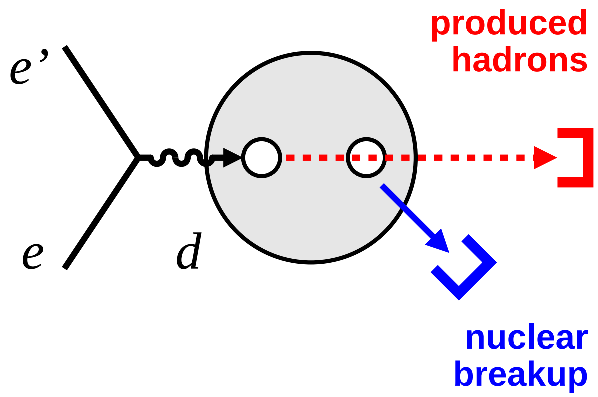
Final-state interactions in tagged deuteron DIS

C. Weiss (JLab), Exploring QCD with tagged processes, Institut Pascal, Paris, 18 Oct 2021



FSI mechanisms change with x, Q^2: JLab, EIC

Critical for initial-state studies: SRC, EMC effect, diffraction

Connected with target fragmentation, hadronization dynamics, transparency

- Tagged deuteron DIS

  Applications

  Theoretical description

  Light-front nuclear structure

  Impulse approximation and final-state interactions

- Final-state interactions

  DIS $x \gtrsim 0.1$: Hadrons from nucleon fragmentation

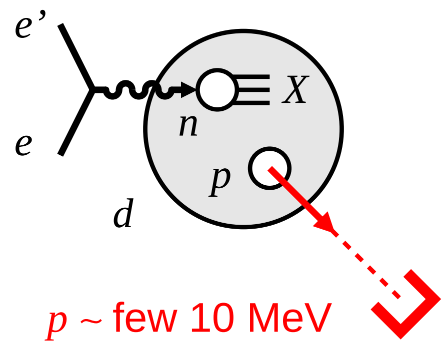
  DIS $x \ll 0.1$: Diffraction and coherence

  Finite W, Q^2: Resonance production

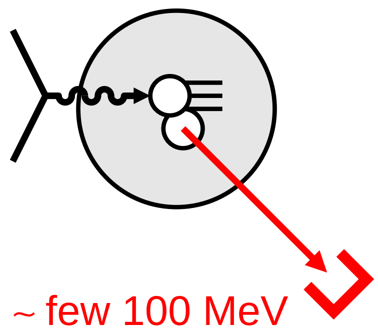
- Extensions

  Polarized deuteron, exclusive processes, $A > 2$

Tagging: Applications



p ~ few 10 MeV



p ~ few 100 MeV

Tagged inclusive scattering (DIS)
$e + d \to e' + X + p(n)$

Also exclusive processes, e.g.
$e + d \to e' + M + p + n$

- Neutron structure extraction

  Tagged momenta $p \sim$ few 10 MeV

  Free neutron from on-shell extrapolation

- Nuclear interactions: EMC effect, SRCs

  Tagged momenta $p \sim$ few 100 MeV

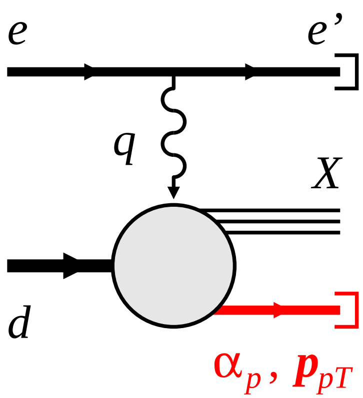
  Configuration dependence of EMC effect

- Coherent phenomena in QCD at small x

  Nuclear shadowing in $A = 2$ system

Idea: Use spectator momentum to control nuclear configuration during high-energy process

Tagging: Cross section and observables



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

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

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

→ Talk Cosyn

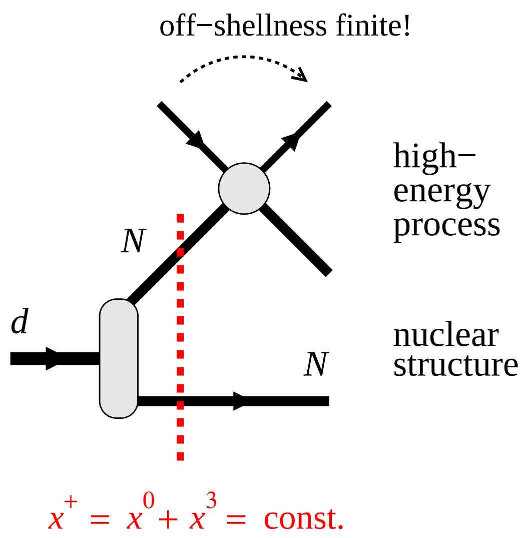
- Semi-inclusive DIS cross section $e + d \to e' + X + p$

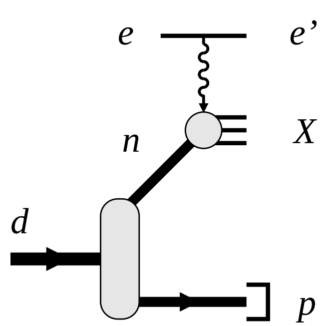
- Tagged proton momentum described by LF components $p_p^+ = \alpha_p p_d^+/2$, $\boldsymbol{p}_{pT}$, simply related to $\boldsymbol{p}_p$(restframe)

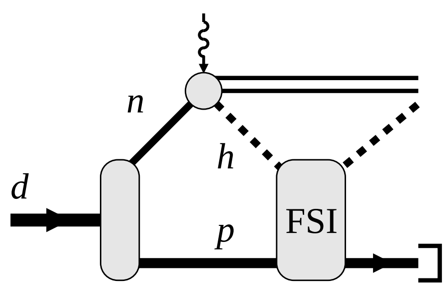
- Special case of target fragmentation: QCD factorization, leading-twist
  Trentadue, Veneziano 93; Collins 97

- No a-priori assumptions re composite nuclear structure, $A = \sum N$, etc.

Tagging: Theoretical description







- Light-front quantization

  Nuclear structure described at fixed light-front time $x^+ = x^0 + x^3 =$ const.

  Off-shellness of nucleon scattering process remains finite in high-energy limit, permits matching with on-shell nucleon amplitudes Frankfurt, Strikman 80's

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

  Low-energy nuclear structure ↔ non-relativistic theory

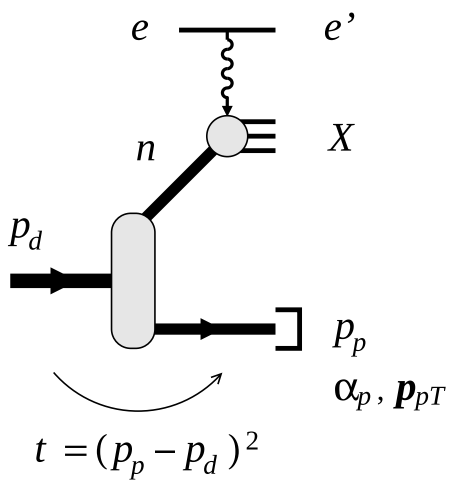
- Composite description

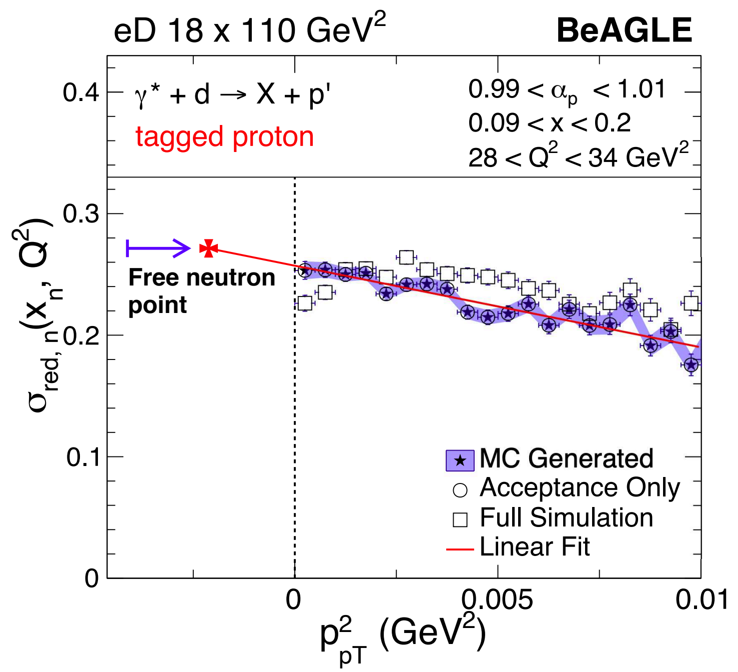
  Impulse approximation IA: DIS final state and spectator nucleon evolve independently

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

  Idea: Use tagged momentum as variable to control nuclear binding, minimize/maximize FSI

Tagging: Free neutron structure





Simulation of proton/neutron tagging and pole extrapolation with EIC far-forward detectors. Jentsch, Tu, Weiss 2108.08314

- Nucleon pole in deuteron wave function

  Configurations with size $\to \infty$, nucleons free

  Contained in IA spectral function

- Free neutron from pole extrapolation

  Measure tagged cross section at physical $p_{pT}^2 > 0$ and fixed α_p

  Extrapolate to pole $p_{pT}^2 = -a_T^2 < 0$, corresponding to $t - m^2 = 0$

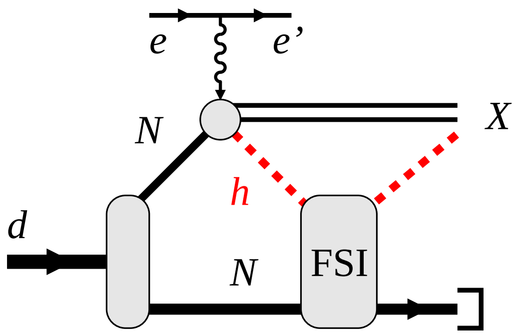
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 05

  Extension to polarized DIS $\to$ Talk Cosyn

- EIC simulations

  Far-forward detection of protons/neutrons

FSI: Final-state interactions



- Final state of DIS process can interact with spectator

  Changes observed nucleon distribution in tagging

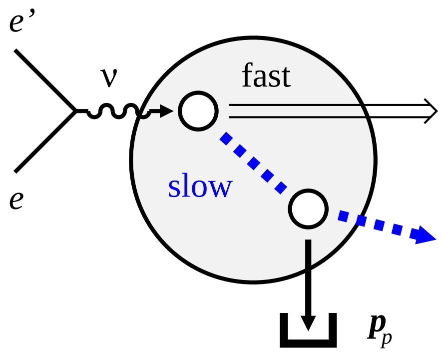
  No effect on total cross section – closure

  What states are produced in DIS process?
  How do they interact with spectator?
  Depends on kinematic regime

- Physical pictures of FSI

DIS, $x \gtrsim 0.1$	$h =$ target fragmentation hadrons on-shell rescattering	Ciofi degli Atti, Kaptari, Kopeliovich 2004- Strikman CW 2018 ←
DIS, $x \ll 0.1$	$h =$ diffractive nucleons QM rescattering, orthogonality	Guzey, Strikman, CW; in progress
Finite W, Q^2 resonance region	$X = \sum N^*$	Sargsian, Strikman 2006 Cosyn, Sargsian, Melnitchouk 2011-

FSI: Tagged DIS at x $\gtrsim$ 0.1



- Space-time picture in nuclear rest frame
  Strikman, CW, PRC97 (2018) 035209

  DIS limit $\nu \gg$ hadronic scale, Q^2/ν fixed,
  large phase space for hadron production

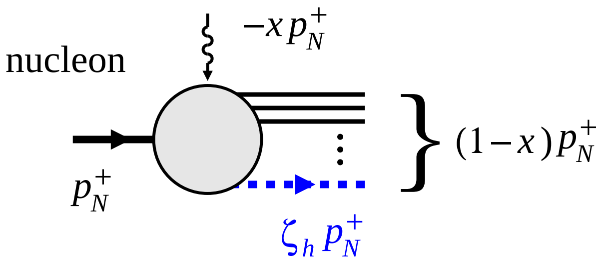
- Nucleon DIS final state has two components [current and target jet]

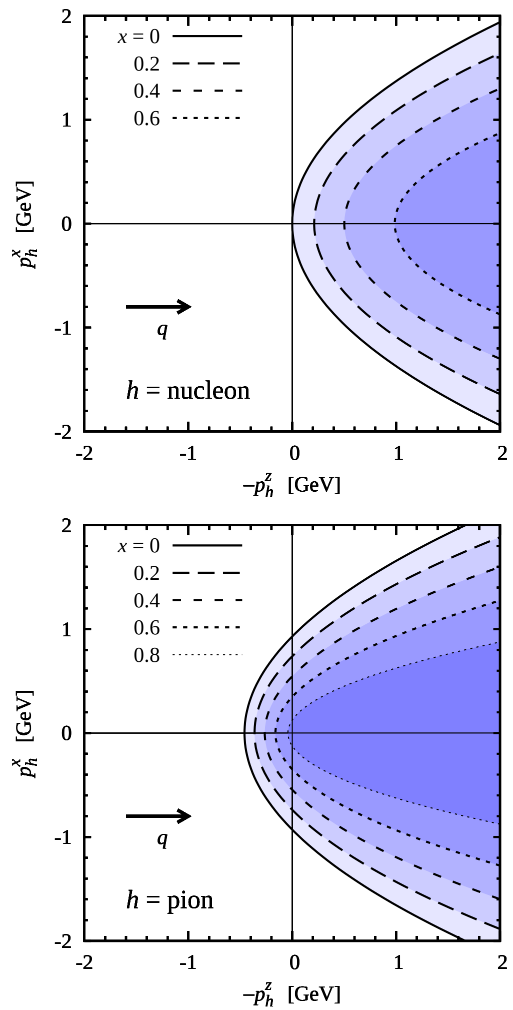
"Fast"	$E_h = O(\nu)$	hadrons formed outside nucleus interact weakly with spectators
"Slow"	$E_h = O(\mu_{\mathrm{had}}) \sim 1$ GeV	formed inside nucleus interacts with hadronic cross section dominant source of FSI $\leftarrow$

- Respects QCD factorization for target fragmentation
  Trentadue, Veneziano 1993; Collins 1997

  FSI only modifies soft breakup of target, no long-range rapidity correlations

FSI: Hadron distributions from DIS





- Kinematic variables

  $\zeta_h, \boldsymbol{p}_{hT}$ hadron LC momentum

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

  $\zeta_h < 1 - x$ kinematic limit

  $\zeta_h/(1-x) \approx -x_{\mathrm{F}}$ relation to Feynman var

- Momentum distribution in rest frame

  Constrained by LC momentum conservation

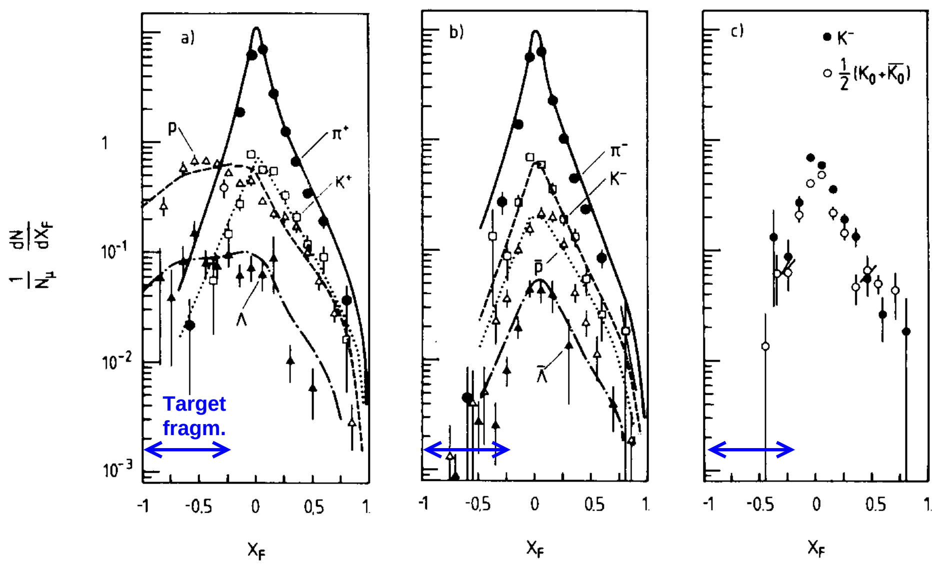
  Cone opening in virtual photon direction $\boldsymbol{q}$

  $h =$ nucleon: $\boldsymbol{p}_h$ forward, grows for $x \to 1$

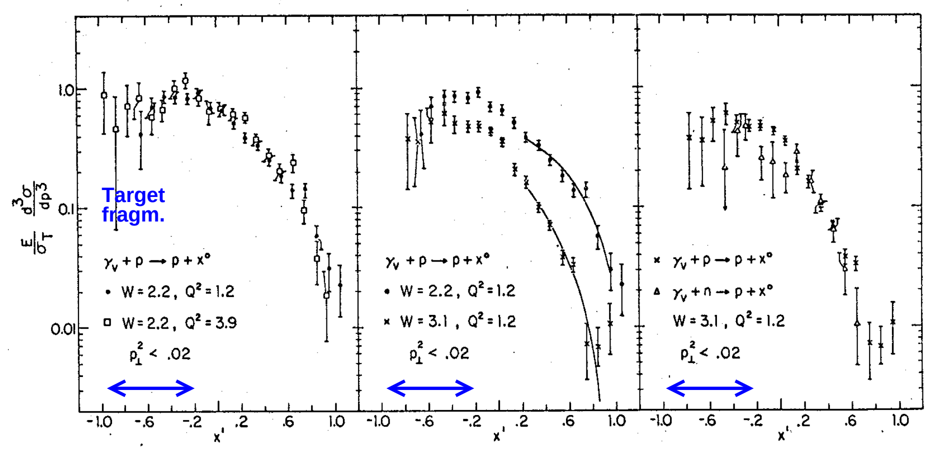
  $h =$ pion: $\boldsymbol{p}_h$ forward or backward

FSI: Hadron distributions from DIS

EMC hadron xF distributions. Phys Lett B 150 (1986) 458



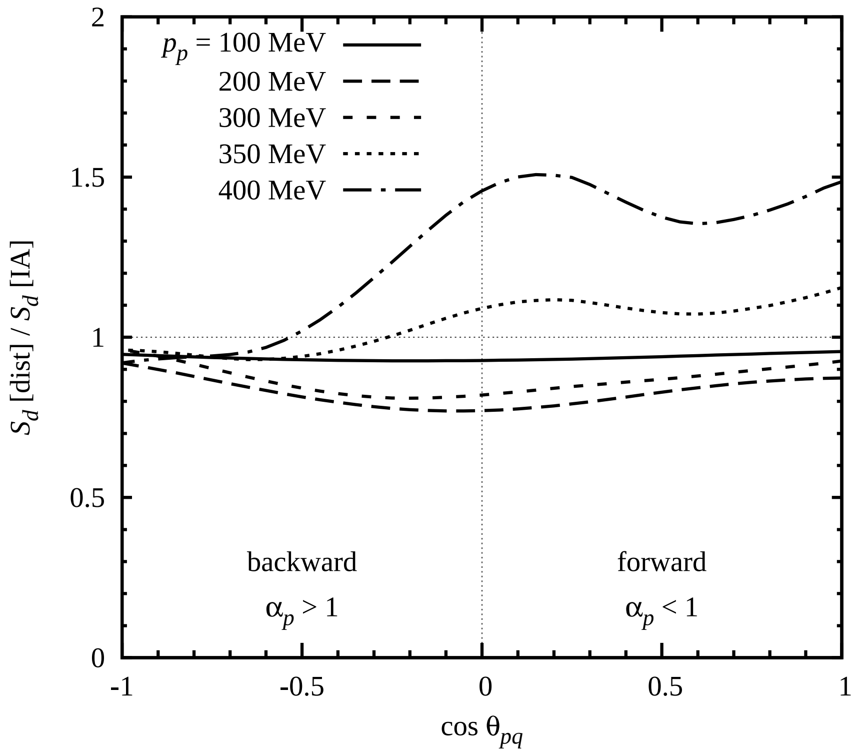
Cornell proton distributions in DIS. Hanson 1976

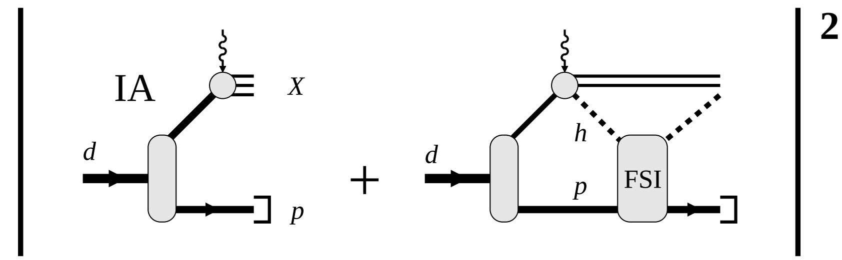


- Measurements of target fragmentation $(x_{\mathrm{F}} < 0)$
  EMC μp 1986 $x > 0.02$: x_{F} distributions of $p, \bar{p}, \pi^{\pm}, K^{\pm}, \Lambda$
  HERA ep 2009/2014 $x < 0.01$: x_{F} distributions of p, n
  Cornell ep 1975 $x > 0.1$: Momentum distributions of p, π
  Neutrino DIS: FNAL-E-0031 1977, CERN-WA-021 1981

- JLab12 and EIC should measure target fragmentation → Talk Strikman
  Spin/flavor dependence? Kinematic dependences?
  Interesting nucleon structure physics + necessary input for nuclear FSI!
  Workshop “Target Fragmentation Physics with EIC,” CFNS Stony Brook, 28-30 Sep 2020 [Webpage].
  EIC Yellow Report arXiv:2103.05419

FSI: Strength and momentum dependence





- Quantum-mechanical description: Interference, absoprtion
  Strikman, CW, PRC97 (2018) 035209

- Momentum and angle dependence in rest frame

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

- FSI vanishes at nucleon pole $t - m^2 \to 0$; pole extrapolation feasible

FSI: Open questions in DIS regime

- FSI at backward angles

  Present calculation includes only FSI from $h =$ nucleons in DIS final state

  FSI from pions?

- FSI at $x \to 1$

  Depletion of slow hadrons in nucleon fragmentation

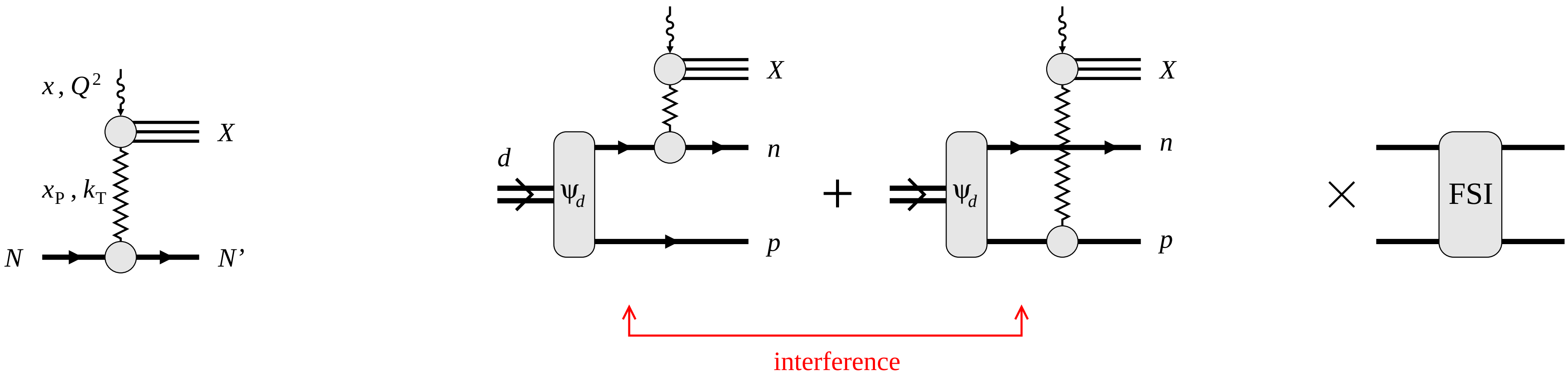
  Absence of FSI?

FSI: Finite W, Q^2 regime

- Calculations based on picture of resonance production
  Cosyn, Sargisan 2011+; Cosyn, Sargsian, Melnitchouk 2014

- Questions: Connection with DIS regime of fast $\leftrightarrow$ slow hadrons?
  Subasymptotic corrections? Coherence and color transparency?

FSI: Diffractive DIS at small x



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

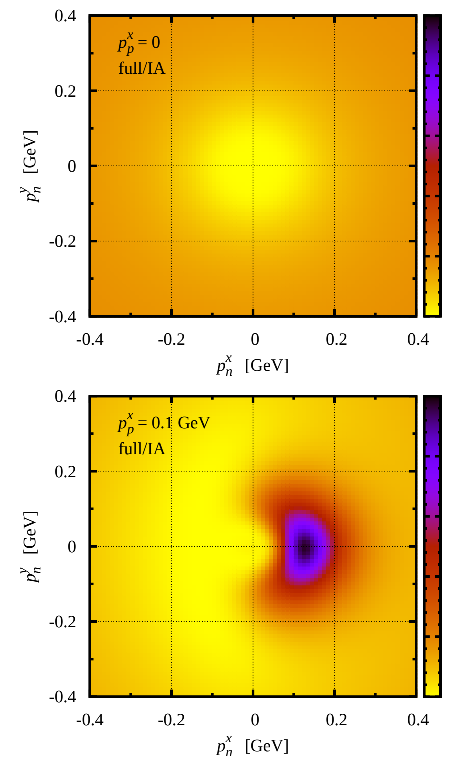
- Shadowing: QM interference of diffractive scattering on neutron or proton
  Observed in inclusive nuclear scattering

- Final-state interactions

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

  pn breakup state must be orthogonal to d bound state

  Large distortion, qualitative deviations from IA
  Guzey, Strikman, CW; in progress



Extensions: FSI in tagged DIS

- Tagged DIS with polarized deuteron

  Tagging controls S/D wave ratio: Vector and tensor polarized observables → Talk Cosyn
  Frankfurt, Strikman 1983; Cosyn, Weiss, PLB799 (2019) 135035; Phys.Rev.C 102 (2020) 065204

  Spin-dependence in hadron production and FSI?

  T-odd structures in ϕ_p dependence proportional to FSI, can serve as test

- Tagged exclusive processes

  Meson production or DVCS on neutron

  "Know" forward-going hadron: Simpler FSI calculations, test picture/models

- Tagging with nuclei $A > 2$

  Much more complex: Wave function overlap in IA, multiple trajectories in FSI

  Requires input from low-energy nuclear structure
  Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent [Webpage].
  Emerging collaboration with low-energy nuclear structure community

Summary

- Tagged DIS on deuteron permits control of nuclear configuration during high-energy process and differential treatment of nuclear effects

- Free neutron structure can be extracted model-independently using pole extrapolation, not affected by FSI

- FSI in tagged DIS at $x \gtrsim 0.1$

  Induced by "slow" hadrons from target fragmentation of active nucleon

  Need experimental data on target fragmentation in DIS, x_F distributions

  FSI effects are $O(1)$ for at p(tagged) $\sim$ few 100 MeV

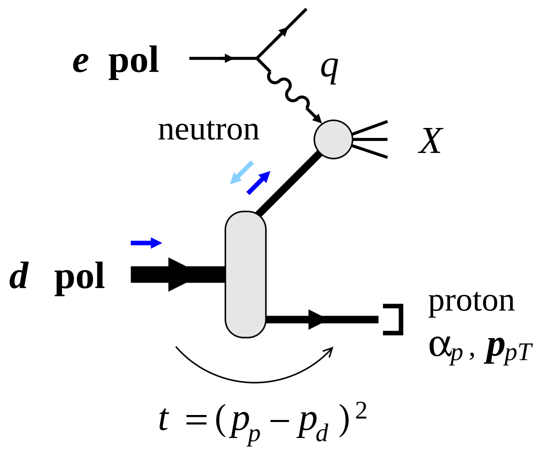
- FSI in diffractive DIS at $x \ll 0.1$

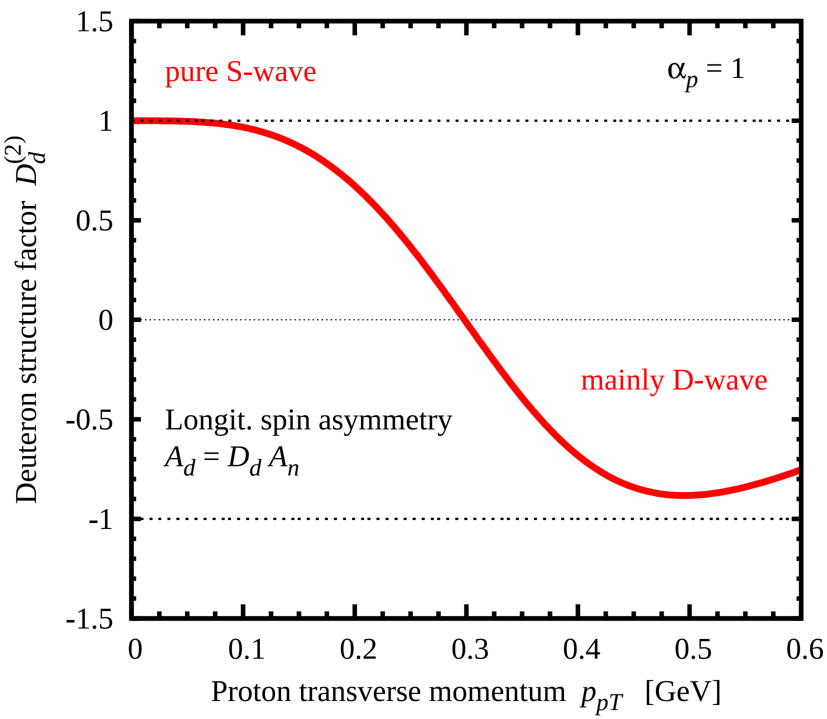
  Large effects, qualititative changes to IA at $p_T \to 0$

- Exciting prospects for programs at JLab12, EIC, J-PARC

Supplementary material

Tagging: Neutron spin structure





Cosyn, CW, PLB799 (2019) 135035

- Nuclear binding: Neutron polarization?

  S + D waves, depolarization

- Control neutron polarization

  Measure tagged spin asymmetries

  D-wave drops out at $\boldsymbol{p}_{pT} = 0$:
  Pure S-wave, neutron 100% polarized

  [$|\boldsymbol{p}_{pT}| \approx$ 400 MeV: D-wave dominates]

- Free neutron spin structure

  On-shell extrapolation of asymmetry

- EIC simulations

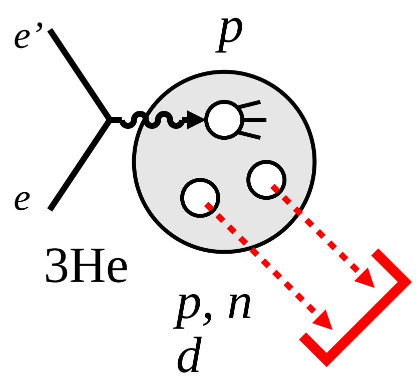
  Possible with int lumi $\sim$ few 10 fb^{-1}

Extensions: Tagging with nuclei $A > 2$

- Potential applications

  Isospin dependence neutron $\leftrightarrow$ proton

  Universality of bound nucleon structure



- Simplest example: A-1 ground state recoil

  3He (e, e' d) X, including polarization
  Ciofi, Kaptari, Scopetta 99; Kaptari et al. 2014; Milner et al. 2018

  Bound proton $\leftrightarrow$ free proton structure

- Nuclear breakup much more complex than A=2

  IA: Wave function overlap, large amplitude factors

  FSI: Multiple trajectories

  Requires new nuclear structure imput:
  Light-front spectral functions, decay functions, FSI
  Workshop "Polarized light ion physics with EIC", 5-9 Feb 2018, Ghent [Webpage]. Emerging collaboration with low-energy nuclear structure community