# Newsletter Interview

## 10th ANNIVERSARY OF THE DISCOVERY OF THE HIGGS BOSON

Interview *with Stefano Giagu, researcher at the INFN Roma division, coordinator of the ATLAS experiment Italian collaboration, and with Lucia Silvestris, researcher at the INFN Bari division, coordinator of the CMS experiment Italian collaboration.*

The discovery of the Higgs boson, whose 10th anniversary was celebrated last 4 July, undoubtedly represented a historic milestone for particle physics. An achievement in which INFN played a leading role and which, while it completed our Standard Model theory, also paved the way towards new physics. Representing the journey so far and the important future challenges ahead in seeking answers to the questions still unanswered, at CERN, the 4th July celebration of the tenth anniversary of the Higgs boson passes the baton to the start of the new physics program (Run 3) at the Large Hadron Collider (LHC) on 5th July with the first high-energy collisions. The resumption of scientific activities at the most powerful particle accelerator ever and its experiments follows an intense work period (Long Shutdown 2) lasting nearly three years, during which both the accelerator chain and the four large detectors underwent significant upgrades and maintenance. Work that will result in an increase in the number of proton collisions and consequently more statistics and detail in the measurements of already known particle properties, and in an increase in sensitivity with respect to possible clues to new physics. Among the collaborations engaged in the intense update activity are also ATLAS and CMS, which were protagonists ten years ago of the discovery of the Higgs boson, in which Italy played and continues to play a central role, thanks to INFN and its community, represented by Stefano Giagu, researcher at the INFN Rome Division, and Lucia Silvestris, researcher at the INFN Bari Division, respectively.

**What were the main steps of the process leading to the identification of the Higgs boson? What feelings prevailed in the ATLAS and CMS communities? And which were, if any, the surprises compared to what you expected to observe?**

[LS] The search for the Higgs boson was the primary goal of the LHC and its ATLAS and CMS experiments. CMS, since its conception, was designed and optimised to provide complete coverage across the entire possible mass spectrum of the Higgs boson. One of the first important steps was the start of the 7 TeV data acquisition at the end of March 2010, which led to the LHC, for the first time, providing the experiments with a useful amount of collisions to study the performance of the detectors. However, it was not until 2011 that the LHC began to provide data with such a high luminosity such as to enable ATLAS and CMS to probe processes with impact sections comparable with those of the Higgs boson production. The first results of the analyses that were beginning to be sensitive to the presence or absence of the boson, and the first combination of the various channels of the particle decay, were presented during the European

Physics Society conference in Grenoble in July 2011, which was followed by a joint presentation between the ATLAS and CMS collaborations in December of that year at CERN, at which we were already able to show the presence of an excess of events observed in the predicted mass region of the 120-127 GeV Higgs boson. To ascertain the origin of this excess, however, it was necessary to wait until early 2012, with the restart of LHC data acquisition at even higher energy and luminosity, which led to the detection of a very clear signal in one of the predicted decay channels, around the 126 GeV mass region. We thus arrived at 4th July 2012, when, in two simultaneous seminars held at CERN and in Melbourne, at the ICHEP conference, ATLAS and CMS spokespersons Fabiola Gianotti and Joseph Incandela presented graphs demonstrating how the CMS excess had become significant in combination with similar data measured by ATLAS. The discovery of the new particle was thus announced to the world, confirming in an almost surprising way the predictions of the Standard Model. An exceptional and unforgettable experience.

[SG] We often fail to realise and appreciate the long and complex process that leads to a major discovery such as the Higgs Boson and the 4th July 2012 announcement. A journey that required 10 years and the effort of thousands of people, including physicists, engineers, technicians, to build ATLAS, and all the other experiments, and of course the LHC itself, which is essential for the production of the Higgs boson in the proton-proton collisions that take place inside it. If the LHC had in fact failed to reach the maximum energy and achieve the number of interactions needed to consolidate the statistics, it would have been impossible to observe the particle. In parallel with the implementation of this very powerful accelerator, there was the equally complex activity of drawing, designing and building the two ATLAS and CMS experiments, which did not end with the commissioning of the apparatuses but continued with an ongoing study to understand their performance and responses in detail. This was an activity, lasting years, that was crucial in being able to detect a signal as rare as the Higgs boson in the multitude of events produced by the LHC. A task that involved close dialogue between experimental and theoretical physicists to try to understand what kind of Higgs boson the theory describes and in what signals it might manifest itself, because until a particle is discovered, even if predicted by theoretical models, it always represents new physics. Finally, the discovery has had and continues to have profound repercussions in the entire physics community, because the Higgs boson underpins the entire standard model and its study can therefore help to improve predictions or develop alternative models. Taking part in such a journey was an incredible experience and what was most surprising, at least from my point of view, was the fact that the discovery came sooner than we expected, showing that the LHC worked better than expected and that preliminary analyses of the possible signals in ATLAS and CMS were correct.

**What did the research activities of the two experiments focus on after 4th July 2012? And what other results have been achieved?**

[SG] After the discovery of the Higgs boson, the ATLAS activity obviously continued. We completed all of the second data-acquisition period, Run2, which ended in 2018, which increased the available statistics on the number of interactions tenfold. This because, although we observed a particle that was definitely the ideal candidate to occupy the Higgs boson box, it was necessary to build the ID card of this new particle of the Standard Model, i.e. study all its properties in detail, to confirm that described by the theory and to refute the various models that predicted Higgs bosons with different characteristics or even described multiple Higgs bosons. Measuring the properties of the Higgs boson was a very long but necessary process: we measured, for example, the spin of the particle, verifying that it is a scalar boson, as predicted by the Standard Model, we measured its mass with great accuracy, and all its possible couplings with every other known particle.

[LS] In addition to analysis activities directed toward top quark physics, flavour physics, direct search for new physics, and the study of heavy ion collisions, the activities related to the study of the Higgs boson continued unabated. After the discovery, the data collected was used to measure the properties of the Higgs boson in the best possible manner, because even small differences compared to the predictions could highlight new physics. Using data from 2011 and

2012, it was also concluded that the observed boson has behaviour that closely resembles that predicted by the standard model. However, not all the couplings were immediately highlighted, since the corresponding analyses were still limited by the available statistics. Additional channels were added, new analysis techniques and frameworks were developed to combine the results, and sensitive phase spaces continued to be investigated to show the presence of new resonances as predicted by theories beyond the standard model.

**LHC and its four large experiments have just started their third data acquisition period. Which were the most important interventions that the ATLAS and CMS detectors were subjected to and what will their next scientific programme focus on?**

[LS] The major upgrades on CMS carried out during the second Long Shutdown (LS2) involved many of the major components of the experiment, starting with the pixel-tracking detector, responsible for reconstructing the paths of high-energy charged particles and also the decay of very short-lived particles, in which the innermost layer was replaced, which will have to withstand the increased radiation associated with increased collisions inside the LHC. The activity also focused on the installation of three next-generation subsystems dedicated to measuring brightness and beam conditions, which are essential for real-time collision rate measurement in CMS, and new electronics in the central region of the hadronic calorimeter, consisting of new silicon photomultipliers (SiPMs), which have three times the photon detection efficiency and 200 times the gain of their predecessors. There were also many interventions in view of the upcoming LHC (High Luminosity) phase, which poses really unique challenges. Therefore, during LS2 we began the planned upgrade phase for muon detectors, installing new GEM (Gas Electron Multiplier) detectors and newly developed CSC (Cathode Strip Chamber) muon detectors dedicated to probing the forward regions of the muon system. Again within the scope of the preparation activities for the high luminosity phase, the tube in which the beams circulate was also replaced with a new one, compatible with the future upgrade of the tracking detector, improving the vacuum and reducing activation.

[SG] During LS2, ATLAS underwent major interventions, upgrading or replacing almost all of its detection components. In fact, new muon forward detectors were included, the luminosity meter was rebuilt, and the electromagnetic calorimeters, hadronic calorimeter, muon spectrometer, and the whole so-called trigger system, which allows real-time selection of events, were upgraded. Not forgetting the experiment's software, which will enable improved data processing. Thanks to these interventions, which will increase measurement precision, during Run 3 one of the goals pursued will be to continue the study of how the Higgs boson couples with other particles and will also continue in the high-luminosity phase of the LHC. A time horizon that will, however, not be sufficient to explore this aspect in detail, since the most interesting information on which upcoming physics programmes will focus is how the Higgs boson interacts with itself, i.e. its own self-couplings, which have a very small probability of occurrence, and for which we will need machines capable of very high intensities. Nevertheless, we hope to provide the first answers with the LHC's high luminosity period. Simultaneously with these kinds of investigations, in Run 3, just as was done in Run 2, ATLAS, together with CMS, will also look at other kinds of physics in an attempt to identify effects that can be traced back to phenomena or particles not included in the standard model, in order to be able to answer outstanding problems, such as those involving the nature of dark matter.