Nucleon structure from lattice QCD with twisted mass fermions

Project summary for the general public – Dr. Krzysztof Cichy

The scientific problem aimed to be solved in the proposed project concerns the fundamental properties of protons and neutrons (collectively called nucleons), particles that make up most of the mass of the visible Universe. The interaction of quarks, the elementary particles found in nucleons, via gluon exchange, is described by the theory of Quantum Chromodynamics (QCD), proposed and developed in the 1960s and 70s. The QCD coupling constant, which describes the strength of the quark-gluon and gluon-gluon interactions, depends on the energy scale or, equivalently, on the distance between particles. At high energies, or at small distances, of the order of 20 GeV (0.01 fm), the coupling constant is small and the interactions can be described by QCD perturbation theory (PT), similarly to the prototype quantum field theory – the extremely successful quantum theory of electromagnetism, Quantum Electrodynamics (QED). On the other hand, at low energies (large distances), of the order of 200 MeV (1 fm), the QCD coupling becomes large and perturbative methods fail. The existence of this regime of QCD leads to the name of strong interactions. Although it is possible to model this regime phenomenologically, the only known method to yield quantitative predictions from first principles, is the formulation of the theory on an Euclidean spacetime grid (the lattice) and evaluation of the relevant path integrals numerically, using Monte Carlo algorithms implemented for world's largest supercomputers. This approach is called Lattice QCD.

The main objective of the research project is to achieve better theoretical understanding of the internal structure of the nucleon, using numerical methods of Lattice QCD with twisted mass fermions. The basic objects that express our knowledge of hadron structure are Parton Distribution Functions (PDFs). They are inherently non-perturbative objects and hence their quantitative computation can, in principle, be done on the lattice. However, their definition, on the so-called light-cone, makes it impossible to use standard lattice techniques which require going to non-zero spatial distances. A way out was proposed by Ji in 2013. The method is to compute slightly different objects, the so-called quasi-PDFs that can be matched to the desired light-cone PDFs.

In our preliminary research, we have shown the computational feasibility of this approach. Our current aim, the main aim of this project, is to compute quark PDFs using Ji's method, with all sources of systematic effects taken into account. These effects include the non-zero lattice spacing, the finiteness of the lattice spacetime volume and the effects from simulating with greater than physical masses of the up and down quarks (which reduces computational cost). The way to investigate such effects is to perform simulations with different lattice spacings, volumes and quark masses, which is an important part of this research project. In particular, we will simulate with physical light quark masses, something that became possible only in the very last years due to advances in supercomputers and algorithmic improvements. All these steps will make the extracted PDFs directly comparable to experiment. Moreover, the importance of PDFs is that they enter into theoretical predictions for scattering experiments at the Large Hadron Collider (LHC) and hence, our computation may lead to a reduction of uncertainties in such predictions. We will also test the feasibility of extending such approach to other kinds of distribution functions, describing other aspects of nucleon structure. These will include, for example, PDFs for the gluons. Their knowledge is important e.g. for theoretical predictions in searches for physics beyond the standard model, which are one of the most important aims of experiments at the LHC.

The project is embedded in an on-going effort of the European Twisted Mass Collaboration (ETMC) to investigate different aspects of the strong interactions from first principles. The hadron structure is one of the most important areas of research, since the results can influence the understanding of nature at the very fundamental level and, moreover, can be relevant for phenomenology and experiment. As the history of science has shown, basic research, such as will be carried out in this project, can lead to technological breakthroughs many years later. Lattice QCD, with its large required computer resources, was actually among the branches of science that influenced most the development of supercomputers and further stimulation of this kind is also foreseen in the future.