

STRONG-2020

HORIZON 2020

Annual Meeting 2024

WP13 (NA2-Small-x): Small-x Physics at the LHC and future DIS experiments

Dionysios Triantafyllopoulos

ECT*, Italy

June 21st 2024

Plan of presentation

01

Progress achieved by the WP during the last year

02

Important highlights of the performed work (last year + full project duration)

03

Tasks and achievements beyond the initial Work Program and/or tasks which could not be carried out

We kindly ask you to focus your presentations on the scientific progress of your WP (financial and administrative aspects of the implementation of the tasks to be included in the written report before 31/07/2024)

Introduction



Participant institutions:

- **BGU**: Ben-Gurion University of the Negev, Beer Sheva, Israel ([M. Lublinsky](#)).
- **CNRS**: École Polytechnique, Université Paris-Saclay, Palaiseau, France ([C. Marquet](#), [S. Munier](#)) + IPHT, Commissariat à l'énergie atomique, Saclay, France ([F. Gelis](#), [E. Iancu](#), [G. Soyez](#)) + Laboratoire de Physique Théorique, Université Paris-Saclay, Orsay, France ([S. Wallon](#)).
- **Consenza**: Università della Calabria, Cosenza, Italia ([A. Papa](#)).
- **CTU**: Czech Technical University, Prague, Czech Republic ([J. Cepila](#), [G. Contreras](#)).
- **ECT***: Trento, Italy ([D. Triantafyllopoulos](#)).
- **Firenze**: Università de Firenze, Italia ([D. Colferai](#)).
- **Granada**: Universidad de Granada, Spain ([J. L. Albacete](#)).
- **Groningen**: University of Groningen, The Netherlands ([D. Boer](#)).
- **Jyväskylä**: University of Jyväskylä, Finland ([T. Lappi](#), [H. Paukkunen](#), [K. J. Eskola](#)).
- **Krakow INP**: Henryk Niewodniczański Institute of Nuclear Physics, Krakow, Poland ([K. Golec-Biernat](#), [K. Kutak](#), [S. Sapeta](#)).
- **Krakow JU**: Jagiellonian University, Krakow, Poland ([Leszek Motyka](#), [Michał Praszalowicz](#)).
- **Madrid**: Universidad Autónoma de Madrid, Spain ([A. Sabio Vera](#)).
- **Regensburg**: University of Regensburg, Germany ([G. Chirilli](#)).
- **Santiago**: Universidade de Santiago de Compostela, Spain ([N. Armesto](#)).
- **Warsaw**: National Centre for Nuclear Research, Warsaw, Poland ([T. Altinluk](#), [L. Szymanowski](#)).

- Initially 15 institutions; several additional contacts:
 - B. Blok (Technion)
 - G. Chachamis (LIP)
 - M. Hentschinski (Puebla)
 - C. Royon (KU)
 - S. Schlichting (Bielefeld)
 - W. Xiang (Guizhou U)
 - G. Chirilli (now at Salento)



Progress made



Task 1: Nuclear PDFs.

- Impact of Inclusive Electron Ion Collider Data on Collinear Parton Distributions
Phys. Rev. D 109 (2024) 5, 5; N. Armesto (USC), T. Cridge, F. Giuli, L. Harland-Lang, P. Newman, B. Schmookler, R. Thorne, K. Wichmann.
- Evolution of structure functions in momentum space,
Eur. Phys. J. C 84 (2024) 1, 84; T. Lappi, H. Mäntysaari, H. Paukkunen, M. Tevio (JYV)
- Predictions for exclusive Upsilon-Upsilon photoproduction in ultraperipheral Pb+Pb collisions at the LHC at next-to-leading order in perturbative QCD
Eur. Phys. J. C 83 (2023) 8, 758; K. J. Eskola, C. Flett, V. Guzey, T. Löytäinen, H. Paukkunen (JYV)
- Nuclear PDFs After the First Decade of LHC Data
e-Print: 2311.00450 [hep-ph]; M. Klasen, H. Paukkunen (JYV)



Progress made



Task 2: New NLO-based precision phenomenology in CGC and BFKL.

Technical aspects in the CGC and BFKL:

- On running coupling in the JIMWLK evolution and its Langevin formulation
JHEP 03 (2024), 131; T. Altinoluk (NCBJ), G. Beuf (NCBJ), M. Lublinsky (BGU), V. V. Skokov
- On the breakdown of eikonal approximation and survival of Reggeization in presence of dimension-5 Higgs-gluon coupling
JHEP 04 (2024) 078; M. Fucilla (CNRS), M.A. Nefedov (CNRS), A. Papa (Cosenza)
- One-loop Lipatov vertex in QCD with higher ϵ -accuracy
JHEP 04 (2023) 137; V.S. Fadin, M. Fucilla (CNRS), A. Papa (Cosenza)
- Probing gluon saturation via diffractive jets in ultra-peripheral nucleus-nucleus collisions
Eur. Phys. J. C 83 (2023) 11, 1078; E. Iancu (CEA), A. H. Mueller, D. N. Triantafyllopoulos, S. Y. Wei (ECT*)
- Renormalization group improved photon impact factors and the high energy virtual photon Scattering
JHEP01 (2024) 106; D. Colferai (Firenze), W. Li, A. M. Stasto



Progress made



Task 2: New NLO-based precision phenomenology in CGC and BFKL.

Technical aspects in the CGC and BFKL:

- 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)

- Complete next-to-leading order calculation of single inclusive π^0 production in forward proton-nucleus collisions

Phys. Rev. D 109 (2024) 3, 034018; H. Mäntysaari, J. Tawabutr (JYV)

- Rapidity gap distribution of diffractive small- x_p events at HERA and at the EIC

Phys. Rev. D 108 (2023) 11, 114023; T. Lappi, A. D. Le, H. Mäntysaari (JYV)

- Diffractive single hadron production in a saturation framework at the NLO

JHEP 02 (2024) 165; M. Fucilla (CNRS), A. Grabovsky, E. Li (CNRS), L. Szymanowski (NCBJ), S. Wallon (CNRS)

- Breakdown of collinear factorization in the exclusive photoproduction of a π^0 -gamma pair with large invariant mass

e-Print: 2311.09146 [hep-ph]; S. Nabeebaccus (CNRS), J. Schoenleber, L. Szymanowski(NCBJ), S. Wallon

(CNRS)

Annual Meeting, 20-21 June 2024

NA2: Dionysios Triantafyllopoulos,





Progress made



Task 2: New NLO-based precision phenomenology in CGC and BFKL.

Technical aspects in the CGC and BFKL:

- Next-to-eikonal corrections to dijet production in Deep Inelastic Scattering in the dilute limit of the Color Glass Condensate

e-Print: 2403.04603 [hep-ph]; P. Agostini, T. Altinoluk, N. Armesto (NCBJ, SCQ)

- Solutions to the Balitsky-Kovchegov equation including the dipole orientation

Phys. Lett. B 848 (2024) 138360, e-Print: 2309.02910 [hep-ph]; J. Cepila, J. G. Contreras, M. Vaculciak (CTU)



Progress made



Task 2: New NLO-based precision phenomenology in CGC and BFKL.

Phenomenology:

- Energy dependent nuclear suppression from gluon saturation in exclusive vector meson production
Phys. Rev. D 109 (2024) 7, L071504; H. Mäntysaari, F. Salazar, B. Schenke (JYV)
- Inferring the initial condition for the Balitsky-Kovchegov equation
Phys. Rev. D 109 (2024) 5, 054018; C. Casuga, M. Karhunen, H. Mäntysaari (JYV)
- Searching for saturation in forward dijet production at the LHC
Eur. Phys. J. C 83 (2023) 10, 947; A. van Hameren (INP), H. Kakkad, P. Kotko, K. Kutak (INP), S. Sapeta (INP)
- Incoherent J/psi production at large |t| identifies the onset of saturation at the LHC
Phys. Lett. B 852 (2024) 138613, e-Print: 2312.11320 [hep-ph]; J. Cepila, J. G. Contreras, M. Matas, A. Ridzikova (CTU)
- Proton PDFs with nonlinear corrections from gluon recombination
Phys. Rev. D 109 (2024) 9, 094004, e-Print: 2312.12993 [hep-ph]; P. Duwentäster, V. Guzey, I. Helenius, H. Paukkunen (JYV)



Progress made



Task 2: New NLO-based precision phenomenology in CGC and BFKL.

Proposal of new facilities and contribution to new projects:

- Extracting the partonic structure of colorless exchanges at the Electron Ion Collider
e-Print: 2406.02227 [hep-ph]; N. Armesto (USC)., P. R. Newman, W. Slominski (JU), A. Stasto
- Electroweak Evolution Equations and Isospin Conservation
e-Print: 2403.08583 [hep-ph]; P. Ciafaloni, G. Co, D. Colferai (Firenze)
- Fully charmed tetraquarks from LHC to FCC: Natural stability from fragmentation
2405.14773 [hep-ph], F.G. Celiberto, G. Gatto, A. Papa (Cosenza)
- A high-energy QCD portal to exotic matter: Heavy-light tetraquarks at the HL-LHC
Phys. Lett. B 848 (2024) 138406; F. G. Celiberto, A. Papa (Cosenza)



Progress made



Task 3: TMDs at small x (relation with JRA4 and JRA5)

- The evolution of the transverse-momentum dependent gluon distribution at small x
e-Print: 2406.04238 [hep-ph]; P. Caucal, E. Iancu (CEA)
- TMD factorisation for diffractive jets in photon-nucleus interactions
2402.14748 [hep-ph]; S. Hauksson, E. Iancu (CEA), A. H. Mueller, D. N. Triantafyllopoulos (ECT*), S. Y. Wei
- Sudakov double logs in single-inclusive hadron production in DIS at small x from the Color Glass Condensate formalism
e-Print: 2406.08277 [hep-ph], T. Altinoluk (NCBJ), J. Jalilian-Marian, C. Marquet (CNRS)



Progress made



Task 4: Multi-particle correlations & Thermalization.

- Particle Production in pA Collisions at Mid-Rapidity in the Color Glass Condensate
Universe 10 (2024) 2, 58; . Agostini, T. Altinoluk, N. Armesto (NCBJ, SCQ)
- Limiting attractors in heavy-ion collisions
Phys. Lett. B 852 (2024) 138623; K. Boguslavski, A. Kurkela, T. Lappi, F. Lindenbauer, J. Peuron (JYV)
- Jet quenching parameter in QCD kinetic theory
2312.00447 [hep-ph]; K. Boguslavski, A. Kurkela, T. Lappi, F. Lindenbauer, J. Peuron (JYV)
- Heavy quark diffusion coefficient in heavy-ion collisions via kinetic theory
Phys. Rev. D 109 (2024) 1, 014025; K. Boguslavski, A. Kurkela, T. Lappi, F. Lindenbauer, J. Peuron (JYV)
- Jet momentum broadening during initial stages in heavy-ion collisions
Phys.Lett.B 850 (2024) 138525; K. Boguslavski, A. Kurkela, T. Lappi, F. Lindenbauer, J. Peuron (JYV)
- Conserved energy–momentum tensor for real-time lattice simulations
Eur. Phys. J. C 84 (2024) 4, 36; K. Boguslavski, T. Lappi, J. Peuron, P. Singh (JYV)



Progress made



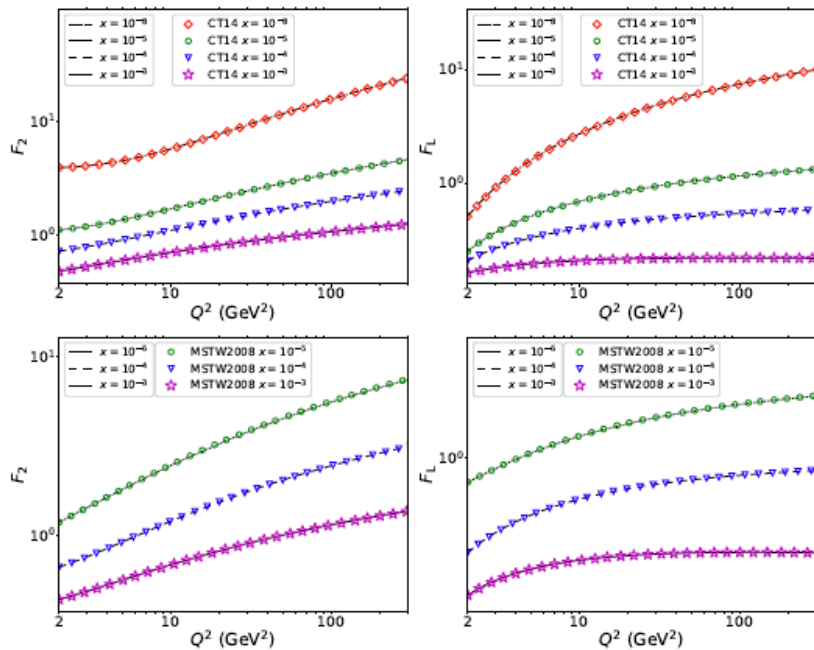
Task 4: Multi-particle correlations & Thermalization.

- Quark production and thermalization of the quark-gluon plasma
e-Print: 2311.07450 [hep-ph]; S. Barrera Cabodevila, C. A. Salgado, B. Wu (USC)
- Entanglement entropy of proton and its relation to thermodynamics entropy
e-Print: 2310.18510 [hep-ph]; K. Kutak (INP)
- The Dynamics of Particle-Particle Correlations and the Ridge Effect in Proton-Proton Collisions
arXiv:2405.12062 [hep-ph]; G. Cale, G. Chachamis, A. Sabio Vera (UAM)
- Von Neumann entropy and Lindblad decoherence in the high energy limit of strong interactions
Phys. Rev. D 109 (2024) 5, 054015, arXiv:2312.16743 [hep-th]; G. Chachamis, M. Hentschinski, A. Sabio Vera
- Low projectile density contributions in the dilute-dense CGC framework for two-particle correlations
JHEP 10 (2023) 159, e-Print: 2303.08711 [hep-ph]; A. K. Kohara, C. Marquet (CNRS), V. Vila (LIP, USC, INP)

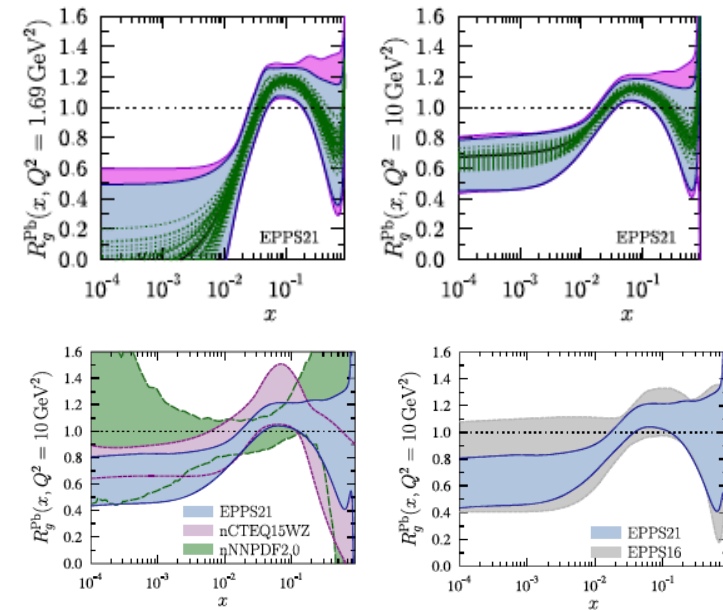
Highlights

Task 1: Nuclear PDFs.

Last year: Evolution of structure functions in momentum space, Eur. Phys. J. C 84 (2024) 1, 84 (JYV); DGLAP evolution in physical basis



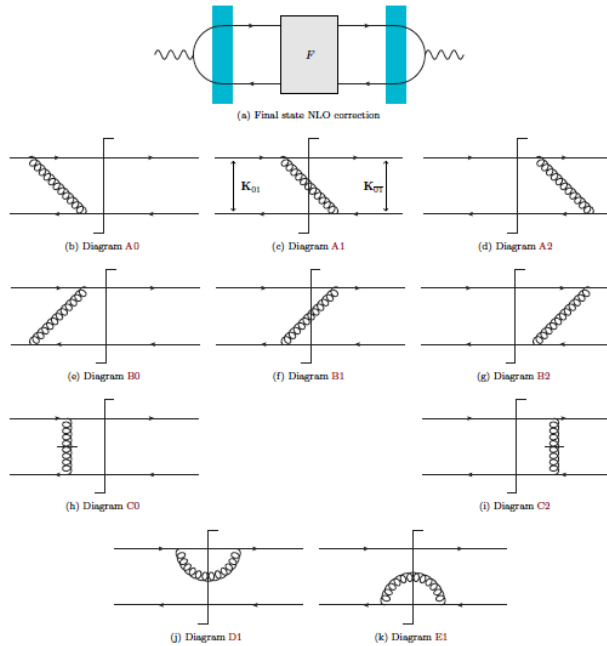
Full project duration: Nuclear PDFs with new LHC Run 2 data plus proton baseline uncertainties, Eur. Phys. J. C 82 (2022) 5, 413 (JYV-USC); EPPS21: new benchmark.



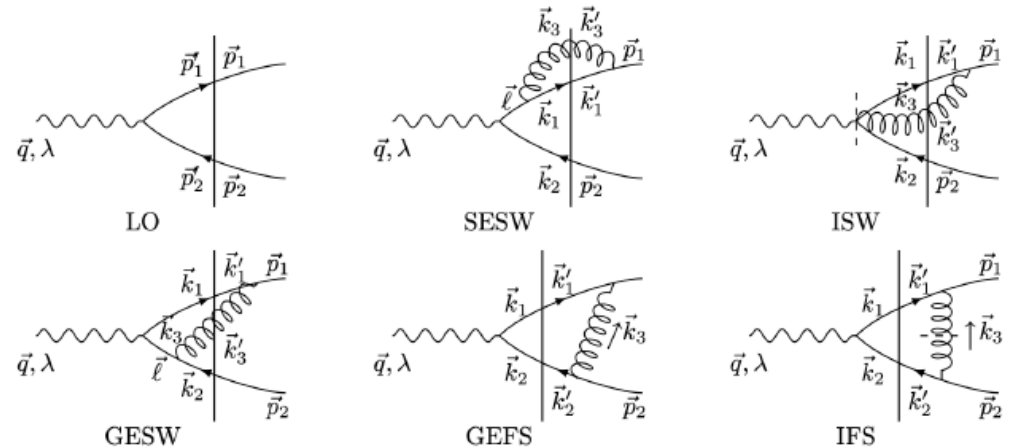
Highlights

Task 2: New NLO-based precision phenomenology in CGC and BFKL.

Last year: Diffractive deep inelastic scattering at NLO in the dipole picture, JHEP 05 (2024) 024 (JYV); complete calculation of inclusive diffraction in DIS at small x.



Full project duration: Dijet photoproduction at low x at next-to-leading order and its back-to-back limit, JHEP 10 (2022) 184 (CPhT-NCBJ): the Sudakov logarithms and the kinematic constraints to the small-x evolution are intimately linked.

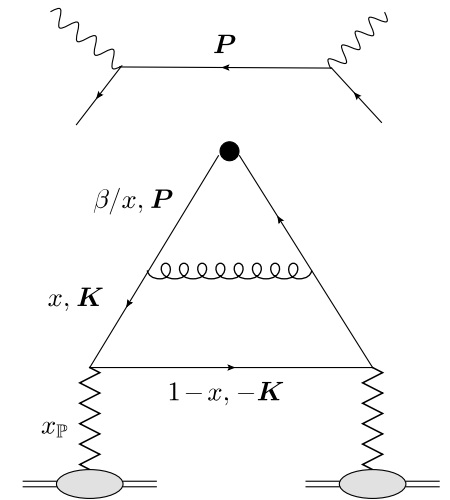
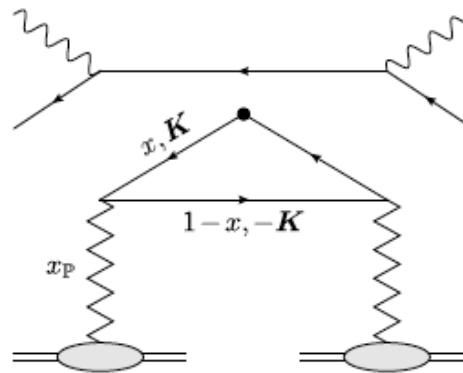
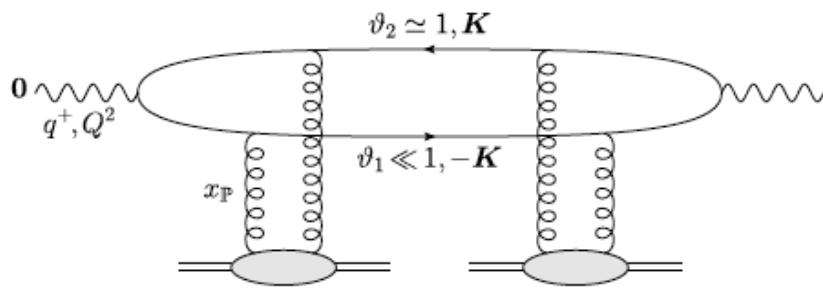


Highlights

Task 3: TMDs at small x (relation with JRA4 and JRA5)

Last year: Sudakov double logs in single-inclusive hadron production in DIS at small x from the Color Glass Condensate formalism, e-Print: 2406.08277 [hep-ph (NCBJ, CNRS): further evidence of the interplay between linear evolution of projectile and small x of target.

Full project duration: TMD factorisation for diffractive jets in photon-nucleus interactions 2402.14748 [hep-ph] (CNRS, ECT*); TMD factorization at small x established in exclusive dijet production in DIS.



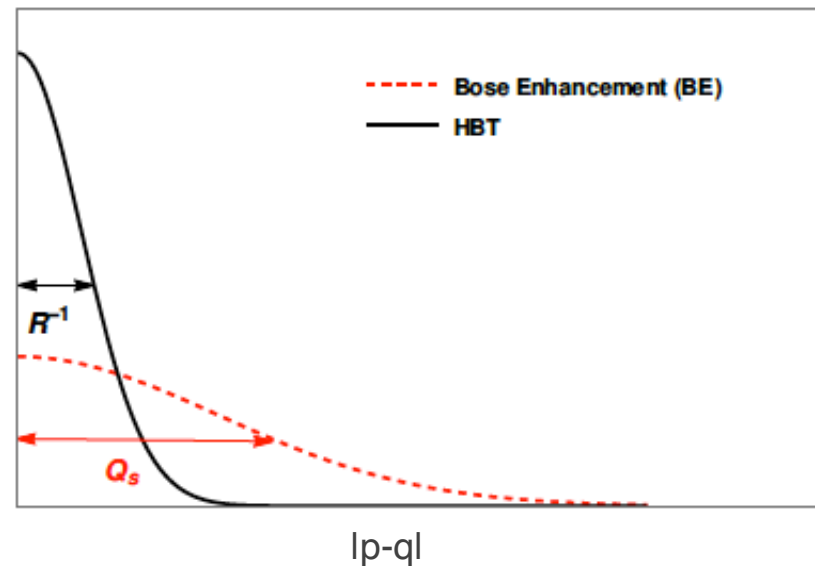
Highlights

Task 4: Multi-particle correlations & Thermalization.

Last year: Von Neumann entropy and Lindblad decoherence in the high energy limit of strong interactions, Phys. Rev. D 109 (2024) 5, 054015 (UAM-LIP); entropy and decoherence energy evolution from BFKL, including IR regulation.

$$C(\mathbf{p}, \mathbf{q}) = 1 + C(\mathbf{p}, \mathbf{q})|_{\text{BE}} + C(\mathbf{p}, \mathbf{q})|_{\text{HBT}}$$

Full project duration: Particle correlations from the initial state, Eur. Phys. J. A 56 (2020) 8, 215 (NCBJ-USC); full picture of azimuthal correlations coming from the initial state including non-eikonal corrections.



Deliverables and milestones

Deliverable Number ¹⁴	Deliverable Title	Lead beneficiary	Type ¹⁵	Dissemination level ¹⁶	Due Date (in months) ¹⁷
D13.1	NPDFs	23 - JYU	Report	Public	48
D13.2	Resummed NLO cross sections	1 - CNRS	Report	Public	36
D13.3	TMD factorization	37 - IFJ PAN	Report	Public	48
D13.4	Initial vs final state correlations	20 - USC	Report	Public	36

MS11	Reweightings of nPDFs including new LHC data	WP13	20 - USC	24	Publications and presentations in conferences, and software released and validated by a user group
MS12	Dipole cross section from resummed JMWLK evolution	WP13	20 - USC	24	Publications and presentations in conferences, and software released and validated by a user group
MS13	TMD factorization at small x for 3 final-state particles	WP13	20 - USC	24	Publications and presentations in conferences
MS14	Completion of the calculation of multi-particle correlations in the dilute limit of the CGC	WP13	20 - USC	24	Publications and presentations in conferences

Deliverable No.	Deliverable name	Lead Beneficiary	Nature	Dissemination level	Delivery month from Annex I	Delivered (yes/no)	Actual delivery month	Comments
D13.1	NPDFs	23-JYU	Report	PU	48	Yes	36	https://research.hip.fi/qcdtheory/nuclear-pdfs/
D13.2	Resummed NLO cross sections	1 - CNRS	Report	PU	36	yes	35	https://doi.org/10.5281/zenodo.4229269 , 2204.11650 [hep-ph]
D13.3	TMD factorization	37 – IFJ PAN	Report	PU	48	yes	57	https://inspirehep.net/literature/2760756
D13.4	Initial vs. final state correlations	20 - USC	Report	PU	36	yes	26	Eur.Phys.J.C 81 (2021) 8, 760, e-Print: 2103.08485 [hep-ph]

Progress beyond



MS11	Reweightings of nPDFs including new LHC data	WP13	20 - USC	24	Publications and presentations in conferences, and software released and validated by a user group
MS12	Dipole cross section from resummed JIMWLK evolution	WP13	20 - USC	24	Publications and presentations in conferences, and software released and validated by a user group
MS13	TMD factorization at small x for 3 final-state particles	WP13	20 - USC	24	Publications and presentations in conferences
MS14	Completion of the calculation of multi-particle correlations in the dilute limit of the CGC	WP13	20 - USC	24	Publications and presentations in conferences

New nPDF set (EPPS21) including LHC data

Growing understanding of the interplay beyond linear and small- x evolution

TMD factorization at NLO and for a variety of processes with 2 particles in the final state

Increasing understanding of thermalisation in Glasma and at weak coupling in transport



Other aspects



Workshop/conference organisation:

- BEYOND-EIKONAL METHODS IN HIGH-ENERGY SCATTERING, ECT*, May 20th-24th 2024.
- DIFFRACTION AND GLUON SATURATION AT THE LHC AND THE EIC, ECT*, June 10th-14th 2024.

Postdoc: Florian Cougoulic will be at USC until end of August 2024.

Money spent (all travel money).

- USC 1852,88 EUR,
- JYV 2 900,13 EUR,
- ECT* 1173.14 EUR,
- Firenze 741.38 EUR,