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Gauge and Yukawa unification with broken R-parity

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Abstract

We study Yukawa coupling unification in the simplest extension of the Minimal Supersymmetric Standard Model (MSSM) which incorporates R-parity violation through a bilinear superpotential term. In contrast to what happens in the MSSM, we show that bottom-tau unification at the scale M_{GUT} where the gauge couplings approximately unify can be achieved for any value of $\tan\beta$ by choosing appropriately the sneutrino vacuum expectation value. Moreover, we show that in contrast with the MSSM where large $\tan\beta$ solutions exist, in our case *for sufficiently large sneutrino VEV* v_3, *large* $\tan\beta$ *becomes incompatible with bottom-tau unification.*

The Standard Model (SM) of particle physics is very successful in describing the interactions of the elementary particles, except possibly neutrinos. Although it is regarded as a good low-energy effective theory, the SM has many theoretical problems. Its gauge symmetry group is the direct product of three groups $SU(3) \times SU(2) \times U(1)$ and the corresponding gauge couplings are unrelated. It does not explain the three family structure of quarks and leptons, and their masses are fixed by arbitrary Yukawa couplings, with neutrinos being prevented from having mass. The Higgs sector, responsible for the electroweak symmetry breaking and for the fermion masses, has not been verified experimentally and the Higgs boson mass is unstable under radiative corrections. As a result, say, the hierarchy between the electroweak scale and the Planck scale is not understood.

In supersymmetry (SUSY) [1] the Higgs mass is stabilized under radiative corrections because the loops containing standard particles is partially cancelled by the contributions from loops containing supersymmetric particles. If we add to the Minimal Supersymmetric Standard Model (MSSM) [2] the notion of Grand Unified Theory (GUT), then we find that the three gauge couplings approximately unify at a certain scale M_{GUT} [3]. Indeed, measurements of the gauge couplings at the CERN e^+e^- collider LEP and neutral current data [4] are in much better agreement with the MSSM–GUT with the SUSY scale $M_{\mathrm{SUSY}} \leq 1$ TeV [5] than the SM.

Besides achieving gauge coupling unification [6], GUT theories also reduce the number of free parameters in the Yukawa sector. For example, in $SU(5)$ models, the bottom quark and the tau lepton Yukawa

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couplings are equal at the unification scale, and the predicted ratio m_b/m_τ at the weak scale agrees with experiments. Furthermore, a relation between the top quark mass and $\tan\beta$, the ratio between the vacuum expectation values of the two Higgs doublets is predicted. Two solutions are possible, characterized by low and high values of $\tan\beta$ [7]. In models with larger groups, such as $SO(10)$ and E_6, both the top and bottom Yukawa couplings are unified with the tau Yukawa [8]. However, in this case, only the large $\tan\beta$ solution survives.

In this letter, we show that the minimal extension of the MSSM–GUT [10] in which R-parity violation is introduced via a bilinear term in the MSSM superpotential [11,12], allows $b-\tau$ Yukawa unification for any value of $\tan\beta = v_u/v_d$ and satisfying perturbativity of the couplings. We also analyze the $t-b-\tau$ Yukawa unification and find that it is easier to achieve than in the MSSM, occurring in a slightly wider high $\tan\beta$ region.

For simplicity, we consider only the third generation of quarks and leptons, so the superpotential is given by

$$W = h_t \hat{Q}_3 \hat{U}_3 \hat{H}_u + h_b \hat{Q}_3 \hat{D}_3 \hat{H}_d + h_\tau \hat{L}_3 \hat{R}_3 \hat{H}_d + \mu \hat{H}_u \hat{H}_d + \epsilon_3 \hat{L}_3 \hat{H}_u \qquad (1)$$

where the first four terms correspond to the MSSM and the last one is the bilinear term which violates R-parity. This superpotential is motivated by models of spontaneous breaking of R-parity [13]. Here, R-parity and lepton number are violated explicitly by the ϵ_3 term.

It is clear from Eq. (1) that the scalar potential contains terms which induce a non-zero vacuum expectation value (VEV) of the tau sneutrino $\langle \tilde{\nu}_\tau \rangle = v_3/\sqrt{2}$. It contributes to the W mass according to $m_W^2 = \frac{1}{4} g^2 (v_d^2 + v_u^2 + v_3^2)$, where $v_d/\sqrt{2}$ and $v_u/\sqrt{2}$ are the VEVs of the two Higgs doublets H_d and H_u respectively. The R-parity violating parameters ϵ_3 and v_3 violate tau-lepton number, inducing a non-zero ν_τ mass $m_{\nu_\tau} \propto (\mu v_3 + \epsilon_3 v_d)^2$, which arises due to mixing between the weak eigenstate ν_τ and the neutralinos [14]. The latest ν_τ mass limit from ALEPH is $m_{\nu_\tau} \lesssim 18$ MeV [15]. The ν_e and ν_μ remain massless in first approximation. They acquire typically smaller masses from supersymmetric loops [16]. As already mentioned, in what follows we consider only the third generation of quarks and leptons.

It is important to note that the ϵ-term in Eq. (1) is a physical parameter and cannot be eliminated [10] by a redefinition [17] of the superfields $\hat{H}_d$ and $\hat{L}_3$. The reason is that, after the rotation, bilinear terms which induce a tau sneutrino VEV are re-introduced in the soft scalar sector. Moreover, in contrast to many prejudices, we wish to stress that the R-parity violating parameters v_3 and ϵ_3 need not be small. In models with universality of soft supersymmetry breaking mass parameters m_{ν_τ} is naturally small because it arises from a seesaw mechanism in which the the *effective* mixing arises only radiatively, and may lie in the eV range [10].

R-Parity violation also implies that the charginos mix with the tau lepton, through a mass matrix given by

$$\boldsymbol{M}_C = \begin{bmatrix} M & \frac{1}{\sqrt{2}} g v_u & 0 \\ \frac{1}{\sqrt{2}} g v_d & \mu & -\frac{1}{\sqrt{2}} h_\tau v_3 \\ \frac{1}{\sqrt{2}} g v_3 & -\epsilon_3 & \frac{1}{\sqrt{2}} h_\tau v_d \end{bmatrix} \qquad (2)$$

Imposing that one of the eigenvalues reproduces the observed tau mass m_τ, the tau Yukawa coupling h_τ can be solved exactly as [12]

$$h_\tau^2 = \frac{2 m_\tau^2}{v_d^2} \frac{1}{1+\delta} \qquad (3)$$

where the δ depends on m_τ, on the SUSY parameters $M, \mu, \tan\beta$ and on the R-parity violating parameters ϵ_3 and v_3. One can easily be shown to vanish in the MSSM limit $\epsilon_3 \to 0$ and $v_3 \to 0$. On the other hand, the bottom and top Yukawa couplings are related to the bottom and top masses according to

$$m_t = h_t \frac{v}{\sqrt{2}} \sin\beta \sin\theta\,, \quad m_b = h_b \frac{v}{\sqrt{2}} \cos\beta \sin\theta \qquad (4)$$

where we use spherical coordinates for the VEVs, defining $v = 2m_W/g$, $\tan\beta = v_u/v_d$, and $\cos\theta = v_3/v$.

We now turn to the study of the renormalization group evolution of the various relevant parameters of the model such as the gauge and Yukawa couplings, the SM quartic Higgs coupling and the third generation fermion masses. We follow closely the procedure of Barger et al. [7]. In our approach we divide the evolution into three ranges: (i) from M_{SUSY} to M_{GUT}, where we use the two-loop RGEs of our model, (ii) from m_t to M_{SUSY}, where we use the two-loop SM RGEs including the quartic Higgs coupling and (iii) from M_Z to m_t we use running fermion masses and gauge couplings.

We randomly vary the low energy data over their allowed ranges [18] $\alpha_{em}^{-1}(m_Z) = 128.896 \pm 0.090$, $\sin^2\theta_w(m_Z) = 0.2322 \pm 0.0010$, and $\alpha_s(m_Z) = 0.118 \pm 0.003$, extrapolating to higher energies and looking for solutions compatible with approximate unification, with a unification scale M_{GUT} and a unified coupling α_{GUT}. We use the approximation of a common decoupling scale $M_{SUSY} \lesssim 1$ TeV for all the supersymmetric particles. The solutions we find are concentrated in a region of the M_{GUT}–α_{GUT} plane. For the simpler case where the SUSY scale coincides with the top mass, $M_{SUSY} = m_t$, this region is centered at the point $M_{GUT} \approx 2.3 \times 10^{16}$ GeV and $\alpha_{GUT}^{-1} \approx 24.5$, which we adopt from now on. Note that this procedure give us only approximate gauge unification. This is justified because the results presented here, i.e., unification of Yukawa couplings, are not qualitatively altered by the details of gauge coupling unification. A dedicated study of gauge unification will be presented elsewhere, addressing the difficulties of the MSSM in obtaining perfect unification at low values of α_s and how this is affected by the R-parity breaking hypothesis.

Next, we study the unification of Yukawa couplings using two-loop RGEs. We take $m_W = 80.41 \pm 0.09$ GeV, $m_\tau = 1777.0 \pm 0.3$ MeV, and $m_b(m_b) =$ 4.1 to 4.5 GeV [18]. We calculate the running masses $m_\tau(m_t) = \eta_\tau^{-1} m_\tau(m_\tau)$ and $m_b(m_t) = \eta_b^{-1} m_b(m_b)$, where η_τ and η_b include three-loop order QCD and one-loop order QED [9]. At the scale $Q = m_t$ we keep the running top quark mass $m_t(m_t)$ as a free parameter and vary randomly the SM quartic Higgs coupling λ. Using SM RGEs we evolve the gauge, Yukawa, and Higgs couplings from $Q = m_t$ up to $Q = M_{SUSY}$. The initial conditions for the SM Yukawa couplings are $\lambda_i^2(m_t) = 2m_i^2(m_t)/v^2$, with $i = t,b,\tau$ and $v = 246.2$ GeV.

At the scale $Q = M_{SUSY}$, below which all SUSY particles are decoupled (including the heavy Higgs bosons) we impose the following boundary conditions for the quark Yukawa couplings

$$\lambda_t(M_{SUSY}^-) = h_t(M_{SUSY}^+)\sin\beta\sin\theta,$$
$$\lambda_b(M_{SUSY}^-) = h_b(M_{SUSY}^+)\cos\beta\sin\theta \quad (5)$$

where h_i denote the Yukawa couplings of our model and λ_i those of the SM. Due to its mixing with charginos, the boundary condition for the tau Yukawa coupling is slightly more complicated:

$$\lambda_\tau(M_{SUSY}^-) = h_\tau(M_{SUSY}^+)\cos\beta\sin\theta\sqrt{1+\delta} \quad (6)$$

Finally, the boundary condition for the quartic Higgs coupling is given by

$$\lambda(M_{SUSY}^-) = \tfrac{1}{4}\left[\left(g^2(M_{SUSY}^+) + g'^2(M_{SUSY}^+)\right]\right.$$
$$\times\left(\cos 2\beta\sin^2\theta + \cos^2\theta\right)^2 \quad (7)$$

The MSSM limit is obtained setting $\theta \to \pi/2$ i.e. $v_3 = 0$.

At the scale $Q = M_{SUSY}$ we vary randomly the SUSY parameters M, μ and $\tan\beta$, as well as the R-parity violating parameter ϵ_3. The parameter $v_3 = v\cos\theta$ is calculated from Eq. (7). Since λ (or equivalently the SM Higgs mass $m_H^2 = 2\lambda v^2$) is varied randomly, in practice we also scan over θ. This way, we consider all possible initial conditions for the RGEs at $Q = M_{SUSY}$, and evolve them up to the unification scale $Q = M_{GUT}$. The solutions that satisfy $b-\tau$ unification are kept.

In Fig. 1 we illustrate our result by plotting the (pole) top quark mass as a function of $\tan\beta$. For simplicity we have taken $M_{SUSY} = m_t$ but it should be clear that a different M_{SUSY} choice would not change qualitatively our results. Each selected point in our scan satisfies bottom-tau unification $h_b(M_{GUT}) = h_\tau(M_{GUT})$ (to within 1%) and it is placed in one of the shaded regions according to the value of $|v_3|$. The first region with $v_3 = \epsilon_3 =$ 0corresponds to the MSSM and sits at the top of the plot. Points with $|v_3| < 1$ GeV fall in the region just

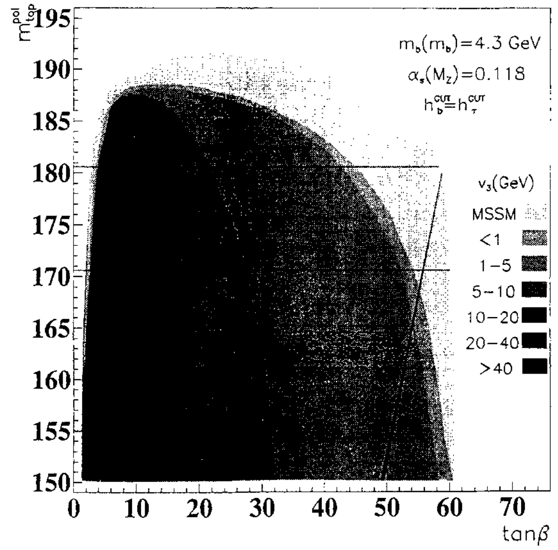

Fig. 1. Top quark mass as a function of $\tan\beta$ for different values of the R-parity violating parameter v_3. Bottom quark and tau lepton Yukawa couplings are unified at M_{GUT}. The horizontal lines correspond to the 1σ experimental m_t determination. Points with $t-b-\tau$ unification lie in the diagonal band at high $\tan\beta$ values. We have taken $M_{SUSY}=3Dm_t$.

below. The subsequent regions labelled by $1<|v_3|<5$ GeV up to $|v_3|>40$ GeV respectively are obtained when v_3 gets higher. They are narrower in $\tan\beta$. Note that, in contrast with the MSSM, in our model *for sufficiently large* $|v_3|$ *the large* $\tan\beta$ *is inconsistent with b-tau unification.* Note also that there is a certain overlap of the two regions characterized by $v_3<5$ GeV with the MSSM region: we find solutions with non-zero $v_3<5$ GeV also in the MSSM region, but not the other way around. The two horizontal lines correspond to the top quark mass within a 1σ error. In the MSSM limit we can see the two solutions compatible with the experimental value of the top quark mass, one with $\tan\beta\approx 1$ and the other with $\tan\beta\approx$ 53–61. It is clear from the figure that by selecting appropriately the value of $|v_3|$ we can find $b-\tau$ unification for any $\tan\beta$ value within the perturbative region $1\lesssim\tan\beta\lesssim 61$ of the Yukawa couplings. For $|v_3|\lesssim 20$ GeV one has, as in the MSSM, two disconnected solutions for $b-\tau$ unification, one with $\tan\beta\approx 1$, and a large $\tan\beta$ range which, for intermediate v_3 can be quite broad. Note that for $20<|v_3|<40$ GeV only the $\tan\beta$ range from 2 to 8 or so is consistent with the 1 σ top mass measurement, for the chosen α_s and $m_b(m_b)$ values. Similarly, the $|v_3|$ range above 40 GeV would be even smaller.

The above results do not depend qualitatively on the definition chosen for $\tan\beta$. For example, if we define $\tan\beta$ in the way which is natural in the basis where the ϵ_3-term disappears from the superpotential, $\tan\beta'\equiv v_u/\sqrt{v_d^2+v_3^2}$ we also can find $b-\tau$ unification for any $\tan\beta'$ value.

We now study the dependence of our results on the weak scale values of the strong coupling constant and the bottom quark mass. The effect of varying α_s in Fig. 1 is that the upper bound on $\tan\beta$, which is $\tan\beta\lesssim 61$ for $\alpha_s=0.118$, increases with α_s and becomes $\tan\beta\lesssim 63$ (59) for $\alpha_s=0.122$ (0.114). On the other hand the MSSM region is narrower if α_s increases, specially at high $\tan\beta$ values. We have verified that the same trend extends to the regions with large v_3. Finally, we mention that the top mass value for which unification is achieved for any $\tan\beta$ value within the perturbative region increases with α_s, as in the MSSM. Notice that, in contrast to Carena et al. [8], we do not impose universality of soft scalar masses.

Turning to the dependence on m_b, the behaviour is the opposite one. In Fig. 1 we have taken $m_b(m_b)=4.3$ GeV. As before the value of $\tan\beta$ is bounded from above by $\tan\beta\lesssim 61$ due to the perturbativity condition of the bottom quark Yukawa coupling. If we consider $m_b(m_b)=4.1$ (4.5) GeV then the upper bound of this parameter is given by $\tan\beta\lesssim 64$ (58). In addition, the MSSM region is narrower (wider) at high $\tan\beta$ compared with the $m_b(m_b)=4.3$ GeV case shown in Fig. 1. In addition this study of the uncertainty of $m_b(m_b)$ allows us to estimate the error we make in neglecting the non-logarithmic corrections to the bottom-quark mass. Although the resulting small corrections do affect the shape of Fig. 1 they do not in any case affect our main point, namely, that we do find b-tau unification for all $\tan\beta$ values, provided the magnitude of the R-parity-violating VEV v_3 is chosen suitably.

Finally we have studied the possibility of top-bottom-tau unification in our model. The diagonal line at high $\tan\beta$ values corresponds to points where $t-b-\tau$ unification is achieved. Since the region with $|v_3|<5$ GeV overlaps with the MSSM region, it follows that $t-b-\tau$ unification is possible in this model for values of $|v_3|$ up to about 5 GeV, instead of 50 GeV or so, which holds in the case of bottom-tau unification. Within the MSSM, $t-b-\tau$ unification is achieved in the range $55 \lesssim \tan\beta \lesssim 57$ with m_t completely inside the 1σ region. In this case, bilinear R-parity violation enlarges slightly the allowed $\tan\beta$ region to 53 as its lower limit. At the 2σ level our model allows $t-b-\tau$ unification for $52 \lesssim \tan\beta \lesssim 58$ while in the MSSM 55 remains as the lower limit. In addition, we have checked that the region with $t-b-\tau$ unification in the MSSM case shrinks if α_s is increased. The space left out by the MSSM is taken over by the regions with $|v_3| < 5$ GeV so that, for large α_s, $t-b-\tau$ unification occurs in a even wider $\tan\beta$ range than possible in the MSSM.

In conclusion, we have summarized the results of the first systematic study of Yukawa coupling unification in a model where we introduce bilinear R-parity violation. This possibility was mentioned earlier in the context of models with tri-linear breaking of R-parity, see, e.g. [19]. In contrast with such models, ours is the simplest alternative to the MSSM which, in addition, has the theoretical merit of parametrizing in an effective way many of the features of models of spontaneous breaking of R-parity. Apart from its intrinsic theoretical as well as phenomenological interest, our study is motivated also *a posteriori* in view of the striking results we have obtained: (i) We showed that, in contrast to the MSSM, where bottom-tau unification is achieved in two disconnected $\tan\beta$ regions, in our model $b-\tau$ unification occurs *for any* $\tan\beta$ *value, provided we choose appropriately the value of the tau sneutrino vacuum expectation value* v_3 and (ii) We showed that, in contrast with the MSSM, where two well-separated $\tan\beta$ branches exist, in our case, for sufficiently large v_3 these approach each other in such a way that *large* $\tan\beta$ *becomes ruled out*. As a last result, we showed that $t-b-\tau$ unification is achieved for $|v_3| \lesssim 5$ GeV at high values of $\tan\beta$ in a slightly wider region than that of the MSSM.

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