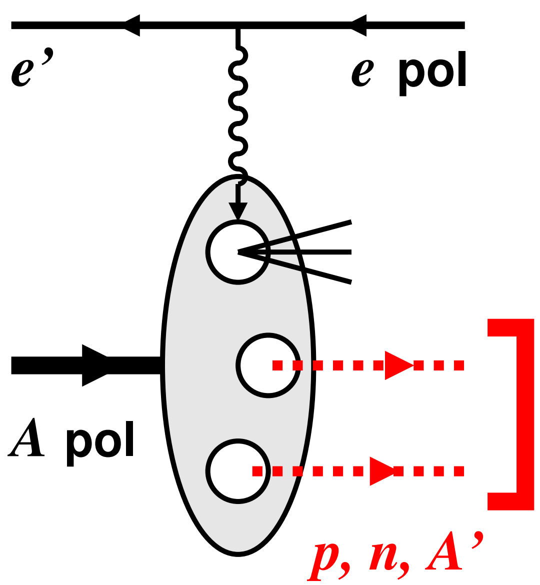
# Light-ion physics with EIC: Nuclear structure meets high-energy processes

C. Weiss (Jefferson Lab), Ohio University INPP Seminar, 10 Oct 2023

Jefferson Lab




**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

**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, NN interactions

Future: A > 2 systems, EFT methods, …

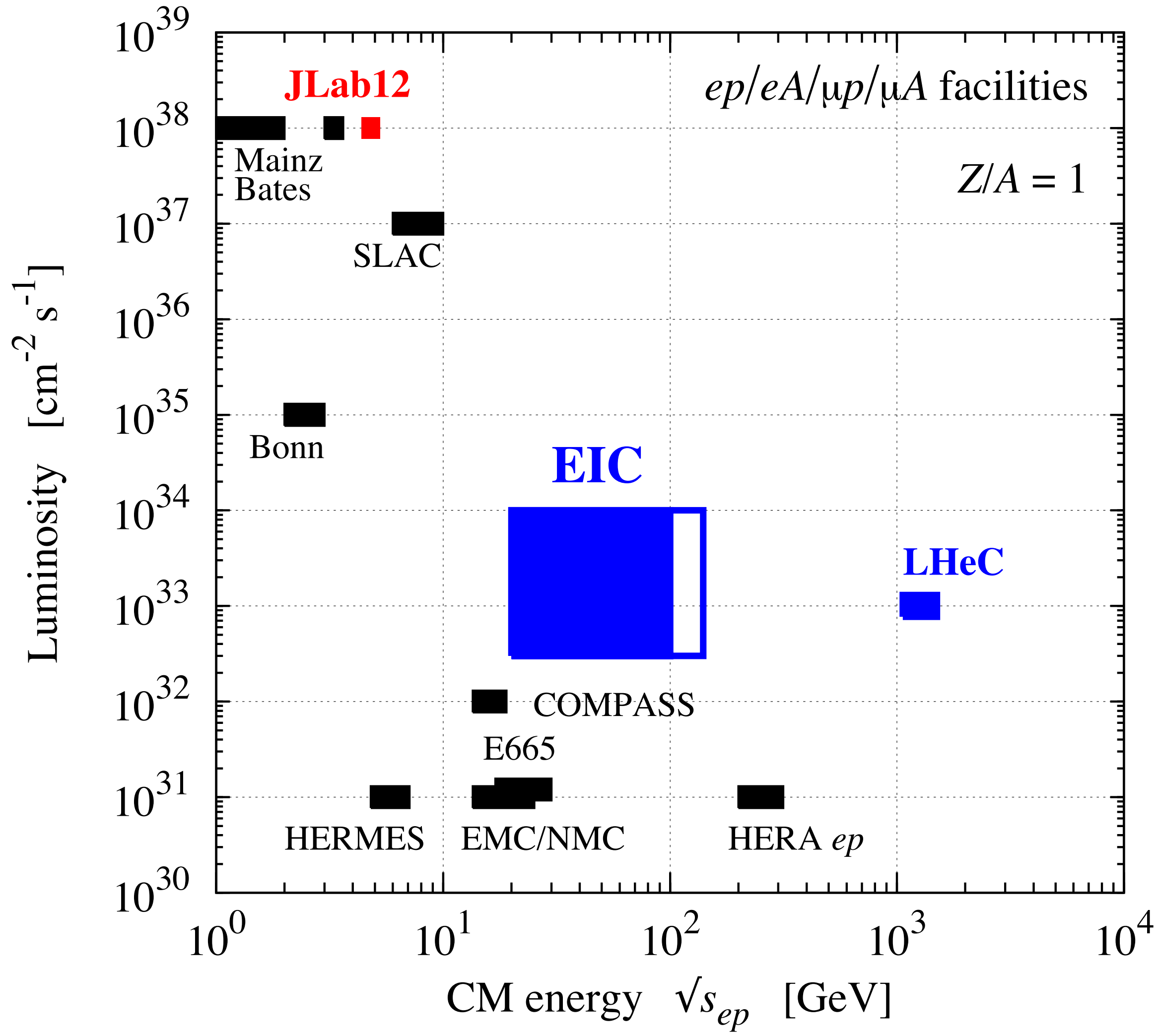
**Coherent processes with light nuclei**

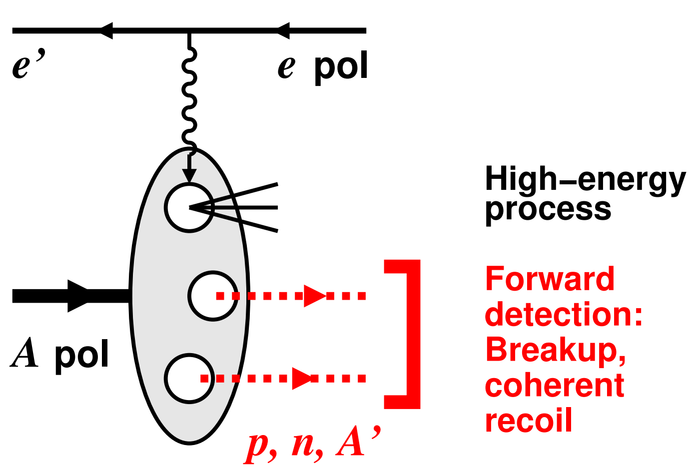
Nuclear GPDs, shadowing dynamics

**EIC far-forward detectors**

# Light ions: EIC capabilities






## CM energy

$\sqrt{s}_{ep}$ = 20 — 100 (140) GeV

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

High-energy processes: DIS, diffraction

## Luminosity

Up to ~$10^{34}$ $cm^{-2}$ $s^{-1}$ (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

## Forward detection of p, n, A'

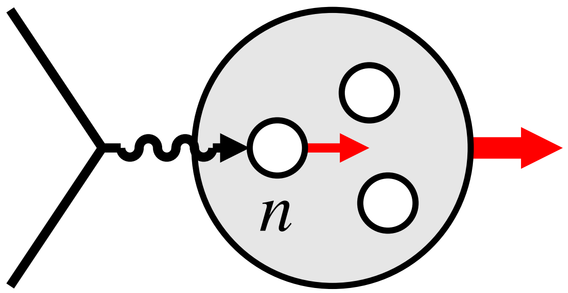
Nuclear breakup, spectator tagging

Exclusive and diffractive processes

Coherent nuclear processes A→A

# Light ions: Physics objectives

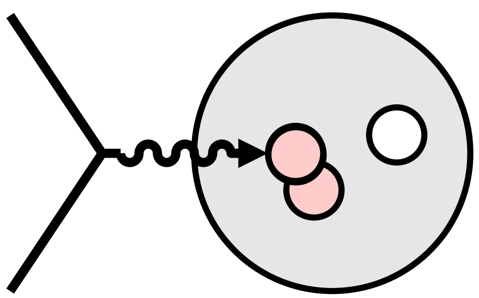





## Neutron structure

Flavor decomposition of quark distributions and spin

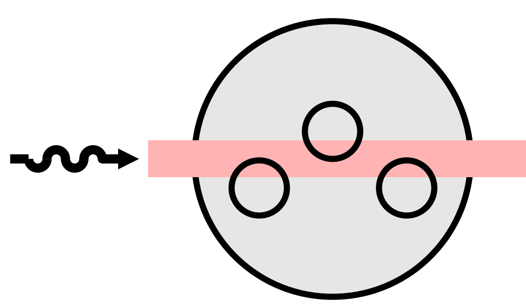
Singlet-nonsinglet separation in QCD evolution for $\Delta G$



## 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

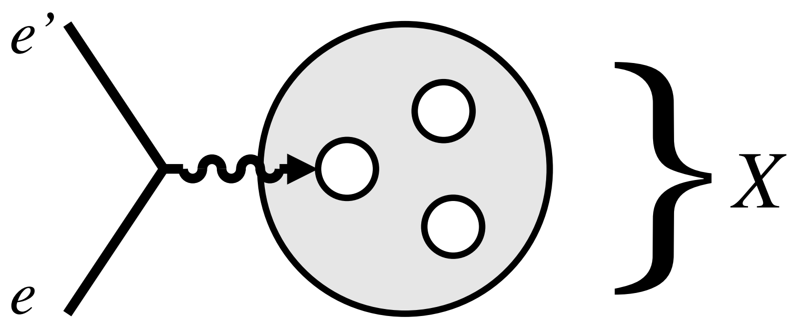
Nuclear shadowing $x \ll 0.1$

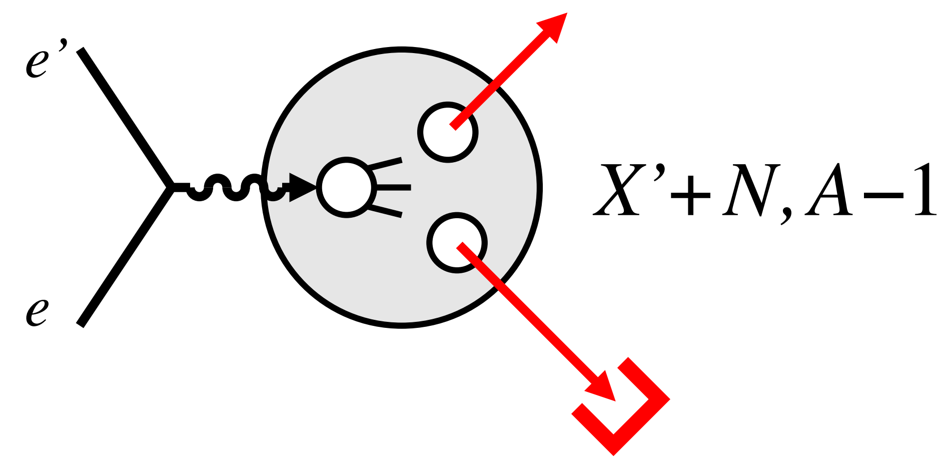
Buildup of coherence, interaction with 2, 3, 4… nucleons?
$\leftrightarrow$ Shadowing and saturation in heavy nuclei

[Nucleus rest frame view]

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

# Light ions: 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 $\Sigma_X$

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

## Nuclear breakup detection - tagging

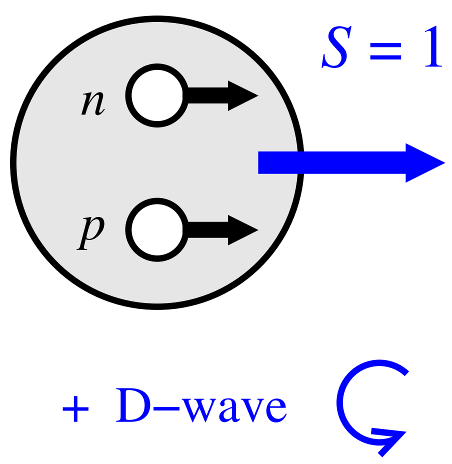
Potential information on initial-state nuclear configuration

Study effects in defined configurations, much simpler

Final-state interactions important, influence breakup amplitudes

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

# Light ions: Deuteron and spectator tagging



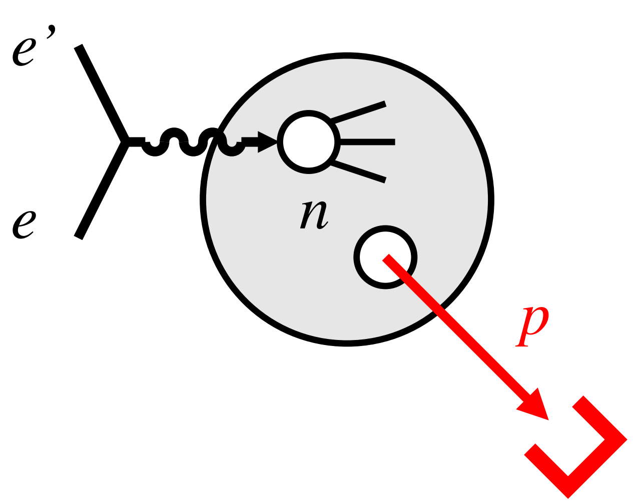

## Deuteron as simplest system

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

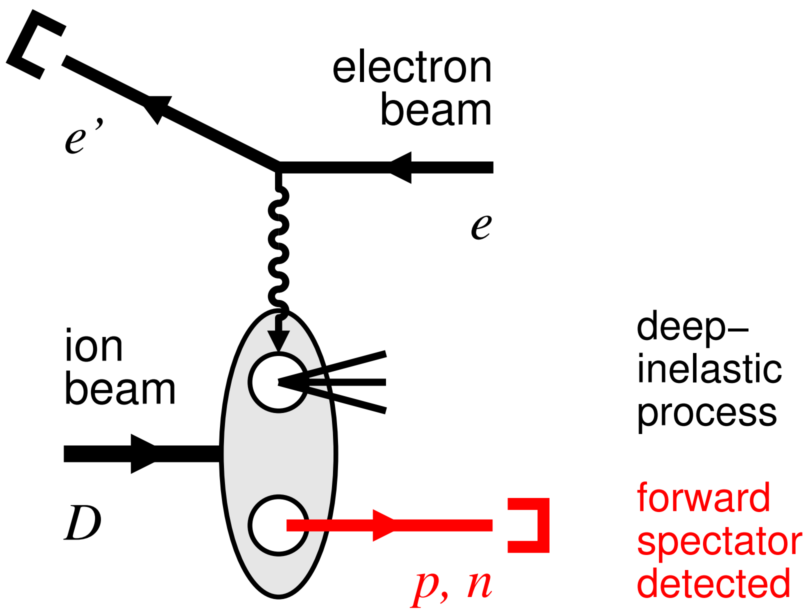
Controls configuration through recoil momentum:
spatial size → interactions, S/D wave

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

# Light ions: Spectator tagging with EIC






[Collider frame view]

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 $$P_{\parallel p} \approx \frac{P_D}{2}\left(1 + \frac{p_p^z}{m}\right)$$

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

**Advantages over fixed-target**

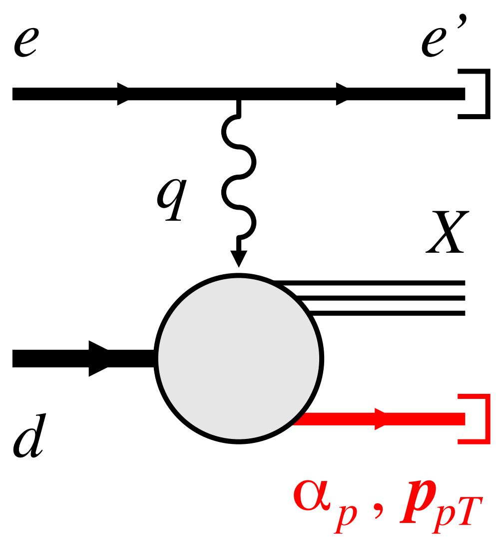
No target material. Can detect spectators with rest frame momenta down to ~zero

Setup acts as magnetic spectrometer for protons, good acceptance and resolution

Neutron detection with Zero-Degree Calorimeter

Unique opportunity for EIC!

# Theory: Tagged DIS cross section




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

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

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

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

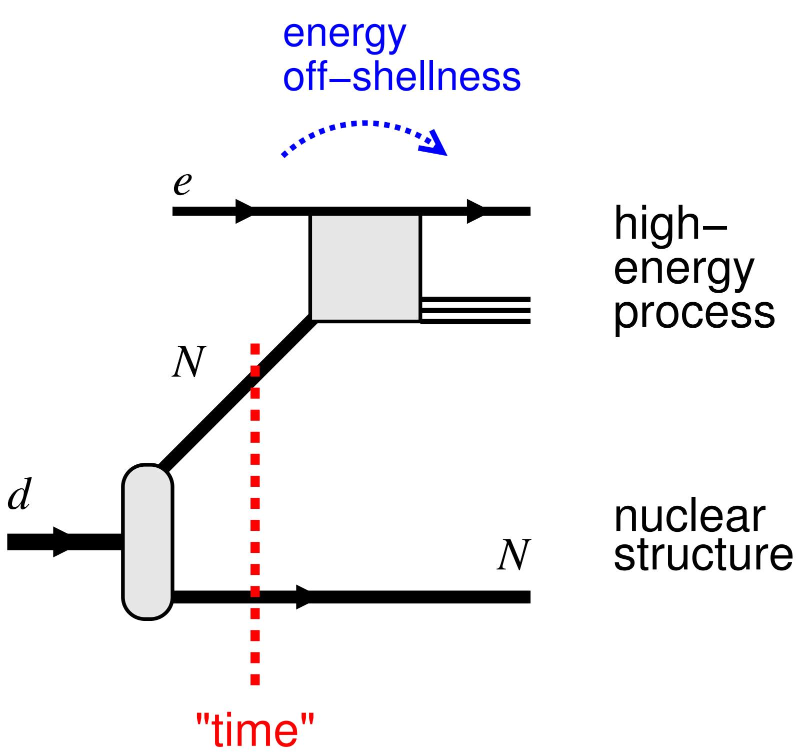
Collinear frame: Virtual photon and deuteron momenta collinear $\mathbf{q} \parallel \mathbf{p}_d$, along z-axis

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]




**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

Energy off-shellness depends on choice of “time” variable

**High-energy limit** $s \to \infty$

Usual time $x^0$: Energy off-shellness grows with $s$

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

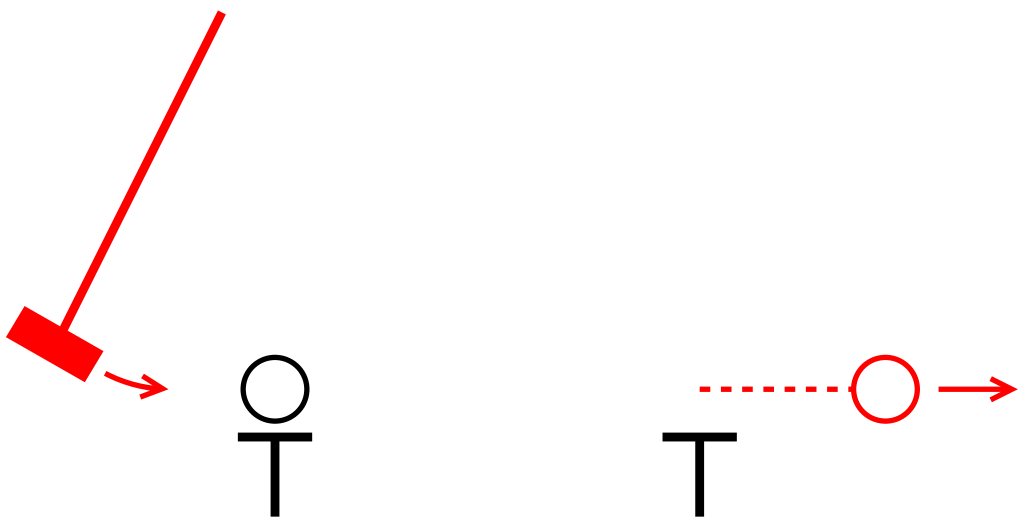
Enables composite description of high-energy scattering on nucleus:
Separation of nucleus and nucleon structure
Use of on-shell nucleon amplitudes/cross sections, measured in eN scattering
Limited role of non-nucleonic DoF

[Frankfurt, Strikman 80s]

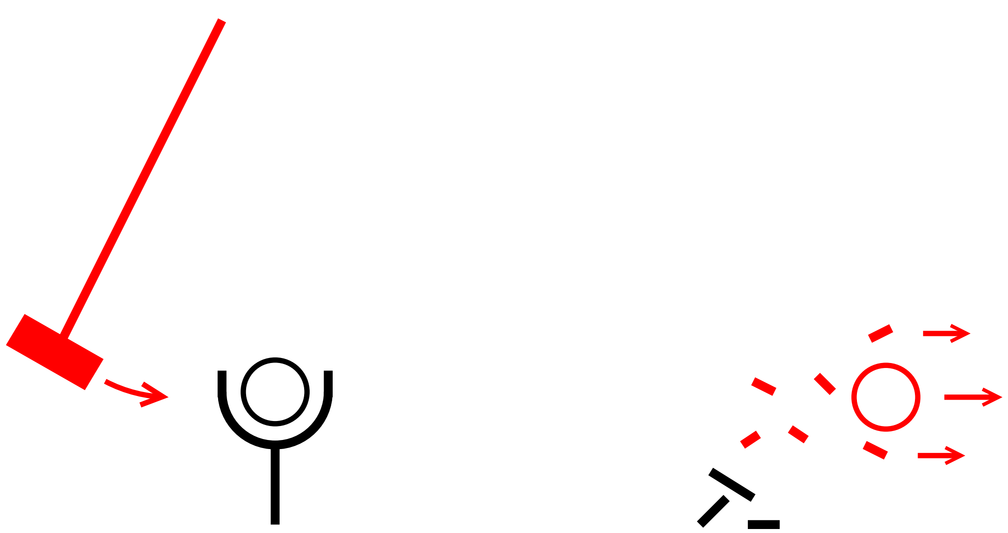
# Theory: Light-front quantization



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

# Theory: Nuclear light-front wave function

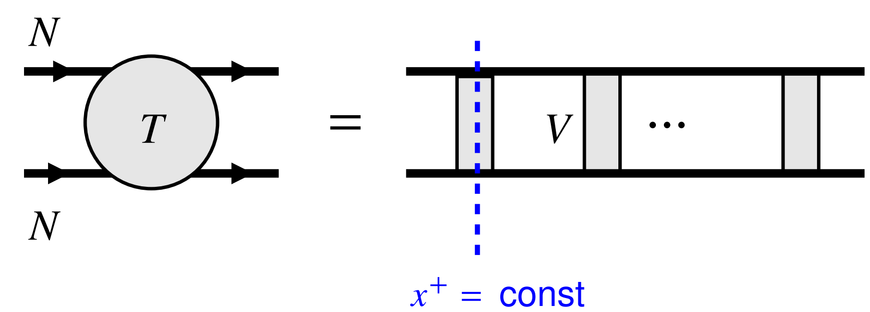
**LF bound state equation**

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]




**Approximation constructed from nonrelativistic wave function (A = 2)**

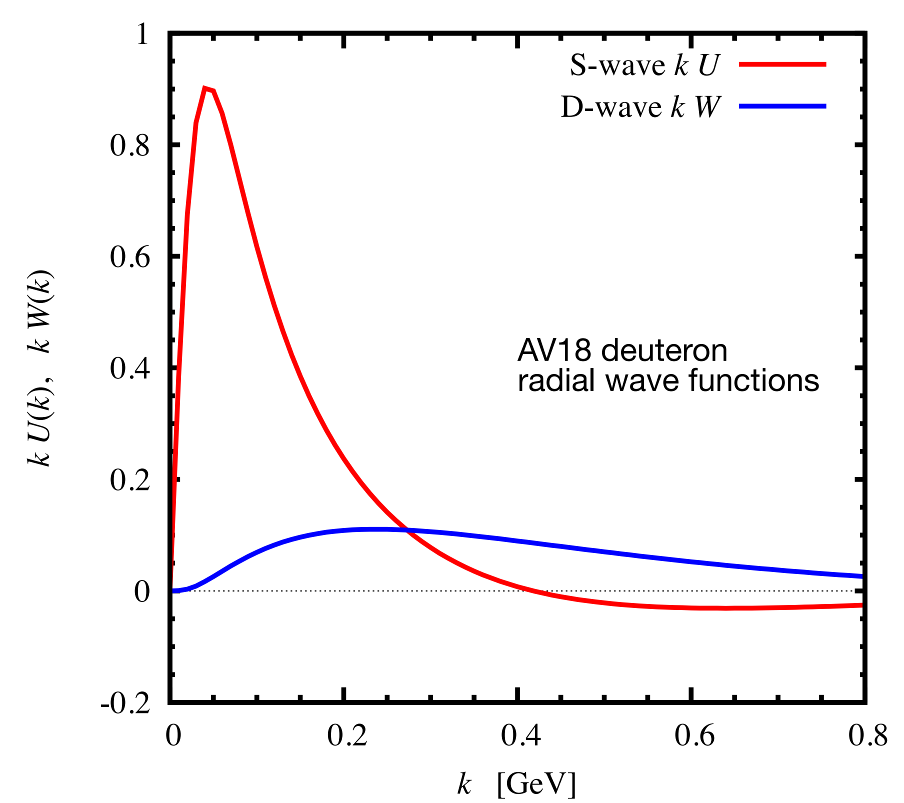
Rotationally symmetric representation of LF variables:
$\mathbf{k}(\alpha_p, p_{pT})$ = 3-momentum in pn CM frame [Terentev 1976]

Match LF and nonrelativistic wave functions:

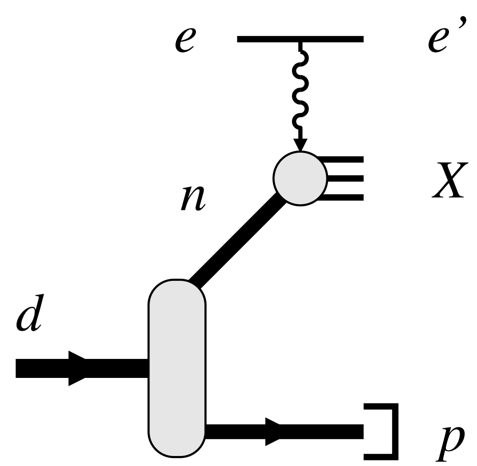
$$\Psi_{\rm LF}(\alpha_p, p_{pT}) \;=\; N\,\Psi_{\rm nonrel}(\mathbf{k})$$

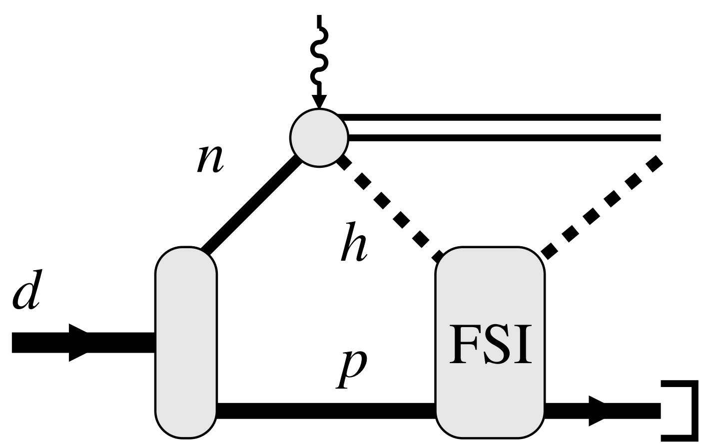
Approximation safe for $k \lesssim$ 300 MeV, possibly larger

Imports knowledge of NN interactions in non-relativistic NMBT



# Tagging: 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

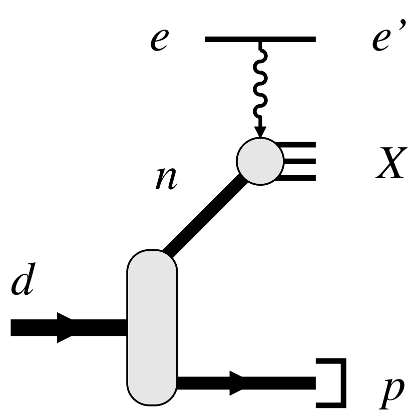
**Strategy**

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

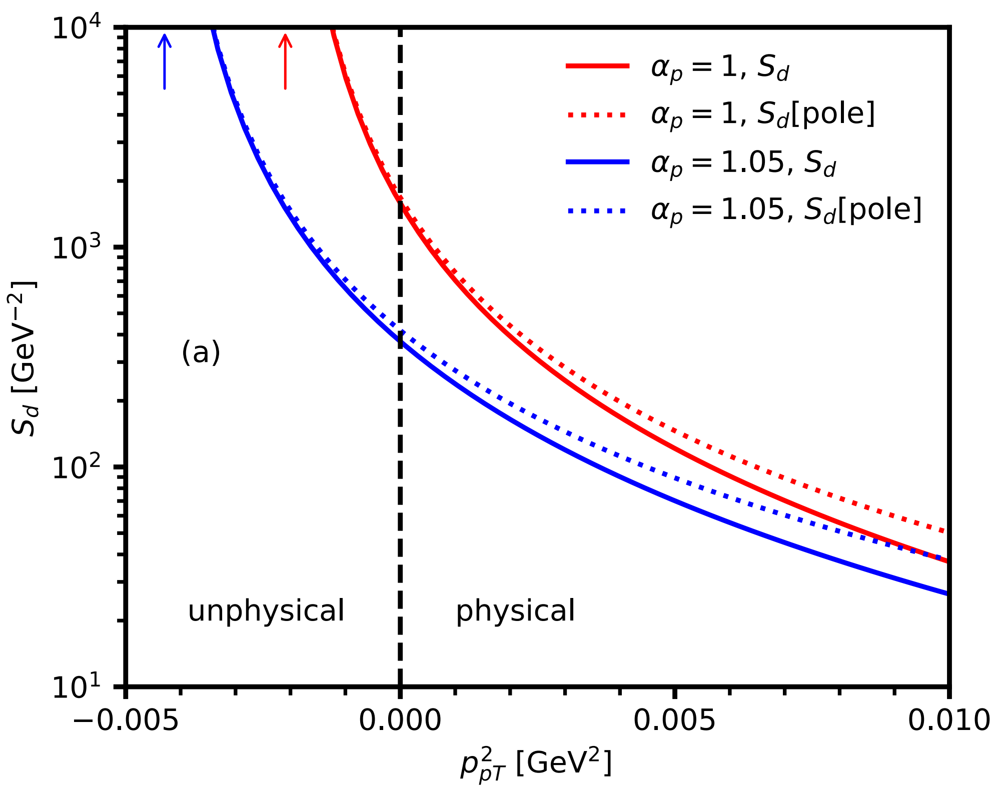
"Select configurations" in nucleus

# Tagging: Free neutron structure






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




Deuteron wave function has pole in unphysical region describing $pn$ configurations of size $\rightarrow \infty$

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 $\alpha_p$ as function of $p_{pT}^2 > 0$

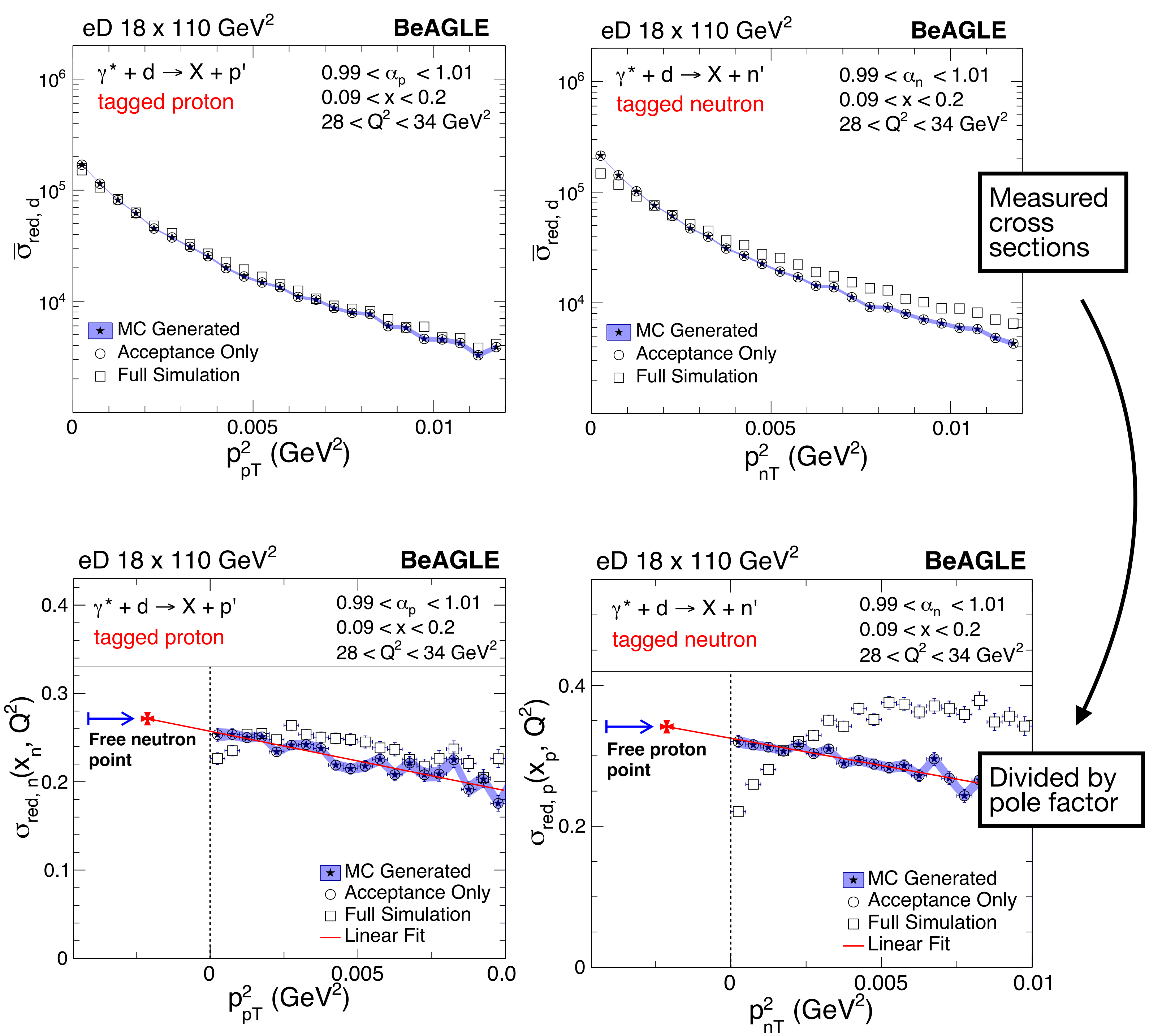
Divide data by pole term of spectral function

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

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

# Tagging: Free neutron structure






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

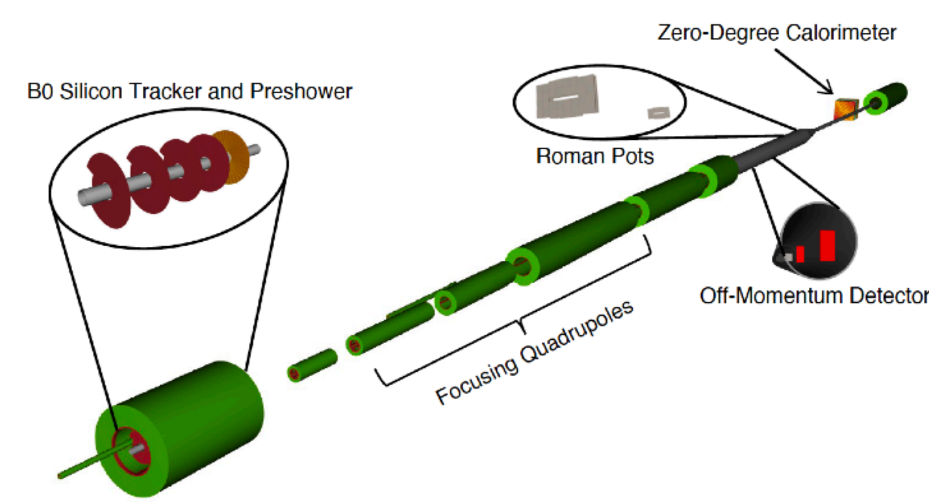
EIC Yellow Report 2021

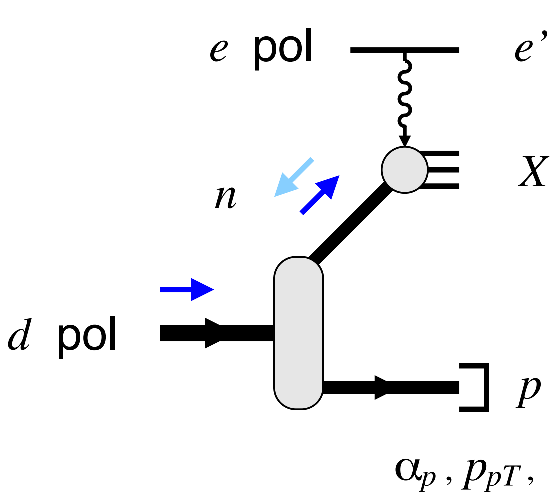
EIC simulations: p and n tagging, pole extrapolation, uncertainty analysis, validation

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.



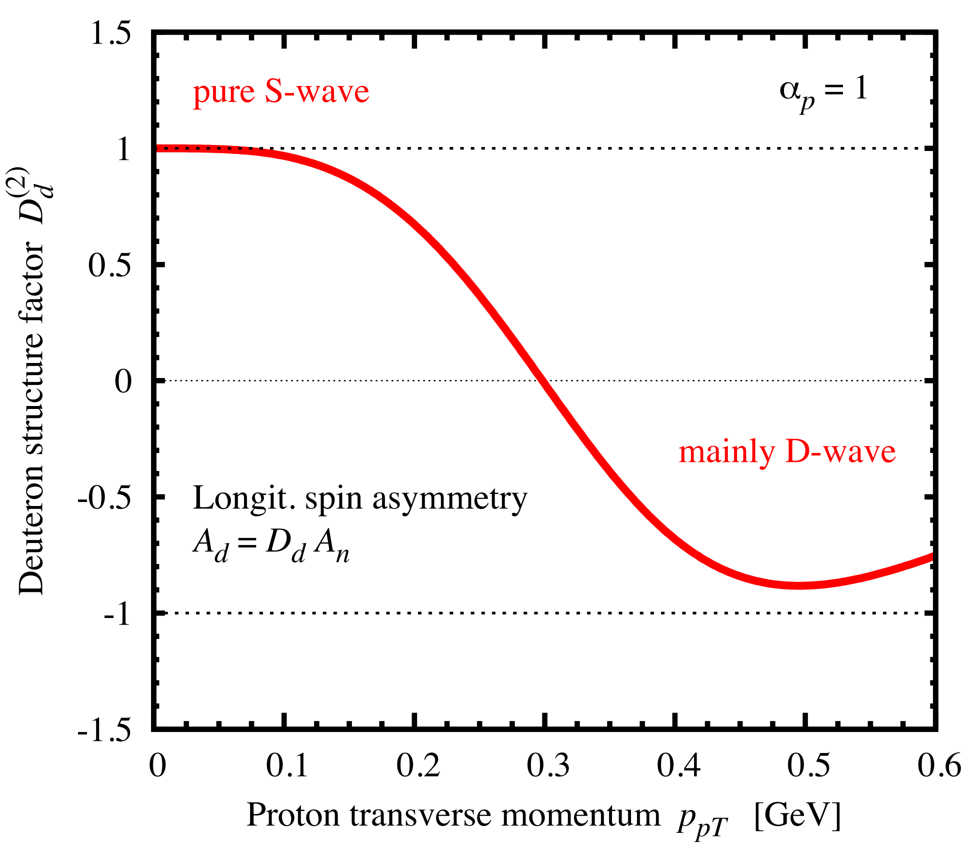



$A_{\parallel,d}(x, Q^2; \alpha_p, p_{pt})$ tagged longitud double spin asymmetry

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

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

$D_d(\alpha_p, p_{pT})$ 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!

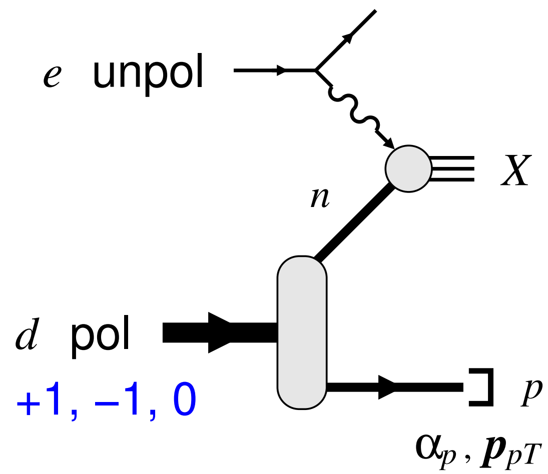
EIC simulations: JLab LDRD 2014/15

Frankfurt, Strikman 1983

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

# Tagging: Tensor polarized asymmetry



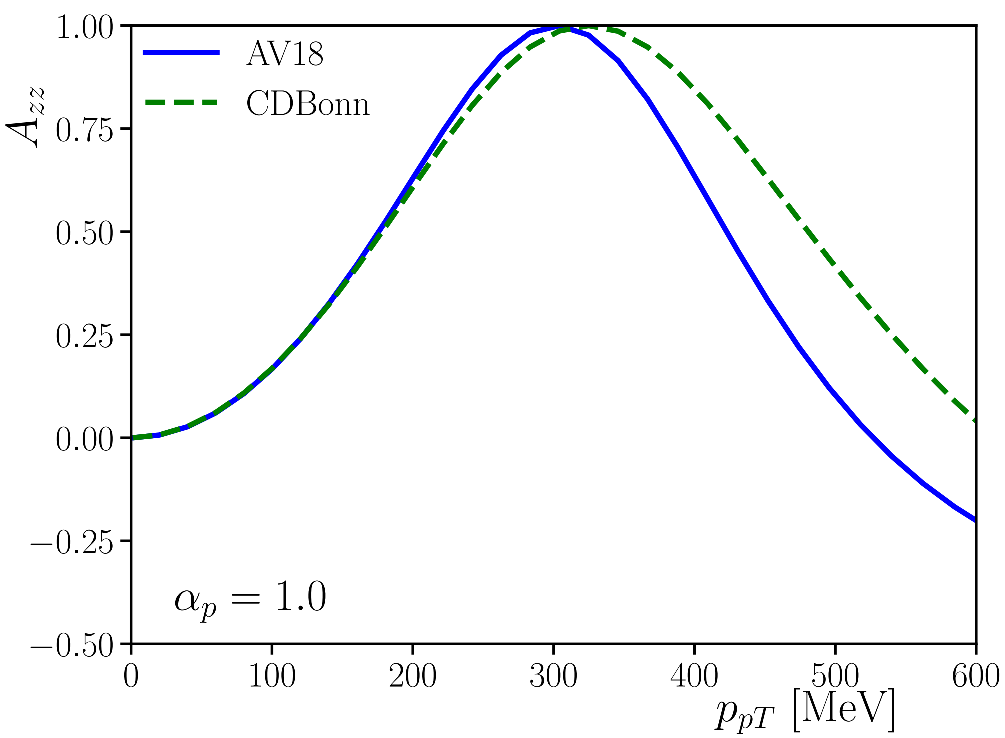



$$A_{zz,\,d}(x, Q^2; \alpha_p, \mathbf{p}_{pt})$$ tagged tensor polarized asymmetry

$$= \frac{d\sigma(+1) + d\sigma(-1) - 2d\sigma(0)}{d\sigma(+1) + d\sigma(-1) + d\sigma(0)}$$ $-2 < A_{zz,\,d} < 1$

$$= \frac{S_d(\alpha_p, p_{pT})[T_{LL}]}{S_d(\alpha_p, p_{pT})[U]}$$ effective tensor polarization, depends on tagged momentum

$$= \frac{\frac{1}{\sqrt{2}} UW + \frac{1}{4} W^2}{U^2 + W^2} \times \text{Angular}$$ requires 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

**Tagged EMC effect**

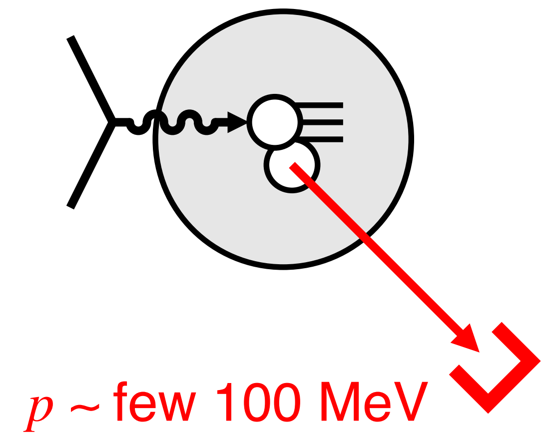
Modification of nuclear parton density observed at $0.3 < x < 0.7$

What NN distances/momenta cause modification?

Use spectator momentum to fix momentum/size of pn configuration

Tagged cross section also affected by final-state interactions.
Needs theoretical estimates → Supplement
Strikman, Weiss 2017

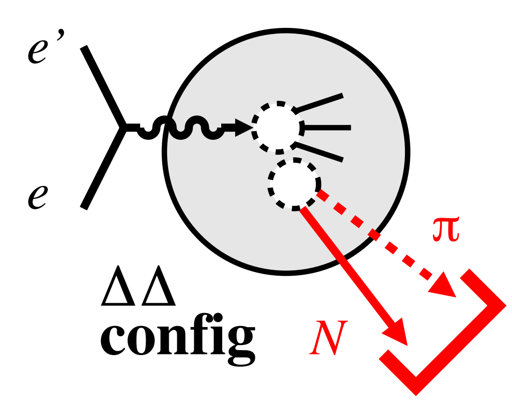
EIC simulations in progress
Jentsch, Tu, Weiss, in progress




**Tagging ΔΔ configurations**

Measure $e + D \rightarrow e' + X' + \pi + N$, reconstruct $\Delta$

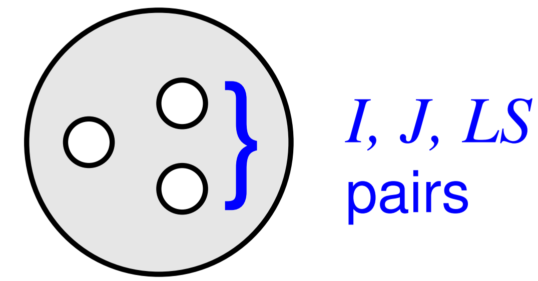
Direct demonstration of non-nucleonic degrees of freedom



# Tagging: 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

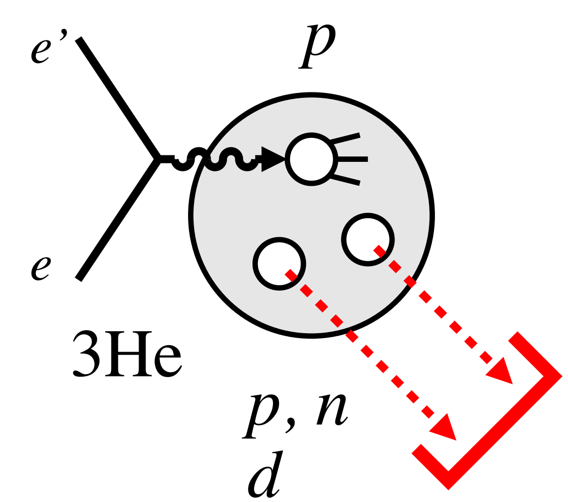



Light-front structure more complex:
Angular momentum coupling, LF ↔ nonrelativistic correspondence
Lev 1990s; Salme et al. 2000s

**Nuclear breakup processes A > 2**

2-body: e + 3He → e’ + X + d

3-body: e + 3He → e’ + X + pn, pp

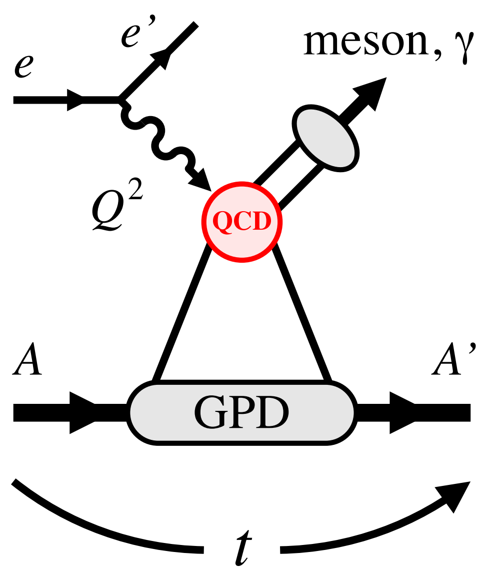


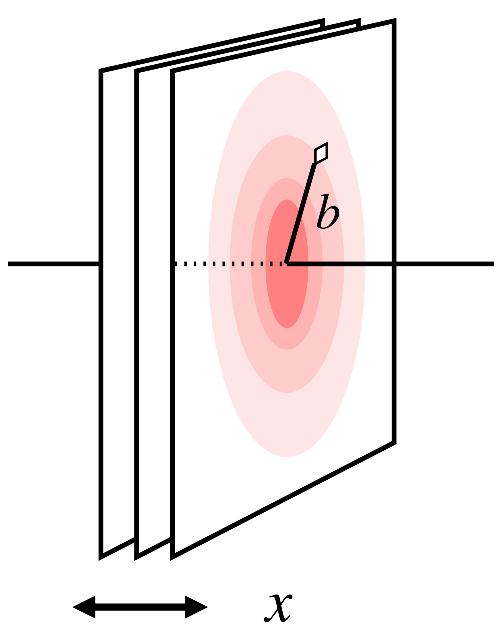

Breakup more complex: Nuclear interactions in final state, distorted waves, wave function overlap factors

Needs extensive nuclear structure input!

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

# Coherent processes: Nuclear GPDs




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

## 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 ↔ gluon, charge ↔ matter distributions

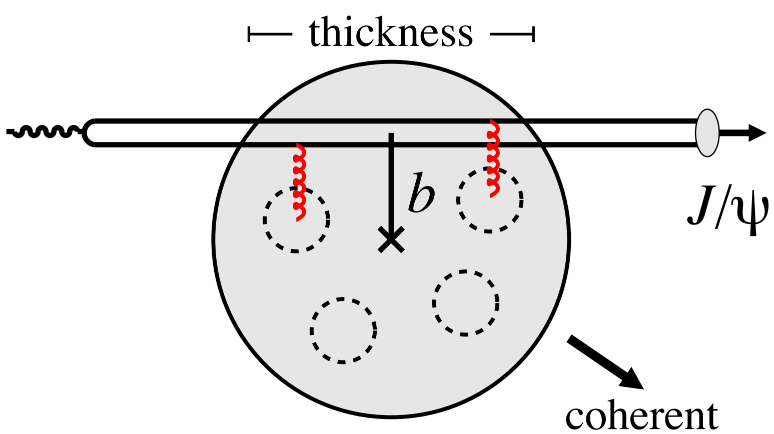
Dynamics: Spatial distributions change with $x$, polarization

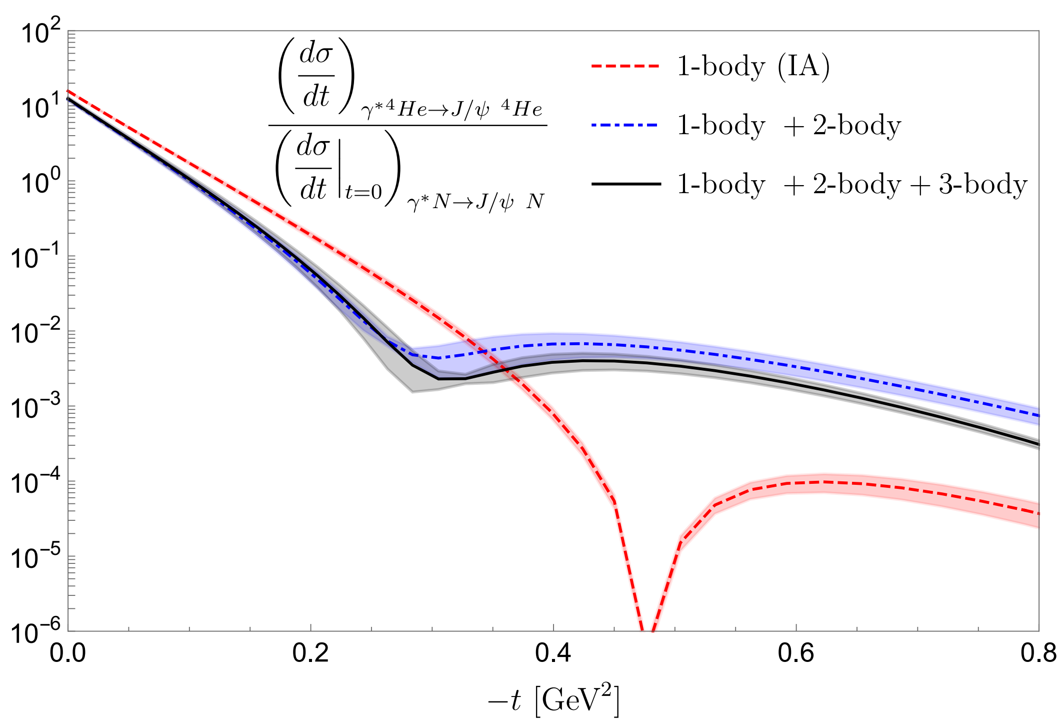
## Nuclear quark/gluon imaging with EIC

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

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

# Coherent processes: Nuclear shadowing




Guzey, Rinaldi, Scopetta, Strikman, Viviani 2022

## 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 $J/\psi$ photoproduction in ultraperipheral AA collisions at LHC

## Light nuclei

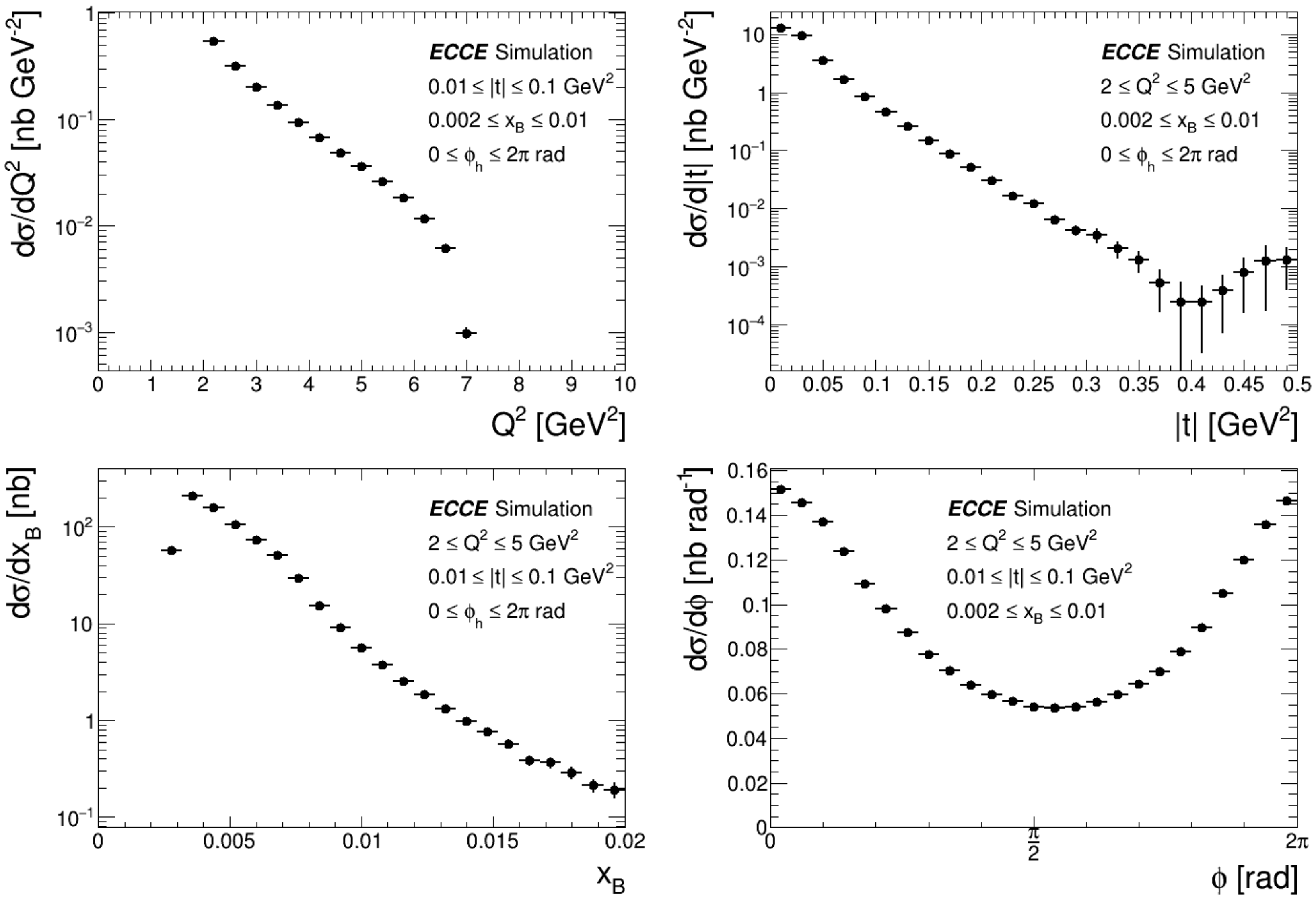
$d\sigma/dt =$ 1-body + 2-body + ... multiple scattering

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

# Coherent processes: EIC simulations





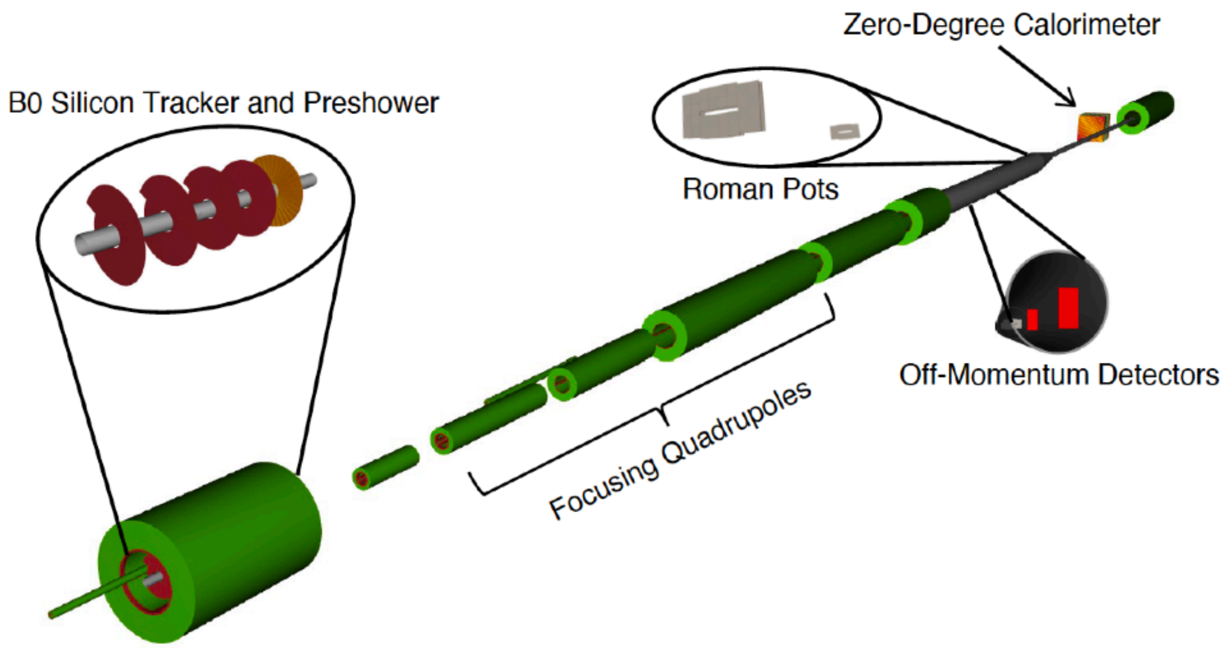

Simulations of coherent DVCS on 4He with ECCE detector

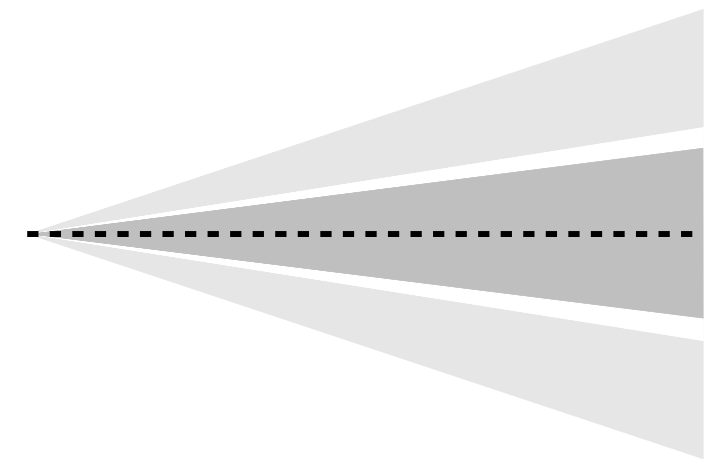
Bylinkin et al 2022

Event generator TOPEG

Dupre, Fucini 2022

# EIC far-forward detectors 




**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 $\theta$

Complex system,
integration is major challenge

# EIC far-forward detectors

| Protons | $\theta$ | $x_L$ | |
|---|---|---|---|
| | < 5 mrad | 0.2 — 0.6 | Off-momentum det |
| | < 5 mrad | > 0.6 | Roman Pots |
| | 5.5 — 20 mrad | any | B0 tracker |

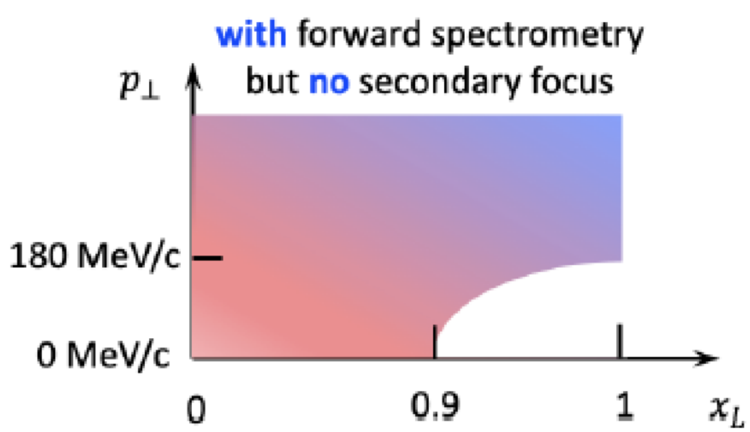
| Neutrons | | | |
|---|---|---|---|
| | < 4 mrad | any | ZDC |

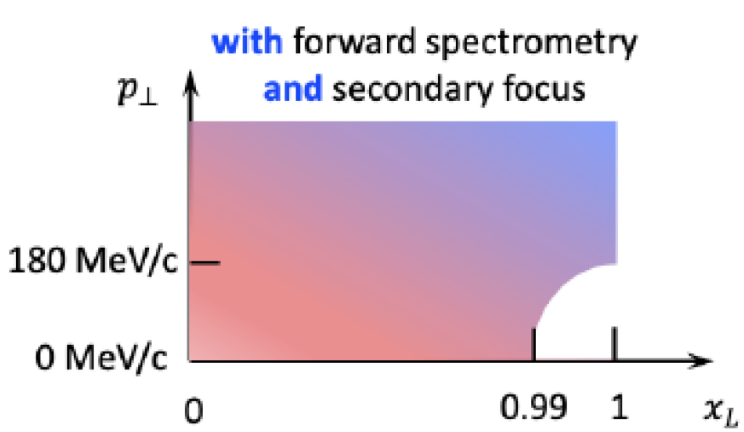
**Spectator tagging**

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

Different subsystems used depending on spectator proton kinematics

Detector resolution → Supplement




**Coherent scattering**

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

$x_B \approx 1 - x_L$ longitudinal momentum loss

Need acceptance at $x_L \to 1$

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

# Summary



Light ion physics most interesting and novel 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

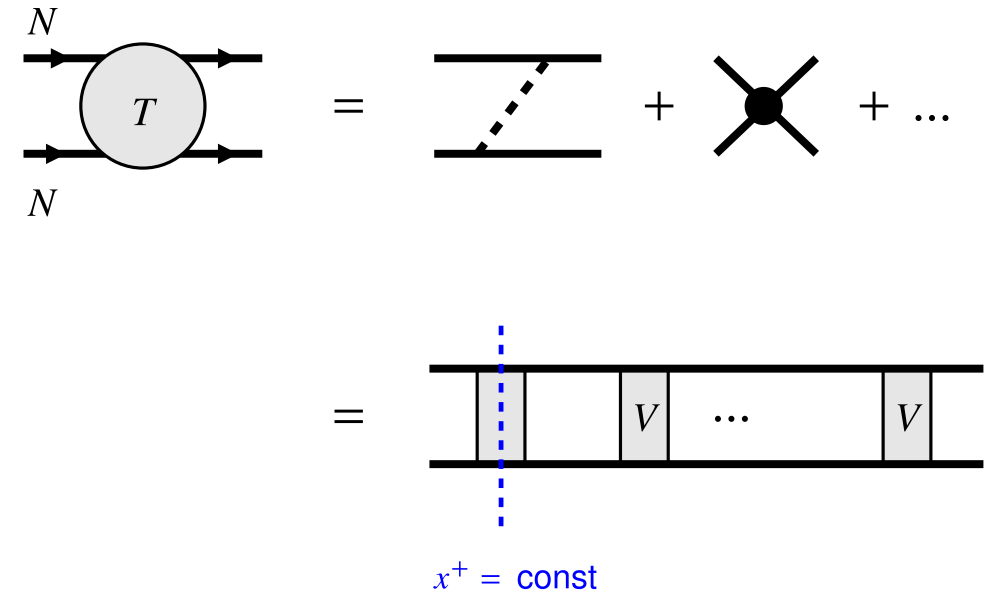
Coherent scattering on light ions: Quark-gluon imaging of nuclei, origin of nuclear shadowing

*Synergies with JLab12 + beyond*

*Rising program — many opportunities, long-term prospects*

# Supplemental material

# Theory: EFT interactions




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

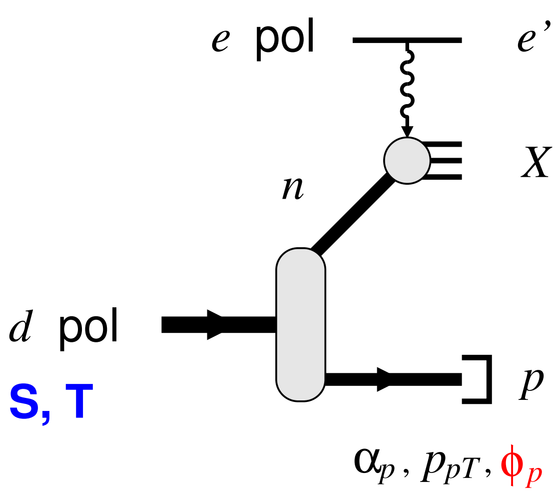
Planned: F. Vera, Weiss

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

# Tagging: Polarized deuteron observables




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

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

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

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

**Vector and tensor polarization**

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

3 vector, 5 tensor parameters

**Spin observables**

U + S + T cross section

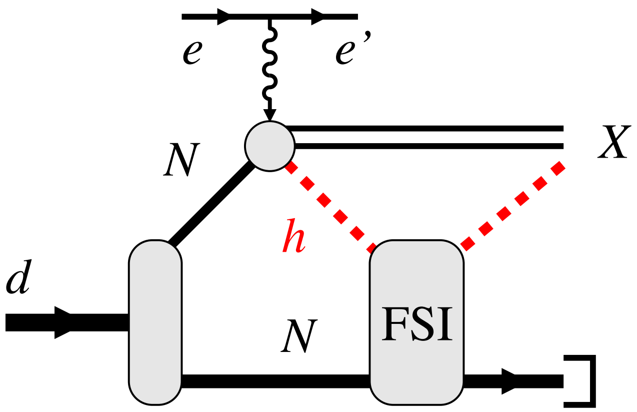
$\phi_p$-dependent structures

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

T cross section has 23 new structures, some with $\phi_p$-dep unique to T polarization

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

# Tagging: Final-state interactions

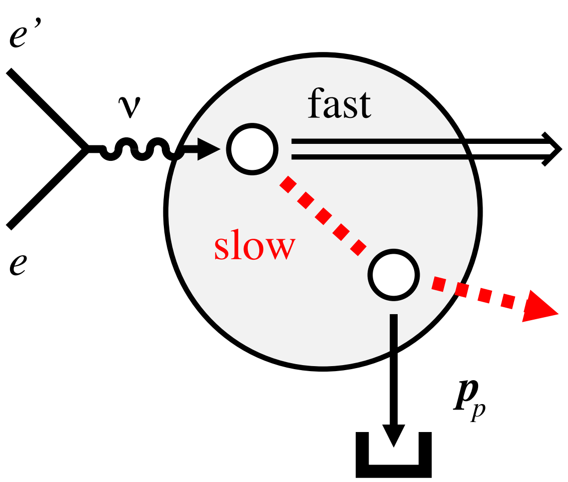



Part of final state of high-energy process interacts with spectator

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)**




[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

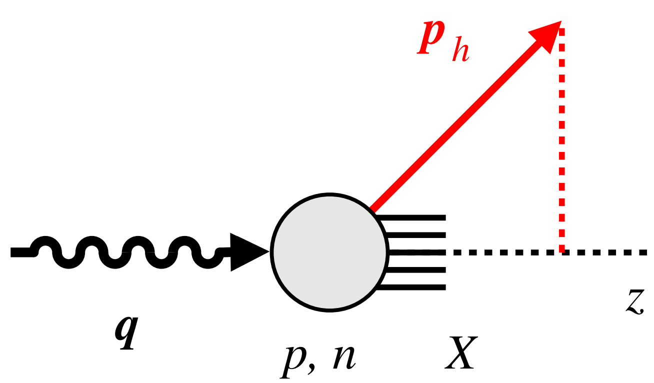
"Fast" hadrons $E_h = \mathcal{O}(\nu)$ —current fragmentation region:
Formed outside nucleus, interaction with spectator suppressed

"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!

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

Picture respects QCD factorization of target fragmentation: FSI only
modifies soft breakup of target, no long-range rapidity correlations

# Tagging: Final-state interactions

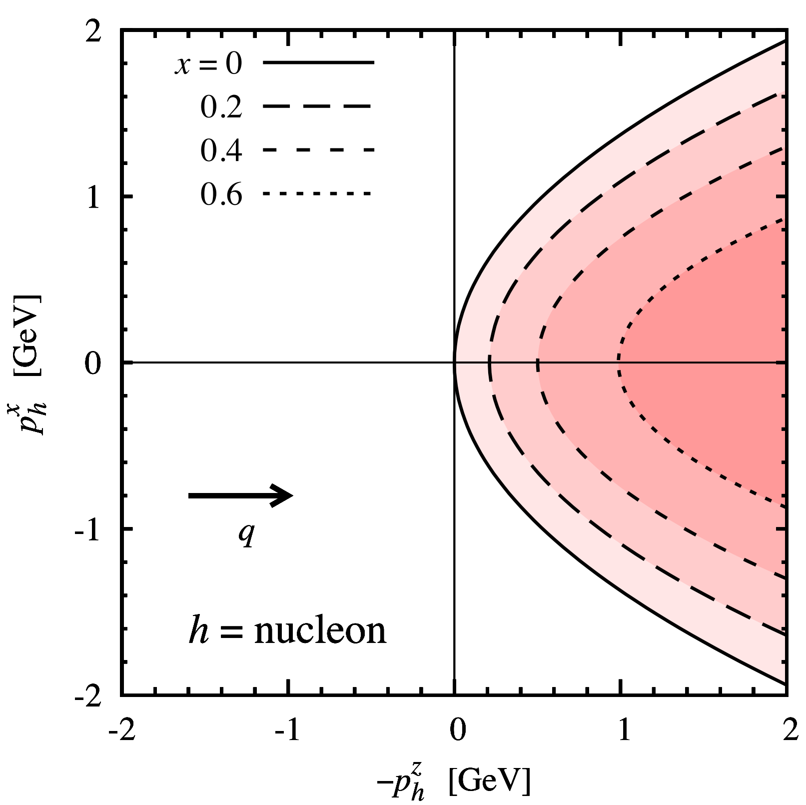



Studied distributions of slow hadrons in DIS on nucleon — target fragmentation

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

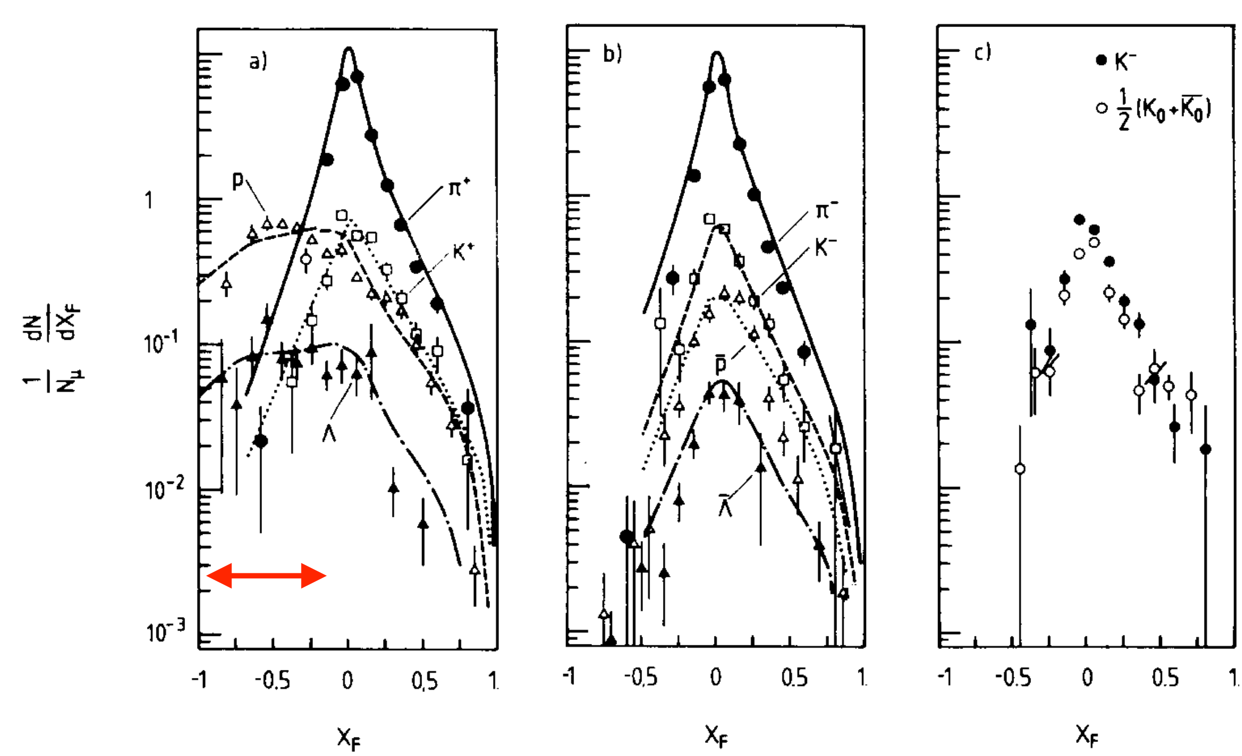
Used experimental distributions: HERA, EMC, neutrino DIS

Need better data on target fragmentation: JLab12, EIC!




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

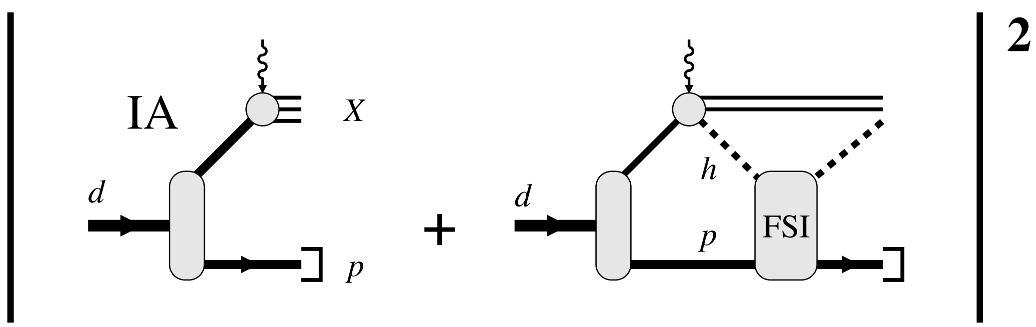
Hadron xF distributions EMC 1986

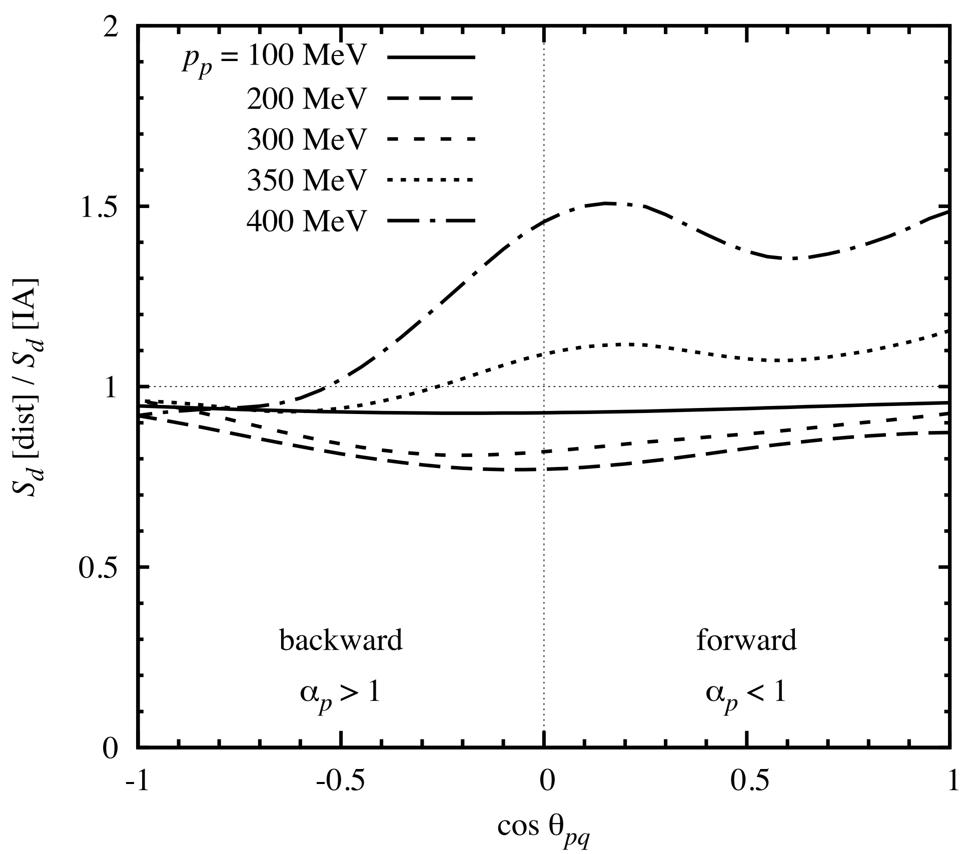



Strikman, Weiss PRC97 (2018) 035209

# Tagging: Final-state interactions






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

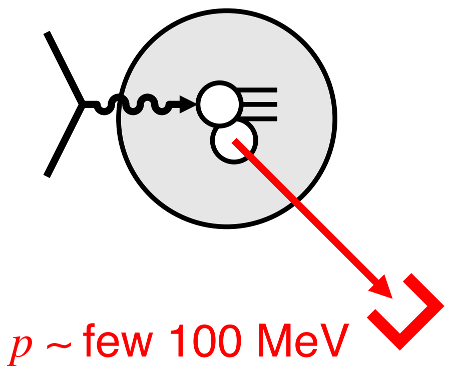
## Momentum and angular dependence

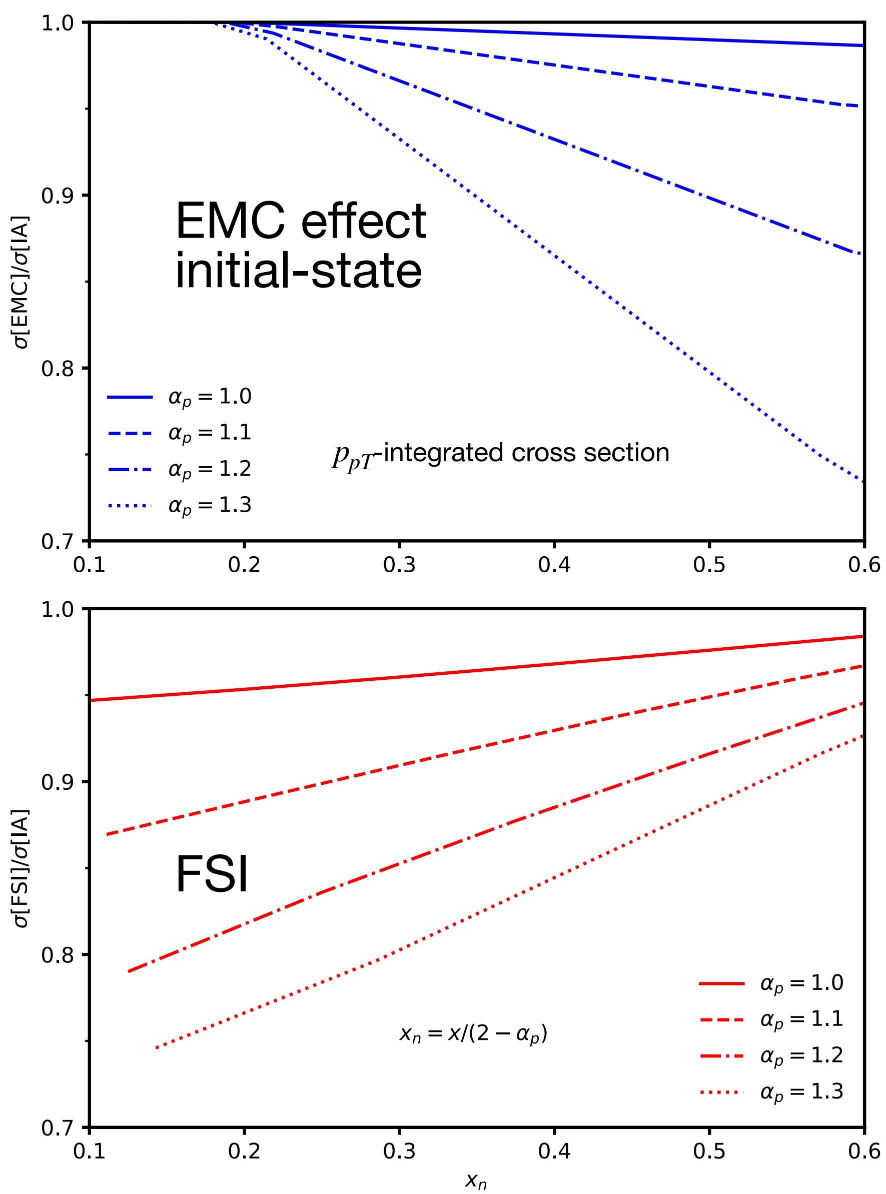
$p_p \lesssim$ 300 MeV: IA x FSI interference, absorptive, weak angular dependence

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

Results used in EIC simulations, analysis of JLab12 BAND experiment

# Tagging: Tagged EMC effect




**EMC effect**

Modification observed in nuclear DIS $0.3 < x < 0.7$

What NN distances/momenta cause modification?

Control configurations with tagging!

**EIC simulations**

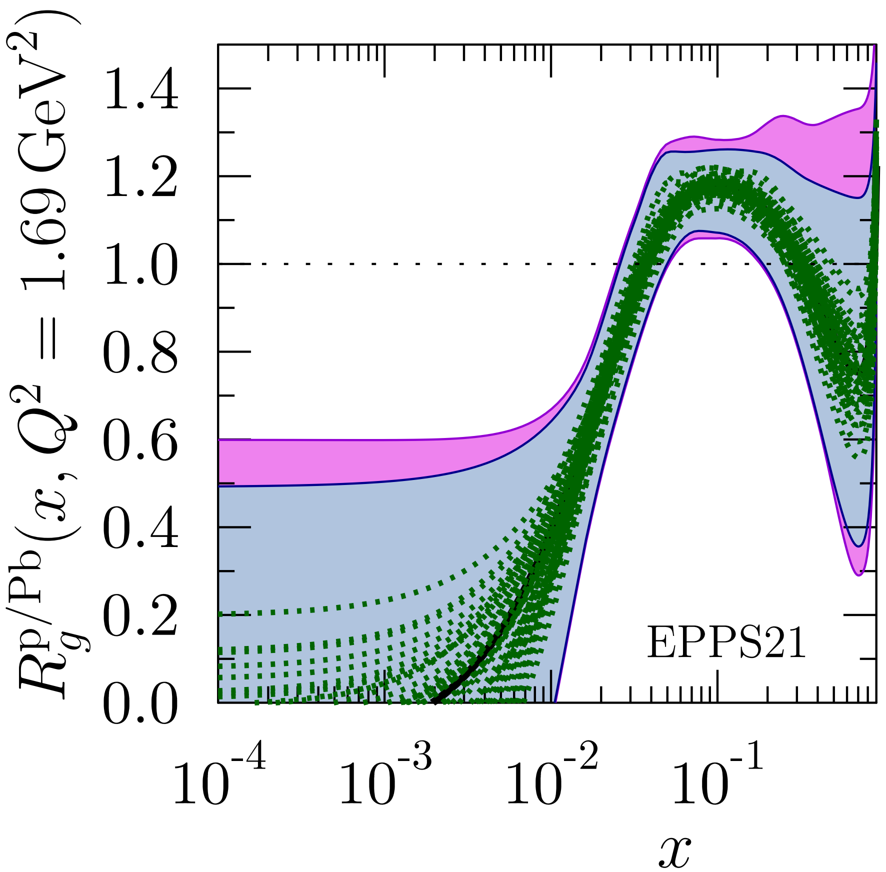
Use proton and neutron tagging
$\alpha_{p,n} > 1,\ p_T \sim$ few 100 MeV

Initial-state modifications and final-state interactions are of the same order, need strategy for separation

Simulations including statistics, optimization of analysis
Jentsch, Tu, Weiss, in progress

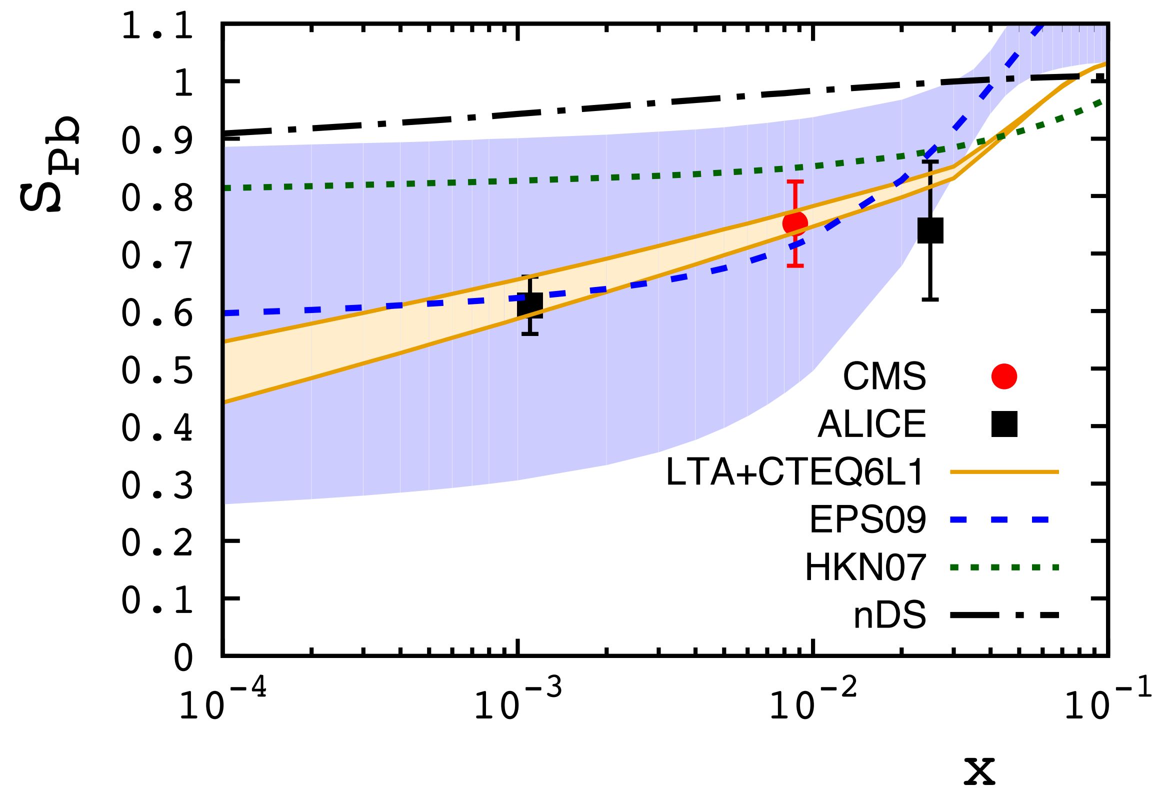
Could be extended to polarized deuteron

# Shadowing: Gluon shadowing in heavy nuclei



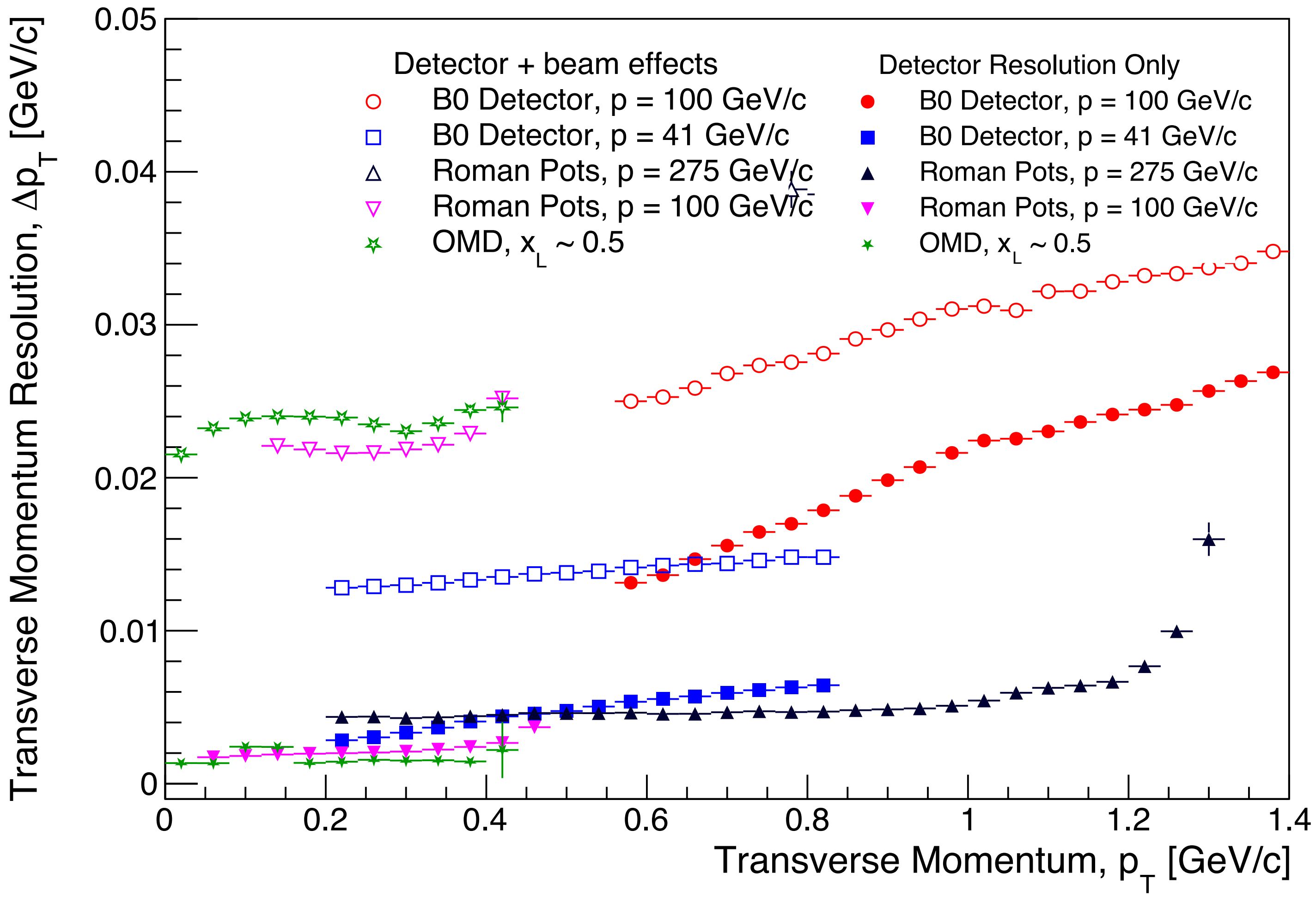

Nuclear gluon PDF ratio $R_g$ in Pb extracted in EPPS21 global analysis

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

# EIC far-forward detectors: Momentum resolution




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

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

with present ZDC design