Партонные распределения в ядрах

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Nuclear parton distributions and the Drell-Yan process

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S. A. Kulagin and R. Petti

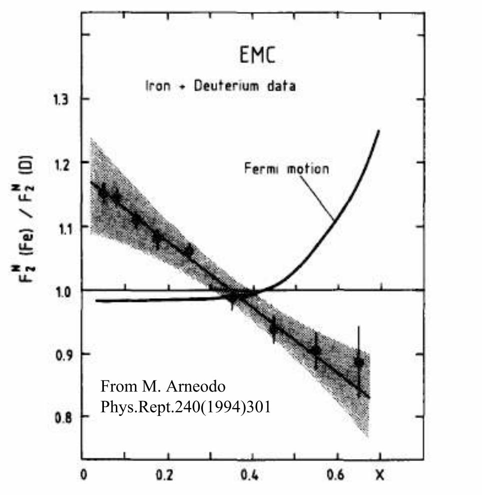
In this work we study nuclear PDFs and discuss how nuclear corrections depend on C-parity ($q+\bar{q}$ vs. $q-\bar{q}$) and isospin ($u+d$ vs. $u-d$). We also calculate the DY process cross section and compare in detail our results with the data of E772 and E866 experiments at Fermilab.

This work is based on previous studies

S.K. & R. Petti, Nucl. Phys. A765 (2006) 126;
Phys Rev D76 (2007) 094023;

Phys Rev C82 (2010) 054614

Historic EMC measurement of nuclear effects in DIS

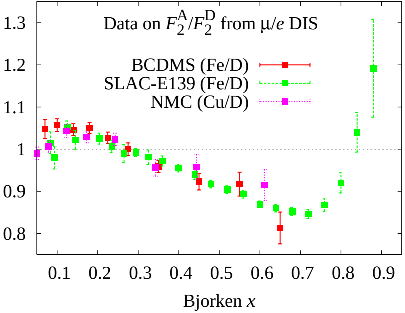


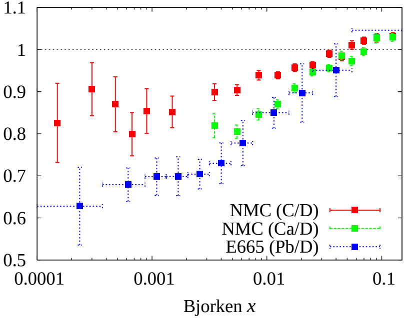
Exciting observation, although the small-x part turned out to be time dependent (the effect changed sign with time).

Available DIS data span the region $10^{-4} < x < 1.5$ and $0 < Q^2 < 150$ GeV^2. About 800 data points for the cross section ratio (or F_2^A/F_2^B) with $Q^2 > 1$ GeV^2. Nuclear targets from ^{2}H to ^{208}Pb.

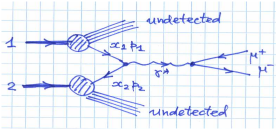
Features of data: a weak Q^2 dependence and a strong x dependence of **oscillating shape**:

- Suppression (shadowing) at small x ($x < 0.05$).
- Enhancement (antishadowing) at $0.1 < x < 0.25$.
- A well with a minimum at $x \sim 0.6 \div 0.75$ (EMC effect).
- Enhancement at large values of $x > 0.75 \div 0.8$ (Fermi motion region).





Hadronic muon pair production (Drell–Yan process)



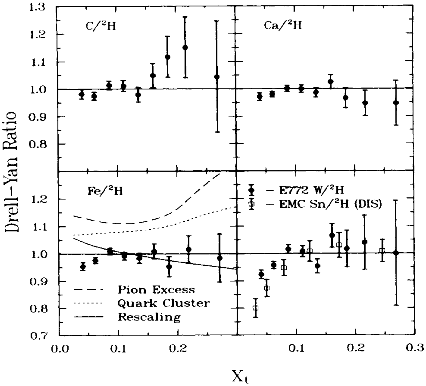


FIG. 3. Ratios of the Drell-Yan dimuon yield per nucleon, $Y_A/Y_{^2\mathrm{H}}$, for positive x_F. The curves shown for Fe/^{2}H are predictions of various models of the EMC effect. Also shown are the DIS data for Sn/^{2}H from the EMC (Ref. 4).

Drell-Yan production of a lepton pair in hadron collisions:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_B \mathrm{d}x_T} = \frac{4\pi\alpha^2}{9Q^2} K \sum_a e_a^2 \left[q_a^B(x_B)\bar{q}_a^T(x_T) + \bar{q}_a^B(x_B) q_a^T(x_T) \right]$$

$$x_T x_B = Q^2/s,$$

Selecting **small** Q^2/s and **large** x_B we probe the target's sea. In E772 experiment $s = 1600$ GeV^2. At $x_B > 0.1$ the process is dominated by $q^B\bar{q}^T$ annihillation $\Longrightarrow$ DY process probes antiquarks in the target.

$$\frac{\sigma_A^{\mathrm{DY}}}{\sigma_B^{\mathrm{DY}}} \approx \frac{\bar{q}_A(x_T)}{\bar{q}_B(x_T)}$$

Why nuclear corrections survive at high energy?

In the lab frame it is useful to think of PDFs as scattering amplitudes. Typical DIS space-time regions in the target rest frame as derived from uncertainty principle:

- DIS proceeds near the light cone: $t^2 - z^2 \sim Q^{-2}$ and $r_\perp \sim Q^{-1}$.
- Characteristic DIS time and longitudinal distance $t \sim z \sim L = (Mx)^{-1}$ NOT small in hadronic scale (in the target rest frame) $\Rightarrow$ the reason for nuclear effects to survive even at high Q^2.

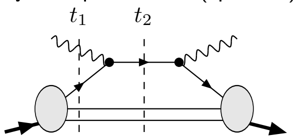
L has to be compared with average distance between bound nucleons r_{NN}
$\Rightarrow$ two different kinematical regions:

- $L < r_{\mathrm{NN}}$ (or $x > 0.2$) $\Rightarrow$ Nuclear DIS $\approx$ incoherent sum of contributions from bound nucleons.
- $L \gg r_{\mathrm{NN}}$ (or $x \ll 0.2$) $\Rightarrow$ Coherent effects of interactions with a few nucleons are important.

Understanding the nuclear corrections

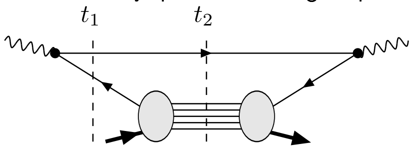
In the lab frame it is useful to think of PDFs as scattering amplitudes.
Two different mechanisms of DIS:

(I) Quasielastic scattering off bound quark. This process dominates at intermediate and large values of x and the structure functions are determined by the quark wave (spectral) functions.



Nuclear effects are due to averaging with nucleon distributions in a nucleus.

(II) Conversion $\gamma^* \to q\bar{q}$ with subsequent propagation of a $q\bar{q}$ state dominates at small x since the life time of a $q\bar{q}$ state grows as $(Mx)^{-1}$. The structure functions are determined by quark scattering amplitudes.



Nuclear effects are due to propagation of $q\bar{q}$ state in nuclear environment.

Note that (II) will dominate at small values of Bjorken x while (I) will be relevant at large x.

Modelling nuclear corrections

A quantitative model of nuclear corrections:

S.K. & R.Petti, Nucl.Phys.A765 (2006) 126

$$q^A = q_{\text{incoh}} + \delta_{\text{coh}} q + \delta_{\text{MEC}} q$$

Incoherent scattering contribution: $q_{\text{incoh}} = \int \mathrm{d}y \mathrm{d}p^2\, f_{N/A}(y, p^2) q_N(x/y, Q^2, p^2)/y$

- $f_{N/A}$ is the bound nucleon distribution. The calculations of $f_{N/A}$ were discussed intensively starting from the work of INR group *S.V.Akulinichev, G.M.Vagradov, SK (1984)*.
- $q_N(x, Q^2, p^2) = q_N(x, Q^2)(1 + \delta f\, \frac{p^2 - M^2}{M^2})$ is the parton distribution in a nucleon with four-momentum p.
- δf is a function describing off-shell behavior of PDF
- $\delta_{\text{coh}} q$ is a correction from coherent multiple scattering effect of propagation of intermediate states. Relevant at small x.
- $\delta_{\text{MEC}} q$ is a meson-exchange current correction

Model ctd.

Shape a quantitative model

- We aim to determine the unknown off-shell function $\delta f(x)$ and effective scattering amplitude a_T of intermediate hadronic component of virtual photon in a fit to data on nuclear DIS.
- In particular we study the ratios $R_2(A/B) = F_2^A/F_2^B$ in DIS region for a variaty of targets. The data are available for $A/^2H$ and $A/^{12}C$ ratios (overall about 560 points for data before 1996).
- Verify the model by comparing the calculations with data not used in analysis (newer measurements).

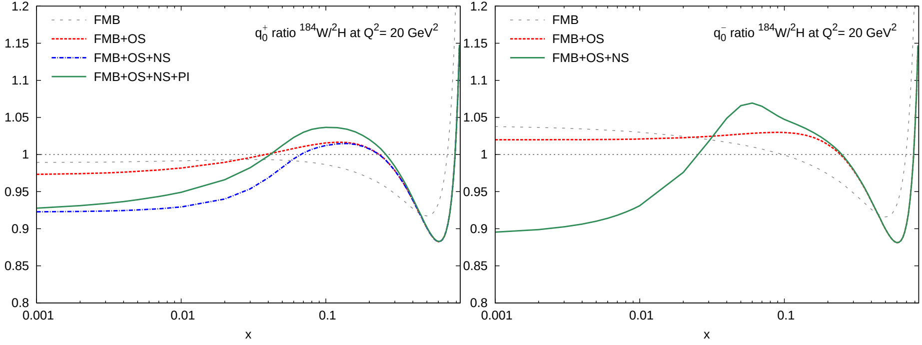
Results

- The x, Q^2 and A dependencies of the nuclear ratios are reproduced for all studied nuclei (^{4}He to ^{208}Pb) in a 4-parameter fit with $\chi^2/\text{d.o.f.} = 459/556$.
- Global fit to all data is consistent with the fits to different subsets of nuclei (light, medium, heavy nuclei).
- Parameters of the off-shell function δf and effective amplitude a_T are determined with a good accuracy.

For detailed discussion and comparison with data see *S.K. & R.Petti, Nucl Phys A765(2006)126*.

Nuclear corrections for C-even vs. C-odd PDFs

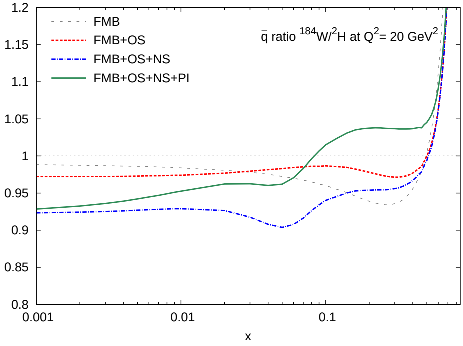
Relative nuclear corrections for C-even $q_0^+ = u + d + \bar{u} + \bar{d}$ and C-odd $q_0^- = u + d - \bar{u} - \bar{d}$ calculated for ${}^{184}W/D$ at $Q^2 = 20\ \text{GeV}^2$.



Nuclear antiquarks

Nuclear corrections for antiquark distribution $\delta\mathcal{R}_{\rm sea} = \delta\bar{q}_A/\bar{q}_N$ are directly derived from those for C-even $q+\bar{q}$ and C-odd $q-\bar{q} = q_{\rm val}$ PDFs

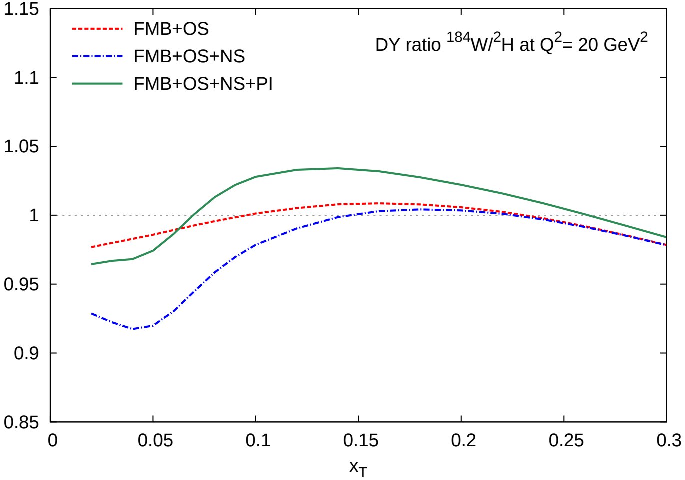
$$\delta\mathcal{R}_{\rm sea} = \delta\mathcal{R}^+ + \frac{q_{\rm val/N}(x)}{2\bar{q}_N(x)}\left(\delta\mathcal{R}^+ - \delta\mathcal{R}^-\right)$$



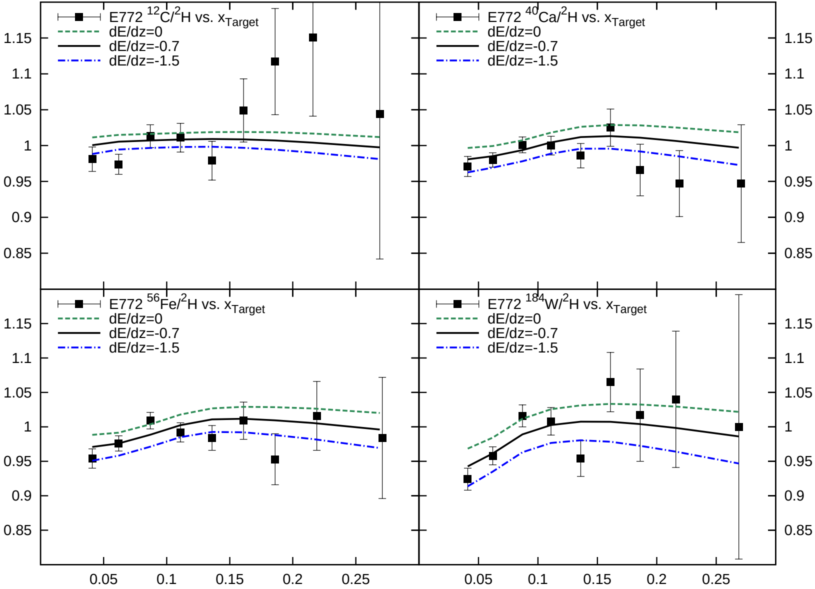
Note a partial cancellation between pion and shadowing effects for nuclear antiquark distribution for large $x \sim 0.05 - 0.15$.

Nuclear corrections for Drell-Yan production cross sections

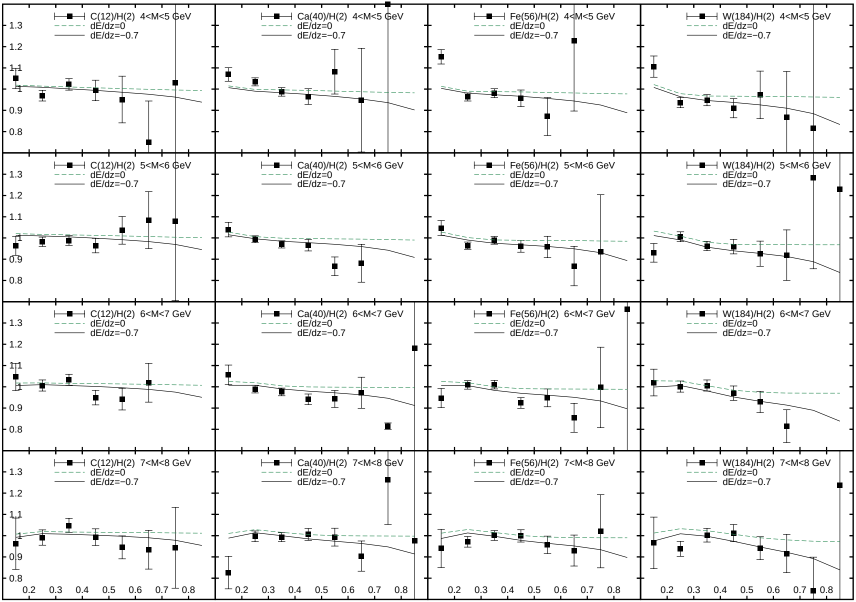
DY process cross section $\propto \sum e_q^2 \left[q^B(x_B)\bar{q}^T(x_T) + \bar{q}^B(x_B)q^T(x_T) \right]$. The kinematic variables are related as $Q^2 = s x_B x_T$. For E772 kinematics $s \approx 1600$ GeV^2.



Comparison with E772 data



Detailed compasison for each of Q^2-bins



Summary

- A detailed semi-microscopic model of nuclear DIS was developed which includes the QCD treatment of nucleon structure function and addresses a number of nuclear effects such as shadowing, Fermi motion and nuclear binding, nuclear pion and off-shell corrections to bound nucleon structure functions
- A quantitative study of existing data from charged lepton-nucleus DIS has been performed in a wide kinematic region of x and Q^2.
- Note the importance of the nuclear binding along with the off-shell corrections to the bound nucleon structure function. Those corrections are responsible for a large fraction of nuclear effects at intermediate and large Bjorken x.
- Nuclear effects on PDFs are not universal. We predict the dependence on C parity and isospin.
- The nuclear DY process is also sensetive to partonic energy loss in nuclei.
- Good agreement with the Drell-Yan data from E772 and E866 experiments. Here we note a cancellation between different nuclear effects.