Coherent Phenomena in Tagged DIS on Deuteron

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Outline

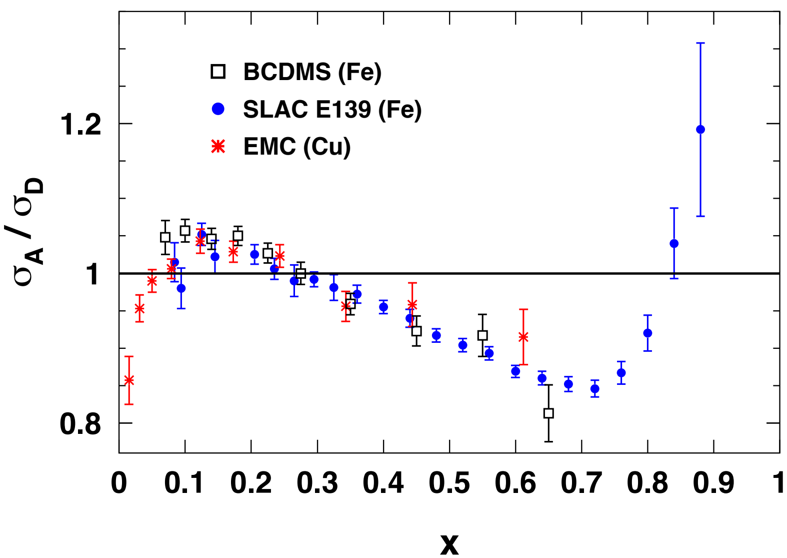
- Nuclear shadowing in inclusive DIS on deuteron
- Nuclear shadowing in tagged DIS on deuteron
- Polarized inclusive DIS on D
- Directions for future work

**Workshop "High Energy Nuclear Physics with Spectator Tagging",
Old Dominion University, March 9-11, 2015**

Nuclear shadowing: experiment

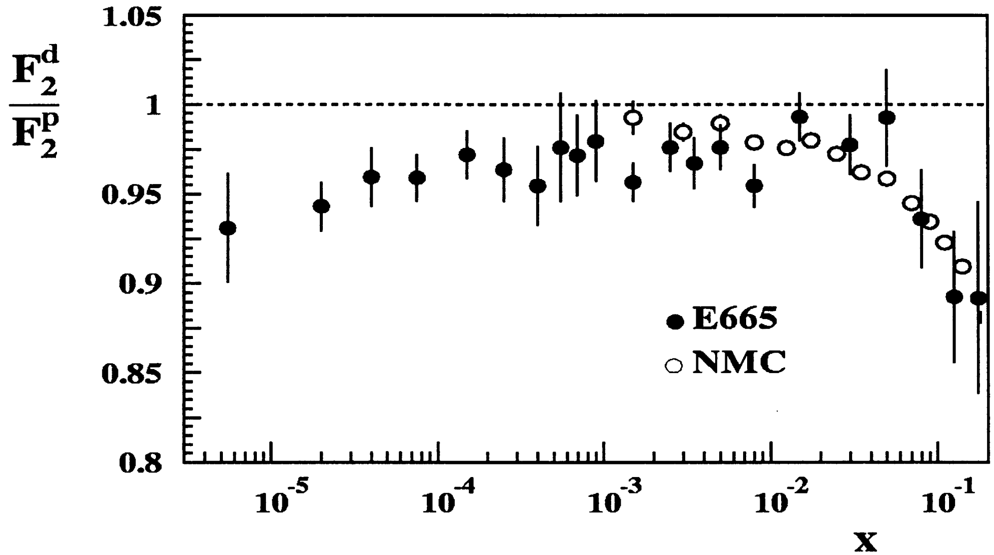
Nuclear shadowing is a high-energy (small x) coherent nuclear effect that $\sigma_A < A\,\sigma_N$.

For heavy nuclei, the shadowing suppression is as large as 20%.



For deuterium, shadowing is 1-2% effect.

Reviews by Arneodo (1994); Piller, Weise (2000)



In extraction of nuclear parton distribution functions (PDFs), some groups ignore ***all*** nuclear effects in deuterium (EPS09, DSSZ), some include them (HKN07, nCTEQ).

Even 1-2% shadowing matters for the extraction of F2p-F2n from deuterium data because F2p-F2n is small at small x → implications for global fits for proton PDFs.

Nuclear shadowing: theory

- At small x, a high-energy probe interacts *coherently (simultaneously)* with all nucleons of the nucleus target.
- Nuclear shadowing is a result of destructive interference among the amplitudes for the interaction with 1, 2, 3, etc. nucleons of the target.
- Total pion-deuteron cross section:

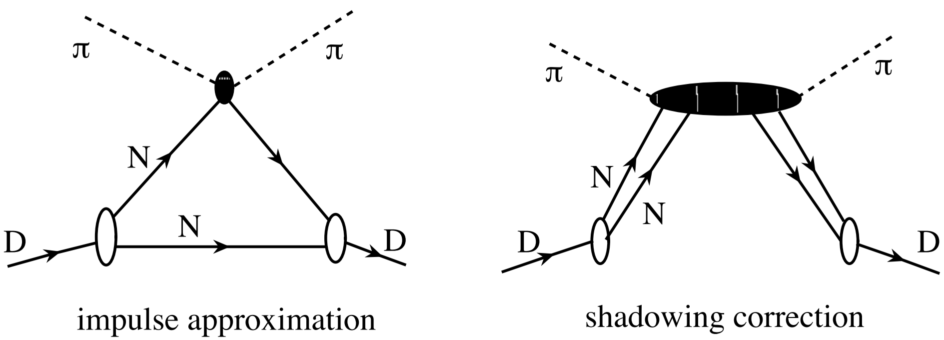
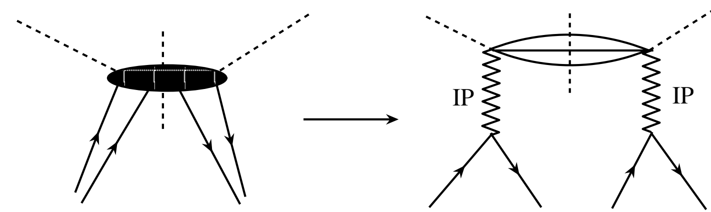


Figure 2: Graphs for pion-deuteron scattering.



The shadowing term can be expressed in terms of pion-proton diffractive cross section

$$\sigma_{\rm tot}^{\pi D} = 2\sigma_{\rm tot}^{\pi N} - 2\int d\vec{k}^2 \rho_D(4\vec{k}^2)\frac{d\sigma_{\rm diff}^{\pi N}(k)}{d\vec{k}^2}$$

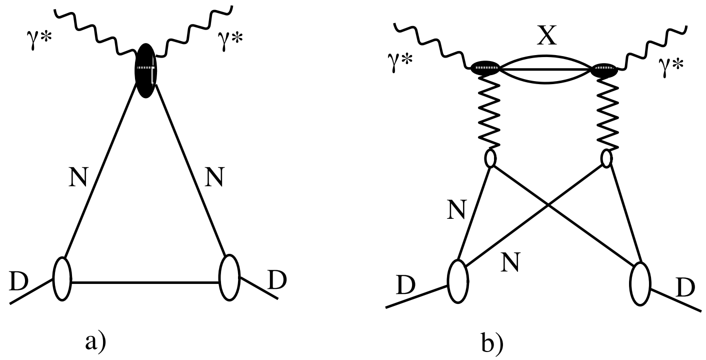
Glauber (1955);
Gribov (1969)

Deuteron form factor

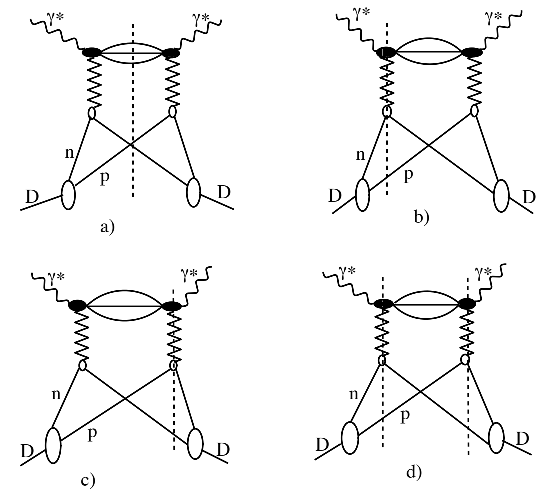
Pion-proton diffractive cs

Nuclear shadowing in unpolarized inclusive eD DIS

• Forward Compton scattering amplitude:



Impulse approx.   Shadowing correction



Imaginary part of shadowing is given by diffractive cut due to AGK cutting rules

Abramowski, Gribov, Kancheli (1973)

• Calculation using Gribov-Glauber theory or direct evaluation of Feynman graphs in the virtual nucleon approximation (VNA):

$$\begin{aligned} F_{2D}(x,Q^2) &= F_{2p}(x,Q^2)+F_{2n}(x,Q^2) \\ &-2\frac{1-\eta^2}{1+\eta^2}B_{\rm diff}\int_x^{0.1} dx_{I\!P}\, dk_t^2\, F_2^{D(3)}\left(\beta,Q^2,x_{I\!P}\right) e^{-B_{\rm diff}\,k_t^2}\rho_D\left(4k_t^2+4(x_{I\!P}m_N)^2\right) \end{aligned}$$

Frankfurt, VG, Strikman (2012)

$B_{\rm diff} \approx 6$ GeV^{-2} ± 15% (HERA)

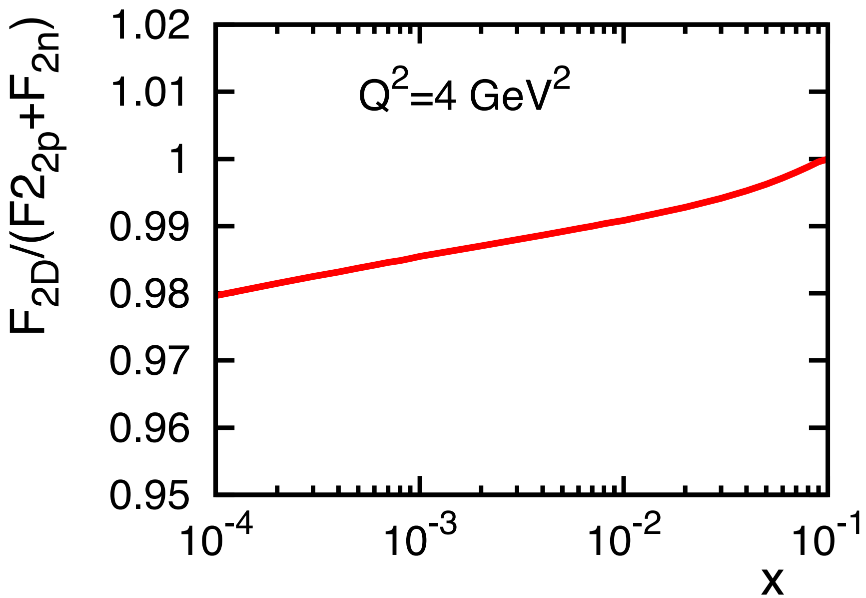
η=Re/Im ≈ 0.17

Leading-twist proton diffractive structure function, measured at HERA

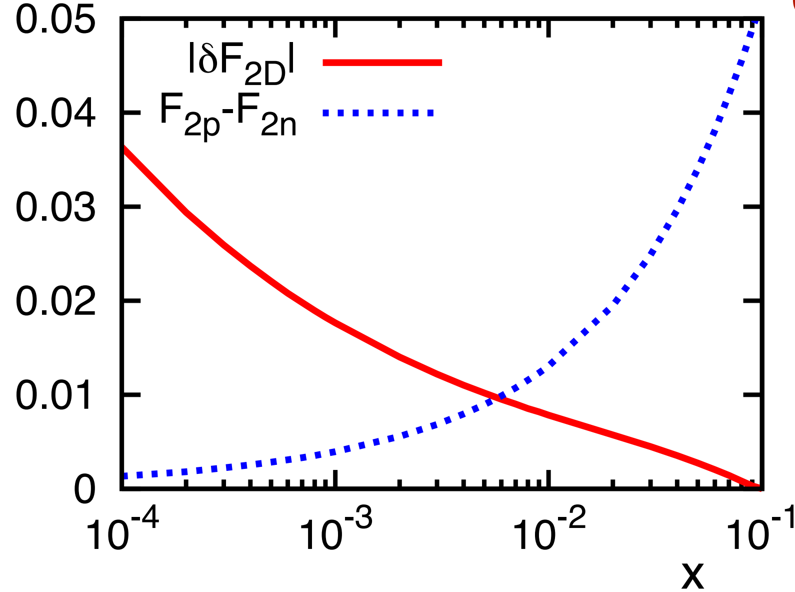
deuteron FF from wave function

Nuclear shadowing in unpolarized inclusive eD DIS (2)

Frankfurt, VG, Strikman (2012)



Q2=4 GeV2



1-2% leading-twist shadowing

shadowing compatible to F2p-F2n

Agrees with earlier calculations using
VMD+Pomeron exchange model

Meltnitchouk, Thomas (1993); Piller, Niesler, Weise (1997)

- Even 1-2% shadowing is important for the extraction of Δ=F2p-F2n:

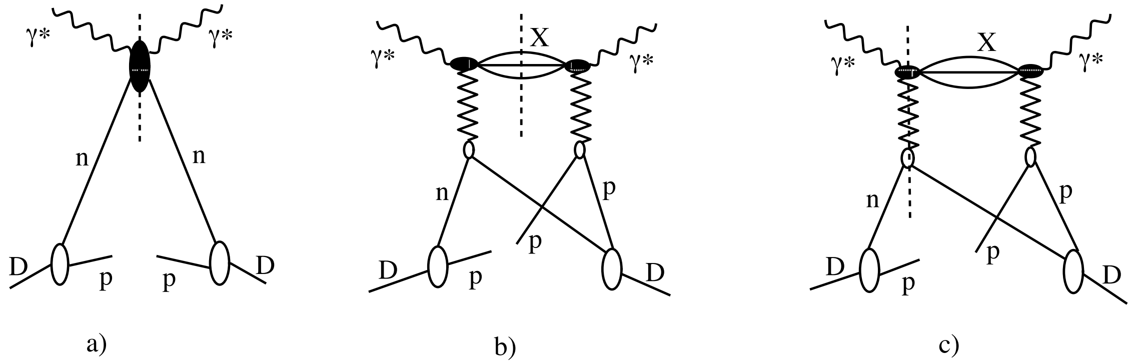
$$F_{2D}(x) = F_{2p}(x) + F_{2n}(x) - \delta F_{2D}(x) \equiv 2F_{2p}(x) - \Delta - \delta F_{2D}(x)$$
$$F_{2D}(x) = F_{2p}(x) + F^0_{2n}(x) = 2F_{2p}(x) - \Delta^0 \, ,$$

$$\Delta - \Delta^0 = \delta F_{2D}(x)$$

shadowing effect for Δ is 2x larger than for $F_{2D}/2F_{2N}$

Nuclear shadowing in unpolarized tagged eD DIS

- Forward Compton scattering amplitude for tagged DIS on D (proton detected):



Frankfurt, VG, Strikman, 2003 and 2006

Impulse approx. $= F_{2n}(x)\rho_D(p,p)$ Shadowing correction

- Direct calculation, same framework as in the inclusive case:

≈ 50% enhancement due to AGK rules (only partial cancellation)

$$F_{2D}(x,Q^2,\vec{p}) = F_{2D}^{\mathrm{IA}}(x,Q^2,\vec{p}) - \frac{3-\eta^2}{1+\eta^2}\int_x^{0.1} dx_{I\!P}\,\frac{d^2\vec{k}_t}{\pi}\,F_2^{D(4)}(\beta,Q^2,x_{I\!P},t)$$
$$\times \left[u(\vec{p})u(\vec{p}+\vec{k}) + w(\vec{p})w(\vec{p}+\vec{k})\left(\frac{3}{2}\frac{(\vec{p}\cdot(\vec{p}+\vec{k}))^2}{p^2(p+k)^2} - \frac{1}{2}\right)\right],$$

Nuclear shadowing is larger in the tagged DIS than in the inclusive case due to:

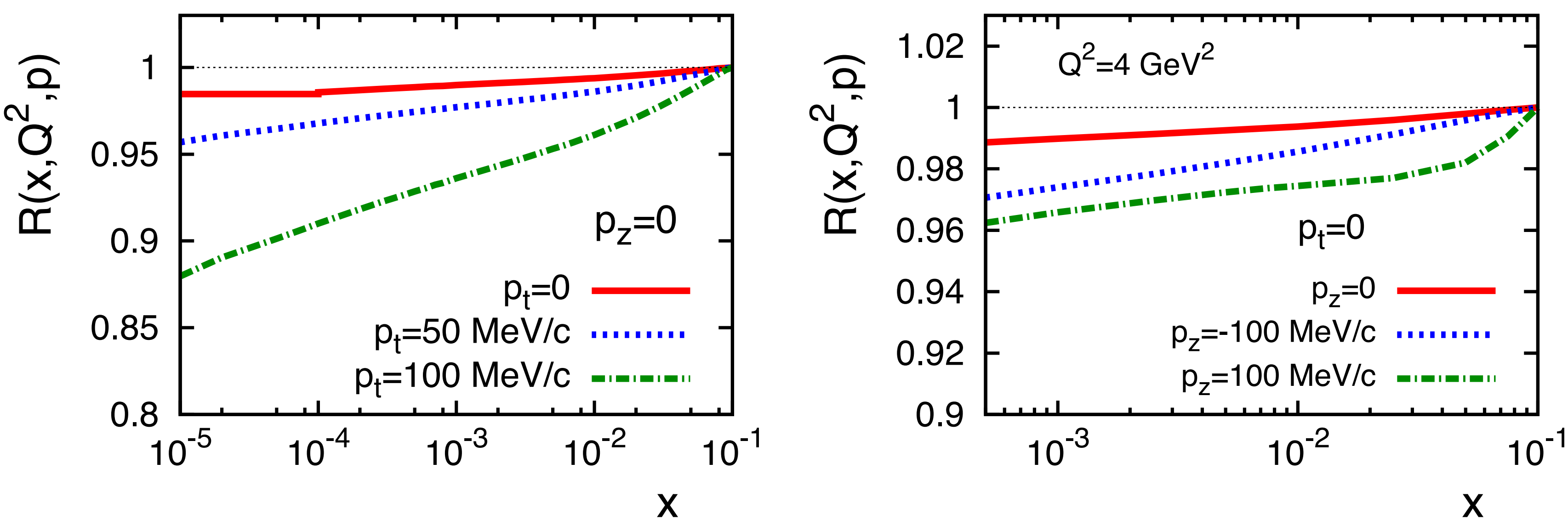
- AGK enhancement
- IA drops with spectator momentum faster than the shadowing term

Nuclear shadowing in unpolarized tagged eD DIS (2)

Example of calculations for $R(x, Q^2, \vec{p}) = \frac{F_{2D}(x, Q^2, \vec{p})}{F_{2D}^{\mathrm{IA}}(x, Q^2, \vec{p})}$

Q2=4 GeV2

Frankfurt, VG, Strikman (2003)



- Nuclear shadowing increases with an increase of spectator momentum:
  - larger pt correspond to smaller transverse distance between p and n → more shadowing
  - no symmetry along z; forward-moving spectator corresponds to larger shadowing

- Two strategies of extraction F2n(x):
  - select small p and neglect shadowing correction
  - measure proton spectrum as function of p → determine/verify the shadowing correction → correct data for the shadowing effect

Nuclear shadowing in polarized eD DIS

- By analogy with unpolarized case, shadowing correction to deuteron spin structure function g1D(x):

Frankfurt, VG, Strikman (2003)

$$g_1^D(x,Q^2) = \left(1-\frac{3}{2}P_D\right)(g_1^p(x,Q^2)+g_1^n(x,Q^2))$$

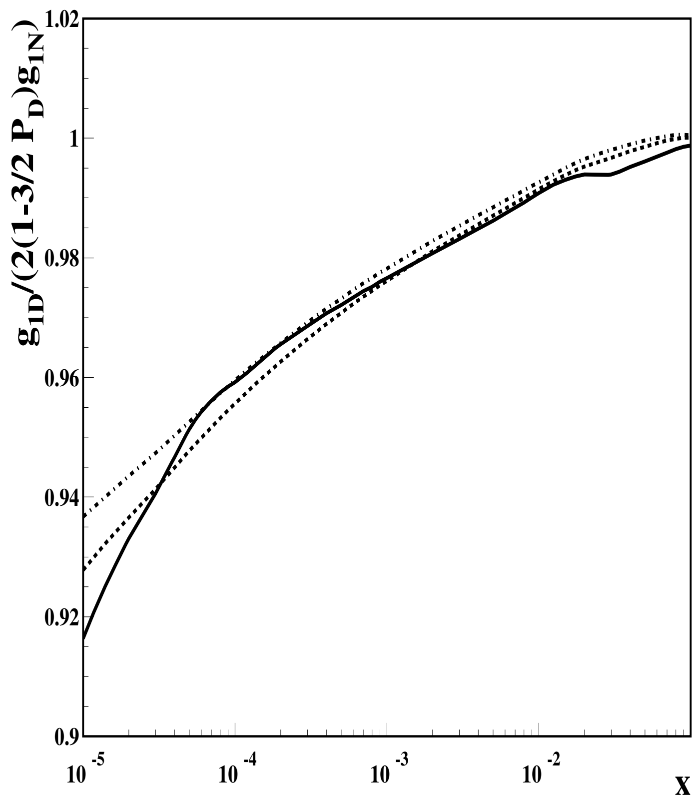
$$-2\frac{1-\eta^2}{1+\eta^2}\int_x^{x_0} dx_{\mathbb{P}}\, dq_t^2\, \Delta F^{D(4)}(\beta,Q^2,x_{\mathbb{P}},t)\rho_D^{11}(4q_t^2+4(x_{\mathbb{P}}m_N)^2)$$

unknown polarized proton diffractive structure function. Assumption:

$$\frac{\Delta F^{D(4)}}{g_1^N} = 2\frac{F_2^{D(4)}}{F_2^N}$$

longitudinally-polarized deuteron form factor

Q2=4, 25, 100 GeV2



- Shadowing correction to g1D(x) is a few % effect
  → negligible since g1p(x) ≈ - g1n(x) at small x

Agrees with earlier calculations by
Edelmann, Piller, Weise (1998)

Nuclear shadowing in polarized eD DIS (2)

- In eD DIS with unpolarized beam and polarized target, shadowing correction gives rise to $T_{20}(x)$ asymmetry:

$$T_{20} = \frac{\sigma^+ - \sigma^0}{\frac{1}{2}(\sigma^+ + \sigma^0)}$$

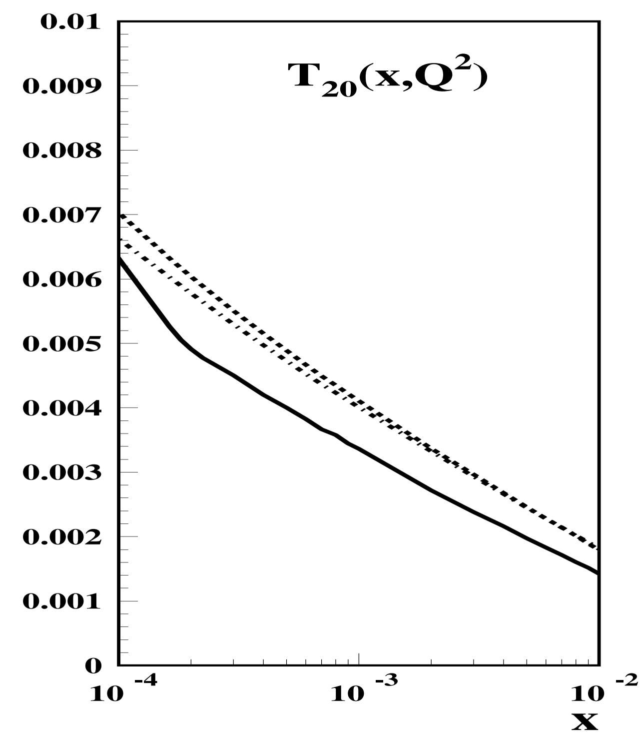
σ+ and σ0 are γ-D cross sections, + and 0 are deuteron helicity

$$T_{20}(x,Q^2) = \frac{2}{F_2^D(x,Q^2)} \frac{1-\eta^2}{1+\eta^2} \times \int_x^{x_0} dx_{\mathbb{P}}\, dq_t^2\, F_2^{D(4)}(\beta,Q^2,x_{\mathbb{P}},t)\rho_D^{20}(4q_t^2+4(x_{\mathbb{P}}m_N)^2)$$

Frankfurt, VG, Strikman (2003)

proton diffractive structure function

polarized deuteron form factor

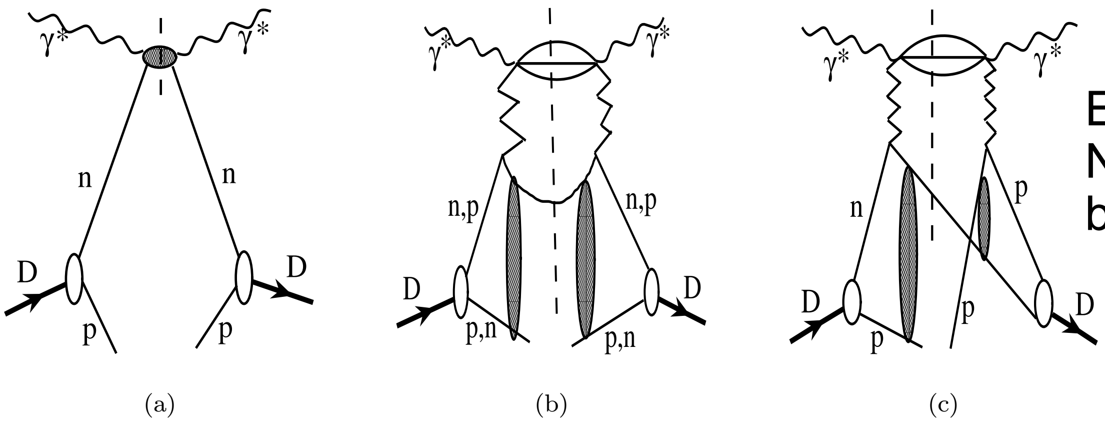


- Nuclear shadowing gives rise to ≈ 1% $T_{20}(x)$

Agrees with earlier calculations by Edelmann, Piller, Weise (1998)

Directions for future work:

- Final state interactions (FSI) for unpolarized tagged eD DIS:



Estimates using non-relativistic S-wave NN potential made Frankfurt, VG, Strikman (2006) but more theoretical work is required.

- Application of this formalism to polarized tagged eD DIS.

- Coherent diffraction eD DIS:

  - inclusive diffraction: direct implementation of leading twist nuclear shadowing

  - VM production, DVCS: requires theoretical work

Conclusions:

• In inclusive unpolarized DIS, nuclear shadowing is a 1-2% effect, which is nevertheless important for the extraction of F2p(x)-F2n(x) from F2D(x).

• In inclusive polarized DIS, the shadowing corrections is larger, but is small correction for extraction of g1n(x) from g1D(x). However, gives rise to 1% $T_{20}(x)$.

• In tagged DIS, the shadowing correction is enhanced by the AGK combinatoric factor and has slower dependence on the spectator momentum than impulse approximation.

• Two strategies of extraction of F2n(x): (i) measurement at small p, where shadowing is small, and (ii) measurement in a wide range of p to determine shadowing and correct the data.

• This conclusion is affected by FSI which need to be estimated.

• Leading twist nuclear shadowing formalism can be straightforwardly applied to coherent diffraction in eD DIS.

• Exclusive vector meson production and DVCS is an important direction, but requires additional theoretical work.

Additional Slides

Deuteron form factors used in this talk

Frankfurt, VG, Strikman (2003)

- Unpolarized deuteron form factor:

$$\rho_D(4q_t^2+4(x_{\mathbb{P}}m_N)^2) = \int d^3p\left[u(p)u(p+q)+w(p)w(p+q)\left(\frac{3}{2}\frac{(\mathbf{p}\cdot(\mathbf{p}+\mathbf{q}))}{p^2(p+q)^2}-\frac{1}{2}\right)\right]$$

- Longitudinally-polarized deuteron form factor:

$$\rho_D^{11}(4q_t^2+4(x_{\mathbb{P}}m_N)^2) = \int d^3p\left[u(p)u(p+q)+\frac{u(p)w(p+q)}{\sqrt{2}}\left(\frac{3}{2}\frac{(p_z+q_z)^2}{(p+q)^2}-\frac{1}{2}\right)\right.$$
$$+\frac{u(p+q)w(p)}{\sqrt{2}}\left(\frac{3}{2}\frac{p_z^2}{p^2}-\frac{1}{2}\right)$$
$$+w(p)w(p+q)\left(\frac{9}{2}\frac{(\mathbf{p}_t\cdot(\mathbf{p}_t+\mathbf{q}_t))(\mathbf{p}\cdot(\mathbf{p}+\mathbf{q}))}{p^2(p+q)^2}\right.$$
$$\left.\left.+\frac{3}{4}\frac{p_z^2}{p^2}+\frac{3}{4}\frac{(p_z+q_z)^2}{(p+q)^2}-1\right)\right]. \qquad (6)$$

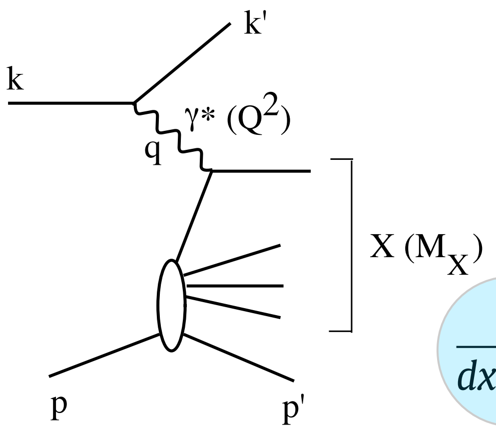
- Polarized deuteron form factor for T20(x):

$$\rho_D^{20}(4q_t^2+4(x_{\mathbb{P}}m_N)^2) = \frac{3}{2}\int d^3p\left[\frac{u(p)w(p+q)}{\sqrt{2}}\left(1-\frac{3(p_z+q_z)^2}{(p+q)^2}\right)\right.$$
$$+\frac{u(p+q)w(p)}{\sqrt{2}}\left(1-\frac{3p_z^2}{p^2}\right)$$
$$+w(p)w(p+q)\left(1-\frac{3}{2}\left[\frac{(p_z+q_z)^2}{(p+q)^2}+\frac{p_z^2}{p^2}\right.\right.$$
$$\left.\left.\left.+\frac{(\mathbf{p}\cdot(\mathbf{p}+\mathbf{q}))(\mathbf{p}\cdot(\mathbf{p}+\mathbf{q})-3p_z(p_z+q_z))}{p^2(p+q)^2}\right]\right)\right]$$

Diffraction in ep DIS at HERA

• One of main HERA results is the discovery of large fraction of diffractive events (~10%)
→ diffraction is a leading twist phenomenon (H1 and ZEUS, 1994-2006)

$$e + p \to e' + X + p'$$



$$t = (p' - p)^2 ,$$

$$x_{I\!P} = \frac{q \cdot (p - p')}{q \cdot p} \approx \frac{M_X^2 + Q^2}{W^2 + Q^2} ,$$

$$\beta = \frac{Q^2}{2q \cdot (p - p')} = \frac{x}{x_{I\!P}} \approx \frac{Q^2}{Q^2 + M_X^2}$$

$$\frac{d^4\sigma_{ep}^D}{dx_{\mathbb{P}}\, dt\, dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1 + (1-y)^2\right) F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) - y^2 F_L^{D(4)}(x, Q^2, x_{\mathbb{P}}, t)\right]$$

• Collinear factorization (Collins '97) → diffractive parton distributions

$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = \beta \sum_{j=q,\bar{q},g} \int_\beta^1 \frac{dy}{y} C_j\left(\frac{\beta}{y}, Q^2\right) f_j^{D(4)}(y, Q^2, x_{\mathbb{P}}, t)$$

• Measurement of the t-dependence of diffractive cross section: $B_{\text{diff}} = 6\ \text{GeV}^{-2} \pm 15\%$

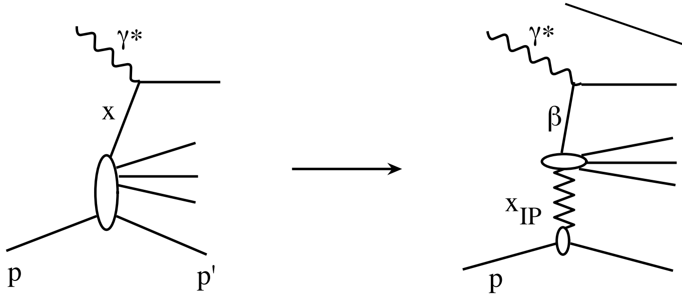
$$F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t) = e^{B_{\text{diff}}(t - t_{\min})} F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t_{\min})$$

$$F_2^{D(3)}(x, Q^2, x_{\mathbb{P}}) = \int_{-1\,\text{GeV}^2}^{t_{\min}} dt F_2^{D(4)}(x, Q^2, x_{\mathbb{P}}, t)$$

Diffraction in ep DIS at HERA (2)

- It is convenient to use (supported by data):

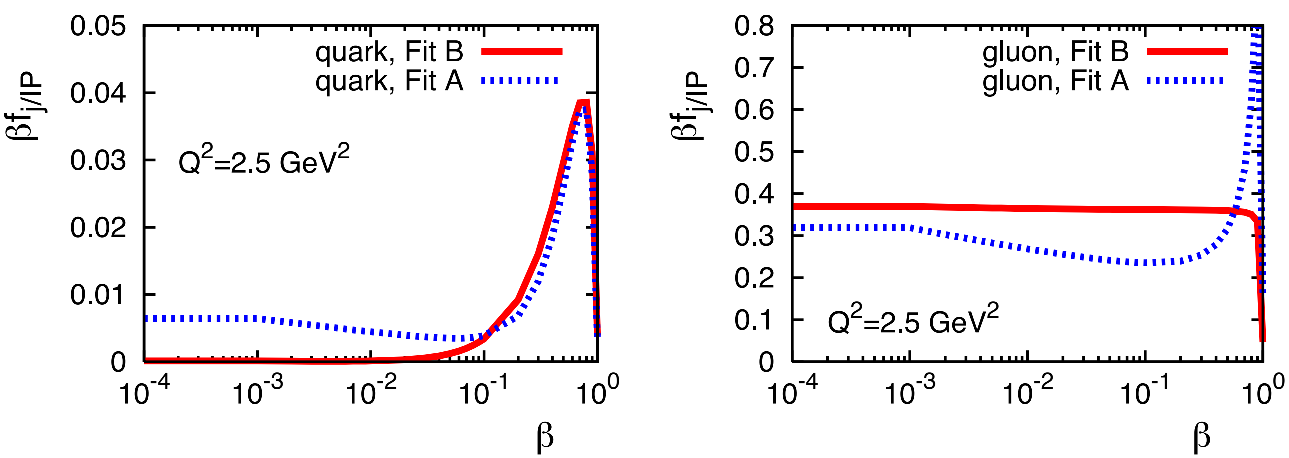
$$f_j^{D(3)}(\beta, Q^2, x_{I\!P}) = f_{I\!P/p}(x_{I\!P}) f_{j/I\!P}(\beta, Q^2) + n_{I\!R} f_{I\!R/p}(x_{I\!P}) f_{j/I\!R}(\beta, Q^2)$$



"Pomeron" flux

"Pomeron" PDFs

- H1 and ZEUS determined "Pomeron" PDFs:



- Necessary information for numerical prections.
  Important that $g_P >> q_P$.