Final State Interactions in Deep Inelastic Processes

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Correlations in Partonic and Hadronic Interactions 2018
Yerevan

based on
WC, M. Sargsian,
arXiv:1704.06117
Why care about final-state interactions

- **Partonic** FSI generate non-zero SSA
  - Hwang, Schmidt, Brodsky, Ji, Burkhardt;...

- We need measurements on **nuclear** targets to fully understand non-perturbative dynamics of QCD
  - flavor separation of distr. functions
  - short-range structure of the *NN* force
  - medium modifications of nucleon properties

- Inclusive DIS on nuclei: use closure over final-states
  - (anti-)shadowing corrections at low $x$
  - FSI corrections at large $x$ where there is limited phase-space in the final state

- Nuclear FSI **definitely** play a role in semi-inclusive and exclusive processes
  - FSI modify your signal, need to be accounted for
  - **Use** these FSI to study space-time evolution of DIS process
Main focus so far has been nuclear ratios of semi-inclusive production of leading mesons or jets
    - sensitive to sum of formation, coherence and production time

DIS off a (light) nuclear target with a slow (relative to nucleus c.m.) nucleon detected in the final state (target fragmentation region)

Control nuclear configuration, intranucleon distances

Precision nuclear structure input available

Wealth of possibilities to study (nuclear) QCD dynamics

Will be possible in a wide kinematic range @ EIC (polarized)
Final-state interactions: three physical pictures

- **Shadowing in inclusive DIS** $x \ll 10^{-1}$
  - Diffractive DIS on single nucleon (leading twist, HERA)
  - Interference of DIS on nucleon 1 and 2
  - Calculable in terms of nucleon diffractive structure functions [Gribov 70s, Frankfurt, Guzey, Strikman ’02+]

- **FSI** between slow hadrons from the DIS products and spectator nucleon, fast hadrons hadronize after leaving the nucleus.
  - Data show slow hadrons in the target fragmentation region are mainly nucleons.
  - Input needed from nucleon target fragmentation data → possible at EIC
    M. Strikman, Ch. Weiss PRC’18

- **Rescattering** of resonance-like structure with spectator nucleon in eikonal approximation [Deeps, BONuS].
  WC, M. Sargsian arXiv:1704.06117
Large $x$ model

- $X$: details about composition and evolution unknown
- Use general properties of soft scattering theory, without specifying $X$
- Factorized approach

W.C., M. Sargsian, PRC84 014601 ('11)

- Generalised Eikonal Approximation
  - takes spectator recoil into account
  - can use realistic nuclear wf
- Ideal for light nuclei! ($D$, $^3He$, ...)

- Scattering amplitude: diffractive form
  \[
  \langle p_r, X|\mathcal{F}|p_r', X'\rangle = \sigma_{tot}(W, Q^2)(i+\epsilon(W, Q^2))e^{\frac{\rho(W, Q^2)}{2}t}\delta_{s_r, s_r'}\delta_{s_X}
  \]

- Invariant mass of $X$ can change in rescattering
D(e,e'p_{s})X calculation without fits \((p_{s} = 300 - 560 \text{ MeV})\)

- Plane-wave calculation shows little dependence on spectator angle
- FSI effects grow in forward direction, different from quasi-elastic case
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M. Sargsian PRC82 014612 ('10)
Calculation with $\sigma_{XN}$ and $\beta_{XN}$ fitted at $Q^2 = 1.8$ GeV$^2$ increasing $p_s$.

Increasing invariant mass of $X$:

- Data: Klimenko et al. (JLab CLAS), PRC73 035212 ('06) calc: W.C., M.S. PRC84 014601 ('11)
Calculation with $\sigma_{XN}$ and $\beta_{XN}$ fitted at $Q^2=2.8$ GeV$^2$

Increasing $p_s$

Data: Klimenko et al. (JLab CLAS), PRC73 035212 ('06)  calc: W.C., M.S. PRC84 014601 ('11)
What can the $\sigma_{XN}$ fit teach us?

- $\sigma$ rises with invariant mass $W$, no sign of hadronisation plateau
- $\sigma$ 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
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$Q^2 = 1.8 \text{ GeV}^2$
$Q^2 = 2.8 \text{ GeV}^2$
Comparison with BONuS ($p_s = 70 - 140$ MeV)

\begin{align*}
\text{Beam} &= 5 \text{ GeV, } Q^2 = 1.66 \text{GeV}^2 \\
W &= 1.17 \text{ GeV, } p = 78 \text{ MeV} \\
W &= 1.17 \text{ GeV, } p = 93 \text{ MeV} \\
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W &= 1.17 \text{ GeV, } p = 135 \text{ MeV} \\
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\end{align*}

\[ \cos \theta \]

\[ W = 2.44 \text{ GeV, } p = 135 \text{ MeV} \]

\[ \text{FSI} \]

\[ \text{BONuS} \]

\[ \text{IA} \]


- In backward region FSI not necessarily small (compared to forward region) in these kinematics!
Pole extrapolation for on-shell nucleon structure

- Allows to extract free neutron structure in a **model independent** way
  - Recoil momentum $p_R$ controls off-shellness of neutron $t' \equiv t - m_N^2$
  - Free neutron at pole $t - m_N^2 \to 0$: “on-shell extrapolation”
  - Small deuteron binding energy results in small extrapolation length
  - Eliminates nuclear binding and FSI effects

- Esp. suited for colliders: spectators still move forward with $\sim 1/2$ the beam momentum
- D-wave suppressed at on-shell point $\to$ neutron $\sim 100\%$ polarized
- Precise measurements of neutron (spin) structure at an EIC
Use Bonus data: $F_{2n}/F_{2p}$

- Robust results wrt deuteron wave function, fsi parameters, normalization of the data used in the extraction.
- Striking rise of the ratio at high $x$, would mean large $d/u$ ratio at high $x$
- Ratio highest at largest $Q^2$ value ... Duality arguments??
- Sign of hard isosinglet quark-quark correlation, analogous to $np$ pairing in nuclei?

W.C., M. Sargsian, PRC93 ’16
Inclusive DIS

- **Optical theorem**: relate hadronic tensor for inclusive process to imaginary part of forward scattering amplitude
  \[ W_{D,\text{incl}}^{\mu\nu} = \frac{1}{2\pi M_D} \frac{1}{3} \sum s_D, N \text{Im}(A_{D,\text{incl}}^{\mu\nu}) \]

- Effective rescattering amplitude: **only** possible FSI diagram

- FSI amplitude contains double on-shell and double off-shell rescatterings. On-shell off-shell cross terms cancel.

- Symmetrical \((X' = X)\) and assymmetrical rescatterings considered.

W.C., M. Sargsian, W. Melnitchouk, PRC89, 014612 (2014)
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**Challenge**: description of the FSI amplitude over the whole \(x, Q^2\) range.

W.C., M. Sargsian, W. Melnitchouk, PRC89, 014612 (2014)
Use three effective resonances in the FSI diagram and continuum contribution (distribution)

- Take scattering parametrizations from our fit to the Deeps data
- We don’t take into account any possible relative phases between the resonances: maximum possible effect
Inclusive DIS calculations

- Higher twist effect: available phase space for rescattering shrinks with higher $Q^2$
Inclusive DIS calculations

Ratio to $F_{2N}$

Deuteron wf dependence

\[ \frac{F_{2D}}{F_{2N}} \]

\[ Q^2 = 2 \text{ GeV}^2 \]

(a)

(b)

\[ Q^2 = 20 \text{ GeV}^2 \]

\[ Q^2 = 10 \text{ GeV}^2 \]

Wim Cosyn (UGent)
Features of the FSI of slow hadrons with spectator nucleon are similar to what is seen in quasi-elastic deuteron breakup.

Inclusion FSI diagram adds two contributions: FSI term ($\sim$ absorption, negative) and FSI$^2$ term ($\sim$ refraction, positive)

At low momenta ($p_r < 200$ MeV) FSI term dominates, at larger momenta FSI$^2$ dominates.

Both contributions vanish at the pole → pole extrapolation still feasible

Strikman, Weiss, 1706.02244, PRC '18
Conclusions

- FSI can help us **understand space-time evolution** of DIS process.
- Important to measure semi-inclusive processes on nuclei in **kinematics with high FSI** to constrain models.
- Model for FSI in tagged spectator DIS on the deuteron based on general properties of soft rescattering in high $x$ regime.
- Fair description of the Deeps and Bonus data.
- Cross section rises with $W$ and shows no signs of a plateau (hadronization) yet and **drops** with higher $Q^2$ (CT-like effect!)
- Extraction of neutron structure possible w **pole extrapolation** (EIC), intriguing result from our analysis of the BONuS data.
- In inclusive DIS: natural suppression of FSI at high $Q^2$ (HT)
- Model results at intermediate $x$ (EIC) shares features with QE FSI.