Unitarity Triangle and New Physics

Paride Paradisi[a]

[a]Physik-Department, Technische Universität München, D-85748 Garching, Germany

The Unitarity Triangle (UT) Analysis represents a powerful tool to test the SM and therefore to probe New Physics effects. After summarizing various tensions in the present UT analyses, we consider a number of Supersymmetric models showing their capability to solve these tensions. Moreover, we show how the characteristic patterns of correlations among flavour observables allow to distinguish between these different SUSY scenarios. We propose a "DNA-Flavour Test" of NP models, with the aim of showing a tool to distinguish between these NP scenarios, once additional data on flavour changing processes become available.

1. INTRODUCTION

In the last few years, the two B factories have established that flavor-changing and CPV processes of B_d mesons are well described by the Standard Model (SM) up to an accuracy of $(10-20)\%$. This observation, together with the good agreement between data and SM expectations in the kaon system, implies tight constraints on flavor-changing phenomena beyond the SM and a potential problem for a natural solution of the hierarchy problem, that calls for new physics (NP) not far from the electroweak scale [1].

In this context, the question we intend to address is whether it is still possible (and to which extent) to expect NP phenomena to appear in the B_s system where the SM has not been experimentally tested at the same accuracy level as in the B_d system. In particular, it is well known that $b \to s$ transitions represent a special ground where to perform efficient tests of NP scenarios. Indeed, CP violation in $b \to s$ transitions is predicted to be very small in the SM, thus, any experimental evidence for sizable CP violating effects in the B_s system would unambiguously point towards a NP evidence. Recent messages from the CDF and D0 experiments seem to indicate that this indeed could be the case.

On the theoretical side, there exist many well motivated NP scenarios predicting large effects especially in $b \to s$ transitions. Among them are supersymmetric (SUSY) flavour models based on abelian and non-abelian flavour symmetries naturally leading to large NP contributions in $b \to s$ processes while maintaining, at the same time, the NP contributions occurring in $s \to d$ and (sometimes) $b \to d$ transitions, under control. Moreover, also Grand Unified Theories (GUTs) represent a suitable ground where large NP effects in $b \to s$ transitions can be generated. In fact, GUTs link leptonic and hadronic sources of flavour and CP violation and the observed large atmospheric neutrino mixing is transmitted to a large flavour violation in $b \leftrightarrow s$ transitions.

In the following, we focus on the NP predictions for the $b \to s$ transitions within SUSY models and their correlations with other observables relative to K, B, D and charged lepton decays [2]. In particular, when we deal with specific models, the source of the flavour and CP violation for $b \to s$ transitions will simultaneously generate not only $\Delta B = 2$ and $\Delta B = 1$ processes that will turn out to be correlated, but will also have impact on observables outside the B meson system. The questions we will address in the following are:

i) to quantify the NP room left for $b \to s$ transitions compatible with all the available experimental data on $\Delta F = 2$ and $\Delta F = 1$ processes,

ii) to outline strategies to disentangle different NP scenarios by means of a correlated analysis of low energy observables.

2. UT analysis

The present unitarity triangle (UT) analyses are dominated by $\Delta F = 2$ processes. We begin by reviewing the status of the UT trying to outline transparently possible hints of NP and related tests to falsify or to confirm them. We remind that there exist two different UTs: 1) the so-called reference unitarity triangle (RUT) [3], determined entirely from tree level decays hence, likely unaffected by any significant NP pollution, and 2) the universal unitarity triangle (UUT) [4], determined by means of loop-induced FCNC processes and hence potentially sensitive to NP effects. Therefore, a comparative UT analysis performed by means of the RUT and UUT may unveil NP effects.

In particular, the above UTs are characterized by the following parameters

$$\begin{aligned} V_{us} &\equiv \lambda\ ,\ V_{cb}\ ,\ R_b\ ,\ \gamma \qquad \text{RUT}\,, \\ V_{us} &\equiv \lambda\ ,\ V_{cb}\ ,\ R_t\ ,\ \beta \qquad \text{UUT}\,, \end{aligned} \tag{1}$$

where $R_b \equiv |V_{ud}V_{ub}^*|/|V_{cd}V_{cb}^*|$, $R_t \equiv |V_{td}V_{tb}^*|/|V_{cd}V_{cb}^*|$ and the angles β and γ are such that $V_{td} = |V_{td}|e^{-i\beta}$ and $V_{ub} = |V_{ub}|e^{-i\gamma}$. Moreover, R_t and β can be expressed in terms of R_b and γ as

$$\begin{aligned} R_t &= \sqrt{1 + R_b^2 - 2R_b\cos\gamma}\ , \\ \cot\beta &= \frac{1 - R_b\cos\gamma}{R_b\sin\gamma}\ . \end{aligned} \tag{2}$$

In terms of physical observables we can write

$$\begin{aligned} R_t &= \xi\frac{1}{\lambda}\sqrt{\frac{m_{B_s}}{m_{B_d}}}\sqrt{\frac{\Delta M_d}{\Delta M_s}}\sqrt{\frac{C_{B_s}}{C_{B_d}}}\ , \\ S_{\psi K_S} &= \sin(2\beta + 2\phi_{B_d})\ , \end{aligned} \tag{3}$$

with the SM limit recovered for $C_{B_q} = 1$ and $\phi_{B_d} = 0$.

The last observable that is relevant for our UT analysis is ϵ_K. In the SM, ϵ_K can be written as [5]

$$\begin{aligned} |\epsilon_K| &= \kappa_\epsilon C_\epsilon \hat{B}_K |V_{cb}|^2|V_{us}|^2 \\ &\times \left[\frac{|V_{cb}|^2}{2}R_t^2\sin 2\beta\eta_{tt}S_0(x_t) + \right. \\ &+ \left. R_t\sin\beta(\eta_{ct}S_0(x_c,x_t) - \eta_{cc}x_c)\right] \end{aligned} \tag{4}$$

where all the parameters entering the above expression are reported in Ref.[2]. As stressed in [5], the SM prediction of ϵ_K implied by the measured value of $\sin 2\beta$ may be too small to agree with experiment. The main reasons are the decreased value of $\hat{B}_K$ and the decreased value of ϵ_K in the SM arising from a multiplicative factor, estimated as $\kappa_\epsilon = 0.94 \pm 0.02$ [6]. The total suppression of $\epsilon_K \propto \hat{B}_K\kappa_\epsilon$ compared to the commonly used formulae is typically of order 15%. Using the inputs of Ref.[2], eq. (3) for the SM case (where $C_{B_s} = C_{B_d} = 1$), and eq. (4), one finds

$$|\epsilon_K|^{\rm SM} = (1.92 \pm 0.25) \times 10^{-3}\ , \tag{5}$$

where we have also included the NNLO-QCD corrections to the QCD factor η_{ct} [7]. This has to be compared with the experimental measurement [8]

$$|\epsilon_K|^{\rm exp} = (2.229 \pm 0.010) \times 10^{-3}\ . \tag{6}$$

In fig. 1, we show the above tensions in the $R_b - \gamma$ plane.

In the left plot of fig. 1, we show the regions corresponding to the 1σ allowed ranges for $\sin 2\beta$, R_t and $|\epsilon_K|^{\rm SM}$ as calculated by means of (3) and (4), respectively, using the numerical input parameters of Ref. [2]. As shown, there are three different values of (R_b, γ), dependently which two constraints are simultaneously applied.

Possible solutions to this tension can be obtained assuming:

1) a positive NP effect in ϵ_K, at the level of $\approx +20\%$, leaving $\sin 2\beta$ and $\Delta M_d/\Delta M_s$ SM-like [5].

2) ϵ_K and $\Delta M_d/\Delta M_s$ NP free while $S_{\psi K_S}$ affected by a NP phase in B_d mixing of $\approx -6.5^\circ$ [9].

3) ϵ_K and $S_{\psi K_S}$ NP free while $\Delta M_d/\Delta M_s$ affected by NP at the level of $\approx -20\%$ [2].

In tab. 1, taken from Ref. [2], we show the values of the relevant CKM parameters corresponding to each case, where the values of the two variables characteristic for a given scenario are assumed not to be affected by NP.

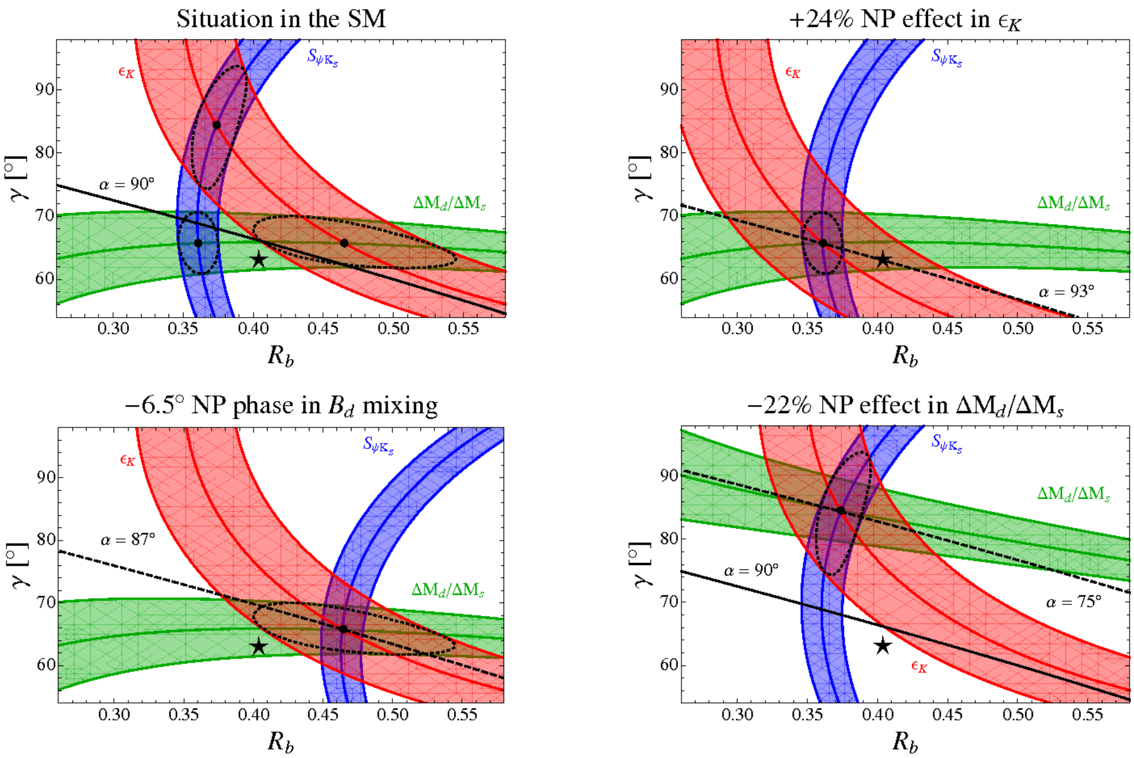

Figure 1. The $R_b - \gamma$ plane assuming: **i)** $\sin 2\beta$, R_t and ϵ_K not affected by NP effects (upper left), **ii)** $\sin 2\beta$ and R_t NP free while ϵ_K affected by a positive NP effect at the level of $+24\%$ compared to the SM contribution (upper right), **iii)** ϵ_K and R_t NP free while $\sin 2\beta$ affected by a NP phase in B_d mixing of $-6.5°$ (lower left), **iv)** ϵ_K and $\sin 2\beta$ NP free while $\Delta M_d/\Delta M_s$ affected by a negative NP effect at the level of -22% compared to the SM contribution (lower right). The black star indicates the values for R_b and γ obtained in the NP UT fit of [10]. From [2].

	$\bar\rho$	$\bar\eta$	$\alpha[°]$	$\gamma[°]$	R_b	$\vert V_{ub}\vert \times 10^3$
1)	$0.148^{+0.029}_{-0.029}$	$0.329^{+0.018}_{-0.017}$	$93.2^{+5.0}_{-5.0}$	$65.7^{+4.9}_{-4.9}$	$0.361^{+0.014}_{-0.014}$	$3.44^{+0.17}_{-0.16}$
2)	$0.191^{+0.059}_{-0.049}$	$0.424^{+0.063}_{-0.055}$	$86.6^{+4.2}_{-3.8}$	$65.7^{+4.3}_{-3.9}$	$0.465^{+0.080}_{-0.065}$	$4.44^{+0.77}_{-0.64}$
3)	$0.036^{+0.064}_{-0.062}$	$0.372^{+0.023}_{-0.019}$	$74.5^{+10.0}_{-9.0}$	$84.4^{+9.4}_{-10.2}$	$0.374^{+0.021}_{-0.018}$	$3.57^{+0.23}_{-0.19}$
UTfit	0.177 ± 0.044	0.360 ± 0.031	92 ± 7	63 ± 7	0.404 ± 0.025	3.87 ± 0.23

Table 1
Predictions of several CKM parameters in the three scenarios as discussed in the text. For comparison, in the last line results are also shown from a global NP fit of the UT [10]. From [2].

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RSc
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 2
"DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★ signals large NP effects, ★★ visible but small NP effects and ★ implies that the given model does not predict sizable NP effects in that observable. From [2].

3. DNA-Flavour Test of New Physics Models

Even if the UT analysis represents a powerful tool in the attempt to unveil NP effects, a complementary and equally important way to look for NP is to monitor the (potential) pattern of deviations, compared to the SM expectations, in a number of selected processes that we call "*golden channels*". The selection of a "*golden channels*" is based on its sensitivity to NP and theoretical cleanness. The former, that is a model-dependent feature, can be increased with the increased precision of experiments and the latter can improve with the progress in theoretical calculations, in particular the non-perturbative ones like the lattice simulations. Without entering a proper description and classification of the "*golden channels*", in the following we list some of them:

i) the mixing induced CP-asymmetry $S_{\psi\phi}(B_s)$ that is tiny in the SM: $S_{\psi\phi} \approx 0.04$, ii) the rare decays $B_{s,d} \to \mu^+\mu^-$ that could be enhanced in certain NP scenarios by an order of magnitude over the SM values, iii) the angle γ of the unitarity triangle (UT) that can be precisely measured through tree level decays, iv) $B^+ \to \tau^+\nu_\tau$ that is sensitive to charged Higgs particles, v) the rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ that belong to the theoretically cleanest decays in flavour physics, vi) lepton flavour violating decays like $\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to \mu\gamma$, decays with three leptons in the final state and $\mu - e$ conversion in nuclei, vii) electric dipole moments of the neutron and heavy atoms, viii) the anomalous magnetic moment of the muon $(g-2)_\mu$ that currently shows a $\sim 3\sigma$ discrepancy between its SM prediction and the experimental measurement.

In order to appreciate the powerful tool offered by the flavor processes in disentangling different NP scenario, in the following, we focus on representative Supersymmetric flavour models, as discussed in Ref. [2].

In particular, we consider scenarios with

i) large $\mathcal{O}(1)$ RR mass insertions,

ii) comparable LL and RR mass insertions that are CKM-like,

iii) only CKM-like LL mass insertions.

The patterns of flavour violation differ from model to model, thereby allowing in the future to find out which of models can survive the future measurements. Undoubtedly, the correlations between various observables that are often characteristic for a given model will be of the utmost importance in these tests.

In tab. 2, we show a summary of the potential size of deviations from the SM results allowed for a large number of observables, when all existing constraints from other observables not listed there are taken into account. This table can be considered as the collection of the DNA's for various models. These DNA's will be modified as new experimental data will be availabe and in certain cases we will be able to declare certain models to be disfavoured or even ruled out. In constructing the table we did not take into account possible correlations among the observables. It will be interesting to monitor the changes in this table when the future experiments will provide new results.

4. CONCLUSIONS

The coming years will witness tremendous progress at the high energy frontier accomplished primarily at the LHC, where the available energy will be increased by one order of magnitude. Equivalently, for the first time we will be able to resolve directly distances well below 10^{-18} m, that have been explored so far. Parallel to these developments, important advances are expected at the high precision frontier through the improved B_s-physics experiments at the Tevatron and in particular LHCb at CERN. At later stages in the coming decade these efforts will be strengthened by new rare K experiments at J-PARC, the NA62 collaboration at CERN and possibly Project X at Fermilab as well as Belle-II at KEK and the planned Super$B$ facility in Rome. The latter two will also provide new insights into the FCNC processes in the D meson system and in charged lepton decays.

While the main goal at the high energy frontier is the discovery of new particles and the determination of their masses, the main goal of flavour physics is the search for the footprints of these new particles in rare processes and the determination of their couplings. As the latter exploration of very short distance scales is indirect, only measurements of a large number of observables and the study of correlations between them in a given extension of the SM and in particular of patterns of flavour violation characteristic for a given model can allow us to identify the correct NP scenario.

As a remarkable example, Ref. [2] has considered a number of representative supersymmetric flavour models that on one hand aim at the explanation of the observed hierarchical fermion masses and mixings and on the other hand provide natural suppression of FCNC transitions.

As shown in Ref. [2], the simultaneous study of various flavour violating processes can indeed allow us to distinguish various NP scenarios.

It will be exciting to monitor upcoming results from Tevatron and the LHC on $S_{\psi\phi}$ and $B_s \to \mu^+\mu^-$. Already these two measurements will be capable of excluding some SUSY flavour models and distinguish them from the LHT and RS model with custodial protection in which $S_{\psi\phi}$ can be large but $B_{s,d} \to \mu^+\mu^-$ remain SM-like. Further observables will help to identify more precisely the correct extension of the SM. In particular, while the branching ratios for $K \to \pi\nu\bar{\nu}$ decays remain SM-like in all the supersymmetric flavour models analyzed in Ref. [2], they can be significantly enhanced in the LHT and RS models.

A DNA-Flavour Test proposed in Ref. [2] and reported in table 2, should give still a deeper insight into the patterns of flavour violation in various scenarios, in particular when it is considered simultaneously with various correlations present in concrete models. The interplay of these efforts with the direct searches for NP will be most exciting.

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