

# Final state interactions in inclusive and tagged spectator DIS

Wim Cosyn

Ghent University, Belgium

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# Outline

1 Tagged spectator DIS

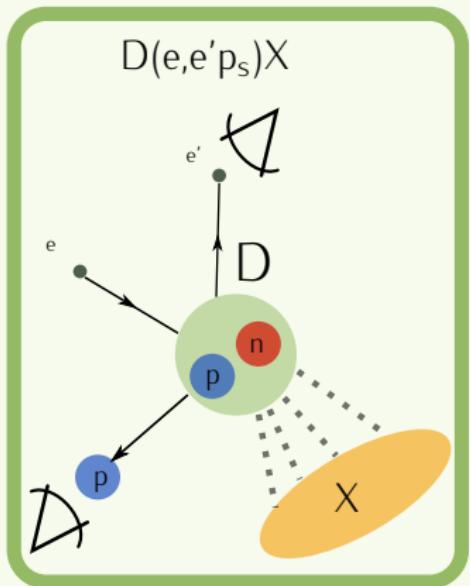
2 Nucleon structure extraction

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

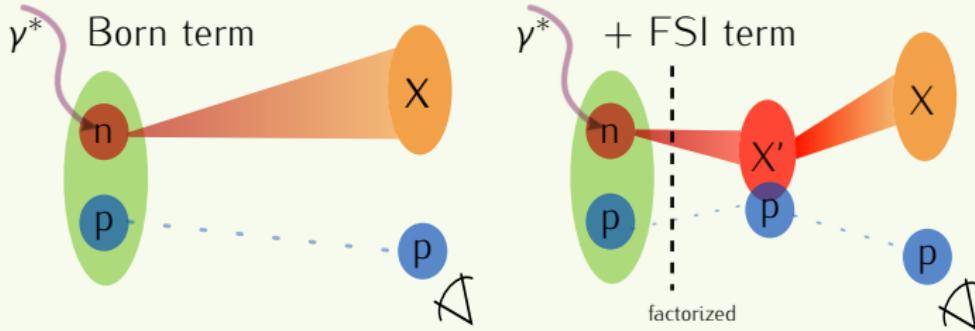
# Tagged Spectator DIS off the deuteron



- Detection of a **slow spectator** proton
- At low proton momenta: extraction of **neutron structure function**
  - ▶ Necessary for flavor separation of pdf's
  - ▶ 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.

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

# 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! ( $D$ ,  ${}^3\text{He}$ , ...)

# Factorization

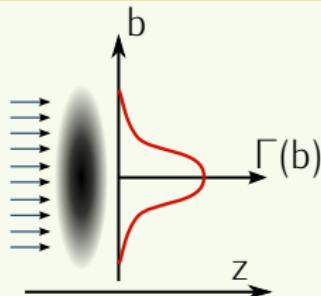
- Relate tagged spectator deuteron structure functions to the **neutron** ones for a moving nucleon at  $\hat{x} = \frac{Q^2}{2\vec{p}_i \cdot \vec{q}} \approx \frac{x}{2-\alpha_s} \dots$

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

- ...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  $X'$ ).

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

# FSI: Generalized eikonal approximation



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

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

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

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

# Comparison with Deeps: approach

- Deeps experiment (JLab CLAS): Klimenko et al., PRC73, 035212 ('06)
- 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  $\int \alpha |\Phi_D(p)|^2 d^3 p = 1$

# Parametrization of the off-shell rescattering amplitude

Three approaches:

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

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

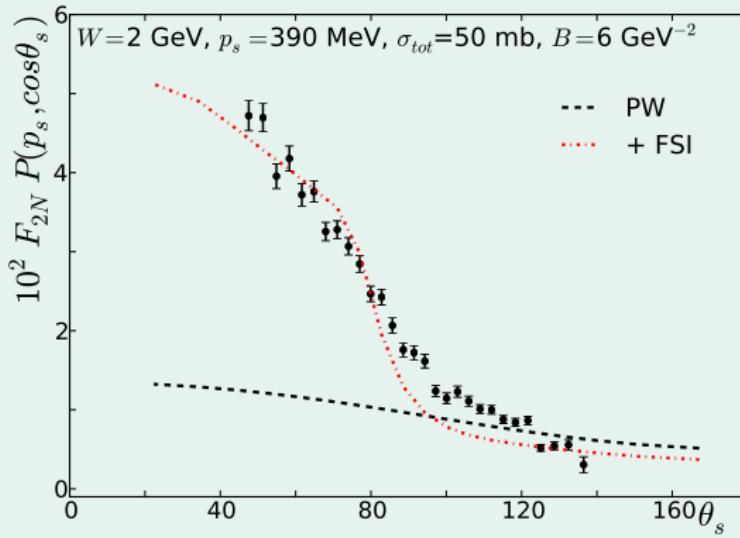
- **maximum off-shell FSI**: off-shell amplitude is taken equal to the on-shell one

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

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

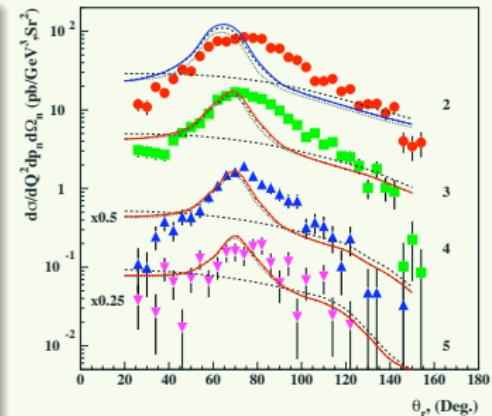
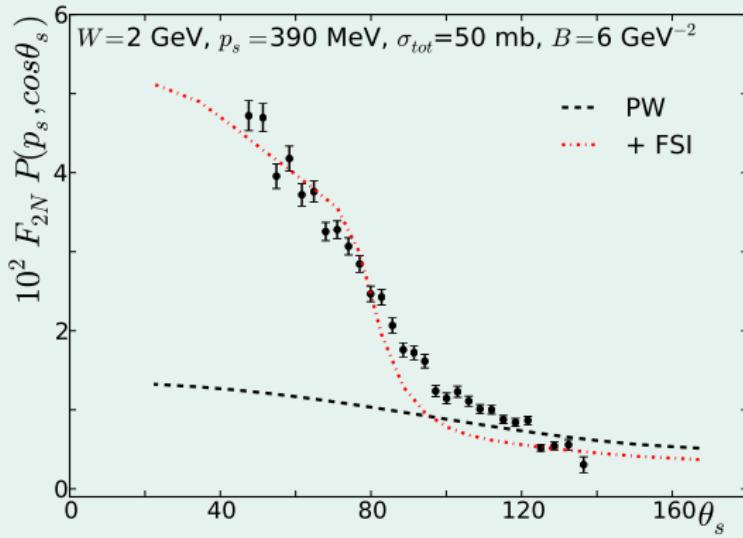
$$f_{X'N,XN}^{\text{off}} = f_{X'N,XN}^{\text{on}} e^{-\mu(x, Q^2)t}$$

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



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

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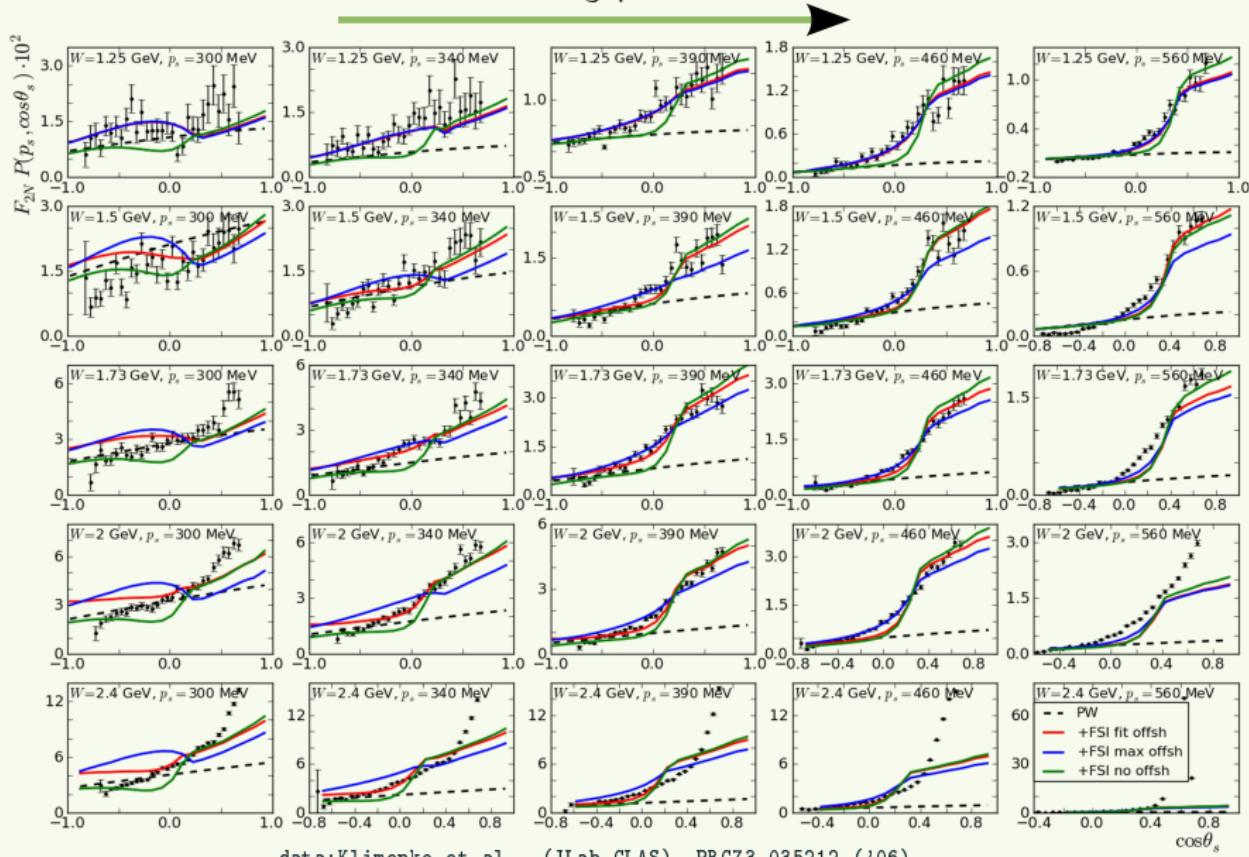


$D(e,e'p_s)n$   
M. Sargsian PRC82 014612 ('10)

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

# Calculation with $\sigma_{XN}$ and $\beta_{XN}$ fitted at $Q^2=1.8$ GeV $^2$

increasing  $p_s$

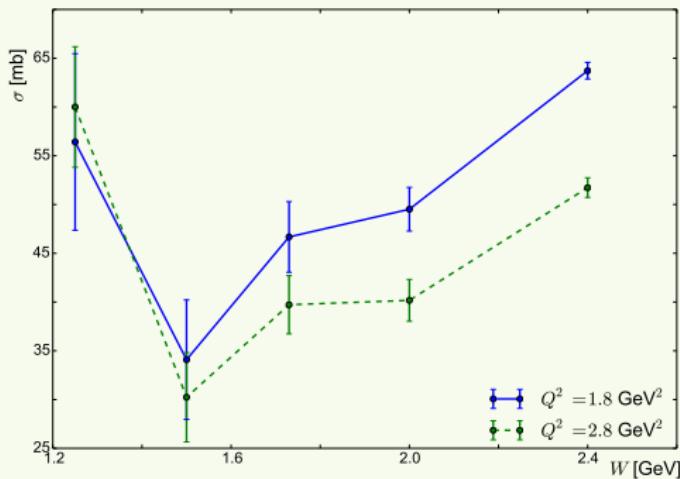


# Results discussion



- 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

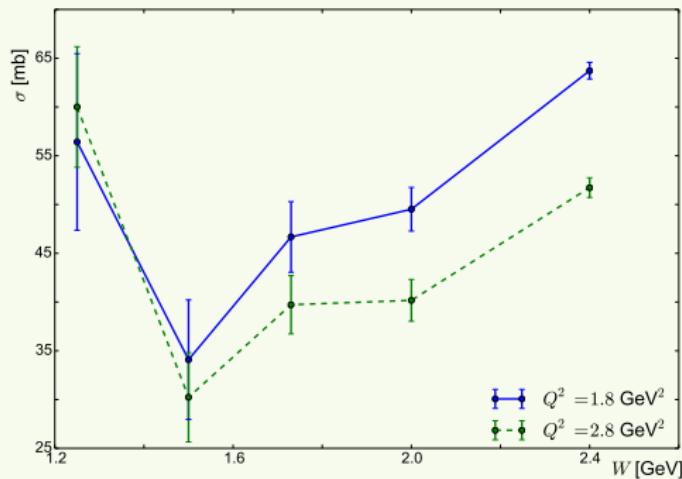
# What can the $\sigma_{XN}$ fit teach us?



- $\sigma$  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 in lattice DIS

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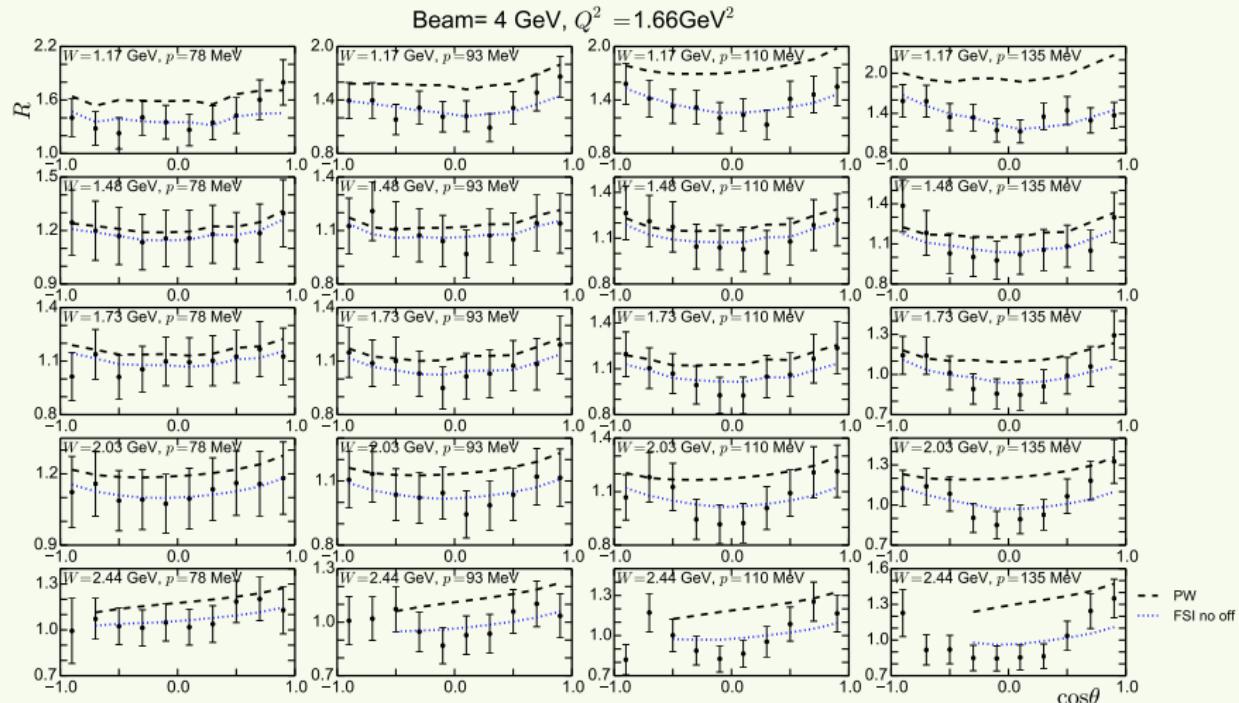
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- Values can be used as input for FSI effects in other calculations, such as inclusive DIS

# 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)  
K. Griffioen's & I. Niculescu's talks
- Detector efficiency varied with  $p_s \rightarrow$  data normalized to a Monte Carlo with plane-wave model.
- Refit normalization to our FSI calculations with rescattering parameters obtained from the Deep 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  $t' = p_i^2 - m_n^2 = (p_D - p_s)^2 - m_n^2 \rightarrow 0$ :  
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)

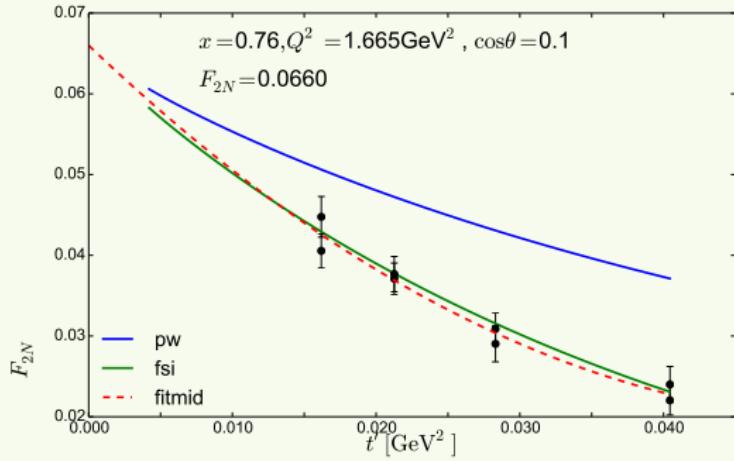
- Small binding energy of deuteron means extrapolation is not that far into the unphysical region
- Similar to Chew-Low extrapolation used to extract pion structure
- Extract the free neutron structure function through

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

This quantity has a **quadratic dependence** in  $t'$ .

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

# Use Bonus data

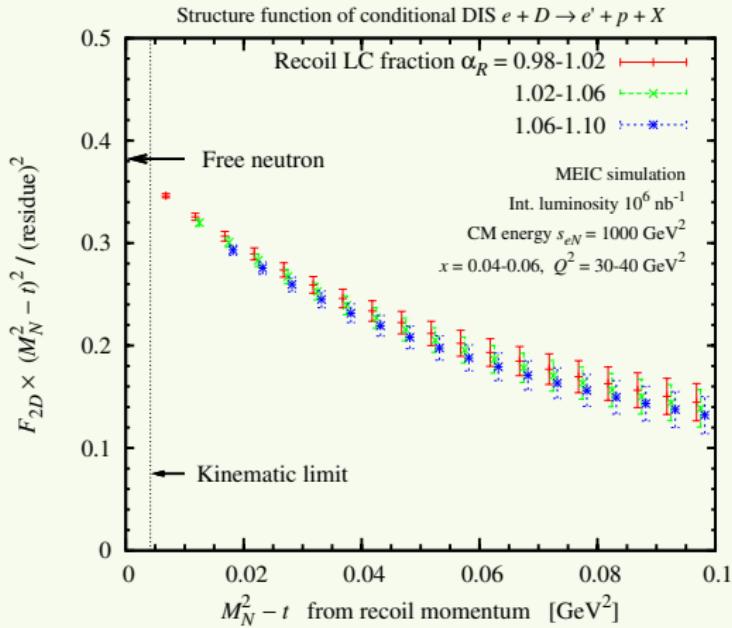


- Data from two beam energies
- Extrapolation feasible
- Of course fitting of the normalization has introduced a model dependence here!
- **Preliminary** results!!!: have to do systematic study of dependence on  $\theta_s$  etc.

# Neutron structure extraction at the Electron-Ion Collider

- JLab LDRD project: C. Weiss, K. Park, Ch. Hyde, P. Nadel-Turonski, D. Higinbotham, S. Kuhn, M. Strikman, M. Sargsian, V. Guzey, W. Cosyn.  
Renewed for '14-'15.
- EIC: next generation facility for QCD and nuclear physics (JLab or BNL) → P. Nadel-Turonski's talk
- High-energy  $eA$  scattering with (polarized) light ions
- Spectator tagging suited for collider: high spectator momenta, forward detectors
- High-energy theory: light-front quantized formalism

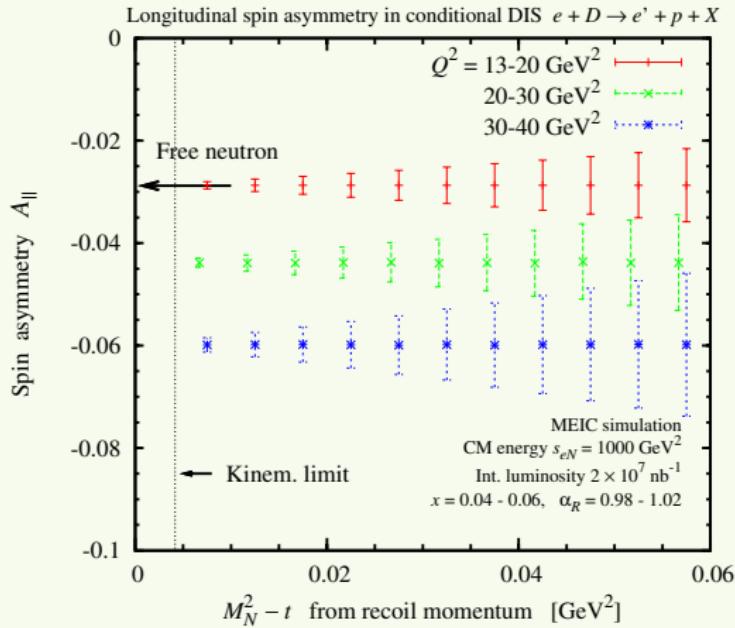
# F2n extraction at EIC



C. Weiss et al., J. Phys. Conf. Ser. 543 (2014) 012007

- Pseudodata generated in plane-wave model
- Systematic errors estimated, same magnitude as statistical ones
- Working on adding our FSI model (LC update of current model, extension to lower  $x$ ) and shadowing (V. Guzey)
- He3 study also underway

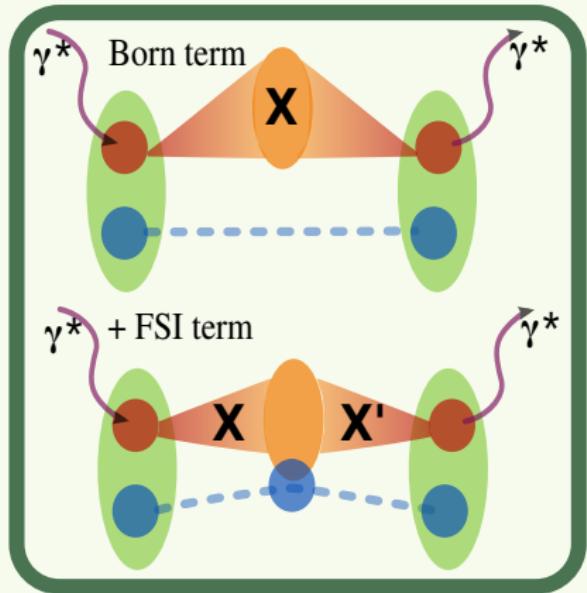
# Polarized deuteron: spin asymmetry at EIC



- $A_{||} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$
- Plane-wave model. At pole very small D-wave contribution → straightforward spin decomposition
- Flat ratios. Gives access to  $g1n/F1n$ .

C. Weiss et al., J. Phys. Conf. Ser. 543 (2014) 012007

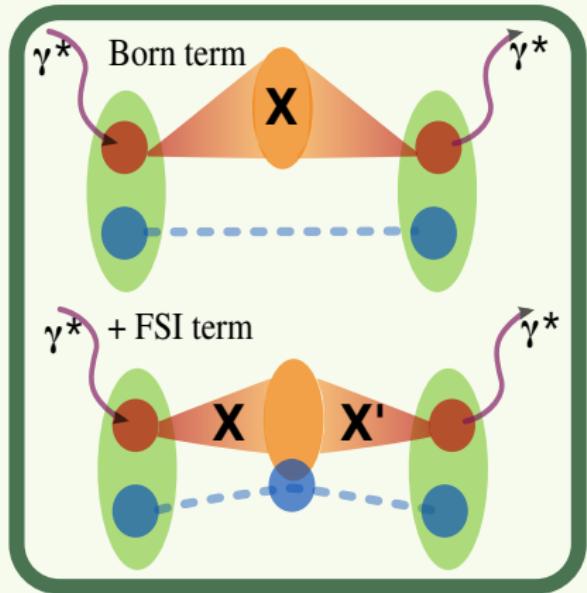
# Inclusive DIS



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

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

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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)

# General formulas using GEA

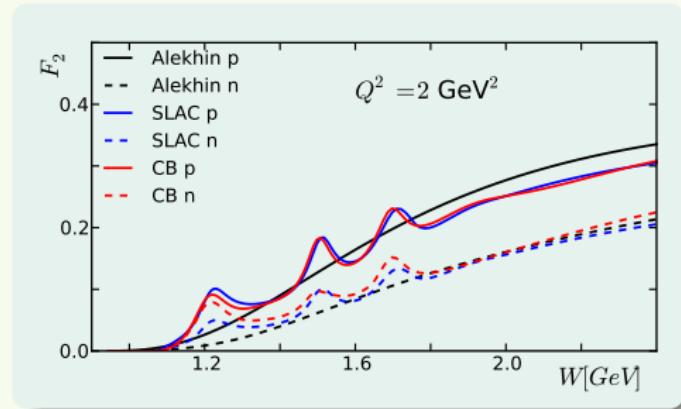
$$W_D^{\mu\nu(\text{pw})} = \frac{2m}{M_D} \sum_N \int d^3 \mathbf{p}_s W_N^{\mu\nu} S(p_s)$$

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

- 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  $\tilde{x} = \left(1 + \frac{m_X^2 - p_i^2}{Q^2}\right)^{-1} \quad (< 1)$

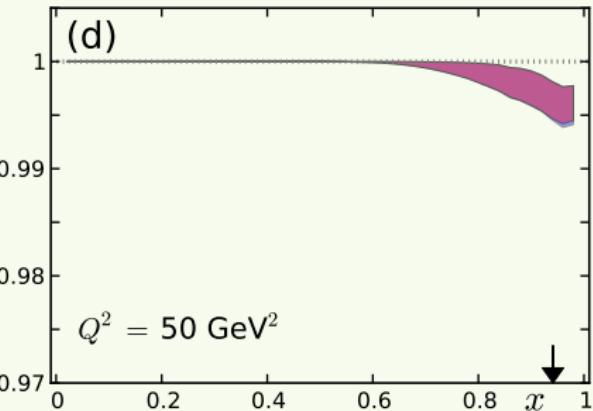
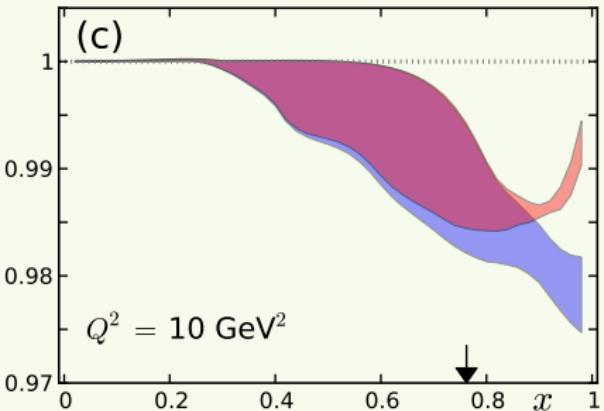
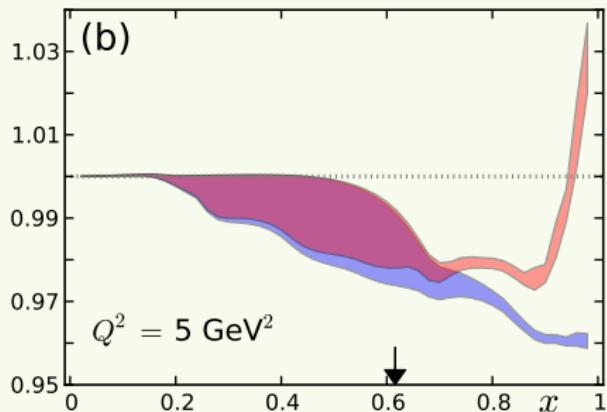
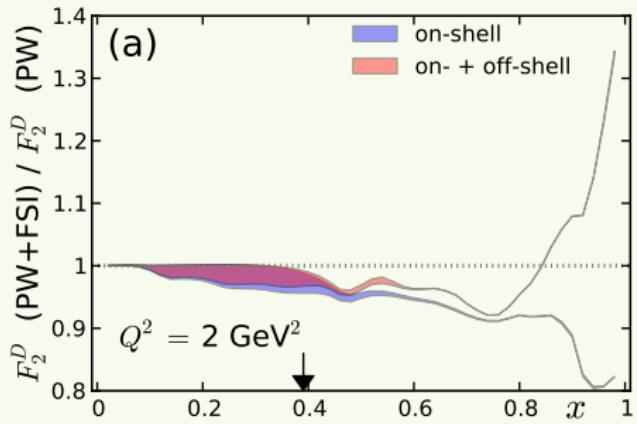
# Model features

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



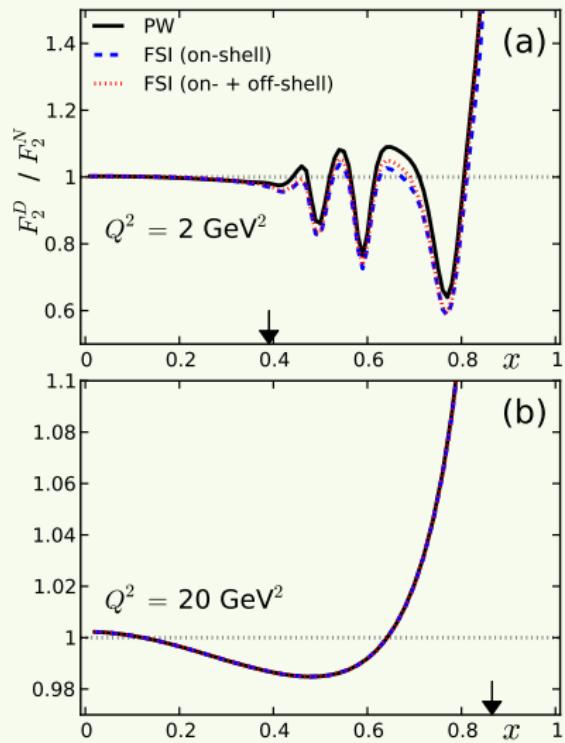
- Take scattering parametrizations from our **fit** to the Deeps data
- We don't take into account any possible relative phases between the resonances: **maximum** possible effect

# Inclusive DIS calculations

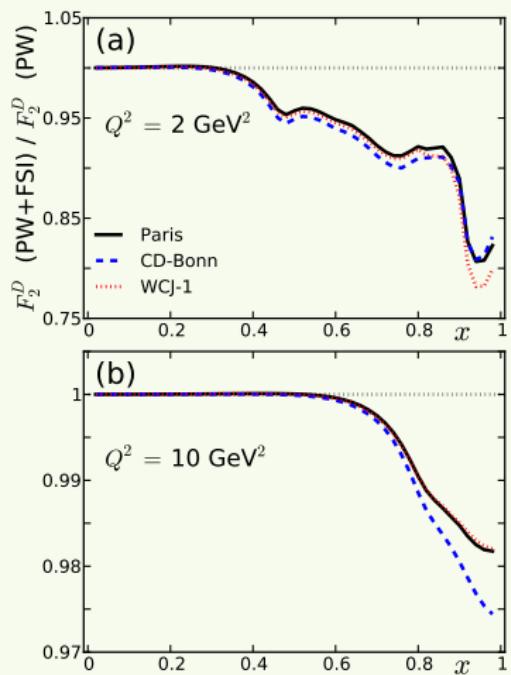


# Inclusive DIS calculations

## 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

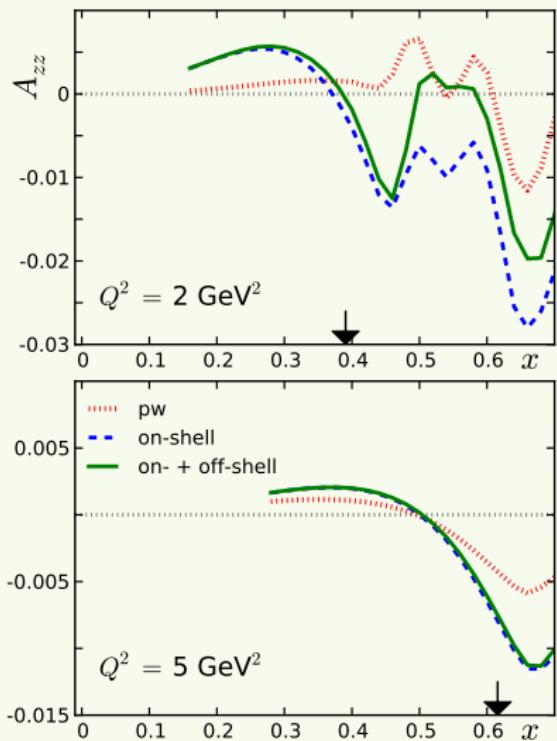
$$\tilde{x} = \frac{1}{1 + \frac{W_X^2 - p_i^2}{Q^2}} (< 1)$$

- Off-shell contribution shown is maximum possible contribution from three effective resonances: large contribution at  $x \gtrsim 0.8$  and  $Q^2 \lesssim 5 \text{ GeV}^2$
- 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 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 (E. Long's talk)
- $A_{zz}$  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

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- 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  $x$  and  $Q^2 \leq 5\text{GeV}^2$