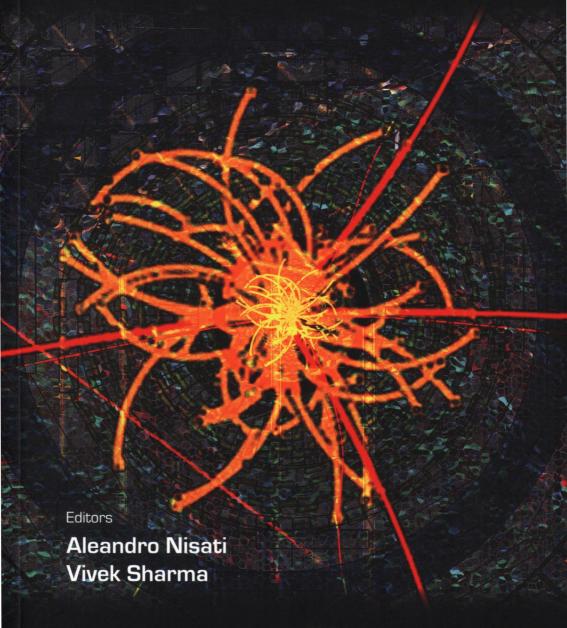
DISCOVERY OF THE HIGGS BOSON





The recent observation of the Higgs boson has been hailed as the scientific discovery of the century and led to the 2013 Nobel Prize in physics. This book describes the detailed science behind the decades-long search for this elusive particle at the Large Electron Positron Collider at CERN and at the Tevatron at Fermilab and its subsequent discovery and characterization at the Large Hadron Collider at CERN. Written by physicists who played leading roles in this epic search and discovery, this book is an authoritative and pedagogical exposition of the portrait of the Higgs boson that has emerged from a large number of experimental measurements. As the first of its kind, this book should be of interest to graduate students and researchers in particle physics.



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Nisati Sharma



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DISCOVERY OF THE HIGGS BOSON



To our families, for their loving and enthusiastic support during the hunt for the Higgs boson.

Preface

The discovery in 2012 by the ATLAS and CMS experiments at CERN of a new boson with a mass near 125 GeV was an extraordinary milestone in the four-decade long experimental search for the mechanism that breaks the electroweak symmetry and generates the masses of all known fundamental particles.

The science that we describe in this book began about fifty years ago when three groups of theoreticians, Englert & Brout, Higgs, and Guralnik, Hagen & Kibble, conjectured a mechanism for the origin of vector boson masses consisting of a complex scalar quantum field with the quantum numbers of the vacuum, which permeates the entirety of our universe. The Higgs boson, a spin-zero excitation of this field, is the experimental footprint of this mechanism that hides the electroweak gauge symmetry. While the interactions of the Higgs boson with the known gauge bosons, quarks and leptons are completely predicted, its mass is a free parameter of the model. Therefore, the mass must be determined experimentally following a rigorous proof of its very existence.

The worldwide experimental search for the Higgs boson began in earnest soon after the consolidation of the electroweak theory into what is now known as the Standard Model (SM) of particle physics. While several model-dependent limits were placed on the existence of Higgs bosons with a mass below 3.6 GeV, it was the model-independent searches by the four experiments, ALEPH, DELPHI, OPAL and L3, at the Large Electron Positron (LEP) collider that ruled out the presence of a SM Higgs boson with a mass below 114.4 GeV at 95% confidence level (CL). Following the shutdown of the LEP collider in 2000, the direct searches for the Higgs boson shifted to the CDF and D0 experiments at the Tevatron $p\bar{p}$ collider at Fermilab. By the summer of 2010, the combined results from up to 6.7 fb⁻¹ of data recorded by CDF and D0 had excluded, at 95% CL, a SM Higgs boson with a mass between 158 GeV and 175 GeV. Their search for

x Preface

a low mass Higgs boson decaying into $b\bar{b}$ continued with more data leading to a broad 3 standard deviations excess observed by the summer of 2012.

The Large Hadron Collider (LHC), the world's highest energy particle collider, was built primarily to collide protons at $\sqrt{s} = 14$ TeV, but on September 10, 2008, an electrical fault between two of the 1232 dipole magnets led to an explosive release of helium coolant from the magnets, causing mechanical damage to about 50 dipoles. Following an extraordinary effort to repair the magnets, on March 30, 2010, the first pp collisions by the LHC were obtained at a center-of-mass energy of 7 TeV, reduced below the design energy as a precautionary measure. While many had thought that, at this energy, the search for the Higgs boson would be a marathon spanning several years of data taking, due to the excellent performance of the LHC machine and the ATLAS and CMS detectors and their analysis tools, the hunt for the Higgs boson was reduced to a sprint! With just $5\,\mathrm{fb^{-1}}$ of 7 TeV data collected in 2011, the LHC experiments ruled out the presence of the Standard Model Higgs boson in a large range of high masses. Interestingly, in the same data, both experiments saw a tantalizing excess near a mass of 125 GeV that, with another 5-6 fb⁻¹ data collected at 8 TeV in early 2012, grew to a significance of about 5 standard deviations in each experiment. This led to the historic announcement on the 4th of July 2012 at a jam-packed meeting at CERN, which was followed by an online audience exceeding a hundred thousand. When the full 8 TeV dataset of about 20 fb⁻¹ were analyzed, a portrait of this new resonance consistent with the characteristics of the Standard Model Higgs boson came into view.

This book describes in scientific detail this epic search for the Standard Model Higgs boson. It is written by physicists who played leading roles in the search and discovery of the new boson. Most chapters are written by teams of two physicists from rival experiments. This book is targeted towards 3rd year graduate students (who have already taken courses in quantum field theory as well as experimental techniques in particle physics), young post-doctoral researchers as well as practicing particle physicists not directly involved in Higgs searches but curious about the scientific details of how we know what we know of this new particle discovered at the LHC. This book can also be used as a supplementary text in a graduate level course on electroweak physics.

The emphasis of this book is on pedagogy and on the big picture in the Higgs boson hunt. By describing not just *what* was done in the analyses but also explaining *why* it was done in that particular way, this book Preface xi

complements the dozens of ATLAS and CMS publications which form the basis of this book.

This book is organized as follows: in Chapter 1 we start with an introduction to the phenomenology of the Standard Model Higgs boson. This is followed in Chapter 2 by a description of the Higgs boson search at the LEP collider. Chapter 3 describes the pioneering searches carried out at the Tevatron. The narrative then shifts to the LHC starting with Chapter 4 which describes the general features of the LHC and the capabilities of the two major Higgs-hunting experiments there: ATLAS and CMS. The observation of a narrow resonance near 125 GeV (H_{125}) in the $H \to ZZ \to 4\ell$ channel and the measurements of its properties are described in Chapter 5. This is followed in Chapter 6 by the description of the properties of the H_{125} resonance in the $H \to \gamma \gamma$ channel. These two "golden" channels provide a precise measure of the mass of the new particle and reveal its bosonic nature. Studies in the $H \to WW^*$ final state described in Chapter 7 complete the profile of the coupling of H_{125} to dibosons. The discussion then turns to the search for the decays of H_{125} to fermions. Chapter 8 describes the evidence for the $H \to \tau\tau$ decay. Chapter 9 describes the search for H_{125} decay into $b\bar{b}$ final state, probably the most complicated channel of investigation at the LHC. Before the LHC experiments converged on the discovery of the H_{125} resonance, a variety of searches were conducted for a high mass Standard Model Higgs boson decaying to vector bosons. They are described in Chapters 10 and 11. Chapter 12 combines the results from all channels investigated by ATLAS and CMS and presents the experimentally measured properties of the H_{125} boson. Chapter 13 presents a short summary of the experimental measurements and concludes that the H_{125} resonance discovered at the LHC fits, within measurement uncertainties, the profile of the Standard Model Higgs boson. Lastly, the Higgs boson searches and its discovery benefited greatly from several sophisticated statistical and multivariate analysis techniques. The technical aspects of these procedures are reviewed in Appendices A and B, respectively.

We hope that the gentle reader will find the book pedagogically insightful and scientifically inspiring. We wish you happy reading!

A. Nisati and V. Sharma



Contents

Preface		ix
1.	The Higgs boson in the Standard Model A. Djouadi and M. Grazzini	1
2.	Searches for the Standard Model Higgs boson at the LEP collider P. Igo-Kemenes and A. L. Read	45
3.	Searches for the Standard Model Higgs boson at the Tevatron collider	71
	W. C. Fisher and T. R. Junk	
4.	Overview of the Large Hadron Collider and of the ATLAS and CMS experiments A. Nisati and V. Sharma	103
5.	Higgs boson observation and measurements of its properties in the $H \to ZZ \to 4\ell$ decay mode A. Korytov and K. Nikolopoulos	127
6.	Observation of the diphoton decay of the Higgs boson and measurements of its properties J. Bendavid and K. Tackmann	179

viii Contents

7.	Observation of the Higgs boson in the $H \to W^+W^{-(*)} \to \ell^+\nu\ell^-\nu$ final state	211
	E. Di Marco and J. Strandberg	
8.	Evidence for Higgs boson decays to τ leptons	245
	M. Bachtis and J. Kroseberg	
9.	Search for the Higgs boson in the $b\bar{b}$ final state at the LHC	273
	J. Konigsberg and G. Piacquadio	
10.	Higgs boson search in the $WW \rightarrow l\nu qq$ final state	323
	P. Govoni and R. Sandström	
11.	Higgs boson search in the $ZZ \to \ell\ell\nu\nu$ and $\ell\ell qq$ final states	345
	C. Gwilliam and A. Vartak	
12.	Higgs combination and properties of the Higgs boson	377
	M. Duehrssen and G. Petrucciani	
13.	Summary and outlook	411
Appendix A. Statistical methods		415
T. 1	R. Junk, A. Korytov, and A. L. Read	
App	pendix B. Multivariate analysis techniques	435
<i>J.</i> E	Bendavid, W. C. Fisher, and T. R. Junk	
Ack	nowledgements	455
About the Authors		457

Chapter 1

The Higgs boson in the Standard Model

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The major goal of the Large Hadron Collider is to probe the electroweak symmetry breaking mechanism and the generation of the elementary particle masses. In the Standard Model this mechanism leads to the existence of a scalar Higgs boson with unique properties. We review the physics of the Standard Model Higgs boson, discuss its main search channels at hadron colliders and the corresponding theoretical predictions. We also summarize the strategies to study its basic properties.

1. Introduction

Establishing the precise mechanism of the spontaneous breaking of the electroweak gauge symmetry has been the central focus in high energy physics for many decades and is certainly the primary goal of the LHC. In the Standard Model (SM), $^{1-6}$ the theory that describes the electromagnetic, weak and strong interactions, explicit mass terms for the electroweak gauge bosons and the fermions are not allowed by the SU(2)_L × U(1)_Y gauge symmetry. Electroweak symmetry breaking (EWSB) is achieved via the Brout–Englert–Higgs mechanism, $^{7-9}$ in which a scalar field, a doublet under weak isospin, acquires a non-zero vacuum expectation value, thus providing masses for the electroweak gauge bosons and for the fermions. One of the four degrees of freedom of the original scalar field corresponds to a physical scalar particle: the *Higgs boson*.

Clearly, the discovery of this last missing piece of the SM has profound importance. In fact, despite of its phenomenal success in explaining the precision data, the SM could not be considered to be completely established until the Higgs boson was observed experimentally. The discovery in July 2012 of a scalar resonance compatible with the SM Higgs boson by the ATLAS and CMS collaborations^{10,11} is, in this respect, historic as it crowns the SM as the correct theory of fundamental particles and interactions among them, at least up to the Fermi energy scale.

In addition, the fundamental properties of the Higgs particle such as its mass, spin and other quantum numbers, as well as its couplings to various matter and gauge particles and its self-couplings must be determined in the most precise way. These studies are important in order to achieve further clarity into the dynamics of the EWSB mechanism. The many important questions which one would like answered by probing the Higgs boson properties are: does the dynamics involve new strong interactions and is the Higgs a composite field? If elementary Higgs particles indeed exist in nature, how many fields are there and in which gauge representations do they appear? Does the EWSB sector involve sizable CP violation? Theoretical realizations span a wide range of scenarios and a complete discussion of Higgs physics thus touches upon almost all the issues under active investigation in theoretical and experimental particle physics. Nevertheless, in this chapter, only the phenomenology of the Higgs sector in the SM will be discussed (for a detailed review, see e.g. Ref. [12]). After summarizing the EWSB mechanism in the SM in Sec. 2 and the pre-LHC theoretical and experimental constraints on the Higgs boson mass in Sec. 3, its decay modes, production cross sections and detection channels at hadron colliders will be described in Secs. 4, 5 and 6, respectively. The theoretical predictions for differential distributions and the Monte Carlo generators used in the experimental analyses are briefly reviewed in Secs. 7 and 8. The strategies to measure the fundamental properties of the Higgs boson are finally summarized in Sec. 9.

2. Electroweak symmetry breaking and mass generation

The Standard Model is based on a very powerful principle: gauge symmetry. The fields corresponding to the particles, as well as the particle interactions, are invariant with respect to local transformations of an internal symmetry group. The model is a generalization of quantum electrodynamics (QED),