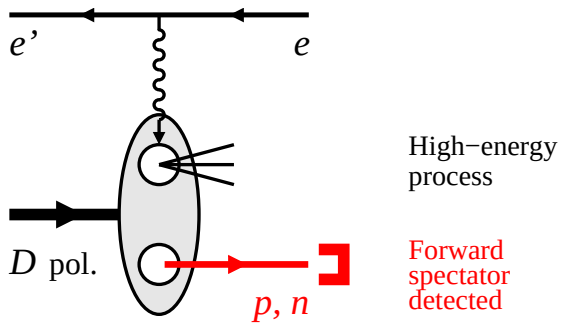
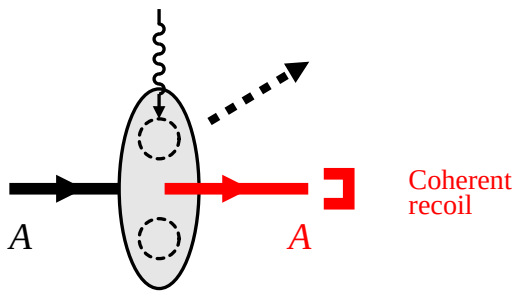
Next-generation nuclear physics with polarized light ions at EIC

C. Weiss (JLab), Physics Opportunities with EIC, 2019 APS DNP Fall Meeting, 14-Oct-2019





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

  Energy, luminosity, polarization, detection

  Objectives and challenges

- Spectator tagging with deuteron

  High-energy process $\leftrightarrow$ low-energy stucture

  Free neutron spin structure

  NN interactions, EMC effect

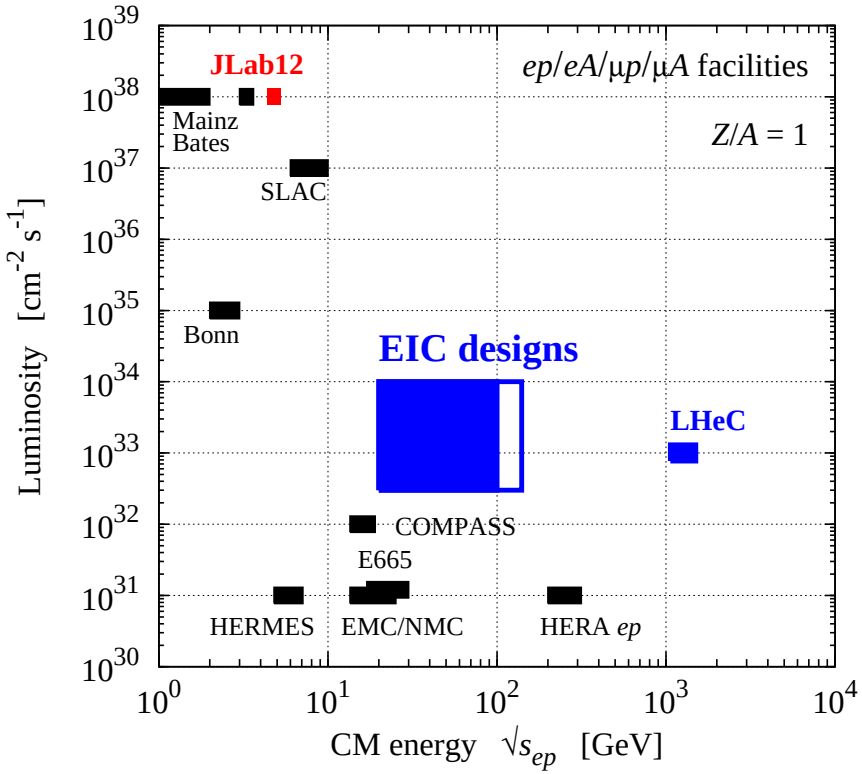
- Coherent processes with light nuclei

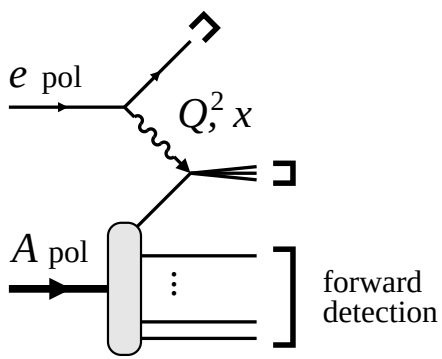
  Quark/gluon spatial distributions

  Dynamics: Nuclear shadowing etc.

- Forward ion detection with EIC

Light ions: EIC capabilities





- CM energy $\sqrt{s_{ep}} \sim$ 20–100(140) GeV

  Factor $\sqrt{Z/A}$ for nuclei

  DIS at $x \gtrsim 10^{-3}$, $Q^2 \lesssim 10^2$ GeV^2

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

  Exceptional configurations in target
  Multi-variable final states
  Polarization observables

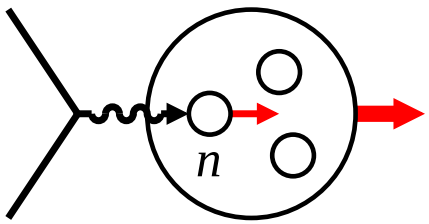
- Polarized protons and light ions

  Polarized deuteron, 3He, ...

- Forward detection of p, n, A

  Exclusive and diffractive processes
  Nuclear breakup and spectator tagging
  Coherent nuclear scattering

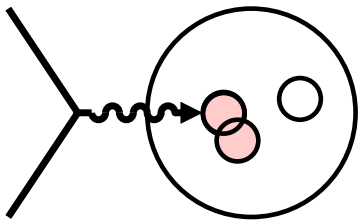
Light ions: Physics objectives



- Neutron structure

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

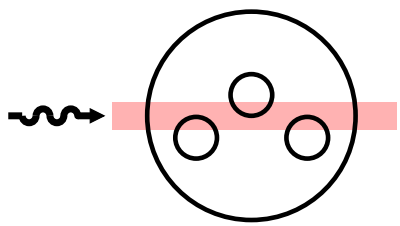
  Eliminate nuclear binding, non-nucleonic DOF!



- 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

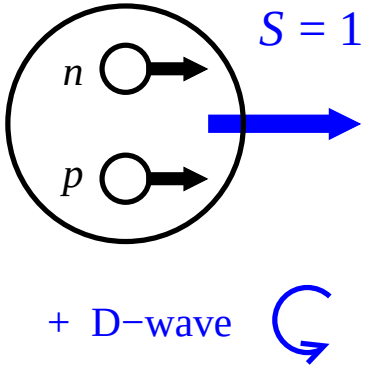
  Coherent interaction of high–energy probe
  with multiple nucleons, shadowing, saturation

  Identify coherent response!

[Nucleus rest frame view]

Common challenge: Effects depend on the nuclear configuration during the high-energy process.
Need to "control" the configurations!

Light ions: Deuteron and spectator tagging

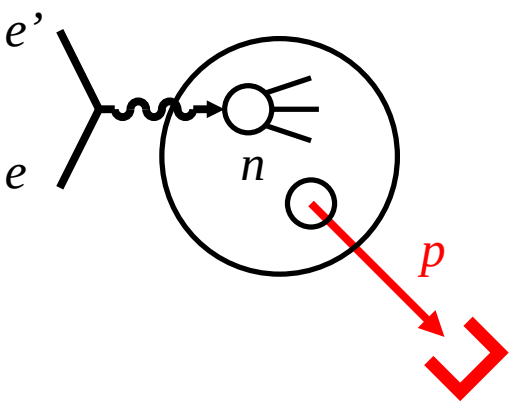


- Deuteron target unpol/pol

  Nucleonic wave function simple, known well including light-front WF for high-energy processes

  Neutron spin-polarized, some D-wave depolarization

  Intrinsic Δ isobars suppressed by isospin $= 0$
  Large Δ component in 3He. Frankfurt etal 96; Bissey etal 02



[Nucleus rest frame view]

- Spectator nucleon tagging

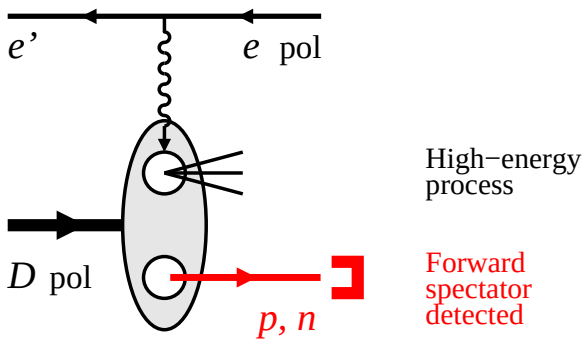
  Identifies active nucleon

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

Light ions: Deuteron and spectator tagging II



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

[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
  Expertise LHC, Tevatron, RHIC, HERA → EIC

- Advantages over fixed-target

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

  Potentially good acceptance and resolution

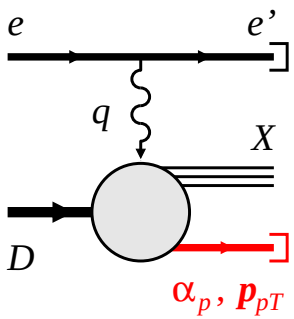
  Deuteron polarization in beam,
  no holding magnets around target

  Forward neutron detection possible

- Unique physics potential

Tagging: Observables and theory

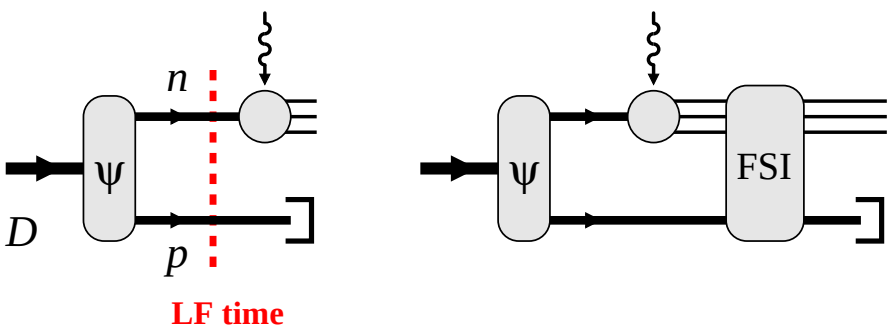
- Tagged DIS cross section $eD \to e' + X + p$



$$\frac{d\sigma}{dx\,dQ^2\,d^3p_p/E_p} = [\text{flux}]\Big[F_{TD}(x,Q^2;\alpha_p,p_{pT}) + \epsilon F_{LD}(..)$$
$$+ \quad \phi_p\text{-dependent} \quad + \quad \text{spin-dependent structures}\Big]$$

Proton momentum longitud $\alpha_p = p_p^+/p_D^+$, transv $\boldsymbol{p}_{pT}$ ($\gamma^* D$ collinear)

- Theoretical description: Separate nuclear $\leftrightarrow$ nucleonic structure

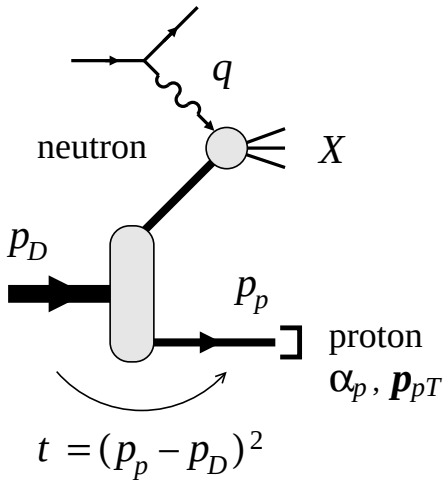


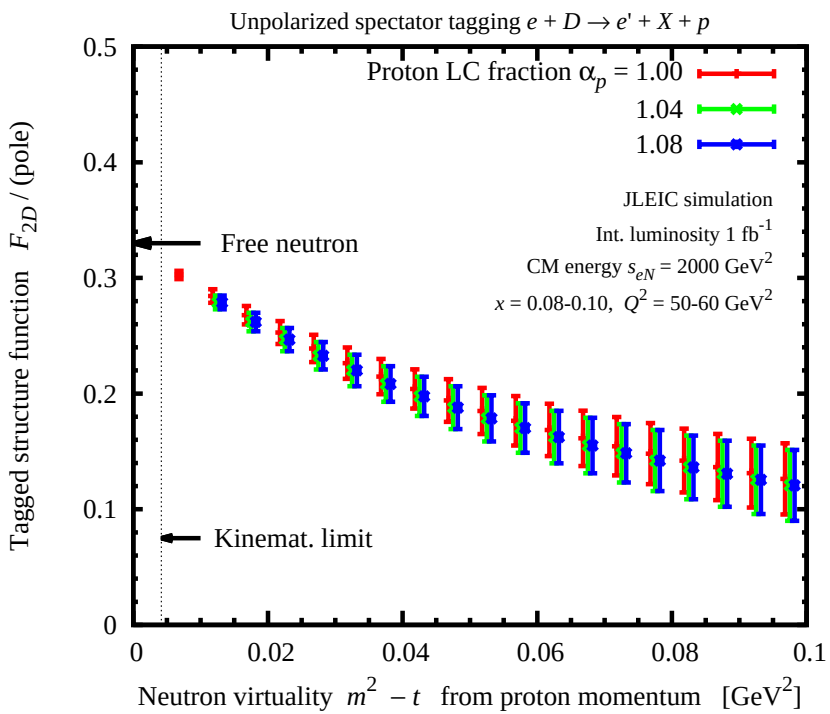
Deuteron wave function $\langle pn|D\rangle$
at fixed light-front time $x^+ = x^0 + x^3$

Impulse approximation,
final-state interactions

Use tagged momentum as variable: Control nuclear binding, minimize/maximize FSI

Tagging: Free neutron structure





- Nuclear binding: Motion, interaction

- Extract free neutron structure

  Measure tagged structure function dependence on proton momentum $\to$ neutron off-shellness $t - m^2 = -2|\boldsymbol{p}_{pT}^2| + t'_{\min}$

  Extrapolate to on-shell point $t - m^2 \to 0$

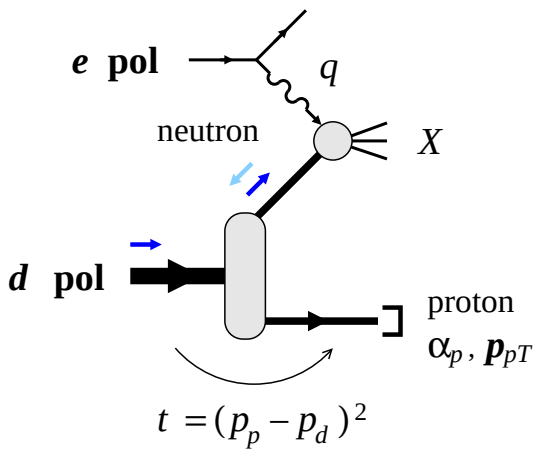
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 05

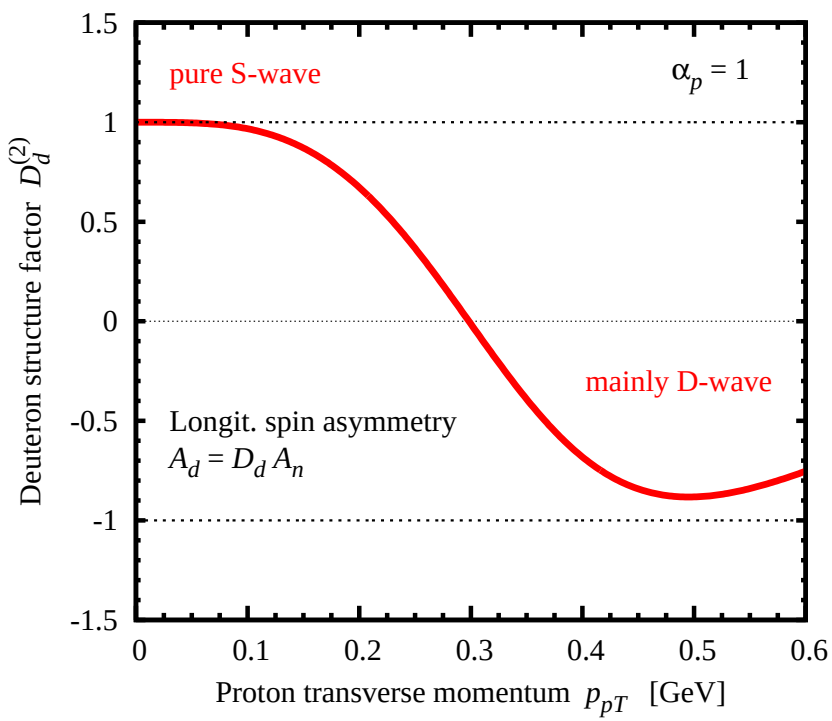
- EIC simulations

  Uncertainty mainly systematic: Proton momentum resolution/smearing
  2014/15 LDRD

  F_{2n} extracted with percent-level accuracy at $x \sim 0.1$, applications $\bar{d}/\bar{u}$

Tagging: Neutron spin structure





Cosyn, CW arXiv:1902.03678

- Nuclear binding: Neutron polarization?

  S + D waves, depolarization

- Control neutron polarization

  Measure tagged spin asymmetries

  D-wave drops out at $\boldsymbol{p}_{pT} = 0$:
  Pure S-wave, neutron 100% polarized

  [$|\boldsymbol{p}_{pT}| \approx$ 400 MeV: D-wave dominates]

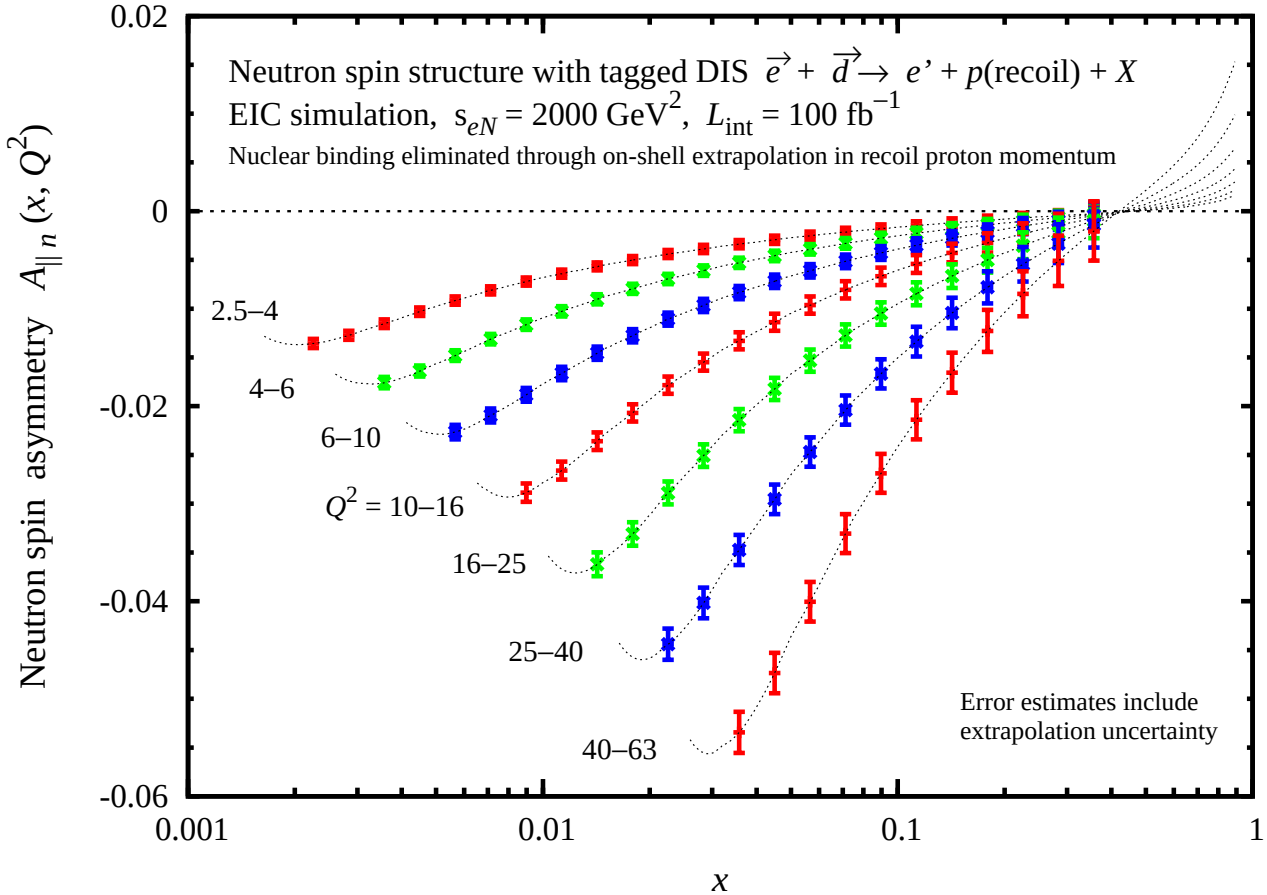
- Free neutron spin structure

  On-shell extrapolation of asymmetry

- EIC simulations

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

Tagging: Neutron spin structure II



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

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

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

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

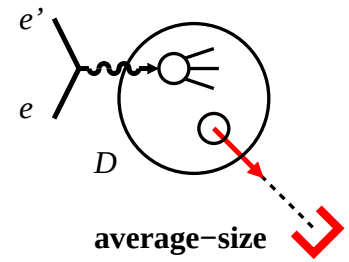
  Nonsinglet $g_{1p} - g_{1n}$ and Bjorken sum rule

Tagging: Nucleon interactions

- Configuration dependence of nuclear partonic structure?

  What momenta/distances cause modifications?

  Connection EMC effect $\leftrightarrow$ NN short-range correlations?
  Gluonic structure: Miller, Sievert, Venugopalan 17

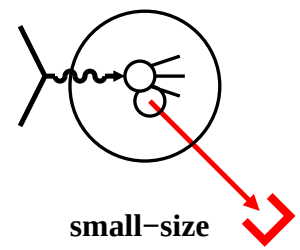


- Tagged nuclear structure functions

  Measure nucleon momentum dependence at $p_T \sim$ few 100 MeV

  Separate initial-state modifications $\leftrightarrow$ final-state interactions?
  Kinematic dependence: Strikman, CW, PRC97 (2018) 035209

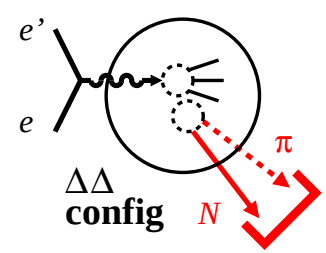
  Proton and neutron detection possible



- Tagging $\Delta\Delta$ configurations

  Measure $e + D \to e' + X + \pi + N$, reconstruct Δ from πN

  Direct demonstration of non-nucleonic degrees of freedom



Tagging: Applications and extensions

- Tagging with tensor-polarized deuteron

  ϕ harmonics specific to tensor polarization
  Cosyn, Sargsian, CW; in progress

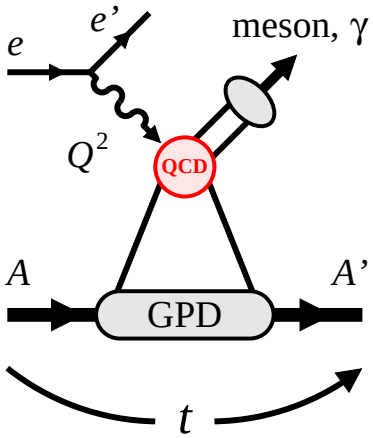
- Tagging with complex nuclei $A > 2$

  Test isospin dependence and/or universality of bound nucleon structure

  Example: $(A-1)$ ground state recoil, e.g. 3He (e, e' d) X
  Ciofi, Kaptari, Scopetta 99; Kaptari et al. 2014

  Requires extensive theoretical input for nuclear structure:
  Spectral functions, decay functions, final-state interactions
  Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent U, Belgium [Webpage]

Coherent processes: Nuclear quark-gluon imaging

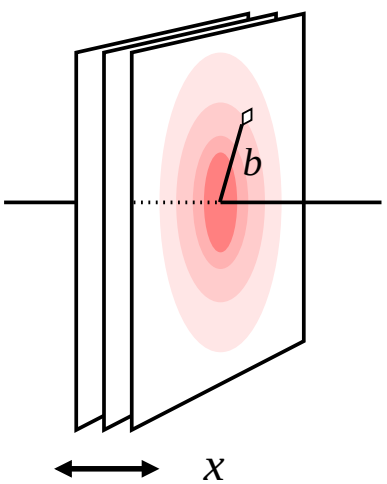


- Hard exclusive processes

  QCD factorization theorem
  Collins, Frankfurt, Strikman 96

  Generalized parton distributions $\langle A'| \hat{\mathrm{O}}_{\mathrm{QCD}} |A\rangle$:
  Unify concepts of quark/gluon density and form factor
  Müller et al. 94; Ji 96, Radyushkin 96

  Probe nuclear structure in QCD degrees of freedom



- Transverse spatial distribution of quarks/gluons

  Compare quark $\leftrightarrow$ gluon, charge $\leftrightarrow$ matter distributions

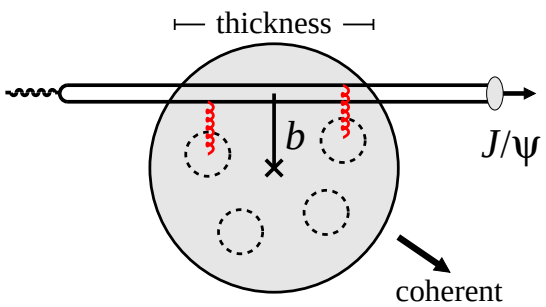
  Dynamics: Distributions change with x, polarization

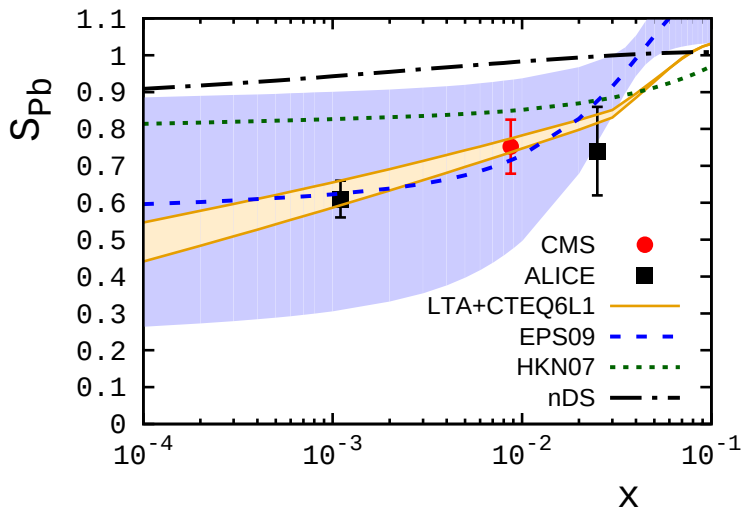
- EIC: Quark-gluon imaging of light nuclei

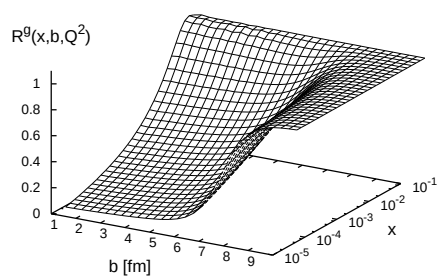
  Probe quarks: Deep-virtual Compton DVCS; π, K, ρ^+
  Probe gluons: J/ψ, ϕ

  Nuclei: D spin-1, 3He spin-1/2, 4He spin-0

Coherent processes: Nuclear shadowing







- Nuclear shadowing

  Small-x probe interacts coherently with nucleons along its path

  Interference of diffractive scattering from different nucleons: shadowing

  Suppresses gluon density at small x
  Seen in ultraperipheral γA at LHC ALICE, CMS

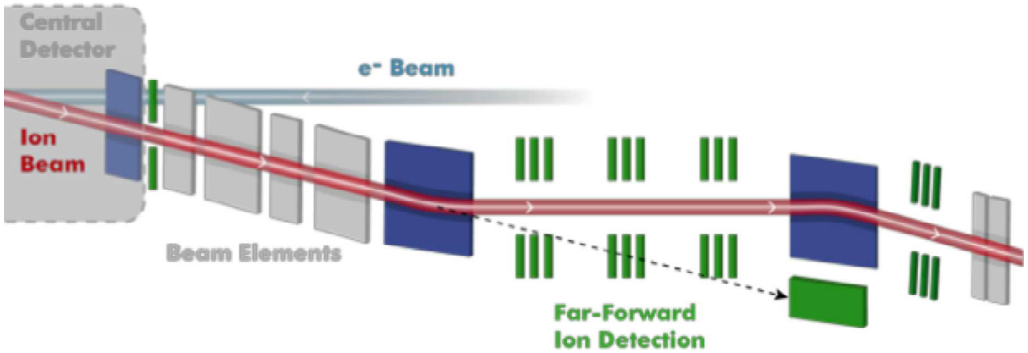
- EIC: Shadowing in coherent processes

  Nuclear gluon density as function of impact parameter $\leftrightarrow$ thickness
  Theoretical models: Guzey et al 09

  Light ions: Test shadowing mechanism in simple systems w. control nuclear structure, positive detection of forward ions

  Heavy ions: Veto nuclear breakup
  Caldwell, Kowalski 09

EIC: Forward detection system



[Drawing not to scale]

- Large-acceptance forward detector

Concept: P. Nadel-Turonski, Ch. Hyde et al.

Beams collide at small crossing angle 25-50 mrad

Forward protons/neutrons/ions travel through ion beam quadrupole magnets

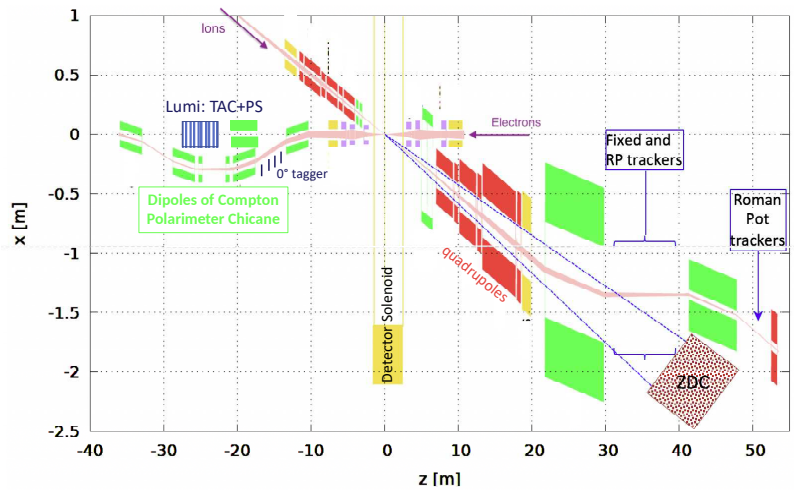
Dispersion generated by dipole magnets

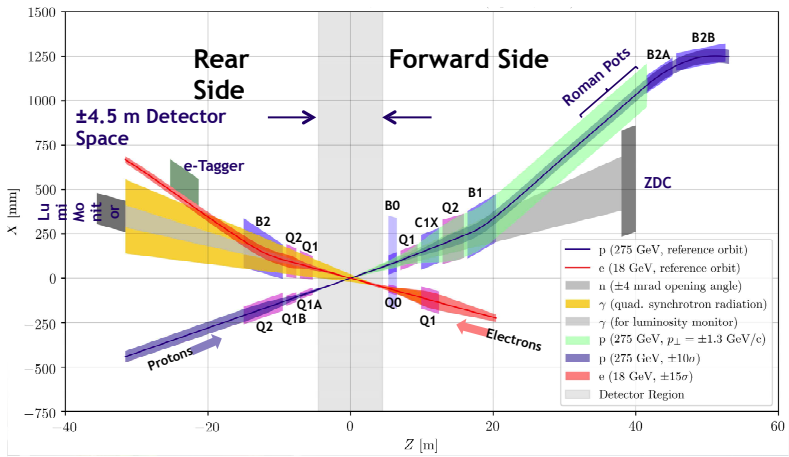
Detection using different systems: Tracking detectors inside dipoles,
Roman Pot detectors for charged forward particles (protons, ions)
Zero-degree calorimeters ZDCs for neutral forward particles (neutrons, photons)

- Major optimization and integration challenge

Forward particles with various momentum/charge ratios (rigidities) $\neq$ beam.
Variable ion beam beam energy. Bore radius of beam elements.
Geometric size of magnets and infrastructure
Much more complex than forward detectors at high-energy colliders: HERA, RHIC, LHC

EIC: Forward detection system II





JLEIC IR design: V. Morozov et al 2019,
eRHIC IR design, Ch. Montag et al 2019

Current status: Workshop Physics and Detector Requirements at Zero Degree, Stony Brook, 24-26 Sep 2019 [Webpage]

- IR designs

  JLEIC and eRHIC designs similar:
  Same concept, physical extent

  Notable differences: Crossing angle
  JLEIC 50 mrad – eRHIC 25 mrad,
  JLEIC secondary focus at RP location

- Forward acceptance and resolution

  Physical requirements $\rightarrow$ Table

  Software framework developed

  Simulations on-going

- Momentum spread in ion beam

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

  Smearing effect $\boldsymbol{p}_T$(vertex) $\neq$ $\boldsymbol{p}_T$(measured),
  systematic uncertainty

Summary

- EIC will enable next-generation physics program in eA(light) scattering

- 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

  Configuration dependence of nuclear modifications, EMC effect

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

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

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

  Dynamics of NN interactions, nuclear shadowing at small x

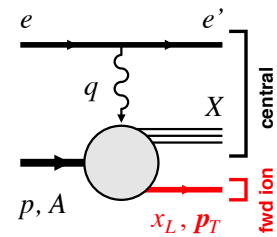
- EIC forward detector design ongoing

  Open for collaboration! Physics, detector, software, other topics.
  Simulation tools available. Ask speaker!

Supplementary material

EIC: Physics requirements for forward detection

Processes	Beam -> Fwd	Rigidity Fwd/	Coverage	Resolution (Charged)	Neutrals	Comments
Exclusive & diffractive scattering on proton	p -> p, n	1	pT = [0, ~2 GeV] xL = [~0.5, ~0.999] 1-xL = [~1E-3, ~0.3]	ΔpT ~ 50 MeV ΔxL/xL << 0.1 Δ(1-xL)/(1-xL) < 0.1	n Λ, Σ0	Inelastic diffraction physics & background
Coherent scattering on light nuclei	A -> A (A = D, He)	1	pT = [0, ~200 MeV] 1-xL = [~1E-3, ~1E-1]	ΔpT ~ 10-20 MeV Δ(1-xL)/(1-xL) < 0.1	none	Momentum spread in ion beam significant
Spectator tagging in deuteron	D -> p (n)	1/2	pT = [0, ~500 MeV] xL = [~0.25, ~0.75]	ΔpT ~ 10-20 MeV ΔxL/xL << 0.1	(n)	Momentum spread in ion beam significant
Breakup of light and heavy nuclei	A -> p, n, A-1	various	pT = [0, ~500 MeV] xL various	?	multiple n	Veto detection for heavy nuclei



xL — longitudinal momentum fraction with respect to proton/ion beam

pT — transverse momentum -> angle θ

[Related to physics variables in photon-ion collinear frame]

Approximate physics requirements for EIC forward detector acceptance and resolution

C. Weiss, Workshop Physics and Detector Requirements at Zero Degree, Stony Brook, 24-26 Sep 2019 [Webpage]