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PHYSICS LETTERS B

SO(10) Yukawa unification with $\mu < 0$

Ilia Gogoladze [1], Qaisar Shafi, Cem Salih Ün *

Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

ABSTRACT

We consider the low energy implications including particle spectroscopy of SO(10) inspired t-b-τ Yukawa coupling unification with $\mu < 0$, where μ is the coefficient of the bilinear Higgs mixing term of the minimal supersymmetric standard model (MSSM). We employ non-universal MSSM gaugino masses induced by SO(10) invariant dimension five operators, such that the total number of fundamental parameters is precisely the same as in Yukawa unified supersymmetric SO(10) models with universal gaugino masses and $\mu > 0$. We find that t-b-τ Yukawa unification with $\mu < 0$ is compatible with the current experimental bounds, including the WMAP bound on neutralino dark matter and the measured value of the muon anomalous magnetic moment. We present a variety of benchmark points which include relatively light squarks ($\sim$ TeV) of the first two families and an example in which the bottom and top squarks are lighter than the gluino. This is quite distinct from Yukawa unification with $\mu > 0$ and universal gaugino masses in which the gluino is the lightest colored sparticle and the squarks of the first two families have masses in the multi-TeV range.

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1. Introduction

Supersymmetric (SUSY) SO(10) grand unified theory (GUT), in contrast to its non-SUSY version, yields third family (t-b-τ) Yukawa unification via the unique renormalizable Yukawa coupling $16 \cdot 16 \cdot 10$, if the Higgs 10-plet is assumed to contain the two Higgs doublets H_u and H_d of the minimal supersymmetric standard model (MSSM) [1]. The matter 16-plet contains the 15 chiral superfields of MSSM as well as the right-handed neutrino superfield. The implications of this Yukawa unification condition at $M_G \sim 2 \times 10^{16}$ GeV have been extensively explored over the years [1,2]. In SO(10) Yukawa unification with $\mu > 0$ and universal gaugino masses, the gluino is the lightest colored sparticle [3,4], which will be tested [5] at the Large Hadron Collider (LHC). The squarks and sleptons, especially those from the first two families, turn out to have masses in the multi-TeV range. Moreover, it is argued in [3,4] that the lightest neutralino is not a viable cold dark matter candidate in SO(10) Yukawa unification with $\mu > 0$ and universal gaugino masses at M_G.

Spurred by these developments we have investigated t-b-τ Yukawa unification [4,6,7] in the framework of SUSY $SU(4)_c \times SU(2)_L \times SU(2)_R$ [8] (4-2-2, for short). The 4-2-2 structure allows us

to consider non-universal gaugino masses while preserving Yukawa unification. An important conclusion reached in [4,6] is that with same sign non-universal gaugino soft terms, Yukawa unification in 4-2-2 is compatible with neutralino dark matter, with gluino co-annihilation [4–6,9] being a unique dark matter scenario for $\mu > 0$.

By considering opposite sign gauginos with $\mu < 0$, $M_2 < 0$, $M_3 > 0$ (where μ is the coefficient of the bilinear Higgs mixing term, M_2 and M_3 are the soft supersymmetry breaking (SSB) gaugino mass terms corresponding respectively to $SU(2)_L$ and $SU(3)_c$). It is shown in [7] that Yukawa coupling unification consistent with the experimental constraints can be implemented in 4-2-2. With $\mu < 0$ and opposite sign gauginos, Yukawa coupling unification is achieved for $m_0 \gtrsim 300$ GeV, as opposed to $m_0 \gtrsim 8$ TeV for the case of same sign gauginos. The finite corrections to the b-quark mass play an important role here [7]. By considering gauginos with $M_2 < 0$, $M_3 > 0$ and $\mu < 0$, we can obtain the correct sign for the desired contribution to $(g - 2)_\mu$ [10]. This enables us to simultaneously satisfy the requirements of t-b-τ Yukawa unification in 4-2-2, neutralino dark matter and $(g - 2)_\mu$, as well as a variety of other bounds.

Encouraged by the abundance of solutions and coannihilation channels available in the case of Yukawa unified 4-2-2 with $M_2 < 0$ and $\mu < 0$, it seems natural to explore Yukawa unification in SO(10) GUT (with $M_2 < 0$ and $\mu < 0$). It has been pointed out [11] that non-universal MSSM gaugino masses at M_G can arise from non-singlet F-terms, compatible with the underlying GUT symmetry such as SU(5) and SO(10). The SSB gaugino masses in

* Corresponding author.
E-mail addresses: ilia@bartol.udel.edu (I. Gogoladze), shafi@bartol.udel.edu (Q. Shafi), cemsalihun@bartol.udel.edu (C. Salih Ün).
[1] On leave of absence from: Andronikashvili Institute of Physics, 0177 Tbilisi, Georgia.

supergravity [12] can arise, say, from the following dimension five operator:

$$-\frac{F^{ab}}{2}M_{\text{Pl}}\lambda^a\lambda^b + \text{c.c.} \tag{1}$$

Here λ^a is the two-component gaugino field, F^{ab} denotes the F-component of the field which breaks SUSY, the indices a, b run over the adjoint representation of the gauge group, and $M_{\text{Pl}} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. The resulting gaugino mass matrix is $\langle F^{ab}\rangle/M_{\text{Pl}}$ where the supersymmetry breaking parameter $\langle F^{ab}\rangle$ transforms as a singlet under the MSSM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. The F^{ab} fields belong to an irreducible representation in the symmetric part of the direct product of the adjoint representation of the unified group.

In SO(10), for example,

$$(45 \times 45)_S = 1 + 54 + 210 + 770. \tag{2}$$

If F transforms as a 54- or 210-dimensional representation of SO(10) [11], one obtains the following relation among the MSSM gaugino masses at M_G:

$$M_3 : M_2 : M_1 = 2 : -3 : -1, \tag{3}$$

where M_1, M_2, M_3 denote the gaugino masses of $U(1)$, $SU(2)_L$ and $SU(3)_c$ respectively. The low energy implications of this relation have recently been investigated in [13] without imposing Yukawa unification.

The outline for the rest of the Letter is as follows. In Section 2 we summarize the scanning procedure and the experimental constraints that we have employed. In Section 3 we present the results from our scan and highlight some of the predictions of an SO(10) model with $\mu < 0$ and the non-universal MSSM gaugino masses at M_G related by Eq. (3). We display some benchmark points which can be tested at the LHC. Our conclusions are summarized in Section 4.

2. Phenomenological constraints and scanning procedure

We employ the ISAJET 7.80 package [14] to perform random scans over the fundamental parameter space. In this package, the weak scale values of gauge and third generation Yukawa couplings are evolved to M_G via the MSSM renormalization group equations (RGEs) in the $\overline{\text{DR}}$ regularization scheme. We do not strictly enforce the unification condition $g_3 = g_1 = g_2$ at M_G, since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [15]. The deviation between $g_1 = g_2$ and g_3 at M_G is no worse than 3–4%. For simplicity we do not include the Dirac neutrino Yukawa coupling in the RGEs, whose contribution is expected to be small.

The various boundary conditions are imposed at M_G and all the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale M_Z. In the evaluation of Yukawa couplings the SUSY threshold corrections [16] are taken into account at the common scale $M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_L}m_{\tilde{t}_R}}$. The entire parameter set is iteratively run between M_Z and M_G using the full 2-loop RGEs until a stable solution is obtained. To better account for leading-log corrections, one-loop step-beta functions are adopted for gauge and Yukawa couplings, and the SSB parameters m_i are extracted from RGEs at multiple scales $m_i = m_i(m_i)$. The RGE-improved 1-loop effective potential is minimized at M_{SUSY}, which effectively accounts for the leading 2-loop corrections. Full 1-loop radiative corrections are incorporated for all sparticle masses.

The requirement of radiative electroweak symmetry breaking (REWSB) imposes an important theoretical constraint on the parameter space. In order to reconcile REWSB with Yukawa unification, the MSSM Higgs soft supersymmetry breaking (SSB) masses should be split in such way that $m_{H_d}^2/m_{H_u}^2 > 1.2$ at M_G [17]. As mentioned above, the MSSM doublets reside in the 10 dimensional representation of SO(10) GUT for Yukawa unification condition to hold. In the gravity mediated supersymmetry breaking scenario [12] the required splitting in the Higgs sector can be generated by involving additional Higgs fields [18], or via D-term contributions [19]. Another important constraint comes from limits on the cosmological abundance of stable charged particles [20]. This excludes regions in the parameter space where charged SUSY particles, such as $\tilde{\tau}_1$ or $\tilde{t}_1$, become the lightest supersymmetric particle (LSP). We accept only those solutions for which one of the neutralinos is the LSP and saturates the WMAP bound on relic dark matter abundance.

We have performed random scans for the following parameter range:

$$0 \leqslant m_0 \leqslant 5 \text{ TeV},$$
$$0 \leqslant m_{H_u} \leqslant 5 \text{ TeV},$$
$$0 \leqslant m_{H_d} \leqslant 5 \text{ TeV},$$
$$0 \leqslant M_{1/2} \leqslant 2 \text{ TeV},$$
$$35 \leqslant \tan\beta \leqslant 55,$$
$$-3 \leqslant A_0/m_0 \leqslant 3 \tag{4}$$

with $\mu < 0$ and $m_t = 173.1$ GeV [21]. Note that our results are not too sensitive to one or two sigma variation in the value of m_t [18]. We use $m_b(m_Z) = 2.83$ GeV which is hard-coded into ISAJET. The set of parameters presented above is usually referred to as NUHM2 [22]. This choice of parameter space was informed by our previous works on t-b-τ Yukawa unification [6,18].

Employing the boundary condition from Eq. (3) one can define the MSSM gaugino masses at M_G in terms of the mass parameter $M_{1/2}$:

$$M_1 = -M_{1/2},$$
$$M_2 = -3M_{1/2},$$
$$M_3 = 2M_{1/2}. \tag{5}$$

In scanning the parameter space, we employ the Metropolis–Hastings algorithm as described in [23]. The data points collected all satisfy the requirement of REWSB, with the neutralino in each case being the LSP. After collecting the data, we impose the mass bounds on all the particles [20] and use the IsaTools package [24] to implement the various phenomenological constraints. We successively apply the following experimental constraints on the data that we acquire from ISAJET:

m_h (lightest Higgs mass)	$\geqslant 114.4$ GeV	[25]
$BR(B_s \to \mu^+\mu^-)$	$< 5.8 \times 10^{-8}$	[26]
$2.85 \times 10^{-4} \leqslant BR(b \to s\gamma)$	$\leqslant 4.24 \times 10^{-4}$ (2σ)	[27]
$0.15 \leqslant \frac{BR(B_u \to \tau\nu_\tau)_{\text{MSSM}}}{BR(B_u \to \tau\nu_\tau)_{\text{SM}}}$	$\leqslant 2.41$ (3σ)	[27]
$\Omega_{\text{CDM}}h^2$	$= 0.111^{+0.028}_{-0.037}$ (5σ)	[28]
$0 \leqslant \Delta(g-2)_\mu/2$	$\leqslant 55.6 \times 10^{-10}$	[10]

3. Yukawa unification and particle spectroscopy

We define the quantity R as,

$$R = \frac{\max(y_t, y_b, y_\tau)}{\min(y_t, y_b, y_\tau)}. \tag{6}$$
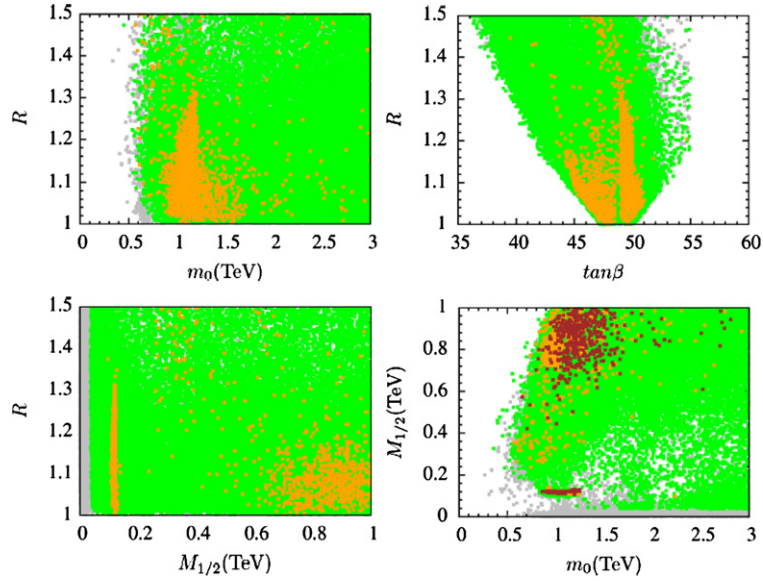
Fig. 1. Plots in R–m_0, R–$\tan\beta$, R–$M_{1/2}$ and $M_{1/2}$–m_0 planes. Gray points are consistent with REWSB and neutralino LSP. Green points satisfy particle mass bounds and constraints from $BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$ and $BR(B_u \to \tau\nu_\tau)$. In addition, we require that green points do no worse than the SM in terms of $(g-2)_\mu$. Orange points belong to a subset of green points and satisfy the WMAP bounds on $\tilde{\chi}_1^0$ dark matter abundance. In the $M_{1/2}$–m_0 plane, points in brown represent a subset of yellow points and satisfy Yukawa coupling unification to within 10%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)
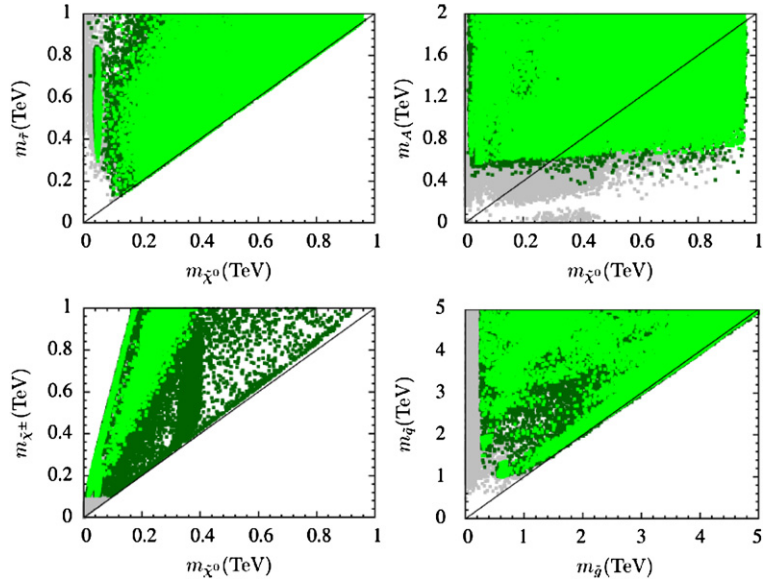

Fig. 2. Plots in the $m_{\tilde{\tau}}$–$m_{\tilde{\chi}_1^0}$, m_A–$m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^\pm}$–$m_{\tilde{\chi}_1^0}$, and $m_{\tilde{q}}$–$m_{\tilde{g}}$ planes. The gray points satisfy the requirements of REWSB and $\tilde{\chi}_1^0$ LSP. Dark green points satisfy particle mass bounds and constraints from $BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$ and $BR(B_u \to \tau\nu_\tau)$. In addition, we require that green points do no worse than the SM in terms of $(g-2)_\mu$. Light green points are a subset of these points which also satisfy Yukawa unification. We show in the $m_{\tilde{\tau}}$–$m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_1^\pm}$–$m_{\tilde{\chi}_1^0}$ planes the unit slope lines representing the respective coannihilation channels. In the m_A–$m_{\tilde{\chi}_1^0}$ plane we show the line $m_A = 2m_{\tilde{\chi}_1^0}$ that signifies the A resonance channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this or Letter.)

Thus, R is a useful indicator for Yukawa unification with $R \leqslant 1.1$, for instance, corresponding to Yukawa unification within 10%.

We next present the results of the scan over the parameter space listed in Eq. (4). In Fig. 1 we show the results in the R–m_0, R–$\tan\beta$, R–$M_{1/2}$ and $M_{1/2}$–m_0 planes. Gray points are consistent with REWSB and neutralino LSP. Green points satisfy particle mass bounds and constraints from $BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$ and $BR(B_u \to \tau\nu_\tau)$. In addition, we require that green points do no worse than the SM in terms of $(g-2)_\mu$. Orange points belong to a subset of green points and satisfy the WMAP bounds on $\tilde{\chi}_1^0$ dark matter abundance. In the $M_{1/2}$–m_0 plane, points in brown rep-

resent a subset of yellow points that are consistent with Yukawa coupling unification to within 10%.

In the R–m_0 plane of Fig. 1 we see that with both $\mu < 0$ and $M_2 < 0$, we can realize Yukawa unification consistent with all constraints mentioned in Section 2 including the one from $(g-2)_\mu$. This is possible because for $\mu < 0$, we can implement Yukawa unification for relatively small $m_0 (\sim 500$ GeV$)$, and, in turn, $(g-2)_\mu$ obtains the desired SUSY contribution proportional to μM_2. This is more than an order of magnitude reduction on the m_0 values required for Yukawa unification with $\mu > 0$ and universal gaugino masses. In the present with 10% or better t-b-τ Yukawa unifi-

cation we obtain a relaxation also of A_0 values similar to the $SU(4)_c \times SU(2)_L \times SU(2)_R$ model in [7], with $-2.5 < A_0/m_0 < 2$. Our observation about relaxing the possible range of $\tan\beta$ that accommodates Yukawa unified models is explicitly shown in the R–$\tan\beta$ plane. In the R–$m_{1/2}$ plane of Fig. 1 we see that employing the boundary conditions for gauginos presented in Eq. (5), the lightest neutralino mass can be as low as 15 GeV consistent with all constraints mentioned in Section 2 including the one from $(g-2)_\mu$. Note that it is impossible to realize a neutralino mass as this in the universal gaugino case due to the chargino mass constraint. A narrow orange strip for low $M_{1/2}$ values indicates the existence of Z and light Higgs resonance solutions for neutralino dark matter. Actually, there are two very narrow strips, one around 45 GeV and a second around 60 GeV, even though they appear as one strip in the figure. In order to better visualize the magnitude of the sparticle masses consistent with t-b-τ Yukawa unification, we present our results in the $M_{1/2}$–m_0 plane, where the brown points correspond to Yukawa unification better than 10%.

In Fig. 2 we show the relic density channels consistent with Yukawa unification in the $m_{\tilde\tau}$–$m_{\tilde\chi_1^0}$, m_A–$m_{\tilde\chi_1^0}$, $m_{\tilde\chi_1^\pm}$–$m_{\tilde\chi_1^0}$, and $m_{\tilde q}$–$m_{\tilde g}$ planes. Gray points shown in this figure satisfy the requirements of REWSB and $\tilde\chi_1^0$ LSP. Dark green points satisfy the particle mass bounds and constraints from $BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$ and $BR(B_u \to \tau\nu_\tau)$. The green points do no worse than the SM in terms of $(g-2)_\mu$. The light green points represent a subset of the dark green points, and correspond to 10% or better t-b-τ Yukawa unification. This choice of color coding is influenced from displaying the sparticle spectrum with and without t-b-τ Yukawa unification, while still focussing on all the other experimental constraints. The idea is to show the myriad of solutions that implement Yukawa unification and are consistent with all known experimental bounds except that on relic dark matter density from WMAP. The appearance of a variety of Yukawa unified solutions with a very rich sparticle spectrum is a characteristic feature of $\mu < 0$ [7].

We can see in Fig. 2 that a variety of coannihilation and resonance scenarios are compatible with Yukawa unification and neutralino dark matter. Included in the m_A–$m_{\tilde\chi_1^0}$ plane is the line $m_A = 2m_{\tilde\chi_1^0}$ which shows that the A-funnel region is compatible with Yukawa unification. In the $m_{\tilde\tau}$–$m_{\tilde\chi_1^0}$ plane in Fig. 2, we draw the unit slope line which indicates the presence of stau coannihilation scenarios. From the $m_{\tilde\chi_1^\pm}$–$m_{\tilde\chi_1^0}$ plane, it is easy to recognize the light Higgs (h) and Z resonance channels. We expect that other coannihilation channels like the stop coannihilation scenario are also consistent with Yukawa unification, although we have not found them, perhaps due to lack of statistics.

Let us remark on the low mass neutralino solutions that we have found in our model (with $\mu < 0$). Because of the M_G scale gaugino mass relations in Eq. (5), it is possible in principle to have small M_1 values, thus giving rise to a light neutralino. The neutralino mass nonetheless is bounded from below because of the relic density bounds on dark matter. The SO(10) model with nonuniversal gaugino masses, as in this Letter, has all the ingredients to bring down the neutralino mass to the lowest possible value consistent with the various constraints. The solution with the neutralino (mass ~ 43 GeV) is consistent with Yukawa unification and corresponds the Z-resonance dark matter scenario.

Finally, in Table 1 we present some benchmark points for the SO(10) t-b-τ Yukawa unified model with $\mu < 0$ and non-universal gaugino masses. All of these points contain WMAP compatible with neutralino dark matter and satisfy the constraints mentioned in Section 2. Point 1 depicts a solution with essentially perfect Yukawa unification corresponding to the A-funnel region. Points 2 and 3 correspond to the light Higgs and Z-resonance solutions,

Table 1

Sparticle and Higgs masses (in GeV). All of these benchmark points satisfy the various constraints mentioned in Section 2 and are compatible with Yukawa unification. Point 1 depicts a solution corresponding to the A-funnel region. Points 2 and 3 display the light Higgs and Z-resonance solutions, while point 4 represents the stau coannihilation solution.

	Point 1	Point 2	Point 3	Point 4
m_0	1208	1027	1125	679
M_1	−677	−111	−122	−216
M_2	−2031	−333	−366	−648
M_3	1354	222	244	432
m_{H_d}	1689	1395	1511	1263
m_{H_u}	1260	1001	1093	724
$\tan\beta$	48.1	49.3	49.6	48.2
A_0/m_0	0.56	−0.24	−0.26	0.95
m_t	173.1	173.1	173.1	173.1
μ	−938	−246	−276	−263
m_h	119	111	112	112
m_H	672	593	608	680
m_A	668	590	604	675
$m_{H^\pm}$	679	601	616	686
$m_{\tilde\chi_{1,2}^0}$	313, 945	47, 211	52, 240	94, 261
$m_{\tilde\chi_{3,4}^0}$	949, 1729	256, 333	286, 362	272, 566
$m_{\tilde\chi_{1,2}^\pm}$	961, 1709	211, 333	240, 363	263, 559
$m_{\tilde g}$	2957	604	659	1040
$m_{\tilde u_{L,R}}$	3072, 2785	1142, 1108	1250, 1214	1192, 1099
$m_{\tilde t_{1,2}}$	2197, 2602	691, 749	757, 815	817, 915
$m_{\tilde d_{L,R}}$	3074, 2795	1145, 1131	1253, 1237	1195, 1124
$m_{\tilde b_{1,2}}$	2227, 2585	630, 718	687, 785	721, 898
$m_{\tilde\nu_1}$	1771	1034	1134	782
$m_{\tilde\nu_3}$	1565	857	939	601
$m_{\tilde e_{L,R}}$	1774, 1257	1038, 1051	1137, 1150	787, 723
$m_{\tilde\tau_{1,2}}$	449, 1569	654, 861	714, 943	112, 607
$\Delta(g-2)_\mu$	0.26×10^{-9}	0.18×10^{-8}	0.68×10^{-9}	0.19×10^{-8}
σ_{SI} (pb)	0.56×10^{-9}	0.12×10^{-7}	0.86×10^{-8}	0.10×10^{-7}
σ_{SD} (pb)	0.2×10^{-6}	0.43×10^{-4}	0.27×10^{-4}	0.38×10^{-4}
$\Omega_{CDM}h^2$	0.08	0.104	0.08	0.12
R	1.00	1.02	1.00	1.00

while point 4 represents the stau coannihilation solution. It is interesting to note that for the light Higgs and Z-resonance solutions, there is an upper bound on the gluino mass. Employing the boundary condition in Eq. (5) this turns out to be $m_g \approx 700$ GeV. Hence, the light Higgs and Z-resonance solutions are not compatible with this model if the gluinos are founded to be heavier than ≈ 700 GeV.

The ATLAS [29] and CMS [30] Collaborations have been regularly updating the mass bounds for squarks and gluinos. In particular, the available parameter space for low scale supersymmetric models has been reduced. As we can see in Fig. 2, in the panel $m_{\tilde q}$ vs. $m_{\tilde g}$, the lower mass bounds for the squarks of the first two generations are around 1 TeV, which will soon be tested by ATLAS and CMS. Besides, we can see from this figure that the gluinos in this model can be as light as 400 GeV, which also can be tested soon. The ATLAS Collaboration has mostly studied the so called simplified model containing only squarks of the first two generations, gluino and "massless" LSP neutralino. In this case the gluino masses below 725 GeV are excluded at the 95% confidence level. If this result will be confirmed for the more general case, then all models with light gluinos will be ruled out. In particular, this result will rule out the light Higgs resonance solution in the CMSSM, while still allowing it to be viable in the present model. The reason is the non-universal boundary condition in Eq. (3) for

gauginos at M_{GUT}, which allows one to have gluino masses heavier than 700 GeV with the lightest neutralino mass of around 60 GeV.

4. Conclusion

We have shown that SO(10) t-b-τ Yukawa unification with $\mu < 0$ and non-universal gaugino masses is nicely consistent with all available experimental data. We have considered a variety of WMAP compatible neutralino dark matter scenarios, including some examples in which the LSP neutralino can be rather light, about half the Z-boson mass (Z-resonance solution) or the SM-like Higgs mass (light Higgs resonance solution). Neutralino dark matter solutions corresponding to the A-funnel region and stau-coannihilation are also shown to exist. With $\mu M_2 > 0$, the SUSY contributions to the muon anomalous magnetic moment can help provide better agreement than the SM with the experimental data. Finally, in comparison to SO(10) with $\mu > 0$ and universal gaugino masses, there exist some important differences, even though the number of fundamental parameters in the two cases are the same. The lack of WMAP compatible neutralino dark matter in the $\mu > 0$ case is one of them. Also, with $\mu < 0$, we find examples in which the first two squark families are relatively light ($\sim$ TeV), and the third family b and t squarks can be lighter than the gluino (which happens to be the lightest colored sparticle in SUSY SO(10) with $\mu > 0$).

Note added

As we were finishing this work, Stuart Raby pointed out that M. Badziak, M. Olechowski and S. Pokorski are also investigating SO(10) Yukawa unification with $\mu < 0$.

Acknowledgements

References

[1] B. Ananthanarayan, G. Lazarides, Q. Shafi, Phys. Rev. D 44 (1991) 1613;
B. Ananthanarayan, G. Lazarides, Q. Shafi, Phys. Lett. B 300 (24) (1993) 5;
Q. Shafi, B. Ananthanarayan, Trieste HEP Cosmol. (1991) 233.
[2] L.J. Hall, R. Rattazzi, U. Sarid, Phys. Rev. D 50 (1994) 7048;
M. Olechowski, S. Pokorski, Phys. Lett. B 214 (1988) 393;
T. Banks, Nucl. Phys. B 303 (1988) 172;
V. Barger, M. Berger, P. Ohmann, Phys. Rev. D 49 (1994) 4908;
M. Carena, M. Olechowski, S. Pokorski, C. Wagner, Nucl. Phys. B 426 (1994) 269;
B. Ananthanarayan, Q. Shafi, X. Wang, Phys. Rev. D 50 (1994) 5980;
G. Anderson, et al., Phys. Rev. D 47 (1993) 3702;
G. Anderson, et al., Phys. Rev. D 49 (1994) 3660;
R. Rattazzi, U. Sarid, Phys. Rev. D 53 (1996) 1553;
T. Blazek, M. Carena, S. Raby, C. Wagner, Phys. Rev. D 56 (1997) 6919;
T. Blazek, S. Raby, K. Tobe, Phys. Rev. D 62 (2000) 055001;
H. Baer, M. Diaz, J. Ferrandis, X. Tata, Phys. Rev. D 61 (2000) 111701;
H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana, X. Tata, Phys. Rev. D 63 (2001) 015007;
C. Balazs, R. Dermisek, JHEP 0306 (2003) 024;

C. Pallis, Nucl. Phys. B 678 (2004) 398;
U. Chattopadhyay, A. Corsetti, P. Nath, Phys. Rev. D 66 (2002) 035003;
T. Blazek, R. Dermisek, S. Raby, Phys. Rev. Lett. 88 (2002) 111804;
T. Blazek, R. Dermisek, S. Raby, Phys. Rev. D 65 (2002) 115004;
M. Gomez, T. Ibrahim, P. Nath, S. Skadhauge, Phys. Rev. D 72 (2005) 095008;
K. Tobe, J.D. Wells, Nucl. Phys. B 663 (2003) 123;
I. Gogoladze, Y. Mimura, S. Nandi, Phys. Lett. B 562 (2003) 307;
W. Altmannshofer, D. Guadagnoli, S. Raby, D.M. Straub, Phys. Lett. B 668 (2008) 385;
S. Antusch, M. Spinrath, Phys. Rev. D 78 (2008) 075020;
H. Baer, S. Kraml, S. Sekmen, JHEP 0909 (2009) 005;
S. Antusch, M. Spinrath, Phys. Rev. D 79 (2009) 095004;
D. Guadagnoli, S. Raby, D.M. Straub, JHEP 0910 (2009) 059;
K. Choi, D. Guadagnoli, S.H. Im, C.B. Park, JHEP 1010 (2010) 025;
S. Dar, I. Gogoladze, Q. Shafi, C.S. Un, arXiv:1105.5122 [hep-ph];
N. Karagiannakis, G. Lazarides, C. Pallis, arXiv:1107.0667 [hep-ph].
[3] H. Baer, S. Kraml, S. Sekmen, H. Summy, JHEP 0803 (2008) 056;
H. Baer, M. Haider, S. Kraml, S. Sekmen, H. Summy, JCAP 0902 (2009) 002.
[4] I. Gogoladze, R. Khalid, Q. Shafi, Phys. Rev. D 79 (2009) 115004.
[5] H. Baer, S. Kraml, A. Lessa, S. Sekmen, JHEP 1002 (2010) 055;
D. Feldman, Z. Liu, P. Nath, Phys. Rev. D 80 (2009) 015007;
M.A. Ajaib, T. Li, Q. Shafi, K. Wang, JHEP 1101 (2011) 028.
[6] I. Gogoladze, R. Khalid, Q. Shafi, Phys. Rev. D 80 (2009) 095016.
[7] I. Gogoladze, R. Khalid, S. Raza, Q. Shafi, JHEP 1012 (2010) 055, arXiv:1008.2765 [hep-ph].
[8] J.C. Pati, A. Salam, Phys. Rev. D 10 (1974) 275.
[9] S. Profumo, C.E. Yaguna, Phys. Rev. D 69 (2004) 115009;
D. Feldman, Z. Liu, P. Nath, Phys. Rev. D 80 (2009) 015007.
[10] G.W. Bennett, et al., Muon G-2 Collaboration, Phys. Rev. D 73 (2006) 072003.
[11] See, for instance, S.P. Martin, Phys. Rev. D 79 (2009) 095019;
U. Chattopadhyay, D. Das, D.P. Roy, Phys. Rev. D 79 (2009) 095013;
B. Ananthanarayan, P.N. Pandita, Int. J. Mod. Phys. A 22 (2007) 3229;
S. Bhattacharya, A. Datta, B. Mukhopadhyaya, JHEP 0710 (2007) 080;
A. Corsetti, P. Nath, Phys. Rev. D 64 (2001) 125010, and references therein.
[12] A. Chamseddine, R. Arnowitt, P. Nath, Phys. Rev. Lett. 49 (1982) 970;
R. Barbieri, S. Ferrara, C. Savoy, Phys. Lett. B 119 (1982) 343;
N. Ohta, Prog. Theor. Phys. 70 (1983) 542;
L.J. Hall, J.D. Lykken, S. Weinberg, Phys. Rev. D 27 (1983) 2359;
for a review see S. Weinberg, Supersymmetry, The Quantum Theory of Fields, vol. 3, Cambridge University Press, 2000, 442 p.
[13] N. Okada, S. Raza, Q. Shafi, arXiv:1107.0941 [hep-ph].
[14] H. Baer, F.E. Paige, S.D. Protopopescu, X. Tata, arXiv:hep-ph/0001086.
[15] J. Hisano, H. Murayama, T. Yanagida, Nucl. Phys. B 402 (1993) 46;
Y. Yamada, Z. Phys. C 60 (1993) 83;
J.L. Chkareuli, I.G. Gogoladze, Phys. Rev. D 58 (1998) 055011.
[16] D.M. Pierce, J.A. Bagger, K.T. Matchev, R.-j. Zhang, Nucl. Phys. B 491 (1997) 3.
[17] M. Olechowski, S. Pokorski, Phys. Lett. B 344 (1995) 201;
D. Matalliotakis, H.P. Nilles, Nucl. Phys. B 435 (1995) 115;
H. Murayama, M. Olechowski, S. Pokorski, Phys. Lett. B 371 (1996) 57.
[18] I. Gogoladze, R. Khalid, S. Raza, Q. Shafi, JHEP 1106 (2011) 117.
[19] M. Drees, Phys. Lett. B 181 (1986) 279;
C.F. Kolda, S.P. Martin, Phys. Rev. D 53 (1996) 3871, arXiv:hep-ph/9503445.
[20] K. Nakamura, et al., Particle Data Group Collaboration, J. Phys. G 37 (2010) 075021.
[21] Tevatron Electroweak Working Group, CDF Collaboration, D0 Collaboration, arXiv:0903.2503 [hep-ex].
[22] See for instance J.R. Ellis, K.A. Olive, P. Sandick, Phys. Rev. D 78 (2008) 075012, and references therein.
[23] G. Belanger, F. Boudjema, A. Pukhov, R.K. Singh, JHEP 0911 (2009) 026;
H. Baer, S. Kraml, S. Sekmen, H. Summy, JHEP 0803 (2008) 056.
[24] H. Baer, C. Balazs, A. Belyaev, JHEP 0203 (2002) 042;
H. Baer, C. Balazs, J. Ferrandis, X. Tata, Phys. Rev. D 64 (2001) 035004.
[25] S. Schael, et al., Eur. Phys. J. C 47 (2006) 547.
[26] T. Aaltonen, et al., CDF Collaboration, Phys. Rev. Lett. 100 (2008) 101802.
[27] E. Barberio, et al., Heavy Flavor Averaging Group, arXiv:0808.1297 [hep-ex].
[28] E. Komatsu, et al., WMAP Collaboration, Astrophys. J. Suppl. 180 (2009) 330.
[29] ATLAS Collaboration, ATLAS-CONF-2011-086.
[30] S. Chatrchyan, et al., CMS Collaboration, arXiv:1107.1279 [hep-ex].