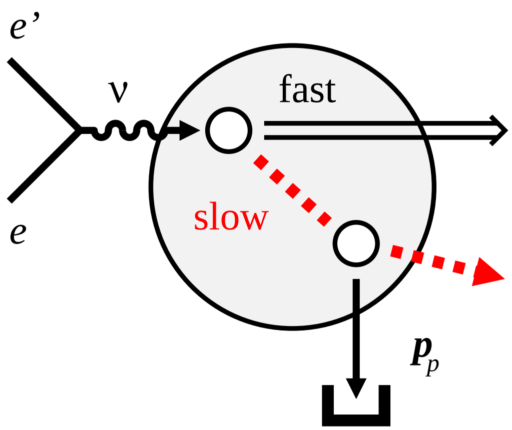
# Nuclear final-state interactions in tagged deuteron DIS at EIC

C. Weiss (JLab), 2018 EIC User Group Meeting, Catholic U., 31-Jul-2018




- Tagged deuteron DIS

  DIS in controled nuclear configurations

  On-shell extrapolation

- Final-state interactions

  Slow hadrons from nucleon fragmentation

  Interactions with spectator

  Momentum and angular dependence

- Extensions

  Diffraction at $x \ll 0.1$

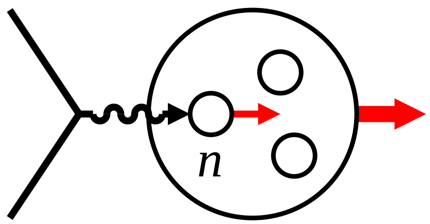
  FSI in tagged DIS at $x \to 1$

**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 ions: Physics objectives

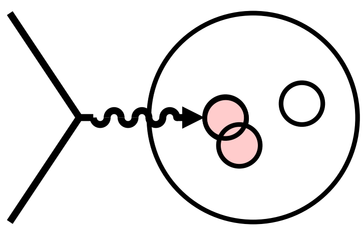





- Neutron structure

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

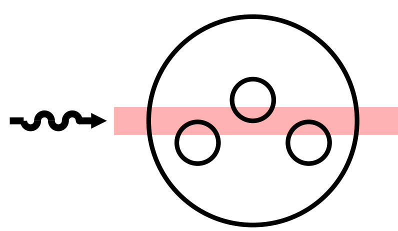
  Eliminate nuclear binding, non-nucleonic DOF!



- 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

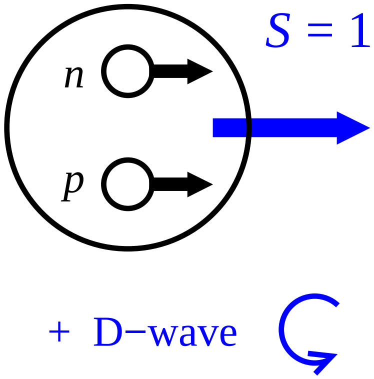
  Identify coherent response!

[Nucleus rest frame view]

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

# Light ions: Deuteron, spectator tagging



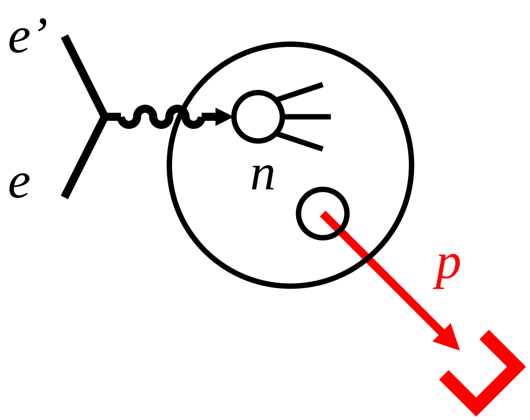



- Polarized deuteron

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

  Neutron spin–polarized

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




- Spectator nucleon tagging

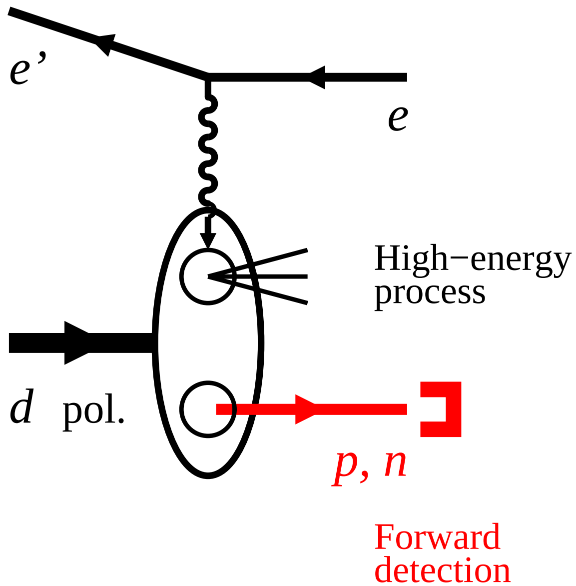
  Identifies active nucleon

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

  Tagging in fixed-target experiments
  CLAS6/12 BONUS, recoil momenta $p$ = 70-150 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, $\boldsymbol{p}_p(\text{restframe}) \rightarrow 0$ possible

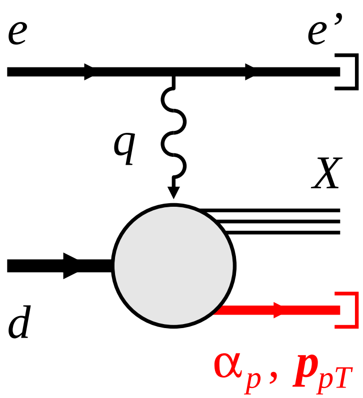
  Potentially full acceptance, good resolution

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

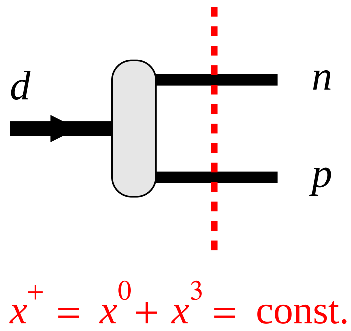
Proton recoil momentum $p_p^+ = E_p + p_p^z$, $\boldsymbol{p}_{pT}$,
light-front momentum fraction $p_p^+ = \alpha_p p_d^+/2$,
simply related to $\boldsymbol{p}_p$(restframe)

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 



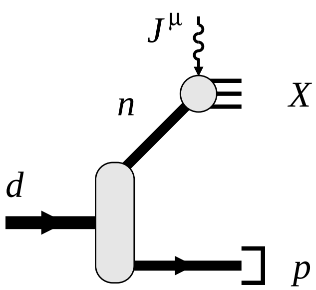

- Light-front quantization

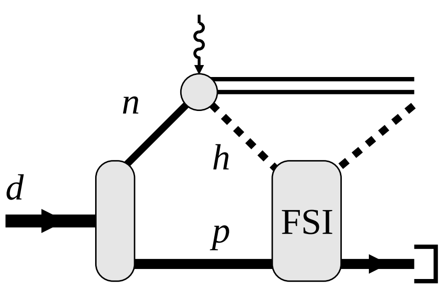
  High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 =$ const.

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

  Matching nuclear $\leftrightarrow$ nucleonic structure
  Frankfurt, Strikman 80's

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



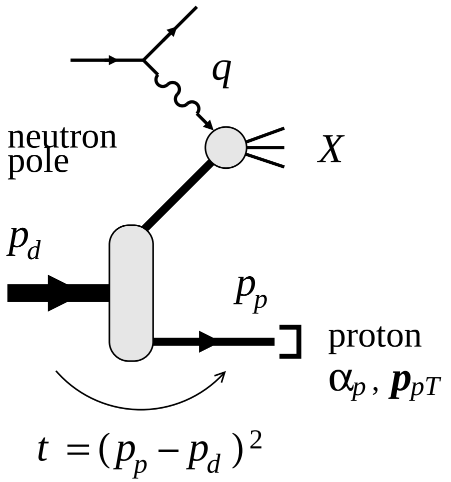



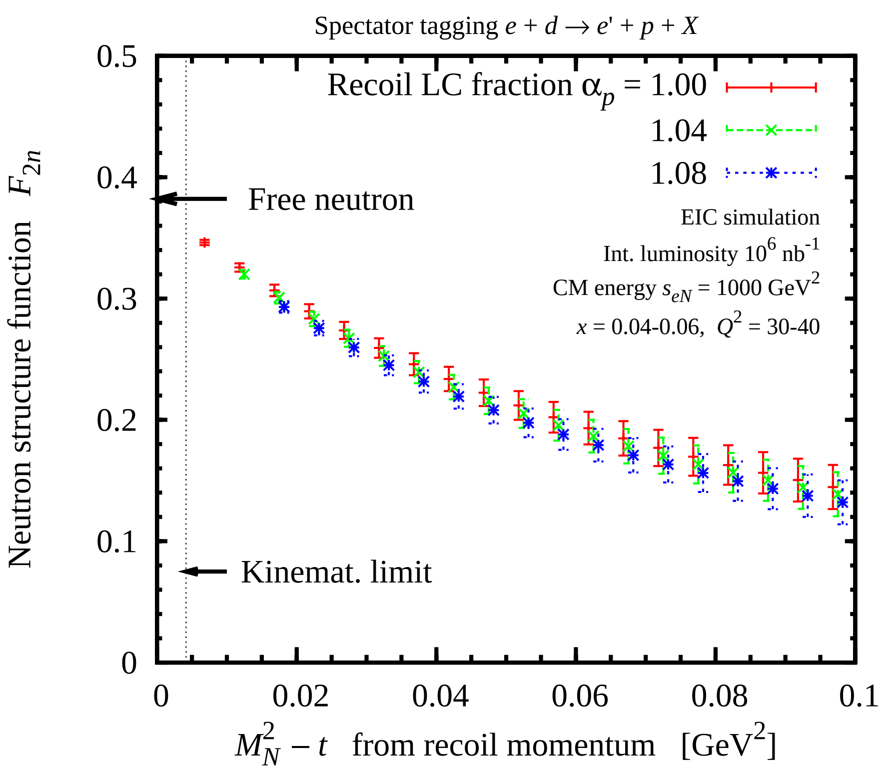

- Composite description

  Impulse approximation: DIS final state and spectator nucleon evolve independently

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

# Tagging: Free neutron structure




- On-shell extrapolation

  Proton momentum defines invariant
  $t - M_N^2 = -2|\boldsymbol{p}_p|^2 + t_{\rm min}$
  "neutron off-shellness"

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

  Eliminates nuclear binding effects
  and FSI Sargsian, Strikman 05

- Free neutron structure $F_{2n}$

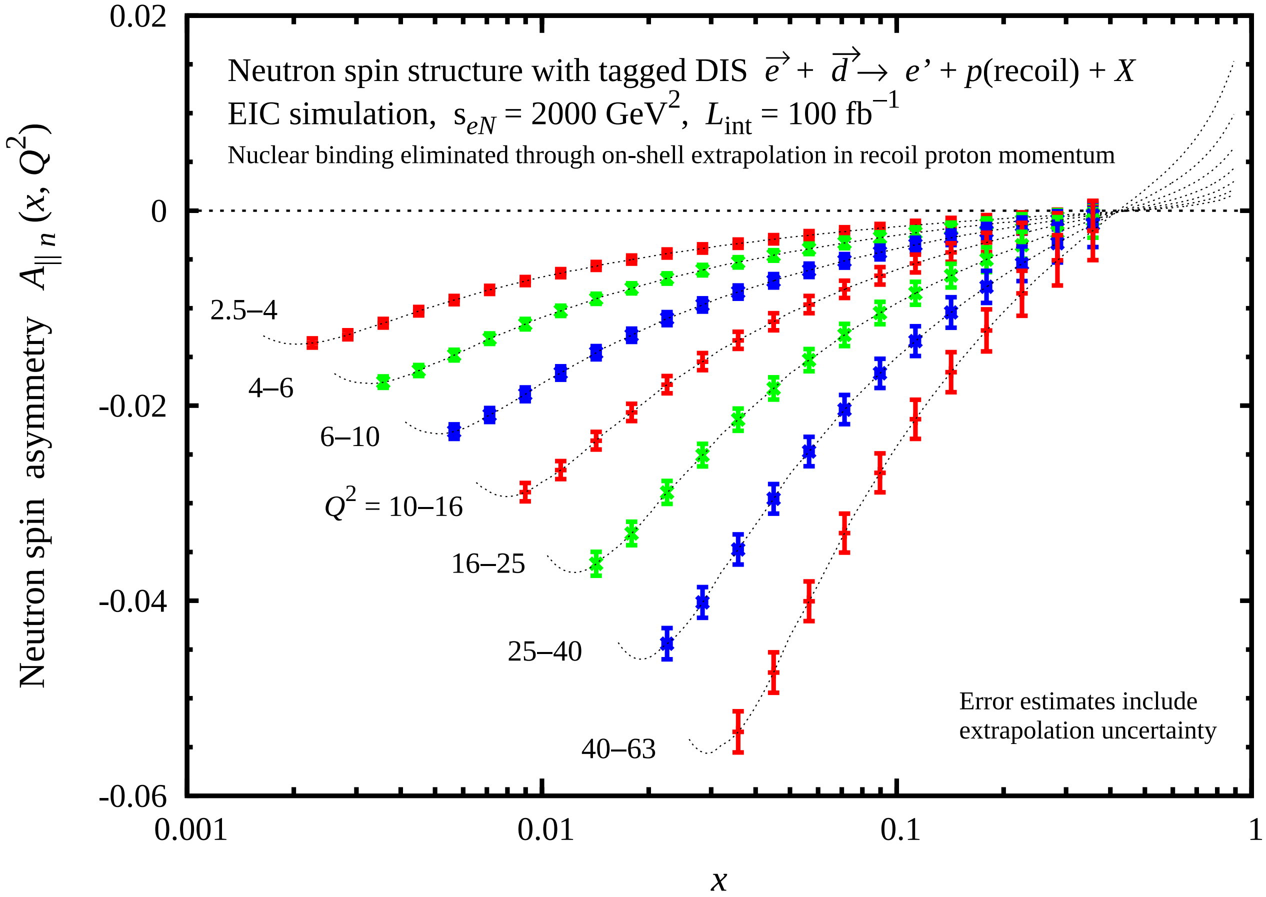
  Uncertainty mainly systematic
  JLab LDRD: Detailed estimates

- Extension to spin structure $g_{1n}$

  On-shell extrapolation of asymmetry

  D-wave suppressed at $\boldsymbol{p}_p = 0$:
  Neutron 100% polarized

# Tagging: Neutron spin structure




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

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

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

depolarization factor

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

- Precise measurement of neutron spin structure

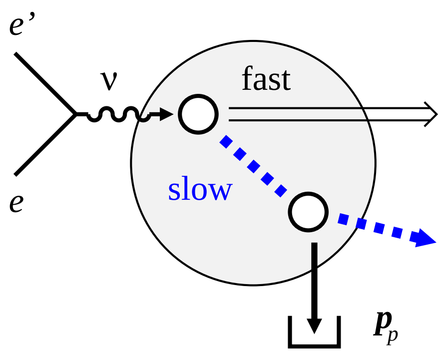
  Wide kinematic range: Leading $\leftrightarrow$ higher twist, nonsinglet $\leftrightarrow$ singlet QCD evolution

  Parton density fits: Flavor separation $\Delta u \leftrightarrow \Delta d$, gluon spin $\Delta G$

  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<br>interact weakly with spectators |
| "Slow" | $E_h = O(\mu_{\rm had}) \sim 1$ GeV | formed inside nucleus<br>interacts with hadronic cross section<br>dominant source of FSI, cf. factorization |

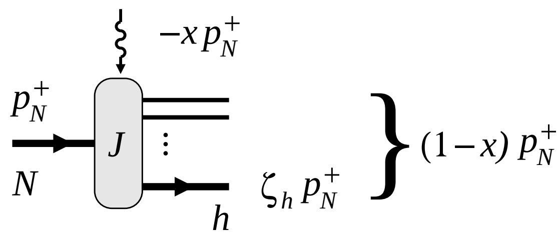
- FSI effects calculated $x \sim$ 0.1–0.5 Strikman, CW, PRC97 (2018) 035209

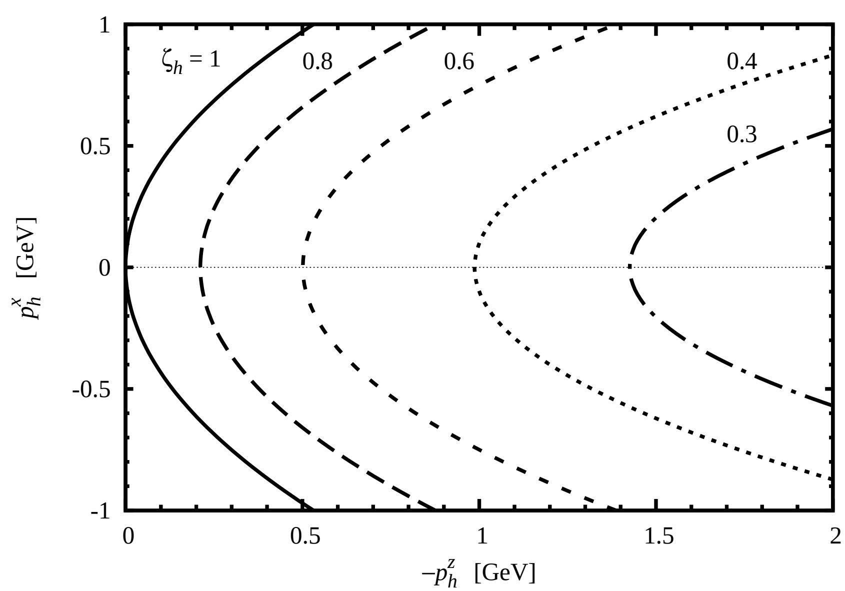
  Experimental slow-hadron multiplicity distributions Cornell, EMC, HERA

  Hadron-nucleon low-energy scattering amplitudes

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

# 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

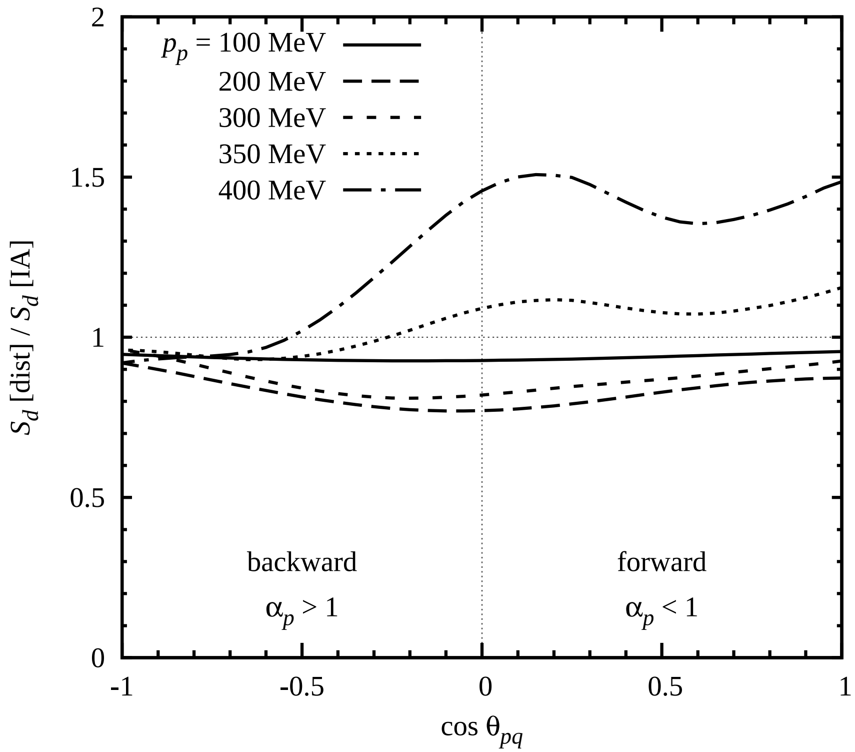
  No backward movers if $h =$ nucleon

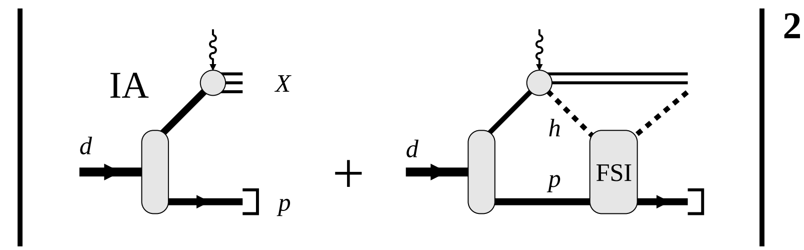
- Experimental data

  HERA $x < 0.01$: $x_\mathrm{F}$ distns of $p, n$, scaling
  Cornell $x > 0.1$: Momentum distns of $p, \pi$
  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

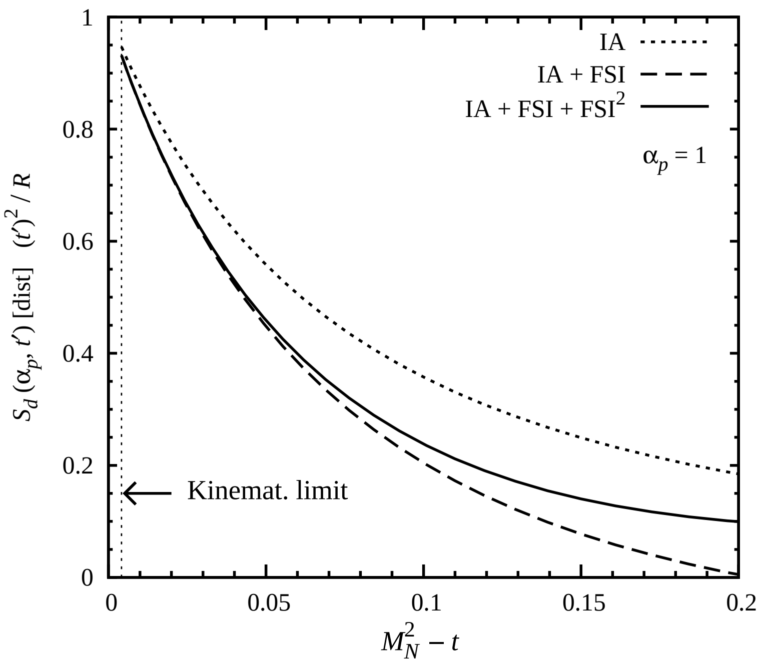
- Momentum and angular dependence in rest frame

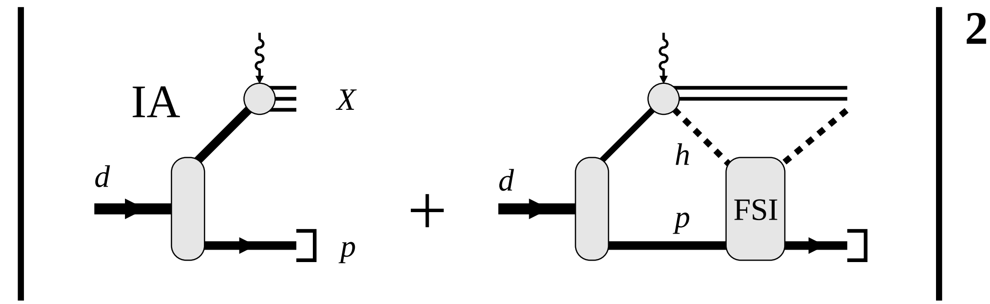
| | |
|---|---|
| $p_p < 300$ MeV | IA $\times$ FSI interference, absorptive, weak angular dependence |
| $p_p > 300$ MeV | $\|\text{IA}\|^2$, refractive, strong angular dependence |

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 $|t - M_N^2| \neq 0 \quad (\lesssim 0.2\,\mathrm{GeV}^2)$

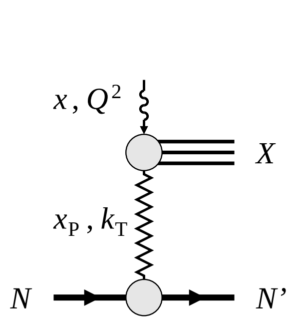
- FSI vanishes at $t - M_N^2 \to 0$; on-shell extrapolation not affected

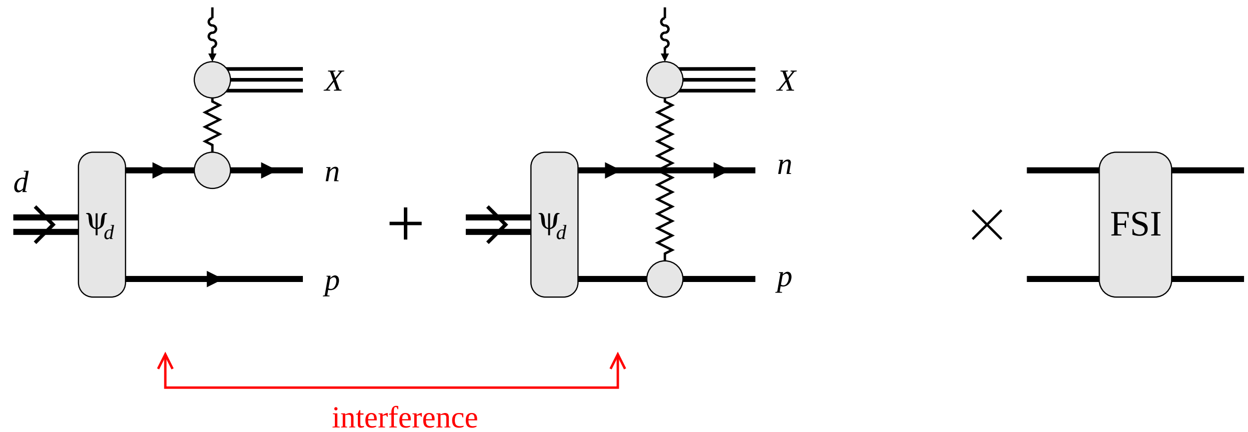
# FSI: Large x

- 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 $J/\psi$ production in UPCs at LHC ALICE.

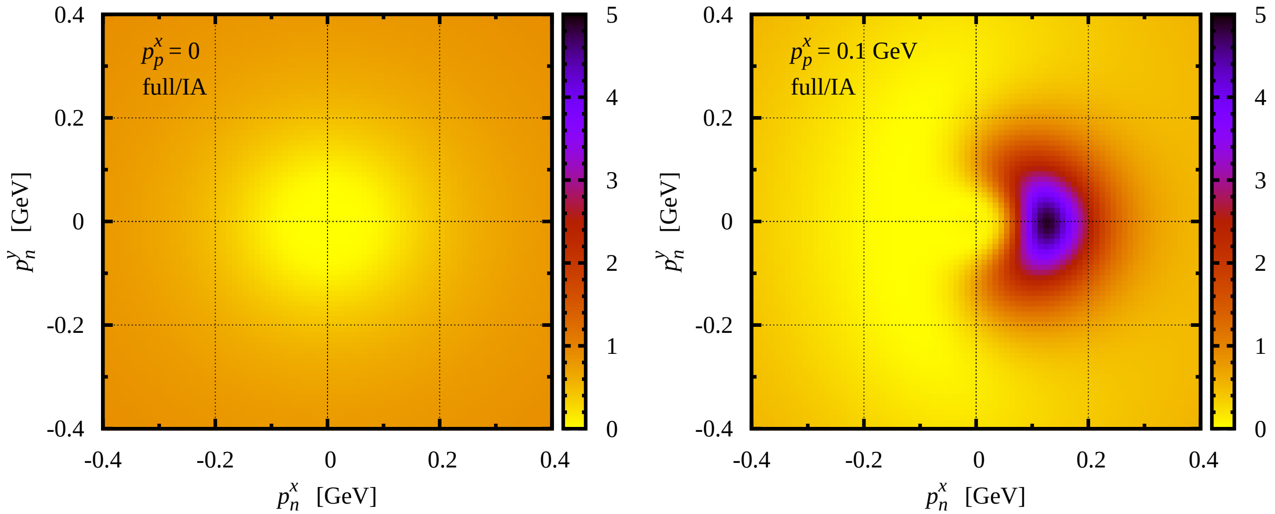
- Diffraction and shadowing in tagged DIS

  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

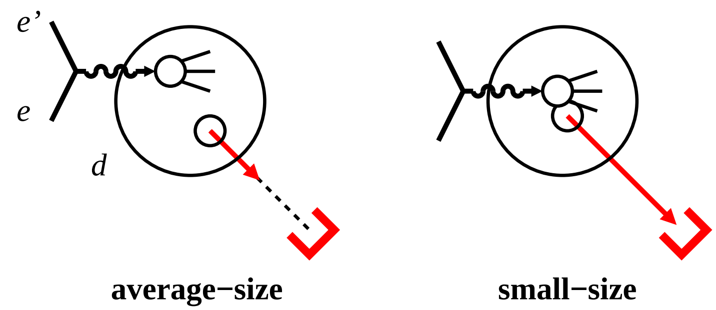
# FSI: Applications and extensions



- Tagged EMC effect

  What momenta/distances in $NN$ interactions cause modification of partonic structure? Connection with $NN$ short-range correlations?

  FSI theory essential




- Tagged polarized DIS

  FSI effects can be calculated using same techniques

  Spin dependence of slow-hadron distributions unknown – need experimental input

- Breakup of 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.

# 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 (C. Weiss et al.) [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

- On-shell extrapolation feasible in presence of FSI

- FSI suppressed in tagged DIS at $x \to 1$

- Future applications: Neutron spin structure, tagged EMC effect, . . .