INTRODUCTION

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The Final Meeting of the HiggsTools Initial Training Network took place in Durham from September 11–15, 2017. This meeting was the culmination of the EU funded HiggsTools project (ITN 2012 HiggsTools 316704) which ran from January 1, 2014 to December 30, 2017. HiggsTools focused on the investigation of electroweak symmetry breaking. This question lies at the very frontier of knowledge of theoretical particle physics and phenomenology and, in fact, the primary goal of the Large Hadron Collider (LHC) at CERN is to unveil the mechanism of electroweak symmetry breaking.

Prior to the beginning of the HiggsTools network, the LHC discovered a resonance which was a candidate for the Higgs boson of the Standard Model (SM). The spin-0 nature of the resonance was well-established and there was no direct evidence for new physics; furthermore, the available studies on the couplings of the resonance showed compatibility with the Higgs boson of the SM. The experimental discovery of the particle that had been theoretically predicted to exist in 1964, was recognised by the joint award of the Nobel Prize in Physics in 2013 to Francois Englert and Peter Higgs. The Nobel citation was "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which

recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

This was, therefore, a perfect time to initiate a network whose main goal was to provide excellent initial training to young researchers in the field of high-energy particle physics, equipping them with knowledge and skills to contribute to study the fundamental nature of the Universe at a time when new discoveries were eagerly expected, and when the new Standard Model of Particle Physics was about to be forged.

The HiggsTools network consists of 10 Full Partners and 10 Associated Partners from European Universities and Research Institutes, one International Organisation (CERN), and 6 Associated Partners from the private sector. A key element of HiggsTools is the synergy obtained through the collaboration of experimentalists and theorists in the best interpretation of the data. Our network included many of the leading experimentalists working on the identification of the signals of electroweak symmetry breaking within the ATLAS and CMS experiments as well as many of the leading theoretical physicists in Europe who are developing the necessary tools and calculations to explore the new frontier in particle physics. HiggsTools could, therefore, maximise the impact of the LHC by confronting theoretical predictions with observations and using experimental data to build the new Standard Model. In order to effectively operate on the interface between experiment and theory, we were very concerned to emphasize our (network) view on re-inventing a common language (*lingua franca*) between the two communities. The work of the experimentalist and the theorist is very different. They do not naturally speak the same language and their very experience of the world is different. Building up the communication between the two communities naturally followed on from the excellent work started in the Higgs Cross Section Working Group that many in the network contributed to, and in some sense represented the ethos of the network as a whole. The most perfect manifestation of this approach is theoretically well-motivated experimental measurements, accompanied by experimentally relevant theoretical calculations.

After the kick-off meeting at the University College London in April 2014, recruitment of Early Stage Researchers (ESRs) started in earnest. Altogether, all of the 500 person/months funded by the network were filled with 23 recruitments to the 21 ESR positions[1] with 19 in post by Autumn 2014. The gender split of those appointed was 74% male (17/23) and 26% female (6/23).

[1] Two resigned their positions and left for posts in the private sector.

The first young researchers meeting took place in February 2015 at Lumley Castle on the outskirts of Durham City. Here, the ESRs met for the first time as a group to work on collaborative teamwork and communication.

The first annual meeting was in Freiburg in April 2015. As part of their training, each ESR was asked to give a first public presentation about their research project. The standard was extremely high and each of the ESRs successfully demonstrated their ability to make scientific presentations. As for all of the annual meetings, representatives of the private sector partners — in this case Maplesoft and Wolfram Research — attended the meeting and gave presentations on the opportunities for secondments. A further highlight was the public lecture by Professor Rolf Heuer (now former Director General of CERN) entitled *Das Higgs-Teilchen und das frühe Universum.*

After an almost two-year shutdown and several months re-commissioning, the LHC restarted on June 3, 2015 at the unprecedented energy of 13 TeV, almost double the collision energy of Run 1. The increased energy in Run 2 increased the chance of creating Higgs bosons in collisions, which meant more opportunities to measure the properties of the Higgs boson precisely and to probe its rarer decays, and hopefully to detect small, subtle differences between what the boson looks like in experiments, and what the Standard Model predicts.

For our ESRs, scientific training continued unabated at the first Summer School in the Aosta Valley in July 2015. The school covered all of the main topics in Higgs physics with lectures from both theorists and experimentalists, intensively focusing on Higgs physics. The second young researchers meeting in Brussels in October initiated working groups on Beyond the Standard Model, Top Quark Physics and Vector Boson Scattering.

As well as producing more Higgs bosons, the data taken at 13 TeV in 2015 provided some real excitement. Over the course of 2015, a sample with an integrated luminosity of about 4 fb^{-1} was collected. In December, the first analyses were presented, and showed intriguing glimpses of a possible new resonance in the two-photon channel. It looked very much like the early signs of the Higgs boson, but at a much higher invariant mass of 750 GeV. The significance of the signal was very low, but more data was on the way, and if it were really a genuine signal, the textbooks would have to be rewritten.

By the time of the second annual meeting in April 2016, everyone was still excited and several talks proposed models to explain the putative diphoton resonance. The more conservative amongst us pointed to the rather experimental large uncertainties, and the shortcomings of many of the proposed models. It was an excellent example to practice our skills of critical thinking and creativity.

As part of their continued training, each ESR gave a presentation about their ongoing research project. Maplesoft, Shell R&D and RISC Software GmbH represented the private sector, and the public lecture was given by Professor Juan Fuster Verdu (IFIC Valencia) *La fisica del boson de Higgs y los nuevos retos que plantea: cientificos y tecnologicos.*

The second HiggsTools Summer School took place in Zuoz in August 2016 and gave the ESRs a broader training that covered all aspects of high-energy physics including non-LHC topics like axions and cosmology. Around this time, an update of the diphoton analysis was presented at the 38^{th} International Conference on High Energy Physics in Chicago. Unfortunately, the preliminary analyses that included the early 2016 data in an increased sample of about 18 fb^{-1} (*i.e.* about 4 times larger than the 2015 data sample alone) showed that the excess reported in December was almost certainly a statistical fluctuation. Nevertheless, this was a very exciting time!

In October 2016, the third young researcher meeting in Berlin served two purposes with training in scientific writing and workshops on the common project we started at the second young researchers meeting. The aim was to turn this work into a scientific article — the HiggsTools Handbook. More about this later!

Throughout 2016, the LHC operated at 13 TeV according to plan, and by the end of 2016, had accumulated a total integrated luminosity of around 40 fb^{-1}.

The third annual meeting took place in Torino in May 2017. Apart from reviewing the state of the art, the main focus was on the common working project initiated at the earlier young researchers meetings and each of the ESRs gave presentations on their contribution to the project. Professor Alberto Lerda (INFN Torino) gave a public lecture titled *What next? A brief review of open problems in theoretical high energy physics.*

The young editors of school which took place immediately after the Annual Meeting focussed on completing the report. We operated informal writing workshops with senior physicists of the network and guest scientist Dr. Andre David (CERN) to work with the ESRs on scientific writing and specifically to convert their work into a publishable report discussing various aspects of state-of-the-art Higgs physics at the LHC in a pedagogic manner. The report involved fifteen of the ESRs and is now published by the *Journal of Physics G* [1].

The first part of the Report is devoted to a description of phenomenological searches for new physics at the LHC. As the experimental measurements become more and more precise, there is a pressing need for a consistent framework in which deviations from the Standard Model predictions can be computed precisely. We critically reviewed the use of the κ-framework, fiducial and simplified template cross sections, effective field theories, pseudo-observables and phenomenological Lagrangians.

In the second part of the Report, we proposed ϕ^*_η as a new and complementary observable for studying Higgs boson production at large transverse momentum in the case where the Higgs boson decays to two photons. We made a detailed study of the phenomenology of the ϕ^*_η variable, contrasting the behaviour with the Higgs boson transverse momentum distribution using a variety of theoretical tools including event generators and fixed order perturbative computations.

The final meeting was held at the University of Durham in September 2017. Each of the ESRs gave presentations on the work they had been doing during the project, many of which are published in this volume[2]. The final talk by Professor J. van der Bij presented the vision for the future of particle physics and is reproduced here.

Professor Frank Krauss (IPPP Durham) gave a typically challenging outreach talk titled *From Complexity to Simplicity and Back* aimed at researchers in other fields. Approximately 80 physicists of all levels attended this excellent talk, which generated a lot of discussion both directly after the meeting and in the following days.

By the end of 2017, the LHC had more than doubled the amount of data taken at 13 TeV and high-energy operations will continue again in 2018 (completing Run 2). The ESRs of our network have played a key role in developing the theoretical tools that enable the properties of the Higgs boson to be studied precisely. As the full data set is accumulated, many of our ESRs will continue to study the rarer decays of the Higgs boson and possibly detect small, subtle differences between what the boson looks like in experiments, and what the Standard Model predicts.

It is interesting to reflect on what the network achieved as a whole. The ESRs we recruited worked on both theoretical and experimental projects. Several of the ESRs are now full members of CMS (Haddad, Pata) or ATLAS (Gutierrez, Gonella, Megy, Wolf, Bahmani, Melini). Over the course of the network, the need for dialogue between the two communities was continuously emphasised, through common working groups, and particularly through the production of the HiggsTools Handbook. We deliberately focussed on a single cohort to build up the ability to communicate freely between theorists and experimentalists, and we believe that the bonds established between the ESRs and the senior scientists are extremely positive and will be one of the long-lasting effects of HiggsTools.

Twelve of the ESRs have now completed their Ph.D., two of them are working in the private sector, one is taking a well-earned vacation, and nine are continuing their research in particle physics. The remaining ESRs are still working in the network and will complete their Ph.Ds in 2018. Twelve

[2] Some of the proceedings for members of ATLAS and CMS were not approved by the collaborations.

of the ESRs undertook secondments with our private sector partners, Shell R&D, RISC, Maplesoft, Wolfram Research and, a late addition, Lingvist in Estonia. In the large majority of cases, these were viewed as very rewarding experiences which opened the eyes of the ESRs to the opportunities in the private sector.

Scientifically, over the course of the project, our focus gradually shifted from the final analysis of data from Run 1, to preparing for the restart at higher energy in 2015 and then on to data-taking and analysis of Run 2 data. During this period, something almost unique happened as the paradigm shifted from testing the SM as a function of the Higgs boson mass to searching for SM deviations. There were extensive discussions about the relative merits of top–down or ultraviolet complete theories compared to bottom–up models based on effective theories. It has been our job to guide the ESRs through this exceptional period in high-energy physics, a phase which was particularly open to competition between the different theoretical ideas and often rational disagreements about their relative merits. Much of this work was discussed at the final meeting and that is the topic of these proceedings.

REFERENCES

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