**Template NA**

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| **Work package number** | WP13 | **Start date** | 01/06/2019 |
| **Activity Type** | Networking activity | | |
| **Work package acronym** | NA2-Small-x | | |
| **Work package title** | Small-x Physics at the LHC and future DIS experiments | | |

1. Work carried out and overview of progress
   1. **Project objectives**

*[Please give an overview of the project objectives for the third reporting period (June 2022 – July 2024), with regard to the overall objectives as described in the Annex 1 of the Grant Agreement and summarized below.]*

The objective of this WP is to strengthen the communication and collaboration between the European groups involved in theoretical and phenomenological studies in small-x physics.

Understanding the dynamics of the strong interaction at high energies is one of the central topics in nuclear and particle physics. A genuinely new, non-linear regime of QCD is expected to occur at high energies. Here the Color Glass Condensate (CGC) effective theory provides a controlled weak coupling description applicable in spite of the non-perturbatively large gluonic field strengths. Hints of the breaking of fixed-order perturbation theory have been found at HERA and RHIC, but only data from the LHC and future DIS experiments can unambiguously establish the existence of the non-linear regime. The behavior of gluons carrying only a small fraction x of the proton and nuclear momentum determines the bulk of particle production in relativistic heavy ion collisions. These gluons provide the initial conditions for the subsequent evolution towards a quark-gluon plasma in nuclear collisions at the LHC. A good control of these initial conditions is paramount for understanding the emergence of collectivity at the macroscopic level from the microscopic QCD dynamics.

* 1. **Progress made during the reporting period towards the objectives**

*[Please describe the progress made during the third reporting period in line with your Gantt chart and the project overall tasks as described in the Annex 1 of the Grant Agreement and summarized below.]*

***Table 1.2 Progress made during the reporting period towards objectives***

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| ***Task 1: Nuclear PDFs. The determination of parton densities inside nuclei and the searches for collinear factorization breaking effects at small x, both by refining the methods for PDF extraction and by using new data sets from the LHC and RHIC will be improved*** |
| During the reporting period, the activities on this task can be divided into three directions. First, we have developed a new way to implement QCD evolution directly on physical observables and not on PDFs, as developed in the paper Eur. Phys. J. C 84 (2024) 1, 84.  Second, studies of the future impact of EIC data on the determination of proton and nuclear PDFs, were developed in Phys. Rev. D 109 (2024) 5, 5.  Third, studies of the possibilities and uncertainties for constraining nuclear parton densities in ultraperipheral collisions at the LHC, were developed in Eur. Phys. J. C 83 (2023) 8, 758.  Many of these developments are summarized in the review *Nuclear PDFs After the First Decade of LHC Data*, e-Print: 2311.00450 [hep-ph], M. Klasen, H. Paukkunen (JYV), to appear in Ann. Rev. Nucl. Part. Sci. |
| ***Task 2: New NLO-based precision phenomenology in CGC and BFK.*** |
| Concerning technical aspects in the CGC and BFKL, several lines have been pursued:   * On the CGC side, there have been works on the interpretation of improvements on evolution (feasibility of a Langevin implementation at NLO in JHEP 03 (2024), 131; impact parameter dependence in Phys. Lett. B 848 (2024) 138360), NLO implementation of forward particle production (Phys. Rev. D 109 (2024) 3, 034018), several works on NLO calculations for diffraction, either inclusive (JHEP 05 (2024) 024; Phys. Rev. D 108 (2023) 11, 114023) or exclusive (e-Print: 2311.09146 [hep-ph]; JHEP 02 (2024) 165; Eur. Phys. J. C 83 (2023) 11, 1078), and on the implementation of non-eikonal corrections (JHEP 07 (2024) 137). * On the BFKL side, theory computations at higher order for evolution (JHEP 04 (2024) 078; JHEP 04 (2023) 137) and impact factors (JHEP 01 (2024) 106).   On a more phenomenological side, several studies on the possibility to disentangle saturation in exclusive vector meson production in ultraperipheral collisions (Phys. Rev. D 109 (2024) 7, L071504; Phys. Lett. B 852 (2024) 138613) and dijet production in pA collisions (Eur. Phys. J. C 83 (2023) 10, 947), as well as extractions of initial conditions for non-linear evolution (Phys. Rev. D 109 (2024) 5, 054018) and its influence on the extraction of parton densities (Phys. Rev. D 109 (2024) 9, 094004).  Finally, there has been several theoretical studies relevant for future facilities concerning diffraction at the EIC (e-Print: 2406.02227 [hep-ph], to appear in Phys. Rev. D), production of exotic hadrons in high energy factorization (2405.14773 [hep-ph]; Phys. Lett. B 848 (2024) 138406) and new evolution equations including the electro-weak sector at ultrahigh energies (e-Print: 2403.08583 [hep-ph]). |
| ***Task 3: TMDs at small x*** |
| On this task, and related with activities in JRA4 and JRA5, there has been work on the relation between TMD and small x evolutions and the possibility of obtaining a consistent TMD-factorized form for the cross sections at small x (e-Print: 2406.04238 [hep-ph]; e-Print: 2406.08277 [hep-ph]).  Furthermore, and as a new deliverable, TMD factorization has been established for diffractive dijet production in photoproduction on nuclei at next-to-leading order: *TMD factorisation for diffractive jets in photon-nucleus interactions,* JHEP 06 (2024) 180, S. Hauksson, E. Iancu (CEA), A. H. Mueller, D. N. Triantafyllopoulos (ECT\*), S. Y. Wei. |
| ***Task 4: Multi-particle correlations & Thermalization*** |
| Concerning this task, there has been activities on three directions: First, initial state explanations of long range two-particle correlations in hadronic collisions, i.e., the ridge, in the CGC (JHEP 10 (2023) 159; Universe 10 (2024) 2, 58; arXiv:2405.12062 [hep-ph]).  Second, entanglement and entropy in the hadronic wave functions and the influence of small-x evolution (e-Print: 2310.18510 [hep-ph]; Phys. Rev. D 109 (2024) 5, 054015).  Finally, studies of the onset of thermalization or isotropization in the early stages of hadronic collisions using transport equations or Glasma simulations, with several different aspects:   * Theoretical aspects like the existence of attractors (Phys. Lett. B 852 (2024) 138623) and the form of the energy momentum tensor (Eur. Phys. J. C 84 (2024) 4, 36). * Studies of momentum broadening of light and heavy partons in the initial stages (Phys. Rev*.* D 110 (2024) 3, 034019; Phys. Rev. D 109 (2024) 1, 014025; Phys. Lett. B 850 (2024) 138525). * Studies of the influence of quarks in the equilibration process (JHEP 06 (2024) 145). |

**1.3 Highlights of significant results**

*[Include an overview of the project results towards the objectives in line with the structure of the Annex 1 to the Grant Agreement*.*]*

The highlight concerning Task 1 for this reporting period is the development of a framework to make the QCD evolution incarnated in the DGLAP equations, directly for physical quantities like structure functions in DIS, and not on quantities like parton densities which are dependent on the choice of scheme separation between short and long distance pieces in the physical observables, and on the renormalization scheme. This work, reflected in the publication *Evolution of structure functions in momentum space*, Eur. Phys. J. C 84 (2024) 1, 84, T. Lappi, H. Mäntysaari, H. Paukkunen, M. Tevio (JYV), allows the elimination of ambiguities in evolution, while yielding the same result as the traditional approach checked up to next-to-leading order.

The highlight of Task 2 is the complete calculation of diffractive structure functions and cross sections in DIS at next-to-leading order, including both real and virtual corrections. The calculation, made in the framework of the CGC and the dipole model, and contained in the publication *Diffractive deep inelastic scattering at NLO in the dipole picture,* JHEP 05 (2024) 024, G. Beuf, T. Lappi, H. Mäntysaari, R. Paatelainen, J. Penttala (JYV), is a step forward in precision for the comparison of experimental data from HERA and the future EIC or eventual new DIS colliders, with QCD predictions implementing high-energy evolution and saturation. It required the development of several techniques to deal with the existing singularities, techniques that will become of wider use.

Concerning Task 3, the highlight of the period is establising TMD factorization at next-to-leading order in dijet photoproduction off nuclei, as shown in publication *TMD factorisation for diffractive jets in photon-nucleus interactions*, JHEP 06 (2024) 180, S. Hauksson, E. Iancu (CEA), A. H. Mueller, D. N. Triantafyllopoulos (ECT\*), S. Y. Wei. Establishing such factorisation is one of the expected deliverables (D13.3) of WP13 and complements in a different system the efforts in inclusive DIS to clarify the different divergences and the corresponding evolutions, finding a strong interplay between small-x and standard TMD evolution, see the corresponding publications above.

Finally, the highlight for Task 4 is the study on entanglement, decoherence and evolution of entropy in the BFKL framework, reflected in publication *Von Neumann entropy and Lindblad decoherence in the high energy limit of strong interactions*, Phys. Rev. D 109 (2024) 5, 054015, G. Chachamis, M. Hentschinski, A. Sabio Vera (UAM-LIP). In this work a rigorous approach to evolution in the BFKL setup was adopted, which demanded a regulation in the infrared. It complements more phenomenological studies and offers a link with the physics of open quantum systems through the Lindblad equation.

1. Critical Implementation risks and mitigation actions

**2.1 Risk materialization**

*[Provide the information on the project risks described in Annex 1 to the Grant Agreement*.*]*

1. Existing data from the LHC constrain nPDFs too weakly or are inconsistent with existing analyses (low)

Whether the risk has materialized? (Yes/No) No

1. Existing observables on particle correlations in small systems cannot distinguish the hydrodynamic from the microscopic CGC description (low)

Whether the risk has materialized? (Yes/No) No

**2.2 Risk-mitigation measures applied**

*[Please indicate whether the risk-mitigation plan described in Annex 1 to the Grant Agreement and corresponding to the risk number was applied in the reporting period*.*]*

1. Propose other observables to be measured in future runs at the LHC that could be constraining or verify the found inconsistencies

Whether the risk-mitigation plan was applied? (Yes/No) No

1. Propose alternative observables, or consistency checks for both explanations

Whether the risk-mitigation plan was applied? (Yes/No) No

**2.3 Comments/new risk-mitigation measures proposed**

*[Provide any significant comments on the risks encountered and the mitigation plan applied. Give any unforeseen risks encountered during the reporting period and not mentioned above*.*]*

3. Deviations from Annex 1 (Description of Action) and Annex 2 (Estimated budget for Action) (if applicable)

**3.1 Deviations from planned objectives and tasks, and their impact on the progress of the work package**

*[Explain the reasons for deviations, the consequences and the proposed corrective actions.]*

No deviation from the planned scientific objectives and tasks is observed, as shown in Table 1.2. Workshops at ECT\* have been organized in May 2023 (<https://www.ectstar.eu/workshops/color-glass-condensate-at-the-electron-ion-collider/>) and June 2024 (<https://www.ectstar.eu/workshops/diffraction-and-gluon-saturation-at-the-lhc-and-the-eic/>).

**3.2 Deviations between actual and planned person months**

*[Explain deviations between actual and planned person-months. If applicable, propose corrective actions.]*

The use of person-months funded by the project has proceeded as planned. Florian Cougoulic was a joint postdoc between JYU and USC, partially funded by STRONG2020. He has been at JYU until the end of April 2022 (i.e., person-months at JYU are spent), started at USC at the beginning of May 2022 (person-months are spent), to continue at USC until the end of August 2024 supported by other grants. Víctor Vila was a joint postdoc between CNRS (Polytechnique) and IFJ PAN and has been for 12 months at École Polytechnique (i.e., person-months spent) and afterwards 12 months at IFJ PAN (person-months spent), to later go to IST-Lisbon supported by other funds.

1. Deliverables and milestones tables

**4.1 Deliverables**

*[Please list all the deliverables due in this reporting period, as indicated in Annex I.*

*Deliverables must also be accompanied by a short report (deliverable description and technical documentation, such as photo, list of publications, etc.), so that the European Commission has a record of their existence.]*

***Table 4.1 List of deliverables***

| **Deliverable No.** | **Deliverable name** | **Lead Beneficiary** | **Nature** | **Dissemination level[[1]](#footnote-2)** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| D13.1 | NPDFs | 23 - JYU | Report | PU | 54 | yes | 36 | https://research.hip.fi/qcdtheory/nuclear-pdfs/ |
| D13.3 | TMD factorization | 37 - IFJ PAN | Report | PU | 54 | yes | 57 | <https://inspirehep.net/literature/2760756>, JHEP 06 (2024) 180 |

*In case a deliverable has been delivered in the reporting period and a report exists in the Participant Portal, you can indicate “uploaded report” in correspondence of a deliverable*

**4.2 Milestones**

*[Please complete the table if milestones are specified in Annex I.*

*Milestones will be assessed against specific criteria and performance indicators as defined in Annex I.]*

***Table 4.2 List of milestones***

| **Milestone number** | **Milestone name** | **Lead beneficiary** | **Delivery month from Annex I** | **Delivered**  **(yes/no)** | **Actual delivery month** | **Comments** |
| --- | --- | --- | --- | --- | --- | --- |
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**No Milestones in the RP3 (months 37-62).**

**4.3 Deliverable Reports**

*[Please provide, per each deliverable listed in Table 4.1, a brief description, including if possible some technical documentation (photos, list of publications, etc.). Use as many pages as needed per each report.]*

Deliverable 13.1 is a new set of nuclear parton densities, EPPS21, which, for the first time, includes in the fit data from pPb collisions at the LHC Run 2 and considers the uncertainties in the proton baseline. The set is made publicly available in the web page <https://research.hip.fi/qcdtheory/nuclear-pdfs/>, and also in the LHAPDF tool (the standard in high-energy physics). This set constitutes a new benchmark to which all other sets are compared, and the description of the work was contained in publication *Nuclear PDFs with new LHC Run 2 data plus proton baseline uncertainties*, Eur. Phys. J. C 82 (2022) 5, 413, K. J. Eskola, P. Paakkinen, H. Paukkunen, C. A. Salgado (JYV-USC); it has already achieved 114 citations in the INSPIRE database.

Deliverable 13.3 is the derivation of TMD factorization at next-to-leading order in dijet photoproduction of nuclei, as shown in publication *TMD factorisation for diffractive jets in photon-nucleus interactions*, JHEP 06 (2024) 180, S. Hauksson, E. Iancu (CEA), A. H. Mueller, D. N. Triantafyllopoulos (ECT\*), S. Y. Wei. Establishing such factorisation complements in a different system the efforts in inclusive DIS to clarify the different divergencies and the corresponding evolutions, finding a strong interplay between small-x and standard TMD evolution. By itself it is a most important result and means the culmination of many works at next-to-leading order of the same group and others within WP13, like JHEP 10 (2022) 184, e-Print: 2406.08277 [hep-ph], Phys. Rev. Lett. 128 (2022) 20, 202001, JHEP 10 (2022) 103, Eur. Phys. J. C 83 (2023) 11, 1078 and e-Print: 2406.04238 [hep-ph], and multitude of previous works not including next-to-leading virtual corrections.

1. PU = Public

   PP = Restricted to other programme participants (including the Commission Services).

   RE = Restricted to a group specified by the consortium (including the Commission Services).

   CO = Confidential, only for members of the consortium (including the Commission Services). [↑](#footnote-ref-2)