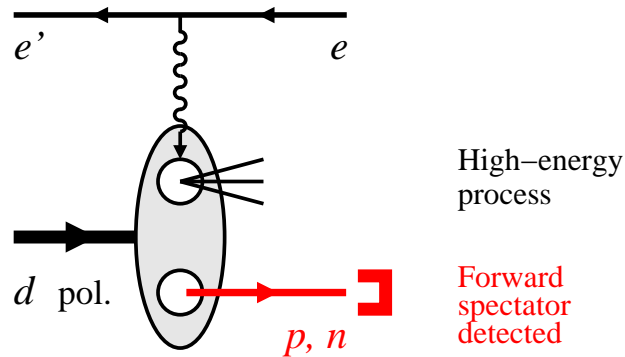


Next-generation nuclear physics with polarized light ions at EIC

C. Weiss (JLab), Theory Seminar, U. Complutense Madrid, 26-Jul-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

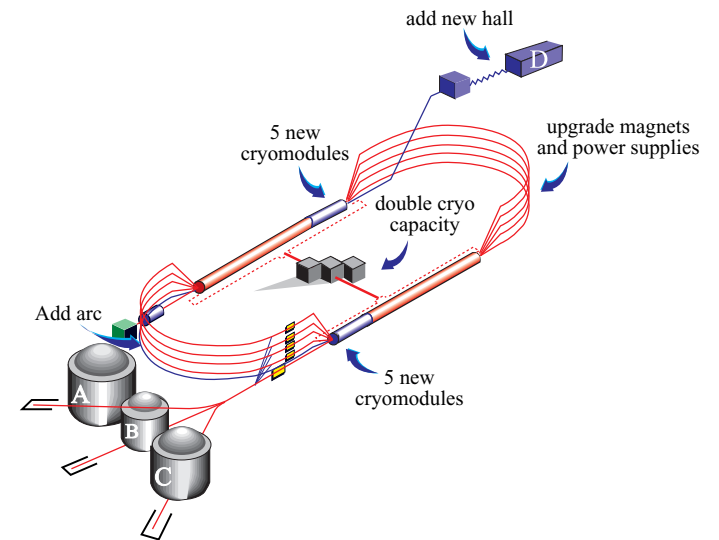
- JLab 12 GeV operations started

Hall A & D first physics results,
Hall C and CLAS12 physics runs

Four-hall operation demonstrated

Expect physics results 5-10 years

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



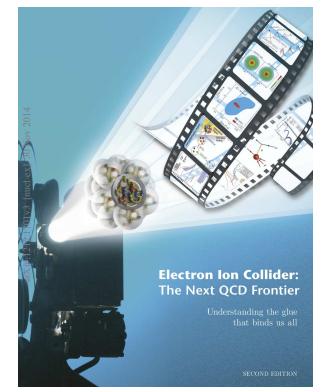
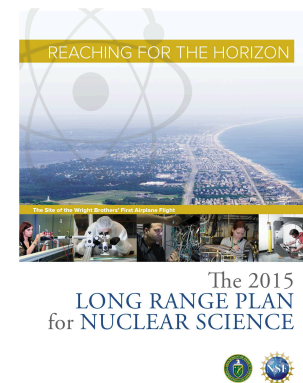
- Electron-Ion Collider as future facility

Recommended in 2015 NSAC Long-Range Plan

Designs by BNL and JLab

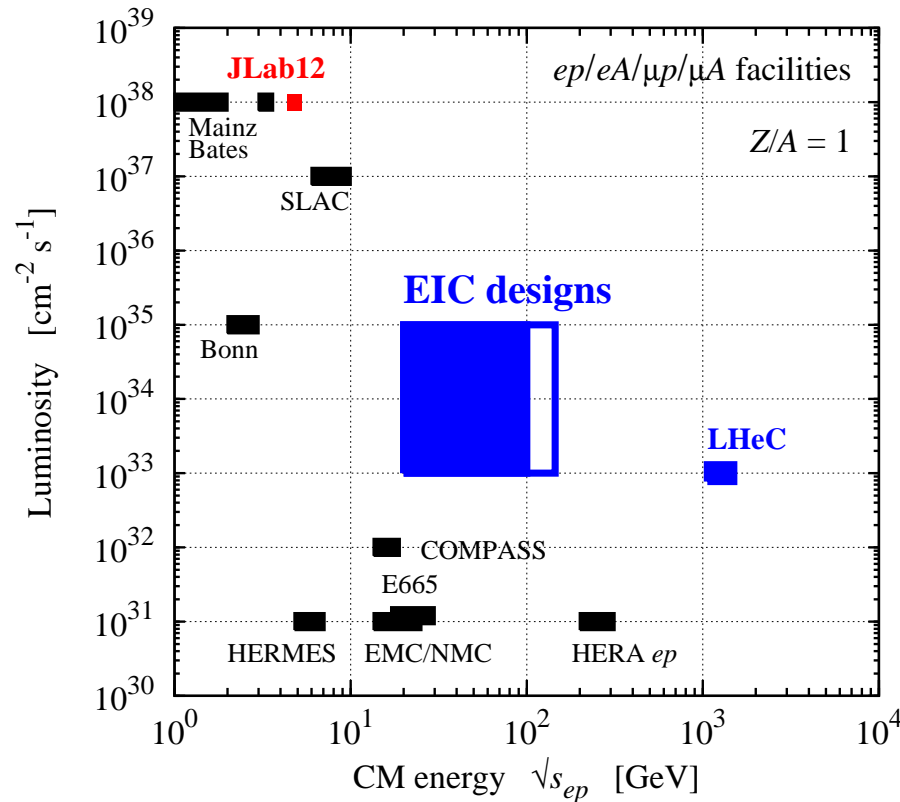
Vigorous accelerator and detector R&D

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 $\sqrt{s_{ep}} \sim 20\text{--}100$ GeV

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

Deep-inelastic scattering at $x \sim 10^{-1}\text{--}10^{-3}$, $Q^2 \lesssim 10^2$ GeV²

- Luminosity $\sim 10^{34}$ cm⁻² s⁻¹

Exceptional configurations in target
Multi-variable final states
Polarization observables

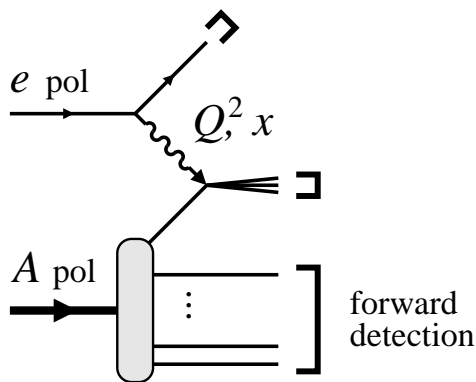
- Polarized protons and light ions

eRHIC: pol ³He

JLEIC: pol *d* and ³He with figure-8

- Forward detection of *p, n, A*

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



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

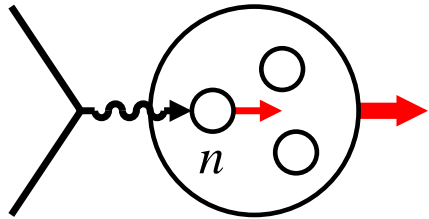
Nuclear quark/gluon densities, NN interactions in QCD
Color transparency and opacity
Nonlinear effects and gluon saturation at small x

III) Emergence of hadrons from color charge

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

...

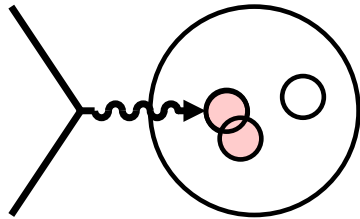
Measurements with $\left\{ \begin{array}{l} ep \\ eA(\text{light}) \\ eA(\text{heavy}) \end{array} \right. \leftarrow \text{this seminar}$



- Neutron structure

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

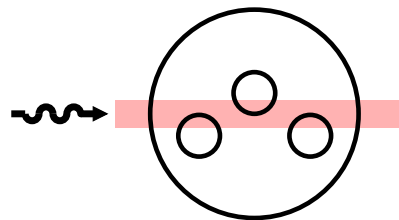
Eliminate nuclear binding, non-nucleonic DOF!



- 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

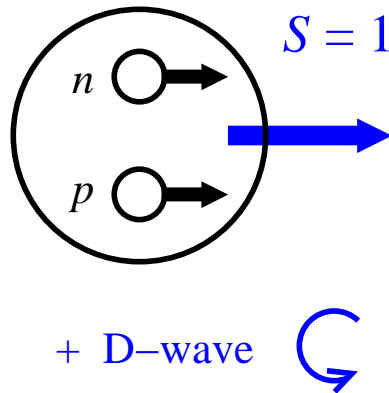
Coherent interaction of high-energy probe
with multiple nucleons, shadowing, saturation

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

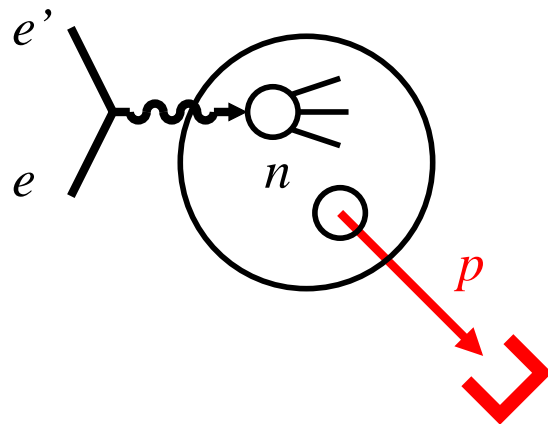


- Polarized deuteron

pn wave function simple, known well
incl. light-front WF for high-energy procs

Neutron spin-polarized

Intrinsic Δ isobars suppressed by Isospin = 0
 $|\text{deuteron}\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$



- Spectator nucleon tagging

Identifies active nucleon

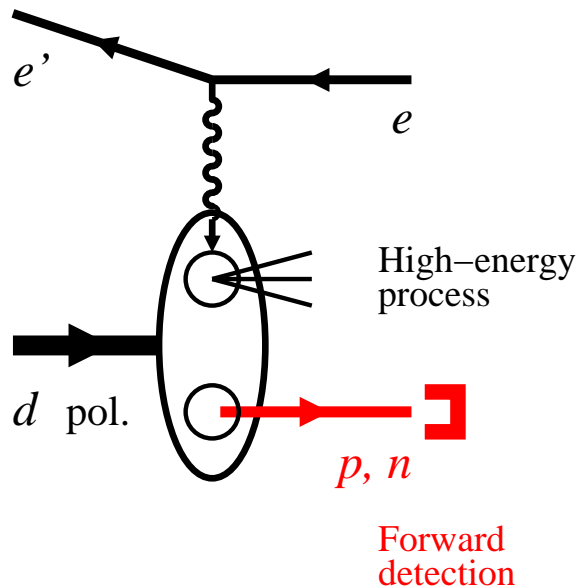
Controls configuration through recoil momentum:
Spatial size, $S \leftrightarrow D$ wave

Tagging in fixed-target experiments

CLAS6/12 BONUS, recoil momenta $p = 70\text{-}150$ MeV

[Nucleus rest frame view]

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, $p_p(\text{restframe}) \rightarrow 0$ possible

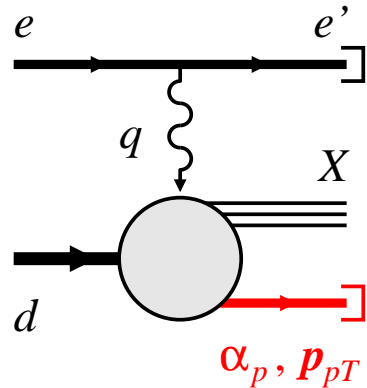
Potentially full acceptance, good resolution

Can be used with polarized deuteron

Forward neutron detection possible

- Unique physics potential

Tagging: Cross section and observables



$$\frac{d\sigma}{dx dQ^2 (d^3 p_p / E_p)} = [\text{flux}] \left[F_{Td}(x, Q^2; \alpha_p, \mathbf{p}_{pT}) + \epsilon F_{Ld}(\dots) \right. \\ \left. + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_p F_{LT,d}(\dots) + \epsilon \cos(2\phi_p) F_{TT,d}(\dots) \right. \\ \left. + \text{spin-dependent structures} \right]$$

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

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

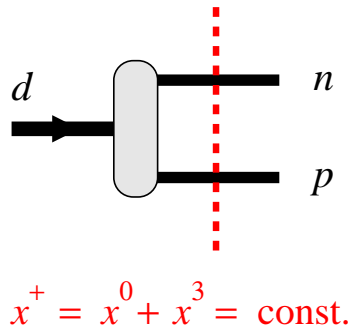
Conditional structure functions

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

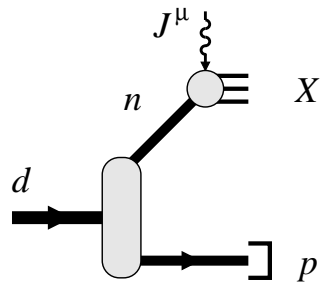
High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 = \text{const.}$

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

Matching nuclear \leftrightarrow nucleonic structure

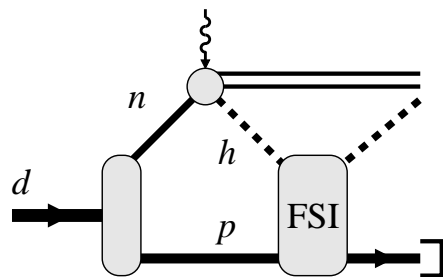
Frankfurt, Strikman 80's

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

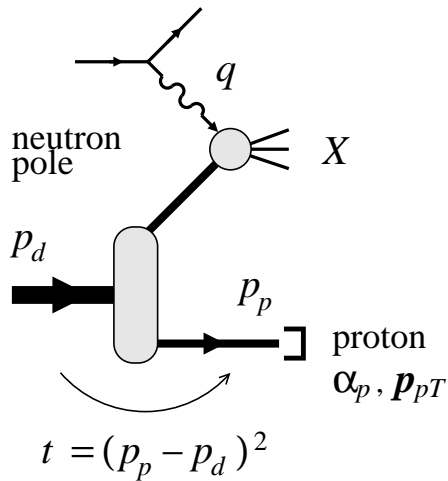


- Composite description

Impulse approximation: DIS final state and spectator nucleon evolve independently



Final-state interactions: Part of DIS final state interacts with spectator, transfers momentum

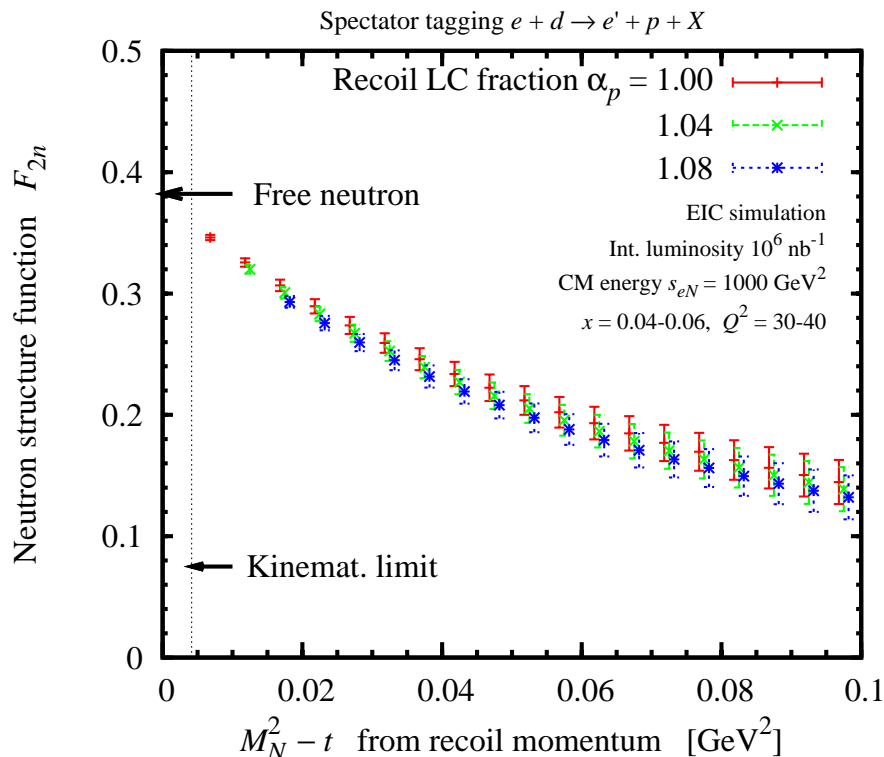


- Extract free neutron structure

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

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

Eliminates nuclear binding effects and FSI [Sargsian, Strikman 05](#)

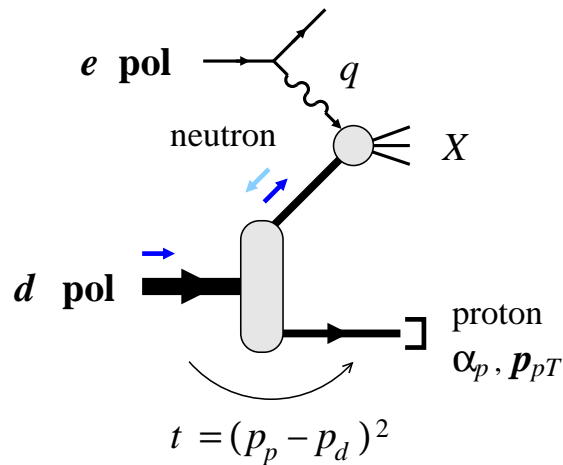


- Precise measurements of F_{2n}

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 $\bar{d} - \bar{u}$



- Neutron spin structure with pol deuteron and proton tagging

On-shell extrapolation of asymmetry

D-wave suppressed at $p_p = 0$:
Neutron 100% polarized

- Systematic uncertainties cancel

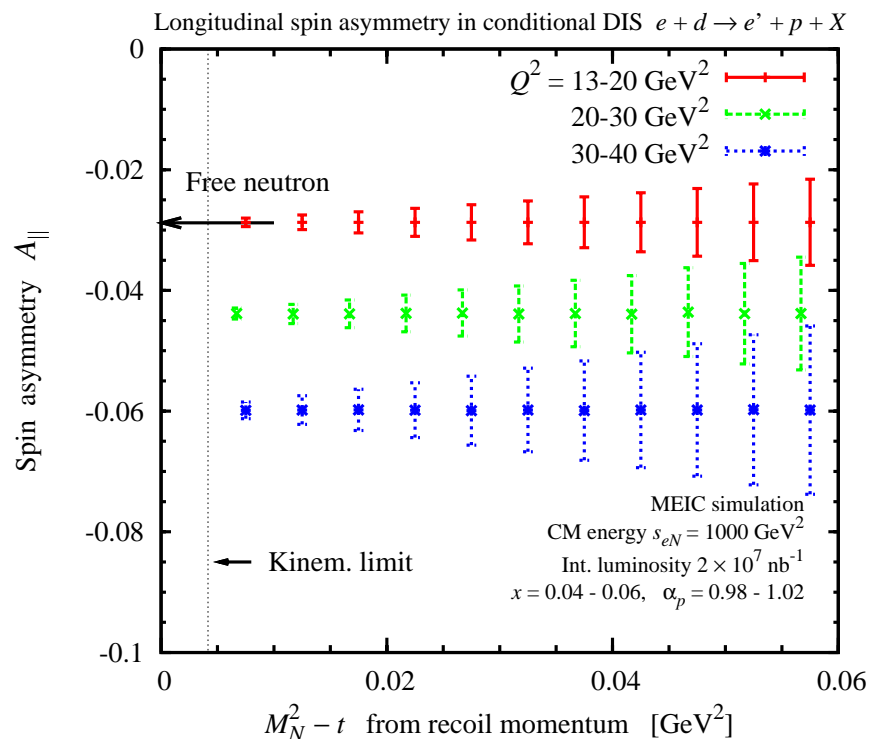
Weak off-shell dependence of asymmetry

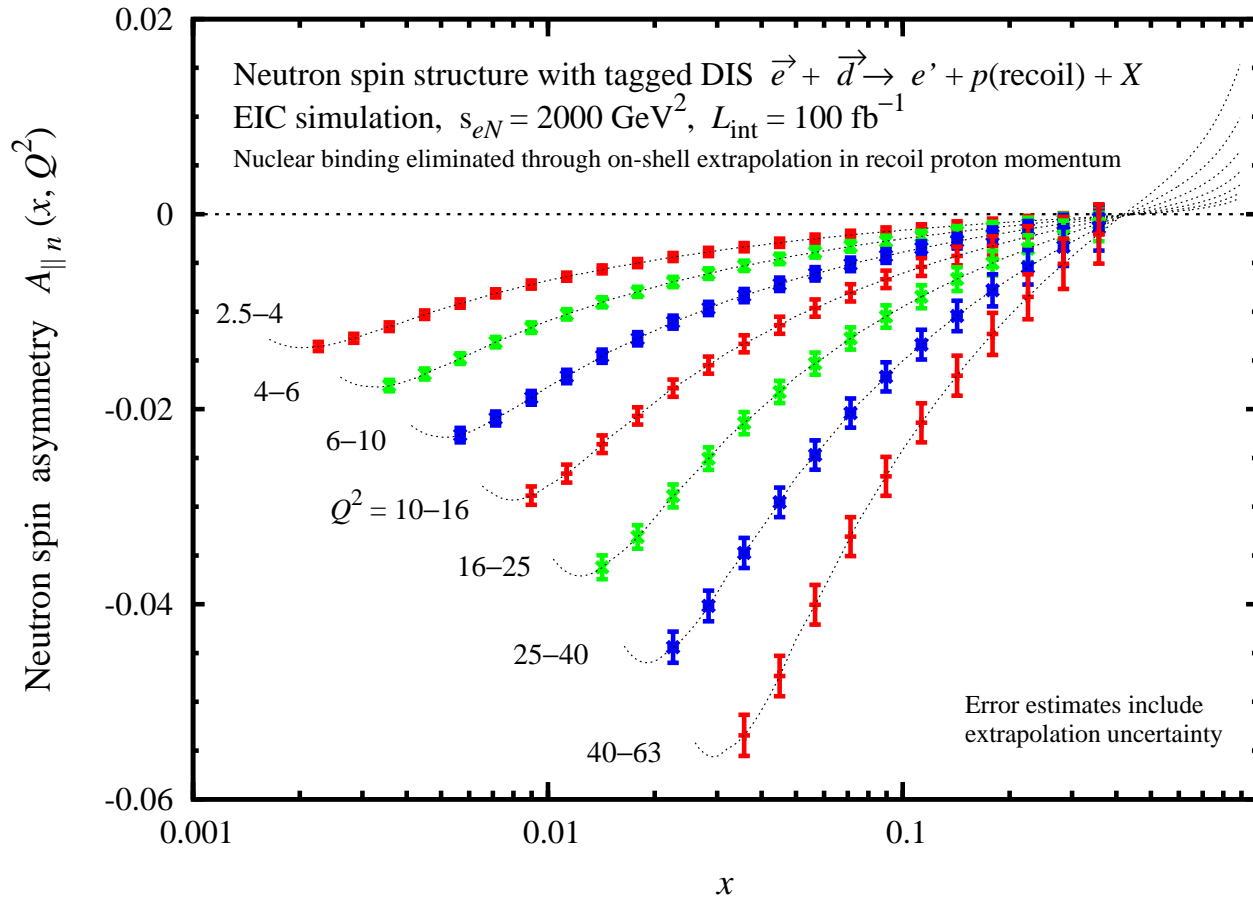
Momentum smearing/resolution effects largely cancel in asymmetry

- Statistics requirements

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

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





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

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

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

depolarization factor

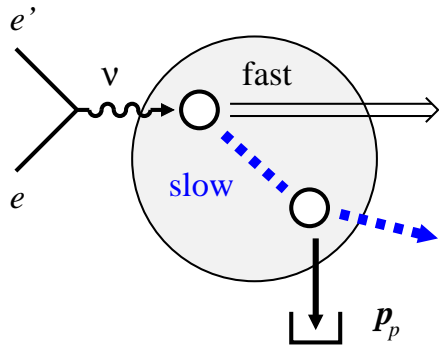
$$y = \frac{Q^2}{xs_{eN}}$$

- 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



- 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” $E_h = O(\mu_{\text{had}}) \sim 1 \text{ GeV}$

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

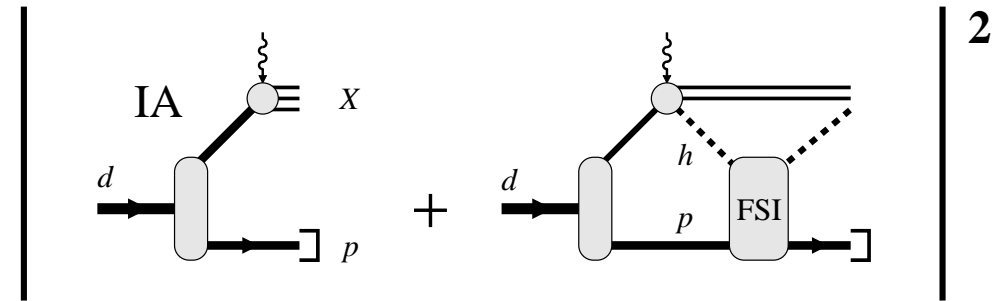
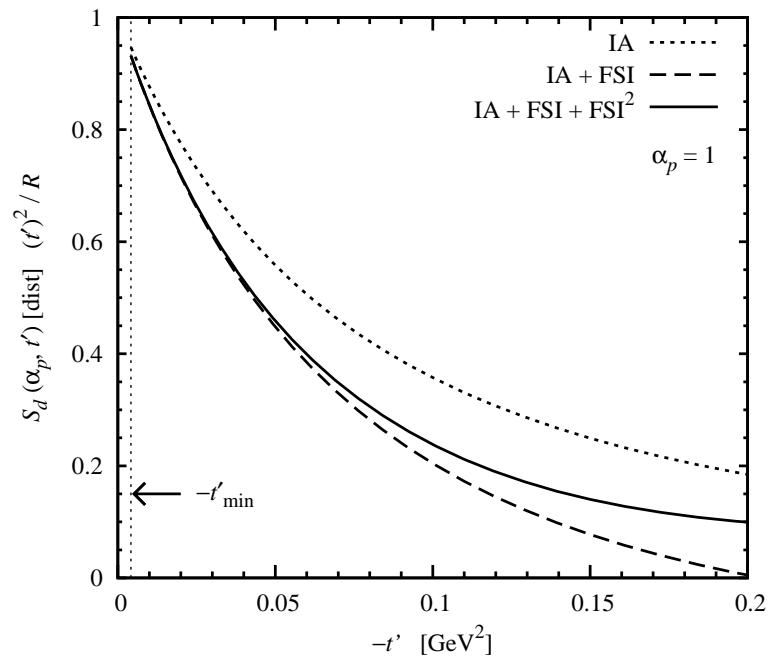
Experimental slow hadron multiplicity distributions

Cornell, EMC, HERA

Hadron-nucleon low-energy scattering amplitudes

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

Frankfurt, Strikman 81



Strikman, CW 18

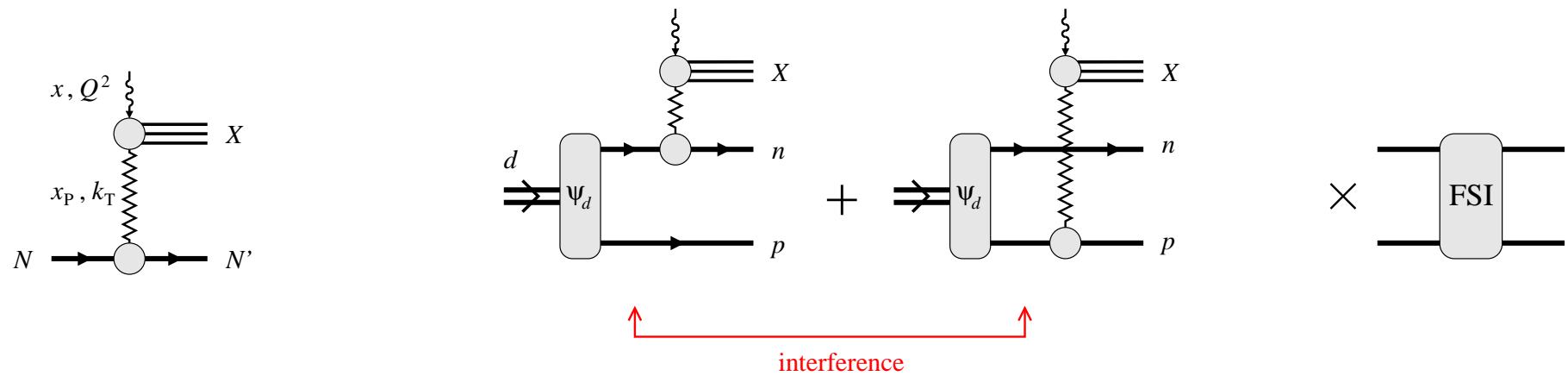
- FSI reduces IA cross section at $|t - M_N^2| \neq 0$ ($\lesssim 0.2 \text{ GeV}^2$)
- FSI vanishes at $t - M_N^2 \rightarrow 0$; on-shell extrapolation not affected
- [• Other interesting aspects

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

Analogy with FSI in quasi-elastic deuteron breakup

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

Tagging: Diffraction and shadowing



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

Nucleon remains intact, recoils with $k \sim \text{few } 100 \text{ MeV}$ (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.

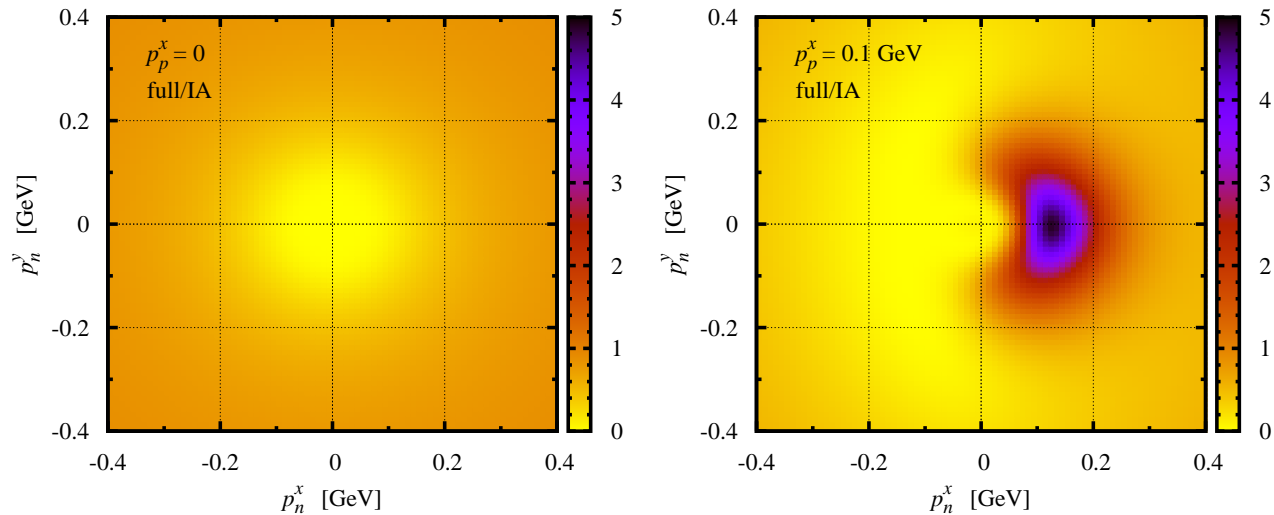
[Frankfurt, Strikman, Guzey 12](#). Great interest. Hints seen in J/ψ production in UPCs at LHC ALICE.

- 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](#)



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

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

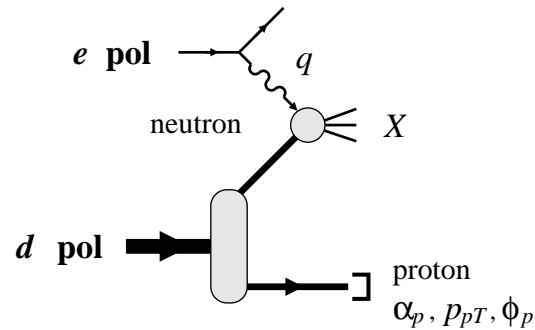
Large FSI effects due to orthogonality

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

$$\frac{d\sigma}{dx dQ^2 (d^3p_p / E_p)} = [\text{flux}] (F_U + F_S + F_T) \quad F_I = \text{functions}(x, Q^2, \alpha_p, p_{pT}, \phi_p)$$

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

$$F_S = S_L \left[\sqrt{2\epsilon(1+\epsilon)} \sin \phi_h F_{US_L}^{\sin \phi_h} + \epsilon \sin 2\phi_h F_{US_L}^{\sin 2\phi_h} \right]$$

$$+ S_L h \left[\sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)} \cos \phi_h F_{LS_L}^{\cos \phi_h} \right]$$

$$+ S_{\perp} \left[\sin(\phi_h - \phi_S) \left(F_{UST,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UST,L}^{\sin(\phi_h - \phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{UST}^{\sin(\phi_h + \phi_S)} \right]$$

$$+ \epsilon \sin(3\phi_h - \phi_S) F_{UST}^{\sin(3\phi_h - \phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left(\sin \phi_S F_{UST}^{\sin \phi_S} + \sin(2\phi_h - \phi_S) F_{UST}^{\sin(2\phi_h - \phi_S)} \right) \Big]$$

$$+ S_{\perp} h \left[\sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LS_T}^{\cos(\phi_h - \phi_S)} + \right.$$

$$\left. \sqrt{2\epsilon(1-\epsilon)} \left(\cos \phi_S F_{LS_T}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h - \phi_S)} \right) \right],$$

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

- 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

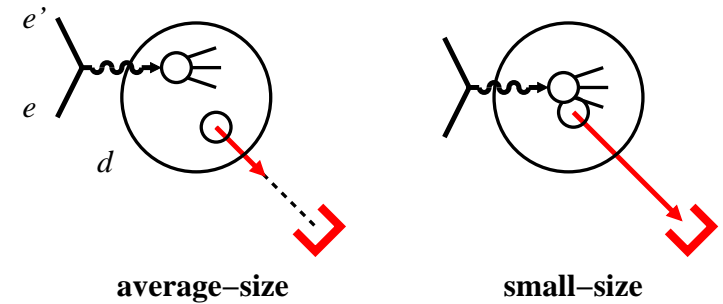
ϕ -harmonics specific to tensor polarization — new handle

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

- Tagged EMC effect

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

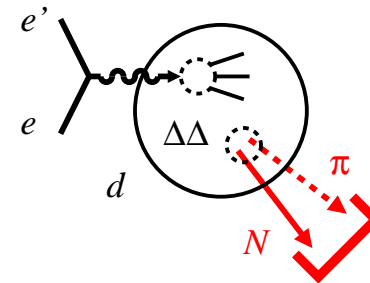
Connection with NN short-range correlations?



- Tagging Δ isobars

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

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



- Tagging with complex nuclei $A > 2$

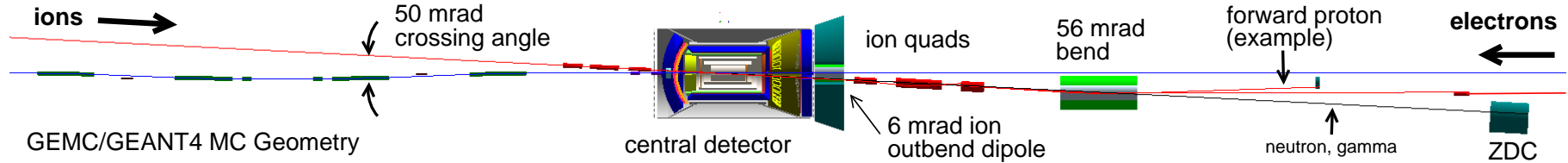
Could test isospin dependence and/or universality of bound nucleon structure

$(A - 1)$ ground state recoil, e.g. ${}^3\text{He} (e, e' d) X$

[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.](#)



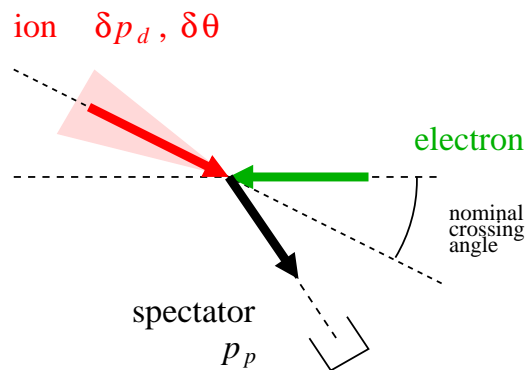
- Forward detector integrated in interaction region and beam optics

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

Dominant systematic uncertainty in tagged neutron structure measurements. Correlated, x and Q^2 -independent. [JLab LDRD](#)

- 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 \[webpage\]](#)