Final State Interactions in Tagging

Wim Cosyn

Ghent University, Belgium

High Energy Nuclear Physics with Spectator Tagging
Old Dominion University
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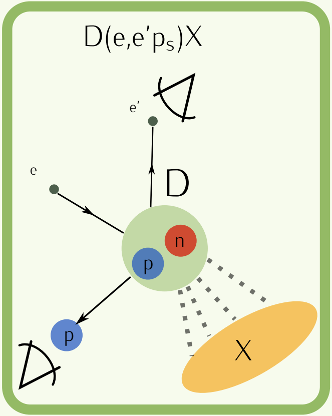
Outline

1. Tagged spectator DIS
2. Nucleon structure extraction
3. Inclusive DIS

Motivation

- (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 → closure approximation not applicable
- Study influence of final-state interactions (FSI) through **effective** rescattering amplitudes

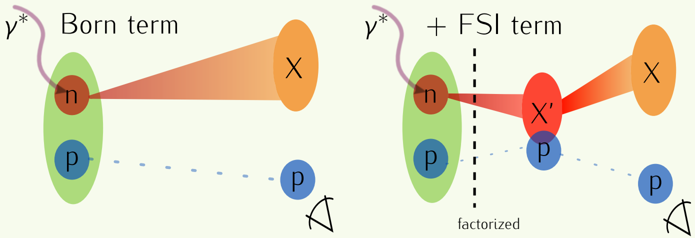
Tagged Spectator DIS off the deuteron



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

- 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.

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, ^{3}He, ...)

Factorization

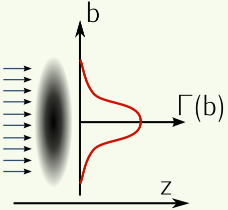
- Relate semi-inclusive deuteron structure functions to the **neutron** ones for a moving nucleon at $\hat{x} = \frac{Q^2}{2p_i \cdot q} \approx \frac{x}{2-\alpha_s}$...

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

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

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

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

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

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

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: $\Phi_D(p) = \Phi_D^{\text{NR}}(p)\sqrt{\frac{M_D}{2(M_D - E_s)}}$
  Obeys baryon number conservation $\int \alpha |\Phi_D(p)|^2 d^3p = 1$

Parametrization of the off-shell rescattering amplitude

Three approaches:

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

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

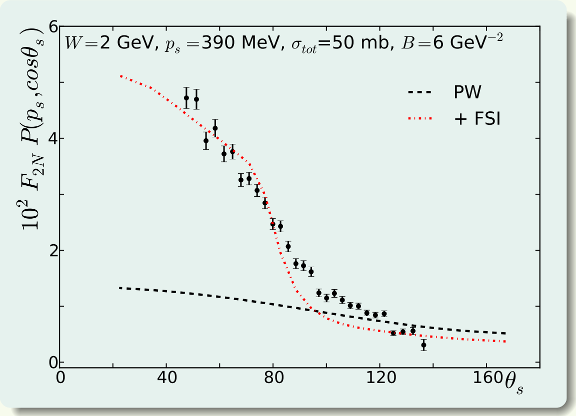
- maximum off-shell FSI: off-shell amplitude is taken equal to the on-shell one

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

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

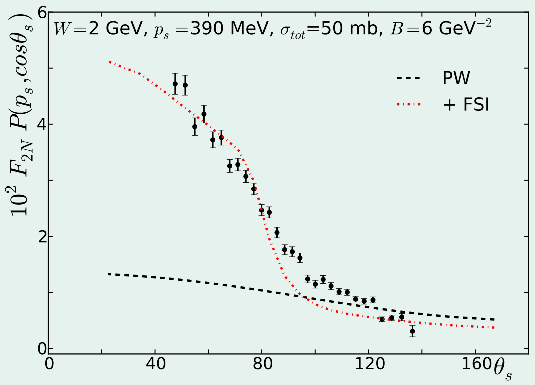
$$f^{\text{off}}_{X'N,XN} = f^{\text{on}}_{X'N,XN} e^{-\mu(x,Q^2)t}$$

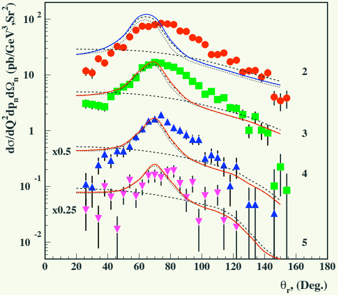
D(e,e'p_s)X calculation without fits



- Plane-wave calculation shows little dependence on spectator angle
- Small contribution from off-shell amplitude
- FSI effects grow in forward direction, different from quasi-elastic case

D(e,e'p$_s$)X calculation without fits





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

M. Sargsian PRC82 014612 ('10)

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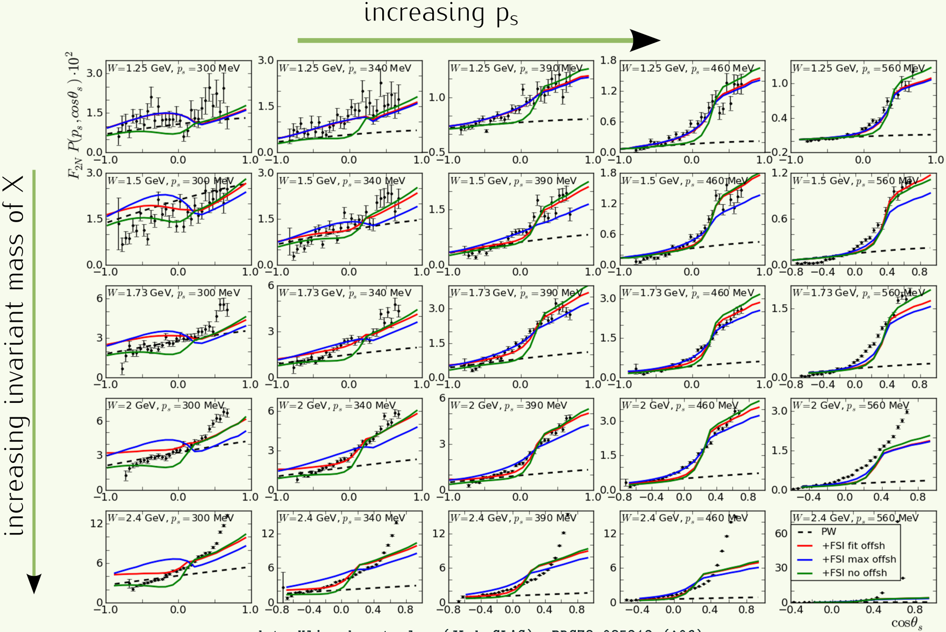
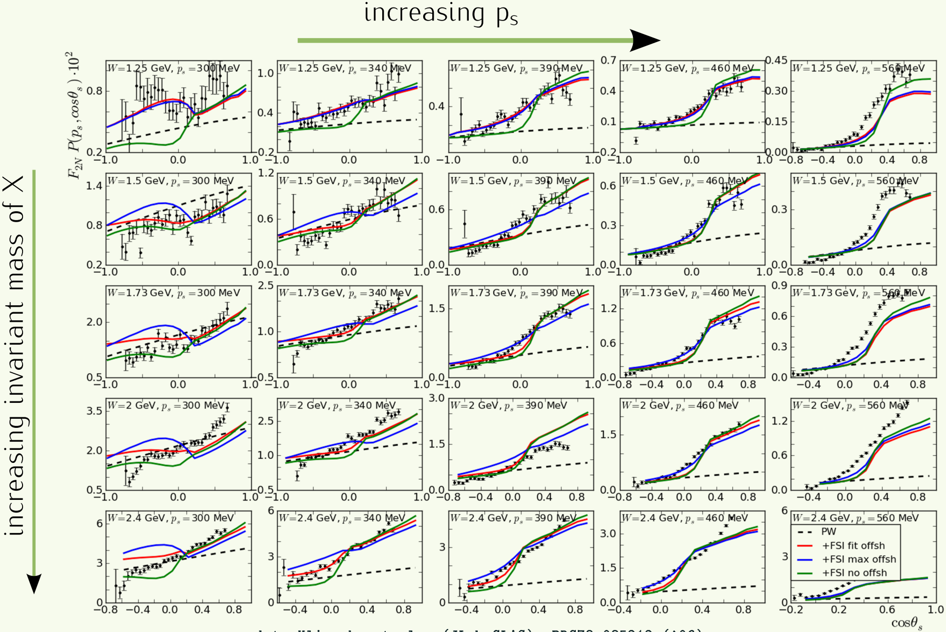
Calculation with σ_{XN} and β_{XN} fitted at Q^2=1.8 GeV^2



data:Klimenko et al. (JLab CLAS), PRC73 035212 ('06)

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



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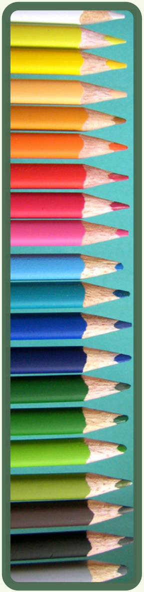
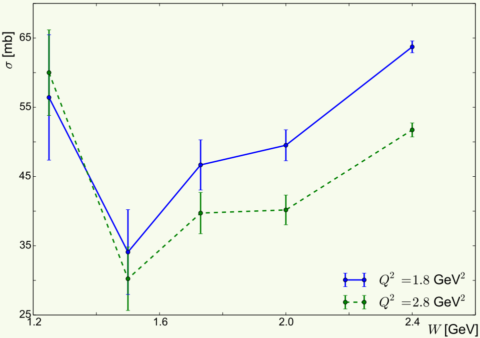
Results discussion



- 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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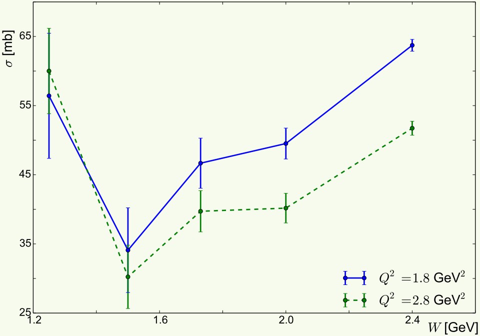

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Comparison with BONuS

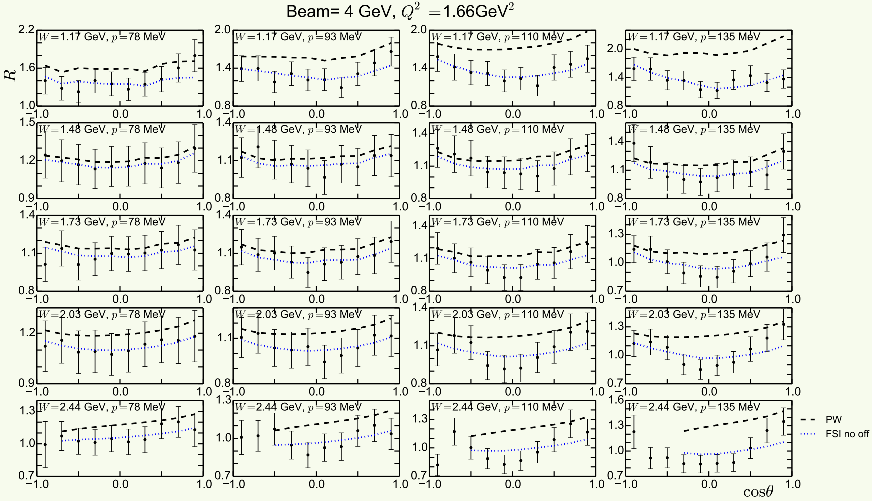
- BONuS experiment (JLab CLAS): lower spectator momenta
  `S. Tkachenko et al., Phys.Rev. C89 (2014) 045206,`
  `N. Baillie et al., Phys. Rev. Lett. 108, 142001 (2012)`

- 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.

Comparison with BONuS



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

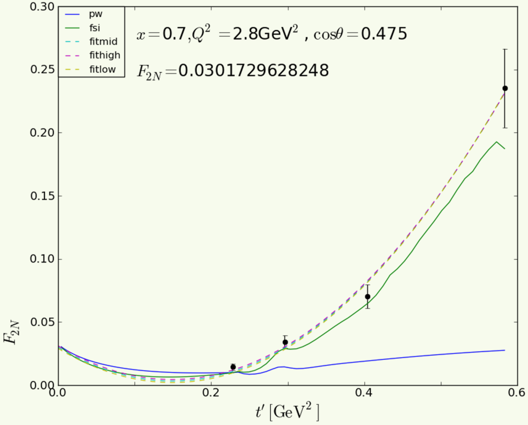
  `M. Sargsian, and M. Strikman, PLB639, 223(2006)`

- 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
- Extract the free neutron structure function through

$$F_{2n}^{\text{extr}}(Q^2, x) = \lim_{t' \to 0} \frac{t'^2}{[\text{Res}(\Phi_D(t'=0))]^2} \frac{F_L^{D,\text{exp}}(x, Q^2) + v_T F_T^{D,\text{exp}}(x, Q^2)}{\frac{2\hat{x}\nu}{m_n}\left[\left(\frac{\alpha_i}{\alpha_q} + \frac{1}{2\hat{x}}\right)^2 + \frac{p_T^2}{2Q^2}\left(\frac{Q^2}{|q|^2} + \frac{2\tan^2\frac{\theta_e}{2}}{1+R}\right)\right]}$$

This quantity has a quadratic dependence in t'.

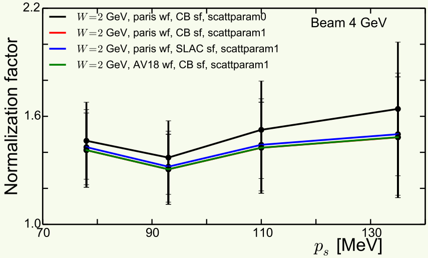
Quadratic fit

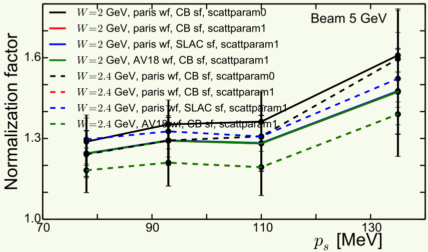


W.C., M.S., AIP Conf.Proc.1369 121 ('11)

- Minimum depends on *FSI* term, use that
- Quadratic fit with data and extra constraints gives reasonable value
- Extrapolated value varies with θ_s, not robust
- More data at lower p_s needed for this method...

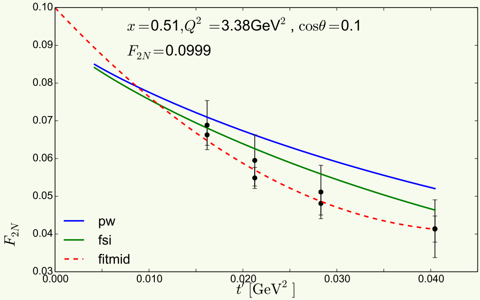
Use Bonus data: normalization





- Fix normalization of the data at high $Q^2 = 3.38\text{GeV}^2$, $W = 2, 2.4$ GeV settings: "true" DIS, beyond resonance region, small difference between different structure function parametrizations
- One set for each beam setting (systematics)
- Dependence on deuteron wf, SF parametrization, rescattering parameters minimal
- Use these normalizations for the whole data set

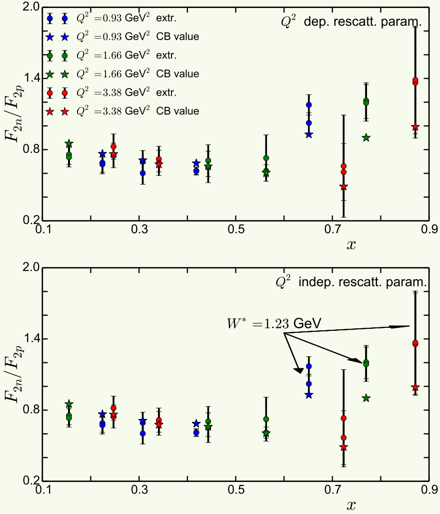
Use Bonus data: extrapolation



- Data from two beam (4 and 5 GeV) energies
- Spectator angle around $\alpha_s \approx 1$ gives cleanest quadratic dependence (M Sargsian & M Strikman, PLB639 (06))

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

PRELIMINARY!!

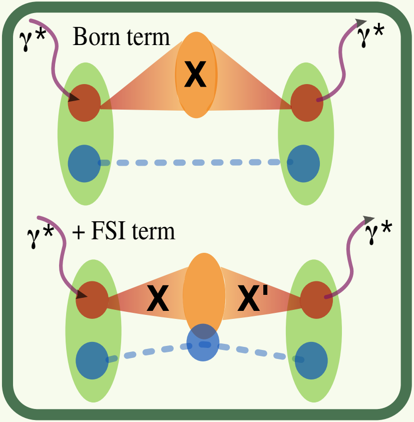


CB = Christy & Bosted F2 parametrization

- 2 angles around $\alpha_s \approx 1$ used to obtain extrapolated values
- Two different rescattering parametrization (one with Q^2 suppression, other without) produce similar results
- Striking rise of the ratio at high x
- Δ contribution? Ratio highest at largest Q^2 value (Δ should get suppressed)... Duality arguments??
- CB value at $W = \Delta$ also shows rise (but no real Q^2 dependence) $\rightarrow$ resonance effects?

PRC81, 055231 ('10); PRC77, 065206 ('08)

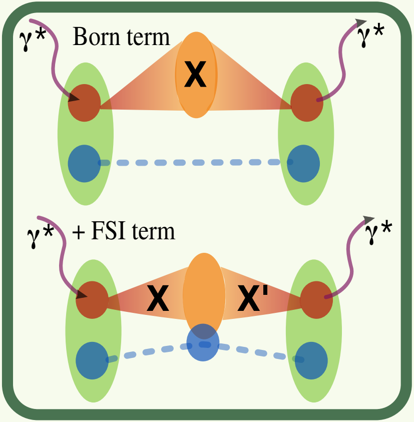
Inclusive DIS



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.

General formulas using GEA

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

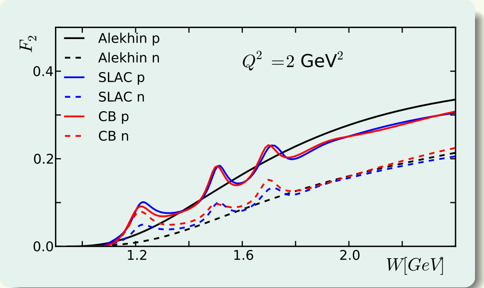
$$W_{\text{FSI}}^{\mu\nu(\text{on})} = -\frac{\pi(2\pi)^3}{3M_D} \sum_{N,X_1,X_2} \sum_{\text{spins}} \Im m \int \frac{d^3\boldsymbol{p}_{s_1}}{(2\pi)^3} \frac{d^3\boldsymbol{p}_{s_2}}{(2\pi)^3} \frac{\Psi_D^{s_D \dagger}(p_{i_2}, s_{i_2}; p_{s_2}, s_{s_2}) \Psi_D^{s_D}(p_{i_1}, s_{i_1}; p_{s_1}, s_{s_1})}{2\sqrt{E_{s_2}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

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

- Currents not known! $\to$ 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 $\tilde{x} = \left(1 + \frac{m_X^2 - p_i^2}{Q^2}\right)^{-1} \quad (< 1)$

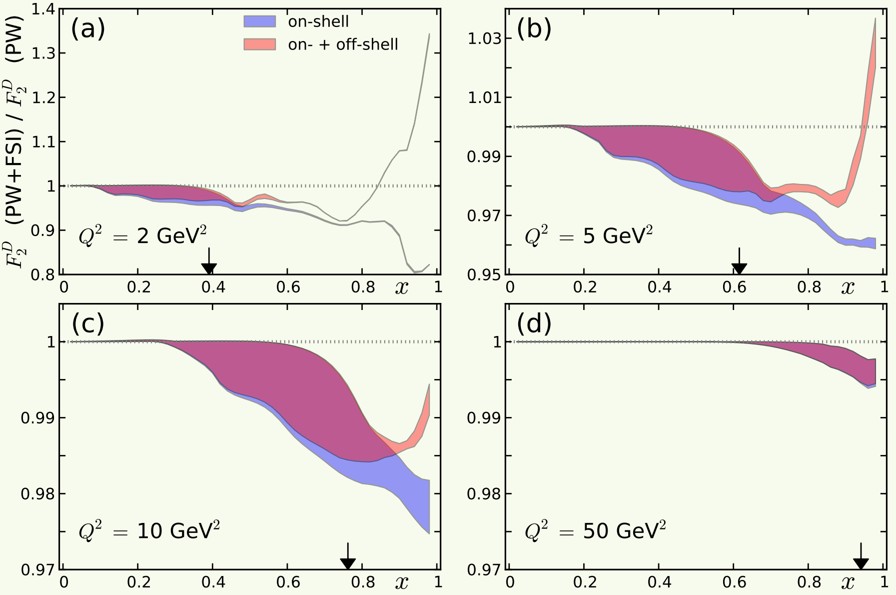
Model features

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



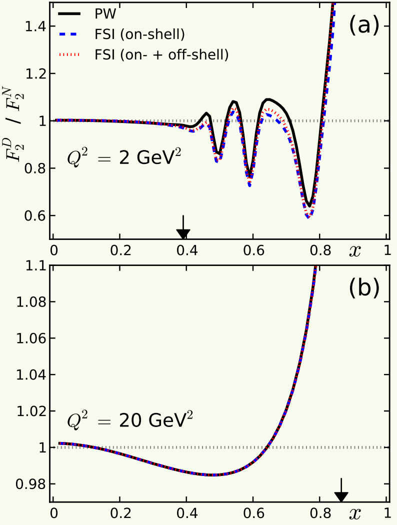
- Take scattering parametrizations from our fit to the Deeps data
- We don't take into account any possible relative phases between the resonances: maximum possible effect

Inclusive DIS calculations

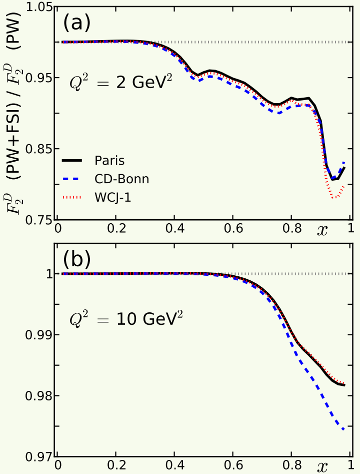


Inclusive DIS calculations

Ratio to F_{2N}



Deuteron wf dependence



Inclusive DIS calculations

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

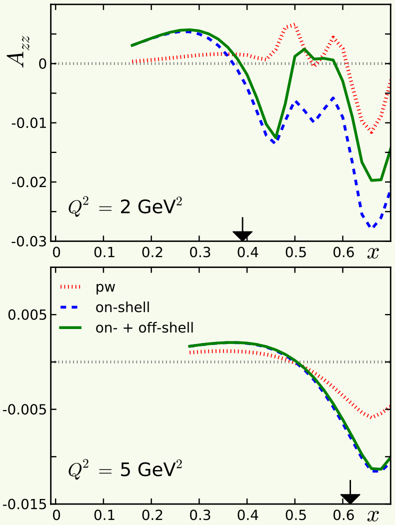
$$\tilde{x} = \frac{1}{1 + \frac{W_X^2 - p_i^2}{Q^2}} (< 1)$$

- Off-shell contribution shown is maximum possible contribution from three effective resonances: large contribution at $x \gtrsim 0.8$ and $Q^2 \lesssim 5$ 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 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 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

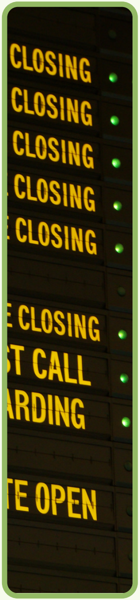
A_{zz} in inclusive DIS



WC, M. Sargsian, arXiv:1407.1653

- Only resonance contribution considered in the FSI, NO DIS continuum contribution
- JLab 12 GeV kinematics considered
- Non-negligable contribution from FSI even at low x, but still nowhere near the Hermes value.
- Convolution (D-wave dominance → 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)
- In inclusive DIS: natural suppression of FSI at high Q^2
- FSI effects of a few percent in inclusive DIS at large Bjorken x

Outlook

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