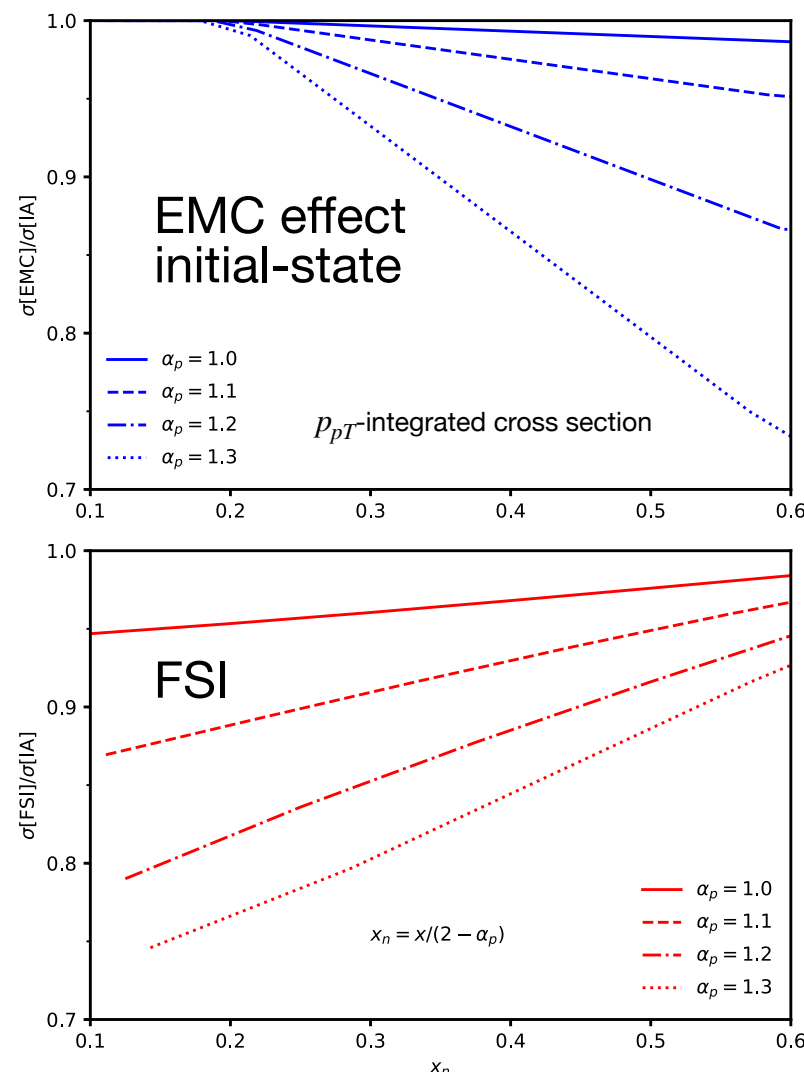
EMC effect

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

What NN distances/momenta cause modification?

Deuteron: Control configurations with tagging!

EIC simulations

Use proton and neutron tagging
$\alpha_{p,n} > 1, p_T \sim$ 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
FSI theory: Strikman, Weiss PRC97 (2018) 035209; ongoing development

EIC simulations including statistics, optimization of analysis
Jentsch, Tu, Weiss, in progress


EMC effect
initial-state

$\alpha_p = 1.0$
$\alpha_p = 1.1$
$\alpha_p = 1.2$ p_{pT}-integrated cross section
$\alpha_p = 1.3$

FSI

$x_n = x/(2 - \alpha_p)$

$\alpha_p = 1.0$
$\alpha_p = 1.1$
$\alpha_p = 1.2$
$\alpha_p = 1.3$

Tagged diffractive scattering

Study configuration dependence of nuclear shadowing ↔ heavy nuclei

Tagging with A > 2 nuclei, esp. 3He(pol)

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

Theory much more complex: Light-front structure of 3-body system,
multiple breakup channels, complex amplitudes. Requires investment
Lev 1990s; Salme et al. 2000+; Ciofi, Kaptari, Scopetta et al 2000+
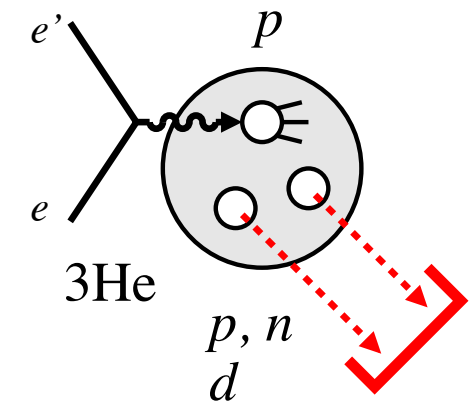
**Light-front nuclear structure from Chiral EFT interactions**

Systematic construction, controlled uncertainties.
Standard in low-energy nuclear structure
Long-term project: F. Vera, Weiss. Collaboration with low-energy nuclear structure experts

Final-state interactions

Critical for all breakup processes.
Needs theory development and MC implementation
Strikman, Weiss. Collaboration with MIT group O. Hen et al.
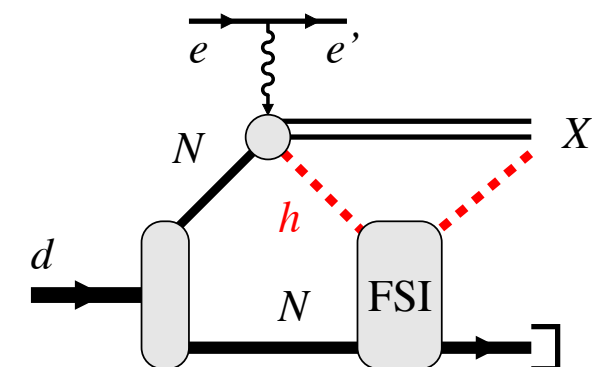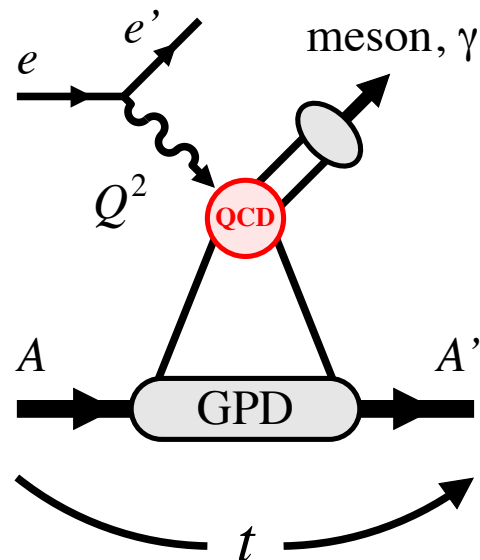
Hard exclusive processes
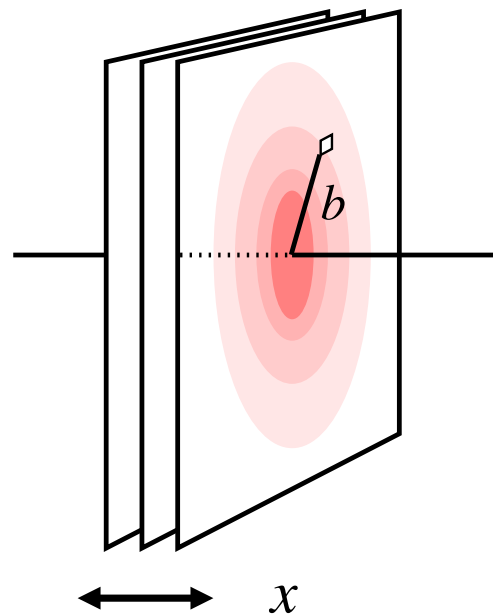
$Q^2, W^2 \gg$ hadronic scale: QCD factorization

Generalized parton distributions $\langle A' | \hat{\mathcal{O}}_{\mathrm{QCD}} | A \rangle$
Unify concepts of quark/gluon density and form factor

Probe nuclear structure in quark/gluon degrees of freedom

Transverse spatial distribution of quarks/gluons

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

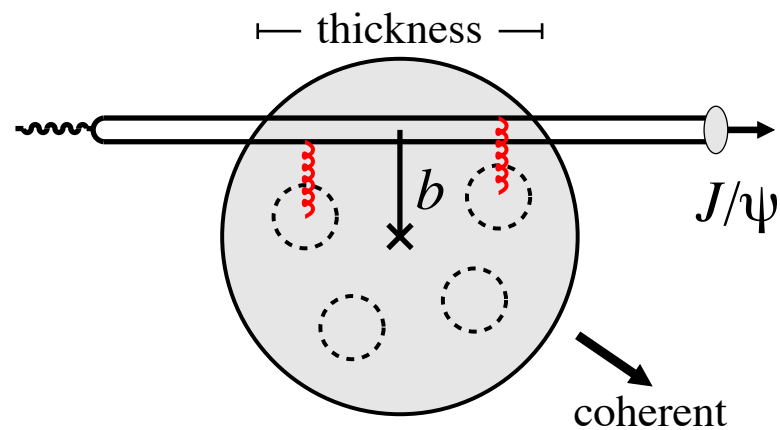Dynamics: Spatial distributions change with x, polarization

Nuclear quark/gluon imaging with EIC

Probe quarks: Deeply-virtual Compton scattering
Probe gluons: $J/\psi, \phi$ production

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

Other application of nuclear GPDs: Nuclear matrix elements of QCD energy-momentum tensor. Hatta et al, Zahed et al.

thickness

b

J/ψ

coherent

Nuclear shadowing

Small-x probe interacts coherently across nucleus

Interference of diffractive scattering from different nucleons along the path

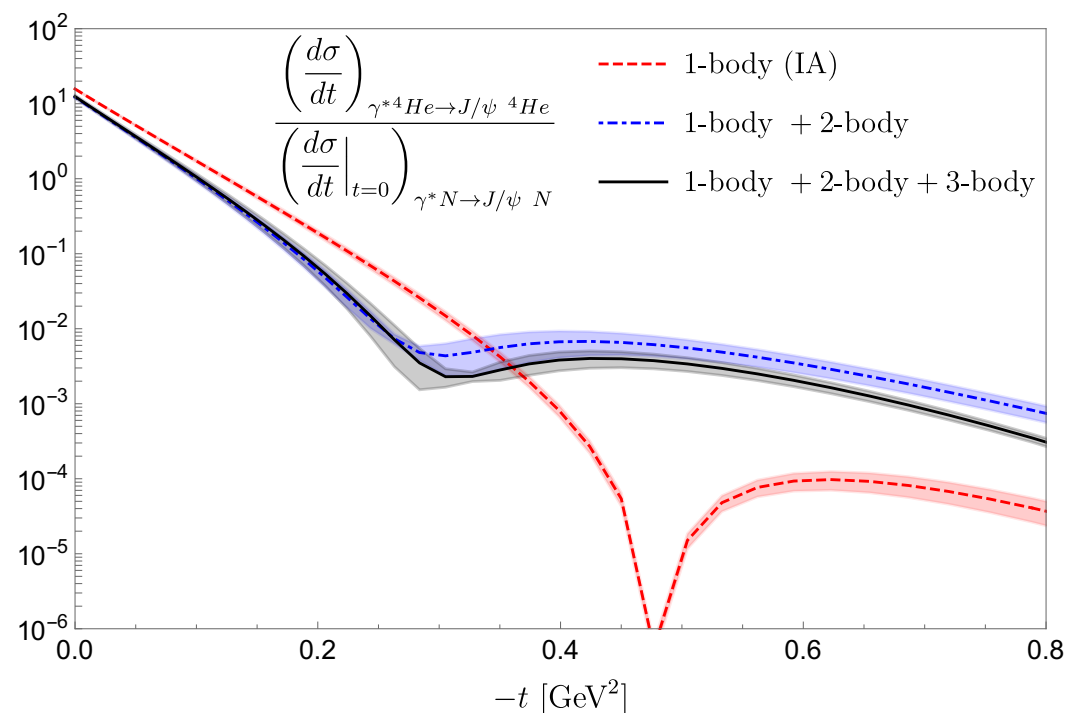Reduction of nuclear gluon density

Heavy nuclei

Shadowing observed in coherent J/ψ photoproduction in ultraperipheral AA collisions at LHC

Light nuclei

$d\sigma/dt = $ 1-body + 2-body + ...   multiple scattering

1-body cross section has diffractive minimum
2-body cross section fills it up

Study onset of coherence and shadowing in coherent processes on light nuclei — new approach

$$\frac{\left(\frac{d\sigma}{dt}\right)_{\gamma^{*4}He \to J/\psi\ ^4He}}{\left(\frac{d\sigma}{dt}\bigg|_{t=0}\right)_{\gamma^* N \to J/\psi\ N}}$$

- - - - 1-body (IA)
-·-·- 1-body + 2-body
——— 1-body + 2-body + 3-body

$-t\ [\mathrm{GeV}^2]$

Guzey, Rinaldi, Scopetta, Strikman, Viviani 2022
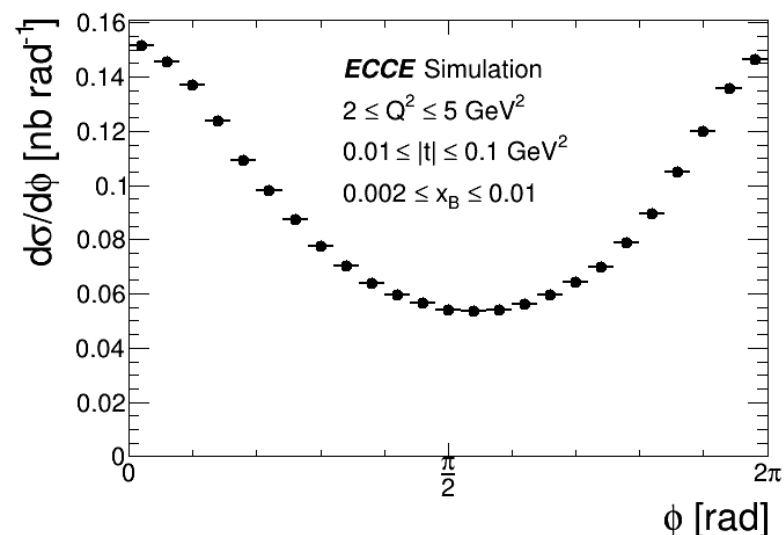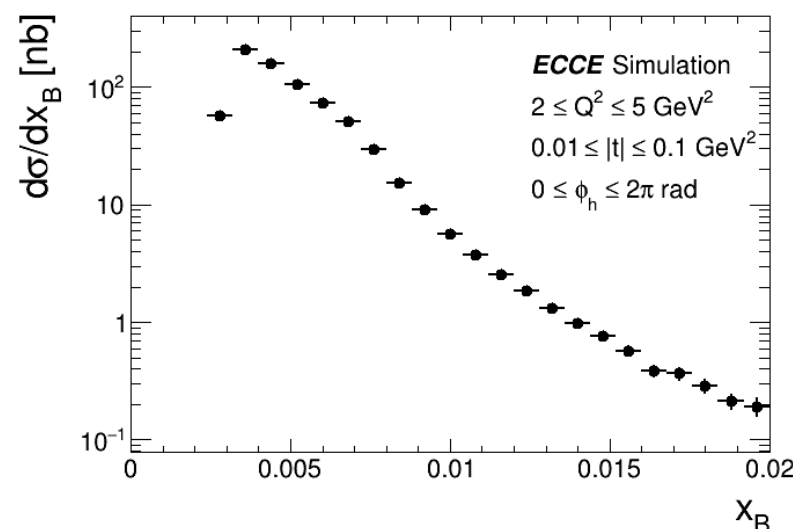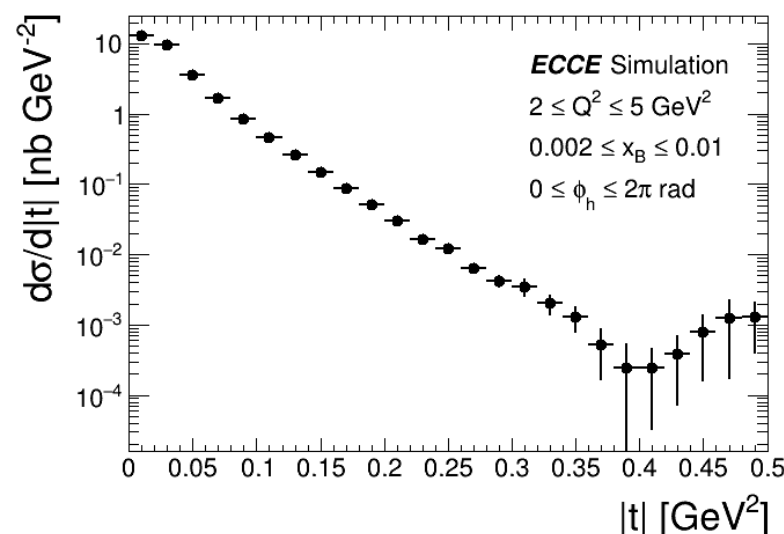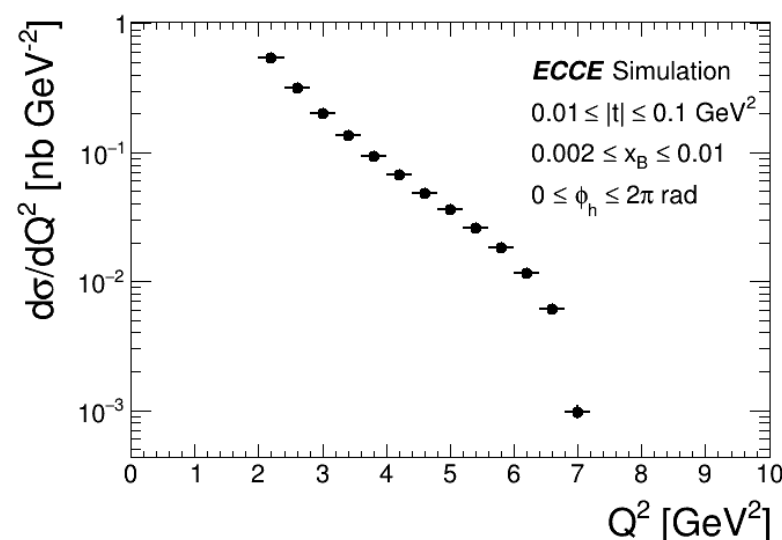
Simulations of coherent DVCS on 4He with ECCE detector

Bylinkin et al 2022

Event generator TOPEG

Dupre, Fucini 2022

Coherent processes on light ions pose specific challenges for far-forward detection:
Small longitudinal momentum loss (< 0.1) and small transverse momenta (~< 100 MeV)

Critical benefits from "secondary focus" ($\beta_x \approx 0$) at Roman Pots location.
Discussed for IR8; possible also at IR6

Summary

Light ion physics most novel and least explored part of EIC science program 😉

Nuclear breakup measurements permit control of nuclear configuration in high-energy process and differential analysis of nuclear effects — new opportunities, new challenges for theory

Light-front formulation of nuclear structure essential for separating low-energy nuclear structure and high-energy process. EFT-based formulation in progress

Unique applications of deuteron tagging at EIC: Free neutron extraction, controlled neutron polarization, large tensor asymmetries, tagged EMC effect, …

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

Coherent scattering on light ions: Quark-gluon imaging of nuclei, origin of nuclear shadowing, nuclear matrix elements of QCD energy-momentum tensor

Synergies with JLab12 experimental program, low-energy nuclear structure theory

Emerging program — many opportunities, long-term prospects

Supplemental material

NN interactions can be generated from Chiral EFT

Scattering amplitude T → Potential V

Parametric approach: Systematic, controlled uncertainties, organizes N-body forces, current operators

Standard in low-energy nuclear structure

Weinberg; Kaplan et al.; Epelbaum, Meißner et al; Van Kolck et al 1990s/2000s

Schiavilla, Pastore, Piarulli et al 2010s

Machleidt et al. 2000s

Can be extended to light-front NN interactions
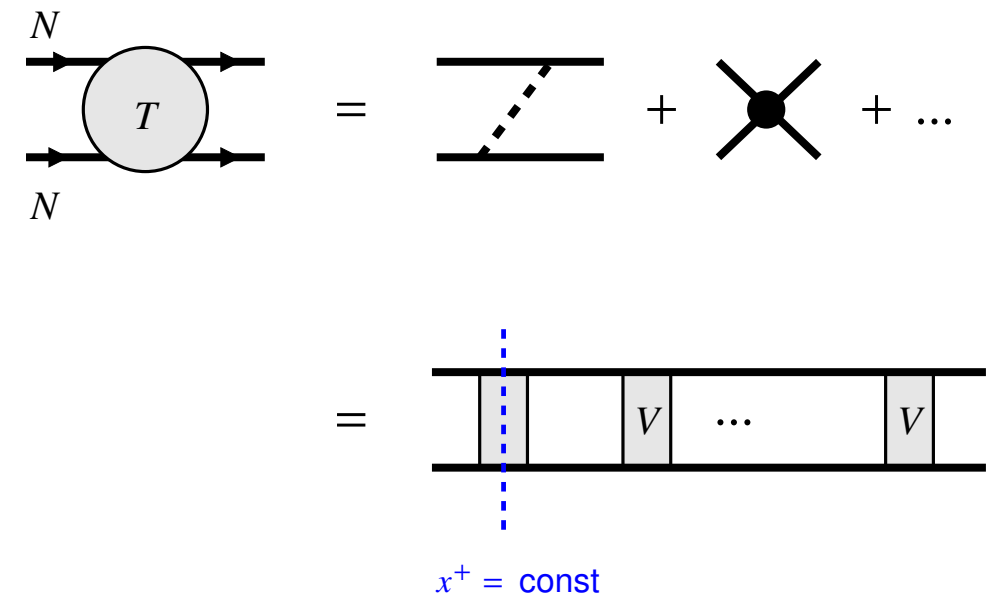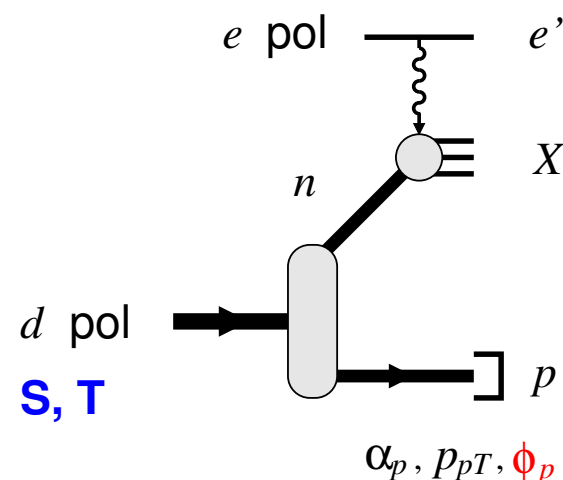
Planned: F. Vera, Weiss

Technical questions: Rotational invariance, Fock expansion with chiral counting

Applications: Nuclear pions → antishadowing
Nuclear modifications of PDFs through 2-body operators

Matching with Lattice QCD possible

e pol e'
X
n
d pol
S, T
p
α_p, p_{pT}, ϕ_p

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

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

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

Vector and tensor polarization

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

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

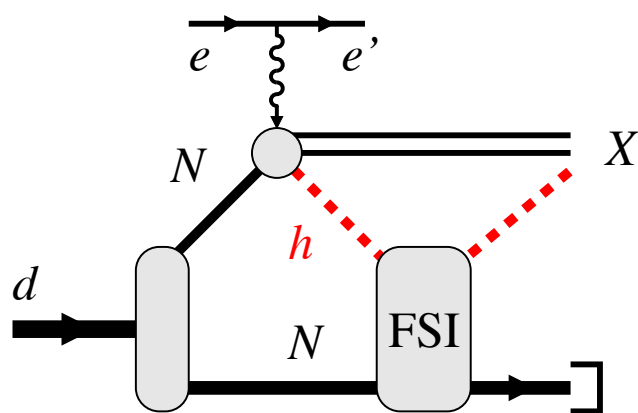T cross section has 23 new structures, some with ϕ_p-dep unique to T polarization

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

[Deuteron rest frame view]

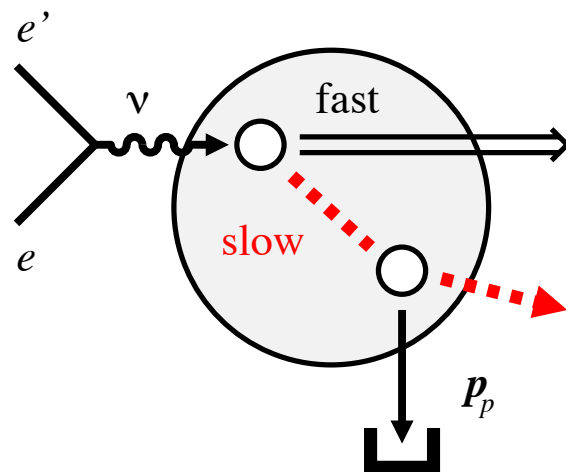[Resonance region: Cosyn, Sargsian Melnitchouk 2011/14]

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

Final-state interactions in DIS at intermediate x ($\gtrsim$ 0.1)

Space-time picture in deuteron rest frame   Strikman, Weiss PRC97 (2018) 035209

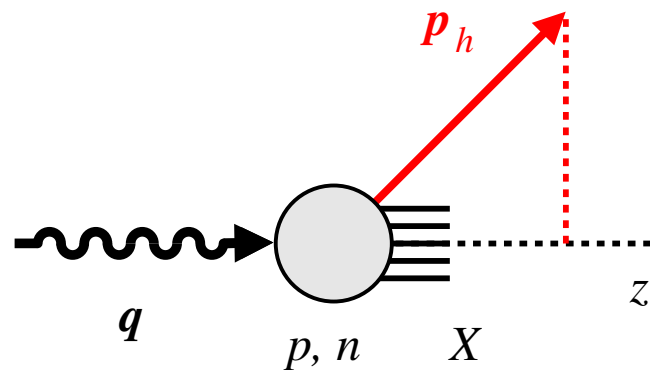$\nu \gg$ hadronic scale: Large phase space for hadron production

"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, no long-range rapidity correlations

Tagging: Final-state interactions
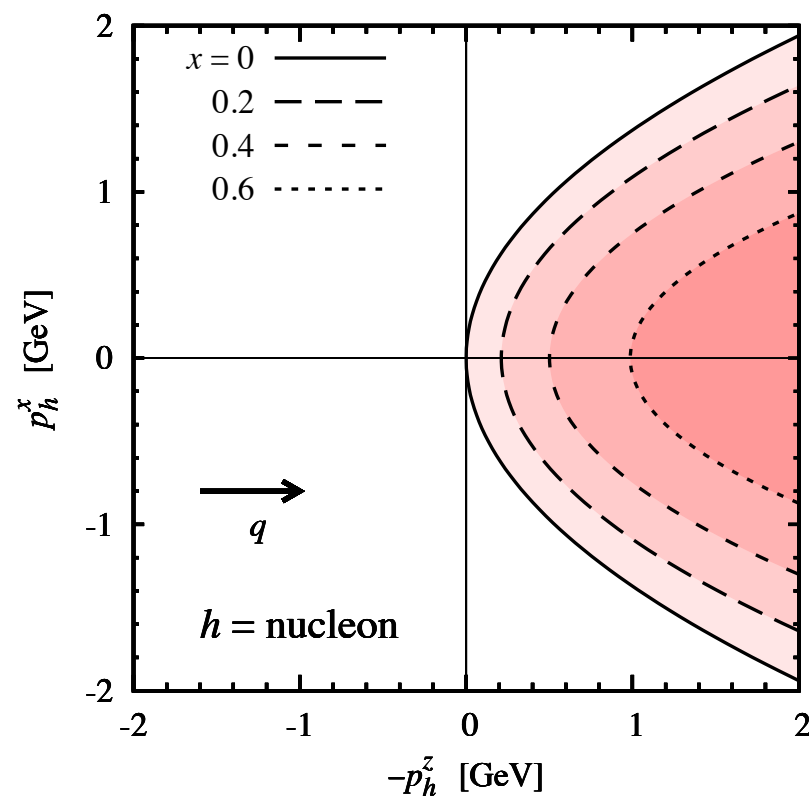
p_h

q

p, n X

z

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

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

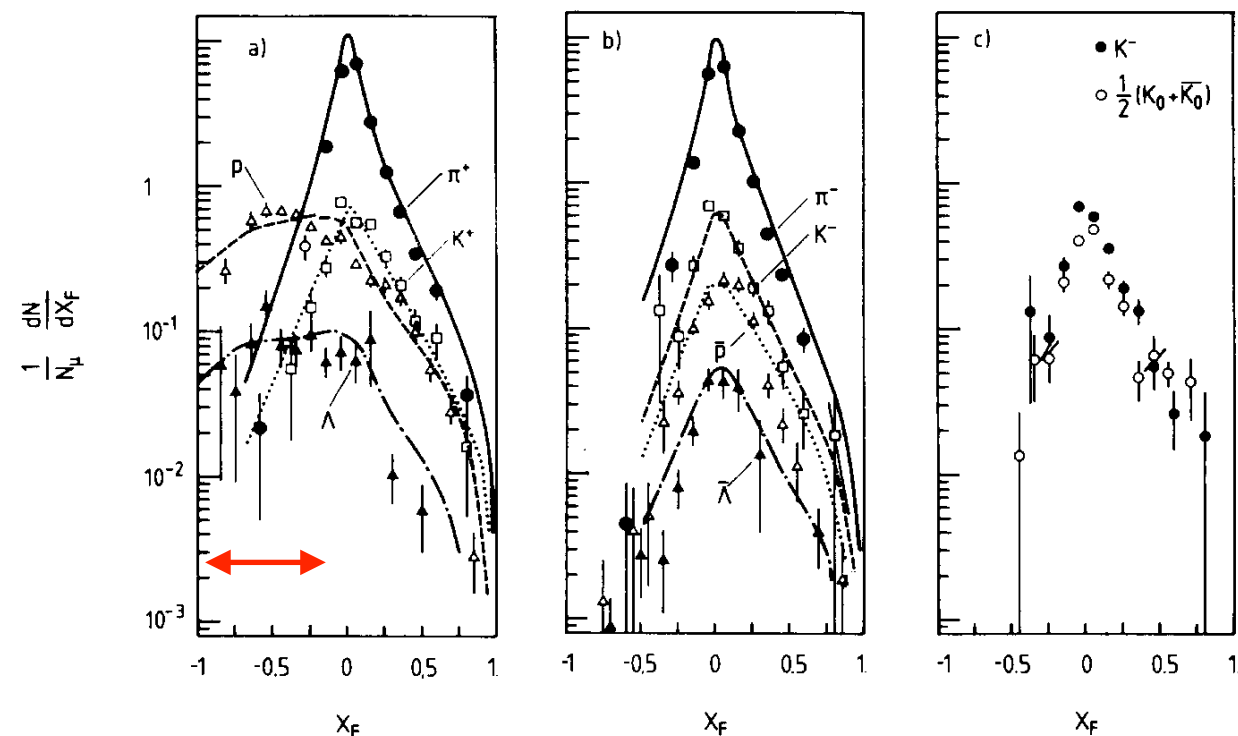Used experimental distributions: HERA, EMC, neutrino DIS

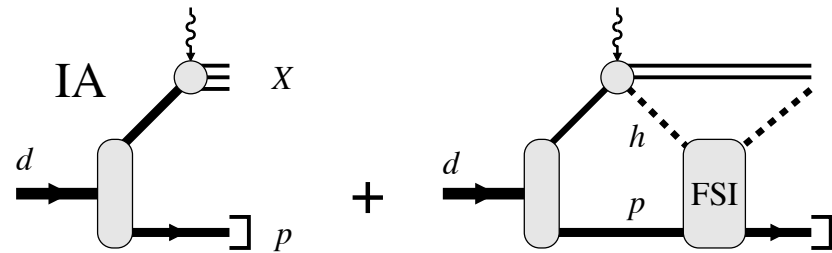Need better data on target fragmentation: JLab12, EIC!

p_h^x [GeV]

$x = 0$
0.2
0.4
0.6

q

$h = \text{nucleon}$

$-p_h^z$ [GeV]

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

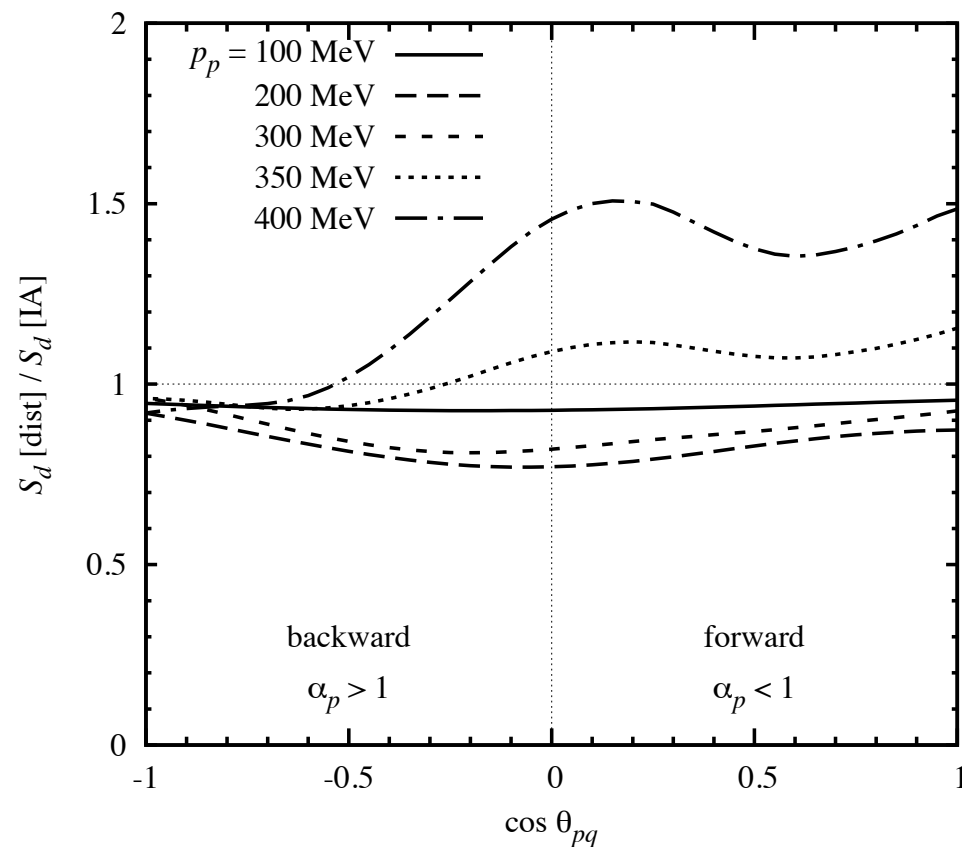Strikman, Weiss PRC97 (2018) 035209

Hadron xF distributions EMC 1986

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: |FSI|², refractive,
strong angular dependence

FSI angular dependence in deuteron rest frame

Results used in EIC simulations,
analysis of JLab12 BAND experiment

Strikman, Weiss PRC97 (2018) 035209

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

I, J, LS
pairs

Light-front structure more complex:
Angular momentum coupling, LF $\leftrightarrow$ nonrelativistic correspondence
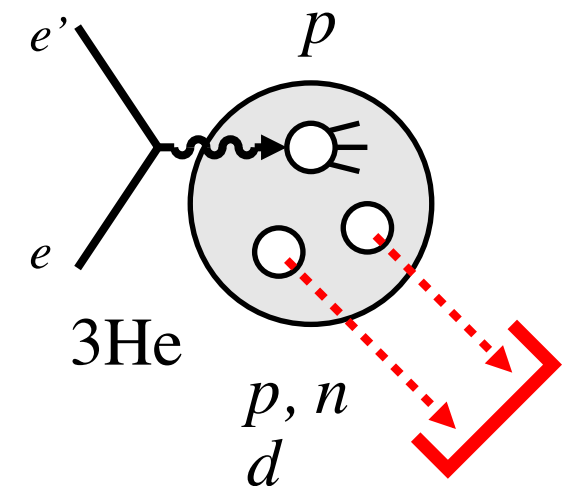Lev 1990s; Salme et al. 2000s
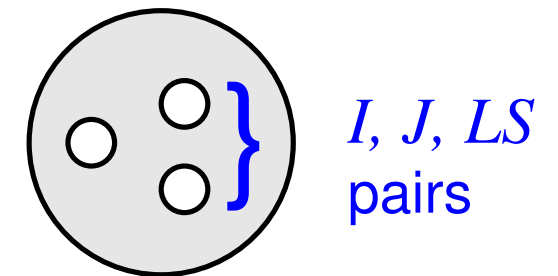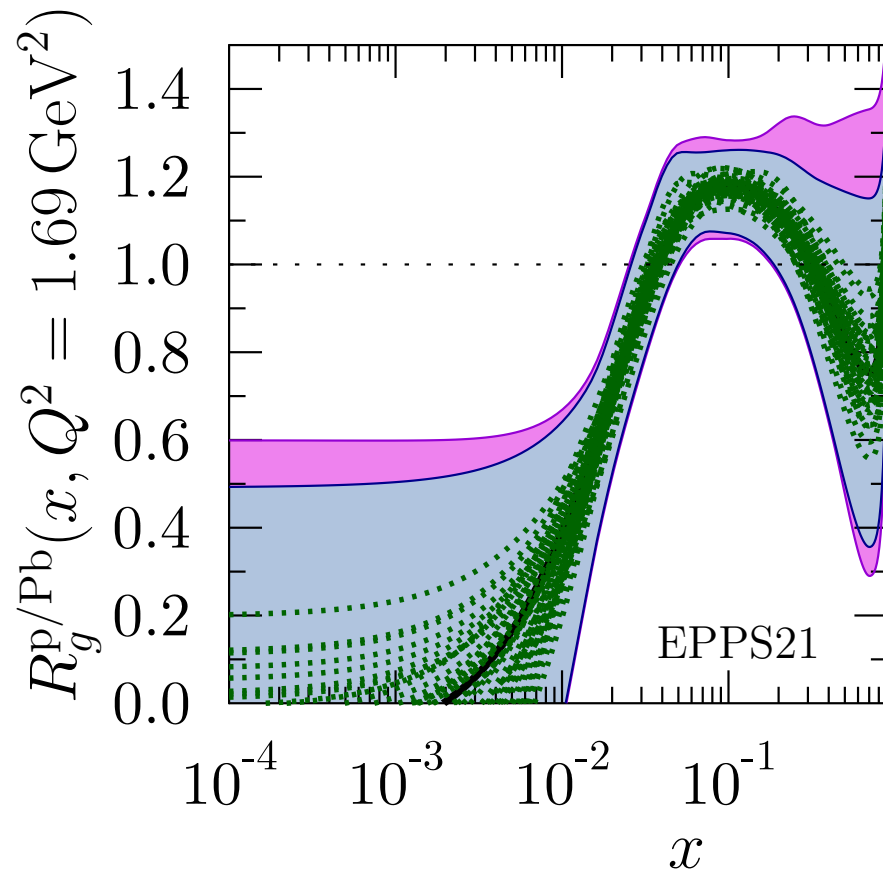
Nuclear breakup processes A > 2

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
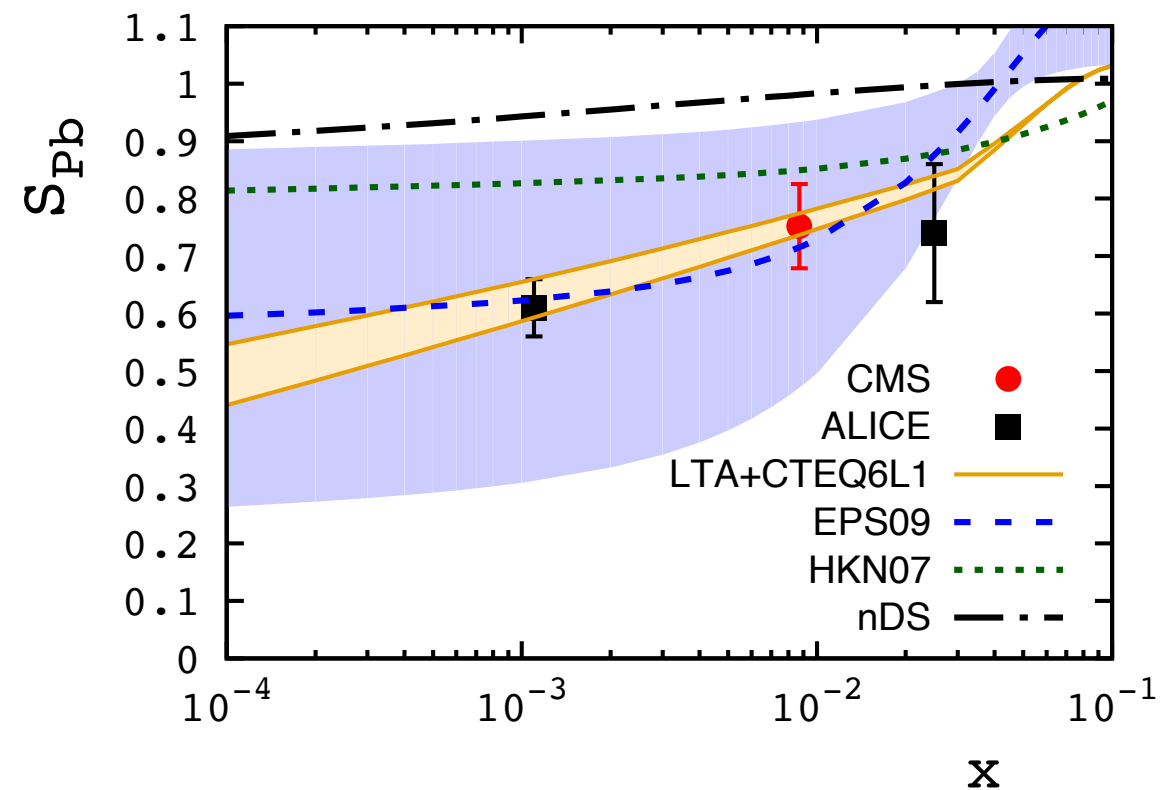
Needs extensive nuclear structure input!
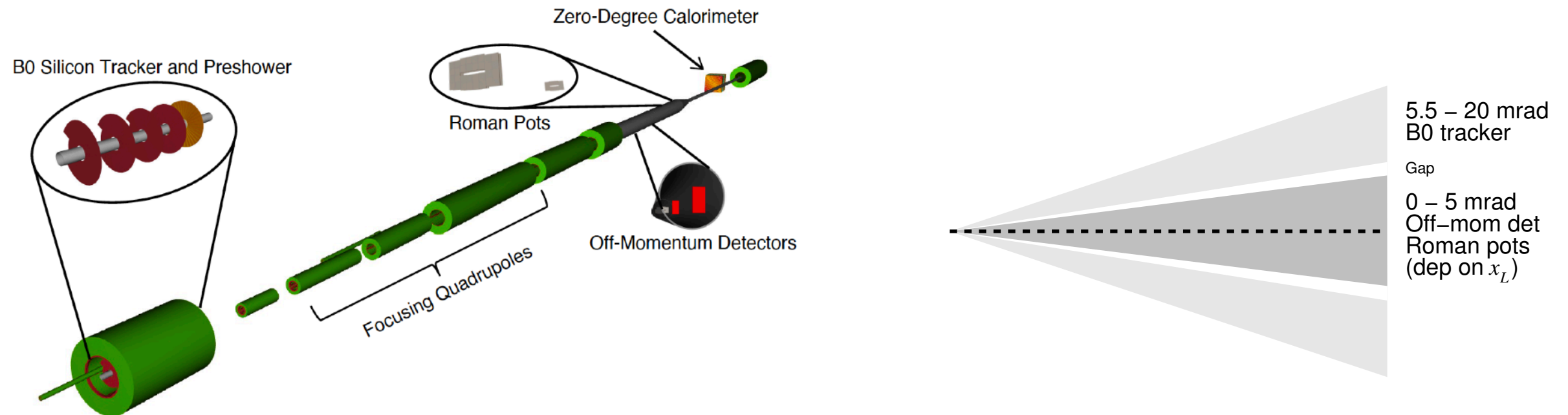
3He: Ciofi, Kaptari, Scopetta e al 2000+

Nuclear gluon PDF ratio R_g in Pb extracted in EPPS21 global analysis

Eskola, Paakkinen, Paukkunen, Salgado 2021

Experimental results in coherent J/psi photoproduction in ultra peripheral AA collisions at LHC CMS and ALICE, compared to leading-twist gluon shadowing and other predictions

Charged particles

Magnetic spectrometer integrated in accelerator optics, several detector subsystems

Transport governed by magnetic rigidity = momentum/charge   (for beam and detected particle)

Acceptance depends on $x_L \equiv p_\parallel(\text{particle})/p(\text{beam})$, $\theta = p_\perp/p_\parallel(\text{particle})$ (for given particle)

Neutral particles

Zero-degree calorimeter

Acceptance depends only on angle θ

Complex system,
integration is major challenge

Protons	θ	x_L	
	< 5 mrad	0.2 − 0.6	Off-momentum det
	< 5 mrad	> 0.6	Roman Pots
	5.5 − 20 mrad	any	B0 tracker
Neutrons			
	< 4 mrad	any	ZDC

Spectator tagging

Rigidity(spectator) $\neq$ Rigidity(beam)

Different subsystems used depending on spectator proton kinematics

Detector resolution $\rightarrow$ Supplement

Coherent scattering
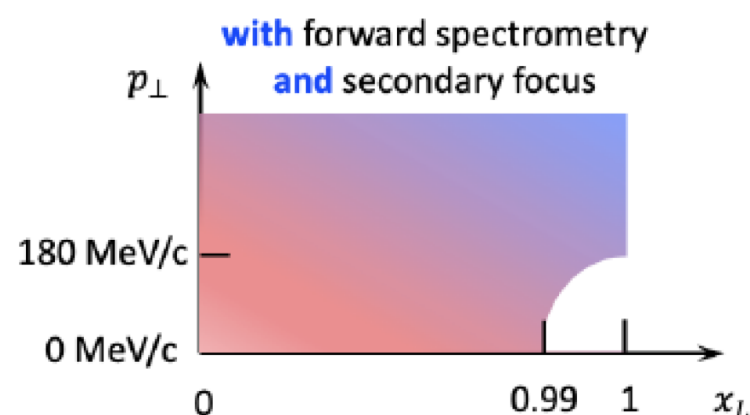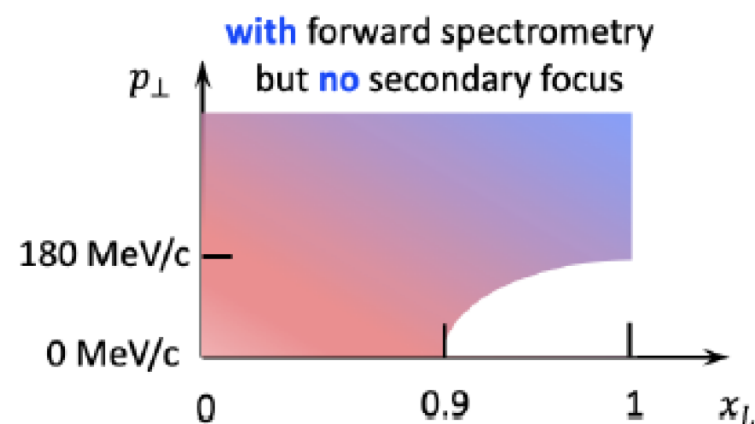
Rigidity(spectator) $\approx$ Rigidity(beam)

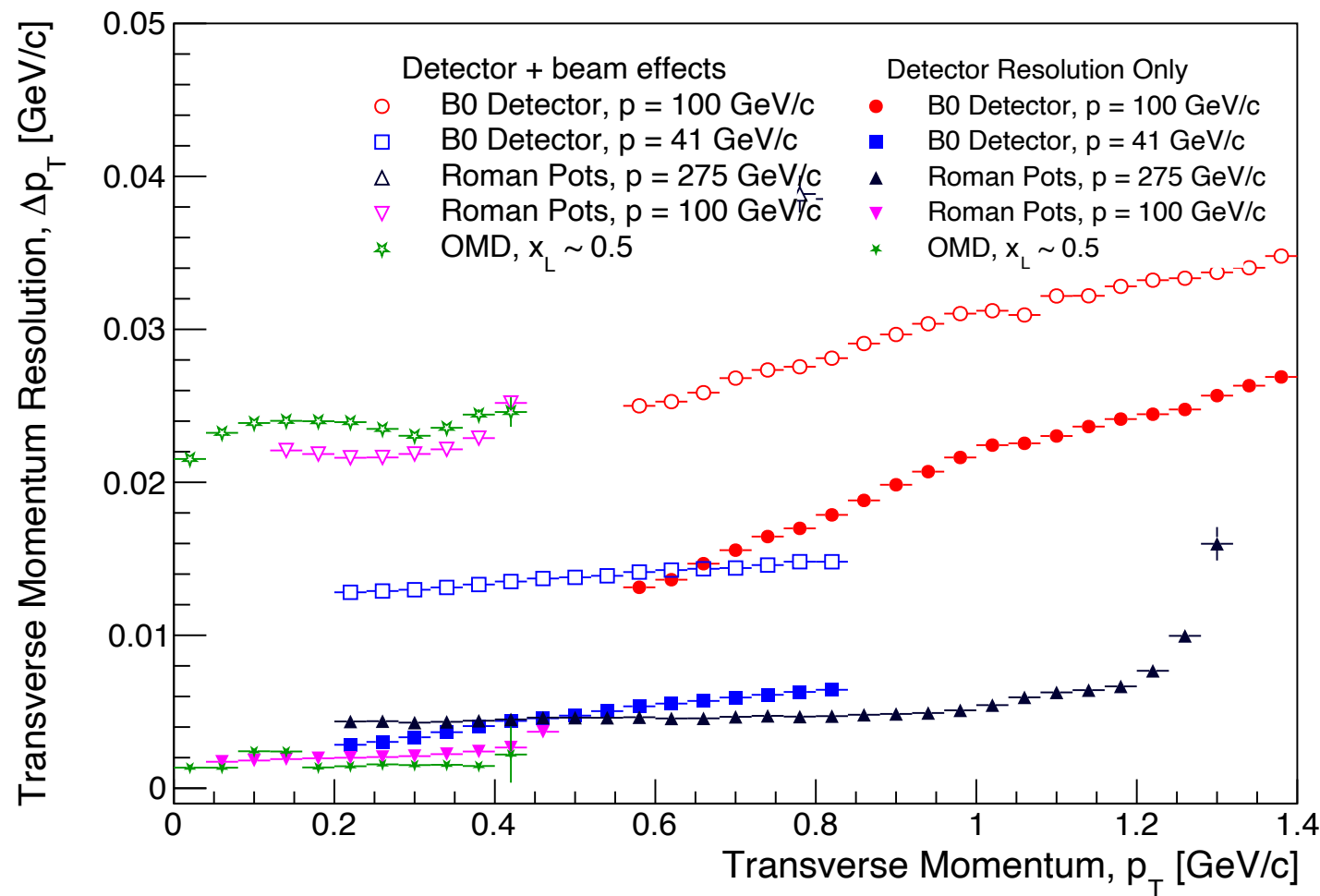$x_B \approx 1 - x_L$ longitudinal momentum loss

Need acceptance at $x_L \rightarrow 1$

Limited by accelerator; can be improved by secondary focus $\beta_x \approx 0$ at Roman Pots location

Critical benefits for coherent processes with light ions

Discussed for IR8; possible also at IR6

with forward spectrometry but **no** secondary focus

$p_\perp$ · 180 MeV/c · 0 MeV/c · 0 · 0.9 · 1 · x_L

with forward spectrometry and **secondary focus**

$p_\perp$ · 180 MeV/c · 0 MeV/c · 0 · 0.99 · 1 · x_L

Summary prepared by A. Jentsch

Proton momentum resolution

Simulations include detector resolution and beam effects: angular divergence, crabbing rotation, vertex smearing

Details depends on kinematics: Beam energy, subsystems used

Transverse momentum resolution achieved $\Delta p_T \sim 20$ MeV at low p_T

Longitudinal momentum resolution typically $\Delta\alpha_p/\alpha_p \lesssim 5\%$, significantly better for $\alpha_p \sim 1$

Neutron momentum resolution

$$\frac{\Delta E}{E} = \frac{50\,\%}{\sqrt{E}} \oplus 5\,\% \qquad\qquad \frac{\Delta\theta}{\theta} = \frac{3\,\text{mrad}}{\sqrt{E}}$$

with present ZDC design