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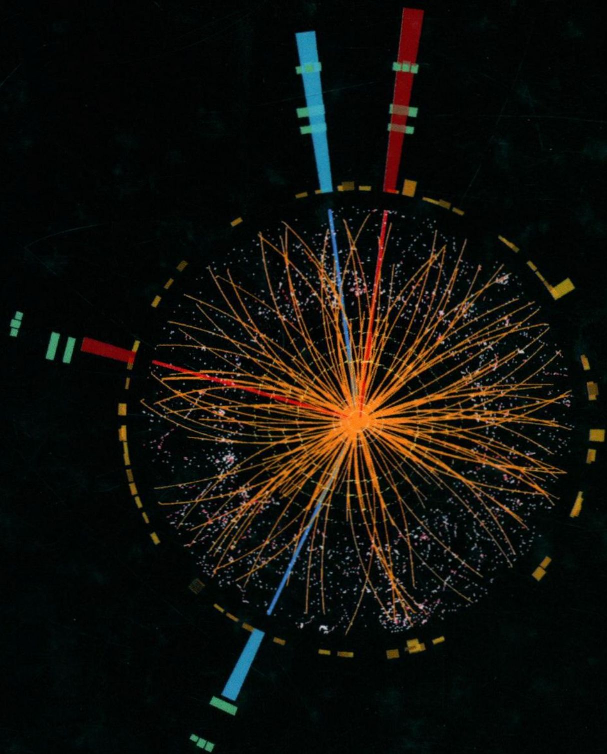
The Black Book of Quantum Chromodynamics

A Primer for the LHC Era



John Campbell | Joey Huston | Frank Krauss

The Black Book of Quantum Chromodynamics is an in-depth introduction to the particle physics of current and future experiments at particle accelerators. The book offers the reader an overview of practically all aspects of the strong interaction necessary to understand and appreciate modern particle phenomenology at the energy frontier. It assumes a working knowledge of quantum field theory at the level of introductory textbooks used for advanced undergraduates or in standard postgraduate lectures. The book expands this knowledge with an intuitive understanding of relevant physical concepts, an introduction to modern techniques, and their application to the phenomenology of the strong interaction at the highest energies. Aimed at graduate students and researchers, it also serves as a comprehensive reference for LHC experimenters and theorists.

John Campbell is Senior Scientist at the Fermi National Accelerator Laboratory.

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"This excellent and very timely book, written by leading practitioners in the study of strong interactions at hadron colliders, is incredibly broad, covering the full range of concepts and techniques necessary to understand this rich, complex and rapidly developing subject. It captures many of the recent technological advances in perturbative QCD in a clear and concise manner, and combines it with an insightful and comprehensive study of Tevatron and Run 1 LHC data. It is pitched at exactly the right level both to imbue theorists with the necessary depth of understanding of data and to introduce experimentalists to the advantages and disadvantages of different theoretical descriptions. It is a valuable resource one could use as a basis for a graduate course in collider physics, or for more experienced practitioners to dip into."

Nigel Glover, Professor, FRS, Institute of Particle Physics Phenomenology, Durham University

"The complexity of carrying out precise experimental measurements at high-energy colliders such as the LHC is matched by the complexity of the calculations needed to attain the same level of precision in the theoretical predictions. In recent decades there has been significant progress in understanding how to manipulate the underlying quantum field theory, Quantum Chromodynamics, to enable such calculations to be performed. This book, written by world experts in the field, provides a magnificently comprehensive and accessible user guide to the concepts and techniques for doing precision QCD calculations for LHC physics."

W.J. Stirling, FRS, CBE, Provost, Imperial College London

Cover image: Event display of a Higgs boson candidate decaying to four electrons recorded by the ATLAS experiment on May 18, 2012. Reprinted with permission from CERN.

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THE BLACK BOOK OF QUANTUM CHROMODYNAMICS

To our families, with love.

To colleagues and friends,
who shaped our understanding of
particle physics, with gratitude.

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`http://www.ippp.dur.ac.uk/BlackBook`

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Contents

1 Introduction

1.1 The physics of the LHC era

1.1.1 Particle physics in the LHC era

The turn-on of the LHC in 2008 culminated an almost 20-year design and construction effort, resulting in the largest particle accelerator (actually the largest machine) ever built. At its inception a competition still existed with the TEVATRON which, although operating at a much lower energy, had a data sample with a large integrated luminosity and well-understood detectors and physics-analysis software. The TEVATRON had discovered the top quark and was continuing its search for the Higgs boson. As is well known, the LHC suffered considerable damage from a cryogenic quench soon after turn-on that resulted in a shut-down for about 1.5 years. Its (re)turn-on in 2010 was at a much lower energy (7 TeV rather than 14 TeV) and at much lower intensities. The small data sample at the lower energy can be considered in retrospect as a blessing in disguise. There was not enough data to even consider a search for the Higgs boson (or even for much in the way of new physics), but there was enough data to produce W and Z bosons, top quarks, photons, leptons and jets — in other words, all of the particles of the Standard Model except for the Higgs boson. The result was the *re-discovery of the Standard Model* (a coinage for which one of the authors takes credit) and the development of the analysis tools and the detailed understanding of the detectors that allowed for the discovery of the Higgs boson on July 4, 2012, with data from 7 TeV in 2011 and 8 TeV in 2012. The LHC turned off again in early 2013 for repairs and upgrades (to avoid the type of catastrophic quench that occurred in 2008). The LHC detectors also used this two-year period for repairs and upgrades. The LHC ran again in 2015, at an energy much closer to design (13 TeV). The increased energy allowed for more detailed studies of the Higgs boson, but more importantly offered a much greater reach for the discovery of possible new physics. At the time of completion of this book, a great deal of physics has been measured at the operating energy of 13 TeV. Given the new results continually pouring out at this new energy, the decision was made to concentrate in this book on results from 7 and 8 TeV running. This is sufficient for the data comparisons needed to illustrate the theoretical machinery developed here.

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1.1.2 The quest for the Higgs boson — and beyond

1.1.2.1 Finding the Higgs boson

The LHC was designed as a discovery machine, with a design centre-of-mass energy a factor of seven larger than that of the TEVATRON. This higher collision energy opened up a wide phase space for searches for new physics, but there was one discovery that the LHC was *guaranteed* to make; that of the Higgs boson, or an equivalent mechanism for preventing WW scattering from violating unitarity at high masses.

The Higgs boson couples directly to quarks, leptons and to W and Z bosons, and indirectly (through loops) to photons and gluons. Thus the Higgs boson final states are just the building blocks of the SM with which we have much experience, both at the TEVATRON and the LHC. The ATLAS and CMS detectors were designed to find the Higgs boson and to measure its properties in detail.

The cross-section for production of a Higgs boson is not small. However, the final states for which the Higgs boson branching ratio is large (such as $b\bar{b}$) have backgrounds which are much larger from other more common processes. The final states with low backgrounds (such as $ZZ^* \to \ell^+\ell^-\ell^+\ell^-$) suffer from poor statistics, primarily due to the Z branching ratio to leptons. The Higgs$\to \gamma\gamma$ final state suffers from a small branching ratio and a large SM background. Thus one might not expect this final state to be promising for a Higgs boson search. However, due to the intrinsic narrow width of the Higgs boson, a diphoton signal can be observable if the experimental resolution of the detector is good enough that the signal stands out over the background.

The measurable final states of the Higgs boson decays were further subdivided into different topologies so that optimized cuts could be used to improve on the signal-to-background ratio for each topology (for example, in ATLAS the diphoton channel was divided into 12 topologies). The extracted signal was further weighted by the expectations of the SM Higgs boson in those topologies. In this sense, the Higgs boson that was discovered in 2012 was indeed the Standard Model Higgs boson. However, as will be discussed in Chapter 9, detailed studies have determined the properties of the new particle to be consistent with this assumption.

1.1.2.2 The triumph of the Gauge Principle

The discovery of the Higgs boson by the ATLAS and CMS collaboration, reported in July 2012 and published in [15, 368], is undoubtedly the crowning achievement of the LHC endeavour so far. It is hard to overestimate the importance of this discovery for the field of particle physics and beyond.

The Higgs boson is the only fundamental scalar particle ever found, which in itself makes it unique; all other scalars up to now were bound states, and the fundamental particles found so far have been all either spin-1/2 fermions or spin-1 vector bosons. This discovery is even more significant as it marks a triumph of the human mind: the Higgs boson is the predicted visible manifestation of the Brout–Englert–Higgs (BEH) mechanism [516, 601, 619–621, 675], which allows the generation of particle masses in a gauge-invariant way [580, 835, 888]. Ultimately, this discovery proves the paradigm of gauge invariance as the governing principle of the sub-nuclear world at the smallest distances and largest energies tested in a laboratory so far. With this discovery a 50-year-old prediction concerning the character of nature has been proven

The question now is not whether the Higgs boson exists but instead what are its properties? Is the Higgs boson perhaps a portal to some new phenomena, new particles, or even new dynamics? There are some hints from theory and cosmology that the discovery of the Higgs boson is not the final leg of the journey.

1.1.2.3 Beyond the Standard Model

By finding the last missing particle and thereby completing the most accurate and precise theory of nature at the sub-nuclear ever constructed, the paradigms by which it has been constructed have proved overwhelmingly successful. Despite this there are still fundamental questions left unanswered. These questions go beyond the realm of the SM, but they remain of utmost importance for an even deeper understanding of the world around us.

Observations of matter — Earth, other planets in the Solar System or beyond, other stars, or galaxies — suggest that the symmetry between matter and anti-matter is broken. This is a universe filled by matter and practically devoid of anti-matter. While naively there is no obvious reason why one should be preferred over the other, at some point in the history of the Universe — and presumably very early — this asymmetry had to emerge from what is believed to have been a symmetric initial state. In order for this to happen, a set of conditions, the famous **Sakharov conditions** [710, 834] had to be met. One of these intricate conditions is the violation of **CP**, which demands that the symmetry under the combined parity and charge–conjugation (CP) transformation must be broken. Experimentally, the existence of CP violation has been confirmed and is tightly related to the existence of at least three generations of matter fields in the SM. Due to the BEH mechanism, particles acquire masses, and their mass and electroweak interaction eigenstates are no longer aligned after EWSB. The existence of a complex phase in the CKM matrix, which parametrizes the interrelation between these two set of eigenstates, ultimately triggers CP violation in the quark sector. However, the amount of CP violation established is substantially smaller than necessary to explain how the universe evolved from an initial symmetric configuration to the matter-dominated configuration seen today [358].

Likewise, the existence of dark matter (DM) is now well established, first evidenced by the rotational curves of galaxies [831]. DM denotes matter which interacts only very weakly with normal matter (described by the SM) and therefore certainly does not interact through electromagnetism or the strong nuclear force. Despite numerous attempts it has not been directly detected. DM interacts through gravity and thereby has influenced the formation of large-scale structures in the Universe. Cosmological precision measurements by the WMAP and PLANCK collaborations [125, 623, 862] conclude that dark matter provides about 80% of the total matter content of the Universe. This in turn contributes about 25% of the overall energy balance, with the rest of the energy content of the Universe provided by what is known as dark energy (DE), which is even more mysterious than DM. The only thing known is that the interplay of DM and DE has been crucial in shaping the Universe as observed today and will continue to determine its future. One possible avenue in searches for DM particles at collider experiments is that they have no coupling to ordinary matter through gauge interactions but instead couple through the Higgs boson.

These examples indicate that the SM, as beautiful as it is, will definitely not provide the ultimate answer to the questions concerning the fundamental building blocks of the world around us and how they interact at the shortest distances. The SM will have to be extended by a theory encompassing at least enhanced CP violation, dark matter, and dark energy. Any such extension is already severely constrained by the overwhelming success of the gauge principle: the gauge sector of the SM has been scrutinized to incredibly high precision, passing every test up to now with flying colours. See for example [179] for a recent review, combining data from e^-e^+ and hadron collider experiments. The Higgs boson has been found only recently, and it is evident that this discovery and its implications will continue to shape our understanding of the micro–world around us. The discovery itself, and even more so the mass of the new particle and our first, imprecise measurements of its properties, already rule out or place severe constraints on many new physics models going beyond the well-established SM [515].

Right now, we are merely at the beginning of an extensive programme of precision tests in the Higgs sector of the SM or the theory that may reveal itself beyond it. It can be anticipated that at the end of the LHC era, either the SM will have prevailed completely, with new physics effects and their manifestation as new particles possibly beyond direct human reach, or alternatively, we will have forged a new, even more beautiful model of particle physics.

1.1.3 LHC: Accelerator and detectors

1.1.3.1 LHC, the machine

The LHC not only is the world's largest particle accelerator but it is also the world's largest machine, at 27 km in circumference. The LHC is a proton-proton collider (although it also operates with collisions of protons on nuclei, and nuclei on nuclei), located approximately 100 m underground and straddling the border between France and Switzerland. The LHC occupies the tunnel formerly used for the LEP accelerator in which electrons and positrons collided at centre-of-mass energies up to 209 GeV. The LHC contains 9593 magnets, including 1232 superconducting dipole magnets, capable of producing magnetic fields of the order of 8.3 T, and a maximum proton beam energy of 7 TeV (trillion electron-volts), leading to a maximum collision energy of 14 TeV. Thus far, the LHC has run at collision energies of 7 TeV (2010, 2011), 8 TeV (2012) and 13 TeV (2015,2016), greatly exceeding the previous record of the Fermilab TEVATRON of 1.96 TeV.[1] The large radius of the LHC is necessitated because of the desire to reach as high a beam energy as possible (7 TeV) using dipoles with the largest magnetic fields possible (in an accelerator). Running at full energy, the power consumption (including the experiments) is 750 GWh per year. At full power, the LHC will collide 2808 proton bunches, each approximately 30 cm long and 16 microns in diameter and containing 1.15×10^{11} protons, leading to a luminosity of $10^{34}\text{cm}^{-2}/\text{s}$ and a billion proton-proton collisions per second. The spacing between the bunches is 25 ns leading to collisions occurring every 25 ns; thus, at full **luminosity** there will

[1] Unlike the LHC, the TEVATRON was a proton-antiproton collider.