Phenomenology of Particle Physics

Written for a two-semester Master's or graduate course, this comprehensive treatise intertwines theory and experiment in an original approach that covers all aspects of modern particle physics. The author uses rigorous step-by-step derivations and provides more than 100 end-of-chapter problems for additional practice to ensure that students will not only understand the material but also be able to apply their knowledge. Featuring up-to-date experimental material, including the discovery of the Higgs boson at CERN and of neutrino oscillations, this monumental volume also serves as a one-stop reference for particle physics researchers of all levels and specialties. Richly illustrated with more than 450 figures, the text guides students through all the intricacies of quantum mechanics and quantum field theory in an intuitive manner that few books achieve.

André Rubbia is a professor in experimental particle physics at ETH Zurich. After obtaining his Ph.D. in particle physics at the Massachusetts Institute of Technology, he worked on the research staff at CERN in Geneva, Switzerland. His research interests include high-energy physics and, in particular, studies of neutrino properties, and he has been a primary contributor to the development of novel particle detectors. He has proposed, developed, and led several international projects in Europe, Asia, and the USA. While continuing his focus on research in particle physics, he has acquired an extended experience in teaching undergraduate and Master's-level courses.

Phenomenology of Particle Physics

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To my family – wife and children

"Life can only be understood backwards; but it must be lived forwards."
Soren Kierkegaard

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Preface

The purpose of this textbook is to teach particle physics, addressing both its phenomenology and its theoretical foundations. **Why bother about the phenomenology of particle physics and quantum field theory?** I would say that one of the main reasons is because the current Standard Model of particle physics can account for (almost) all observed phenomena down to length scales of $\sim 10^{-18}$ m. That's truly impressive! We only know how to compute observables (mostly probabilities for various scattering or decay processes) at those scales using quantum field theories, but we can compute such observables very precisely, and high-precision experiments compare extremely well with those predictions. This is quite a formidable achievement. There are indeed exceptions and the hope is that further theoretical and experimental developments will one day lead to a more complete theory of elementary particles. In the meantime, the Standard Model is the best of what we have, although it is generally accepted that it cannot be the "ultimate theory of everything."

This textbook is primarily addressed to Master's and Doctoral students, as well as young Postdocs. A solid knowledge of classical physics and non-relativistic quantum mechanics coupled to a mastery of mathematical tools is assumed. **Symmetries** and mathematical groups will play an important role throughout the book. We present particle physics according to the so-called **inductive method**, which comes closest to the methodology of real-life progress in physics: starting with some key experiments, the new science is developed. However, this is not the only path. On the contrary, particle physics is filled with examples where theoretical developments guided new experimental discoveries. When this was the case, we present the material in that order. Clearly, students and researchers who want to stay at the forefront of the field need to master both experimental and theoretical aspects. This is one of the reasons I wrote this book, as will be explained below.

The motivation to write this textbook came from my lecturing the course on particle physics at ETH Zurich, since the end of the 1990s. It started off from my hand-written notes to an electronic version that was distributed to the students. After more than two decades of teaching lectures to Master's and Doctoral students at ETHZ, it seemed to me desirable to compile and cleanup the material which formed the basis of the lecture. The substance of the course came from two main sources: on the one hand, I had prepared quite a lot of material based on my own personal experience as a young student and throughout the years as a researcher. On the other hand, I had also accumulated many bits and pieces from different sources, the most relevant ones being listed in the "Textbooks" section at the end of this book. **During the course of my lecturing, this material was subjected to repeated communication with bright ETHZ students, who provided a constant source of constructive questions and criticisms, which triggered on my side the quest for possible improvements**. So, teaching was an opportunity to develop and perfect a vast amount of material under a single coherent form. Based on the very positive feedback I received, I completed and significantly expanded these notes into the present textbook to provide a more coherent and comprehensive version, that would cover both theoretical and experimental aspects of the subject. **While the course was a phenomenological one, my desire was always to remain as mathematically rigorous as possible, for we simply cannot ignore the truly fundamental interplay between theory and experiment in particle physics**. To cite an example that comes to my mind, let us consider one of the brightest physicists of the twentieth century: Enrico Fermi. Within the many successes of his extraordinary career, I was always struck by the fact that he developed the first theory of weak interactions and also ran the first nuclear reactor. What extraordinary achievements in both theory and experiment! These facts were a driving "ideal" to develop the basic structure of this book. The structure of the chapters is graphically shown in Figure 1. The basic idea is to start from classical Newtonian mechanics and

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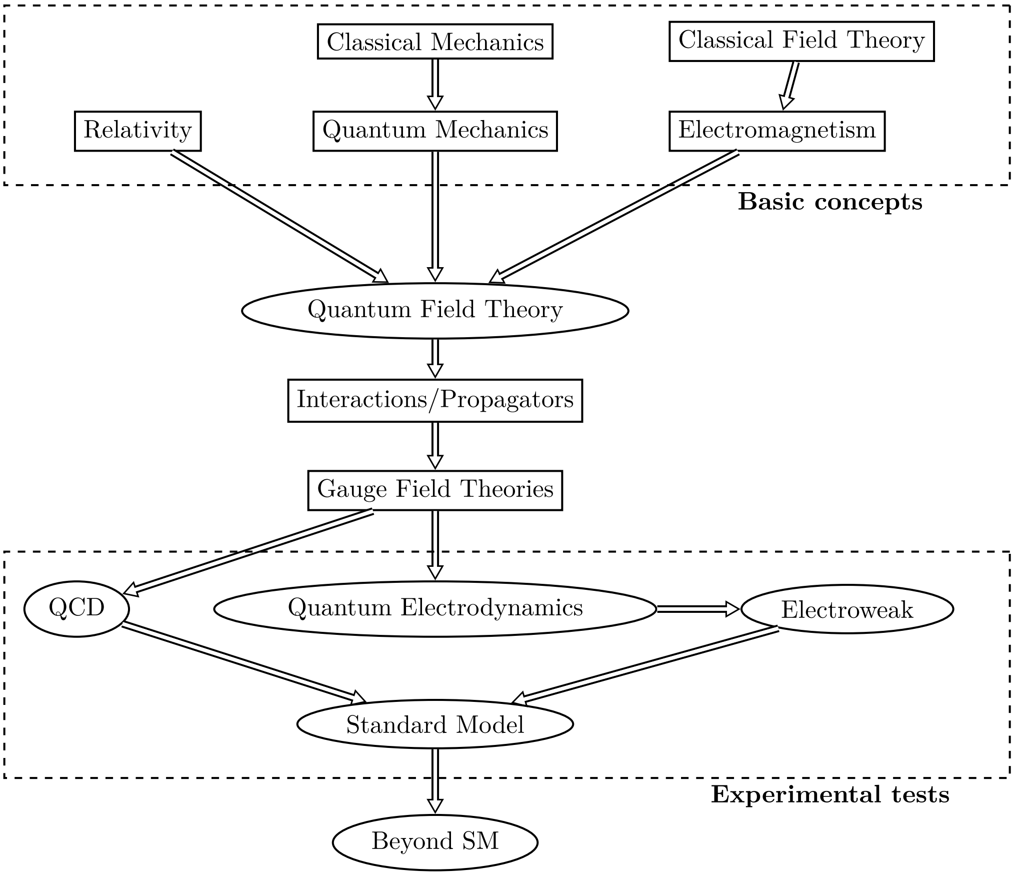

Figure 1 Overview of the material discussed in this book.

Maxwell's electromagnetism, and their failed attempt to explain *all* experimental results, in particular at the atomic level, collected towards the end of the nineteenth century and beginning of the twentieth. On the one hand, it was known that Newtonian mechanics failed at high velocities and needed to be addressed by Einstein's special relativity. On the other hand, it was realized that the description of atomic processes required theories to be "quantized." This means that for **any** given classical theory, one should look for a **quantum theory** that reduces to the classical one in the classical limit! Since Maxwell's theory was known before the actual Quantum Mechanics (QM), the attempts to quantize it actually preceded the developments of QM. But QM was historically developed first as a very successful non-relativistic quantum theory. QM and its **first quantization** introduced new concepts beyond those of classical physics. In particular, QM is "indeterminate," which states that there are physical measurements whose results are not definitely determined by the state of the system prior to the measurement. This understanding represented an incredible step forward in the description of the atomic and subatomic world. As we will discover throughout the chapters, the consequence of combining special relativity with QM implies that energy can quite generally be converted into quanta and particles, and vice versa. Particles are said to be "created" or "annihilated" and conservation of quantum numbers requires the existence of matter as well as antimatter! Theoretically, a relativistic QM theory requires one to abandon the single-particle approach of QM in favor of a multi-particle framework in the context of quantum field theory (QFT). This step involves what is commonly called the **second quantization**. A big success of QFT is

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its ability to describe interactions and propagators. Gauge field theories introduce the concept that the laws of Nature, to be described within the QFT framework, are constrained by local symmetries. From this concept emerge the three basic descriptions of the electromagnetic, weak, and strong interactions. Inherent to these theories arises the issue of **divergences**, both at large distances (IR divergence) and at short distances (UV divergence). There may be a true physical cutoff at short distances and QFT might not be able to handle physics at infinitely small distances. On the other hand, "effective" quantum field theories with a finite cutoff do make sense and allow us to calculate processes over a very large range of energies. In this context, **the Standard Model (SM) represents the merging of the unified electroweak theory and the strong interaction and is considered the most successful effective theory we have at our disposal today**. But, as the SM cannot be the theory of everything, one seeks a theory "beyond the SM." Whether this theory is just an extended QFT or something completely new is still the subject of debate.

So, this is the program that we would like to pursue. It is a challenge to introduce both experimental and theoretical aspects of a vast field within a single volume. Of course, an introductory course cannot (and should not) cover exhaustively the entire field. Consequently, it has not been possible to be fully comprehensive and much excellent literature exists that treats most of the covered subjects often in more detail. **My hope is that the reader will find this textbook sufficient to get a rock-solid start on the subject**, inviting him/her to look into the list of books and references listed in the "Textbooks" and "References" sections to dive further into this fascinating field. I do believe, however, that a deepening of knowledge beyond the level of this textbook will likely require the young reader to select a specialized "direction," either in experimental or in theoretical particle physics.

I have worked to provide references for every topic that is covered in the book. For the most important topics, I have also included extensive extracts and figures from the original literature, immediately available without the need to access the original publication. Of course, this does not (and should not) preclude the reader also accessing directly the original papers. In this context, it is worth mentioning the existence of 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 arXiv is a preprint server for many fields, including particle physics, where scientists post their completed papers before journal publication. It enables the rapid transmission of ideas, and almost every paper on particle physics written in the past 25 years is available there for free!

Let me conclude with several acknowledgments. For my lectures and for the perfecting of the manuscript, I am greatly indebted to all the students and assistants who actively participated in the course and the exercises over the years and who have carefully read and commented on the entire text in great detail. It is impossible to list them all. However, with my apologies to those I might have inadvertently omitted, I sincerely thank Dr. Andreas Badertscher, Prof. Antonio Bueno, Dr. Laura Molina Bueno, Prof. Mario Campanelli, Tit. Prof. Paolo Crivelli, Dr. Sebastien Murphy, Dr. Balint Radics, Dr. Christian Regenfus, Katharina Lachner, Matthias Schlomberg, and very specially Loris Pedrelli and Alexander Stauffer for their invaluable help and for investing a significant fraction of their time to provide me many corrections, several constructive criticisms, and very useful feedback.