Large $\tan\beta$ MSSM effects in Flavor Physics

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We present an overview of the phenomenological implications of a particularly interesting corner of the MSSM: the large $\tan\beta$ regime. We stress the role of low-energy flavour observables in shedding light on physics beyond the SM outlying their interplay with the direct new physics searches at the LHC.

I. INTRODUCTION

The Standard Model (SM) theory of elementary particles has successfully passed all the electroweak tests at the LEP and also all the low-energy flavor physics tests. On the other hand, there is a general agreement that the SM has to be considered as an effective field theory, valid up to some unknown scale of new physics (NP). A natural solution of the hierarchy problem would points towards a scale of new physics close to the TeV, an energy scale that will be explored by the LHC.

Besides the direct search for New Physics (NP) at the colliders (the so-called *high-energy frontier*), a complementary tool to shed light on NP is provided by high-precision low-energy experiments (the so-called *high-intensity frontier*) specially to determine the symmetry properties of the underlying NP theory. Unfortunately, the hadronic uncertainties and the overall good agreement of flavor-changing neutral current (FCNC) data with the SM predictions prevent any conclusive evidence of NP effects in the quark sector.

In this respect, the FCNC phenomenology in the lepton sector is definitively more promising. In fact, the extreme suppression predicted by the SM (with massive neutrinos) for processes like $\ell_i \to \ell_j\gamma$ implies that any experimental evidence for $\ell_i \to \ell_j\gamma$ would unambiguously point towards a NP signal.

Besides the FCNC decays, also *precision tests* of the SM, as the Lepton Flavor Universality (LFU) tests in $K_{\ell 2}$ and $\pi_{\ell 2}$ systems, offer a unique opportunity to probe the SM and thus, to shed light on NP: the smallness of NP effects is more than compensated by the excellent experimental resolution and the good theoretical control.

A. Minimal Flavour Violation and the large $\tan\beta$ scenario in the MSSM

The idea of Minimal Flavour Violation (MFV) [1] is that the CKM matrix rules the strength of FCNC transitions also in theories beyond the SM. As a result, NP contributions to FCNC transitions turn out to suppressed to a level consistent with experiments even for $\Lambda \sim$ few TeV. The MFV ansatz is based on a renormalization-group-invariant symmetry argument, which can easily be extended to TeV-scale effective theories, such as Supersymmetry (see e.g. [2]). The importance of flavour observables in specific models, such as MSSM scenarios with MFV, has been discussed in many works. In the following, we focus on the MSSM scenarios with MFV in the so called large $\tan\beta$ scenario, providing a survey of the most interesting low-energy flavour observables.

The Higgs sector of the MSSM consists of two $SU(2)_L$ scalar doublets, coupled separately to up- and down-type quarks

$$\begin{aligned}\mathcal{L}_{\rm H}^{\rm tree} &= \bar{Q}_L Y_U U_R H_U + \bar{Q}_L Y_D D_R H_D + \\ &+ \bar{L}_L Y_E E_R H_D + V(H_U, H_D) + \text{h.c.}\ . \end{aligned} \quad (1)$$

A key parameter of this sector is the ratio of the two Higgs vevs: $\tan\beta = \langle H_U\rangle/\langle H_D\rangle$. Varying $\tan\beta$ leads to modify the overall normalization of the two Yukawa couplings and, for $\tan\beta \sim 40$–50, we can achieve the interesting unification of top and bottom Yukawa couplings.

If the model has a MFV structure, the phenomenological consequences of $\tan\beta \gg 1$ show up only in few observables sensitive to helicity-suppressed amplitudes. The most interesting observables are the charged-current processes $B(K) \to \ell\nu$ and the FCNC transitions $B_{s,d} \to \ell^+\ell^-$ and $B \to X_s\gamma$.

It is worth to stress that, besides the theoretical interest, the large $\tan\beta$ regime of the MSSM could also provide a natural explanation of the $a_\mu = (g-2)_\mu/2$ anomaly, which is now a solid 3σ effect: $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} \approx (2.9 \pm 0.9) \times 10^{-9}$ [3, 4]. The size of this discrepancy is large compared to the electroweak SM contribution ($\Delta a_\mu^{\rm e.w.} \approx 1.5\times 10^{-9}$). This large discrepancy can easily be explained by the fact that a_μ is a(flavour-conserving) helicity suppressed observable, whose non-standard contribution can be enhanced compared to the SM one by increasing the value of $\tan\beta$ [5]:

$$\Delta a_\mu^{\rm MSSM} \approx \tan\beta \times \left(\frac{m_W}{m_{\tilde{\ell}}}\right)^2 \times \Delta a_\mu^{\rm e.w.} \quad (2)$$

For values of $\tan\beta \gtrsim 10$ the $m_W/m_{\tilde{\ell}}$ suppression can easily be compensated for sleptons well above the W mass, in prefect agreement with the constraints of electroweak precision tests.

1. $B \to \ell\nu$

The charged-current processes $P \to \ell\nu$ are the simplest flavour-violating helicity suppressed observables and the SM and Higgs-mediated contributions appear already at the tree level. The $H^{\pm}$ contribution is proportional to the Yukawa couplings of quarks and leptons, but it can compete with the $W^{\pm}$ exchange thanks to the helicity suppression of $P \to \ell\nu$ [6]. Taking into account the resummation of the leading $\tan\beta$ corrections to all orders, the $H^{\pm}$ contributions to the $P \to \ell\nu$ amplitude within a MFV supersymmetric framework leads to the following ratio [7, 8]:

$$R_{P\ell\nu} = \left[1 - \left(\frac{m_P^2}{m_{H^\pm}^2}\right)\frac{\tan^2\beta}{(1+\epsilon_0\tan\beta)}\right]^2 \qquad (3)$$

where $R_{P\ell\nu} = \mathcal{B}^{\rm SM}(P\ell\nu)/\mathcal{B}^{\rm SUSY}(P\ell\nu)$ and ϵ_0 denotes the effective coupling which parametrizes the non-holomorphic corrections to the down-type Yukawa interaction. For a natural choice of the MSSM parameters, Eq. (3) implies a suppression with respect to the SM in B decays of few $\times 10\%$ (but an enhancement is also possible for very light $M_{H^\pm}$).

In the B case only the τ modes has been observed: $\mathcal{B}(B_u \to \tau\nu)^{\rm exp} = (1.41 \pm 0.43) \times 10^{-4}$ [9, 10].

2. $B \to \ell^+\ell^-$

The important role of $\mathcal{B}(B_{s,d} \to \ell^+\ell^-)$ in the large $\tan\beta$ regime of the MSSM has been widely discussed in the literature (see e.g. Ref. [7, 11, 12] for a recent discussion). The leading non-SM contribution in $B \to \ell^+\ell^-$ decays is generated by a single tree-level type amplitude: the neutral Higgs exchange $B \to A, H \to \ell^+\ell^-$. Since the effective FCNC coupling of the neutral Higgs bosons appears only at the quantum level, in this case the amplitude has a strong dependence on other MSSM parameters of the soft sector in addition to M_H and $\tan\beta$. In particular, a key role is played by the μ term and the up-type trilinear soft-breaking term (A_U), which control the strength of the non-holomorphic terms. The leading parametric dependence of the scalar FCNC amplitude from these parameters is given by

$$\mathcal{A}_{\rm Higgs}(B \to \ell^+\ell^-) \propto \frac{m_b m_\ell}{M_A^2}\frac{\mu A_U}{M_{\tilde q}^2}\tan^3\beta \times f_{\rm loop}$$

For $\tan\beta \sim 50$ and $M_A \sim 0.5$ TeV the neutral-Higgs contribution to $\mathcal{B}(B_{s,d} \to \ell^+\ell^-)$ can easily lead to an $\mathcal{O}(100)$ enhancement over the SM expectation. This possibility is already excluded by experiments: the upper bound $\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ [13] is only about 15 times higher that the SM prediction of 3.5×10^{-9} [14].

This limit poses interesting constraints on the MSSM parameter space, especially for light M_H and large values of $\tan\beta$.

However, given the specific dependence on A_U and μ, the present $\mathcal{B}(B_s \to \mu^+\mu^-)$ bound does not exclude the large $\tan\beta$ effects in $(g-2)_\mu$ and $P \to \ell\nu$ already discussed.

3. $B \to X_s\gamma$

As it is well known, $\mathcal{B}(B \to X_s\gamma)$ is a particularly sensitive observable to possible non-standard contributions and it provides a non-trivial constraint on the SUSY mass spectrum given its precise experimental determination and the very accurate SM calculation at the NNLO [15]. According to the recent NNLO analysis, the SM prediction is $\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6~{\rm GeV})^{\rm SM} = (3.15 \pm 0.23) \times 10^{-4}$ [15]. Combining this result with the experimental average [16–18] $\mathcal{B}(B \to X_s\gamma; E_\gamma > 1.6\,{\rm GeV}))^{\rm exp} = (3.55 \pm 0.24) \times 10^{-4}$ it is found that

$$R_{Bs\gamma} = \frac{\mathcal{B}^{\rm exp}(B \to X_s\gamma)}{\mathcal{B}^{\rm SM}(B \to X_s\gamma)} = 1.13 \pm 0.12\,. \qquad (4)$$

Within a SUSY MFV framework, the dominant SUSY contributions to $\mathcal{B}(B \to X_s\gamma)$ arise from the one-loop charged-Higgs and chargino-squark amplitudes. Charged-Higgs effects unambiguously increase the rate compared to the SM expectation, while the chargino-squark ones can have both signs depending on the sign of $sign(\mu A_U)$. The solution with $\mu > 0$ is preferred by the $(g-2)_\mu$ constraints and in this case $sign(A_U) < 0$ implies destructive interference between chargino and charged Higgs contributions. An illustration of the typical correlations of the low-energy flavour constraints in the M_H–$\tan\beta$, in a generic scenario with heavy squarks and dark-matter conditions satisfied in the A-funnel region, is shown in Fig. 1. One of the most interesting aspects of this scenario is the fact that a supersymmetric contribution to a_μ of $\mathcal{O}(10^{-9})$ is both compatible with the present constraints from $\mathcal{B}(B \to X_s\gamma)$ and it implies a suppression of $\mathcal{B}(B_u \to \tau\nu)$ with respect to its SM prediction of at least 10% [19]. A more precise determination of $\mathcal{B}(B_u \to \tau\nu)$ is therefore a key element to test this scenario.

II. LEPTON FLAVOR VIOLATION IN SUSY

The discovery of neutrino masses and oscillations has unambiguously pointed out the existence of the Lepton Flavor Violation (LFV) thus, we expect this phenomenon to occur also in the charged-lepton sector.

Within a SM framework with massive neutrinos, FCNC transitions in the lepton sector like $\ell_i \to \ell_j\gamma$

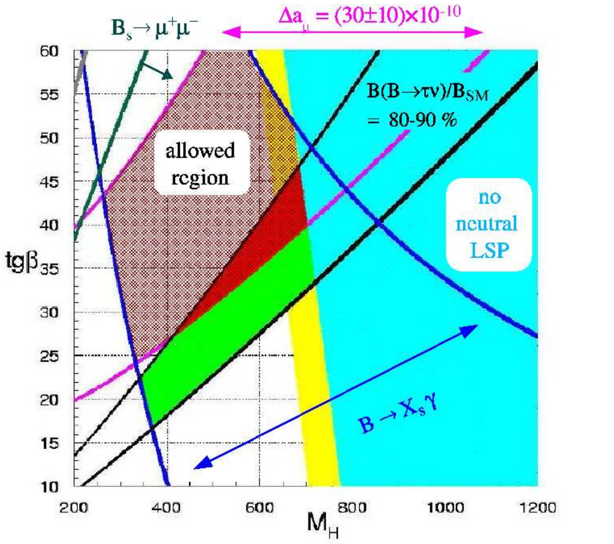

FIG. 1: Combined bounds from low-energy observables in the $\tan\beta$–M_H plane assuming heavy squarks and dark-matter constraints in the A-funnel region [19] ($M_{\tilde{q}} = 1.5$ TeV, $A_U = -1$ TeV, $\mu = 0.5$ TeV, $M_{\tilde{\ell}} = 0.4$ TeV, $1.01 < R_{Bs\gamma} < 1.24$; the light-blue area is excluded by the dark-matter conditions).

are strongly suppressed by the GIM mechanism at the level of $\mathcal{B}(\ell_i \to \ell_j\gamma) \sim (m_\nu/m_W)^4 \sim 10^{-50}$ well beyond any realistic experimental resolution. In this sense, the search for FCNC transitions of charged leptons is one of the most promising directions where to look for physics beyond the SM.

Within a SUSY framework, LFV effects originate from any misalignment between fermion and sfermion mass eigenstates. In particular, if the light neutrino masses are obtained via a see-saw mechanism, the radiatively induced LFV entries in the slepton mass matrix $\delta^{ij}_L = (m^2_{\tilde{L}})_{ij}/m_{\tilde{\ell}}$ (where $m_{\tilde{\ell}}$ stands for a typical slepton mass) are given by [20]:

$$\delta^{ij}_L \approx -\frac{3}{8\pi^2}(Y_\nu Y_\nu^\dagger)_{ij} \ln\left(\frac{M_X}{M_R}\right) , \qquad (5)$$

where M_X denotes the scale of SUSY-breaking mediation. The effective light-neutrino mass matrix obtained from a see-saw mechanism is $m_\nu = -Y_\nu \hat{M}_R^{-1} Y_\nu^T \langle H_u\rangle^2$, where $\hat{M}_R$ is the $3{\times}3$ right-handed neutrino mass matrix and Y_ν are the $3{\times}3$ Yukawa couplings between left- and right-handed neutrinos (the potentially large sources of LFV), and $\langle H_u\rangle$ is the vacuum expectation value of the up-type Higgs.

Since the see–saw equation allows large $(Y_\nu Y_\nu^\dagger)$ entries, sizable effects can stem from this running [20].

The determination of δ^{ij}_L would imply a complete knowledge of the neutrino Yukawa matrix $(Y_\nu)_{ij}$, which is not possible even if all the low-energy observables from the neutrino sector were known. As a result, the predictions of leptonic FCNC effects will remain undetermined even in the very optimistic situation where all the relevant NP masses were measured at the LHC.

This is in contrast with the quark sector, where similar RGE contributions are completely determined in terms of quark masses and CKM-matrix elements.

More stable predictions can be obtained embedding the SUSY model within a Grand Unified Theory (GUT) where the see-saw mechanism can naturally arise (such as $SO(10)$). In this case the GUT symmetry allows us to obtain some hints about the unknown neutrino Yukawa matrix Y_ν. Moreover, in GUT scenarios there are other contributions stemming from the quark sector [21]. These effects are completely independent from the structure of Y_ν and can be regarded as new irreducible LFV contributions within SUSY GUTs. For instance, within $SU(5)$, as both Q and e^c are hosted in the **10** representation, the CKM matrix mixing the left handed quarks will give rise to off diagonal entries in the running of the right-handed slepton soft masses [21].

There exist to different classes of LFV contributions to rare decays:

i) Gauge-mediated LFV effects through the exchange of gauginos and sleptons [20–22]

ii) Higgs-mediated LFV effects through effective non-holomorphic Yukawa interactions [23] .

The above contributions decouple with the heaviest mass in the slepton/gaugino loops m_{SUSY} (case i)) or with the heavy Higgs mass m_H (case ii)).

In principle, m_H and m_{SUSY} refers to different mass scales. Higgs mediated effects start being competitive with the gaugino mediated ones when m_{SUSY} is roughly one order of magnitude heavier then m_H and for $\tan\beta \sim \mathcal{O}(50)$ [24].

While the appearance of LFV transitions would unambiguously signal the presence of NP, the underlying theory generating LFV phenomena will remain undetermined, in general.

A powerful tool to disentangle among NP theories is the study of the correlations of LFV transitions among same families [24, 25].

Interestingly enough, the predictions for the correlations among LFV processes are very different in the gauge- and Higgs-mediated cases [24]. In this way, if several LFV transitions are observed, their correlated analysis could shed light on the underlying mechanism of LFV. In the case of gauge-mediated LFV amplitudes the $\ell_i \to \ell_j\ell_k\ell_k$ decays are dominated by the $\ell_i \to \ell_j\gamma^*$ dipole transition, which leads to the unambiguous prediction [22, 24, 25]:

$$\frac{\mathcal{B}(\ell_i \to \ell_j\ell_k\ell_k)}{\mathcal{B}(\ell_i \to \ell_j\gamma)} \simeq \frac{\alpha_{el}}{3\pi}\left(\log\frac{m^2_{l_i}}{m^2_{l_k}} - 3\right) \qquad (6)$$

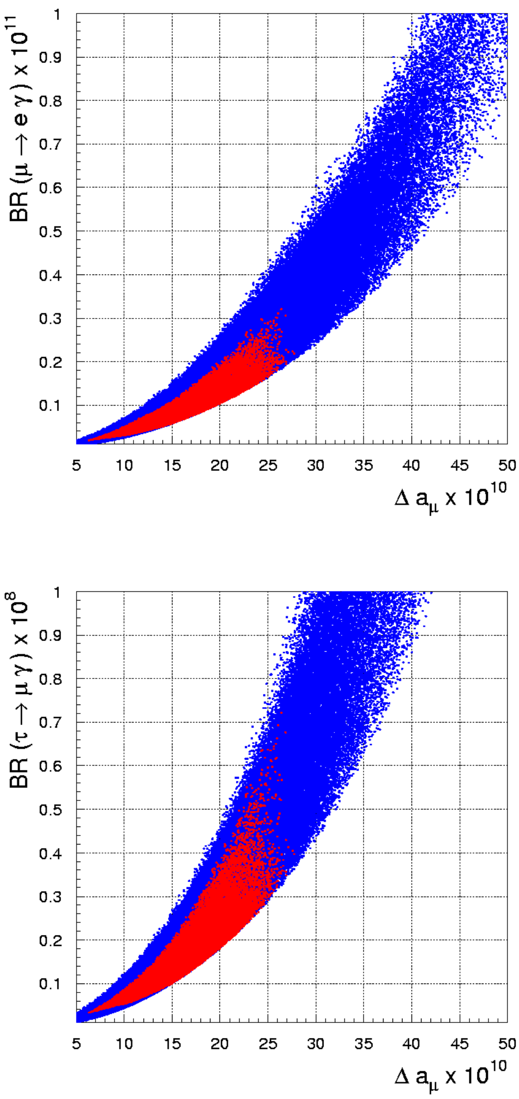

FIG. 2: Expectations for $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ vs. $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$, assuming $|\delta^{12}_{LL}| = 10^{-4}$ and $|\delta^{23}_{LL}| = 10^{-2}$ [19]. The red areas correspond to points satisfying the B-physics constraints [$\mathcal{B}(B_s \to \mu^+\mu^-) < 8 \times 10^{-8}$, $1.01 < R_{Bs\gamma} < 1.24$, $0.8 < R_{B\tau\nu} < 0.9$, $\Delta M_{B_s} = 17.35 \pm 0.25$ ps^{-1}].

$$\frac{\mathcal{B}(\mu \to e \text{ in Ti})}{\mathcal{B}(\mu \to e\gamma)} \simeq \alpha_{el}\,. \qquad (7)$$

If some ratios different from the above were discovered, then this would be clear evidence that some new process is generating the $\ell_i \to \ell_j$ transition, with Higgs mediation being a potential candidate. Given that both $\ell_i \to \ell_j\gamma$ and $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$ are generated by dipole operators, it is natural to establish a link between them [19, 26]. To understand the relative size of the correlation, it is useful to consider the limit of degenerate SUSY spectrum

$$\mathcal{B}(\ell_i \to \ell_j\gamma) \approx \left[\frac{\Delta a_\mu}{3\cdot 10^{-9}}\right]^2 \cdot \left\{ \begin{array}{l} 3\cdot 10^{-12}\left|\delta^{e\mu}_L/10^{-4}\right|^2 \,, \\ 5\cdot 10^{-9}\left|\delta^{\mu\tau}_L/10^{-2}\right|^2 \,. \end{array} \right. \qquad (8)$$

A more detailed analysis of the stringent correlation between the $\ell_i \to \ell_j\gamma$ transitions and Δa_μ is illustrated in Fig.2 where the red areas are the regions where the B-physics constraints are fulfilled.

III. LEPTON FLAVOR UNIVERSALITY TESTS

High precision electroweak tests, such as deviations from the SM expectations of the LFU breaking, represent a powerful tool to probe the SM and, hence, to constrain or obtain indirect hints of new physics beyond it. Kaon and pion physics are obvious grounds where to perform such tests, for instance in the $\pi \to \ell\nu_\ell$ and $K \to \ell\nu_\ell$ decays, where $l = e$ or μ. In particular, the ratios

$$R_P^{\mu/e} = \frac{\mathcal{B}(P \to \mu\nu)}{\mathcal{B}(P \to e\nu)} \qquad (9)$$

can be predicted with excellent accuracies in the SM, both for $P = \pi$ (0.02% accuracy [27]) and $P = K$ (0.04% accuracy [27]), allowing for some of the most significant tests of LFU.

As pointed out in Ref. [28], large departures from the SM expectations can be generated within a SUSY framework with R-parity only once we assume i) LFV effects, ii) large $\tan\beta$ values.

Denoting by $\Delta r_{NP}^{e-\mu}$ the deviation from $\mu - e$ universality in R_K due to NP, i.e.: $R_K^{\mu/e} = (R_K^{\mu/e})_{SM}\left(1 + \Delta r_K^{e-\mu}\right)$, it turns out that [28]:

$$\Delta r_K^{e-\mu} \simeq \left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2 \tan^6\!\beta. \qquad (10)$$

The deviations from the SM could reach $\sim 1\%$ in the $R_K^{\mu/e}$ case [28] (not far from the present experimental resolution [29]) and $\sim$ few $\times\, 10^{-4}$ in the $R_\pi^{\mu/e}$ case while maintaining LFV effects in τ decays at the 10^{-10} level. In the pion case the effect is quite below the present experimental resolution [30], but could well be within the reach of the new generation of high-precision $\pi_{\ell 2}$ experiments planned at TRIUMPH and at PSI. Larger violations of LFU are expected in $B \to \ell\nu$ decays, with $\mathcal{O}(50\%)$ deviations from the SM in $R_B^{\mu/\tau}$ and even order-of-magnitude enhancements in $R_B^{e/\tau}$ [7]. In Fig. 3, we show $\Delta r_K^{e/\mu}$ as a function of M_H (upper plot) and the regions of the $\tan\beta - M_H$ plane probed by $\Delta r_K^{e/\mu}$ (lower plot) [**?**].

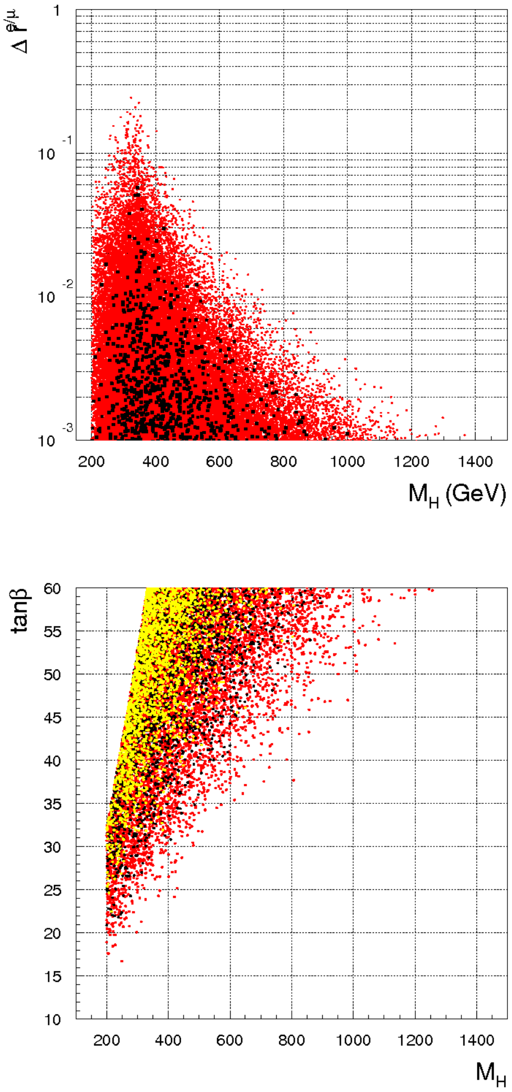

FIG. 3: Upper plot: $\Delta r_K^{e/\mu}$ as a function of M_H. Black dots refer to the points satisfying $1 \times 10^{-9} < \Delta a_\mu < 5 \times 10^{-9}$ [28]. Lower plot: regions of the parameter space in the $\tan\beta - M_H$ plane where $0.001 < |\Delta r_K^{e/\mu}| < 0.003$ (red dots), $0.003 < |\Delta r_K^{e/\mu}| < 0.005$ (black dots) and $|\Delta r_K^{e/\mu}| > 0.005$ (yellow dots) [28].

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