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Global fits of the Unitarity Triangle: Summer 2025 update from the UTfit collaboration

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Flavour physics represents a fundamental testbed of the Standard Model (SM). New measurements performed at the LHC experiments and at the B-factories are now providing unprecedented opportunities to study the Cabibbo-Kobayashi-Maskawa (CKM) matrix with high precision. In this picture, Unitarity Triangle Analysis (UTA) represents a fundamental tool to provide very precise SM predictions through global analyses and to uncover possible New Physics (NP) effects. In this proceeding we present the results of the latest SM global fits performed by the **UT***fit* collaboration including all the most updated inputs from experiments, lattice QCD and phenomenological calculations. Going beyond the SM, we also extend the UTA in order to constrain the parameter space in some possible NP scenarios. To this end, we update the stringent constraints on the NP scale from the most general structure of the $|\Delta F| = 2$ effective Hamiltonian by determining the allowed NP contributions in the kaon, D, B_d, and B_s sectors.

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Flavour physics is the best framework to test the Standard Model (SM) with high precision in order to quantify the coherence of its picture, and to explore in an indirect way very high energy scales (much higher than the one presently investigated at colliders). In this sense, the Unitarity Triangle Analysis (UTA) gives us an incredible amount of information both within the SM and beyond the SM. In the former case, it provides the most accurate determination of the parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] through a global study of all the (available) flavour results, also giving predictions of the yet unmeasured flavour SM observables. In the latter case, instead, the UTA provides limits on the allowed deviations from the SM, allowing to obtain bounds on the New Physics (NP) energy scale.

The UTA discussed in this proceedings has been performed by the **UT***fit* Collaboration, following the general method described in Ref. [2]. We updated the analysis by exploiting the latest determinations of the theoretical inputs and the latest measurements of the experimental observables, as described in many details in what follows. The continuously updated set of numerical values used as inputs can be found at `www.utfit.org`.

1. Updated inputs and results of the global fit in the Standard Model

The full list of measurements used as inputs in the global fit is given in the first and second columns of Table 1.

Table 1: Full SM inputs with their predictions from the SM global fits.

Input	Measurement	Prediction	Pull ($\#\sigma$)
$\sin 2\beta$	0.700 ± 0.015	0.768 ± 0.029	2.08
γ	65.7 ± 2.5	65.7 ± 1.3	~ 0
α	95.0 ± 8.0	91.7 ± 1.4	0.41
$\hat{B}_K$	0.763 ± 0.006	0.845 ± 0.051	1.60
$\lvert V_{cb}\rvert \cdot 10^3$	41.18 ± 0.76	42.07 ± 0.42	1.02
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	40.12 ± 0.55		2.81
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	41.97 ± 0.48		0.15
$\lvert V_{ub}\rvert \cdot 10^3$	3.82 ± 0.34	3.74 ± 0.08	0.22
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	3.63 ± 0.26		0.40
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.13 ± 0.26		1.43

Several inputs have been updated w.r.t. the previous UTA by the UTfit Collaboration [3, 4]. The most important changes concern:

- the kaon bag parameter $\hat{B}_K = 0.7627(60)$ (thanks to new averages of lattice results as outlined in Ref. [5]);
- the CKM matrix element $V_{ud} = 0.97433(21)$ (due to novel averages performed by the FLAG Collaboration in Ref. [6] and to the updated extraction of V_{ud} from nuclear beta transitions as in Ref. [7]);
- the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$;
- the unitary triangle angles.

Regarding $|V_{cb}|$ and $|V_{ub}|$, we have used:

$|V_{cb}|_{\rm excl}$: the exclusive value $|V_{cb}|_{\rm excl} = 40.12(55) \cdot 10^{-3}$ is an average of the results obtained in Refs. [8–10] for the semileptonic $B \to D$, $B_s \to D_s^{(*)}$ and $B \to D^*$ decays, respectively[1].

$|V_{ub}|_{\rm excl}$: the exclusive value $|V_{ub}|_{\rm excl} = 3.63(26) \cdot 10^{-3}$ is the result of an update of the study carried out in Ref. [12] for semileptonic $B \to \pi$ decay[2].

$|V_{ub}/V_{cb}|$: the value $|V_{ub}/V_{cb}| = 0.087(9)$ has been computed in Ref. [10] through the study of semileptonic $B_s \to K$ and $B_s \to D_s$ decays.

$|V_{cb}|_{\rm incl}$: the inclusive value $|V_{cb}|_{\rm incl} = 41.97(48) \cdot 10^{-3}$ has been taken from Ref. [16].

$|V_{ub}|_{\rm incl}$: the inclusive value $|V_{ub}|_{\rm incl} = 4.13(26) \cdot 10^{-3}$ has been read from the last PDG review [17].

All these values are shown in the left panel of Fig. 1, from which it is clear that a special treatment has to be reserved to the computation of their average. In this sense, the **UT***fit* two-dimensional (2D) average (i.e. the red larger ellipse) is calculated through the skeptical procedure outlined in Ref. [18] with $\sigma = 1$. While the exclusive and the inclusive values of $|V_{ub}|$ are well compatible at the 1σ level, some $\sim 2\sigma$ tension still persists in the $|V_{cb}|$ case. The effect of these differences in the global fit results are shown in the central and in the right plots of Fig. 1, following the original discussion developed by the **UT***fit* collaboration since 2006 in Ref. [19]. Let us also highlight that, as clearly pointed out by the **UT***fit* collaboration in all the previous UTAs, the **UT***fit* prediction of $|V_{cb}|$ is much more in agreement with the inclusive value, while the **UT***fit* prediction of $|V_{ub}|$ is much more compatible with the exclusive value.

Regarding the angle inputs, the values used are as follows:

β (or ϕ_1): the value of $\sin 2\beta$ is taken from the latest HFLAV average [20] using all charmonium modes, which give $\sin 2\beta = 0.710 \pm 0.011$. We then add a correction factor of -0.01 ± 0.01 as data-driven theory uncertainty (obtained with the method described in Ref. [21]), finding $\sin 2\beta = 0.700 \pm 0.015$.

α (or ϕ_2): the value of the angle α is obtained by **UT***fit* isospin analyses of the three contributing final states $\pi\pi$, $\rho\rho$ and $\rho\pi$. The various probability distributions (obtained including also the very recent measurements by Belle-II in Refs. [22, 23]) are shown in the left panel of Fig. 2 together with the combined one, which is used as input to our global fit.

γ (or ϕ_3): the value of the angle γ is taken from the novel analysis carried out in Refs. [24, 25], which develops a Bayesian analysis of all charm and beauty observables together with neutral D mixing and CP-violating parameters.

The results of the global SM fit are given as 2D probability distributions in the plan of the CKM parameters $\bar\rho$ and $\bar\eta$, as shown in Fig. 3. There is an overall nice consistency of the SM fit. The numerical results for the Wolfenstein parameters read:

$$\bar\rho = 0.159 \pm 0.009, \qquad \lambda = 0.2250 \pm 0.0006,$$
$$\bar\eta = 0.353 \pm 0.008, \qquad A = 0.827 \pm 0.008.$$

[1] As recently pointed out in Ref. [11], the value $|V_{cb}| = 41.6(1.1) \cdot 10^{-3}$ for the semileptonic $B \to D^*$ decay can be obtained by exploiting the PDG average of the total branching ratio. We prefer, however, to use the estimate $|V_{cb}| = 39.92(64) \cdot 10^{-3}$ [10] as representative of this decay channel in our average, since it is more precise.

[2] The lattice results recently obtained by the JLQCD Collaboration in Ref. [13] have been added to the lattice datasets of Refs. [14, 15], already used in Ref. [12]. Starting from this larger input dataset, a proper extrapolation of the relevant hadronic form factors has been, then, developed through the so-called dispersive matrix method and has allowed to obtain an updated exclusive value of $|V_{ub}|$.

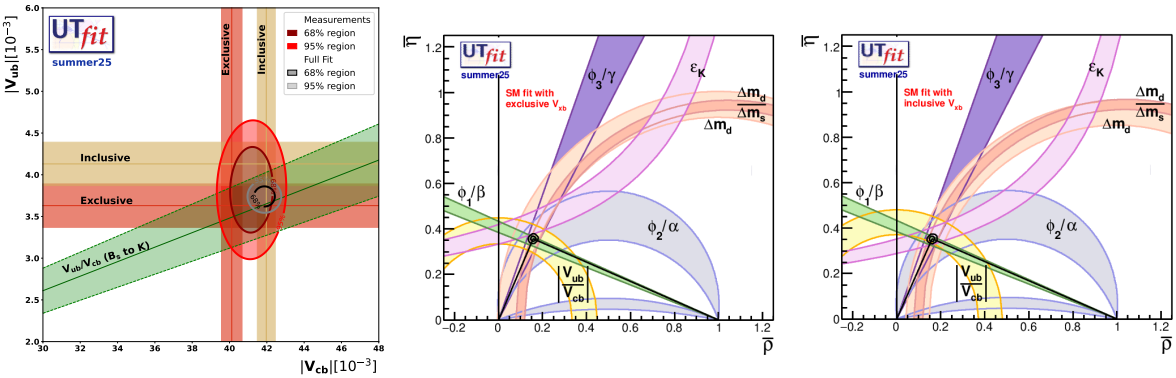

Figure 1: *Left*: $|V_{cb}|$ vs $|V_{ub}|$ plane showing the values reported in Table 1 and discussed in the main text. *Centre-Right*: $\bar{\rho}$-$\bar{\eta}$ plane with the results of the SM global fit using only exclusive inputs for both $|V_{ub}|$ and $|V_{cb}|$ (*centre*) and using only inclusive inputs (*right*).

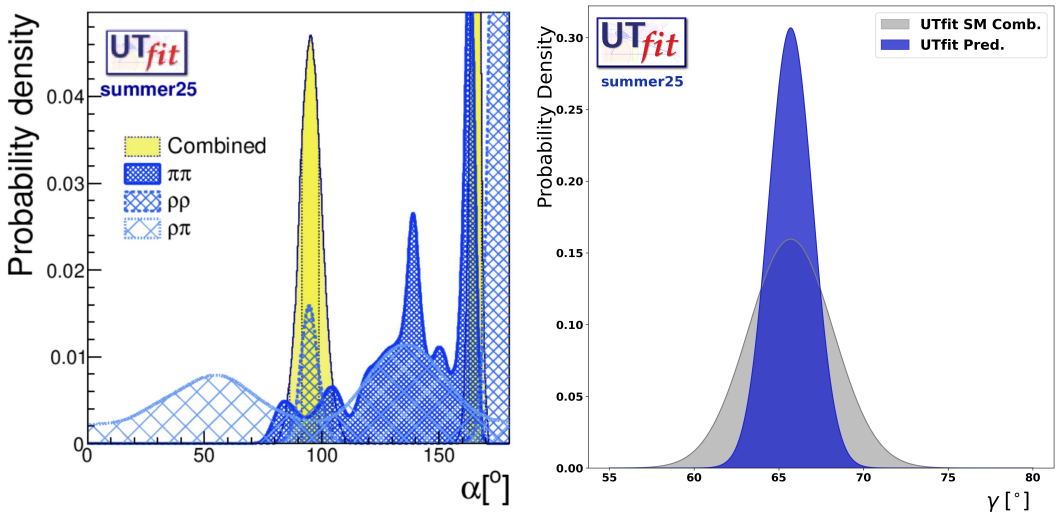

Figure 2: *Left*: global fit input distribution for the angle α (in yellow), together with the three separate distributions coming from $\pi\pi$, $\rho\rho$ and $\rho\pi$ final states. *Right*: global fit input distribution for the angle γ (in gray) from Refs. [24, 25], compared with the global **UT***fit* prediction for the same angle (in blue).

It is worth noticing that the results of the global SM fit for $\bar{\rho}$ and $\bar{\eta}$ have reached a level of precision of 5.6% and 2.2%, respectively.

Finally, the so-called "pull plots" in Figs. 4-5 are extremely useful to assess the agreement of a single measurement with the indirect determination from the fit (using the other inputs). The coloured areas represent the level of agreement between the predicted values and the measurements at better than 1, 2, ... $n\sigma$. Furthermore, the markers have the coordinates (x, y) = (central value, error) of the direct measurements considered. We note that some tension at the 2σ level or more is observed only in the $\sin 2\beta$ and in the $|V_{cb}|$ cases.

2. Results from the global fit beyond the Standard Model

The global fit can now be extended in order to include possible model-independent NP contributions in the UTA. To be more specific, the NP effects considered here are those entering the neutral meson mixing ($\Delta F = 2$ transitions). They are parameterised in a general

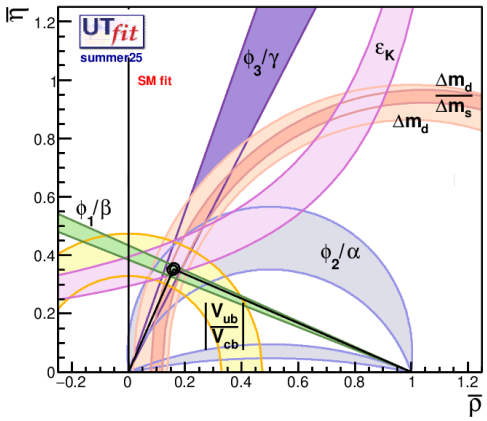

Figure 3: $\bar{\rho}$-$\bar{\eta}$ plane with the SM global fit results. The black contours display the 68% and 95% probability regions selected by the such a global fit. The 95% probability regions selected are also shown for each constraint considered.

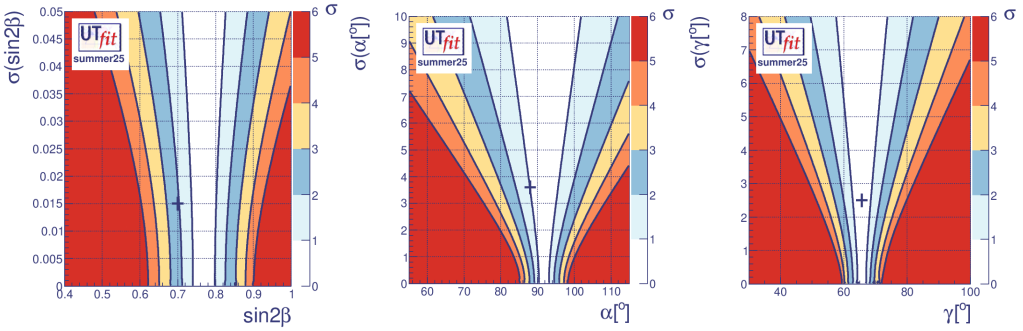

Figure 4: Pull plots (see text) for $\sin 2\beta$ *(left)*, α *(centre)* and γ *(right)* inputs.

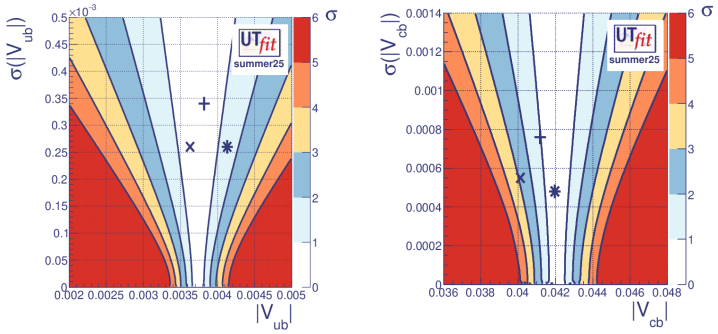

Figure 5: Pull plots (see text) for $|V_{ub}|$ *(left)* and $|V_{cb}|$ *(right)* inputs.

way as a NP amplitude $A_q^{\rm NP}$ and a NP phase $\phi_q^{\rm SM}$, where $q = d$ or s [26]. Note that within the SM one has that $A_q^{\rm NP} = 0$ and $\phi_q^{\rm NP} = 0$.

At this point, by considering the most general effective Hamiltonian for $\Delta F = 2$ processes ($H_{\rm eff}^{\Delta F=2}$), we translate the current constraints into allowed ranges for the Wilson coefficients of $H_{\rm eff}^{\Delta F=2}$ [26]. These coefficients have the general form $C_i(\Lambda) = F_i \cdot L_i/\Lambda^2$, where F_i is a function of the (complex) NP couplings, F_i is a loop factor (that is present only in models where tree-level Flavour Changing Neutral Currents are absent also in presence of NP) and, finally, Λ is the scale of NP, i.e. the typical mass of the new particles mediating $\Delta F = 2$ processes.

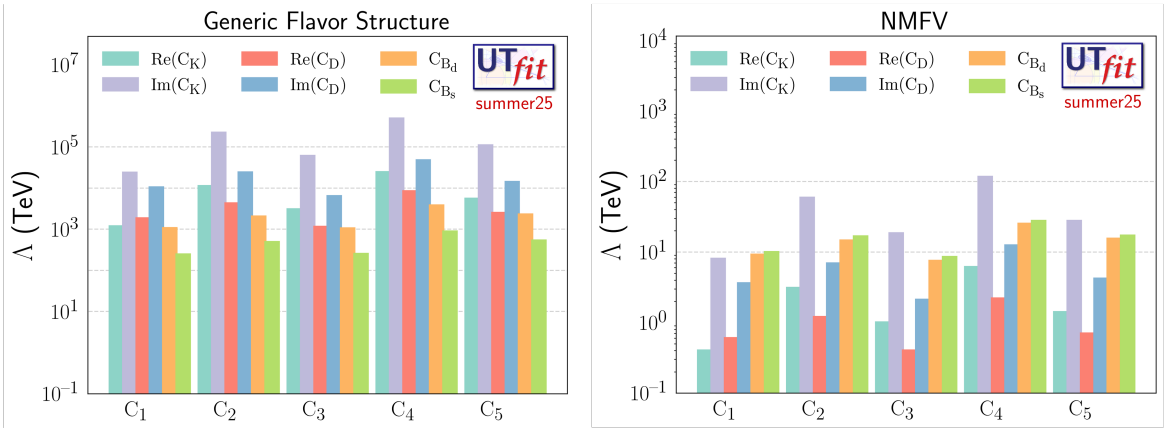

Figure 6: Summary of the 95% probability lower bounds on the NP scale Λ for strongly-interacting NP. A general NP scenario *(left)* and the NMFV scenario *(right)* have been considered in the inclusion of NP effects in the UTA. Results from all the neutral meson systems are shown. The strongest constraints Λ come always from the kaon sector, while the B_s system provides quite stringent constraints in the NMFV case.

In general, the values of the functions F_i and L_i depend on the assumptions we make on the flavour structure of NP. For instance, for a generic strongly-coupled NP and/or tree-level NP with arbitrary flavour structure, one in general expect to have $|F_i| \sim 1$ with arbitrary phase and $L_i \sim 1$. Specific assumptions on the precise flavour structure of NP, instead, bring to a modification of the F_i functions. Taking into consideration, for example, Next-to-Minimal [27] Flavour Violation (NMFV), we have $|F_i| = F_{\rm SM}$, where $F_{\rm SM}$ is the combination of CKM matrix elements appearing in the top-quark mediated SM mixing amplitude, with an arbitrary phase. Note that, in order to obtain the lower bound on the NP scale Λ for loop-mediated contributions, it is sufficient to multiply the bounds we quote in the following by $\alpha_s \sim 0.1$ or by $\alpha_W \sim 0.03$.

Our results are summarized in Fig. 6. The overall strongest constraints on the NP scale come always from the kaon sector, although it is worth highlighting that the B_s system provides quite stringent constraints in the specific case of the NMFV scenario. For NP with generic flavour structure, we obtain $\Lambda_{\rm gen} > 4.9 \cdot 10^5$ TeV (this bound has increased by a factor of 2 with respect to the first UTfit NP analysis in [26]). For NMFV, instead, the CKM suppression in $|F_i|$ induces a lower value for the bound on the NP scale, i.e. $\Lambda_{\rm NMFV} > 150$ TeV (this bound has increased by a factor of 2.5 with respect to the first UTfit NP analysis in [26]).

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