Elementary Particle Physics

This modern introduction to particle physics equips students with the skills needed to develop a deep and intuitive understanding of the physical theory underpinning contemporary experimental results.

The fundamental tools of particle physics are introduced and accompanied by historical profiles charting the development of the field. Theory and experiment are closely linked, with descriptions of experimental techniques used at CERN accompanied by detail on the physics of the Large Hadron Collider and the strong and weak forces that dominate proton collisions. Recent experimental results are featured, including the discovery of the Higgs boson. Equations are supported by physical interpretations, and end-of-chapter problems are based on data sets from a range of particle physics experiments including dark matter, neutrino, and collider experiments. A solutions manual for instructors is available online. Additional features include worked examples throughout, a detailed glossary of key terms, appendices covering essential background material, and extensive references and further reading to aid self-study, making this an invaluable resource for advanced undergraduates in physics.

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Elementary Particle Physics

An Intuitive Introduction

ANDREW J. LARKOSKI
Reed College

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Cambridge University Press
978-1-108-49698-8 — Elementary Particle Physics
Andrew J. Larkoski
Frontmatter
More Information

For Patricia and Henry

Contents

Preface — *page* xiii
Overview of This Book — xiv
Acknowledgements — xviii

1 Introduction — 1
1.1 A Brief History of Forces — 2
1.2 The Standard Model of Particle Physics — 3
1.3 The Large Hadron Collider — 5
1.4 Units of Particle Physics and Dimensional Analysis — 8
Exercises — 10

2 Special Relativity — 15
2.1 Symmetries and Their Consequences — 15
2.1.1 Rotational Invariance — 17
2.1.2 Relativistic Invariance — 19
2.1.3 Applying Relativity — 22
2.2 Relativistic Wave Equations — 25
2.2.1 The Klein–Gordon Equation — 26
2.2.2 The Dirac Equation — 32
2.2.3 Electromagnetism — 37
Exercises — 44

3 A Little Group Theory — 51
3.1 Groups as Symmetries — 51
3.2 The Rotation Group — 54
3.2.1 Two-Dimensional Rotations: SO(2) — 55
3.2.2 Three-Dimensional Rotations: SO(3) — 57
3.2.3 SO(3), SU(2), and Spin — 60
3.3 Isospin and the Quark Model — 63
3.3.1 Isospin — 64
3.3.2 What is a “Particle”? — 68
3.3.3 The Quark Model — 70
3.4 Why the Photon Has Two Polarizations — 72
Exercises — 75

4 Fermi's Golden Rule and Feynman Diagrams 79
4.1 Invitation: The Barn 80
4.2 Scattering Systematics 81
4.2.1 The Scattering Cross Section 85
4.2.2 Fermi's Golden Rule 88
4.3 Feynman Diagrams 92
4.3.1 Diagrams in Physics: Circuits 93
4.3.2 Diagrams in Physics: Electron–Muon Scattering 95
4.3.3 Feynman Diagrams: Summary 100
4.3.4 Feynman Diagrams: Caveat Emptor 101
Exercises 102

5 Particle Collider Experiment 111
5.1 Before Collision: Particle Acceleration 111
5.2 At Collision: Particle Detection 115
5.3 Detector Coordinates 117
5.4 Detector Components 119
5.4.1 Tracking System 120
5.4.2 Calorimetry 122
5.4.3 Muon System 123
5.4.4 Unobservable Neutrinos 124
5.5 After Collision: Triggering and Data Acquisition 127
5.6 Statistical Analyses 128
5.6.1 Statistical Uncertainties 129
5.6.2 Derivation of Poisson Distribution 131
5.6.3 Significance and Discovery 133
Exercises 134

6 Quantum Electrodynamics in e^+e^- Collisions 144
6.1 $e^+e^- \to \mu^+\mu^-$ 144
6.1.1 Solutions to the Massless Dirac Equation 145
6.1.2 Helicity Configurations 147
6.1.3 Calculating the Cross Section 152
6.1.4 Inclusive Cross Sections 154
6.1.5 Exclusive Cross Sections 155
6.2 $e^+e^- \to$ Hadrons 157
6.2.1 Inclusive Hadronic Cross Sections 157
6.2.2 Properties of the Inclusive Cross Section: Color 158
6.2.3 Properties of the Inclusive Cross Section: Spin 161
Exercises 163

7 Quarks and Gluons 170
7.1 Crossing Symmetry 170
7.1.1 Electron–Quark Scattering 173

7.2 Deeply Inelastic Scattering 175
7.2.1 Physical Interpretation of Bjorken Scaling 180
7.3 Three-Jet Events 188
7.3.1 The Glue That Binds the Proton 189
7.3.2 External Gluon Wavefunction 190
7.3.3 Fermion Propagator 192
7.3.4 The Cross Section for $e^+e^- \to q\bar{q}g$ 193
7.3.5 Tests of a Spin-1 Gluon 197
7.4 Spinor Helicity 204
Exercises 205

8 Quantum Chromodynamics 213
8.1 Color Symmetry 213
8.2 Non-Abelian Gauge Theory 217
8.2.1 Covariant Derivative 218
8.2.2 Connections and Curvature 220
8.3 Consequences of Quantum Chromodynamics 225
8.3.1 Masslessness of the Gluon 225
8.3.2 Gluon Degrees of Freedom 226
8.3.3 Self-Interaction of the Gluon 226
8.3.4 The Running Coupling and Asymptotic Freedom 229
8.3.5 Low-Energy QCD 236
Exercises 239

9 Parton Evolution and Jets 246
9.1 Scale Transformations 246
9.1.1 Scale Invariance of QCD 250
9.1.2 Fractals and Scale Invariance 252
9.2 Parton Evolution 253
9.2.1 Collinear Divergences in QCD 253
9.2.2 Energy Dependence of Parton Distributions 256
9.2.3 Physical Interpretation of the DGLAP Equations 259
9.3 Jets 262
9.3.1 All-Orders Predictions: Thrust 264
Exercises 270

10 Parity Violation 279
10.1 Decay of the Neutron 279
10.2 Discrete Lorentz Transformations 281
10.2.1 Parity Transformations 281
10.2.2 Time Reversal and Charge Conjugation 285
10.2.3 CPT Theorem 287
10.3 Parity Violation in Nuclear Decays 288
10.3.1 Consequences of Parity Violation 291

10.4 The $V-A$ Theory 292
10.4.1 Decay of the Muon 293
Exercises 300

11 The Mass Scales of the Weak Force 309
11.1 Problems with the $V-A$ Theory 309
11.2 Spontaneous Symmetry Breaking 311
11.2.1 Quantum Mechanics Analogy 311
11.2.2 Goldstone's Theorem for the Mexican Hat Potential 316
11.2.3 Higgs Mechanism in Superconductivity 317
11.3 Electroweak Unification 320
11.3.1 Properties of the Weak Force Carriers 320
11.3.2 Spontaneous Breaking of Electroweak Symmetry 324
11.3.3 The Broken Weak Theory 327
11.3.4 Four Predictions of the Broken Weak Theory 330
Exercises 343

12 Consequences of Weak Interactions 349
12.1 Flavor Mixing in the Weak Interactions 350
12.2 The Weak Interactions in the Quark Sector: CP Violation 352
12.2.1 Weak Interactions of Charged Leptons 352
12.2.2 Weak Interactions of Quarks 357
12.2.3 CP Violation of the Weak Interactions 361
12.2.4 Fermion Masses in the Standard Model and Tests of Unitarity 368
12.2.5 CP Violation and the Early Universe: Sakharov Conditions 370
12.3 The Weak Interactions in the Lepton Sector: Neutrino Mixing 372
12.3.1 Neutrino Oscillations 373
12.3.2 Neutrino Oscillation Measurement 383
12.3.3 Neutrino Astrophysics 385
Exercises 387

13 The Higgs Boson 393
13.1 Searching for the Higgs Boson at LEP 394
13.1.1 $e^+e^- \to Z$ 395
13.1.2 $e^+e^- \to H$ 399
13.1.3 $e^+e^- \to ZH$ 401
13.2 Searching for the Higgs Boson at Tevatron and LHC 406
13.2.1 $pp \to H$ 407
13.2.2 $pp \to H \to W^+W^-$ 413
13.2.3 The Golden Channels: $pp \to H \to \gamma\gamma$ and $pp \to H \to 4\ell$ 415
13.3 Properties of the Higgs Boson 422
13.3.1 Scalar Potential Coupling λ 422

Cambridge University Press
978-1-108-49698-8 — Elementary Particle Physics
Andrew J. Larkoski
Frontmatter
More Information

13.3.2 Coupling Strength Proportional to Mass 423
13.3.3 Spin-0 424
Exercises 427

14 Particle Physics at the Frontier 433
14.1 Neutrino Masses 433
14.2 Dark Matter 436
14.3 Higgs Self-Coupling 437
14.4 End of Feynman Diagrams? 439
14.4.1 Failure of Convergence of Feynman Diagrams 439
14.4.2 More Efficient Calculational Techniques 442
14.5 The Future of Collider Physics 444
14.5.1 International Linear Collider (ILC) 444
14.5.2 Circular Electron Positron Collider (CEPC) 445
14.5.3 Future Circular Collider (FCC) 445
Exercises 447

Appendix A Useful Identities 449

Appendix B Review of Quantum Mechanics 454

Appendix C Particle Physics Jargon Glossary 461

Bibliography 466
Index 482

Cambridge University Press
978-1-108-49698-8 — Elementary Particle Physics
Andrew J. Larkoski
Frontmatter
More Information

Preface

Not only God knows, I know, and by the end of the semester, you will know.

Sidney Coleman

Particle physics is a subject that strikes both awe and fear into students of physics. Awe because particle physics is extremely far-reaching: its realm ranges from the inner workings of atoms to the mechanisms for fusion in the center of stars to the earliest moments of the universe. From a small number of fundamental principles, all of these phenomena can be consistently described and understood. On the other hand, fear because particle physics is notorious for being a mathematically dense and abstract topic, and one for which its experimental validation is often reduced to interpreting obscure plots. Fancy mathematics can be mistaken for physical rigor, and a mathematics-heavy approach to particle physics often hides a much simpler structure.

Textbooks on particle physics for undergraduates are often organized historically, which can add to confusion. Throughout the twentieth century, more and more was learned about the subatomic world, but the way it progressed was never linear. For example, hundreds of particles that we now call hadrons were discovered in the mid-twentieth century, with no clear organizing principle at the time. It wasn't until the development of the strong force, quantum chromodynamics (QCD), in the 1970s that an explanation of all of these hadrons as combinations of only five fundamental particles, the quarks, was firmly established. Only after introducing this zoo of particles would a textbook that proceeds historically identify the simple principles underlying this structure. The **why** should take precedence over **how** physical phenomena manifest themselves, and a book that builds from the ground up can't proceed historically.

Additionally, particle physics is very much an active field of physics with new data and discoveries. A modern book on particle physics needs to include discussions of recent results, the most prominent of which is the discovery of the Higgs boson at the Large Hadron Collider (LHC) in 2012. However, to describe and motivate why the discovery of the Higgs was so important requires significant background, covering topics ranging from electroweak symmetry breaking to the dynamics of proton scattering, quantum loops in Feynman diagrams, particle detector experiments, and statistical analyses, among others. Therefore, in some sense, there simply isn't space in a modern particle physics textbook to describe every major result since the 1920s. By the end of the course a student should be able to understand almost any plot produced by the experiments at the LHC.

This book was born out of the particle physics class at Reed College, which I taught during the spring semester of 2017. The twin goals of this textbook are to be up-to-date and to build concepts from the ground up, based firmly on physical intuition. This book provides an intuitive explanation for the physics being introduced. This is necessarily an ahistorical approach, which has consequences for how topics are introduced and motivated as compared to other textbooks. With a modern viewpoint, we can identify past results and predictions that had an outsized impact on the field as a whole. For example, interpreting results at the LHC requires use of proton collision simulations, referred to as parton shower programs. The physical basis for the parton shower is the DGLAP splitting functions, which were developed in the 1970s as a consequence of QCD. Thus it is vital for interpretation of results from the LHC to understand and appreciate the DGLAP splitting functions. Chapter 9 covers this topic.

A potential drawback of this approach is that it is not encyclopedic. Any undergraduate textbook on particle physics suffers from this, however. A full mathematical treatment of particle physics requires quantum field theory, which is (at least) a year-long graduate-level course. So, there will be some things for which the motivation is less than ideal. The most prominent of these is the construction and calculation of Feynman diagrams, which are motivated in this book in analogy to circuit diagrams, but their mathematical justification lies well beyond such a course. Similarly, to understand all of the intricacies of experimental measurements requires years of actually working on the experiments. Only then can you understand where the systematic uncertainties come from, the limitations of your detector, and all of the blood, sweat, and tears that went into a measurement, which is sometimes just a single number.

Overview of This Book

This textbook is organized into three broad themes:

- The Tools of Particle Physics
- The Strong Force
- The Weak Force.

I don't claim to have invented this organization; at least two other modern particle physics textbooks use a similar organizational scheme. However, I do think that this is the correct approach for such a course. Of the four fundamental forces, three are relevant for particle physics (strong, weak, electromagnetism), and of those three, the strong and weak forces have no long-distance classical counterpart. So, it is natural, then, to focus on them, especially because their phenomena dominate the description of the physics probed at the LHC.

The Tools of Particle Physics

The first five chapters cover the tools of particle physics and are material that I think is required in such a course. Chapter 1 sets the stage, introducing the Standard Model of Particle Physics and the LHC to frame the content of the rest of the book. Additionally, just like at the beginning of an introductory physics course, appropriate units to describe particle physics phenomena are introduced. Chapter 2 is a review of special relativity and relativistic wave equations from a Lagrangian viewpoint. The Lorentz invariance of the wave equations is verified mathematically, as well as understood physically, by demonstrating that total angular momentum of the Klein–Gordon and Dirac Lagrangians is 0. Perhaps the fundamental guiding principle of particle physics is Noether's theorem, which provides the connection of group symmetries and conservation laws. Chapter 3 introduces groups and their importance in particle physics, starting from identification of the symmetries of an equilateral triangle. This chapter also motivates Hermitian operators in quantum mechanics from probability conservation and the way this framework enables a concrete definition of what a "particle" is. Fermi's Golden Rule and Feynman diagrams are introduced in Chapter 4. While this chapter will provide enough detail for students to perform calculations of Feynman diagrams and construct cross sections, my goal here is to de-emphasize Feynman diagrams somewhat, as compared to some other textbooks. Feynman diagrams are particle physics, but particle physics is much more than just Feynman diagrams. Chapter 5 introduces the LHC and its two largest experiments, ATLAS and CMS. Detailed discussions of proton acceleration, proton collision, detector components, and statistics are provided to present students with the tools to understand experimental results. Similar topics are not often covered in other books.

The Strong Force

Chapters 6 through 9 cover the phenomena of the strong force, QCD. Chapter 6 is the introduction to QCD, where electron–positron collisions are studied in detail. This chapter begins with a detailed study of $e^+e^- \to \mu^+\mu^-$ scattering within quantum electrodynamics (QED). This provides a framework for discussion of the importance of inclusive cross sections and evidence for both the three colors of QCD as well as the spin-1/2 nature of quarks. With evidence for quarks established, Chapter 7 introduces partons and Bjorken scaling as evidence for point-like, nearly free constituents of the proton. A detailed interpretation of Bjorken scaling is provided by Fourier transforming to position space, where its consequences become clear. This chapter also discusses evidence for the gluon from three-jet events, in analogy to photon emission in QED. These pieces then set the stage for Chapter 8 in which the three colors of QCD, the spin-1 gluon, and the spin-1/2 quarks are put together in a consistent theoretical framework. Physical arguments are provided to augment the geometrical construction of QCD and non-Abelian gauge theories in general. This chapter also surveys some of the more non-trivial consequences of QCD, of which the most profound is the property of asymptotic freedom. The discussion of QCD ends in Chapter 9 with its most shocking prediction: the formation of high-energy, collimated streams of particles called jets. The prediction of jets is guided by the observation that QCD at high energies is approximately scale invariant, which has consequences for parton evolution manifested in the DGLAP equations. Very uniquely, this chapter also has a simple, explicit, all-orders prediction of jet structure for an observable in electron–positron collisions called thrust.

The Weak Force

The final third of the book, Chapters 10 through 14, is devoted to the weak force. Chapter 10 invites the reader to study this force with the observation of parity violation in nuclear decays, from detailed discussions of the Wu experiment and its motivation. The $V - A$ theory is introduced as a phenomenological model of parity violation and the decay rate of the muon is calculated. Numerous idiosyncrasies of this parity-violating interaction are mentioned in Chapter 11. These motivate spontaneous symmetry breaking and the Higgs mechanism, which is introduced by analogy with similar situations in quantum mechanics. By connecting electromagnetism with charged and neutral currents observed in electron–positron scattering, we are able to construct the electroweak theory and its pattern of symmetry breaking. Consequences of the weak force for properties of the fermions of the Standard Model is the topic of Chapter 12. The mechanism of flavor mixing and CP violation in the quark sector is provided in detail and motivated by non-commutation of mass and flavor operators. Neutrino oscillation is also introduced, but no apology is made for imprecision of the calculation. When and why neutrinos oscillate was only relatively recently clearly elucidated and involves ideas of entanglement, interference, and decoherence. Chapter 13 is the culmination of the book with the discovery of the Higgs boson. This is also one of the few places in this book where a historical organization is presented, with the method of discovery of the Higgs motivated from searches at the Large Electron–Positron Collider (LEP), to early searches at Tevatron and LHC, and finally to its discovery in 2012. A review of the current established properties of the Higgs closes the chapter. As with any book on particle physics, the final chapter, Chapter 14, looks forward to the open questions and where the field will go in the future.

Key Features

Worked Examples and Supplementary Appendices

Along with the intuitive discussion of topics, each chapter contains worked examples focused around understanding a relevant measurement. There is really nothing as satisfying in physics as seeing a prediction which started from some very simple assumptions validated by concrete data. The goal of the worked examples is both to show the student the application of these ideas and to share the excitement of working in the field of particle physics, where experiment and theory are so closely connected. Additionally, appendices provide background or summary information as a quick and easy reference for students. The appendices cover a background of quantum mechanics (likely from a perspective students haven't seen), details about Dirac δ-functions, Fourier transforms, a collection of results from the main body of the text, and a bibliography of suggested reading for delving further. Key particle physics terms are emphasized in bold throughout the text, and a glossary of a substantial number of the terms is also provided, as significant jargon is used in particle physics.

Exercises on Recent Results

The exercises at the end of each chapter cover a broad range of applications to test the student's understanding of the topic of the particular chapter. Most of the exercises are relatively standard calculations for the student, but two or three of the exercises are in much more depth and involve studying data from experiment in the context of the material of the chapter. This broadens and deepens the topics covered in the worked examples, and exposes students to relevant experiments and results that couldn't be covered within the main text. Examples of these exercises include analyzing dark matter mass and interaction rate bounds, estimating the mass of the top quark from its decay products, studying LHC event displays, a simple extraction of quark parton distribution functions from data for the Z boson rapidity, lowest-order predictions for jet masses at the LHC, predicting neutrino scattering rates in the IceCube experiment, validating the left-handed nature of the top quark decay, and estimating backgrounds in searches for the Higgs boson decay. Additionally, the final exercise in each chapter is the statement of an open problem in particle physics, intended to expose the student to some of the big questions of the field.

Historical Profiles

It is sometimes easy to forget that physics is a human endeavor done by people. I have included historical profiles throughout the text to provide context and a bit of humanity to the topic. I have highlighted scientists who contributed significantly to the subject at hand, but have attempted to focus on those people who haven't been overly deified (e.g., not Fermi or Feynman). Historical profiles include mini-biographies of Emmy Noether (p. 16), Paul Dirac (p. 34), Fabiola Gianotti (p. 127), Mary Gaillard and Sau Lan Wu (p. 188), Gerardus't Hooft (p. 235), Guido Altarelli (p. 258), Chien-Shiung Wu (p. 291), Helen Quinn (p. 367), and Benjamin Lee (p. 407). A few "legendary" particle physics stories are presented, including the etymology of the barn unit of cross section (p. 81), the origin of penguin diagrams (p. 337), and the Higgs boson discovery announcement (p. 417).

Extensive In-Text Referencing

I have also worked to provide extensive (and where possible, exhaustive) references to the original literature for every topic covered in this book. References are provided as footnotes, so that one can immediately identify the paper without flipping back and forth to the end of the chapter or end of the book. I have also collected all in-text references in the bibliography for ease of searching. The only way that the referencing could be as thorough as it is is through innumerable searches of my own on InSpire (`http://inspirehep.net`) and arXiv (`http://arxiv.org`). InSpire is an online database of essentially every publication relevant to particle physics in history. The reference format used in this book is that provided by InSpire, which is ubiquitous in technical papers on particle physics. arXiv is the preprint archive for particle physics (and now many more fields), where scientists post their completed papers before journal publication. It enables the rapid transmission of ideas, and every paper on particle physics written in the past 25 years is available there for free.

How to Use this Book

My class at Reed College had about 24 students in it with roughly an equal mix of juniors and seniors (third- and fourth-year undergraduates). This was an interesting challenge for a subject like particle physics: the seniors had completed classes on electromagnetism and quantum mechanics, while the juniors were taking quantum mechanics concurrently. This required a shift in the presentation of the material focusing on analogies and physical intuition, hence the motivation for this book. The level of the course seemed to strike a happy medium in which both sets of students were satisfied with the level of the lectures. That said, I do feel that a course on particle physics requires students to have completed at least a first semester of electromagnetism and a sophomore-level (second-year) modern physics course. Not having previous exposure to quantum mechanics or classical field theory severely restricts the breadth of topics that can be covered.

In the semester-long course of 26 80-minute lectures, I succeeded in introducing most of the topics covered in this book. However, that isn't to say that much time was spent on them. For example, the treatment of neutrino oscillations in class consisted of a single lecture, and most of that time was used to perform the standard two-state interference calculation. To completely and honestly motivate the reason for neutrino oscillation would require at least one more lecture on the topic, which may not be possible depending on time constraints and interests of the instructor. Nevertheless, I do think that topics covered in every chapter of this book could fill a course, regardless of the time available.

That said, some topics are more important than others. As mentioned earlier, I see the first five chapters of this book as required. Units, special relativity, group theory, Feynman diagrams, and experimental techniques are fundamental to being able to speak the language of particle physics. A substantial number of experimental measurements are provided in these first chapters so that, even if the course does not cover much more, students would see modern results. For a course with limited time, a number of topics in the strong and weak force sections could be skipped. For the strong force, I view Chapter 6, Chapter 7 through the beginning of Section 7.3, and the consequences of QCD discussed in Section 8.3 as required. If there's a bit more time in the course, then covering one of the parton evolution or jets topics in Chapter 9 would add significant content. For the weak force, I view Chapter 10, the first half of Chapter 11, and Section 13.2 as required. With a bit more time, a course could cover one of the topics of Chapter 12 (quark mixing or neutrino oscillations), or add more details about the Higgs boson discovery in Chapter 13.

Finally, I have attempted to keep the prose light and the enthusiasm high because, after all, this is physics and it should be fun. I hope students can enjoy reading this book and gain an appreciation for this beautiful subject.

Acknowledgements

First, I want to thank the 2017 Physics 366 class at Reed College for their enthusiasm for particle physics and especially their feedback on the original exercises for that course.

Much has improved in going from hand-written lectures to typeset chapters, and these students were the original motivation.

The existence of this textbook and the exposition contained in it are due to a large number of people who have influenced the way I think about particle physics. I have had the exceptional fortune to have excellent mentors and advisors throughout my career who were patient enough to answer my questions and provide detailed explanations. I thank Brian Batell, David Ellis, Stephen Ellis, Matthew Schwartz, Iain Stewart, Matthew Strassler, Jesse Thaler, and especially my Ph.D. advisor Michael Peskin for their guidance. As a graduate student I benefitted from amazing fellow students at Stanford with whom I had numerous illuminating discussions, reading groups, and seminar series. I wish to especially thank Camille Boucher-Veronneau, Kassahun Betre, Randall Cotta, Martin Jankowiak, Jeffrey Pennington, and Tomas Rube.

The intuitive approach of the explanations in this book is due to several influences. As an undergraduate, I worked as a teaching assistant for the Physics Education Group at the University of Washington, where physics tutorials were developed. I thank Mila Kryjevskaia, Peter Shaffer, and MacKenzie Stetzer for their guidance, helping me focus on the fundamental issues and work to a qualitative explanation of physical phenomena. In graduate school, I benefitted from excellent courses on particle physics taught by Savas Dimopoulos and Michael Peskin. While their teaching styles differed widely, I have attempted to balance Savas's heuristic approach with Michael's "shut up and calculate" approach in this book. I owe a huge debt of gratitude to Patricia Burchat, for whom I was a teaching assistant in her undergraduate courses on quantum mechanics and particle physics. Patricia's excellent courses were the first time that I taught particle physics to undergraduates and were some of the first physics classes at Stanford to employ physics by inquiry techniques. I also thank Lauren Tompkins and Paul Simeon for discussions and sharing of materials from the particle physics class that Lauren taught at Stanford in 2017.

Getting this book to completion was due to a number of people. I thank my colleague Joel Franklin at Reed College for suggesting that I turn my lecture notes into a book and publish it. The writing benefitted from my participation in the Stanford Writers' Group, and especially from comments from Priscilla Burgess. Bruce Van Buskirk at Reed College was very helpful in addressing questions that I had about copyrights. I thank Fred Olness for inviting me to lecture at the 2017 CTEQ Summer School, where I developed the explanation for the resummation of thrust presented in Chapter 9. I thank my editors at Cambridge University Press, Nicholas Gibbons and Heather Brolly, for their comments and criticisms on the manuscript, and especially to Heather for her assistance in making the final product so polished.

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In writing and describing the physics presented in this book, I relied on a number of well-worn references. Michael Peskin and Daniel Schroeder's *An Introduction to Quantum Field Theory* and Matthew Schwartz's *Quantum Field Theory and the Standard Model* were particularly used, especially Schwartz's description of the spin group (in my Chapter 3) and Peskin and Schroeder's description of the β-function and asymptotic freedom (in my Chapter 8).

I thank my parents, Tim and Colleen, who always supported my education and have wholeheartedly attempted to understand my world of physics academia.

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