Final-State Interactions in Nuclear Breakup Measurements From JLab to EIC

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Why Intermediate and High-Energy Nuclear Reactions?

Study emergent QCD phenomena: properties of hadrons

- Neutron structure (flavor separation)
- Influence of **nuclear interactions**, medium modifications
  → talks Arrington, Hauenstein
- Hadronization: how does a colored struck q evolve into a colorless hadron?
  - **space-time evolution** through interactions with the nuclear medium
    → talk Vitev
- Scattering properties of unstable hadrons through secondary interactions
  - scattering lengths of strange baryons (CLAS, ALICE)
- Some phenomena are **unique** to nuclei
  - spin $> \frac{1}{2}$, superfast quarks with $x > 1$
- Color transparency → talk Dutta
- Gluon saturation at low x (EIC)
- ...

Why Nuclear Reactions?

Learn more about nuclear structure

- What is the nature of the **hard core** in the *NN* interaction
  - deuteron breakup at very high momenta
- What are the limits of the nuclear shell model?
  - nature and role of **short-range correlations**
    $\rightarrow$ talk Fomin
- **Non-nucleonic** degrees of freedom in nuclei
  - delta isobars, hidden color
- 3D imaging of nuclear bound states in quark and gluon degrees of freedom
  - **coherent** hard exclusive reactions

Measurements

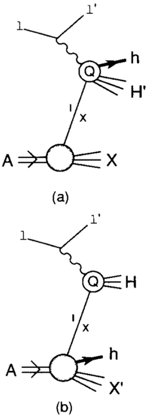
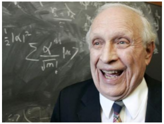


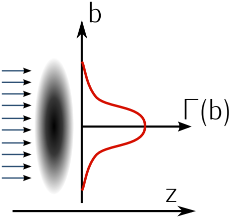
Image: HERA

- Inclusive scattering: SRCs (a_2), F_{2A}, F_{2n}, ...
  - Averages over all nuclear configurations
- Detect additional hadrons in
  - (a) current fragmentation region: select reaction
  - (b) target framentation region:

    control initial nuclear configuration
    - recoil nucleon partner from a SRC
    - nuclear fragments for light nuclei
      $\rightarrow$ difficult for low momentum in fixed target, but EIC!
    - veto incoherent in eA
- Cuts to ensure a particular residual system (e.g. $A-1$)
- Detected particles are subject to **final-state interactions**
  - needs to be accounted for
  - interplays with other reaction effects (medium modifications), how to disentangle?
  - can also be **used** to study hadronization, scattering, dynamics
    $\rightarrow$ **data with large FSI are useful!**

Quasi-Elastic: FSI in configuration space

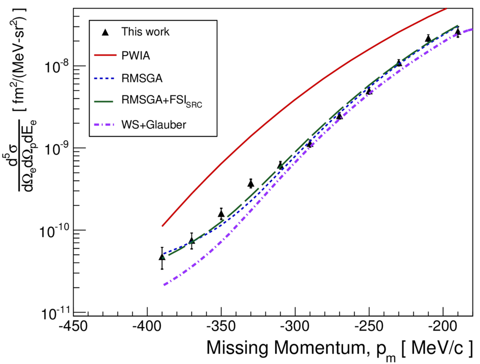




- Medium and heavy nuclei
- Glauber theory has origins in optics
- High-energy **diffractive** scattering: small angles
- **Eikonal** method
  $\phi_{\text{scat}}(\boldsymbol{r}) = e^{i\chi(\boldsymbol{r})}\phi_{\text{in}}(\boldsymbol{r}) = (1 - \Gamma(\boldsymbol{b}))\,\phi_{\text{in}}(\boldsymbol{r})$
- Parameters taken from data (NN) or educated guesses

In an ideal world... $A(e,e'p)$

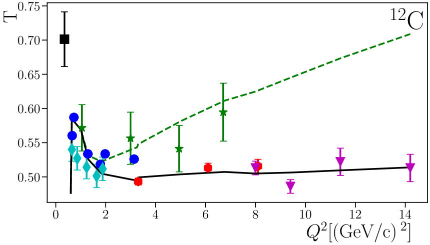
- $d^5\sigma \approx K\sigma_{ep}S(p_m)$
- Cross section vs relativistic **unfactorized** calculation



P. Monaghan et al. (JLab Hall A), JPG41 105109 ('14)

- Proton knockout from valence $p_{3/2}$ shell
- FSI: Relativistic Multiple Scattering Glauber Approximation
- Nice agreement between RSMGA calculations and data up to very high missing momenta
  $\rightarrow$ **No** free parameters!

CT in proton knockout? A(e,e'p)



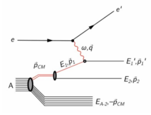
`W.C., J. Ryckebusch, MDPI Physics ('22)`
`data: Bhetuwal et al. (Hall C) PRL '21`

- RMSGA: excellent agreement with A(e,e'p) world data (JLab, SLAC, MIT Bates)
- No signs of CT yet

- Similar machinery (including charge exchange) applied to $A(e, e'NN)$ JLab measurements

MC implementation: BEAGLE example

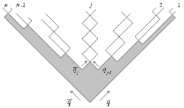
GCF
See: F. Hauenstein et al.,
PRC 105(2002) 3 034001



Primary interaction

PyQM: Nuclear Geometry + optional gluon radiation in medium.

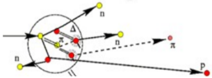
Hadronization handled by **PYTHIA6.**



Hadronization

Cascade process
handled by **DPMJET.**

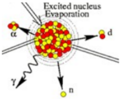
Formation time.
Stochastic.



Intra-nuclear cascade

Nuclear remnant
evaporation and
break up by **FLUKA.**

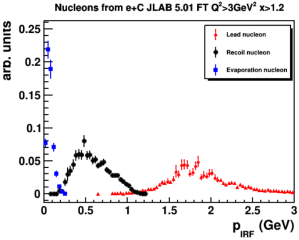
Nuclear remnant
evaporation & breakup



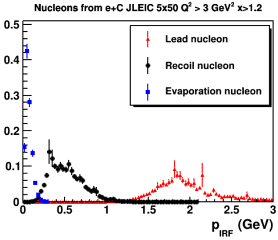
Courtesy of M. Baker
W. Chang et al. PRD 106 ('22) 2204.11998

Beagle: INC in A(e,e'NN)

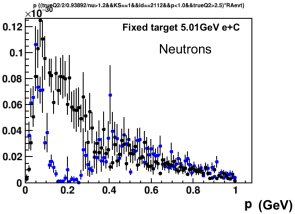
JLAB 5.01 GeV FT e+C
$Q^2>3$ GeV^2, $x>1.2$



EIC 5x50 e+C
$Q^2>3$ GeV^2, $x>1.2$

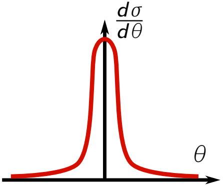


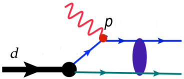
Blue is no INC $x>1.2$, $Q^2>2.5$ GeV^2
Black is full BeAGLE $x>1.2$, $Q^2>2.5$ GeV^2



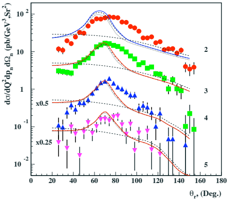
Courtesy of M. Baker

FSI in momentum space





quasi-elastic breakup

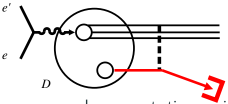


- Eikonal picture: rescatterings are forward peaked
- Effective Feynman diagrammatic rules, takes recoil of medium into account

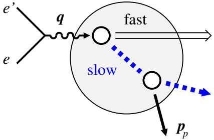
  [Frankfurt, Sargsian, Strikman]
- Light nuclei!
- FSI peak at deuteron around 70°
- Reduction cross section for spectator momenta ~ 100 MeV
  $\rightarrow$ interference IA-FSI
- Enhancement cross section for spectator momenta > 300 MeV
  $\rightarrow$ FSI^2 term

[Sargsian PRC82]

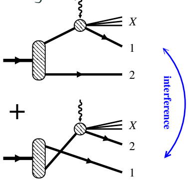
FSI in DIS: physical pictures



subasymptotic regime: low Q^2, high x



DIS regime, intermediate x



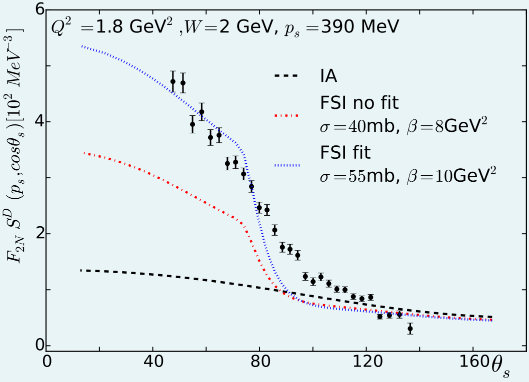
shadowing, low x

- rescattering of resonance-like structure with spectator nucleon in eikonal approximation [Deeps,BONuS].

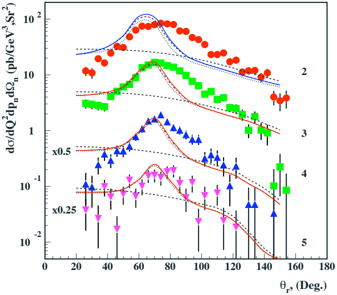
`WC,M. Sargsian arXiv:1704.06117`

- FSI between slow hadrons from the DIS products and spectator nucleon, fast hadrons hadronize after leaving the nucleus.
- Shadowing in DIS $x \ll 10^{-1}$
- The lower the x the more low-energy NP the FSI become

FSI: DIS subasymptotic vs QE



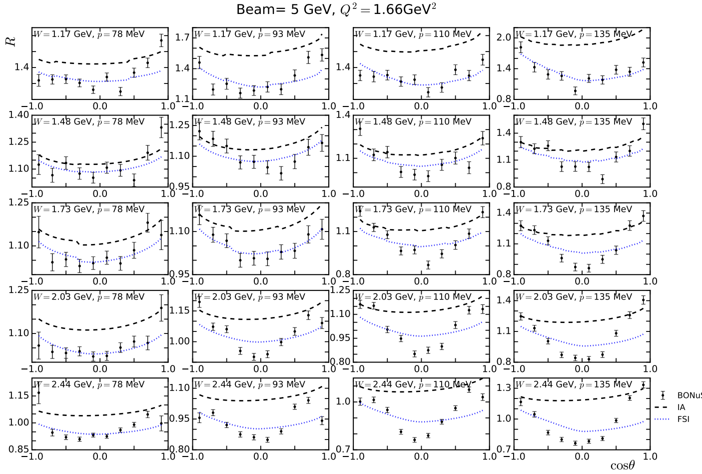
D(e,e'p$_s$)X   WC, M. Sargsian PRC84



D(e,e'p$_s$)n

M. Sargsian PRC82 014612 ('10)

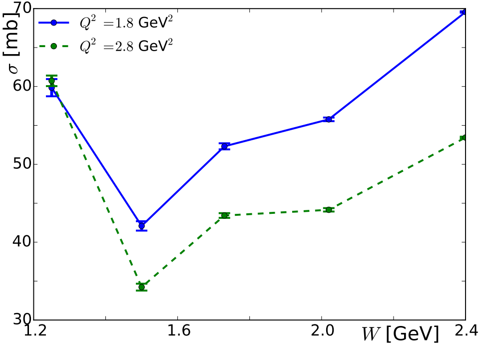
- Plane-wave calculation shows little dependence on spectator angle
- FSI effects grow in forward direction, different from quasi-elastic case
- Needs more data to **constrain**!



data: BONuS S. Tkachenko et al., Phys.Rev. C89 (2014) 045206
WC, M. Sargsian PRC '14

- In backward region FSI not necessarily small (compared to forward region) in these kinematics!

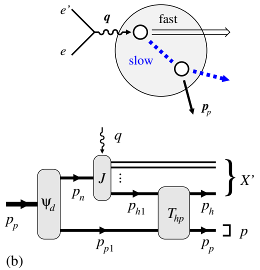
What can the σ_{XN} fit teach us?

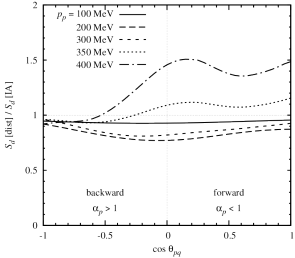


- σ rises with invariant mass W, no sign of hadronisation plateau
- σ drops with Q^2, sign of Color Transparency?

- More measurements at higher Q^2 needed
- Values can be used as input for FSI effects in other calculations, such as **inclusive** DIS
  `[WC, Melnitchouk, Sargsian PRC '14]`

Intermediate x model (EIC): deuteron

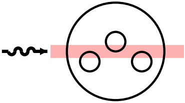




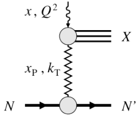
Strikman, Weiss, 1706.02244, PRC '18

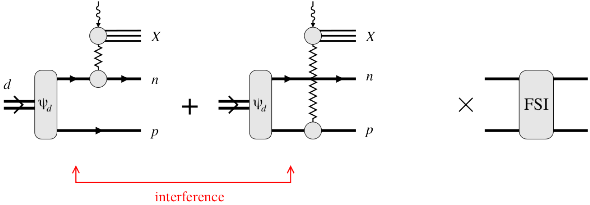
- Data show slow hadrons in the target fragmentation region are mainly nucleons.
- Input needed from nucleon target fragmentation data → possible at EIC
- Features similar to quasi-elastic deuteron breakup.
- FSI diagram adds two contributions: FSI term (∼ absorption, negative) and FSI^2 term (∼ refraction, postive)
- At low momenta ($p_r < 200$ MeV) FSI term dominates, at larger momenta FSI^2 dominates.

Nuclear shadowing



- interaction of high-energy probe with coherent quark-gluon fields

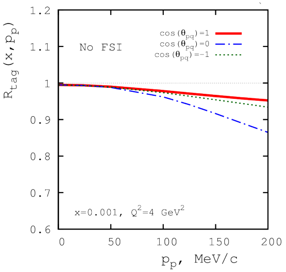


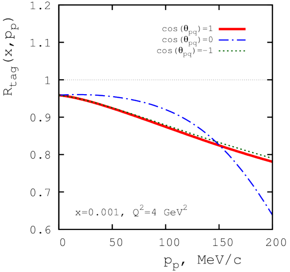


- **Shadowing** is manifestation of coherence
  - **Diffractive** DIS at $x \ll 0.1$: 10–15% of events at HERA
  - **Interference** between diffractive amplitudes
    $\rightarrow$ reduction of cross section, leading twist
  - Extensively studied in heavy nuclei
  - Is especially clean in the **deuteron**, effects can be calculated
  - **Dynamics** of shadowing can be explored in tagging: **single** and **double**
  - Tagging also results in **FSI** between the slow n and p

[Guzey,Strikman,Weiss; in preparation]

Shadowing: tagged DIS





[Guzey,Strikman,Weiss; in preparation]

- Explore shadowing through recoil momentum dependence
- Shadowing **enhanced** in tagged DIS compared to inclusive
  - enhancement factor from AGK rules
  - shadowing term drops slower with p_R than IA
- Large FSI effects in **diffractive** amplitudes ($\sim$ 40%), also at zero spectator momenta due to orthogonality of *np* state to deuteron
- Effects smaller in all tagged as diffractive are $\sim$ 10% of total events

Conclusions

- FSI can be a nuisance and but can also be used to study QCD dynamics
- Different FSI dynamics depending on Bjorken x
- Magnitude of FSI depends on detected hadron kinematics
- Quite well understood for quasi-elastic, tagged DIS (deuteron)
  $\rightarrow$ but more data helps, especially for DIS
- What needs work
  - Tagged DIS for $A > 3$
  - polarized FSI
  - Tagged DVCS, SIDIS, ...
- Ongoing work in MC development
- A lot I couldn't cover here