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TASI lectures on flavor physics

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This set of lectures covers the basics of flavor physics and the latest developments of the field. These notes are based on the lectures I gave at the TASI 2018 summer school.

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1. Brief introduction

The aim of these lectures is two-fold: first, I would like to introduce the basics of flavor physics to non-experts, including a few historical remarks. Second, I would like to convey the excitement in the field, highlighting more recent developments, both from an experimental and a theory perspective. In fact, flavor physics has been a very active and particularly fruitful field in recent years with the LHCb run producing many qualitatively new measurements. Furthermore, very soon our next generation B-physics experiment, Belle-II, will start entering the game, complementing and extending the LHCb capabilities. Hopefully, after reading these lectures you will have enough background on the subject and, more importantly, enough curiosity, that you will go on and learn more about flavor physics (many references are included in these lecture notes).

There is a huge literature on flavor, and it is impossible to coherently review it within the limited length of this review. Other great lectures presenting an introduction to flavor physics can be found at [1, 2, 3, 4, 5, 6, 7, 8]. For more details on the calculation of SM flavor transitions, as e.g. meson mixings, I would refer the reader to some of my previous notes based on the lectures I gave at the 2015 European School of High-Energy Physics [9]. The longer version of these lecture notes will be submitted to the arXiv [10] and will also contain the discussion on (1) what we can learn on flavor physics using high energy measurements of the Higgs boson; (2) what we can learn on Dark Matter using the flavor physics experiments we discuss in these notes.

What is new in these TASI flavor lectures? The first part of these lectures (Sec. 2) will set the stage on flavor physics, introducing the SM flavor structure, the SM and NP flavor puzzles, and ways to address the NP flavor puzzle. We will also discuss the SM sources of CP violation. In Sec. 3, we discuss an interesting ansatz to address the NP flavor puzzle: the Minimal Flavor Violation idea. We will also analyze ways of testing this idea either at the LHC or studying the correlation of different flavor transitions at low energy experiments. Due to the very interesting developments in the last few years in the field of flavor physics, in Sec. 4 we review the latest measurements and we discuss recent anomalies in B-physics, and their possible theoretical interpretation. We also give an overview of some of the future goals of the field.

2. Flavor structures within and beyond the SM

2.1 The ugly: the SM flavor puzzle

Before introducing the Yukawa interactions, the Standard Model (SM) Lagrangian has an elegant structure, and is fully determined by only a small set of free parameters. In particular, the gauge interactions are characterized by three interaction strengths, g_3, g_2, and g_1, one for each gauge group: $SU(3)$, $SU(2)$, and $U(1)_Y$. The Higgs potential is fully fixed after specifying two free parameters, the Higgs mass, m_h, and the Higgs vacuum expectation value, v [1].

This relatively simple picture becomes much more involved once we introduce the Yukawa interactions between the Higgs and the matter fields

$$\mathscr{L}_{\rm yuk} = -Y_d^{ij}\bar{Q}_L^i\phi d_R^j - Y_u^{ij}\bar{Q}_L^i\tilde{\phi}u_R^j - Y_e^{ij}\bar{L}_L^i\phi e_R^j + \text{h.c.}, \tag{2.1}$$

[1] In these lectures, we will use the convention $v = 246$ GeV.

where ϕ is the Higgs field ($\phi = (1,2,1/2)$ under $SU(3)\times SU(2)\times U(1)_Y$), $\tilde{\phi}$ is its conjugate representation $\tilde{\phi} = i\tau_2\phi^\dagger$, $Y_{d,u,e}$ are the three Yukawa couplings, and i,j are flavor indices ($i,j = 1,2,3$). The quark and lepton fields transform under the $SU(3)\times SU(2)\times U(1)_Y$ gauge group as

$$Q_L = (3,2,1/6),\ L_L = (1,2,-1/2),\ u_R = (3,1,2/3),\ d_R = (3,1,-1/3),\ e_R = (1,1,-1). \quad (2.2)$$

One can show that the Yukawa Lagrangian in (2.1) contains 13 additional physical parameters, 10 in the quark sector and 3 in the lepton sector (in the case of no right-handed neutrinos). On top of this, contrary to the gauge and Higgs sectors of the Lagrangian, the Yukawa sector's free parameters are highly hierarchical for apparently no reason. For example the ratio between the third generation up-quark mass – the top mass – and the first generation up-quark mass – the up mass – is $m_t/m_u = \mathscr{O}(10^5)$! A similar feature arises in the mixings between different generation quarks (see (2.6) for more details). The Standard Model itself does not provide any explanation of these features. This is the "Standard Model flavor puzzle". This puzzle became even deeper after the measurement of non-zero neutrino masses and mixings, because no hierarchy in these parameters have been established, and, at the same time, neutrino masses are many orders of magnitude lighter than any other matter field.

Several proposals to address this fundamental puzzle have been pushed forward. Broadly speaking, the proposals are based either (1) on flavor symmetry principles, (2) on geometry, or (3) on loop suppression. (1) One possible mechanism to suppress (some of) the fermion masses is to forbid them by a flavor symmetry that is then spontaneously broken. This mechanism was first proposed by Froggatt and Nielsen in 1978[11]. Their model utilized a broken $U(1)$ flavor symmetry generating masses of the type $M_{ij} \propto \varepsilon^{a_i+b_i}$ where ε is the small flavor symmetry breaking parameter and a_i, b_i the charges of the corresponding left-handed (LH) and right-handed (RH) fields. (2) Hierarchies in quark and lepton masses and mixings can also be traced back to a different localization of the fermions in a fifth dimension, resulting in a different overlap with the Higgs field. This has been realized both in flat extra dimensional models [12, 13] and in warped models [14, 15, 16]. (3) Finally, hierarchies in between quark and lepton masses can be induced from loop suppressions in models where light fermion masses are generated radiatively [17] (for more recent investigations both in the framework of supersymmetric and non supersymmetric theories see e.g. [18, 19, 20] and [21, 22], respectively).

2.2 The good: small FCNCs

A Flavor-Changing-Neutral-Current (FCNC) process is a process in which the initial and final states have the same electric charge but a different flavor. Plenty of FCNC processes have been measured and turned out to be very small. In spite of the several free parameters of the flavor sector of the SM, many FCNC observable can be precisely predicted in the SM. Do these predictions agree with the measurements? Does the SM need a large fine tuning in the parameters such to accommodate tiny FCNCs?

The SM can easily accommodate small FCNCs. This is due to several features of the SM flavor sector: **(1)** No tree-level FCNCs are generated in the SM; **(2)** The off-diagonal entries of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [23, 24] are small; **(3)** the Glashow-Iliopoulos-Maiani (GIM) mechanism [25] suppresses many FCNCs by small quark masses. As we will discuss in the remaining of this section, these three features result in FCNC processes that are suppressed by (at least) one loop factor, by small CKM elements, and by small quark masses, and are therefore much smaller than flavor conserving or charged-current weak interaction processes.

(1) The SM gauge Lagrangian possesses a large flavor continuous symmetry: $\mathscr{G}_{\rm flavor} = U(3)^5 = SU(3)^5 \times U(1)^5$, with each $SU(3)\times U(1)$ acting in the 3-dimensional generation space and, independently, on one of the five irreducible representations of the SM gauge group (see Eq. (2.2)). The $SU(3)^5$ subgroup is broken by the Yukawa interactions in (2.1). Bi-unitary transformations are needed to pass from quark and lepton flavor eigenstates to mass eigenstates after electroweak symmetry breaking (EWSB). In particular, we can find U_L and U_u unitary matrices such that the up-quark Yukawa is diagonalized: $U_L Y_u U_u^\dagger = {\rm diag}(y_u^1, y_u^2, y_u^3) = \sqrt{2}(m_u, m_c, m_t)/v$. However, it is not possible to simultaneously diagonalize the two Yukawa matrices, Y_u and Y_d without breaking the $SU(2)$ gauge invariance. In particular, fixing U_L and U_u as discussed above, the down-quark Yukawa:

$$Y_d = V\cdot {\rm diag}(y_d^1, y_d^2, y_d^3) = \frac{\sqrt{2}}{v} V\cdot (m_d, m_s, m_b), \tag{2.3}$$

where we have defined the CKM matrix as $V = U_L U_{dL}^\dagger$, where U_{dL} is such $U_{dL} Y_d U_d^\dagger = {\rm diag}(y_d^1, y_d^2, y_d^3)$. In the SM, the $SU(2)$ gauge symmetry is broken spontaneously by the Higgs field and therefore, one can rotate left-handed up and down quarks independently, diagonalizing simultaneously up and down quark masses. By performing these transformations, the CKM dependence moves into the couplings of up and down quarks with the W boson. In particular, the charged-current part of the quark covariant derivatives can be rewritten in the mass eigenstate basis as

$$-\frac{g}{2}\bar{Q}_L^i \gamma^\mu W_\mu^a \tau^a Q_L^i \to {\rm mass-basis} - \frac{g}{\sqrt{2}}(\,\bar{u}_L\;\bar{c}_L\;\bar{t}_L\,)\gamma^\mu W_\mu^+ V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}. \tag{2.4}$$

This equation shows the appearance of W boson flavor changing (tree-level) couplings. Following this discussion, it is straightforward to demonstrate that both the Z boson and the Higgs (as well as gluons and photons) do not have flavor changing couplings. Therefore, the W interactions are the only flavor changing interaction in the SM. From here we can conclude that FCNC processes in the SM can only arise through diagrams with an even number of $W^\pm$ vertices, and, therefore, are always suppressed at least by one loop factor.

(2) The CKM matrix is a 3×3 unitary matrix. It is easy to demonstrate that it is fully determined by 4 free parameters: 3 real parameters and one phase. As we will now discuss, these free parameters have been very well experimentally measured.

The unitarity of the CKM matrix implies several relations between its elements and, in particular, the existence of six unitarity triangles:

$$\sum_{k=u,c,t} V_{ki}V_{kj}^* = 0,\;\; i,j = d,s,b,\; i\neq j. \tag{2.5}$$

Each of these relations, for fixed i and j, can be represented as a triangle in the complex plane, where each side corresponds to the complex number $V_{ki}V_{kj}^*$ for the three different $k = u,c,t$. Among these six relations, the most stringent experimental test is provided for the $i = 1$ and $j = 3$ case: this is the “standard unitary triangle", $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ (see left panel of Fig. 1).

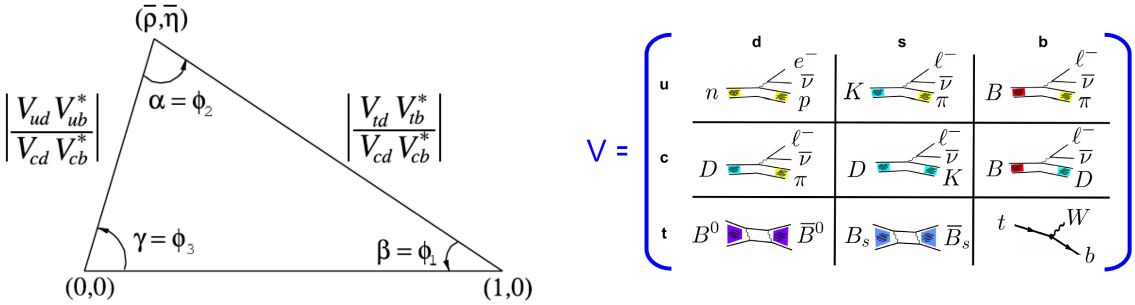


Figure 1: Left: The "standard unitarity triangle". **Right:** List of the most sensitive observables used to determine the several elements of the CKM matrix.

Many measurements have been performed that over-constrain the unitarity triangle. This includes: inclusive and exclusive charmless semi-leptonic K, B and D meson decays, mass splittings in the B and B_s meson systems, and B to D meson decays (see right panel of Fig. 1). It turned out that the structure of the CKM matrix is very hierarchical with large diagonal entries and small off-diagonal terms. This implies that flavor violating transitions are further suppressed by small CKM elements, if compared to flavor conserving transitions (see Eq. (2.4)). More specifically, fitting all measurements in the framework of the CKM matrix, one finds[26]:

$$\begin{aligned} V \simeq & \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \\ \sim & \begin{pmatrix} 0.974 & 0.225 & e^{-i66.8^\circ}(3.65\times10^{-3}) \\ -e^{i0.035^\circ}0.225 & e^{i(-1.88^\circ\times10^{-3})}0.973 & 42.4\times10^{-3} \\ e^{-i22.2^\circ}(8.69\times10^{-3}) & -e^{i1.056^\circ}(41.2\times10^{-3}) & 0.999 \end{pmatrix}, \end{aligned} \tag{2.6}$$

with $\lambda\sim 0.23$ the Cabibbo angle and the parameters A,ρ,η roughly of order 1. The first line of the equation shows the Wolfenstein parametrization of the CKM matrix [27] and is valid up to $\mathscr{O}(\lambda^4)$ corrections. From this structure of the CKM matrix, it follows that, for example, $u\to d$ transitions will be more probable than $u\to s$ transitions and even more probable than $u\to b$ transitions.

(3) The first indirect evidence for the existence of the charm quark came from the measurement of a very small branching ratio of $K_L\to\mu^+\mu^-$ that could not be explained within a model with only three quarks. In 1970, Glashow, Iliopoulos, and Maiani proposed the existence of a fourth quark coupled by the weak interaction to the superposition of d and s quarks, s_C, with the current given by

$$J_\mu^{\rm charm} = \bar c\gamma_\mu(1-\gamma_5)s_C, \quad s_C = -\sin\theta d+\cos\theta s, \tag{2.7}$$

where θ is a mixing angle (later denoted as the Cabibbo angle, λ). For each up quark-line exchanged in any FCNC diagram (and, in particular, in a diagram for $K_L\to\mu^+\mu^-$), the charm quark provides a second diagram with a coupling of opposite sign. In fact, were the masses of the charm and up quarks equal, the two diagrams would exactly cancel. For unequal masses, the result can only be proportional to the mass difference, $m_c^2 - m_u^2$. This additional mass suppression of the $K_L \to \mu^+\mu^-$ transition shows the power of the GIM mechanism[2].

2.3 The bad: the NP flavor puzzle

Since flavor transitions are very suppressed in the SM, FCNC processes are highly sensitive to flavor violating New Physics (NP) interactions. As we will discuss in this section, if NP is not too far away from the TeV scale, then its flavor structure has to be highly non trivial, since, otherwise, NP corrections to flavor transitions would be (several orders of magnitude) too large, if compared to measurements.

Let us assume, for example, that there exist new degrees of freedom which complete the SM theory that are heavier than the SM particles, so that we can integrate them out and describe the beyond the SM (BSM) theory by means of an effective theory approach (see Sec. 3.1 for more details). An example can be a new heavy Z' gauge boson that interacts with the SM quarks in a non-diagonal fashion. New dimension-6 four-quark operators will be generated in the effective Lagrangian, after integrating out the Z' particle. In particular, processes violating flavor by two units will receive contributions from the effective Lagrangian operators

$$\mathscr{L}_{eff} \supset \frac{c_{ij}^{\rm VLL}}{m_{Z'}^2}(\bar{q}^i\gamma_\mu P_L q^j)(\bar{q}^i\gamma^\mu P_L q^j) + \frac{c_{ij}^{\rm VRR}}{m_{Z'}^2}(\bar{q}^i\gamma_\mu P_R q^j)(\bar{q}^i\gamma^\mu P_R q^j) + \frac{c_{ij}^{\rm LR}}{m_{Z'}^2}(\bar{q}^i\gamma_\mu P_L q^j)(\bar{q}^i\gamma^\mu P_R q^j), \tag{2.8}$$

where c_{ij} are the Wilson coefficients of the several operators, i, j are flavor indices, and $P_{L,R}$ are the left and right-handed projection operators: $P_{L,R} = (1 \mp \gamma_5)/2$. Measurements of meson-antimeson mixings are all in relatively good agreement with the SM prediction and this leads to powerful bounds on the several combinations $c_{ij}/m_{Z'}^2$. As an example, if the Z' mediates a flavor transition $d \leftrightarrow s$, then measurements of Kaon-anti Kaon mixing observables impose the Wilson coefficients to be smaller than $\mathscr{O}(10^{-6})$ for $m_{Z'} = \mathscr{O}(1\text{ TeV})$. This is the new physics flavor puzzle: if NP exists not too far from the TeV scale, why are these coefficients so small?

2.4 CP violation

Before concluding this section, we would like to briefly comment on CP violation in the SM. In the SM, the only measured source of CP violation is the phase of the CKM matrix. In fact, the first (indirect) evidence for the existence of a third generation quarks was the discovery of CP violation by Cronin and Fitch in 1964. Indeed, a model with only two generation quarks, as proposed by Glashow, Iliopoulos, and Maiani, does not allow phases in the CKM matrix, and therefore CP violation. In 1973, Kobayashi and Maskawa suggested the possibility that the existence of a third family of quarks could explain CP violation in the SM. This happened even before the experimental evidence for the 4th quark! (the charm quark was only discovered a year later, in 1974). The third generation quarks was discovered a few years later: the bottom quark in 1977 and the top quark in 1994.

In the Wolfenstein parametrization discussed in Sec. 2.2, a phase convention is used such that, for example, V_{cb} is real. This is, of course, not invariant under flavor rotations. Is there a way to

[2] The analysis of this FCNC process in the full $SU(2)\times U(1)$ gauge theory, performed by Gaillard and Lee [28] lead to a prediction for the charm quark mass "to be less than, say, 10 GeV".

obtain a phase-independent measurement of the amount of CP violation in the SM? One can define the Jarlskog invariant [29] in terms of the Yukawas introduced in (2.1):

$$J_Y \equiv \mathrm{Im}\left(\det[Y_d Y_d^\dagger, Y_u Y_u^\dagger]\right) . \tag{2.9}$$

It is easy to demonstrate that (1) J_Y is invariant under flavor rotations; (2) J_Y can also be expressed as

$$J_Y = J_{\mathrm{CP}} \prod_{i>j} \frac{m_i^2 - m_j^2}{v^2/2} , \tag{2.10}$$

where $m_{i,j}$ are quark masses and the invariant measure of CP violation is given by

$$J_{\mathrm{CP}} = \mathrm{Im}[V_{us} V_{cb} V_{ub}^* V_{cs}^*] = \lambda^6 A^2 \eta \simeq \mathscr{O}(10^{-5}) . \tag{2.11}$$

One can also demonstrate that J_{CP} is proportional to the area of the unitarity triangle, that is, therefore, invariant under flavor rotations.

Interestingly enough, by now CP violation has been discovered in all meson mixing systems involving down-type quarks: first in $K-\bar{K}$ mixing, second in $B_d-\bar{B}_d$ mixing, and then finally in $B_s-\bar{B}_s$ mixing [3].

3. Minimal Flavor Violating theories

Several (exact or approximate) flavor symmetries have been proposed to address the NP flavor problem. New degrees of freedom consistent with the measurements of FCNC processes could still arise not too far away from the TeV scale, thanks to their protected flavor structure. In general, the flavor symmetry group, $\mathscr{G}_{\mathrm{flavor}}$, must be contained in the full global symmetry group of the SM in the limit of vanishing Yukawa couplings, $U(3)^5$ (see Sec. 2.2). Examples are models with an approximate $U(2)$ [31, 32, 33] flavor symmetry, or models based on the Minimal Flavor Violation (MFV) ansatz [34, 35, 36, 37], that we will discuss next.

One can view the Yukawa couplings of the SM as dimensionless auxiliary fields (spurions) which transform under $U(3)^5$ in a way that makes the SM Lagrangian formally invariant under $\mathscr{G}_{\mathrm{flavor}}$. It is easy to show that this flavor invariance can be achieved if the Yukawas defined in (2.1) transform as

$$Y_d \sim (3,1,\bar{3})_{SU(3)_q^3},\ Y_u \sim (3,\bar{3},1)_{SU(3)_q^3},\ Y_e \sim (3,\bar{3})_{SU(3)_\ell^2}, \tag{3.1}$$

where we have defined $SU(3)_q^3 = SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$ and $SU(3)_\ell^2 = SU(3)_{L_L} \times SU(3)_{e_R}$. The flavor invariance is then broken by the background value of the spurions which are bi-fundamentals of $\mathscr{G}_{\mathrm{flavor}}$. MFV theories do not contain additional sources of $U(3)^5$ breaking beyond these SM Yukawas. This ansatz can be applied to any NP theory. Note that the invariance under CP of the NP contributions may or may not be imposed in addition to this criterion. Next, we will discuss the impact of the MFV ansatz on NP effective field theories (Sec. 3.1) and on NP theories containing light new degrees of freedom (Sec. 3.2).

[3] CP violation has been very recently discovered in D-meson decays [30]. CP violation in $D-\bar{D}$ mixing has not been yet discovered.

Operator	Kaon system Re(c_n)	Kaon system Im(c_n)	B_d meson system Re(c_n)	B_d meson system Im(c_n)	B_s meson system Re(c_n)	B_s meson system Im(c_n)	D meson system Re(c_n)	D meson system Im(c_n)
$O_1^{\rm VLL}$	$9\cdot10^{-7}$	$3.4\cdot10^{-9}$	$2.3\cdot10^{-6}$	$1.1\cdot10^{-6}$	$5\cdot10^{-5}$	$1.7\cdot10^{-5}$	$5.6\cdot10^{-7}$	$1.0\cdot10^{-7}$
$O_2^{\rm LR}$	$6.9\cdot10^{-9}$	$2.6\cdot10^{-11}$	$3.9\cdot10^{-7}$	$1.9\cdot10^{-7}$	$8.8\cdot10^{-6}$	$2.9\cdot10^{-6}$	$5.7\cdot10^{-8}$	$1.1\cdot10^{-8}$

Table 1: Most updated bounds on some dimension-6 operators that mediate meson mixing, assuming a NP scale of 1 TeV. Adapted from [9, 26].

3.1 MFV SMEFTs

One can remain agnostic of the exact theory beyond the Standard Model, and study the Standard Model Effective Field Theory (SMEFT) that is constructed out of a series of $SU(3)\times SU(2)\times U(1)_Y$ invariant higher dimensional operators built out of the SM fields. Many higher dimensional operators can be generated in the effective theory. In particular, if we limit ourselves to the study of a SMEFT with operators up to dimension-6, there exist 59 operators that conserve flavor, as well baryon and lepton numbers [38, 39]. Adding flavor violating operators bring the count to more than 1000 independent operators [40]. Flavor violating operators are generically well constrained by low energy flavor measurements. As an example, let us go back to the discussion of meson mixing mentioned in Sec. 2.3. In total, eight dimension-6 operators contribute to meson mixing observables:

$$\begin{aligned} O_1^{\rm VLL} &= (\bar q_i \gamma_\mu P_L q_j)^2, \\ O_1^{\rm LR} &= (\bar q_i \gamma_\mu P_L q_j)(\bar q_i \gamma^\mu P_R q_j), \\ O_2^{\rm LR} &= (\bar q_i P_L q_j)(\bar q_i P_R q_j), \\ O_1^{\rm SLL} &= (\bar q_i P_L q_j)^2, \\ O_2^{\rm SLL} &= (\bar q_i \gamma_{\mu\nu} P_L q_j)^2, \end{aligned} \tag{3.2}$$

plus the corresponding O_i' operators ($O_1'^{\rm VLL}, O_1'^{\rm SLL}, O_2'^{\rm SLL}$) obtained through the exchange $P_L \to P_R$. Here we have defined $\gamma_{\mu\nu} \equiv \frac{i}{2}[\gamma_\mu, \gamma_\nu]$. Similarly to the discussion below Eq. (2.8), the Wilson coefficients of these operators are severely constrained by the measurement of the difference in mass of meson and anti-meson and of the CP violation in the several systems. In Table 1, we report the most updated bounds on the real and imaginary part of the Wilson coefficients, c_n, of some of these dimension-6 operators assuming a NP scale of 1 TeV. As shown in the table, very stringent constraints arise especially from the Kaon system ($s \to d$ transitions).

The SMEFT satisfies the MFV ansatz if all higher dimensional operators, constructed from the SM fields and the spurions Y_u, Y_d, Y_e, are invariant under the flavor group, $\mathscr{G}_{\rm flavor}$. This criterion leads to a relatively small set of bilinear invariants. These are given by [4]

$$\bar Q_L Y_u Y_u^\dagger Q_L,\ \bar D_R Y_d^\dagger Y_u Y_u^\dagger Q_L,\ \bar D_R Y_d^\dagger Y_u Y_u^\dagger Y_d D_R\,. \tag{3.3}$$

MFV allows only higher dimensional operators that are combinations of these invariants. For this reason, the dimension-6 operators in (3.2) will have Wilson coefficients with a very specific

[4] We do not explicitly write the bilinear invariants for the up-sector as they tend to be very small since suppressed by two powers of bottom Yukawas (instead of top Yukawas, as for the bilinears for the down-sector in (3.3)).

structure, and therefore it will be easier to address the constraints reported in Tab. 1. More in particular, one can show that the leading terms for the Wilson coefficients of the operators in Tab. 1 are given by

$$\begin{aligned} c_1^{\rm VLL} &\simeq Z_1^{\rm VLL} y_t^4 (V_{ti}^* V_{tj})^2, \\ c_2^{\rm LR} &\simeq Z_2^{\rm LR} y_i y_j y_t^4 (V_{ti}^* V_{tj})^2, \end{aligned} \tag{3.4}$$

where Z_n are generic flavor blind $\mathscr{O}(1)$ coefficients, $y_{i,j}$ are the down-type Yukawa couplings for the i and j flavor, and y_t the top Yukawa coupling. All Wilson coefficients are suppressed by a combination of small CKM elements and (some of them) by small down-type Yukawas. Using the numbers in Tab. 1 and the expressions in (3.4), one can show that thanks to these suppressions (directly arising from the MFV ansatz), NP not too far away from the TeV scale is allowed by meson-mixing measurements. (More specifically, in generic MFV theories, the most stringent flavor constraint on the NP scale of the operators in Tab. 1 arises from the B_d mixing system and is at around 6 TeV, in the case of the $O_1^{\rm VLL}$ operator.) Even more interesting, this conclusion generically applies to any flavor transition and not only to the $\Delta F = 2$ meson mixing systems discussed here.

Before concluding this section, we also want to mention that, beyond alleviating the NP flavor puzzle, MFV theories are also very interesting as they predict testable correlations between different flavor transitions. The classic example is the correlation between the NP effect in the branching ratio of $B_s \to \mu^+\mu^-$ and the one in the $B_d \to \mu^+\mu^-$ decay. Independently on the structure of the operator contributing to these rare decays, MFV theories predict, up to corrections suppressed by small light-quark masses [41]

$$\frac{{\rm BR}(B_s \to \mu^+\mu^-)}{{\rm BR}(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_d}{\hat{B}_s}\frac{\tau(B_s)}{\tau(B_d)}\frac{\Delta M_s}{\Delta M_d}, \tag{3.5}$$

where $\hat{B}_d$ is a renormalization group invariant parameter related to the bag parameter of the B_i meson-system ($\hat{B}_d = 1.26 \pm 0.11$ and $\hat{B}_s = 1.33 \pm 0.06$, see [42, 43] for details), $\tau(B_i)$ is the life-time of the B_i meson, and ΔM_i is the difference in mass of the $B_i - \bar{B}_i$ meson mixing system. This prediction for the ratio of branching ratios is obviously the same prediction as in the SM.

3.2 New MFV particles

The flavor SMEFTs discussed in the previous section can arise from integrating out heavy (if compared to the scale involved in the flavor process) NP degrees of freedom. If this new particle is within the reach of the LHC, it is very interesting to study its phenomenology. This is the topic of this section.

As a first "warm-up example", let us consider a new Z' gauge boson that couples to quarks in a MFV manner (see e.g. [44]). The leading quark couplings will be of the type $Z'_\mu(\bar{Q}_L \Delta_q \gamma^\mu Q_L)$ where the coupling matrix will have the form

$$\Delta_q = \kappa_0 \mathbf{I_{3\times 3}} + \kappa_1 Y_u Y_u^\dagger + \cdots . \tag{3.6}$$

The first term proportional to κ_0 will lead to a Z' coupled universally to same-flavor quarks, while the second term proportional to κ_1 will lead to flavor violating couplings of the type $y_t^2 V_{ti}^* V_{tj} Z'_\mu(\bar{d}_L^i \gamma^\mu d_L^j)$. If κ_0 is not too small, Z's at around the TeV scale will be copiously produced at the LHC.

A second interesting example are models with an extended Higgs sector. We know that the ballpark of the W and Z boson mass, as well as of the masses of third generation fermions come from the SM Higgs mechanism. However, we do not know if this is the entire story for mass generation of the massive SM particles. Notably, experimentally, we do not yet know if the SM Higgs is responsible of giving mass to the first and second generation quarks and leptons. An additional Higgs doublet could participate to electroweak symmetry breaking and contribute to the generation of mass of SM quarks and leptons, as well as massive gauge bosons. If we have more than one Higgs doublet in Nature, what is the flavor structure of the Two Higgs Doublet Model (2HDM)?

The most studied 2HDMs are based on the assumption of Natural Flavor Conservation (NFC) [45]: all fermions of a given electric charge get their masses from only one Higgs doublet. This condition is normally enforced by global Z_2 symmetries, which may be softly broken in the scalar sector. The NFC hypothesis leads to four different types of Yukawa structures: a "Type-I" where all fermions couple to one Higgs doublet; a "Type-II" where the up-type quarks couple to one doublet and the down-type quarks and leptons couple to the other; a "Type-III" where quarks couple to one doublet and leptons to the other; and a "Type-IV" where up-type quarks and leptons couple to one doublet and down-type quarks couple to the other. It is straightforward to convince ourselves that NFC also implies (a particular type of) MFV. Furthermore, because the fermion mass matrices are proportional to the Yukawa matrices, diagonalizing the fermion mass matrices diagonalizes also the Yukawa matrices, resulting in no tree-level FCNCs mediated by the two Higgs bosons, h,H. However, NFC is not sufficient to protect FCNCs if the theory has additional degrees of freedom at the TeV scale. In fact, even if the new degrees of freedom do no break the Z_2 symmetry, they can induce higher dimensional operators that do spoil the Type I-IV Yukawa structure [46]. One example are the Z_2 conserving operators

$$\mathscr{L} \supset \frac{c_1}{\Lambda^2}\bar{Q}_L X^{(6)}_{d1} D_R H_1 |H_2|^2 + \frac{c_2}{\Lambda^2}\bar{Q}_L X^{(6)}_{d2} D_R H_1 |H_1|^2 \,, \tag{3.7}$$

that induce a coupling of both Higgs doublets to down-type quarks, breaking in such a way the NFC ansatz and, generically, generating large NP effects in FCNC processes.

The most general Yukawa Lagrangian that obeys the MFV ansatz is given by

$$-\mathscr{L}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.} \,, \tag{3.8}$$

with the X_i couplings given by

$$\begin{aligned}
X_{d1} &= P_{d1}(Y_uY_u^\dagger, Y_dY_d^\dagger)\times Y_d \equiv Y_d \,, \\
X_{d2} &= P_{d2}(Y_uY_u^\dagger, Y_dY_d^\dagger)\times Y_d = \\
&\quad \varepsilon_0 Y_d + \varepsilon_1 Y_dY_d^\dagger Y_d + \varepsilon_2 Y_uY_u^\dagger Y_d + \varepsilon_3 Y_uY_u^\dagger Y_dY_d^\dagger Y_d + \varepsilon_4 Y_dY_d^\dagger Y_uY_u^\dagger Y_d + \cdots \,, \\
X_{u1} &= P_{u1}(Y_uY_u^\dagger, Y_dY_d^\dagger)\times Y_u = \\
&\quad \varepsilon'_0 Y_u + \varepsilon'_1 Y_uY_u^\dagger Y_u + \varepsilon'_2 Y_dY_d^\dagger Y_u + \varepsilon'_3 Y_uY_u^\dagger Y_dY_d^\dagger Y_u + \varepsilon'_4 Y_dY_d^\dagger Y_uY_u^\dagger Y_u + \cdots \,, \\
X_{u2} &= P_{u2}(Y_uY_u^\dagger, Y_dY_d^\dagger)\times Y_u \equiv Y_u \,,
\end{aligned} \tag{3.9}$$

where $P_i(Y_uY_u^\dagger, Y_dY_d^\dagger)$ are generic polynomials of $Y_uY_u^\dagger$ and $Y_dY_d^\dagger$, and where, in the second line, we show the explicit expansion in powers of $Y_uY_u^\dagger, Y_dY_d^\dagger$, after having defined the first and fourth

Yukawas as those breaking the flavor symmetry. The coefficients $\varepsilon_i^{(\prime)}$ are generic complex numbers of $\mathscr{O}(1)$. One can demonstrate that, because of terms like $Y_u Y_u^\dagger Y_d$, the Higgs-quark interactions and the quark mass matrices cannot be diagonal in the same basis. Therefore, Higgs FCNCs arise at the tree-level. *Are these flavor violating interactions too large to allow the new Higgs boson, H, to be not too far from the TeV scale?* The short answer is no.

These Higgs mediated FCNCs will contribute to many flavor transitions, such as meson mixing and rare B meson decays, like $B_s \to \mu^+\mu^-$. However, as we will now show, the NP contributions are relatively small, thanks to the suppression of small CKM elements, as well as small quark masses. Let us, for example, discuss the contribution to meson mixings. For simplicity, we can assume to be in the alignment limit [47], in which the lightest Higgs boson is SM-like and does not contribute to FCNCs. In this limit, one can show that, up to v^2/m_H^2 corrections, $m_A \simeq m_H$, where A is the pseudo-scalar. One can easily match to the EFT discussed in the previous section, and show that the most relevant operator that is generated via integrating out the heavy Higgs bosons, H and A, is the operator $O_2^{\rm LR}$ with a Wilson coefficient given by [46]

$$c_2^{\rm LR} = -\frac{(a_0^* + a_1^*)(a_0 + a_2)}{m_H^2} y_i y_j y_t^4 (V_{ti}^* V_{tj})^2 , \tag{3.10}$$

for the $i \to j$ $\Delta F = 2$ flavor transition. The coefficients a_i are given in terms of the coefficients $\varepsilon_i^{(\prime)}$ in (3.9) by

$$\begin{aligned} a_1 + a_0 &= \frac{r_V}{y_t^2\left[1+(\varepsilon_0+\varepsilon_1)t_\beta\right]}, \quad a_2 - a_1 = \frac{(\varepsilon_4-\varepsilon_3)t_\beta}{y_t^2\left[1+\varepsilon_0 t_\beta\right]}\left[1+(\varepsilon_0+\varepsilon_1-\varepsilon_2-\varepsilon_3)t_\beta\right], \\ r_V &\equiv \frac{(\varepsilon_2+\varepsilon_3)t_\beta}{1+(\varepsilon_0+\varepsilon_1-\varepsilon_2-\varepsilon_3)t_\beta}, \end{aligned} \tag{3.11}$$

t_β is the ratio between the VEVs of the two Higgs doublets: $t_\beta \equiv \tan\beta = v_2/v_1$. Using these Wilson coefficients and the bounds given in Table 1, one can show that, fixing e.g. the benchmark $\varepsilon_{0,1} = 1$, $\varepsilon_{2,3} = 0.5$, $\varepsilon_4 = 0.4$, $t_\beta = 5$, and maximal phases, m_H as low as ~ 600 GeV is consistent with all constraints from meson mixing observables.

4. Latest measurements, theory interpretations, and next goals

4.1 Flavor experiments

Several experiments aimed at testing the flavor and CP structure of Nature are running now and will be running in the coming years. On the one side, the LHCb and Belle II experiments will deliver the most precise measurements of B meson properties. On the other side, the NA62 experiment at CERN and the KOTO experiment at J-PARC will measure novel properties of the Kaon system. Finally, several experiments will have a much better sensitivity to electric dipole moments (EDMs). Examples are the neutron EDM experiments at PSI, TRIUMF, and SNS; the muon EDM experiment at JPARC; the ACME electron EDM experiment at Harvard (for a review, see e.g. [48]).

LHCb has so far accumulated ~ 8 fb^{-1} of integrated luminosity. The LHCb detector will be upgraded in the long shutdown of the LHC during 2018-2020, to run at a luminosity of up to

2×10^{33} cm^{-2}s^{-1}, a factor of 5 increase, if compared to Run-II. The expected integrated luminosity for Run-III and IV will be ~ 50 fb^{-1}. Finally, preliminary investigations have shown the possibility of a High-Luminosity run of LHCb, collecting 300 fb^{-1} or more [49].

Belle has completed data taking in 2010, colliding e^+e^- mainly at the $\Upsilon(4S)$ and $\Upsilon(5S)$ centre of mass energies and accumulating ~ 1ab^{-1} luminosity. Several analyses are still in the pipeline. At the same time, last year the upgraded Belle-II experiment got online and collected ~ 0.5fb^{-1} at the $\Upsilon(4S)$ resonance. This year Belle-II has started collecting data using for the first time the full detector (the first data collection was before the installation of the silicon inner detectors). The aim will be to collect a few fb^{-1} by the end of this summer. The final goal will be the collection of ~ 50 ab^{-1} data by 2027, where at least $\sim 10\%$ of this data will be collected off the $\Upsilon(4S)$ resonance.

Several milestones have been achieved by these experiments in the past few years. Here we would like to mention some of them. Belle had the first observation of CP violation in the B-meson system already with less than 1/10 of the collected luminosity [50]. In addition, Belle showed the first evidence for D-meson mixing [51], as well as for some B-rare decay modes, such as $B\to\tau\nu$ [52]. A summary of some of the important achievement by the Belle collaboration in shown in the left panel of Fig. 2. More recently, the LHCb collaboration has set for the first time precision constraints on the B_s mixing phase [53]; had the first measurement of the rare $B_s\to\mu^+\mu^-$ decay [54]; delivered the first angular analysis of the $b\to s\ell\ell$ system [55]. Very recently, at Moriond 2019, the LHCb collaboration announced the discovery of CP violation in the charm system [30].

Furthermore, interestingly enough, in the past few years, anomalies appeared in several low energy flavor observables. Among them are the B-physics anomalies:

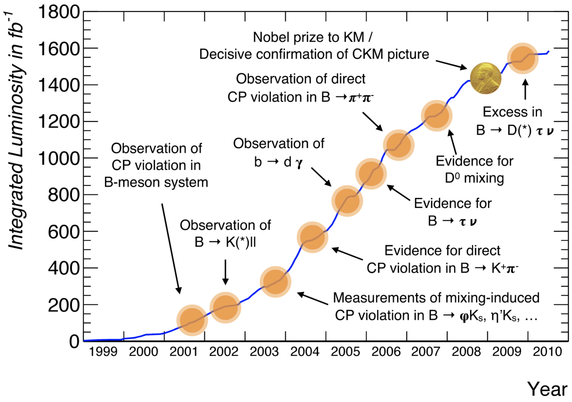
- An anomaly in the $B\to K^*\mu^+\mu^-$ angular distribution;
- An anomaly in the ratio of branching ratios $R_{D^{(*)}}\equiv \mathrm{BR}(B\to D^{(*)}\tau\bar\nu)/\mathrm{BR}(B\to D^{(*)}\ell\bar\nu)$, $\ell=e,\mu$;
- An anomaly in the ratio of branching ratios $R_{K^{(*)}}\equiv \mathrm{BR}(B\to K^{(*)}\mu^+\mu^-)/\mathrm{BR}(B\to K^{(*)}e^+e^-)$.

As we will discuss in the next section, several of these observables are theoretically very well understood, since the hadronic uncertainties are very small. A summary of the significance of these anomalies and of the importance of hadronic uncertainties in the SM computation of the several observables is shown in the right panel of Fig. 2.

4.2 Lepton universality

In the SM without neutrino masses, the photon, the W, and the Z bosons couple in exactly the same manner to the three lepton generations. Any measurable departure from this “lepton universality” (once the kinematic differences due to the different lepton masses have been corrected for) would be a clear sign of NP.

High energy measurements have so far confirmed lepton universality. For example, LEP measured the ratio of widths of the Z boson decaying to taus, muons, and electrons. The several measured ratios are consistent with unity at the per-mille level [56]. Similarly, W boson decays to leptons and neutrinos have been measured to be consistent with lepton universality at the percent



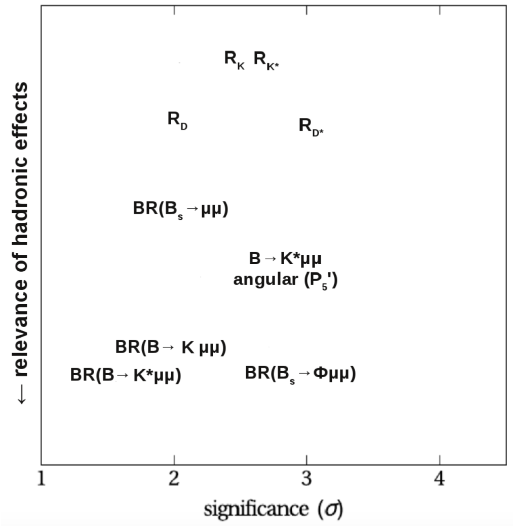


Figure 2: Left: Summary of some of the milestone measurements achieved by the Belle collaboration as a function of the collected luminosity. (from the talk by V. Savinov at the "Flavor 2019: new Physics in flavor from LHC to Belle-II" workshop) **Right**: Summary of present flavor physics anomalies. The "relevance of hadronic effects" gives an estimate of the relative theoretical cleanness of the several observables. (adapted from Z. Ligeti)

level [57]. In the past ~ 5 years, low energy experiments have reported anomalies in several B-physics observables testing lepton universality, particularly in $b \to s\ell^+\ell^-$ transitions and in $b \to c\ell\nu$ transitions.

4.2.1 Lepton universality in $b \to s$ transitions

Decays of B hadrons involving a loop-level transition of the type $b \to s\ell^+\ell^-$ provide an ideal laboratory to test lepton universality. The leading contributions to these transitions proceed through a $Z-$penguin, or a W^+W^- box. Ratios of branching fractions allow very precise tests of lepton universality, since hadronic uncertainties in the SM predictions are largely reduced, QED corrections are controlled at the $\sim 1\%$ level, and experimental systematic uncertainties cancel to a large extent. In the SM, such ratios are expected to be close to unity for di-lepton invariant masses, $q^2 \equiv m^2_{\ell\ell}$, above the di-muon threshold [58]:

$$R_K^{\rm SM} = 1.00 \pm 0.01 \ , \ \text{for } q^2 \in [1,6]\ \text{GeV}^2 \ , \tag{4.1}$$

$$R_{K^*}^{\rm SM} = \begin{cases} 0.91 \pm 0.03 \ , \ \text{for } q^2 \in [0.0045, 1.1]\ \text{GeV}^2 \ , \\ 1.00 \pm 0.01 \ , \ \text{for } q^2 \in [1.1, 6]\ \text{GeV}^2 \ , \end{cases} \tag{4.2}$$

where

$$R_{K^{(*)}} \equiv \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}e^+e^-)} \ . \tag{4.3}$$

Note that the SM prediction for R_{K^*} in the low-q^2 bin is slightly below 1 due to phase space effects.

Single measurements of these ratios have shown some $(2-3)\sigma$ inconsistency with these SM predictions. In Table 2, we collect the most relevant measurements of these ratios in the several

Experiment, Year	Observable	q^2 [GeV]	Value	Ref.
LHCb, 2014	R_K	1.0 - 6.0	$0.745^{+0.090}_{-0.074} \pm 0.036$	[59]
LHCb, 2017	R_{K^*}	0.045 - 1.1	$0.66^{+0.11}_{-0.03} \pm 0.05$	[60]
LHCb, 2017	R_{K^*}	1.1 - 6.0	$0.69^{+0.11}_{-0.07} \pm 0.05$	[60]
LHCb, 2019	R_K	1.1 - 6.0	$0.846^{+0.06}_{-0.054}{}^{+0.016}_{-0.014}$	[61]
Belle, 2019	R_{K^*}	0.1 - 8.0	$0.9^{+0.27}_{-0.21} \pm 0.1$	[62]
Belle, 2019	R_{K^*}	15.0 - 19.0	$1.18^{+0.52}_{-0.32} \pm 0.1$	[62]

Table 2: Summary of the most important $R_{K^{(*)}}$ measurements in the several q^2 bins. The first uncertainty is statistical and the second one is systematic. Note that the latest LHCb measurement has been performed using Run-I + 2 fb^{-1} Run-II LHCb data. This corresponds to about one third of the full Run-II data set.

q^2 bins. Some earlier measurements by Belle and Babar are omitted since they have much larger uncertainties, compared to the measurements reported in the table.

One can analyze these anomalies either in the context of EFTs, or in specific NP models. Particularly, model independent global fit of EFTs mediating $b \to s\ell^+\ell^-$ transitions have been performed keeping into account not only the measurements of $R_{K^{(*)}}$, but other $b \to s\ell^+\ell^-$ observables like $B_s \to \mu^+\mu^-$, angular observables in $B \to K^*\mu^+\mu^-$, branching ratios of $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, ... [5]. For the global fits performed after the new results presented at Moriond 2019, see [65, 66, 67, 68, 69, 70, 71].

At dimension-6, the relevant NP effective Hamiltonian contributing to these processes is[6]

$$\mathcal{H}_{\rm eff}^{bs\ell\ell} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2}\left(C_7^{bs}O_7^{bs} + C_7^{\prime bs}O_7^{\prime bs} + \sum_{\ell=e,\mu}\sum_{i=9,10,S,P}\left(C_i^{bs\ell\ell}O_i^{bs\ell\ell} + C_i^{\prime bs\ell\ell}O_i^{\prime bs\ell\ell}\right)\right) + \text{h.c.}\,, \tag{4.4}$$

where the operators are defined as

$$\begin{aligned}
O_7^{bs} &= \frac{m_b}{e}(\bar{s}\gamma_{\mu\nu}P_R b)F^{\mu\nu}\,, & O_7^{\prime bs} &= \frac{m_b}{e}(\bar{s}\gamma_{\mu\nu}P_L b)F^{\mu\nu}\,, \\
O_9^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, & O_9^{\prime bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,, \\
O_{10}^{bs\ell\ell} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,, & O_{10}^{\prime bs\ell\ell} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,, \\
O_S^{bs\ell\ell} &= m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, & O_S^{\prime bs\ell\ell} &= m_b(\bar{s}P_L b)(\bar{\ell}\ell)\,, \\
O_P^{bs\ell\ell} &= m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)\,, & O_P^{\prime bs\ell\ell} &= m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell)\,.
\end{aligned} \tag{4.5}$$

All $b \to s\ell^+\ell^-$ data is well described by NP contributions in the $O_9^{bs\mu^+\mu^-}$ and $O_{10}^{bs\mu^+\mu^-}$ operators. In particular, the best fit is obtained via fixing

$$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -0.53\,, \tag{4.6}$$

[5] Generically EFTs can not generate a sizable NP effect in the low q^2 bin of R_{K^*} ($0.045 - 1.1$ GeV^2). This is due to the fact that in the SM the low q^2 bin is dominated by the photon pole which strongly dilutes NP effects in the low-q^2 bin. To generate measurable NP effects, new light ($\mathcal{O}$(100MeV)) particles are required [63, 64].

[6] The most important operators generated in the SM are $O_7^{bs}, O_9^{bs}, O_{10}^{bs}$.

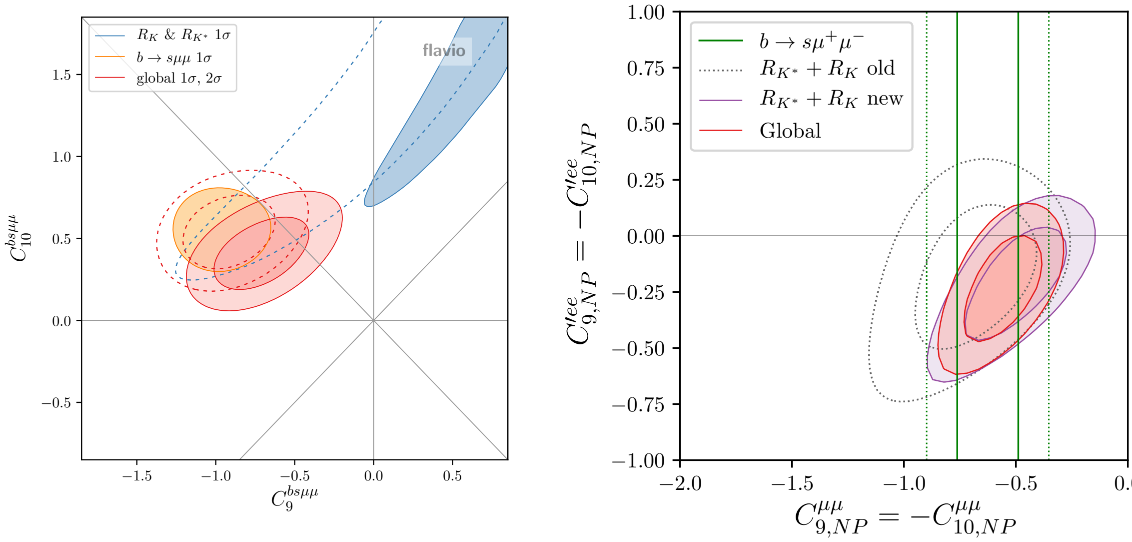


Figure 3: Left: Projection of the fit to $b \to s\mu\mu$ data in the plane of the Wilson coefficients $C_9^{bs\mu\mu}$ and $C_{10}^{bs\mu\mu}$. Individual constraints are shown at 1σ, the result of the global fit is shown at 1 and 2σ (red dotted and solid lines, respectively). All the other Wilson coefficients are set to 0. From [70]. **Right**: Projection of the fit in the the plane of the Wilson coefficients $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ and $C_9^{\prime bsee} = -C_{10}^{\prime bsee}$. From [69].

and all the other Wilson coefficients set to 0 (see also left panel of Fig. 3). This shows the preference for left-handed currents both in the quark and lepton sectors. The Wilson coefficients in (4.6) correspond to a scale of ~ 30 TeV in specific NP scenarios with $\mathscr{O}(1)$ couplings. This best fit scenario leads to an improvement of the χ^2, if compared to the SM, by $\Delta\chi^2 \sim 6.5\sigma$ [70]. Other operators like $O_{S,P}^{(\prime)bs\ell\ell}$ cannot receive a too large NP contribution due to stringent constraints from $B_s \to \mu^+\mu^-$ measurements. NP contributions in the electron current $O_9^{bse^+e^-}$ and $O_{10}^{bse^+e^-}$ also lead to a global fit that performs better than the SM. However, due to the anomalies in the angular observables of the decay $B \to K^{(*)}\ell\ell$, the fit performs slightly worst than the one obtained using a muonic current. This is shown in the right panel of Fig. 3.

Discussing all possible NP models able to reproduce these patterns of short-distance physics is beyond the scope of these lectures (for a comprehensive review see [72]). However, here we want to briefly overview the class of models that have been proposed to address the $b \to s$ lepton universality anomalies. In all generality, supersymmetric theories have difficulties addressing the anomalies still being consistent with LHC constraints [73, 74]. Composite Higgs models can generate right size contributions more easily [75]. From a low energy perspective, the leading models are models with Z' gauge bosons, or models with leptoquarks. In particular, minimal Z' models obtained via gauging the $L_\mu - L_\tau$ symmetry have been proposed to generate $C_9^{bs\mu\mu}$-type contributions (for the first studies see [76, 77, 78]). This type of models can easily evade constraints from other collider experiments due to the absence of tree-level couplings to electrons, as well as light quarks. A contribution of the type $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$ can be obtained e.g. in Z' models with loop-induced couplings [79] or in Z' models with heavy vector-like fermions [80, 81]. A single representation of vector leptoquarks ($U_1 = (3,1,2/3)$ under $SU(3) \times U(2) \times U(1)_Y$) can also generate

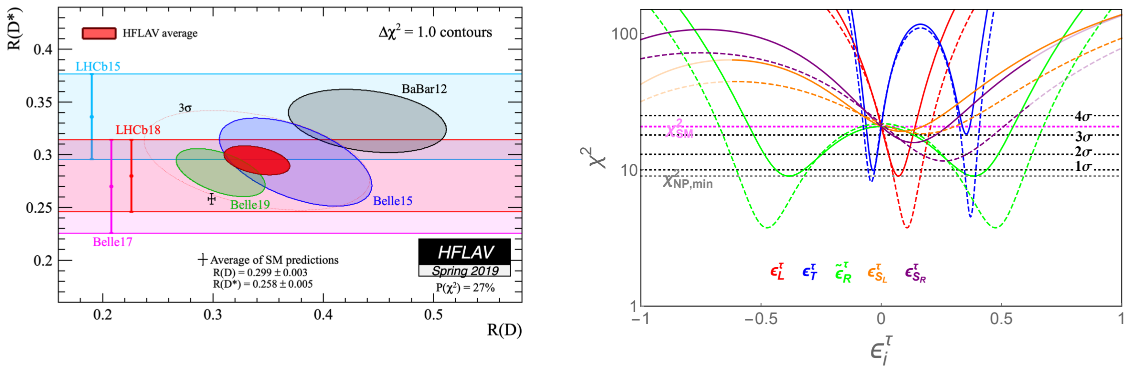


Figure 4: Left: Summary of the several measurements of $R_{D^{(*)}}$ and their SM predictions. From [89]. **Right**: The χ^2 of the fits to $R_{D^{(*)}}$ with one Wilson coefficients active at a time (setting the others to 0). The solid (dashed) lines correspond to the fits of the 2019 (2018) HFLAV world average. Faded regions for the operators $O^{bc\tau\bar{\nu}}_{\rm SL,SR}$ represent the bound from the measurement of the B_c^- life-time. From [96].

a $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$- type contribution (for the first studies see [82, 83, 84]).

4.2.2 Lepton universality in $b \to c$ transitions

The tree-level $B \to D^{(*)}\mu\bar{\nu}_\mu$ and $B \to D^{(*)}e\bar{\nu}_e$ decays are generally assumed to be free of NP contributions and they are used to perform measurements of the CKM matrix element V_{cb} (see right panel of Fig. 1). The large τ mass could, instead, make the $B \to D^{(*)}\tau\bar{\nu}_\tau$ decays more susceptible to NP. For this reason, their measurement is very important.

Contrary to the case of $R_{K^{(*)}}$ discussed in the previous section, the lepton universality observables $R_{D^{(*)}}$, defined as

$$R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathrm{BR}(B \to D^{(*)}\ell\bar{\nu}_\ell)}, \quad \ell = e, \mu, \tag{4.7}$$

are predicted to be different than one, because of kinematics. Particularly, the latest SM prediction reads [85] (see also [86, 87, 88])

$$R_D^{\rm SM} = 0.299 \pm 0.003, \quad R_{D^{(*)}}^{\rm SM} = 0.257 \pm 0.003 \,. \tag{4.8}$$

Several measurements have been done by the Belle, Babar, and LHCb collaborations taking into account different τ decay modes. In Table 3, we summarize the results. In the left panel of Fig. 4, we also present the comparison between some of the measurements and the SM predictions. The world average that includes also the latest Belle measurement reads [89]

$$R_D^{\rm exp} = 0.340 \pm 0.027 \pm 0.013, \quad R_{D^{(*)}}^{\rm exp} = 0.295 \pm 0.011 \pm 0.008 \,, \tag{4.9}$$

showing a 1.4σ (2.5σ) discrepancy with respect to the SM prediction for R_D (R_{D^*}). The combined significance is $\sim 3.1\sigma$. Taken at face value, this is a very large NP effect since it roughly corresponds to 30% of the SM prediction (of processes that arise already at the tree-level in the SM).

Experiment, Year	Observable	Value	Ref.
Babar, 2013,	R_D	$0.440 \pm 0.058 \pm 0.042$	[90]
Babar, 2013,	R_{D^*}	$0.332 \pm 0.024 \pm 0.018$	[90]
Belle, 2015,	R_D	$0.375 \pm 0.064 \pm 0.026$	[91]
Belle, 2015,	R_{D^*}	$0.293 \pm 0.038 \pm 0.015$	[91]
LHCb, 2015,	R_{D^*}	$0.336 \pm 0.027 \pm 0.030$	[92]
Belle, 2017,	R_{D^*}	$0.270 \pm 0.035\ ^{+0.028}_{-0.025}$	[93]
LHCb, 2017,	R_{D^*}	$0.280 \pm 0.018 \pm 0.029$	[94]
Belle, 2019	R_D	$0.307 \pm 0.037 \pm 0.016$	[95]
Belle, 2019	R_{D^*}	$0.283 \pm 0.018 \pm 0.014$	[95]

Table 3: Summary of the several $R_{D^{(*)}}$ independent measurements. The first uncertainty is statistical and the second one is systematic.

Due to the good agreement between the SM predictions and the measurements of the branching ratios into light lepton final states, most of the EFT analyses assume that NP is present in $B \to D^{(*)}\tau\bar{\nu}_\tau$ and not in $B \to D^{(*)}\ell\bar{\nu}_\ell$, $\ell = e, \mu$. At dimension-6, the relevant NP effective Hamiltonian contributing to these processes is[7]

$$\mathscr{H}_{\rm eff}^{bc\tau\bar{\nu}} = \frac{1}{\Lambda_{\rm NP}^2} \sum_i C_i \mathscr{O}_i^{bc\tau\bar{\nu}}\,, \tag{4.10}$$

where the operators are defined as

$$\begin{aligned} O_{\rm VL}^{bc\tau\bar{\nu}} &= (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)\,, & O_{\rm VR}^{bc\tau\bar{\nu}} &= (\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu)\,, \\ O_{\rm SL}^{bc\tau\bar{\nu}} &= (\bar{c}P_L b)(\bar{\tau}P_L \nu)\,, & O_{\rm SR}^{bc\tau\bar{\nu}} &= (\bar{c}P_R b)(\bar{\tau}P_L \nu)\,, \\ O_{\rm T}^{bc\tau\bar{\nu}} &= (\bar{c}\gamma_{\mu\nu} P_L b)(\bar{\tau}\gamma^{\mu\nu} P_L \nu)\,, \end{aligned} \tag{4.11}$$

plus the corresponding operators with $P_L \to P_R$. All these operators could in principle lead to a relatively good fit to the $R_{D^{(*)}}$ data. This is shown in the right panel of Fig. 4[8]. However, all operators except $O_{\rm VL}^{bc\tau\bar{\nu}}$ are severely constrained by other measurements. For example, differential distributions in the $B \to D^*\tau\bar{\nu}$ decay and the total lifetime of the B_c^- meson strongly constraint the right-handed operator $O_{\rm VR}^{bc\tau\bar{\nu}}$ [72]. Also the Wilson coefficients of the scalar and pseudoscalar operators have stringent constraints from the total lifetime of the B_c^- meson (faded regions in the right panel of Fig. 4 represent the bound from the measurement of the B_c^- lifetime). In addition, scalar and pseudo-scalar models ($O_{\rm SL,SR}^{bc\tau\bar{\nu}}$) can be constrained by LHC searches for $\tau^+\tau^-$ resonances (this has some model dependency). Finally, the tensor operators are not easily generated by NP theories at the electroweak scale without additional contributions to other operators [97]. Overall,

[7]The only operator generated in the SM is the $O_{\rm VL}^{bc\tau\bar{\nu}}$ operator.

[8]In this plot, taken from [96], the authors use a different normalization of Wilson coefficients, if compared to Eq. (4.10): $\varepsilon_i = \frac{C_i}{\Lambda_{\rm NP}^2}\frac{\sqrt{2}}{4G_F V_{cb}} \sim 7 \times 10^5 {\rm GeV}^2 \frac{C_i}{\Lambda_{\rm NP}^2}$.

a good fit to all data favors a NP effect in the $O_{\rm VL}^{bc\tau\bar{\nu}}$ SM operator with a Wilson coefficient that corresponds to a pretty low NP scale of $\Lambda_{\rm NP} \sim 3$ TeV, for order 1 couplings (see right panel of Fig. 4).

Various models with single light mediators have been proposed in the literature to address these $b \to c$ anomalies. Heavy charged vector bosons (W') (for early studies see e.g. [98]), heavy charged scalars (H') (for early studies see e.g. [99, 100]) or colored vector or scalar leptoquarks (for early studies see e.g. [101, 102]) could satisfy $R_{D^{(*)}}$ data. However, as already discussed, W' and H' models are typically more constrained by LHC direct searches or other flavor data, favoring therefore models with leptoquarks. Three different scalar leptoquark representations ($S_1 = (\bar{3},1,1/3), R_2 = (3,2,7/6), S_3 = (3,3,-1/3)$ under $SU(3)\times SU(2)\times U(1)_Y$) and three different vector leptoquarks ($U_1 = (3,1,2/3), V_2 = (3,2,-5/6), U_3 = (3,3,2/3)$ under $SU(3)\times SU(2)\times U(1)_Y$)) can give a good fit to data. Interestingly, models containing the U_1 leptoquark representation can give a good fit to both $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies [103].

4.3 Future key measurements

As discussed in Sec. 4.1, the field of flavor physics is undergoing a big upgrade in available statistics. Due to the large increase of luminosity by the LHCb collaboration and to the large data collection by Belle-II in the coming several years, many new key measurements are expected. In addition, the NA62 and KOTO experiments will play a crucial role in testing Kaon physics.

The constraints on the elements of the CKM matrix are thus set to become much more precise in the future (for the prospect to measure the unitarity triangle at LHCb and at Belle-II see [104] and [105], respectively. See also the left panel of Fig. 5 for the LHCb prospects). Particularly, the γ angle is the least known among the CKM angles and the LHCb collaboration will be able to improve its precision by almost a factor of ~ 10 [106].

Additional B-meson rare decays will be measured by the LHCb and Belle-II collaboration. Particularly, the branching ratios for $B_d \to \mu^+\mu^-$ and $B \to K^{(*)}\nu\bar{\nu}$ will be measured for the first time by LHCb and Belle-II, respectively. At present, LHCb gives the most stringent bound on the BR$(B_d \to \mu^+\mu^-)$ ($\lesssim 3.4\times 10^{-10}$) [108]. This bound is still ~ 3 times larger than the SM prediction at $(1.06\pm 0.09)\times 10^{-10}$ [109]. LHCb is expected to have a first evidence for this very rare decay mode already after collecting 50 fb^{-1} data. Correspondingly, also the uncertainty on the measurement of the branching ratio of $B_s \to \mu^+\mu^-$ is expected to improve by a factor of ~ 5 by LHCb with 50 fb^{-1} data [106]. As mentioned in Sec. 3.1, the simultaneous measurement of these two very rare decay modes will be crucial to test MFV theories (see Eq. (3.5)). Finally, the $B \to K^{(*)}\nu\bar{\nu}$ decay mode will be measured by Belle-II at the 10% level [110]. So far the branching ratio is only weakly constrained by Babar searches [111]:

$$\text{BR}(B^+ \to K\nu\bar{\nu}) < 3.2\times 10^{-5}\,,\quad \text{BR}(B \to K^*\nu\bar{\nu}) < 7.9\times 10^{-5}\,, \tag{4.12}$$

to be compared to the SM prediction given by [112]

$$\text{BR}(B^+ \to K\nu\bar{\nu})^{\rm SM} = (4.0\pm 0.5)\times 10^{-6}\,,\quad \text{BR}(B \to K^*\nu\bar{\nu})^{\rm SM} = (9.2\pm 1.0)\times 10^{-6}\,. \tag{4.13}$$

These decay modes are very interesting since they are theoretically cleaner than the related $B \to K^{(*)}\ell\ell$ decays and have complementary NP sensitivity. Furthermore, they can give access to dark sectors (see the extended version of these TASI lectures [10]).

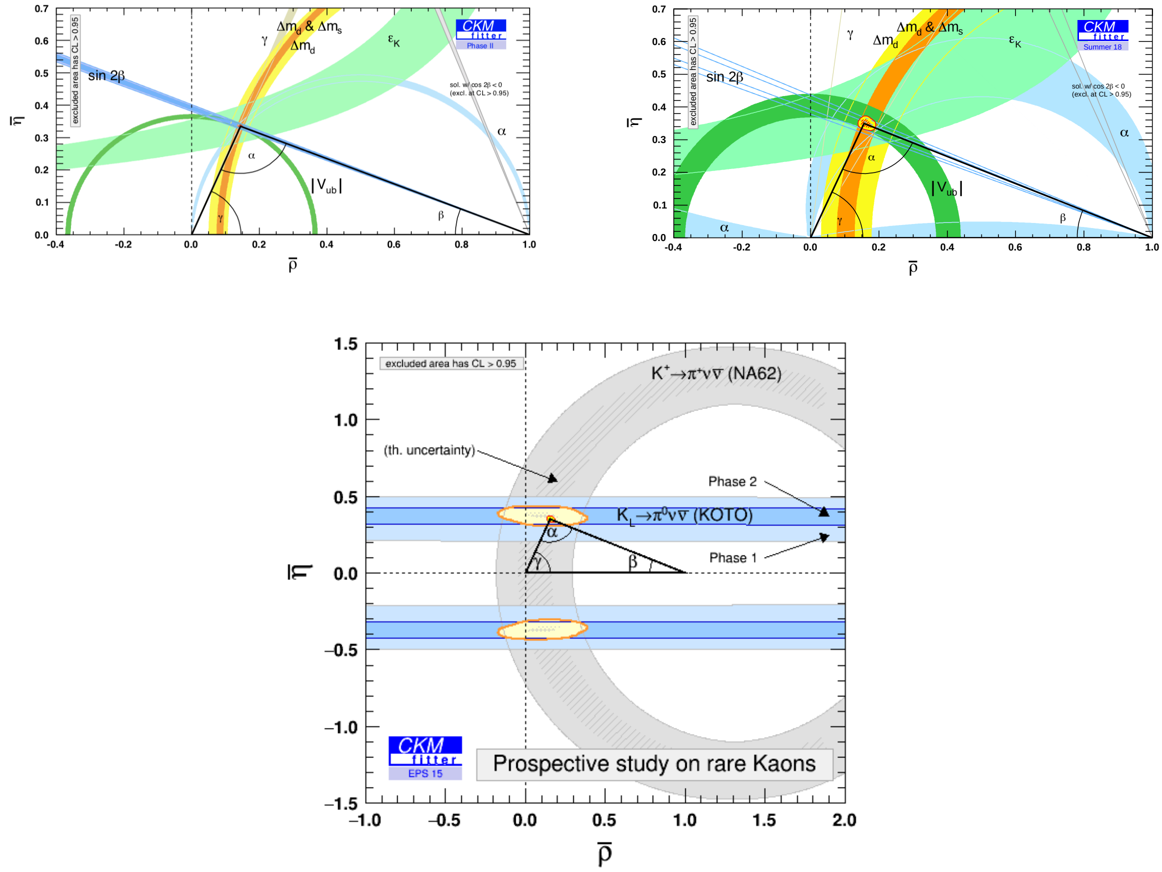


Figure 5: Left: Constraints in the $\bar\rho - \bar\eta$ plane from LHCb measurements and improvements in lattice QCD calculations, using the anticipated improvements from the data accumulated by 2035 with 300 fb^{-1} of integrated luminosity (from [106]). **Right**: For comparison, we also show the current status of the unitarity triangle fit. **Bottom**: Fit of the unitarity triangle using only Kaon results from the NA62 and KOTO experiments. KOTO Phase 1 (2) corresponds to a 3σ evidence for $K_L \to \pi^0 \nu\bar\nu$ (10% measurement). A 10% measurement of $K^+ \to \pi^+ \nu\bar\nu$ by NA62 is assumed (from [107]).

Also our understanding of Kaon physics is expected to make a big step forward in the coming years. In particular, the very rare and theoretically clean (CP conserving) $K^+ \to \pi^+ \nu\bar\nu$ and (CP violating) $K_L \to \pi^0 \nu\bar\nu$ decay modes will be measured for the first time with an uncertainty at the level of 10% by the NA62 and KOTO collaborations. At present, the most stringent limits on the branching ratios are given by [113, 114]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar\nu) < 14 \times 10^{-10}\,, \quad \mathrm{BR}(K_L \to \pi^0 \nu\bar\nu) < 3 \times 10^{-9}\,, \tag{4.14}$$

to be compared to the SM prediction given by [115, 116]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar\nu)^{\mathrm{SM}} = (9.11 \pm 0.72) \times 10^{-11}\,, \quad \mathrm{BR}(K_L \to \pi^0 \nu\bar\nu)^{\mathrm{SM}} = (3.00 \pm 0.30) \times 10^{-11}\,, \tag{4.15}$$

where the main source of uncertainty is the measurement of the CKM element V_{ub}. The measurement of these decay modes will test the Grosmann-Nir bound [117] and will also be able to test the unitarity of the CKM matrix, in a completely independent manner, without using B-physics measurements [118] (see the lower panel of Fig. 5).

All these measurements will tell us a lot more on the flavor structure of Nature. Complementary probes will be delivered by the ATLAS and CMS collaborations through high energy flavor measurements such as flavor violating Higgs, top, and Z decays (for a discussion of flavor physics at high energy, see the longer version of these TASI lectures that will be submitted to the arXiv [10]).

5. Concluding remarks

The field of flavor physics has seen a two-fold development in the last few years. On the one hand the CKM picture that describes flavor violation in the Standard Model has been experimentally tested with an unprecedented accuracy. Measurements seem to agree well with SM predictions (some of them at the $\mathscr{O}(1\%)$ level) and this leads to tight bounds on additional NP contributions to flavor transitions. From these measurements one can conclude that, if NP is not too far from the TeV scale, its flavor structure has to be highly non trivial (Minimal Flavor Violation?). On the other hand, lately, several anomalies have appeared in data, especially in the context of observables breaking the SM lepton flavor universality. If confirmed, these patterns of flavor violation will lead to completely new flavor structures for the ultimate theory of flavor. One of the exciting parts of the story is that several qualitatively (and quantitatively) new measurements both at low and at high energy are expected soon, so *stay tuned!*

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