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Dark Matter and Lepton Flavour Violation in Yukawa Unification with Massive Neutrinos

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The WMAP dark matter constraints on b-τ Yukawa Unification in the presence of massive neutrinos is revisited. The predictions for the bottom quark mass are observed to be modified by the large neutrino mixing suggested by the data. This enables Yukawa unification also for large $\tan\beta$, and for positive μ that were previously disfavoured. Consequently, the allowed parameter space for neutralino dark matter differs from the MSSM one. We also find that the parameter space being compatible with dark matter also predicts detectable rates for Lepton Flavour Violation at the LHC.

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1. Introduction

The amount of Cold Dark Matter (CDM) deduced from the Wilkinson Microwave Anisotropy Probe (WMAP) data [1, 2] puts severe constraints on possible Dark Matter Candidates, inluding the lightest supersymmetric particle (LSP). Additional constraints on the model parameters are obtained by imposing Yukawa unification, and by taking into account the bounds from Flavour Changing Neutral Currents (FCNC).

In addition to the above, the neutrino data of the past years provided evidence for the existence of neutrino oscillations and masses, pointing for the first time to physics beyond the Standard Model. As expected, the additional interactions required to generate neutrino masses also affect the energy dependence of the couplings of the MSSM, and thus modify the Yukawa unification predictions. A first observation had been that the additional interactions of neutrinos, which affect the tau mass, may spoil bottom-tau unification for small $\tan\beta$ [3]. Subsequently, however, it has been realised that large lepton mixing naturally restores unification, and even allows Unification for intermediate values of $\tan\beta$ that were previously disfavoured [4, 5, 6]. This is done by making the simple observation that the $b-\tau$ equality at the GUT scale refers to the $(3,3)$ entries of the charged lepton and down quark mass matrices, while the detailed structure of the mass matrices is not predicted by the Grand Unified Group itself. It is then possible to assume mass textures, such that,*after* diagonalisation at the GUT scale, the $(m_E^{diag})_{33}$ and $(m_D^{diag})_{33}$ entries are no-longer equal.

The present paper is based on [7, 8] and pay attention to the issues of Dark Matter and Yukawa Unification taking into account the effects of massive neutrinos and large lepton mixing in See-Saw models, and extending previous results to large $\tan\beta$. Those issues in mind, we also analyse the prospects for the detection of Lepton Flavour violation (LFV) at the LHC via *neutralino* decays.

2. Massive Neutrinos and Unification

In the presence of massive neutrinos, the predictions for m_b and unification clearly get modified. Radiative corrections from the neutrino Yukawa couplings have to be included in RGE when running from M_{GUT} down to M_N (scale of the heavy right-handed neutrinos). Below M_N, right-handed neutrinos decouple from the spectrum and an effective see-saw mechanism is operative; the relevant equations are given in [9]. In addition, if the GUT scale lies significantly below a scale M_X, at which gravitational effects can no longer be neglected, the renormalization of couplings at scales between M_X and M_{GUT} may induce additional effects to the running and the simplest example is provided by minimal SU(5) [10] (however, modifications to soft masses are in this simplest case proportional to the V_{CKM} mixing [10], and thus are significantly suppressed). Nevertheless, it has been realized that the influence of the runs above the GUT scale on the Dark Matter abundance can be very sizeable [11], due to changes in the relation between $m_{\tilde{\tau}}$ and m_χ, which is crucial in the coannihilation area. This we discuss in a subsequent section.

In supersymmetric models, unification is very sensitive to the model parameters, particularly the Higgs mixing parameter, μ. To correctly obtain pole masses within this framework, the Standard model and supersymmetric threshold corrections have to be included; for the bottom quark, these corrections result to a Δm_b that can be very large, particularly for large values of $\tan\beta$. Constraints from BR($b\to s\gamma$) and $g_\mu - 2$ [12] are also included in the analysis. Before passing to the results, however, let us summarise a few facts on the possible range of the mass of the bottom quark: the 2-σ range for the $\overline{MS}$ bottom running mass, $m_b(m_b)$, is from 4.1-4.4 GeV. Moreover, $\alpha_s(m_Z) = 0.1172 \pm 0.002$, and the central value of α_s corresponds to $m_b(m_Z)$ from 2.82 to 3.06 GeV.

In Fig. 1, we summarize the predictions for m_b in mSUGRA, where all CP phases are either zero or π (defining the sign of μ). In order to discuss the dependence of $m_b(M_Z)$ on $\tan\beta$, we consider the following representative set of soft parameters: $m_{\frac{1}{2}} = 800$ GeV, $A_0 = 0$, $m_0 = 600$ GeV. We study each set for both $\mu > 0$ and $\mu < 0$; setting $\alpha_s(M_z) = 0.1132$ or $\alpha_s(M_z) = 0.1212$ (upper and lower experimental bounds). The figure exhibits the well-known fact that in the absence of phases or large trilinear terms, Δm_b is positive for μ positive, and therefore the theoretical prediction for the b quark pole mass is too high to be reconciled with $b-\tau$ unification. On the other hand, for $\mu < 0$, Δm_b is negative and the theoretical prediction for the b quark mass can lie within the experimental range for values of $\tan\beta$ between roughly 25 and 45; clearly, for a large $\tan\beta$ it is mandatory to take into account the large supersymmetric corrections to m_b [13, 14].

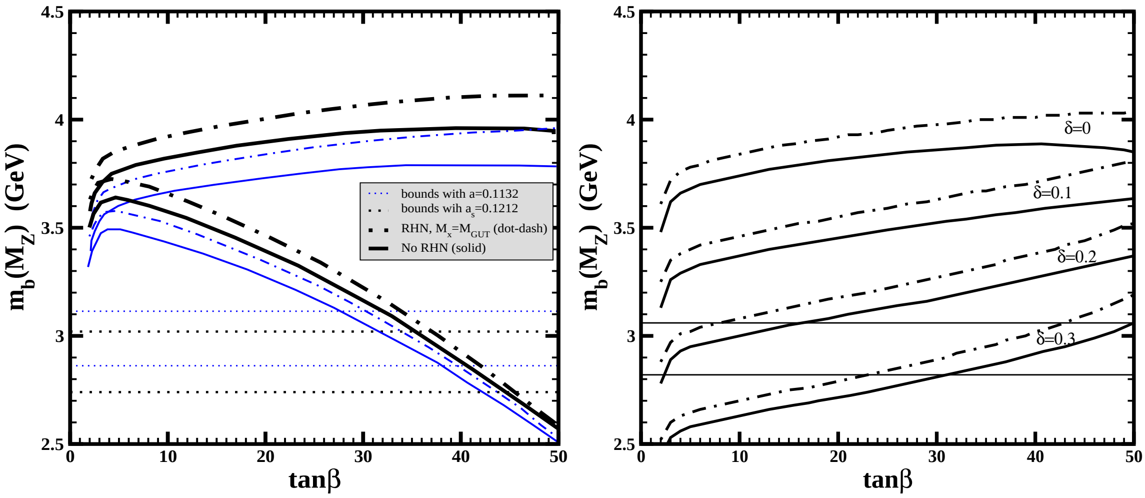

Figure 1: *The value of $m_b(M_Z)$ versus $\tan\beta$ assuming $\alpha_s(M_Z) = 0.1212$ (black) and $\alpha_s(M_Z) = 0.1132$ (blue), $\lambda_b = \lambda_\tau$ at the high scale in the absence of lepton mixing for the set of parameters defined in the text. The experimental range of m_b (horizontal lines) is also shown, for the same values of $\alpha(M_Z)$. In the right panel, we show m_b as a function of $\tan\beta$, when including lepton mixing effects for different values of δ and impose $m_b(M_Z) = 2.92$ GeVs for $\mu > 0$ and $\mu < 0$.*

In Fig. 1, the analysis is performed also in the presence of massive neutrinos (dashed lines), keeping only the third generation couplings , from the M_{GUT} to the scale of the right handed neutrino masses, and evolve the light neutrino mass operator from this scale down to M_Z. A large value of the Dirac-type neutrino Yukawa coupling, λ_N at the GUT scale may arise naturally within the framework of Grand Unification, and its value is determined by demanding a third generation low energy neutrino mass of $m_{\nu_3} = 0.05$ eV. The predictions for $m_b(M_Z)$ using the lower and upper bounds of the 2-σ experimental range of α_s and the correponding range for $m_b(M_Z)$ after the evolution of the bounds on $m_b(m_b)$ are shown for a scale $M_N = 3 \times 10^{14}$ GeV.

We observe that for $\mu > 0$ the prediction for $m_b(M_Z)$ is always very large, despite its dependence on the soft terms through Δm_b. We have also checked in ref. [7] that runs above the

GUT scale have no significant impact (their impact is however not negligeble for our subsequent considerations on Dark Matter, as shown in ref. [11])

The results are significantly modified once we consider the effects of lepton mixing in the diagonalisation and running of couplings from high to low energies. In order to show this, we focus on $b-\tau$ unification within the framework of SU(5) gauge unification and flavour symmetries that provide consistent patterns for mass and mixing hierarchies, and naturally reconcile a small V_{CKM} mixing with a large charged lepton one. Taking into account the particle content of SU(5) representations (with symmetric up-type mass matrices, and down-type mass matrices that are transpose to the ones for charged leptons), one finds the approximate relations

$$\mathscr{M}_d^0 \propto A \begin{pmatrix} 0 & 0 \\ x & 1 \end{pmatrix}, \ \mathscr{M}_\ell^0 \propto A \begin{pmatrix} 0 & x \\ 0 & 1 \end{pmatrix} \tag{2.1}$$

which, after diagonalization, lead to

$$\frac{m_b^0}{1+x^2} = \frac{m_\tau^0}{1-x^2} \to m_b^0 = m_\tau^0 \left(1 - \underbrace{2x^2}_{\delta} + \mathscr{O}\left(\delta^2\right) \right) \tag{2.2}$$

where δ parametrises the flavour mixing in the (2,3) sector.

In the right pannel of Fig.1 we show the change of m_b as a function of $\tan\beta$, when the effects from large lepton mixing are appropriately considered. Comparing with the previous plots, we see how solutions with positive μ are now viable, for the whole range of $\tan\beta$. The appropriate size of the parameter δ in each case can be determined by imposing the relation $\lambda_\tau = \lambda_b(1+\delta)$ at M_{GUT} and investigating the values that are required in order to obtain a correct prediction for $m_b(M_Z)$.

3. Dark Matter constraints and Yukawa unification

In mSUGRA (or the CMSSM) for choices of soft terms below the TeV scale, the LSP is Bino like and the prediction for $\Omega_\chi h^2$ is typically too large for models that satisfy the experimental constraints on SUSY. In fact, the values of WMAP can essentially be obtained in two regions: (i) $\chi - \tilde{\tau}$ coannihilation region that occurs for $m_\chi \sim m_{\tilde{\tau}}$; and (ii) that of resonances in the $\chi - \chi$ annihilation channel, which occur for $m_A \sim 2m_\chi$.

Since the above areas are "fine-tuned", they will inevitably be sensitive to the changes induced by GUT unification and sizeable mixing in the charged lepton sector. The runs corresponding to $M_X > M_{GUT}$ have a big impact on the neutralino relic density. The large values of the gauge unified coupling $\alpha_{SU(5)}$ tend to increase the values of $m_{\tilde{\tau}}$, even if we start with small m_0 at M_X.

We see that the consideration of mixing effects, in combination to the inclusion of effects from the runs above M_{GUT}, significantly enhances the allowed parameter space (green area), an effect that is more visible for large $\tan\beta$. The reduction of the allowed parameter space for smaller values of $\tan\beta$, is already evident for $\tan\beta = 35$. The case with $\mu < 0$ and a more detailed discussion of lepton mixing effects are presented in [7].

In ref. [8], we study the optimal conditions within the above-described theoretical framework for τ flavour violation to be observable in $\chi_2 \to \chi + \tau^\pm \mu^\mp$ at LHC. Fig. 3, taken from [8], shows the simulated signal (using PYTHIA) for LHC conditions of lepton number violation, as the excess

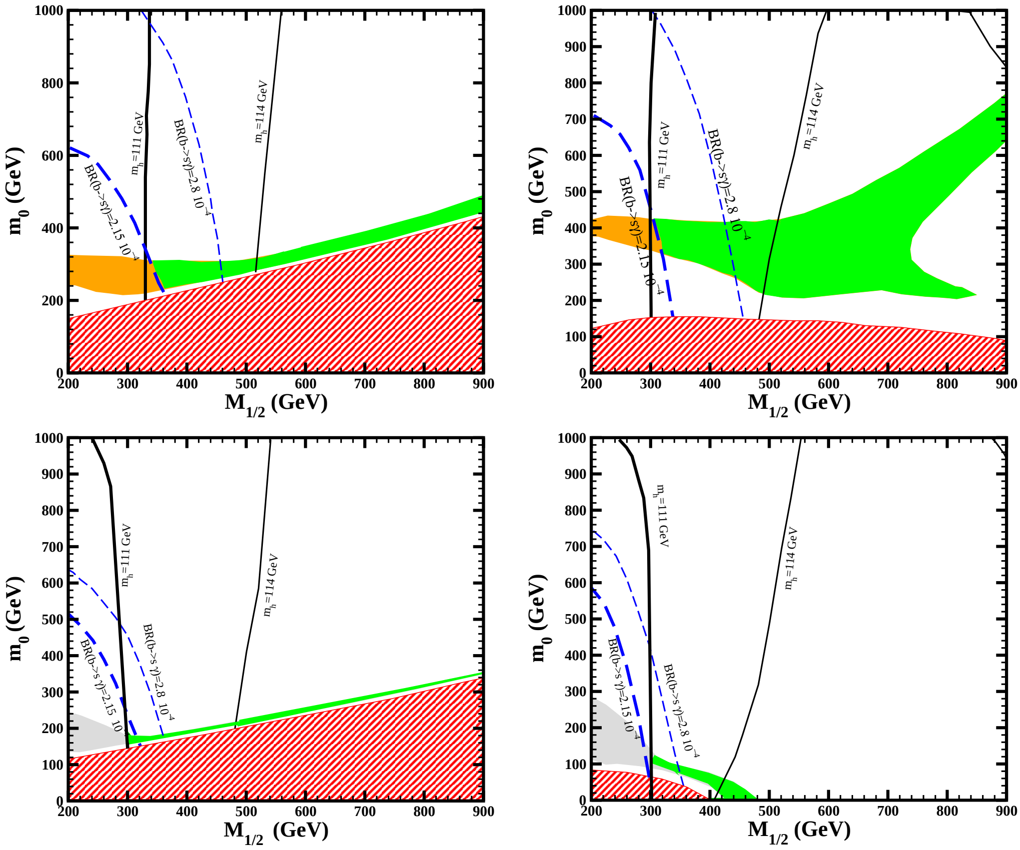

Figure 2: *WMAP area for the case of* $\tan\beta = 45$ *(top) and* $\tan\beta = 35$ *(down),* $\mu > 0$, $A_0 = m_0$*, the central value of the bottom mass* $m_b(M_Z) = 2.92$ *GeV and* $\delta \sim 0.42$ *without (left) and with (right) the* $SU(5)$ *running.*

of $\mu - \tau$ over $e - \tau$ pairs, for an optimal set of parameters allowed by the WMAP constraints in Fig. 2.

4. Conclusions

We revisited the WMAP dark matter constraints on Yukawa Unification in the presence of massive neutrinos. Large neutrino mixing, as indicated by the data modifies the predictions for the bottom quark mass, and enables Yukawa also for large $\tan\beta$ and for positive μ that were previously disfavoured. A direct outcome is that the allowed parameter space for neutralino dark matter also increases, particularly for areas that are tuned, namely the ones with resonant enhancement of the neutralino relic density.

For completeness, we also note that for the cosmologically favoured parameter region, we found lepton flavour violating rates very close to the current experimental bounds [7] and study its possible detection at LHC. Finally, interesting effects may arise in the case of non-universal soft terms. These are also discussed in detail in [7].

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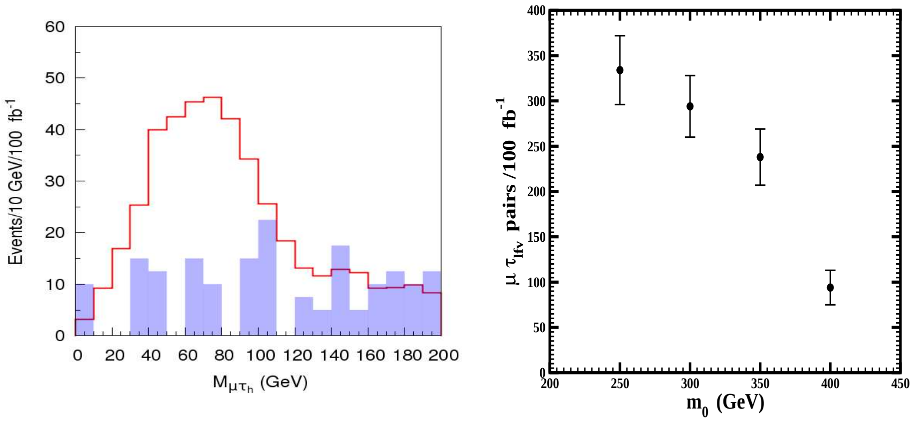

Figure 3: *Left: the signal for excess $\mu\tau_h$ LFV pairs (red solid lines) and subtracted $\mu\tau_h - e\tau_h$ Standard Model backgrounds (shaded) for an optimal set of parameters allowed by WMAP constraints. Right: number of LFV pairs for different values of m_0 and $M_{1/2}$ fixed at 500 GeV. (see [8] for the complete definition of parameters).*

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References

[1] C. L. Bennett *et al.*, Astrophys. J. Suppl. **148**, 1 (2003)

[2] D. N. Spergel *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **148**, 175 (2003)

[3] F. Vissani and A. Y. Smirnov, Phys. Lett. B **341**, 173 (1994), A. Brignole, H. Murayama and R. Rattazzi, Phys. Lett. B **335**, 345 (1994)

[4] G. K. Leontaris, S. Lola and G. G. Ross, Nucl. Phys. B 454 (1995) 25.

[5] M. Carena, J. Ellis, S. Lola and C. Wagner, Eur. Phys. J. C12 (2000) 507.

[6] M. E. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, Phys. Rev. D **70** (2004) 035014 and Phys. Rev. D **72** (2005) 095008.

[7] M. E. Gomez, S. Lola, P. Naranjo and J. Rodriguez-Quintero, in preparation.

[8] E. Carquin, J. Ellis, M. E. Gomez, S. Lola and J. Rodriguez-Quintero, arXiv:0812.4243 [hep-ph].

[9] B. Grzadkowski and M. Lindner, Phys. Lett. B **193** (1987) 71; Yu. F. Pirogov and O. V. Zenin, Eur. Phys. J. C **10** (1999) 629; N. Haba, N. Okamura and M. Sugiura, Prog. Theor. Phys. **103** (2000) 367, Eur. Phys. J. C **10** (1999) 677

[10] J. Hisano and D. Nomura, Phys. Rev. D **59**, 116005 (1999)

[11] L. Calibbi, Y. Mambrini and S. K. Vempati, JHEP **0709**, 081 (2007)

[12] G. W. Bennett et al. [Muon g-2 Collaboration], Phys. Rev. D **73**, 072003 (2006); Phys. Rev. Lett. **92**, 161802 (2004)

[13] L. J. Hall, R. Rattazzi and U. Sarid, Phys. Rev. D **50**, 7048 (1994)

[14] M. S. Carena, M. Olechowski, S. Pokorski and C. E. M. Wagner, Nucl. Phys. B **426**, 269 (1994)