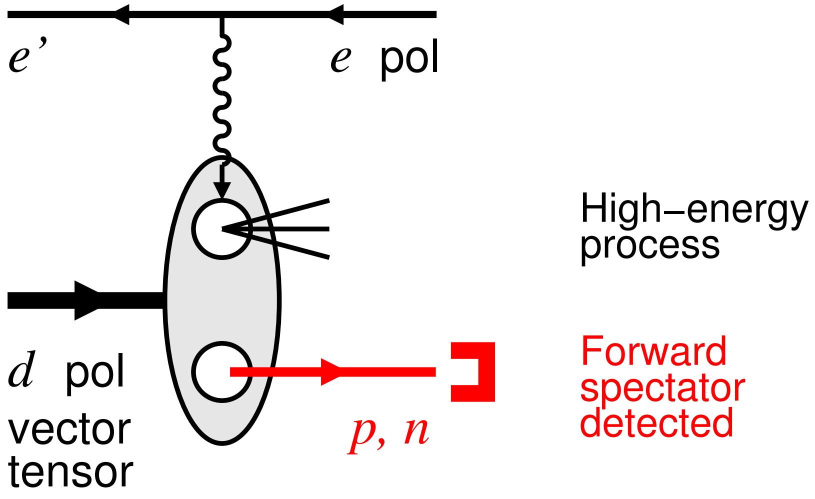
Spectator tagging with polarized deuteron at EIC

C. Weiss, SPIN 2023, Durham NC, 25 Sep 2023



Idea: Control nuclear configuration during high-energy process through spectator detection

→ Identify active neutron or proton

→ Control nuclear interactions, modifications

→ Control neutron polarization, S/D wave

This presentation:
Review tagging with unpolarized deuteron at EIC
Discuss opportunities with polarized deuteron

Polarized light ion physics

Objectives and challenges

Control nuclear configurations!

Deuteron and spectator tagging

Cross section $e + d \to e' + p + X$

Polarized deuteron structure

Applications at EIC

Free neutron structure with tagging

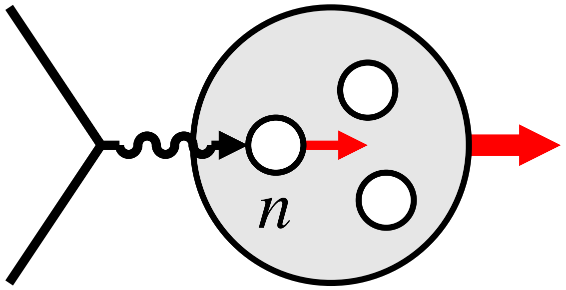
Neutron spin structure with tagging

Tensor-polarized asymmetries

Initial-state modifications EMC effect

Technical realization

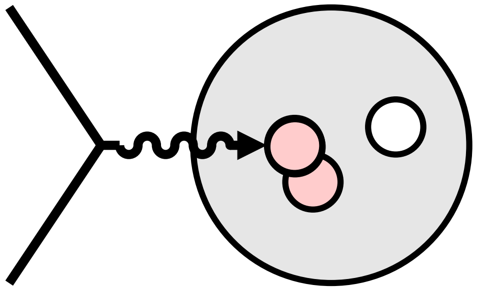
Light ions: Physics objectives



Neutron spin structure

Flavor decomposition of quark PDFs/spin, GPDs, TMDs

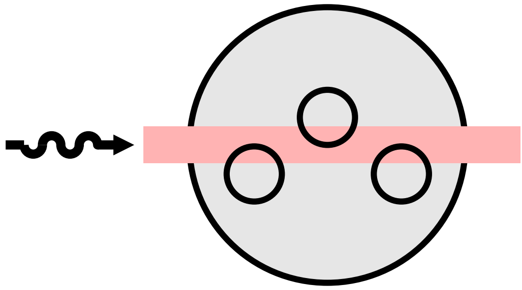
Singlet-nonsinglet separation in QCD evolution for ΔG



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

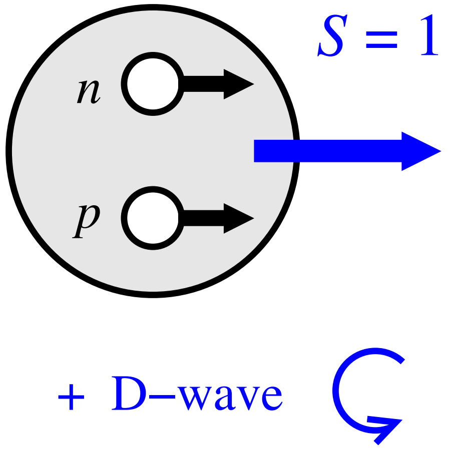
Nuclear shadowing $x \ll 0.1$

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 ions: Deuteron and spectator tagging



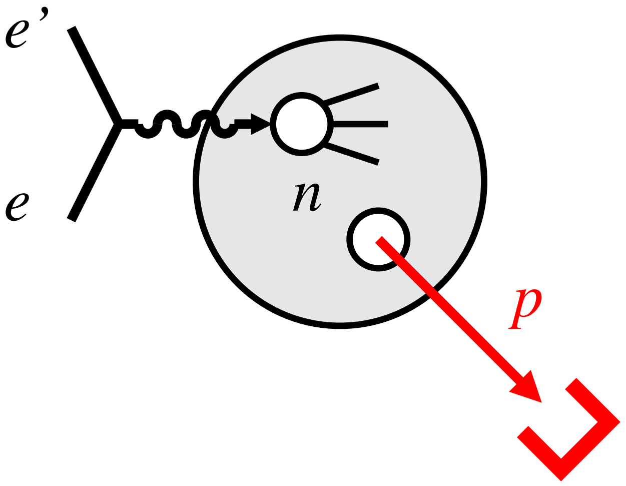
Deuteron as simplest system

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

Nucleons spin-polarized, some D-wave depolarization

Non-nucleonic DoF suppressed: Δ isobars, π

Frankfurt, Strikman 81. Large Δ component in 3He → see below



Spectator nucleon tagging

Identifies active nucleon

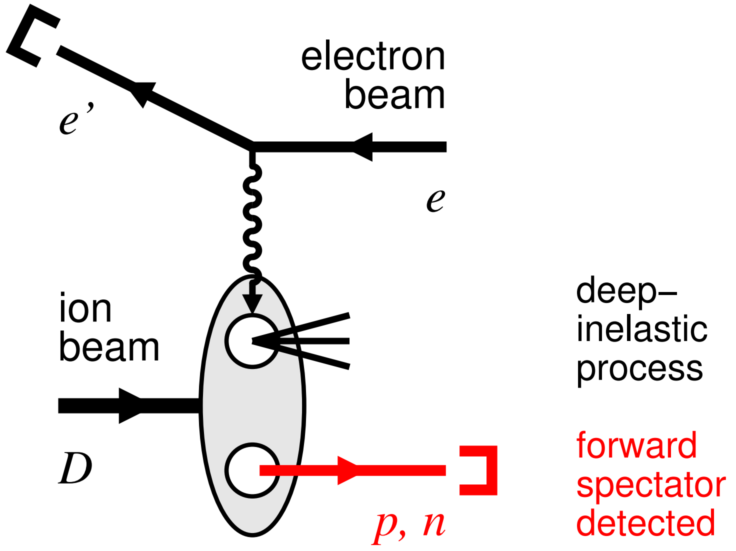
Controls configuration through recoil momentum:
spatial size → interactions, S/D wave → polarization

Average configurations ~ few 10 — 100 MeV
Small-size configurations ~ 200-500 MeV

Fixed-target experiments: JLab BONuS 6/12 GeV, ALERT (protons), BAND (neutrons)

[Nucleus rest frame view]

Light ions: Spectator tagging with EIC



[Collider frame view]

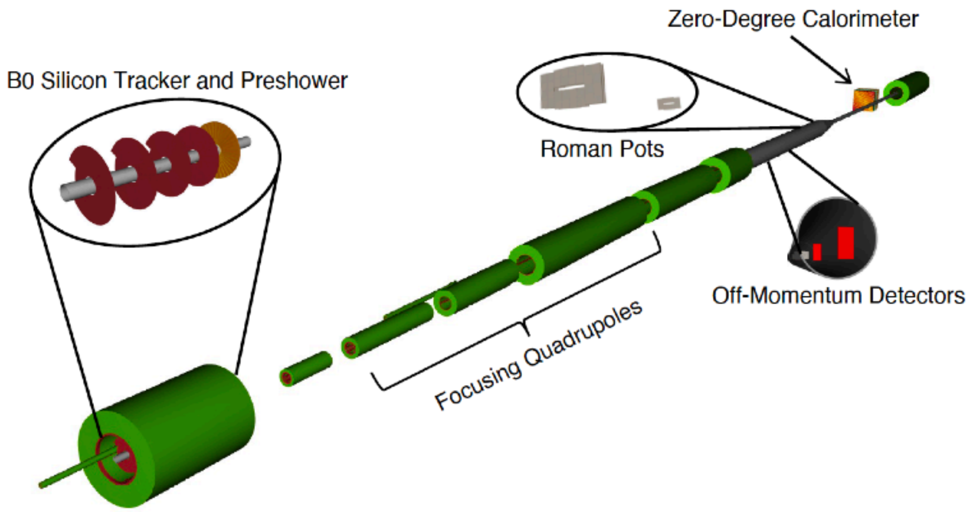
Spectator moves forward in ion beam direction

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 detectors



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

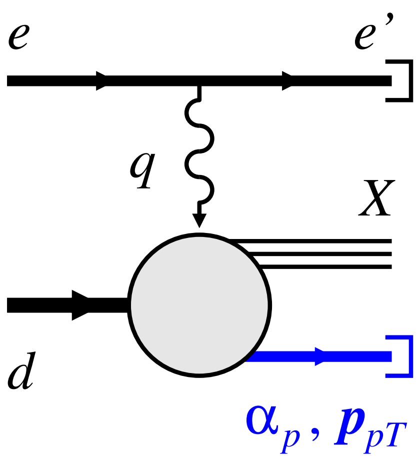
Zero-Degree Calorimeter for neutron

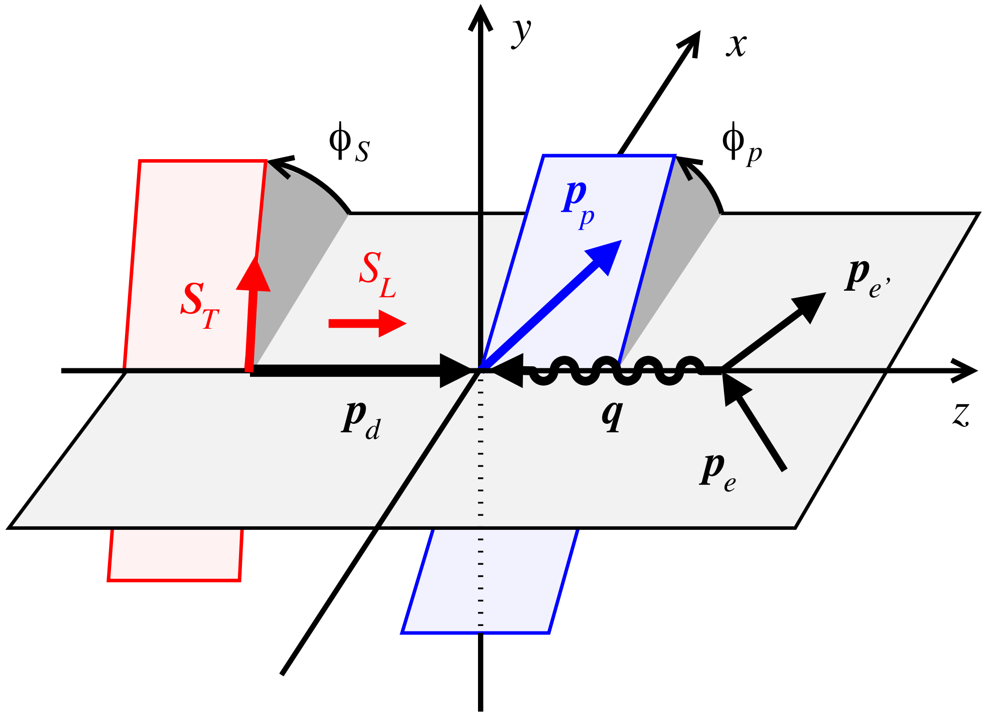
Advantage over fixed target: No target material, can detect spectators with rest frame momenta down to ~zero

Ion polarization prepared in beam, no holding magnets

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

Tagging: Cross section





$$\frac{d\sigma}{dx\,dQ^2\,(d^3p_p/E_p)} = \text{Flux} \times \sum \text{Kin}(y) \times F_d(x,Q^2;\alpha_p,p_{pT}) \times \text{Harmonic}(\phi_p)$$

+ spin dependence

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

Jeschonnek, Ford, Van Orden 2013
Cosyn, Weiss 2020

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: $p_p^+ = \alpha_p p_d^+/2, \quad \mathbf{p}_{pT}$
Related in simple way to rest-frame 3-momentum

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

Tagging: Cross section spin dependence

$$\sigma = \sum_{\lambda,\lambda'} \rho_{\lambda\lambda'} \langle d, \lambda' | \ldots | d, \lambda \rangle$$

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

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

Here $\phi_h \equiv \phi_p$

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

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

Invariant formulation, suitable for collider and fixed-target

General result, valid for any spin-1 target

Deuteron polarization

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

3 vector, 5 tensor parameters

Fixed by beam polarization measurements

Polarized cross section

Average with deuteron spin density matrix

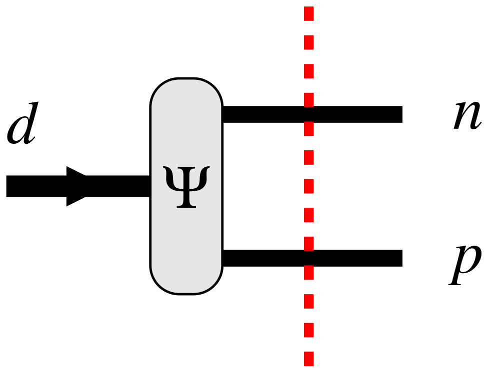
U + S + T structures

U + S cross section has same form and ϕ_p-dep as for spin-1/2 target
Bacchetta et al 2007

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

Integration over tagged proton momentum: Recover inclusive tensor-polarized structures $b_1 \ldots b_4$

Tagging: Deuteron structure



$x^+ = x^0 + x^3 =$ const.

Deuteron light-front structure

pn wave function at fixed light-front time $x^+ = x^0 + x^3$

Permits matching with high-energy/DIS processes on nucleon
[Frankfurt, Strikman 80s]

Contains low-energy nuclear structure ← NN interactions

Polarized deuteron light-front wave function

$\Psi_d(\alpha_p, \mathbf{p}_{pT}; \lambda_p, \lambda_n \,|\, \lambda_d)$

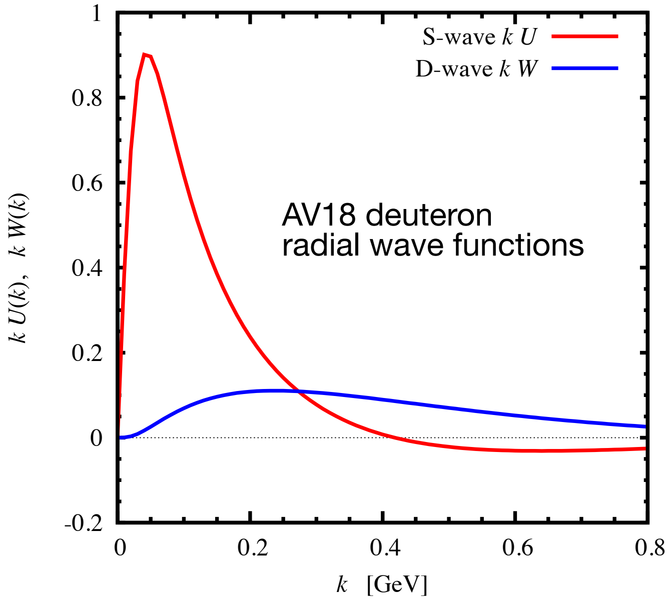
$\uparrow$ light-front helicity

$\Psi_d(\mathbf{k}; \sigma_p, \sigma_n \,|\, \sigma_d)$

canonical spin

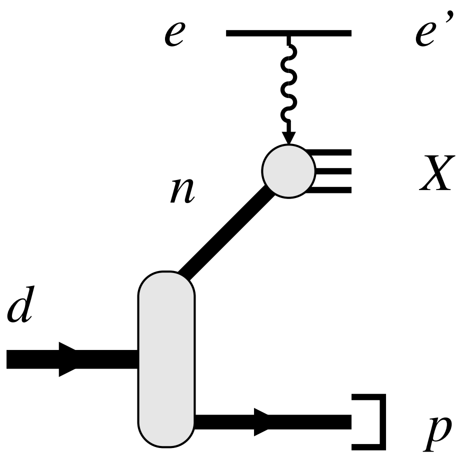
Spins described by light-front helicity states

Light-front WF constructed from 3D WF in pn CM frame, including transformation of spin states (Melosh rotation)



Contains S and D waves

Tagging: DIS process

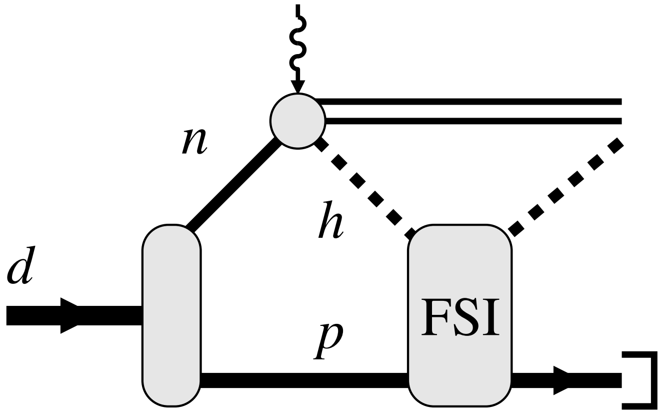


Impulse approximation

Spectator and DIS final state evolve independently

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

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



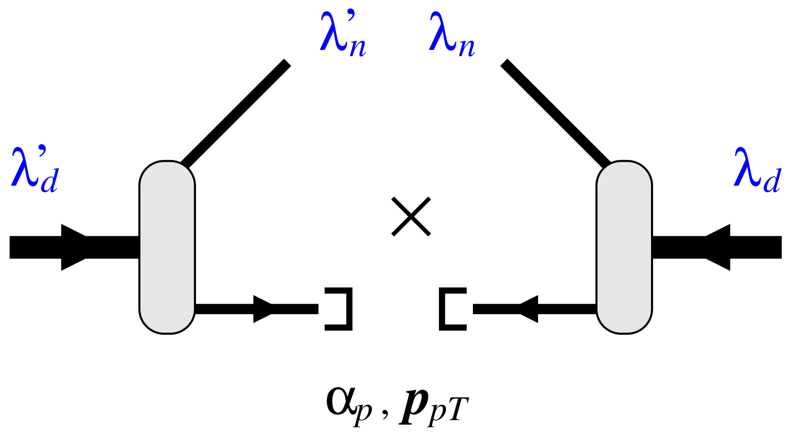
Final-state interactions

Part of DIS final state interacts with spectator, transfers momentum

Requires theoretical modeling → later

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.

Tagging: Deuteron spectral function

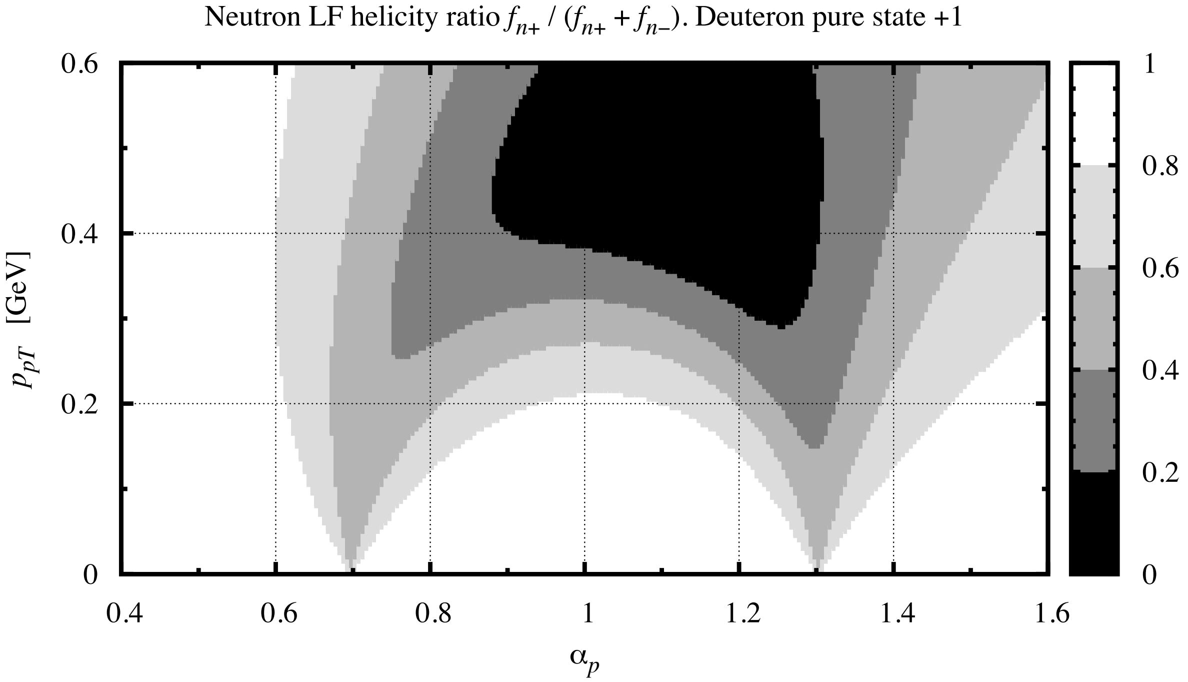


Deuteron spectral function

Describes distribution of neutrons depending on tagged proton momentum α_p, p_{pT}

Depends on deuteron and neutron spin

Satisfies momentum and spin sum rules


Neutron LF helicity ratio $f_{n+} / (f_{n+} + f_{n-})$. Deuteron pure state +1

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

Neutron polarization in deuteron

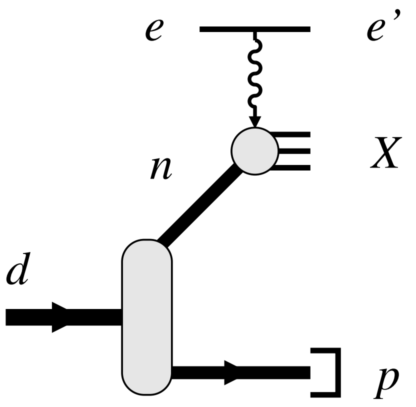
Effective neutron polarization depends on tagged proton momentum: S vs D wave

Example: Deuteron in pure spin state +1.

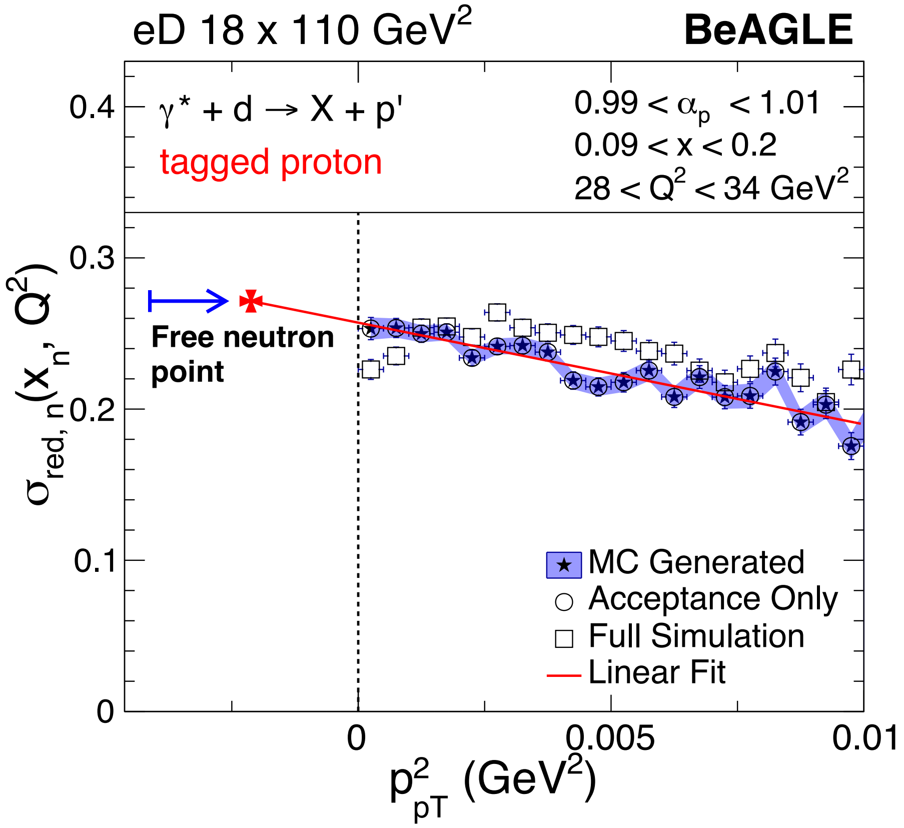
Plot shows probability that neutron has helicity +1/2 i.e. is polarized along deuteron spin direction

Tagged proton momentum controls effective neutron polarization!

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: NN configs have finite size, nucleons interact

Analytic continuation to unphysical momenta $|\mathbf{p}_p|^2 < 0$ can reach configs with "infinite" size, nucleons free!

Bethe-Peierls pole in momentum, asymptotic S-wave at large distances

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

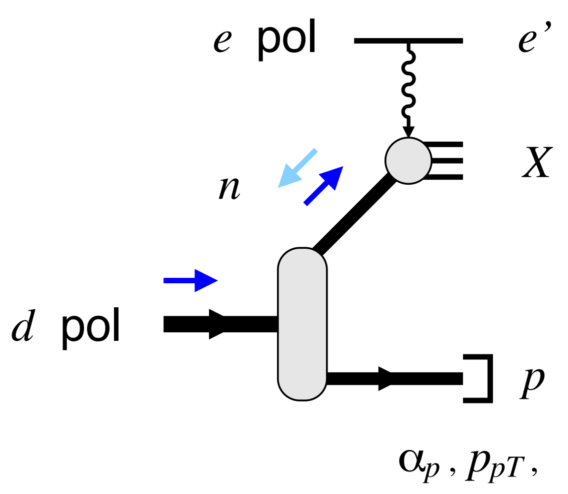
Measure proton-tagged cross section at fixed α_p as function of $p_{pT}^2 > 0$

Divide data by pole term of spectral function

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

Simulated at EIC, appears feasible

Applications: Effective neutron polarization

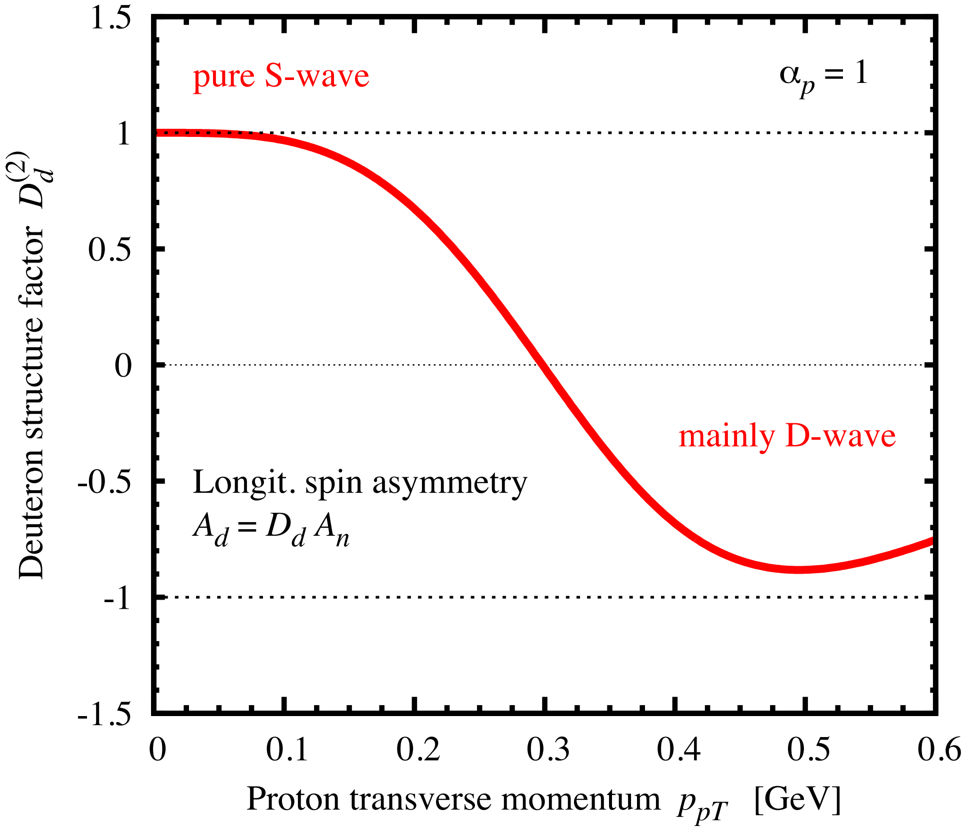


$A_{\parallel,d}(x_n, Q^2; \alpha_p, p_{pt})$ tagged longitud double spin asymmetry

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

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

effective neutron polarization,
depends on tagged proton momentum



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

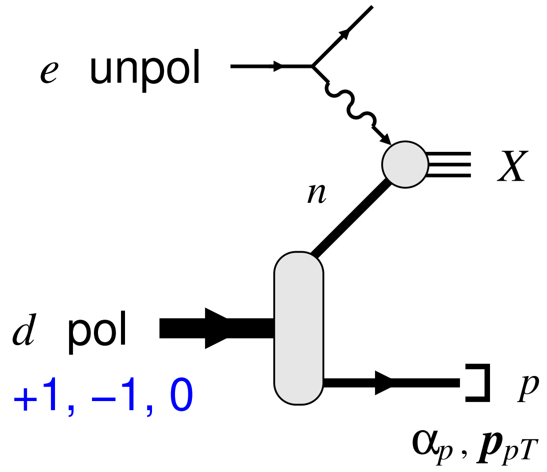
D wave dominates at $p_{pT} \sim$ 400 MeV:
Neutron polarized opposite to deuteron spin!

Tagged proton momentum controls
effective neutron polarization in deuteron

Frankfurt, Strikman 1983

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

Applications: Tensor polarized asymmetry



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

tagged tensor polarized asymmetry

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

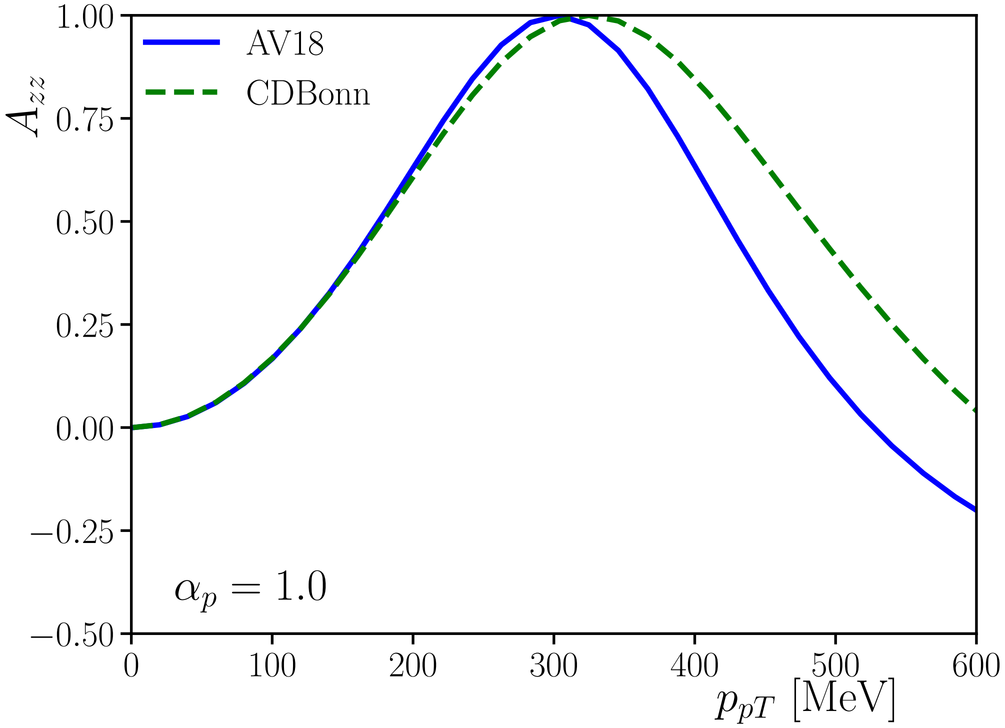
$$-2 < A_{zz,d} < 1$$

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

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



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

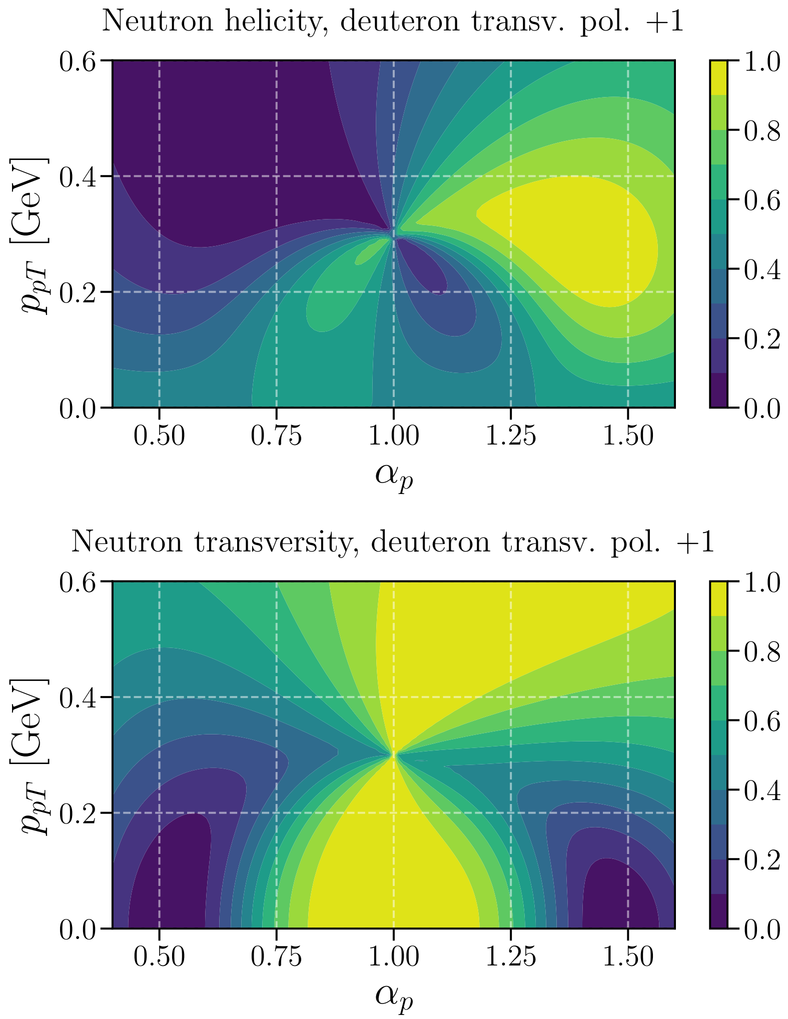
Cosyn, Weiss, in progress

Applications: More polarization observables

Transverse vector polarization of deuteron

Induces transverse nucleon polarization (transversity)
deforms longitudinal nucleon polarization (spin-orbit)

Tagged measurements of g_{2n} neutron spin structure function?
Challenge for light-front method. Involves “bad components” of EM current



Neutron helicity, deuteron transv. pol. +1

Neutron transversity, deuteron transv. pol. +1

Cosyn, Weiss, in progress

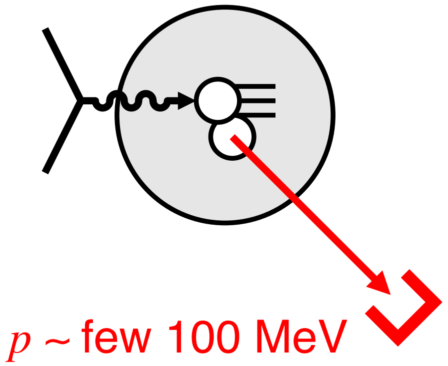
Final-state interactions

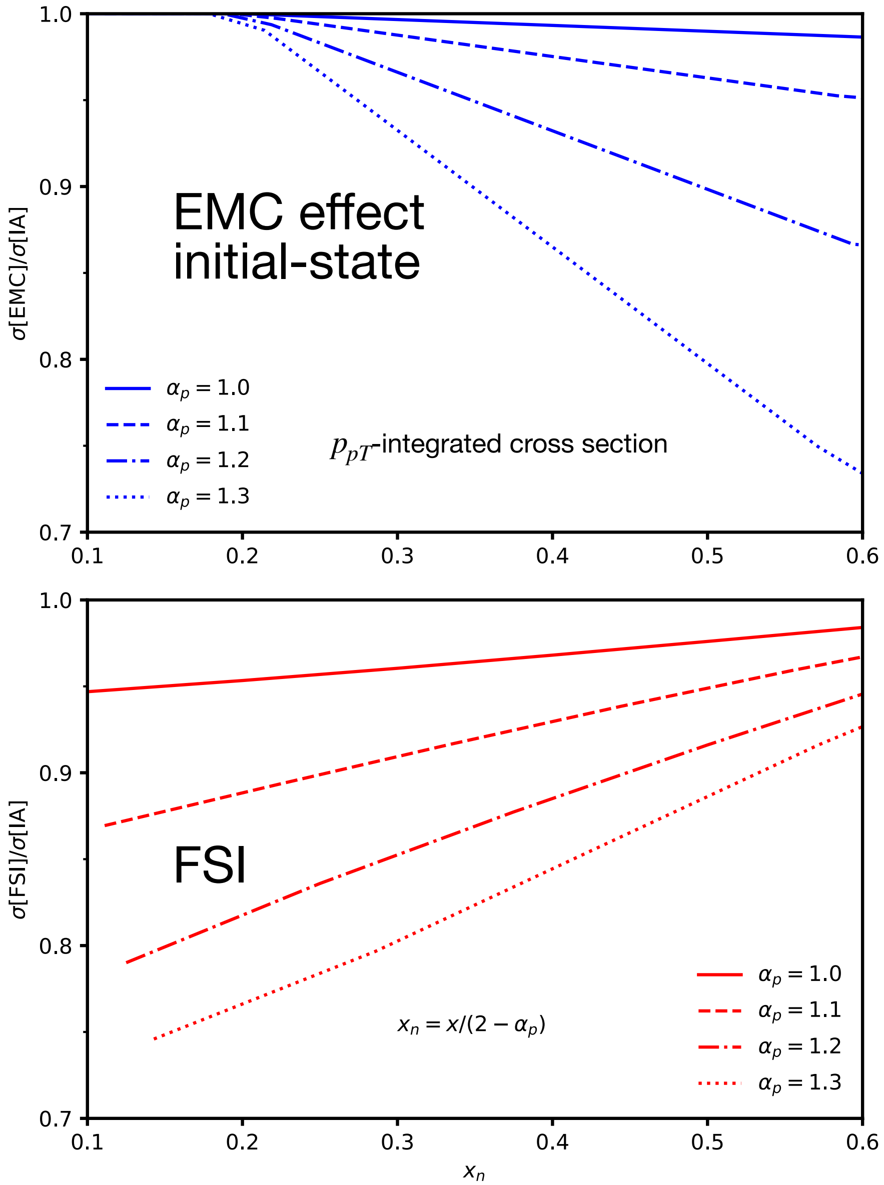
Large effects at $p_{pT} > 300$ MeV, should be included in calculations of tagged spin observables

Description based on space-time picture in deuteron rest frame: Fast and slow hadrons
Strikman, Weiss PRC97 (2018) 035209

ϕ_p dependent tagged cross section includes T-odd structures: Zero in impulse approximation, require final state interactions, can provide sensitive tests (→ Sivers effect in SIDIS)

Applications: 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

Deuteron polarization at EIC

Present EIC design provides polarized proton and 3He beams for spin physics
EIC Yellow Report 2021 [INSPIRE]

Deuteron’s small anomalous magnetic moment makes manipulation of its spin in synchrotron very challenging, requires high magnetic field. Not possible with present full Siberian Snake design.

Technical possibilities for deuteron polarization exist and are being studied
Recent update: Huang, Méot, Ptitsyn, Ranjbar, Roser, Report at IPAC 2021 [INSPIRE]

Deuteron polarization could be considered in connection with a possible future EIC facility upgrade

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 and experiment

- Spectator tagging with unpolarized deuteron feasible with EIC far-forward detectors, studied in physics and detector simulations. Applications to free neutron structure, EMC effect, shadowing/diffraction at small x

- Spectator tagging with polarized deuteron would enable several unique applications

  Control effective neutron polarization in vector-polarized deuteron, longitudinal or transverse

  Realize tensor-polarized asymmetries O(1)

  Theory input on final-state interactions essential for interpretation, requires investment

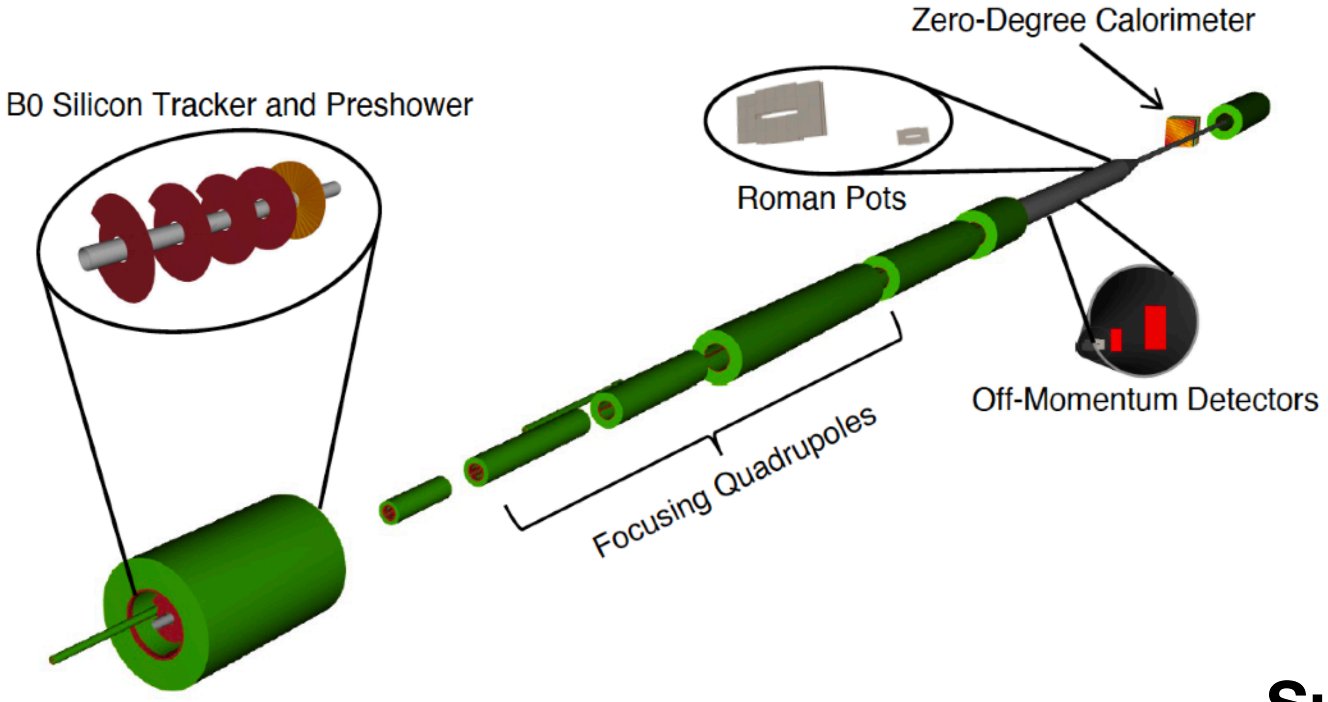
[Not covered here: Untagged DIS on polarized deuteron at EIC and impact on spin physics]

- Deuteron polarization at EIC considered technically possible, discussed as facility upgrade

- Community should formulate polarized deuteron program for EIC and initiate technical development

Supplemental material

EIC: Far-forward detectors



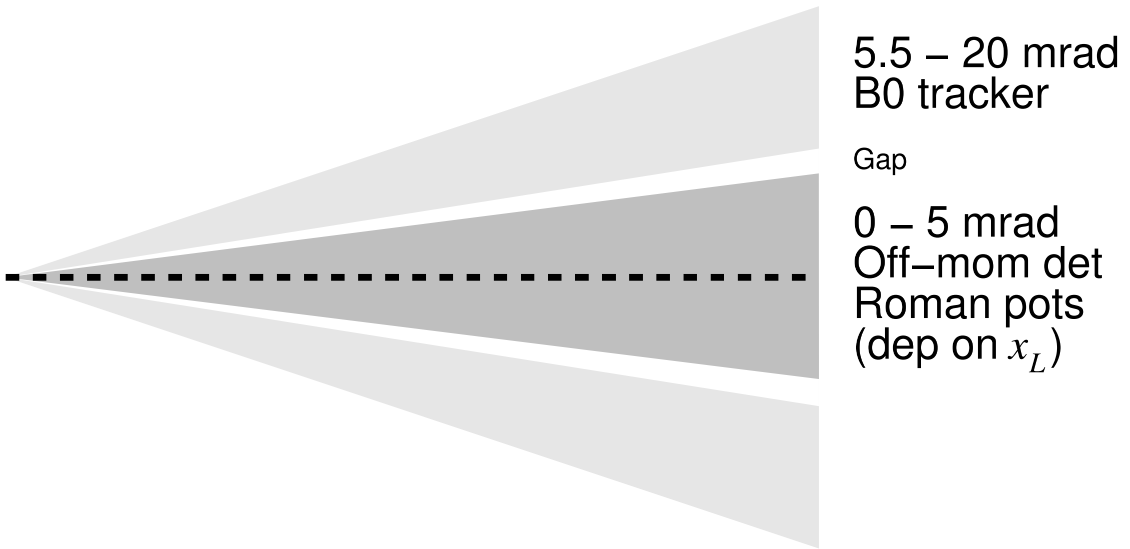
Magnetic spectrometer and detectors for charged particles, integrated in accelerator optics, several subsystems

Zero-degree calorimeter for neutrals

[This version EIC Yellow Report 2022;
fur updates see EPIC Collaboration]

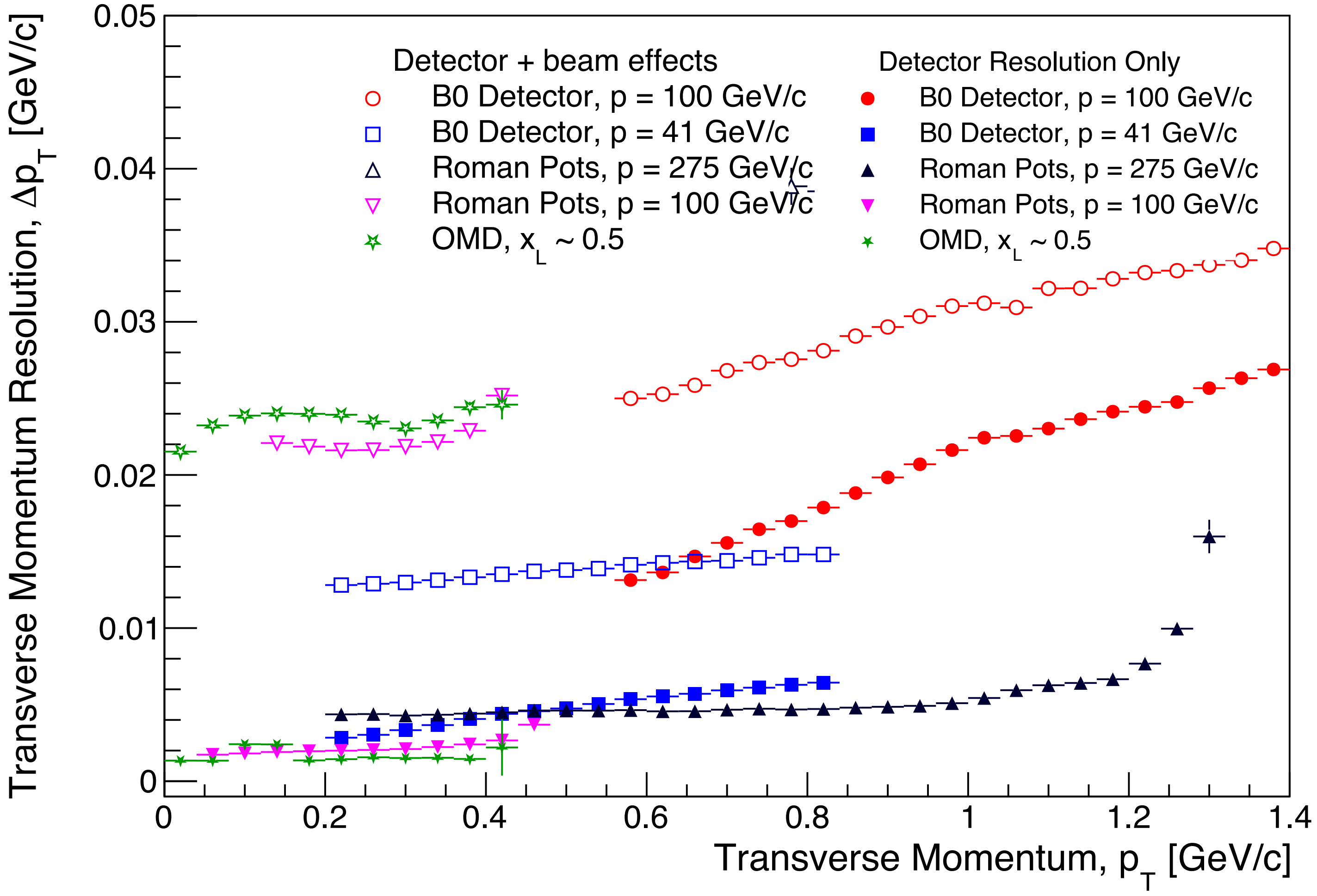
Subsystems used in spectator tagging

Protons	$\theta < 5\,\mathrm{mrad}$ $0.2 < x_L < 0.6$	Off-mom detectors	Used in free neutron
Protons	$\theta < 5\,\mathrm{mrad}$ $x_L > 0.6$	Roman Pots	Bound nucleon/EMC
Protons	$5.5 < \theta < 20\,\mathrm{mrad}$	B0 tracker	
Neutrons	$\theta < 4\,\mathrm{mrad}$	ZDC	



Proton acceptance = function(θ, x_L)

EIC: 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 $\alpha_p/\alpha_p \lesssim$ 5%, significantly better for $\alpha_p \sim 1$

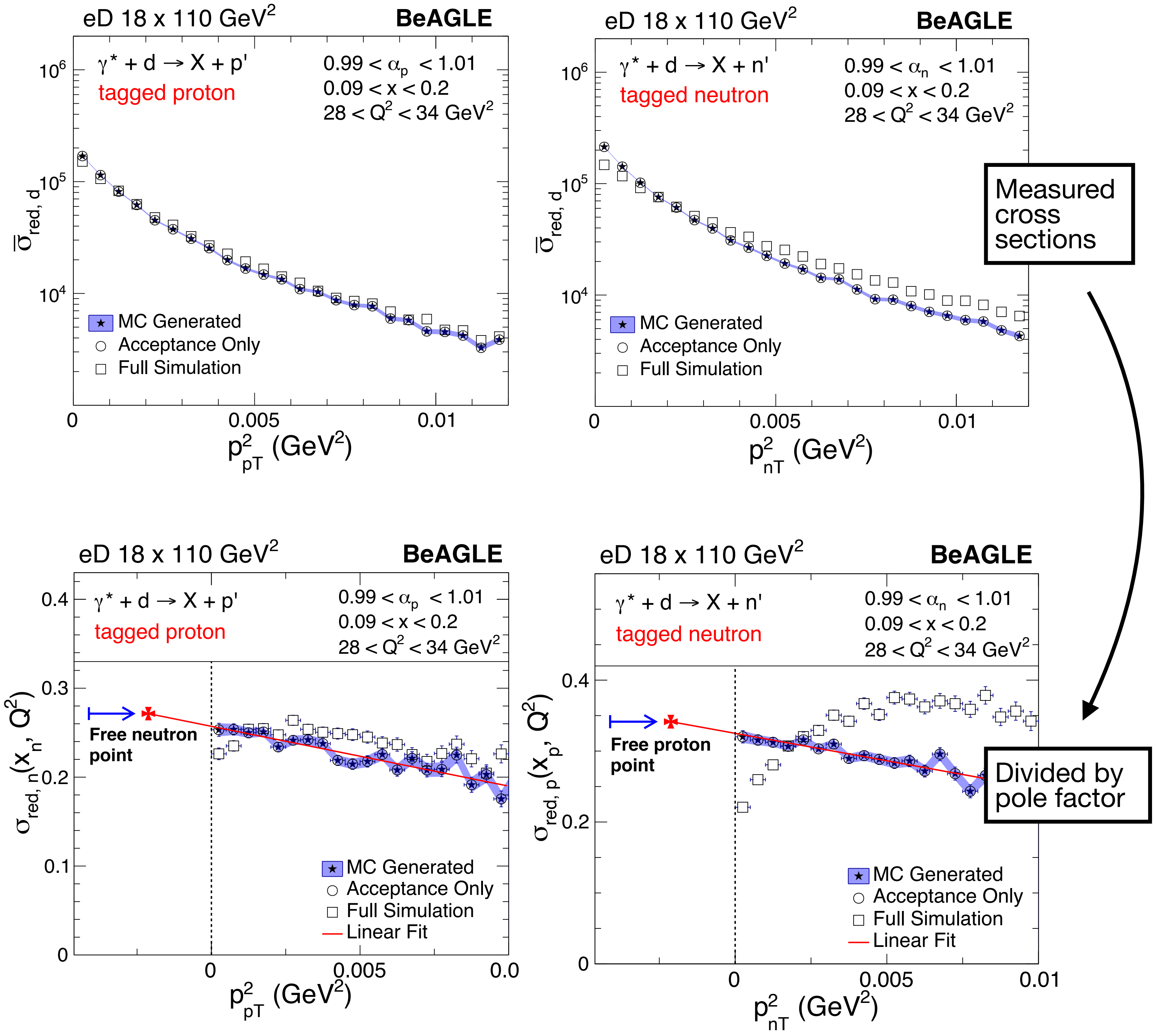
Figures in supplement

Neutron momentum resolution

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

with present ZDC design

Free nucleon: EIC simulations



Measured cross sections

Divided by pole factor

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

Tagged cross section measured with excellent coverage

Significant uncertainties in evaluation of pole factor due to p_T resolution

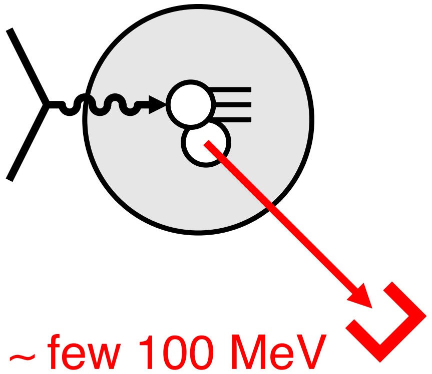
Pole factor evaluated in event-averaged analysis (binned in p_T^2) to allow for correction of resolution effects (unfolding)

Uncertainties analyzed, results validated by comparison with input

Pole extrapolation realistic for proton spectator, exploratory for neutron spectator

Final uncertainties depend on ability to correct for resolution

Tagging: Bound nucleon structure - EMC effect



EMC effect

Observed in inclusive DIS $0.3 < x < 0.7$

What NN distances/momenta cause modification?

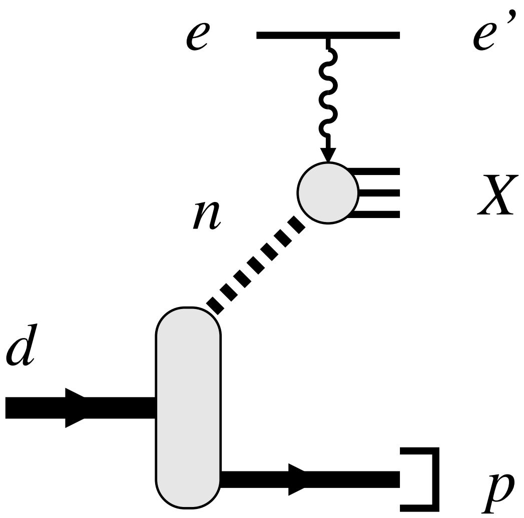
Control configurations with tagging!

Estimate: Nucleon virtuality dependence

Frankfurt, Strikman 1988

$$\frac{\sigma_n[\text{bound}]}{\sigma_n[\text{free}]} = 1 + \frac{V}{\langle V \rangle} f_{\text{EMC}}(x_n) \qquad V = V(\alpha_p, p_{pT})$$

depends on spectator mom



Parameters fixed by inclusive EMC effect data and average virtuality $\langle V \rangle_A \sim 2\langle p^2 \rangle_A$ from nuclear structure calculations

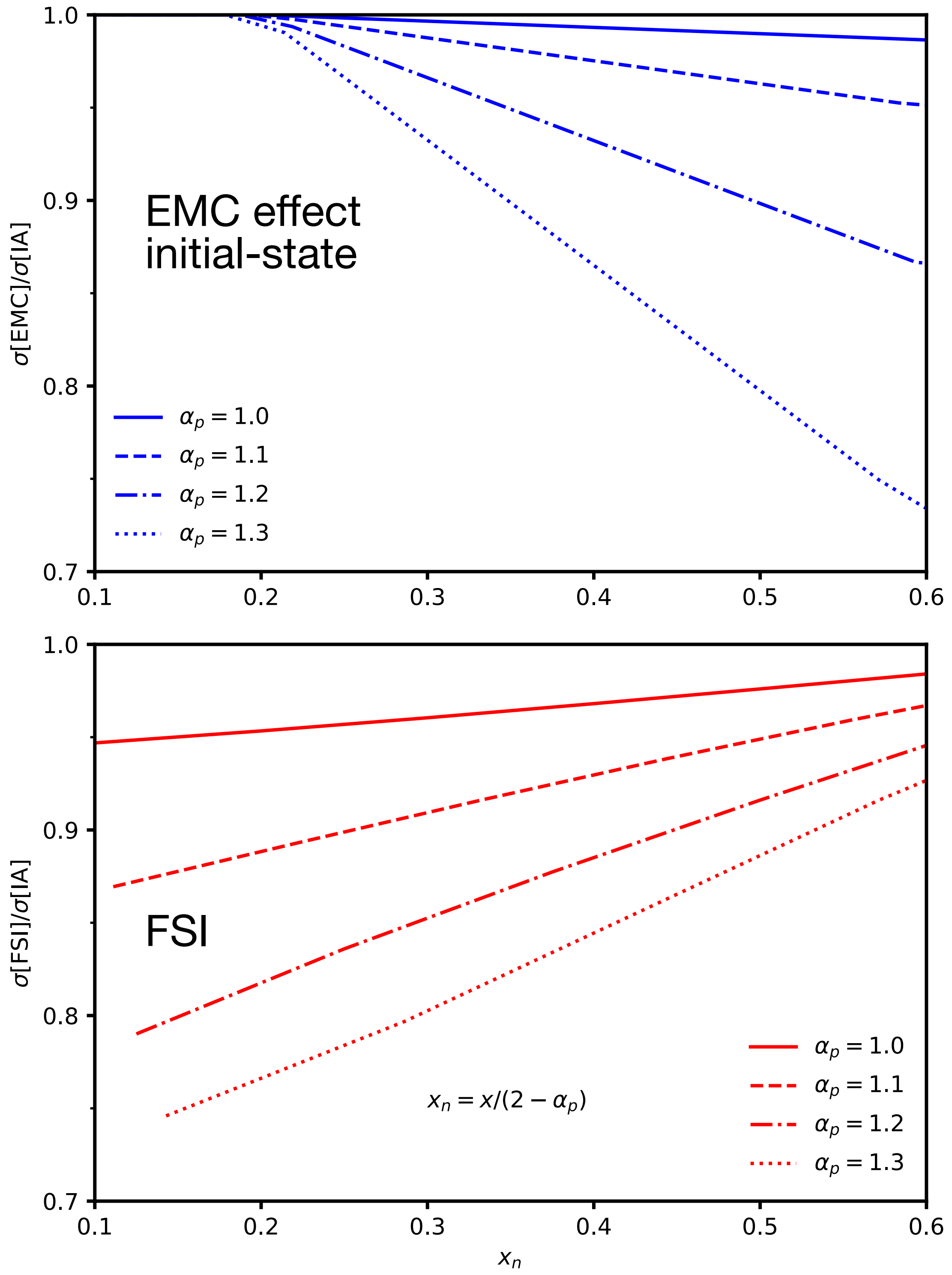
Ciofi degli Atti, Frankfurt, Kaptari, Strikman 2007

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

Modifications ~20-30%, depending on α_p and p_{pT}

Initial-state modification vs final-state interactions?

Tagged EMC effect: Initial vs final state



p_{pT} - integrated cross section

$$\sigma = \int_{p_{pT}[\text{max}]} d^2 p_{pT}\; S_d(\alpha_p, p_{pT})\; \sigma_n(x_n)$$

Here: $p_{pT}[\text{max}] = 0.4$ GeV

Compare EMC effect and FSI

Same order-of magnitude,
requires careful assessment

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