Reg. No: 2015/19/P/ST2/03007; Principal Investigator: dr Sebastian Sapeta

The youngest known member of the family of elementary particles, the Higgs boson, corresponds to a field that pervades all space to give masses to other members of the family. When our Universe was very young, the vacuum was really empty and all particles appeared as massless. At some point in time, referred to as the electroweak symmetry breaking, the Higgs field populated the space and that gave other particles their masses. This mechanism has a macroscopic analogy, in which an object travels through a dense, transparent medium. Because the object needs to work its way through the medium, it moves slower compared to an object travelling in the vacuum. But to an external observer, who does not see the medium, this looks as if the object was heavier.

But couldn't the particles just have masses rather than acquiring them from the Higgs field? It turns out that some of them cannot and the underlying reason is: the symmetry. In order to understand why, we need to say a few words about our current theory of fundamental constituents of matter, called the Standard Model. The Standard Model describes all the interactions between elementary particles, except gravity, which is negligible for such small objects. These are: the electromagnetic, the weak and the strong interactions. The first two used to be just one, electroweak interaction in the early Universe, before the electroweak symmetry breaking.

The Standard Model is elegantly defined with a single mathematical object called the Lagrangian. Terms in the Lagrangian specify interactions and masses of particles. But the Lagrangian can be consistently written down only if it respects certain symmetries. And these symmetries are violated if one introduces mass terms for the particles.

Hence, the Standard Model can correctly predict all the content of the family of elementary particles and all the interactions between, yet, this is possible only if the particles are massless. However, we have an ample, experimental evidence that most particles are massive. Therefore, the inability to account for that in the Lagrangian of the Standard Model poses a serious problem.

Fortunately, it turns out that there is a way to satisfy the symmetries of the Lagrangian and, at the same time, make the particles massive. And this is to break the symmetry between the electromagnetic and the weak force at the level of the vacuum. Hence, the Lagrangian is still symmetric but the vacuum is not, and it is no longer empty - it is filled with the Higgs "medium". The above mechanism was proposed several decades ago but it was confirmed experimentally only recently, with the finding of the Higgs particle.

The Higgs boson was discovered in 2012 at the Large Hadron Collider (LHC), a 27 km long particle accelerator at CERN, near Geneva. Over the last years, most properties of Higgs, like the production rates and couplings to other particles, have been measured with precision around 10%. And, up to now, they all agree with theoretical predictions from the Standard Model.

But there is much more to come in the next years as the LHC has just restarted at a much higher energy. This will allow the experimentalists to increase the precision of the measurements by reducing the uncertainties to just a few percent. That has a chance to uncover new secrets about the Higgs boson. It may turn out, for example, that the Higgs particle is not exactly what is predicted by the Standard Model but it only resembles it. That would require an extension of the Standard Model to a more general theory. And testing of this possibility is the primary goal of the LHC.

However, we will know the answer to these questions only if we are able to compare the new, extremely precise measurements from the LHC with theoretical predictions of similar accuracy. And this is exactly what is missing, as the state-of-the-art theoretical results are in most cases less precise than what is expected to be delivered by the LHC in the coming years. Hence, the goal of this project is to move the accuracy of theoretical predictions for Higgs production to the next level.

Theoretical results are calculated as a series, with each next term being smaller than the previous one. The more terms are included, the more precise the result. In turns out that in the particular case of Higgs production, convergence of the series is slow. On one hand, this is good, because the higher terms significantly increase the production rate and that is why the experimentalists are able to register many Higgs particles. For theorists, however, this means that we need to calculate at least the first four terms in order to arrive at predictions which will be accurate enough to fully exploit the potential of the LHC measurements.

Calculation of the contribution from the fourth term in the series is the subject of this research project. And that will involve use of the most sophisticated concepts and methods of theoretical physics. It will also demand significant effort because of great complexity characteristic to the calculations at that high accuracy.

The endeavour is, however, worth taking, as, once the theoretical results of that precision are available, we will be much closer to knowing the answer to one of the most fundamental scientific questions of our times: is the Standard Model of particle physics all we need at the energies currently available at particle colliders, or perhaps, Nature has prepared some surprises for us, which are waiting to be discovered just behind the corner.