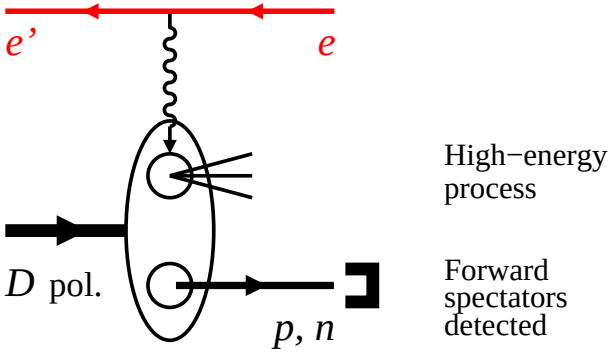
Nuclear DIS with spectator tagging: New applications at intermediate and small x

C. Weiss (JLab), POETIC 6, Ecole Polytechnique, 10–Sep–15

Jefferson Lab



Energy and luminosity:
Kinematic reach, rates

$\times$

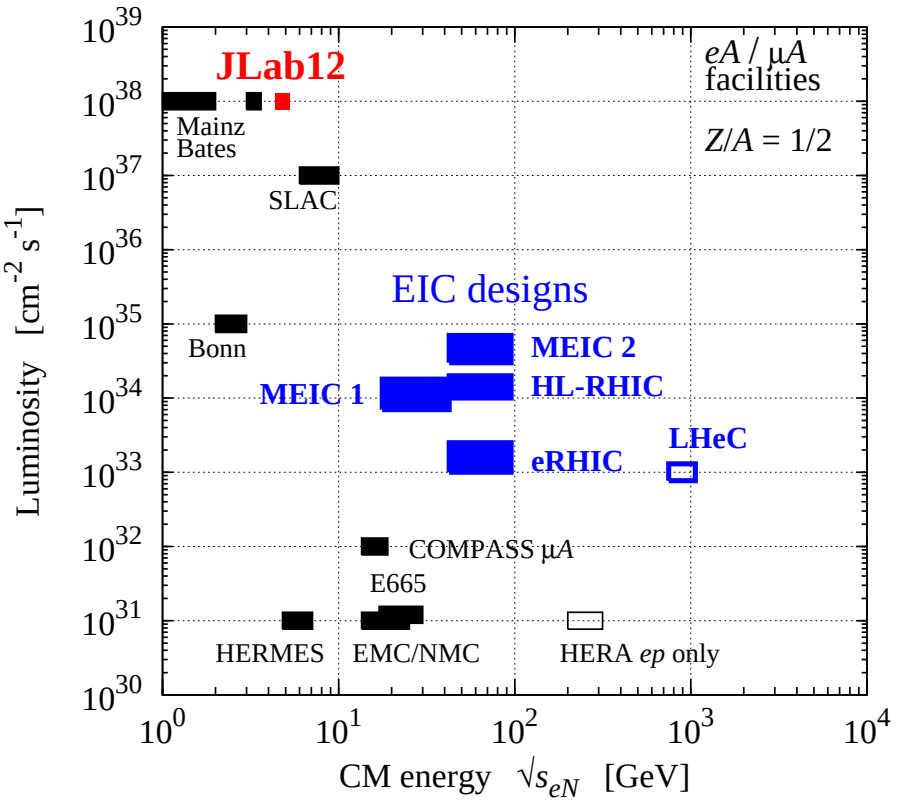
Ion polarization: Deuteron
L, T, tensor; 3He

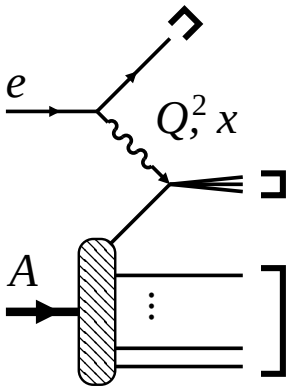
$\times$

Forward detection of p, n,
$A-1$: Precision, control

- Light ion physics at EIC
  - Energy, luminosity, polarization
  - Physics objectives
- Deuteron DIS with spectator tagging
  JLab 2014/15 R&D project
  - Free neutron with on-shell extrapolation
  - Neutron spin structure
  - Bound nucleon and EMC effect
  - Coherence and shadowing at $x \ll 0.1$
  - Theoretical developments, extensions → **W. Cosyn**
- Experimental apparatus
  - MEIC forward detection → **Ch. Hyde**
  - Simulation tools and results → **K. Park**

Light ions: Energy, luminosity, polarization





- CM energy $\sqrt{s_{eN}} \sim$ 20–100 GeV

  $Q^2 \sim$ few 10 GeV^2 for DIS

  $x \sim 10^{-1}$–10^{-3} for sea quarks, gluons

- Luminosity $\sim 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

  Exceptional configurations in target

  Multi-variable final states

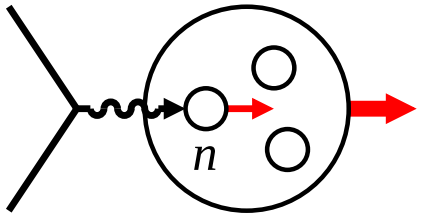
  Polarization observables

- Polarized light ions

  eRHIC: unpol D, pol $^3\mathrm{He}$

  MEIC: polarized D and $^3\mathrm{He}$ with figure-8 ring layout

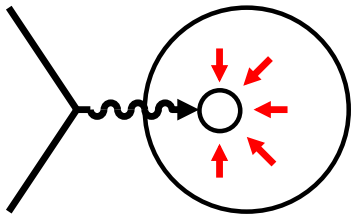
Light ions: Physics objectives



- Neutron structure

  Flavor decomposition of quark PDFs/GPDs/TMDs, sea quarks, singlet vs. non-singlet QCD evolution

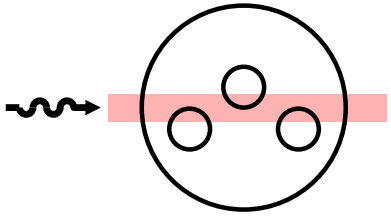
  How to account for nuclear binding, non-nculeonic DOF?



- Bound nucleon in QCD

  Modification of basic quark/gluon structure by nuclear medium, QCD origin of nuclear forces

  How to control nuclear environment?



- Coherence and saturation

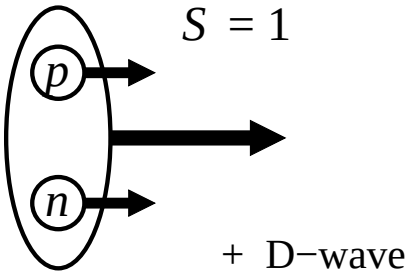
  Interaction of high–energy probe with coherent quark/gluon fields

  How to verify onset of coherence?

[Nucleus rest frame view]

Challenges to be addressed by theory and new experimental techniques! ←

Light ions: Deuteron, spectator tagging



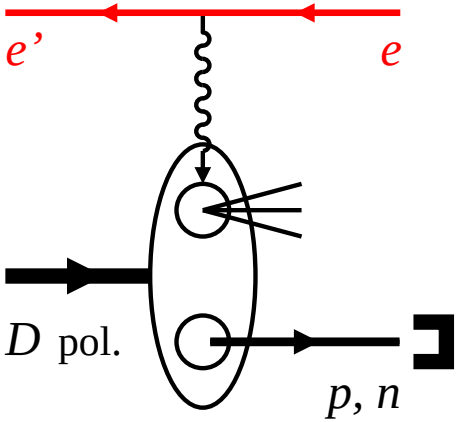
- Polarized deuterium

  Wave function simple, known well
  NN light-front WF for high–energy processes

  Neutron spin–polarized

  Non-nucleonic DOF suppressed
  $|D\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$

  Limited possibilities for nuclear final–state interaction



High−energy process

Forward spectators detected

- Spectator nucleon tagging

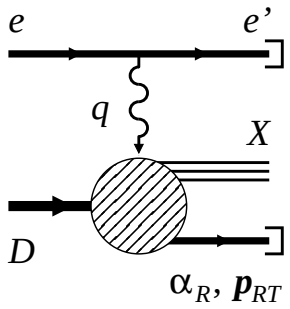
  Detection of forward proton or neutron

  Identifies active nucleon, controls quantum state

  Unique for collider: No target material, forward detection of charged/neutrals, transverse polarization possible
  Tagging with fixed target: CLAS BONUS, limited to recoil momenta $p_R > 100$ MeV

Tagging: Observables and structures

- Conditional DIS cross section $eD \to e' + X + N$

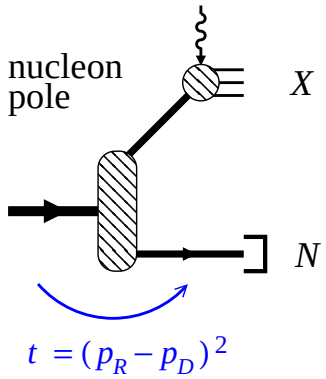


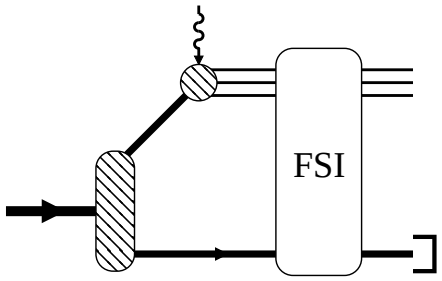
$$\frac{d\sigma}{dx dQ^2\, d^3p_R/E_R} = [\ldots]\Big[F_2^D(x,Q^2;\alpha_R,p_{RT}) - (1-\epsilon)F_L^D(..)$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\,\cos\phi_R F_{LT}^D(..) \;+\; \epsilon\,\cos(2\phi_R) F_{TT}^D(..)$$

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

- Conditional structure function





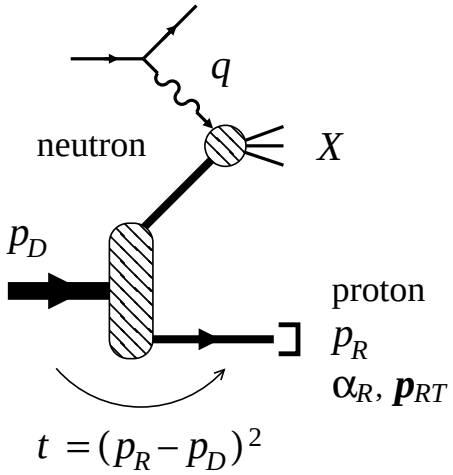
Impulse approximation:
$F_2^D = |\psi_{\rm LF}^D(\alpha_R, p_{RT})|^2 \times F_2^N$

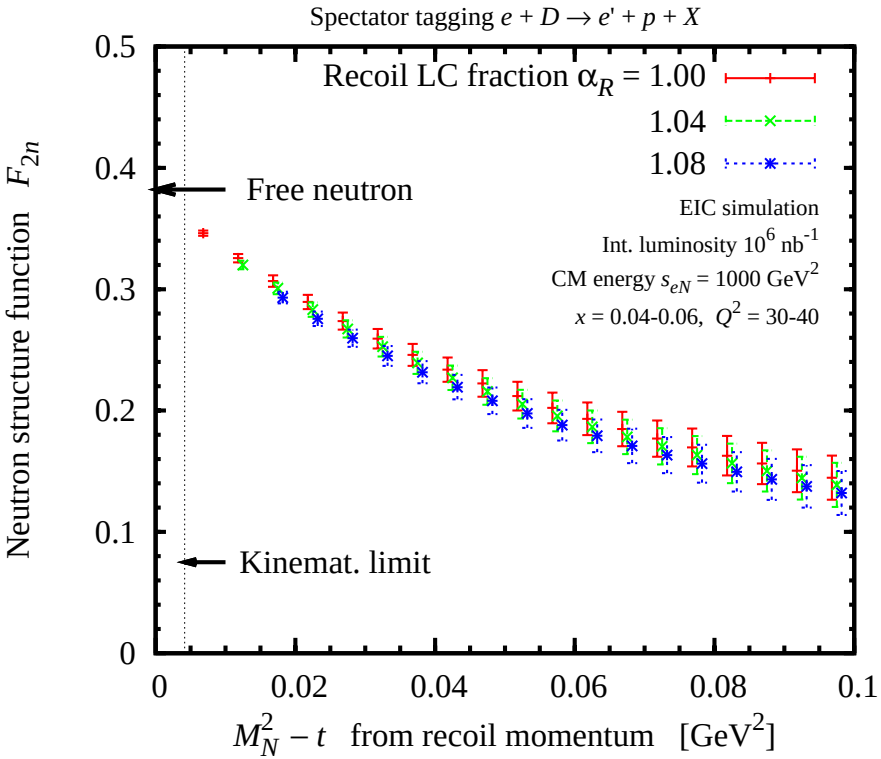
Deuteron NN light-front wave function

Final-state interaction

Recoil momentum as variable: Separate nucleon/nuclear structure, control nuclear binding, eliminate FSI

Tagging: Free neutron structure





- Extract free neutron structure

  Recoil momentum defines/controls neutron off-shellness $t - M_N^2$

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

  Eliminates nuclear binding effects and FSI Sargsian, Strikman 05

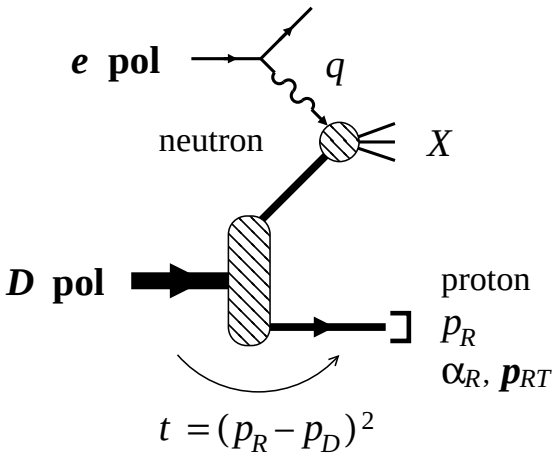
- Precise measurements of F_{2n}

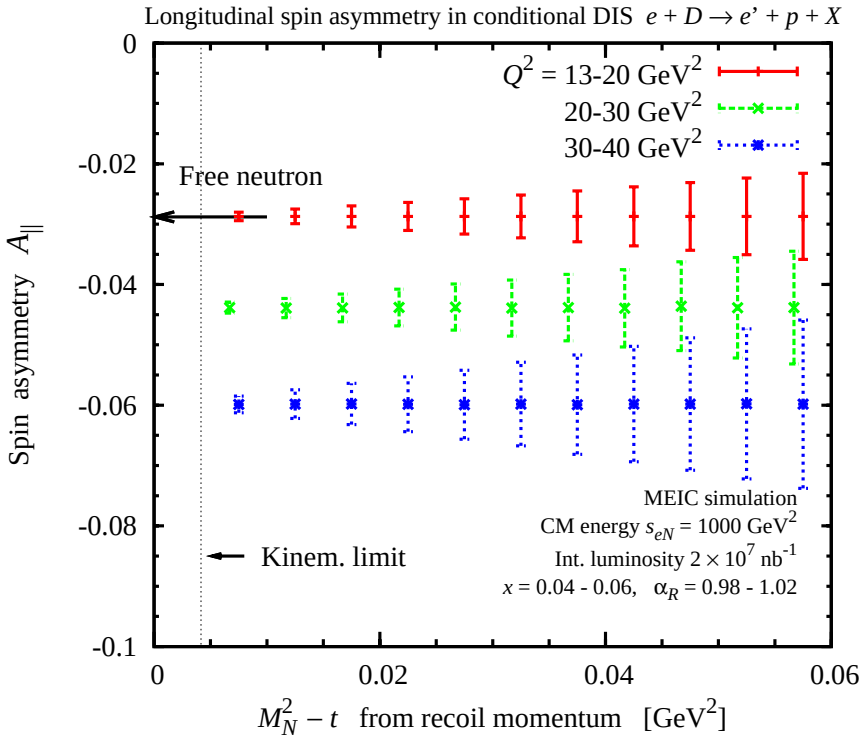
  F_{2n} extracted with percent-level accuracy at $x < 0.1$

  Uncertainty mainly systematic
  JLab LDRD project: Detailed estimates

  Non-singlet $F_{2p} - F_{2n}$ at $x \lesssim 0.1$, sea quark flavor asymmetry $\bar{d} - \bar{u}$

Tagging: Polarized neutron structure





- Neutron spin structure with polarized D and proton tagging

  On-shell extrapolation of asymmetry

  D–wave suppressed at on-shell point: Neutron 100% polarized

- Systematic uncertainties cancel

  Weak off-shell dependence of asymmetry

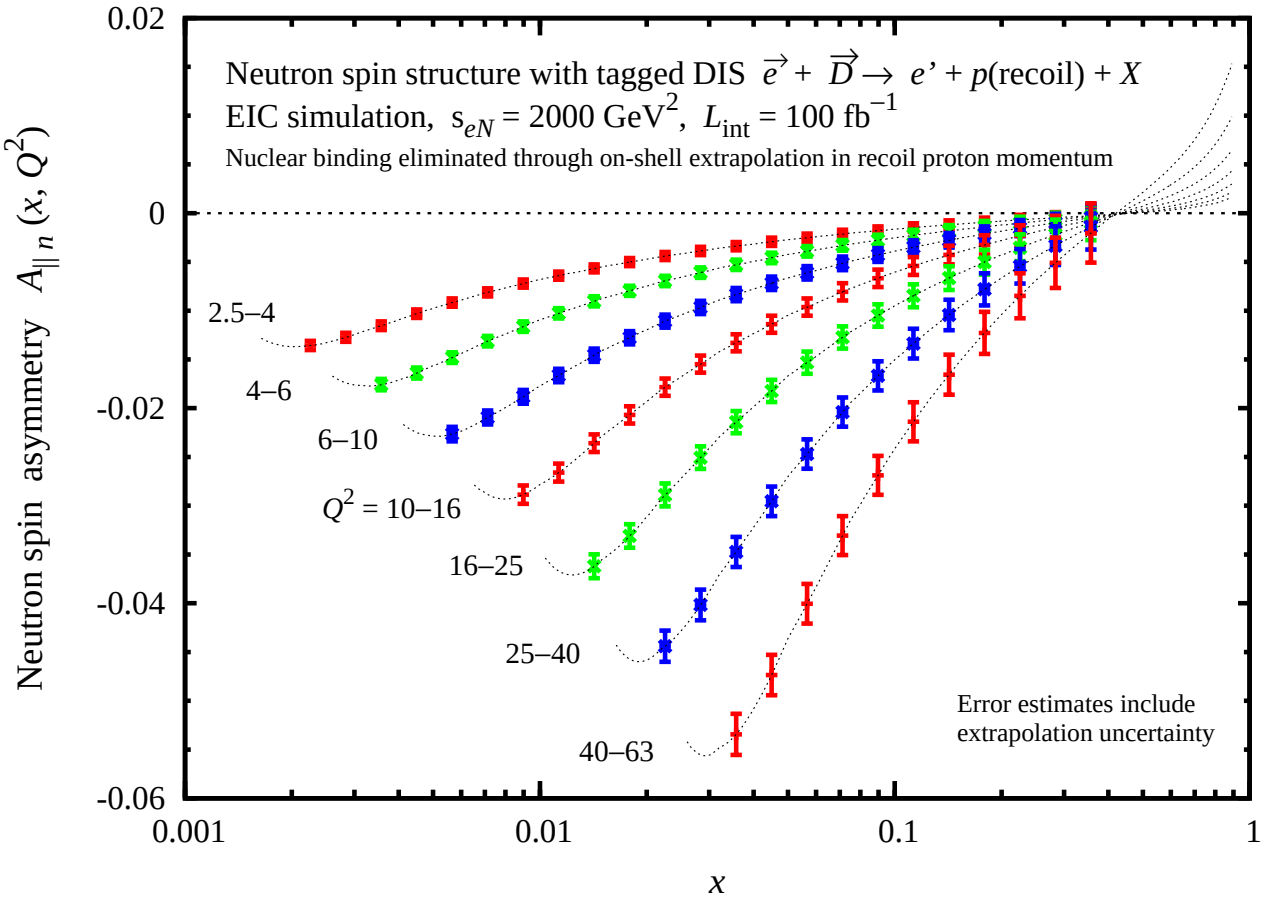
  Momentum smearing/resolution effects largely cancel in asymmetry

- Statistics requirements

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

  Requires luminosity $\sim 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Tagging: Polarized neutron structure II



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

$$= D \frac{g_1}{F_1} + \ldots$$

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

depolarization factor

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

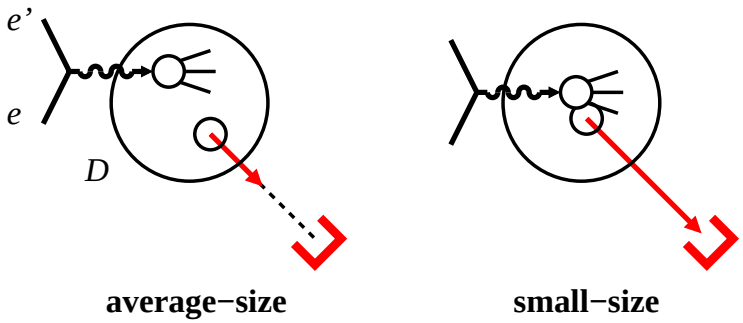
- Precise measurement of neutron spin structure

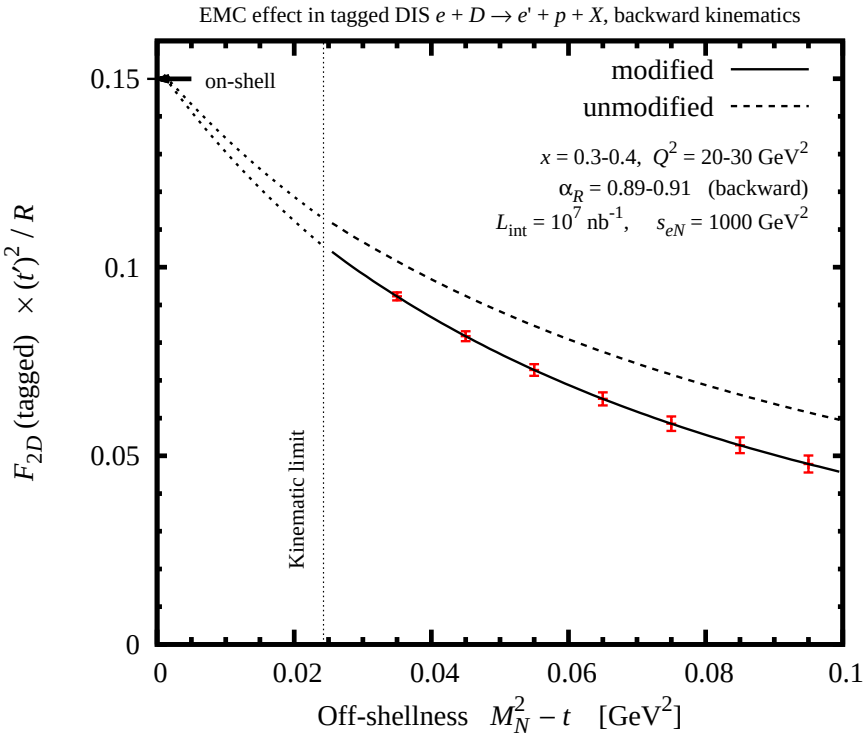
  Wide kinematic range: Leading ↔ higher twist, nonsinglet ↔ singlet QCD evolution

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

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

Tagging: EMC effect





- Nucleon's quark/gluon structure modified in nucleus $A \neq \sum N$

  Seen in inclusive DIS: EMC effect

  Dynamical origin?

  What momenta and distances in nuclear wave function cause modification?

  Spin–isospin dependence?

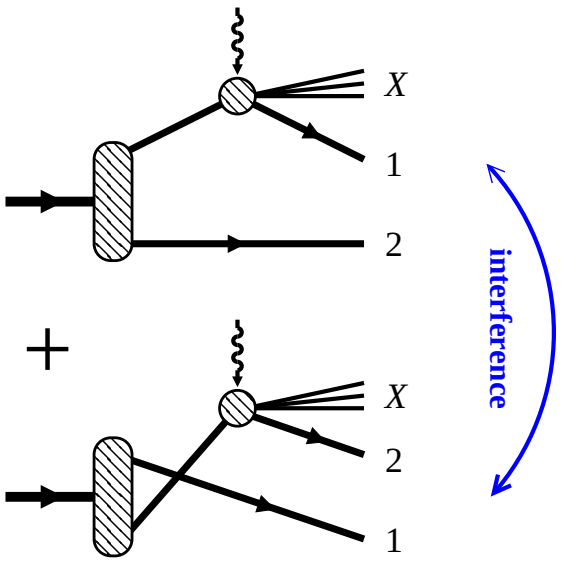
- EMC effect in tagged DIS

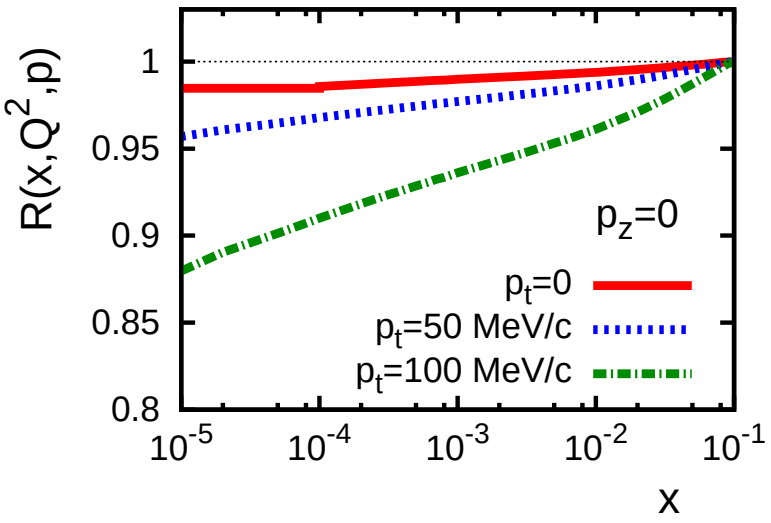
  Study modification as function of recoil momentum $\leftrightarrow$ off-shellness

  Control size of nuclear configuration!

  EIC: Q^2 evolution, gluons, spin dependence with polarized D

Tagging: Coherence and shadowing at small x





V. Guzey (2014)

- Shadowing in inclusive DIS $x \ll 10^{-1}$

  Diffractive DIS on single nucleon
  Leading-twist effect! Seen at HERA

  Interference of DIS on nucleon 1 and 2

  Nuclear effect calculable in terms of nucleon's diffractive structure functions
  Gribov 70's. Frankfurt, Guzey, Strikman 02+

- Shadowing in tagged DIS

  Explore shadowing through recoil momentum dependence
  Guzey, Strikman, CW; in progress

  Reveal nuclear momentum components building up coherent fields at small x

  Study coherence in $A = 2$ system, complementary to $A \gg 1$

  Quantify approach to saturation at small x

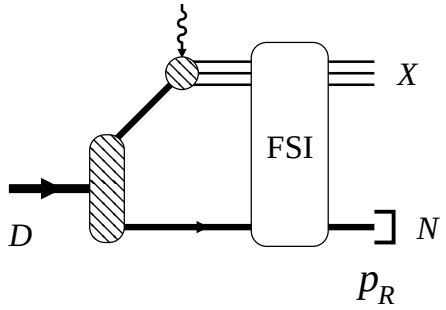
- Coherent scattering $eD \to e + M + D$
  Exclusive meson production, DVCS, nuclear GPDs

Tagging: Developments and extensions

- Final-state interaction in tagged eD → **W. Cosyn**

  Distorts recoil momentum dependence at $t \neq M_N^2$

  Nucleon DIS final state at $x < 0.1$: Broad momentum distribution, different interactions of slow and fast debris
  Cosyn, Sargsian, Strikman, CW; in progress. Ciofi, Kopeliovich 02: String model



  Maximized/minimized by choice of kinematics
  Sargisan, Strikman 05; Ciofi, Kaptari, Kopeliovich 13

  Azimuthal and spin observables test Re/Im: T-odd structures → **D. Sivers**

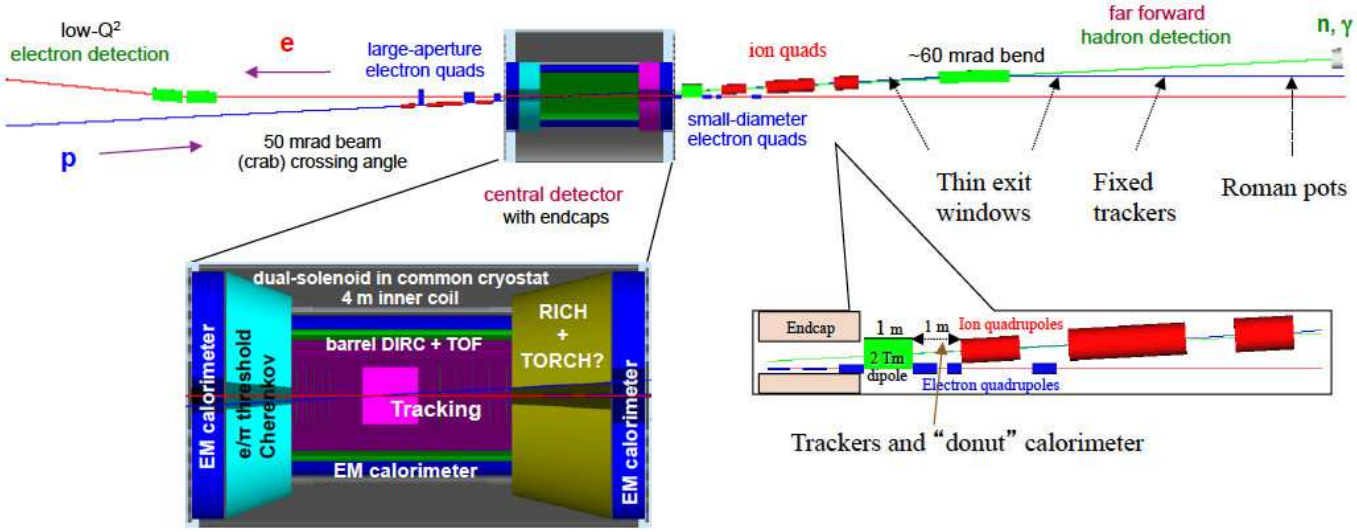
- Tagging with complex nuclei $A > 2$

  Could test isospin dependence, 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

- Resolved final states: Semi-inclusive DIS on neutron, exclusive channels

Apparatus: MEIC full–acceptance detector



P. Nadel-Turonski et al.

- Forward detector integrated in interaction region & beam optics
- Good acceptance for spectators and ion fragments
  Rigidity different from beam. Large magnet apertures, small gradients
- Good acceptance for elastic recoil
  Rigidity same as beam. Large dispersion generated *after* IP
  Longitudinal momentum up to 99.5% of beam, angles down to 2 mrad (10 σ)
- Good momentum and angular resolution
  Longitudinal $dp/p \sim 4 \times 10^{-4}$, angular $\delta\theta \sim 0.2$ mrad
  $p_{TR} \sim 15\,\mathrm{MeV}/c$ resolution for tagged 50 GeV/A deuterium beam

R&D project at JLab

Develop simulation tools (physics models, event generators, analysis tools) for DIS on light ions with spectator tagging at MEIC and study physics impact. W. Cosyn, V. Guzey, D. Higinbotham, Ch. Hyde, K. Park, P. Nadel-Turonski, M. Sargsian, M. Strikman, C. Weiss
Tools, documentation, results publicly available. Open for collaboration!
https://www.jlab.org/theory/tag/

Summary

- Spectator tagging in eD scattering with EIC enables next-generation measurements with maximal control and unprecedented accuracy

  Neutron structure functions, including spin
  Nuclear modifications of quark/gluon structure
  Coherence and shadowing

- Recoil momentum dependence permits separation of nuclear and nucleon structure

  On-shell extrapolation, controled size of NN configuration, FSI

- Great opportunities, new physics applications