PROCEEDINGS OF SCIENCE

Updates in the Unitarity Triangle fits with UTfit

Fabio Ferrari* for the **UT***fit* collaboration†

Dipartimento di Fisica e Astronomia "Augusto Righi", Università di Bologna,
via Irnerio 46, Bologna, Italy
INFN, Sezione di Bologna
viale B. Pichat 6/2, Bologna, Italy

E-mail: fabio.ferrari@cern.ch

In these proceedings, the results of the latest Standard Model analysis performed by the UTfit collaboration including the most updated inputs from experiments, lattice QCD and phenomenological calculations as of Summer 2021 are presented. In addition, the results of a New Physics analysis in which the most generic loops to all sectors have been added are also reported, together with the New Physics contributions to $\Delta F = 2$ transitions.

PoS(CKM2021)078

11th International Workshop on the CKM Unitarity Triangle (CKM2021)
22-26 November 2021
The University of Melbourne, Australia

*Speaker

†The **UT***fit* collaboration: Marcella Bona (Queen Mary University of London), Marco Ciuchini (INFN Sezione di Roma Tre), Denis Derkach (HSE University), Fabio Ferrari (Università di Bologna and INFN Sezione di Bologna), Enrico Franco (INFN Sezione di Roma), Vittorio Lubicz (INFN Sezione di Roma Tre), Guido Martinelli (Università di Roma La Sapienza), Maurizio Pierini (CERN), Luca Silvestrini (INFN Sezione di Roma), Silvano Simula (INFN Sezione di Roma Tre), Cecilia Tarantino (INFN Sezione di Roma Tre), Vincenzo Vagnoni (INFN Sezione di Bologna), Mauro Valli (Stony Brook University) and Ludovico Vittorio (Scuola Normale Superiore e INFN Sezione di Pisa).

1. Introduction

Flavor physics represents a powerful tool to test the Standard Model (SM) and to search for possible New Physics (NP) effects up to scales far above the reach of present colliders. By fitting the flavour observables belonging to the Unitarity Triangle (UT), one can obtain the most precise determination of the CKM matrix parameters [1, 2].

In the last two decades, the **UT***fit* collaboration has regularly provided updates of the UT analysis both in the form of papers [3] and online results.[1] The UT analysis enables to impose strong constraints on the CKM elements and angles as well as on several quantities related to neutral mesons mixing to be imposed. Some of the most important constraints used in the UT fit are: the magnitude of the CKM matrix elements $V_{\rm ub}$ and $V_{\rm cb}$ obtained from semileptonic B decays, the B_d and B_s mesons oscillation frequencies Δm_d and Δm_s, the neutral kaon mixing parameter ε_K and the CKM angles α, $\sin(2\beta)$, and γ obtained from charmless hadronic B decays, $B^0 \to c\bar{c}K^0$ decays and charm hadronic B decays, respectively.

The UT fit has been performed in two different scenarios. The first one is a SM analysis in which the results are compared to the SM parameters, their compatibility is assessed and the most accurate predictions for the flavour SM observables are provided. Secondly, a NP analysis is also performed, in which the most generic NP loops are added to the SM structure to probe their contribution to $\Delta F = 2$ transitions. This allows the presence of NP effects to be constrained up to scales much larger than the current reach of experimental searches, depending on the assumed couplings.

2. Updated inputs and results of the global SM fit

The values used for the magnitudes of the CKM matrix elements $V_{\rm ub}$ and $V_{\rm cb}$ are shown in the left part of Fig. 1 and reported in Table 1. Both exclusive values are taken from the 2021 FLAG review [4]. The inclusive $|V_{\rm cb}|$ value is obtained from Ref. [5], while the inclusive $|V_{\rm ub}|$ value is taken from the latest HFLAV average [6]. In the left part of Fig. 1 the $|V_{\rm ub}|/|V_{\rm cb}|$ values measured by the LHCb collaboration in $B_s^0 \to K^-\mu^+\nu_\mu$ [7] and $\Lambda_b^0 \to p\mu^-\overline{\nu_\mu}$ [8] decays are also shown. The former is included in the combination, whereas the latter is not, following the FLAG recommendations. The **UT***fit* average is calculated with a two-dimensional procedure inspired by the skeptical method of Ref. [9] with $\sigma = 1$. This value is very similar to the one calculated following the PDG prescriptions [10]. The compatibility between the inclusive and exclusive values of $|V_{\rm ub}|$ is at the level of 1.6 σ, while for $|V_{\rm cb}|$ it is about 3.2 σ.

The input value for the CKM angle α is $(93.6 \pm 4.2)^\circ$ and it is obtained from charmless two-body B decays to $\pi\pi$, $\rho\pi$ and $\rho\rho$ final states via isospin analyses [11]. The input value for the CKM angle γ is $(66.2 \pm 3.5)^\circ$ and it is measured with $B \to D^{(*)}K^{(*)}$ decays [6]. Using these inputs and the **UT***fit* Bayesian framework, a global fit is performed to extract the CKM matrix parameters $\overline{\rho}$ and $\overline{\eta}$. Their value are found to be 0.155 ± 0.011 and 0.350 ± 0.010, respectively. The $\overline{\eta} - \overline{\rho}$ plane with the results of the SM fit overlaid is shown in the right part of Fig. 1. A summary of the input values used, together with the prediction obtained by excluding the given constraint from the fit, is reported in Table 2.

[1]The complete set of numerical input values and results is constantly kept updated at www.utfit.org

PoS(CKM2021)078

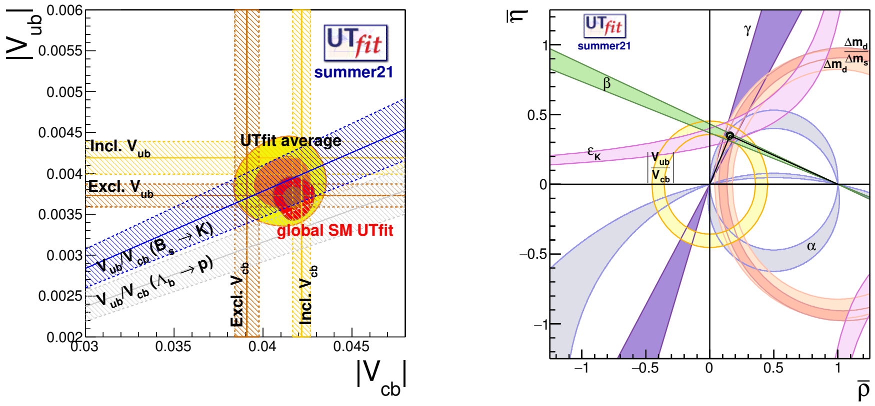

Figure 1: (Left) $|V_{ub}|-|V_{cb}|$ plane showing the comparison between the inclusive and exclusive determinations together with the **UT***fit* average and prediction. (Right) $\overline{\eta}-\overline{\rho}$ plane with the results of the SM fit for the UT apex. The various constraints and allowed regions (95% probability) are also shown.

Table 1: Exclusive and inclusive values of $|V_{ub}|$ and $|V_{cb}|$ used in the UT fit. The 2D average is also reported in the last column for comparison. The second uncertainty reported for the inclusive determination of $|V_{ub}|$ is flat and due to the spread of the central values used in the average.

	exclusive $[10^{-3}]$	inclusive $[10^{-3}]$	2D average $[10^{-3}]$
$\lvert V_{ub}\rvert$	3.63 ± 0.14	$4.19 \pm 0.17 \pm 0.18$	3.89 ± 0.21
$\lvert V_{cb}\rvert$	39.48 ± 0.68	42.16 ± 0.50	41.1 ± 1.0

Table 2: Summary of the input values and fit predictions obtained for the main observables in the SM UT fit. Tha last column reports the compatibility of the given input value with the **UT***fit* prediction obtained by removing the corresponding constraint from the fit.

Observable	Input value	Prediction	Pull ($\#\sigma$)
$\sin(2\beta)$	0.668 ± 0.020	0.750 ± 0.027	1.8
γ	66.2 ± 3.5	65.8 ± 1.9	< 1
α	93.6 ± 4.2	90.5 ± 1.9	< 1
ε_K $[\times 10^3]$	2.228 ± 0.001	1.99 ± 0.14	1.7
$\lvert V_{cb}\rvert$ $[\times 10^3]$	41.1 ± 1.0	41.9 ± 0.5	< 0.5
$\lvert V_{cb}\rvert$ incl. $[\times 10^3]$	42.16 ± 0.50	–	< 1
$\lvert V_{cb}\rvert$ excl. $[\times 10^3]$	39.08 ± 0.68	–	3.6
$\lvert V_{ub}\rvert$ $[\times 10^3]$	3.89 ± 0.21	3.68 ± 0.10	< 1
$\lvert V_{ub}\rvert$ incl. $[\times 10^3]$	4.19 ± 0.17	–	1
$\lvert V_{ub}\rvert$ excl. $[\times 10^3]$	3.72 ± 0.13	–	< 1
$BR(B \to \tau\nu_\tau)$ $[\times 10^4]$	1.09 ± 0.24	0.88 ± 0.05	< 1
A_{SL}^d $[\times 10^3]$	-2.1 ± 1.7	-0.32 ± 0.03	< 1
A_{SL}^s $[\times 10^3]$	-0.6 ± 2.8	0.014 ± 0.001	< 1

3. Result of the fit allowing for New Physics

Possible NP effects entering this analysis are those affecting neutral meson mixing ($\Delta F = 2$ transitions), that can be parameterised in a model-independent way by using the two following relations:

$$\frac{\langle B_q | H_{\text{eff}}^{\text{full}} | \overline{B}_q \rangle}{\langle B_q | H_{\text{eff}}^{\text{SM}} | \overline{B}_q \rangle} = C_{B_q} e^{2i\phi_{B_q}} = \left(1 + \frac{A_q^{\text{NP}}}{A_q^{\text{SM}}} e^{2i(\phi_q^{\text{NP}} - \phi_q^{\text{SM}})} \right), \tag{1}$$

where $q = d$ or s. Within the SM, $C_{B_q} = 1$ and $\phi_{B_q} = 0$ or, equivalently, $A_q^{\text{NP}} = 0$ and $\phi_q^{\text{NP}} = 0$. The SM $\Delta F = 2$ effective Hamiltonian is indicated as $H_{\text{eff}}^{\text{SM}}$, while its extension for a generic NP contribution is written as $H_{\text{eff}}^{\text{full}}$.

The following inputs are added to the fit to extract information on the B_s system: the semilpetonic asymmetry in B_d and B_s decays, the di-muon charge asymmetry [12], the B_s lifetime from flavour-specific final states, and the CP-violating and decay-width difference for B_s mesons from the time-dependent angular analyses of $B_s \to J/\psi\phi$ decays. All the used values are taken from Ref. [6], except for the B_s semileptonic asymmetry where an updated average has been computed by the LHCb collaboration in Ref. [13].

The $\overline{\rho}$ and $\overline{\eta}$ values obtained from the NP fit are $\overline{\rho} = 0.174 \pm 0.025$ and $\overline{\eta} = 0.380 \pm 0.025$. The NP parameters extracted from the fit are $C_{B_d} = 1.05 \pm 0.10$, $\phi_{B_d} = (-3.1 \pm 1.8)°$, $C_{B_s} = 1.04 \pm 0.07$ and $\phi_{B_s} = (-0.3 \pm 0.6)°$ and are compatible with the SM expectations $C_{B_q} = 1$ and $\phi_{B_q} = 0$. Figure 2 shows the $\phi_{B_q} - A_q^{\text{NP}}/A_q^{\text{SM}}$ planes with the obtained 68% and 95% probability regions. Despite the good compatibility of the NP parameters with the SM expectations, NP contributions at the level of $10 - 20\%$ are still allowed.

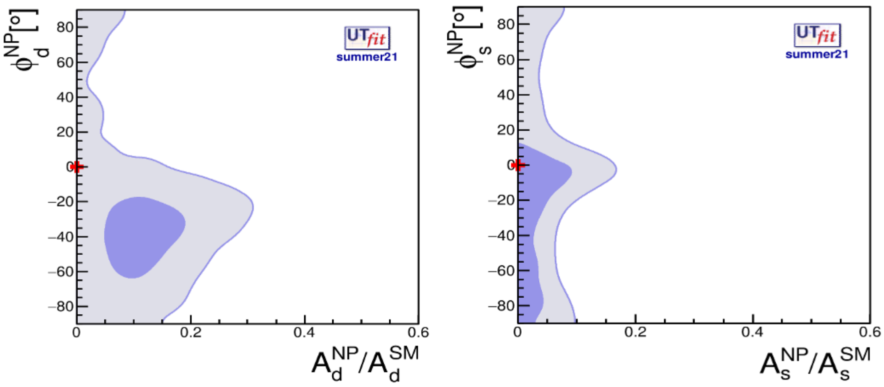

Figure 2: NP parameters for the (left) B_d and (right) B_s system in the $\phi_{B_q} - A_q^{\text{NP}}/A_q^{\text{SM}}$ plane. The (light shaded) 68% and (dark shaded) 95% probability regions are also shown. The red cross centered in $(0, 0)$ represents the SM expectation.

By considering the most general Hamiltonian for $\Delta F = 2$ transitions ($H_{\text{eff}}^{\Delta F=2}$), the results can be translated into allowed ranges for the Wilson coefficients of the effective Hamiltonian. A detailed description of the procedure employed is available in Ref. [14]. In general, these coefficients can be written as:

$$C_i(\Lambda) = \frac{F_i L_i}{\Lambda^2}, \tag{2}$$

where F_i are functions of the NP flavour couplings, L_i are loop factors present in NP models with no tree-level flavour-changing neutral currents, and Λ is the NP scale, *i.e.* the typical mass of NP particles mediating $\Delta F = 2$ transitions.

To probe the NP scale, assumptions on the F_i and L_i need to be made. If one considers a generic strongly interacting theory with arbitrary flavour structure, then $F_i \sim L_i \sim 1$ and thus the allowed ranges for the coefficients C_i can be translated into a lower bound on Λ. Different assumptions on the NP flavour structure, for example Next-to-Minimal [15] Flavour Violation (NMFV), lead to different choices for the F_i functions. In particular, in this case one has that $|F_i| = F_{\rm SM}$ with an arbitrary phase. The NP-scale lower bounds in a NMFV scenario are shown in the left part of Fig. 3. To obtain the lower bounds one needs to multiply the values quoted in the following by $\alpha_s \sim 0.1$ or $\alpha_w \sim 0.03$ depeding on whether the coupling is via strong or weak interactions. The strongest bound is obtained from Im $\rm C_K$ of the fourth coefficient and corresponds to $\Lambda_{\rm NMFV} > 89$ TeV. In the case of a generic NP scenario the constraints are much tighter due to the absence of CKM suppression. The right plot in Fig. 3 shows the lower bound on Λ for this scenario. The strongest bound on the NP scale comes from Im $\rm C_K$ of the fourth coefficient also in this case and corresponds to $\Lambda > 4.3 \cdot 10^5$ TeV.

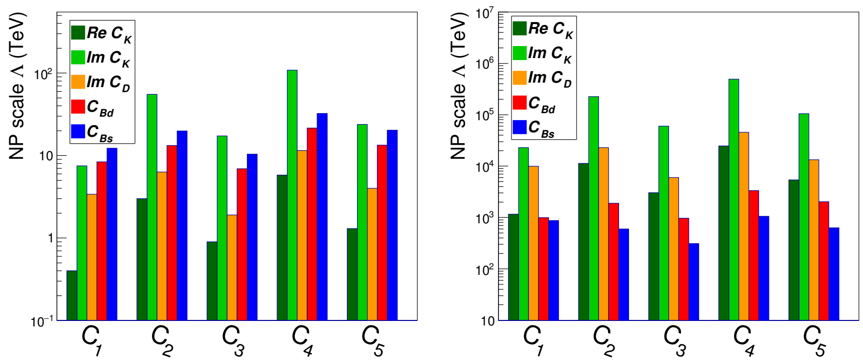

Figure 3: Summary of the 95% probability lower bound on the NP scale Λ for (left) a strongly-interacting NP in the NMFV scenario and (right) a generaic NP scenario. Results from all neutral meson systems are shown.

4. Conclusions

The **UT***fit* collaboration has performed two different UT fits exploiting the most up-to-date experimental, LQCD and phenomenological inputs available. The SM analysis shows a very good overall consistency, but the tension between the exclusive and inclusive determinations of $|V_{\rm ub}|$ and $|V_{\rm cb}|$ is still present, and more data will be needed to have a clearer picture. The NP analysis provides the determination of NP contributions to $\Delta F = 2$ amplitudes, currently leaving room for NP at the $10 - 20\%$ level. The NP scale is much above the reach of current colliders reach for a generic NP scenario, whereas it appears to be barely reachable for a NMFV scenario with weak couplings.

References

[1] N. Cabibbo, *Unitary Symmetry and Leptonic Decays*, Phys. Rev. Lett. **10** (1963), 531-533.

[2] M. Kobayashi and T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction*, Prog. Theor. Phys. **49** (1973), 652-657.

[3] M. Bona *et al.* [UTfit collaboration], *The Unitarity Triangle Fit in the Standard Model and Hadronic Parameters from Lattice QCD: A Reappraisal after the Measurements of $\Delta m_{(s)}$ and $BR(B \to \tau\nu_\tau)$*, JHEP **10** (2006), 081 [hep-ph/0606167].

[4] Y. Aoki, T. Blum, G. Colangelo, S. Collins, M. Della Morte, P. Dimopoulos, S. Dürr, X. Feng, H. Fukaya and M. Golterman, *et al. FLAG Review 2021*, [arXiv:2111.09849 [hep-lat]].

[5] M. Bordone, B. Capdevila and P. Gambino, *Three loop calculations and inclusive $V_{\rm cb}$*, Phys. Lett. B **822** (2021), 136679 [arXiv:2107.00604 [hep-ph]].

[6] Y. S. Amhis *et al.* [HFLAV], *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018*, Eur. Phys. J. C **81** (2021) no.3, 226 [arXiv:1909.12524 [hep-ex]].

[7] R. Aaij *et al.* [LHCb collaboration], *First observation of the decay $B_s^0 \to K^-\mu^+\nu_\mu$ and Measurement of $|V_{\rm ub}|/|V_{\rm cb}|$*, Phys. Rev. Lett. **126** (2021) no.8, 081804 [arXiv:2012.05143 [hep-ex]].

[8] R. Aaij *et al.* [LHCb collaboration], *Determination of the quark coupling strength $|V_{\rm ub}|$ using baryonic decays*, Nature Phys. **11** (2015), 743-747 [arXiv:1504.01568 [hep-ex]].

[9] G. D'Agostini, *Sceptical combination of experimental results: General considerations and application to ε'/ε*, [arXiv:hep-ex/9910036 [hep-ex]].

[10] P.A. Zyla *et al.* [Particle Data Group], *Review of Particle Physics*, PTEP **2020** (2020) no.8, 083C01.

[11] M. Bona [UTfit collaboration], *Unitarity Triangle analysis in the Standard Model from the UTfit collaboration*, PoS **ICHEP2016** (2016), 554.

[12] V. M. Abazov *et al.* [D0 collaboration], *Measurement of the anomalous like-sign dimuon charge asymmetry with 9 fb^{-1} of $p\bar{p}$ collisions*, Phys. Rev. D **84** (2011), 052007 [arXiv:1106.6308 [hep-ex]].

[13] R. Aaij *et al.* [LHCb], *Measurement of the CP asymmetry in $B_s^0 - \overline{B}_s^0$ mixing*, Phys. Rev. Lett. **117** (2016) no.6, 061803 [arXiv:1605.09768 [hep-ex]].

[14] M. Bona *et al.* [UTfit collaboration], *Model-independent constraints on $\Delta F = 2$ operators and the scale of new physics*, JHEP **03** (2008), 049 [arXiv:0707.0636 [hep-ph]].

[15] K. Agashe, M. Papucci, G. Perez and D. Pirjol, *Next to minimal flavor violation*, [arXiv:hep-ph/0509117 [hep-ph]].