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Large $\tan\beta$ effects in flavour physics

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We discuss $B_u \to \tau\nu$, ΔM_{B_s} and other low-energy observables in the framework of the MSSM at large $\tan\beta$. We show that for heavy squarks and A terms ($M_{\tilde{q}},\ A_U\ \gtrsim 1$ TeV) such scenario has several interesting virtues. It naturally describes: i) a suppression of $\mathcal{B}(B_u \to \tau\nu)$ of (10-40)%, ii) a sizable enhancement of $(g-2)_\mu$, iii) a heavy SM-like Higgs ($m_{h^0} \sim 120$ GeV), iv) small non-standard effects in ΔM_{B_s} and $\mathcal{B}(B \to X_s\gamma)$ (all in agreement with present observations). The possibilities to find more convincing evidences of such scenario with future flavour-phyiscs measurements are briefly outlined.

1. Introduction

In many extensions of the SM, including the so-called Minimal Supersymmetric extension of the SM (MSSM), the Higgs sector consists of two $SU(2)_L$ scalar doublets, coupled separately to up- and down-type quarks. A key parameter of all these models is $\tan\beta = v_u/v_d$, the ratio of the two Higgs vacuum expectation values. This parameter controls the overall normalization of the Yukawa couplings. The regime of large $\tan\beta$ [$\tan\beta = \mathcal{O}(m_t/m_b)$] has an intrinsic theoretical interest since it allows the unification of top and bottom Yukawa couplings, as predicted in well-motivated grand-unified models.

The large $\tan\beta$ regime of both supersymmetric and non-supersymmetric models has a few interesting signatures in B physics. One of the most clear ones is the suppression of $\mathcal{B}(B_u \to \tau\nu)$ with respect to its SM expectation. Potentially sizable effects are expected also in $\mathcal{B}(B \to X_s\gamma)$, ΔM_{B_s} and $\mathcal{B}(B_{s,d} \to \ell^+\ell^-)$. Motivated by the recent experimental results on both $\mathcal{B}(B_u \to \tau\nu)$ [1] and ΔM_{B_s} [2] we present a new analysis of all these observables within the large $\tan\beta$ limit of the MSSM [3].

The generic MSSM contains in principle several free parameters in addition to $\tan\beta$. Given the absence of significant non-standard effects both in the electroweak and in the flavour sector, we limitit our analysis to the so-called Minimal Flavour Violating (MFV) scenario, with squark masses in the TeV range. In addition, we take into account the important information on the model derived by two flavour-conserving observables: the anomalous magnetic moment of the muon and the lower limit on the lightest Higgs boson mass.

The present central values of the measurements of $\mathcal{B}(B_u \to \tau\nu)$ and $(g-2)_\mu$ are substantially different from the corresponding SM expectations. Although both these effects are not statistically significant yet, we find that these central values can naturally be accommodated within this scenario (for a wide range of μ, $\tan\beta$ and the charged Higgs mass). More interestingly, if the trilinear term A_U is sufficiently large, this scenario can also explain why the lightest Higgs boson has not been observed yet. Finally, the parameter space which leads to these interesting effects can also naturally explain why $\mathcal{B}(B \to X_s\gamma)$ and ΔM_{B_s} are in good agreement with the SM expectations. We are therefore led to the conclusion that, within the supersymmetric extensions of the SM, the scenario with large $\tan\beta$ and heavy soft-breaking terms in the squark sector is one of the most interesting and likely possibilities.

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2. B-physics observables

The SM expectation for the $B_u \to \tau\nu$ branching fraction is

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

Using $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$ from inclusive $b \to u$ semileptonic decays, $\tau_B = 1.643 \pm 0.010$ ps [4], and the recent unquenched lattice result $f_B = 0.216 \pm 0.022$ GeV [5], this implies $\mathcal{B}(B_u \to \tau\nu)^{\rm SM} = (1.59 \pm 0.40) \times 10^{-4}$. This prediction should be compared with Belle's recent result [1]: $\mathcal{B}(B_u \to \tau\nu) = (1.06^{+0.34}_{-0.28}({\rm stat})^{+0.18}_{-0.16}({\rm syst})) \times 10^{-4}$.

Within two-Higgs doublet models, the charged-Higgs exchange amplitude induces an additional tree-level contribution to semileptonic decays. Being proportional to the Yukawa couplings of quarks and leptons, this additional contribution is usually negligible. However, in $B \to \ell\nu$ decays the $H^\pm$ exchange can compete with the $W^\pm$ exchange thanks to the helicity suppression of the latter. Interestingly, in models where the two Higgs doublets are coupled separately to up- and down-type quarks, the interference between $W^\pm$ and $H^\pm$ amplitudes is necessarily *destructive* [6].

Taking into account the resummation of the leading $\tan\beta$ corrections to all orders, the charged-Higgs contributions to the $B_u \to \tau\nu$ amplitude within a MFV supersymmetric framework lead to the following ratio:

$$R_{B\tau\nu} = \frac{\mathcal{B}(B_u \to \tau\nu)}{\mathcal{B}^{\rm SM}(B_u \to \tau\nu)} \overset{\rm SUSY}{=} \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right) \frac{\tan^2\beta}{(1+\epsilon_0 \tan\beta)}\right]^2 \ , \qquad (2)$$

where ϵ_0 denotes the effective coupling which parametrizes the non-holomorphic correction to the down-type Yukawa coupling induced by gluino exchange [8, 9]. We stress that the result in Eq. (2) takes into account all the leading $\tan\beta$ corrections both in the redefinition of the bottom-quark Yukawa coupling and in the redefinition of the CKM matrix.[2]

For a natural choice of the parameters ($30 \lesssim \tan\beta \lesssim 50$, $0.5 \lesssim M_{H^\pm}/{\rm TeV} \lesssim 1$, $\epsilon_0 \sim 10^{-2}$) Eq. (2) implies a (5-30)% suppression with respect to the SM. This would perfectly fit with Belle's experimental result [1], which implies

$$R_{B\tau\nu}^{\rm exp} = 0.67^{+0.24}_{-0.21}\,{}_{\rm exp} \pm 0.14_{|f_B|} \pm 0.10_{|V_{ub}|} \ . \qquad (3)$$

Apart from the experimental error, one of the difficulties in obtaining a clear evidence of a possible deviation of $R_{B\tau\nu}$ from unity is the large parametric uncertainty induced by $|f_B|$ and $|V_{ub}|$. As suggested by Ikado [7], an interesting way to partially circumvent this problem is obtained by normalizing $\mathcal{B}(B_u \to \tau\nu)$ to the B_d–$\bar{B}_d$ mass difference (ΔM_{B_d}). Neglecting the tiny isospin-breaking differences in masses, life-times and decay constants, between B_d and B_u mesons, we can write

$$R'_{B\tau\nu} = \frac{\mathcal{B}(B_u \to \tau\nu)}{\tau_B \Delta M_{B_d}} \overset{\rm SM}{=} 1.77 \times 10^{-4} \times \times \left(\frac{|V_{ub}/V_{td}|}{0.464}\right)^2 \left(\frac{0.836}{\hat{B}_{B_d}}\right) \ . \qquad (4)$$

Following standard notations, we have denoted by $S_0(m_t^2/M_W^2)$, η_B and B_{B_d} the Wilson coefficient, the QCD correction factor and the bag parameter of the $\Delta B = 2$ operator within the SM (see e.g. Ref. [12]). Using the unquenched lattice result $\hat{B}_{B_d} = 0.836 \pm 0.068$ [15] and $|V_{ub}/V_{td}| = 0.464 \pm 0.024$ from the UTfit Collaboration [16], we then obtain

$$(R'_{B\tau\nu})^{\rm exp} = 0.73^{+0.27}_{-0.22} \pm 0.06_{|\hat{B}_{B_d}|} \pm 0.07_{|V_{ub}/V_{td}|} \ . \qquad (5)$$

The following comments follow from the comparison of Eqs. (3) and (5):

- The two results are perfectly compatible and with similar overall errors. However, the parametric/theoretical component is much smaller in Eq. (5). The latter could

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[2] The result in Eq. (2) can easily be obtained by means of the charged-Higgs effective Lagrangian in Eq. (52) of Ref. [10], which systematically takes into account the redefinition of Yukawa couplings and CKM matrix elements. The explicit application to $B_u \to \tau\nu$ has been presented first in Ref. [11].