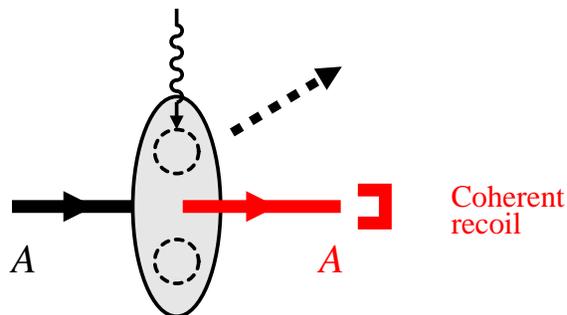
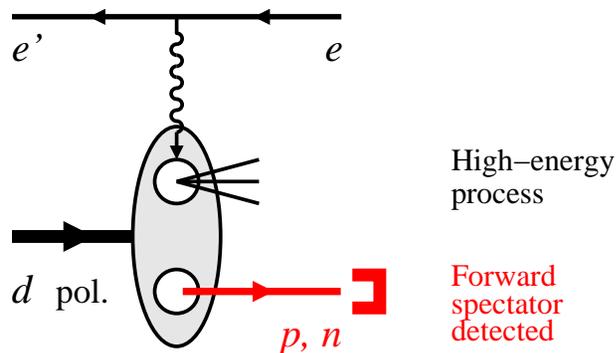


Light ion physics with forward detection at EIC

C. Weiss (JLab), Forward Physics and Instrumentation, CFNS Stony Brook, 17-Oct-2018



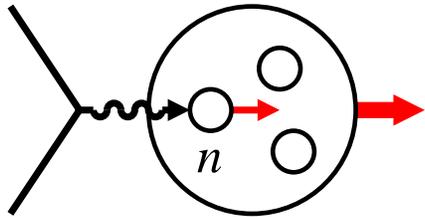
- Light-ion physics with EIC
 - Objectives and challenges
- Spectator tagging with deuteron
 - High-energy process \leftrightarrow low-energy structure
 - Free neutron from on-shell extrapolation
 - Tagging with polarized deuteron
 - Recent: Final-state interactions, diffraction
- Coherent processes with light nuclei
 - Quark/gluon spatial distributions
 - Dynamics: Nuclear shadowing etc.

- [• Forward detection with EIC]

EIC simulations: JLab 2014/15 LDRD project
W. Cosyn, V. Guzey, D. Higinbotham, Ch. Hyde,
K. Park, P. Nadel-Turonski, M. Sargsian,
M. Strikman, C. Weiss [Webpage]
+ ongoing theoretical research

Light ions: Physics objectives

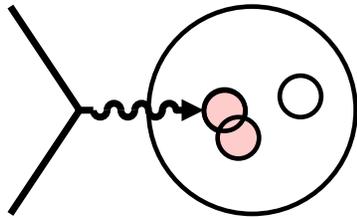
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- Neutron structure

Flavor decomposition of PDFs/GPDs/TMDs,
singlet vs. non-singlet QCD evolution, polarized gluon

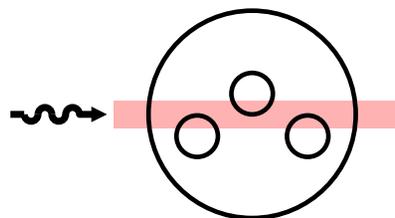
Eliminate nuclear binding, non-nucleonic DOF!



- Nucleon interactions in QCD

Nuclear modification of quark/gluon densities
Short-range correlations, non-nucleonic DOF
QCD origin of nuclear forces

Associate modifications with interactions!



- Coherent phenomena in QCD

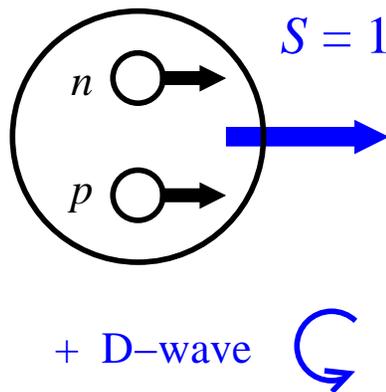
Coherent interaction of high-energy probe
with multiple nucleons, shadowing, saturation

Identify coherent response!

[Nucleus rest frame view]

Common challenge: Many possible nuclear
configurations during high-energy process.
Need to “control” configurations!

Light ions: Deuteron and spectator tagging

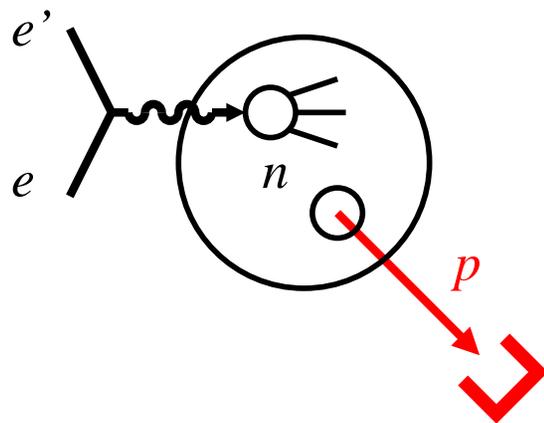


- Polarized deuteron

pn wave function simple, known well
incl. light-front WF for high-energy procs

Neutron spin-polarized

Intrinsic Δ isobars suppressed by isospin = 0
 $|\text{deuteron}\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$ negligible
3He spin structure distorted by Δ 's
Guzey, Strikman, Thomas et al 01



[Nucleus rest frame view]

- Spectator nucleon tagging

Identifies active nucleon

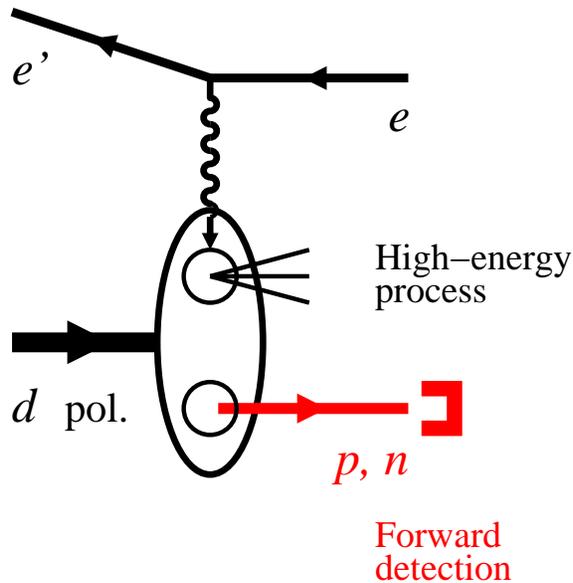
Controls configuration through recoil momentum:
Spatial size, $S \leftrightarrow D$ wave

Typical momenta \sim few 10 – 100 MeV (rest frame)

Tagging in fixed-target experiments

CLAS6/12 BONUS, recoil momenta $p = 70\text{-}150$ MeV
JLab12 ALERT, Hall A

Light ions: Deuteron and spectator tagging



- Spectator tagging with colliding beams

Spectator nucleon moves forward with approx. 1/2 ion beam momentum

Detection with forward detectors integrated in interaction region and beams optics

LHC $pp/pA/AA$, Tevatron $p\bar{p}$, RHIC pp , ultraperiph. AA

- Advantages over fixed-target

No target material, $\mathbf{p}_p[\text{rest}] \rightarrow 0$ possible

Potentially full acceptance, good resolution

Can be used with polarized deuteron

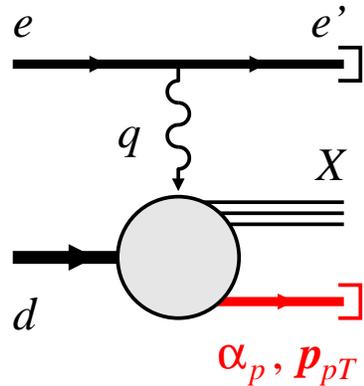
Forward neutron detection possible

$$p_{p\parallel} = \frac{1}{2} \left[1 + \mathcal{O} \left(\frac{p_p[\text{rest}]}{m} \right) \right]$$

[Collider frame view]

- Unique physics potential

Tagging: Cross section and observables



$$\frac{d\sigma}{dx dQ^2 (d^3p_p/E_p)} = [\text{flux}] \left[F_{Td}(x, Q^2; \alpha_p, \mathbf{p}_{pT}) + \epsilon F_{Ld}(\dots) \right. \\ \left. + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_p F_{LT,d}(\dots) + \epsilon \cos(2\phi_p) F_{TT,d}(\dots) \right. \\ \left. + \text{spin-dependent structures} \right]$$

- Conditional DIS cross section $e + d \rightarrow e' + X + p$

Structure/response functions in frame $\mathbf{q} \parallel \mathbf{p}_d$

Proton light-front momentum $p_p^+ = \alpha_p p_d^+ / 2, \mathbf{p}_{pT}$

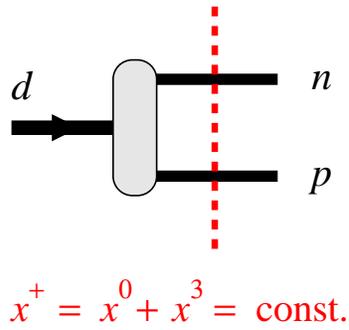
\longleftrightarrow \mathbf{p}_p in rest frame
 $p_{p\parallel}, \mathbf{p}_{p\perp}$ in collider frame

Special case of semi-inclusive DIS — target fragmentation

[QCD factorization Trentadue, Veneziano 93; Collins 97](#)

No assumptions re nuclear structure, $A = \sum N$, etc.

Tagging: Theoretical description



- Light-front quantization

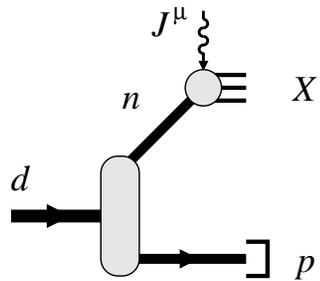
High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 = \text{const.}$

Deuteron LF wave function $\langle pn|d\rangle = \Psi(\alpha_p, \mathbf{p}_{pT})$

Permits matching nuclear \leftrightarrow nucleonic structure
 Conserves LF momentum, baryon number

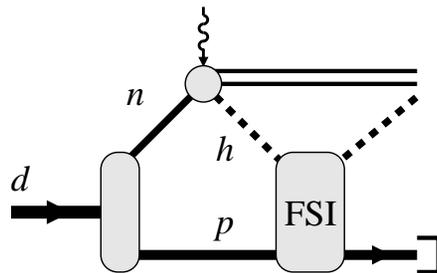
[Frankfurt, Strikman 80's](#)

Low-energy nuclear structure, cf. non-relativistic theory!



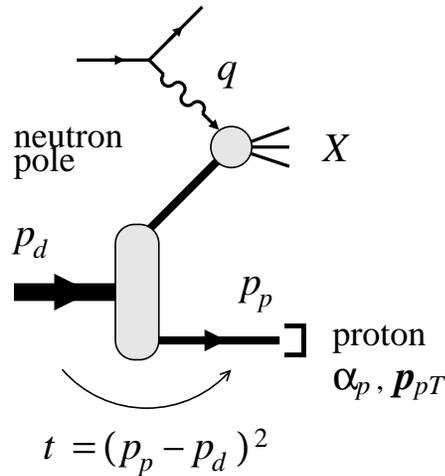
- Composite description

Impulse approximation: DIS final state and spectator nucleon evolve independently



Final-state interactions: Part of DIS final state interacts with spectator, transfers momentum

Tagging: Free neutron structure

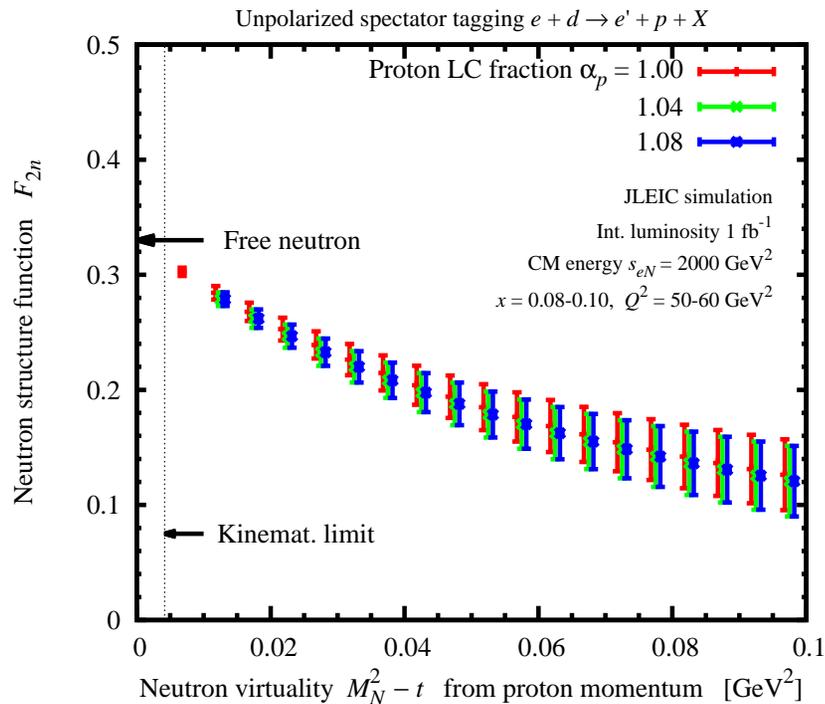


- Extract free neutron structure

Proton momentum defines neutron virtuality
 $t - M_N^2 = -2|\mathbf{p}_p(\text{rest})|^2 + t_{\text{min}}$

Free neutron at pole $t - M_N^2 = 0$:
 On-shell extrapolation

Eliminates nuclear binding effects
 and FSI [Sargsian, Strikman 05](#)



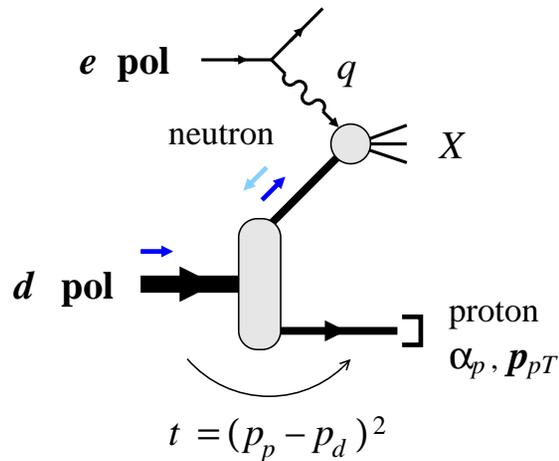
- Precise measurements of F_{2n}

F_{2n} extracted with few-percent
 accuracy at $x \gtrsim 0.1$

Uncertainty mainly systematic
[LDRD project: Detailed estimates](#)

Non-singlet $F_{2p} - F_{2n}$,
 sea quark flavor asymmetry $\bar{d} - \bar{u}$

Tagging: Neutron spin structure



- Neutron spin structure with pol deuteron and proton tagging

On-shell extrapolation of asymmetry

D-wave suppressed at $\mathbf{p}_p(\text{rest}) = 0$:
Neutron 100% polarized

- Systematic uncertainties cancel

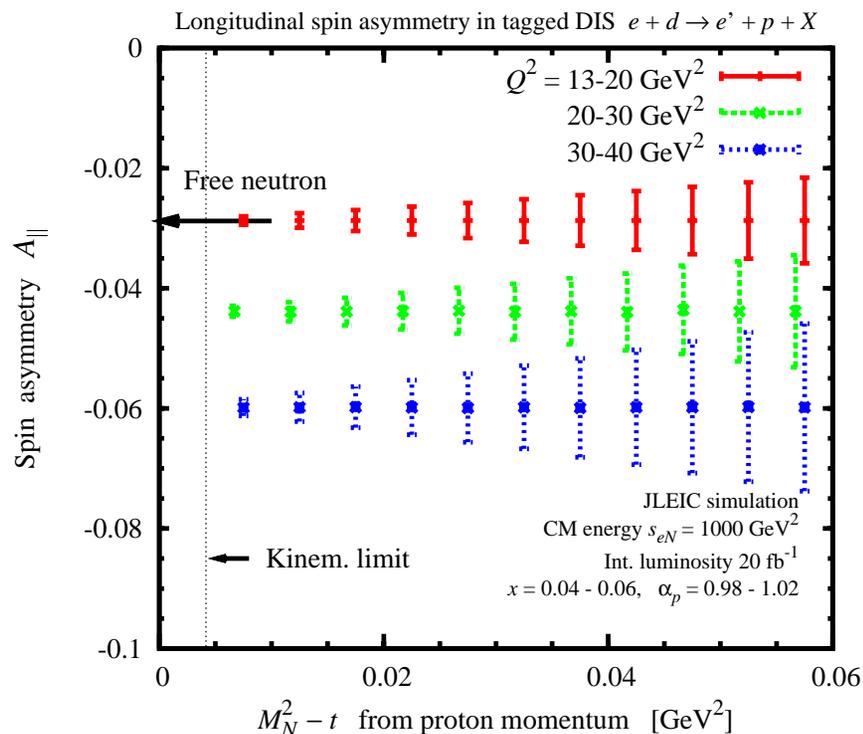
Weak off-shell dependence of asymmetry

Momentum smearing/resolution effects largely cancel in asymmetry

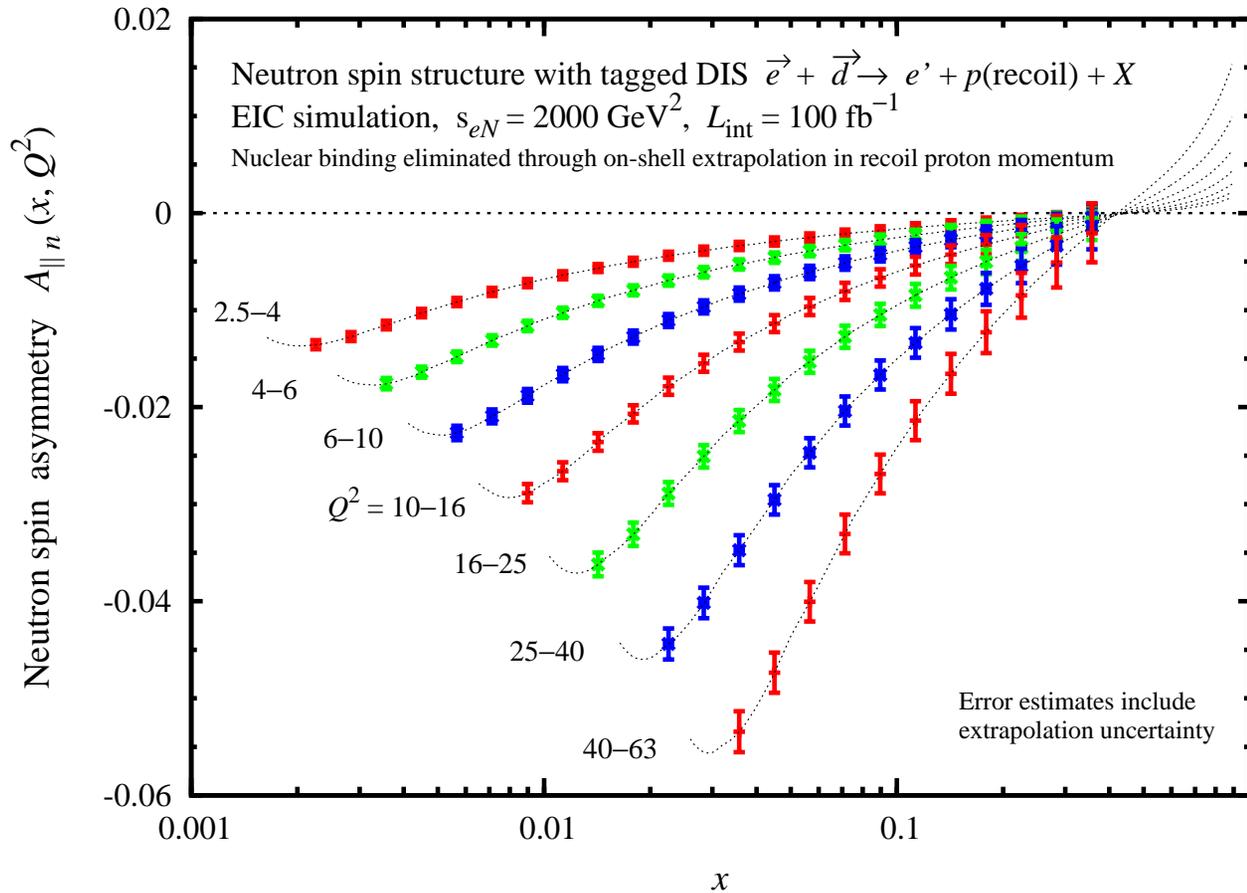
- Statistics requirements

Physical asymmetries ~ 0.05 - 0.1 ,
effective polarization $P_e P_D \sim 0.5$

Possible with int lumi \sim few 10 fb^{-1}



Tagging: Neutron spin structure II



$$A_{\parallel n} = \frac{\sigma(+ -) - \sigma(+ +)}{\sigma(+ -) + \sigma(+ +)}$$

$$= D \frac{g_{1n}}{F_{1n}} + \dots$$

$$D = \frac{y(2 - y)}{2 - 2y + y^2}$$

depolarization factor

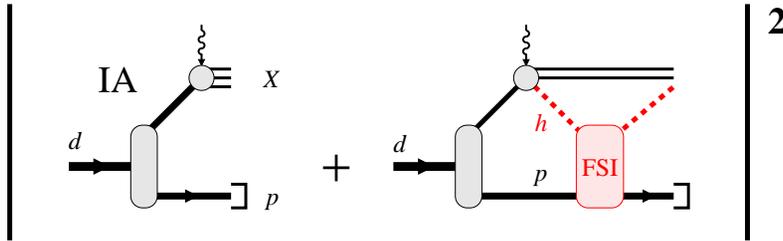
$$y = \frac{Q^2}{xs_{eN}}$$

- Precise measurement of neutron spin structure

Wide kinematic range: Leading \leftrightarrow higher twist, nonsinglet \leftrightarrow singlet QCD evolution

Parton density fits: Flavor separation $\Delta u \leftrightarrow \Delta d$, gluon spin ΔG

Nonsinglet $g_{1p} - g_{1n}$ and Bjorken sum rule

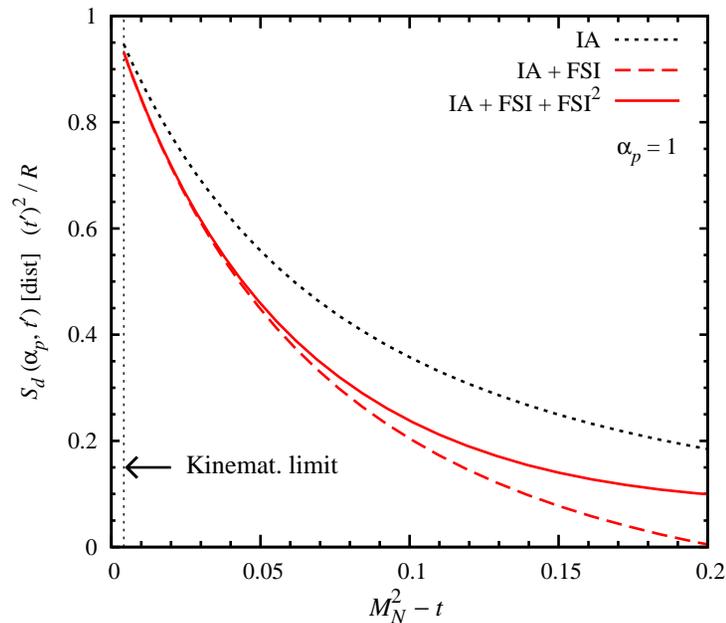


- FSI mechanism ($x \sim 0.1$)

Slow hadrons in DIS final state: Neutron fragmentation, $p_h \sim 1-2$ GeV (rest frame)

Interact with spectator proton

Change spectator momentum distribution, not change inclusive cross section – closure



- FSI effects calculated

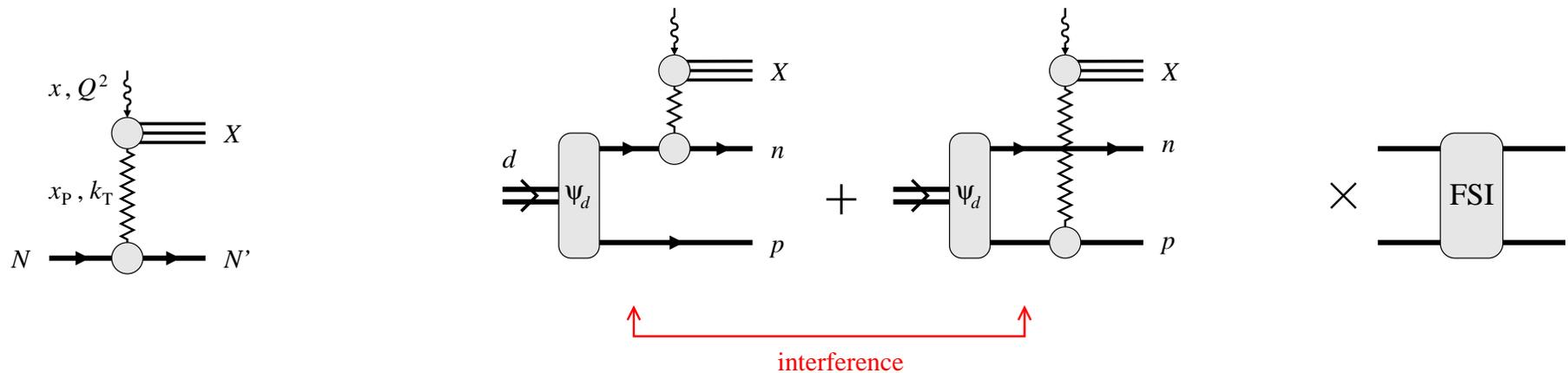
Sizable effects at $p_p \sim$ few 100 MeV

Vanish at $t - M_N^2 \rightarrow 0$, on-shell extrapolation not affected

Interesting aspects: Angular dependence, x -dependence, spin effects

[Strikman, Weiss, PRC97 \(2018\) 035209 \[INSP\]](#)

Tagging: Diffractive DIS at small x



- Diffraction in nucleon DIS at $x \ll 0.1$

Nucleon remains intact, recoils with $k \sim$ few 100 MeV (rest frame)

Detailed studies at HERA: QCD factorization, diffractive PDFs

- Shadowing in deuteron DIS

Diffraction can happen on neutron or proton: QM interference

Reduction of cross section compared to IA — shadowing. Leading-twist effect.

[Review Frankfurt, Strikman, Guzey 12. Hints seen in \$J/\psi\$ production on nuclei in UPCs at LHC.](#)

- Diffraction and shadowing in tagged DIS

Differential studies as function of recoil momentum

Large FSI effects. Outgoing pn scattering state must be orthogonal to d bound state

[Guzey, Strikman, CW; in preparation](#)

Tagging: Applications and extensions

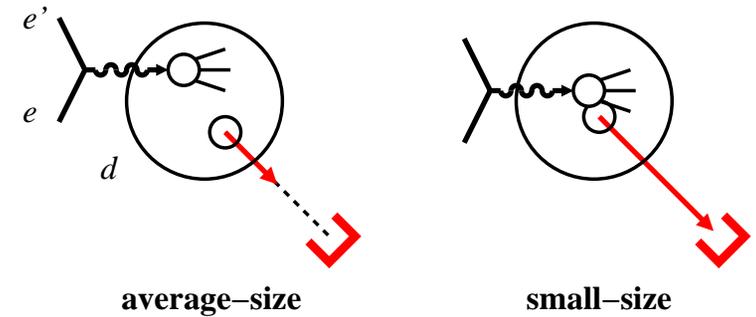
12

- Tagged EMC effect

What momenta/distances cause modification?

Connection with NN short-range correlations?

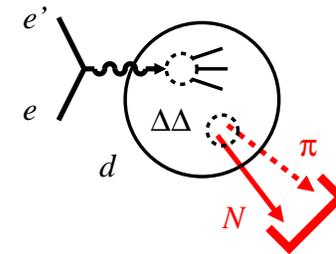
FSI effects large — need theory, data



- Tagging Δ isobars

Tagged DIS $e + d \rightarrow e' + \pi + N$, reconstruct Δ

Partonic structure of non-nucleonic DoF

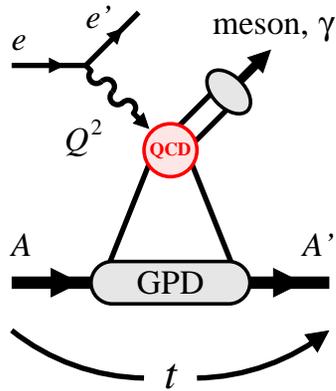


- Tagging with complex nuclei $A > 2$

Test isospin dependence and/or universality of bound nucleon structure

$(A - 1)$ ground state recoil, e.g. $^3\text{He} (e, e' d) X$ [Ciofi, Kaptari, Scopetta 99](#); [Kaptari et al. 2014](#)

Theoretically challenging, cf. experience with quasielastic breakup [JLab Hall A](#)



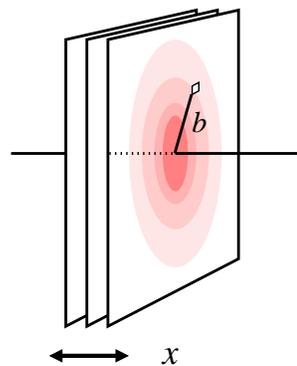
- Hard exclusive processes

QCD factorization theorem

[Collins, Frankfurt, Strikman 96](#)

Generalized parton distributions $\langle A' | O[\text{Twist-2}] | A \rangle$

Transverse distribution of quarks/gluons in nucleus



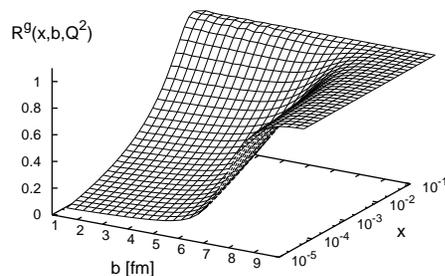
- Explore structure and dynamics

GPDs for spin-1 ^2H , spin-1/2 $^3\text{He}/^3\text{H}$, spin-0 ^4He

Large x : Nuclear modifications cf. EMC effect, nucleon spin flip transitions

Small x : Nuclear shadowing as function of impact parameter \leftrightarrow thickness

[Guzey et al 09](#)

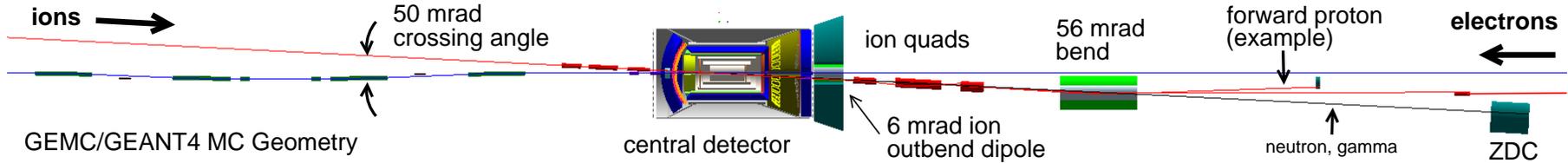


Forward ion detection

Light ions $A \lesssim 4$: Positive detection

Heavy ions: Veto nuclear breakup

[Caldwell, Kowalski 09](#)



- Forward detector integrated in IR and beam optics

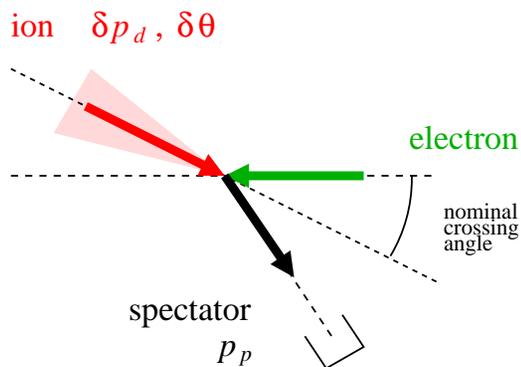
→ this meeting

Protons/neutrons/fragments/ions travel through ion beam quadrupole magnets

Dispersion generated by dipole magnets

Detection using forward detectors — Roman pots, ZDCs

Tagging studies: Full acceptance, proton momentum resolution longit $\delta p/p \sim 10^{-3}$, angular $\delta\theta \sim 0.2$ mrad [JLEIC: P. Nadel-Turonski, Ch. Hyde et al.](#)



- Intrinsic momentum spread in ion beam

Transverse momentum spread $\sigma \sim$ few 10 MeV

Smearing effect $\mathbf{p}_{pT}(\text{vertex}) \neq \mathbf{p}_{pT}(\text{measured})$, partly corrected by convolution

Dominant systematic uncertainty in tagged neutron structure measurements. Correlated, x and Q^2 -independent. [JLab LDRD](#)

- Forward detection of nuclear final states – breakup/coherent – significantly extends physics reach of eA(light) scattering at EIC
- Spectator tagging with deuteron overcomes main limiting factor of nuclear DIS: Control of nuclear configurations during high-energy process

Free neutron from on-shell extrapolation, eliminates nuclear binding and D-wave

[JLab 2014/15 LDRD Project \[Webpage\]](#)

Tagged EMC effect, nuclear shadowing, other applications

Theory well developed, separate high-energy process \leftrightarrow low-energy structure

Extension to $A > 2$ possible but challenging, requires substantial nuclear structure input

[Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent U, Belgium \[Webpage\]](#)

- Coherent nuclear processes create image of nucleus directly in terms of fundamental quark/gluon degrees of freedom

Dynamics of nuclear modifications at large x , shadowing at small x

- Need forward detector to make it work – coverage, resolution, various Z/A