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Unitarity Triangle analysis in the Standard Model from the UTfit collaboration

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Flavour physics represents a unique test bench for the Standard Model (SM). New analyses performed at the LHC experiments are now providing unprecedented insights into Cabibbo-Kobayashi-Maskawa (CKM) metrology and new evidences for rare decays. The CKM picture can provide very precise SM predictions through global analyses. We present here the results of the latest global SM analysis performed by the **UT***fit* collaboration including all the most updated inputs from experiments, lattice QCD and phenomenological calculations.

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1. Introduction

Flavour physics represents a powerful tool to test the SM, to quantify the coherence of its picture and to explore possible departures from it. From the flavour global fit we can extract the most accurate determination of the parameters of the CKM matrix [1, 2], as well as the best SM predictions of flavour observables. The Unitarity Triangle (UT) analysis here presented is performed by the **UT***fit* Collaboration following the method described in refs. [3, 4]. We updated the analysis with the latest determinations of the theoretical inputs and the latest measurements of the experimental observables. The basic constraints used in the global fit and contributing to the sensitivity of the CKM matrix elements are: $|V_{ub}/V_{cb}|$ from semileptonic B decays, Δm_d and Δm_s from $B^0_{d,s}$ oscillations, ε_K from neutral K mixing, α angle from charmless hadronic B decays, γ angle from charm hadronic B decays, and $\sin 2\beta$ from $B^0 \to J/\psi K^0$ decays.

Most experimental inputs are taken from the Heavy Flavour Averaging Group [5], however when most updated results are available the **UT***fit* collaboration performs its own averages. Below specific updates are discussed for selected experimental inputs. On the theoretical side, the non-perturbative QCD parameters are taken from the most recent lattice QCD determinations: as a general prescription, we average the $N_f = 2+1+1$ and $N_f = 2+1$ FLAG numbers [6], using eq. (28) in Ref. [7] and including the results in Ref. [8]. The complete set of numerical values used as inputs can be found at URL [9] in the Summer 2016 section, together with past and future updates.

2. Updated inputs

For the inputs coming from the semileptonic B decays, we use the values shown in Fig. 1 and listed in Table 1, where the 2D average is calculated with a two-dimensional procedure inspired by the skeptical method of Ref. [10] with $\sigma = 1$. Very similar results are obtained from a two-dimensional *á la* PDG [11] procedure. It is evident that exclusive and inclusive results persist to be only marginally compatible in particular in the case of V_{ub}. For V_{cb} the latest updates from the lattice community have reduced the discrepancy at the level of about 1.3σ, while for V_{ub} it remains at $\sim 3\sigma$. We include in the new average procedure the LHCb ratio measurement [12] that is shown in the left plot in Fig. 1 as a diagonal band. The figure shows the obtained two-dimensional average with the 68% and 95% probability areas in orange and yellow, respectively. Superimposed are also the posterior from the global fit performed without using the semileptonic decays as inputs. The right plot in Fig. 1 shows the predictions on $\sin 2\beta$ from the SM global fits obtained when changing the inputs relative to the semileptonic B decays, using only exclusive inputs for both V_{ub} and V_{cb}, using only inclusive inputs or not using the V_{ub} and V_{cb} inputs at all. The experimental value for $\sin 2\beta$ is also shown. These inclusive-vs-exclusive discrepancies have been highlighted and discussed by the **UT***fit* collaboration since 2006 [13].

Table 1: V_{cb} and V_{ub} experimental inputs are shown as values. The individual V_{cb} and V_{ub} exclusive and inclusive numbers are taken from the HFAG average [5].

$[10^{-3}]$	**excl.**	**incl.**	$\mathbf{\lvert V_{ub}\rvert / \lvert V_{cb}\rvert}$	**2D average**
$\mathbf{\lvert V_{cb}\rvert}$	40.1 ± 1.2	42.00 ± 0.64	$(8.3 \pm 0.6)10^{-2}$	41.7 ± 1.0
$\mathbf{\lvert V_{ub}\rvert}$	3.62 ± 0.14	4.41 ± 0.22		3.74 ± 0.21

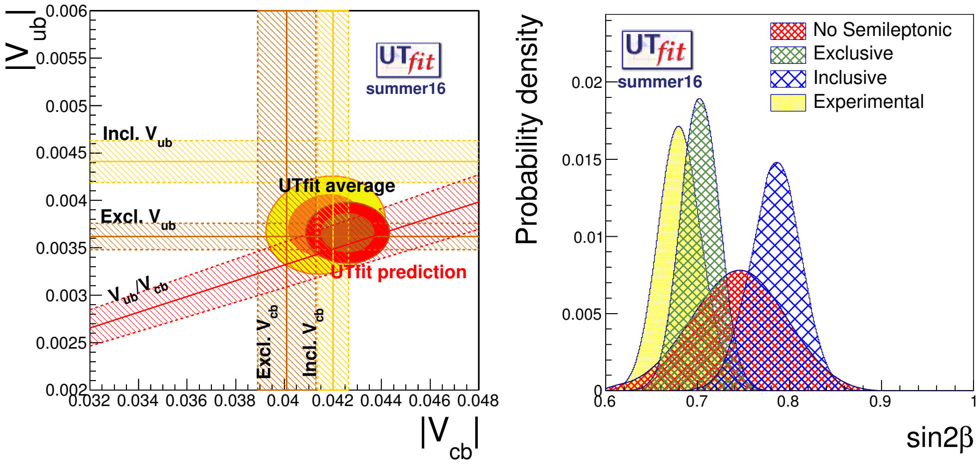

Figure 1: *Left*: $|V_{cb}|$ vs $|V_{ub}|$ plane showing the values reported in table 1. *Right*: predictions on $\sin 2\beta$ from the SM global fits obtained when changing the inputs as indicated in the legend.

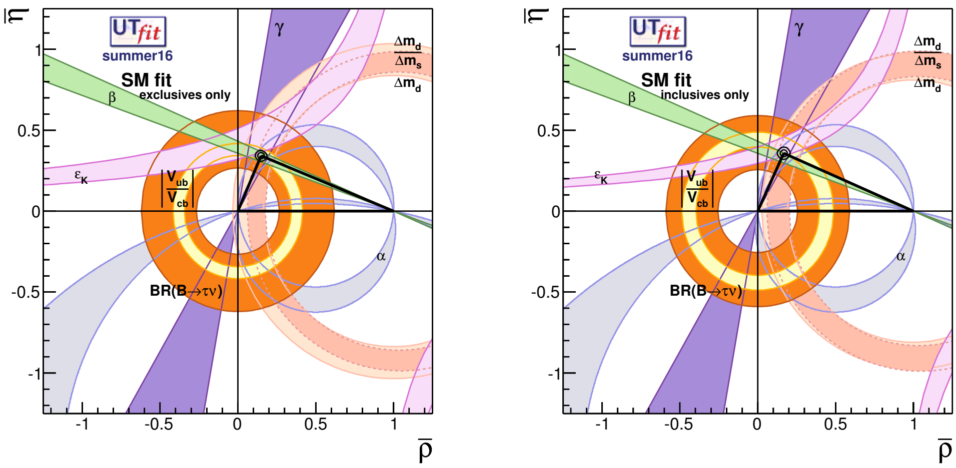

Figure 2: $\bar{\rho}$-$\bar{\eta}$ plane with the SM global fit results using only exclusive inputs for both V_{ub} and V_{cb} (*Left*) and using only inclusive inputs (*Right*).

The angle γ of the UT can be measured comparing V_{cb} and V_{ub} mediated transitions in $B \to D^{(*)}K^{(*)}$ decays. The decays proceed through tree diagrams, so this constraint is practically free from NP contributions, similarly to the semileptonic B decays just discussed. To obtain the input γ distribution for the global fit, we combine within our statistical method [4] the results from the various experiments and the various methods. The observables of the methods also depend on the amplitude ratio $r_B \equiv \frac{A(b\to u)}{A(b\to c)}$ and the relative CP-conserving phase δ_B between the two amplitudes. These parameters depend on the considered B decay and the ratio r_B in particular drives the sensitivity on γ. Left plot in Fig. 3 shows the **UT***fit* γ combination giving an average value of $(70.5 \pm 5.7)^\circ$ and the **UT***fit* prediction is also shown as comes from the global fit without using the γ constraint. The middle plot in Fig. 3 presents the historical evolution of central values and uncertainties since 2005 when **UT***fit* first started to extract γ estimates from the $D^{(*)}K^{(*)}$ decays: after a decade of analyses and almost 50 papers published, the world average uncertainty has decreased by a factor three.

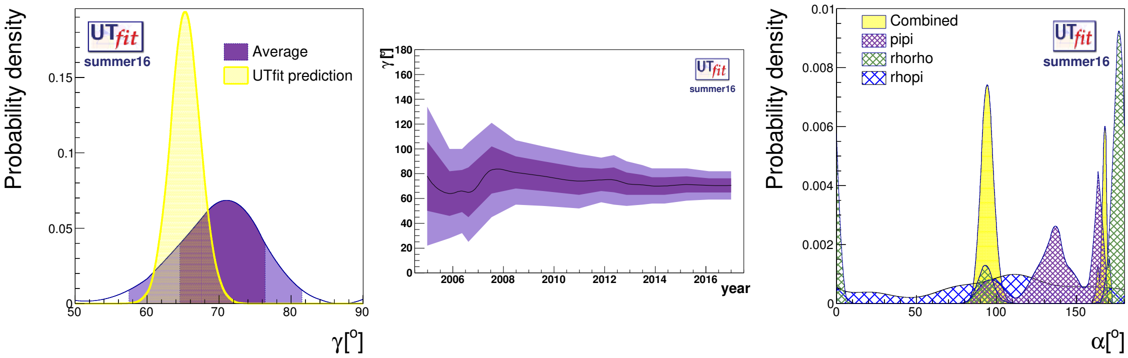

Figure 3: *Left*: γ (or ϕ_3) angle input distribution as obtained by averaging the various experimental results from the methods mentioned in the text. The **UT***fit* prediction is also shown as comes from the global fit without using the γ constraint. *Middle*: historical plot showing the central values and the uncertainties since 2005 when **UT***fit* first started to extract γ estimates from the $D^{(*)}K^{(*)}$ decays. *Right*: α (or ϕ_2) angle extracted from the $\pi\pi$, $\rho\rho$ and $\rho\pi$ final states with the relative isospin analyses.

Finally the angle α of the CKM triangle can be measured exploiting the charmless two-body B decays in $\pi\pi$, $\rho\rho$ or $\rho\pi$ final states via isospin analyses. Belle [14] and LHCb [15] have updated results for the $\rho\rho$ final states and they are now included in our most updated α determination. Right plot in Fig. 3 shows the probability distribution used as input in the global fit for α: the central value of the SM solution corresponds to $(94.2 \pm 4.5)^\circ$ (see Table 2).

3. Result of the global fit in the Standard Model

Using the above inputs and our Bayesian framework, we perform the global fit to extract the CKM matrix parameters $\bar{\rho}$ and $\bar{\eta}$: we obtain $\bar{\rho} = 0.154 \pm 0.015$ and $\bar{\eta} = 0.344 \pm 0.013$. Fig. 4 shows the result of the SM fit on the $\bar{\rho}$-$\bar{\eta}$ plane. We also perform our fit separating two sets of

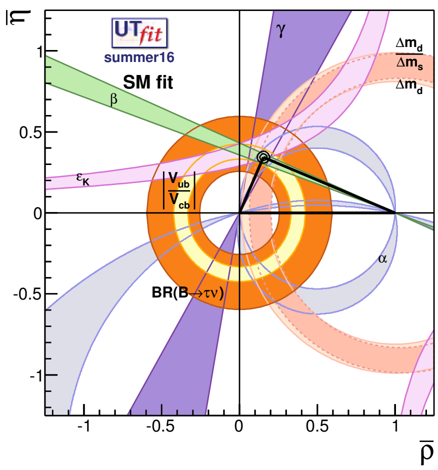

Figure 4: $\bar{\rho} - \bar{\eta}$ plane showing the result of the SM fit. The black contours display the 68% and 95% probability regions selected by the given global fit. The 95% probability regions selected by the single constraints are also shown.

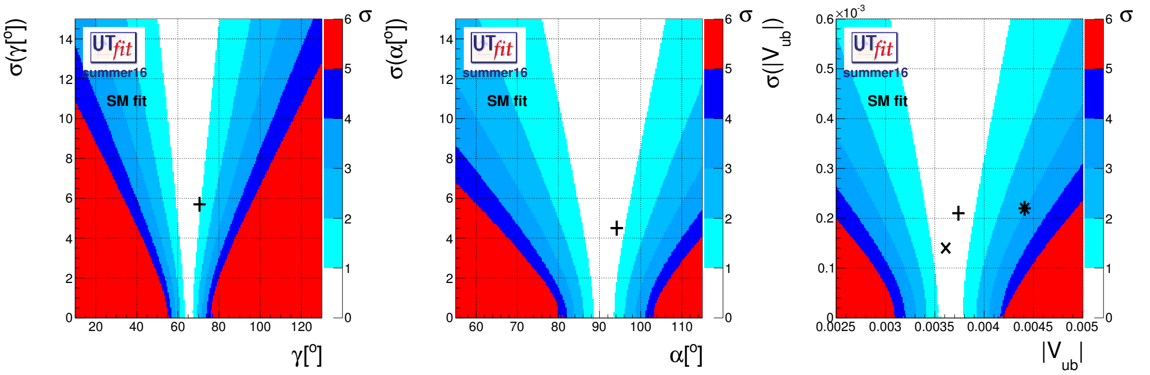

Figure 5: Compatibility plots where the compatibility regions from 1σ to 6σ are displayed. The cross displays the position (value/error) of the measurement. *From left to right*: γ, α, and V_{ub}. In the V_{ub} plot, the asterisk corresponds to the inclusive value while the $\times$ cross corresponds to the exclusive value.

inputs: the "sides-and-kaon-mixing" fit using $|V_{ub}/V_{cb}|$, Δm_d, Δm_s, and ε_K and the "angle-only" fit using as constraints β, α and γ measurements. From the "angle-only" fit we obtain $\bar{\rho} = 0.147 \pm 0.022$ and $\bar{\eta} = 0.333 \pm 0.016$. From the "sides-and-kaon-mixing" fit we obtain $\bar{\rho} = 0.160 \pm 0.018$ and $\bar{\eta} = 0.359 \pm 0.021$.

The consistency of the picture is tested constraint by constraint using compatibility plots. They compare two different p.d.f.'s: the one obtained from the UT fit without using the constraint being tested and the other from the direct measurement. Fig. 5 shows some compatibility plots related to

Table 2: Summary table showing the values for the input values and the SM **UT***fit* predictions for the main observables and lattice QCD parameters used in the global fit. The last column gives an indication of the agreement of the given measurement with the **UT***fit* prediction obtained from the global fit removing the observable itself.

Observable	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.680 ± 0.023	0.725 ± 0.030	~ 1.2
γ [°]	70.5 ± 5.7	65.4 ± 2.1	< 1
α [°]	94.2 ± 4.5	90.9 ± 2.5	< 1
$V_{cb} \cdot [10^3]$	41.7 ± 1.0	42.6 ± 0.7	< 1
$V_{ub} \cdot [10^3]$	3.74 ± 0.21	3.66 ± 0.11	< 1
$V_{ub} \cdot [10^3]$ (incl.)	4.41 ± 0.22	–	~ 2.9
$V_{ub} \cdot [10^3]$ (excl.)	3.62 ± 0.14	–	< 1
β_s	0.97 ± 0.94	1.05 ± 0.04	< 1
$BR(B \to \tau\nu) \cdot [10^4]$	1.06 ± 0.20	0.81 ± 0.06	~ 1.2
$A_{SL}^d \cdot [10^3]$	0.2 ± 2.0	-0.283 ± 0.024	< 1
$A_{SL}^s \cdot [10^3]$	1.7 ± 3.0	0.013 ± 0.001	< 1
B_K	0.740 ± 0.029	0.81 ± 0.07	< 1
f_{B_s} (GeV)	0.226 ± 0.005	0.220 ± 0.007	< 1
f_{B_s}/f_{B_d}	1.203 ± 0.013	1.210 ± 0.030	< 1
B_{B_s}/B_{B_d}	1.032 ± 0.036	1.07 ± 0.05	< 1
B_{B_s}	1.35 ± 0.08	1.30 ± 0.07	< 1

some key constraints. We can see how they all show very good agreement with the rest of the fit. The pull values in Table 2 are obtained from these compatibility tests. As already mentioned above, the only tension still present comes from the inclusive-vs-exclusive values of the V_{ub} determination: the inclusive value shows a $\sim 2.9\sigma$ discrepancy with respect to the rest of the fit.

This consistency of the SM picture can be reinterpreted in terms of the amount of new physics (NP) contributions: we can determine the NP that could still be allowed in the various sectors and, in various NP scenarios, we can obtain bounds for the NP scale as a function of NP couplings. The results of the NP analysis by the **UT***fit* collaboration can be found here [16, 9].

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