General audience project summary

Probably everyone has heard about quarks – elementary particles that build protons and neutrons, which in turn form nuclei of all atoms that we are made of. The present project concerns Quantum Chromodynamics – the theory describing interaction of quarks and creation of various states of quark matter.

In principle, one could think of quarks as particles similar to electrons, if not for one thing: each quark has an additional 'tag' – a quantum number physicists call color (obviously this has nothing to do with colors we sense by our eyesight). Quarks can have different color, therefore there has to be a way to exchange it. Due to principles that lie in the foundations of modern physics, it is not possible to communicate at a distance without a carrier that travels at most with the speed of light. In particular, it is not possible to exchange a color between quarks without a particle called gluon – a carrier of color. Thus, quarks interact by an exchange of gluons, but gluons, having color themselves, can also interact with other gluons. The mathematical theory of such complicated interactions is the Quantum Chromodynamics. It is an incredibly rich theory with plenty of unsolved puzzles. For example, to this day it is not properly understood how it happens that colorful quarks and gluons bind together to build colorless protons and neutrons.

One of the greatest achievements in physics and modern technology are particle colliders. One of them is Large Hadron Collider (LHC), where scientists study head-on collisions of two protons at high energies. By looking at the products of such collisions we can learn about internal structure of protons in terms of quarks and gluons. Essential ingredients to compare theory and data are so-called scattering amplitudes – special complex functions describing all possible ways the colliding individual quarks and gluons can produce other particles, mostly other quarks and gluons. For example, we can have a scattering amplitude for two colliding gluons to produce a quark–anti-quark pair, or two gluons. We can also have amplitudes to produce many particles: gluons and quark-anti-quark pairs. The amplitudes can be represented by a set of so-called Feynman diagrams, each corresponding to a particular way the particles split or merge to produce the final states. The diagrams are really a convenient representation of certain mathematical expressions. The full amplitude is given by sum of all possible Feynman diagrams, corresponding to all possible ways the scattering process can be realized.

The problem of calculating scattering amplitudes is essential for understanding the structure of matter in terms of the most fundamental constituents, but is very difficult in general. Part of the difficulty lies in the fact that mathematical expressions corresponding to Feynman diagrams are very complicated, except for the simplest processes where quarks or gluons split into another quarks or gluons, without being reabsorbed. However, even for those simple processes the number of Feynman diagrams to be calculated can be huge: for example the scattering amplitude of two gluons to produce ten gluons consists of 5348843500 Feynman diagrams! Despite this, amazingly, expressions for some amplitudes end up with a simple form after summing all the diagrams. The simplest are so-called maximally helicity violating (MHV) amplitudes, where the name corresponds to a particular configuration of helicities of particles. This fact triggered intense activity towards finding alternative methods of calculating scattering amplitudes – without use of individual Feynman diagrams. It was found that one can recursively build scattering amplitudes for given number of particles from amplitudes with smaller number of particles.

It turns out that it is even possible to reformulate the whole Quantum Chromodynamics in such a way that the interactions are realized entirely through effective blocks directly related to the MHV scattering amplitudes. In that formulation, there are much fewer effective Feynman diagrams and the theory unravels interesting mathematical properties.

The goal of the project is to explore this novel formulation in hope that it will allow for further progress, not only in calculating scattering amplitudes, but also in better understanding the underlying theory of strong interactions.