The discovery of the long-anticipated Higgs Boson was announced by the LHC experiments ATLAS and CMS in July 2012, and will go down as one of the great achievements in twenty-first century science. The effectiveness of scientific reasoning was revealed in its full glory: a beautiful theoretical argument, building on decades of previous experimental and theoretical work, was used to predict a new particle, which was discovered 50 years later. Such are the stories that we, as scientists, are most proud of and use to explain the power of the scientific approach. However, what does it mean for particle physics as a discipline? Is our work now complete? Was the Higgs Boson the final piece missing from the Standard Model so that now we can rest on our laurels? The answers to these questions form the contents of this special issue of Annalen der Physik and have guided the choice of articles that appear in this volume. We, the guest editors, have asked a number of renowned scientists to give us their view of the perspectives in their specific areas of expertise, covering a broad range of topics in particle physics and beyond. The volume begins with two longer articles setting the stage for the discovery of the Higgs particle. In the remaining articles we have asked the authors to look beyond this discovery and discuss the prospects for the future from both a theoretical and experimental perspective. In addition, a number of authors have submitted contributed papers which complement the invited papers with more specific perspectives. What has resulted is both a broad but compact and compelling overview of current and future research directions in particle physics.

In the first article, Michael Peskin provides an overview establishing the necessity for the Higgs mechanism in the Standard Model from very general relativistic and quantum mechanical considerations. As is made clear, the Higgs mechanism is at the heart of many processes in particle physics even if no Higgs particle is explicitly involved. Oft-discussed issues such as the hierarchy, naturalness and other problems of the Standard Model are outlined. Peskin stresses that spontaneous symmetry breaking is also found in other areas of physics, and often the underlying physical basis for the spontaneous symmetry breaking can be identified. He discusses theoretical extensions to the Standard Model including Supersymmetry, the Higgs as a Gauge Boson of some higher symmetry and the Higgs as a Goldstone Boson for a new set of strong interactions, otherwise known as "little Higgs" models. The inescapable conclusion is that a very rich field of new particles and interactions may be almost within our grasp.

Jim Virdee also discusses the genesis of the Standard Model and the main features of the Higgs before tracing the history of the LHC and the experimental collaborations. The general features and main challenges that ATLAS and CMS faced, particularly their calorimeters, are discussed. As Virdee explains, other essential elements of infrastructure, such as the LHC Grid computing, were vital to the success of the LHC. The performance in the "rediscovery" of Standard Model particles in the early LHC data implied that both experiments were ready to probe the unknown. The confidence in the detectors was such that the discovery of the Higgs in both detectors in several channels was established in the summer of 2012, a triumph for the LHC accelerator builders and experimenters.

There are many logically satisfactory ways in which the remaining commissioned articles could be organised. We have chosen a “cosmological” ordering, beginning with Roberto Battiston’s contribution, which sets the development of particle physics in the context of astronomy and cosmic-ray physics. Subsequent topics are introduced in the order in which they most strongly affected the development of the universe after the Big Bang. Cognate articles, for example theoretical and experimental aspects of similar subjects, are grouped together. Finally we look at the accelerators and techniques that will be needed to make progress with many of these vital questions and conclude where we began, at an energy that we can never achieve at accelerators - in cosmic rays with a survey by Elisa Resconi.

Roberto Battiston’s article starts from the fact that accelerator-based experiments provide very precise information on the Standard Model, which describes only 5% of the observed universe. The remainder, which consists of dark matter and dark energy, is inferred from astronomical observations and from increasingly precise measurements of the cosmic microwave background. Within the cosmological standard model, general relativity plays a crucial role. As Battiston describes, both ground- and space-based interferometers are either currently operating or being readied for direct detection of gravitational waves and other experiments test the validity of Einstein’s basic concepts. Other space missions are observing the universe at all wavelengths, from radio to gamma rays, and at all distances. As a tantalizing result, Battiston points to recent high-precision results on cosmic ray composition and fluxes up to energies in excess of 1 TeV which are increasingly difficult to explain by known astrophysical effects.

Maybe the biggest puzzle in theoretical physics is the value and meaning of the cosmological constant. Introduced by Einstein in his development of General Relativity, it is directly related to the energy density of the Universe and closely linked to the mysterious dark energy. Decades of effort in trying to understand it have so far resulted in many new theoretical models but little obvious progress. As Ed Copeland points out, the biggest problem is not just the size of the constant, which is 121 orders of magnitude different from expectations from quantum mechanical zero-point energies, but the fact that fine-tuned corrections are not radiatively stable. Copeland reviews some models that have been constructed to resolve these puzzles, including some with a direct link to the Higgs boson. Gia Dvali and Cesar Gomez ask whether a positive cosmological constant is even possible in a fully quantum-mechanical Universe, and answer with a resounding NO. This leads them to conclude that we have perhaps been asking the wrong question and should instead be focusing on the consistency of a cosmological constant in a quantum-mechanical universe. Could this be a step towards a deeper understanding of this fundamental puzzle?

Dark Matter has been discussed for more than 80 years. That it really exists as a source of gravitational interactions is now incontrovertible, but its underlying nature remains elusive. In her article, Laura Baudis describes the search for Weakly Interacting Massive Particles (WIMPs) and Axions, two of the most compelling candidates for a particle solution to Dark Matter. Both are well motivated by theoretical studies - Supersymmetry in the case of WIMPs and the absence of CP Violation in QCD for Axions. She also reviews briefly the outlook for the LHC to find signs of Dark Matter particles. Could a new round of significantly more sensitive experiments finally lead to a solution of this deep mystery?

Many of the articles in this volume discuss Supersymmetry, a compelling theoretical construct for which there in no iota of experimental evidence. Indeed, the Standard Model is still in perfect shape after the discovery and measurement of the first properties of the Higgs particle. Nevertheless, it needs to be extended to account for known facts, such as Dark Matter, for which it currently gives no explanation. SUSY provides the most elegant way to provide naturalness, that is to stabilize the mass of the Higgs against radiative corrections larger than the mass itself. It can also provide particles that could give an explanation for Dark Matter. Stefan Pokorski argues that SUSY might well be more hidden than often expected and offers various theoretical scenarios that are still available for exploration.

Neutrinos could also provide at least a component of the Dark Matter in the Universe. Hirohisa Tanaka outlines the origin of the neutrino postulate, its experimental confirmation and the properties of this most enigmatic of elementary particles. The possibility that the tiny neutrino masses, not accounted for in the Standard Model, may be of Majorana origin and the consequences of neutrino mixing for the evolution of the Universe are discussed. Many of the current and foreseen experiments to investigate the parameters of neutrino mixing and the concomitant CP violation are described. Tanaka concludes with an overview of the techniques required to establish whether the neutrino is a Majorana particle by searching for neutrinoless double-beta decay. The answer to any of the open questions about neutrinos would have profound effects on our understanding of the evolution of the Universe.

One of the key features of the Standard Model is that only certain reactions between the constituent particles are allowed (e.g., only left-handed weak interactions between quarks and charged leptons). The details of this “Flavour Physics” are inserted by hand into the Standard Model; a more fundamental theory should explain the pattern of allowed interactions. In his article, Andrzej Buras gives an overview of the topic from a theorist’s perspective. He outlines the outstanding experimental data and provides a 'DNA Chart' to guide the discovery of new physics processes beyond the Standard Model. Neville Harnew focuses on the experimental aspects, and provides both the shorter-term perspectives made available by the ongoing (LHC-b) and expected (Belle II, NA62, KOTO) experimental programs as well as a discussion of possible future experiments. It is abundantly clear from these articles that flavour physics provides an alternative and complementary road to accessing new physics processes at high energy scales, which could bring the first concrete results for physics beyond the Standard Model.

Paths to new physics similar to that of flavour physics, via precision and rare processes, are described by Klaus Jungmann and David Hertzog. Jungmann describes an experimental program of low-energy precision experiments to identify signs of the breaking of Lorentz invariance (CPT violation). The core of the measurements is to identify any difference in the properties of particles and antiparticles, in both elementary-particle and gravitational interactions. Another option is to search for signs of strong CP violation. Hertzog describes high precision measurements of variables which have precise theoretical expectations. These include searches for permanent electric dipole moments or charged lepton-number violations, measurements of the muon anomalous magnetic moment or the running of the electroweak parameter $\sin^2\theta_W$.

Moving to the future realm of accelerator experiments, Beate Heinemann summarises the perspectives for our sole “energy-frontier” machine, the Large Hadron Collider. The LHC experiments have discovered the Higgs boson, performed precision measurements involving the production of heavy vector bosons and the top quark and scanned the phase space of a multitude of final, more or less exotic, states for signs of new physics, so far to no avail. The expected upgrades of energy and luminosity of the LHC will take us up to 2037 with a potential to increase the precision on the Higgs coupling from the present 30% and the sensitivity to new physics by an order of magnitude.

Quantum Chromodynamics is well established as the theory for the strong interaction. However, there are vast gaps in our understanding of phenomena related to strong interactions. Perhaps most striking is an explanation for why the colored constituents of nucleons (quarks and gluons) are confined into colorless states. Similarly puzzling is the partonic explanation for the observed spin angular momentum of hadrons. In his article, Raju Venogopalan focuses on such issues and makes the case for a new collider (in particular the proposed Electron-Ion Collider) to provide vastly better data to help us understand how the fundamental degrees of freedom - quarks and gluons - lead to the observed hadrons. Max Klein discusses the physics potential of the proposed LHeC, a super-HERA collider where a newly built electron beam would collide with the LHC proton beam, making precision measurements in a new kinematic regime. In addition to the QCD physics accessible at the LHeC, Klein points out the feasibility of studying the Higgs Boson properties at the LHeC as well as making precise measurements of the strong coupling constant.

The much cleaner experimental situation at a lepton collider is the rationale for linear electron-positron colliders, discussed by Hitoshi Yamamoto. He describes the two main options for a future linear collider, ILC and CLIC and summarises the advantages of a lepton collider over a hadron collider for precision measurements of the properties of the Higgs and top physics. In addition, linear colliders can also be powerful machines to discover physics beyond the Standard Model and have unique discovery potential compared to hadron machines.

To round off our perspective for accelerator physics, Massimo Ferrario gives an accelerator physicist’s overview of large-scale facilities, starting with the current operation of the LHC and looking ahead to upgrades such as the high-luminosity LHC. Possible future facilities are discussed, including FCC, ILC and CLIC. The potential application of plasma wakefield acceleration in energy-frontier colliders and its advantages and drawbacks are discussed. Finally, the potential and feasibility of muon colliders is explored.

We end our concise survey of the perspectives for particle physics after the Higgs discovery by returning to the beginning, both of this volume and of particle physics. As we have seen, many of the compelling questions in particle physics have been posed by observations of particles and radiation from space. It is therefore natural that the study of cosmic particles is important for the future of particle physics. Elisa Resconi looks forward to discoveries via the observation of charged particles as well as neutrinos and photons (X-rays and gamma rays). For example, the highest-energy cosmic rays can access physics at scales unreachable by accelerators, while low-energy X-rays could point to right-handed neutrinos, a potential Dark Matter candidate.

The progress in particle physics and cosmology since the Guest Editors of this volume began their research careers is truly staggering. This volume documents very clearly that the road ahead promises at least as much excitement and illumination. We hope that you will enjoy reading it as much as we have enjoyed putting it together.

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