Probing the TeV scale (and above) with Flavor Physics

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Abstract. Generalizing the unitarity triangle analysis to include new physics effects, we derive upper bounds on the coefficients of the most general $\Delta F = 2$ effective Hamiltonian. These upper bounds can be translated into lower bounds on the scale of new physics that contributes to these low-energy effective interactions. We conclude that the scale of new physics in models that generate new $\Delta F = 2$ operators, such as next-to-minimal flavor violation, has to be much higher than the scale of minimal flavor violation, and it most probably lies beyond the reach of direct searches at the LHC. Updated results are available on http://www.utfit.org.

The relevance of $\Delta F = 2$ processes in constraining new physics (NP) has been established since long time [1]. In particular, it has been noticed how the constraints from the mixing of neutral mesons is particularly stringent for models that generate transitions between quarks of different chiralities [2, 3, 4]. In Ref. [5], we updated the study of $\Delta F = 2$ processes, combining the most recent experimental developments to constrain NP in $K^0 - \bar{K}^0$, $D^0 - \bar{D}^0$, $B_d - \bar{B}_d$, and $B_s - \bar{B}_s$ mixing processes. We summarize here the main results of this analysis. The first step consists in generalizing the relation among the experimental observables and the elements of the CKM [6] matrix, introducing effective model-independent parameters that quantify the deviation of the experimental results from the Standard Model (SM) expectations. In the case of $B_q - \bar{B}_q$ mixing ($q = d, s$), we introduce a complex effective parameter defined as:

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q|H_{\text{full}}^{\text{eff}}|\bar{B}_q\rangle}{\langle B_q|H_{\text{SM}}^{\text{eff}}|\bar{B}_q\rangle}$$

and write all the measured observables as a function of these parameters and the SM ones ($\bar{\rho}$, $\bar{\eta}$, and additional parameters such as masses, form factors, and decay constants). Details are given in refs. [5, 7, 8]. In a similar way, one can write

$$C_{\tau_K} = \frac{\text{Im}[\langle K^0|H_{\text{full}}^{\text{eff}}|K^0\rangle]}{\text{Im}[\langle K^0|H_{\text{SM}}^{\text{eff}}|K^0\rangle]}, \quad C_{\Delta m_K} = \frac{\text{Re}[\langle K^0|H_{\text{full}}^{\text{eff}}|K^0\rangle]}{\text{Re}[\langle K^0|H_{\text{SM}}^{\text{eff}}|K^0\rangle]}.$$  

Concerning $\Delta m_K$, to be conservative, we add to the short-distance contribution a possible long-distance one that varies with a uniform distribution between zero and the experimental value of $\Delta m_K$. For $D\bar{D}$ mixing we use the result of the analysis performed in Ref. [9]. All the other experimental and theoretical inputs used are quoted in Ref. [5]. The combined fit of all the experimental observables selects a region of the $(\bar{\rho}, \bar{\eta})$ plane ($\bar{\rho} = 0.167 \pm 0.051$ and $\bar{\eta} = 0.386 \pm 0.035$ at 68% probability, see the left plot of Fig. 1) which is consistent with the

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result of the SM analysis [10]. This indicates that NP has to show up not as an $O(1)$ effect, but as a correction to the SM picture. The fit also constrain the effective NP parameters, as summarized in the other plots of Tab. 1 and shown in Fig. 1.

This information can then be translated into a lower bound on the NP scale for a specific flavor structure of the NP model, following the strategy described in Ref. [5]. We considered the following scenarios:

- minimal flavor violation (MFV) models with low or large values of $\tan \beta$.
- MFV models with very large values of $\tan \beta$.
- next to minimal flavor violation (NMFV) models [12]
- models with generic flavor structure.

In the first two cases, NP enters only as a shift on the mixing amplitudes, with the same phase as in the SM. This is why the measurement of $|V_{ub}/V_{cb}|$ from semileptonic $B$ decays and the determination of the three angles of the UT triangle can be used to determine the CKM as in the SM case, while $\Delta m_q$ and $\epsilon_K$ allow to put a lower bound on the NP scale $\Lambda$. In this way we obtain $\Lambda > 5.5$ TeV ($\Lambda > 5.1$) for small (large) values of $\tan \beta$. For very large values of $\tan \beta$ additional contributions can be generated by Higgs exchange. In this case, one can put a lower bound on the mass of non-standard Higgs bosons. We obtain $M_H > 5\sqrt{(a_0 + a_1)(a_0 + a_2)} \left(\frac{\tan \beta}{\sin \alpha}\right)$ TeV, where the $a_i$ are the couplings in the model that one needs to specify (together with $\tan \beta$) to obtain a lower bound on $M_H$.

The case of NMFV and generic flavor structures are more complicated, since NP can enter also in the determination of the other experimental observables, as long as they are not performed with tree-level processes. Starting from the results of Tab. 1, one can fit the Wilson coefficients $C_i(\Lambda)$ of the operators defining the most general NP effective Hamiltonian, and extract an upper-bound on $\Lambda$ imposing $C_i(\Lambda) = a_i \times F_i/\Lambda^2$, where $F_i$ is a equal to one (the proper combination of CKM matrix elements) for generic (NMFV) flavor structure and $a_i$ couplings are $O(1)$ for strongly coupled NP models or $O(\alpha_W)$ ($O(\alpha_s)$) for NP models couple to SM particles through weak (strong) loops. The result is shown in Fig. 2 for $O(1)$ couplings.

Table 1. Determination of NP and UT parameters from the UT fit.

| Parameter | 68% Probability | Parameter | 68% Probability |
|-----------|-----------------|-----------|-----------------|
| $C_{B_d}$ | $1.04 \pm 0.34$ | $\phi_{B_d}$ | $-4.1 \pm 2.1$ |
| $C_{B_s}$ | $1.04 \pm 0.29$ | $\phi_{B_s}$ | $(-75 \pm 14)$ |
| $C_{\Delta m_K}$ | $0.93 \pm 0.32$ | $C_{\epsilon_K}$ | $0.88 \pm 0.14$ |

Figure 1. From left to right, determination of $\bar{\rho}$ and $\bar{\eta}$, $\phi_{B_d}$ vs. $C_{B_d}$, $\phi_{B_s}$ vs. $C_{B_s}$, and $C_{\epsilon_K}$ vs $C_{\Delta m_K}$ from the NP generalized analysis. 68% and 95% probability regions for $\bar{\rho}$ and $\bar{\eta}$ are shown. For left plot, the $2\sigma$ contours given by the tree-level determination of $|V_{ub}|$ and $\gamma$ are shown as a reference.
Figure 2. Summary of the 95% probability lower bound on the NP scale $\Lambda$ for strongly-interacting NP in NMFV (left) and general NP (right) scenarios.

| Scenario                        | strong/tree | $\alpha_s$ loop | $\alpha_W$ loop |
|---------------------------------|-------------|-----------------|-----------------|
| MFV (small tan $\beta$)        | 5.5         | 0.5             | 0.2             |
| MFV (large tan $\beta$)        | 5.1         | 0.5             | 0.2             |
| $M_H$ in MFV at large tan $\beta$ | 5 $\sqrt{(a_0 + a_1)(a_0 + a_2)}$ (tan $\beta$) | |
| NMFV                            | 62          | 6.2             | 2               |
| General                         | 24000       | 2400            | 800             |

Table 2. Summary of the 95% probability lower bound on the NP scale $\Lambda$ (in TeV) for several possible flavor structures and loop suppressions.

The summary of the lower bounds on $\Lambda$ is given in Tab. 2. While MFV scenarios are still accessible at the energy scale that LHC will cover, a loop suppression is needed in all scenarios to obtain NP scales that can be reached at the LHC. For NMFV models, an $\alpha_W$ loop suppression might not be sufficient. Anyhow, in case an accidental suppression of the NP contribution to $\epsilon_K$ is induced by additional features of the considered model, the scale for weak loop contributions might be as low as 0.5 TeV.

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