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Highlights of the LHC run 1 / Résultats marquants de la première période d'exploitation du GCH

Foreword

The Large Hadron Collider (LHC) at CERN has opened in the last years a new territory for particle physics exploration. By colliding protons at high energy, it has allowed us to investigate an energy regime about one order of magnitude larger than previous colliders, and correspondingly, distance scales about ten times smaller.

Many of the open questions about the elementary constituents of the matter and their interactions are investigated using the large amount of data collected at the LHC during the years 2010 to 2012. One fundamental problem that has seen spectacular progress during this period is the origin of the mass of elementary particles and of the breaking of the symmetry between the electromagnetic and the weak interactions.

The Standard Model of particle physics emerged in the 1960s and 1970s. It has been supported by several generations of high-precision experiments, like the ones that took place at LEP, the e^+e^- collider at CERN that operated between 1989 and 2000, where many precision tests have been done, which the Standard Model has successfully passed. In the Standard Model, the breaking of the symmetry between the electromagnetic and weak interactions is realized by the Brout–Englert–Higgs mechanism, which is a spontaneous symmetry breaking applied to gauge interactions. This mechanism predicts the existence of one scalar neutral particle, the Higgs boson, which had not been seen until the beginning of LHC operation. The discovery of a scalar particle consistent with this Standard Model Higgs boson at the LHC in 2012 has received a considerable interest and is certainly one of the main results of this first phase of operation of the LHC and of its detectors.

The observation of this particle, even if it completes the Standard Model, does raise many new questions. This is the only known elementary scalar (i.e. without intrinsic angular momentum) particle. Are there other scalar particles at higher masses? Unlike fermion particles, the mass of scalar particles is not protected by any symmetry. What mechanism gives to this scalar particle the mass that is observed and not a mass many orders of magnitude higher, which would be more natural? Is there any fundamental reason why the coupling of the top quark (which is the heaviest of the six known quarks, the two lightest ones being the constituents of the protons and neutrons) to the Higgs boson is close to unity? Answers to these questions motivate theories that go beyond the Standard Model. New physics is also expected to explain dark matter in the universe. All these theories often predict new particles at a mass scale accessible at the LHC. No such particles have been found yet, and thus the data from the first phase of the LHC have already constrained these theories.

The discovery of the Higgs boson should also not overshadow the very large physics program accessible at the LHC, covering a wide range of topics. Many precision measurements of Standard Model particles are accessible. The LHC can also be seen as a "top quark factory". These measurements, as well as the detailed studies of the Higgs boson, are also possible thanks to the spectacular progress achieved in the last years in theoretical predictions of Standard Model processes.

Not only can the LHC explore the high energy frontier, but it also explores the intensity frontier by allowing one to perform precise measurements of properties of hadrons containing b and c quarks (the heavy quarks lighter than the top quark) and to study the matter–antimatter symmetry breaking in these systems. Such precision studies open a window to indirect effects of physics at significantly higher energy scale that would enter as virtual effects in heavy flavor physics.

Finally, the LHC is not only a proton–proton collider, but it can also accelerate and collide heavy nuclei, like lead. These lead–lead collisions at high energy create a very hot and dense nuclear media, in which nuclear matter is expected to be in the de-confined state of the quark–gluon plasma instead of the ordinary nucleus. These collisions are also recreating a state of matter close to what existed shortly after the big-bang.

As the start of the second phase of exploitation of the LHC, which will produce collisions at higher energy and at a higher rate, is approaching, it is timely to review the wealth of results produced from the first phase.

The first paper in this dossier is devoted to the accelerator itself, and the challenges posed by its operation, related to the high energy and high intensity circulating beams. The second paper explains how detectors have been designed, to cope with the challenges given by the accelerator. These detectors have benefited from a strong research and development program that started more than 20 years before the first collisions at the LHC. The third paper describes the Standard Model computations of processes appearing in high-energy proton–proton collisions and how they are tested experimentally. The fourth paper is devoted to the discovery of a Higgs boson and the measurement of its properties using the full dataset

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collected during the first operation phase of the LHC. This is followed by a paper discussing in details the theoretical implications of the discovery of a Higgs boson. Direct search for physics beyond the Standard Model and the implications of the LHC results is a topic of the next paper. A paper is devoted to top quark physics, where the properties of this very heavy quark (the heaviest known elementary particle, about 175 times the proton mass) are studied at the LHC, exploiting the large rate at which this quark is produced at the LHC (about 600 top–antitop quark pairs per hour at the maximum collision rate in 2012). The picture of the physics programme of the LHC is completed by a paper discussing heavy flavor results (which has also seen spectacular measurements like the observations of Bs mesons decaying to muon pairs, a very rare process corresponding to one in 300 millions Bs decays) and by a paper describing the large amount of data collected to characterize collisions between heavy ions at high energy.

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