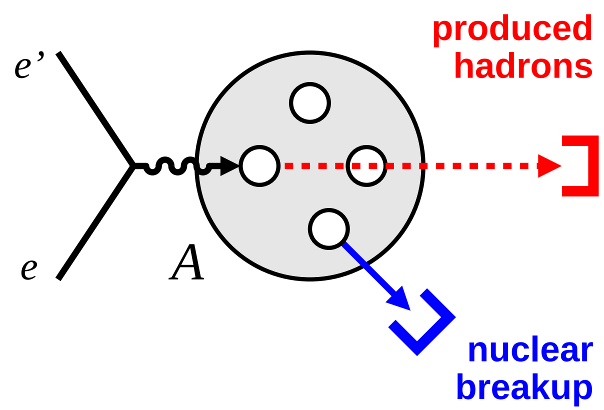
Hadronization and final-state interactions in nuclear breakup measurements

C. Weiss (JLab), Future of Color Transparency and Hadronization Studies, 7-8 Jun 2021



Produced hadrons
Formation time?
Color transparency?

$\downarrow\uparrow$?

Nuclear breakup
Initial-state configurations?
Final-state interactions?

- Tagged DIS on deuteron

  Applications and theory

  Impulse approximation and final-state interactions

- Final-state interactions

  Hadron distributions in DIS final state

  Hadron formation

  FSI in tagged DIS $x \gtrsim 0.1$

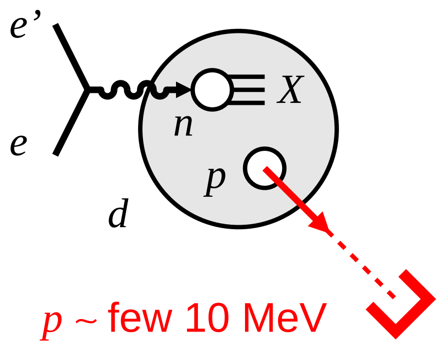
- Extensions

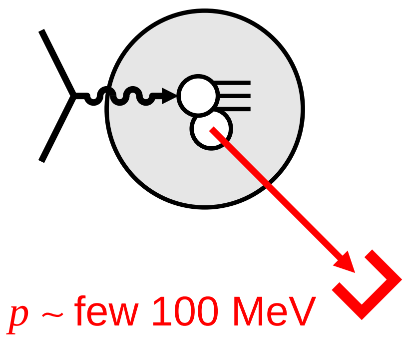
  Polarized tagged DIS

  Exclusive processes

  Breakup of nuclei $A > 2$

Tagged DIS: Applications





- 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

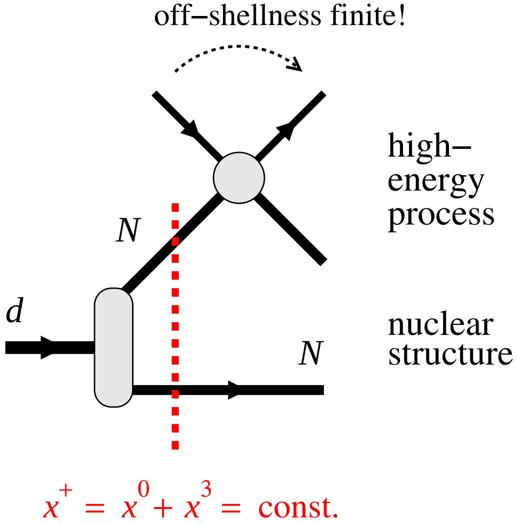
  Nuclear shadowing in $A = 2$ system]

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

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

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

Tagged DIS: Theory



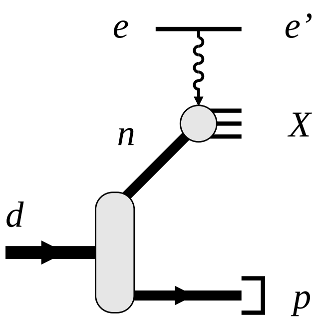
- Light-front quantization

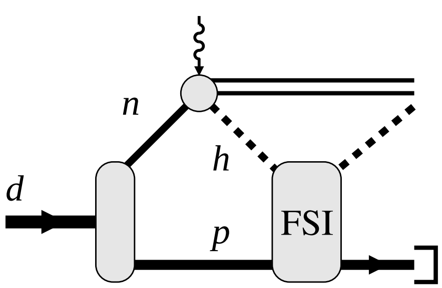
  Nuclear structure described at LF time $x^+ = x^0 + x^3$

  Off-shellness of nucleon scattering process remains finite in high-energy limit, permits matching with on-shell nucleon amplitudes Frankfurt, Strikman 1980's

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

  Low-energy nuclear structure $\leftrightarrow$ non-relativistic theory





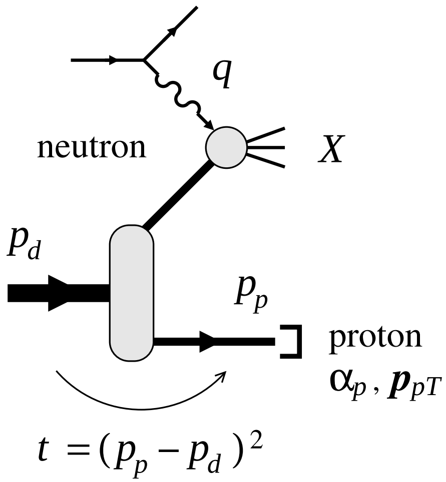
- Composite description

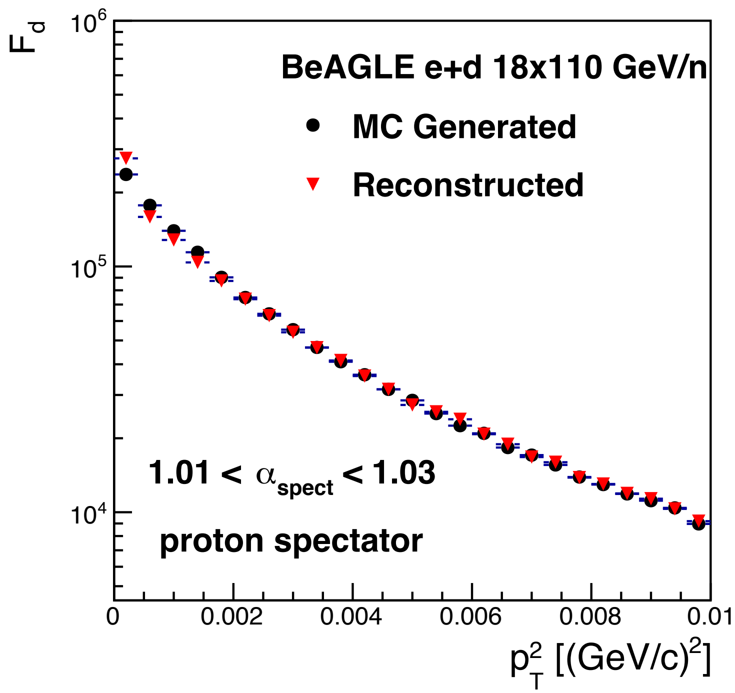
  Impulse approximation IA: DIS final state and spectator nucleon evolve independently

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

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

Tagged DIS: Neutron structure extraction





Simulation EIC forward detector IR1 2021

- Nuclear binding: Motion, interactions
- Free neutron from on-shell extrapolation

  Measure tagged structure function dependence on proton momentum → neutron off-shellness $t - m^2 = -2|\boldsymbol{p}_{pT}^2| + t'_{\min}$

  Extrapolate to on-shell point $t - m^2 \to 0$

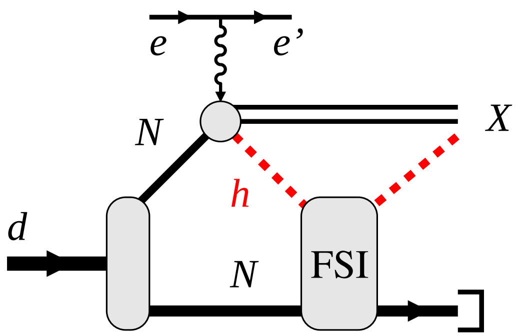
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 2005

  EIC simulations
  JLab LDRD 2014/15; Jentsch, Tu, CW 2021

- Extension to polarized DIS

  Tagged proton momentum controls S/D ratio, effective neutron polarization
  Frankfurt, Strikman 1983; Cosyn, CW 2020

FSI: Final-state interactions



- DIS final state can interact with spectator

  Changes momentum distributions in tagging

  No effect on total cross section – closure

Questions

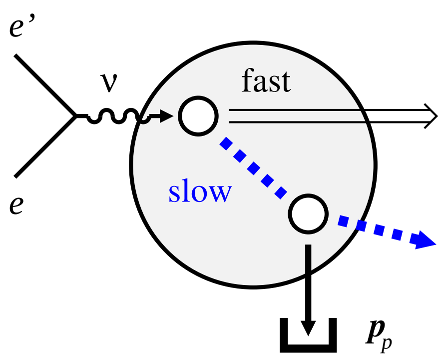
- Hadrons produced in DIS on nucleon: Momentum/angle distributions, spectra, exp data?
- Hadron formation: Times/distances, dependence on kinematics?
- Interaction with spectator: Amplitudes, off-shell effects?

Answers depend on x and Q^2 of DIS process

[Similar questions in exclusive processes]

Need input from nuclear transparency measurements!

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 mass scale, Q^2/ν fixed,
  large phase space for hadron production

- Nucleon DIS final state has two components

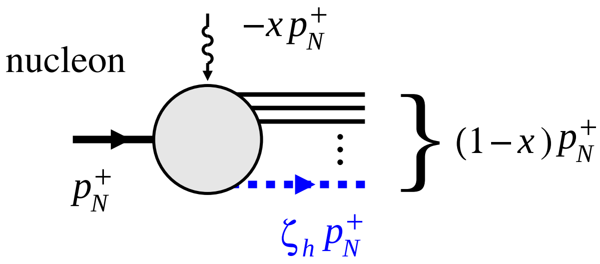
"Fast"	$E_h = O(\nu)$	hadrons formed outside nucleus interact weakly with spectators
"Slow"	$E_h = O(\mu_{\text{had}}) \sim 1$ GeV	formed inside nucleus interacts with hadronic cross section dominant source of FSI $\leftarrow$

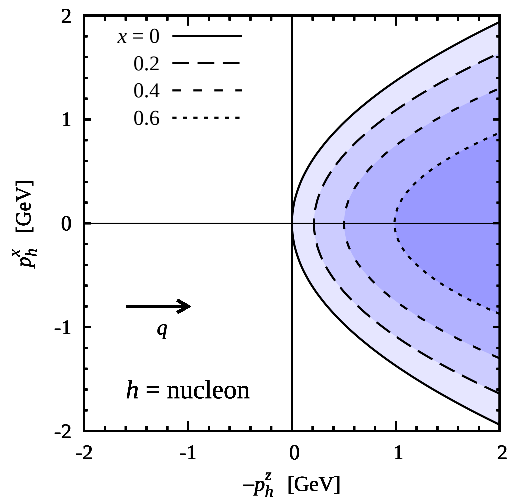
["current" and "target" fragmentation regions]

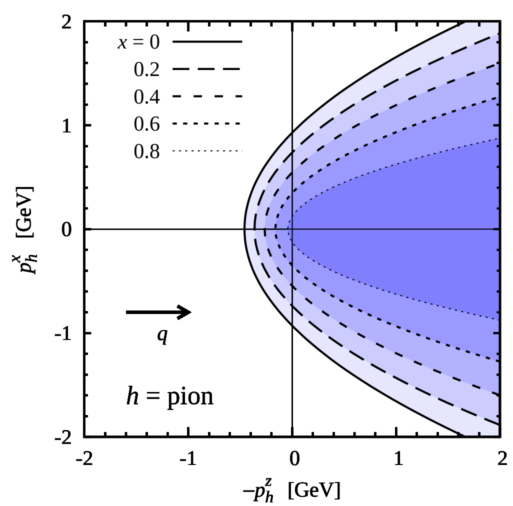
- Respects QCD factorization for target fragmentation
  Trentadue, Veneziano 1993; Collins 1997

  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

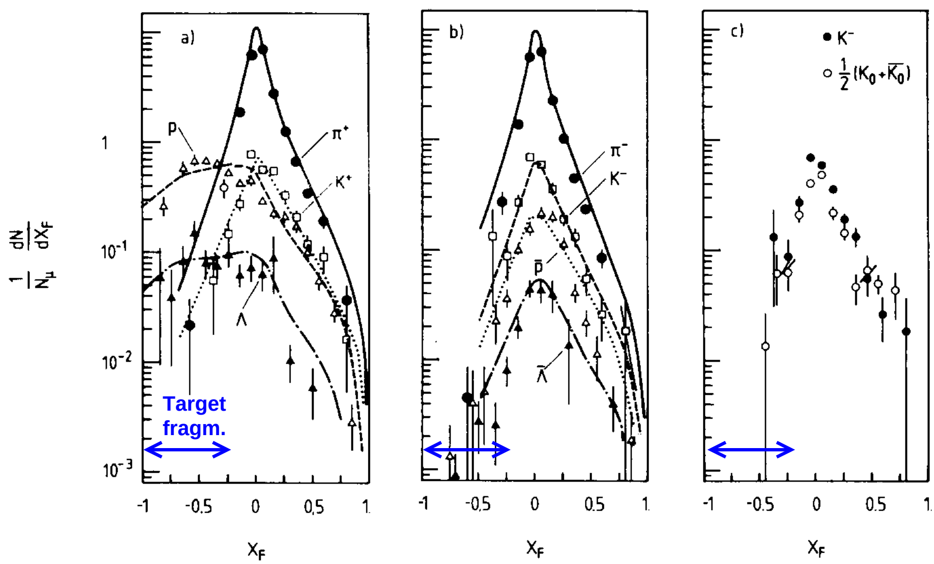
  Cone opening in virtual photon direction $\boldsymbol{q}$

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

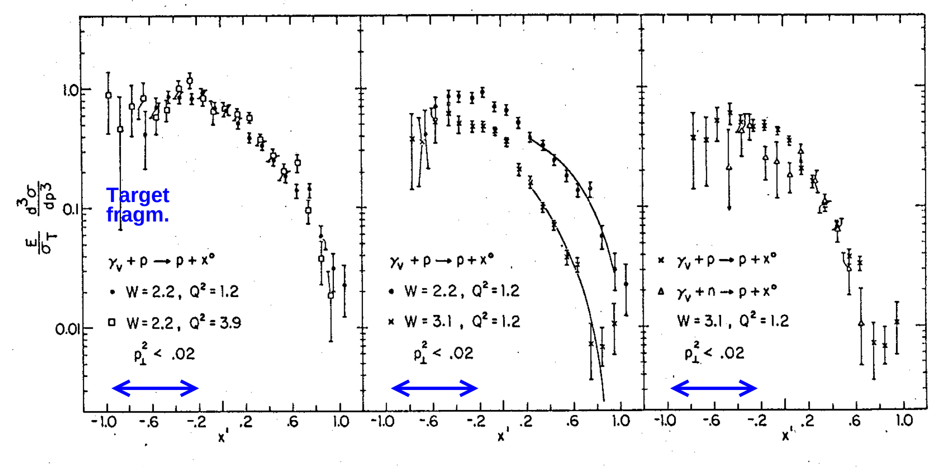
  $h =$ pion: $\boldsymbol{p}_h$ forward or backward

FSI: Hadron distributions from DIS

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



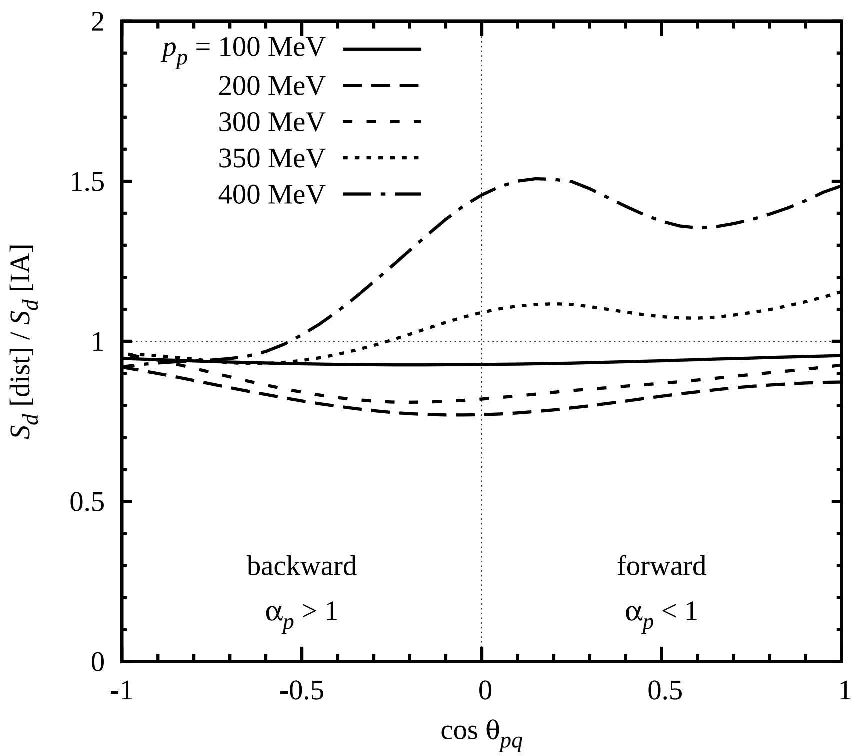
Cornell proton distributions in DIS. Hanson 1976

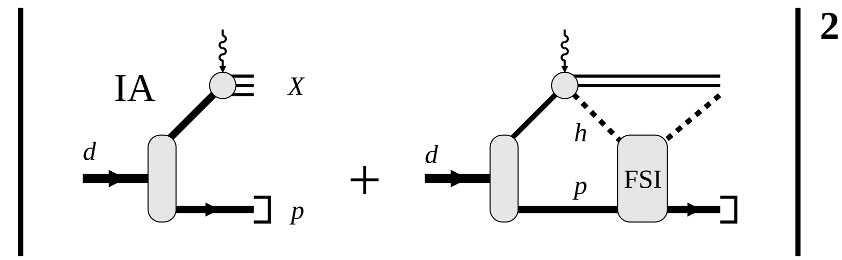


- Measurements of target fragmentation $(x_\mathrm{F} < 0)$
  EMC μp 1986 $x > 0.02$: x_F distributions of $p, \bar{p}, \pi^\pm, K^\pm, \Lambda$
  HERA ep 2009/2014 $x < 0.01$: x_F distributions of p, n
  Cornell ep 1975 $x > 0.1$: Momentum distributions of p, π
  Neutrino DIS: FNAL-E-0031 1977, CERN-WA-021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

- JLab12 and EIC should measure target fragmentation
  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 on-shell point $t - m^2 \to 0$; extrapolation feasible

FSI: Open questions

- FSI in backward region → JLab BAND experiment

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

  FSI from pions?

- Subasymptotic regime of finite ν and Q^2 → JLab 6/12 GeV kinematics

  Present treatment assumes DIS limit – large phase space,
  distinction between fast and slow part of final state

  Connection with resonance region?
  Cosyn, Sargsian, Melnitchouk 2011–

Extensions: Tagging with deuteron

- Tagged DIS with polarized deuteron

  Tagging controls S/D wave ratio
  Frankfurt, Strikman 1983

  Vector-polarized deuteron: Eliminate D-wave depolarization, neutron 100% polarized
  Cosyn, Weiss, PLB799 (2019) 135035; Phys.Rev.C 102 (2020) 065204

  Tensor-polarized deuteron: Realize maximum tensor polarization $[+1, -2]$

  Spin-dependent effects in FSI?

- Tagged DIS at $x \ll 0.1$

  Study configuration dependence of nuclear shadowing

  Diffractive DIS as new source of slow nucleons: Strong FSI, QM treatment
  Guzey, Strikman, CW; in progress

- Tagged exclusive processes

  Meson production or DVCS on neutron

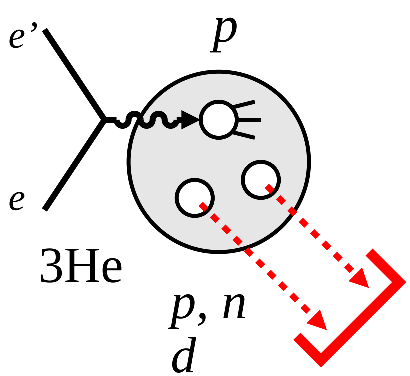
  "Know" forward-going hadron: Simpler FSI calculations, test picture/models

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

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

- Final-state interactions in tagged DIS at $x \gtrsim 0.1$

  Space-time picture of hadron formation and interactions – fast and slow hadrons

  Need experimental data on target fragmentation in DIS, x_F distributions

  Interactions essentially quantum-mechanical – interference, absorption

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

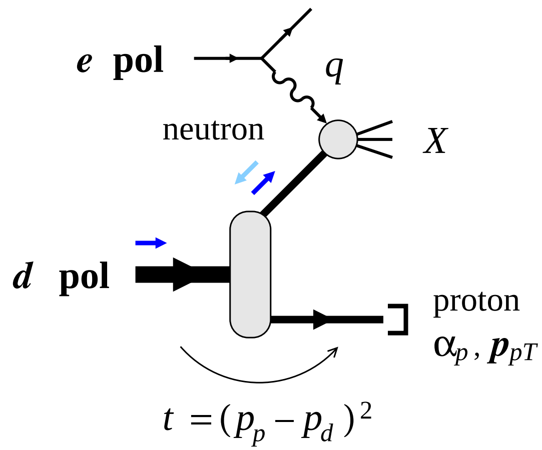
  Can we use tagged DIS to learn about hadronization?

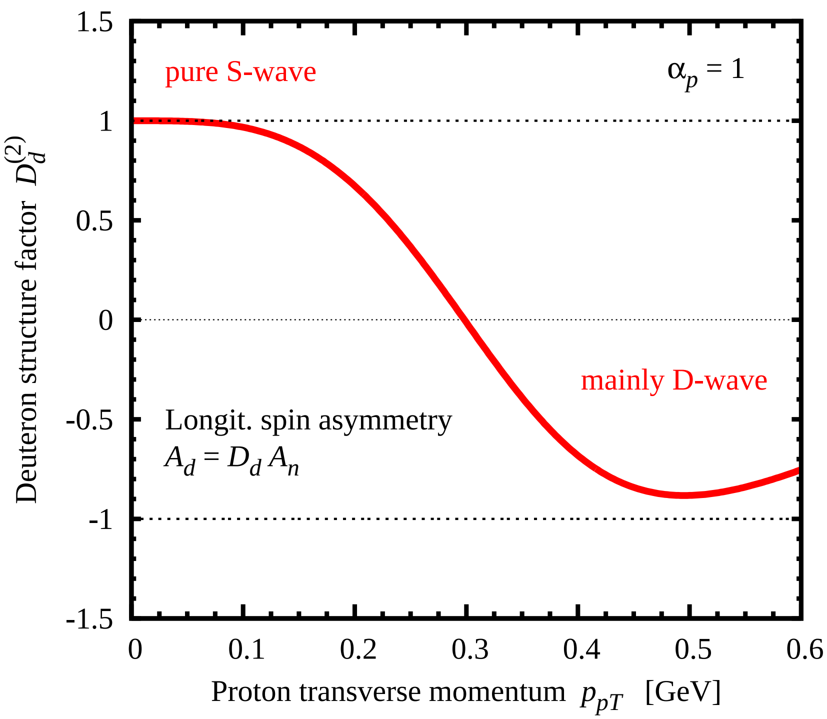
- Extensions of tagging to $A > 2$ require major theoretical development

- 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]

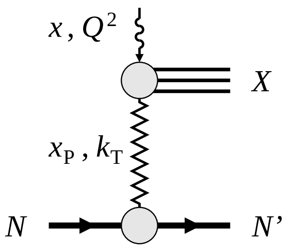
- Free neutron spin structure

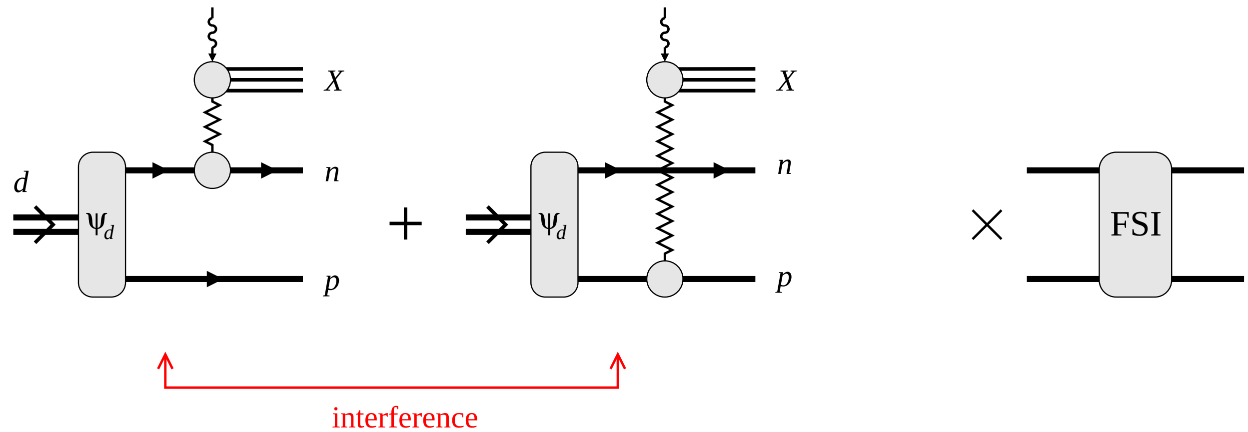
  On-shell extrapolation of asymmetry

- EIC simulations

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

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, deviations from IA
  Guzey, Strikman, CW; in progress