Nuclear Shadowing in Tagged DIS at small x

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Outline

- Nuclear shadowing in DIS at small x
- Nuclear shadowing and final-state interactions (FSI) in tagged DIS on D
- Polarized inclusive DIS on D
- Summary and Outlook

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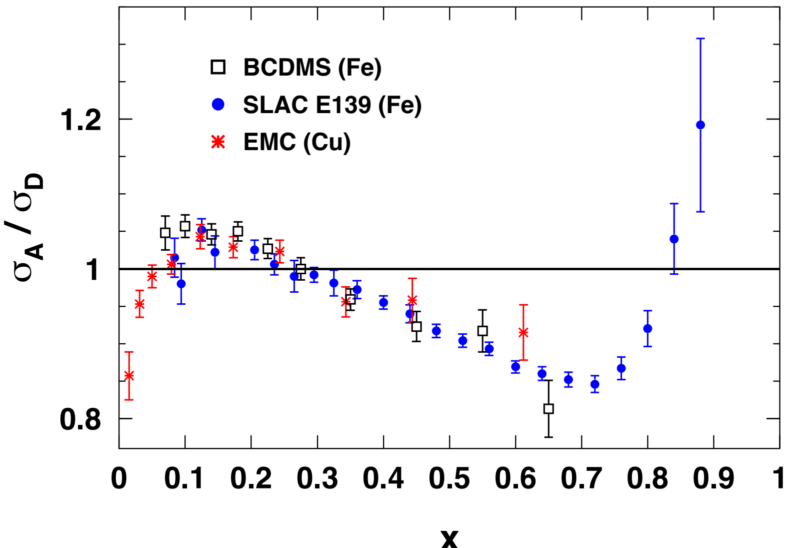
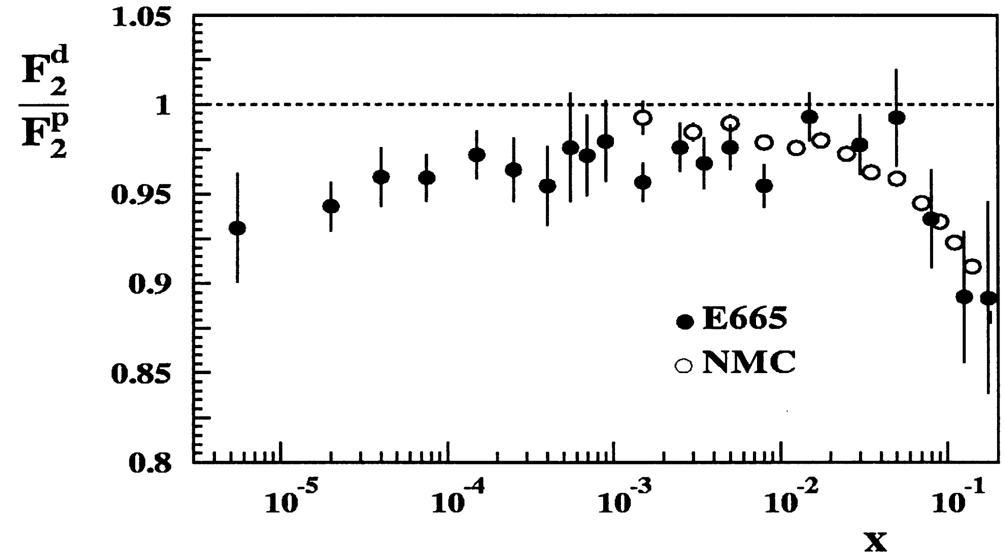
Nuclear shadowing in DIS at small x

- Nuclear shadowing is a high-energy coherent nuclear effect suppressing the nuclear cross section (structure functions) $\sigma_A < A\,\sigma_N$ at small $x < 0.01$.

For heavy nuclei, shadowing is as large as 20% for $Q^2 > 1$ GeV^2.



For deuterium, shadowing is 1-2% effect.



Arneodo, Phys. Rept. 240 (1994) 301; Piller, Weise, Phys. Rept. 330 (2000) 1

- Collinear factorization and global QCD fits translate nuclear modifications into nuclear parton distributions (nPDFs): (nDS) de Florian, Sassot, PRD 69 (2004) 074028; (HKN07) Hirai, Kumano, Nagai, PRC 76 (2007) 065207; (EPS09) Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065; (nCTEQ15) PRD93 (2016) no.8, 085037; (EPPS16) Eskola, Paakkinen, Paukkunen, Salgado EPJ C77 (2017) 163

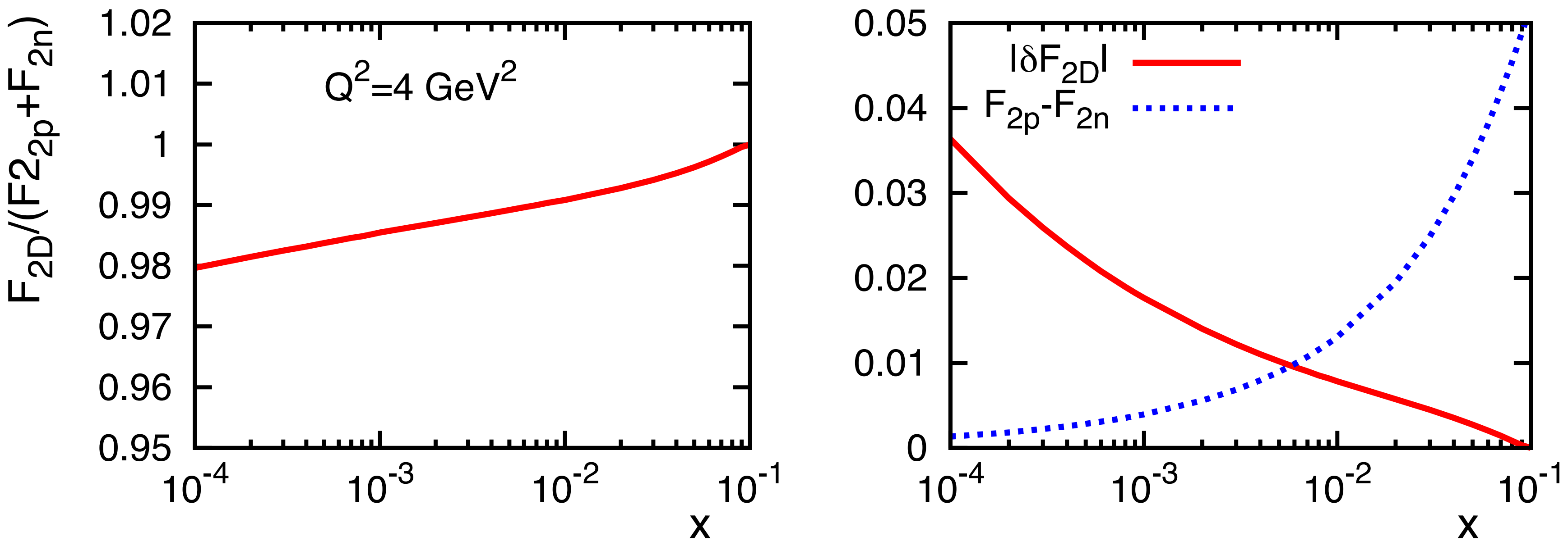
- Open question: magnitude of shadowing for different parton flavors for $x < 0.005$ → we need to better understand dynamics of shadowing.

Nuclear shadowing in DIS on D at small x

- In global QCD of nPDFs, some groups ignore nuclear effects in deuterium (EPS09, DSSZ, EPPS16), some include them (HKN07, nCTEQ15).

- Even 1-2% shadowing matters for the extraction of F_{2p}-F_{2n} from deuterium data since F_{2p}-F_{2n} is small at small x:

$$F_{2n} - F_{2p} = F_{2D} - 2F_{2p} + 2\Delta^{\text{shad}} F_{2p}$$



Meltnitchouk, Thomas, PRD47 (1993) 3783; Piller, Niesler, Weise, Z. Phys. A358 (1997) 403; Frankfurt, Guzey, Strikman, PRL 91 (2003) 202001

- For polarized structure functions $g_{1p} \approx -g_{1n}$ → shadowing is a small correction for extraction of g_{1n} - g_{1p} from deuteron g_{1d}.

Nuclear shadowing in DIS at small x: qualitative

- In high-energy scattering on nuclear targets, nuclear shadowing is well-understood as due to distractive, QM interference among amplitudes for interaction with N=1, 2, …A target nucleons:
  - pion-deuteron scattering for E < 5 GeV, Glauber, PRD 100 (1955) 242; hadron-nucleus scattering, Bassel, Wilkin, PR 174 (1968) 1179
  - pion-deuteron scattering for E > 5 GeV, Gribov, Sov Phys JETP 29 (1969) 483
  - extension of Gribov-Glauber model to lepton-nucleus DIS, Frankfurt, Strikman, Phys Rept. 160 (1988) 235; Meltnitchouk, Thomas, PRD47 (1993) 3783; Armesto, Capella, Kaidalov, Lopez-Albacete, Salgado (1993); Frankfurt, Strikman, EPJ A 5 (1999) 293; Piller, Weise, Phys. Rept. 330 (2000) 1; Adeluyi, Fai, PRC 74 (2006) 054904; Frankfurt, Guzey, Strikman, Phys, Rept. 512 (2012) 255
  - calculations in dipole model also have similar shadowing mechanism, Nikolaev, Zakharov (1993); Armesto, J. Phys. G. 32 (2006) R367

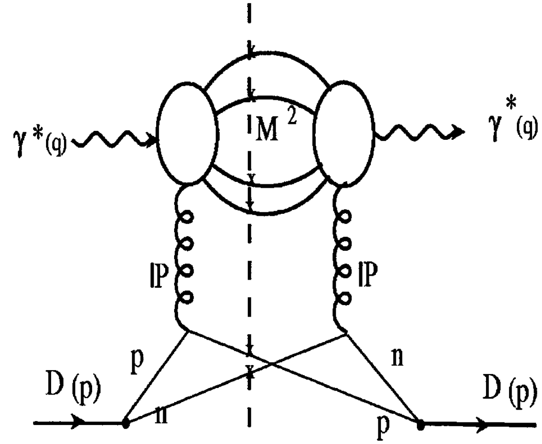
- In DIS, shadowing is important, when the photon coherence length (γ^* lifetime) $l_c \sim 1/(2\, m_N x)$ is compatible with inter-nucleon distance r_{NN}~1.7 fm → $x < 0.05$.

- Magnitude of shadowing is controlled by ratio of rescattering cross section σ~25 mb and nuclear geometrical size. For deuteron, $\sigma/(\pi R_d^2)$ ~ few percent.

- For tagged DIS, shadowing can be enhanced at $t \neq 0$ by $\delta F_A(t)/|F_A(t)|^2$, where $F_A(t)$ is the nuclear factor.

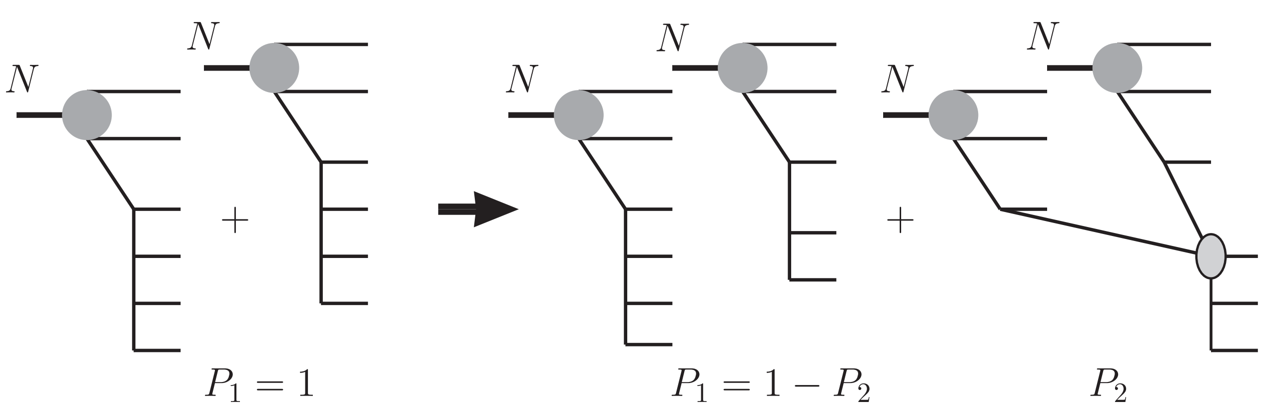
Nuclear shadowing in DIS at small x: qualitative

- Shadowing and diffraction:
  - at high energies, γ^* can interact with two target nucleons by first dissociating into hadronic state → to have small momentum transfer to each nucleon, the interaction is diffractive → no mismatch between in nucleon momenta in *in* and *out* states → interference diagram leads to shadowing
  - negative (shadowing) correction due to unitarity (AGK cutting rules for multiplicities due to Pomeron exchanges)



Frankfurt, Strikman, EPJ A 5 (1999) 293

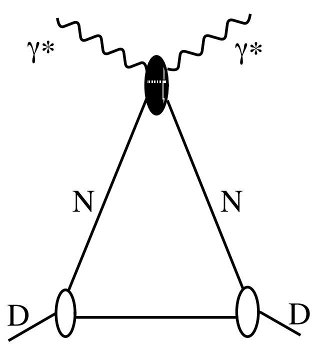
- Both shadowing and anti-shadowing arise from parton ladders (Pomerons) attaching to two different nucleons → the ladders can merge (shadowing, right, P_2) or be independent (antishadowing middle, P_1) → anti-shadowing compensates shadowing locally in rapidity $\ln(x_P/x) < 1$, Frankfurt, Guzey, Strikman, PRC 95 (2017) no.5, 055208



Nuclear shadowing in inclusive DIS on D

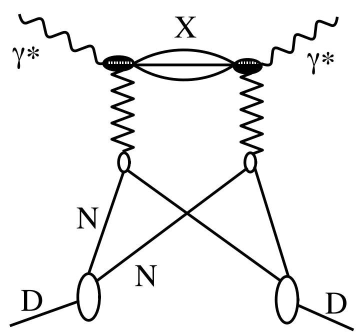
- There are several ways to derive shadowing correction to D structure functions:
  - direct generalization of Gribov-Glauber model to DIS + AGK rules, Frankfurt, Strikman, EPJ A 5 (1999) 293; Guzey, Strikman, Phys, Rept. 512 (2012) 255
  - calculations of covariant Feynman graphs with subsequent non-relativistic reduction (virtual nucleon approximation), Bertocchi, Nuovo Cim. A11 (1972) 45; Sargsian, Int. J. Mod. Phys. E10 (2001) 405
  - light-front perturbation theory, Strikman, Weiss, arXiv:1706.02244.

- Forward Compton scattering amplitude → imaginary part gives structure function



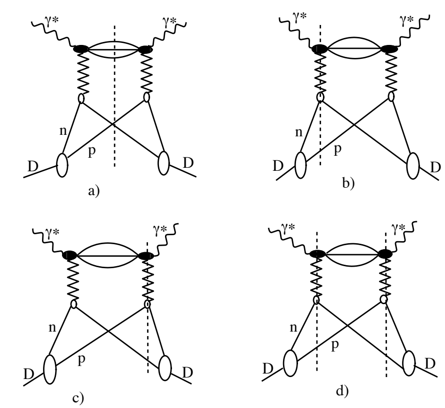
a)

Impulse approx.



b)

Shadowing correction



Imaginary part of shadowing = diffractive cut due to AGK cutting rules

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

Frankfurt, Guzey, Strikman, PRL 91 (2003) 202001

$B_{\text{diff}} \approx 6$ GeV^{-2}

η=Re/Im ≈ 0.17

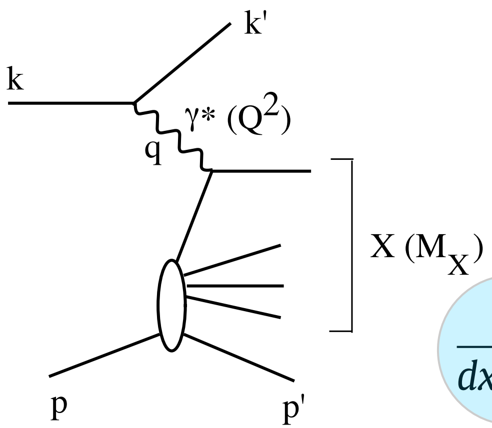
Leading-twist proton diffractive structure function measured@HERA

deuteron form factor

Diffraction in ep DIS at HERA

- One of main HERA results is 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

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

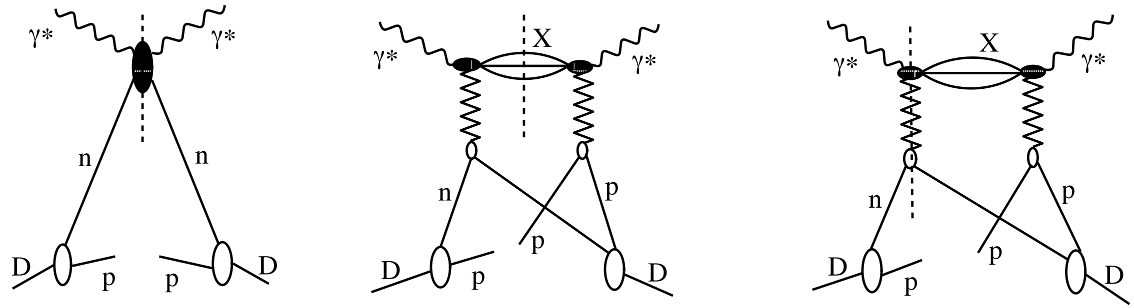
- Measurement of the t-dependence of diffractive cross section: $B_{diff} = 6\ \mathrm{GeV}^{-2} \pm 15\%$

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

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

Nuclear shadowing in unpolarized tagged DIS on D

- Forward Compton scattering amplitude for tagged DIS on D (proton detected) → imaginary part gives tagged structure function $F_{2d}(x,Q^2,p_s)$, Frankfurt, Guzey, Strikman, PRL 91 (2003) 2022001, Mod. Phys. Lett. A21 (2006) 23, Phys. Rept. 512 (2012) 255.



a) b) c)

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

- Calculation as in the inclusive case:

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

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

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

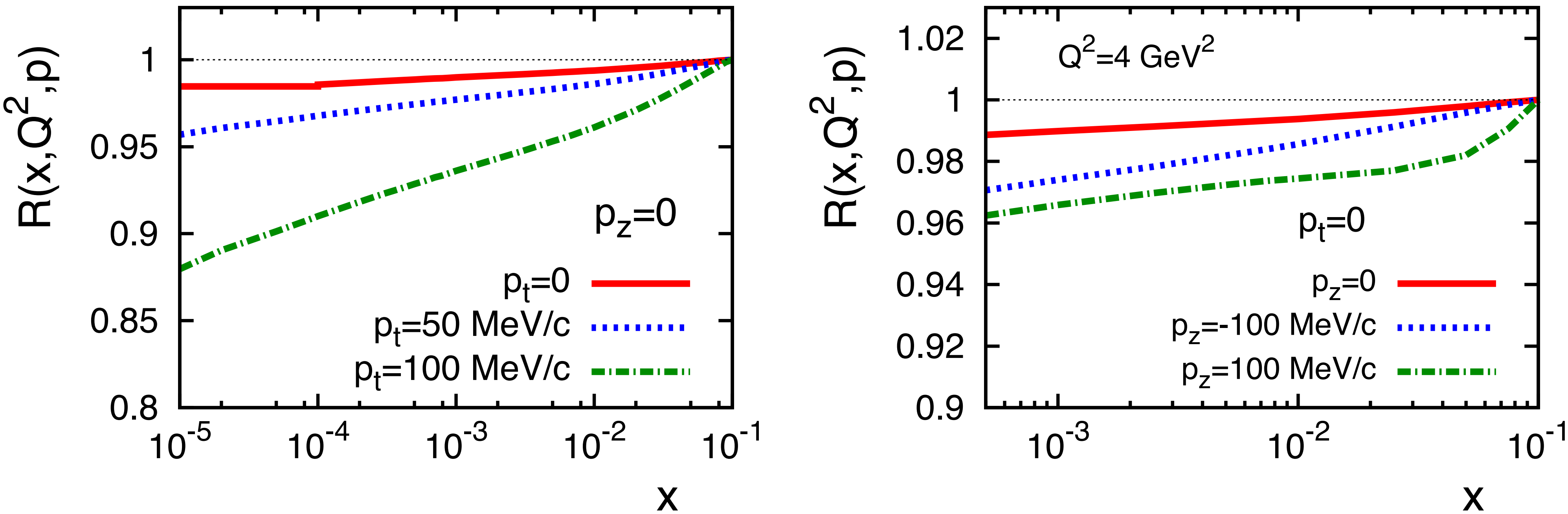
- AGK enhancement
- IA drops with spectator momentum faster than the shadowing term

Nuclear shadowing in unpolarized tagged DIS on D

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

Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Q^2=4 GeV^2

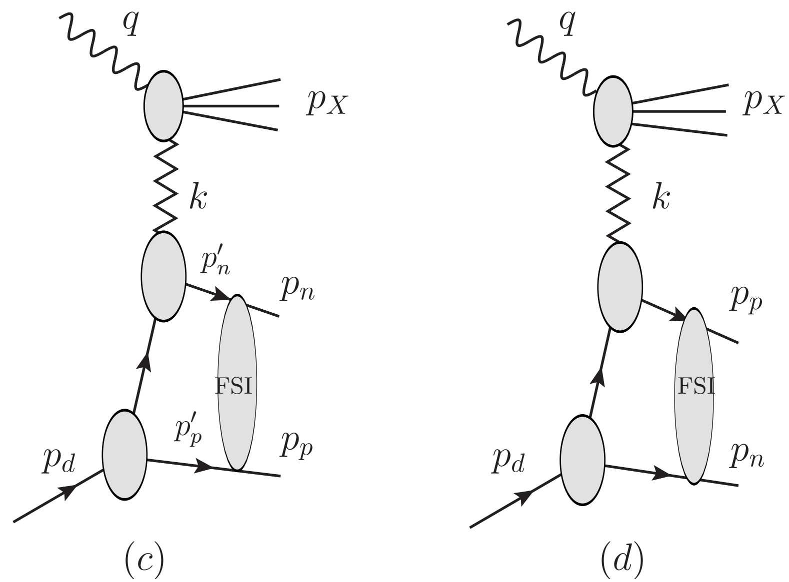


- Nuclear shadowing increases with an increase of spectator momentum:
  - larger pt correspond to smaller transverse distance between p and n → more shadowing
  - no symmetry along z; forward-moving spectator corresponds to larger shadowing

- Extraction $F_{2n}(x)$:
  - measure proton spectrum as function of p → determine/verify the shadowing correction → correct data for the shadowing effect

Final-state interactions in tagged DIS on D

- Shadowing correction comes from interference of diffractive scattering on p and n in D → in tagged DIS, there are potential FSI between p and n



- Momentum transfer is ~ few 100 MeV → strong FSI between the final-state p and n, which can be calculated using potential scattering, Frankfurt, Guzey, Strikman, Mod. Phys. Lett. A21 (2006) 23; Guzey, Strikman, Weiss (2018), JLab LDRD project "Physics potential of polarized light ions with EIC@JLab"

- Plane wave pn wave function → pn continuum wave function

$$(J^{\rm diff}_{n/d})^\mu = (J^{\rm diff,IA}_{n/d})^\mu + (J^{\rm diff,FSI}_{n/d})^\mu = \sqrt{2(2\pi)^3 2E_p} \sum_{s'_n,s'} j^\mu_{N,\rm diff}(k) \int d^3p'_p \psi^*_{NN}(p'_p + k/2, p_p + k/2)\Psi_d(p'_p, s'_p; p', s')$$

Final-state interactions in tagged DIS on D

- Continuum pn and D are orthogonal → strong suppression due to FSI
- We used the effective range approximation (S-wave) with $\alpha = \sqrt{m_N |E_d|} \approx 0.045\ \mathrm{GeV}$:

$$\Psi_d(\boldsymbol{p}_p) = \frac{\sqrt{\alpha}}{\pi(\alpha^2 + |\boldsymbol{p}_p|^2)} \chi_1(s_p, s_n; s_d)$$

$$\Psi_{pn}(\boldsymbol{p}', s_p', s_n' | \boldsymbol{p}, s_p, s_n) = \left[\delta^{(3)}(\boldsymbol{p}_p - \boldsymbol{p}_p') + \frac{1}{2\pi^2} \frac{[f(p_p)]^*}{|\boldsymbol{p}'|^2 - |\boldsymbol{p}|^2 + i\epsilon} \right] \langle s_p', s_n' | \hat{P}_t | s_p, s_n \rangle \qquad f(|\boldsymbol{p}_p|) = -\frac{1}{\alpha + i|\boldsymbol{p}_p|}$$

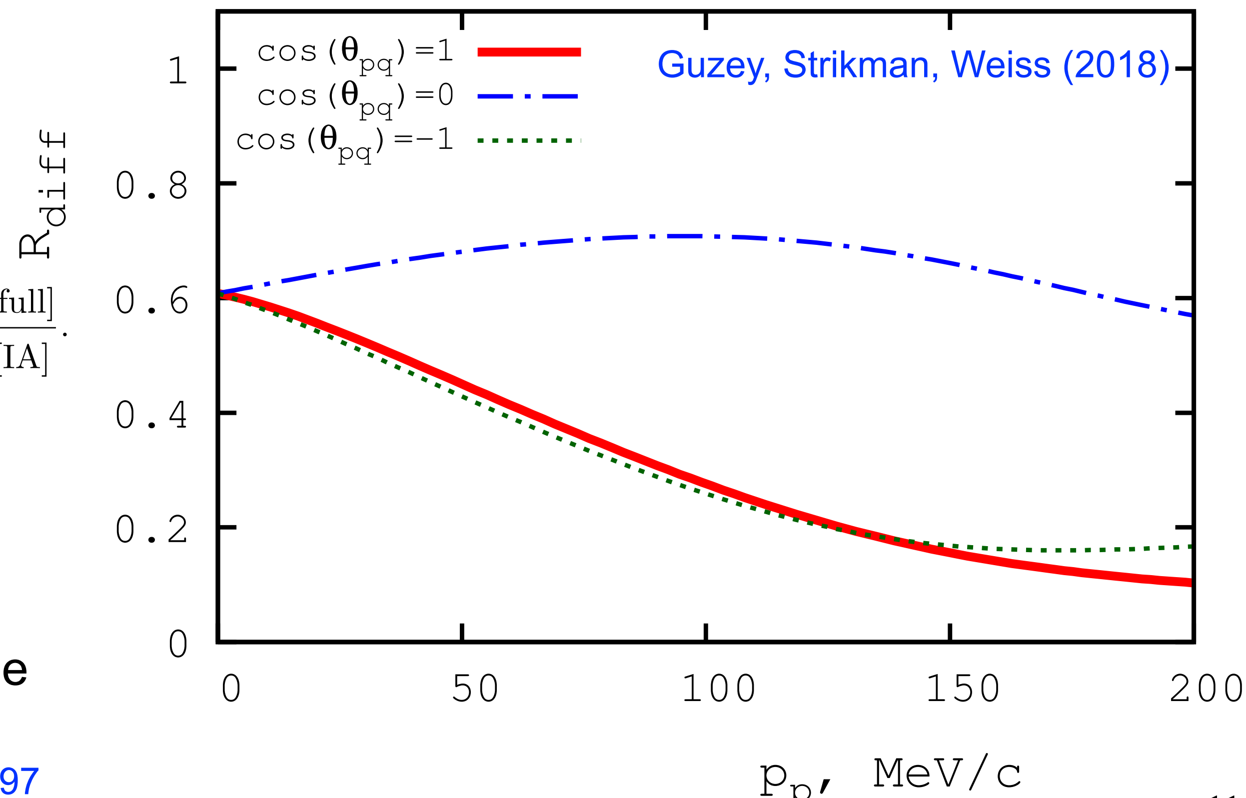
- FSI in e+d → e+X+p+n

$$R_{\rm diff}(x, Q^2, \alpha_p, |\boldsymbol{p}_{pT}|) \;\equiv\; \frac{d\sigma(ed \to e' X p)[\text{full}]}{d\sigma(ed \to e' X p)[\text{IA}]}$$

$$= \frac{\int d\tilde{\Gamma}_n \, \sigma_r^{(3)}(x, Q^2, x_{I\!P}) \, e^{-B_{\rm diff}|t|} \, D(\alpha_p, \boldsymbol{p}_{pT}; \alpha_n, \boldsymbol{p}_{nT})[\text{full}]}{\int d\tilde{\Gamma}_n \, \sigma_r^{(3)}(x, Q^2, x_{I\!P}) \, e^{-B_{\rm diff}|t|} \, D(\alpha_p, \boldsymbol{p}_{pT}; \alpha_n, \boldsymbol{p}_{nT})[\text{IA}]}.$$

$$D \;=\; (p \text{ active} + n \text{ active})^* \times (p \text{ active} + n \text{ active})$$

- FSI depend on p_p direction
- Differs from angular dependence for deuteron quasi-elastic break up at large momentum transfer, Frankfurt, Greenberg, Miller, Sargsian, Strikman, Z. Phys. A 352 (1995) 97



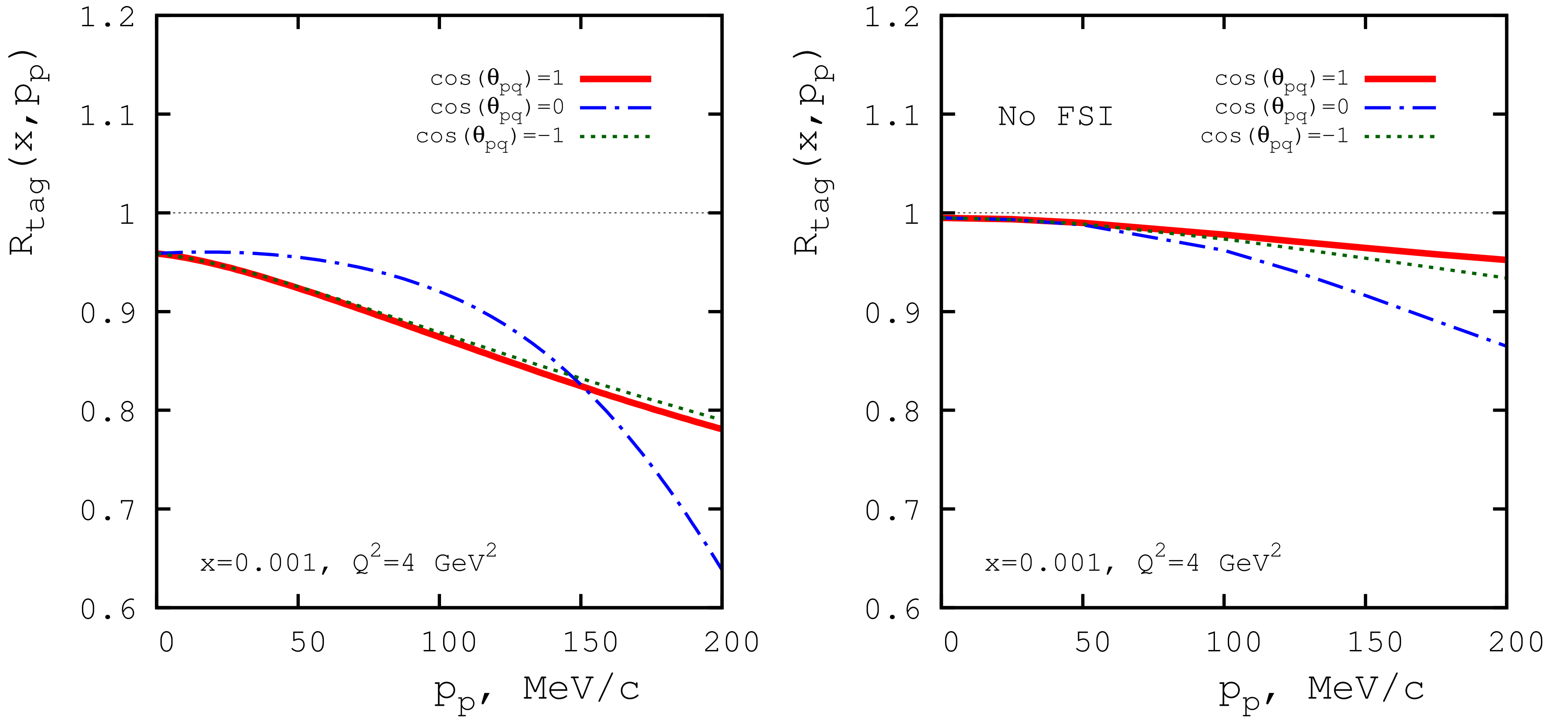
Final-state interactions in tagged DIS on D

- FSI affect shadowing in tagged DIS (no FSI to inclusive DIS due to completeness):

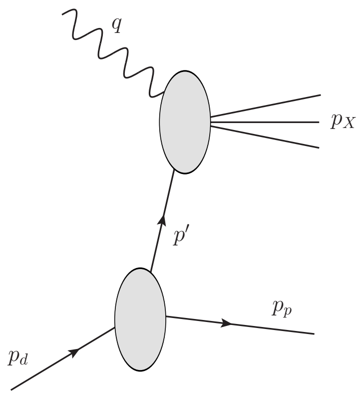
$$
\begin{aligned}
d\sigma(eD \to e'Xp) &= \frac{2\pi\alpha_{\rm em}^2}{xQ^4} Y_+ \Bigg\{ \sigma_r(x,Q^2) D(\boldsymbol{p}_p,\boldsymbol{p}_n)[\mathrm{IA}, nn] - B_{\rm diff} \int d\tilde{\Gamma}_n \sigma_r^{D(3)}(x,Q^2,x_{I\!P}) e^{-B_{\rm diff}|t|} \\
&\times \Big[D(\boldsymbol{p}_p,\boldsymbol{p}_n)[\mathrm{IA},nn] - D(\boldsymbol{p}_p,\boldsymbol{p}_n)[nn] + D(\boldsymbol{p}_p,\boldsymbol{p}_n)[\mathrm{IA},pp] - D(\boldsymbol{p}_p,\boldsymbol{p}_n)[pp] \\
&- 2\,\mathrm{Re}\, D(\boldsymbol{p}_p,\boldsymbol{p}_n)[np] + \frac{4}{1+\eta^2} D(\boldsymbol{p}_p,\boldsymbol{p}_n)[\mathrm{IA},np] \Big] \Bigg\} \frac{dx}{2} dQ^2 d\Gamma_p \,,
\end{aligned}
$$

$$
R_{\rm tag}(x,Q^2,p_p,\cos\theta_{pq}) = \frac{d\sigma(eD \to e'Xp)}{d\sigma^{\rm IA}(eD \to e'Xp)}
$$

Guzey, Strikman, Weiss (2018)



Extraction of F_{2n} from tagged DIS on D at small x



- Virtuality of bound-state neutron:

$$t = p'^2 - m_N^2 \approx M_d(M_d - 2m_N - \frac{|\vec{p}_p|^2}{m_N})$$

- On-shell limit for neutron corresponds to unphysical, negative kinetic energy of spectator → exactly where D wave function (Paris) has a pole

- Impulse approximation (IA) is the most singular in t → 0 limit, while shadowing and FSI terms are less singular → similar to Sargsian, Strikman, PLB 639 (2006) 223

$$\begin{aligned}
\rho_d(p_p, p_p) &\sim \frac{1}{t^2}\,, \\
\rho_d(p_p, p_p) - \rho_d^{\rm FSI}(p_p, p_p; k) &\sim \frac{1}{t}\,, \\
\rho_d(p_p + k, p_p) &\sim \frac{1}{t}\,, \qquad \rho_d^{\rm FSI}(p_p + k, p_p; k) \sim \frac{1}{t} \\
\rho_d(p_p + k, p_p + k) - \rho_d^{\rm FSI}(p_p + k, p_p + k; k) &\sim t^0\,.
\end{aligned}$$

- We do not see it at p_p=0 since this asymptotic behavior takes place very rapidly on the interval between p_p=0 and t=0 → lessons for on-shell extrapolation.

Nuclear shadowing in polarized eD DIS

- The same approach can be used for shadowing correction to deuteron spin structure function $g_{1D}(x)$, Edelmann, Piller, Weise, Z. Phys. A357 (1997) 129, PRC 57 (1998) 3392; Frankfurt, Guzey, Strikman, Mod. Phys. Lett. A21 (2006) 23.

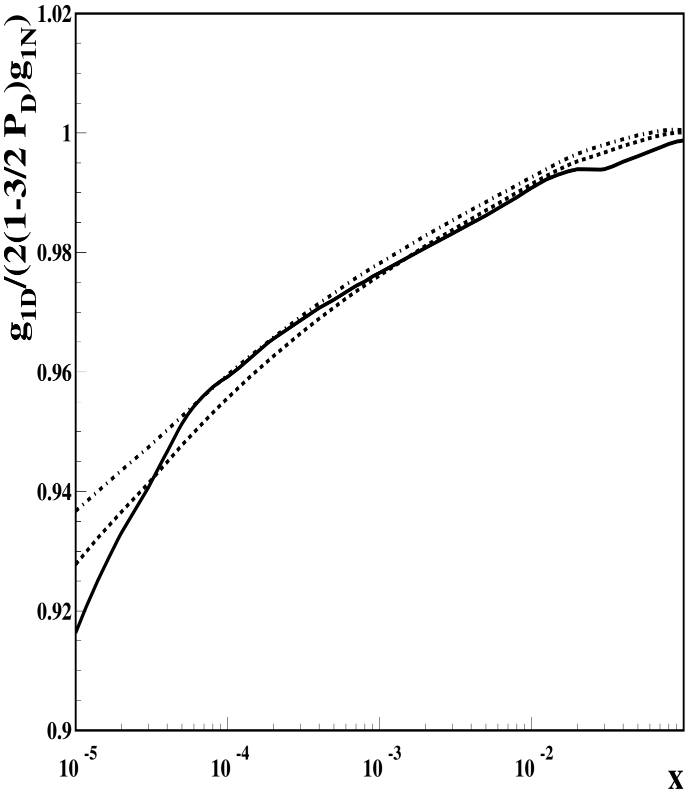
$$g_1^D(x,Q^2) = \left(1-\frac{3}{2}P_D\right)\left(g_1^p(x,Q^2)+g_1^n(x,Q^2)\right)$$
$$-2\frac{1-\eta^2}{1+\eta^2}\int_x^{x_0} dx_{\mathbb{P}}\, dq_t^2\, \Delta F^{D(4)}(\beta,Q^2,x_{\mathbb{P}},t)\rho_D^{11}(4q_t^2+4(x_{\mathbb{P}}m_N)^2)$$

unknown polarized proton diffractive structure function. Assumption of maximal shadowing:

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

longitudinally-polarized deuteron form factor

Q²=4, 25, 100 GeV²



- Shadowing correction to $g_{1D}(x)$ is a few % effect → negligible since $g_{1p}(x) \approx - g_{1n}(x)$ at small x

- Similar calculations of shadowing corrections in polarized DIS on 3He, 7Li, 6LiD, Guzey, Strikman, PRC 61 (2000) 014002; Bissey, Guzey, Strikman, Thomas, PRC 65 (2002) 064317; Guzey, PRC 64 (2001) 045201

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, Frankfurt, Guzey, Strikman, Mod. Phys. Lett. A21 (2006) 23:

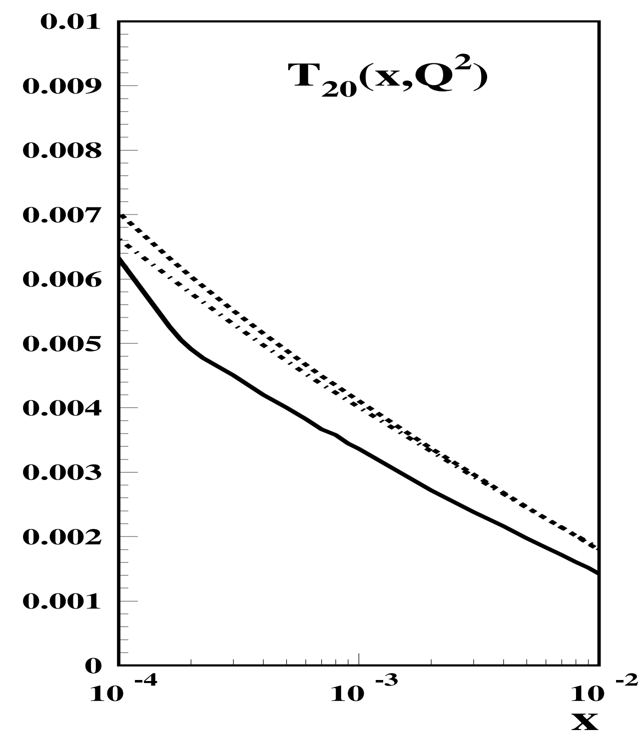
$$T_{20} = \frac{\sigma^+ - \sigma^0}{\frac{1}{2}(\sigma^+ + \sigma^0)}$$

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

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

proton diffractive structure function

polarized deuteron form factor



- Nuclear shadowing gives rise to ≈ 1% $T_{20}(x)$ → small x rise of $b_1(x)$ deuteron structure function

Agrees with earlier calculations by Edelmann, Piller, Weise, Z. Phys. A357 (1997) 129, PRC 57 (1998) 3392

Summary and Outlook:

• In inclusive unpolarized DIS on D, nuclear shadowing is a 1-2% effect, which is nevertheless important for the extraction of $F_{2p}(x)$-$F_{2n}(x)$ from $F_{2D}(x)$.

• In inclusive polarized DIS on D, shadowing is larger, but it is small correction for extraction of $g_{1n}(x)$ from $g_{1D}(x)$. However, gives rise to ~1% $T_{20}(x)$ and $b_1(x)$.

• In tagged DIS on D, the shadowing correction is enhanced by the AGK combinatoric factor and the slower dependence on the spectator momentum than impulse approximation → possibility to test dynamics of nuclear shadowing.

• Final-state interactions in tagged DIS on D are strong and suppressed the final proton spectrum.

• The on-shell extraction exhibits very rapid dependence on spectator momentum → need to develop best strategy for $F_{2n}(x)$ extraction.

• Developed formalism of FSI can be readily applied to tagged polarized DIS, quasi-elastic exclusive meson production and DVCS.