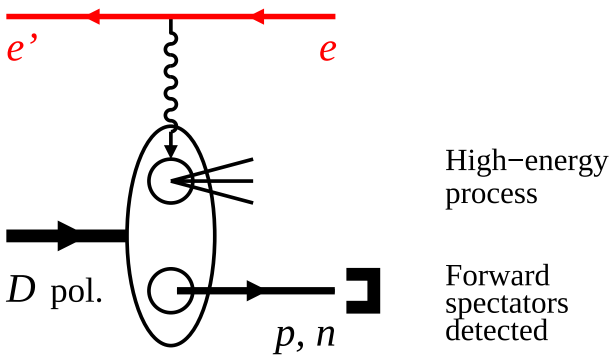
Spectator tagging and short-range correlations with an Electron-Ion Collider

C. Weiss (JLab), EMMI Workshop "Cold dense nuclear matter", GSI Darmstadt, 13–16 Oct 2015



Energy and luminosity

$\times$

Polarized ion beams
2H L, T, tensor; 3He

$\times$

Forward detection of p, n,
$A - 1$ fragments

- Light ion physics at EIC

  Energy, luminosity, polarization

  Physics objectives

- Deuteron DIS with spectator tagging
  JLab 2014/15 R&D project

  Free neutron from on-shell extrapolation

  Neutron spin structure

  Bound nucleon structure and SRCs

  Final-state interactions

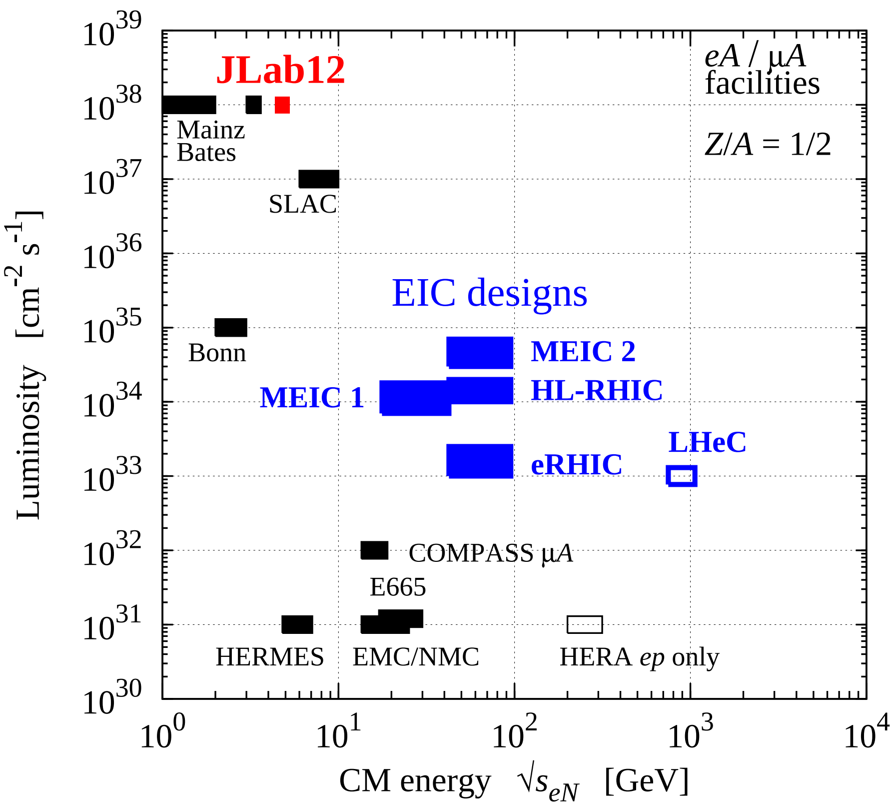
  Extensions: Tagging Δ's, $A > 2$ nuclei

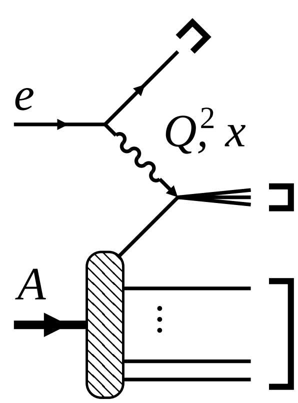
- Experimental apparatus

  MEIC forward detection

  Simulation tools and results

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

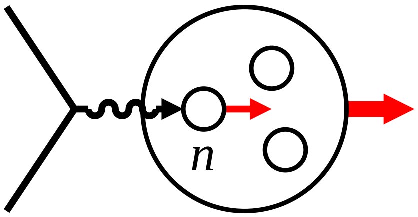
  Polarization observables

- Polarized light ions

  eRHIC: unpol D, pol ^{3}He

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

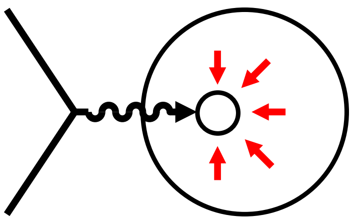
Light ions: Physics objectives



- Neutron structure

  Flavor decomposition of polarized quark densities, singlet vs. non-singlet QCD evolution, polarized gluon

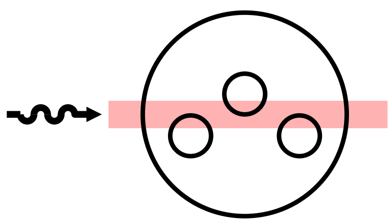
  How to account for nuclear binding, non-nucleonic DOF?



- Bound nucleon in QCD

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

  How to control nuclear environment?



- Coherent phenomena in QCD

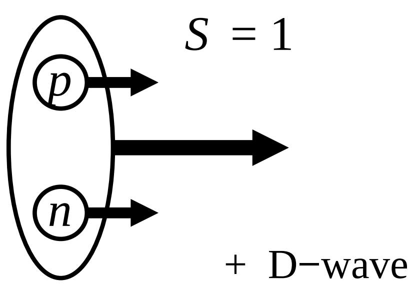
  Interaction of high–energy probe with coherent quark/gluon fields at small x

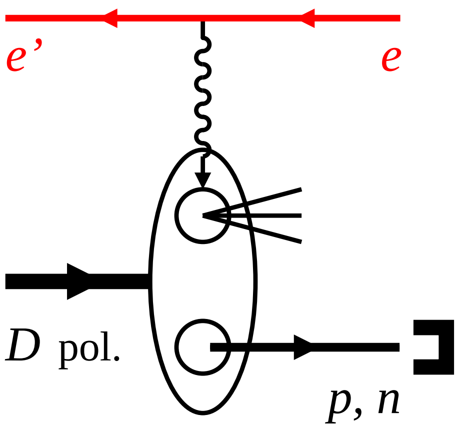
  How to verify onset of coherence?

[Nucleus rest frame view]

Common challenge: Control nuclear configurations during high-energy process. Main systematic uncertainty. New experimental techniques! $\longleftarrow$

Light ions: Deuteron, spectator tagging





- Polarized deuteron

  Wave function simple, known well
  incl. light-front WF for high–energy procs
  → **Talk Frankfurt**

  Neutron spin–polarized

  Non-nucleonic DOF suppressed
  $|\text{deuteron}\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$

  Limited possibilities for nuclear
  final–state interaction

- Spectator nucleon tagging

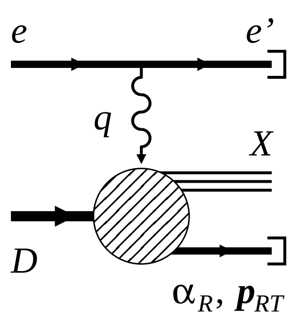
  Identifies active nucleon,
  controls quantum state

  Detection of forward protons/neutrons
  with approx. $1/2$ beam momentum

  Unique for collider: No target material,
  potentially full acceptance, good resolution,
  can be used with polarized deuteron
  Tagging with fixed target: CLAS BONUS,
  limited to recoil momenta p_R = 70-150 MeV

Tagging: Observables and structures

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

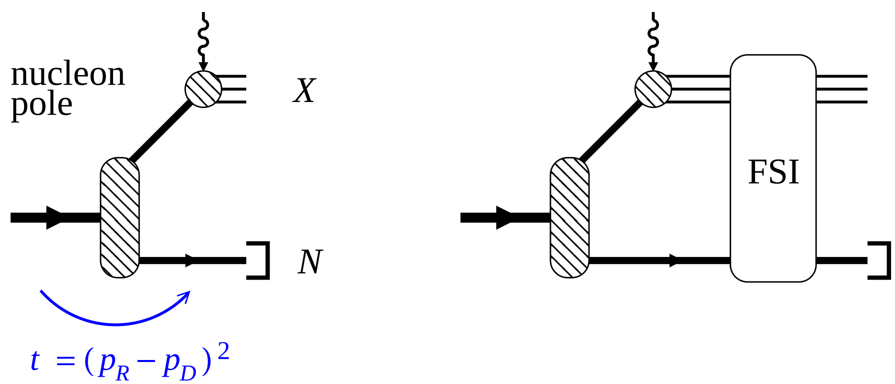


$$\frac{d\sigma}{dx dQ^2 \, d^3p_R/E_R} = [\ldots] \Big[F_2^D(x, Q^2; \alpha_R, p_{RT}) - (1-\epsilon) F_L^D(..)$$

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

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

- Conditional structure function



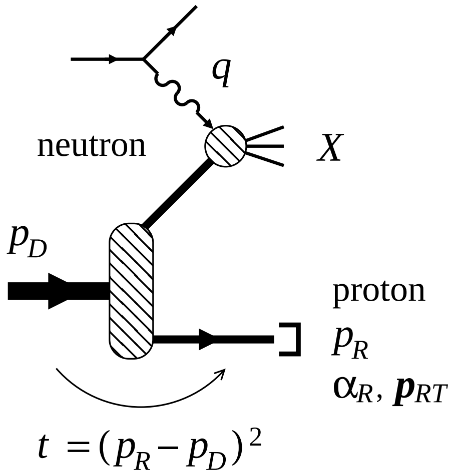
Impulse approximation:
$F_2^D = |\psi_{\mathrm{LF}}^D(\alpha_R, p_{RT})|^2 \times F_2^N$

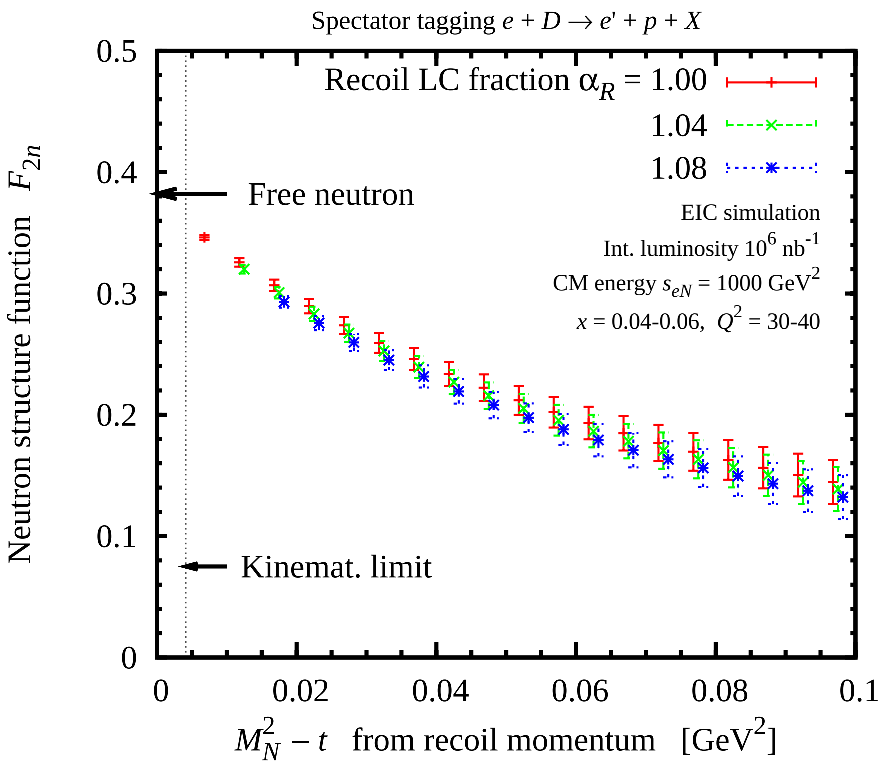
Deuteron NN light-front wave function

Final-state interaction

Recoil momentum as variable: Separate nucleon $\leftrightarrow$ nuclear structure, control nuclear binding, minimize or maximize 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**

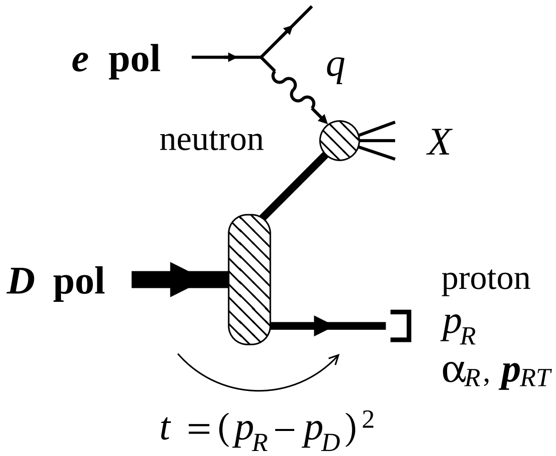
- Precise measurements of F_{2n}

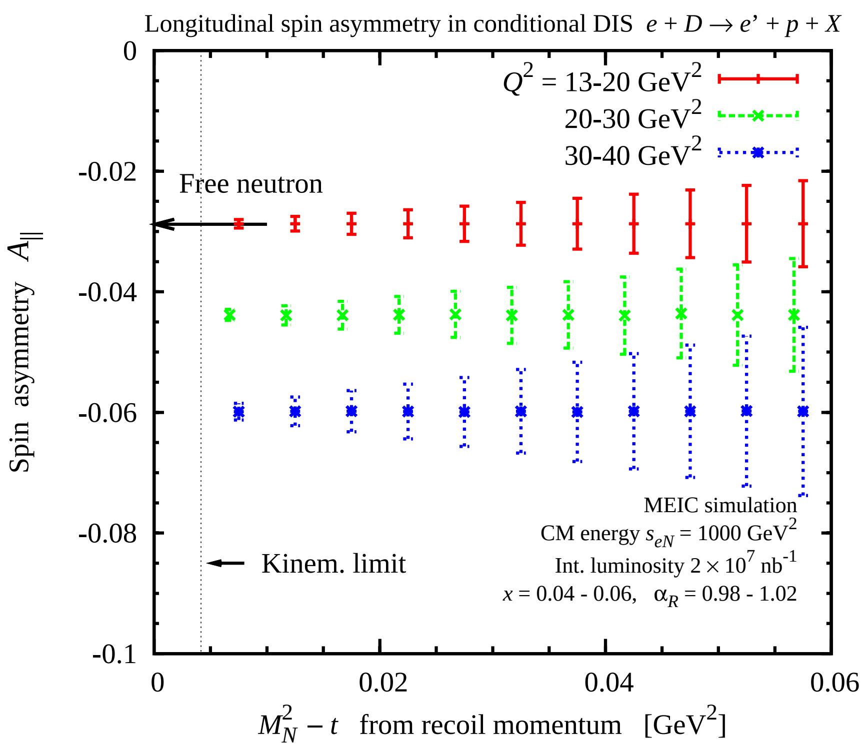
  F_{2n} extracted with percent-level accuracy at $x < 0.1$

  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

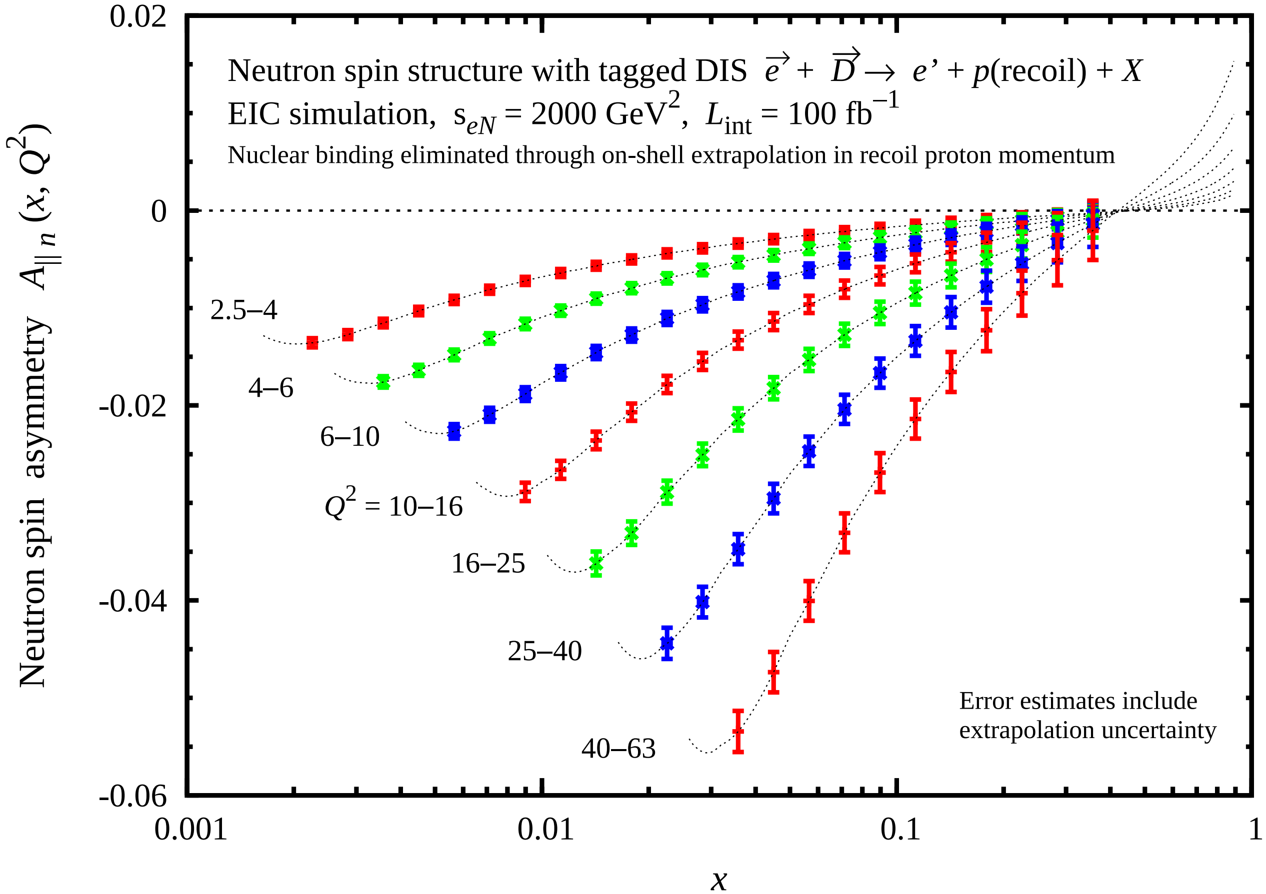
  Momentum smearing/resolution effects largely cancel in asymmetry

- 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



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

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

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

depolarization factor

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

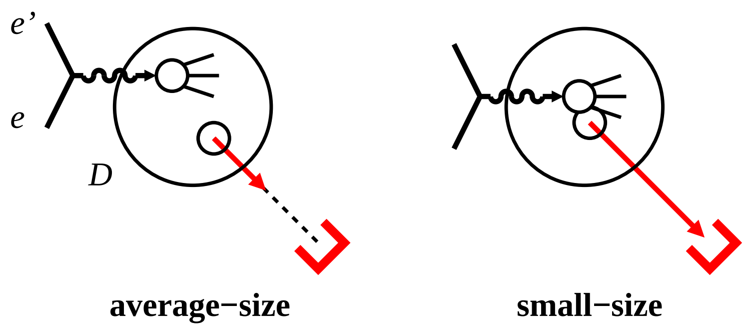
- Precise measurement of neutron spin structure

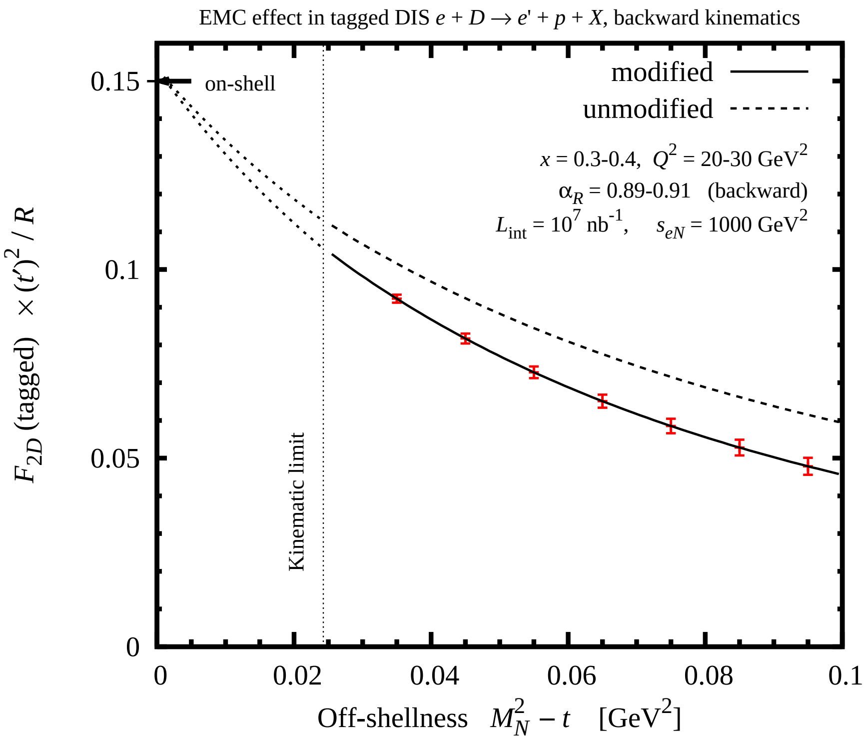
  Wide kinematic range: Leading ↔ higher twist, nonsinglet ↔ singlet QCD evolution

  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 $A \neq \sum N$
  → **Talks Strikman, Hen, Arrington**

  Dynamical origin?

  What momenta and distances in nuclear wave function cause modification?

  Spin–isospin dependence?

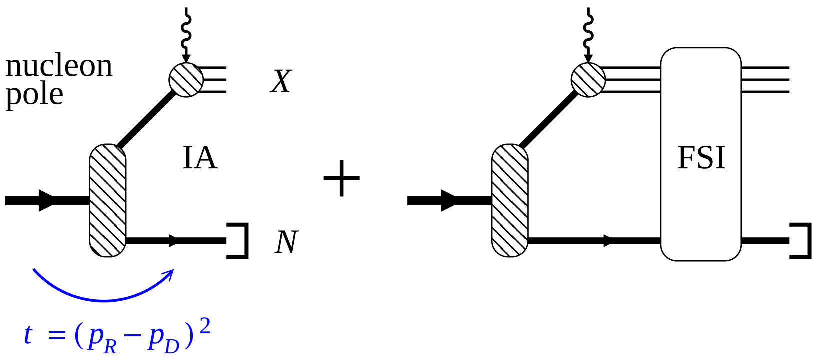
- EMC effect in tagged DIS

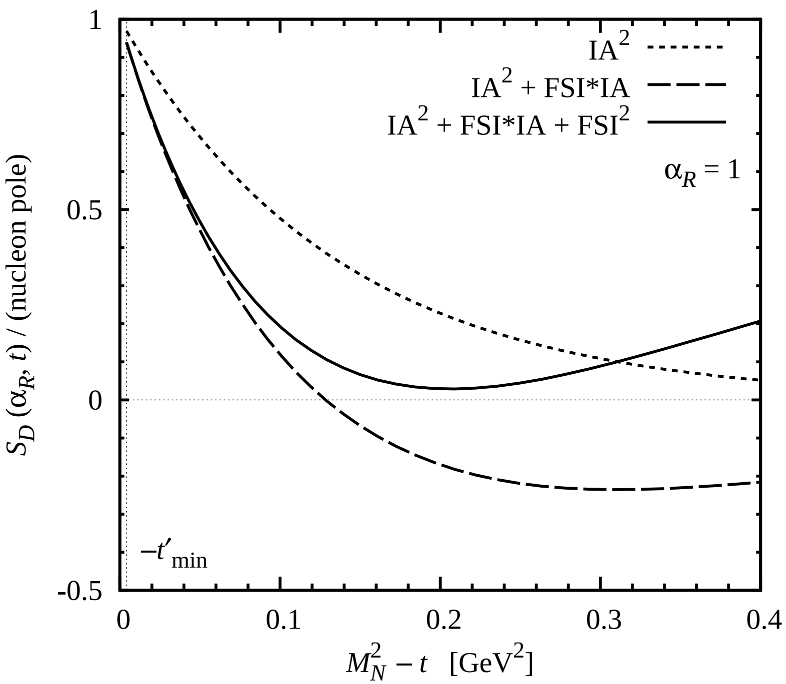
  Study modification as function of recoil momentum ↔ off-shellness

  Control size of nuclear configuration!

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

Tagging: Final–state interactions





- FSI in tagged DIS → **Talk Cosyn**

  Does note modify nucleon pole
  Sargsian, Strikman 05

  Distorts recoil momentum spectrum away from pole $t \neq M_N^2$

  Should not affect total cross section: Closure, momentum sum rule

- Schematic model for $x \lesssim 0.1$

  DIS on active nucleon produces hadrons with broad momentum distribution

  Dominant FSI from interactions of slow DIS hadrons with spectator: Rest-frame momenta $p_h \sim 1\,\mathrm{GeV}$

  Estimate FSI using empirical hadron distributions and NN interactions

  Can be maximized/minimized through choice of kinematics

Strikman, CW 15

Also azimuthal & spin-dep cross section, esp. T-odd structures

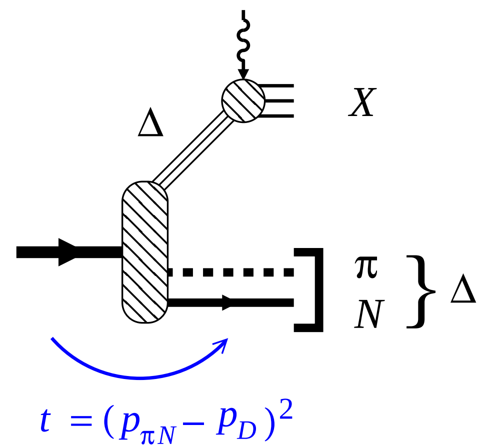
Tagging: Extensions

- Diffraction and shadowing in tagged DIS at $x \lesssim 0.01$ **Guzey et al. 14/15**

- Tagging Δ isobars? $\rightarrow$ **Talk Strikman**

  Tagged DIS $e + D \rightarrow e' + \pi + N$,
  reconstruct Δ from πN

  Structure function of Δ defined
  through recoil momentum dependence



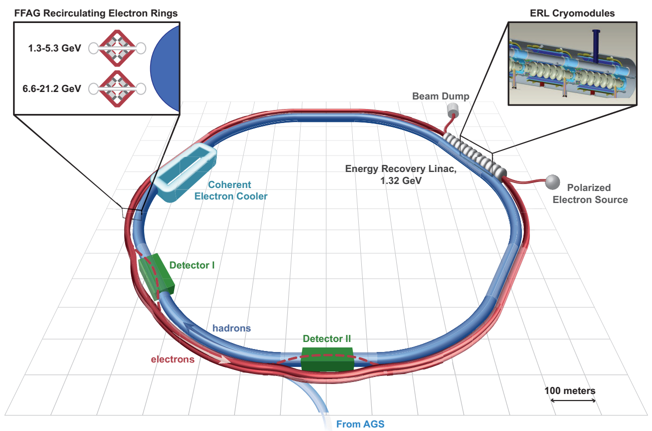
- Tagging with complex nuclei $A > 2$?

  Could 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**

  Much more complex than basic deuteron tagging, but should be explored!

Apparatus: EIC accelerator designs



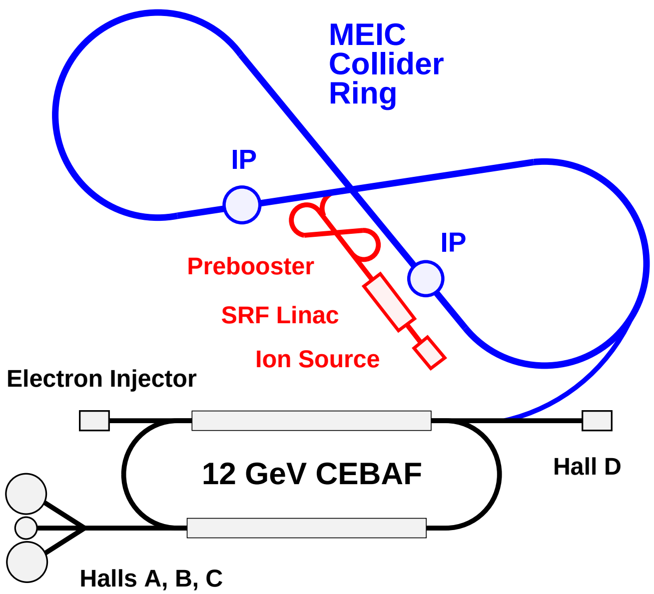
- BNL linac–ring design eRHIC

  RHIC 250 GeV proton beam, 170 GeV 3He

  2–20 GeV pol electron ERL in tunnel

  Luminosity $\sim 10^{33-34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ over wide range

  Re-use RHIC detectors? **PHENIX, STAR**



- JLab ring–ring design MEIC

  12 GeV CEBAF as injector **continued fixed-target op**

  1 km ring with 3-11 GeV e on 60-100 GeV p

  2.5 km ring with 250 GeV p as upgrade

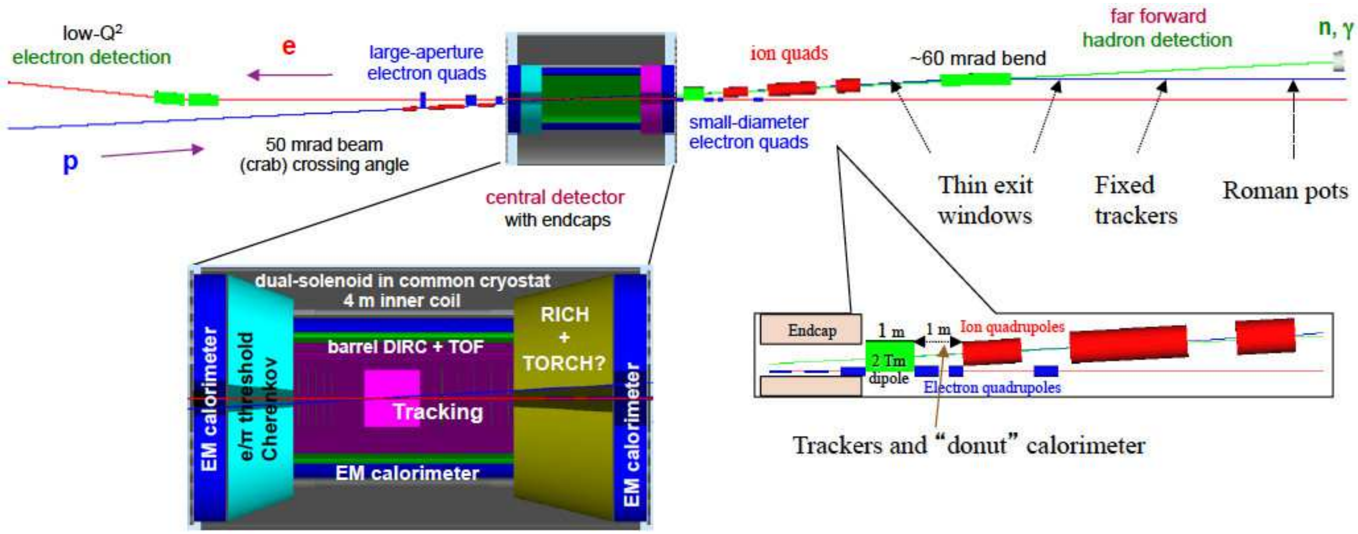
  Luminosity $\sim 10^{34}$ over wide range

  Figure–8 for polarized deuteron

- Related proposals: CERN LHeC, EIC@China design target similar to JLab MEIC

Different technological challenges!

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

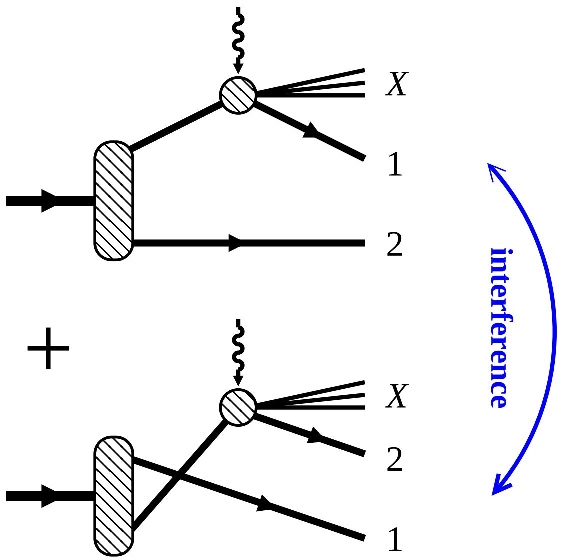
- Recoil momentum dependence permits separation of nuclear and nucleon structure

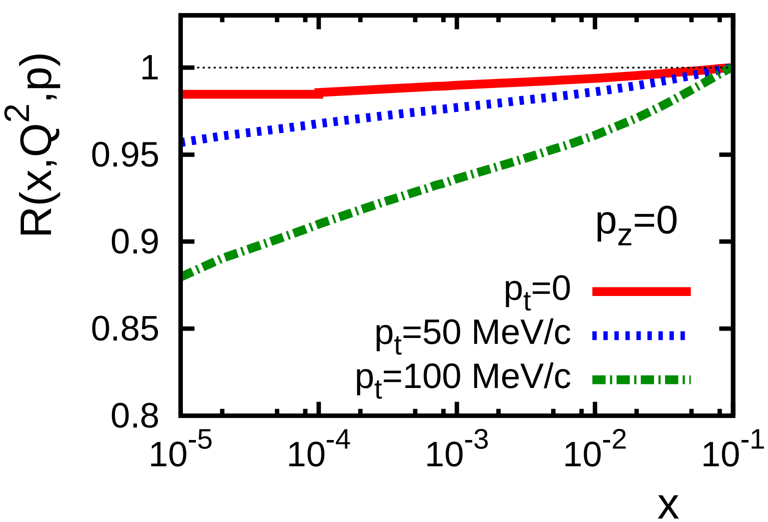
  On-shell extrapolation, controled size of NN configuration, FSI

- Explore further applications to SRCs

Supplementary material

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