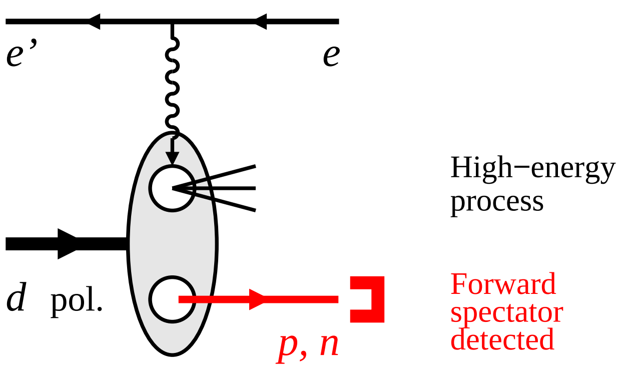
Next-generation nuclear physics with polarized light ions at EIC

C. Weiss (JLab), UConn PAN Seminar, 30-Apr-2018



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]

$+$ continuing theory research

- Light ion physics at EIC

  Energy, luminosity, polarization, detection

  Physics objectives

- Deuteron and spectator tagging

  Theoretical framework
  Strikman, Weiss, PRC97 (2018) 035209 [INSPIRE]

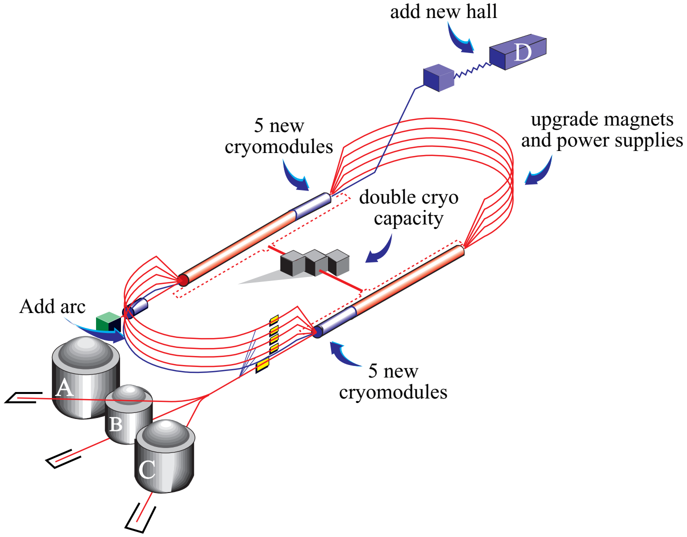
  Free neutron from on-shell extrapolation

  Recent results: Neutron spin structure, diffraction and shadowing at small x, tensor polarization, ...
  Cosyn, Guzey, Sargsian, Strikman CW, in preparation

- Forward detection with EIC

- Future plans

Nuclear physics with EM probes



- JLab 12 GeV operations started

  Hall A & D first physics results, Hall C physics running, CLAS12 engineering run

  Four-hall operation demonstrated

  Expect physics results 5-10 years

  Other EM facilities: COMPASS, MAMI, ELSA, MIT Bates

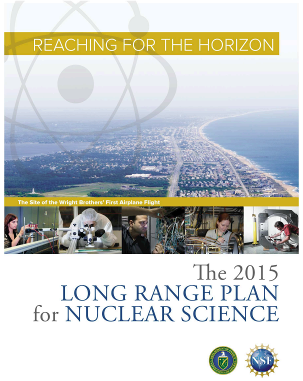
- Electron-Ion Collider as future facility

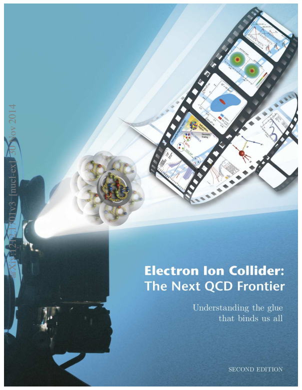
  Recommended in 2015 NSAC Long-Range Plan

  Designs by BNL and JLab

  Vigorous accelerator and detector R&D

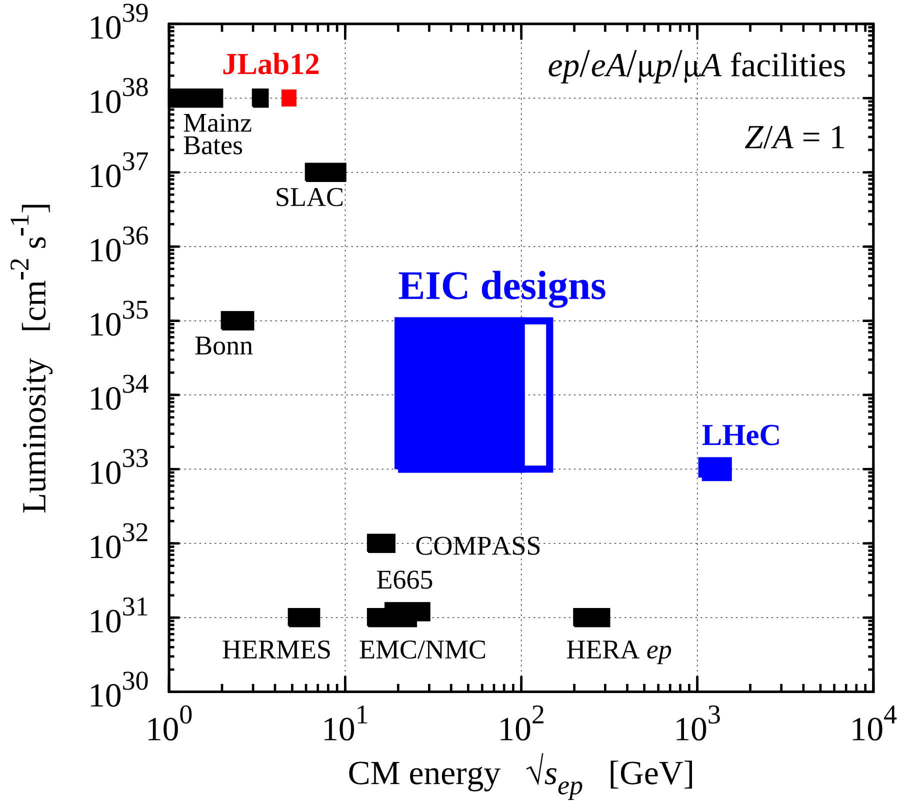
  Driving physics research in exp and thy

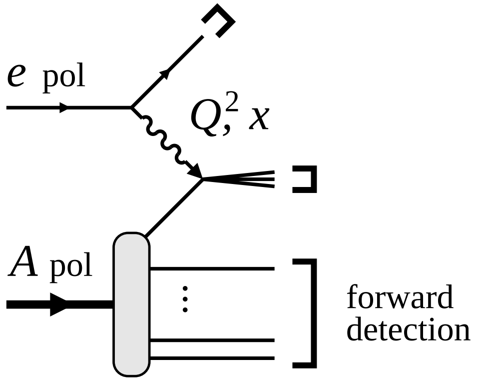




- Hadron probes: LHC, RHIC $pA/AA/\gamma A$, JPARC, GSI FAIR, FRIB

EIC ep/eA capabilities





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

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

  Deep-inelastic scattering at
  $x \sim 10^{-1}$–10^{-3}, $Q^2 \lesssim 10^2$ GeV^2

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

  Exceptional configurations in target
  Multi-variable final states
  Polarization observables

- Polarized protons and light ions

  eRHIC: pol ^3He
  JLEIC: pol d and ^3He with figure-8

- Forward detection of p, n, A

  Diffractive and exclusive processes
  Nuclear breakup and spectator tagging
  Coherent nuclear scattering

EIC physics topics

I) 3D nucleon structure and spin

Sea quark and gluon polarization, nucleon spin decomposition
Spatial distributions and orbital motion of quarks/gluons
Quark-gluon correlations

II) QCD in nuclei

Nuclear quark/gluon densities, NN interactions in QCD
Color transparency and opacity
Nonlinear effects and gluon saturation at small x

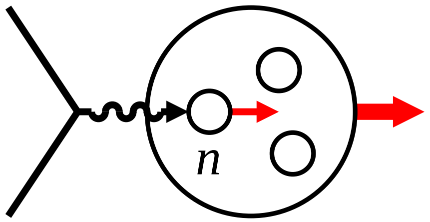
III) Emergence of hadrons from color charge

Quark/gluon fragmentation and hadronization
Interaction of color charge with matter

. . .

Measurements with $\begin{cases} ep \\ eA(\text{light}) & \leftarrow \text{this seminar} \\ eA(\text{heavy}) \end{cases}$

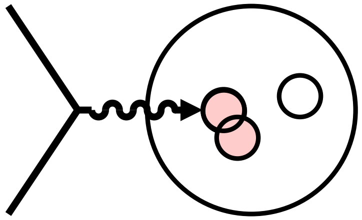
Light ions: Physics objectives



- Neutron structure

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

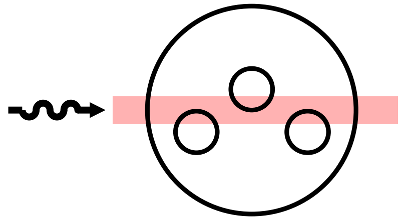
  Eliminate nuclear binding, non-nucleonic DOF!



- 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

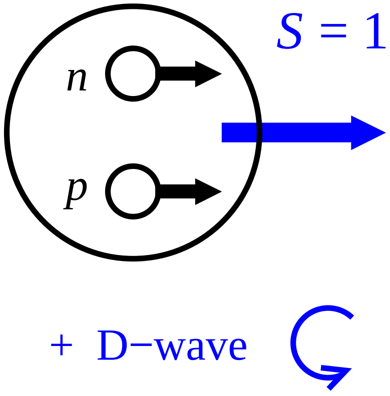
  Coherent interaction of high–energy probe with multiple nucleons, shadowing, saturation

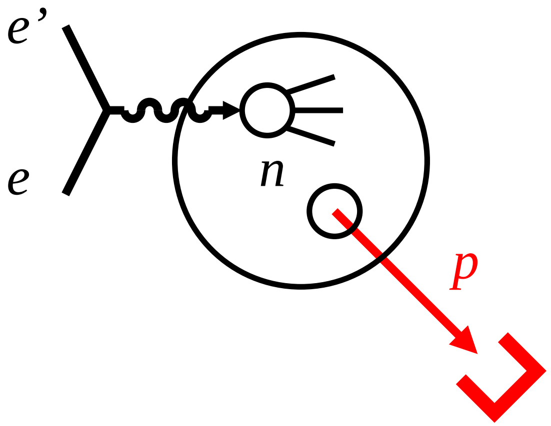
  Identify coherent response!

[Nucleus rest frame view]

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

Light ions: Deuteron, 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 $= 0$
  $|\mathrm{deuteron}\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$

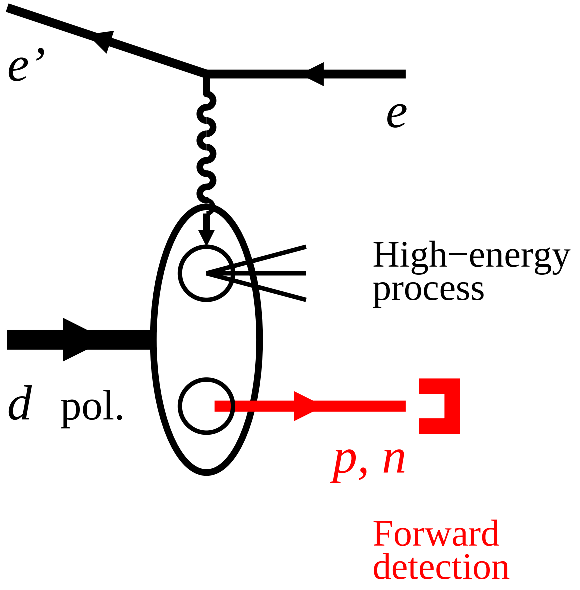
- Spectator nucleon tagging

  Identifies active nucleon

  Controls configuration through recoil momentum:
  Spatial size, S ↔ D wave

  Tagging in fixed-target experiments
  CLAS6/12 BONUS, recoil momenta $p =$ 70-150 MeV

Light ions: Deuteron, spectator tagging



- Spectator tagging with colliding beams

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

  Detection with forward detectors integrated
  in interaction region and beams optics
  LHC $pp/pA/AA$, Tevatron $p\bar{p}$, RHIC pp, ultraperipheral AA

- Advantages over fixed-target

  No target material, $\boldsymbol{p}_p(\text{restframe}) \rightarrow 0$ possible

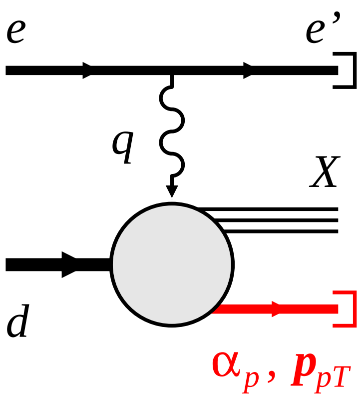
  Potentially full acceptance, good resolution

  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 $e + d \to e' + X + p$

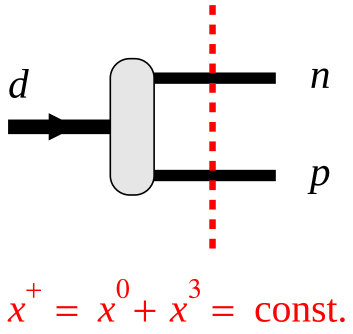
Proton recoil momentum $p_p^+ = E_p + p_p^z$, $\boldsymbol{p}_{pT}$,
light-front momentum fraction $p_p^+ = \alpha_p p_d^+/2$,
simply related to $\boldsymbol{p}_p$(restframe)

Conditional structure functions

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



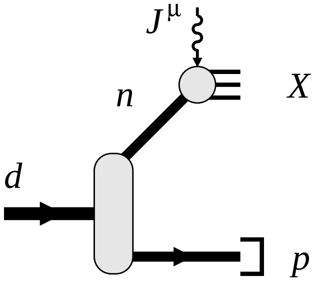
- Light-front quantization

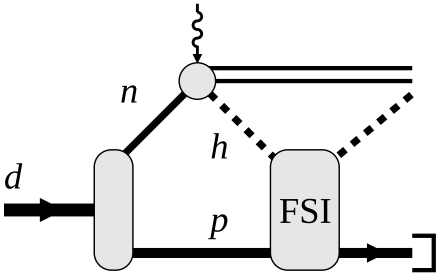
  High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 =$ const.

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

  Matching nuclear ↔ nucleonic structure
  Frankfurt, Strikman 80's

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



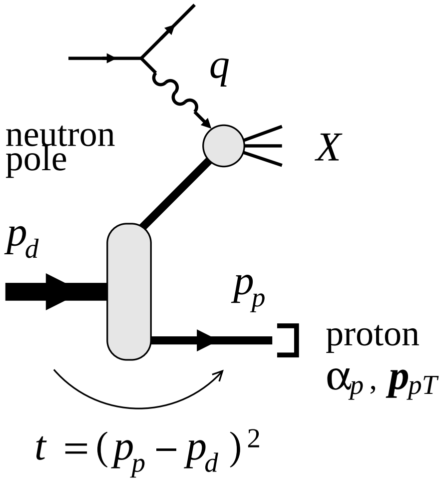


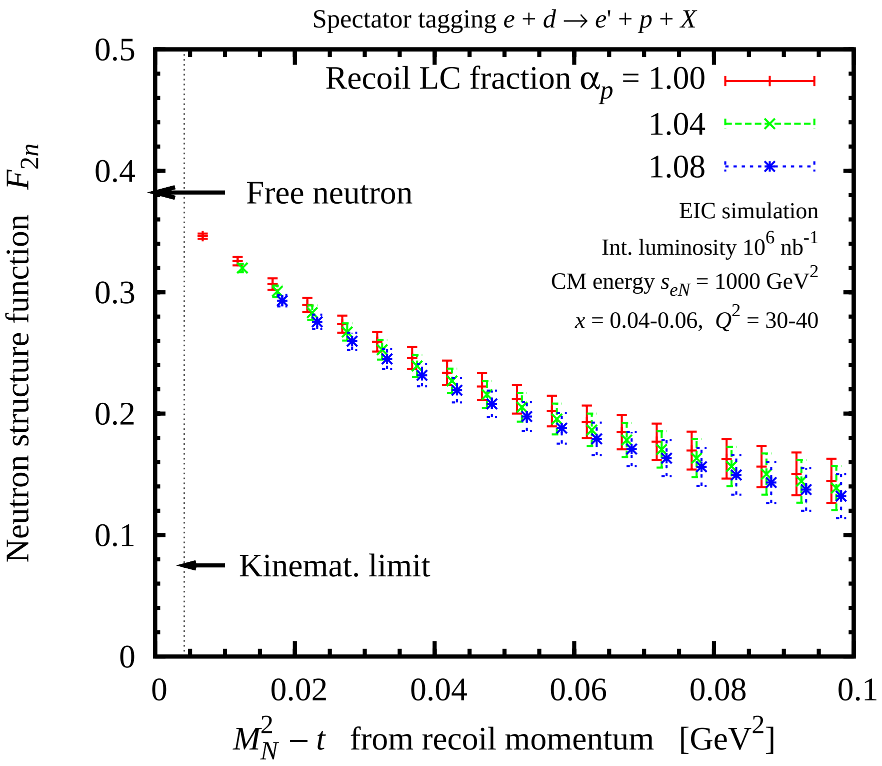
- Composite description

  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 invariant
  $t - M_N^2 = -2|\boldsymbol{p}_p|^2 + t_{\min}$
  “neutron off-shellness”

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

  Eliminates nuclear binding effects
  and FSI Sargsian, Strikman 05

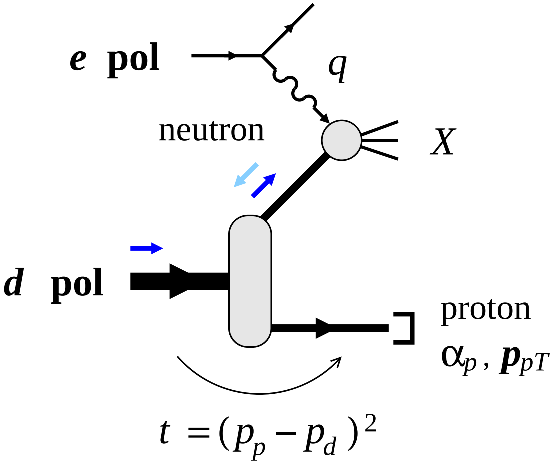
- Precise measurements of F_{2n}

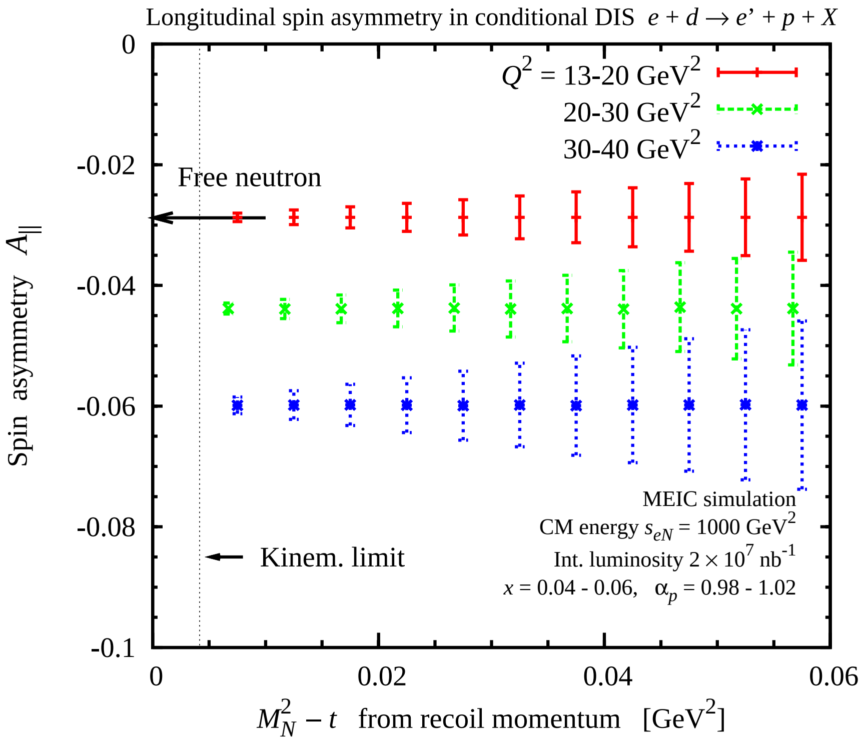
  F_{2n} extracted with few-percent
  accuracy at $x \gtrsim 0.1$

  Uncertainty mainly systematic
  JLab LDRD: 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 $\boldsymbol{p}_p = 0$: Neutron 100% polarized

- Systematic uncertainties cancel

  Weak off-shell dependence of asymmetry

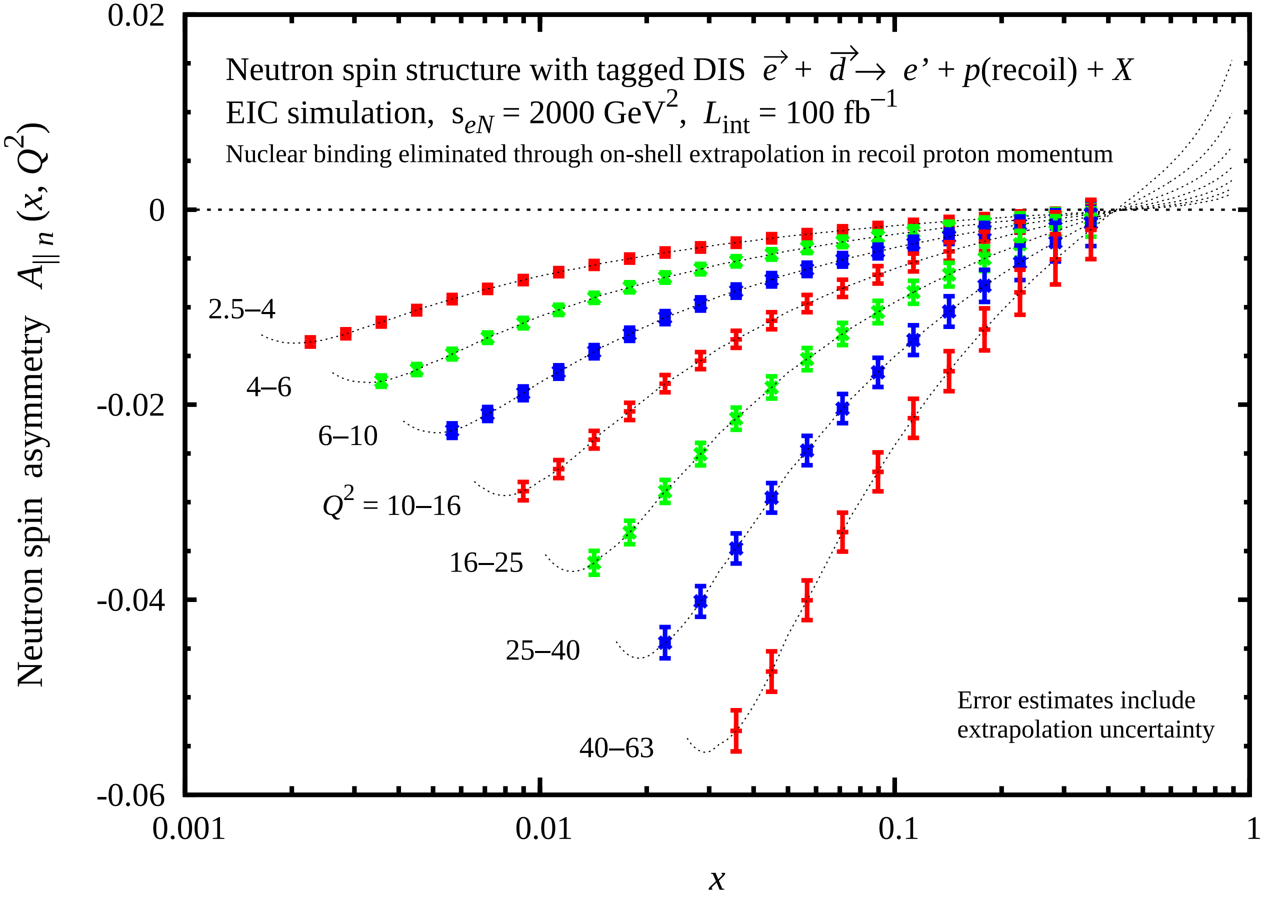
  Momentum smearing/resolution effects largely cancel in asymmetry

- Statistics requirements

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

  Possible with lumi $\sim 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Tagging: Neutron spin structure II



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

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

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

depolarization factor

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

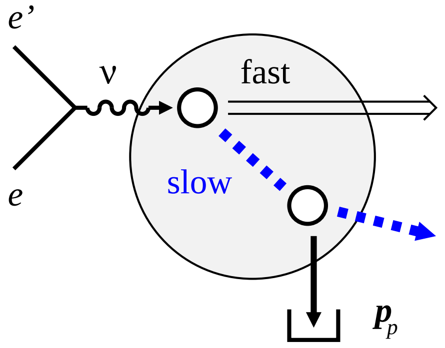
- Precise measurement of neutron spin structure

  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: Final-state interactions



- DIS final state can interact with spectator

  Changes recoil momentum distributions in tagging

  No effect on total cross section – closure

- Nucleon DIS final state has two components

"Fast"	$E_h = O(\nu)$	hadrons formed outside nucleus interact weakly with spectators
"Slow"	$E_h = O(\mu_{\text{had}}) \sim 1$ GeV	formed inside nucleus interacts with hadronic cross section dominant source of FSI

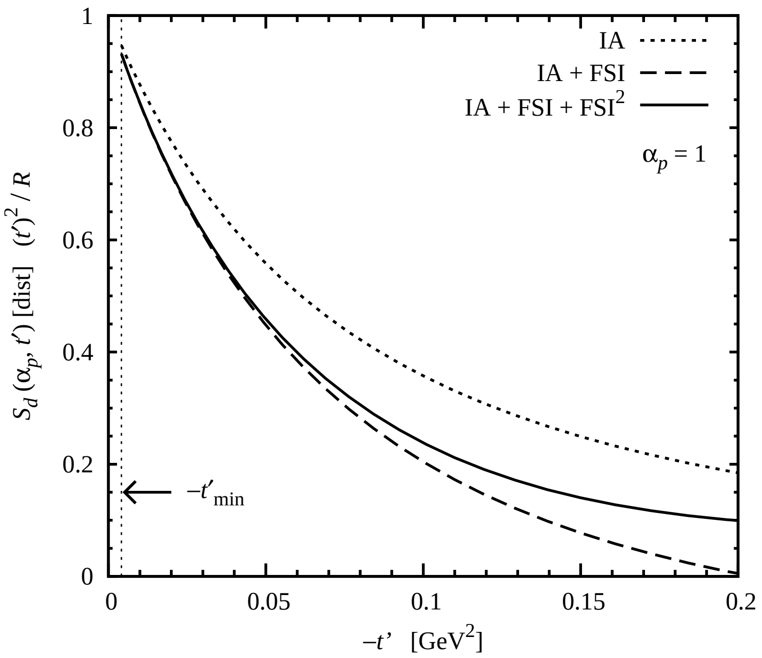
- FSI effects calculated $x \sim$ 0.1–0.5 Strikman, CW, PRC97 (2018) 035209

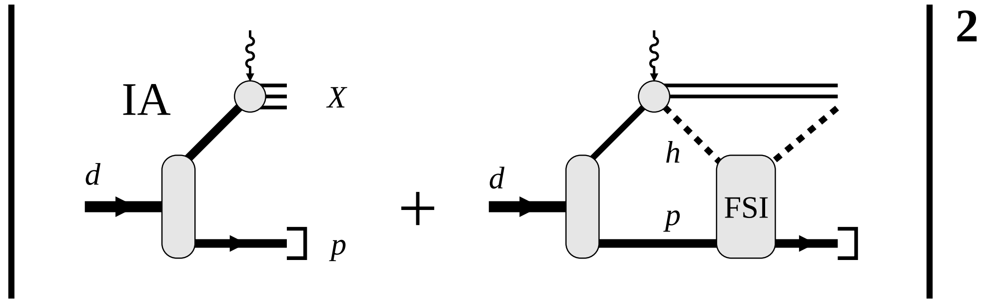
  Experimental slow hadron multiplicity distributions Cornell, EMC, HERA

  Hadron-nucleon low-energy scattering amplitudes

  Light-front QM: Deuteron pn wave function, rescattering process Frankfurt, Strikman 81

Tagging: Final-state interactions II





Strikman, CW 18

- FSI reduces IA cross section at $|t - M_N^2| \neq 0 \quad (\lesssim 0.2\,\mathrm{GeV}^2)$

- FSI vanishes at $t - M_N^2 \to 0$; on-shell extrapolation not affected

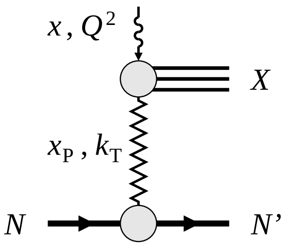
[• Other interesting aspects

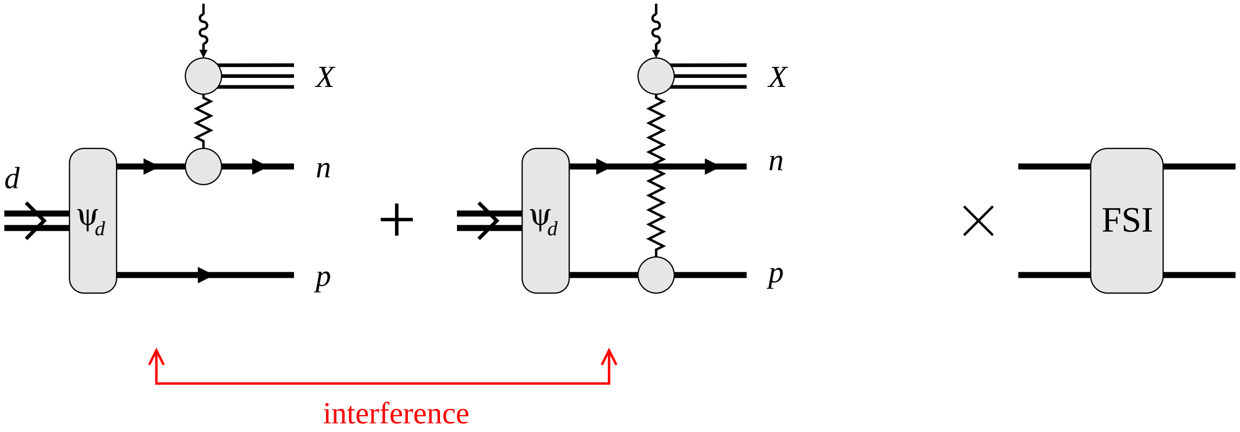
  FSI depends on recoil momentum angle in rest frame: forward-sideways-backward regions

  Analogy with FSI in quasi-elastic deuteron breakup

  FSI suppressed for $x \to 1$: Minimum momentum of DIS hadrons grows

Tagging: Diffraction and shadowing





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

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

  10-15% of events diffractive. Detailed studies at HERA: QCD factorization, diffractive PDFs

- Shadowing in deuteron DIS

  Diffraction can happen on neutron or proton: QM interference

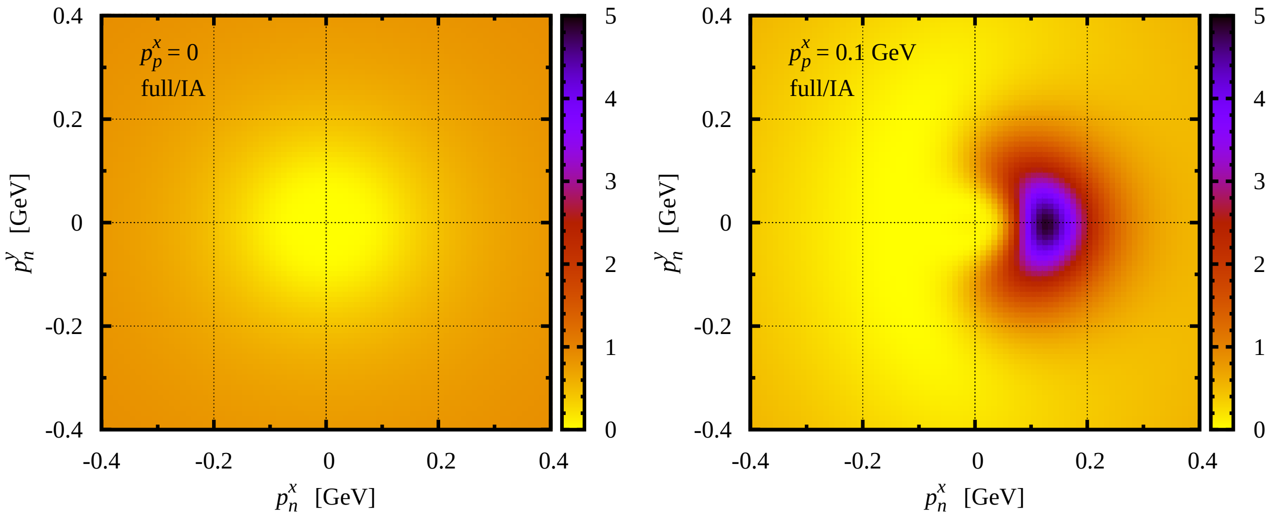
  Reduction of cross section compared to IA — shadowing. Leading-twist effect.
  Frankfurt, Strikman, Guzey 12. Great interest. Hints seen in J/ψ production in UPCs at LHC ALICE.

- 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 18

Tagging: Diffraction and shadowing



$R = \frac{d\sigma(\text{full})}{d\sigma(\text{IA})}$ as function of neutron $\boldsymbol{p}_{nT}$ for fixed proton $\boldsymbol{p}_{pT}$

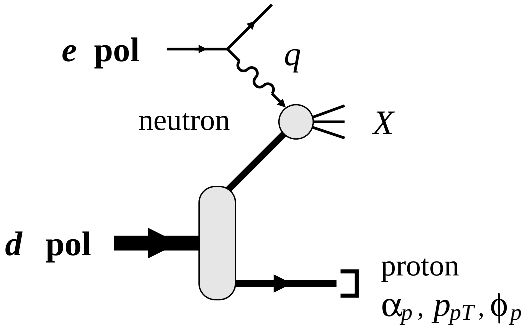
- Final-state interactions in diffractive tagged DIS $e + d \rightarrow e' + X + n + p$

  Large FSI effects due to orthogonality

  Shadowing effects also calculated; can be studied in selected kinematics
  Guzey, Strikman, CW, in preparation

  Other application: High-p_T deuteron breakup and gluonic structure of small-size pn configuration Miller, Sievert, Venugopalan 17

Tagging: Polarized deuteron



- Deuteron spin density matrix $\rho_{\lambda\lambda'}(S,T)$

  3 vector parameters, 5 tensor parameters

  Fixed by polarization measurements
  cf. Stokes' parameters for photon

- Polarized tagged cross section

Cosyn, Sargsian, CW 17

$$\frac{d\sigma}{dx\,dQ^2(d^3p_p/E_p)} = [\text{flux}](\mathsf{F}_U + \mathsf{F}_S + \mathsf{F}_T) \qquad \mathsf{F}_I = \text{functions}(x, Q^2, \alpha_p, p_{pT}, \phi_p)$$

$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$\begin{aligned}
F_S = {} & S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{US_L}^{\sin\phi_h} + \epsilon\sin 2\phi_h F_{US_L}^{\sin 2\phi_h}\right] \\
& + S_L h\left[\sqrt{1-\epsilon^2}F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LS_L}^{\cos\phi_h}\right] \\
& + S_\perp\left[\sin(\phi_h-\phi_S)\left(F_{US_T,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h-\phi_S)}\right) + \epsilon\sin(\phi_h+\phi_S)F_{US_T}^{\sin(\phi_h+\phi_S)}\right. \\
& \left.+\epsilon\sin(3\phi_h-\phi_S)F_{US_T}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\left(\sin\phi_S F_{US_T}^{\sin\phi_S} + \sin(2\phi_h-\phi_S)F_{US_T}^{\sin(2\phi_h-\phi_S)}\right)\right] \\
& + S_\perp h\left[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LS_T}^{\cos(\phi_h-\phi_S)} +\right. \\
& \left.\sqrt{2\epsilon(1-\epsilon)}\left(\cos\phi_S F_{LS_T}^{\cos\phi_S} + \cos(2\phi_h-\phi_S)F_{LS_T}^{\cos(2\phi_h-\phi_S)}\right)\right] ,
\end{aligned}$$

Tagging: Polarized deuteron II

$$\begin{aligned} F_T = T_{LL} \Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \Big] \\ & + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\ & + T_{L\perp} [\cdots] + T_{L\perp} h [\cdots] \\ & + T_{\perp\perp} \Big[\cos(2\phi_h - 2\phi_{T_\perp}) \Big(F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T_\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T_\perp})} \Big) \\ & + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_\perp})} \\ & + \sqrt{2\epsilon(1+\epsilon)} \Big(\cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_\perp})} \Big) \Big] \\ & + T_{\perp\perp} h [\cdots] \end{aligned}$$

- U + S cross sections identical to spin-1/2 target

Bacchetta et al. 07

- T cross section has 23 new tensor structure functions specific to spin-1
  4 structure functions survive in inclusive DIS, cf. $b_1 - b_4$

Hoodbhoy, Jaffe, Manohar 88

ϕ-harmonics specific to tensor polarization — new handle

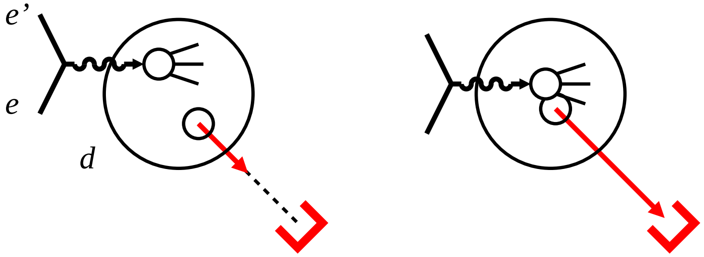
- T-odd structures vanish in impulse approximation,
  provide sensitive tests of FSI

Tagging: Applications and extensions

- Tagged EMC effect

  What momenta/distances in NN interactions cause modification of partonic structure?

  Connection with NN short-range correlations?

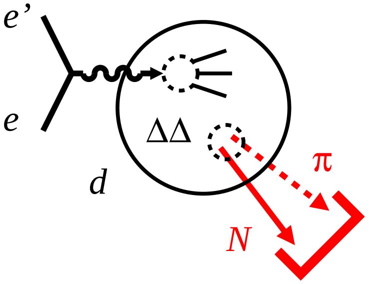


average−size **small−size**

- Tagging Δ isobars

  Tagged DIS $e + d \to e' + \pi + N$, reconstruct Δ from πN

  Δ structure function defined at pole, reached by on-shell extrapolation



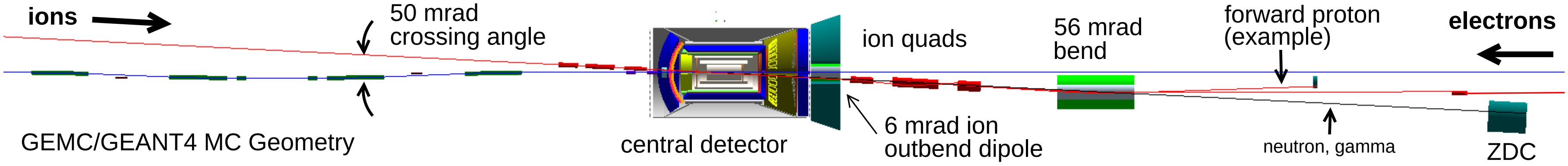
- Tagging with complex nuclei $A > 2$

  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
  Needs input from 3-body Faddeev calculations for structure and breakup. Bochum-Krakow group.

Simulations: Forward detection



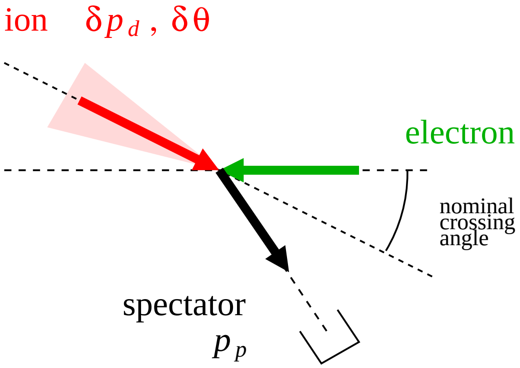
- Forward detector integrated in interaction region and beam optics

  Protons/neutrons/fragments travel through ion beam quadrupole magnets

  Dispersion generated by dipole magnets

  Detection using forward detectors — Roman pots, ZDCs

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



- Intrinsic momentum spread in ion beam

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

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

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

Summary

- Light-ion physics program with EIC has great potential,
  could be developed & articulated at same level as ep and eA(heavy)

- Deuteron and spectator tagging overcome main limiting factor of nuclear DIS:
  Control of nuclear configurations during high-energy process

- Intersection of low-energy nuclear structure and high-energy scattering:
  Need to recruit methods and expertise of nuclear structure community
  Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent U, Belgium [webpage]

Outlook

- Expand theoretical methods for nuclear structure in high-energy scattering:
  EFT interactions, polarization phenomena, $A > 2$

- Interpret results of JLab 12 GeV experiments with nuclei:
  Short-range correlations, EMC effect, tagged DIS
  Or Hen + group (MIT), M. Sargsian (FIU), M. Strikman (PSU), R. Dupre (Orsay), I. Cloet (ANL), ...

- Develop EIC science case through simulations with next-gen physics models
  In collaboration with JLab EIC effort and EIC Center at Stony Brook/BNL (A. Deshpande & group).
  Simulation tools from 2014/15 JLab LDRD project available at [webpage]