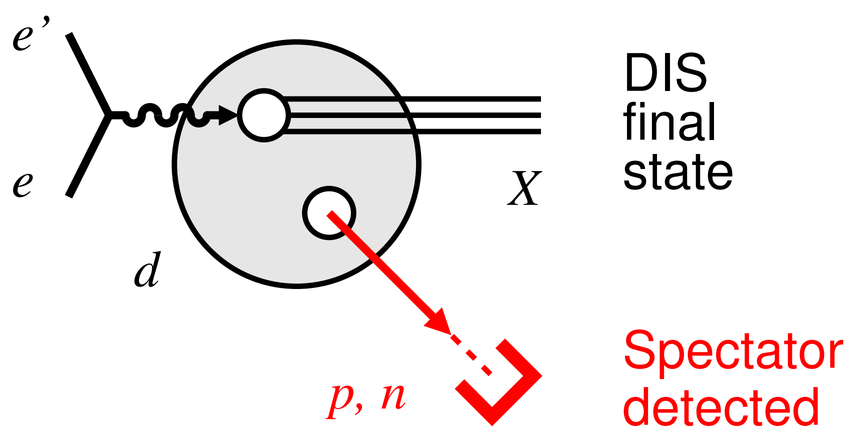
Initial-state modifications vs final-state interactions in tagged DIS

C. Weiss, Short-distance nuclear structure and PDFs, ECT* Trento, 17-21 July 2023



Goal: Use spectator momentum to control nuclear configurations during high-energy process: Momentum/size, interactions, S/D wave

Challenge: Separate initial-state modifications from final-state interactions

Experiments: JLab12 BONuS, ALERT, BAND
EIC far-forward detectors

FSI at EIC: Strikman, Weiss PRC 97, 035209 (2018)

EIC simulations: Jentsch, Tu, Weiss, PRC 104, 065205 (2021) + in progress

Deep-inelastic scattering on light nuclei

- Controlling nuclear configurations

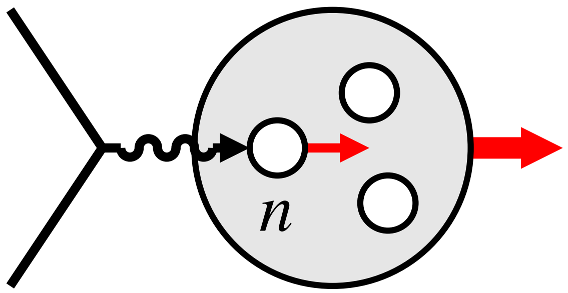
Spectator tagging with deuteron

- Cross section
- Light-front methods: Nucleus ↔ nucleon structure
- Impulse approximation and final-state interactions
- Free neutron structure extraction

Tagged EMC effect

- Initial-state modifications vs final-state interactions
- Prospects/needs for JLab12 and EIC

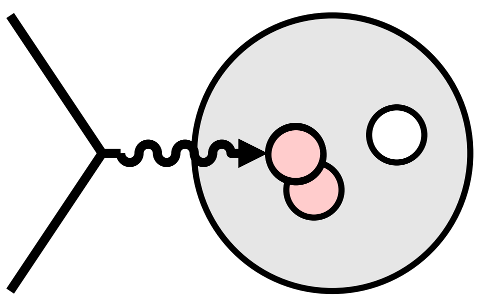
DIS on light nuclei: Physics objectives



Neutron structure and spin

Flavor decomposition of quark PDFs/spin, GPDs, TMDs

Singlet-nonsinglet separation in QCD evolution for ΔG

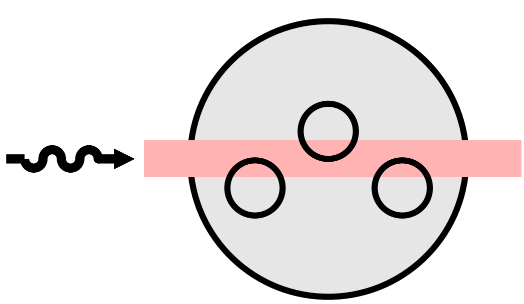


Nuclear modifications of partonic structure

EMC effect $x > 0.3$, antishadowing $x \sim 0.1$

→ Talk Strikman

Quarks/antiquarks/gluons? Spin, flavor?
Dynamical mechanism?



Coherent phenomena

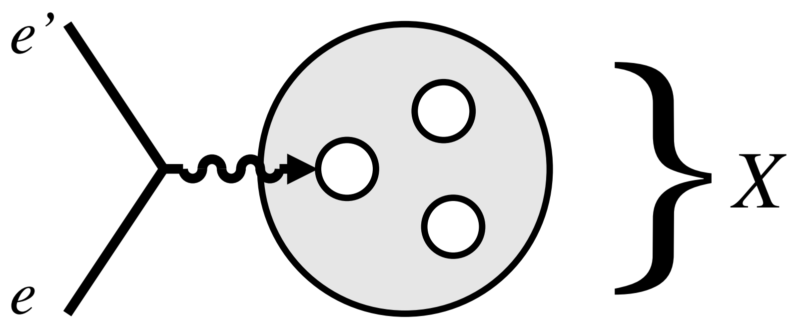
Nuclear shadowing $x \ll 0.1$

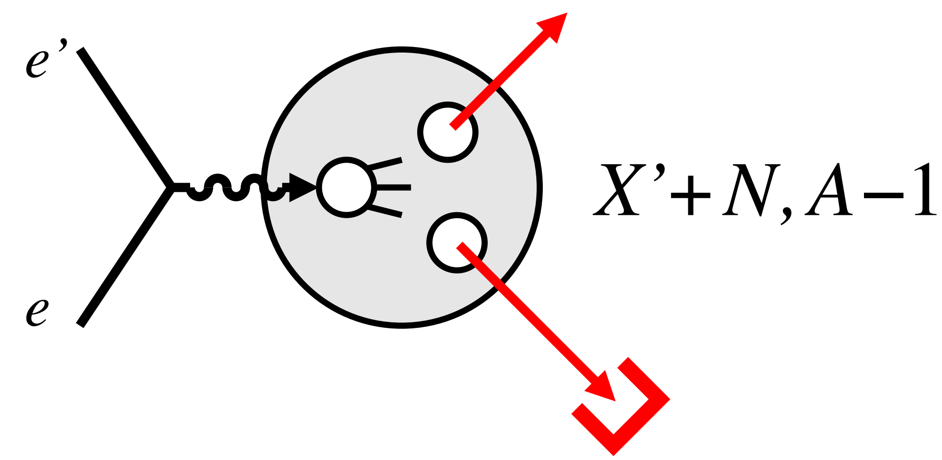
Buildup of coherence, interaction with 2, 3, 4… nucleons?
↔ Shadowing and saturation in heavy nuclei

[Nucleus rest frame view]

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

DIS on light nuclei: 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 Σ_X

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

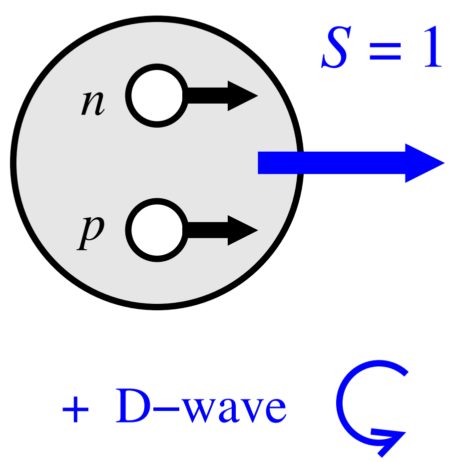
Nuclear breakup detection - tagging

Potential information on initial-state nuclear configuration

Study effects in defined configurations, much more direct

Final-state interactions important, influence breakup amplitudes

New opportunities with JLab12 and EIC
New challenges for detection and theory!

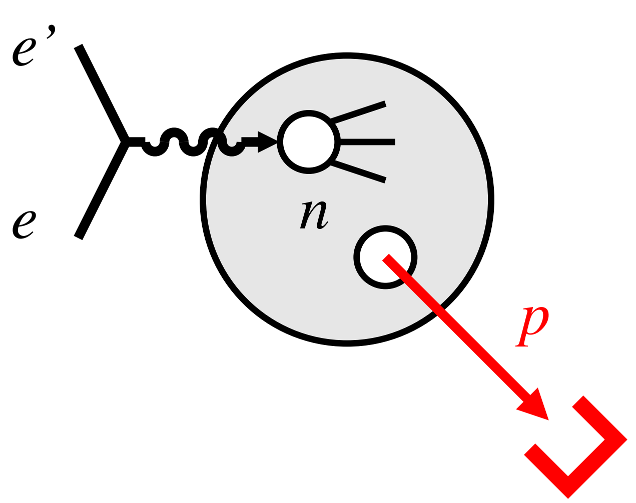


Deuteron as simplest system

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. Frankfurt, Guzey, Strikman 1996



[Nucleus rest frame view]

Spectator nucleon tagging

Identifies active nucleon

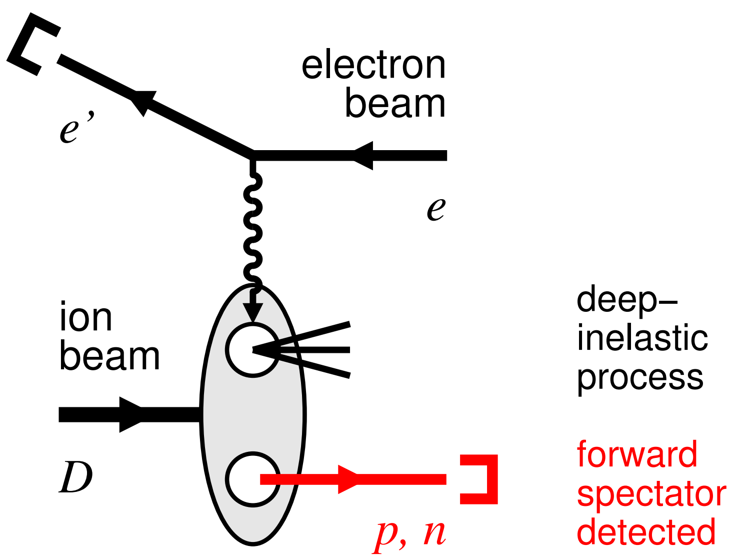
Controls configuration through spectator momentum:
spatial size → interactions, S/D wave → polarization

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 Kutz

DIS on light nuclei: Spectator tagging with EIC



[Collider frame view]

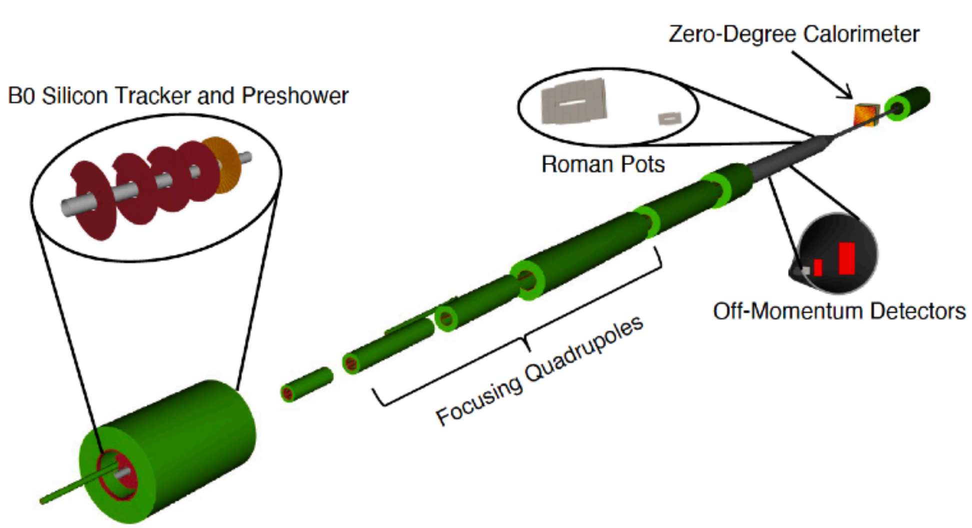
Spectator moves forward in ion beam direction

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

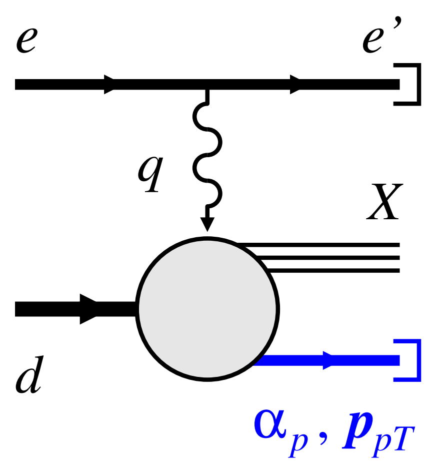
Zero-Degree Calorimeter for neutron

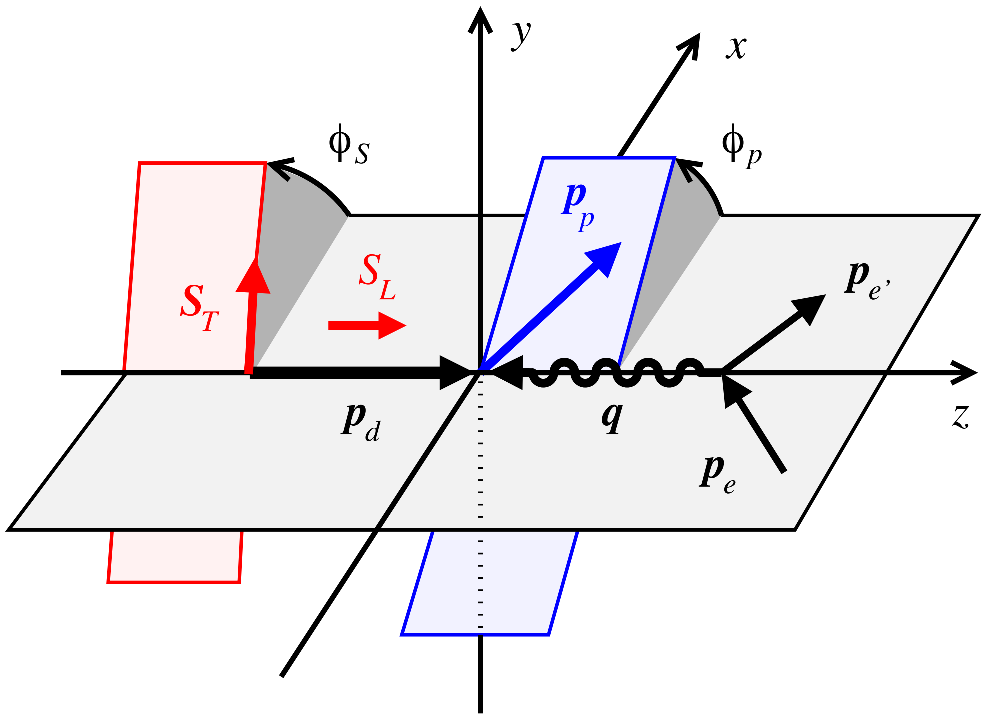
Advantage over fixed target: No target material, can detect spectators with rest frame momenta down to ~zero

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

→ Talk Tu

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

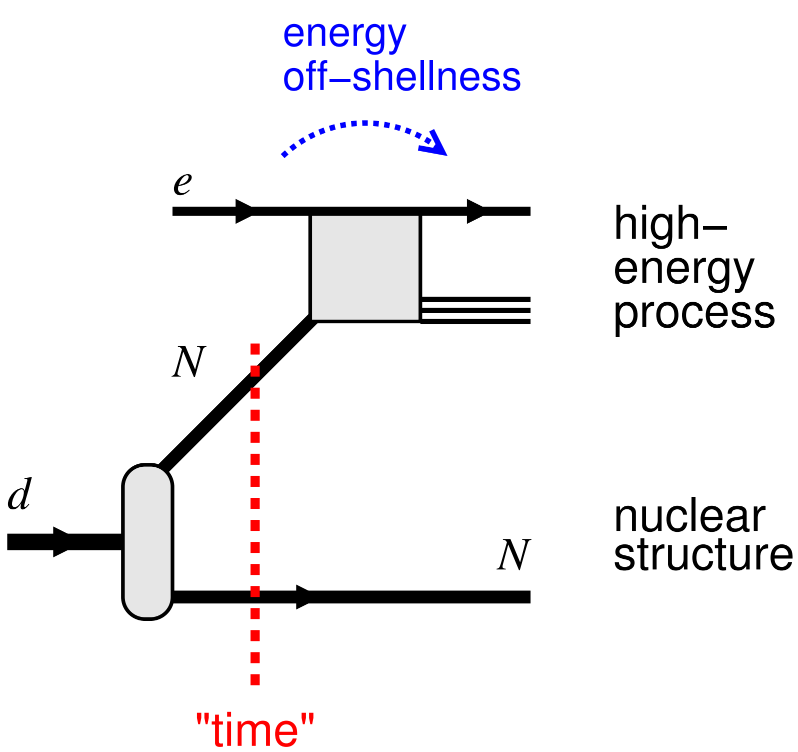
Semi-inclusive cross section $e + d \rightarrow e' + X + p$ (or n)

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!



Light-front quantization

Nuclear structure described at fixed light-front time $x^+ = x^0 + x^3$

Off-shellness of electron-nucleon scattering amplitude remains finite in high-energy limit — unique scheme

Permits matching with on-shell nucleon scattering amplitude and structure functions

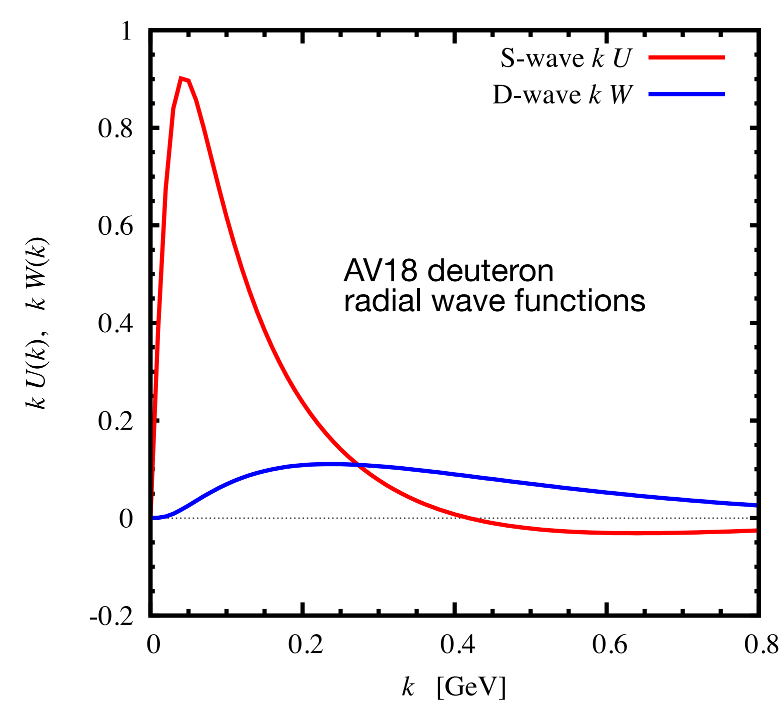
Frankfurt, Strikman 80s

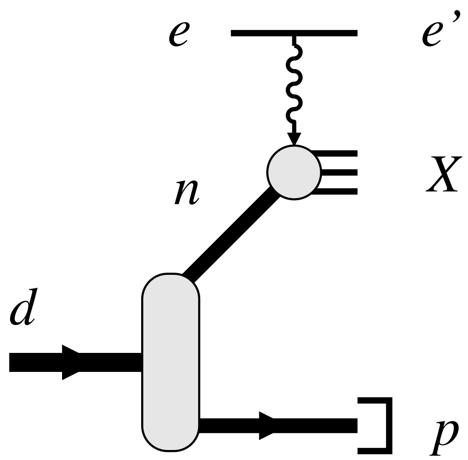
Nuclear structure in nucleon degrees of freedom

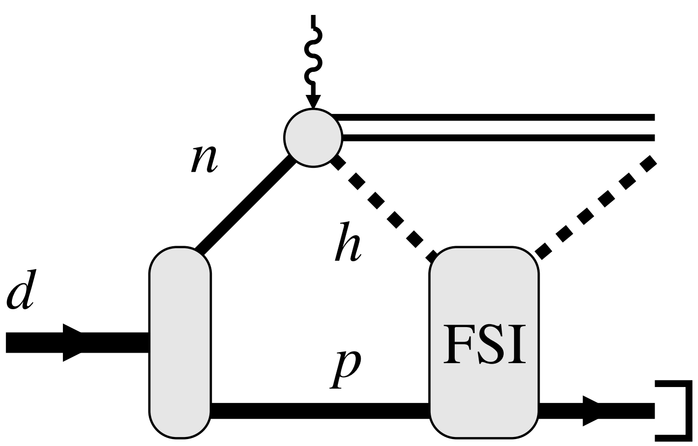
Nucleus described by wave function at fixed light-front time $_{x^+}\langle pn \,|\, d \rangle = \Psi(\alpha_p, p_{pT})$

Contains low-energy nuclear structure, just "organized" in manner suitable for high-energy processes

Can be computed from microscopic NN interactions, or constructed approx. from nonrelativistic wave function







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

One-body current
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

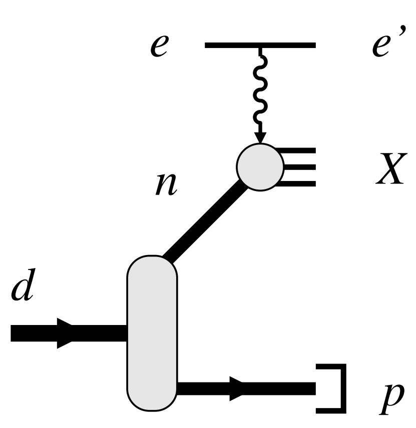
Requires theoretical modeling

Strategy

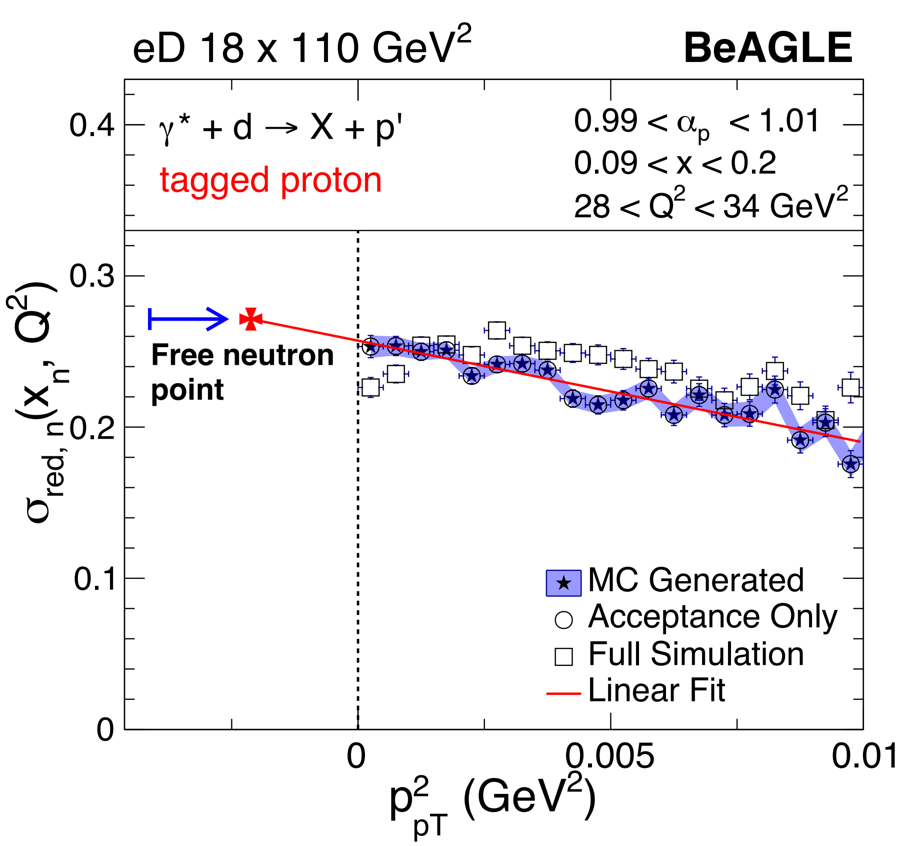
Use measured spectator momentum to control nuclear binding in initial state, interactions in final state

“Select configurations” in nucleus

Tagging: Free neutron structure



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



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 $p_{pT}^2 > 0$

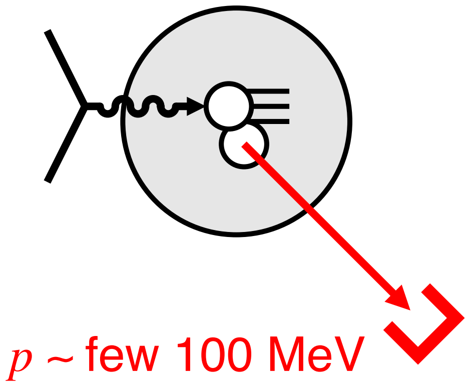
Divide data by pole term of spectral function

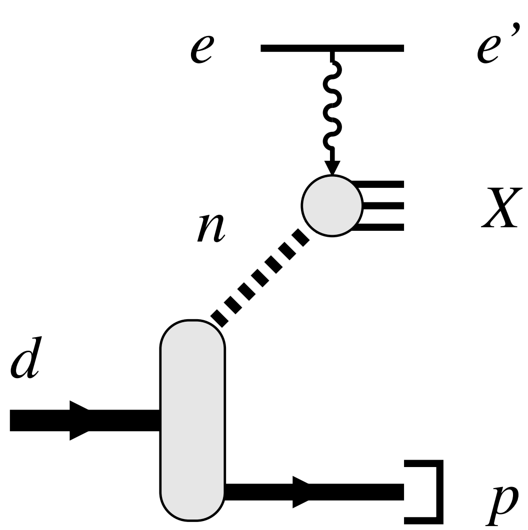
Extrapolate to pole position $p_{pT}^2 \to -a_T^2 < 0$

Simulated at EIC, appears feasible

→ Talk Tu

Tagging: Bound nucleon structure - EMC effect





EMC effect

Observed in inclusive DIS $0.3 < x < 0.7$ → Talks Hague, Cotton, Sharda

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

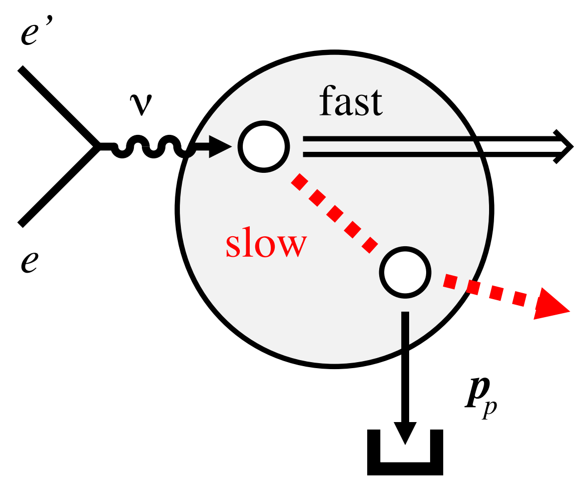
Parameters fixed by inclusive EMC effect data and average virtuality $\langle V \rangle_A \sim 2\langle p^2 \rangle_A$ from nuclear structure calculations
Ciofi degli Atti, Frankfurt, Kaptari, Strikman 2007

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?

FSI: Physical picture



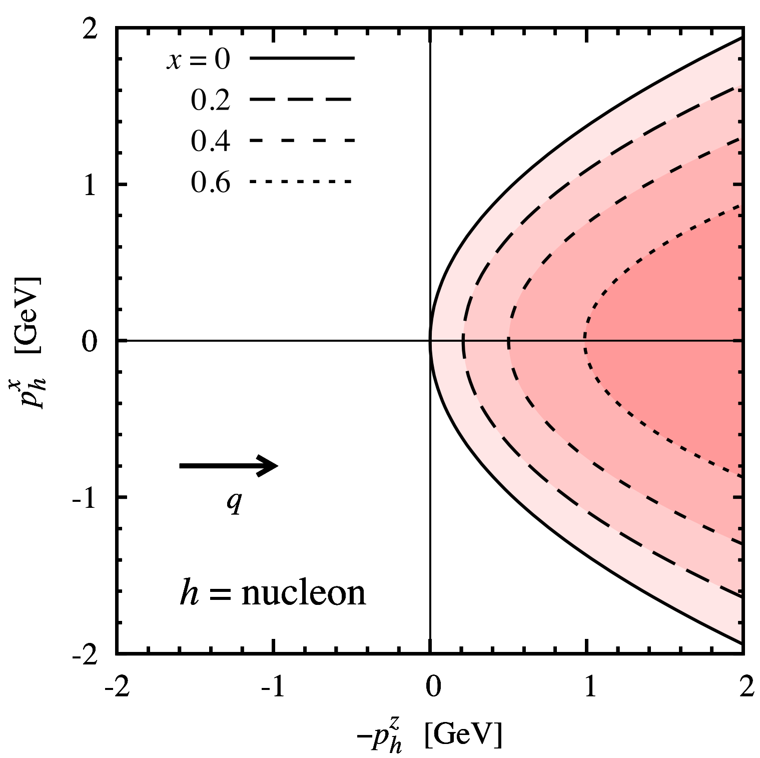
Space-time picture in deuteron rest frame $x \gtrsim 0.1$

$\nu \gg$ 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!

Strikman, Weiss PRC97 (2018) 035209



Momentum distribution of slow nucleons in target rest frame: Cone in virtual photon direction

Implementation

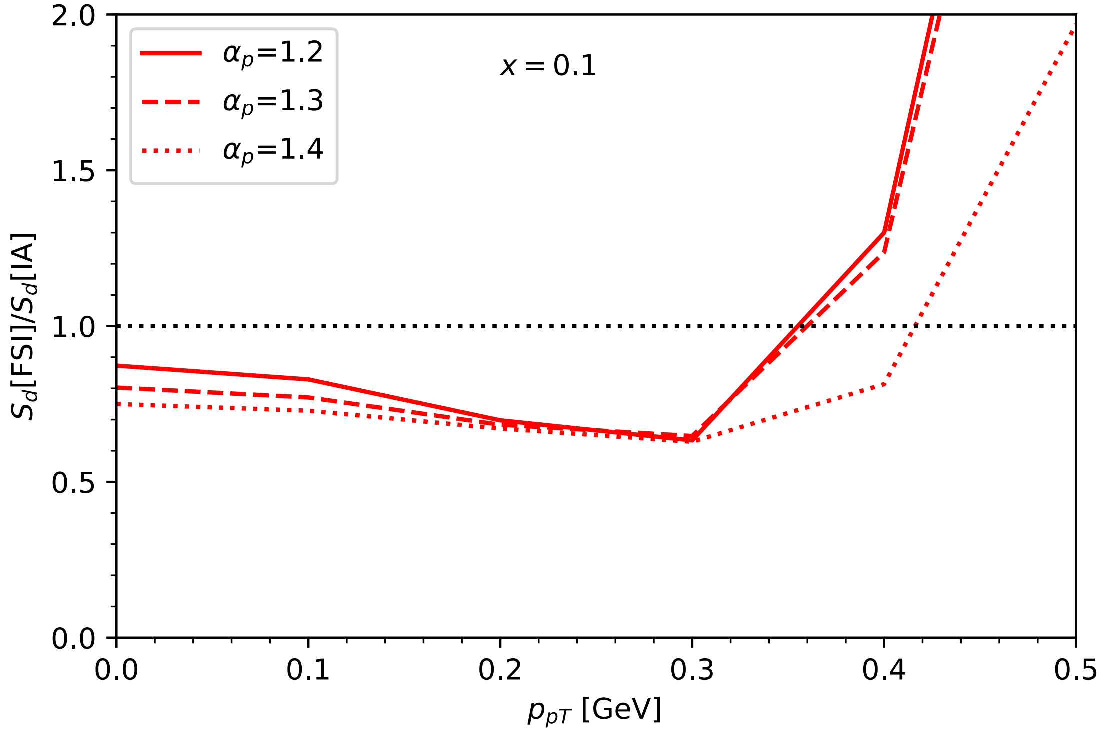
Distributions of slow hadrons in DIS on nucleon:
Kinematic dependence, empirical distributions

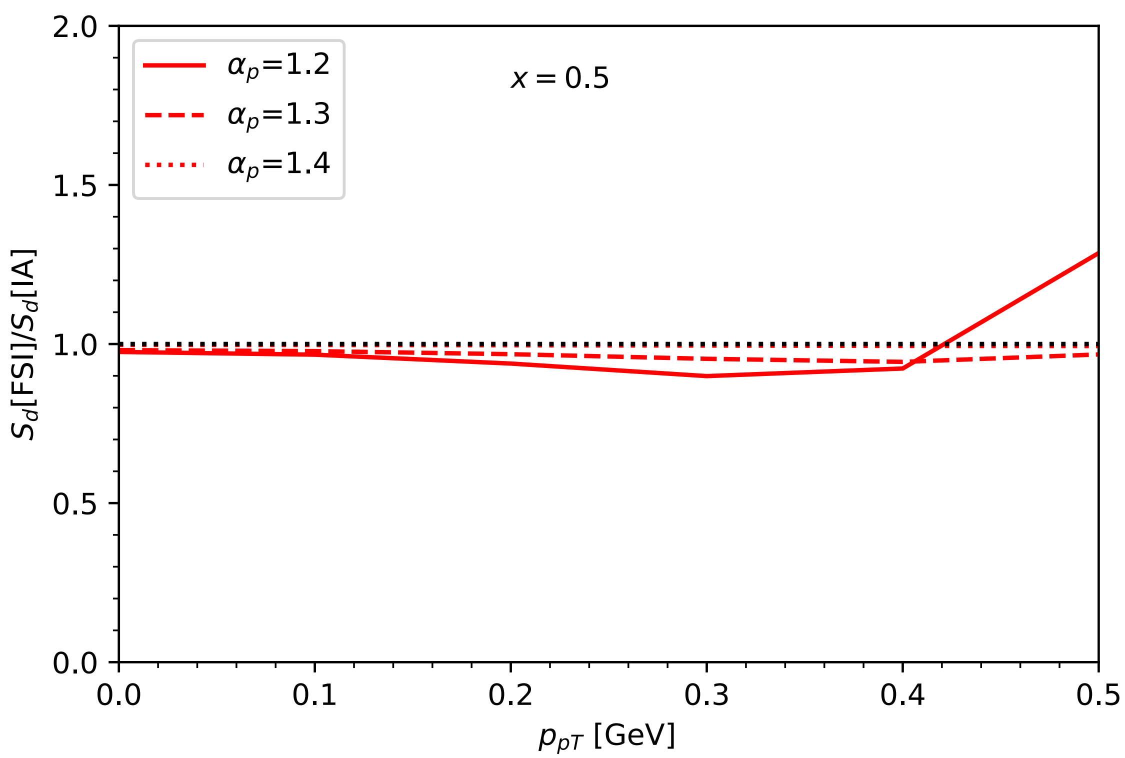
Hadron-nucleon scattering amplitudes: Im/Re

Calculation of rescattering process: $|\text{IA} + \text{FSI}|^2$,
QM interference

Study kinematic dependences: x, α_p, p_{pT}

FSI: Kinematic dependence





FSI ratio S_d[FSI]/S_d[IA]

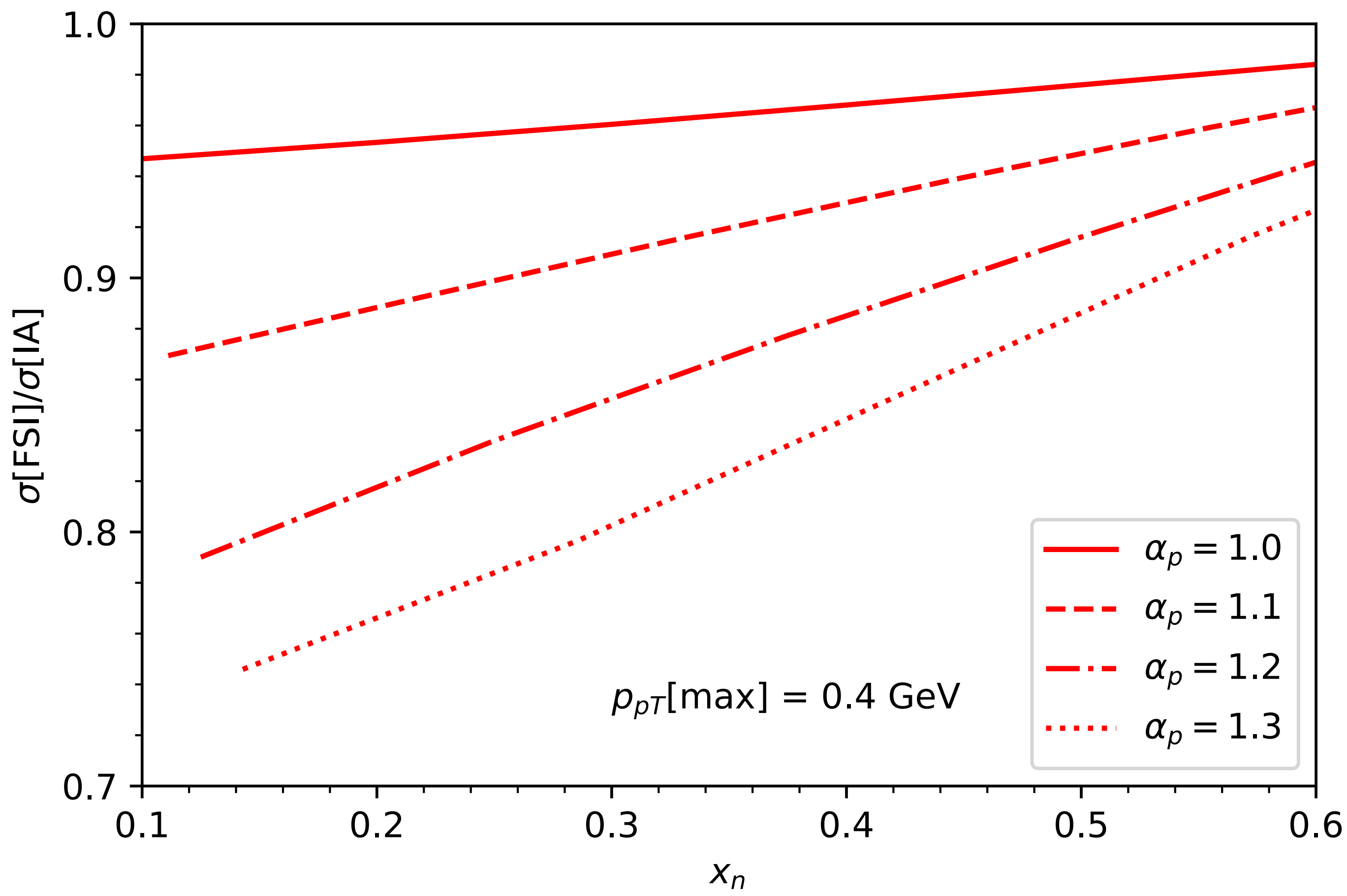
p_{pT} dependence: Weak up to ~0.3 GeV, strong rise above

α_p dependence: FSI increases with $\alpha_p - 1$ at small p_{pT}

x dependence: FSI decreases with increasing x due to depletion of slow hadrons

[Here showing dependence on LC momenta α_p and p_{pT} used in DIS. Also can show dependence on $|p_p|$ and θ_{pq} used in low-energy processes]

FSI: pT-integrated cross section



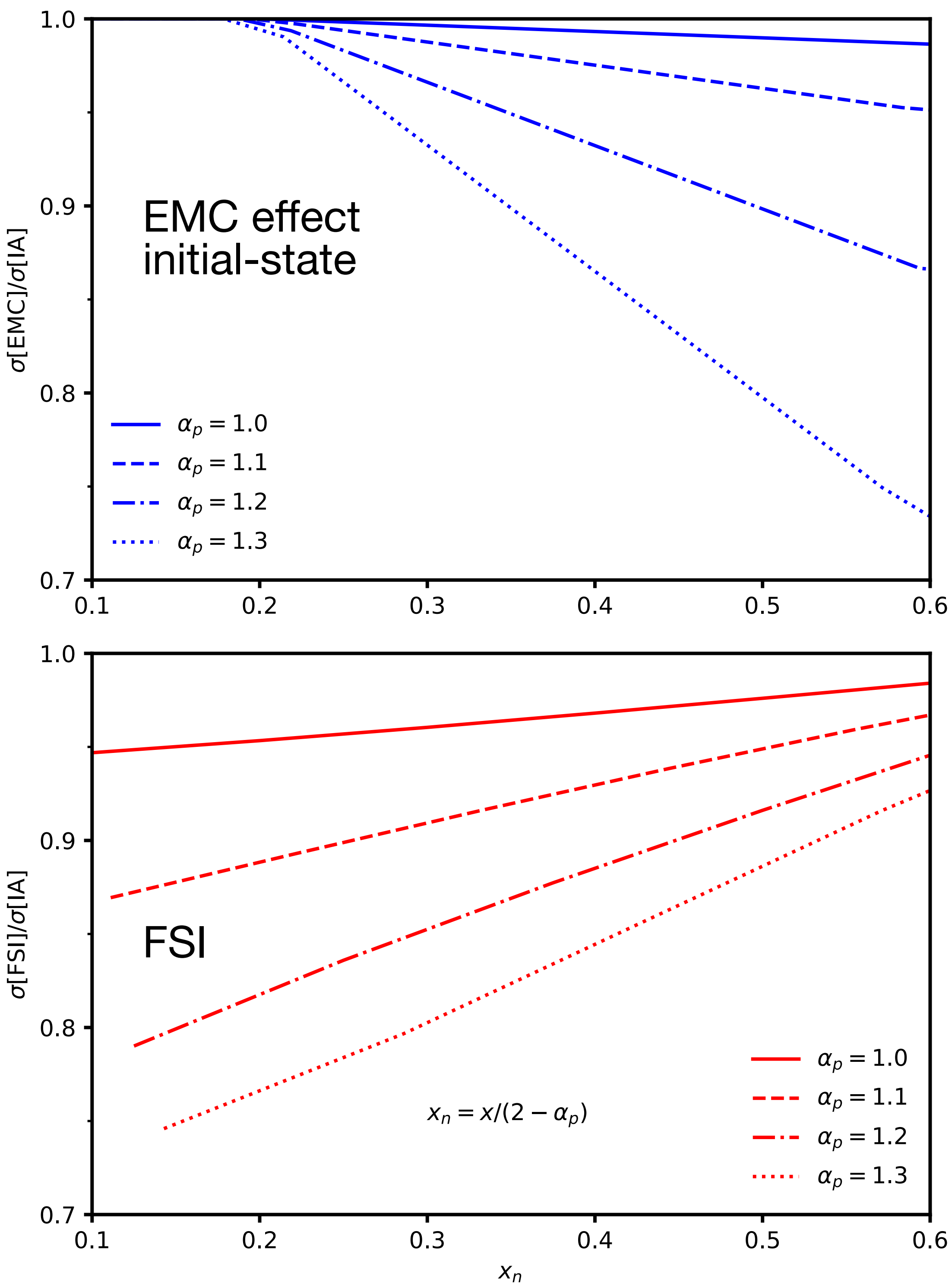
p_{pT} - integrated cross section: $\sigma = \int_{p_{pT}[\text{max}]} d^2 p_{pT} \; S_d(\alpha_p, p_{pT}) \; \sigma_n(x_n)$

Here: Plotted as function of $x_n = x/(2 - \alpha_p)$

Simple dependence on α_p and x_n

FSI effect typically ~10-20%

Tagged EMC effect: Initial vs final state



Here: p_{pT} - integrated cross section, p_{pT}[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

Tagged EMC effect: Prospects and needs

JLab 12 GeV

Limited kinematics for DIS, esp. $W(\gamma^* - \text{nucleon})$.
Not asymptotic situation, measurements close to boundaries of phase space

Impulse approximation: Uncertainties from power-suppressed effects Mass$^2/Q^2$,
various sources, should be investigated

Final-state interactions: DIS or resonance-based description?
Challenges with implementing coherence/asymptotics in resonance-based description
Cosyn, Sargsian, Melnitchouk 2011/14; Cosyn, Sargsian 2017

Statistics sufficient for differential measurements at large x

complementary
capabilities

EIC

Proper DIS kinematics. Asymptotic expressions should be applicable

Statistics limits measurements at large x and large spectator momenta.
No fully differential measurements, need to integrate or choose wide bins

Explore tradeoffs between initial-state modifications and final-state interactions
in partially integrated cross sections with reasonable statistics
Jentsch, Tu, Weiss, in progress

Possibility of proton and neutron tagging

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

Active experimental programs at JLab12 and EIC

Free neutron structure extraction through pole extrapolation simulated at EIC, appears feasible

Tagged EMC effect can reveal configuration dependence, but requires reliable theory of FSI

Reference model of FSI at $x > 0.1$ developed based on space-time picture of hadronization, can be refined

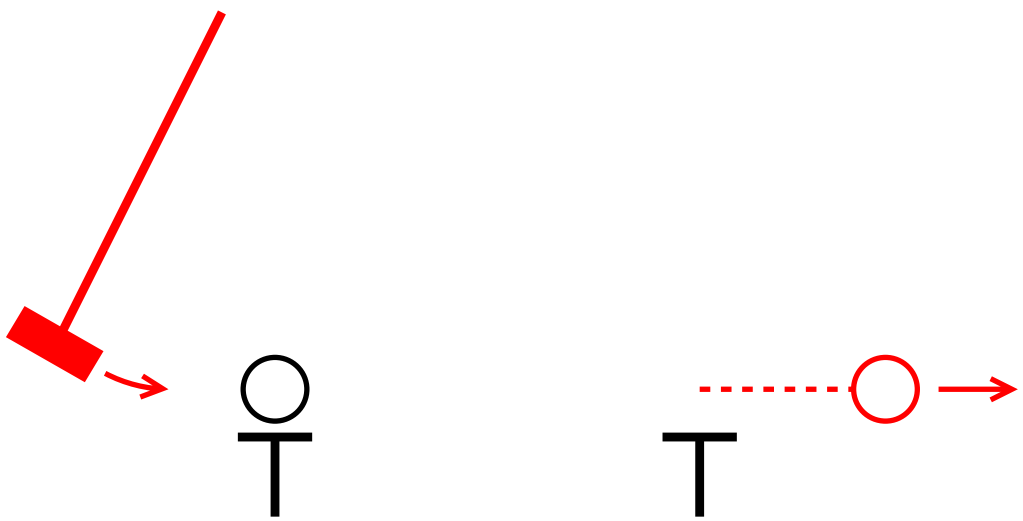
Other applications of spectator tagging (not covered here):

- Polarized deuteron: Tagging controls S/D wave ratio, vector and tensor polarized observables
  → ECT* Workshop “Tensor spin observables” July 10-14
- Diffractive DIS at small x: Configuration dependence of nuclear shadowing
- Tagged exclusive processes: DVCS, meson production

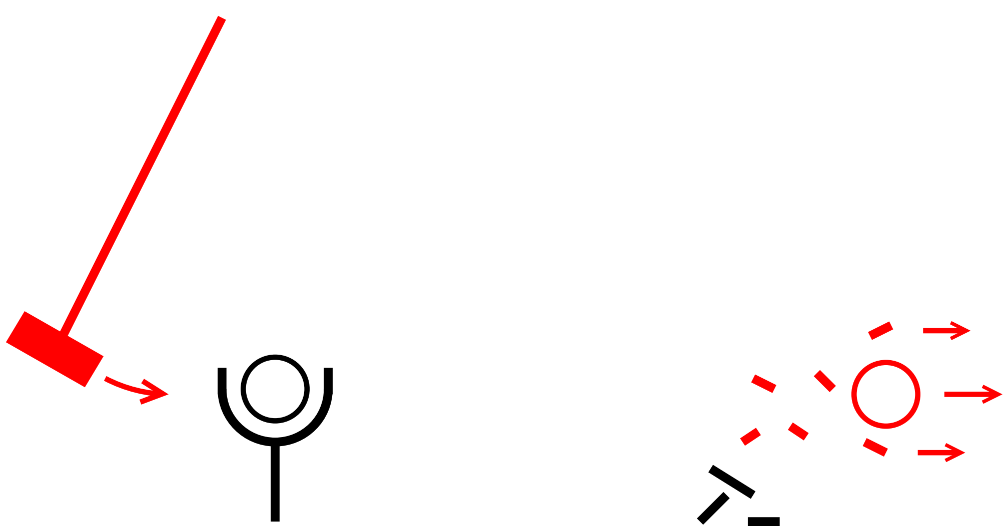
Supplemental material

Theory: Light-front quantization

Analogue: Teeing up a golf ball

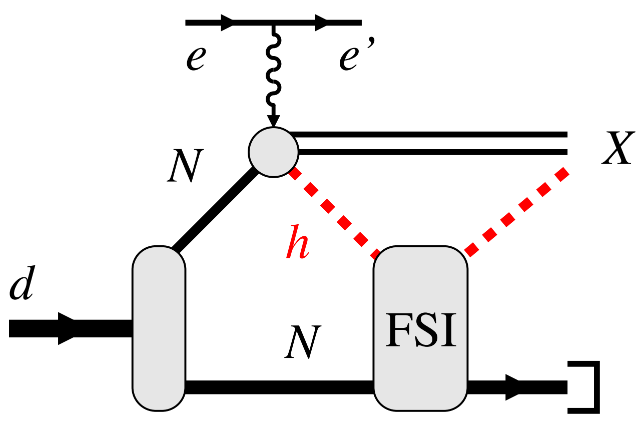


Light-front quantization:
Low-energy structure aligned with direction of high-energy process



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

FSI: Physical picture

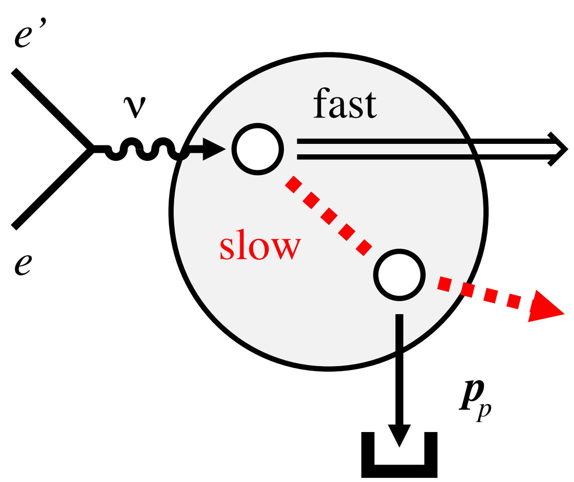


Part of final state of high-energy process interacts with spectator

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

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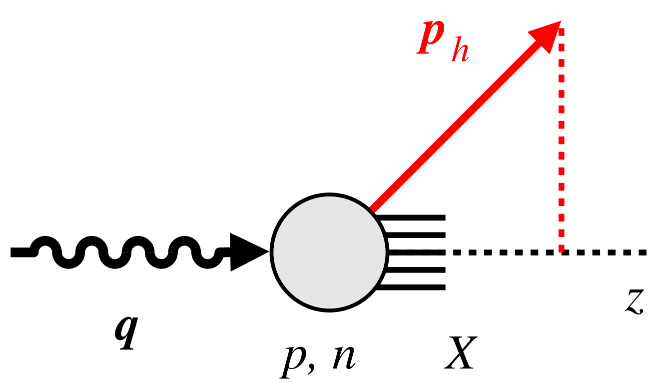
Formed inside nucleus, interact with hadronic cross sections
Source of FSI in tagged DIS!

[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

FSI: DIS hadron spectrum

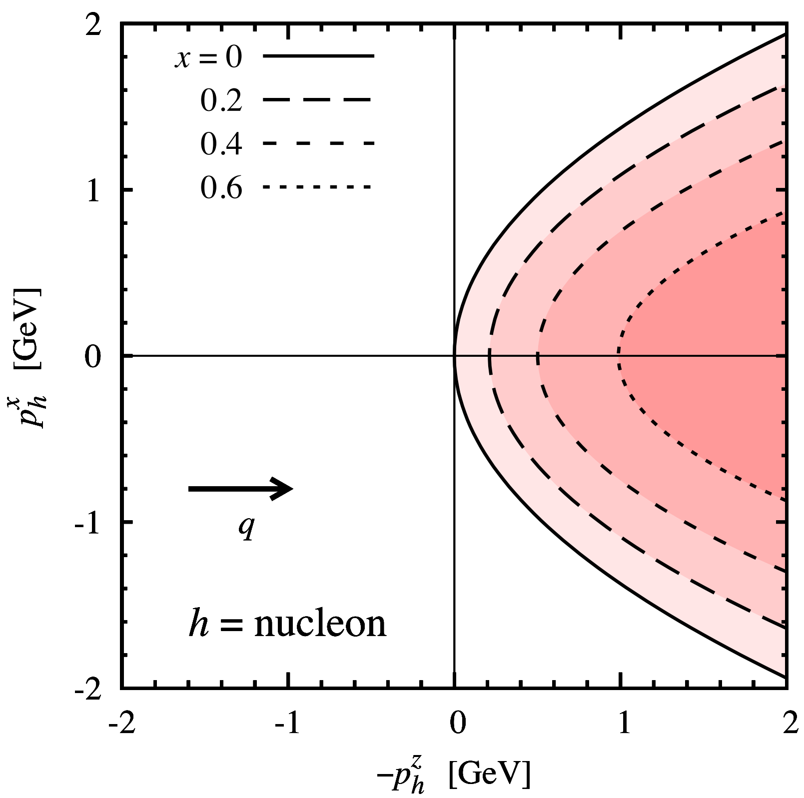


Studied distributions of slow hadrons in DIS on nucleon — target fragmentation

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

Used experimental distributions: HERA, EMC, neutrino DIS

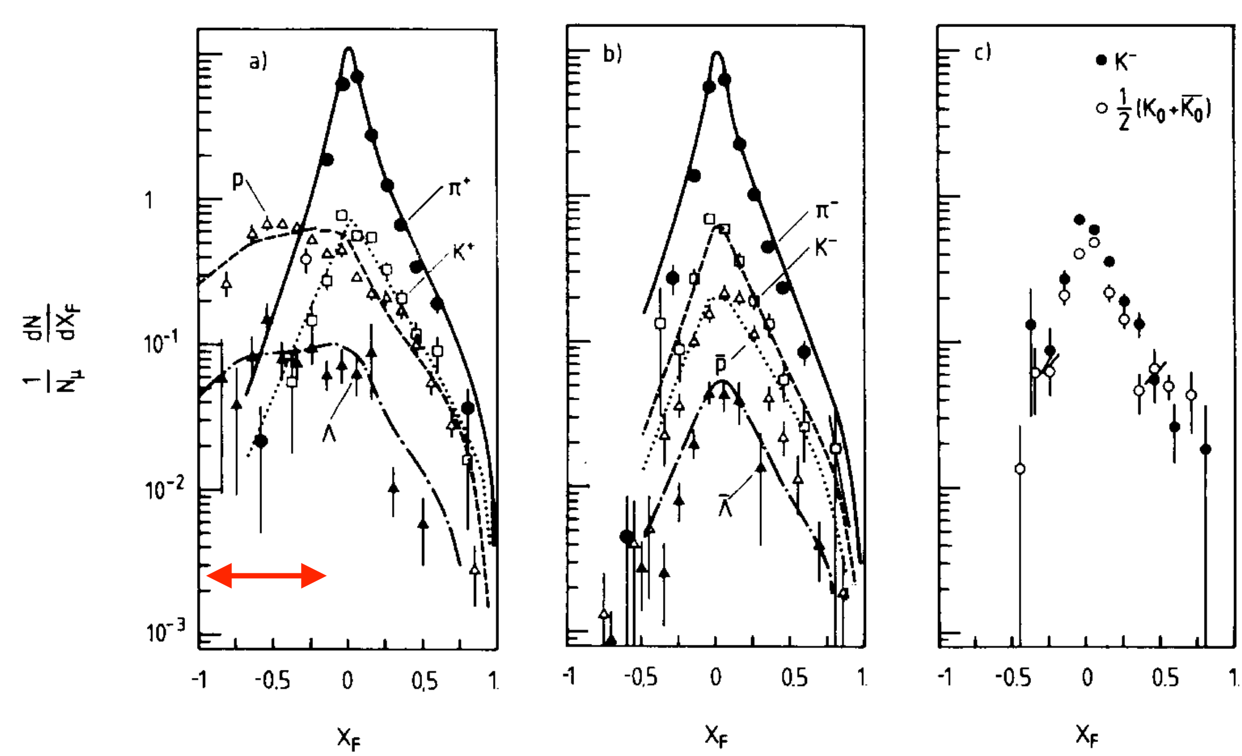
Need better data on target fragmentation: JLab12, EIC!

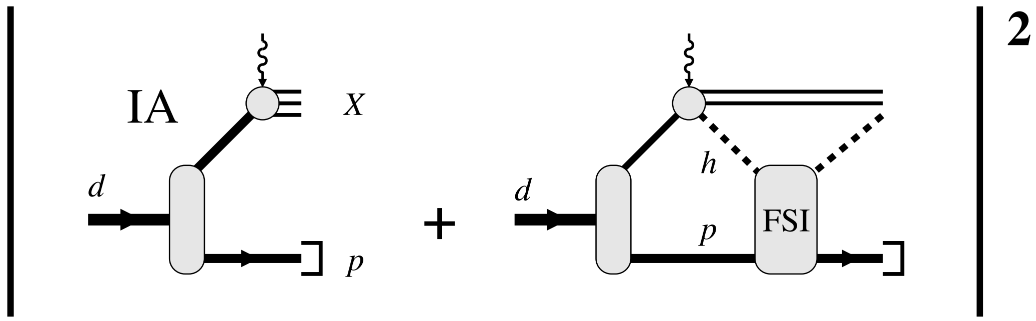


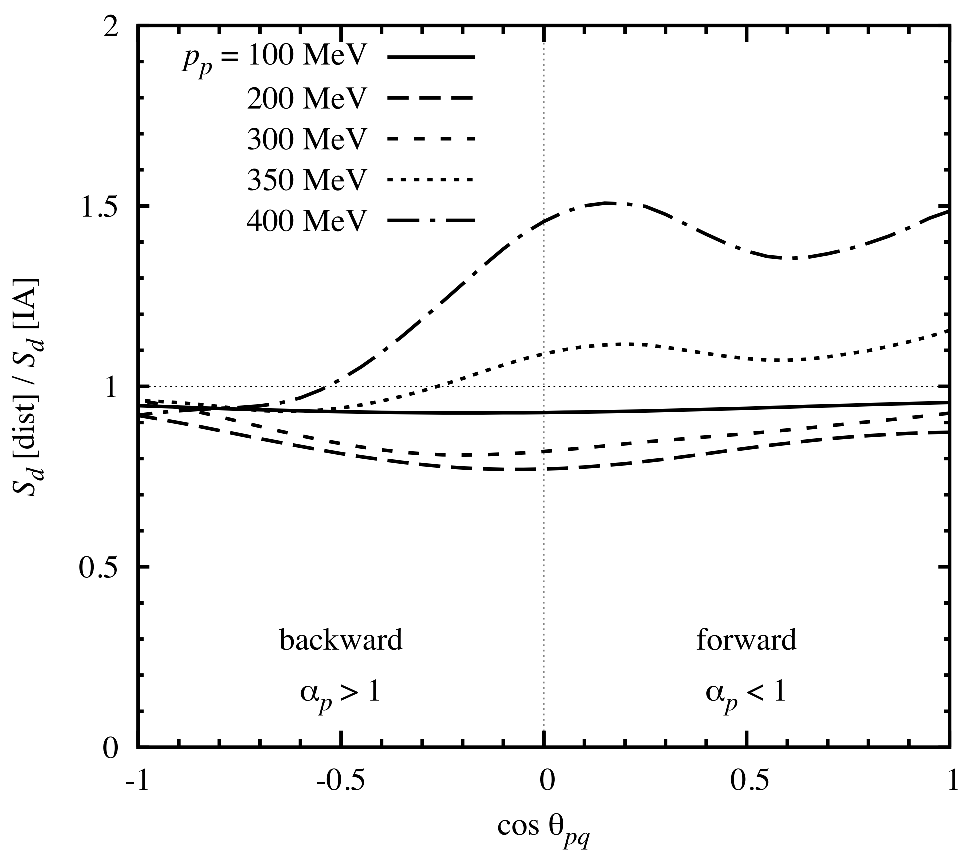
Momentum distribution of slow hadrons in nucleon rest frame: Cone in virtual photon direction

Strikman, Weiss PRC97 (2018) 035209

Hadron xF distributions EMC 1986







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