

Final-state interactions in DIS (in the deuteron)

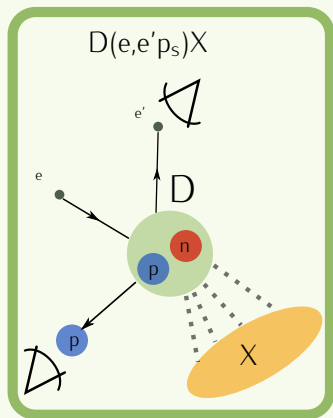
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EMMI Workshop
GSI, Darmstadt
Oct 16 2015



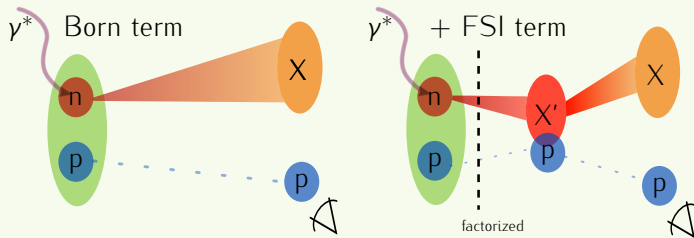
Tagged Spectator DIS off the deuteron



- Detection of a **slow spectator** proton
- At low proton momenta: extraction of **neutron structure function**
 - ▶ Necessary for flavor separation of pdf's (u/d ratio)
 - ▶ Constrain quark models of the nucleon
- At higher proton momenta: probe **high density** configurations, nucleon modifications, 6 quark configurations,...?
- For kinematics with **high FSI**: study space-time evolution of **hadronization**, constrain rescattering models.

- (tagged spectator) DIS with intermediate Q^2 , high Bjorken x
- Resonance region $W \lesssim 2.5$ GeV
- **Limited phase space** for the final hadronic state $\rightarrow$ closure approximation not applicable in inclusive DIS
- Study influence of final-state interactions (**FSI**) through **effective** rescattering amplitudes

Reaction diagrams



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

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

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

Factorization

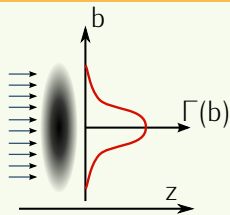
- Relate semi-inclusive deuteron structure functions to the **neutron** ones for a moving nucleon at $\hat{x} = \frac{Q^2}{2p_i \cdot q} \approx \frac{x}{2-\alpha_s} \dots$

$$F_T^D(x, Q^2) = [2F_{1N}(\hat{x}, Q^2) + \frac{p_T^2}{m_i \hat{v}} F_{2N}(\hat{x}, Q^2)] \times S^D(p_r) (2\pi)^3 2E_r$$

- ...times a **distorted spectral function** that contains a **plane-wave** and **FSI** contribution. FSI amplitude has an **on-shell** and **off-shell** part (related to propagator of intermediate X').

$$S^D(p_r) = \frac{1}{3} \sum_{M, s_r, s_s} \left| \overbrace{\Phi_D^M(p_i s_i, p_s s_s)}^{PW} - \int \overbrace{\frac{d^3 p_{s'}}{(2\pi)^3} \chi(p_{s'}, m_{x'}) \langle p_r X | \mathcal{F} | p_{s'} X' \rangle}_{FSI} \frac{\Phi_D^M(p_{i'} s_i, p_{s'} s_s)}{(p_{s'}^z - p_s^z + \Delta')} \right|^2$$

FSI: Generalized eikonal approximation



- Scattering amplitude is parametrized with the standard **diffractive** form

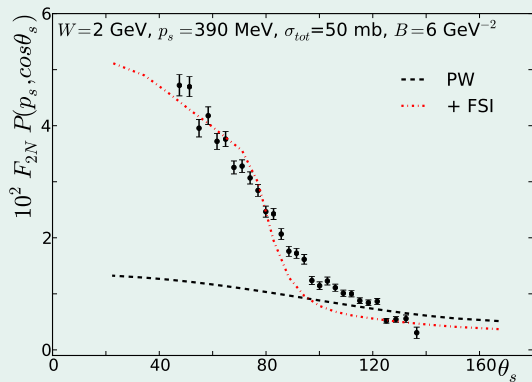
$$\langle p_r, X | \mathcal{F} | p_{r'}, X' \rangle = \sigma_{\text{tot}}(W, Q^2) (i + \epsilon(W, Q^2)) e^{\frac{\beta(W, Q^2)}{2} t} \delta_{s_r, s_{r'}} \delta_{s_X s_{X'}}$$

- Eikonal regime gives approximate conservation law $p_s^+ = p_{s'}^+$ in the high q limit. This leads to $m_{X'}^2 > m_X^2$, and yields pole values in the FSI integral of

$$p_{s,z} - p'_{s,z} = \Delta = \frac{\nu + M_D}{|\vec{q}|} (E_s - m_p) + \frac{m_X^2 - m_{X'}^2}{2 |\vec{q}|} \quad \text{for } m_{X'}^2 \leq m_X^2,$$

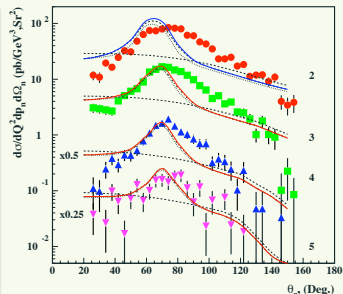
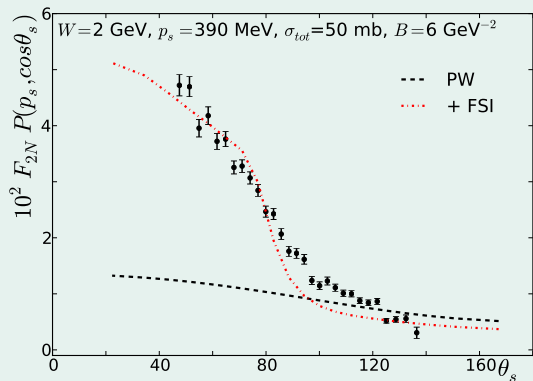
$$p_{s,z} - p'_{s,z} = \Delta = \frac{\nu + M_D}{|\vec{q}|} (E_s - m_p) \quad \text{for } m_{X'}^2 > m_X^2.$$

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

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



D(e,e'p_s)n

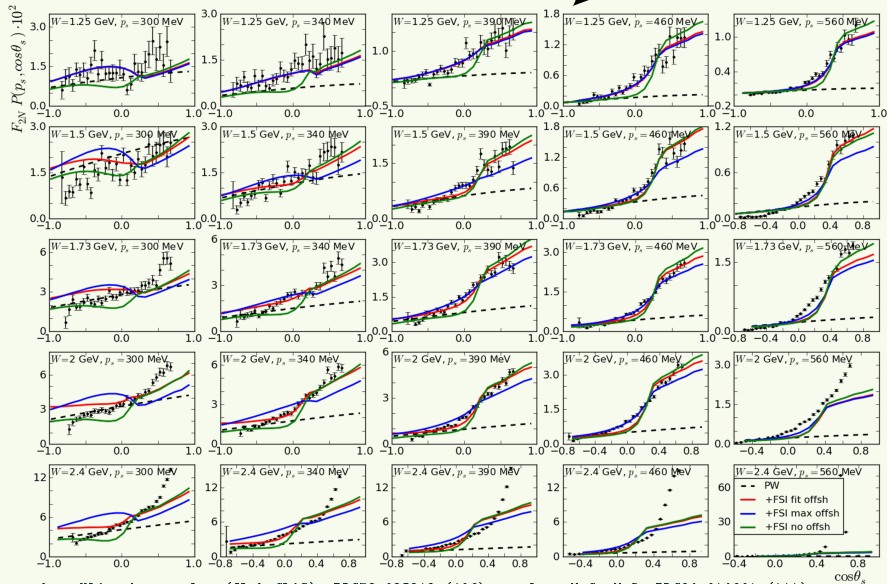
M. Sargsian PRC82 014612 ('10)

- Plane-wave calculation shows little dependence on spectator angle
- FSI effects **grow** in forward direction, different from quasi-elastic case

Calculation with σ_{XN} and β_{XN} fitted at $Q^2=1.8 \text{ GeV}^2$

increasing invariant mass of X

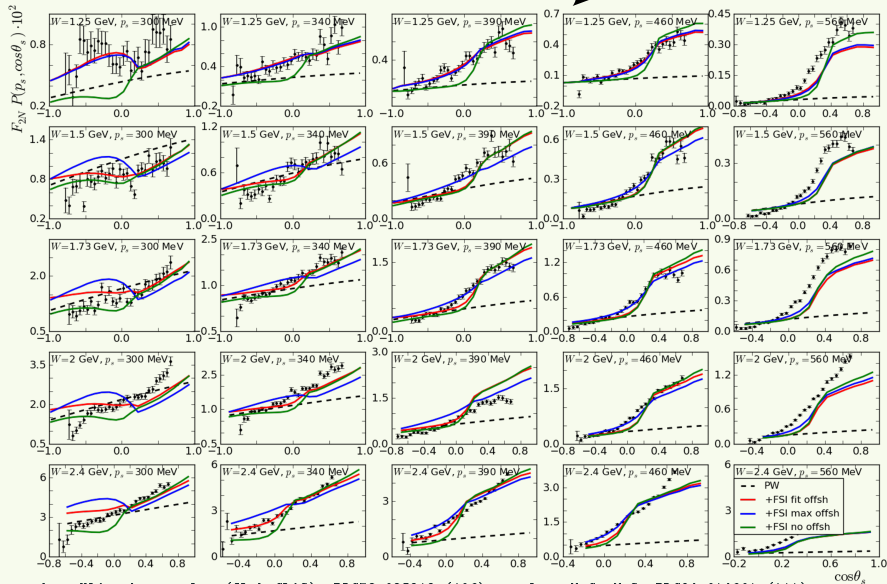
increasing p_s



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

increasing invariant mass of X

increasing p_s

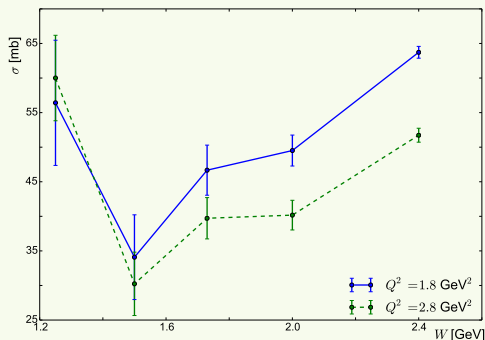


Results discussion



- Overall very nice agreement between the calculations and JLab CLAS Deeps data
- Systematic **underestimation** of data at $p_s=560$ MeV, breakdown of factorization, contribution from current fragmentation
- At lowest spectator momentum plane-wave and FSI amplitude **comparable in magnitude**, sensitive to small differences
- Fitted off-shell calculations correspond more with no off-shell ones, pointing to **suppressed** off-shell amplitude

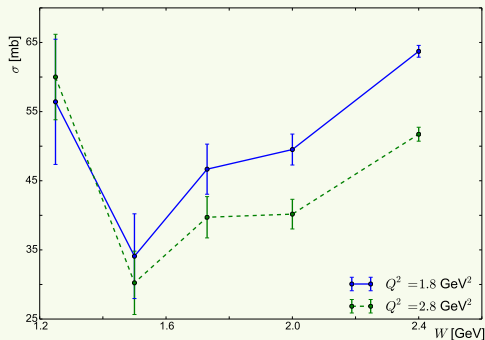
What can the σ_{XN} fit teach us?



- 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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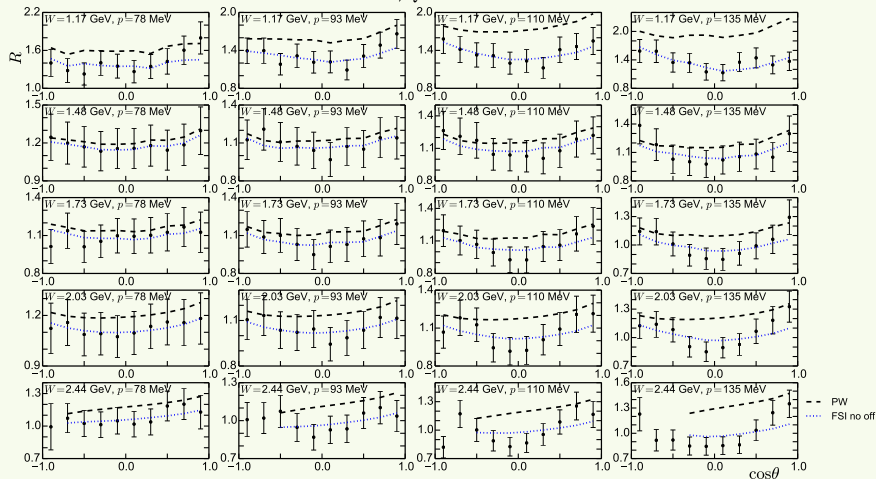


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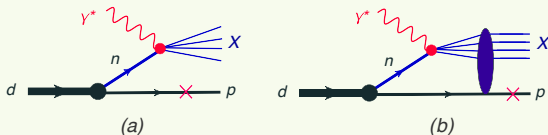
Comparison with BONuS ($p_s = 70 - 140$ MeV)

Beam= 4 GeV, $Q^2 = 1.66\text{GeV}^2$



- Plane-wave calculation shown here with same normalization as the FSI one (so not fitted)

Free neutron F_{2n} extraction



- On-shell neutron: take limit $t' = p_i^2 - m_n^2 = (p_D - p_s)^2 - m_n^2 \rightarrow 0$: plane-wave part of the spectral function has a quadratic pole while the FSI part has not (loop theorem).

M. Sargsian, and M. Strikman, PLB639, 223(2006)

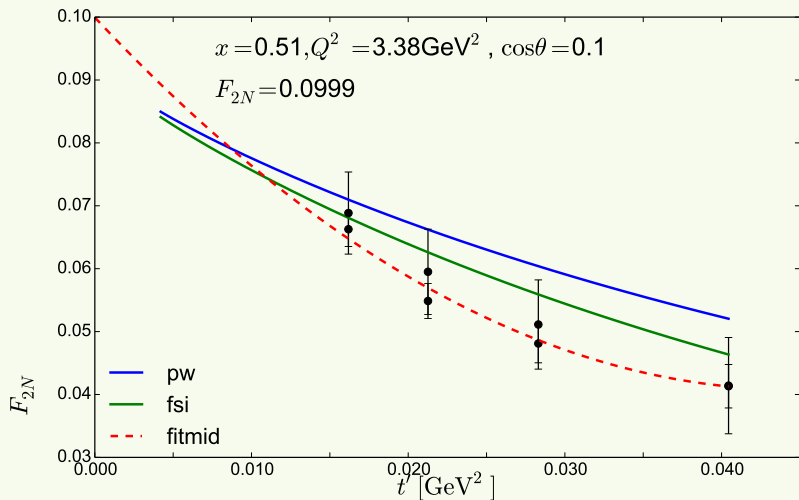
- Provides **model independent** manner of extracting neutron structure. FSI, Fermi motion effects naturally disappear.
- Small binding energy of deuteron means extrapolation is not that far into the unphysical region
- Similar to Chew-Low extrapolation used to extract pion structure
- Application for EIC: JLab LDRD project ((un)polarized D,³He)

Talk by C. Weiss

Use Bonus data: extrapolation

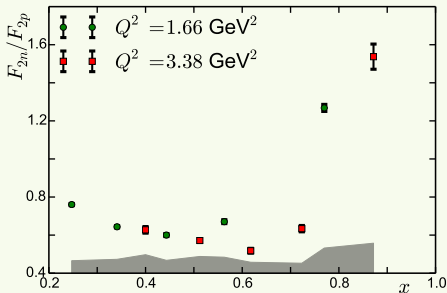
- Normalization issue with BONuS data: detector efficiency varied with p_s . Cross sections normalized to plane-wave model in backward spectator region
- Refitted this normalization of the data for the highest Q^2, W bins ($\rightarrow$ “low” x), where F_{2n} is well established.
- Introduces some model dependence in this particular analysis. **Not** an issue in collider kinematics: no target material, forward detection, extrapolation distance is smaller...
- For each W, Q^2 bin, extrapolation done as a weighted average over all spectator angle bins

Use Bonus data: extrapolation



■ Data from two beam (4 and 5 GeV) energies

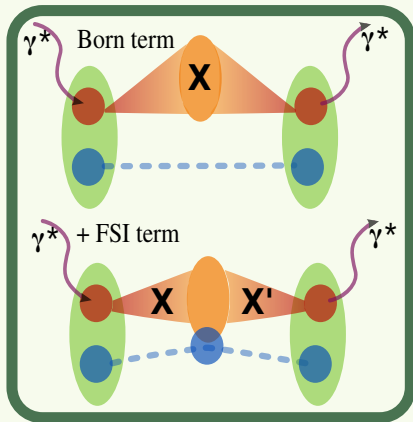
Use Bonus data: F_{2n}/F_{2p}



W.C., M. Sargsian,
arXiv:1506.01067

- 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
- Δ contribution? Ratio highest at largest Q^2 value (Δ should get suppressed)... Duality arguments??
- Sign of hard isosinglet quark-quark correlation, analogous to np pairing in nuclei?

Talk by M. Sargsian

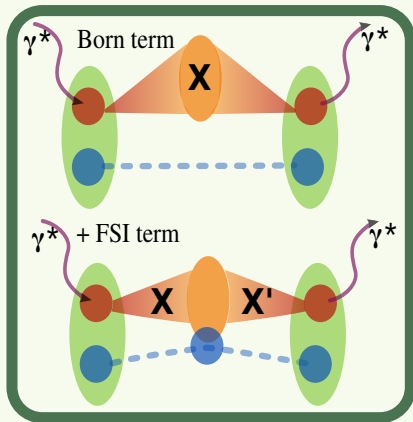


- **Optical theorem**: relate **hadronic tensor** for inclusive process to imaginary part of **forward scattering amplitude**

$$W_{D, \text{incl}}^{\mu\nu} = \frac{1}{2\pi M_D} \frac{1}{3} \sum_{s_D, N} \text{Im}(A^{\mu\nu}_{s_D})$$

- 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 asymmetrical 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.

General formulas using GEA

$$W_D^{\mu\nu(\text{pw})} = \frac{2m}{M_D} \sum_N \int d^3 \mathbf{p}_s W_N^{\mu\nu} S(p_s)$$

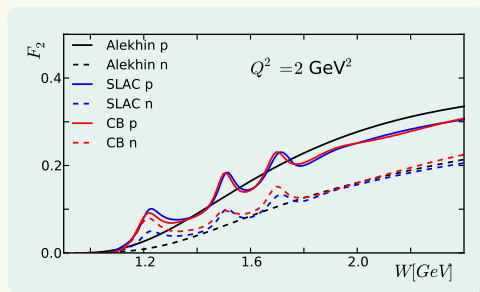
$$W_{\text{FSI}}^{\mu\nu(\text{on})} = -\frac{\pi(2\pi)^3}{3M_D} \sum_{N, X_1, X_2} \sum_{\text{spins}} \mathfrak{L} m \int \frac{d^3 \mathbf{p}_{s_1}}{(2\pi)^3} \frac{d^3 \mathbf{p}_{s_2}}{(2\pi)^3} \frac{\Psi_D^{SD\dagger}(p_{i_2}, s_{i_2}; p_{s_2}, s_{s_2}) \Psi_D^{SD}(p_{i_1}, s_{i_1}; p_{s_1}, s_{s_1})}{2\sqrt{E_{s_2} E_{s_1}}} \\ \times \langle p_{X_2}, s_{X_2}; p_{s_2}, s_{s_2} | F_{NX_1, NX_2}^{(\text{on})} | p_{X_1}, s_{X_1}; p_{s_1}, s_{s_1} \rangle J_{\gamma NX_2}^{\mu\dagger}(p_{i_2}, s_{i_2}; p_{X_2}, s_{X_2}) \\ \times J_{\gamma NX_1}^{\nu}(p_{i_1}, s_{i_1}; p_{X_1}, s_{X_1}) \delta(p_{X_1}^2 - m_{X_1}^2) \delta(p_{X_2}^2 - m_{X_2}^2)$$

$$W_{\text{FSI}}^{\mu\nu(\text{off})} = \frac{(2\pi)^3}{3\pi M_D} \sum_{N, X_1, X_2} \sum_{\text{spins}} \mathfrak{L} m \int_{\mathcal{P}} \frac{d^3 \mathbf{p}_{s_1}}{(2\pi)^3} \frac{d^3 \mathbf{p}_{s_2}}{(2\pi)^3} \frac{\Psi_D^{SD\dagger}(p_{i_2}, s_{i_2}; p_{s_2}, s_{s_2}) \Psi_D^{SD}(p_{i_1}, s_{i_1}; p_{s_1}, s_{s_1})}{2\sqrt{E_{s_2} E_{s_1}}} \\ \times \langle p_{X_2}, s_{X_2}; p_{s_2}, s_{s_2} | F_{NX_1, NX_2}^{(\text{off})} | p_{X_1}, s_{X_1}; p_{s_1}, s_{s_1} \rangle J_{\gamma NX_2}^{\mu\dagger}(p_{i_2}, s_{i_2}; p_{X_2}, s_{X_2}) \\ \times J_{\gamma NX_1}^{\nu}(p_{i_1}, s_{i_1}; p_{X_1}, s_{X_1}) \frac{1}{p_{X_1}^2 - m_{X_1}^2} \frac{1}{p_{X_2}^2 - m_{X_2}^2}$$

- Currents not known! $\rightarrow$ factorization and relate to $W_N^{\mu\nu}$
- In contrast with SIDIS, unknown intermediate masses m_{X_1}, m_{X_2} .
- FSI contributions decrease with increasing Q^2 : follows naturally from limited phase space $\tilde{x} = \left(1 + \frac{m_X^2 - p_i^2}{Q^2}\right)^{-1} (< 1)$

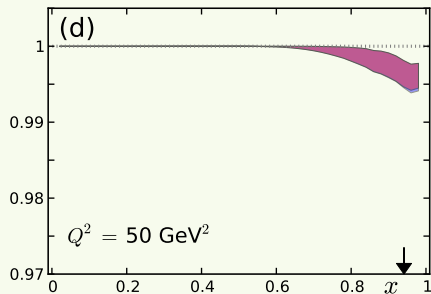
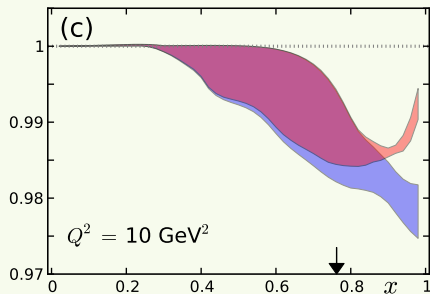
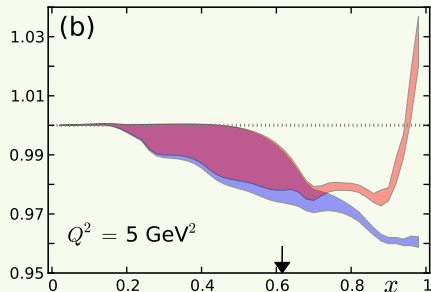
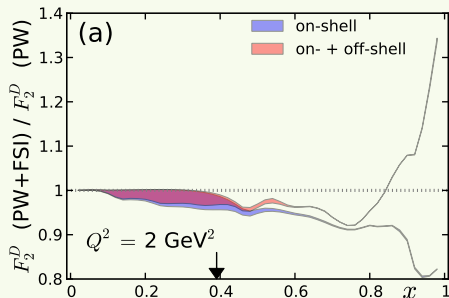
Model features

Use three effective resonances in the FSI diagram and continuum contribution (distribution)



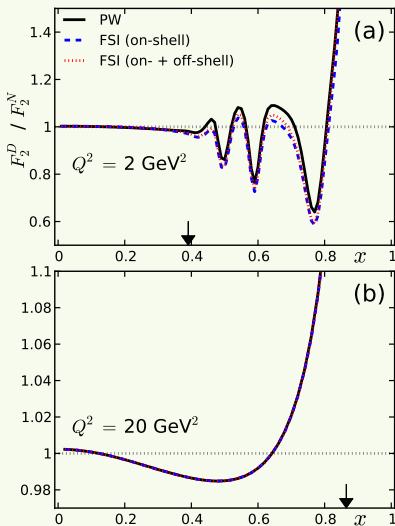
- Take scattering parametrizations from our **fit** to the Deeps data
- We don't take into account any possible relative phases between the resonances: **maximum** possible effect

Inclusive DIS calculations

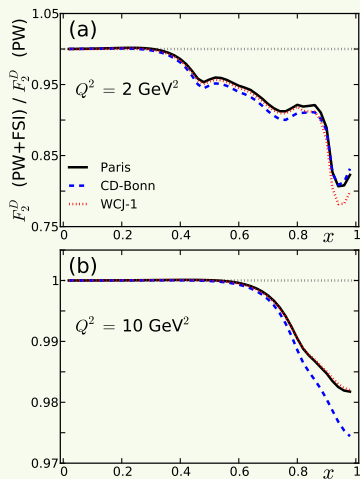


Inclusive DIS calculations

Ratio to F_2^N



Deuteron wf dependence



- FSI on-shell contribution effects largest at high x
- Decreases with increasing Q^2 : follows naturally from limited phase space

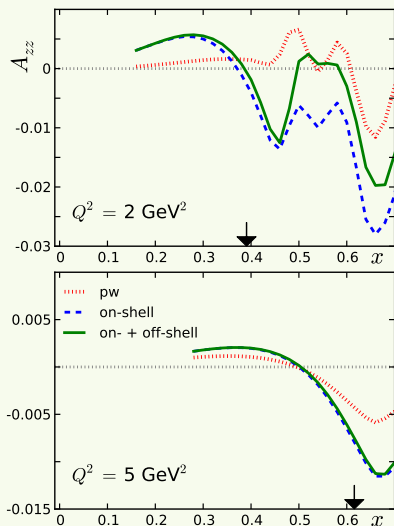
$$\tilde{x} = \frac{1}{1 + \frac{W_X^2 - p_i^2}{Q^2}} (< 1)$$

- Off-shell contribution shown is maximum possible contribution from three effective resonances: large contribution at $x \gtrsim 0.8$ and $Q^2 \lesssim 5 \text{ GeV}^2$
- Can be taken into account in neutron structure function extractions
- Dependence on deuteron wave function much smaller than size of FSI effects

A_{zz} in inclusive DIS

- Scattering from a tensor polarized deuteron target (unpolarized electron) $d\sigma = d\sigma_u(1 + \frac{1}{2}P_{zz}A_{zz})$, sensitive to 4 new structure functions compared to the spin 1/2 case.
- Observable $\propto (2\sigma^{+1} - \sigma^0)$ is identical 0 for a S -wave deuteron, **very small** when D -wave is included. Sensitive to non-nucleonic contributions such as hidden color (G. Miller, PRC89 (2014) 045203)
- Hermes measured $A_{zz} = 0.157 \pm 0.69$ at $x = 0.45$, $Q^2 \approx 5\text{GeV}^2$
- Upcoming approved JLab12 experiment will improve our knowledge: E12-13-011
- A_{zz} through density matrix: $\rho_{02}=1/\sqrt{2}\text{diag}(1, -2, 1)$ (z-axis along photon)
- Only nucleonic contributions in our model

A_{zz} in inclusive DIS



- Only resonance contribution considered in the FSI, **No** DIS continuum contribution
- JLab 12 GeV kinematics considered
- Non-negligible contribution from FSI even at low x , but still nowhere near the Hermes value.
- Convolution (D-wave dominance $\rightarrow$ high spectator momenta) can pick up resonance contributions through the convolution
- Size of FSI effects decreases at higher Q^2

Conclusions



- Model for (tagged spectator) DIS on the deuteron based on general properties of soft rescattering.
- Fair description of the Deeps 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 (JLab LDRD project), intriguing result from our analysis of the BONuS data
- In inclusive DIS: natural suppression of FSI at high Q^2
- FSI effects of a few percent in inclusive DIS at large Bjorken x



- Method extendable to quasi-elastic inclusive $A(e, e')$, DVCS & SIDIS on nuclear targets
- Extension for diffractive FSI at lower x values (two-component model)
- ^3He target and beyond

Comparison with Deeps: approach

- Deeps experiment (JLab CLAS): Klimenko et al., PRC73, 035212
- Use **SLAC parametrization** for neutron structure functions (as in data analysis)
- Take $\sigma_{\text{tot}}(W, Q^2)$ [and $\beta(W, Q^2)$] as **free parameter** in the distorted spectral function. Fits are done for each W, Q^2 over the 5 measured spectator momenta (300–560 MeV).
- Deuteron wave function: $\Phi_D(\mathbf{p}) = \Phi_D^{\text{NR}}(\mathbf{p}) \sqrt{\frac{M_D}{2(M_D - E_s)}}$
Obeys baryon number conservation $\int \alpha |\Phi_D(\mathbf{p})|^2 d^3p = 1$

Parametrization of the off-shell rescattering amplitude

Three approaches:

- **no off-shell FSI**: off-shell rescattering amplitude is zero

$$f_{X'N,XN}^{\text{off}} \equiv 0$$

- **maximum off-shell FSI**: off-shell amplitude is taken equal to the on-shell one

$$f_{X'N,XN}^{\text{off}} = f_{X'N,XN}^{\text{on}}$$

- **fitted off-shell FSI**: off-shell amplitude is parametrized as the on-shell one with a suppression factor dependent on (x, Q^2)

$$f_{X'N,XN}^{\text{off}} = f_{X'N,XN}^{\text{on}} e^{-\mu(x, Q^2)t}$$

Comparison with BONuS

- BONuS experiment (JLab CLAS): lower spectator momenta
S. Tkachenko et al., Phys.Rev. C89 (2014) 045206,
N. Baillie et al., Phys. Rev. Lett. 108, 142001 (2012)
- Detector efficiency varied with p_s , data normalized to a Monte Carlo with plane-wave model.
- Normalization compared to model can be consequence of overall normalization and difference between used parametrization of F_2 and “real” F_2^n
- Refit normalization for each Q^2, W, p_s setting to our FSI calculations with rescattering parameters obtained from the Deeps data.