An Improved Standard Model Prediction Of $BR(B \to \tau \nu)$
And Its Implications For New Physics

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The recently measured $B \to \tau \nu$ branching ratio allows to test the Standard Model by probing virtual effects of new heavy particles, such as a charged Higgs boson. The accuracy of the test is currently limited by the experimental error on $BR(B \to \tau \nu)$ and by the uncertainty on the parameters $f_B$ and $|V_{ub}|$. The redundancy of the Unitarity Triangle fit allows to reduce the error on these parameters and thus to perform a more precise test of the Standard Model. Using the current experimental inputs, we obtain $BR(B \to \tau \nu)_{\text{SM}} = (0.84 \pm 0.11) \times 10^{-4}$, to be compared with $BR(B \to \tau \nu)_{\text{exp}} = (1.73 \pm 0.34) \times 10^{-4}$. The Standard Model prediction can be modified by New Physics effects in the decay amplitude as well as in the Unitarity Triangle fit. We discuss how to disentangle the two possible contributions in the case of minimal flavour violation at large $\tan \beta$ and generic loop-mediated New Physics. We also consider two specific models with minimal flavour violation: the Type-II Two Higgs Doublet Model and the Minimal Supersymmetric Standard Model.

\section*{INTRODUCTION}

Flavour physics offers the opportunity to probe virtual effects of new heavy particles using low-energy phenomena, involving Standard Model (SM) particles as external states. New Physics (NP) can generate large effects in Flavour Changing Neutral Currents (FCNC) and CP violating phenomena even for NP particle masses much above the TeV scale, if new sources of flavour and CP violation besides the Yukawa couplings are present. The strong NP sensitivity is mainly due to the Glashow-Iliopoulos-Maiani (GIM) suppression of FCNC processes in the SM \textsuperscript{1}. However, other suppression mechanisms can be at work in the SM, making a few non-FCNC decays interesting for NP searches. In particular, the helicity suppression of the charged current decay $B \to \tau \nu$ makes it potentially sensitive to the tree-level effects of new scalar particles \textsuperscript{2}. A typical example is given by the exchange of charged Higgs bosons in multi-Higgs extensions of the SM, such as the type-II Two Higgs Doublet Model (2HDM-II) or the Minimal Supersymmetric Standard Model (MSSM), in the large $\tan \beta$ regime.

In the SM, the branching ratio of $B \to \tau \nu$ can be written as:

$$BR(B \to \tau \nu) = \frac{G_F^2 m_B m_\tau}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B .$$

The Fermi constant $G_F$, the $B$ ($\tau$) mass $m_B$ ($m_\tau$) and the $B$ lifetime $\tau_B$ are precisely measured \textsuperscript{3}. The decay constant of the $B$ meson $f_B$ is known with $\mathcal{O}(10\%)$ uncertainty. We use the lattice QCD (LQCD) average $f_B = 200 \pm 20$ MeV \textsuperscript{4}. Concerning the error attached to lattice averages, we combine in quadrature the statistical and systematic errors, assuming Gaussian distributions. This is justified since present lattice systematic errors arise from the combination of several independent sources of uncertainty. Therefore they are well described by a Gaussian distribution, no matter what the distributions of the individual sources are. \textsuperscript{5}

The absolute value of the Cabibbo-Kobayashi-Maskawa (CKM) \textsuperscript{5} matrix element $V_{ub}$ is determined from the measurements of the branching ratios of ex-

\textsuperscript{1} Notice that in the past we used to assign a flat distribution to the lattice systematic errors, since they were dominated by the uncertainty associated to the quenched approximation.
exclusive and inclusive semileptonic $b \to u$ decays. Its precision is limited by the uncertainty of the theoretical calculations. Although inclusive determinations are systematically higher than exclusive ones, the two values are compatible, once the spread of inclusive determinations using different theoretical models is considered. For the exclusive decays, we use the HFAG averages \[7\]

$$BR(B \to \pi\ell\nu)_{q^2<16\text{GeV}^2} = (0.94 \pm 0.05 \pm 0.04) \times 10^{-4},$$
$$BR(B \to \pi\ell\nu)_{q^2>16\text{GeV}^2} = (0.37 \pm 0.03 \pm 0.02) \times 10^{-4},$$

together with the theoretical estimates of the relevant normalized form factors

$$FF(q^2 < 16\text{GeV}^2) = 5.44 \pm 1.43 \text{[8]},$$
$$FF(q^2 > 16\text{GeV}^2) = 2.04 \pm 0.40 \text{[4]},$$

to obtain $|V_{ub}|^{\text{excl}} = (33.3 \pm 2.7) \times 10^{-4}$. For inclusive decays, we quote $|V_{ub}|^{\text{incl}} = (40.0 \pm 1.5 \pm 4.0) \times 10^{-4}$, where we define the second error as a flat range accounting for the spread of the different models \[9\].

Our grand average of inclusive and exclusive determinations is $|V_{ub}| = (36.7 \pm 2.1) \times 10^{-4}$, obtained from the probability density function (p.d.f.) in Fig. 1. From this p.d.f. we get

$$BR(B \to \tau\nu) = (0.98 \pm 0.24) \times 10^{-4},$$

compatible with $BR_{\text{exp}} = (1.73 \pm 0.34) \times 10^{-4}$ \[10\] at $\sim 1.8\sigma$.

A few percent precision is expected to be reached by LQCD using Petaflop CPUs for $f_B$ and the form factors entering the exclusive determination of $|V_{ub}|$ \[11\]. Considering how challenging the measurement of $BR(B \to \tau\nu)$ in a hadronic environment is, it is difficult to imagine a similar improvement in precision of the experimental measurement, unless a SuperB factory will be built, leading also to a better direct determination of $|V_{ub}|$. On the other hand, it has been pointed out in Ref. \[12\] that the indirect determination of $|V_{ub}|$ from the Unitarity Triangle (UT) fit in the SM is more accurate than the measurements, yielding a central value close to the exclusive determination. Therefore a more precise prediction of $BR(B \to \tau\nu)$ in the SM can be obtained combining the direct knowledge of $|V_{ub}|$ and $f_B$ with the indirect determination from the rest of the UT fit.

**UTFIT-IMPROVED STANDARD MODEL PREDICTION**

In the UT fit \[12\] \[11\], CP-conserving and CP-violating measurements are combined to constrain $\rho$ and $\eta$. The fit also provides an *a-posteriori* determination of $|V_{ub}|$ which includes the direct measurement as well as the indirect determination from the other constraints. Similarly, an improved determination of $f_B$ from both LQCD and experimental constraints is obtained \[12\].

![Figure 1](image.png)

**FIG. 1:** P.d.f. of $|V_{ub}|$ obtained combining inclusive and exclusive measurements of the $b \to u$ semileptonic decays. The dark (light) region corresponds to the 68% (95%) probability interval.

The most accurate prediction of $BR(B \to \tau\nu)$ in the SM can then be obtained performing the SM fit without including the measurement of $BR(B \to \tau\nu)$ as a constraint. The fit gives $\rho = 0.149 \pm 0.021$ and $\eta = 0.334 \pm 0.013$ together with $f_B = (196 \pm 11)$ MeV and $|V_{ub}| = (35.2 \pm 1.1) \times 10^{-4}$. The posterior p.d.f.’s are shown in Fig. 2.

The same SM fit gives the p.d.f. in Fig. 3 from which we obtain

$$BR(B \to \tau\nu)_{\text{SM}} = (0.84 \pm 0.11) \times 10^{-4}. \quad (3)$$

In Fig. 4 we present the compatibility plot for $BR(B \to \tau\nu)_{\text{SM}}$. The colored regions represent the pull from the UT fit result. The present experimental value, represented by a cross in the plot, displays a deviation of $\sim 2.5\sigma$. This deviation can be interpreted as a similar same-sign statistical fluctuation (or a correlated systematic error) in BaBar and Belle results or as a hint of NP effects. A more definite answer needs new data to be collected.

From Eq. 3, one can easily predict the SM value of $BR(B \to \mu\nu)$ and $BR(B \to e\nu)$. We obtain

$$BR(B \to \mu\nu)_{\text{SM}} = (3.8 \pm 0.5) \times 10^{-7}, \quad (4)$$
$$BR(B \to e\nu)_{\text{SM}} = (8.8 \pm 1.2) \times 10^{-12}.$$

The precision on the experimental measurements \[15\] is still far from probing such small values. The current best limits are $BR(B \to \mu\nu) < 1.0 \times 10^{-6}$ \[16\] and $BR(B \to e\nu) < 1.0 \times 10^{-6}$ \[7\] at 90% C.L.
FIG. 2: Posterior p.d.f. for $|V_{ub}|$ (top) and $f_B$ (bottom), obtained from the UT fit, without taking $BR(B \to \tau\nu)$ as input. The dark (light) region corresponds to the 68% (95%) probability interval.

MODEL-INDEPENDENT PREDICTIONS

Let us assume in the following that NP is at work. In this case, the prediction in Eq. (3) could be modified by i) NP effects in the decay amplitude and/or ii) NP effects in the UT fit. If more precise measurements will provide evidence of a discrepancy, one should be careful in interpreting it as evidence of NP in the $B \to \tau\nu$ decay amplitude. In fact, other inputs of the UT analysis (for example $\Delta m_q$ ($q = d, s$)) might be affected by the presence of contributions beyond the SM. We would like to disentangle the two possible NP effects. To this aim, we compute the prediction of $BR(B \to \tau\nu)$ in several NP scenarios assuming that NP contributions to the $B \to \tau\nu$ decay amplitude are negligible. This prediction will be denoted as $BR_{\text{model}}$. A discrepancy between $BR_{\text{model}}$ and $BR_{\text{exp}}$ would unambiguously reveal NP contributions to the $B \to \tau\nu$ decay amplitude in the considered scenario.

As is common practice in the literature, we also provide results in terms of the ratio

$$R_{\text{model}}^{\text{exp}} = \frac{BR_{\text{exp}}}{BR_{\text{model}}}. \quad (5)$$

The use of $R_{\text{model}}^{\text{exp}}$ is particularly convenient for NP models with Minimal Flavour Violation (MFV) [17, 18], defined as models where the only source of flavour violation are the quark masses and the CKM matrix [18]. Indeed, $BR_{\text{MFV}}$, the full prediction of the branching ratio including NP in the decay amplitude, and $BR_{\text{MFV}}$ have the same dependence on $|V_{ub}|$ and $f_B$, so that they cancel in the ratio $R_{\text{MFV}} = BR_{\text{MFV}}/BR_{\text{MFV}}$. Therefore, $R_{\text{MFV}}$ can be computed theoretically without specifying
the value of $|V_{ub}|$ and $f_B$. $R_{\text{MFV}}$ is constrained by $R_{\text{exp}}$, which contains the experimental error as well as the uncertainty on $|V_{ub}|$ and $f_B$.

Following Ref. [19], we distinguish several scenarios according to the NP flavor structure. In each scenario, we remove all the inputs that might be affected by NP from the UT-fit-based determination of $BR(B \to \tau \nu)$. This gives a NP-independent prediction of $BR$. In MFV models one expects the tree-level processes and the angles of the UT not to deviate from the SM prediction, while the values of $\Delta m_q$ and $\epsilon_K$ are expected to change.\footnote{In MFV models one has to assume that the large measured value of the $B_s$ mixing phase is a statistical fluctuation. Otherwise, MFV would be excluded [20].} We can then replace the full SM UT fit with the Universal UT (UUT) construction [21]. In the case of the UUT, the knowledge of $f_B$ is given by LQCD only, resulting in a larger error on $BR_{\text{UUT}}$. Using the currently available experimental inputs, we obtain $BR_{\text{UUT}} = (0.87 \pm 0.20) \times 10^{-4}$ corresponding to $R_{\text{UUT}} = 2.0 \pm 0.6$, as shown in Fig. 5 (for comparison, see the SM result in Eq. (3)). Clearly, the determination of $BR_{\text{UUT}}$ will benefit considerably from the expected improvements in future LQCD calculations.

In MFV models with one Higgs doublet (or two Higgs doublets at small $\tan \beta$), one expects negligible NP effects in the $B \to \tau \nu$ decay amplitude, while a deviation could be induced on $\Delta m_{d}$, $\Delta m_{s}$, and $\epsilon_K$. Should $R_{\text{UUT}}$ deviate from one significantly, these models would then be excluded.

In the case of MFV models with two Higgs doublets at large $\tan \beta$, the value of $R_{\text{UUT}}$ could be shifted from one by the contribution of the charged Higgs boson to the decay amplitude.

CONSTRANTS ON 2HDM-II

As an explicit example of the discussion above, we consider the 2HDM-II. In this model, the interaction between quarks and the charged Higgs $H^\pm$ is defined by the Lagrangian

$$\mathcal{L} = (2\sqrt{2}G_F)^{1/2} \sum_{i,j=1}^{3} \bar{u}_i \left( \frac{1}{\tan \beta} m_{u_{ij}} V_{ij} \frac{1 - \gamma_5}{2} \right)\bar{d}_j H^+ + \text{H.c.}, \quad (6)$$

and FCNC are absent at the tree level. We can write [22]:

$$R_{2\text{HDM}} = \left( 1 - \tan^2 \beta \frac{m_{\tilde{B}}^2}{m_{H^+}^2} \right)^2, \quad (7)$$

where $m_{H^+}$ is the mass of the charged Higgs boson. Eq. (7), together with the p.d.f. of $R_{\text{UUT}}$ provided by the UUT fit, gives a constraint on $\tan \beta/m_{H^+}$ as shown in Fig. 6. The charged Higgs contribution typically suppresses $BR(B \to \tau \nu)$ with respect to the SM, contrary to current experimental results. An excess can be obtained if $\tan \beta > \sqrt{2} m_{H^+}/m_B$ (corresponding to the rightmost peak in the left plot of Fig. 6) with $\tan \beta = (29 \pm 2) m_{H^+}/(100 \text{ GeV})$, yielding an upper limit on $m_{H^+}$ for a given value of $\tan \beta$. The current direct searches [23] give a lower limit of $m_{H^+} > 79 \text{ GeV}$ at 95\% C.L. [24], while the measurement of $BR(B \to X_{s\gamma})$ implies $m_{H^+} > 295 \text{ GeV}$ at 95\% C.L. for the 2HDM-II charged Higgs boson [24]. This bound excludes the rightmost peak in Fig. 6 for $\tan \beta < 80$. In addition, one can consider the bound on $\tan \beta/m_{H^+}$ from $BR(B \to D_{\tau\nu})/BR(B \to D_{\tau\nu})$ where $\ell$ denotes light leptons [25]. Using the world average (49 \pm 10)\% [26] and formula (9) of Ref. [27] we obtain the following 95\% probability regions for $\tan \beta/m_{H^+}$: $\tan \beta/m_{H^+} < 0.17 \text{ GeV}^{-1}$ and $0.46 \text{ GeV}^{-1} < \tan \beta/m_{H^+} < 0.55 \text{ GeV}^{-1}$ (see the right plot in Fig. 6). In this case, as for the $B \to \tau \nu$ bound, there is an allowed region at large $\tan \beta/m_{H^+}$. Assuming flat priors in $[5, 120]$ for $\tan \beta$ [28] and $[100, 10000]$ GeV for $m_{H^+}$, we obtain the plot in Fig. 7. For $\tan \beta \gtrsim 22$ $B \to \tau \nu$ gives a lower bound on $m_{H^+}$ stronger than the one from $B \to X_{s\gamma}$. The fine-tuned regions for large $\tan \beta/m_{H^+}$ allowed individually by the $B \to \tau \nu$ and the $B \to D_{\tau\nu}$ constraints do not overlap and are therefore excluded. We thus obtain an absolute bound

$$\tan \beta < 7.4 \times \frac{m_{H^+}}{100 \text{ GeV}}. \quad (8)$$

In addition, we compute the prediction for $BR(B_s \to \mu^+ \mu^-)$ and obtain

$$BR(B_s \to \mu^+ \mu^-) = (4.3 \pm 0.9) \times 10^{-9} \quad (9)$$

[$(2.5, 6.2) \times 10^{-9}$ at 95\% prob.].
Our results are in agreement with Ref. [29], where the effect of \( Br(B \rightarrow \tau \nu) \) and other constraints on the 2HDM-II has been recently analysed. However, our analysis differs in several aspects. First, in the UUT analysis we keep all the angles, which are unaffected by MFV NP effects. Second, we neglect sub-percent contributions to tree-level decays, allowing us to use all determinations of \(|V_{ub}|\). Third, we only consider the dominant constraints from \( B \rightarrow X_s \gamma \) and \( B \rightarrow \tau \nu \). Finally, we use the Bayesian approach detailed in Ref. [31].

One of the most interesting features of the relation in Eq. (7) is that it does not depend on the flavour of the final lepton [22], since the helicity suppression in the SM compensates the scaling of the Higgs couplings with the mass. This means that, provided the evidence of a discrepancy in \( B \rightarrow \tau \nu \), the same effect should be observed in \( B \rightarrow \ell \nu \) (\( \ell = e, \mu \)). For these decays, we get

\[
\overline{BR}(B \rightarrow \mu \nu)_{UUT} = (3.9 \pm 0.9) \times 10^{-7}, \quad (10)
\]

\[
\overline{BR}(B \rightarrow e \nu)_{UUT} = (9.2 \pm 2.1) \times 10^{-12},
\]

where \( \overline{BR} \) for these decays is defined in analogy with the \( B \rightarrow \tau \nu \) case.

Beyond MFV, the UUT construction is no longer adequate. Indeed, in the most general case, assuming only that NP contributions to semileptonic decays are negligible, the prediction of \( Br(B \rightarrow \tau \nu) \) cannot be improved using the UT fit and the result can be read from Eq. (2), \( \overline{BR}_{\text{no-fit}} = (0.98 \pm 0.24) \times 10^{-4} \).

To summarize our results, we collect in Table I our predictions for \( \overline{BR} \) in the considered scenarios.

| Scenario | \(|V_{ub}| \times 10^{4}\) | \(f_B\) (MeV) | \(\overline{BR} \times 10^{4}\) | Pull |
|----------|-----------------|-------------|----------------|-----|
| UT       | 35.2 \pm 1.1    | 196 \pm 11  | 0.84 \pm 0.11  | 2.5\sigma |
| UUT      | 35.0 \pm 1.2    | 200 \pm 20  | 0.87 \pm 0.20  | 2.2\sigma |
| no-fit   | 36.7 \pm 2.1    | 200 \pm 20  | 0.98 \pm 0.24  | 1.8\sigma |

TABLE I: Results for \(|V_{ub}|\), \(f_B\), \(\overline{BR}\) and the pull between \(\overline{BR}\) and \(Br(B \rightarrow \tau \nu)_{\exp}\) in different scenarios (see text).

**CONSTRAINTS ON THE MSSM PARAMETERS**

It has been pointed out that the MSSM with MFV, TeV sparticles and large \( \tan \beta \) could give negligible contributions to flavour physics except for \( B \rightarrow \tau \nu\), \( \Delta m_s\), \( B_s \rightarrow \mu^+ \mu^-\) and \( B \rightarrow X_s \gamma\) [32]. We show that, with present data, the combination of the first three constraints leaves little space for large \( \tan \beta \). This can be easily understood as this model typically predicts a suppression of \( Br(B \rightarrow \tau \nu) \) rather than the enhancement required by the present measurements. An enhancement can be obtained only for very large values of \( \tan \beta \) which, however, are disfavoured by the other constraints.

We reanalyze the model of Ref. [32] with the following a-priori flat ranges for the relevant low-energy SUSY parameters: \( \mu = [-950, -450] \cup [450, 950] \) GeV, \( A_\mu = [-3, 3] \) TeV, \( \tan \beta = [5, 65], m_{H^+} = [100, 1000] \) GeV,
\( m_{\tilde{q}} = [400, 1000] \text{ GeV}, \quad m_{\tilde{g}} = [400, 1000] \text{ GeV} \). The expressions of \( B \to \tau \nu, B_s \to \mu^+\mu^- \) and \( \Delta m_s \) can be found in Eqs. (3), (11) and (14) of Ref. [32] respectively. The experimental constraints are \( \Delta m_s = 17.77 \pm 0.12 \text{ ps}^{-1} \) [33] and the upper bound \( BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8} \) at 95\% C.L. [34].

In Figs. 8 we show the p.d.f. in the plane \( (\tan \beta, m_{H^+}) \) for \( \mu > 0 \). For completeness, in Figs. 9 and 10 we present the corresponding one-dimensional p.d.f. for \( m_{H^+} \) and \( \tan \beta \). As expected, the constraint from \( B \to \tau \nu \) resembles the one obtained in the 2HDM analysis above (see Fig. 7). Once the other constraints are included, however, the region at large \( \tan \beta/m_{H^+} \) is disfavoured. The combined exclusion region is roughly bounded by a straight line, giving \( \tan \beta < 7.3 m_{H^+}/(100 \text{ GeV}) \) at 95\% probability, with a remarkable similarity to the 2HDM-II case.

For \( \mu < 0 \), the constraint from \( B \to \tau \nu \) is less stringent for large \( \tan \beta \), see Figs. 11 and 13. In fact, for \( \mu < 0 \) and very large \( \tan \beta \), the interference with the SM in \( B \to \tau \nu \) becomes positive. However the combined bound is more severe than for \( \mu > 0 \): for \( m_{H^+} < 1 \text{ TeV} \), there is an absolute bound on \( \tan \beta < 38 \) with at least 95\% probability, while from the one-dimensional distribution in Fig. 13 we obtain \( \tan \beta < 32 \) at 95\% probability.

For both signs of \( \mu \), large values of \( \tan \beta \) for sub-TeV charged Higgses are strongly disfavoured, including the fine-tuned region where the SUSY contribution enhances \( BR(B \to \tau \nu) \) improving the agreement with the experimental average.

From our analysis we also derive the following ranges for \( BR(B_s \to \mu^+\mu^-) \):

\[
\begin{align*}
[3, 8] \times 10^{-9} \text{@68\% prob.} & \quad (11) \\
[2, 26] \times 10^{-9} \text{@95\% prob.} &
\end{align*}
\]

for \( \mu > 0 \), and

\[
\begin{align*}
[3, 6] \times 10^{-9} \text{@68\% prob.} & \quad (12) \\
[2, 17] \times 10^{-9} \text{@95\% prob.} &
\end{align*}
\]

for \( \mu < 0 \). These ranges can be compared with the SM prediction \( BR(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.7 \pm 0.5) \times 10^{-9} \).
FIG. 8: 68% (dark) and 95% (light) probability regions in the \((m_{\mu^+}, \tan\beta)\) plane obtained using \(BR(B \to \tau\nu)\) (top left), \(BR(B_s \to \mu^+\mu^-)\) (top right), \(\Delta m_s\) (bottom left), all constraints (bottom right) for \(\mu > 0\) in the considered MFV-MSSM for the parameter ranges specified in the text.

FIG. 9: 68% (dark) and 95% (light) probability regions for \(m_{\mu^+}\) obtained using \(BR(B \to \tau\nu)\) (top left), \(BR(B_s \to \mu^+\mu^-)\) (top right), \(\Delta m_s\) (bottom left), all constraints (bottom right) for \(\mu > 0\) in the considered MFV-MSSM for the parameter ranges specified in the text.

FIG. 10: 68% (dark) and 95% (light) probability regions for \(\tan\beta\) obtained using \(BR(B \to \tau\nu)\) (top left), \(BR(B_s \to \mu^+\mu^-)\) (top right), \(\Delta m_s\) (bottom left), all constraints (bottom right) for \(\mu > 0\) in the considered MFV-MSSM for the parameter ranges specified in the text.

FIG. 11: Same as Fig. 8 for \(\mu < 0\).

CONCLUSIONS

We have shown how the use of the UT fit allows to improve the prediction of \(BR(B \to \tau\nu)\) in the SM, thanks to a better determination of \(|V_{ub}|\) and \(f_B\). Considering the generalization of the UT fit to various NP scenarios, we have obtained results for \(\overline{BR}\), defined as the prediction of \(BR(B \to \tau\nu)\) assuming negligible NP contributions to the decay amplitude. The comparison of \(\overline{BR}\) to the experimental result provides an improved probe of the presence of NP in the decay amplitude. Our results are summarized in Table 1. Finally, we studied the present constraints on the 2HDM-II and on the MFV-MSSM with TeV sparticles. In both models, we find that large values of \(\tan\beta\) for sub-TeV charged Higgs masses are disfavoured by present data.
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