Introduction

Grand View of the Standard Model

What are the fundamental building blocks of matter? This question is easy to understand, but it took centuries and required tremendous theoretical and experimental efforts to approach an answer. The desire to know what everything is made of led to big scientific achievements, new technologies, and a better understanding of our universe. Since the 1860s we have known that atoms are basic building blocks of matter. But opposed to what was originally thought, they are neither indestructible nor fundamental as they are composed of protons, neutrons, and electrons. The finding that the whole periodic table is made of only three basic ingredients was already a big step forward toward answering the question of what everything is made of. However protons and neutrons are again not fundamental particles but rather complicated objects. Simplified one can say that they consist of three quarks: two up quarks and one down quark for the proton and vice versa for the neutron. It is amazing to know at first sight that everyday objects are made of only up and down quarks and electrons. Nevertheless this is not the end of the story as these quarks have to be bound in protons and neutrons, and this happens with the help of strong interactions that bring in new particles: gluons. Moreover pairs of quarks and antiquarks, not only of up and down quarks but also heavier quarks can also be present deep in protons and neutrons. This shows that the true picture of protons and neutrons is not as simple as often presented to pedestrians. What is amazing is the fact that this picture has been developed only in the last fifty years. This is now where the Standard Model of particle physics (SM) enters the stage.

The SM describes the properties of all elementary particles and three out of the four fundamental forces in nature: the weak force, electromagnetic force, and strong force. From a quantum field theoretical point of view the latter two are called, respectively, quantum electrodynamics (QED) and quantum chromodynamics (QCD). These forces are mediated by the exchange of gauge bosons. The weak force is mediated by the exchange of $W^{\pm}$ and Z^0 boson, the photon γ is the mediator of electromagnetic interactions, and gluons G^a are mediators of strong interactions. Gravity is not included in the SM. It is by far the weakest of the fundamental forces and not relevant for particle physics at the energy scales presently explored in experiments.

The SM sorts the elementary particles by their properties: there are the matter particles with spin-$\frac{1}{2}$ (fermions), the gauge bosons with spin-1, and one scalar particle with spin-0, the so-called Higgs boson. The fermions can be divided into quarks and leptons. The six

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Table I.1 Particle content of the SM.

Fermions: three generations			Gauge Bosons
ν_e	ν_μ	ν_τ	γ
e	μ	τ	G^a
u	c	t	$W^\pm$
d	s	b	Z^0
	Higgs		

quarks – up u, down d, charm c, strange s, top t, and bottom b – feel all three interactions, as they have a weak charge (called weak isospin), an electric charge, and a color charge related to strong interactions. Leptons do not participate in the strong interactions as they are color neutral. The three charged leptons – electron e, muon μ, and tau τ – participate in the electromagnetic and weak interactions, whereas the neutral leptons – the three neutrinos ν_e, ν_μ, and ν_τ – only feel the weak force.

Similar to the periodic table of elements where you have both a horizontal and a vertical order, the SM collects leptons and quarks into three generations as seen in Table I.1. The first generation consists of electron neutrino ν_e, electron e, up u, and down quark d. It is the first generation of particles that all the matter around us is made of. Nothing else at first sight is needed. However there exist also a second (ν_μ, μ, c, s) and a third generation (ν_τ, τ, t, b), which are in principle exact copies of the first generation (same charges and properties as seen in Table 2.1) except that they are heavier and thus unstable. At the end they decay into particles of the first generation. That is why the muon is sometimes called the heavy brother of the electron: They have the same quantum numbers, but differ in mass. Flavor physics studies such transitions between different generations that are mediated by the weak interaction. We cannot answer yet why there are exactly three generations, but so far we could already learn a lot about their properties in studying weak decays.

The SM is a theoretical model based on a (gauge) symmetry principle and very successful in describing and predicting experimental results. From this symmetry principle it follows that all fermions and gauge bosons must be massless, which is obviously not the case. Only photons and gluons are massless. This is now where the Higgs boson (or more precisely the Higgs field together with spontaneous symmetry breaking) enters the scene. It is responsible within the SM for the masses of quarks, charged leptons, and in particular gauge bosons of weak interactions. Even if the discovered nonvanishing neutrino masses around the turn of the millennium were not predicted within this model, its success in describing most of the data made the majority of particle physicists believe in the existence of the Higgs boson, and a lot of effort was put into finding this last missing piece of the SM. Its discovery in 2012 was a great scientific achievement – a true milestone.

The development of the SM was a big step forward to answer our initial question. Nevertheless, we still do not think that the story ends here. Despite its great success the SM does not answer several important questions about the nature surrounding us, and most physicists think that it is only an effective theory of a more fundamental theory. We will now address this important topic. Before continuing we would like to stress that this Grand View and the following one has been written by Jennifer Girrbach-Noe.

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Grand View of New Physics

The ultimate question of elementary particle physics is: What is the fundamental Lagrangian of nature surrounding us? The Lagrangian of the SM is very successful in describing nature at the currently available energy range. The discovery of the Higgs boson completed the particle spectrum of the SM and it is another proof of how well the SM, works. Nevertheless, the SM cannot be the end of the story, and it is for sure not the fundamental Lagrangian of nature. The Lagrangian of the SM loses its validity at the latest at the Planck scale where gravitational effects become noticeable. Most physicists think of the SM as an *effective theory* that has to be replaced by a more fundamental theory above the TeV scale. What the word *effective* really means will hopefully be clear at later stages of our book. For the time being we will list some problems and open questions of the SM.

What Is Dark Matter Made Of?

We know that dark matter-energy makes up around 27 percent of the universe. Ordinary matter that is built of particles of the SM account for only 5 percent of the mass-energy of the universe. The remaining part is dark energy about which we know even less than about dark matter. Consequently we do not understand 95 percent of the universe's energy budget. Dark matter is called dark because it does not interact with photons and thus is electrically neutral and cannot be seen directly with telescopes. However, dark matter has gravitational effects that can be observed. This additional matter is needed to explain the rotational speeds of galaxies, gravitational lensing, and the anisotropies in the cosmic microwave background. Consequently the existence of dark matter is generally accepted, but we have no idea what dark matter is really made of. No particle of the SM can explain it. Some models beyond the SM have appropriate particle candidates for dark matter, e.g., the lightest neutralino in Supersymmetry with R-parity, and the search for this particle is one of major efforts in particle physics.

Why Is There More Matter Than Antimatter in the Universe?

Everything around us is made of matter, from the smallest life forms on Earth to the largest stellar objects. Antimatter, produced, for example, in particle collisions in experiments or in the atmosphere, can only exist for a very short time because matter and antimatter annihilate each other, and only pure energy in the form of photons is left over. According to Einstein's famous equation $E = mc^2$, mass and energy can be transformed into each other. In the big bang the same amount of matter and antimatter must have been created out of energy in the early universe. Matter and antimatter particles are produced in pairs out of energy, and if they come in contact, they annihilate each other. To create the observed matter abundance and not a universe made of pure energy, a mechanism that creates a tiny asymmetry between matter and antimatter is needed: Only about one particle per billion must have managed to survive; all others particles annihilated with their antiparticle. In the SM there actually is a mechanism that treats matter and antimatter differently, called CP

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violation. However, its strength is much too small to explain the observed matter-antimatter asymmetry, which is essential for our existence. Combined with the puzzling aspects of dark matter and dark energy, in principle we do not understand the 5 percent of ordinary matter either!

Why Are Atoms Electrically Neutral?

The simplest atom is a hydrogen atom: It consists of a proton and an electron, and both have exactly the same charge but with opposite sign such that hydrogen is electrically neutral. Although this might sound plausible, it is highly nontrivial. A proton consists of three quarks: two up quarks and one down quark with charges $+\frac{2}{3}e$ and $-\frac{1}{3}e$, respectively. The electron has charge $-e$. Now in the SM there is at least at first sight no connection or relation between quarks and electrons although the self-consistency of the theory at the quantum level requires some relations between quarks and leptons in order to remove the so-called *gauge anomalies* to be discussed briefly at later stages of our book. In any case, the fact that the charges of the proton and electron sum up to zero exactly is remarkable. Is it just an accident or is a deeper reason behind this? In principle the electric charge of a particle could be anything.[1] So why are the electric charges quantized? This problem can be solved if the SM is embedded in a grand unified theory.[2]

Why Are the Forces of Nature of Such Different Strengths?

The four forces of nature are of very different strengths. Gravity is by far the weakest of all forces. Is it possible that all forces have the same origin and thus the same strength at a certain energy scale. Did they develop from the same force present in the early universe? The idea to unify different forces or interactions goes back very far in the history of physics. Already Isaac Newton (1642–1727) linked the planetary motions with the falling of the stone on earth. James C. Maxwell (1831–1879) accomplished unifying electricity and magnetism to electromagnetism. Nearly 100 years later Sheldon Glashow, Abdus Salam, and Steven Weinberg achieved unifying QED with the weak interactions to the electroweak interactions. Together with QCD they build the SM of particle physics. Is it now also possible to unify strong and electroweak force at a higher energy? The energy dependence of the strength of the forces in a quantum field theory suggests that this might be possible, although an exact unification cannot be achieved without modifying the theory along all the energy range. Embedding the SM into a Grand Unified Theory (GUT) would also solve the problem of why atoms are neutral as discussed earlier. Such GUT models further predict correlations between quantum numbers and masses of quarks and leptons not present in the SM. Theoretically many GUT models were studied and their predictions compared with experimental measurements. But so far no clear hints for the existence of such a unified interaction are found.

[1] This is due to the fact that the electromagnetic force is based on an abelian U(1) symmetry in which the normalization of the coupling and charges are arbitrary. However, in the case of nonabelian symmetries like SU(5) or SO(10) the electric charges are fixed.

[2] As soon as the U(1) force is embedded in a larger nonabelian symmetry group also the U(1) charges are automatically quantized.

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Why Are Neutrino Masses Nonzero and So Small?

Neutrino masses are special in two ways. First of all, it is because neutrinos are exactly massless in the SM. Consequently we already found physics beyond the SM! It is possible to incorporate neutrino masses in the Lagrangian of the SM but there are different ways to do this. Either new particles as right-handed neutrinos or Higgs-triplets have to be added to the particle spectrum, and an additional heavy mass scale for Majorana masses is needed or a symmetry that forbids this mass term. Either way, neutrino masses require a nontrivial extension of the SM. The second thing is that neutrino masses are much smaller than the masses of other fermions. There is already a large mass hierarchy between the electron and the top quark of roughly six orders of magnitude, and neutrino masses extend this hierarchy to another six orders. This is a part of the so-called *flavor problem.*

Why Are There Three Generations of Particles?

The objects around us are all made up of particles of the first generation, namely electron e, up u, and down d. Out of up and down quarks we can build protons p and neutrons n and that is all we need for the atoms of the periodic table of elements. The electron neutrino ν_e is emitted in radioactive decays of those atoms. If that's all we need, why are there more matter particles? The muon μ, the heavy brother of the electron was first found in cosmic rays and belongs to the second particle generation. It has exactly the same properties as the electron but it is roughly 200 times heavier and consequently unstable. It decays and finally ends up in particles of the first generations. The same applies to the other particles of the second and third generation. The strange quark s and the bottom quark b are heavier versions of the down quark d. All these particles were not discovered at once. When "half" of a generation was found, it was expected that the other half must also exist due to symmetry principles. For example the charm quark was predicted at times when the strange quark was already found and similarly for the top quark when the bottom quark was already known. We do not know why there are exactly three generations and not two, four, five ... or only one. But it is very satisfying that one could exclude additional generations through the study of Higgs decays. On the other hand, in a SM with only two or one generation there would be no CP violation,[3] thus no matter-antimatter asymmetry. This is only possible with more than two generations. However as already mentioned earlier, the CP violation present in a SM with three generations is still way too small to explain the matter abundance of the universe. On the other hand, it is sufficiently large to accommodate other phenomena observed in nature, and we will discuss them in detail in this book.

How Can We Stabilize the Electroweak Scale?

This is also called the hierarchy problem and is often seen as one of the biggest (theoretical) problems of the SM. If the SM is considered as an effective theory we get an additional higher energy scale Λ, which characterizes the valid energy range of the SM. Λ corresponds to the mass of new heavy particles. Under the hierarchy problem one understands the

[3] We put here aside, the so-called strong CP violation to be briefly discussed in Section 17.3.

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difficulty to stabilize – under the presence of this scale Λ – the electroweak scale in every order of perturbation theory and to explain the large gap between the electroweak scale $v = 246$ GeV and the GUT scale $M_{\text{GUT}} = 10^{16}$ GeV or Planck scale $M_{\text{Pl}} = 10^{19}$ GeV. Fermion masses m_f are proportional to the only scale in the SM, $m_f \propto v$. They are protected by the chiral symmetry, which is only broken by the mass parameter such that radiative corrections stay small: $\delta m_f \propto m_f \log \frac{\Lambda}{m_f}$. These corrections vanish for $m_f \to 0$, that is in the limit of exact chiral symmetry. The mass of the photon on the other hand is also protected, namely by the gauge symmetry, and stays zero in all orders of perturbation theory. This relation between symmetry and a small parameter is summarized in the naturalness principle by 't Hooft [4]: A small parameter of a theory is natural if and only if the symmetry of the system enlarges when this parameter is set to zero. Fine-tuning between different large contributions to a given quantity by hand with the goal to obtain a much smaller total contribution than the individual ones is regarded as unnatural. The problem here is of course how to quantify this. How much fine-tuning is still natural? In the SM this problem arises in connection with the Higgs mass that is not protected by any symmetry. The Higgs mass gets quadratic corrections proportional to the highest present scale, e.g., $\delta m_h^2/m_h^2 \propto \Lambda^2$ and thus destabilizes the electroweak scale.

Naturalness is of course not a necessary condition for a theory to be internally consistent, but it is also not only an aesthetic requirement. It assumes the lack of certain conspiracies between phenomena occurring at very different energy scales. Naturalness might be – and often was in the past – a helpful guiding principle to infer the energy scale at which an effective theory breaks down. The separation of scales is inherent in effective theories, and applying the naturalness principle could help to find the energy scale where new physics (NP) enters, e.g., the problem of the electromagnetic energy of a classical electron is cured by the positron.

There are different possibilities to end up with a Higgs mass at the electroweak scale and not at a much higher scale:

- Fine-tuning: It could be that the parameters of the Lagrangian are fine-tuned such that the physical Higgs mass is at 125 GeV. However, this accidental cancellations up to 32 significant digits ($M_{\text{Pl}}^2/M_W^2 \approx 10^{32}$) must happen in every order of perturbation theory (and not only once).
- Symmetry: There might be an additional symmetry that protects the Higgs mass from large radiative corrections. Supersymmetry, which connects bosons and fermions, is the most prominent example for this.
- The Higgs is not a fundamental scalar particle, but composed of further particles.
- A softly broken scale invariance: In the SM only the mass parameter μ of the Higgs potential breaks scale invariance. If this is the only symmetry breaking parameter all corrections would be proportional to μ^2.

These are some of the reasons why one can think that the SM should be extended to a more fundamental theory. However, it is not clear in which way NP will manifest itself. In principle only the hierarchy problem requires new phenomena not too far away from the electroweak scale and thus reachable by the LHC. Also dark matter studies suggest that the new dark matter particles should be weakly interacting and around the electroweak

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scale (so called WIMP, weakly interacting massive particles). It is also possible that some of the other problems might be solved at a much higher energy scale not reachable within the near future with the help of a high energy collider.

After this list of problems and open questions of the SM, we shortly want to indicate how to look for new particles and new interactions beyond the SM. In order to discover NP there are in principle two strategies:

- **Direct Detection**

  In collider experiments new particles could be produced and directly detected. The limiting factor here is the center of mass energy of the experiment. According to $E = mc^2$, if this energy is too small or the new particle too heavy, it cannot be produced as a real particle but only exists as a virtual particle. The advantage of a direct detection is, of course, that one really sees the new particle. The direct detection of the Higgs boson was the final proof that it really exists. Prior to its detection some indirect hints and limits where known, and from the theory side it was predicted to exist somewhere around the electroweak scale. With the LHC it is possible to reach distance scales of $5 \cdot 10^{-20}$ m or equivalent energy scales in the ballpark of 5–7 TeV if sufficient statistics are available.
- **Indirect Detection**

  The existence of new particles can become noticeable indirectly through quantum fluctuations, which results in deviation (often a very small one) between SM prediction and measurement. To trace such small effects a very high precision both from theory and experiment is required. This way is followed by weak decay experiments LHCb, SuperKEKB and NA62 and as we will demonstrate in this book these decays are in principle sensitive to distance scales as small as 10^{-21} m and even smaller scales. The influence of new particles as a sign of physics beyond the SM, is for example, possible in some weak decays that are suppressed in the SM such that NP effects can compete with the SM contributions. A historic example not related to particle physics is the discovery of the Neptune by Le Verrier in 1846. He studied the deviations of the orbit of the Uranus from the predicted one and concluded that it must be due to gravitational effects of a further planet whose position he predicted with an accuracy of 1°. Similarly one can try to track new particles, and it was often done in the past.

  Indeed, already in 1987 a heavy top quark was predicted at the B factory DORIS at DESY with the ARGUS experiment, where for the first time $B_d - \overline{B}_d$ oscillations were discovered. Similarly, the existence of charm quark was predicted by measuring and calculating the rate for $K_L \to \mu^+\mu^-$. Without the charm quark the theoretical prediction for the rate of the decay $K_L \to \mu^+\mu^-$ was predicted to be much larger than experimentally measured. Including the charm quark, which together with the strange quark builds a doublet under the electroweak gauge symmetry, the branching ratio for $K_L \to \mu^+\mu^-$ could be suppressed and made consistent with data. Even more, Gaillard and Lee [5], calculating the $K_L - K_S$ mass difference ΔM_K and comparing it with its measured value, could predict in 1974 the mass of the charm quark to be in the ballpark of 2 GeV before its discovery. But even in 2019 we do not know whether at some level NP enters both $B_d - \overline{B}_d$ oscillations and ΔM_K because of theoretical and parametric uncertainties.

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In this context of particular interest are rare decays of leptons, like $\mu \to e\gamma$ or $\tau^- \to \mu^- e^+ e^-$ for which the predicted branching ratios are so small in the SM that they probably will never be measured if the SM is the whole story. Here NP contributions could be much larger than the SM ones making their measurement possible. Observation of such decays would be then a clear signal of NP. In fact, the next years could bring discoveries in this sector of particle physics. Similar comments apply to electric dipole moments of leptons, the neutron, the proton, and atoms and anomalous magnetic moments of leptons and quarks. Also here new discoveries could take place in the coming years.

After these two grand views we are almost ready to start our expedition. It will first dominantly take place within the SM reaching distance scales of the order of 10^{-18} m (*the Attouniverse*) corresponding roughly to the mass of the heaviest SM particle, the top quark. However, already in this part we will develop a powerful technology that will allow us to go in the later parts of our book to much shorter distances scale, reaching eventually the (*Zeptouniverse*) and possibly even shorter distance scales. What we still need is an efficient strategy and corresponding outline of our expedition. The construction of such a strategy and the outline in question is our next task.

The Grand View of the Expedition and the Strategy

Writing a long book reminds me of expeditions to Himalayas, which I know only from several books. Reading books about great composers I see some similarities to composing symphonies or operas. I believe that despite differences in these three fields, it is crucial to have a plan for these expeditions and the strategy for reaching the goals. The construction of the plan for this book was rather challenging in view of many topics present in the field of weak decays. While the number of topics discussed in this book is large, some topics will be only mentioned or discussed very briefly. The principles that guided me in choosing the topics were as follows:

- I wanted to present in detail first of all the material that I know and that I developed over many years with many collaborators, in particular with many of my PhD students and postdoctoral fellows. This is quark flavor physics in the SM and beyond.
- This includes in particular calculations of QCD corrections to weak decay processes at the leading and next-to-leading order, which dominated the topics in my research group at TUM in the 1990s.
- However, I included also topics on which I wrote only few papers until now but which in my view are very important. Hopefully not only the topics but also my papers. These are in particular lepton flavor violating decays, electric dipole moments of atoms, molecules, leptons, and nucleons, and of course anomalous magnetic moments like $g-2$ of the muon. Here I benefited from many reviews that I will list in the relevant chapters.
- I put significant effort into explaining how the derivations of predictions for most important observables both within the SM and its extensions are made. This requires

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often tedious Feynman diagram calculations, and the related quantum field technology had to be developed to reach this goal. However, only a subset of results could be derived here as otherwise the book would be much longer.

- But what is equally important is the development of skills in connecting the results of such calculations to observables measured by experimentalists. In this context I will stress the correlations between many observables that turn out often crucial not only for the tests of the SM but also to distinguish between its various possible extensions.
- Concerning the latter, we will first devote one chapter to the technology of the so-called *SM gauge invariant effective field theory* (SMEFT), which became very popular in recent years. This tool allows in a model independent manner to look beyond the SM, which is useful but in my view contains too many free parameters so that additional model assumptions have to be made in order to reach some definite conclusions.
- In the latter context we will discuss first the so-called *simplified models*, which contain only few parameters. Models with the so-called constrained *Minimal Flavor Violation* are the best examples here. But also models with a new heavy neutral gauge boson Z', new heavy scalars, and those with flavor changing Z couplings are sufficiently simple that we can discuss them in some detail. Already these simple models will give us some idea on what experimentalists are telling us and hopefully some hints for the construction of new theories and the identification of NP at very short distance scales beyond the reach of the LHC. Yet, we will warn the reader that very simple models can often miss the physics hidden in the complicated quantum effects described by SMEFT, and we will try to expose this problem in a few examples.
- Few chapters will be devoted to concrete nonsupersymmetric models, like models with vectorlike fermions, leptoquark models, and explicit models with new heavy-gauge bosons and scalars. In these cases no derivations will be present. Supersymmetric models will not be discussed in this book because this would require too many pages for its introduction. Instead we will give a collection of references to useful papers.
- We will also give some outlook for the future of this field.

With these goals in mind the book consists, similar to a symphony, of four parts:

PART I: Basics of Gauge Theories
PART II: The Standard Model
PART III: Weak Decays in the Standard Model
PART IV: Weak Decays beyond the Standard Model

The last part includes also observables like electric dipole moments and anomalous magnetic moments. These four parts consist of twenty chapters, which are the steps in our expedition. We are now ready to list these steps and indicate how they are related to each other. This will hopefully make our book more transparent. In this context it is advisable to read the description of a given step, presented next, before making that step. Therefore here comes an important message:

PLEASE READ THE OUTLINE OF EACH STEP BEFORE MAKING IT!

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Step 1: Chapter 1

We will begin by presenting the general structure of gauge theories, stressing their symmetries and their breakdown. The structure of the Lagrangians in this step will be fundamental for the full book. We will encounter Lagrangians involving spin-0, spin-$\frac{1}{2}$ and spin-1 fields. We will also collect literature in which further details can be found. But the information provided in this step should be sufficient for following the next steps.

Step 2: Chapter 2

We will next move to discuss the SM of electroweak and strong interactions. We will present the basic SM Lagrangian, and we will discuss various properties of this simplest theory but we will not do any phenomenology at this stage. There are many excellent books on the dynamics of the SM, and we will in most cases skip derivations of well-known formulas to save space and in particular energy for the later steps that are not covered in detail in textbooks. The most important result of this step will be collection of the Feynman rules for those interactions present in the SM that we will need for explicit calculations as we proceed. For readers' convenience we will collect these rules in Appendix B.

Step 3: Chapter 3

Having the Feynman rules at hand, we will present the simplest calculations, the so-called *tree-level* calculations that do not yet require a deep knowledge of quantum field theory like renormalization and renormalization group. This step will give us leading formulas for the determination of various parameters of the SM like the Fermi constant G_F and the parameters of the CKM matrix, which will be introduced and discussed in detail. These formulas will also give us a transparent picture of the leading decays of mesons and leptons and will allow approximate determination of the parameters in question. Yet, for a serious phenomenology we will need various corrections to these leading expressions. They will be calculated or simply listed in later steps when we turn to the phenomenology at the frontiers of weak decays. In this step we will also find out that in the case of meson decays some entries in the decay amplitudes cannot be calculated in perturbation theory. These are hadronic matrix elements of quark currents and in particular hadronic matrix elements of four-quark operators. This task will be left for other steps. But seeing how these matrix elements enter the decay amplitudes will turn out to be useful when our climb will become technically more difficult, and we will have to concentrate on other matters.

Step 4: Chapter 4

This step will show us the technology of quantum field theory at the one-loop level, including general comments and results of two and higher loop calculations that we will need later on. But the first goal of this step is the detailed presentation of the dimensional regularization and the development of the technology for one-loop calculations. The next goals in this chapter are the presentation of the renormalization and the renormalization group methods. This step is rather technical but crucial. While our presentation is

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rather general, we will show explicit results only in QCD and QED. The case of the renormalization of electroweak interactions is much more involved because of spontaneous symmetry breakdown. It deserves a separate book, and definitely we do not want to get too exhausted before entering the most interesting parts of this book related to flavor physics. Yet, we will have a brief compact presentation of the most important issues involved here. We will need this information later on. One of the important results of this step will be the collection of integrals necessary not only to perform the renormalization of QED and QCD, but also those that will be crucial for one-loop calculations at all stages of our expedition. We collected these integrals in Appendix C.

Step 5: Chapter 5

This is one of the most important steps in our expedition. Here we will first discuss the concept of the operator product expansion (OPE) and the renormalization group equations for the Wilson coefficient functions of the operators present in the SM. In this part we will first concentrate our discussion on the simplest operators: current-current operators. We will calculate their coefficients including not only leading QCD effects (LO) but also non-leading ones (NLO). In more complicated cases we will indicate how such calculations should be done and present only the results for them.

Step 6: Chapter 6

Step 5 will be very tough, and after completing it we will first relax a bit discussing *flavor changing neutral current* (FCNC) processes. In the SM such processes can only occur first at the one-loop level due to Glashow–Iliopoulos–Maiani (GIM) mechanism [6], a very important mechanism in the field of weak decays. We will first present the general structure of these processes, which will involve a set of *basic master one-loop functions*. We will calculate most of these functions explicitly without including first QCD corrections. Subsequently we will show how these functions enter the operator product expansion. Using then technology of Step 5, we will be able to include QCD and electroweak corrections to a number of FCNC processes. This will result in a number of effective Hamiltonians for most important processes that involve new operators not encountered in Step 5: the so-called penguin operators. In this step we will study several properties of these Hamiltonians, but we will postpone detailed phenomenology of these processes to later steps.

Step 7: Chapter 7

We will see in Step 6 that the phenomenological application of the collected formulas will require input from lattice QCD and other nonperturbative approches. In particular we will need the values of hadronic matrix elements of quark currents and those of four-quark operators. While we cannot go into details here, we will collect all results for hadronic matrix elements, weak decay constants, and other nonperturbative objects in one place so that they can be looked up quickly whenever necessary. But before presenting the results obtained by purely numerical lattice QCD calculations, we will discuss the application of

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the so-called *dual QCD approach* to weak decays that was developed by Bardeen, Gérard, and myself over many years. While not as accurate as the lattice QCD method, it offers in my view a better insight in the dominant QCD dynamics at long-distance scales than lattice QCD (LQCD) itself. But it can only be applied efficiently to K meson physics, while LQCD can be applied in principle to all low-energy processes. Yet, the application of LQCD to nonleptonic decays of B mesons is very difficult, and therefore in this part we will also devote a section to the QCD factorization approach, stressing its successes and limitations.

Step 8: Chapter 8

In this step we will present a detailed discussion of the particle-antiparticle mixing in the SM and perform the classification of various types of CP violation. We will discuss the determination of the CKM parameters in tree-level decays and also the determination of the so-called Unitarity triangle from particle-antiparticle mixing both from $B_{s,d}$ and K meson systems and tree-level decays in question. In this context we will present various methods for the determination of the angles α, β, and γ in this triangle from certain leading decays. The considered decays are subject to only small contributions from NP so that the CKM parameters can be extracted without knowledge of what happens beyond the SM. This is useful as then the results of tree-level determinations of CKM parameters can be used to find SM predictions for particle-antiparticle mixing observables considered already in this step and for rare processes considered in the next two steps. As both particle-antiparticle mixing and rare processes are subject to potential NP contributions, this could help us to identify NP through the pattern of deviations of the data for them from SM predictions.

Step 9: Chapter 9

In this step we will discuss most important rare K and $B_{s,d}$ decays and related observables. We will base our discussion on the information gained in previous steps. In particular we will collect many formulas that are necessary to perform the phenomenology of weak decays of mesons within the SM. This step will be rather long but a very important one for the subsequent steps. The general expressions for various observables will remain often unchanged in many NP models, and only the master functions of Step 6 will be modified. But in order to be prepared for the study of the physics beyond the SM we will already here present rather general formulas that contain new operators that are absent in the SM or are very strongly suppressed.

Step 10: Chapter 10

This step deals exclusively with $K \to \pi\pi$ decays and in particular with their two pillars: the so-called $\Delta I = 1/2$ rule and the ratio ε'/ε. We devote a separate chapter to it because the QCD analysis of both perturbative and nonperturbative contributions to these decays is very challenging. Moreover, it appears that the SM has significant problems in explaining

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the data for ε'/ε, and presently it is not yet clear whether SM dynamics are fully responsible for the $\Delta I = 1/2$ rule. We present several analytical formulas for ε'/ε and its numerical value as a function of most important hadronic parameters that should allow us to monitor future progress in the evaluation of this ratio.

Step 11: Chapter 11

This step deals with basic aspects of flavor physics in the charm sector. I have written only two papers on charm physics in the last thirty years, and consequently this step will not be as detailed as other ones. Yet, it will contain some fundamentals related to CP violation in the charm sector.

Step 12: Chapter 12

After the long investigations presented in Steps 8–11 we will be able to collect various lessons and thereby gain a grand picture of how the SM faces the data in 2019. In particular it will be important to collect possible deviations from its predictions that these days carry the name of *anomalies.* This will show us that indeed the SM has significant difficulties in describing all the flavor data simultaneously. Not all of these anomalies are still fully convincing because of theoretical and experimental uncertainties, but they give us strong motivations for making an important step toward the identification of NP that could be responsible for them.

Step 13: Chapter 13

We will next go beyond the SM. It will be strategically useful to present first the general structure of effective Hamiltonians beyond the SM and identify new operators that are absent in the SM. This step will deal with physics at the electroweak scale and below it as we already encountered in previous chapters, but now particular emphasis will be put on new operators generated by some NP at much higher scale than at the electroweak scale and below it will contribute to various processes. What will be discussed here is the low-energy effective field theory that carries the name LEFT in order to distinguish it from the effective theory discussed in the next chapter. Here the basic symmetry for finding possible operators is simply the symmetry $\mathrm{SU}(3)_C \times \mathrm{U}(1)_Q$, that are the symmetries of QCD and QED. Simply the color and electric charges have to be conserved.

Step 14: Chapter 14

To properly describe the physics above the electroweak scale, we will discuss next the so-called gauge invariant *Standard Model Effective Field Theory* (SMEFT). This theory became very popular in view of the fact that the LHC until now did not discover directly any new particles. It offers a model independent formulation of NP beyond the SM in terms of operators that are invariant under the full SM gauge group, which implies, among other things, that not only color and charge have to be conserved but also hypercharge.

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This eliminates certain operators allowed in the previous chapter. Moreover, the $SU(2)_L$ invariance implies certain relations between observables.

While more constrained than LEFT, SMEFT is in my view too general to give us a definite view about NP beyond the LHC scales without additional dynamic assumptions. But this is a very important framework, and many techniques developed in this decade in the context of SMEFT are crucial for serious phenomenological applications to obtain model independent results. Moreover, SMEFT technology plays an important role in the derivation of predictions in concrete models as well. We will see this in this chapter and subsequent chapters of the book. But already in this step we will discuss implications of SMEFT in a number of general NP scenarios in which only a subset of operators is relevant. Moreover, we will present a few general formulas, in particular the one for the ratio ε'/ε.

Step 15: Chapter 15

Chapter 14 is rather general, and it will be strategically useful to look at specific simple examples of NP. Having already all relevant SM formulas for flavor observables at hand it will be of interest to see how they generalize beyond the SM. In this step we will first discuss the concept of minimal flavor violation (MFV), based on the flavor symmetry $U(3)^3$, that is the most modest modification of the flavor violating effects found in the SM. In fact, there is the full class of MFV models, which can be characterized by a number of correlations between flavor observables, which depend often on only few new parameters and occasionaly are parameter free. We will see that the method of master one-loop functions introduced in Step 6 will offer a very transparent and simple description of MFV models, but we will also find that the anomalies found in Steps 8–10 cannot be explained in this class of models.

Therefore already in this step we will go beyond MFV models beginning first with models based on reduced flavor symmetry $U(2)^3$. Subsequently we will present the so-called *simplified models* in which NP contributions to flavor violating processes are dominated by tree-level exchanges of neutral bosons, in particular the SM Z-boson, a heavy neutral gauge boson Z', and a heavy scalar S or pseudoscalar A. In these models, then, the GIM mechanism is not working, and FCNC processes appear already at tree-level modifying in a striking manner the pattern of flavor violation found in the SM and in MFV models. Yet, also in this case the method of master functions will turn out to be very efficient in exhibiting these differences. We will see that some of these simplified models will give us some insight into the origin of anomalies found in previous steps. However, in contrast to the SM, MFV models, and $U(2)^3$ models, the simplified models discussed in this step will offer correlations between various flavor observables only within a given meson system. While already quite restrictive, they cannot be the whole story and one should expect that a fundamental theory of flavor would imply correlations between observables of different meson systems. While such a fundamental theory has still to be constructed, several models in the literature, that go beyond MFV, imply correlations between observables of different meson systems.

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Step 16: Chapter 16

To illustrate what happens in specific models, we will discuss three classes of models: the so-called 331 models, models with heavy vector like quarks, and models with leptoquarks, either of spin-0 or spin-1. Leptoquarks are known from grand unified theories in which the strong and electroweak forces are unified and in which leptoquarks have typical masses of $O(10^{16})$ GeV. But here we will concentrate on models with leptoquarks having sufficiently low masses so that they could be in principle discovered by the LHC. But even if the masses of new particles in the models considered will turn out to be beyond the reach of the LHC, their presence can still be identified in the rare processes discussed by us.

These three classes of models are sufficiently simple so that we can present them here in some details. The new aspect of these models will be larger involvement of leptons than in previous chapters. Yet, in this chapter we will confine the phenomenology to quark flavor observables, postponing the discussion of lepton flavour violation to the next step. There are several more complicated models that we will only briefly mention here. These are the Littlest Higgs model with T-parity (LHT), Randall–Sundrum models with custodial protection (RSc), left-right symmetric models, models with gauged flavour symmetries and supersymmetric models. As the structure of these models and their phenomenology are rather involved we will mainly refer to papers investigating weak decays in these models.

Step 17: Chapter 17

Until now we have discussed dominantly flavor physics of quarks. But our book must also contain flavour physics of leptons, in particular charged lepton decays mediated by flavor changing neutral currents. While very strongly suppressed within the SM, lepton flavor violation (LFV) can be by many orders of magnitude larger in NP models. Therefore finding such transitions would be a clear signal of NP. The nice feature of most of these decays is the absence of QCD corrections making the theoretical analysis much simpler than was the case of meson decays. Another important topic is electric dipole moments (EDMs) of various atoms, molecules, nuclei, and nucleons that all are very strongly suppressed in the SM. They test CP violation without flavor violation. Similar to LFV, a measurement of any nonvanishing EDM would be a clear signal of NP at work. But in contrast to LFV there are large nonperturbative uncertainties in this case. In this part we will also discuss anomalous magnetic moments of charged leptons.

These topics are somehow related to each other, and we will begin this part with a general look on them. Subsequently we will present a compendium of formulas for the transitions like $\mu \to e\gamma$ and processes involving only leptons. These formulas are quite general so that one can use them for various models. We will illustrate them on a few examples. Again, one of the goals of this step will be the identification of correlations between various observables. It will be a good exercise in using the collected formulas in simple setting.

We will then move to discuss EDMs and anomalous magnetic moments, collecting formulas that are useful for phenomenology and summarizing the present status of these

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topics. Finally, we will only mention some aspects of neutrino oscillations and stress the importance of neutrinoless double β decay.

Step 18: Chapter 18

We will next attempt a grand summary of NP models discussed by us comparing the different patterns of flavor violation present in these models. While they have been discussed already previously in some detail, it will be instructive to compare how different models face various anomalies listed in Step 12. This chapter is really a general view on the literature related to various anomalies and after being completed will hopefully motivate the readers to study numerous papers containing many ideas with the goal to construct their own models.

Step 19: Chapter 19

With all this knowledge, we will show how a "Flavor Expedition to the Zeptouniverse" could in principle take place. Here we will address the question which of the processes considered in our book could give us best information about NP beyond the SM. In this context we will collect low-energy observables that could be useful for the search for NP, in particular beyond the reach of the LHC. Subsequently, with the goal to distinguish various NP models, we will discuss DNA charts proposed already in a number of papers.

Step 20: Chapter 20

Finally, we will be able to present a grand summary of weak decays, list open questions, and present a shopping list for the coming years.

A careful reader certainly noted that in listing the steps we did not mention detailed expositions on P, C, CP, and T transformations. They are presented in detail in textbooks on relativistic quantum mechanics and on advanced quantum field theory. In particular the book [7] contains an impressive amount of information on this topic and should be looked up whenever necessary. But in order to facilitate the reading of our book, we have made a collection of our phase conventions in Appendix A.2. A number of appendices collects useful formulas that we will need as we proceed. These are in particular Fierz identities and integrals for one-loop calculations among others. Two older books on weak decays [8, 9] are also very useful. Other books will be recommended in the course of our expedition.

There are still the following points about this book that should be emphasized. While the first chapters are devoted to the introduction of the field in simple terms, they assume that readers have some elementary knowledge of the field theory and in particular of the SM. Similarly in subsequent chapters we will refer from time to time to some concepts that cannot be explained in any detail. Otherwise this book would be much longer. Most importantly, we will present in detail only topics that the author thinks to have fully under control and is familiar with through his publications and lectures. But as we will see, this material will already cover a significant part of the field of weak decays. The presentation of remaining topics will be rather brief, but should provide sufficient input for the phenomenological analyses performed in this book. Moreover, we will refer to the rich

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literature where more details on these topics can be found. This applies in particular to the papers that appeared in the last five years, up to the fall of 2019.

Introducing Main Players

The title of our book makes it clear who the main players are in our long expedition. These are weak decays of various particles as described by gauge theories. In addition to global quantities like branching ratios for the weak decays in question, there is a multitude of more local quantities that are related to them, and in addition there are transitions, like particle-antiparticle oscillations, known under the name of particle-antiparticle mixing. Also a number of measurable quantities (observables) are related to them.

While, these objects will enter the scene in various chapters one by one, it is useful to see them already now together, even if for some readers, not familiar with the subject, the next pages will be difficult to follow. They can then skip them and return later to test how much they have learned. But a better attitude is to go through these pages in order to become acquainted at least with the names of main players and realize their importance. Reference to literature related to statements made soon will be given in the course of our expedition.

In my view the processes listed next will turn out to be the superstars and stars of 2020–2030 in quark flavor and lepton flavor physics and belong to the most promising observables in the search for NP. There are many measurements one can do and many observables one can calculate, but in my view the following ones will lead the tests of the SM and searches for NP in the coming ten years within the *quark flavor physics*:

- Particle-Antiparticle mixing or in short $\Delta F = 2$ observables with F meaning any quark flavor:

$$\boxed{\Delta M_s, \qquad \Delta M_d, \qquad S_{\psi K_S} \qquad S_{\psi\phi}, \qquad \varepsilon_K, \qquad \Delta M_K\,,}$$

  with ΔM_s and ΔM_d denoting mass differences between mass eigenstates in $B^0_{s,d} - \bar{B}^0_{s,d}$ mixings and $S_{\psi K_S}$ and $S_{\psi\phi}$ being mixing induced CP-asymmetries that are measured in $B^0_d \to \psi K_S$ and $B^0_s \to \psi\phi$ decays. ε_K is a measure of CP violation in $K_L \to \pi\pi$ decays induced by $K^0 - \bar{K}^0$ mixing and ΔM_K is the mass difference in $K^0 - \bar{K}^0$ system, analogous to $\Delta M_{s,d}$. Despite the nonleptonic nature of all these observables, we expect that during the coming years all of them will be known very precisely within the SM due to advances in LQCD. ΔM_s, ΔM_d, ε_K, and ΔM_K are already very well measured. $S_{\psi K_S}$ and $S_{\psi\phi}$ should be precisely measured in the coming years.
- Angular observables and branching ratios in the decays ($\ell = e, \mu, \tau$)

$$\boxed{\bar{B} \to \bar{K}^* \ell^+ \ell^-, \qquad \bar{B} \to \bar{K} \ell^+ \ell^-\,, \qquad B_s \to \phi \ell^+ \ell^-\,,}$$

  with $B = B_d, B^\pm$ and correspondingly for K^* and K. The ones with $\ell = e, \mu$ are presently among the stars of flavor physics with the data signaling intriguing violation of $\mu - e$ universality, that is, the difference between rates for decays into muons and electrons.

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- The branching ratios

$$\boxed{\mathcal{B}(B_s \to \mu^+\mu^-), \qquad \mathcal{B}(B_d \to \mu^+\mu^-),}$$

that should be known very precisely in the SM once the accuracy on the CKM elements $|V_{ts}|$ and $|V_{td}|$ will be improved at Belle II at the beginning of this decade. Experimentally $\mathcal{B}(B_s \to \mu^+\mu^-)$ should be known rather precisely by 2025, while it may take longer time for $\mathcal{B}(B_d \to \mu^+\mu^-)$. These decays, in particular taken together, offer very powerful tests of the SM and of its extensions. We do not list yet $\mathcal{B}(B_d \to \tau^+\tau^-)$, as the present upper bound is larger by several orders than its SM expectation. Moreover, its measurement is very challenging. We will encounter few other observables in these decays related to the time evolution in $B_s \to \mu^+\mu^-$.

- The branching ratios

$$\boxed{\mathcal{B}(\bar{B} \to \bar{K}\nu\bar{\nu}), \qquad \mathcal{B}(\bar{B} \to \bar{K}^*\nu\bar{\nu}), \qquad \mathcal{B}(B \to X_s\nu\bar{\nu}),}$$

which offer powerful means to study the effects of right-handed currents.

- The branching ratios for $K^+ \to \pi^+\nu\bar{\nu}$, $K_{\rm L} \to \pi^0\nu\bar{\nu}$, $K_{L,S} \to \mu^+\mu^-$ and the ratio ε'/ε with ε' being another measure of CP violation in $K_L \to \pi\pi$ decays in addition to ε_K:

$$\boxed{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}), \qquad \mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu}), \qquad \mathcal{B}(K_{L,S} \to \mu^+\mu^-), \qquad \varepsilon'/\varepsilon.}$$

The first two branching ratios are basically free from hadronic uncertainties as opposed to the remaining three observables, which suffer from these uncertainties, but they should be reduced in the coming years. These five quantities taken together and in particular in correlation with all observables listed earlier offer very powerful means to test the SM and in identifying NP beyond the LHC scales. Moreover, present theoretical calculations of ε'/ε signal significant departures from the SM.

- The branching ratios

$$\boxed{\mathcal{B}(B^+ \to \tau^+\nu_\tau), \qquad \mathcal{B}(\bar{B} \to D\tau\nu_\tau), \qquad \mathcal{B}(\bar{B} \to D^*\tau\nu_\tau)}$$

play important roles in searching for NP effects mediated by charged scalars, charged gauge bosons and leptoquarks. The present data on the last two signal the largest departures from the SM among decays that occur at tree-level in this model. Not only branching ratios but in particular various differential decay rates will be crucial for the identification of NP in these decays.

- Finally the branching ratios

$$\boxed{\mathcal{B}(B \to X_s\gamma), \qquad \mathcal{B}(B \to K^*(\varrho)\gamma)}$$

should not be forgotten with the first one providing already for years a very stringent test of the SM and bounding NP contributions.

There is no question that *lepton flavor physics* will also play a very important role in identifying NP beyond the SM. In particular, the following decays should provide a deep insight into the dynamics at short-distance scales:

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- First of all the branching ratios

$$\boxed{\mathcal{B}(\mu \to e\gamma), \qquad \mathcal{B}(\tau \to e\gamma), \qquad \mathcal{B}(\tau \to \mu\gamma),}$$

that similar to $B \to X_s\gamma$ are governed by dipole operators. They are tiny within the SM, and any observation of these decays would be a clear signal of NP. They already now put significant constraints on the parameters of various extensions of the SM. Improved upper bounds and even their measurements are expected from PSI, Belle II, and the LHCb.

- Next come

$$\boxed{\mathcal{B}(\mu^- \to e^-e^+e^-), \qquad \mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-), \qquad \mathcal{B}(\tau^- \to e^-e^+e^-)\,.}$$

These decays are very interesting as they are strongly correlated with $\mu \to e\gamma$, $\tau \to e\gamma$, and $\tau \to \mu\gamma$, and these correlations are different for different NP models.

- Also the four branching ratios

$$\boxed{\mathcal{B}(\tau^- \to e^-\mu^+e^-), \qquad \mathcal{B}(\tau^- \to \mu^-e^+\mu^-),}$$

$$\boxed{\mathcal{B}(\tau^- \to \mu^-e^+e^-), \qquad \mathcal{B}(\tau^- \to e^-\mu^+\mu^-)}$$

will enrich the search for NP.

- $\mu - e$ conversion in nuclei, even if subject to hadronic uncertainties, could become the star of lepton flavor physics in the coming decade. The dedicated J-PARC experiment PRISM/PRIME should reach a sensitivity of $O(10^{-18})$. Also, semileptonic τ decays like $\tau \to \pi\mu e$ should not be forgotten.

Of special interest are decays that proceed through both quark flavor and lepton flavor violating transitions. These are in particular

$$\boxed{K_{L,S} \to \mu e, \qquad K_{L,S} \to \pi^0 \mu e\,,}$$

$$\boxed{B_{d,s} \to \mu e, \qquad B_{d,s} \to \tau e, \qquad B_{d,s} \to \tau \mu\,,}$$

$$\boxed{B_d \to K^{(*)}\tau^\pm\mu^\mp, \qquad B_d \to K^{(*)}\mu^\pm e^\mp\,.}$$

A natural mechanism responsible for such transitions are tree-level exchanges of lepto-quarks or tree-level Z' exchanges. But they can also be generated in certain models at one-loop level.

Another set of observables is

$$\boxed{\text{Electric Dipole Moments(EDMs)}, \qquad (g-2)_{e,\mu}\,.}$$

Even if these observables are flavor conserving, they put strong bounds on extensions of the SM. Both are governed by dipole operators. EDMs are CP-violating, $(g-2)_{e,\mu}$ conserve CP. In certain models there are correlations between them. The $(g-2)_\mu$ anomaly (departure

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from SM prediction) found at Brookhaven should be clarified by Fermilab in 2020. As EDMs are very strongly suppressed in the SM, any measurement of a nonvanishing EDM would signal NP.

In addition to all these processes, charm physics will play a significant role in constraining NP models, but I did not list any processes here to emphasize that from my point of view the observables listed earlier will be more powerful in searching for NP because of smaller hadronic uncertainties. An exception here is CP violation in D decays as it is predicted to be tiny in the SM.

This list contains very many processes and including, in addition to branching ratios, various local observables, that is, various distributions and asymmetries related to them, gives us great opportunities for making progress in the search for fundamental laws of nature. Measuring all these observables precisely one day will surely allow us to get a deep insight into the NP dynamics beyond the LHC scales provided the departures from the SM predictions in at least some of them will be significant. But to reach this goal we have to develop strategies for a transparent use of these future data. This will also be one of the important goals of this book.

How to Use This Book Optimally

Writing this book was a real challenge for two reasons:

- There are many important weak decays that have to be considered.
- There are many NP models describing these decays often in a rather different manner.

As weak decays of mesons and leptons, EDMs and anomalous magnetic moments will play the crucial role in the search for new dynamics beyond LHC scales before a new collider will be built, it was mandatory to extensively discuss NP models independent of whether presently observed departures from SM predictions (anomalies) will remain or not. The point is that there is no doubt that some presently unknown dynamics exist at very short-distance scales, and I am confident that with improved precision of experiments and theory we will one day find out with the help of decays discussed by us what this dynamics is.

Of course, we had to present first of all weak decays within the SM, and it is very important to read this part first. It is not crucial to do all the loop calculations presented in this part, even if this should be useful for theorists. More important is to get an idea about the general structure of effective Hamiltonians governing weak decays and about the pattern of flavor violation in the SM that is governed by

- Left-handed nature of charged current interactions
- GIM mechanism at tree-level and its breakdown at one-loop that is enhanced in K and $B_{s,d}$ decays and mixings through large top Yukawa coupling
- CKM matrix that contains the weak phase necessary for the description of CP violation observed in several processes

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In the beyond SM (BSM) part, it is probably advisable for beginners to first have a look at the simplest extensions of the SM that could be considered as *simplified models*. Several of them are presented in Chapter 15. This allows one to get an idea what could happen beyond the SM in simple settings. For those readers who know already a lot about flavor physics, the natural starting point is Chapter 13, in which the reader will meet a number of new operators that are absent in the SM. However, even more important is Chapter 14, in which the SMEFT is discussed in some detail. Seeing so many operators in these two chapters at once for the first time is a bit of a shock, but SMEFT is presently a popular language to discuss BSM physics, and it is advisable to learn this language as soon as possible. To make this chapter hopefully transparent and to facilitate reaching this important goal, I presented a number of examples in the form of various NP scenarios in which only a subset of operators plays the dominant role and the implications are simpler. With the knowledge gained in Chapters 13–15, it should not be too difficult to follow the material presented in the rest of the book.

In particular in Chapter 19 we will develop specific strategies for learning about NP beyond the LHC scales on the basis of processes presented in this book. These strategies, involving the so-called *DNA-charts*, will certainly turn out to be more useful in this decade than in the previous one, after hopefully many deviations from SM predictions for observables considered by us will be found in the coming years.

The BSM part contains many references to papers published in the last five years. They are only briefly described in our book but hopefully will give readers a general view on the efforts made these days by many theorists and experimentalists to find out which summits on the front cover of our book play the crucial role in nature. As the titles of all references have been exhibited, it is possibly a good idea to get a general view of the material presented in our book by first reading the titles of all references. This could appear to some readers as a crazy idea, but it is an original idea, and I have no doubts some readers will enjoy performing this experiment.

In the spirit of the last sentence, most importantly, I hope reading this book will be fun. Therefore our book does not contain any exercises so that the readers will not feel obliged to work if they just want to get general ideas and simply read this book. But if they are sufficiently motivated, they can check several calculations either performed in detail or sketched by the author. The collection of useful integrals and the list of papers in which Feynman rules for several concrete models can be found should make this task doable. Moreover, I tried to avoid long and complicated derivations of formulas that can be found in the literature to which we will refer frequently. More important are final results of these derivations and their phenomenological implications.

But there are additional reasons for not having exercises in our book. First of all, they take a lot of space, in particular if also solutions to them are provided. Having them would not allow me to present a number of important topics. Finally, in the last forty years I have read many books on field theory and particle physics that contained many exercises. I ignored them altogether. The reason is simple: I did not want anybody, even if much more experienced than me, to tell me what I should do. The great joy in research is to find problems and exercises by ourselves and have fun in solving them. In the spirit of the last statements, the readers could ignore all my advice on how to use optimally this book, even

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if I hope for some beginners this advice may turn out to be useful. This is in particular the case of recommendations for a number of papers and reviews, made rather frequently in this book, that I hope will help the readers to get their own ideas for the exploration of flavor physics. It will also motivate the readers to begin the day with the opening of **http://arxiv.org/** in order to find new papers and of course **http://www.slac.stanford.edu/spires/hep/** in order to find out the status of their own citations. The latter database allows also to find any paper listed at the end of this book by simply inserting there its identification number instead of the author's name. However, one can reach this goal even faster by inserting this number into the Google machine.

While for some readers the absence of exercises will be considered as a deficiency, it is compensated by several author's ideas for research projects, which could not be realized before the submission of the text for printing. I hope that at least some of these projects will be completed in the year 2019 and will appear in the hep-arxiv by the time this book has been printed. Combining them with the present version will extend the book beyond the assigned page limit.

We will encounter many equations on our route. I have put the most important ones in shaded boxes or white frames. There is no strict logic between these two choices. Roughly speaking, a given group of formulas has been collected in a shaded box, while the separate results have been put in white frames. Shaded boxes and white frames appeared already earlier. I hope this procedure makes the presentation more transparent.

We have mentioned two websites earlier. A very useful collection of other relevant websites can be found at the end of Langacker's book [10]. For our expedition, the following three are most important, and we should have them in our smartphones. These are

HFLAV = Heavy Flavour Averages: **http://hflav.web.cern.ch/**
PDG= Particle Data Group: **http://pdg.lbl.gov/**
FLAG = Flavour Lattice Averaging Group: **http://flag.unibe.ch/**

WE ARE NOW READY TO START OUR EXPEDITION!

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