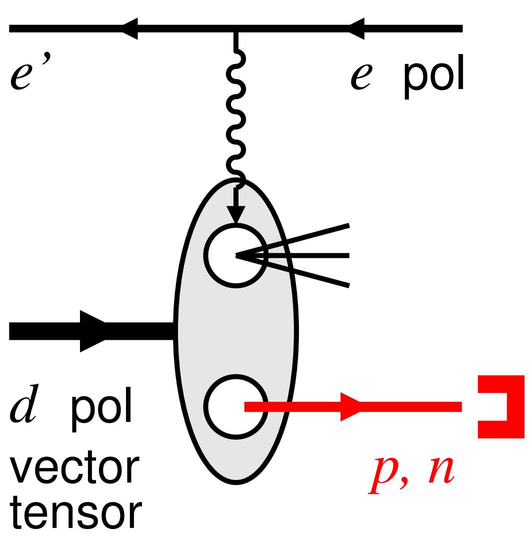
Spectator tagging with polarized deuteron: Observables and applications

C. Weiss, Electron-Nuclei Interaction at EIC, CNF Stony Brook, 6-7 July 2023



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

→ relative momentum, spatial size
→ interactions, non-nucleonic DoF
→ nucleon polarization, S/D wave

Frankfurt, Strikman, NPA 405, 557 (1983)

JLab LDRD 2014-15

Cosyn, Weiss, PLB 799, 135035 (2019), PRC 102 065204 (2020) + in progress

Polarized light ions

Physics objectives

Controlling nuclear configurations

Spectator tagging with polarized deuteron

Cross section e + d(pol) → e' + X + p(n)

Deuteron x nucleon structure

Spin observables

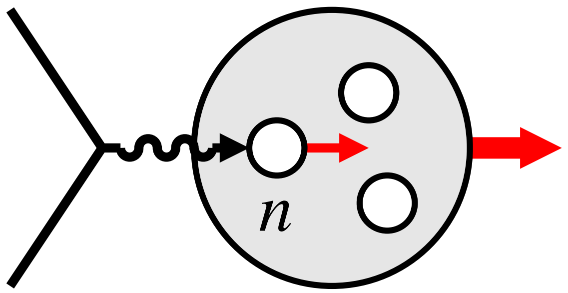
Applications

Vector L: Effective neutron polarization

Tensor L: Maximum tensor polarization

More: Vector T, small-x shadowing, …

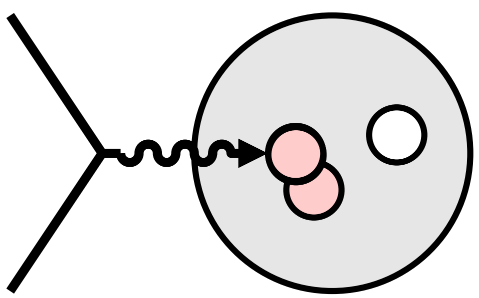
Light ions: Physics objectives



Neutron spin structure

Flavor decomposition of quark PDFs/spin, GPDs, TMDs

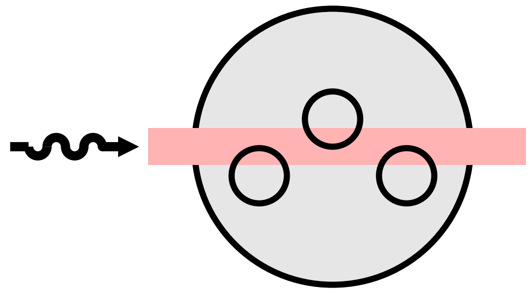
Singlet-nonsinglet separation in QCD evolution for ΔG



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

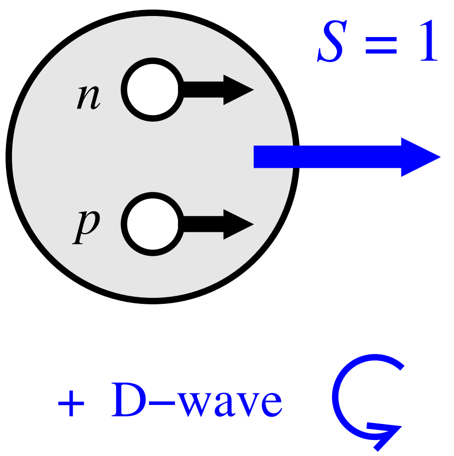
Nuclear shadowing $x \ll 0.1$

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

[Nucleus rest frame view]

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

Light ions: Deuteron and spectator tagging



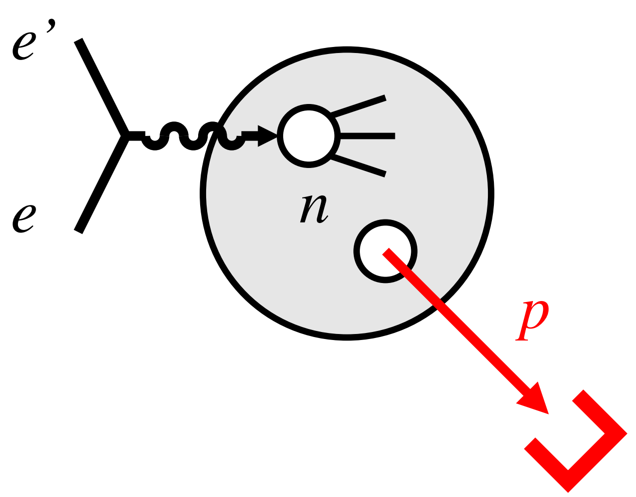
Deuteron as simplest system

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

Nucleons spin-polarized, some D-wave depolarization

Intrinsic Δ isobars suppressed by Isospin = 0

Large Δ component in 3He Bissey, Guzey, Strikman, Thomas 2002



[Nucleus rest frame view]

Spectator nucleon tagging

Identifies active nucleon

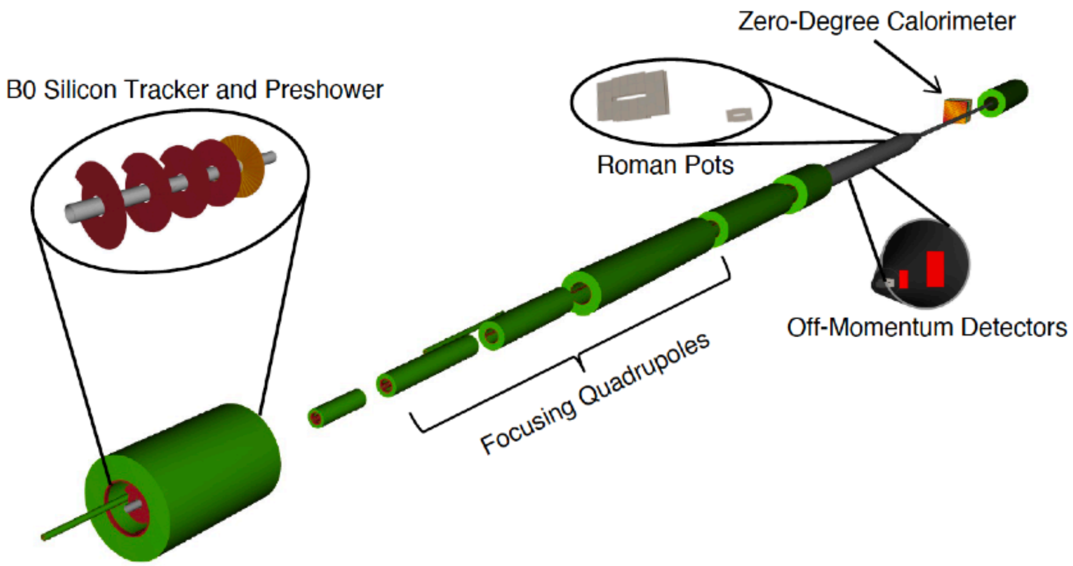
Controls configuration through recoil momentum:
spatial size → interactions, S/D wave → polarization

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

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

→ Talk Kuhn

Light ions: Spectator tagging with EIC

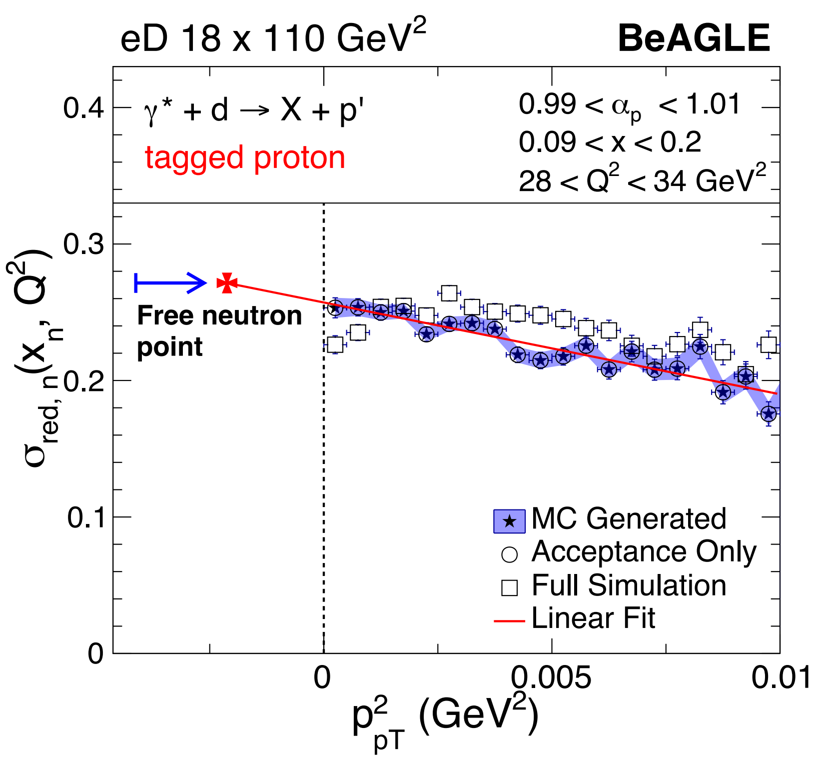


Far-forward detectors

Magnetic spectrometer for protons, 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 → zero



Physics-detector simulations

Free neutron structure from proton tagging and pole extrapolation
Jentsch, Tu, Weiss, PRC 104, 065205 (2021)

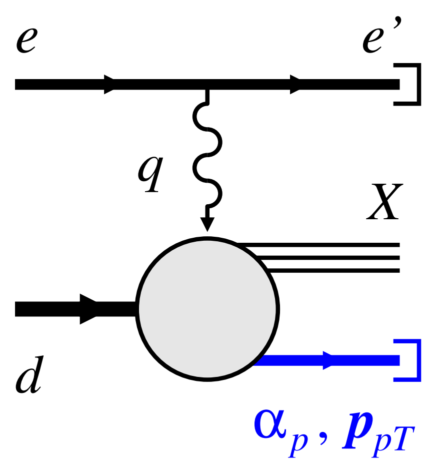
Configuration dependence of EMC effect from proton and neutron tagging
in progress

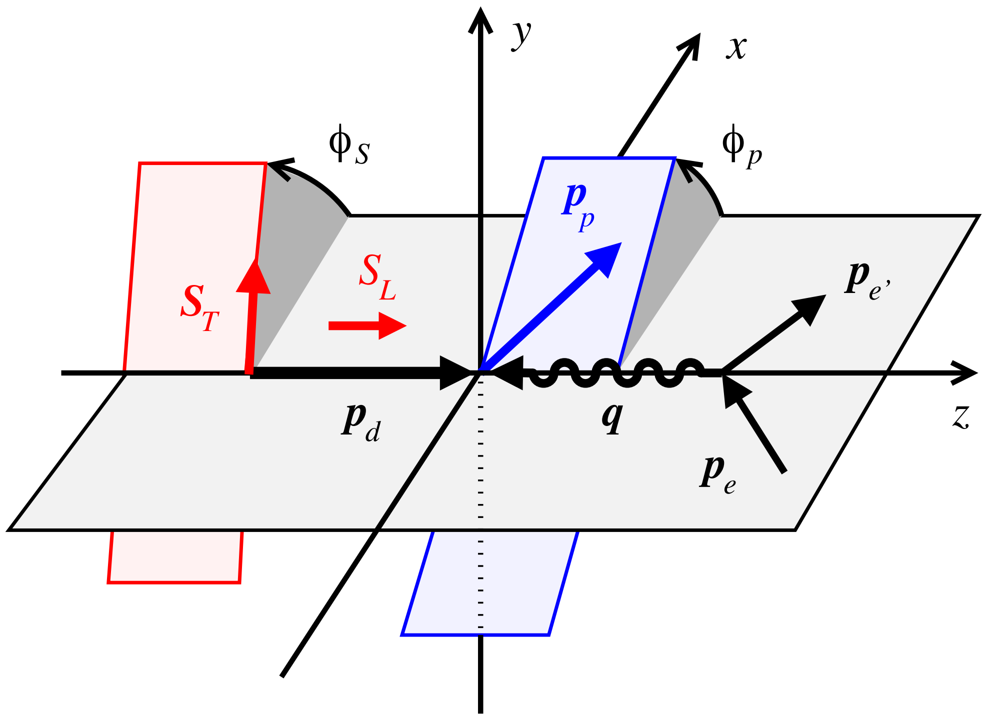
Method works… can we extend it to polarized deuteron?

Further information: EIC Yellow Report 2021 [INSPIRE]

→ Talk Jentsch

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)

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

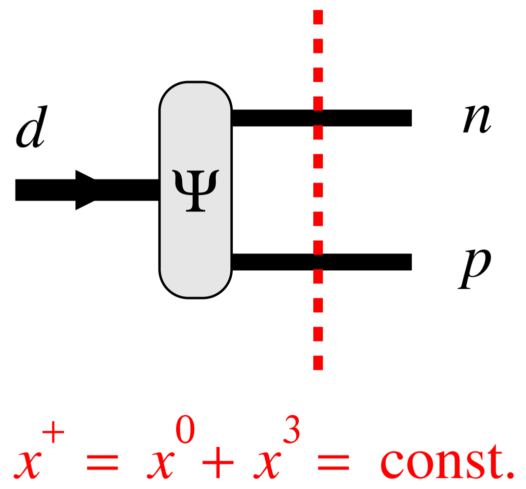
U + S + T structures

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



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

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

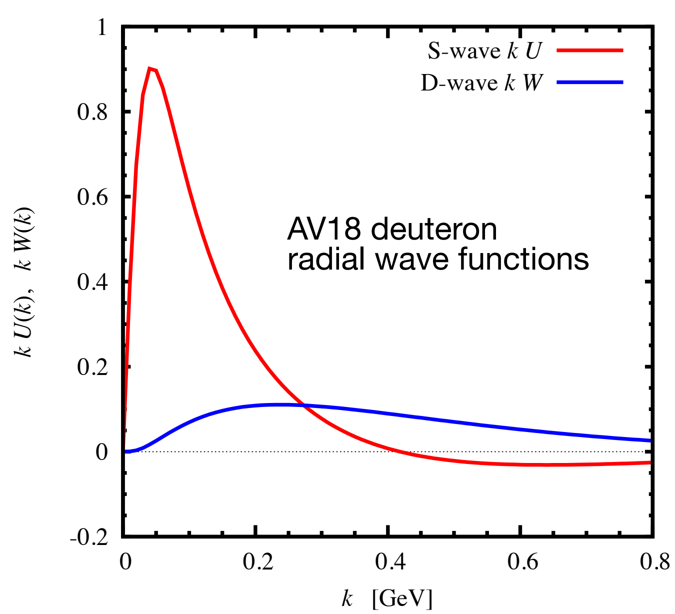
↑ light-front helicity

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

canonical spin

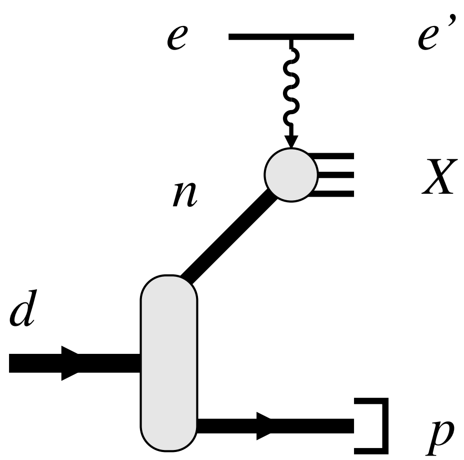
Spins described by light-front helicity states

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

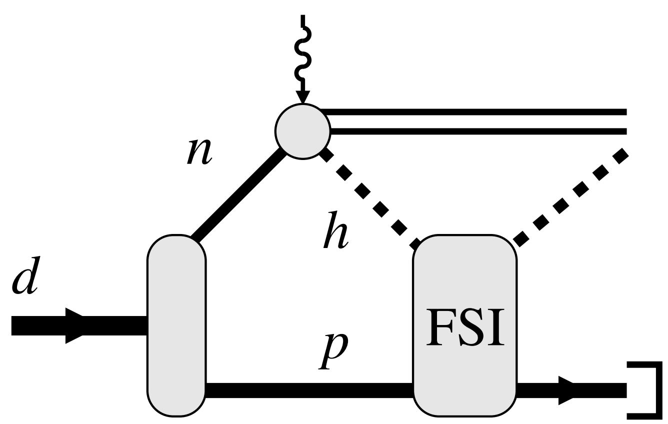


Impulse approximation

Spectator and DIS final state evolve independently

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

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



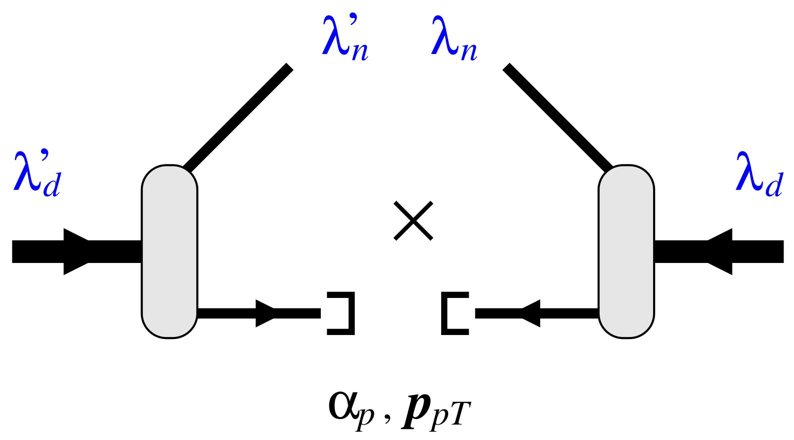
Final-state interactions

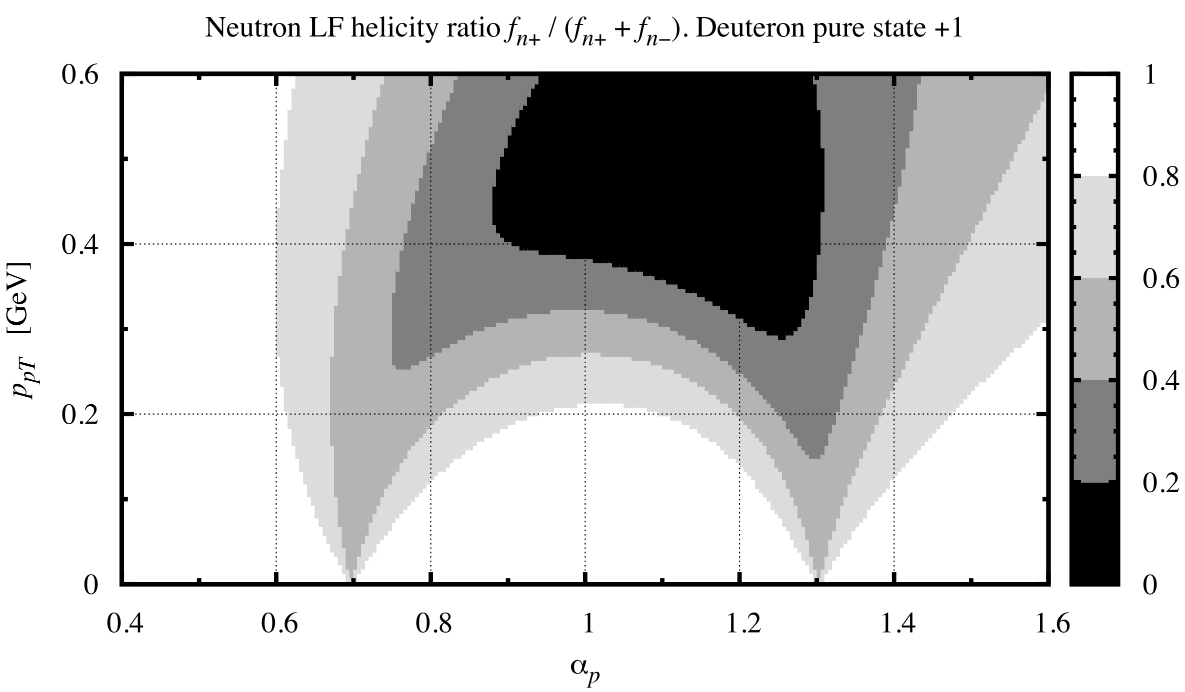
Part of DIS final state interacts with spectator, transfers momentum

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





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

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 polarization in deuteron

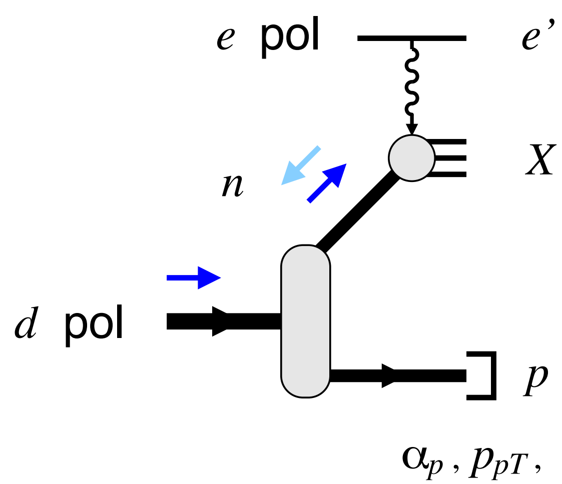
Effective neutron polarization depends on tagged proton momentum: S vs D wave

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: Longitudinal double spin asymmetry

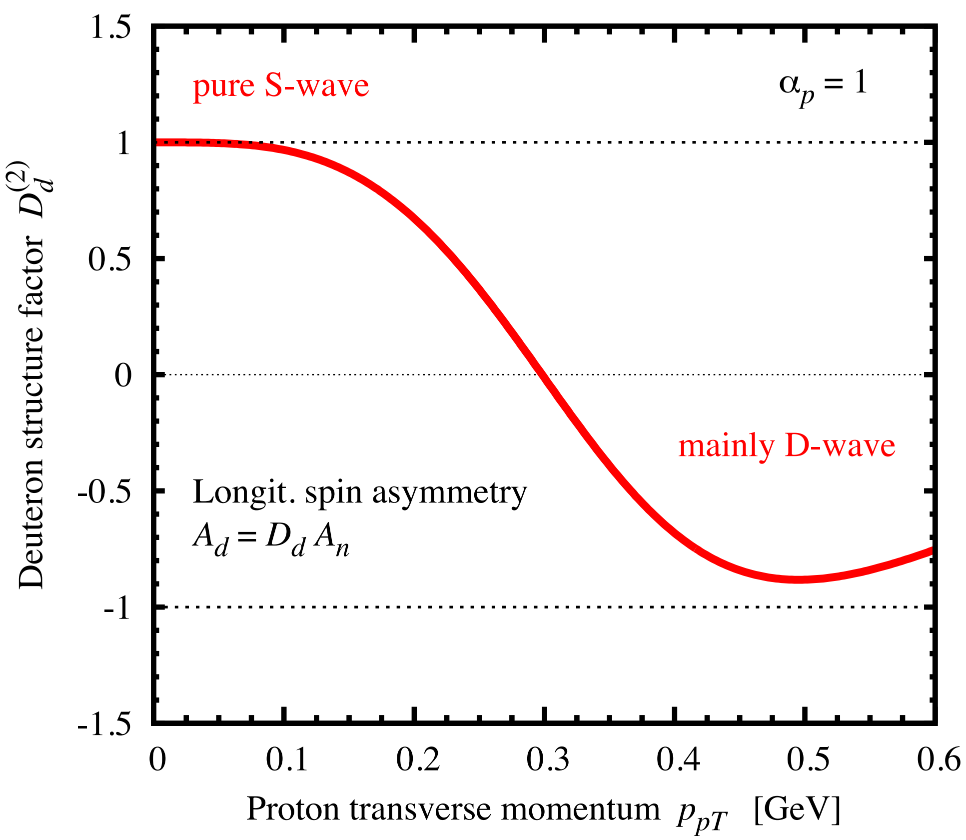


$A_{\parallel,d}(x_n, Q^2; \alpha_p, p_{pt})$ tagged longitud double spin asymmetry

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

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

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



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

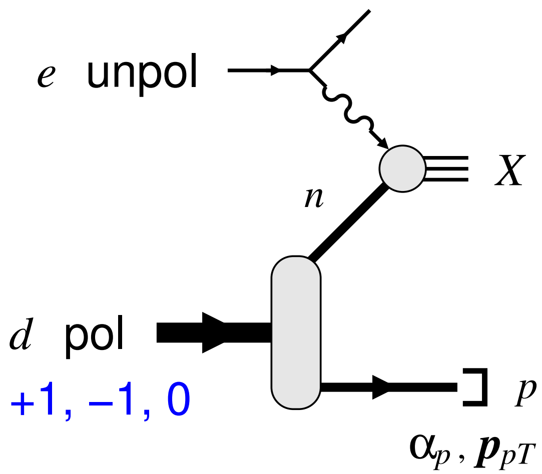
D wave dominates at $\mathbf{p}_{pT} \sim$ 400 MeV:
Neutron polarized opposite to deuteron spin!

Tagged proton momentum controls
effective neutron polarization in deuteron

Frankfurt, Strikman 1983

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

Applications: Tensor polarized asymmetry

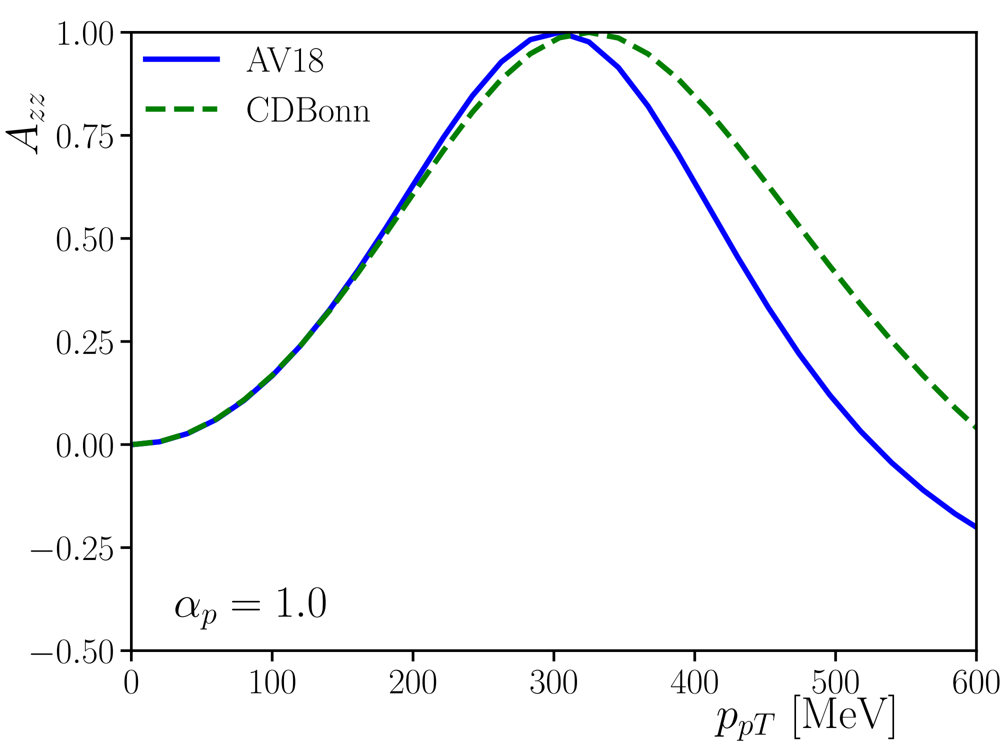


$$A_{zz,d}(x, Q^2; \alpha_p, \mathbf{p}_{pt})$$ tagged tensor polarized asymmetry

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

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



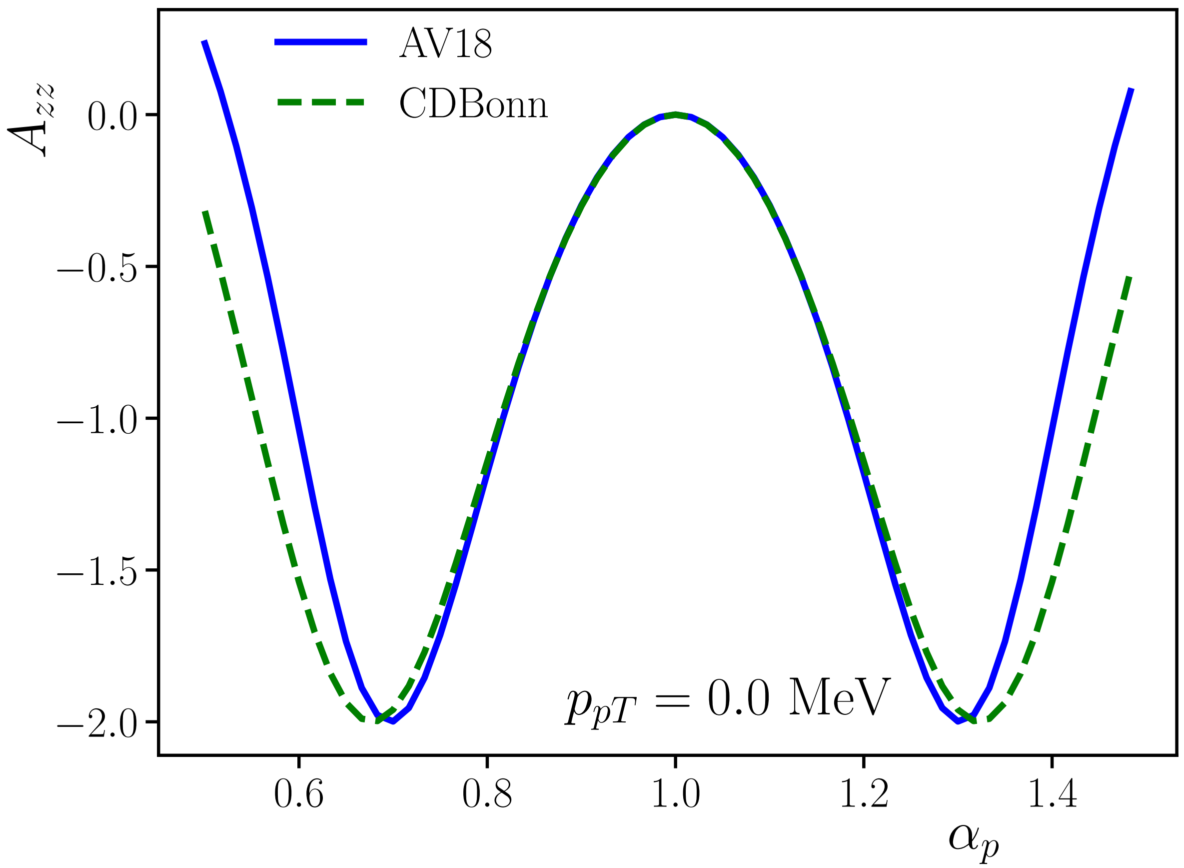
Maximal tensor polarization $A_{zz} = 1$ can be achieved at $p_{pT} \approx$ 300 MeV and $\alpha_p = 1$

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: Tensor polarized asymmetry



Frankfurt, Strikman 1983

Cosyn, Weiss, in progress

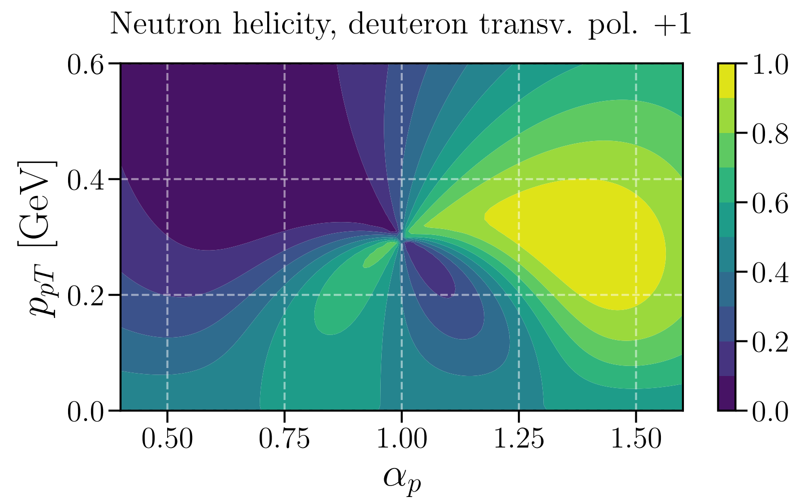
Tensor polarization $A_{zz} = -2$
achieved at $p_{pT} = 0$ and $\alpha_p - 1 \approx \pm 0.3$

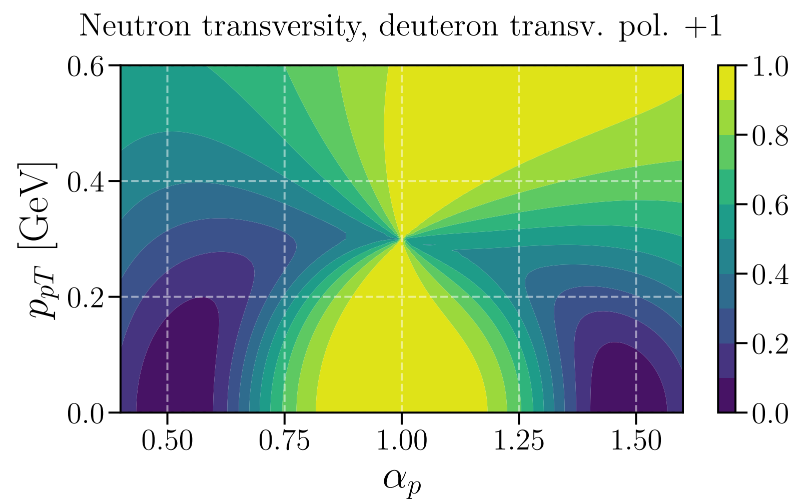
Spectator tagging can realize tensor asymmetries O(1) through control of S/D wave ratio

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





Cosyn, Weiss, in progress

Polarization effects in shadowing at small x

Deuteron tensor polarization controls alignment of nucleons along reaction axis → probability of multiple scattering, shadowing at small x

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)

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 & experiment

Spectator tagging with EIC far-forward detectors simulated in unpolarized DIS, shown to be feasible at spectator momenta $p_{pT} \lesssim$ 200 MeV, limited by rates/luminosity at larger p_{pT}

Spectator tagging with polarized deuteron controls S/D ratio and would enables unique applications:
— Control/reverse effective neutron polarization
— Achieve tensor polarization O(1)

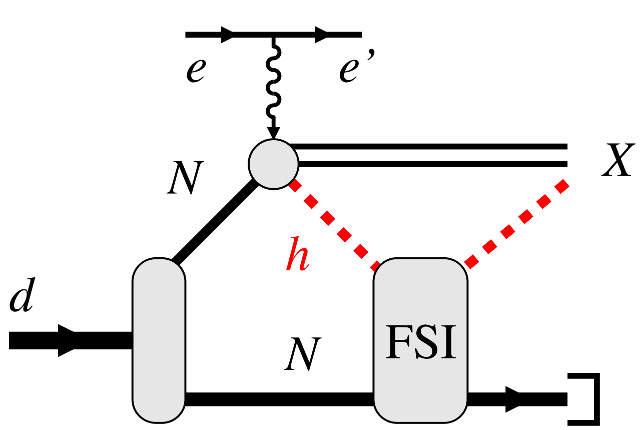
Practical challenges at EIC:
— Polarization of deuteron beam
— Luminosity requirements for spin asymmetries + tagging

Tensor-polarized asymmetries appear as best option: Electron unpolarized, asymmetries O(1), unpolarized nucleon cross sections cancel. Should be simulated!

[Also important: Polarized deuteron for inclusive spin structure]

Supplemental material

Final-state interactions: Basics



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

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

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

Kinematic regimes and mechanisms

DIS, $x \gtrsim 0.1$

$h =$ target fragmentation hadrons
on-shell rescattering

Ciofi degli Atti, Kaptari, Kopeliovich 2004+
Strikman, Weiss 2018

DIS, $x \ll 0.1$

$h =$ diffractive nucleons
QM rescattering, interplay of coherent and incoherent channels

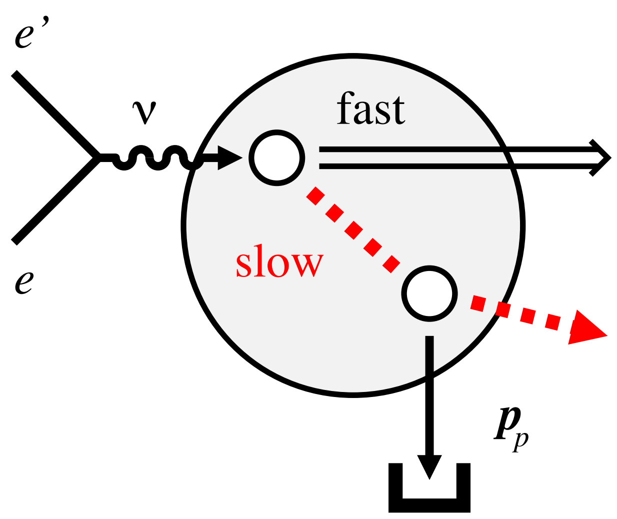
Guzey, Strikman, Weiss, in progress

Finite W, Q^2
(JLab 6/12 GeV)

$X = \sum N^*$ resonances
challenge to implement coherence, color transparency

Cosyn, Sargsian, Melnitchouk 2011/14
Cosyn, Sargsian 2017

Final-state interactions: DIS at x >~ 0.1



[Deuteron rest frame view]

Space-time picture in deuteron rest frame

Strikman, Weiss PRC97 (2018) 035209

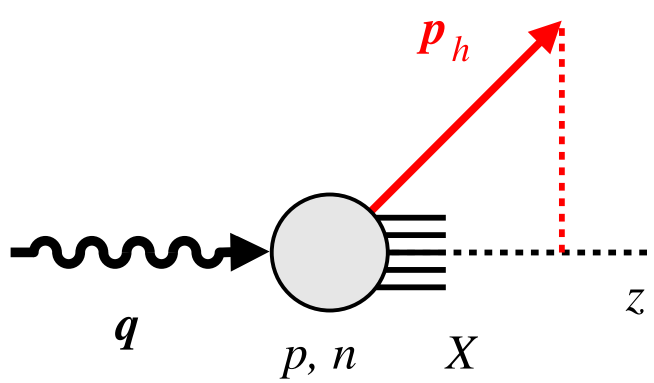
$\nu \gg$ hadronic scale: Large phase space for hadron production

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

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

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

Final-state interactions: DIS at x >~ 0.1

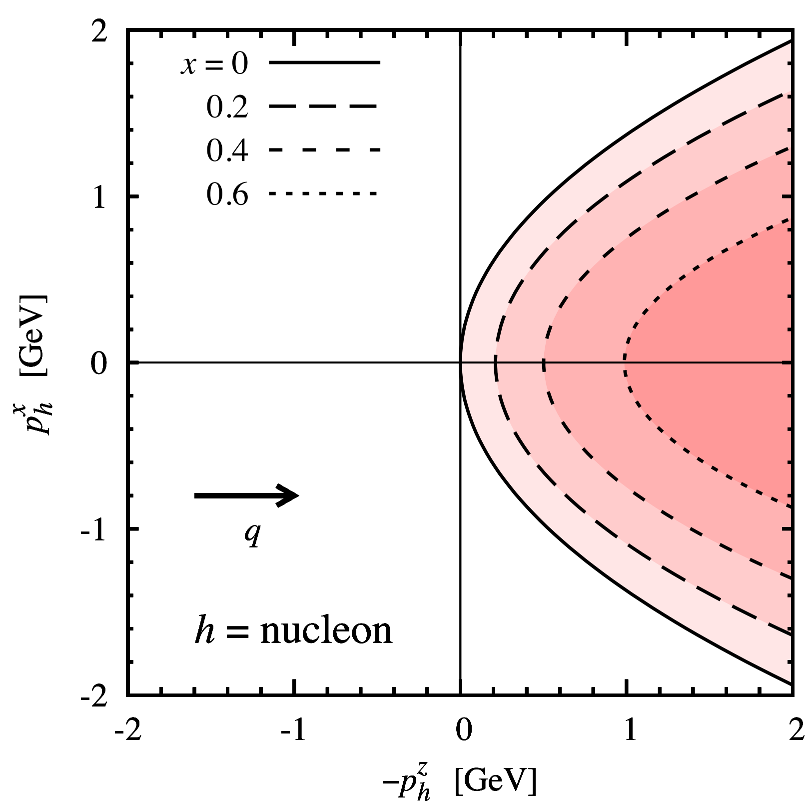


Studied distributions of slow hadrons in DIS on nucleon — target fragmentation

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

Used experimental distributions: HERA, EMC, neutrino DIS

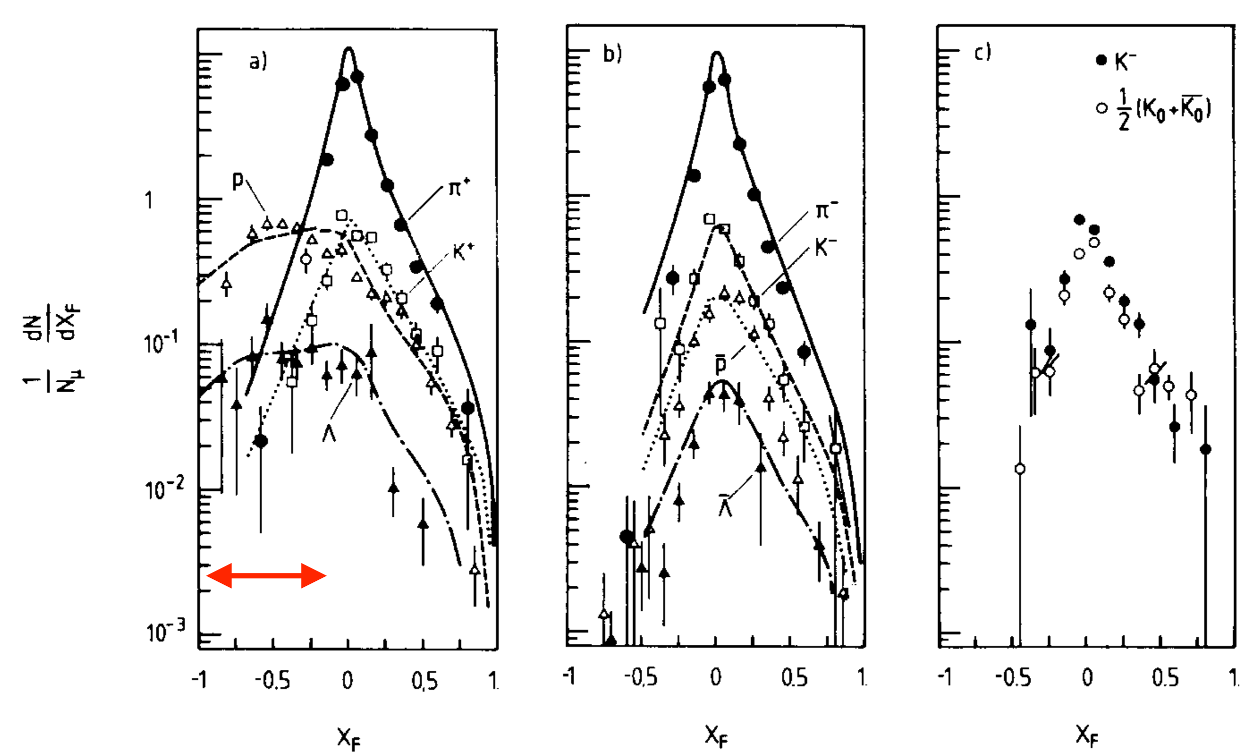
Need better data on target fragmentation: JLab12, EIC!



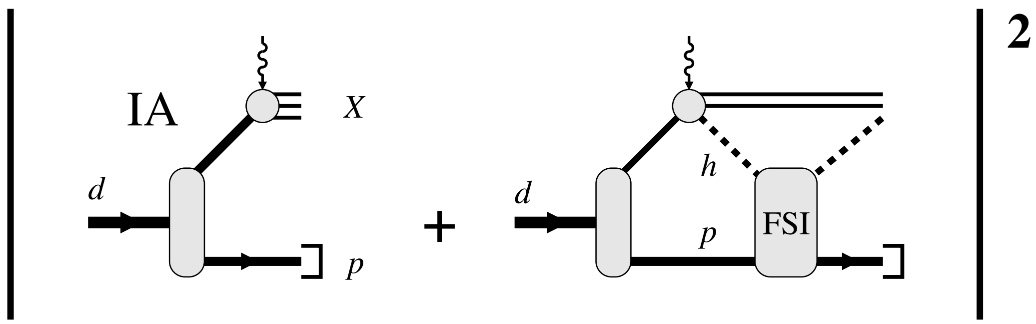
Momentum distribution of slow hadrons in nucleon rest frame: Cone in virtual photon direction

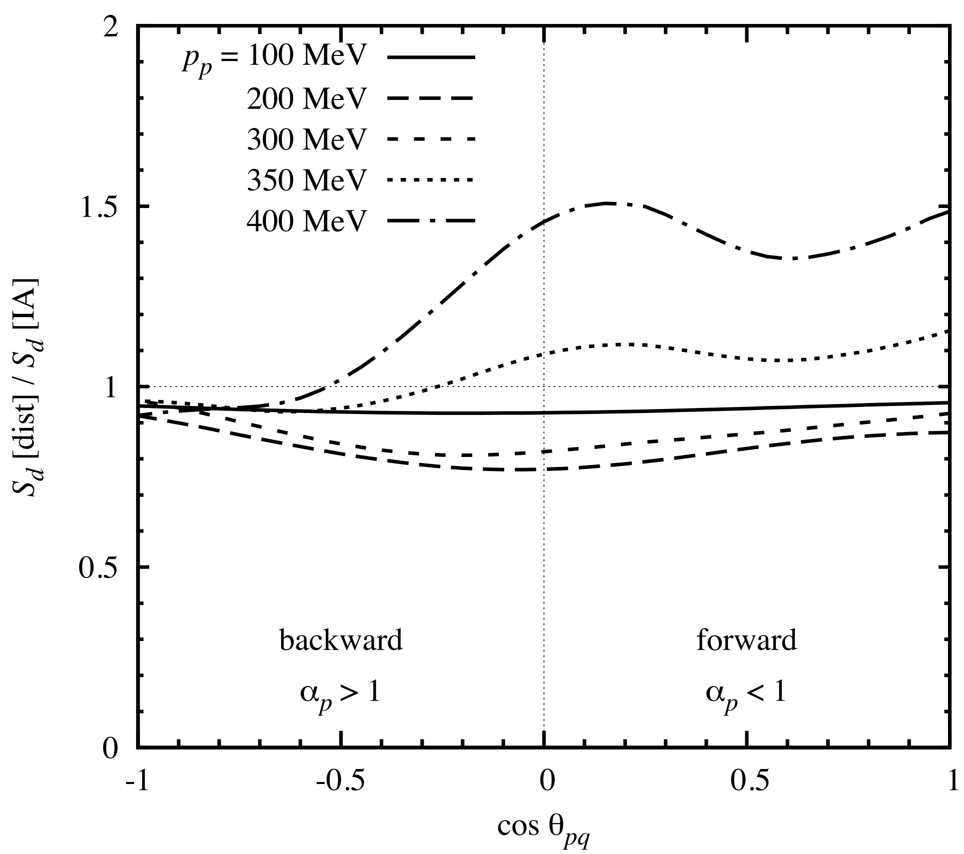
Strikman, Weiss PRC97 (2018) 035209

Hadron xF distributions EMC 1986



Final-state interactions: DIS at x >~ 0.1





FSI angular dependence in deuteron rest frame

Strikman, Weiss PRC97 (2018) 035209

FSI calculation

Evaluated scattering of slow hadrons from spectator

QM description: IA + FSI amplitudes, interference

FSI amplitude has imaginary and real part:
Absorption and refraction

Momentum and angular dependence

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

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

Results used in EIC simulations,
analysis of JLab12 BAND experiment