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The H Boson

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Séminaire Poincaré XIX

Le Boson H

Samedi
29 novembre 2014

F. Englert : Le boson de Brout - Englert - Higgs • *10h*

Y. Sirois : La découverte du boson H au LHC • *11h*

P. Fayet : Bosons scalaires et supersymétrie • *14h*

L. Fayard : Recherches futures sur les bosons scalaires • *15h*

A. Djouadi : Implications de la découverte du boson H • *16h*

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Foreword

This book is the sixteenth in a series of Proceedings for the *Séminaire Poincaré*, which is directed toward a broad audience of physicists, mathematicians, and philosophers of science.

The goal of the Poincaré Seminar is to provide up-to-date information about general topics of great interest in physics. Both the theoretical and experimental aspects of the topic are covered, generally with some historical background. Inspired by the *Nicolas Bourbaki Seminar* in mathematics, hence nicknamed *"Bourbaphy"*, the Poincaré Seminar is held on a yearly basis at the Institut Henri Poincaré in Paris, with written contributions prepared in advance. Particular care is devoted to the pedagogical nature of the presentations, so that they may be accessible to a large audience of scientists.

This new volume of the Poincaré Seminar Series, **The H Boson**, in the Birkhäuser Series *Progress in Mathematical Physics* corresponds to the nineteenth such seminar, held on November 29, 2014, at Institut Henri Poincaré in Paris. Its first aim is to provide a detailed description of the seminal theoretical construction in 1964, independently by Robert Brout and François Englert, and by Peter W. Higgs, of a mechanism for short-range fundamental interactions, now called the *Brout–Englert–Higgs* (*BEH*) *mechanism.* It accounts for the non-zero mass of elementary particles and predicts the existence of a new particle – an elementary massive scalar boson. The second aim of the present volume is then to describe the experimental discovery of this fundamental missing element in the *Standard Model* of particle physics. The H boson, also called the Higgs boson, was produced and detected in the Large Hadron Collider (LHC) of CERN near Geneva by two large experimental collaborations, ATLAS and CMS, which announced its discovery on the 4th of July 2012.

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"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 does not seem to preclude a later awarding of another Nobel Prize in Physics, this time to the CERN organization, for such an experimental achievement of historical importance. The present volume is a testimony to the extraordinary fifty-year long scientific adventure which led to the discovery of the H boson.

Englert's and Higgs' Nobel Lectures, delivered on 8 December 2013 at Aula Magna in Stockholm University[1] were introduced by Lars Brink, Chairman of the Nobel Committee for Physics, who also gave the Presentation Speech at the Award Ceremony on 10 December 2013. Brink was in charge for the Class for Physics of the Royal Swedish Academy of Sciences of the very detailed report on the Scientific Background on the Nobel Prize in Physics 2013, "The BEH-Mechanism, interactions with short-range forces and scalar particles", which can be found on the internet[2].

The first article in this volume, entitled "The BEH Mechanism and its Scalar Boson", is the text of the Nobel Lecture given by François Englert. Using the example of the effective thermodynamical potential of a ferromagnet above and below the Curie point, the author explains how, at a given minimum, the curvature of the effective potential measures the inverse susceptibility, which is the analog of mass in relativistic particle physics. At non-zero magnetization, the curvature vanishes along rotations of the order parameter, while it is positive in the longitudinal direction. As discovered by Y. Nambu on 1960 in the context of the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity, and established generally by J. Goldstone, such massless modes are the characteristic signature of *spontaneously broken continuous symmetries*. Inspired by BCS theory, where the quantum phase symmetry is broken by a condensation of electron pairs bound by an attractive force due to phonon exchange, Nambu introduced spontaneous symmetry breaking (SSB) in relativistic quantum field theory, and showed how a fermion condensate could break the (approximate) chiral symmetry of strong interactions, leading to the emergence of (nearly) massless pseudoscalar particles called *pions*. He was awarded half of the 2008 Nobel Prize in Physics *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, while the other half was awarded jointly to M. Kobayashi and T. Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*. However, as shown by P.W. Anderson in 1963, in superconductivity the presence of long-range Coulomb interactions converts the massless Nambu–Goldstone (NG) mode into a "massive" plasmon mode of electron density oscillations, as the longitudinal partner of transverse electromagnetic modes. F. Englert explains why NG bosons similarly no longer exist when the spontaneously-broken symmetry is gauged to a *local* symmetry, a fact understood in 1964 studies by Brout and Englert, by Higgs, by Migdal and Polyakov (delayed in USSR to 1965), and by Guralnik, Hagen and Kibble. Via their coupling to the gauge fields, the NG massless bosons are replaced by extra polarizations for the spin-1 gauge bosons which, by relativistic invariance, must be massive. This BEH mechanism accommodates in the same theory both long-range and short-range interactions, by leaving part of the gauge symmetry unbroken and the

[1] see http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/

[2] see http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

corresponding vector bosons massless. The most impressive success of these ideas is the unification of weak and electromagnetic interactions within the *Standard Model* of particle physics. Its validity required the discovery of one missing, new massive particle called the *H boson*, the analog of positive-curvature fluctuations in the ferromagnetic picture.

The second article in this volume, "Discovery and Measurements of the H Boson with ATLAS and CMS Experiments at the LHC", is written by Yves Sirois, the leader for France of the CMS collaboration. The author recollects the adventure of the search for the Higgs boson, starting with the LEP e^+e^- collider in the nineties, continuing at the Tevatron $p\bar{p}$ collider and culminating with the recent discovery at LHC. This long road underlines one of the important challenges of the search, the absence of a theoretical prediction for the H boson's mass. Sirois then reviews the measurements of various properties of the new particle (spin, decay modes, etc.), all of which are, up to now, compatible with those expected for the Higgs boson of the Standard Model.

The third contribution, entitled "Scalar Bosons and Supersymmetry", is written by Pierre Fayet, a theoretical physicist at École Normale Supérieure in Paris, who is one of the pioneers of this tanatalizing new symmetry, which relates fermions and bosons and arises in unified theories such as Superstring Theory. The author places the H boson discovery in the larger context of possible extensions of the Standard Model involving supersymmetry. An extended Higgs sector, involving four or more extra scalar particles is predicted by supersymmetric theories, as well as other experimental signals for which the LHC collaborations are actively searching.

In "Future Searches on Scalar Boson(s)", Louis Fayard, a prominent member of the ATLAS Collaboration, reviews the prospects for other experimental discoveries, both at LHC and in future colliders. Indeed, despite its great predictive power and its theoretical appeal, different reasons make one suspect that the Standard Model is an incomplete theory. The author makes a comparative review of the potential for discovering new physics in the upcoming runs 2 and 3 of the LHC, in its possible future High-Luminosity upgrade, and in the two proposed future linear colliders – the Compact Linear Collider (CLIC) and the International Linear Collider (ILC).

This volume ends with an authoritative contribution by Abdelhak Djouadi, a leading phenomenologist at the Laboratoire de Physique Théorique at Université d'Orsay (now part of the new Université Paris-Saclay). His article, entitled "Implications of the H Boson Discovery", complements and extends that by P. Fayet, summarizing the implications of the discovery of a scalar boson with a mass of approximately 125 GeV in the context of both the Standard Model and its minimal supersymmetric extension, called MSSM. Djouadi first describes how the new experimental data both confirm the H boson as the cornerstone of the Standard Model and imply strong new constraints on particle physics. Fundamental consequences may reach as far as the Universe's fate, ultimately linked to the stability of the H boson potential. This thorough review continues with an even more exciting foray into the consequences for physics beyond the Standard Model. The main scenarios based on supersymmetry are discussed in detail and confronted to experimental data. The conclusion stresses that although supersymmetry has not been observed, it is also not ruled out and still remains the most natural protection of the Higgs mass against radiative corrections, and a road towards a possible grand-unification of electroweak and strong interactions. The next round of data from the LHC is eagerly expected.

This book, by the breadth of topics covered in the celebrated prediction and discovery of the H boson, should be of broad interest to physicists, mathematicians, and historians of science. We further hope that the continued publication of this series of Proceedings will serve the scientific community, at both the graduate and professional levels. We thank the Commissariat à l'Énergie Atomique et aux Énergies Alternatives (Direction de la Recherche Fondamentale), the Daniel Iagolnitzer Foundation, and the École polytechnique for sponsoring this Seminar, and the Institut Henri Poincaré in Paris for its continuing support and hospitality. Special thanks are due to Chantal Delongeas for the preparation of the manuscript and to Lars Brink and David A. Kosower for their helpful remarks.

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