PROCEEDINGS OF SCIENCE

Unintegrated gluon density in nuclei with shadowing

Artem Lipatov,[a] **Gennady Lykasov**[b] **and Maxim Malyshev**[a,*]

[a] *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Leninskie Gory 1(2), 119991 Moscow, Russia*

[b] *Joint Institute for Nuclear Research, Joliot-Curie 6, 141980 Dubna, Moscow region, Russia*

E-mail: lipatov@theory.sinp.msu.ru, lykasov@jinr.ru, malyshev@theory.sinp.msu.ru

We present a new unintegrated (transverse momentum dependent, TMD) gluon density in nuclei valid at small x and incorporating the shadowing effect. We start from recently presented TMD gluon distribution in proton (LLM-2024), which shows saturation behavior, and extend it to nuclei using the geometric scaling. The saturation scale is rescaled in a way to describe available data on nuclear structure functions at low x and Q^2 using color dipole approach. This method allows to take into account the shadowing effect at low x in the TMD gluon distribution.

QCD at the Extremes (QCDEX2025)
1–5 Sept 2025
Online

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

https://pos.sissa.it/

PoS(QCDEX2025)025

The high-energy, or k_T-factorization approach has established itself as a quite widely used framework for description of various processes at modern and future colliders. This formalism is based on unintegrated, or transverse momentum dependent (TMD) parton distribution functions (PDFs) and non-collinear evolution equations, such as Catani-Ciafaloni-Fiorani-Marchesini (CCFM) equation (see the review [1] and references therein). A key advantage of the k_T-factorization is its ability to effectively account for a significant class of higher-order perturbative corrections.

While a comprehensive collection of TMD parton densities is available in the TMDLIB library [2], their number remains limited compared to the abundance of collinear PDFs. This scarcity underscores the need for developing new unintegrated parton densities. The situation is particularly acute for nuclear TMD PDFs, where only a few examples of phenomenological applications exist [3–5].

In this paper we present our new unintegrated parton distribution function in nuclei [6]. Since the k_T-factorization approach is valid basically in the small x region, we focus on gluon densities, which contribute dominantly there. A key feature of this region in nuclei is so called shadowing, which means that the nuclear structure function $F_2^A(x, Q^2)$ is supressed compared to the nucleon one (see, for example, the review [7]).

Let us start from a quite general expression for the gluon TMD in proton, which can be valid at low scales $Q^2 \sim 1$ GeV [8]:

$$f_g(x, \mathbf{k}_T^2) = c_g(1-x)^{b_g} \sum_{n=1}^{3} c_n \left[R_0(x)|\mathbf{k}_T|\right]^n \exp\left(-R_0(x)|\mathbf{k}_T|\right),$$
$$b_g = b_g(0) + \frac{4C_A}{\beta_0} \ln \frac{\alpha_s(Q_0^2)}{\alpha_s(\mathbf{k}_T^2)}, \tag{1}$$

where $R_0^2 = 1/Q_0^2\,(x/x_0)^\lambda$, $C_A = N_C$, $\beta_0 = 11 - 2N_f/3$, $Q_0 = 2.2$ GeV. $Q_s \equiv 1/R_0$ plays the role of the saturation scale. The phenomenological parameters essential at low x, namely, λ, x_0, c_1, c_2 and c_3 are to be fitted from data. One can define them from a fit on data on soft hadron spectra and structure function $F_2(x, Q^2)$ at low Q^2 [9]. Since the gluon TMD is believed to saturate at such low scales, the distribution is scale independent. An essential feature of this TMD gluon distribution is that it reveals saturation behaviour at low Q^2. We refer to this gluon density as LLM TMD PDF.

To produce a nuclear TMD PDF, we employ so-called geometric scaling approach [10]. One can demonstrate that data on $\sigma^{\gamma^* p}(x, Q^2)$ cross section over a wide range of Q^2 can be described with a single variable $\tau = Q^2/Q_s^2(x)$, where all x dependence is encoded in the saturation scale $Q_s^2(x) \sim x^{-\lambda}$ with $\lambda \sim 0.3$. The same scaling effect was observed for nuclear cross sections $\sigma^{\gamma^* A}(x, Q^2)$ [11]. One can show, that

$$\frac{\sigma^{\gamma^* A}(\tau)}{\pi R_A^2} = \frac{\sigma^{\gamma^* p}(\tau)}{\pi R_p^2}, \tag{2}$$

where R_h is the radius of the hadronic target and $\tau = \tau_{A,p} \equiv Q^2/Q^2_{s,\,A,p}$. The A-dependence of the

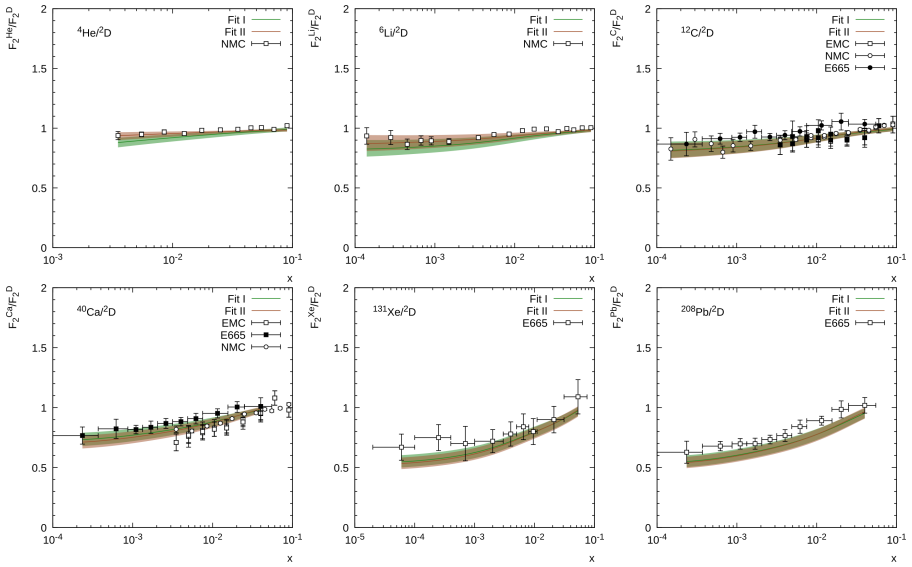

Figure 1: The fit results for structure function ratios $F_2^A(x,Q^2)/F_2^D(x,Q^2)$. Shaded bands represent the fit uncertainties. Experimental data are from NMC, EMC, and E665 (see the references in [6]).

ratio $\sigma^{\gamma^* h}(x,Q^2)/\pi R_h^2$ comes from the A-dependence of $Q_{s,A}(x)$, which reads [11]:

$$Q_{s,A}^2(x) = Q_s^2(x)\left(\frac{A\pi R_p^2}{\pi R_A^2}\right)^{\frac{1}{\delta}} \tag{3}$$

where δ and πR_p^2 are free parameters, which can be fitted from data. The nuclear gluon distribution is then produced from the proton gluon density with a substitution $Q_s^2(x) \to Q_{s,A}^2(x)$ [11] and after applying the overall normalization factor R_A^2/R_p^2. Since the proton LLM TMD includes the saturation behaviour, it can be easily transformed to a nuclear TMD with this method.

We fit the scaling parameters πR_p^2 and δ on data on $F_2^A(x,Q^2)/F_2^D(x,Q^2)$, where the structure functions can calculated in the color dipole approach [12, 13]. The calculation details can be found in [6].

We also need to specify the formula for the nuclear radius, R_A. We take two parametrizations known from the literature [11, 14], $R_A = \left(1.12A^{1/3} - 0.86A^{-1/3}\right)$ fm and $R_A = \left(1.12A^{1/3} - 0.5\right)$ fm. We denote the fit obtained with the former as 'Fit I' and with the latter as 'Fit II'. In the calculations, we consider the deutron to be identical to the proton, so that $R_D = R_p$ and $A_D = 1$.

The fit results in $\pi R_p^2 = 1.74 \pm 0.20$ fm^2, $\delta = 0.751 \pm 0.026$ with $\chi^2/n.d.f. = 2.28$ for Fit I and $\pi R_p^2 = 1.86 \pm 0.20$ fm^2, $\delta = 0.740^{+0.041}_{-0.021}$ with $\chi^2/n.d.f. = 2.19$ for Fit II [6]. The corresponding structure function ratios $F_2^A(x,Q^2)/F_2^D(x,Q^2)$ are shown in Fig. 1. We find that the both fits reasonably describe the data.

In Fig. 2 we present results for integrated over $\mathbf{k}_T^2$ up to a scale μ^2 nuclear gluon distribution functions $xg^A(x,\mu^2)$ normalized to A for some of the nuclei studied as functions of the momentum fraction x in the region of the fit, $x \leq 0.1$. The difference between the Fit I and Fit II appears mainly at low x and is more pronounced for heavier nuclei. The obtained results can be compared with predictions based on the GBW form of the gluon density [12]. In addition, we plot here nPDFs

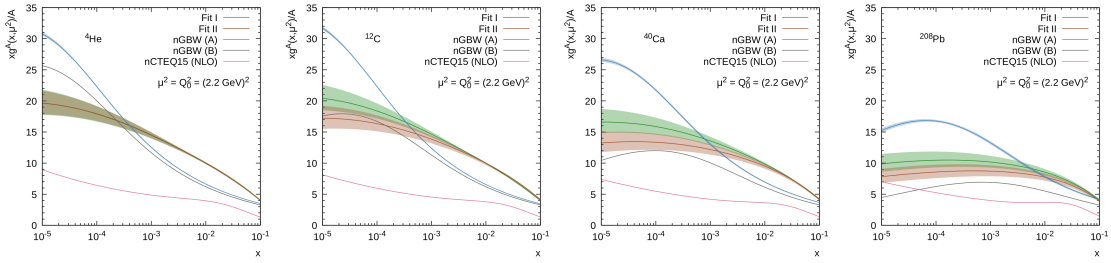

Figure 2: Integrated over $\mathbf{k}_T^2$ gluon densities in ^{4}He, ^{12}C, ^{40}Ca and ^{208}Pb nuclei calculated as functions of x at $\mu^2 = Q_0^2$. For comparison we show here corresponding nPDFs obtained by the nCTEQ Collaboration [15].

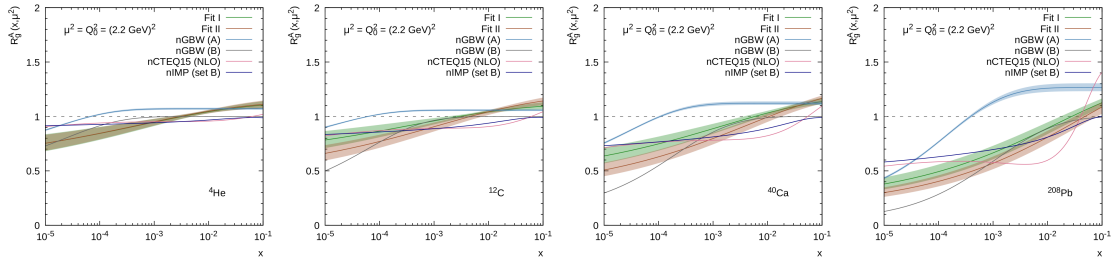

Figure 3: Nuclear modification factor for gluon densities in ^{4}He, ^{12}C, ^{40}Ca and ^{208}Pb nuclei calculated as functions of x at $\mu^2 = Q_0^2$. For comparison we show here corresponding results obtained by the nCTEQ [15] and nIMP [16] groups.

obtained by the nCTEQ Collaboration [15]. It also shows many differences with the approaches discussed above.

In Fig. 3 we demonstrate the nuclear shadowing effects in the calculated nPDFs, which can be expressed in terms of the nuclear modification factor for the integrated gluon distributions $R_g^A(x,\mu^2) = (1/A)xg^A(x,\mu^2)/xg(x,\mu^2)$. One can see that both our fits result in a sizeable gluon shadowing, which is more pronounced as x decreases and A increases. Predictions of Fit I and Fit II at low $x \leq 10^{-4}$ are typically a bit stronger for all nuclei than that of global analyses performed by the nCTEQ [15] or nIMP [16] groups within the collinear framework. Difference in predictions of these approaches is quite notable.

To conclude, we have presented a new unintegrated gluon density in nuclei. We started from an analytical expression for the TMD gluon distribution in proton developed earlier and used the geometric approach to produce a nuclear TMD by modifying the saturation scale $Q_s(x)$ in a way to include nuclear medium effects resulting in shadowing at small x. The parameters of the scale modification have been obtained from a fit to data on ratios $F_2^A(x,Q^2)/F_2^{A'}(x,Q^2)$ for several nuclear targets at low $x < 0.1$. Basing on different formulae for nuclear radius, we have obtained two fits, which provide a good description of the data.

Acknowledgements. We would like to acknowledge S.P. Baranov, H. Jung and A.A. Prokhorov for their interest, important comments and remarks. We also would like to thank the 'QCD at the Extremes' organizers for their excellent work and opportunity to present our results. This research has been carried out at the expense of the Russian Science Foundation grant No. 25-22-00066.

References

[1] A.V. Lipatov, S.P. Baranov, and M.A. Malyshev, *Semihard QCD Processes beyond the Collinear Approximation*, *Phys. Part. Nucl.* **55** (2024) 256 .

[2] N.A. Abdulov *et al. TMDlib2 and TMDplotter: a platform for 3D hadron structure studies*, *Eur. Phys. J. C* **81** (2021) 752 [2103.09741].

[3] E. Blanco *et al.*, *Z boson production in proton-lead collisions at the LHC accounting for transverse momenta of initial partons*, *Phys. Rev. D* **100** (2019) 054023 [1905.07331].

[4] A.V. Lipatov *et al.*, *TMD gluon density in nuclei versus experimental data on heavy flavor production at LHC*, *Phys. Lett. B* **850** (2024) 138486 [2312.00365].

[5] S. Rezaie and K. Azizi, *Z boson production in proton-lead collisions: A study utilizing MRW nuclear TMDs*, *Phys. Lett. B* **868** (2025) 139787 [2502.16878].

[6] A.V. Lipatov, G.I. Lykasov, and M.A. Malyshev, *Gluon shadowing effect in light and heavy nuclei at small x*, *Phys. Rev. D* **112** (2025) 014025 [2505.01770].

[7] M. Arneodo, *Nuclear effects in structure functions*, *Phys. Rept.* **240** (1994) 301.

[8] A.V. Lipatov, G.I. Lykasov, and M.A. Malyshev, *Toward the global fit of the TMD gluon density in the proton from the LHC data*, *Phys. Rev. D* **107** (2023) 014022 [2211.03727].

[9] A.V. Lipatov, G.I. Lykasov, and M.A. Malyshev, *Self-consistent description of HERA data at low Q^2 and soft hadron production at LHC*, *Phys. Lett. B* **848** (2024) 138390 [2310.02672].

[10] A.M. Stasto, K. Golec-Biernat, and J. Kwiecinski, *Geometric scaling for the total $\gamma^* p$ cross-section in the low x region*, *Phys. Rev. Lett.* **86** (2001) 596 [hep-ph/0007192].

[11] N. Armesto, C.A. Salgado, and U.A. Wiedemann, *Relating high-energy lepton-hadron, proton-nucleus and nucleus-nucleus collisions through geometric scaling*, *Phys. Rev. Lett.* **94** (2005) 022002 [hep-ph/0407018].

[12] K. Golec-Biernat and M. Wüsthoff, *Saturation effects in deep inelastic scattering at low Q^2 and its implications on diffraction*, *Phys. Rev. D* **59** (1998) 014017 [hep-ph/9807513]; *Saturation in diffractive deep inelastic scattering*, **60** (1999) 114023 [hep-ph/9903358].

[13] N.N. Nikolaev and B.G. Zakharov, *Color transparency and scaling properties of nuclear shadowing in deep inelastic scattering*, *Z. Phys. C* **49** (1991) 607; V. Barone *et al.*, *Unitarization of structure functions at large $1/x$*, *Phys. Lett. B* **326** (1994) 161.

[14] I.M. Kapitonov, *An Introduction to Physics of Nuclei and Particles*, URSS, Moscow, 2002. (In Russian).

[15] nCTEQ Collaboration, *Modification of Quark-Gluon Distributions in Nuclei by Correlated Nucleon Pairs*, *Phys. Rev. Lett.* **133** (2024) 152502 [2312.16293]

[16] R. Wang, X. Chen, and Q. Fu, *Global study of nuclear modifications on parton distribution functions*, *Nucl. Phys. B* **920** (2017) 1 [1611.03670].