PROCEEDINGS OF SCIENCE

Overview and theoretical prospects for CKM matrix and CP violation from the UTfit Collaboration

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Precision studies of the Cabibbo-Kobayashi-Maskawa matrix offer a very important testbed of the Standard Model (SM). In light of new inputs and measurements, in this proceeding we review the status of the Unitarity Triangle as a fundamental tool to uncover New Physics. We report the results of the latest SM global fits performed by the **UT***fit* Collaboration including all the up-to-date experimental and theoretical inputs as for the *Summer 2023* release. We also update the stringent constraints on New Physics from the generalized $|\Delta F| = 2$ effective Hamiltonian. We conclude highlighting the role of the Unitarity Triangle for future indirect searches on New Physics.

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1. Introduction

The structure of Yukawa couplings of the Standard Model (SM) implies a rich phenomenology, characterized in the quark sector by the appearance of Flavour Changing Neutral Currents (FCNC) only at the loop level, and further suppressed due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [1], rooted in the approximate $U(2)^3$ symmetry of the first two generations.

In the SM transitions with units of flavour violation $|\Delta F| \neq 0$ as well as CP-violating observables can be studied by means of the notion of six quark masses – $m_{u,d,s,c,b,t}$ – and four mixing parameters [2] – $\lambda, A, \bar{\rho}, \bar{\eta}$ – required to describe the unitary Cabibbo-Kobayashi-Maskawa (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 of CP violation in weak interactions, make processes like $|\Delta F| = 2$ transitions very sensitive probes of New Physics (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.

For these reasons, accurate theoretical estimate and measurement of CP-even and CP-odd observables from neutral meson oscillations is of particular interest for the analysis of the so-called Unitarity Triangle (UT), characterized by the determination of: $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$. Being λ and A parameters well-constrained by leptonic and semileptonic meson decays, the UT analysis boils down to the investigation of all possible constraints in the plane $(\bar{\rho}, \bar{\eta})$ [5]. The sensitivity of the CKM metrology is then driven by: $|V_{ub}/V_{cb}|$ from semileptonic B decays, ΔM_d and ΔM_s from $B^0_{d,s} - \bar{B}^0_{d,s}$, ε_K from neutral K mixing, α UT angle from charmless hadronic B decays, γ UT angle from B decays to final states with open charm, and $\sin 2\beta$ from decays like $B^0 \to J/\psi K^0$ [6].

The **UT***fit* Collaboration has recently published a comprehensive study on the SM UT in Ref. [7], and presented a related one beyond the SM in [8]. In this proceeding we update those analyses, collecting and discussing the latest results from the SM and NP global fits of the UT.[1]

2. Updated inputs and measurements

A detailed description of the experimental and theoretical inputs entering in the UT analysis can be found, e.g., in [6, 7]. 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 and hadronic parameters (decay constants, form factors and B-parameters) accounting for the latest progress from lattice QCD [9];[2]
- Form factors for semileptonic B decays related to the exclusive determination of $|V_{cb}|$ and $|V_{ub}|$ in line with the updates from Ref. [10];
- A novel estimate of radiative corrections to neutron decay as recently obtained by the authors of Ref. [11] in relation to the extraction of V_{ud}.

[1]See also *Summer 2023 Fit Results* at http://utfit.org.
[2]See results online from FLAG 2023 .

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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
α [°]	93.8 ± 4.5	92.4 ± 1.4	92.3 ± 1.5	0.3
$\sin 2\beta$	0.689 ± 0.019	0.705 ± 0.014	0.739 ± 0.027	1.5
γ [°]	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_K	0.002228 ± 0.000011	0.002227 ± 0.000014	0.00200 ± 0.00014	1.6
$\mathrm{Re}\,(\varepsilon'_K/\varepsilon_K)$	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

Table 1: *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.*

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 [12] 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: $\alpha = (93.8 \pm 4.5)°$;
- The constraint on β including a new measurement from LHCb on time-dependent CP violation from B decays into charmonium-kaon final states[13], weighting it with Cabibbo-suppressed penguin corrections [14]; 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 [15], along the lines of what done by LHCb in [16];[3] we report $\gamma = (65.4 \pm 3.3)°$ and negligible correlation with D mixing parameters (relevant for NP fits).

3. 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

[3]For more details, see the dedicated EPS-HEP 2023 contribution.

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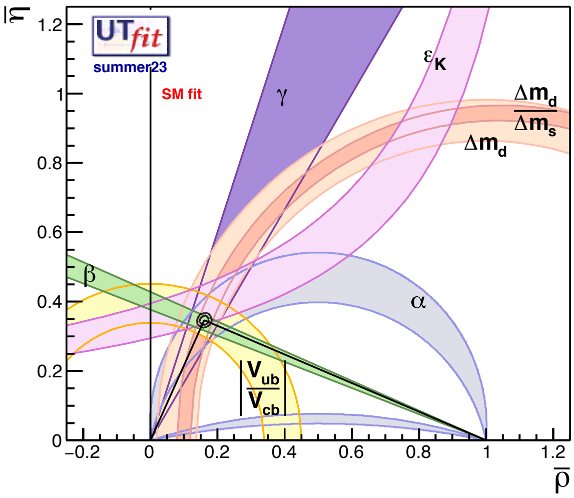

Figure 1: *State-of-the-art UT analysis in the SM implementing all the most relevant constraints in the $(\bar{\rho}, \bar{\eta})$ plane. Contour regions are shown at the 95% probability. Further details on the fit are reported in Table 1.*

exemplified in Figure 1. 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:

$$(\,\bar{\rho} = 0.160 \pm 0.009\;,\;\; \bar{\eta} = 0.346 \pm 0.009\,)\;\; \textbf{SM fit}\,, \tag{1}$$

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:

$$(\,\bar{\rho} = 0.159 \pm 0.016\;,\;\; \bar{\eta} = 0.339 \pm 0.010\,)\;\; \textbf{angles}\;. \tag{2}$$

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_K, parametrizing CP violation from the mixing in the neutral kaon system, see Figure 2. 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

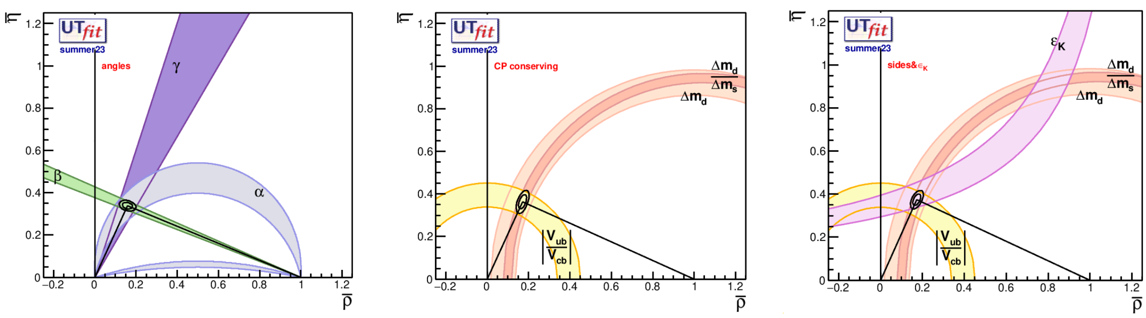

Figure 2: *Determinations of the SM UT using partial information from the constraints available.*

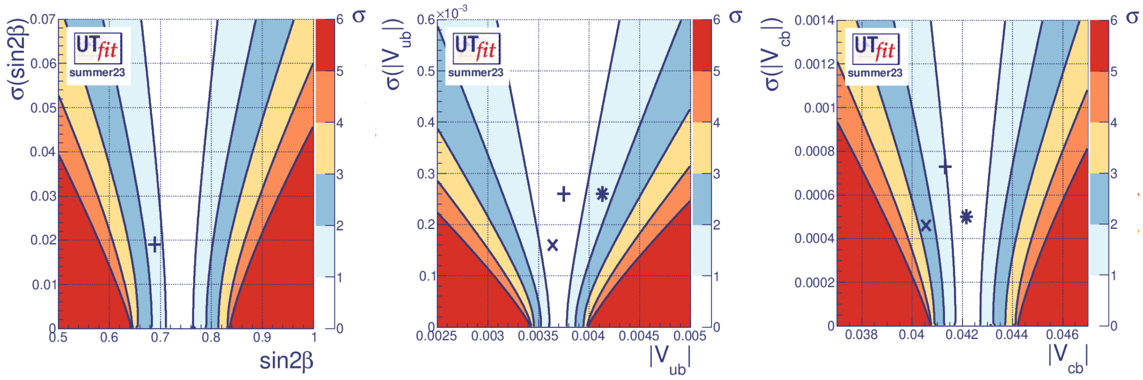

Figure 3: *Highlight on the compatibility plots for the observables predicted in the SM UT analysis. For the case of $|V_{ub}|$ and $|V_{cb}|$ we also report the adopted exclusive and inclusive measurements with "x" and "$*$".*

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 those pictured in Figure 3.

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 major role [17]. 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_K, both pointing to a mild $\sim 1.5\sigma$ tension of the SM against the respective measurements.

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 [18, 19]. 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 $\varepsilon'_K/\varepsilon_K$ as a novel observable in the global fit of the UT, see [7] for more details.

4. New Physics global fits

The UT analysis can be generalized to the case of NP under the key assumption that tree-level flavour-violating processes used to constrain the $(\bar{\rho}, \bar{\eta})$ plane should not be significantly affected by

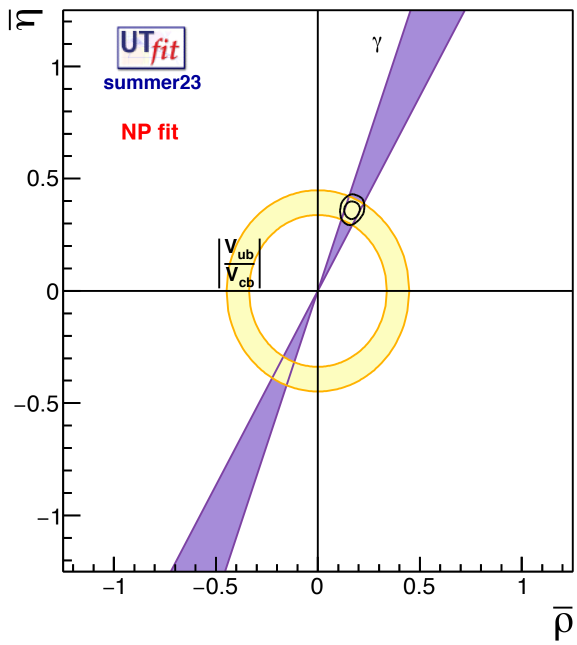

Figure 4: *Constraints in the $(\bar{\rho}, \bar{\eta})$ plane at the 95% probability using tree-level determinations for the UT and generalizing SM loop-induced amplitudes as the ones for meson mixing to account for NP effects.*

physics beyond the SM. On the one hand, one can enlarge the number of fitted parameters and deal with additional $O(10)$ new ones capturing the generic effects of heavy new dynamics affecting the phase and the absolute value of the amplitude of $|\Delta F| = 2$ transitions. At the same time, one can include a larger set of measurements, like 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 flavour violation coming from the up-quark sector in this context. 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 what originally worked out in Ref. [20] 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:

$$(\,\bar{\rho} = 0.167 \pm 0.025\ ,\ \ \bar{\eta} = 0.361 \pm 0.027\,)\ \textbf{NP fit}\,, \tag{3}$$

which stems from the determination of the UT made solely via $|V_{ub}/V_{cb}|$ and γ, together with the information provided in particular by the charge asymmetries in semileptonic B decays, see Figure 4. The presence of NP in meson mixing amplitudes can be simply parametrized as:

$$\mathcal{A}_{\Delta F=2} = \left(1 + |\mathcal{A}^{\rm NP}|/|\mathcal{A}^{\rm SM}|e^{i2(\phi^{\rm NP}-\phi^{\rm SM})}\right)|\mathcal{A}^{\rm SM}|e^{i2\phi^{\rm SM}}\,, \tag{4}$$

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.

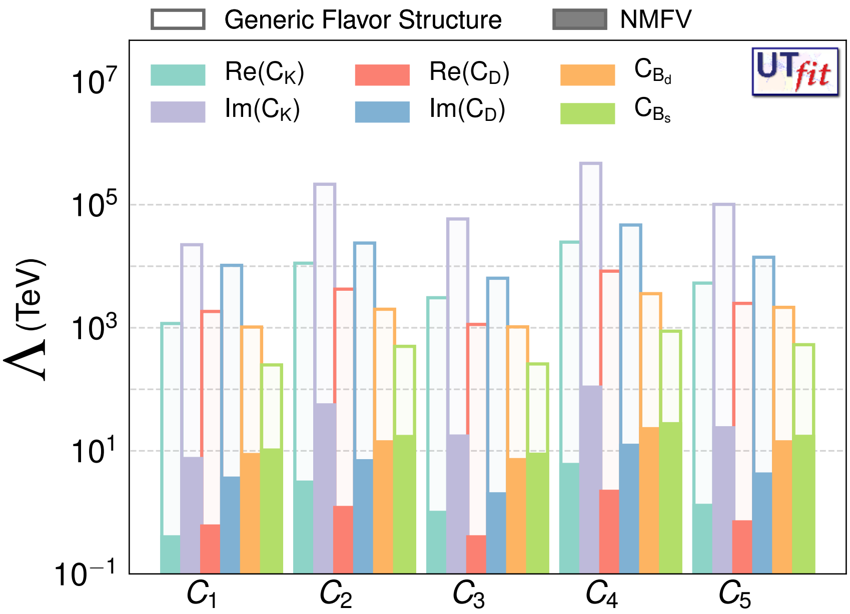

Figure 5: *Constraints from the NP UT analysis on the set of dimension-six operators that generalizes the effective Hamiltonian for $|\Delta F| = 2$ transitions beyond the SM. Filled histograms correspond to bounds on local operators affecting the short-distant physics of neutral meson oscillation amplitudes in the scenario of Next-To-Minimal Flavour Violation, while empty ones apply to a generic flavour structure in the UV.*

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:

$$
\begin{aligned}
O_1 &= \left(\bar{q}_i^{\alpha}\gamma_\mu P_L q_j^{\alpha}\right)\left(\bar{q}_i^{\beta}\gamma^\mu P_L q_j^{\beta}\right), \\
O_2 &= \left(\bar{q}_i^{\alpha} P_L q_j^{\alpha}\right)\left(\bar{q}_i^{\beta} P_L q_j^{\beta}\right), \\
O_3 &= \left(\bar{q}_i^{\alpha} P_L q_j^{\beta}\right)\left(\bar{q}_i^{\beta} P_L q_j^{\alpha}\right), \\
O_4 &= \left(\bar{q}_i^{\alpha} P_L q_j^{\alpha}\right)\left(\bar{q}_i^{\beta} P_R q_j^{\beta}\right), \\
O_5 &= \left(\bar{q}_i^{\alpha} P_L q_j^{\beta}\right)\left(\bar{q}_i^{\beta} P_R q_j^{\alpha}\right),
\end{aligned}
\tag{5}
$$

where $P_{L,R} = (1 \pm \gamma_5)/2$; the pairs i, j and α, β runs over flavour and color indices, respectively, 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 the figure with empty histograms the scenario where the ultraviolet (UV) theory does not enjoy any particular protection against novel sources of flavour 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 Flavour Violation [21], a similar protection in the UV where however new $O(1)$ phases in the flavour violating coupling are allowed is a tightly constrained possibility, probing scales as high as $\Lambda \gtrsim 110$ TeV, still way beyond the partonic $\sqrt{s}$ reach of present and next-generation colliders.

5. Future prospects

An accurate study of the UT delivers a very powerful final message: any theory beyond the Standard Model should engage a flavour structure "clever" enough to minimize the constraining power of flavour data in the era of precision; alternatively, it should manifest as a UV theory with no particular protection against new sources of flavour and CP violation and show up consequently at extremely high energies. In the first case, one may wonder what are the selection rules for a phenomenologically viable theory of flavour nearby the TeV scale [22, 23]. In the second scenario, one may wonder how an expedition directed to resolve the length scale of the Zeptouniverse [24] (or of even shorter distances!) would not encounter first a sign of NP as a possible vestige of the (in)famous hierarchy problem of the electroweak scale [25].

In this regard, the UT analysis remains probably one of the best phenomenological tools we have to search indirectly for NP, offering a different handle from what we can directly probe at colliders, and complementing what we can actually learn, e.g., from electroweak precision tests and precise measurements of the properties of the Higgs [26]. With the upgrade of LHCb, the compelling physics case of Belle II and the possible new experimental avenues offered by the R&D of projects like HIKE and PIONEER, the future of flavour physics looks particularly bright. The quest for going beyond percent precision in the determination of the SM UT is likely a matter of time, and the hope to constrain NP amplitudes in FCNC processes like meson anti-meson oscillation at the level of few percent is a foreseeable achievement for the next decades. Rare processes like $K \to \pi\nu\bar{\nu}$ will provide new information about the triangle, while theoretical progress from lattice QCD will be mandatory in order to bring the NP UT at the percent level of precision [27].

From the mere theoretical side, it is important to notice that direct searches at the LHC might be pointing to the existence of a mass gap between the electroweak scale and the first layer of physics beyond the SM. In such a scenario, the Standard Model Effective Field Theory turns out to be the ideal framework to look for NP effects from precision measurements, including the case of the UT analysis [28]. While specific quantitative studies along this direction have already been carried out, see e.g. [29, 30], a completely general investigation of the Standard Model Effective Field Theory implementing self-consistently the flavour constraints from the UT is still on the way [31, 32].

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