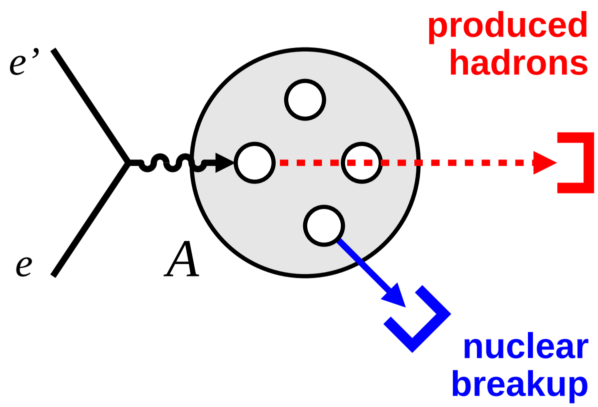
Target fragmentation and nuclear breakup in DIS

C. Weiss (JLab), Fragmentation Functions 2021, INT Seattle, 05 Nov 2021



Nuclear breakup measurements in DIS as special case of target fragmentation

$\rightarrow$ QCD factorization

$\rightarrow$ Structures: p_T, ϕ, spin

$\rightarrow$ Dynamics: Nuclear theory, FSI

$\rightarrow$ Applications

- Target fragmentation in DIS

  QCD factorization

  Conditional PDFs or fracture functions

- Nuclear breakup in DIS

  Simplest case: Deuteron spectator tagging

  Cross section and observables

  Light-front nuclear structure

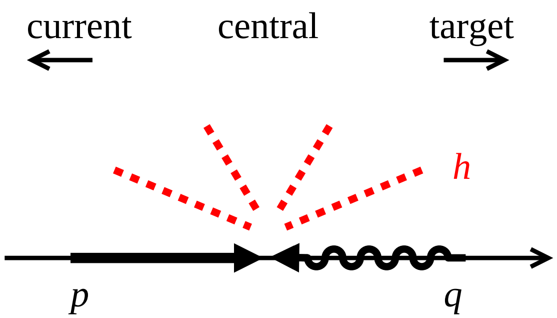
  Final-state interactions

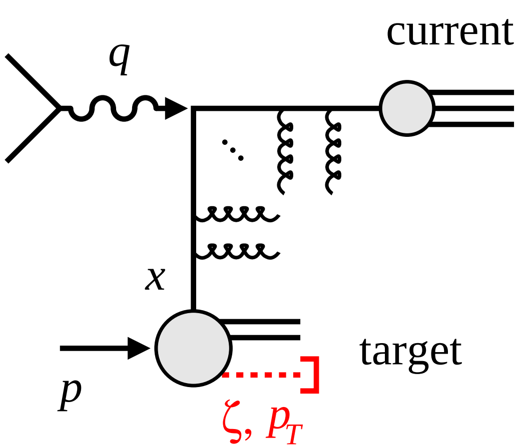
- Applications

  Free neutron structure, EMC effect

  Spin dependence, T-odd structures

Target fragmentation: Basics





- Hadron production in DIS

  Multiplicity $\propto \log W$

  Current – central – target regions

  Variables: Rapidity, x_F, light-cone fraction ζ, ...

- Target fragmentation

  QCD factorization for single-inclusive hadron prodn
  Trentadue, Veneziano 93; Collins 97

  Conditional PDFs or fracture functions

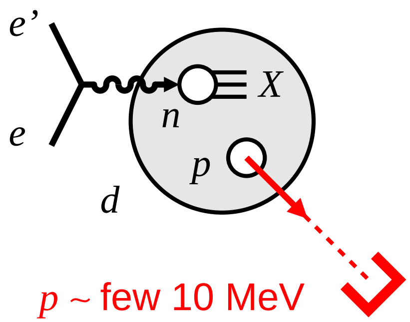
  Leading twist, DGLAP evolution

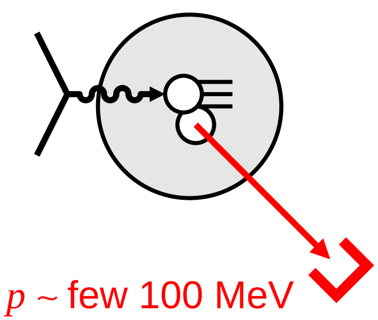
- Applications

  Nucleon: Flavor, spin, parton correlations
  Workshop "Target Fragmentation Physics with EIC,"
  CFNS Stony Brook, 28-30 Sep 2020 [Webpage].
  EIC Yellow Report arXiv:2103.05419

  Nuclei: Nuclear breakup measurements $\leftarrow$

Target fragmentation: Nuclear breakup





[Nuclear rest frame view]

- Nuclear breakup measurements

  Simplest case: $e + d \rightarrow e' + X + p, n$

  "Spectator tagging"

- Applications

  Control nuclear configurations during DIS process:
  Active n or p, size of config $\leftrightarrow$ interactions

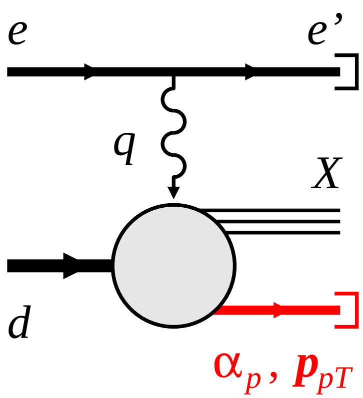
  Neutron structure extraction,
  EMC effect, NN correlations

- Detection

  Fixed-target: Slow nucleons $\sim$ few 10 – 100 MeV
  Protons: JLab6/12 BONUS, ALERT, TDIS
  Neutrons: BAND

  Collider: Far-forward detection
  Excellent capabilities for forward proton and neutrons
  EIC Yellow Report $\rightarrow$ Talk Nguyen

Tagging: Cross section and observables



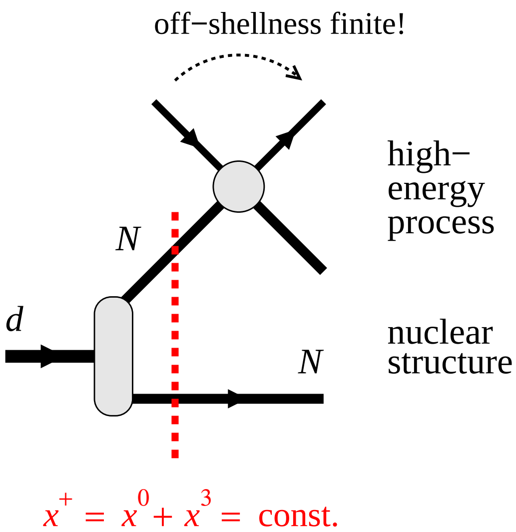
$$\frac{d\sigma}{dx\,dQ^2\,(d^3p_p/E_p)} = [\text{flux}]\Big[F_{Td}(x,Q^2;\alpha_p,p_{pT}) + \epsilon F_{Ld}(..)$$

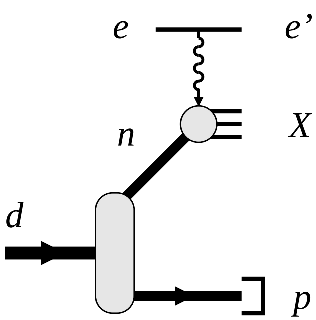
$$+ \sqrt{2\epsilon(1+\epsilon)}\cos\phi_p F_{LT,d}(..) + \epsilon\cos(2\phi_p)F_{TT,d}(..)$$

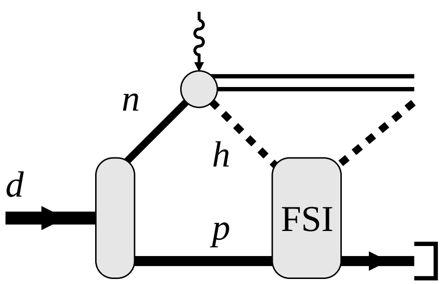
$$+ \text{ spin-dependent structures}\Big]$$

- Semi-inclusive DIS cross section $e + d \rightarrow e' + X + p$
- Tagged proton momentum described by LF components $p_p^+ = \alpha_p p_d^+/2$, $\boldsymbol{p}_{pT}$, simply related to $\boldsymbol{p}_p$(restframe)
- 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 $\leftrightarrow$ non-relativistic theory

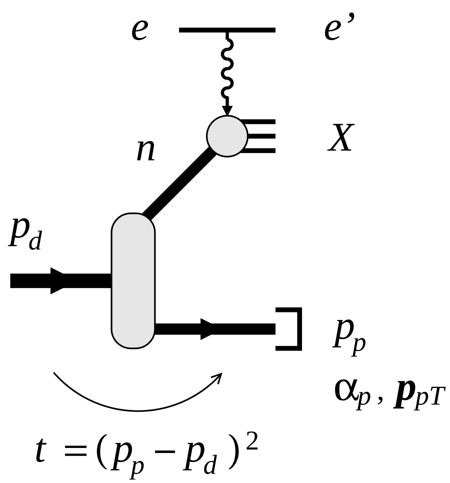
- Composite description

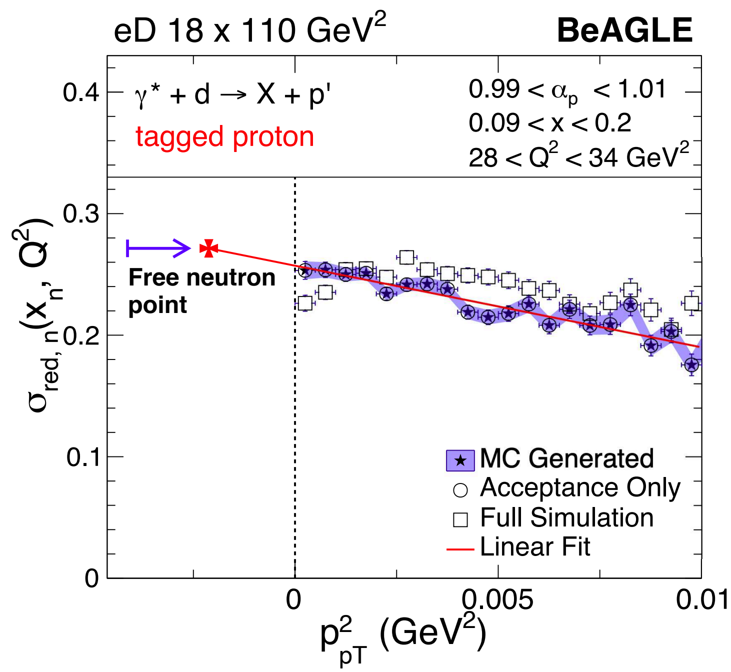
  Impulse approximation IA: DIS final state and spectator nucleon evolve independently

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

  Here: Factorize nuclear and nucleonic structure
  Calculate cross secn from nucleon LT structure functions, not PDFs

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 cross section

- Free neutron from pole extrapolation

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

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

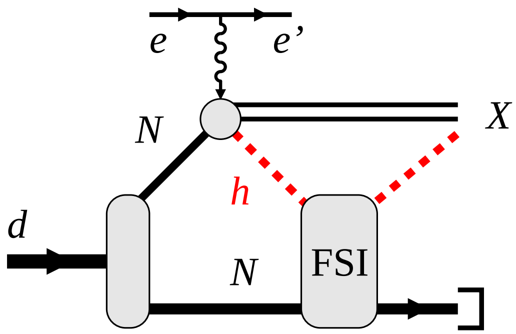
  Eliminates nuclear binding effects and FSI
  Sargsian, Strikman 05

  Extension to polarized DIS
  Cosyn, CW 2020

- EIC simulations

  Far-forward detection of protons/neutrons

Tagging: Final-state interactions



- DIS final state can interact with spectator

  Changes observed nucleon distribution in tagging

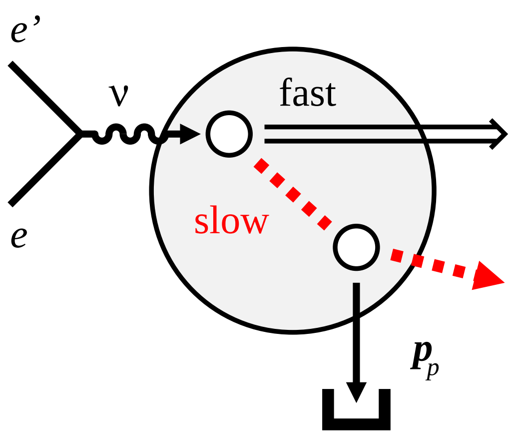
  No effect on total cross section: Closure

  Depends on kinematics: Hadron distributions, formation

- Space-time picture in nuclear rest frame $x \gtrsim 0.1$

  $E_h = O(\nu)$ "fast" hadrons formed outside nucleus interact weakly with spectators

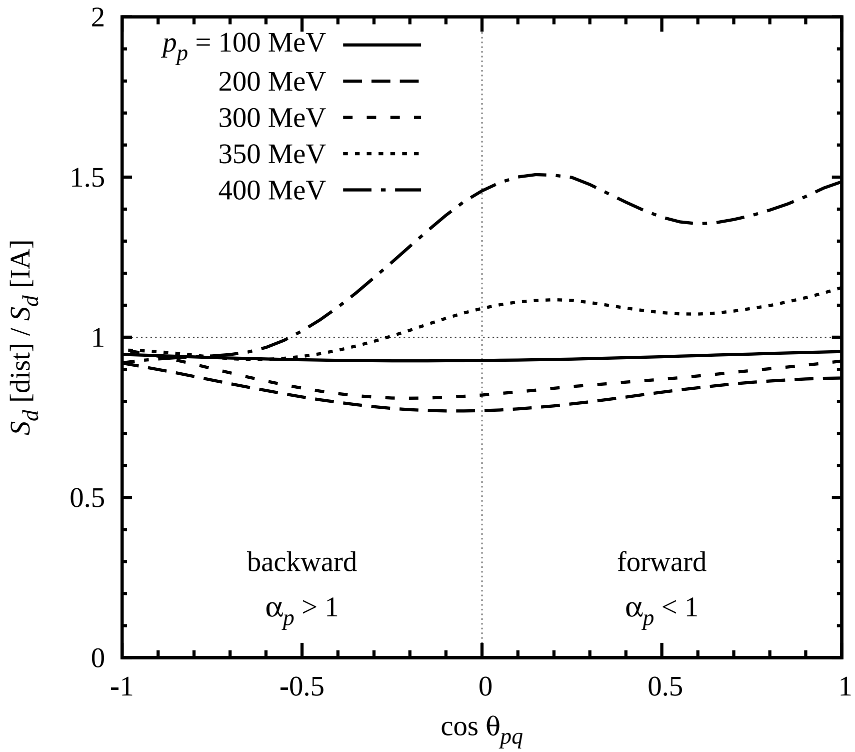
  $E_h = O(\mu_{\mathrm{had}})$ ~ 1 GeV "slow" hadrons formed inside nucleus interact with hadronic cross section dominant source of FSI ←

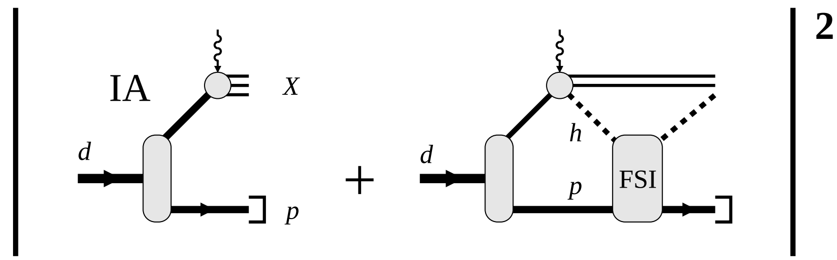


Respects QCD factorization for target fragmentation: FSI only modifies soft breakup of target, no long-range rapidity correlations. FSI leading-twist effect

FSI effect calculated using hadron distribution data, hadronic cross sections
Strikman, CW, PRC97 (2018) 035209

Tagging: Final-state interactions II





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

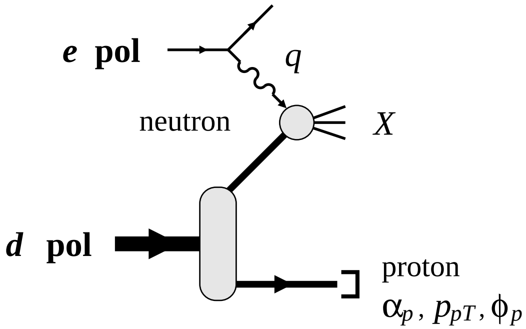
- Momentum and angle dependence in rest frame

  $p_p < 300$ 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

Tagging: Polarized deuteron



- Deuteron spin density matrix $\rho_{\lambda\lambda'}(S, T)$

  3 vector parameters, 5 tensor parameters

  Fixed by polarization measurements
  cf. Stokes' parameters for photon

- Polarized tagged cross section

Cosyn, Sargsian, CW 17

$$\frac{d\sigma}{dx dQ^2 (d^3 p_p / E_p)} = [\text{flux}](\mathsf{F}_U + \mathsf{F}_S + \mathsf{F}_T) \qquad \mathsf{F}_I = \text{functions}(x, Q^2, \alpha_p, p_{pT}, \phi_p)$$

$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h\sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LU}^{\sin\phi_h}$$

$$\begin{aligned}
F_S = {} & S_L \left[\sqrt{2\epsilon(1+\epsilon)} \sin\phi_h F_{US_L}^{\sin\phi_h} + \epsilon \sin 2\phi_h F_{US_L}^{\sin 2\phi_h} \right] \\
& + S_L h \left[\sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_h F_{LS_L}^{\cos\phi_h} \right] \\
& + S_\perp \left[\sin(\phi_h - \phi_S) \left(F_{US_T,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{US_T,L}^{\sin(\phi_h-\phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{US_T}^{\sin(\phi_h+\phi_S)} \right. \\
& \left. + \epsilon \sin(3\phi_h - \phi_S) F_{US_T}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left(\sin\phi_S F_{US_T}^{\sin\phi_S} + \sin(2\phi_h - \phi_S) F_{US_T}^{\sin(2\phi_h-\phi_S)} \right) \right] \\
& + S_\perp h \left[\sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LS_T}^{\cos(\phi_h-\phi_S)} + \right. \\
& \left. \sqrt{2\epsilon(1-\epsilon)} \left(\cos\phi_S F_{LS_T}^{\cos\phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h-\phi_S)} \right) \right] ,
\end{aligned}$$

Tagging: Polarized deuteron II

$$
\begin{aligned}
F_T = T_{LL} \Big[& F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UT_{LL}}^{\cos\phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \Big] \\
& + T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{LT_{LL}}^{\sin\phi_h} \\
& + T_{L\perp} [\cdots] + T_{L\perp} h [\cdots] \\
& + T_{\perp\perp} \Big[\cos(2\phi_h - 2\phi_{T_\perp}) \Big(F_{UT_{TT},T}^{\cos(2\phi_h - 2\phi_{T_\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h - 2\phi_{T_\perp})} \Big) \\
& + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_\perp})} \\
& + \sqrt{2\epsilon(1+\epsilon)} \Big(\cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_\perp})} \Big) \Big] \\
& + T_{\perp\perp} h [\cdots]
\end{aligned}
$$

- U + S cross sections identical to spin-1/2 target — Bacchetta et al. 07

- T cross section has 23 new tensor structure functions specific to spin-1
  4 structure functions survive in inclusive DIS, cf. $b_1 - b_4$ — Hoodbhoy, Jaffe, Manohar 88

  ϕ-harmonics specific to tensor polarization — new handle

- T-odd structures vanish in impulse approximation,
  provide sensitive tests of FSI

Tagging: Applications and extensions

- Spectator tagging + current fragmentation SIDIS

  Use both target and current fragmentation regions – correlations → see also Talk Avakian

  Additional information for flavor separation: $p \leftrightarrow n$ and $\pi^+, K^+ \leftrightarrow \pi^-, K^-$

- Tagged exclusive processes

  Meson production or DVCS on neutron

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

- Tagging with nuclei $A > 2$ → Talk Nguyen

  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

- Nuclear breakup as special case of target fragmentation

  General form of SIDIS cross section, including p_T, ϕ spin dependence

  QCD factorization theorem, leading-twist structures

  "Fracture functions" calculated from nuclear theory

  New possibilities: Spin-1 target, tensor polarization, T-odd structures

  Should be interesting to researchers in SIDIS/fragmentation

- Practical applications

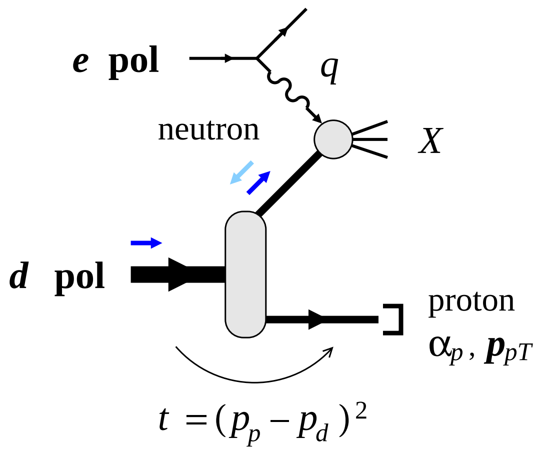
  Initial-state structure: Free neutron, EMC effect, NN correlations, . . .

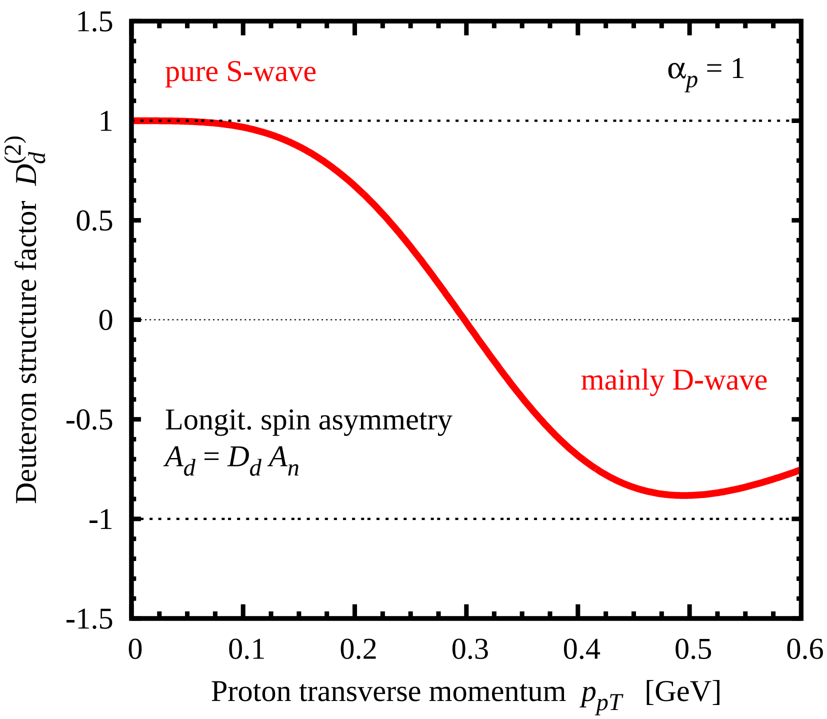
  Final-state interactions: Use nuclear breakup to learn about hadronization process?
  $\rightarrow$ Talk Gallmeister

- Exciting prospects for programs at JLab12 and EIC

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]

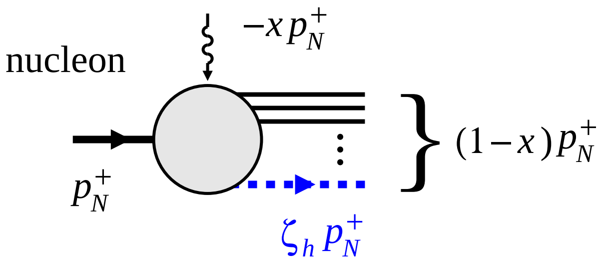
- Free neutron spin structure

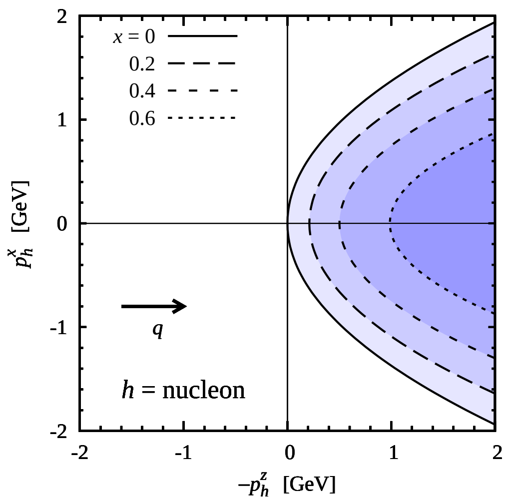
  On-shell extrapolation of asymmetry

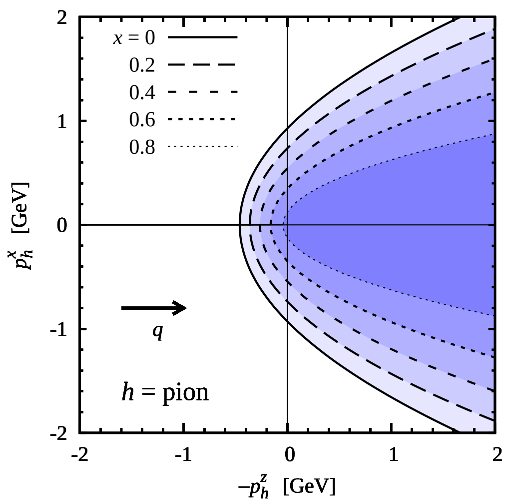
- EIC simulations

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

FSI: 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

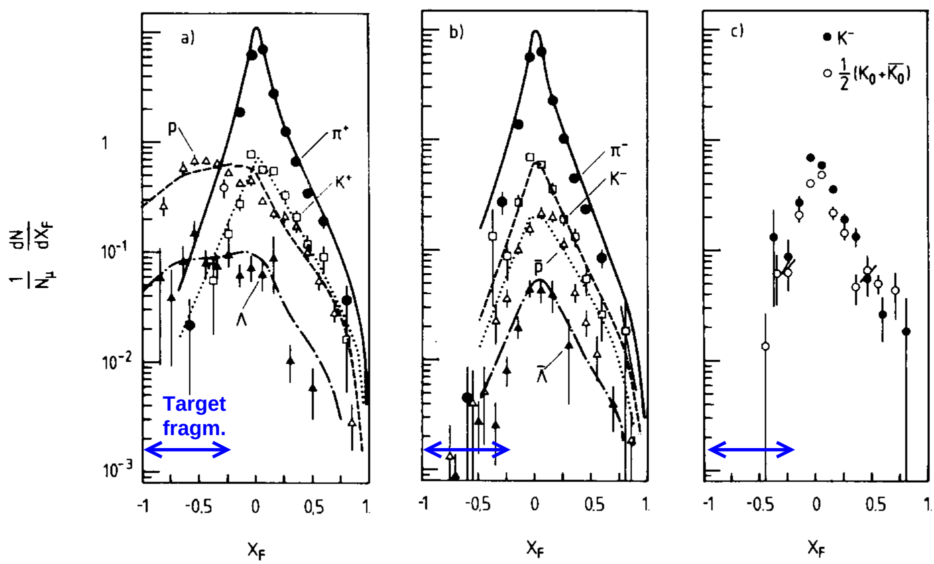
  Cone opening in virtual photon direction $\boldsymbol{q}$

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

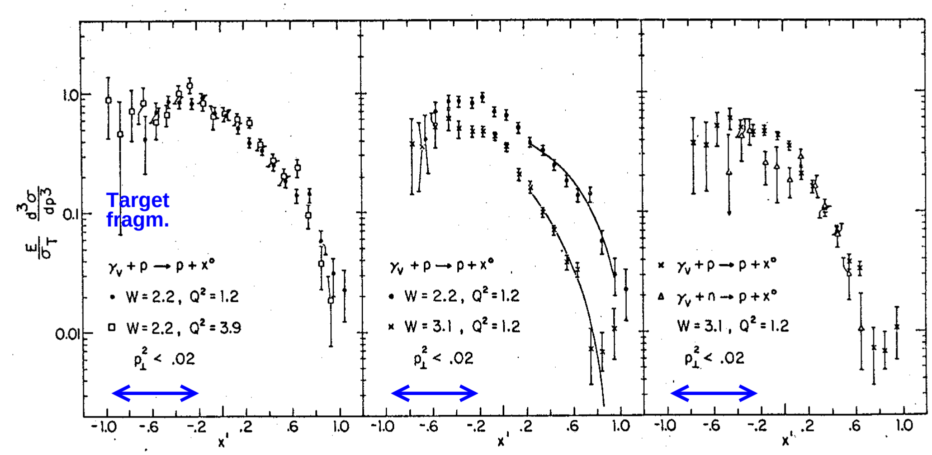
  $h =$ pion: $\boldsymbol{p}_h$ forward or backward

FSI: Hadron distributions from DIS

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



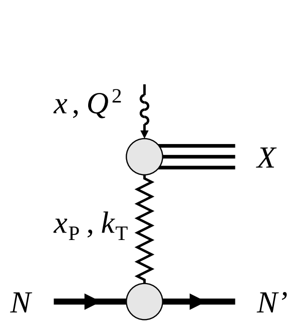
Cornell proton distributions in DIS. Hanson 1976

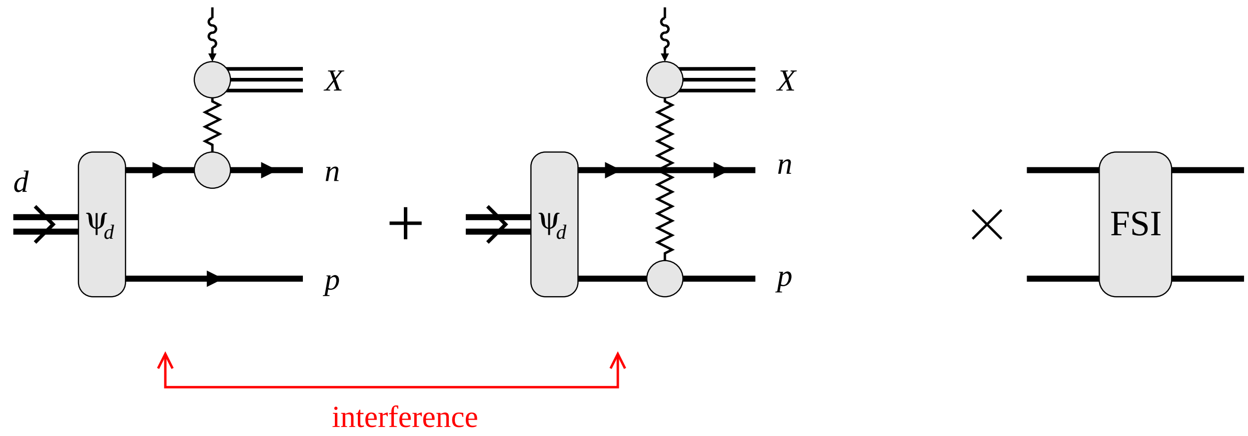


- Measurements of target fragmentation $(x_{\mathrm{F}} < 0)$
  EMC μp 1986 $x > 0.02$: x_{F} distributions of $p, \bar{p}, \pi^{\pm}, K^{\pm}, \Lambda$
  HERA ep 2009/2014 $x < 0.01$: x_{F} distributions of p, n
  Cornell ep 1975 $x > 0.1$: Momentum distributions of p, π
  Neutrino DIS: FNAL-E-0031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

- JLab12 and EIC should measure target fragmentation $\rightarrow$ 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: Diffractive DIS at small x





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

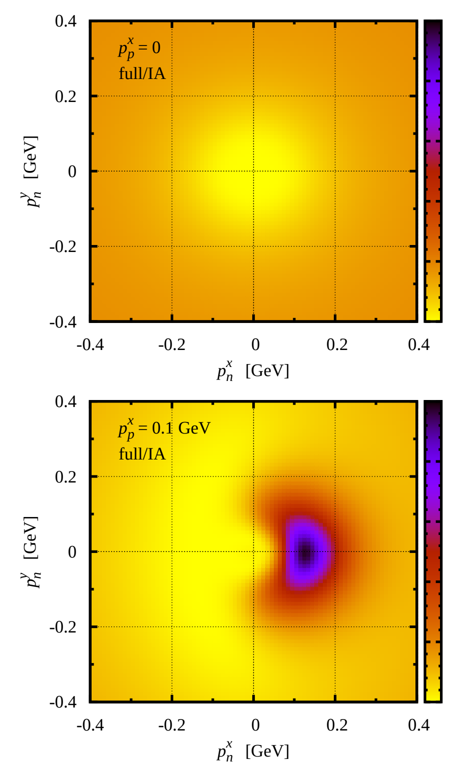
- Shadowing: QM interference of diffractive scattering on neutron or proton
  Observed in inclusive nuclear scattering

- 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

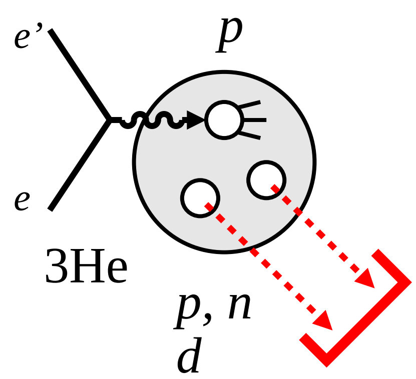


Extensions: Tagging with nuclei $A > 2$

- Potential applications

  Isospin dependence neutron ↔ 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 ↔ 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