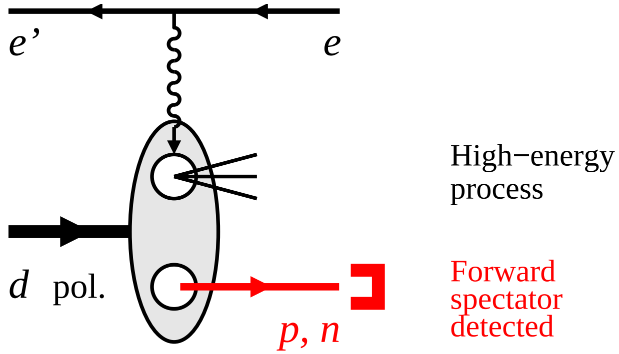
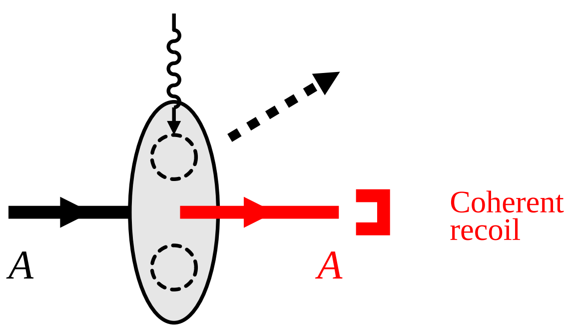
Light ion physics with forward detection at EIC

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





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-ion phyiscs with EIC

  Objectives and challenges

- Spectator tagging with deuteron

  High-energy process ↔ low-energy stucture

  Free neutron from on-shell extrapolation

  Tagging with polarized deuteron

  Recent: Final-state interactions, diffraction

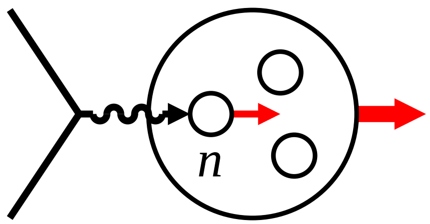
- Coherent processes with light nuclei

  Quark/gluon spatial distributions

  Dynamics: Nuclear shadowing etc.

[• Forward detection with EIC]

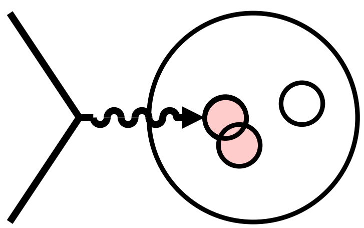
Light ions: Physics objectives



- Neutron structure

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

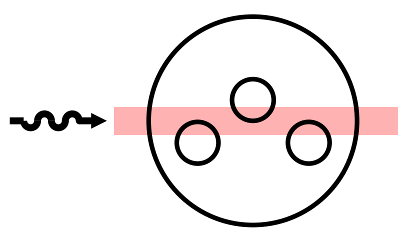
  Eliminate nuclear binding, non-nucleonic DOF!



- 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

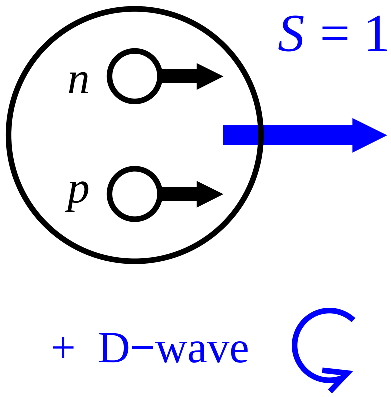
  Coherent interaction of high–energy probe
  with multiple nucleons, shadowing, saturation

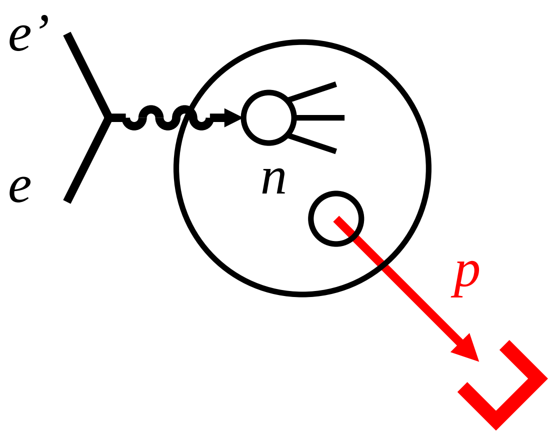
  Identify coherent response!

[Nucleus rest frame view]

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

Light ions: Deuteron and spectator tagging





[Nucleus rest frame view]

- 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

- Spectator nucleon tagging

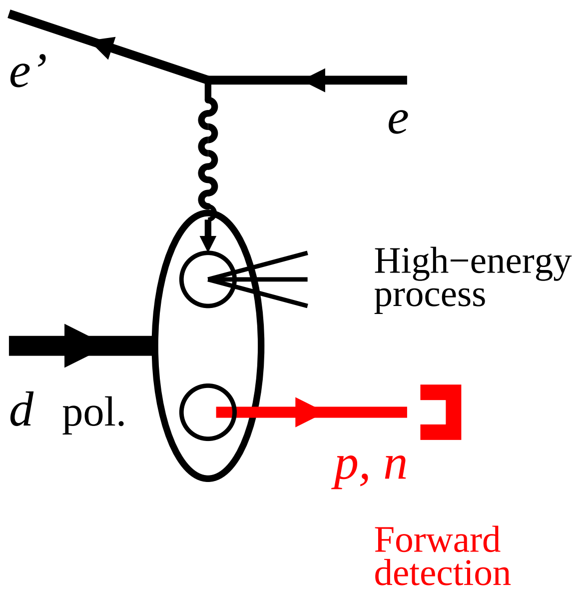
  Identifies active nucleon

  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 $p =$ 70-150 MeV
  JLab12 ALERT, Hall A

Light ions: Deuteron and spectator tagging



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

[Collider frame view]

- 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, $\boldsymbol{p}_p[\mathrm{rest}] \rightarrow 0$ possible

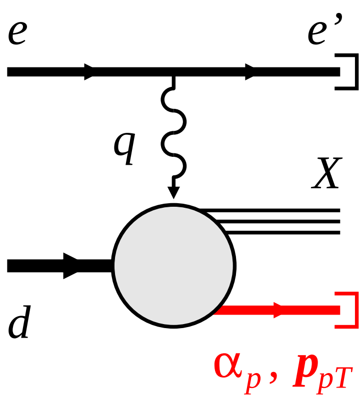
  Potentially full acceptance, good resolution

  Can be used with polarized deuteron

  Forward neutron detection possible

- Unique physics potential

Tagging: Cross section and observables



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

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

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

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

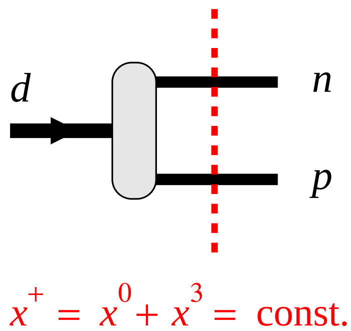
  Structure/response functions in frame $\boldsymbol{q} \parallel \boldsymbol{p}_d$

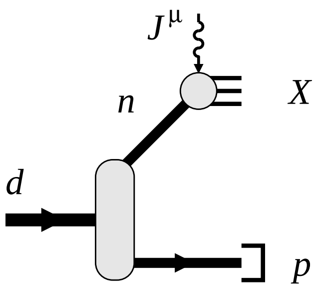
  Proton light-front momentum $p_p^+ = \alpha_p p_d^+/2, \ \boldsymbol{p}_{pT}$ $\longleftrightarrow$ $\boldsymbol{p}_p$ in rest frame
  $p_{p\parallel}, \ \boldsymbol{p}_{p\perp}$ in collider frame

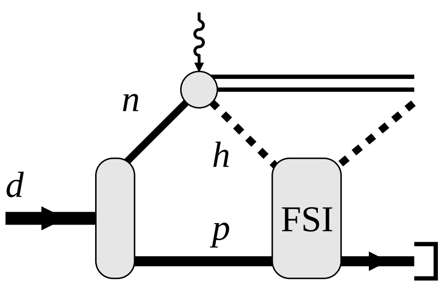
  Special case of semi-inclusive DIS — target fragmentation
  QCD factorization Trentadue, Veneziano 93; Collins 97

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

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

  Permits matching nuclear $\leftrightarrow$ nucleonic structure
  Conserves LF momentum, baryon number
  Frankfurt, Strikman 80's

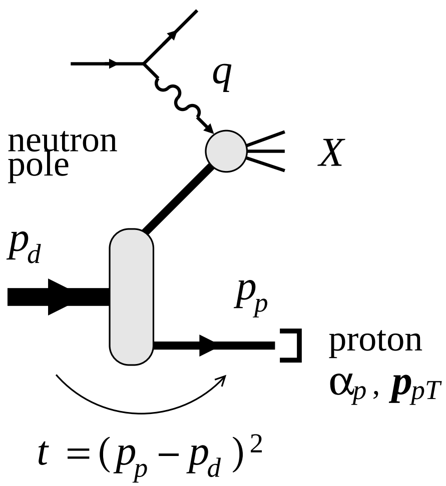
  Low-energy nuclear structure, cf. non-relativistic theory!

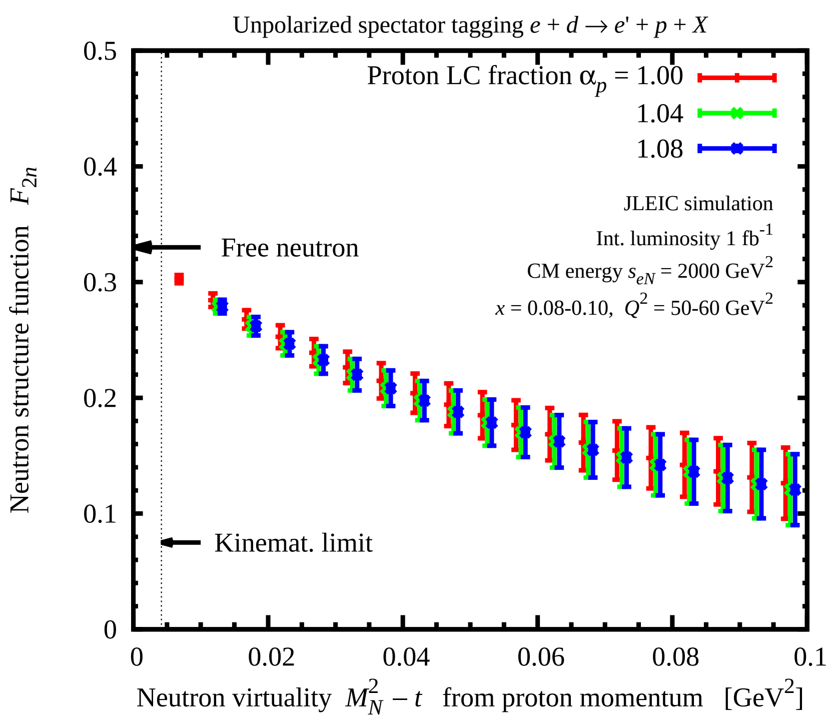
- Composite description

  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
  $t - M_N^2 = -2|\boldsymbol{p}_p(\text{rest})|^2 + t_{\min}$

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

  Eliminates nuclear binding effects
  and FSI Sargsian, Strikman 05

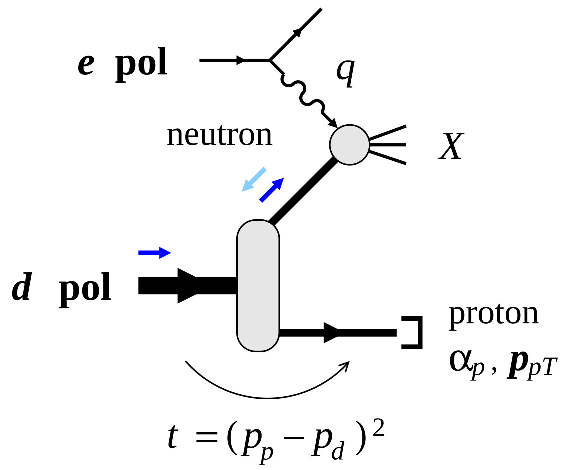
- Precise measurements of F_{2n}

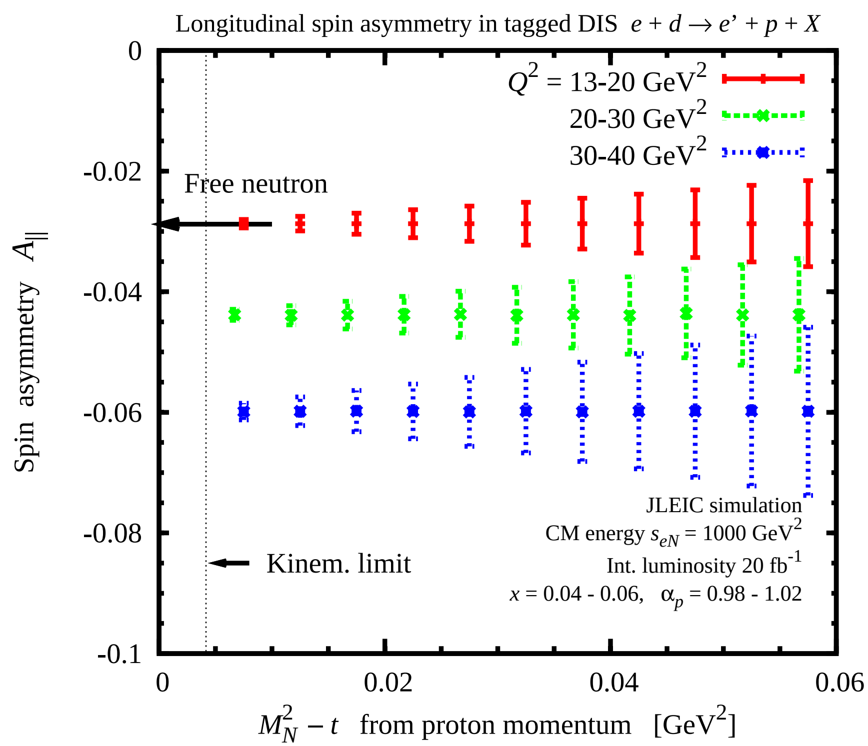
  F_{2n} extracted with few-percent
  accuracy at $x \gtrsim 0.1$

  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 $\boldsymbol{p}_p(\text{rest}) = 0$: Neutron 100% polarized

- Systematic uncertainties cancel

  Weak off-shell dependence of asymmetry

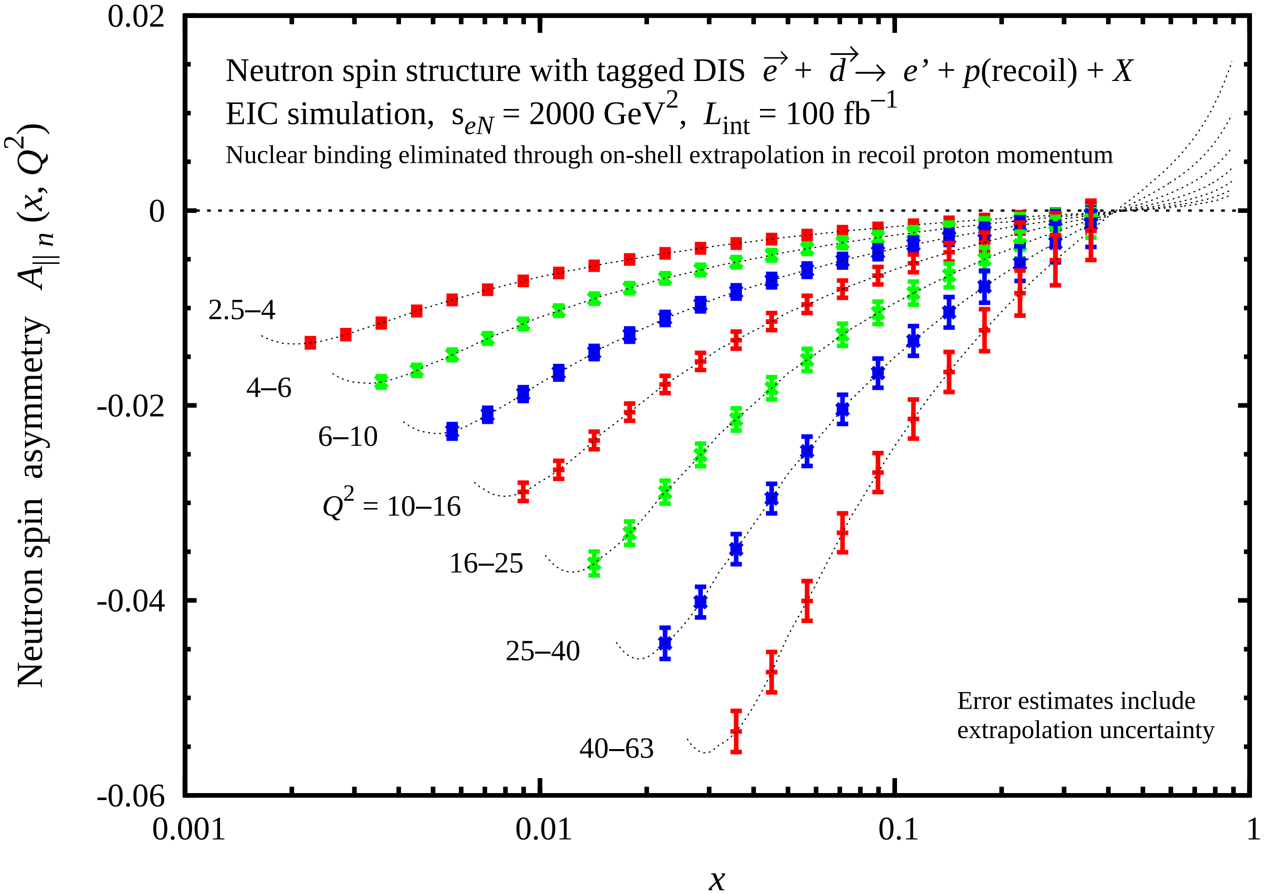
  Momentum smearing/resolution effects largely cancel in asymmetry

- Statistics requirements

  Physical asymmetries $\sim$ 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



$$A_{\parallel n} = \frac{\sigma(+-) - \sigma(++)}{\sigma(+-) + \sigma(++)} = D\,\frac{g_{1n}}{F_{1n}} + \ldots$$

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

depolarization factor

$$y = \frac{Q^2}{x s_{eN}}$$

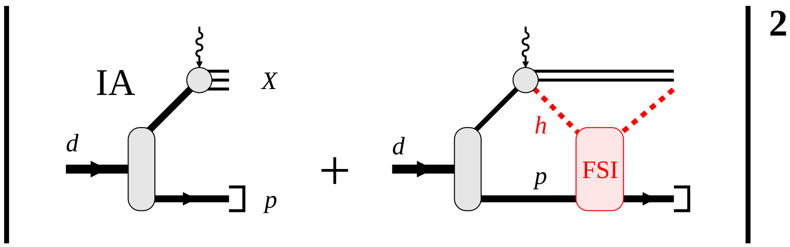
- Precise measurement of neutron spin structure

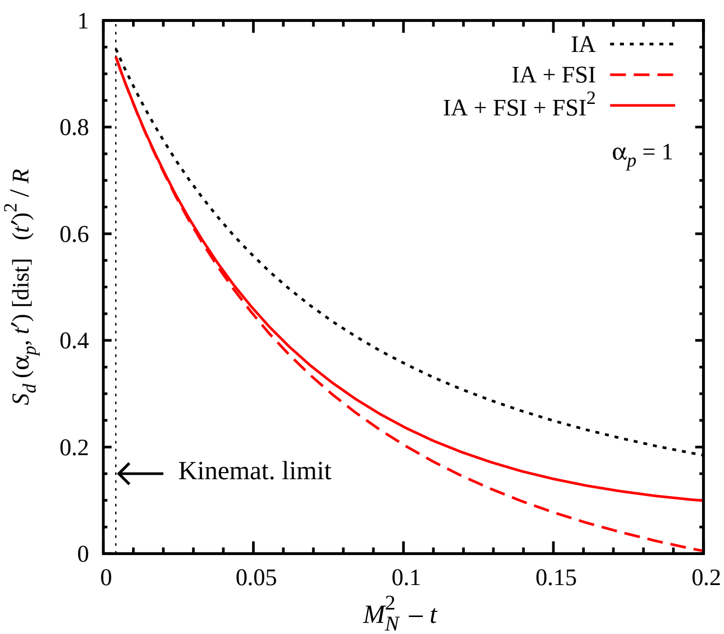
  Wide kinematic range: Leading $\leftrightarrow$ higher twist, nonsinglet $\leftrightarrow$ singlet QCD evolution

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

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

Tagging: Final-state interactions





- FSI mechanism $(x \sim 0.1)$

  Slow hadrons in DIS final state: Neutron fragmentation, p_h ~1–2 GeV (rest frame)

  Interact with spectator proton

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

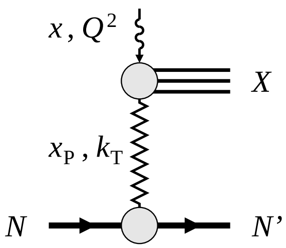
- FSI effects calculated

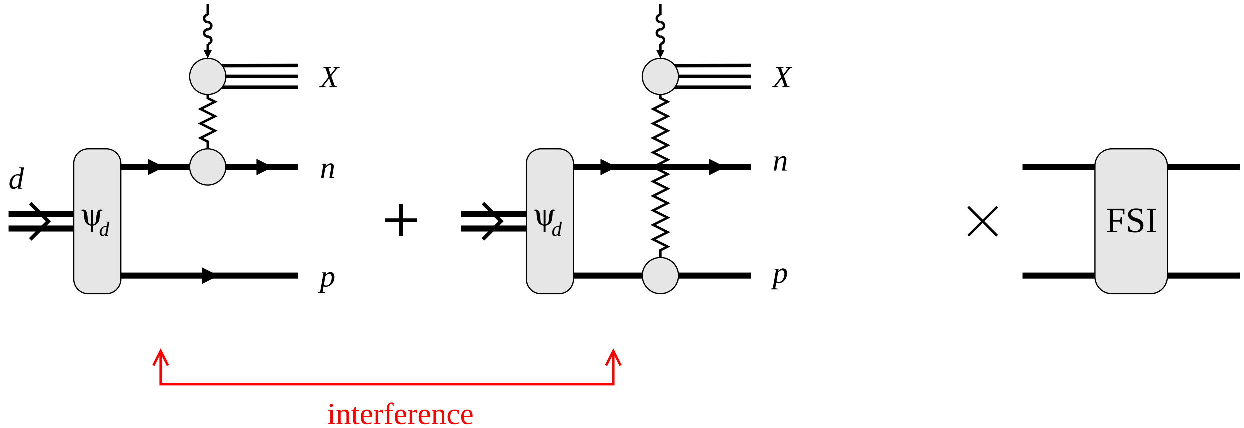
  Sizable effects at $p_p \sim$ few 100 MeV

  Vanish at $t - M_N^2 \to 0$, 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/ψ 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

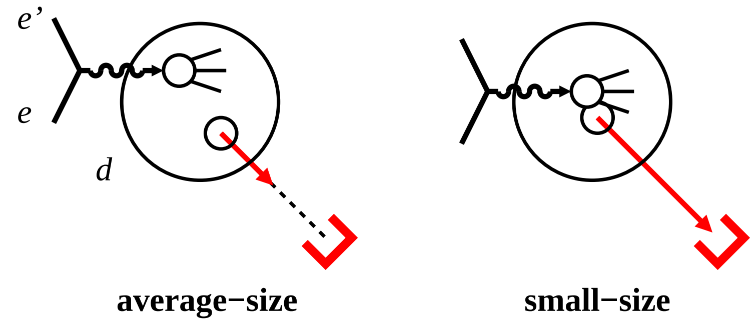
Tagging: Applications and extensions

- Tagged EMC effect

  What momenta/distances cause modification?

  Connection with NN short-range correlations?

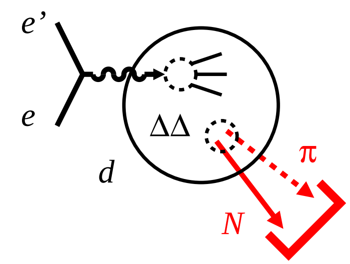
  FSI effects large — need theory, data



- Tagging Δ isobars

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

  Partonic structure of non-nucleonic DoF

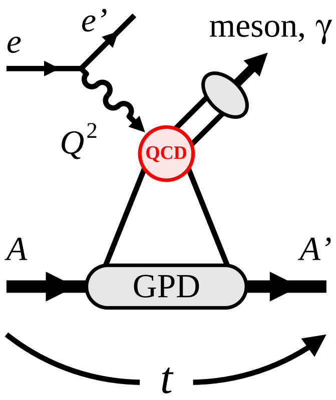


- Tagging with complex nuclei $A > 2$

  Test isospin dependence and/or universality of bound nucleon structure

  $(A-1)$ ground state recoil, e.g. 3He (e, e' d) X Ciofi, Kaptari, Scopetta 99; Kaptari et al. 2014
  Theoretically challenging, cf. experience with quasielastic breakup JLab Hall A

Coherent processes

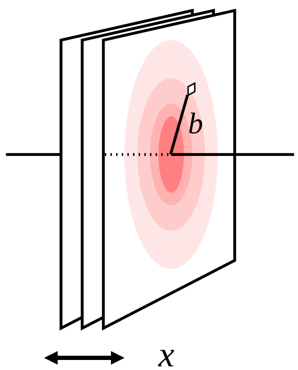


- Hard exclusive processes

  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

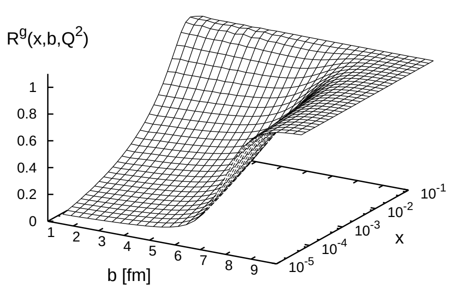


- Explore structure and dynamics

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

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

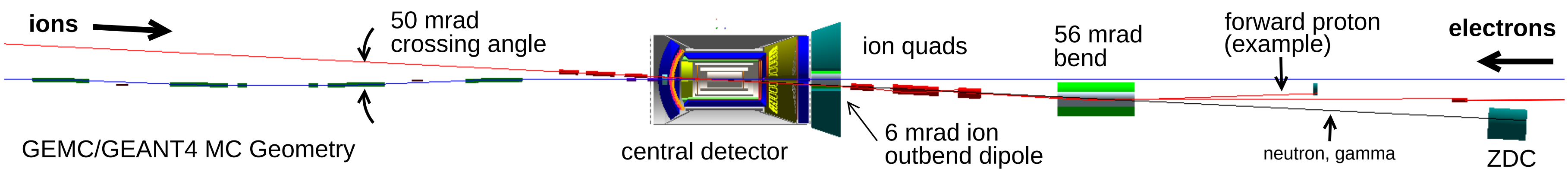
  Small x: Nuclear shadowing as function of impact parameter $\leftrightarrow$ thickness — Guzey et al 09



Forward ion detection

  Light ions $A \lesssim 12$: Positive detection
  Heavy ions: Veto nuclear breakup — Caldwell, Kowalski 09

EIC forward detection



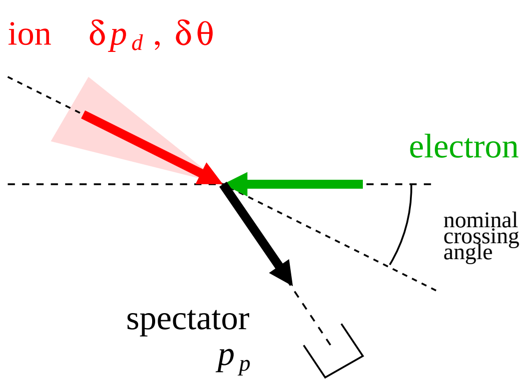
- Forward detector integrated in IR and beam optics → this meeting

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

  Dominant systematic uncertainty in tagged neutron structure measurements. Correlated, x and Q^2-indpendent. JLab LDRD

Summary

- 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