Krzysztof Cichy, **Three-dimensional nucleon structure from lattice QCD**

Protons and neutrons, collectively called nucleons, are the building blocks of ordinary matter and are responsible for almost all of the mass of the visible Universe. For a long time, they were believed to be elementary particles, but experiments at the end of 1960s revealed that they are built out of smaller constituents, quarks and gluons (partons). Further research revealed that the motion of partons inside a nucleon is very complex and thus, nucleons have a rich internal structure. This structure is governed by the strong interaction, one of four fundamental interactions in nature, described within a theory called quantum chromodynamics (QCD). The strength of the strong interaction depends on the energy scale. In particular, at low energies, the QCD coupling becomes very large, implying that the method successful in the description of e.g. electromagnetism, perturbation theory, fails. This large-coupling regime of QCD has far-reaching physical and methodological consequences. It is responsible for the complex structure of the nucleon and also for difficulties in investigating this structure.

A comprehensive investigation of several aspects of nucleon's structure is the main aim of new cutting-edge experiments, such as the huge enterprise of building the Electron-Ion Collider (EIC) at the Brookhaven National Laboratory in the US. The expected experimental progress needs to be accompanied by theoretical developments, in particular calculations of observables describing nucleon's structure from first principles. Without the tool of perturbation theory, such calculations are enabled by the non-perturbative formulation of QCD on the lattice. In this approach, the spacetime continuum is discretized and thus, one can obtain well-defined expressions that can be evaluated numerically. The numerical problem is still very complicated, but it is accessible with highly optimized algorithms ran on world's most powerful supercomputers.

In the last few years, methods to access the partonic structure of the nucleon on the lattice emerged and started being heavily investigated. These calculations consist in evaluating several partonic distributions that quantify different aspects of the nucleon, including the positions and momenta of partons making it up. Such functions are called parton distribution functions (PDFs), generalized parton distributions (GPDs) and transverse-momentum-dependent PDFs (TMDs). PDFs are the simplest and only deal with the momentum dependence in the direction of nucleon's motion. GPDs and TMDs, in turn, probe the full three-dimensional structure. A full quantitative description requires the knowledge of all of them and is, currently, very limited.

Building upon our expertise accumulated over the last 8 years, we will significantly extend this knowledge, in particular about the three-dimensional aspects. The first few years of experience with the different methods of extracting these distributions provided several proofs of concept for these approaches and established their practical feasibility. However, there is a long way to get from the exploratory studies to the stage of precision calculations, with several non-trivial steps and challenges to overcome. These steps include theoretical progress, optimizing the computational methods, performing extensive supercomputer calculations and comprehensive analyses of the obtained data. The final outcome will be distributions with reliably quantified uncertainties, giving insight into different aspects of the inner workings of the nucleon. Combined with extensive experimental data expected from the new experiments, they will contribute to the understanding of nature at the very fundamental level. Apart from the importance of such fundamental understanding, the history of science has shown that basic research can lead to technological breakthroughs many years later.