Final State Interactions in Deep Inelastic Processes

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Correlations in Partonic and Hadronic Interactions 2018
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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

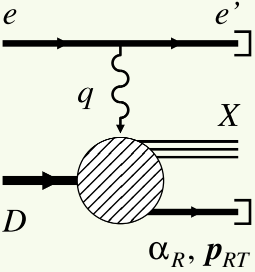
- Inclusive DIS on nuclei: use closure over final-states
  - (anti-)shadowing corrections at low x
  - FSI corrections at large x where there is limited phase-space in the final state

- 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

Study space-time evolution of DIS through FSI

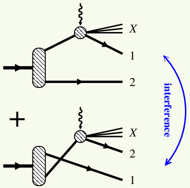
- Main focus so far has been nuclear ratios of semi-inclusive production of leading mesons or jets
  - sensitive to sum of formation, coherence and production time

- 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

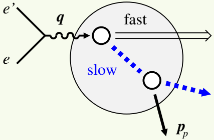


- Wealth of possibilities to study (nuclear) QCD dynamics
- Will be possible in a wide kinematic range @ EIC (**polarized**)

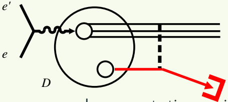
Final-state interactions: three physical pictures



shadowing, low x



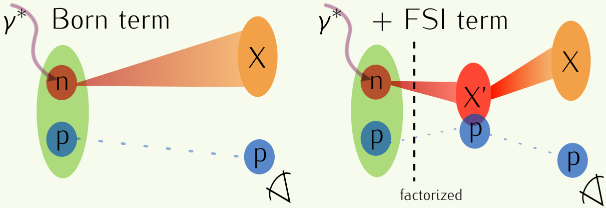
DIS regime, intermediate x



subasymptotic regime: low Q^2, high x

- 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 $\rightarrow$ 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

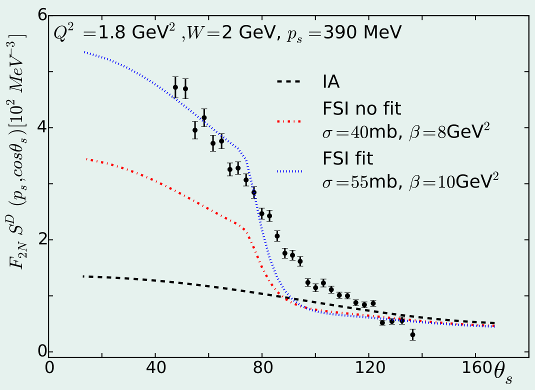
W.C., M. Sargsian, PRC84 014601 ('11)

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

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

- Invariant mass of X can change in rescattering

D(e,e'p$_s$)X calculation without fits ($p_s = 300 - 560$ 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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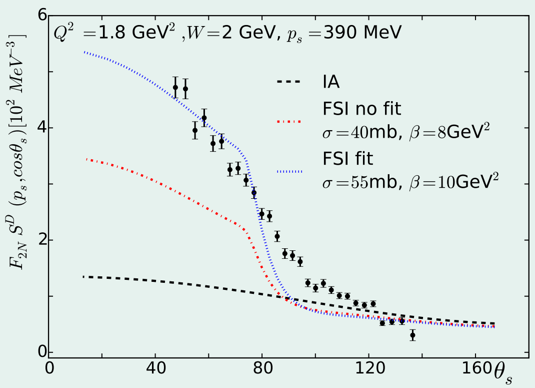

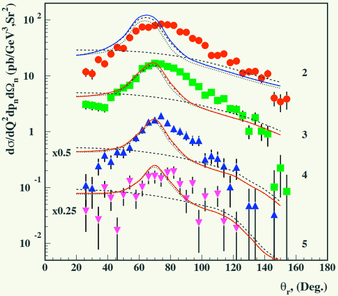

D(e,e'p$_s$)n

M. Sargsian PRC82 014612 ('10)

- Plane-wave calculation shows little dependence on spectator angle
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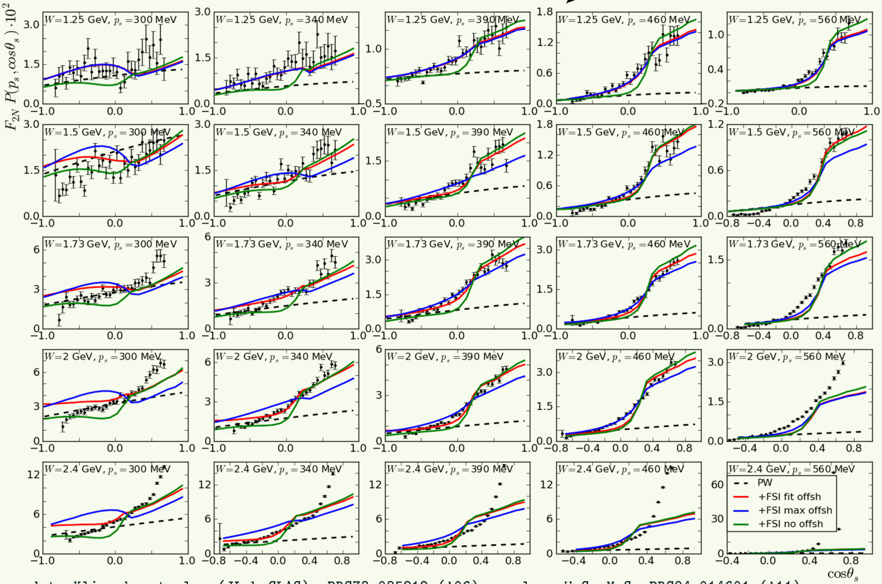
Calculation with σ_{XN} and β_{XN} fitted at $Q^2=1.8$ GeV^2

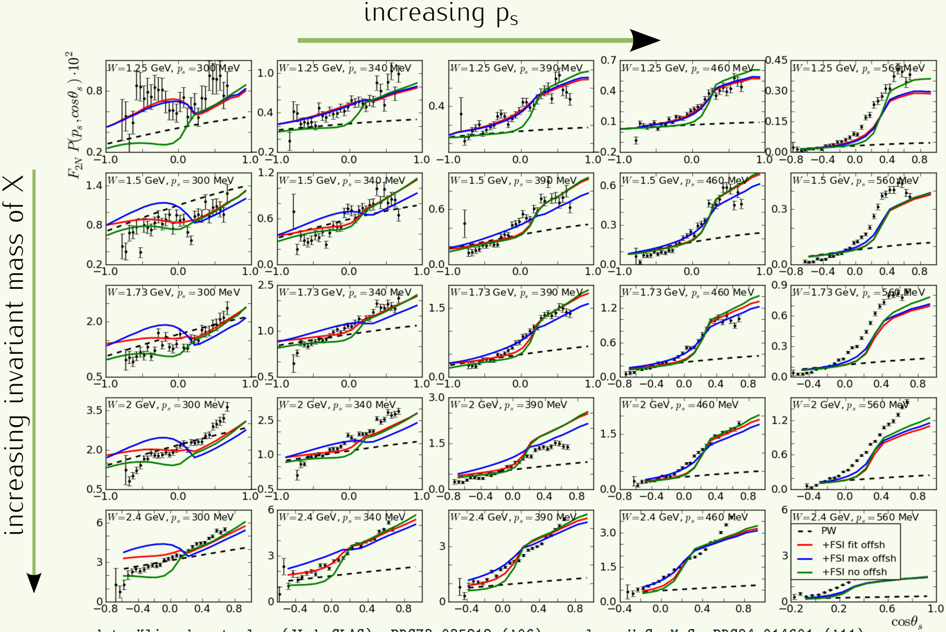
increasing p_s

increasing invariant mass of X



data:Klimenko et al. (JLab CLAS), PRC73 035212 ('06) calc: W.C.,M.S. PRC84 014601 ('11)

Calculation with σ_{XN} and β_{XN} fitted at Q^2=2.8 GeV^2



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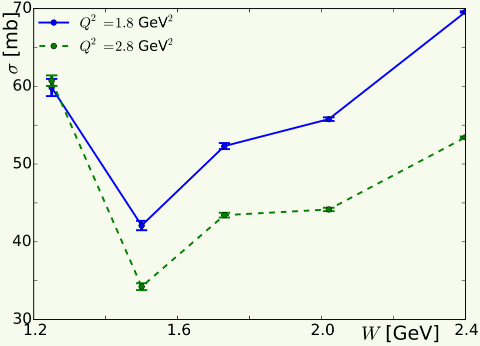
What can the σ_{XN} fit teach us?



- 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

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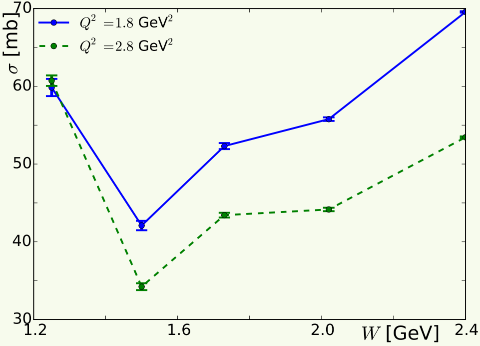

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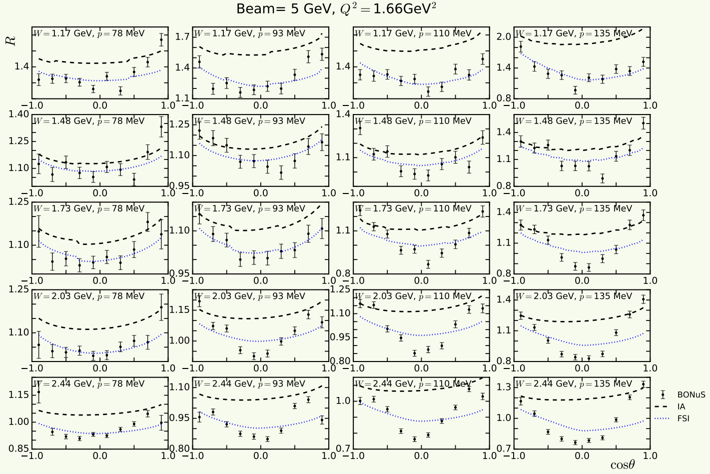
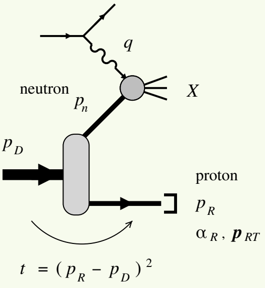
Comparison with BONuS ($p_s = 70 - 140$ MeV)



data: S. Tkachenko et al., Phys.Rev. C89 (2014) 045206

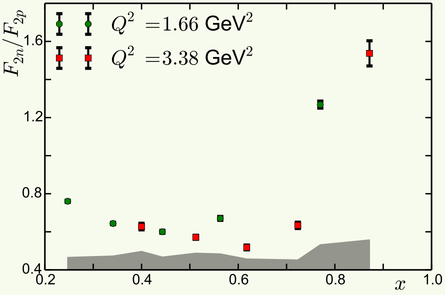
- In backward region FSI not necessarily small (compared to forward region) in these kinematics!

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 [Sargsian,Strikman PLB '05]
- Esp. suited for colliders: spectators still move forward with ∼1/2 the beam momentum
- D-wave suppressed at on-shell point → neutron ∼ 100% polarized
- Precise measurements of neutron (spin) structure at an EIC

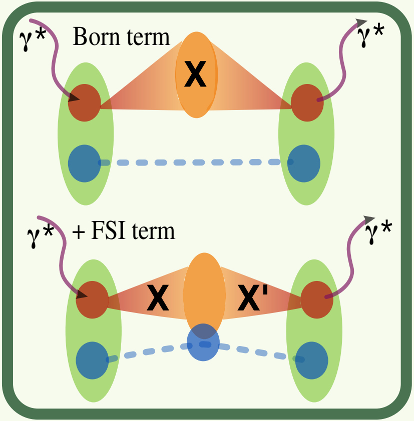
Use Bonus data: F_{2n}/F_{2p}



W.C., M. Sargsian, PRC93 '16

- 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?

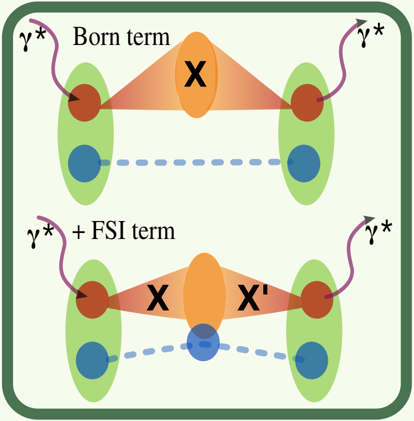
Inclusive DIS



W.C., M. Sargsian, W. Melnitchouk, PRC89, 014612 (2014)

- Optical theorem: relate hadronic tensor for inclusive process to imaginary part of forward scattering amplitude $W^{\mu\nu}_{D,\text{incl}} = \frac{1}{2\pi M_D} \frac{1}{3} \sum_{s_D,N} Im(A^{\mu\nu}{}_{s_D})$
- 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 assymetrical rescatterings considered.

Inclusive DIS



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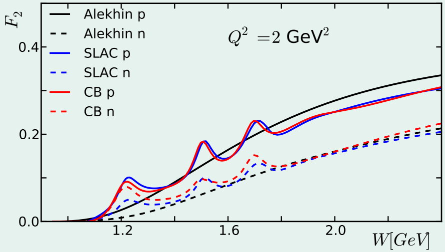
Challenge: description of the FSI amplitude over the whole x, Q^2 range.

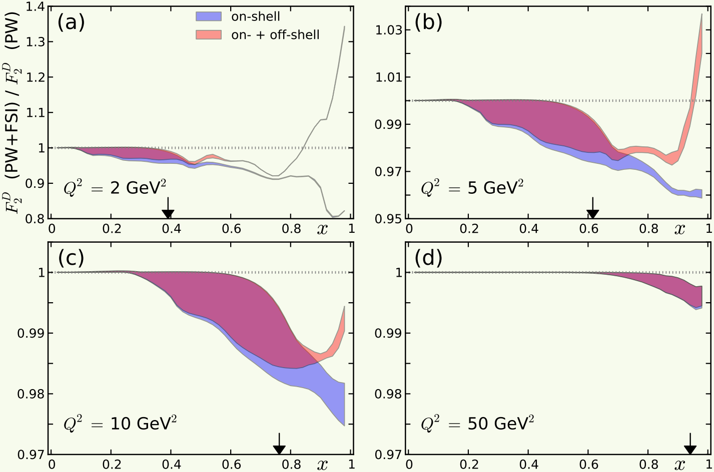
Model features

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

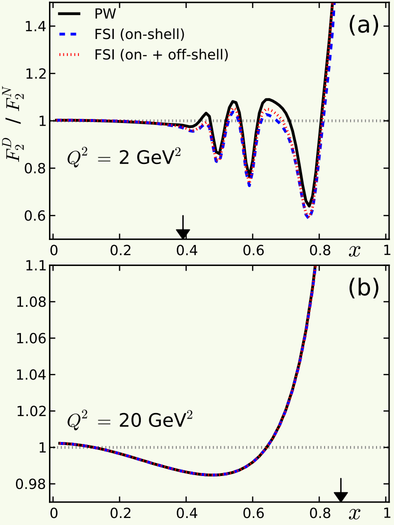
Inclusive DIS calculations



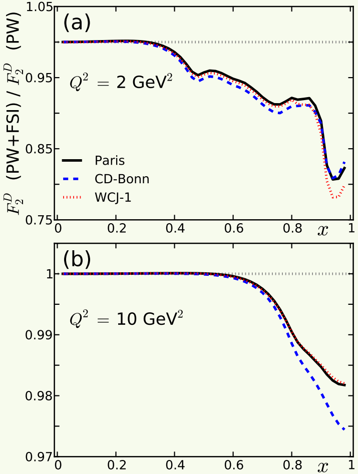
- Higher twist effect: available phase space for rescattering shrinks with higher Q^2

Inclusive DIS calculations

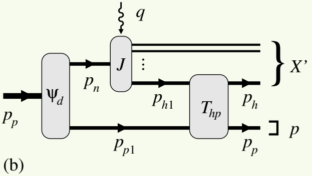
Ratio to F_{2N}

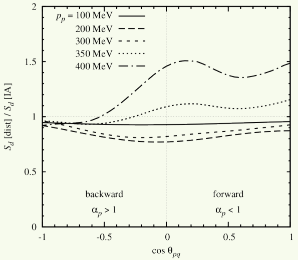


Deuteron wf dependence



FSI: intermediate x model (EIC)





Strikman, Weiss, 1706.02244, PRC '18

- 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, postive)
- At low momenta ($p_r < 200$ MeV) FSI term dominates, at larger momenta FSI^2 dominates.
- Both contributions vanish at the pole $\rightarrow$ pole extrapolation **still feasible**

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