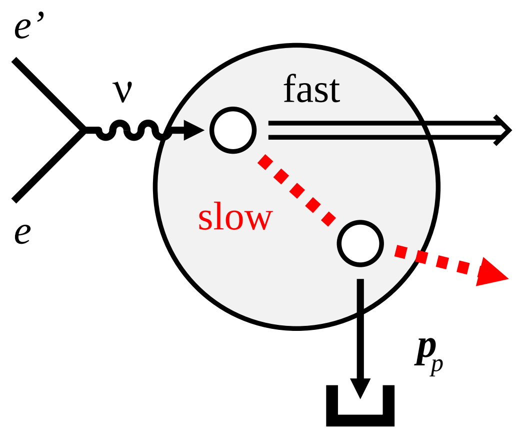
DIS on the deuteron with spectator tagging: Theory, applications, simulations for EIC

C. Weiss (JLab), Short-range nuclear corrleations at EIC, CFNS BNL, 07-Sep-2018

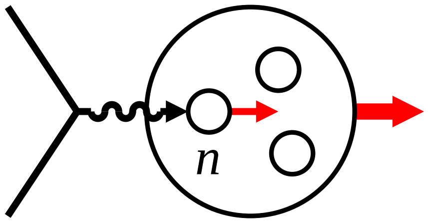


EIC simulations: JLab 2014/15 LDRD
W. Cosyn, V. Guzey, D. Higinbotham, Ch. Hyde, K. Park, P. Nadel-Turonski, M. Sargsian, M. Strikman, C. Weiss∗ [Webpage]

Theory: Continuing effort
Strikman, Weiss, PRC97 (2018) 035209 [INSP] + in preparation

- Light-ion phyiscs with EIC
  - Objectives and challenges
- Deuteron and spectator tagging
  - Theoretical framework
  - Free neutron from on-shell extrapolation
- Final-state interactions
  - Physical picture
  - Momentum and angular dependence
- Applications and extensions
  - Diffractive DIS at $x \ll 0.1$
  - Tensor polarized deuteron, Δ isobars, . . .

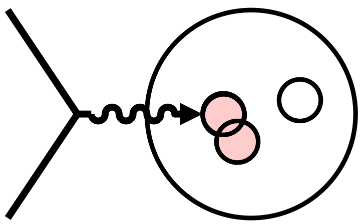
Light ions: Physics objectives



- Neutron structure

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

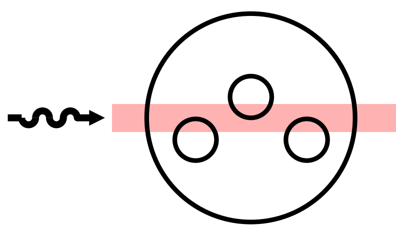
  Eliminate nuclear binding, non-nucleonic DOF!



- 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

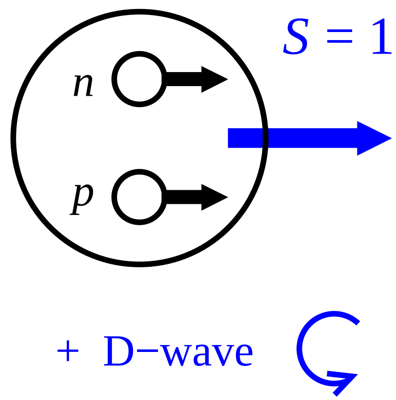
  Coherent interaction of high–energy probe
  with multiple nucleons, shadowing, saturation

  Identify coherent response!

[Nucleus rest frame view]

Common challenge: Many possible nuclear
configurations during high-energy process.
Need to "control" configurations!

Light ions: Deuteron, spectator tagging

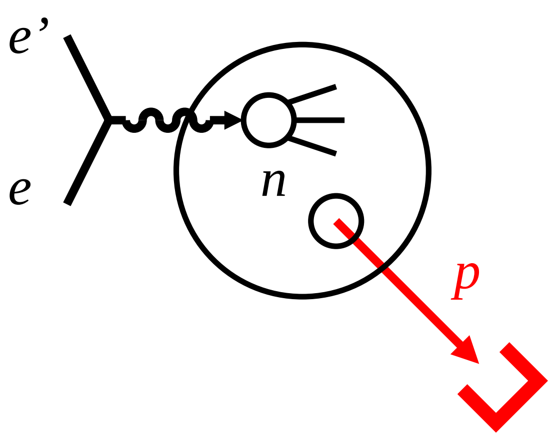


- Polarized deuteron

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

  Neutron spin–polarized

  Intrinsic Δ isobars suppressed by isospin $= 0$
  $|\text{deuteron}\rangle = |pn\rangle + \epsilon|\Delta\Delta\rangle$ negligible
  3He spin structure distorted by Δ's. Guzey, Strikman, Thomas et al 01



[Nucleus rest frame view]

- Spectator nucleon tagging

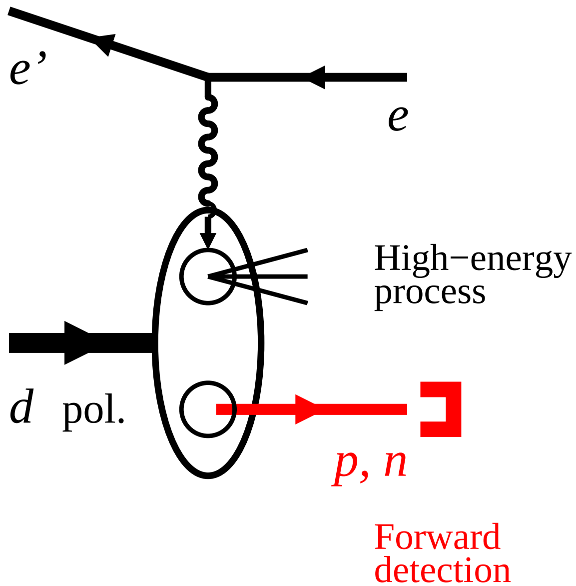
  Identifies active nucleon

  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
  ALERT, JLab Hall A $\rightarrow$ Talks Weinstein, Dupre

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

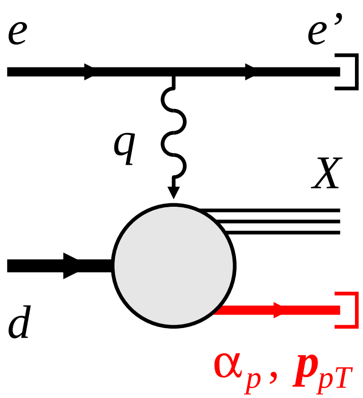
  Potentially full acceptance, good resolution

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

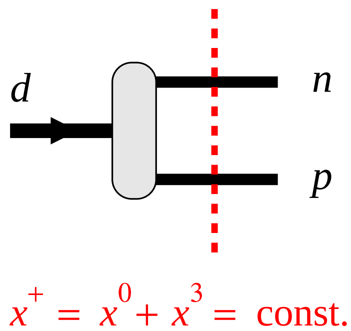
Proton recoil momentum $p_p^+ = E_p + p_p^z$, $\boldsymbol{p}_{pT}$,
light-front momentum fraction $p_p^+ = \alpha_p p_d^+/2$,
simply related to $\boldsymbol{p}_p$(restframe)

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



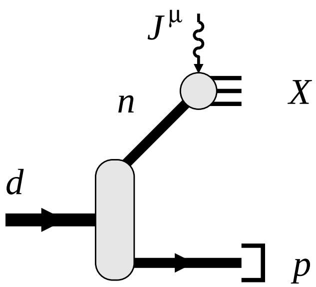
- Light-front quantization → Talks Strikman, Miller

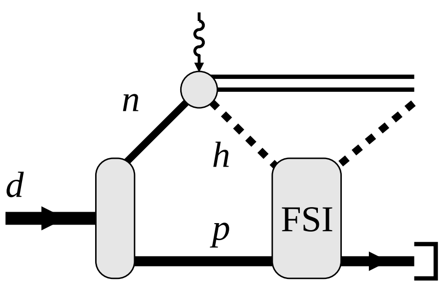
  High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 = \text{const.}$

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

  Permits matching nuclear ↔ nucleonic structure
  Conserves LF momentum, baryon number
  Frankfurt, Strikman 80's

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



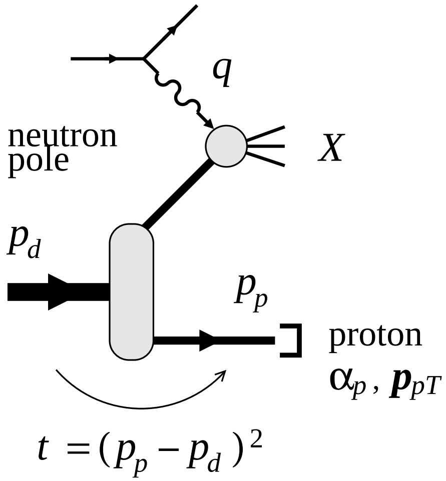


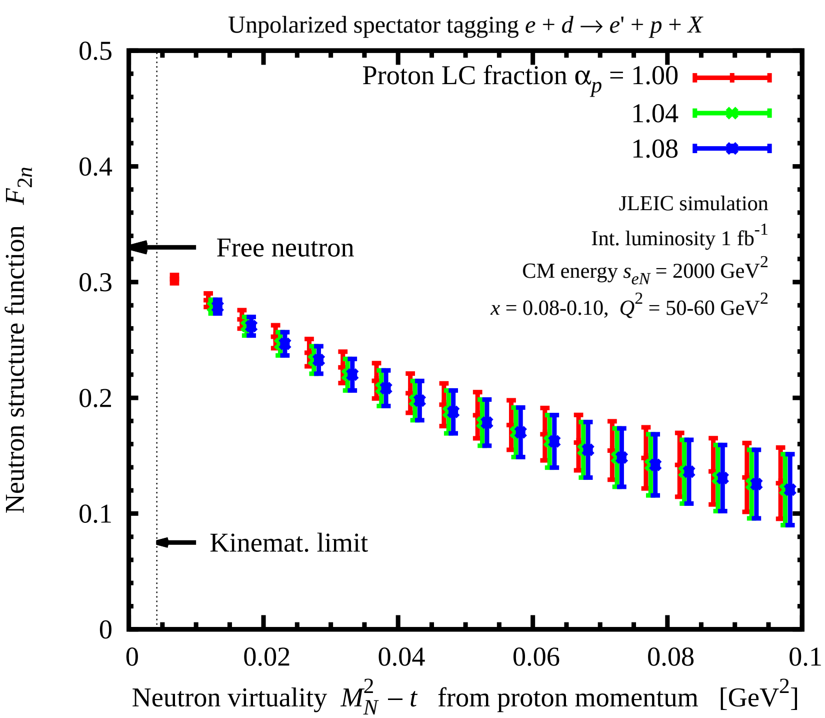
- Composite description

  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 neutron virtuality
  $t - M_N^2 = -2|\boldsymbol{p}_p(\text{rest})|^2 + t_{\text{min}}$

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

  Eliminates nuclear binding effects
  and FSI Sargsian, Strikman 05

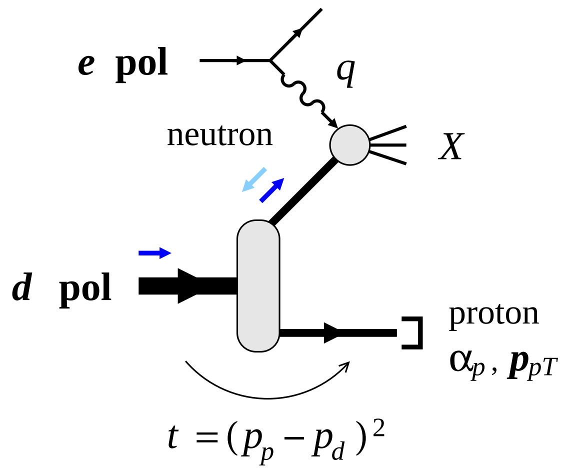
- Precise measurements of F_{2n}

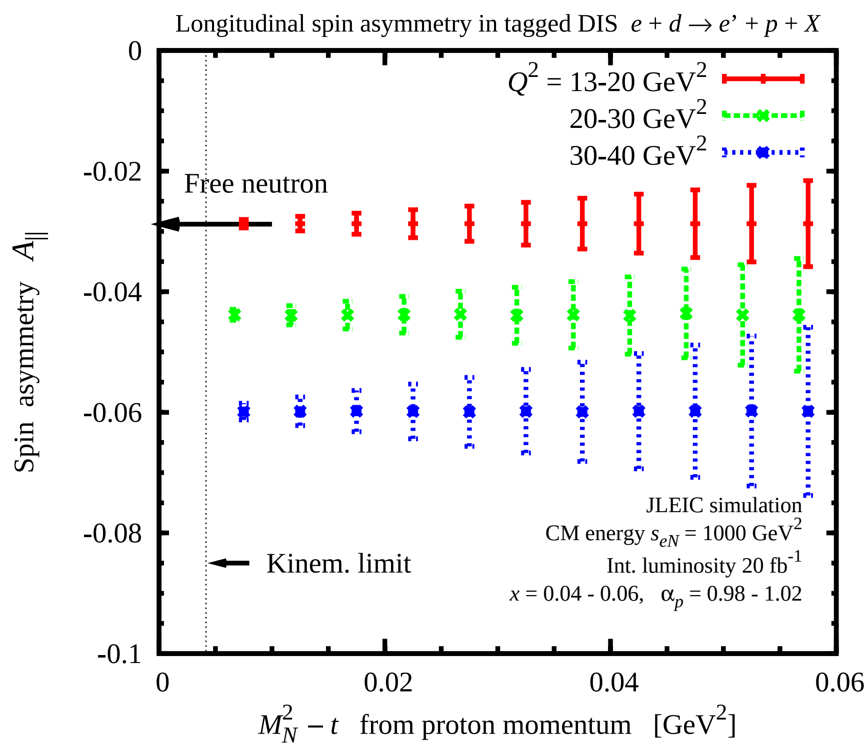
  F_{2n} extracted with few-percent
  accuracy at $x \gtrsim 0.1$

  Uncertainty mainly systematic
  LDRD project: 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 $\boldsymbol{p}_p(\mathrm{rest}) = 0$: Neutron 100% polarized

- Systematic uncertainties cancel

  Weak off-shell dependence of asymmetry

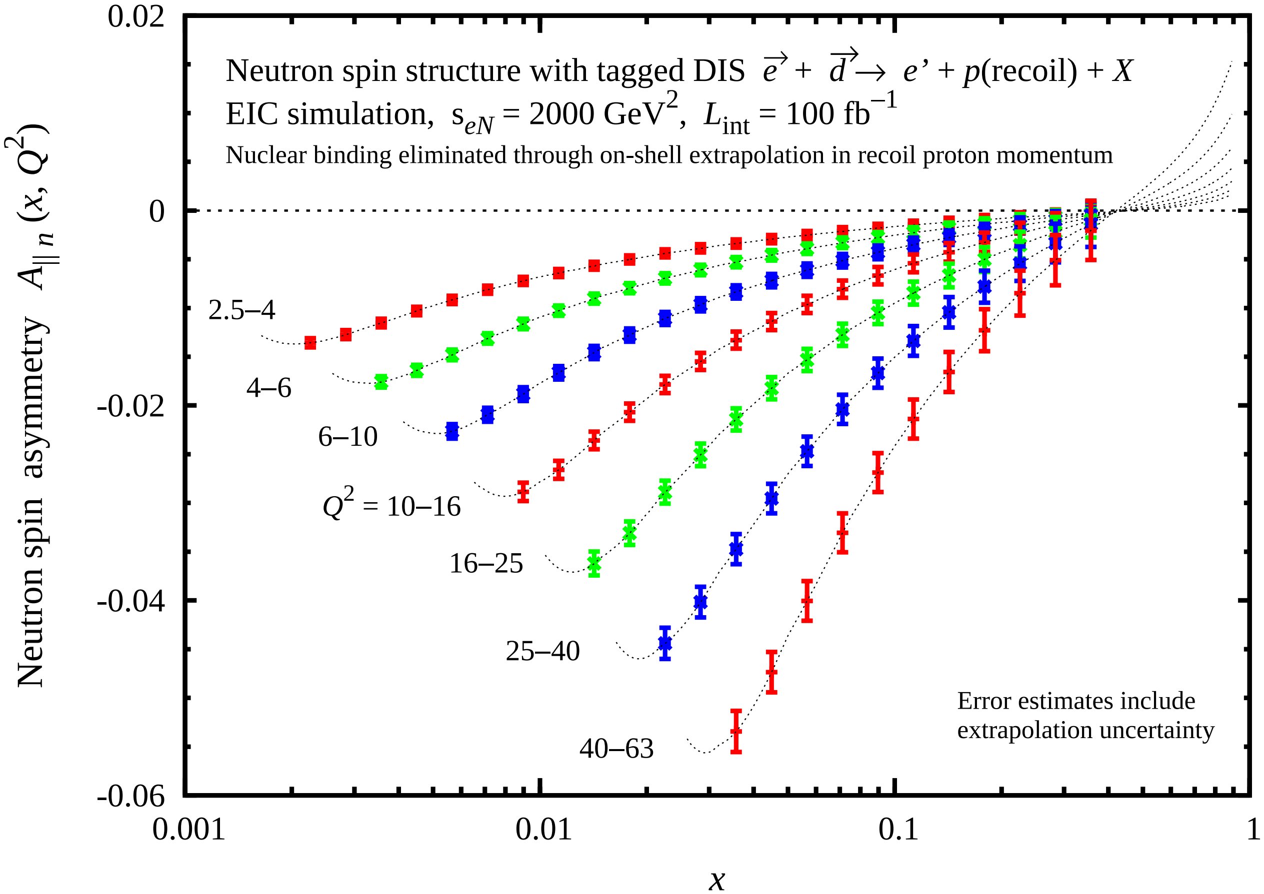
  Momentum smearing/resolution effects largely cancel in asymmetry

- Statistics requirements

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

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

Tagging: Neutron spin 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

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

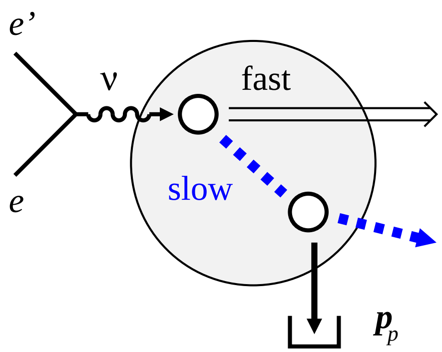
- Precise measurement of neutron spin structure

  Wide kinematic range: Leading $\leftrightarrow$ 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

FSI: Physical picture



- 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, cf. factorization

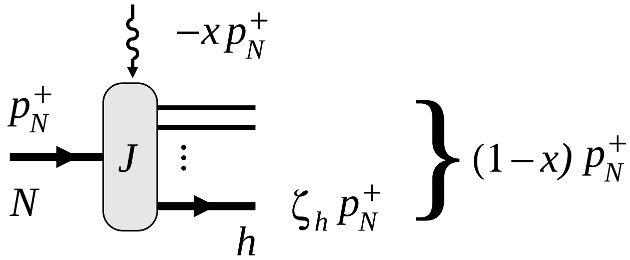
- FSI effects calculated $x \sim 0.1$–0.5 Strikman, CW, PRC97 (2018) 035209

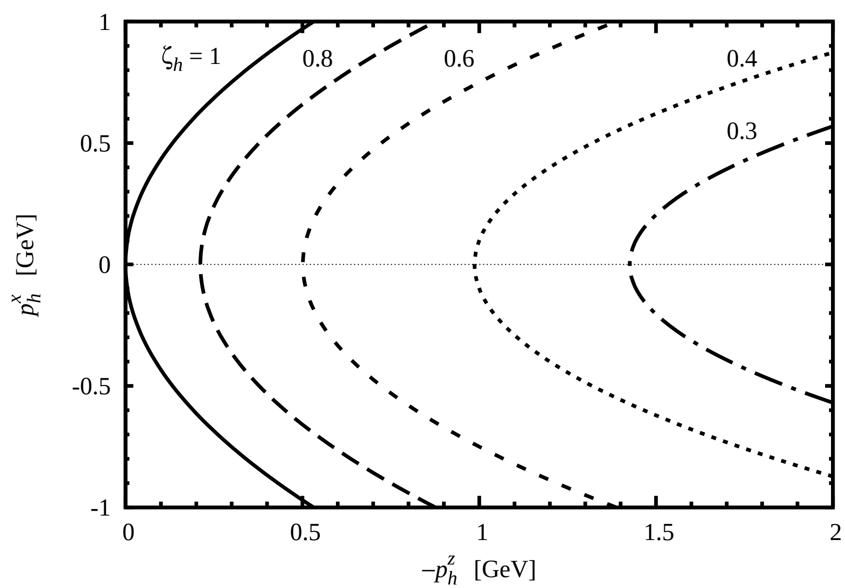
  Experimental slow-hadron multiplicity distributions Cornell, EMC, HERA

  Hadron-nucleon low-energy scattering amplitudes

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

FSI: Slow hadrons from nucleon fragmentation





- Kinematic variables

  $\zeta_h, \boldsymbol{p}_{hT}$ hadron LC mom $\zeta_h \leftrightarrow x_\mathrm{F}$

  Slow hadrons in rest frame have $\zeta_h \sim 1$

  $\zeta_h < 1 - x$ kinematic limit

- Momentum distribution in rest frame

  Cone opening in virtual photon direction

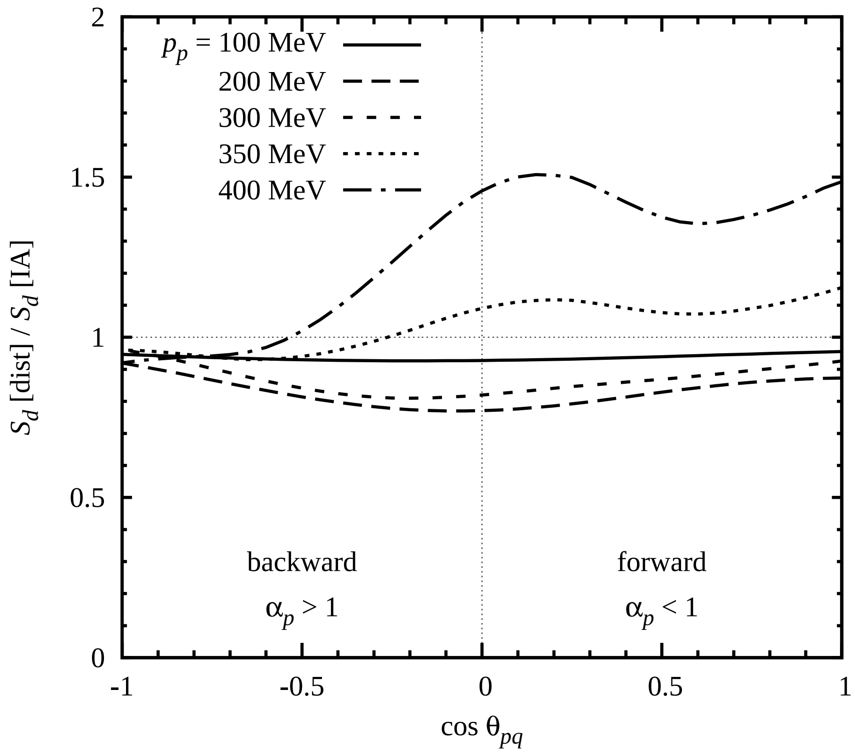
  No backward movers if $h =$ nucleon

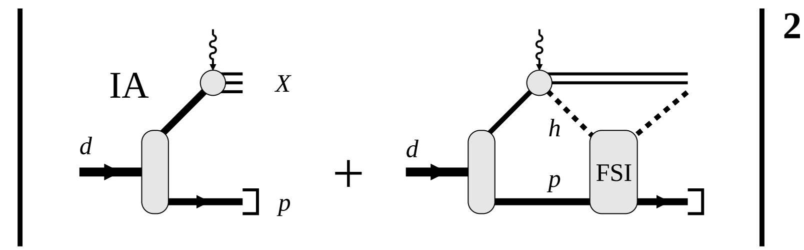
- Experimental data

  HERA $x < 0.01$: x_F distns of p, n, scaling
  Cornell $x > 0.1$: Momentum distns of p, π
  Neutrino DIS data $x \sim 0.1$

  EIC should measure nucleon fragmentation!
  Nucleon structure physics (fracture fns),
  input for nuclear FSI

FSI: Momentum and angular dependence





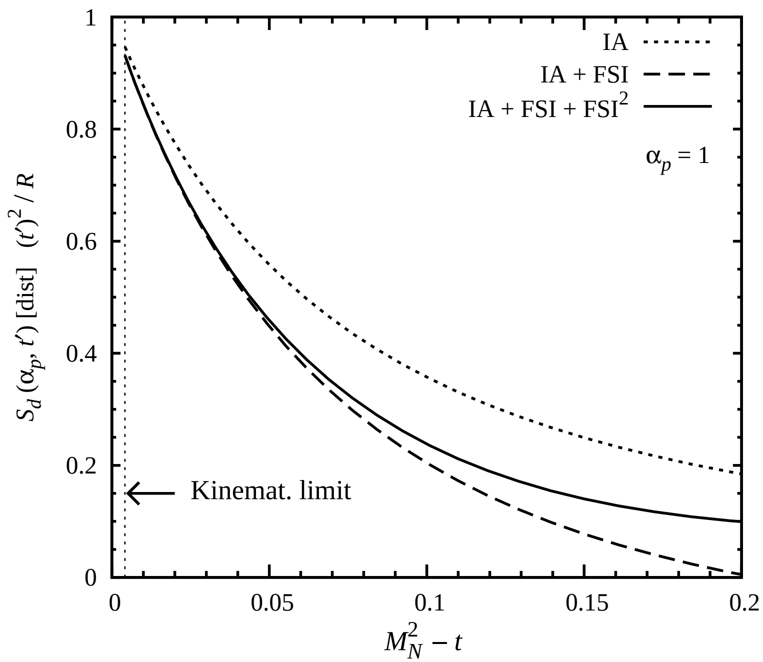
Strikman, CW 18

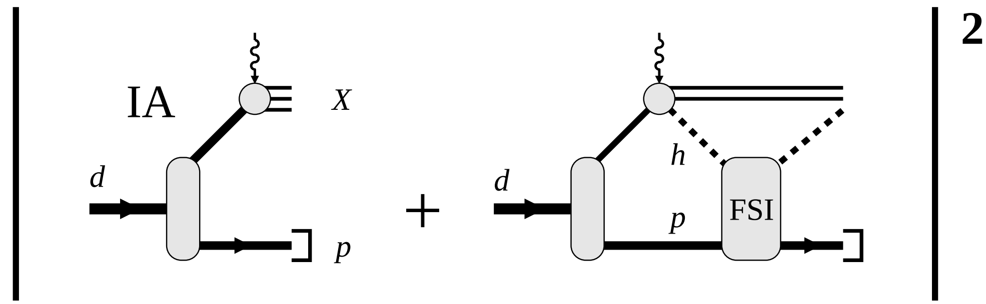
- Momentum and angular dependence in rest frame

$p_p < 300$ MeV	IA $\times$ FSI interference, absorptive, weak angular dependence
$p_p > 300$ MeV	$\|\text{IA}\|^2$, refractive, strong angular dependence

Similar dependence observed in quasi-elastic $e + d \to e' + n + p$

FSI: Effect on on-shell extrapolation





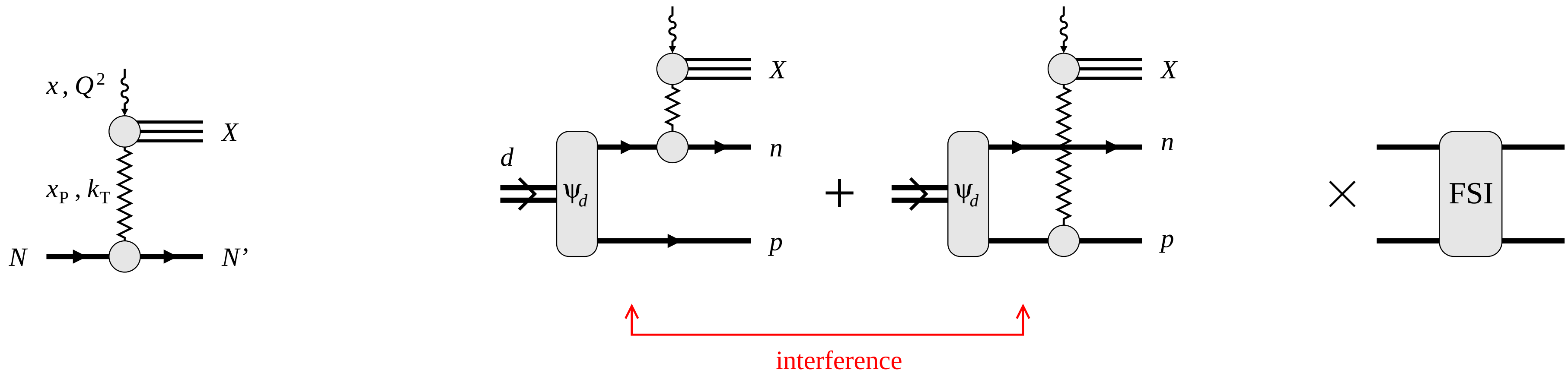
Strikman, CW 18

- 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

FSI: Large x

- FSI suppressed for $x \to 1$: Minimum momentum of "slow" hadrons grows
  FSI in subasymptotic regime, higher-twist: Cosyn, Sargsian 2010+

FSI: Diffraction at small x



- 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

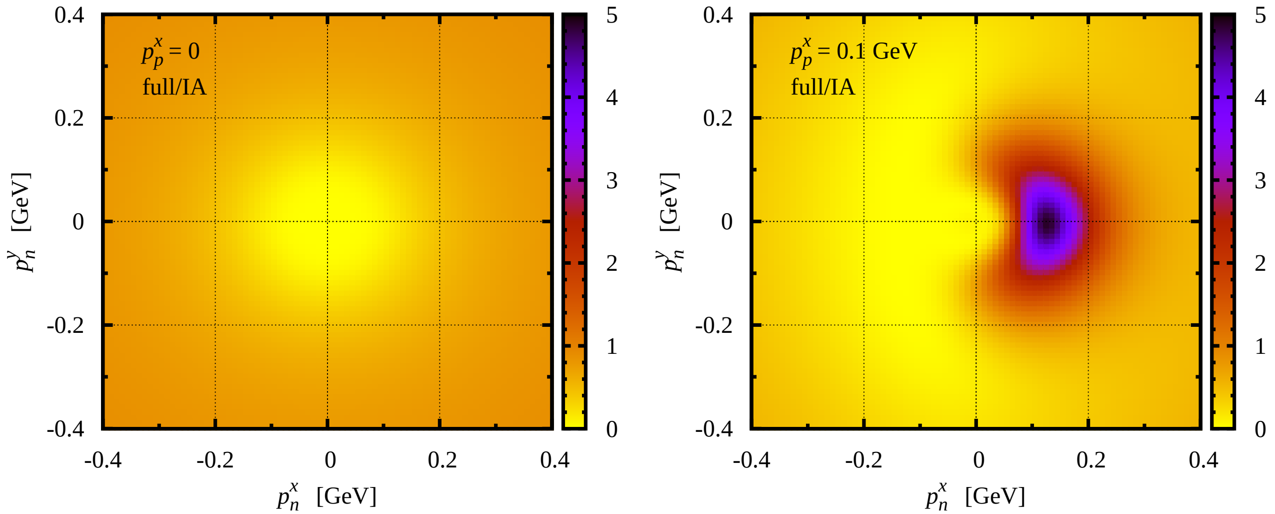
  Reduction of cross section compared to IA — shadowing. Leading-twist effect.
  Frankfurt, Strikman, Guzey 12. Great interest. Hints seen in J/ψ production in UPCs at LHC ALICE.

- 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

FSI: Diffraction at small x



$$R = \frac{d\sigma(\text{full})}{d\sigma(\text{IA})}$$ 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

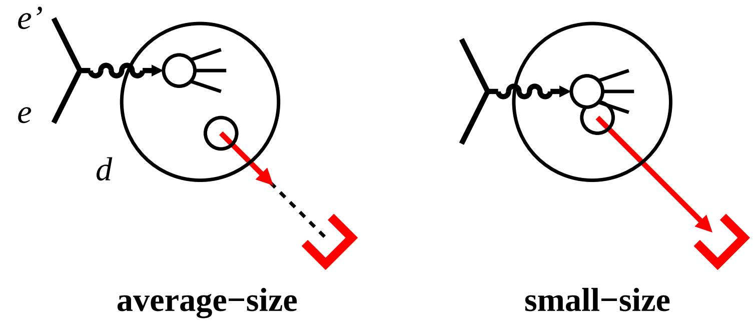
Tagging: Applications and extensions

- Tagged EMC effect

  What momenta/distances cause modification?

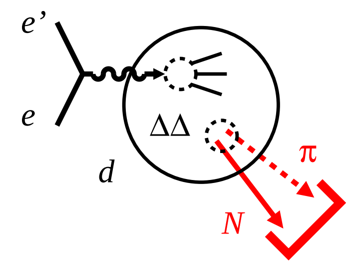
  Connection with NN short-range correlations?

  FSI effects large — need theory, data



- Tagging Δ isobars

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



- Tagging with tensor-polarized deuteron

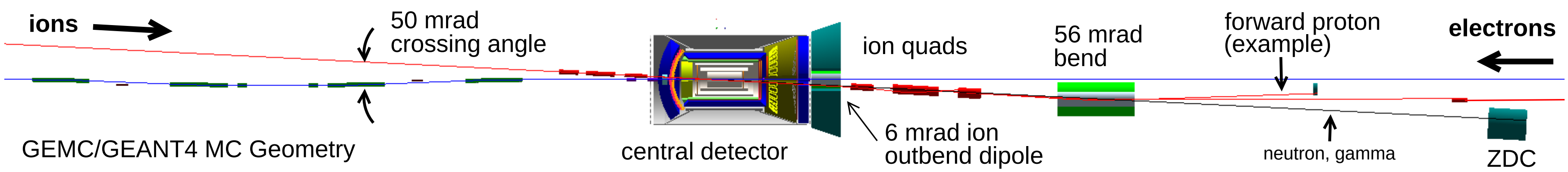
  ϕ harmonics specific to tensor polarization Cosyn, Sargsian, CW; in progress

- Tagging with complex nuclei $A > 2$

  Test isospin dependence and/or universality of bound nucleon structure $\rightarrow$ Talk Dupre

  $(A - 1)$ 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

EIC simulations: Forward detection



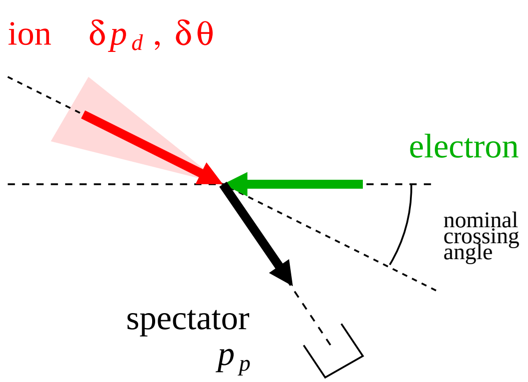
- Forward detector integrated in IR and beam optics → Talks Lee, Baker

  Protons/neutrons/fragments travel through ion beam quadrupole magnets

  Dispersion generated by dipole magnets

  Detection using forward detectors — Roman pots, ZDCs

  Tagging studies: 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 $\boldsymbol{p}_{pT}(\text{vertex}) \neq \boldsymbol{p}_{pT}(\text{measured})$, partly corrected by convolution

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

Summary

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

  Free neutron structure from on-shell extrapolation
  JLab 2014/15 LDRD Project [Webpage]

- FSI between spectator and slow hadrons produced in nucleon fragmentation

  Respects QCD factorization theorem for target fragmentation

  Modifies momentum distribution, preserves total cross section

  Vanishes at on-shell point

  Produces sizable effects for recoil momenta $p_p \sim$ few 100 MeV

- Extension to $A > 2$ light ions requires nuclear structure input

  Light-front momentum distributions, spectral functions, decay functions

  Correspondence light-front $\leftrightarrow$ nonrelativistic structure
  Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent U, Belgium [Webpage]

- Ready for simulations with next-level physics and detector models