b_1 in tagged and inclusive DIS with final-state interactions

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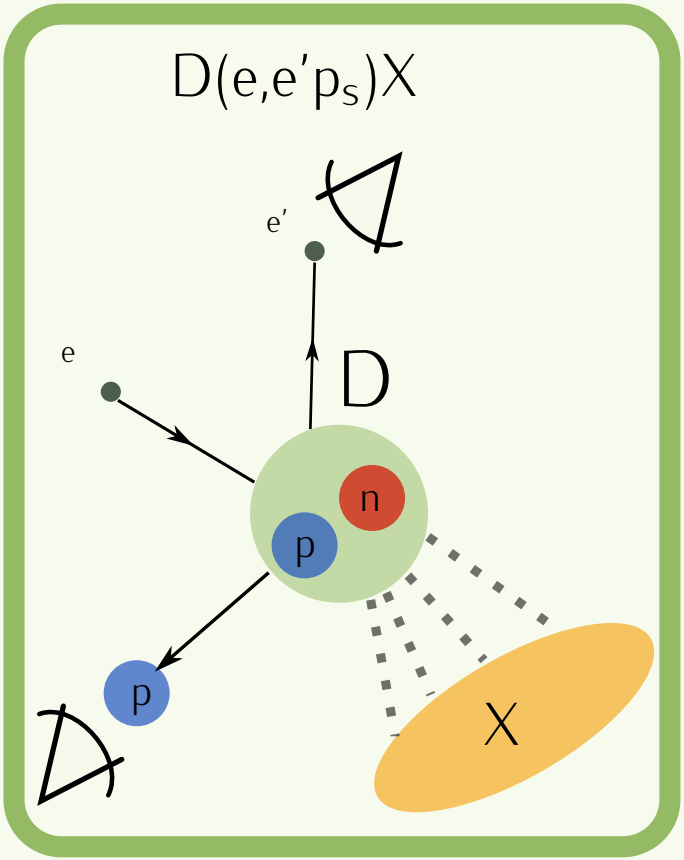
Motivation

- (tagged) 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
- Study influence of final-state interactions (FSI) through **effective** rescattering amplitudes
- tagged DIS $\rightarrow$ inclusive DIS $\rightarrow$ A_{zz} in both processes

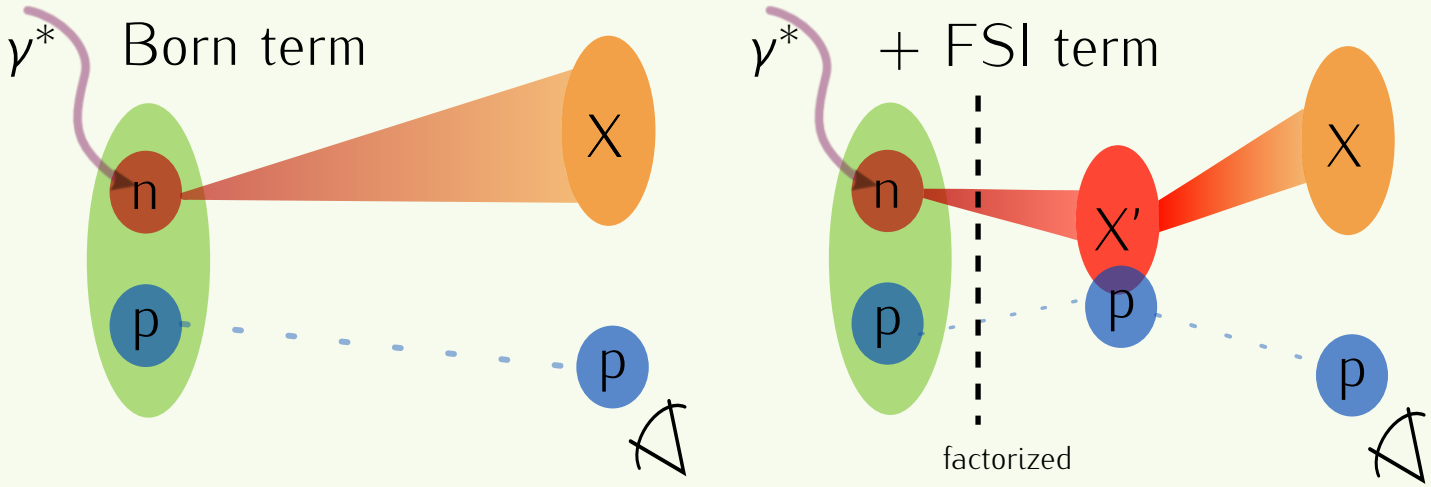
Tagged DIS off the deuteron



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

- Detection of a slow spectator proton
- At low proton momenta: extraction of neutron structure function
  - Helps constrain quark models of the nucleon
  - Gives us u/d pdf ratio at high x
- At higher proton momenta: probe high density configurations, nucleon modifications, 6 quark configurations,...?
- For kinematics with high FSI: study space–time evolution of hadronization

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

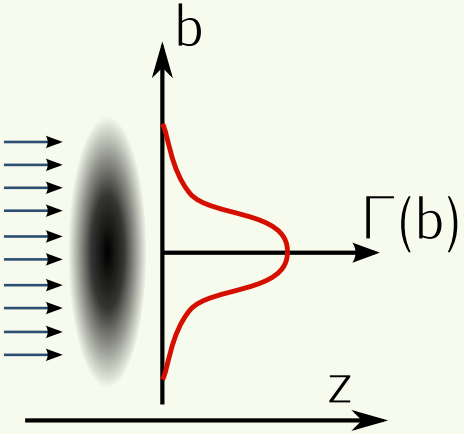
- Relate tagged deuteron structure functions to the **neutron** ones for a moving nucleon at $\hat{x} = \frac{Q^2}{2p_i \cdot q} \approx \frac{x}{2-\alpha_s} \ldots$

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

- ...times a distorted spectral function that contains a **plane-wave** and FSI constribution. FSI amplitude has an **on**-shell and **off**-shell part.

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

FSI: Generalized eikonal approximation



- Scattering amplitude is parametrized with the standard diffractive form

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

- 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

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

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

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

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

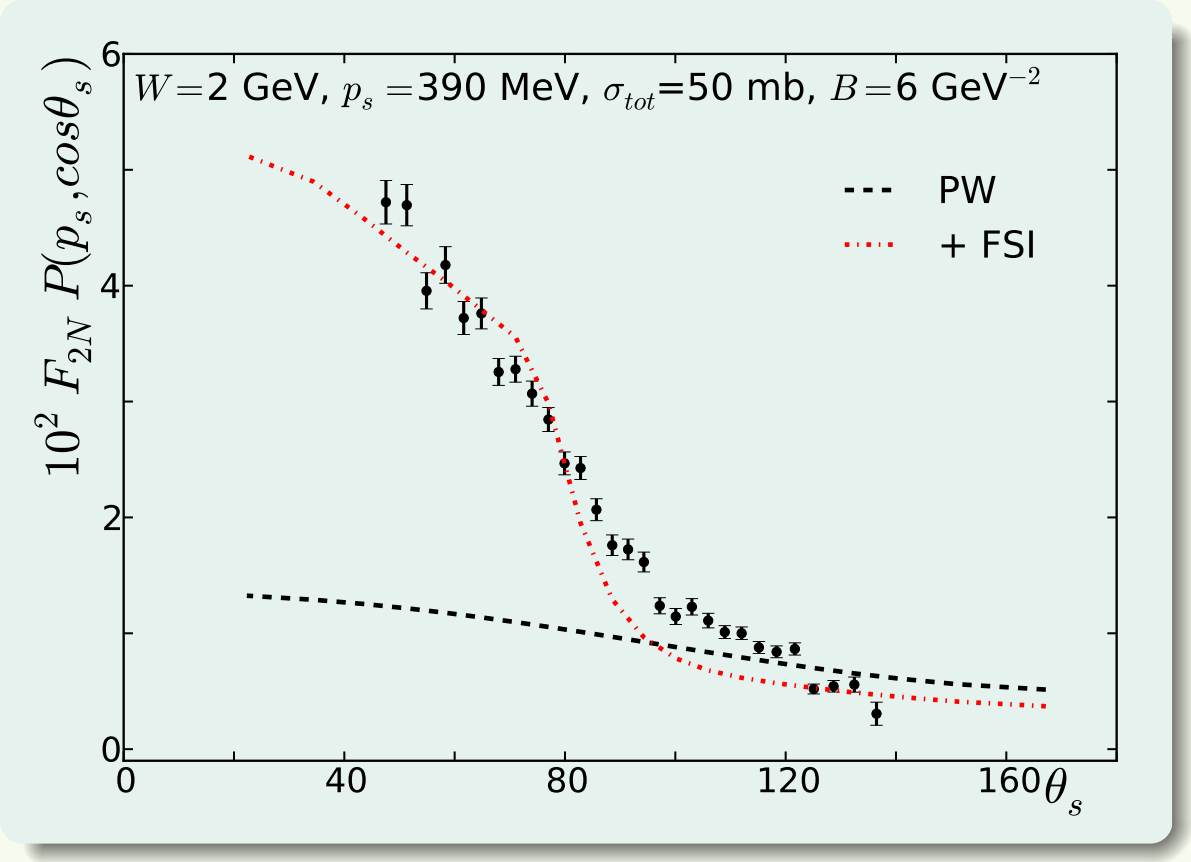
- maximum off-shell FSI: off-shell amplitude is taken equal to the on-shell one

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

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

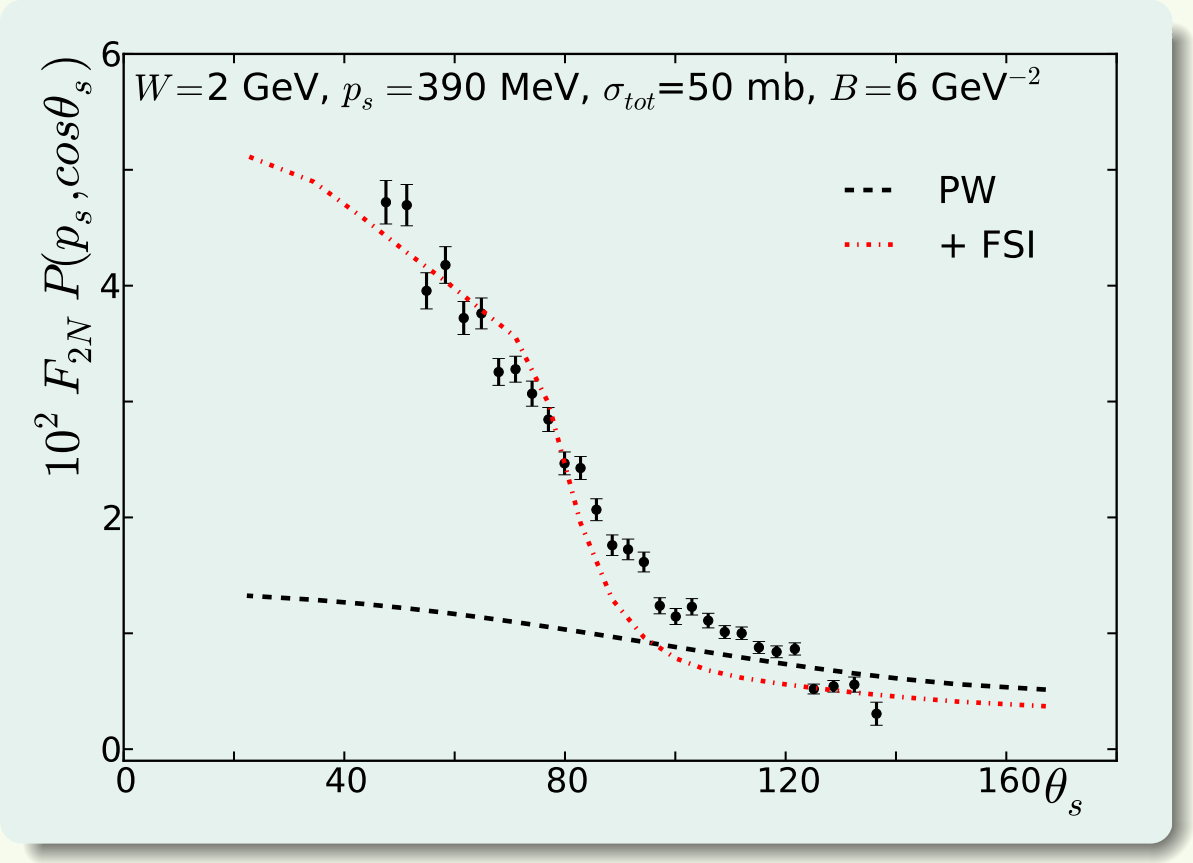
$$f^{\text{off}}_{X'N,XN} = f^{\text{on}}_{X'N,XN} e^{-\mu(x,Q^2)t}$$

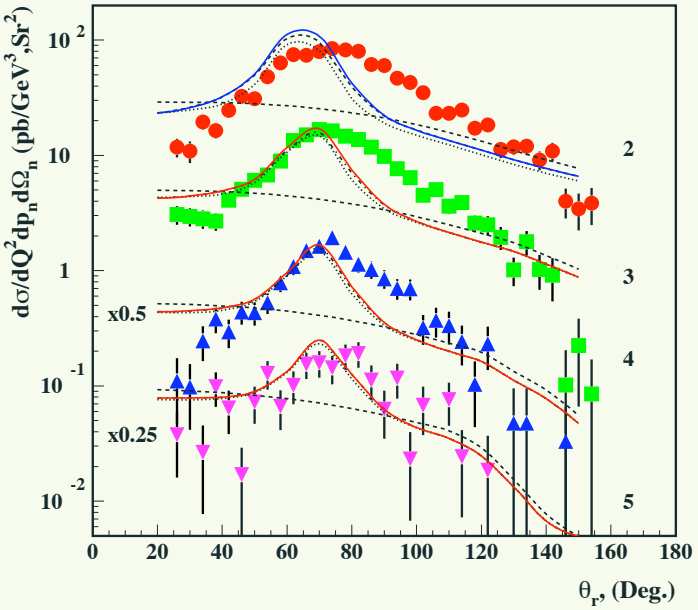
D(e,e'p_s)X calculation without fits



- 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)

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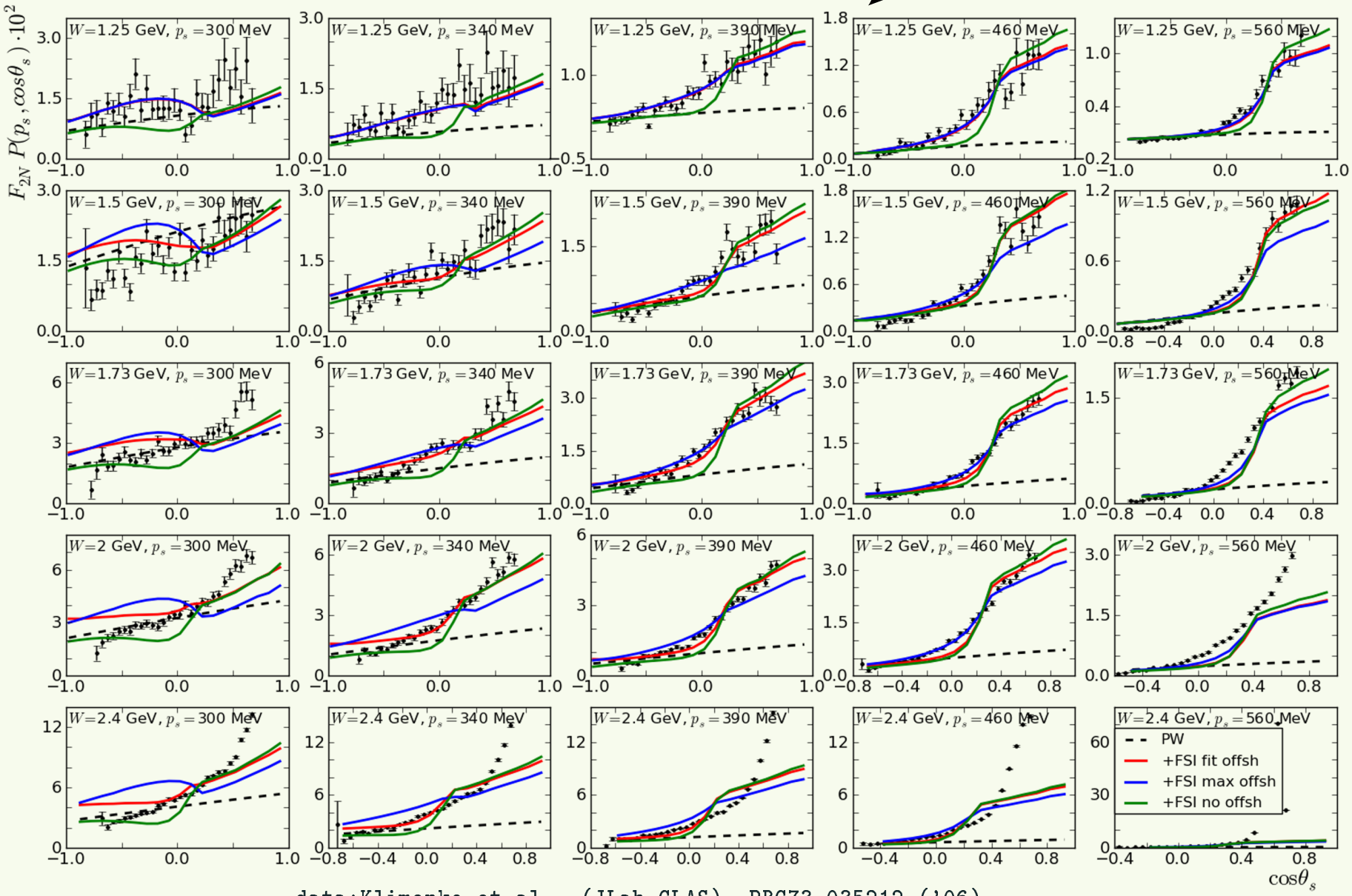
Calculation with σ_{XN} and β_{XN} fitted at Q^2=1.8 GeV^2

increasing p_s

increasing invariant mass of X

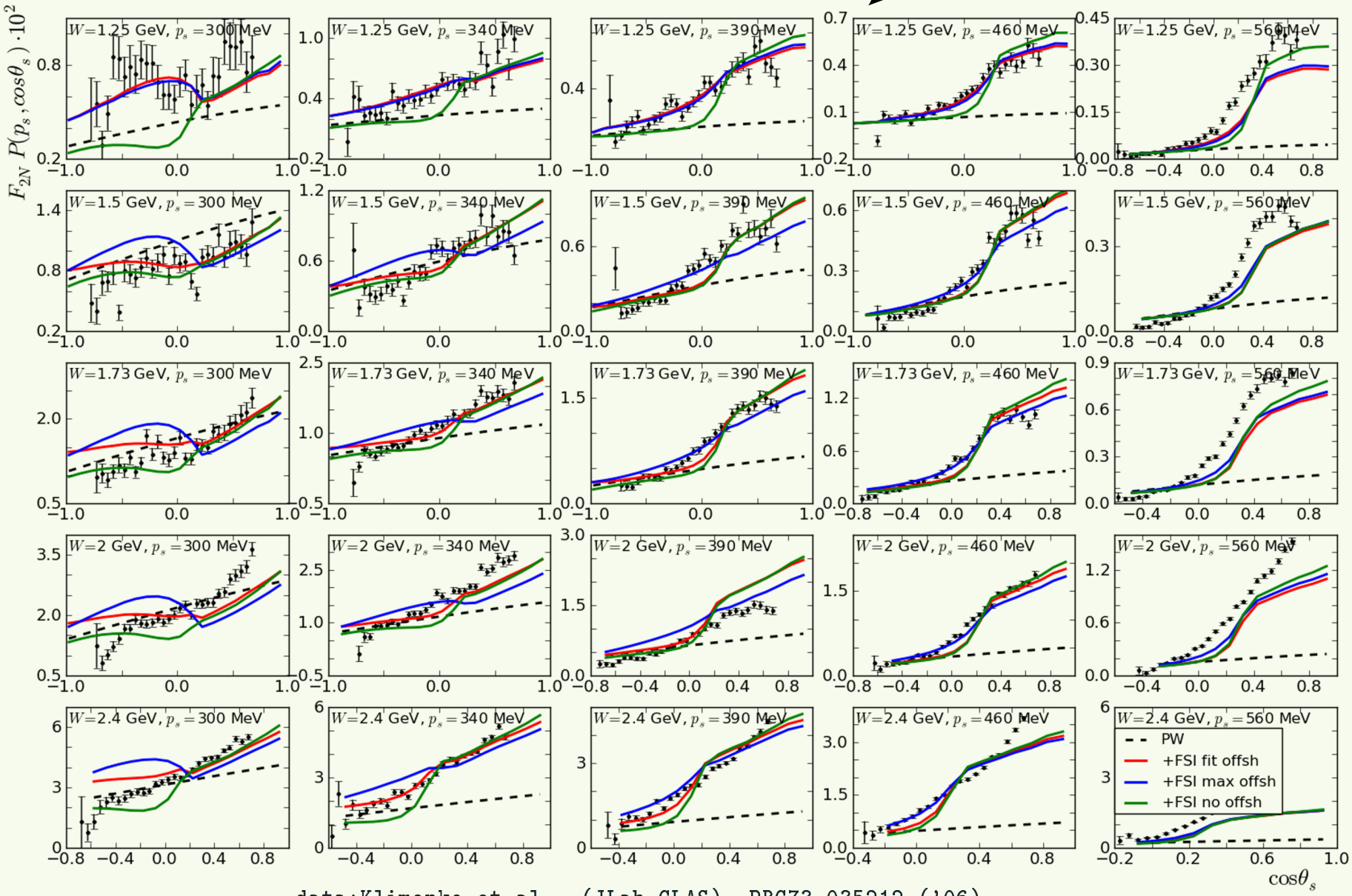


data:Klimenko et al. (JLab CLAS), PRC73 035212 ('06)

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

increasing p_s

increasing invariant mass of X



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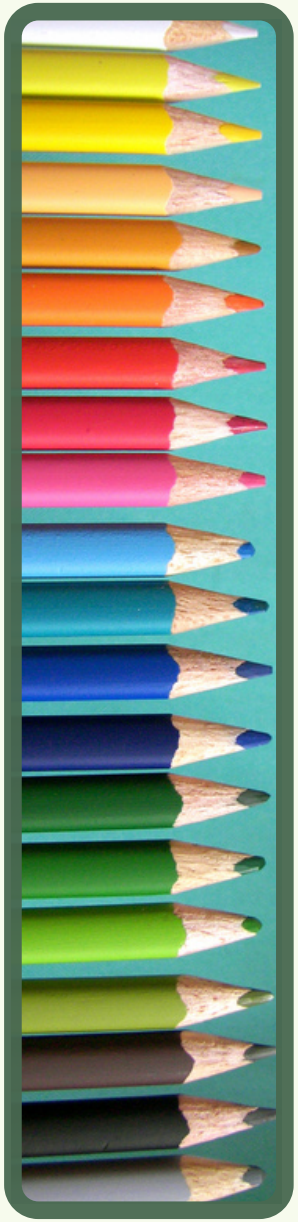
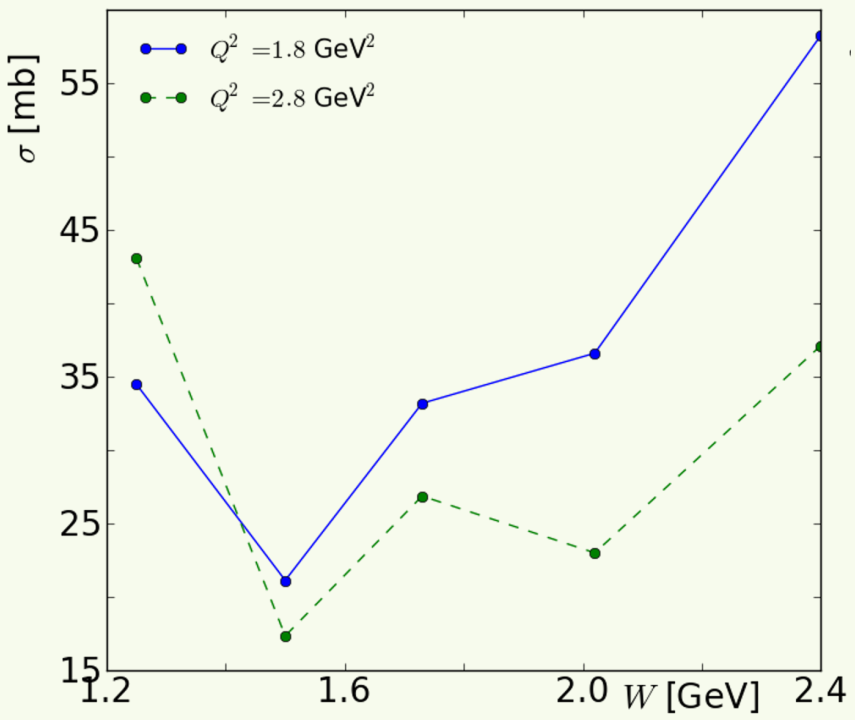
Results discussion



- 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 inclusive DIS

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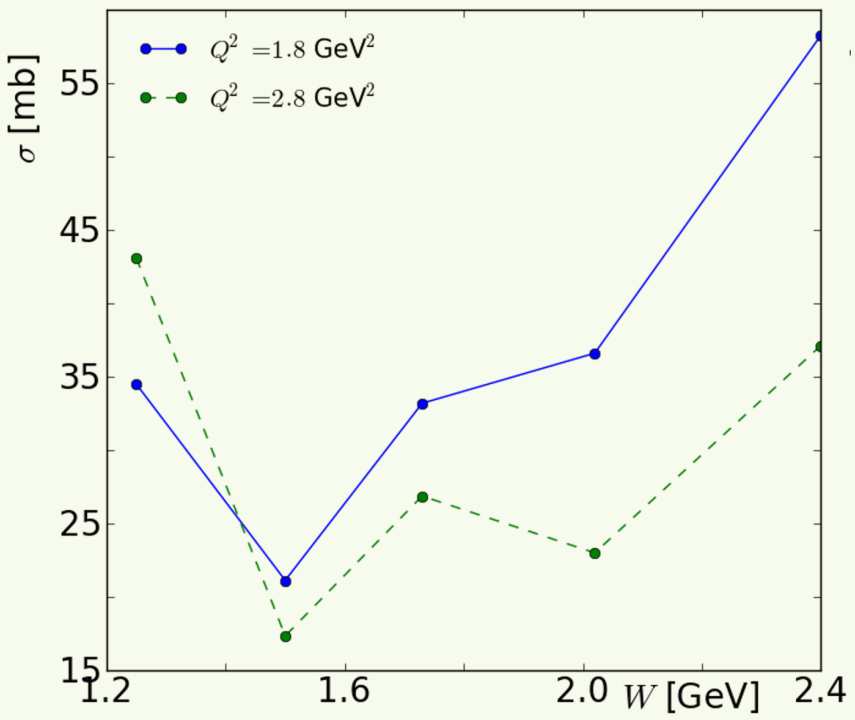

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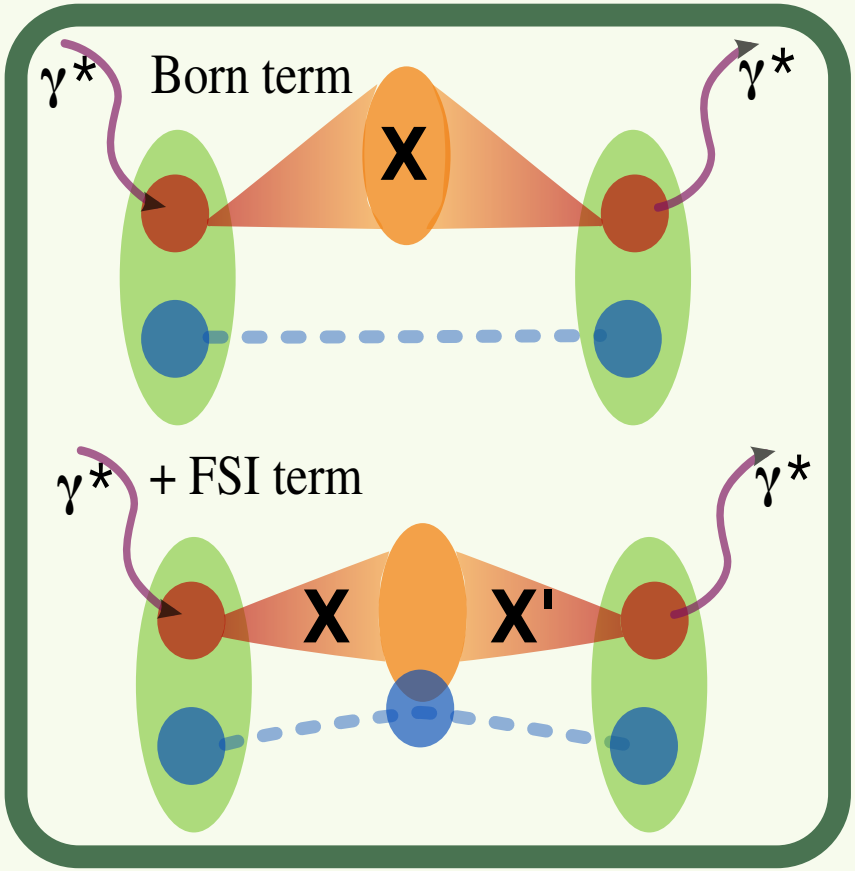
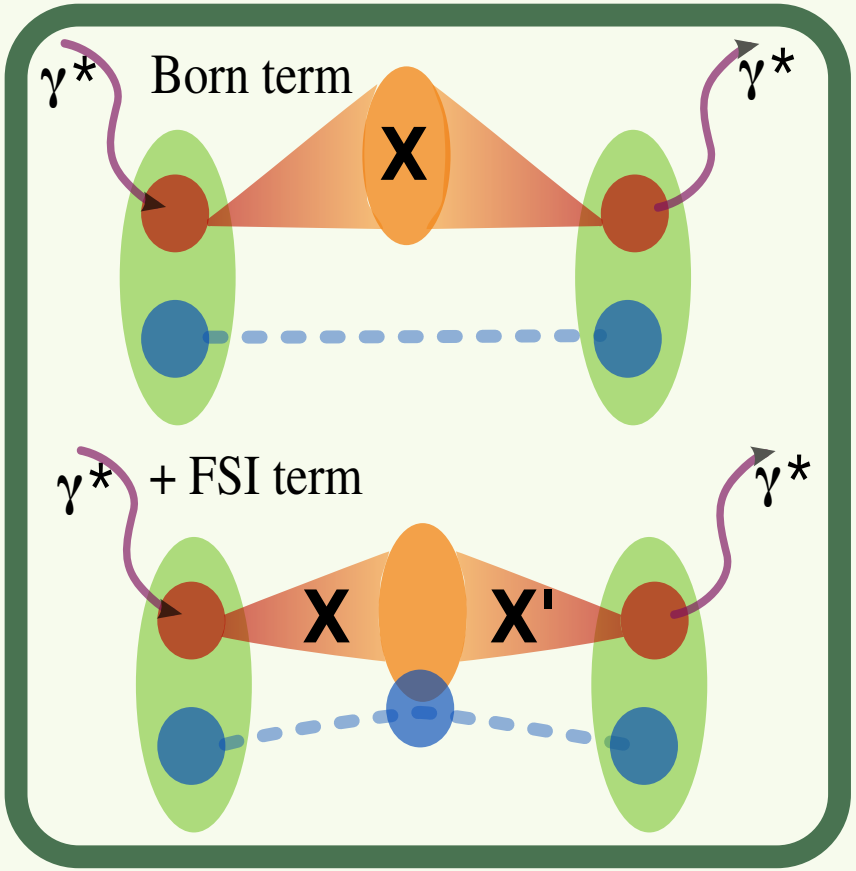
Inclusive DIS



W.C., M.S., 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

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

$$W_{\mathrm{FSI}}^{\mu\nu(\mathrm{on})} = -\frac{\pi(2\pi)^3}{3M_D} \sum_{N,X_1,X_2} \sum_{\mathrm{spins}} \Im m \int \frac{d^3\boldsymbol{p}_{s_1}}{(2\pi)^3} \frac{d^3\boldsymbol{p}_{s_2}}{(2\pi)^3} \frac{\Psi_D^{sD\,\dagger}(p_{i_2}, s_{i_2}; p_{s_2}, s_{s_2}) \Psi_D^{sD}(p_{i_1}, s_{i_1}; p_{s_1}, s_{s_1})}{2\sqrt{E_{s_2} E_{s_1}}}$$

$$\times \langle p_{X_2}, s_{X_2}; p_{s_2}, s_{s_2} | F^{(\mathrm{on})}_{NX_1,NX_2} | p_{X_1}, s_{X_1}; p_{s_1}, s_{s_1} \rangle J^{\mu\dagger}_{\gamma NX_2}(p_{i_2}, s_{i_2}; p_{X_2}, s_{X_2})$$

$$\times J^{\nu}_{\gamma NX_1}(p_{i_1}, s_{i_1}; p_{X_1}, s_{X_1}) \delta(p_{X_1}^2 - m_{X_1}^2) \delta(p_{X_2}^2 - m_{X_2}^2)$$

$$W_{\mathrm{FSI}}^{\mu\nu(\mathrm{off})} = \frac{(2\pi)^3}{3\pi M_D} \sum_{N,X_1,X_2} \sum_{\mathrm{spins}} \Im m \int_{\mathcal{P}} \frac{d^3\boldsymbol{p}_{s_1}}{(2\pi)^3} \frac{d^3\boldsymbol{p}_{s_2}}{(2\pi)^3} \frac{\Psi_D^{sD\,\dagger}(p_{i_2}, s_{i_2}; p_{s_2}, s_{s_2}) \Psi_D^{sD}(p_{i_1}, s_{i_1}; p_{s_1}, s_s)}{2\sqrt{E_{s_2} E_{s_1}}}$$

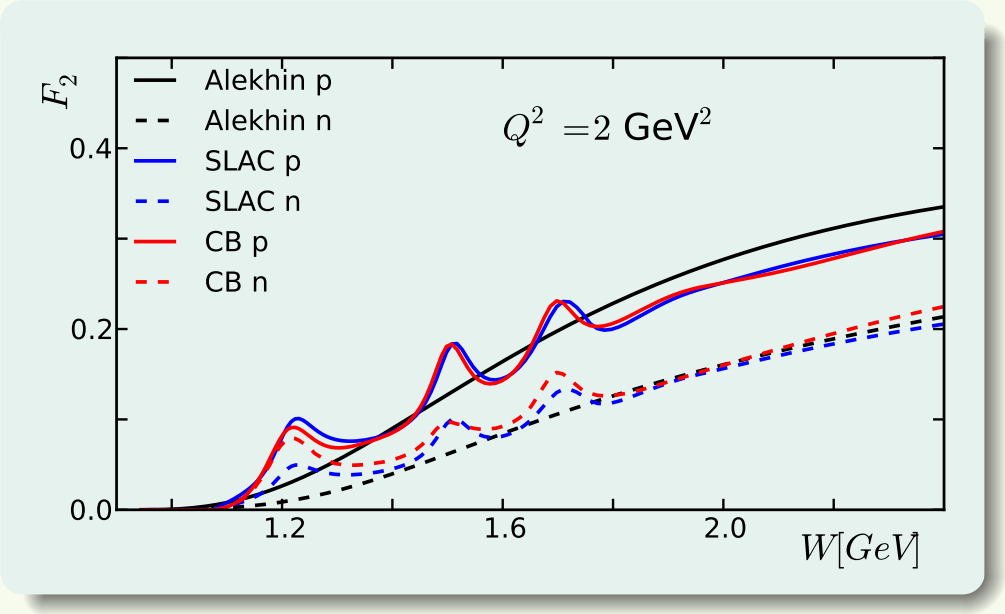
$$\times \langle p_{X_2}, s_{X_2}; p_{s_2}, s_{s_2} | F^{(\mathrm{off})}_{NX_1,NX_2} | p_{X_1}, s_{X_1}; p_{s_1}, s_{s_1} \rangle J^{\mu\dagger}_{\gamma NX_2}(p_{i_2}, s_{i_2}; p_{X_2}, s_{X_2})$$

$$\times J^{\nu}_{\gamma NX_1}(p_{i_1}, s_{i_1}; p_{X_1}, s_{X_1}) \frac{1}{p_{X_1}^2 - m_{X_1}^2} \frac{1}{p_{X_2}^2 - m_{X_2}^2}$$

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

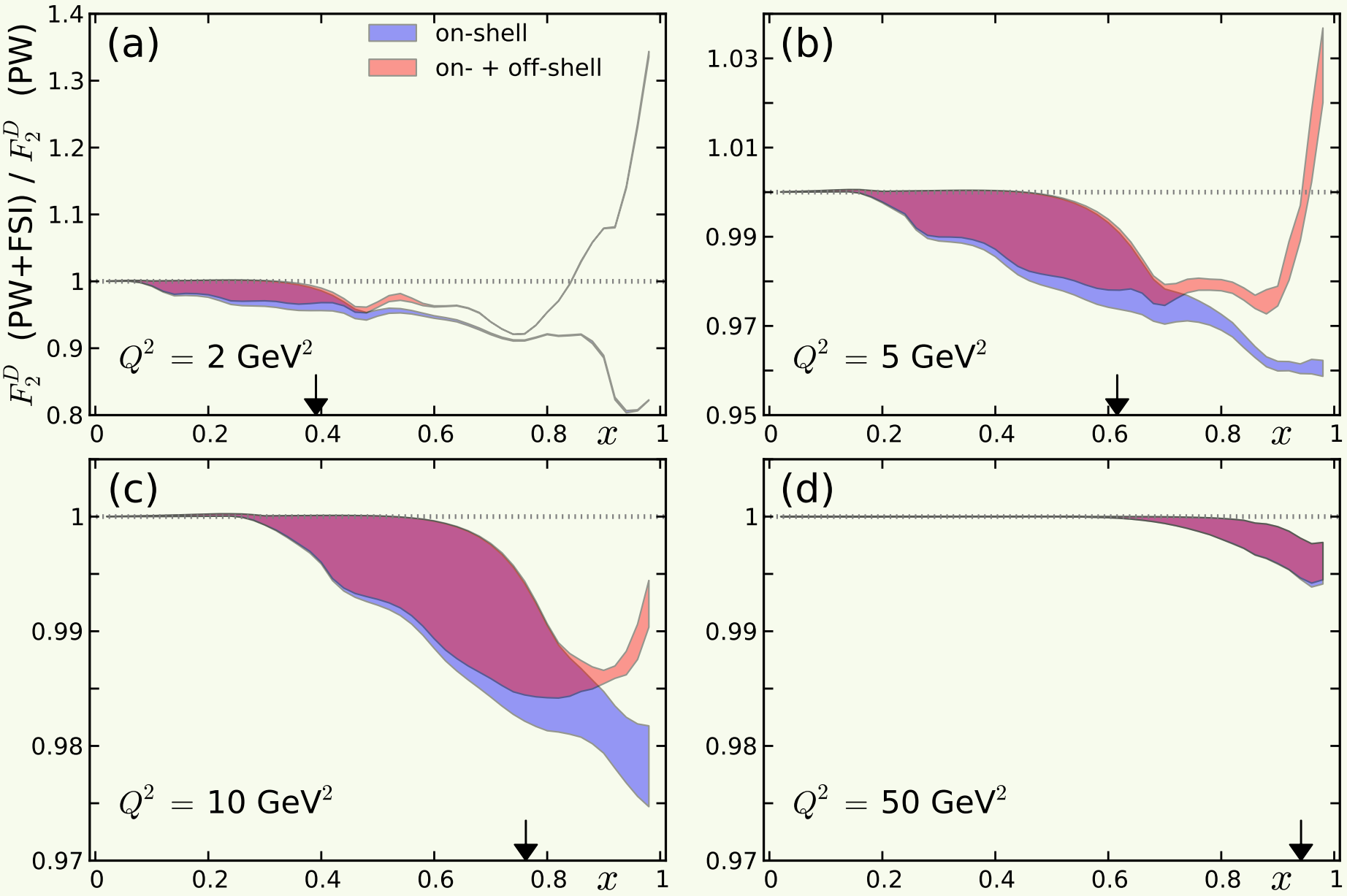
Model features

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



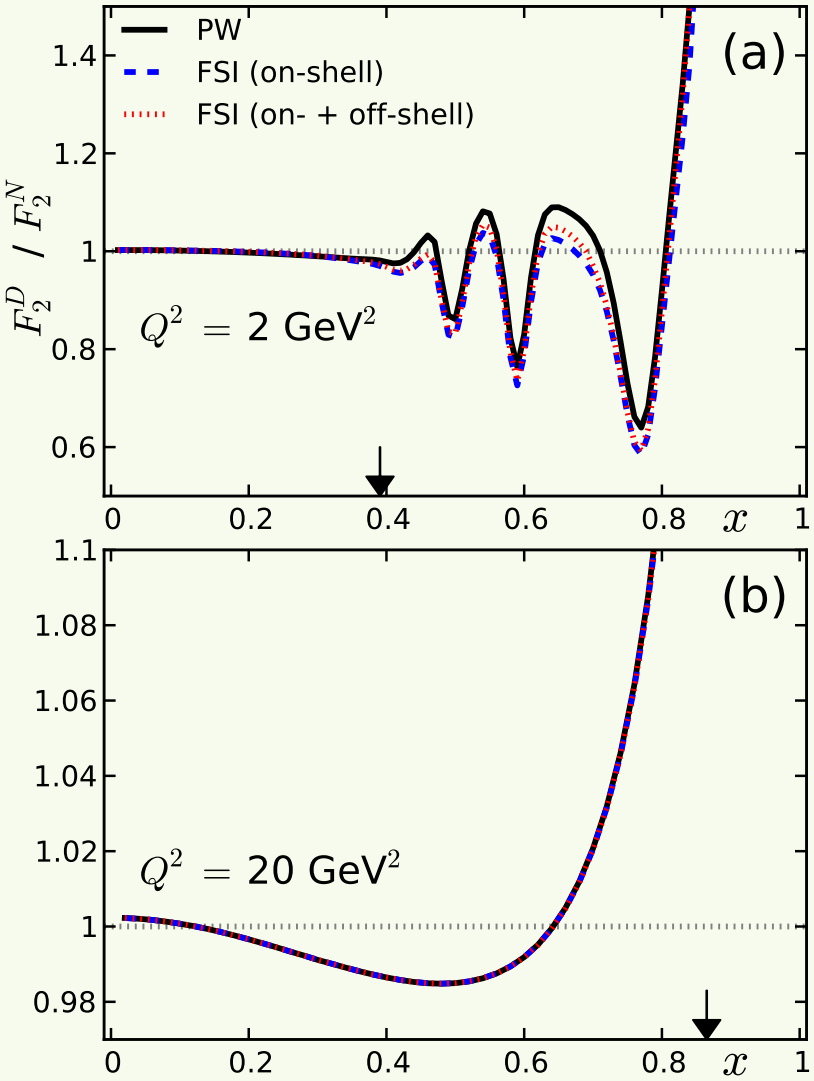
- Resonances: 1.2, 1.5 and 1.75 GeV. Continuum contribution [2-3.5] GeV
- Take scattering parametrizations from our fit to the Deeps data
- We don't take into account any possible relative phases between the resonances: maximum possible effect

Inclusive DIS calculations

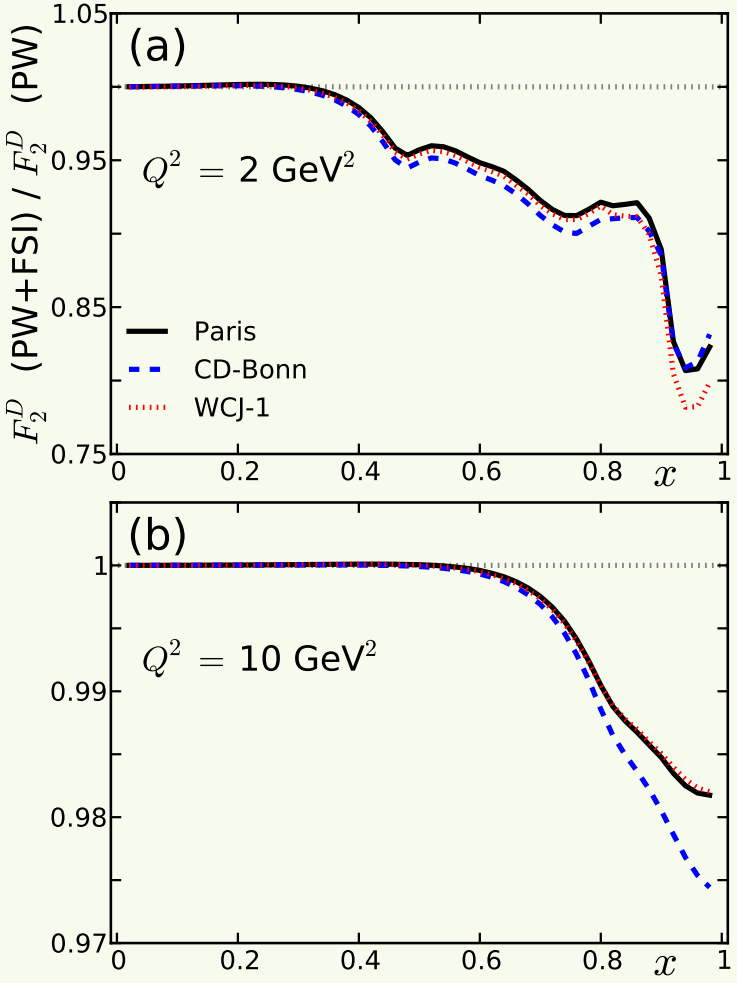


Inclusive DIS calculations

Ratio to F_{2N}



Deuteron wf dependence



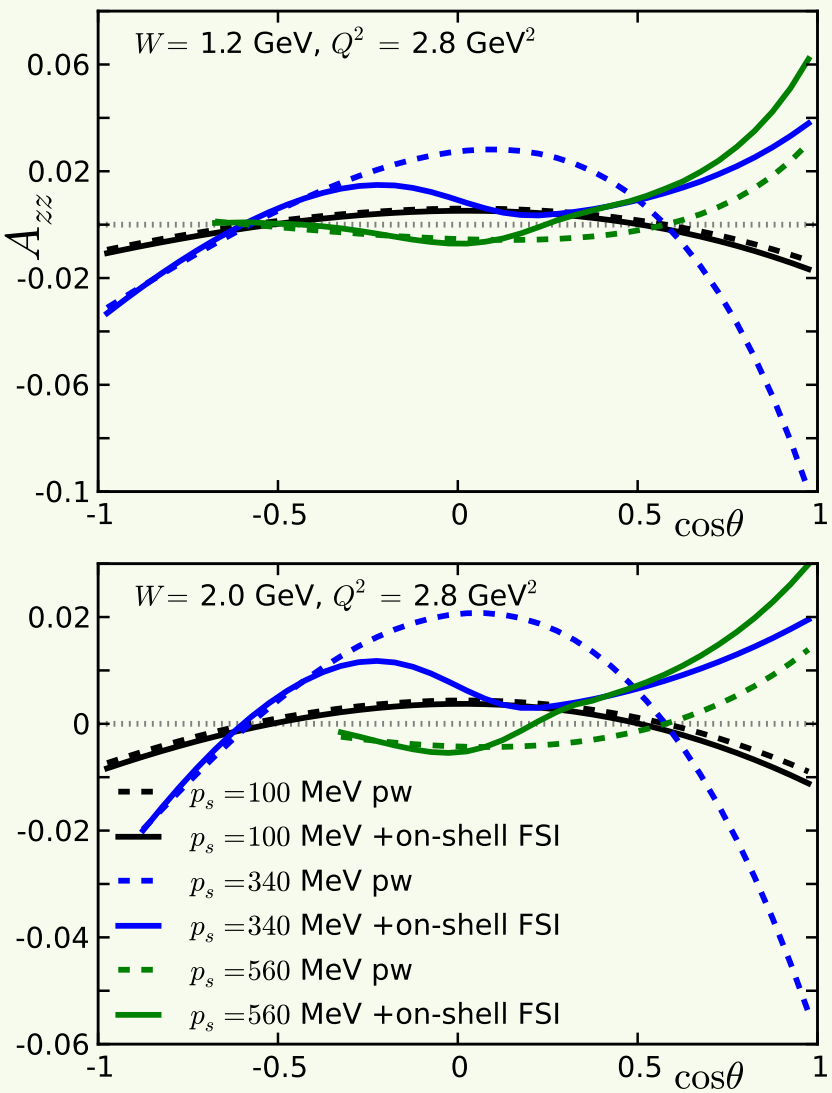
Inclusive DIS calculations

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

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

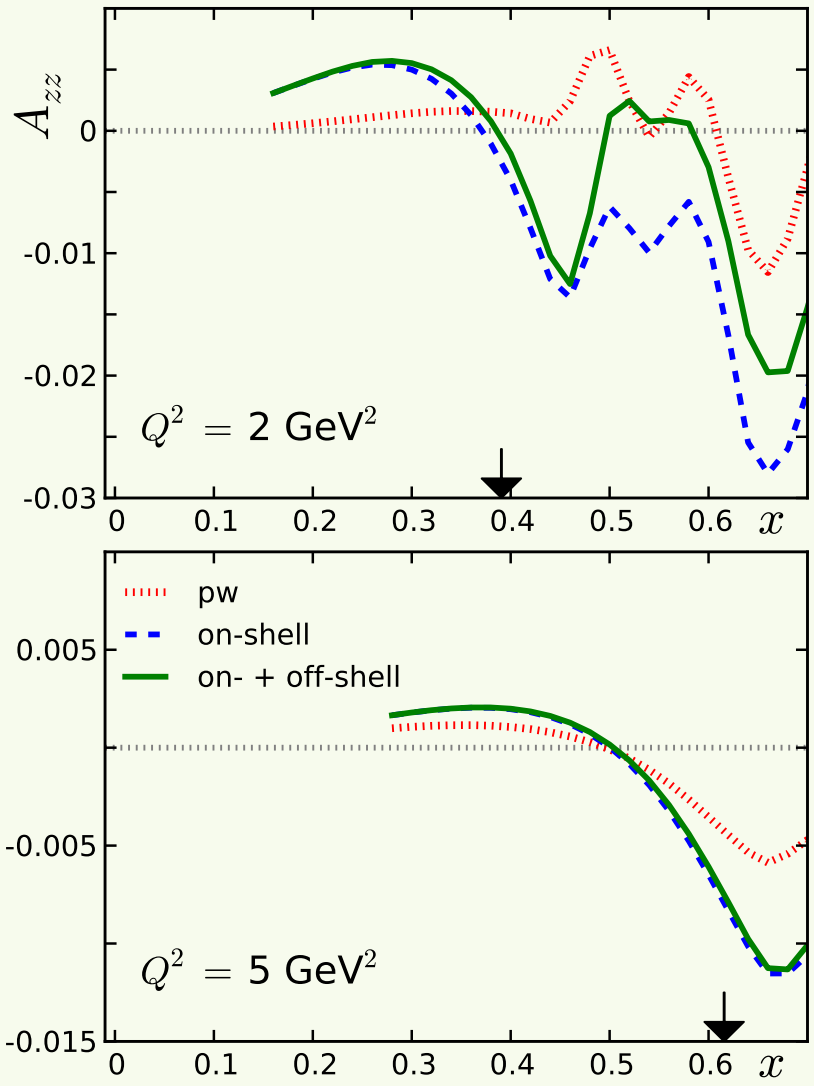
- Off-shell contribution shown is maximum possible contribution from three effective resonances: large contribution at $x \gtrsim 0.8$ and $Q^2 \lesssim 5$ GeV^2
- Can be taken into account in neutron structure function extractions
- Dependence on deuteron wave function much smaller than size of FSI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

A_{zz} in tagged DIS



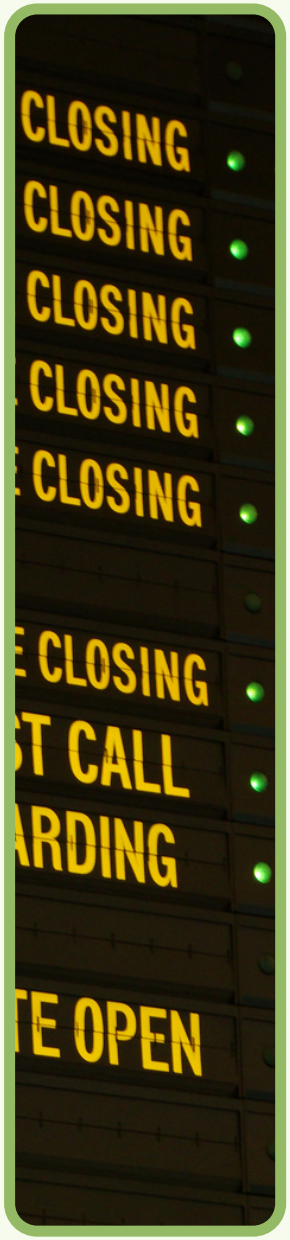
- WARNING: VERY preliminary. Might have missed an overall factor in my coding
- A_{zz} through density matrix: $\rho_{02}=1/\sqrt{2}\mathrm{diag}(1,-2,1)$ (z-axis along photon)
- Tagged DIS: select nucleon spectator, so should be sensitive to the nucleonic component of A_{zz}
- Sensitive to D-wave of deuteron $\rightarrow$ high spectator momenta
- Took Deeps kinematics (avg over spectator ϕ), big difference for intermediate spectator momenta between plane-wave and FSI

A_{zz} in inclusive DIS



- WARNING again:VERY preliminary
- Only nucleonic contributions in our model
- 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
- 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) 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!)
- Would love to see more tagged DIS measurements at 1) higher Q^2, W in kinematics with large FSI; 2) low p_s
- In inclusive DIS: natural suppression of FSI at high Q^2
- FSI effects of a few percent in inclusive DIS at large Bjorken x
- b_1 at low Q^2 sensitive to FSI effects from resonances even in DIS region