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978-0-521-76867-2 - Dynamics of the Standard Model: Second Edition
John F. Donoghue, Eugene Golowich and Barry R. Holstein
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DYNAMICS OF THE STANDARD MODEL

Describing the fundamental theory of particle physics and its applications, this book provides a detailed account of the Standard Model, focusing on techniques that can produce information about real observed phenomena.

The book begins with a pedagogic account of the Standard Model, introducing essential techniques such as effective field theory and path-integral methods. It then focuses on the use of the Standard Model in the calculation of physical properties of particles. Rigorous methods are emphasized, but other useful models are also described.

This second edition has been updated to include recent theoretical and experimental advances, such as the discovery of the Higgs boson. A new chapter is devoted to the theoretical and experimental understanding of neutrinos, and major advances in CP violation and electroweak physics have been given a modern treatment. This book is valuable to graduate students and researchers in particle physics, nuclear physics and related fields.

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SECOND EDITION

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To Lincoln Wolfenstein

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Preface to the second edition

The Standard Model is the basis of our understanding of the fundamental interactions. At the present time, it remains in excellent agreement with experiment. It is clear that any further progress in the field will need to build on a solid understanding of the Standard Model. Since the first edition was written in 1992 there have been major discoveries in neutrino physics, in CP violation, the discoveries of the top quark and the Higgs boson, and a dramatic increase in precision in both electroweak physics and in QCD . We feel that the present is a good moment to update our book, as the Standard Model seems largely complete.

The opportunity to revise our book at this time has also enabled us to survey the progress since the first edition went to print. Besides the experimental discoveries that have taken place during these two decades, we have been impressed by the increase in theoretical sophistication. Many of the topics which were novel at the time of the first edition have now been extensively developed. Perturbative treatments have progressed to higher orders and new techniques have been developed. To cover all of these completely would require the expansion of many chapters into book-length treatments. Indeed, in many cases, entire new books dedicated to specialized topics have been published.¹ Our revision is meant as a coherent pedagogic introduction to these topics, providing the reader with the basic background to pursue more detailed studies when appropriate.

There has also been great progress on the possible New Physics which could emerge beyond the Standard Model – dark matter and dark energy, grand unification, supersymmetry, extra dimensions, etc. We are at a moment where this physics could emerge in the next round of experiments at the Large Hadron Collider (LHC) as well as in precision measurements at the intensity frontier. We look forward with great anticipation to the new discoveries of the next decade.

¹ For example, see [BaP 99, Be 00, BiS 00, EISW 03, FuS 04, Gr 04, IoFL 10, La 10, Ma 04, MaW 07, Co 11]

We thank our colleagues and students for feedback about the first edition of this book. A list of errata for the second edition will be maintained at the homepage of John Donoghue at the University of Massachusetts, Amherst. We encourage readers who find any mistakes in this edition to submit them to Professor Donoghue at donoghue@physics.umass.edu.

From the preface to the first edition

The Standard Model lagrangian \mathcal{L}_{SM} embodies our knowledge of the strong and electroweak interactions. It contains as fundamental degrees of freedom the spin one-half quarks and leptons, the spin one gauge bosons, and the spin zero Higgs fields. Symmetry plays the central role in determining its dynamical structure. The lagrangian exhibits invariance under $SU(3)$ gauge transformations for the strong interactions and under $SU(2) \times U(1)$ gauge transformations for the electroweak interactions. Despite the presence of (all too) many input parameters, it is a mathematical construction of considerable predictive power.

There are books available which describe in detail the construction of \mathcal{L}_{SM} and its quantization, and which deal with aspects of symmetry breaking. We felt the need for a book describing the next steps, how \mathcal{L}_{SM} is connected to the observable physics of the real world. There are a considerable variety of techniques, of differing rigor, which are used by particle physicists to accomplish this. We present here those which have become indispensable tools. In addition, we attempt to convey the insights and ‘conventional wisdom’ which have been developed throughout the field. This book can only be an introduction to the riches contained in the subject, hopefully providing a foundation and a motivation for further exploration by its readers.

In writing the book, we have become all too painfully aware that each topic, indeed each specific reaction, has an extensive literature and phenomenology, and that there is a limitation to the depth that can be presented compactly. We emphasize applications, not fundamentals, of quantum field theory. Proofs of formal topics like renormalizability or the quantization of gauge fields are left to other books, as is the topic of parton phenomenology. In addition, the study by computer of lattice field theory is an extensive and rapidly changing discipline, which we do not attempt to cover. Although it would be tempting to discuss some of the many stimulating ideas, among them supersymmetry, grand unification, and string theory, which attempt to describe physics beyond the Standard Model, limitations of space prevent us from doing so.

Although this book begins gently, we do assume that the reader already has some familiarity with quantum field theory. As an aid to those who lack familiarity with path-integral methods, we include a presentation, in Appendix A, which treats this

subject in an introductory manner. In addition, we assume a knowledge of the basic phenomenology of particle physics.

We have constructed the material to be of use to a wide spectrum of readers who are involved with the physics of elementary particles. Certainly it contains material of interest to both theorist and experimentalist alike. Given the trend to incorporate the Standard Model in the study of nuclei, we expect the book to be of use to the nuclear physics community as well. Even the student being trained in the mathematics of string theory would be well advised to learn the role that sigma models play in particle theory.

This is a good place to stress some conventions employed in this book. Chapters are identified with roman numerals. In cross-referencing equations, we include the chapter number if the referenced equation is in a chapter different from the point of citation. The Minkowski metric is $g_{\mu\nu} = \text{diag}\{1, -1, -1, -1\}$. Throughout, we use the natural units $\hbar = c = 1$, and choose $e > 0$ so that the electron has electric charge $-e$. We employ rationalized Heaviside–Lorentz units, and the fine-structure constant is related to the charge via $\alpha = e^2/4\pi$. The coupling-constants for the $SU(3)_c \times SU(2)_L \times U(1)$ gauge structure of the Standard Model are denoted respectively as g_3 , g_2 , g_1 , and we employ coupling-constant phase conventions analogous to electromagnetism for the other abelian and nonabelian covariant derivatives of the Standard Model. The chiral projection operator for left-handed massless spin one-half particles is $(1 + \gamma_5)/2$, and in analyzing systems in d dimensions, we employ the parameter $\epsilon \equiv (4 - d)/2$. What is meant by the ‘Fermi constant’ is discussed in Sect. V–2.

Amherst, MA, 2013