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

Highlights on searches for supersymmetry and exotic models

Focus sur les recherches sur la supersymétrie et les modèles exotiques

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ABSTRACT

In this review, we present highlight results of the first three years of the LHC running on searches for new physics beyond the Standard Model. The excellent performance of the LHC machine and detectors has provided a large, high-quality dataset, mainly proton–proton interactions at a centre of mass energy of 7 TeV (collected in 2010 and 2011) and 8 TeV (collected in 2012). This allowed the experiments to test the Standard Model at the highest available energy and to search for new phenomena in a considerably enlarged phase space compared to previous colliders.

RÉSUMÉ

Dans cette revue, nous présentons les résultats les plus marquants des trois premières années de fonctionnement du GCH sur la recherche de nouvelle physique au-delà du Modèle standard. L'excellente performance du collisionneur GCH et des détecteurs a fourni une grande quantité de données, principalement des interactions proton–proton à une énergie dans le centre de masse de 7 TeV (récoltées en 2010 et 2011) et 8 TeV (récoltées en 2012). Cela a permis aux expériences de tester le Modèle Standard aux plus hautes énergies accessibles actuellement et de rechercher des signes de nouvelle physique dans un espace de phase considérablement élargi par rapport aux collisionneurs précédents.

1. Introduction

From its very conception, the Large Hadron Collider (LHC) was designed to be a discovery machine. Its two main goals were to elucidate the electroweak symmetry-breaking mechanism and to search for new physics beyond the Standard Model (SM). Important steps towards the first goal were achieved: in July 2012, the two general purpose experiments, ATLAS [1] and CMS [2], announced the discovery of a new particle at a mass of 125 GeV [3,4]. The measured properties of the new particle were found compatible with those of the minimal SM scalar boson proposed in 1964 by Brout, Englert and Higgs [5–7], as is presented in detail in another review of the present dossier of *Comptes rendus Physique*. In particle physics,

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the scalar boson discovery is a main achievement: it has been the missing piece of the SM for more than 40 years. Is this new particle the only elementary scalar particle in nature or are there more to be discovered? In parallel to the discovery and the study of properties of the scalar boson(s), the search for other new particles, as expected from new physics, is also crucial. Indeed, the SM cannot answer several fundamental questions and is generally considered as a low energy effective model of a more fundamental theory.

This review presents highlight results of the first three years of the LHC running on searches for new physics beyond the Standard Model (BSM), and concentrates mainly on analyses of proton–proton collisions performed by the ATLAS and CMS experiments. Results from the two other LHC experiments, LHCb and ALICE, can be found elsewhere in this dossier. The complete set of public results of the ATLAS, CMS and LHCb experiments are available on the web pages given in Refs. [8–10].

The present review is organised as follows. Section 2 gives motivations to search for new physics beyond the SM, and a brief description of the main classes of BSM theory candidates is reported in Section 3. Section 4 summarises the characteristics of the 3-year LHC dataset, called in the following the Run 1 dataset. Precise tests of the SM are reported in Section 5. The following next sections are the core of the review and present a selection of results from the ATLAS and CMS experiments on BSM searches, gathered in four parts: the search for new physics in the scalar sector in Section 6, the search for supersymmetric particles in Section 7, the search for dark matter candidates in Section 8, and a non-exhaustive list of other exotics BSM searches in Section 9. Future plans of the LHC running are reported in Section 10. Finally the conclusions are given in Section 11.

2. Why searching for new physics?

The SM describes successfully all features of electromagnetic, weak and strong interactions between matter constituents, down to distances $\sim 10^{-19}$ m and up to energies of ~ 1 TeV, as presently accessible to experiments. However, despite its incredible success, the SM is clearly not a complete theory, as it does not provide a framework to describe several important observations in the universe: it does not include gravitation; it does not provide candidates to account for the dark matter and the dark energy in the universe, as established by cosmological observations; it does not explain the matter–antimatter asymmetry observed today in the universe. This asymmetry seems inconsistent with the inflation picture of our early universe, as the present structure of the SM treats particles and antiparticles almost similarly: the SM does not include enough source of CP violation to describe the dominance of matter in our present universe, unless new interactions are introduced. Finally, in the minimal version of the SM, the neutrinos are assumed to be massless, which is incompatible with the measurement of neutrino oscillations.

The SM suffers, in addition, from several conceptual problems, in particular the so-called "fine-tuning" problem, linked to the presence of scalar (spin-0) particles in the model. Indeed, the Brout–Englert–Higgs boson candidate discovered recently is rather special in the SM: it is the only elementary spin-0 particle. In the model, a physical mass is computed as a sum of two terms: the bare mass, and contributions from radiative corrections. In the case of spin-0 particle, the radiative corrections are quadratically divergent and proportional to the cut-off scale of the model, i.e. the larger scale where the model is valid. If the cut-off scale is high (for example the Planck scale, 10^{19} GeV), corrections become unsatisfactory large in comparison to the scalar boson physical mass. This behaviour, however, does not appear in radiative corrections to fermion and gauge boson mass terms, as they are protected by chiral and gauge symmetries, respectively. A way to solve the problem is to introduce in the model new particles and new symmetries, at a certain scale, such that radiative corrections from the new particles cancel radiative corrections from the SM ones. The scale should however not be too high, typically a few (tens of) TeV or less, leading to a tuning factor much more acceptable than the ratio between the electroweak symmetry breaking scale (~ 100 GeV) and the Planck scale. Another important issue when extrapolating the SM up to high scale is to keep a stable value of the minimum of the scalar potential that breaks the electroweak symmetry. The extrapolation depends on the top and scalar boson masses, and the current mass measurements are intriguing as they favour a metastable scalar potential [11,12]. This may suggest the existence of possible additional particles coupling to the scalar sector, that could change the shape of the potential at high scale.

A last puzzling point concerns the absence of unification between interactions in the SM: when extrapolated to high energy (typically the Planck scale), the three fundamental forces (electromagnetic, weak, and strong forces) cannot be described as resulting from a unique symmetry. Adding new particles in the model can modify the evolution of the fundamental couplings and unify them at high scale.

Finally, the Brout–Englert–Higgs mechanism provides a way to introduce mass terms in the model, but it gives no explanation on the observed mass values and on the diversity of the observed mass spectrum: for example there is an unexplained large factor of $\sim 10^5$ between the electron mass and the top quark mass. The SM has 19 arbitrary free parameters and an intriguing same structure of three families for quarks and for leptons, which may point to a new symmetry.

It is now generally accepted that the SM model needs to be extended to include and explain the limitations presented above, the SM being then a low-energy approximation, or a visible part, of a larger theory at high energy.

3. New physics models

Many models have been proposed as BSM candidates, addressing some of the issues of the SM, but none of them can answer all the above questions. A rapid description of the main classes of BSM candidates is presented below.