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Unitarity Triangle Analysis and D meson mixing in the Standard Model and Beyond

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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 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. In addition, we update the analysis of D meson mixing: we derive constraints on the parameters M_{12}, Γ_{12} and Φ_{12} that describe D meson mixing using all available data, allowing for CP violation. Finally, the Unitarity Triangle (UT) analysis can be used to constrain the parameter space in possible new physics (NP) scenarios. All of the available experimental and theoretical information on $\Delta F = 2$ processes is reinterpreted including a model-independent NP parametrisation. We determine the allowed NP contributions in the kaon, D, B_d, and B_s sectors and, in various NP scenarios, we translate them into bounds for the NP scale as a function of NP couplings.

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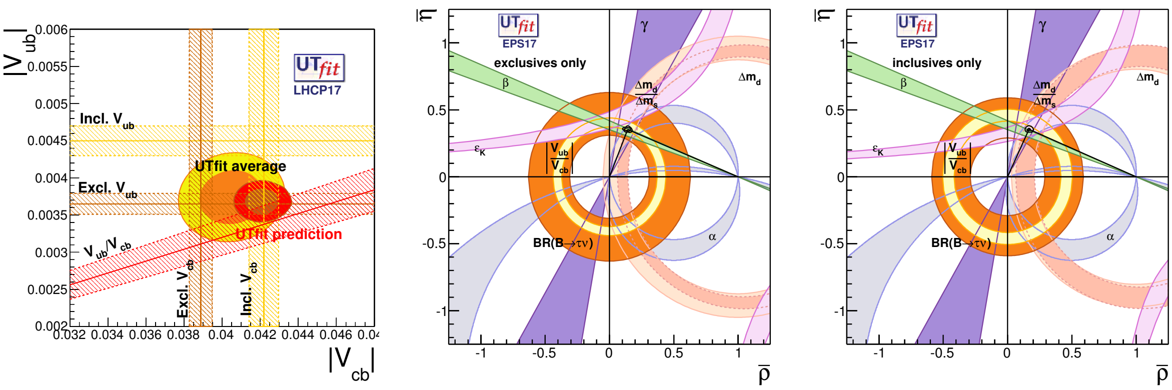

Figure 1: *Left*: $|V_{cb}|$ vs $|V_{ub}|$ plane showing the values reported in Table 1. We include in the average the LHCb ratio measurement [7] that is shown as a diagonal band. *Centre-Right*: $\bar{\rho}$-$\bar{\eta}$ plane with the SM global fit results using only exclusive inputs for both V_{ub} and V_{cb} (*centre*) and using only inclusive inputs (*right*).

1. Introduction

Flavour physics represents a powerful tool to test the Standard Model (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], 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. [2]. 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 UT angle from charmless hadronic B decays, γ UT angle from charm hadronic B decays, and the sine of 2β UT angle from $B^0 \to J/\psi K^0$ decays.

The values of most experimental inputs are taken from the Heavy Flavour Averaging Group (HFLAV) [3], however when most updated individual results are available the **UT***fit* collaboration performs its own averages. Below a specific update is discussed for the $|V_{ub}/V_{cb}|$ experimental input. 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 [4], using eq. (28) in Ref. [5] and including the results in Ref. [6]. The continuously updated set of numerical values used as inputs can be found at URL `http://www.utfit.org/`.

2. Updated inputs and results of the global fit in the SM

For the inputs coming from the semileptonic B decays, we use the values shown in the left plot

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 most updated HFLAV averages [3].

$[10^{-3}]$	**excl.**	**incl.**	$\mathbf{|V_{ub}|/|V_{cb}|}$	**2D average**
$\mathbf{|V_{cb}|}$	38.88 ± 0.60	42.19 ± 0.78	$(8.0 \pm 0.6)10^{-2}$	40.5 ± 1.1
$\mathbf{|V_{ub}|}$	3.65 ± 0.14	4.50 ± 0.20		3.74 ± 0.23

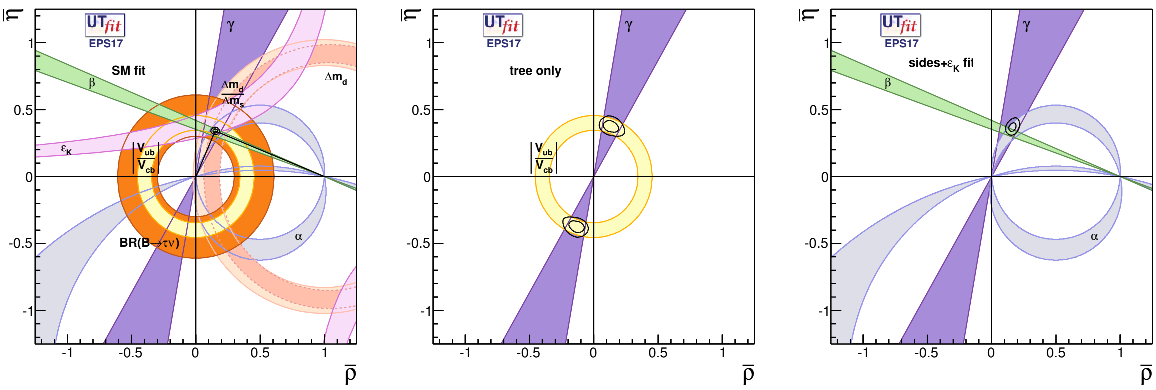

Figure 2: $\bar{\rho} - \bar{\eta}$ planes showing the result of the full SM fit (*left*), the result of the tree-only fit (*centre*) and the result of the SM fit using the UT sides and the kaon mixing compared with the areas of the UT angle constraints (*right*). The black contours display the 68% and 95% probability regions selected by the given global fit. The 95% probability regions selected are also shown for each constraint considered.

Table 2: Results of the fit to D mixing data.

parameter	result @ 68% prob.
$\lvert M_{12}\rvert$ [ps^{-1}]	$(4.3 \pm 1.8) \cdot 10^{-3}$
$\lvert\Gamma_{12}\rvert$ [ps^{-1}]	$(14.2 \pm 1.4) \cdot 10^{-3}$
$\Phi_{M_{12}}$ [°]	(0.3 ± 2.6)

parameter	result @ 68% prob.
x	$(3.5 \pm 1.5) \cdot 10^{-3}$
y	$(5.8 \pm 0.6) \cdot 10^{-3}$
$\lvert q/p\rvert - 1$	0.002 ± 0.018
ϕ[°]	-0.08 ± 0.57

in Fig. 1 and listed in Table 1. The **UT***fit* two-dimensional (2D) average shown is calculated with a 2D procedure inspired by the skeptical method of Ref. [8] with $\sigma = 1$. It is evident that exclusive and inclusive results persist in showing discrepancies at the level of about 3.3σ in the case of V_{cb} and about 3.4σ for V_{ub}. The effect of these deviations in the global fit results are shown in the right plots in Fig. 1. These inclusive-vs-exclusive discrepancies have been highlighted and discussed by the **UT***fit* collaboration since 2006 [9].

Using the latest inputs and our Bayesian framework, we perform the global fit to extract the CKM matrix parameters $\bar{\rho}$ and $\bar{\eta}$: we obtain $\bar{\rho} = 0.151 \pm 0.014$ and $\bar{\eta} = 0.342 \pm 0.013$. The left plot in Fig. 2 shows the result of the SM fit on the $\bar{\rho}$-$\bar{\eta}$ plane, while the central figure shows the "tree-only" fit when only tree-level measurements are included ($|V_{ub}/V_{cb}|$ and γ assumed NP-free). Fig. 2 right plot shows the comparison between the areas coming from the angle measurements and the fit result obtained using all the other constraints (the UT sides and the kaon mixing ε_K). The main tension still present in the global fit comes from the inclusive-vs-exclusive values of the semileptonic determinations: for example, the inclusive $|V_{ub}|$ value shows a $\sim 3.8\sigma$ discrepancy with respect to the rest of the fit.

We update here also the fit to the D mixing experimental data that are reported in Table 1 of the 2014 Ref. [10]: Table 2 here shows the results updated in the 2017 analysis, following the statistical method described in Ref. [2] improved with a Markov-chain Monte Carlo as implemented in the BAT library [11]. The input averages are taken from the Heavy Flavour Averaging Group (HFLAV) [3].

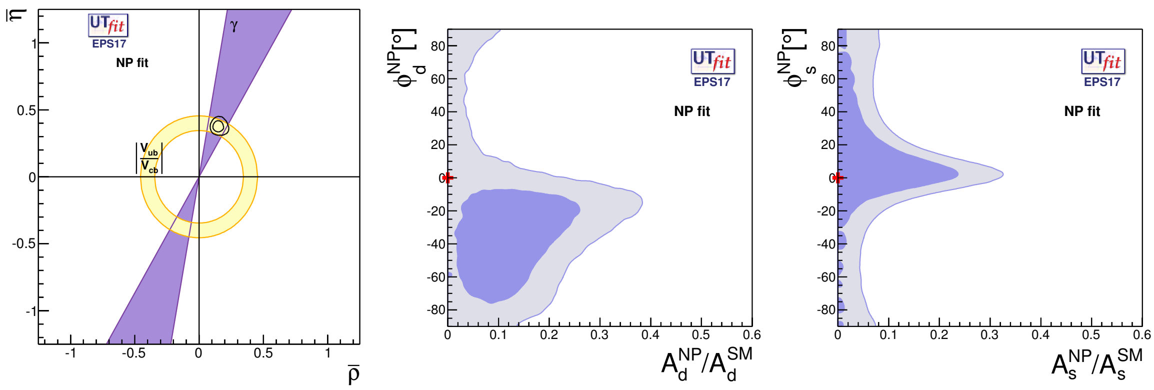

Figure 3: *Left:* $\bar{\rho}-\bar{\eta}$ plane showing the result of the NP fit. The black contours display the 68% and 95% probability regions selected by the NP global fit. The 95% probability regions selected are shown for those constraints not affected by NP in $\Delta F = 2$ transitions, however all the constraints are used in the fit selecting the $\bar{\rho}-\bar{\eta}$ area. *Centre-right:* $A_q^{\rm NP}/A_q^{\rm SM} - \phi_q^{\rm NP}$ NP-parameter plane as selected from the NP fit (*left*) for the B_d system and (*right*) for the B_s system, where 68% (dark) and 95% (light) probability regions are shown. The red cross represents the SM expectation.

3. Result of the global fit beyond the SM

We now consider the UT analysis performed reinterpreting the experimental observables including possible model-independent NP contributions. The NP effects considered are those entering the neutral meson mixing ($\Delta F = 2$ transitions). They are parameterised in a general way as a NP amplitude $A_q^{\rm NP}$ and a NP phase $\phi_q^{\rm SM}$, where $q = d$ or s and in the SM it is $A_q^{\rm NP} = 0$ and $\phi_q^{\rm NP} = 0$.

We perform the NP analysis and the result of the NP global fit selects a region in the $(\bar{\rho},\bar{\eta})$ plane which is consistent with the result of the SM analysis. This is shown in the left plot in Fig. 3. The $\bar{\rho}$ and $\bar{\eta}$ values extracted from the NP global fit are $\bar{\rho} = 0.154\pm0.029$ and $\bar{\eta} = 0.377\pm0.029$. Simultaneously, the NP parameters are extracted and their allowed ranges are shown in the two right plots of Fig. 3. The current tension of the SM picture is reflected in the B_d sector. In general a $30-40$% NP effect is allowed at 95% probability, given the current sensitivities.

If we consider the most general effective Hamiltonian for $\Delta F = 2$ processes ($H_{\rm eff}^{\Delta F=2}$), we can translate the current constraints into allowed ranges for the Wilson coefficients of $H_{\rm eff}^{\Delta F=2}$. The full procedure and analysis details are given in [12]. These coefficients have the general form $C_i(\Lambda) = F_i\, L_i/\Lambda^2$, where F_i is a function of the (complex) NP flavour couplings, L_i is a loop factor that is present in models with no tree-level Flavour Changing Neutral Currents, and Λ is the scale of NP, *i.e.* the typical mass of the new particles mediating $\Delta F = 2$ transitions. For a generic strongly-interacting theory with arbitrary flavour structure, one expects $F_i \sim L_i \sim 1$ so that the allowed range from the fit for each of the $C_i(\Lambda)$ can be immediately translated into a lower bound on Λ. Specific assumptions on the flavour structure of NP, for example Next-to-Minimal [13] Flavour Violation (NMFV), correspond to particular choices of the F_i functions. In the case of NMFV, we have $|F_i| = F_{\rm SM}$ with an arbitrary phase [13]. To obtain the lower bound on Λ for loop-mediated contributions, one simply multiplies the bounds we quote in the following by $\alpha_s \sim 0.1$ or by $\alpha_W \sim 0.03$.

In the case of the general NP scenario, we have arbitrary NP flavour structures ($|F_i| \sim 1$) with arbitrary phase and $L_i = 1$ corresponding to strongly-interacting and/or tree-level NP. The overall strongest constraint on the NP scale comes from the kaon sector and it is translated into $\Lambda_{\rm gen} > 5.0 \cdot 10^5$ TeV. As we are considering arbitrary NP flavour structures, the constraints on the NP scale are very tight due to the absence of the CKM suppression.

In the NMFV case, the strongest bound is again obtained from the kaon sector and it translated into the weaker lower limit $\Lambda_{\rm NMFV} > 114$ TeV. In this latter case and in the current scenario, the B_s system also provides quite stringent constraints.

In conclusion, a loop suppression is needed in all scenarios to obtain NP scales that can be reached at the LHC. For NMFV models, an α_W loop suppression might not be sufficient, since the resulting NP scale is still of the order of 11 TeV. The general model is out of reach even for α_W (or stronger) loop suppression. Finally, the reader should keep in mind the possibility of accidental cancellations among the contribution of different operators, that might weaken the bounds we obtained.

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