Preface

The present theory of elementary particles and of their interactions known under the name of the Standard Model (SM) [1–3] is a relativistic quantum field theory with a specific local gauge symmetry dictated by nature. It incorporates the theory of strong interactions (quantum chromodynamics, QCD) and the unified theory of electroweak interactions (quantum flavor dynamics, QFD). It is a theoretically adequate description of leptons, quarks and their fundamental interactions in accordance with the principles of unitarity, causality, Lorentz invariance, quantum mechanics, and gauge invariance. As such it combines the main achievements of the physics of the twentieth century and includes the Maxwell theory of electromagnetism formulated already in 1865.

The dream of physicists for many centuries was to find a "world formula" by help of which all the phenomena surrounding us could be described and explained. In particle physics the first step toward such a formula is the Lagrangian of the SM, which summarizes the particle content of the present theory and describes the basic structure of particle interactions as we know them at present. As the SM is unable to explain all phenomena around us, other world formulas in the form of Lagrangians appear in the literature. They generally contain all particles and interactions of the SM, but in addition new particles and new interactions are present in these models. As of 2020, we do not know which of these models will turn out to be the next step toward our dream, but it is exciting that in the coming years we might know it.

To a person, not familiar with the subject, these world formulas look like hieroglyphics that appear to us when we visit Egyptian pyramids. Yet, to trained particle physicists, similar to trained archaeologists, these formulas reveal a vast amount of information about the physics of elementary particles. In these formulas the basic dynamics of particle interactions in a given model are compactly encoded, and it is in principle only a matter of will and time to translate this information into the more common language and to derive testable predictions.

In practice the derivation of physical predictions from the Lagrangian of the SM and of its extensions is often not an easy task. It requires generally certain mathematical skills and the knowledge of sophisticated field theoretical methods. Moreover on many occasions the tools that we presently have at our disposal are not yet powerful enough to allow for accurate predictions. Fortunately there exist also many quantities for which accurate calculations have been already made and can be already compared with experimental results. Such a comparison is in fact most exciting as it allows testing a given theory. But this is only possible if experimental results for a given quantity are also available, and this is not always the case. In fact, some phenomena take place very rarely, and this requires large and often expensive experiments to measure the probability for seeing them.

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The first main goal of this book is to describe weak decays of mesons, the bound states of quarks and antiquarks and of leptons within the SM. Starting from the Lagrangian of this model we will derive, as far as it is possible, predictions for decay widths, branching ratios, and various observables that can be used to confront this theory with experimental data. Therefore, in addition to more technical, field theoretical aspects of the SM, we will also devote a large part of this book to phenomenological applications of the derived formulas and to the comparison of the SM predictions with experimental data.

The physics of weak decays is a fascinating subject and constitutes an important part of the SM and particle physics in general. There are several reasons for this:

- This sector probes in addition to weak interactions also electromagnetic and strong interactions at short- and long-distance scales. As such it involves the dominant part of the dynamics of the SM.
- It contains most of the free parameters of the SM and consequently plays an important role in their determination.
- The occurrence of a large class of processes that take place only as "loop effects" automatically tests the quantum structure of the theory.
- The renormalization group effects known also from statistical physics play here an important role in view of the vast difference between the weak interaction $O(100\text{ GeV})$ and strong interaction $O(1\text{ GeV})$ scales.
- The nature of the violation of various symmetries such as charge conjugation (C), parity (P), time reversal (T), and CP can be studied very efficiently.
- It is an ideal laboratory for nonperturbative techniques.
- Very importantly, it is a "window" through virtual effects to very short distances, which may shed light on some outstanding questions in particle physics such as the origin of masses and the number of fermion generations as well as hierarchies in the strength of their interactions. In particular weak decays could help us to identify the origin of the matter-antimatter asymmetry observed in the universe, which is necessary for our existence and which is not understood within the SM. They could also shed some light on dark matter.

The last point brings us to the second main goal of this book: the presentation of weak decays within the most popular extensions of the SM. In particular we will develop efficient methods that will allow us to distinguish the predictions of these extensions for weak decays from the SM ones. This may help us to identify new physics (NP) at very short-distance scales well beyond the reach of the Large Hadron Collider (LHC). But even if the LHC would discover NP in the coming years, a detailed study of the properties of discovered new particles and interactions cannot be made only through high-energy collisions but requires very strong involvement of low-energy processes like weak decays of mesons where these new phenomena manifest themselves through quantum effects.

Similar to the SM, its extensions have also been the subject of intensive research in the last forty years. This implies that it is a challenge to describe adequately only the most important advances in this field in one book. Therefore as in any serious expedition, a strategy for reaching our goals is unavoidable. Before presenting this strategy and the related map of our expedition, it is necessary to present two Grand Views: the first one

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dealing with the SM and the second one dealing with some aspects of NP. These grand views will be brief and superficial. They are only meant to help nonexperts to understand at least roughly the map of this book, which will be presented subsequently and most importantly to motivate any reader to join the author in this expedition.

In the latter context let me remark that the failure of the LHC to discover any new particles until now resulted in some frustration in the particle physics community. Often at conferences the speakers show pictures of the Sahara, meaning that until a new very high energy collider is built, no new particles will be discovered. My view, as a flavor physicist, is much more optimistic. It is represented well by the photo on the book's front cover. We are standing on the mainland representing the SM. There is an energy gap represented by the water, which we have to cross in order to reach eventually the NP summits in the far distance. They represent different possibilities for the grander theory. But in order to find out which summits will answer all our questions, we have to cross the glacier and all of its crevasses, which represent various sophisticated technologies in flavor physics necessary to conquer these summits. But the main reason for showing this photo is its stunning beauty similar to the beauty of flavor physics.

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