Presentation of the Letter Of Intent for HORIZON-INFRA-2025-01-SERV-03

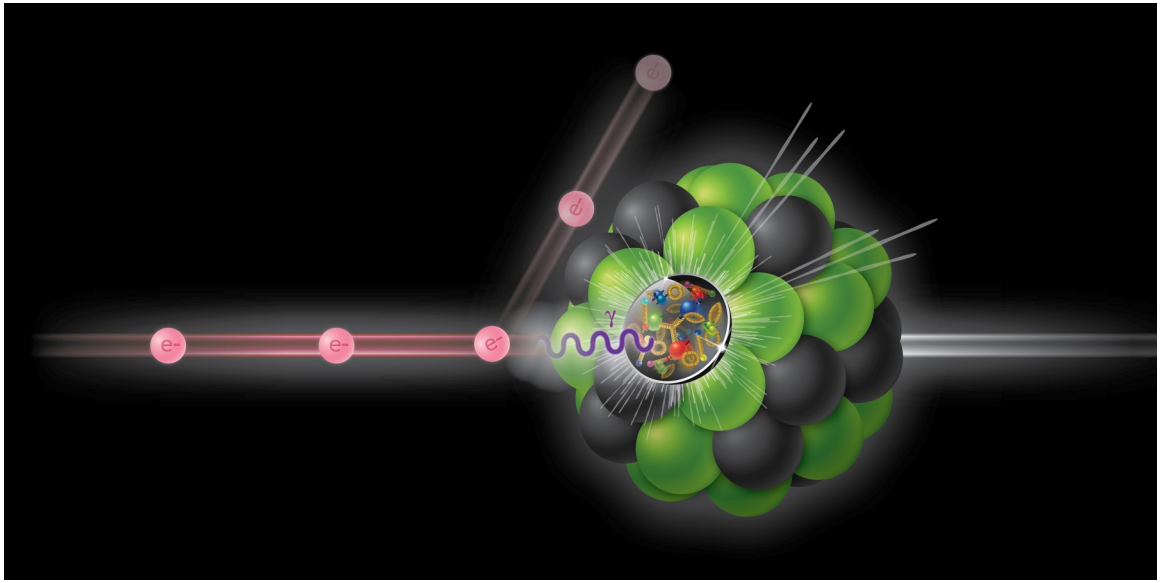
Small-x gluons in colliders

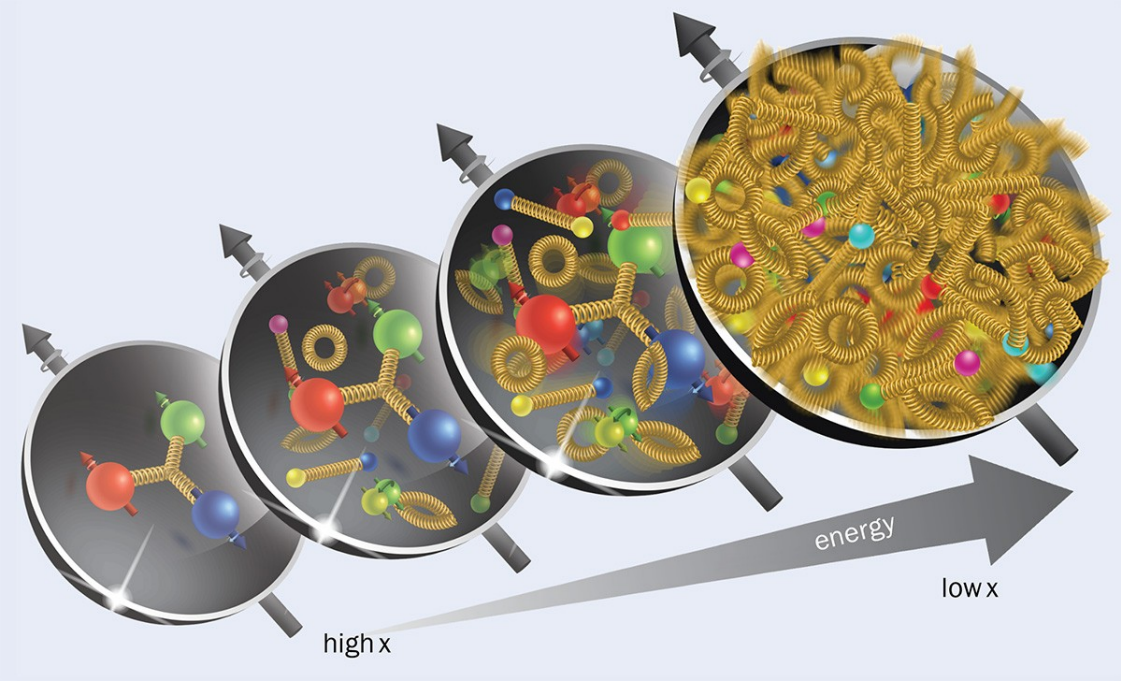
Project leaders:
Andreas van Hameren (IFJ PAN, Krakow, Poland)
Heikki Mäntysaari (University of Jyväskylä, Finland)

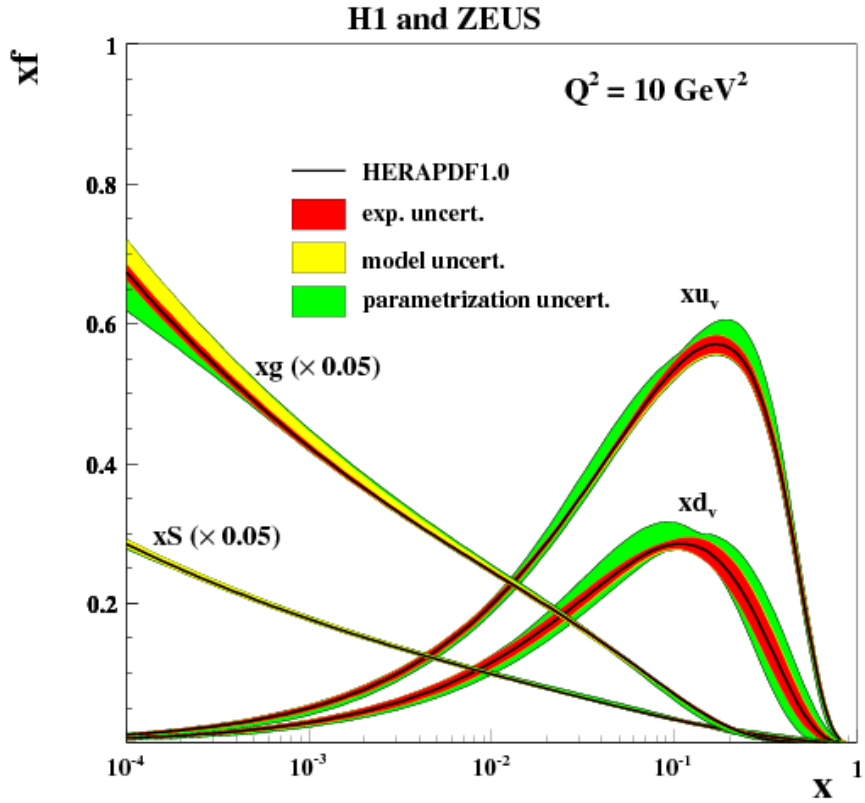
Presented by:
Cyrille Marquet (École polytechnique, Institut Polytechnique de Paris, France)

Quantum Chromodynamics (QCD) is the widely accepted fundamental theory describing strong interactions and has successfully accounted for a broad spectrum of phenomena.

A particularly intriguing domain arises in high-energy collisions involving at least one hadron or nucleus, when transverse momenta of a few GeV are probed.

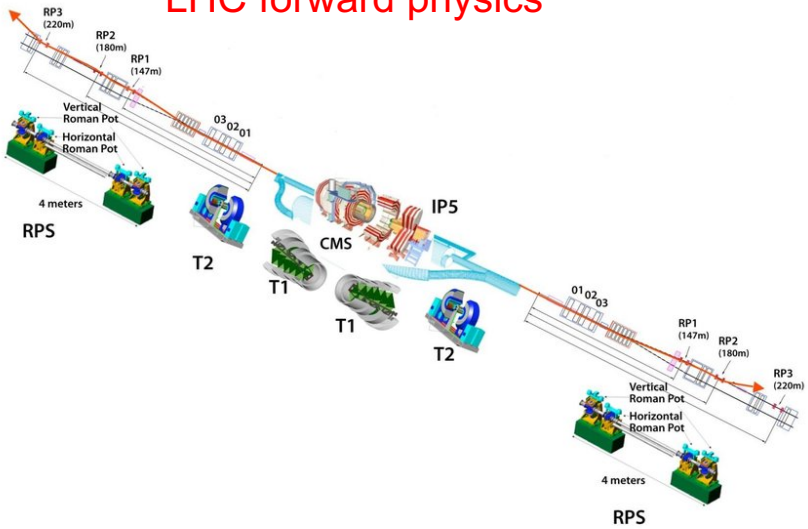




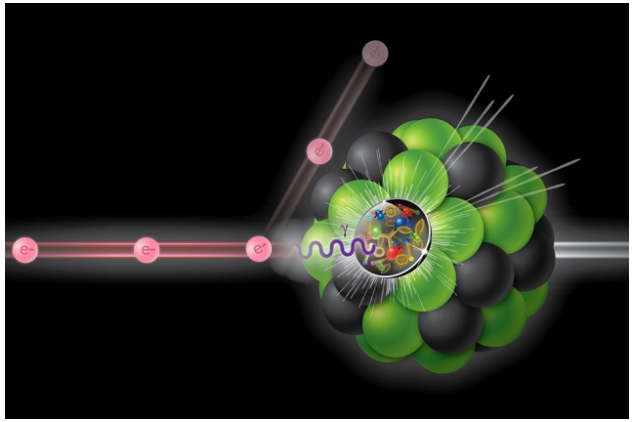


In this semi-hard regime, although perturbative methods remain applicable since the QCD coupling is weak, the parton densities grow significantly at small-x, giving rise to non-linear effects associated with strong gauge fields, ultimately leading to gluon saturation.

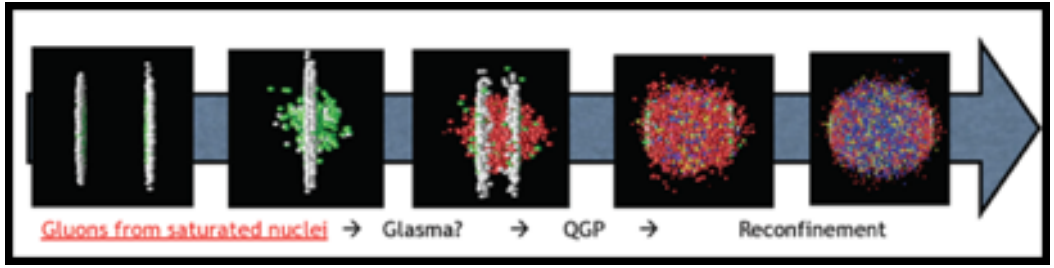
LHC forward physics

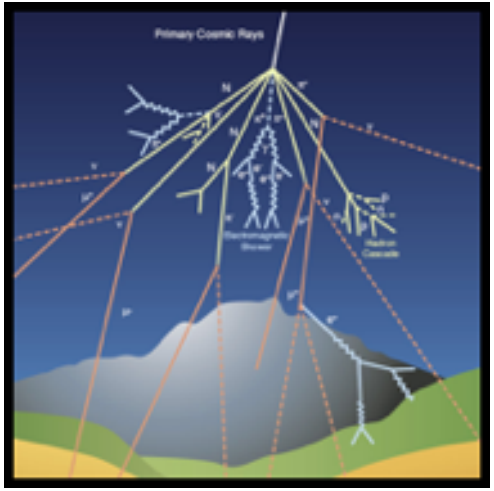


Electron Ion Collider (EIC)



initial stages of heavy-ion collisions

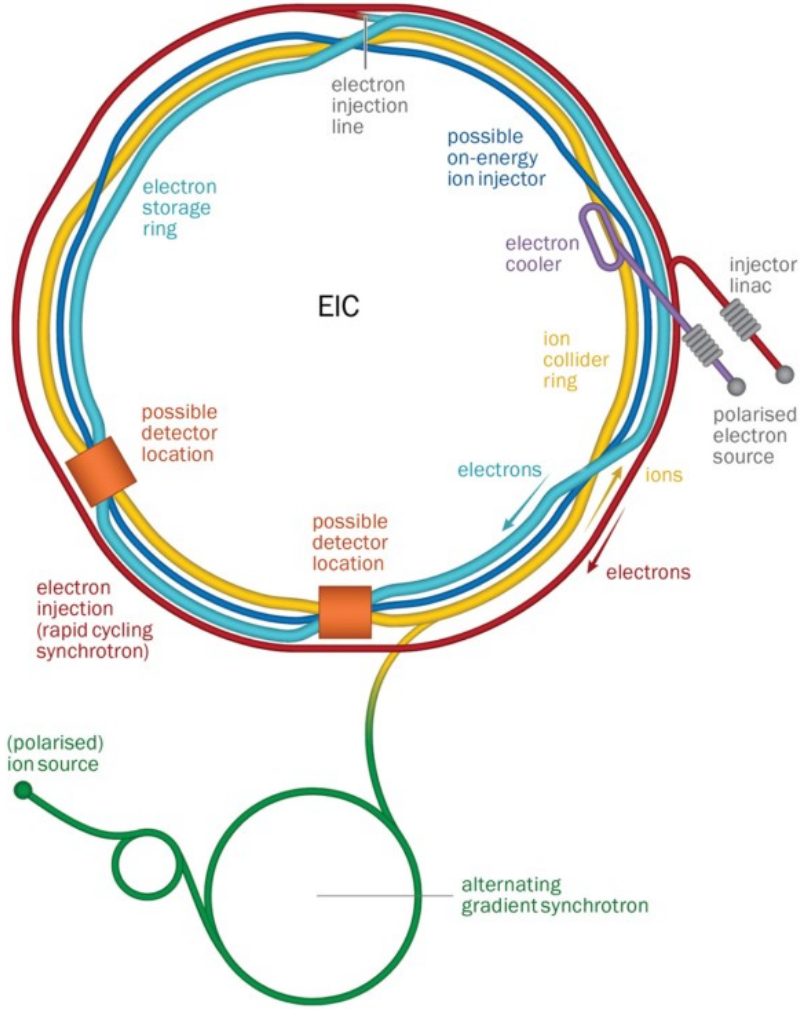




high-energy cosmic rays

The Color Glass Condensate (CGC) effective theory has proven to be a powerful framework for both qualitative and quantitative analysis of such semi-hard processes, as observed in past and current experiments at colliders such as DESY, RHIC, and the LHC.

Looking ahead, Deep Inelastic Scattering (DIS) of electrons off nuclei at the upcoming Electron-Ion Collider (EIC) and also off nuclei and protons at CERN via a possible upgrade to LheC will enter completely unexplored kinematic settings, and will provide more refined and ideal conditions for studying parton dynamics under gluon saturation.



Main objective: consolidate the NLO breakthrough

- the field of high-energy QCD has recently entered the NLO era: higher-order corrections of several kinds are being computed, we are only at the beginning

- next-to-leading order in the coupling: essential to prove factorization and assess robustness of predictions; in most cases, perturbation theory must be done in conjunction with all-order re-summations of various large logarithms

- next-to-eikonal corrections: energy suppressed but give access to spin observables

These must be addressed for less and less inclusive observables measured in experiments: exclusive and diffractive cross sections, correlations measurements, global event properties. The purpose is to reduce the dependence of CGC calculations on un-avoidable non-perturbative inputs.

Current state:

Over the last few years, there have been significant advancements in developing the theoretical machinery for exploring the domain of small-x gluons, which include

- derivations of NLO evolution equations,
- calculations of NLO impact factors for various processes,
- calculations of correlations in cross sections with two or more particles in the final state,
- proofs of TMD factorization in processes with disparate transverse scales and associated resummations of Sudakov effects,
- computations of next to eikonal corrections,
- determination of nuclear PDFs

PROGRESS MADE:

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

- Technical aspects in the CGC:
  - New observables for probing gluon saturation via diffractive 2+n jet production in eA collisions at the EIC, Phys. Rev. Lett. 128 (2022) 20, 202001 [2112.06353] (IPhT-ECT*)
  - NLO JIMWLK evolution with massive quarks, JHEP 07 (2022) 093 [2203.13695] (BGU)
  - Nuclei in the toy world: beyond the Pomeron in zero transverse dimensions, JHEP 05 (2022) 019 [2201.01551] (BGU)
  - NLO calculation of exclusive heavy vector meson production: 2204.14031 and 2104.02349 (JYV)
  - NLO calculation of exclusive light vector meson production: 2203.16911 (JYV)
  - Real corrections to diffractive structure functions at NLO: 2206.13161 (JYV-NCBJ-USC)
  - Finite volume effects in the McLerran–Venugopalan initial condition for the JIMWLK equation, Eur. Phys. J. C 82 (2022) 4, 369 [2111.07427] (Jagiellonian)
  - Hybrid k_T-factorization and impact factors at NLO [2205.09585] (JU-IFJ PAN)
  - Quark and scalar propagators at next-to-eikonal accuracy in the CGC through a dynamical background gluon field, Phys. Rev. D 105 (2022) 7, 7 [2109.01620] (NCBJ)
  - Photon LFWFs and DIS total cross section at NLO in the dipole picture with massive
  - Observables sensitive to high energy QCD dynamics: Jet-jet correlations: Phys. Scripta 97 (2022) 7, 074007 (UAM-LIP); Mueller-Navelet jets at the LHC: hunting data with azimuthal distributions, 2207.05015.
  - Calculation of NLO impact factors for semi-hard processes in the BFKL approach (proton-to-Higgs impact factor) (Cosenza-IJCLab-ECT*): Phys. Rev. D 105 (2022) 11 [2205.13429], 114056, JHEP 08 (2022) 092 [2205.02681].
  - Phenomenology of semi-hard processes at the LHC (inclusive backward/forward processes) and at HERA (inclusive single-forward processes) (Cosenza-IJCLab-ECT*): Bottom-flavored inclusive emissions in the variable-flavor number scheme: A high-energy analysis, Phys. Rev. D 104 (2021) 11, 114007 [2109.11875].
  - Systematic extraction of quarkonium light front wavefunctions from decay data [2111.07087] (JYV)
  - A parton branching with transverse momentum dependent splitting functions, Phys. Lett.B 833 (2022) 137276 [2205.15873] (IFJ PAN)
  - Transverse-momentum dependent factorisation for diffractive jet production in DIS at small Pomeron x: connecting JIMWLK and DGLAP evolutions from first principles, 2207.06268, JHEP to appear (IPhT-ECT*)
  - Dijet photoproduction at low x at next-to-leading order and its back-to-back limit, 2204.11650 (CPhT-NCBJ): the Sudakov logarithms and the kinematic constraints to the small-x evolution are intimately linked.
  - Pseudo and quasi gluon PDF in the BFKL approximation, JHEP 03 (2022) 064, 2111.12709 (Regensburg).
  - Rapidity evolution of TMDs with running coupling, Phys. Rev. D 106 (2022) 3, 034007, 2205.03119 (Regensburg).

Tasks:

- Continuation of the work towards the construction of a more complete set of theory tools. These include,
-- extending CGC calculations to more observables,
-- studying diffractive processes which by definition exhibit a rapidity gap whose presence in high energy collisions can be directly related to gluon saturation,
-- deriving precise impact factors for more processes,
-- understanding the size and the implications of Sudakov corrections,
-- developing a more accurate JIMWLK equation which is necessary for addressing certain multi-gluon amplitudes

Deliverables:

- Proper implementation of the aforementioned theoretical tools (which are either already available or will be available in due time) in flexible numerical algorithms made publicly available
- Creation of a new Virtual Access platform for NLO calculations at small x

Connection to Transnational Access infrastructures (TAs) and Virtual Access projects (VAs)

- The research objectives of the project are directly related to the physics program at CERN and BNL.

- Collaboration meetings to take place at ECT*.

- Researchers from the participating Institutions are expected to provide, apart from the theoretical and phenomenological input, codes which shall be publicly available.

BUDGET REQUEST

- 4 post-doctoral years for theory and software development: 50k€ x 4 years = 200k€

- travel funds for collaboration meetings (mainly at ECT*) and dissemination at conferences:
  2.5k€ x 4 year per institution = 140k€

- Total 340k€

Participating and partner institutions/representing researchers

- Autonomous University of Madrid, Spain (A. Sabio Vera)
- École Polytechnique, Université Paris-Saclay, France (C. Marquet)
- ECT*, Trento, Italy (D. Triantafyllopoulos)
- IPhT, CEA, Université Paris-Saclay, France (E. Iancu)
- Jagiellonian University, Poland (P. Korcyl)
- IFJPAN Krakow, Poland (A. van Hameren)
- AGH Universiy, Krakow, Poland (P. Kotko)
- Université Paris-Saclay, CNRS, IJCLab, 91405 Orsay, France (Samuel Wallon)
- National Centre for Nuclear Research, Warsaw, Poland (T. Altinoluk)
- Subatech, Nantes, France (P. Caucal)
- University of Bielefeld, Germany (S. Schlichting)
- University of Calabria, Italy (A. Papa)
- University of Florence, Italy (D. Colferai)
- University of Jyväskylä, Finland (H. Mäntysaari)
- University of Santiago de Compostela, Spain (N. Armesto)