12 Status of Flavor Physics within the Standard Model

12.1 Successes

It is evident from previous chapters that the SM describes the present data on flavor physics surprisingly well. In particular I find it amazing that the breakdown of GIM mechanism at one-loop level, which is governed by the large top-quark mass, is roughly consistent with the data despite very different diagrams contributing to $\Delta F = 1$ and $\Delta F = 2$ processes. Indeed, within the present uncertainties SM describes simultaneously $\mathcal{B}(B_s \to \mu^+\mu^-)$ governed by Z-penguin diagrams and ΔM_s governed by box diagrams with the relevant CKM parameters extracted from tree-level decays. Also CP-violating observables like ε_K and the asymmetries $S_{\psi K_S}$ and $S_{\psi\phi}$ are on the whole consistent with the data. Finally, the fits of the Unitarity Triangle show, despite few tensions, that the CKM matrix appears at present to be the dominant source of flavor and CP violation observed in low-energy processes.

Yet, fortunately, at a closer look, some deviations from SM predictions have been identified, although we still await their confirmation when the data and the theory improve. We discussed them briefly in previous chapters, but it is strategically useful to collect them here as a preparation for the last and the longest part of this book in which these anomalies will be addressed in various BSM models. We use the word *anomalies* although in several cases the observed deviations, being at the level of 2σ, did not yet deserve this name.

12.2 Summary of the Anomalies

During the last years a number of deviations from SM expectations in $b \to s\ell^+\ell^-$ and $b \to c\tau\bar{\nu}_\tau$ have been observed. They seem to indicate the violation of lepton flavor universality (LFU). Selected reviews on them can be found in [305, 581, 708, 709]. We begin with these anomalies as they were dominating the flavor physics since 2013.

Anomaly 1: Deviations from μ/e universality in neutral currents of the type $b \to s\ell\bar{\ell}$ observed in $B \to K\ell\bar{\ell}$ and $B \to K^*\ell\bar{\ell}$ decays by the LHCb collaboration [490, 491]. We have summarized them in terms of the ratios $R(K)$ and $R(K^*)$ in Section 9.1.6. Both ratios are found below SM predictions. These deviations are consistent with the departure from SM expectations observed in the angular observable P_5' [498]. Similarly, the suppression of the branching ratio for $B \to \phi\mu^+\mu$ below its SM value has been observed [500]. For a

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theoretical summary see [710]. As discussed later, these anomalies decreased slightly after Moriond 2019 but definitely they remained.

Anomaly 2: Deviations from $\tau/(\mu, e)$ universality in charged currents of the type $b \to c\ell\bar{\nu}$, which has been observed in $\bar{B} \to D^*\ell\overline{\nu}$ and $\bar{B} \to D\ell\overline{\nu}$ decays by BaBar [576], Belle [577–579], and LHCb [580] collaborations. See [581] for a review. We have summarized them in terms of the ratios $R(D)$ and $R(D^*)$ in Section 9.4.9. Both ratios are found above the SM expectations. Moreover, the ratio $R(J/\psi)$ involving $B_c \to J/\psi\ell^+\ell^-$ is also found to exceed the SM prediction [582]. But after Belle collaboration presented new results at Moriond 2019 [1344], these anomalies decreased significantly. Yet, as stressed by several authors, even if NP contributions would eventually be found to be small in branching ratios, the increased sensitivity to NP in differential distributions could still allow one to study them when the experimental data and also theory improve.

Possible mediators responsible for these two anomalies, assuming they couple only to SM fields, were classified in [541]. We will return to them in the BSM part of this book.

In addition to these anomalies the following ones deserve to be high on this list.

Anomaly 3: $(g-2)_\mu$ anomaly at the level of $(3-4)\sigma$, which will be considered in Section 17.4. Also the recent anomaly in $(g-2)_e$ at the level of 2.4σ should be mentioned here. Interestingly, while in the case of $(g-2)_\mu$ the data from Brookhaven are above the SM prediction, the new SM estimate of $(g-2)_e$ shows that data are below it. See Section 17.4 for more details.

Anomaly 4: ε'/ε anomaly, discussed already in Chapter 10. We will discuss its implications in the BSM part of this book.

Anomaly 5: Tension in the simultaneous description of ε_K and $\Delta M_{s,d}$ to be discussed in more detail in Section 15.1. While ε_K appears now to be in agreement with the data, ΔM_s and in particular ΔM_d are found in the SM to be significantly above the data if the large value of γ from the LHCb will be confirmed in the future. These tensions are interesting as $\Delta M_{d,s}$ are already very precisely measured, and the tension in question arose after the improved values of hadronic matrix elements from lattice QCD.

Anomaly 6: Tension between the latest RBC-UKQCD result for ΔM_K in (8.18) and the data at the 2σ level [1330] hinting for NP that similar to $\Delta M_{s,d}$ would suppress this difference.

Anomaly 7: The data for the branching ratio for $B_s \to \mu^+\mu^-$ are found by 2σ below rather accurate SM prediction, see Section 9.2.3. It will also be interesting whether Belle II will confirm visible enhancement of $\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)$ over its SM value. See (9.147).

Anomaly 8: The extraction of $|V_{us}|$ from $K \to \pi\ell\nu$ using recent Fermilab-MILC lattice data [711] implies $|V_{us}| = 0.0.22333(60)$ and consequently 2.6σ violation of CKM unitarity [712]. This seems to be in contradiction with the recent LQCD results on $|V_{us}|$ obtained from $\pi^+ \to \mu^+\nu[\gamma]$ and $K^+ \to \mu^+\nu[\gamma]$ [399], which as seen in (8.143) fully agree with the CKM unitarity. But as the decays studied in [711] and [399], differ from each other, it is not excluded that some NP is responsible for this difference. See also the analysis in [713], which using recent determinations of $|V_{us}|$ and $|V_{ud}|$ claims 4 σ violation of CKM unitarity. As far as $|V_{ud}|$ is concerned, see [712, 1328, 1329].

Anomaly 9: $|V_{us}|$ extracted from τ lepton decays shows a 2.5 σ tension compared to $|V_{us}|$ determined from CKM unitarity. In this context we refer to [714] for the discussion

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of $|V_{us}|$, $|V_{ud}|$, $|V_{cd}|$, and $|V_{cs}|$. Certainly this anomaly should be studied together with the previous one.

Anomaly 10: Possible anomaly in $|V_{ub}|$. With $|V_{ub}|$ much larger than the one implied by UT fits a NP phase would be required to obtain the correct value of the CP asymmetry $S_{\psi K_S}$.

Anomaly 11: The ratio g_τ/g_e in charged currents with 1.031 ± 0.013 exhibits breakdown of lepton universality at 2.4σ, implying g_τ anomaly [715, 716] as $g_\mu/g_e = 1.0003 \pm 0.0012$ [717] is fully consistent with the lepton flavor universality.

Anomaly 12: The correlation between the asymmetries $\mathcal{A}_{\rm CP}^{\rm dir}$ and $\mathcal{A}_{\rm mix}^{\rm dir}$ in $B_d^0 \to \pi^0 K_{\rm S}$, predicted in the SM, appears to depart from the data exhibiting in this manner potential anomaly. We refer for details to Section 8.6 of this book and in particular to section 4 of [461], which discusses these finding in detail.

The question then arises what these tensions are telling us about possible NP responsible for them. Many authors addressed this issue in the last years and many papers have been published in which a number of model constructions have been presented that aim to find possible NP behind these anomalies. In the rest of the book we will develop the technology that will allow us to address these anomalies and possible future anomalies in a systematic manner. This will also allow us to describe the most interesting NP scenarios behind the anomalies in questions that have been proposed in the literature. A short look at various theoretical reviews could give the readers additional motivations for the final part of this book. A subset of them can be found in [718, 719]. Other will be listed as we proceed. Also section 7 of [305] is very useful in this respect.

Our strategy for Part IV of this book, which consists of eight steps (13–20), has been already described in the Introduction, and I would like to ask the readers to look at short summaries of these steps presented there. This will facilitate the reading of the rest of the book and to follow the logic of this part, the longest part of this expedition. But before starting these steps, let us summarize in a model independent manner what all these anomalies imply for the Wilson coefficients relevant for the $b \to s\ell\ell$ transitions.

12.3 Implications for the Wilson Coefficients

Several groups have performed global fits of the WCs to existing $b \to s\ell\ell$ data. In particular the most extensive analyses have been done by two groups: CCDMV [486, 494] and ANSS [710, 720, 721]. But also the analyses in [722–733] should be mentioned here.

The two most favorite solutions obtained in various global analyses of $b \to s\ell^+\ell^-$ [494, 721] until Moriond 2019, when only scenarios with a single nonvanishing WC or two WCs being equal or of opposite sign are considered, turned out to be

$$i)\ C_{9\mu}^{\rm NP} < 0, \qquad ii)\ C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} < 0. \tag{12.1}$$

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One assumes here that NP is absent in $b \to se^+e^-$ so that these two coefficients, as indicated by an additional index, apply to $b \to s\mu^+\mu^-$ transitions only. Here

$$\boxed{C_{9\mu} = C_{9\mu}^{\rm SM} + C_{9\mu}^{\rm NP}, \qquad C_{10\mu} = C_{10\mu}^{\rm SM} + C_{10\mu}^{\rm NP}.} \tag{12.2}$$

However, as we will discuss next, other possibilities cannot be excluded at present, when several WCs are considered simultaneously and when the information from Moriond 2019 is taken into account. The following new features can be found in the new analyses that we will summarize briefly here:

- As stressed even before Moriond 2019 [734, 735], NP could affect $b \to se^+e^-$, $b \to s\mu^+\mu^-$, and $b \to s\tau^+\tau^-$ channels through two components, one keeping lepton flavour universality and one breaking it.
- The fact that $R(K)$ differs now visibly from $R(K^*)$ increased the room for RH contributions so that now in several papers also solutions with nonvanishing $C'_{9\mu}$ and $C'_{10\mu}$ can be found. We will discuss them briefly now and in more detail in the BSM part of this book.
- The hints for the anomaly in $B_s \to \mu^+\mu^-$ require the presence of axial muon couplings, that is either $C_{10\mu}^{\rm NP}$ or $C'_{10\mu}$ or both have to be nonvanishing as stressed in [516]. In this manner the second scenario in (12.1) is now favored.
- Possible NP in $b \to se^+e^-$, either lepton flavor universal (LFU) as considered in [516, 734, 735], or not lepton flavor universal [736].

New updated global analyses appeared after Moriond 2019 [516, 730, 736–741]. They take some or all new features listed earlier into account. A global analysis dedicated to $b \to c\tau\nu$ transitions can be found in [553–555]. Numerous tables in these papers show how various scenarios with one, two, or more nonvanishing WCs perform in improving the agreement of the theory with data relative to the SM. The best ones provide the improvement typically by $(5-6)\sigma$ dependent which input has been taken into account and how the numerical analysis has been performed.

It would premature to describe all possible solutions here. We pick up here three:

A: A purely muonic solution $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP}$, well suited to UV-complete interpretations discussed in Section 16.4.11, that according to [516] is now favored with respect to a muonic contribution $C_{9\mu}^{\rm NP}$ only. Considering scenario ii) in (12.1), the authors of [516] find the 1σ range

$$\boxed{-0.62 \le C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} \le -0.45,} \tag{12.3}$$

which gives a fit that is by 6.5σ better than the SM one. If $C_{9\mu}^{\rm NP}$ and $C_{10\mu}^{\rm NP}$ are treated independently, the best fit point gives

$$\boxed{C_{9\mu}^{\rm NP} = -0.72, \qquad C_{10\mu}^{\rm NP} = 0.40.} \tag{12.4}$$

Note that $C_{10\mu}^{\rm NP} > 0$ suppresses $C_{10\mu}$ as $C_{10\mu}^{\rm SM} < 0$ and consequently the branching ratio for $B_s \to \mu^+\mu^-$.

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The authors of [516] find that even a better fit is obtained by allowing an additional flavor universal (LFU) shift in C_9. Such a shift can be RG induced from four-fermion operators above the electroweak scale [742, 743], in particular from semitauonic operators, able to account for the potential discrepancies in $b \to c$ transitions. This then allows a simultaneous explanation of $R(D)$ and $R(D^*)$ anomalies. This scenario is naturally realized in a model with a vector leptoquark U_1, and we will return to it in Section 16.4.11.

B: Solution considered in several analyses listed by us, in particular in [738]

$$\boxed{C_{9\mu}^{\rm NP} = -1.17, \qquad C'_{9\mu} = -C'_{10\mu} = 0.24,} \tag{12.5}$$

so that in this case RH quark currents are present allowing to explain easier $R(K) > R(K^*)$ than it is in the scenario A. This scenario is better by 6.1 σ than the SM. It can be naturally generated in Z' models. With $C'_{10\mu}$ being nonvanishing the $B_s \to \mu^+\mu^-$ anomaly can be explained. Indeed, as verified using formulas in Section 9.2.2, $C'_{10\mu} < 0$ suppresses the branching ratio for $B_s \to \mu^+\mu^-$. Another interesting solution considered already in [734] and updated in [738] is the one with $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.33$ and a negative flavor universal shift in C_9 of -0.72.

C: Still another scenario, advocated in [737], has

$$\boxed{C_{9\mu}^{\rm NP} = -1.38(16), \qquad C'_{10\mu} = -0.37(12).} \tag{12.6}$$

While $C_{9\mu}^{\rm NP}$ is relevant for P'_5, a negative $C'_{10\mu}$ suppresses the branching ratio for $B_s \to \mu^+\mu^-$ and bringing some amount of RH currents helps in fitting the data. This is also the favorite scenario in [740].

Concerning the $b \to c\tau\nu$ anomalies, there exist numerous papers dedicated to them. In particular one can recommend those that appeared after Moriond 2019 where references to earlier literature can be found. These are [552–556]. It turns out that the operators O_V^L and O_T in (9.151) provide the best description of the data. As stressed in [554] the fate of $O_S^{L,R}$ depends strongly on the assumed upper bound on $B_c \to \tau\nu$ branching ratio, and relaxing this bound allows these operators to contribute at a modest level.

Some implications of all these findings for model building will be discussed in the BSM part of this book. However, it cannot be excluded that after Belle II presented first data and the new round of the LHCb measurements has been completed, the 2019 view of these anomalies will be significantly modified. It is expected that at the Winter conference, Moriond 2022, we will be able to make some clear-cut conclusions.

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