One of the most important questions in physics is the fundamental structure of matter in Nature. Since centuries researchers and thinkers posed the questions about basic ingredients of matter and their possible mutual interactions. Current understanding of elementary interactions is encompassed in the quantum theory called the Standard Model. The fundamental ingredients of matter are known as quarks and leptons. According to the Standard Model the interactions between matter particles are governed by another set of particles which are force carriers. There are three forces that are described by the Standard Model: electromagnetic, weak and strong force. Each of them has corresponding elementary particles which are the force carriers. Of those three, the most powerful is the strong force, which is the force between the quarks, responsible for keeping together nucleons in the nuclei. The elementary, quantum carriers of the strong force are particles called gluons. The fundamental interactions between the quarks and gluons are known and are given by the theory of Quantum Chromodynamics which is contained in the Standard Model. A peculiar feature of strong interactions is that quarks are never free. They are confined in the composite particles called hadrons. There are many unknowns in the present understanding of the dynamics of the strong interactions and the phenomenon of confinement.

Current theoretical tools allow to compute a limited subset of processes with some simplifying assumptions. From experiments and theory, we know that with ever increasing collision energy of two hadrons like protons, the number of particles which are produced is increased dramatically. That can be traced back to the increase with energy the number of quarks and gluons that are inside the colliding protons. This phenomenon is related to the fundamental property of the gluons which tend to split into the daughter gluons. This splitting process is enhanced at high energy, and thus leads to the proliferation of gluons. Thus, current theoretical and phenomenological tools need to be modified, or new approaches invented, in order to be able to properly describe the processes occurring in the presence of such complicated multi-body system. The objective of the presented project is the development of theoretical tools which are more accurate in the regime
high energy.

The project consists of four major complementary task, each of them addresses this problem from a different angle. In the first part of the project, specific processes will be analyzed in detail which are particularly sensitive to the gluon and quark dynamics, especially to the transverse motion of these particles. For example, it is proposed to investigate a process in which a spray (jet) of particles is produced, and simultaneously another heavy particle is produced in a collision of two protons. By inspecting the angle between these two objects one can deduce an important information about the internal momenta of the elementary particles which participate in the collision.

The second taks is to analyze the processes which are particularly sensitive to the large gluon density, which may be formed in the high energy collisions. As mentioned above, the gluons at high energy undergo splitting which is enhanced in this regime. An important question then arises, whether this process can continue with increasing collision energies without the limitation. There are strong indications from the theory that there should exists some self-regulating mechanism which is based on the converse process to splitting, namely the recombination of the gluons. This phenomenon is known as the gluon saturation. If in addition, one of the participating initial particles in the collision is the nucleus, then the gluon saturation is enhanced. The objective is to develop a suitable theoretical formalism which allows to include the gluon saturation to describe selected processes in the proton collisions with nuclei. In addition, this formalism will be applied to the processes where the cosmic ray proton interacts with the nucleus in the atmosphere and the heavy quark is produced. The quark then transforms into a hadron which then finally decays into a very energetic neutrino - a very light particle that can travel long distances undisturbed. Such process is relevant for the measurements of the neutrinos performed at the Antarctic observatory IceCube.

The third task of the project will be dedicated to the analysis of the so-called multi-parton interactions. When the energy of the collisions is very high and the corresponding system of gluons very dense, it is very likely that many gluons interact simultaneously in one encounter of the protons. This is called multi-parton interaction process. The objective is the develop theoretical formalism for the multi-parton scattering that includes more exact kinematics with transverse momentum of partons and satisfies certain important conservation laws.
Finally, in the fourth task the objective will be to develop efficient methods for the computation of the elementary processes which involve gluons and quarks with more exact kinematics and for a large number of particles. Traditionally, it is assumed, that in the computation of these elementary processes the incoming elementary particles which are involved in the collision travel along the initial direction of the parent particle. That is, it is assumed that their momenta have only single components aligned with the original hadron. This assumption however is rather crude and has to be relaxed, especially in the high energy limit, as the elementary particles like gluons can posses substantial components of the momenta which are perpendicular to the direction of the incident particles (e.g. protons).
In this part of the project, efficient and automated computation program will developed without of simplifying assumptions. It will be
more suitable for the application to the collisions of hadrons occurring at very high energies.

All the topics of the project are strongly motivated by the present rich experimental program performed at the Large Hadron Collider at CERN, the Relativistic Heavy Ion Collider at Brookhaven National Laboratory and the experiment at Jefferson Laboratory. The results of the calculations will be compared with the experimental data obtained at these experiments. Predictions for the machines which are planned for the future, like the Electron Ion Collider or Large Hadron-electron Collider, will also be made. The calculations will be also relevant to the measurements of the ultrahigh energy neutrino flux performed at the IceCube observatory.