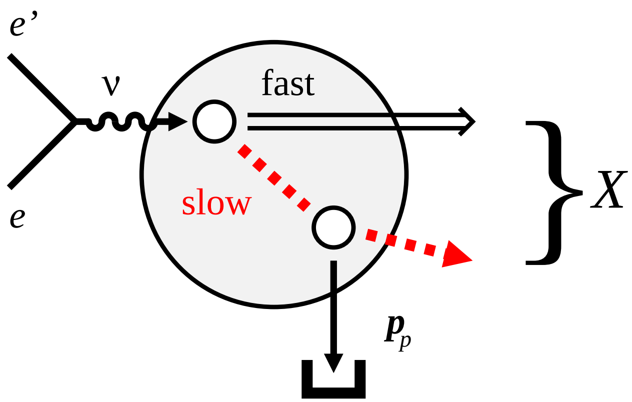
Final-state interactions in tagged deuteron DIS

C. Weiss (JLab), 2nd SRC/EMC Workshop, MIT, 20-23 Mar 2019



- Tagged deuteron DIS

  DIS in controled nuclear configurations

  Impulse approximation, on-shell extrapolation

- Final-state interactions $x \gtrsim 0.1$

  Slow hadrons from nucleon fragmentation

  Interactions with spectator

  Momentum and angular dependence

- Extensions and connections

  Diffraction at $x \ll 0.1$

  FSI in tagged DIS at $x \to 1$

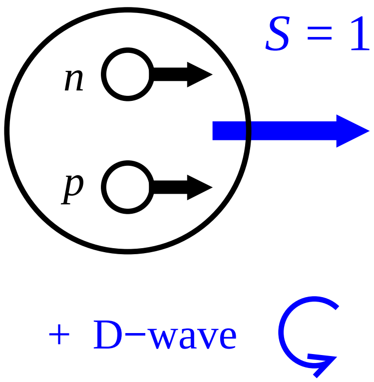
  FSI in quasi-elastic breakup $(e, e'N)$

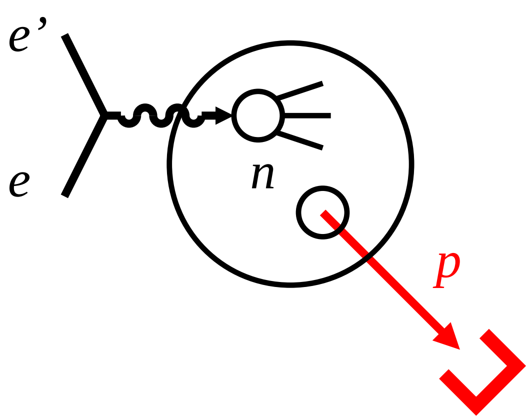
$\rightarrow$ Theory/interpretation of tagged DIS

$\rightarrow$ Comparison with FSI in other breakup processes

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

Tagging: Control nuclear configurations





[Nucleus rest frame view]

- Deuteron, incl. polarized

  pn wave function simple, known well $p_p \lesssim$ 300 MeV
  incl. light-front WF for high-energy procs

  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

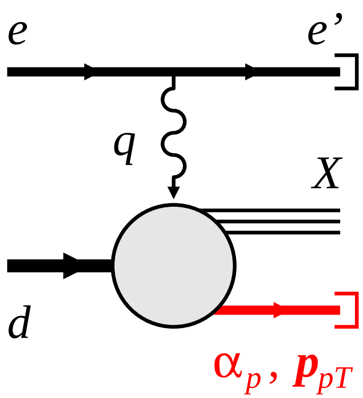
  Applications: Free neutron structure, EMC $\leftrightarrow$ SRC

- Tagging experiments

  Fixed-target JLab 6/12 GeV: BONuS, ALERT, TDIS

  EIC: Forward proton detection

Tagging: Cross section and observables



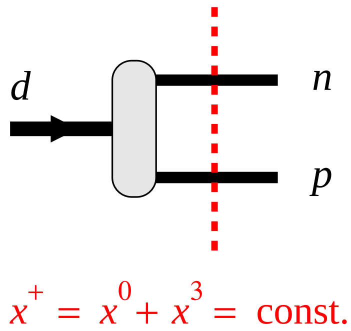
$$\frac{d\sigma}{dx\,dQ^2\,(d^3p_p/E_p)} = [\text{flux}]\Big[F_{Td}(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_{Ld}(..)$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\,\cos\phi_p F_{LT,d}(..) \;+\; \epsilon\,\cos(2\phi_p) F_{TT,d}(..)$$

$$+ \;\text{spin-dependent structures}\Big]$$

- Conditional DIS cross section $e + d \rightarrow e' + X + p$
- Proton recoil momentum described by LF components $p_p^+ = \alpha_p p_d^+/2$, $\boldsymbol{p}_{pT}$, simply related to $\boldsymbol{p}_p$(restframe)
- 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



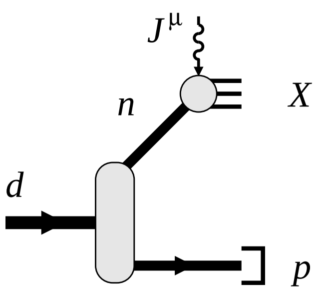
- Light-front quantization

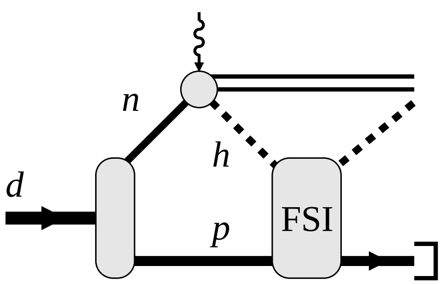
  High-energy scattering probes nucleus at fixed light-front time $x^+ = x^0 + x^3 = $ const.

  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!



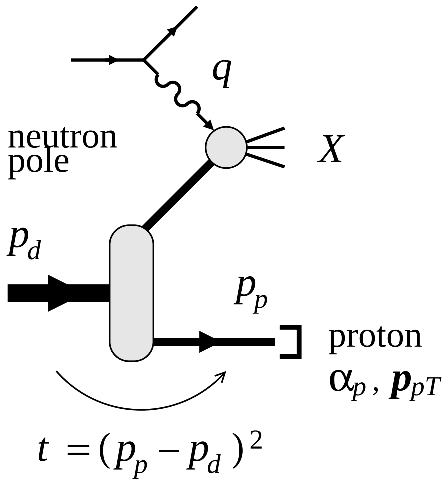


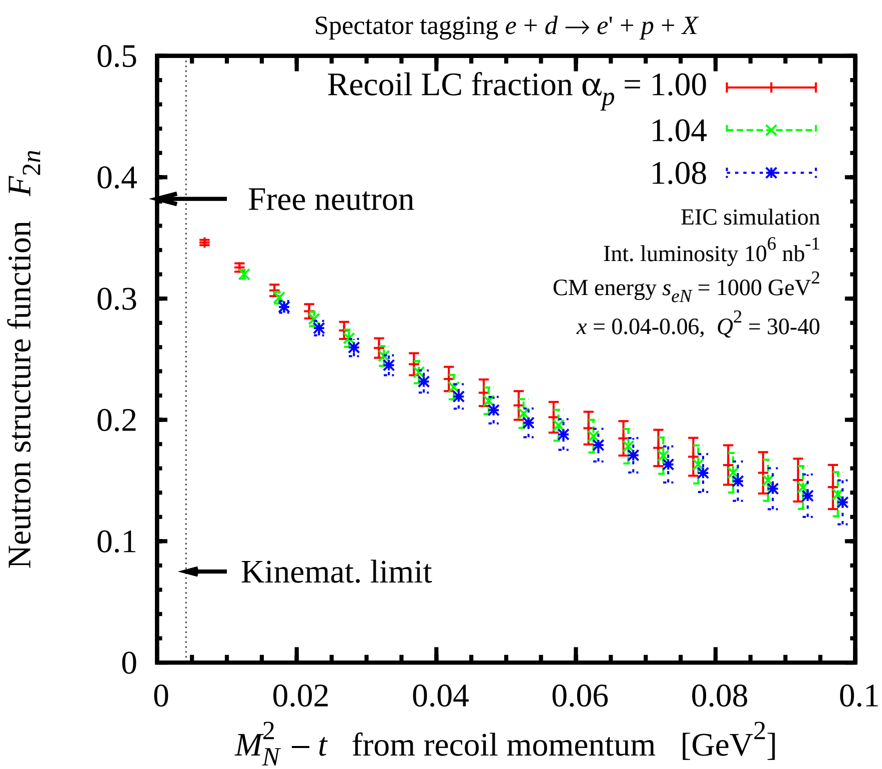
- Composite description

  Impulse approximation IA: DIS final state and spectator nucleon evolve independently

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

Tagging: Impulse approximation and neutron pole





- Neutron pole

  Proton momentum defines invariant
  $t - m^2 = -2|\boldsymbol{p}_p|^2 + t'_{\text{min}}$
  neutron off-shellness, kinematic quantity

  IA cross section has pole at $t - m^2 = 0$

  Residue is free neutron structure function

- On-shell extrapolation

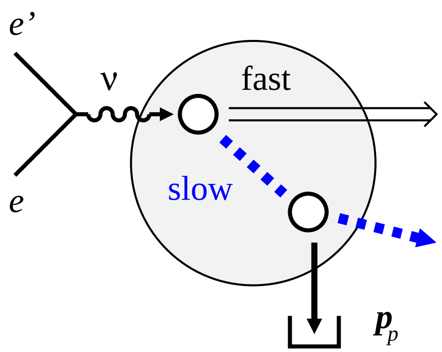
  Measure tagged structure functions in physical region

  Extrapolate to $t - m^2 \to 0$

  Eliminates nuclear binding and FSI
  Sargsian, Strikman 05

- EIC simulations unpol/pol
  2014/15 JLab LDRD Project → Saturday

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

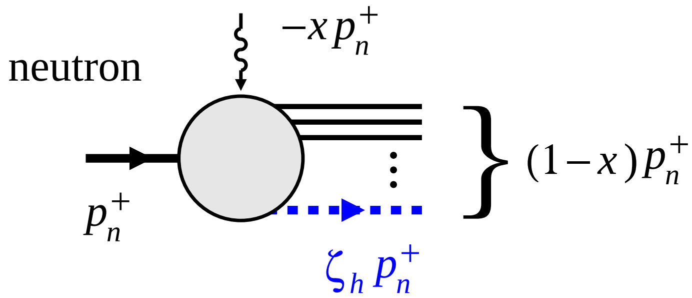
- FSI effects calculated $x \sim 0.1$–0.5 Strikman, CW, PRC97 (2018) 035209

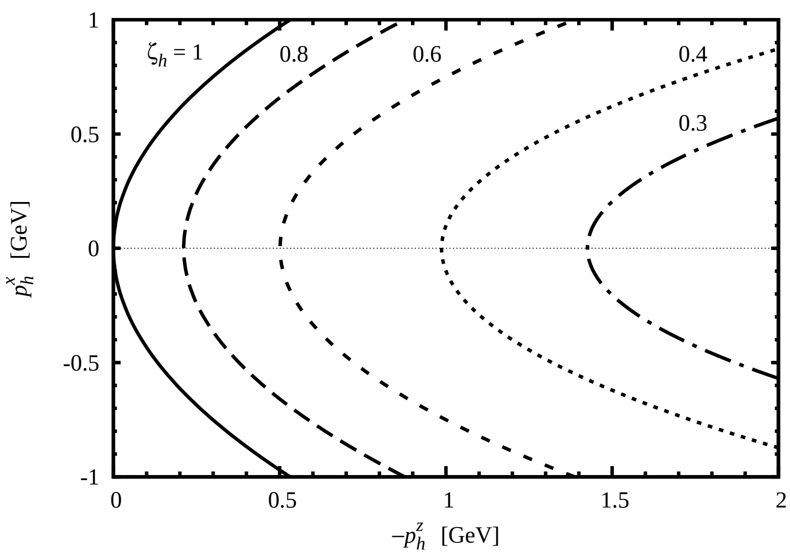
  Experimental slow-hadron multiplicity distributions Cornell, EMC, HERA

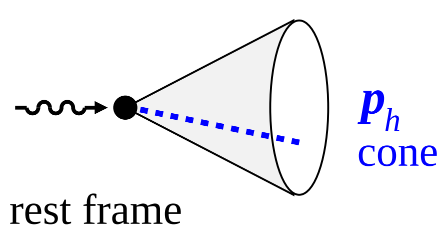
  Hadron-nucleon low-energy scattering amplitudes

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

FSI: Slow hadrons from nucleon fragmentation







- Kinematic variables

  $\zeta_h, \boldsymbol{p}_{hT}$ hadron LC mom $\zeta_h \leftrightarrow x_F$

  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

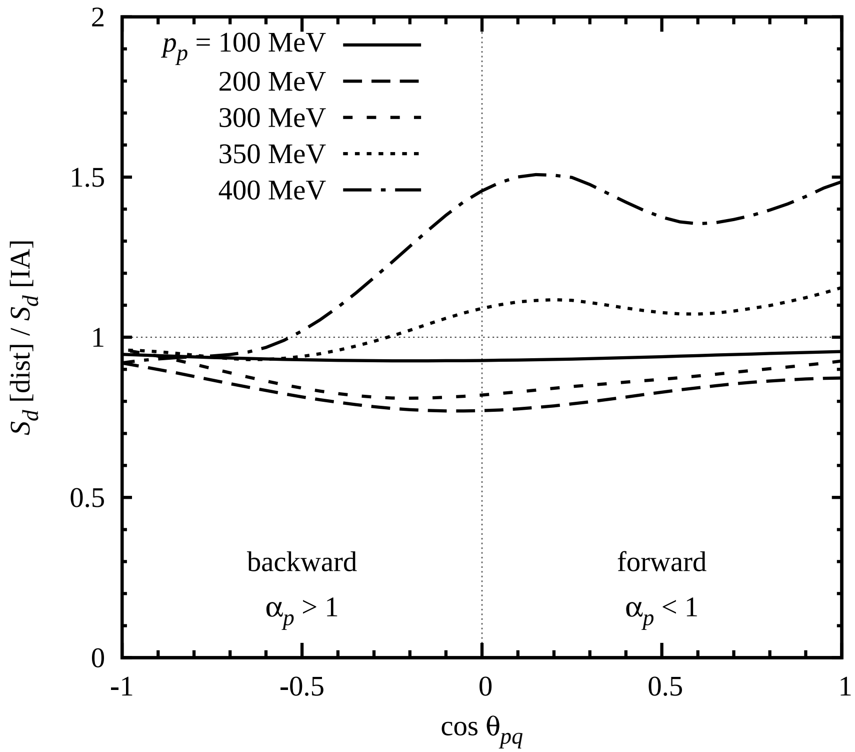
  No backward movers if $h =$ nucleon

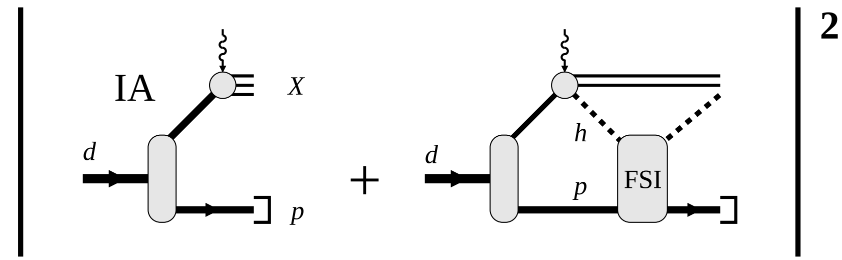
- Experimental data

  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 + input for nuclear FSI

FSI: Momentum and angular dependence





Strikman, CW 18

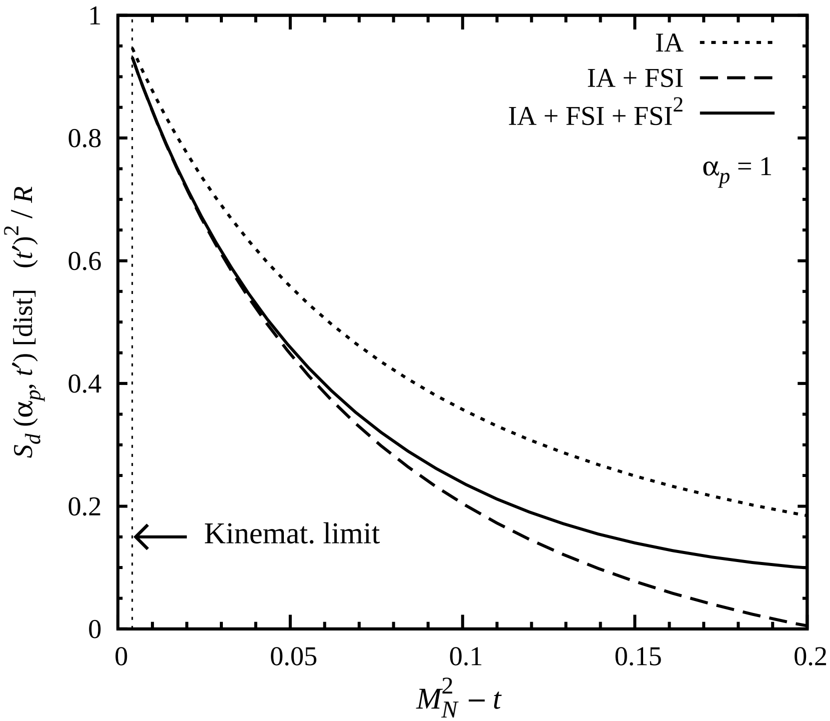
- Momentum and angular dependence in rest frame

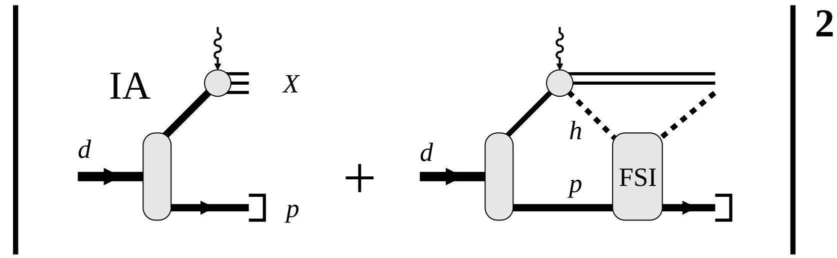
$p_p <$ 300 MeV	IA $\times$ FSI interference, absorptive, weak angular dependence
$p_p >$ 300 MeV	$\|\mathrm{IA}\|^2$, refractive, strong angular dependence

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

  see e.g. Frankfurt, Greenberg, Miller, Sargsian, Strikman 1995

FSI: Effect on on-shell extrapolation





Strikman, CW 18

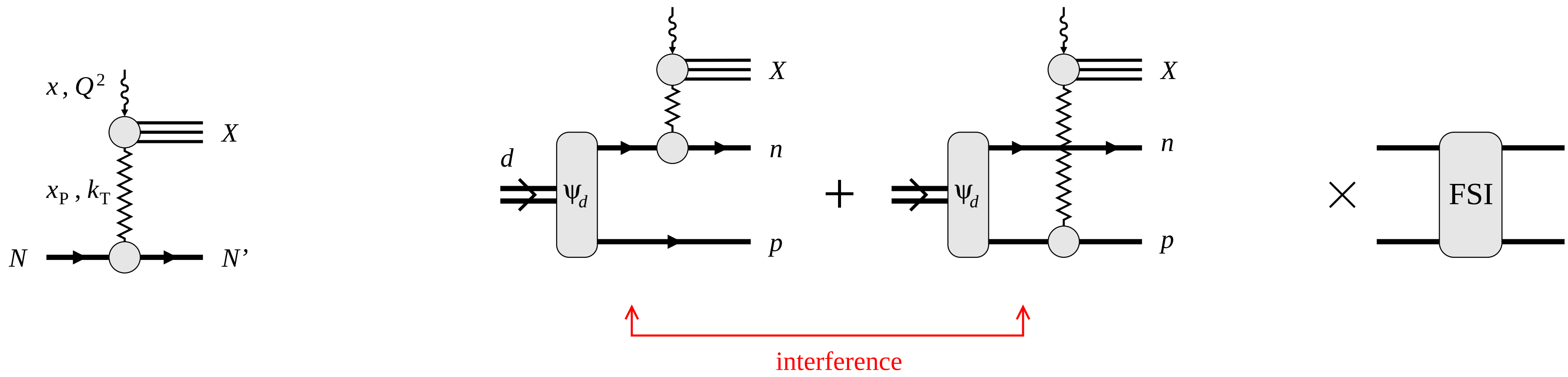
- FSI reduces IA cross section at $|t - m^2| \neq 0 \quad (\lesssim 0.2\,\mathrm{GeV}^2)$
- FSI vanishes at $t - m^2 \to 0$; on-shell extrapolation not affected

FSI: Large x

- FSI suppressed for $x \to 1 - \alpha_p$: No "slow" hadrons among neutron fragments

  FSI in subasymptotic regime, higher-twist: Cosyn, Sargsian 2010+

FSI: Diffraction and shadowing at small x



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

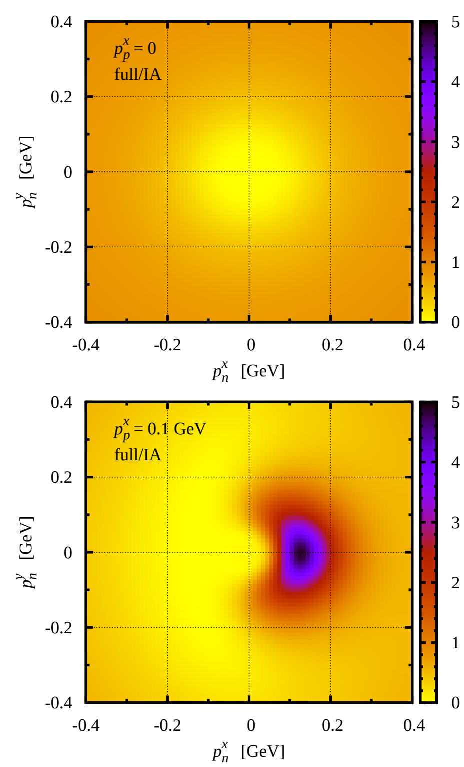
- Shadowing: QM interference of diffractive scattering on neutron or proton
  Observed in inclusive nuclear scattering

- Final-state interactions

  Low-momentum pn system with $S = 1, I = 0$

  pn breakup state must be orthogonal to d bound state

  Large distortion, deviations from IA
  Guzey, Strikman, CW 18

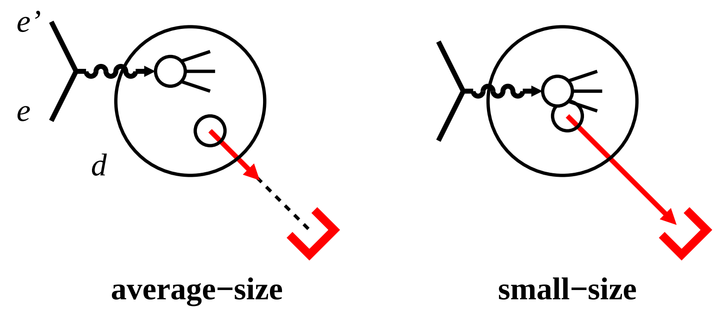


FSI: Applications and extensions

- 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, . . .