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Review

Recent Developments in Flavor Physics, the Unitary Triangle Fit, Anomalies and All That

Guido Martinelli [1,2]

[1] INFN, Sezione di Roma, P.le A. Moro 2, 00185 Roma, Italy; guido.martinelli@roma1.infn.it
[2] Dipartimento di Fisica, Università di Roma La Sapienza, P.le A. Moro 2, 00185 Roma, Italy

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Abstract: Flavor physics represents one of the main fields of investigation to answer some fundamental questions like the baryon anti-baryon asymmetry or the presence of dark matter in our universe. Precision studies of the Cabibbo-Kobayashi-Maskawa matrix offer a very important testing ground of the Standard Model and, in the light of recent theoretical progress and experimental measurements, the status of the Unitarity Triangle is a fundamental tool to uncover physics beyond the Standard Model. The results of the most recent global fits performed by the **UT***fit* Collaboration, including all the up-to-date experimental and theoretical inputs are reported and stringent constraints on New Physics from the generalized $|\Delta F| = 2$ effective Hamiltonian are presented.

Keywords: flavor physics; lattice gauge theory

1. Introduction

Flavor physics is a fundamental part of the Standard Model (SM) and one of the most powerful tools that we have at disposal to discover New Physics (NP) effects. In this talk I will discuss our present understanding of flavor physics and some of the processes that we are studying in order to discover signals of physics beyond the SM.

The plan of the talk is the following: after a brief review of lessons from the past, I will discuss the present situation of flavor physics within the SM by reviewing many different processes and then I will conclude with the searches of signals of physics beyond the SM, expecially in radiative or rare decays, such those involving flavor changing neutral currents.

1.1. Lessons from the Past

The first example of the importance of flavor physics, although at the time it was not called in this way, is the Fermi theory of β decays. This is an example of a non-renormalisable, effective field theory that becomes non unitary at a scale of $O(100)$ GeV, needs to be unitarised by new degrees of freedom at this energy scale and thus it represents an example of indirect evidence for the existence of NP, in this case the Standard Model itself with the W and Z vector bosons. After the Fermi theory many fundamental experimental discoveries and theoretical advances opened the way to new concepts and understanding of our universe from sub-atomic to cosmological distances. Just to mention some of them

- 1963 The Cabibbo angle;
- 1964 The discovery of CP violation in neutral K decays;
- 1970 The GIM Mechanism;
- 1973 Kobayashi-Maskawa showed that CP violation needs at least three quark families;
- 1975 The discovery of the τ lepton, the third lepton family;
- 1977 The discovery of the b quark, the third quark family;
- 2003/2004 The discovery of CP violation in B meson decays.

On the basis of the above progress the present SM has been built as a magnificent construction able to explain and describe an enormous variety of phenomena. In a more recent past theoretical calculations allowed also to predict, prior to their measurements, several quantities like for example the value of $\sin 2\beta$ [1] and the value of the $B_s - \bar{B}_s$ mixing amplitude ΔM_s [2], see below. These predictions, subsequently confirmed by their experimental values, remain a very important test of the model at the quantum level.

1.2. The Standard Model

The modern approach is to consider the Standard Model, a renormalisable gauge theory, as an effective theory valid at low energies, namely at energy scales well below the TeV, above which particles corresponding to new, still undiscovered, degrees of freedom will become manifest. The model can be written in terms of a Lagrangian, based on a $SU(3)_c \times SU(2)_W \times U(1)_Y$ (color $\times$ weak$\times$ hyper-charge) gauge symmetry, spontaneously broken to $SU(3)_c \times U(1)_{em}$, where only the color and the electromagnetic symmetries survive. The symmetry breaking is obtained through the classical Higgs mechanism, with the Higgs field belonging to a weak isospin doublet. The $W^\pm$ and Z^0 vector mesons and the quarks (three families) acquire a mass proportional to their coupling to the Higgs particle. Schematically we may write

$$\begin{aligned} \mathcal{L} = \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 + (D_\mu H)^2 + \\ \bar{\psi} \not{D} \psi + + Y H \bar{\psi} \psi + F^2_{\mu\nu} + F_{\mu\nu} \tilde{F}_{\mu\nu} + \\ \frac{1}{\Lambda} (\bar{L} H)^2 + \frac{1}{\Lambda^2} \sum_i C_i O_i + \dots \,, \end{aligned} \tag{1}$$

where in the first line we have the vacuum energy and the interactions of the Higgs particle with itself and with the gauge fields; in the second line the interactions of the Fermions with the gauge fields and with the Higgs particle are shown toghether with the gauge fields Lagrangian (including the source of strong CP violation); the third line represents the expansion of the (non-renormalisable) effective Lagrangian in terms of operators of higher and higher dimensions ($D \geq 4$) which are the low energy manifestation of physics Beyond the Standard Model (BSM). Thus, for example, the first term in the third line of Equation (1) will give a mass to the neutrinos.

If we only impose the gauge symmetries to our model, this theory is very elegant relying only in three parameters namely the three gauge couplings corresponding to the $SU(3)_c \times SU(2)_W \times U(1)_Y$ symmetry. One can imagine that these couplings will be unified in a single parameter within a Grand Unification scheme (GUT). The introduction of the Higgs field, with the accompanying symmetry breaking, a necessary step in order to give a mass to the vector mesons as dictated by the experiments, introduce 19 arbitrary, measurable parameters

$$3\, g_i + (\lambda, M_H) + 6\, m_q + 3\, m_\ell + 3\theta_{CKM} + \delta + \theta_{QCD} = 19 \,, \tag{2}$$

which correspond to the three gauge couplings, g_i, the Higgs self coupling and mass, λ, M_H, the quark and lepton masses, m_q, m_ℓ, the Cabibbo-Kobayashi-Maskawa (CKM) angles [3,4], θ_{CKM}, and phase, δ, and the coupling of the strong CP violating term θ_{QCD}. The introduction of the neutrino masses and mixing increases by nine the number of arbitrary parameters $3\, m_\nu + (2+1)\, \delta_{PMNS} + 3\, \theta_{PMNS} = 9$.

Thus with the Higgs field, the model becomes chaotic with many unanswered questions: why we have three families and not one or five or any other number (Rabi); why the model includes the fundamental breaking of parity (Landau); the model has too many arbitrary features for its predictions to be taken too seriously (Weinberg). There are other puzzling aspects in the model: the Higgs is the only particle the couplings of which are not gauge couplings and this is at the basis of the instability of the SM at the quantum level and of the hierarchy problem; the masses of the Fermions do not follow any simple rational rule, their values look like the result of a lottery drawing, see Table 1, spanning about five orders of magnitude just for the quark sector; unlike the electro-magnetic, neutral currents and strong interactions couplings, the couplings of weak charged currents are hierarchical with a strong correlation to the quark masses. Flavor physics is indeed the study of the weak couplings and CP violation with the aim of understanding the above puzzles.

Table 1. Full lattice inputs. The values of the quark masses have been obtained by taking the weighted averages of the $N_f = 2 + 1$ and $N_f = 2 + 1 + 1$.

Input	Lattice/Exp
$m_u^{\overline{\rm MS}}(2\,{\rm GeV})$ (GeV)	$2.20(9)\,{\rm MeV}$
$m_d^{\overline{\rm MS}}(2\,{\rm GeV})$ (GeV)	$4.69(2)\,{\rm MeV}$
$m_s^{\overline{\rm MS}}(2\,{\rm GeV})$ (GeV)	$93.14(58)\,{\rm MeV}$
$m_c^{\overline{\rm MS}}(2\,{\rm GeV})$ (GeV)	$993(4)\,{\rm MeV}$
$m_c^{\overline{\rm MS}}(m_c^{\overline{\rm MS}})$ (GeV)	$1277(5)\,{\rm MeV}$
$m_b^{\overline{\rm MS}}(m_b^{\overline{\rm MS}})$ (GeV)	$4196(19)\,{\rm MeV}$
$m_t^{\overline{\rm MS}}(m_t^{\overline{\rm MS}})$ (GeV)	$163.44(43)\,{\rm GeV}$

2. Precision Flavor Physics and the Search for New Physics Signals

In addition to gauge symmetry and renormalizability, the Standard Model is characterised by the so called accidental symmetries, which are present in the model although not required in its construction. Before the introduction of the Higgs and of the symmetry breaking, the flavor symmetries are $U(3)^5$, corresponding to all the possible internal rotations of the Fermion fields. With the symmetry breaking, the only remaining symmetries are those associated to baryon, B, and lepton, L, number conservation, although, beyond perturbation theory, only $B - L$ is conserved. Since at zero temperature B violation is negligible, we may still consider baryon number as a realised accidental symmetry of the SM. Similarly, by neglecting neutrino masses and mixing, we have the separate conservation of the different lepton flavours, $L = L_e \times L_\mu \times L_\tau$.

The most interesting processes to identity signals of physics BSM are those which are forbidden in the Standard Model. For instance, because of an accidental symmetry, proton decay is not allowed if all the symmetries of the Standard Model are preserved, together with its renormalizability: in order to trigger proton decay, maintaining gauge invariance, you would need a new operator with at least dimension 6. In the SM, even if $\mu \to {\rm e}\,\gamma$ is not forbidden since neutrinos have a mass, the branching ratio $BR(\mu \to {\rm e}\,\gamma) \sim \alpha_{em} m_\nu^4/m_W^4 \sim 10^{-52}$ is, however, so small that even a single event would be an indication of new physics. This is precisely what the experiment MEG is looking for.

After the forbidden or almost forbidden processes the most interesting ones to study are those which are heavily suppressed, in particular due to the GIM mechanism, see below, like processes induced by flavour-changing neutral currents, i.e., weak currents where the charge does not change, as for instance

$$q_i \to q_k\, \nu\, \overline{\nu} \qquad q_i \to q_k\, \ell^+\, \ell^- \qquad q_i \to q_k\, \gamma \tag{3}$$

where i and k are flavor indices related to equal charge quarks. These processes are forbidden at three level and, in general, Cabibbo suppressed, see below. For this reason they are particular sensitive to new physics, so that an accurate calculation of the relevant matrix elements from lattice simulations is of particular interest.

Coming back to the Standard Model, one of the salient and most interesting objects of investigation is the CKM matrix, $(\mathbf{V}_{\rm CKM})_{ij} = V_{ij}$, which controls the strength of weak charged currents

$$L^{cc} = \frac{g_W}{\sqrt{2}} \left(\bar{u}_L^i V_{ij} \gamma^\mu d_L^j W_\mu^+ + h.c. \right) , \tag{4}$$

where i and j are the flavor indices, $u^i \equiv (u, c, t)$ and $d^i \equiv (d, s, b)$. The amount of CP violation entailed by a certain process is all contained, after the diagonalization of the mass matrix, in the CKM matrix. With N generations of quarks the CKM matrix is characterised by $N(N-1)/2$ Euler angles and $(N-1)(N-2)/2$ phases which generate CP violation. With $N = 3$ we have three angles and one phase. The standard representation of the CKM matrix is

$$\mathbf{V}_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} . \tag{5}$$

If you look at the strength of weak couplings, you discover that the CKM matrix is very close to the identity matrix since, as you go out of the main diagonal, i.e., as you proceed from the lightest to heaviest quarks, the matrix elements become smaller and smaller. This suggested to Wolfenstein that the CKM matrix $\mathbf{V}_{\rm CKM}$ can be expanded in a small parameter given by $\lambda = s_{12} = \sin\theta_c$ ($s_{23} = \sin\theta_{23} = A\lambda^2$, $s_{13}e^{-\delta_{13}} = \sin\theta_{13}e^{-\delta_{13}} = A\lambda^3(\rho - i\eta)$), where θ_c is the Cabibbo angle. $\mathbf{V}_{\text{CKM}}$ can be written therefore as

$$\mathbf{V}_{\text{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1, \end{pmatrix} + \mathcal{O}(\lambda^4), \quad (6)$$

where we have $\lambda \approx 0.2$, $\eta \approx 0.2$, $A \approx 0.8$ and $\rho \approx 0.3$. Indeed one would expect ρ and η of order one whereas their value is small and of the order of the Cabibbo angle.

Everything I will discuss in the following will be expressed in term of ρ and η. In particular η corresponds to the phase that is necessary to provide CP violation in the CKM matrix. Note that the condition that in the SM at least three generations are needed to have CP violation [4] is necessary but not sufficient because the value of δ_{13} (η) is not a priori determined and could be zero. In this case the observed CP violation could arise from some other mechanism from physics beyond the SM.

As a last remark on the CKM matrix let me recall the properties related to its unitarity. This implies that the scalar product of any two columns or rows is zero, e.g., $V_{11}V_{12}^* + V_{21}V_{22}^* + V_{31}V_{32}^* = 0$. Each of the terms summed in the scalar product is in general a complex number, namely a vector in the complex plane, that we may define as $a_1 = V_{11}V_{12}^*$, $a_2 = V_{21}V_{22}^*$ and $a_3 = V_{31}V_{32}*$. The condition $a_1 + a_2 + a_3 = 0$ defines a *unitary triangle* and you may define as many triangles as scalar products obtained by multiplying any two rows or two columns. If you change the convention on quark phases a triangle will rotate in space and the only physical quantities are those which remain invariant under these rotations, as for instance the length of the sides, the angles between sides and the area. The measure of the area in particular is related to the amount of CP violation and it is zero if $\eta = 0$. The main investigation effort is in the attempt to extract from data such unitary triangles. Among these Unitary Triangles (UT), the most studied, since is the easiest to be measured (none of its sides is too small) and it has been overdetermined by several experimental measurements, is the one defined by the product $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, shown in Figure 1 together with its three related angles.

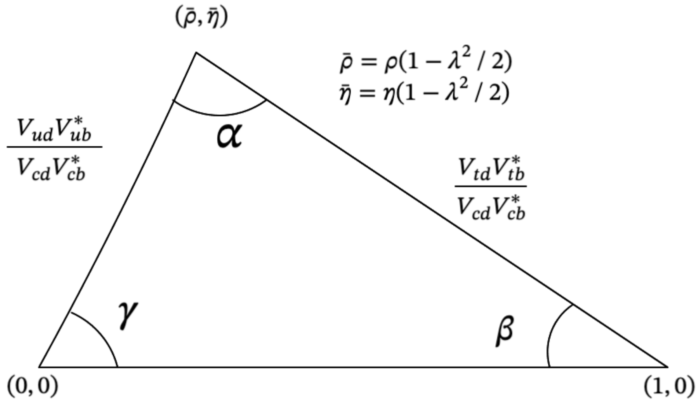

Figure 1. The “standard” unitarity triangle of the Standard Model from the three generations CKM matrix.

In the SM, another possible source of CP violation is the θ_{QCD}-term of strong interactions which was introduced before, i.e., $\mathcal{L}_\theta(x) = \theta_{QCD}\ \text{Tr}[\tilde{G}^{\mu\nu}G_{\mu\nu}] \sim \theta_{QCD}\vec{E}^a \cdot \vec{B}^a$, where the dual strength tensor $\tilde{G}^{\mu\nu}$ is defined as $\tilde{G}^{\mu\nu\, a} = \varepsilon^{\mu\nu\rho\sigma}G^a_{\rho\sigma}$. A non-zero $\mathcal{L}_\theta(x)$ induces an electric dipole moment in the neutron, e_n. Given the present experimental upper limit $e_n < 3 \cdot 10^{-26}$ e cm, see for example [5], and based on lattice calculations which are still rather uncertain, one can put on the value of the θ_{QCD} parameter an upper limit $\theta_{QCD} < 10^{-10}$.

One among the most important results in flavor physics is the determination of the allowed regions in the plane of the two parameters ρ and η of the Wolfenstein parametrisation, in particular the allowed region with respect to η, which controls the amount of CP violation. Accurate theoretical estimates and measurements of CP-even and CP-odd observables from neutral meson oscillations are of particular interest for the analysis of the unitarity triangle characterised by the determination of $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. Being the λ and A parameters well-constrained by leptonic and semi-leptonic meson decays, the UT analysis boils down to the investigation of all possible constraints in the $(\bar{\rho}, \bar{\eta})$ plane [6] ($\bar{\rho} = \rho\,(1 - \lambda^2/2)$ and $\bar{\eta} = \eta\,(1 - \lambda^2/2)$, see Figure 1). The sensitivity of the CKM metrology is then driven by $|V_{ub}/V_{cb}|$ from semi-leptonic B decays, ΔM_d and ΔM_s from $B^0_{d,s}$-$\bar{B}^0_{d,s}$ mixing, ε from neutral K mixing, the angle α, see Figure 1, from charmless ($\pi\pi$, $\pi\rho$, $\rho\rho$) non leptonic decays, γ from B decays with an open charm in the final state and $\sin 2\beta$, where β is defined in Figure 1, from the asymmetries in decays like $B^0 \to J/\psi K^0$. The **UT***fit* Collaboration has recently published a comprehensive study on the SM UT [6], and presented a related one beyond the SM in [7]. Most of the non-perturbative quantities necessary for this analysis are provided by lattice calculations which became more and more accurate over the years [8].

The structure of Yukawa couplings of the SM implies a rich phenomenology, characterized in the quark sector by the appearance of flavor Changing Neutral Currents (FCNC) only at the loop level, and further suppressed due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [9], rooted in the approximate $U(2)^3$ symmetry of the first two generations. Transitions with units of flavor violation $|\Delta F| \neq 0$ as well as CP-violating observables can be studied within a scheme with six quark masses, $m_{u,d,s,c,b,t}$, five of which determined by lattice calculations, and four mixing parameters [10], $\lambda, A, \bar{\rho}, \bar{\eta}$, required to describe the unitary CKM matrix [3,4], V_{ij}, with $i = u, c, t$ and $j = d, s, b$.

The hierarchical structure of the CKM and the fact that the $\bar{\eta}$ parameter is the only source for CP violation in weak interactions, make processes like $|\Delta F| = 2$ transitions very sensitive probes of NP. Indeed, an active interplay of all three generations is required in order to be sensitive to CP-violating effects in the SM, strengthening the important role of loop-induced processes like FCNCs in the phenomenology of weak interactions.

3. Updated Inputs and Measurements

A detailed description of the experimental and theoretical inputs entering in the UT analysis can be found in [2,6]. Here we limit ourselves in highlighting the novelties for the global fits presented in the next sections. The most important theoretical updates for the analyses presented in this work comprise:

- New averages for quark masses accounting for the latest progress from lattice QCD [8]; See the online results from FLAG 2023.
- Form factors for semileptonic B decays related to the exclusive determination of $|V_{cb}|$ and $|V_{ub}|$ in line with the updates from the dispersive matrix method of [11]; See Table 2.
- A novel estimate of radiative corrections to neutron decay as recently obtained by the authors of [12] in relation to the extraction of V_{ud}.

Table 2. Results for the SM global fits. In the first column we report all key observables for the determination of the UT, with corresponding experimental **UT***fit* averages provided in the next column. The third and fourth column reports the outcome for each observable with or without its statistical weight in the likelihood of the global fit. In the last column we show the pull of the SM predictions with respect to the measurements.

Observable	Measurement	Full Fit	Prediction	Pull (#σ)
$\lvert V_{ud}\rvert$	0.97433 ± 0.00017	0.97431 ± 0.00017	0.9737 ± 0.0011	0.6
$\lvert V_{ub}\rvert$	0.00375 ± 0.00026	0.003702 ± 0.000081	0.003696 ± 0.000087	0.2
$\lvert V_{cb}\rvert$	0.04132 ± 0.00073	0.04194 ± 0.00041	0.04221 ± 0.00051	1.0
$\alpha\ [^\circ]$	93.8 ± 4.5	92.4 ± 1.4	92.3 ± 1.5	0.9
$\sin 2\beta$	0.689 ± 0.019	0.705 ± 0.014	0.739 ± 0.027	1.5
$\gamma\ [^\circ]$	65.4 ± 3.3	65.1 ± 1.3	65.2 ± 1.5	0.1
ΔM_d [ps^{-1}]	0.5065 ± 0.0019	0.5067 ± 0.0020	0.519 ± 0.022	0.6
ΔM_s [ps^{-1}]	17.741 ± 0.020	17.741 ± 0.021	17.89 ± 0.65	0.2
ε	0.002228 ± 0.000011	0.002227 ± 0.000014	0.00200 ± 0.00014	1.6
$\mathrm{Re}\,(\varepsilon'/\varepsilon)$	0.00166 ± 0.00033	0.00160 ± 0.00028	0.00146 ± 0.00045	0.3
$\overline{\mathrm{BR}}(B_s \to \mu\mu) \times 10^9$	3.41 ± 0.29	3.44 ± 0.12	3.45 ± 0.13	0.1
$\mathrm{BR}(B \to \tau\nu) \times 10^4$	1.06 ± 0.19	0.872 ± 0.041	0.865 ± 0.041	1.0

Notice that in the UT analysis we employ unitarity in order to determine $|V_{us}|$ from $|V_{ud}|$; the latter is obtained via a skeptical average à la D'Agostini [13] from the study of neutron decay and super allowed $0^+ \to 0^+$ nuclear β processes as well as from a joint analysis of $K_{\mu 2}$, $K_{\ell 3}$ and $\pi_{\mu 2}$ decays. Regarding other key measurements adopted in our study, we update:

- The constraint on α, using the most recent outcome from the isospin study of hadronic B decays into $\pi\pi$, $\rho\rho$

and $\pi\rho$ channels from PDG and HFLAV; after Bayesian marginalization, this yields: $\alpha = (93.8 \pm 4.5)^\circ$;

- The constraint on β including a new measurement from LHCb on time-dependent CP violation from B decays into charmonium-kaon final states[14], weighting it with Cabibbo-suppressed penguin corrections [15]; we obtain: $\sin 2\beta = 0.689 \pm 0.019$;
- The constraint on γ from a preliminary combined analysis of $B \to D^{(*)}K^{(*)}$ modes with D meson oscillations [16], along the lines of what done by LHCb in [17]; For more details, see the dedicated EPS-HEP2023 contribution. we report $\gamma = (65.4 \pm 3.3)^\circ$ and negligible correlation with D mixing parameters (relevant for NP fits).

4. Standard Model Global Fits

The main message of the present UT analysis in the SM is that there is a general consistency, at the percent level, between theory predictions and the experimental measurements. This fact is exemplified in Figure 2. Using all the most informative constraints in order to determine the apex of the UT in the $(\bar\rho, \bar\eta)$ plane as precise as possible, we actually reach 3% precision in the inference of CP violation, namely:

$$(\,\bar\rho = 0.160 \pm 0.009\ ,\ \ \bar\eta = 0.346 \pm 0.009\,)\ \ \textbf{SM fit}\ , \tag{7}$$

with the other Wolfenstein parameters determined to be: $\lambda = 0.2251 \pm 0.0008$, $A = 0.828 \pm 0.010$. It is remarkable that the determination of the UT angles α, β and γ allows for the same level of precision in constraining CP violation from weak interactions in the SM:

$$(\,\bar\rho = 0.159 \pm 0.016\ ,\ \ \bar\eta = 0.339 \pm 0.010\,)\ \ \textbf{angles}\ . \tag{8}$$

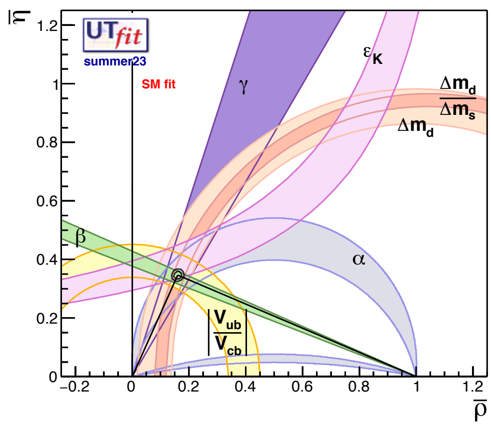

Figure 2. State-of-the-art UT analysis in the SM implementing all the most relevant constraints in the $(\bar\rho, \bar\eta)$ plane. Contour regions are shown at the 95% probability. Further details on the fit are reported in Table 1.

We observe that such a bound on CP violation still holds at the 6% level when one restricts the UT fit only to CP-conserving observables, and marginally improves with the addition in the fit of the observable ϵ, parametrizing CP violation from the mixing in the neutral kaon system, see Figure 3.

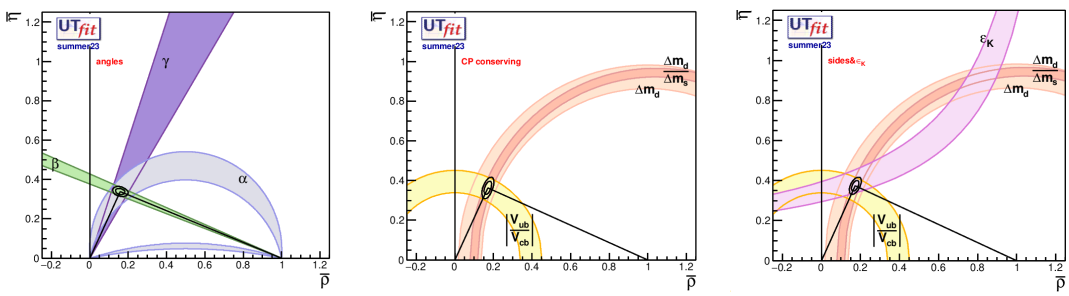

Figure 3. Determinations of the SM UT using partial information from the constraints available.

In Table 1 we report all the key observables for the SM global fits, with the measurements adopted in the analysis, the mean and standard deviation of the posterior from the full fit, and the corresponding predictions obtained removing the statistical weight of the observable under scrutiny from the likelihood. Comparing in absolute value the SM prediction against the corresponding measurement over the theoretical and experimental standard deviations summed in quadrature, we can define a pull for each observable as reported in the last column of Table 1, and perform compatibility tests as the ones pictured in Figure 4.

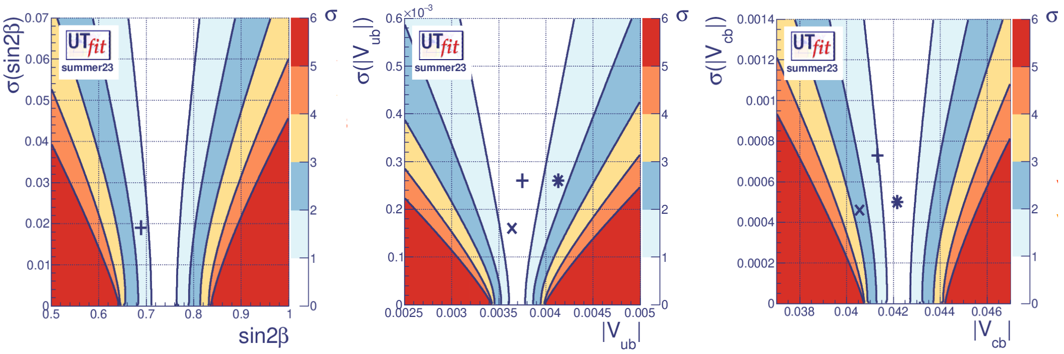

Figure 4. Highlight on the compatibility plots for the observables predicted in the SM UT analysis. For the case of $|V_{ub}|$ and $|V_{cb}|$ we also report the adopted exclusive and inclusive measurements with "x" and "$*$".

We observe that the tension between exclusive and inclusive determination of $|V_{ub}|$ and $|V_{cb}|$, related to the tree-level partonic processes $b \to u\ell\nu$ and $b \to c\ell\nu$, is no longer as severe as in the past. In particular, we report the following pulls from the fit:

$$\text{pull}(\#\sigma) = 2.4\,(0.1) \text{ for } |V_{cb}^{\text{excl}}| \times 10^3 = 40.55 \pm 0.46 \ \ (\text{for } |V_{cb}^{\text{incl}}| \times 10^3 = 42.16 \pm 0.50)\,,$$
$$\text{pull}(\#\sigma) = 1.6\,(0.3) \text{ for } |V_{ub}^{\text{incl}}| \times 10^3 = 4.13 \pm 0.26 \ \ (\text{for } |V_{ub}^{\text{excl}}| \times 10^3 = 3.64 \pm 0.16)\,,$$

underlying an agreement of the SM with data always within the 3σ level. This improved situation with respect to the past might be partly ascribed to an overall better understanding of the systematics in the measurement of the moments of some differential distributions for the semileptonic B decays under the spotlight; most importantly, in this regard a better handle on the theoretical uncertainties stemming from lattice QCD and unitarization techniques adopted for the computation of the relevant form factors has been playing a crucial role [18]. According to Table 1, the largest discrepancies from the outcome of the UT analysis actually shows up in the observables $\sin 2\beta$ and ε, both pointing to a mild $\sim 1.5\sigma$ tension of the SM against the respective measurements.

Given the high precision of the experimental measurements and of the theoretical calculations, we may ask the following question: is the UT analysis in agreement within the SM theoretical expectations? Until one year ago I would have said no, mainly because of the so-called *anomalies*, all of them seemingly connected to leptonic final states. These anomalies not only concerned the difference of the value of $|V_{cb}|$ as determined from exclusive and inclusive decays but also the tension between the measured values of the semi-leptonic ratios of branching ratios

$$R(D) = \frac{\text{BR}(B \to D\tau\nu_\tau)}{\text{BR}(B \to D\ell\nu_\ell)}\,, \qquad R(D^*) = \frac{\text{BR}(B \to D^*\tau\nu_\tau)}{\text{BR}(B \to D^*\ell\nu_\ell)}\,, \tag{9}$$

together with the corresponding SM predictions based on the lattice calculation of the relevant form factors and also the violation of Lepton Flavour Universality (LFU) in $b \to s\ell^+\ell^-$, where ℓ are light leptons (either $e^\pm$ or $\mu^\pm$). The apparent violation of LFU was given by a coherent pattern of tensions based on the ratios of BRs

$$R_X = \frac{\text{BR}(b \to s\mu^+\mu^-)}{\text{BR}(b \to se^+e^-)}\,, \tag{10}$$

which were expected to be very close to one, contrary with the experimental findings. For example, if we define the ratio of branching fractions

$$R_{K^{(*)}}^{[q_1^2,q_2^2]} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}\,, \tag{11}$$

corresponding to a chosen lepton invariant mass interval $q_1^2 \leq q^2 \leq q_2^2$, the values from LHCb were [19,20]

$$R_K^{[1.,1.6]} = 0.847 \pm 0.042\,; \quad R_{K^*}^{[0.045,1.0]} = 0.68 \pm 0.10\,; \quad R_{K^*}^{[1.0,1.6]} = 0.71 \pm 0.10\,. \tag{12}$$

Order thousands papers and many new physics models were written in the last few years to explain such anomalies.

"Unfortunately" for us, unfortunately because anomalies might have indicated new physics, all such anomalies did disappear and the new experimental values of the $B \to K\ell^+\ell^-$ ratios are very close to one, in full agreement with the SM expectations (no explanation was given for the discrepancy with previous measurements of the same quantities) [21]. Moreover a re-examination of the values and uncertainties of the predictions for $|V_{cb}|$ and $R(D^{(*)})$ lowered the discrepancies below the 2.5σ level [11]. The new uncertainties took into account the still large differences in the calculation of the relevant form factors and also to the differences between the experimental data.

On the side of the successful predictions of the SM, it is worth noticing that the branching ratio of the FCNC process $B_s \to \mu^+\mu^-$ shows now remarkable agreement between theory and data, an impactful result for the phenomenology of weak interactions in light of the recent discussion on rare B decay anomalies [22,23]. Eventually, it is also important to stress the excellent agreement of the current measurement of direct CP violation in the kaon system against the SM prediction via the implementation of ε'/ε as a novel observable in the global fit of the UT, see [6] for more details.

5. New Physics Global Fits

The UT analysis can be generalized to the case of NP under the key assumption that tree-level flavor violating processes used to constrain the $(\bar{\rho}, \bar{\eta})$ plane should not be significantly affected by physics beyond the SM. On the one hand, one can enlarge the number of fitted parameters and deal with additional $\mathcal{O}(10)$ ones capturing the effects of heavy new dynamics on the phase and the absolute value of $|\Delta F| = 2$ amplitudes. At the same time, one can include semileptonic charge and same-side dilepton asymmetries measured for the $B_{(s)}$ system, which are helpful in disentangling possible degeneracies in the NP UT fit, as well as D-$\bar{D}$ mixing observables, which provide the only genuine probe of flavor violation coming from the up-quark sector. Finally, one needs to tame long-distance contributions plaguing the estimate of the amplitudes of K-$\bar{K}$ and D-$\bar{D}$ mixing, treating them in a conservative fashion.

Following Ref. [24] and implementing the latest theoretical updates and measurements listed in the previous section, the NP UT analysis provides us today a constraint on the SM CP-violating parameter at the level of 8% of precision:

$$(\,\bar{\rho} = 0.167 \pm 0.025\ ,\ \ \bar{\eta} = 0.361 \pm 0.027\,)\ \ \textbf{NP fit}\ , \tag{13}$$

which stems from the determination of the allowed $\bar{\rho}$-$\bar{\eta}$ region using $|V_{ub}/V_{cb}|$ and γ only, together with the information provided in particular by the charge asymmetries in semileptonic B decays, see Figure 5.

The presence of NP in meson mixing amplitudes can be simply parametrized as:

$$\mathcal{A}_{\Delta F=2} = \left(1 + |\mathcal{A}^{\rm NP}|/|\mathcal{A}^{\rm SM}| e^{i2(\phi^{\rm NP}-\phi^{\rm SM})}\right) |\mathcal{A}^{\rm SM}| e^{i2\phi^{\rm SM}}\ , \tag{14}$$

and from the NP UT analysis it follows that at present the relative size of NP effects with respect to the SM, $|\mathcal{A}^{\rm NP}|/|\mathcal{A}^{\rm SM}|$, in $B_{d(s)}$ mixing amplitudes–characterized in the SM by the short-distance contribution of the top-quark in the loop–is constrained to be at most 30(25)% at 95% probability.

Barring accidental cancellations, the constraints on the NP phase and amplitudes in $|\Delta F| = 2$ processes can be then translated into a bound on the Wilson coefficient of dimension-six effective operators parametrizing in a model-independent fashion the effect of NP in neutral meson mixing:

$$\begin{aligned}
\mathcal{O}_1 &= (\bar{q}_i^\alpha \gamma_\mu P_L q_j^\alpha)\left(\bar{q}_i^\beta \gamma^\mu P_L q_j^\beta\right)\ ,\\
\mathcal{O}_2 &= (\bar{q}_i^\alpha P_L q_j^\alpha)\left(\bar{q}_i^\beta P_L q_j^\beta\right)\ ,\\
\mathcal{O}_3 &= \left(\bar{q}_i^\alpha P_L q_j^\beta\right)\left(\bar{q}_i^\beta P_L q_j^\alpha\right)\ ,\\
\mathcal{O}_4 &= (\bar{q}_i^\alpha P_L q_j^\alpha)\left(\bar{q}_i^\beta P_R q_j^\beta\right)\ ,\\
\mathcal{O}_5 &= \left(\bar{q}_i^\alpha P_L q_j^\beta\right)\left(\bar{q}_i^\beta P_R q_j^\alpha\right)\ ,
\end{aligned} \tag{15}$$

where $P_{L,R} = (1 \pm \gamma_5)/2$; the pair i, j and α, β runs over flavor and color indices, and the independent set of operators obtained via the substitution $P_L \to P_R$ in $O_{1,2,3}$ is not reported for brevity.

In Figure 5 we show the state-of-the-art bounds on the real and imaginary part of the Wilson coefficient of each of the NP operators entering in the $|\Delta F| = 2$ effective Hamiltonian of K-$\bar{K}$ and D-$\bar{D}$ mixing, and the constraint directly on the absolute value of the Wilson coefficient for the set of NP operators related to $B_{d,s}$-$\bar{B}_{d,s}$ mixing (whose SM amplitude is not plagued by long-distance effects). We show in Figure 6 with empty histograms the scenario where the UV theory does not enjoy any particular protection against novel sources of flavor and CP violation: in such a case, CP violation from the mixing in the neutral kaon system yields the strongest constraint on the scale of NP, $\Lambda \gtrsim 5 \times 10^5$ TeV, assuming $\mathcal{O}(1)$ couplings between the SM fields and the heavy new degrees of freedom. While the constraints in Figure 5 can be dramatically relaxed within the ansatz of Minimal Flavor Violation [25], a similar protection in the UV where however new $\mathcal{O}(1)$ phases in the flavor violating coupling are allowed is a tightly constrained possibility, probing scales as high as $\Lambda \gtrsim 110$ TeV, still way beyond the reach of present and next-generation colliders.

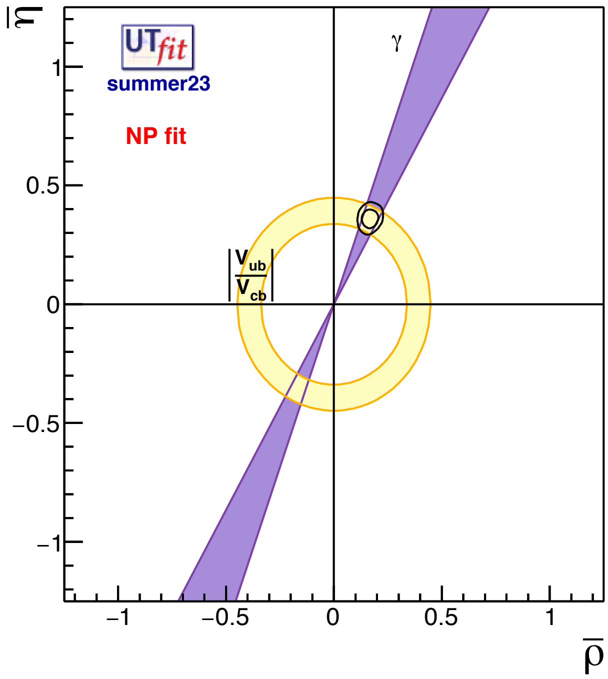

Figure 5. Constraints in the $(\bar{\rho}, \bar{\eta})$ plane at the 95% probability using tree-level determinations for the UT and generalizing SM loop-induced amplitudes as the ones for meson mixing to account for NP effects.

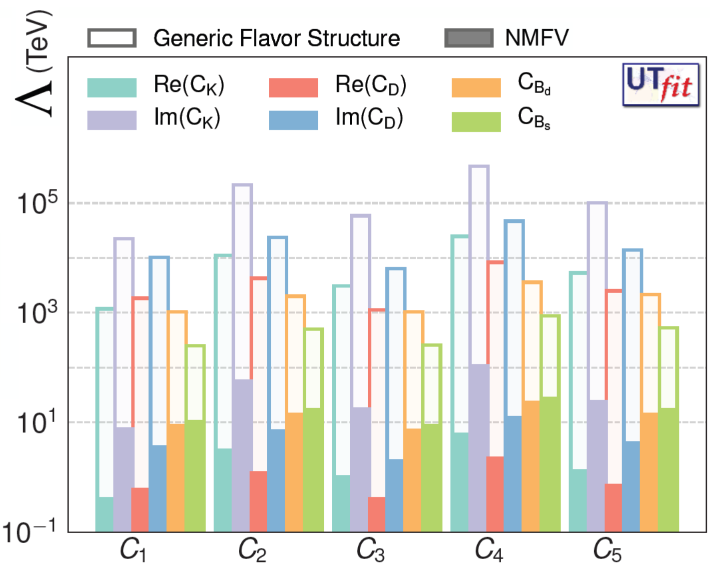

Figure 6. Constraints from the NP UT analysis on the set of dimension-six operators that generalizes the effective Hamiltonian for $|\Delta F| = 2$ transitions beyond the SM. Filled histograms correspond to bounds on local operators affecting the short-distant physics of neutral meson oscillation amplitudes in the scenario of Next-To-Minimal Flavor Violation, while empty ones apply to a generic flavor structure in the UV.

6. Future Prospects

The accuracy of the experimental measurements and the precision reached by theoretical calculations, especially in lattice QCD, allows to put stringent constraints on new physics even for radiative and rare decays. A satisfactory

NP model should produce the strong hierarchy of the Fermion coupling and masses while simultaneously explain the low scale suppression of FCNC and CP violation at an acceptable level. In this regard, the analysis of the unitarity triangle, and its extension/generalisation beyond the Standard Model, remains one of the best phenomenological tools to explore, via virtual effects, very large energy scales that cannot be reached by present and future colliders. Now that the *anomalies* practically disappeared, the quest for going beyond percent precision in the determination of the SM UT is dictated by the absence of any signal of new physics with present data. The hope to constrain NP amplitudes in FCNC processes like meson anti-meson oscillation, including long distance effects, at the level of few percent is a foreseeable achievement for the next decade. Rare processes like $K \to \pi\nu\bar{\nu}$ will provide further information about the triangle, while theoretical progress from lattice QCD will be necessary in order to bring the NP UT at the percent level of precision [26].

From the theoretical point of view, it is important to note that one of the main messages from flavor physics is perhaps the existence of a large gap between the electroweak energy scale and the scale of physics beyond the SM. If this is the case, an Effective Field Theory approach remains the most suitable framework to study NP constraints from precision measurements, including the ones from the UT analysis [27]. While some specific quantitative work along this direction has already been carried out, see e.g., [28,29], a more general study of the Standard Model Effective Field Theory including flavor constraints is still probably only at its infancy [30,31].

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Conflicts of Interest

The author declares no conflict of interest.

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