Coannihilation Scenarios and Particle Spectroscopy in $SU(4)_c \times SU(2)_L \times SU(2)_R$

Ilia Gogoladze\textsuperscript{1} Rizwan Khalid\textsuperscript{2} and Qaisar Shafi

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

Abstract

We identify a variety of coannihilation scenarios in a supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ model with discrete left-right symmetry. Non-universal gaugino masses, compatible with the gauge symmetry, play an essential role in realizing gluino and bino-wino coannihilation regions that are consistent with the WMAP dark matter constraints. We also explore regions of the parameter space in which the little hierarchy problem is partially resolved. We present several phenomenologically interesting benchmark points and the associated sparticle and Higgs mass spectra.

\textsuperscript{1}E-mail: ilia@physics.udel.edu

On leave of absence from: Andronikashvili Institute of Physics, GAS, 380077 Tbilisi, Georgia.

\textsuperscript{2}E-mail: rizwan@udel.edu
1 Introduction

In a recent paper, hereafter referred to as [1], we explored the phenomenology of a supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ (4-2-2) model [2] with third family Yukawa unification [3, 4]. We showed, in particular, that Yukawa unification and neutralino dark matter are readily compatible in this 4-2-2 model, which should be contrasted with the conclusion reached in [5] within the corresponding SO(10) framework where it is extremely hard to do so. The reason for this difference largely stems from the assumption made in 4-2-2 of tree-level gaugino non-universality, which is not possible in SO(10). Thus, in contrast to the latter, there is an additional soft parameter in 4-2-2 which enables one, via gluino coannihilation [6], to make third family Yukawa unification and neutralino dark matter mutually consistent. In [1] we showed some benchmark points highlighting the characteristic sparticle and Higgs mass spectra in the presence of Yukawa unification. A relatively light gluino is a characteristic feature of this 4-2-2 [1] as well as SO(10) [5] model.

In this paper we carry out a more thorough investigation of the 4-2-2 model without insisting on Yukawa unification. We assume low scale gravity mediated supersymmetry breaking [7], and allow the asymptotic gaugino masses to be non-universal at tree level, compatible with the 4-2-2 symmetry [8, 9]. We identify a variety of coannihilation scenarios in this more general model which, as in [1], also has discrete left-right symmetry [2, 10] (more precisely C-parity) [11]. As in [1], non-universal gaugino masses, compatible with the 4-2-2 gauge symmetry, play an essential role in realizing gluino [6] and bino-wino [12] coannihilation regions that are consistent with the WMAP dark matter constraints. We also explore regions of the parameter space in which the little hierarchy problem is partially resolved. We present several benchmark points and the associated sparticle and Higgs mass spectra. Many of the new particles are in a mass range which is accessible at the LHC.

Supplementing 4-2-2 with a discrete left-right (LR) symmetry reduces the number of independent gauge couplings in 4-2-2 from three to two. This is because LR symmetry imposes $SU(2)_L$ and $SU(2)_R$ gauge coupling unification condition at $M_{GUT}$ ($g_L = g_R$). In 4-2-2 the matter fields are unified into three generations of $\psi (4, 2, 1)$, and the antimatter fields are in three generations of $\psi^c (\bar{4}, 1, 2)$. If the minimal supersymmetric standard model (MSSM) electroweak doublets come from the bi-doublet $H(1, 2, 2)$, the third family Yukawa coupling $H \psi^c \psi$ yields the following relation valid at $M_{GUT}$, namely

$$Y_t = Y_b = Y_\tau = Y_{\text{Dirac}}.$$  

In order to get the correct fermion masses and mixings one possibility is to assume that the SM Higgs partially comes from $\Delta (15, 2, 2)$ dimensional representation of 4-2-2 [13]. In other words we have to assume that the SM Higgs doublet is a superposition of $(1, 2, 2)$ and $(15, 2, 2)$ Higgs fields.
In this case, the superpotential for the Yukawa sector of the 4-2-2 model is

\[ Y_{1}^{ij} \psi_{c} \psi H + Y_{2}^{ij} \psi_{c} \psi \Delta \quad (2) \]

With the MSSM Higgs doublets now arising from a linear combination of the Higgs doublets in (1,2,2) and (15,2,2), the Yukawa unification condition in Eq. (1) is in general lost.

We will assume that due to C-parity the soft mass\(^2\) terms, induced at \( M_{\text{GUT}} \) through gravity mediated supersymmetry breaking are equal in magnitude for the scalar squarks and sleptons of the three families. The tree level asymptotic MSSM gaugino masses, on the other hand, can be non-universal from the following consideration. From C-parity, we can expect that the gaugino masses at \( M_{\text{GUT}} \) associated with \( SU(2)_L \) and \( SU(2)_R \) are the same (\( M_2 \equiv M_2^R = M_2^L \)). However, the asymptotic \( SU(4)_c \) and consequently \( SU(3)_c \) gaugino masses can be different. With the hypercharge generator in 4-2-2 given by

\[ Y = \sqrt{\frac{2}{5}}(B-L) + \sqrt{\frac{3}{5}}I_{3R}, \]

where \( B-L \) and \( I_{3R} \) are the diagonal generators of \( SU(4)_c \) and \( SU(2)_R \), we have the following asymptotic relation between the three MSSM gaugino masses:

\[ M_1 = \frac{3}{5}M_2 + \frac{2}{5}M_3. \quad (3) \]

The supersymmetric 4-2-2 model with C-parity thus has two independent parameters (\( M_2 \) and \( M_3 \)) in the gaugino sector. The fundamental parameters of the 4-2-2 model are as follows:

\[ m_0, m_{H_u}, m_{H_d}, M_2, M_3, A_0, \tan \beta, \text{sign } \mu. \quad (4) \]

Thus, compared to the \( NUHM2 \) model of [14], we have one additional parameter in 4-2-2 which plays a crucial role in opening up several distinct coannihilation channels each associated with a characteristic sparticle and Higgs mass spectrum.

The outline for the rest of the paper 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, highlight some of the predictions of the 4-2-2 model, and display some benchmark points. Our conclusions are summarized in Section 4.

2 Phenomenological constraints and scanning procedure

We employ the ISAJET 7.78 package [15] to perform random scans over the parameter space listed in Eq. (4). In this package, the weak scale values of gauge and third generation Yukawa couplings are evolved to \( M_{\text{GUT}} \) via the MSSM renormalization group equations (RGEs) in the \( \overline{DR} \) regularization scheme, where \( M_{\text{GUT}} \) is defined to be the scale at which \( g_1 = g_2 \). We do not enforce the unification condition \( g_3 = g_1 = g_2 \) at \( M_{\text{GUT}} \), since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [16]. At \( M_{\text{GUT}} \), the boundary conditions are imposed and
all the (soft supersymmetry breaking) SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale $M_Z$. The impact of the neutrino Dirac Yukawa coupling in the running of the RGEs is significant only for relatively large values ($\sim 2$ or so) [17]. In our model we expect the largest Dirac coupling to be comparable, at best, to the top Yukawa coupling ($\sim 0.5$).

In the evaluation of Yukawa couplings the SUSY threshold corrections [18] are taken into account at the common scale $M_{SUSY} = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$. The entire parameter set is iteratively run between $M_Z$ and $M_{GUT}$ 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 an optimized scale $M_{SUSY}$, 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) [19] puts an important theoretical constraint on the parameter space. 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 dark matter relic abundance bound.

We have performed random scans for the following parameter range:

\begin{align*}
0 &\leq m_0 &\leq 10 \text{ TeV}, \\
0 &\leq M_2 &\leq 1 \text{ TeV}, \\
0 &\leq M_3 &\leq 1 \text{ TeV}, \\
-30 \text{ TeV} &\leq A_0 &\leq 0, \\
0 &\leq m_{H_u} &\leq 10 \text{ TeV}, \\
0 &\leq m_{H_d} &\leq 10 \text{ TeV}, \\
1 &\leq \tan \beta &\leq 65,
\end{align*}

(5)

with $\mu > 0$, and $m_t = 172.6 \text{ GeV}$ [21]. A more recent estimate by the CDF/D0 collaboration quotes a slightly larger value $m_t = 173.1$ [22]. This does not change our conclusions in any significant way.

We first collected 1 million points for the 4-2-2 model. To this we added the results of constrained MSSM (CMSSM) and CMSSM with non-universal Higgs (150,000 points each), as these are subsets of the 4-2-2 model. All of these points satisfy the requirement of REWSB with the neutralino being the LSP in each case. Furthermore, all of these points satisfy the constraint $\Omega_{CDM} h^2 \leq 10$. This is done so as to collect more points with a WMAP compatible value of cold dark matter relic
abundance. After collecting the data, we use the IsaTools package \cite{23} to implement the following phenomenological constraints:

\[
\begin{align*}
    m_{\tilde{\chi}^\pm} & \geq 103.5 \text{ GeV} \quad [20] \\
m_{\tilde{\tau}} & \geq 86 \text{ GeV} \quad [20] \\
m_{\tilde{t}} & \geq 175 \text{ GeV} \quad [20] \\
m_{\tilde{b}_1} & \geq 222 \text{ GeV} \quad [20] \\
m_{\tilde{g}} & \geq 220 \text{ GeV} \quad [20] \\
m_h & \geq 114.4 \text{ GeV} \quad [24] \\
    BR(B_s \rightarrow \mu^+\mu^-) & < 5.8 \times 10^{-8} \quad [25] \\
    2.85 \times 10^{-4} \leq BR(b \rightarrow s\gamma) & \leq 4.24 \times 10^{-4} \ (2\sigma) \quad [26] \\
    \Omega_{\text{CDM}}h^2 & = 0.111^{+0.028}_{-0.037} \ (5\sigma) \quad [27] \\
    3.4 \times 10^{-10} \leq (g-2)_\mu & \leq 55.6 \times 10^{-10} \ (3\sigma) \quad [28]
\end{align*}
\]

We apply the experimental constraints successively on the data that we acquire from ISAJET. In our plots we exhibit points that satisfy all of the above constraints as well as those that do not satisfy the \((g-2)_\mu\) constraint.

\section{Results}

The asymptotic gaugino mass parameter \(M_1\) is constrained by Eq.\((3)\) at \(M_{\text{GUT}}\) which is characteristically different from the asymptotic relation \(M_1 = M_2 = M_3\) in the case of CMSSM. In the CMSSM, after RGE running, it is therefore not possible to have the three gauginos nearly degenerate in mass at the low scale. Indeed at 1-loop level, we have the relations \(M_3 \sim 6M_1\) and \(M_2 \sim 2M_1\). In the 4-2-2 model, if we start with a low value at \(M_{\text{GUT}}\) of the ratio \(M_3/M_2\), it is possible to realize \(M_3 \sim M_2\) at the \(\text{TeV}\) scale. This scenario offers a relatively light gluino NLSP (next to LSP), so that gluino coannihilation plays an important role in determining the LSP relic density \[6\]. Similarly, if we start with a large value of \(M_3/M_2\) at \(M_{\text{GUT}}\), it is possible to have the wino nearly degenerate with the bino, in which case one opens up the bino-wino coannihilation channel \[12\]. This can be seen in Figure 1 where we plot results in the \(M_2 - M_3\), \(m_0 - M_2\) and \(m_0 - M_3\) planes. Shown in gray are points that satisfy REWSB and the requirement that the LSP is a neutralino. The other three colors depict points that satisfy the above mentioned bounds except the \((g-2)_\mu\) constraint. These include the WMAP bounds on dark matter relic density and various collider constraints \(BR(B_s \rightarrow \mu^+\mu^-), BR(b \rightarrow s\gamma)\), and (s)particle mass bounds). Shown in orange is the gluino coannihilation channel which occurs at low \(M_3\) and high \(M_2\) values. We show the bino-wino coannihilation channel in red which occurs at low \(M_2\) and high \(M_3\). Shown in blue are all other coannihilation channels which have been extensively studied in the CMSSM and CMSSM with non-universal Higgs \[29\]. Figure 2 is similar to Figure 1 except that we now show the effect of imposing in addition the constraint from
The allowed parameter space in this case is appreciably shrunk, which is understandable because as we increase \( m_0 \), the MSSM particles gradually decouple from the theory and we end up with the SM result for \((g - 2)_\mu\). We note, however, the two new coannihilation channels introduced by the 4-2-2 model are also present in Figure 2.

In Figure 3 we show results in the \( A_0 - M_3/M_2 \), \( \tan \beta - M_3/M_2 \), \( m_{H_u}/m_{H_d} - M_3/M_2 \) and \( \mu - M_3/M_2 \) planes. The green points satisfy all the constraints, while the blue ones satisfy all constraints except the one from \((g - 2)_\mu\). We do not distinguish the bino-wino and gluino coannihilation channels in Figure 3. The \( A_0 - M_3/M_2 \) plane shows that the \((g - 2)_\mu\) constraint can only be satisfied for \(|A_0| \lesssim 4\text{TeV}\). The \( \tan \beta - M_3/M_2 \) plane shows a wide range of allowed values for \( \tan \beta \). If we focus on the \( m_{H_u}/m_{H_d} - M_3/M_2 \) plane, we can identify points on the \( M_3/M_2 = 1 \) line with the non-universal Higgs model. The CMSSM corresponds to a single point in the \( m_{H_u}/m_{H_d} - M_3/M_2 \) plane, while the \( m_{H_u}/m_{H_d} = 1 \) line displays the effect of varying the ratio \( M_3/M_2 \) in the \( NUHM1 \) parameter space [14], with \( M_1 \) given by Eq.(3). The results in the \( \mu - M_3/M_2 \) plane show that in the 4-2-2 model we have the possibility of realizing relatively small \( \mu \) values and, hence, there exists the potential for ameliorating the little hierarchy problem [30].

We exhibit in Figure 4 the various coannihilation as well as the resonance channels by plotting the relevant (NLSP) sparticle mass versus the lightest neutralino. The color coding is the same as in Figure 3 except that we now suppress the gray background corresponding to the region allowed by REWSB and a neutralino LSP. In the \( m_{\tilde{\chi}_1^0}(\text{bino}) - m_{\tilde{\chi}_2^0}(\text{wino}) \) plane we show those solutions for which the lightest neutralino is essentially a pure bino and the NLSP is primarily a wino. The unit slope line in this plane corresponds to the bino-wino coannihilation region. In the \( m_{\tilde{\chi}_1^0}(\text{not bino}) - m_{\tilde{\chi}_2^0}(\text{not wino}) \) plane we can recognize the possibility for coannihilation between the two lightest neutralinos with the lightest neutralino not a pure bino and the NLSP not primarily a wino. This case mostly corresponds to the coannihilation of higgsinos.

We display the gluino coannihilation region in the \( m_{\tilde{\chi}_1^0} - m_{\tilde{g}} \) plane. Consistent with all known bounds, the gluino can be as light as 250 GeV or so.

We can recognize the \( A \)-funnel region in the \( 2m_{\tilde{\chi}_1^0} - m_A \) plane where neutralino annihilation occurs through the CP-odd Higgs resonance channel. In the \( m_{\tilde{\chi}_1^0} - m_{\tilde{t}} \) plane we have the stop coannihilation region with the possibility of a stop as light as \( \sim 200 \text{GeV} \). Even though the stop coannihilation region is found in the CMSSM, the possibility of a light stop consistent with all constraints including the one from \((g - 2)_\mu\) is a rather exciting feature of the 4-2-2 model. The stau-coannihilation region is displayed in the \( m_{\tilde{\chi}_1^0} - m_{\tilde{\tau}} \) plane.

In Figure 5 we show the various coannihilation and resonance channels as a function of \( M_3/M_2 \). We have plotted on the y-axis \( m_{i}/m_{\tilde{\chi}_1^0} \) in the case of coannihilations and \( m_{i}/2m_{\tilde{\chi}_1^0} \) in the case of resonance annihilations of the neutralino, where \( m_{i} \) is the NLSP mass. This means that in each
figure, we need to focus close to the line $y = 1$ in order to see coannihilations and resonances. The $M_3/M_2 - m_{\tilde{\chi}_1^0}/m_{\tilde{\chi}_1^0}$ plane shows, once again, that bino-wino coannihilation occurs for a relatively large value of $M_3/M_2 \gtrsim 2.5$. The coannihilations shown in this plane close to $M_3/M_2 \sim 1$ are due to the higgsinos. The $M_3/M_2 - m_{\tilde{g}}/m_{\tilde{\chi}_1^0}$ plane shows that for gluino coannihilations to work, one needs $M_3/M_2 \lesssim 0.1$ at $M_{\text{GUT}}$. It is, therefore, not surprising that these channels are not found in the CMSSM as they need a large splitting in the gaugino sector. The other four planes have coannihilation solutions corresponding to $M_3 \sim M_2$ as well as regions in parameter space that have a splitting between $M_2$ and $M_3$. The $M_3/M_2 - m_{\tilde{t}}/m_{\tilde{\chi}_1^0}$ plane is rather interesting as it shows that stop-coannihilation prefers a ratio of $M_3/M_2$ smaller than 1. This is understandable because with an increase in the gluino mass, the stop will become heavier. It seems from the $M_3/M_2 - m_{\tilde{t}}/m_{\tilde{\chi}_1^0}$ plane that annihilation via the lightest Higgs resonance occurs for $M_3/M_2 \leq 1$. However, this may just be due to a lack of statistics rather than a trend.

Finally we present a few benchmark points in Table 1 highlighting phenomenologically interesting features of the 4-2-2 model. Point 1 has been taken from the bino-wino coannihilation region while point 2 represents a solution in the gluino coannihilation region of the 4-2-2 parameter space. Gluino coannihilations play a crucial role in reconciling the neutralino dark matter relic density with Yukawa coupling unification in the 4-2-2 model, as discussed in [1]. In Point 3, with a neutralino of mass $\sim 46$ GeV, we demonstrate the possibility of resonant enhancement of neutralino annihilation via the $Z$-boson resonance state. Point 4 highlights another distinguishing feature of the 4-2-2 model. In the case of the CMSSM, the left-handed selectron is heavier than the right handed selectron because of the larger strength of the $SU(2)$ interaction. In 4-2-2, it is possible to achieve $m_{\tilde{e}_L} < m_{\tilde{e}_R}$. This happens typically for a small $M_3/M_2$ ratio. Point 4 corresponds to the bino-wino coannihilation channel, while point 5 represents a solution with a relatively small magnitude of $\mu$, so that the little hierarchy problem can be ameliorated.

### 4 Conclusions

We have shown that the Higgs and sparticle spectroscopy arising from the supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$ model with non-universal gaugino masses can be quite distinct from the well studied constrained minimal supersymmetric standard model. Gluino and bino-wino coannihilation scenarios in particular, with their associated spectroscopy, are particularly exciting possibilities which will be tested at the LHC.
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Figure 1: Plots in the $M_2 - M_3$, $m_0 - M_2$ and $m_0 - M_3$ planes. Gray points are consistent with REWSB and $\tilde{\chi}^0_1$ LSP. Blue, orange and red points satisfy the WMAP bounds on $\tilde{\chi}^0_1$ dark matter abundance and various constraints from colliders ($BR(B_s \rightarrow \mu^+\mu^-)$, $BR(b \rightarrow s\gamma)$, and (s)particle mass bounds). Orange points represent the gluino coannihilation channel, red points depict the bino-wino coannihilation channel, while blue points represent all other channels.
Figure 2: Plots in the $M_2 - M_3$, $m_0 - M_2$ and $m_0 - M_3$ planes. Color coding same as in Figure 1, except that now the orange, red and blue points also satisfy the $(g - 2)_\mu$ constraint.
Figure 3: Plots in the $A_0 - M_3/M_2$, $\tan \beta - M_3/M_2$, $m_{H_u}/m_{H_d} - M_3/M_2$ and $\mu - M_3/M_2$ planes. Gray points are consistent with REWSB and $\tilde{\chi}_0^0$ LSP. Blue points satisfy the WMAP bounds on $\tilde{\chi}_1^0$ abundance and various constraints from colliders ($BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$, and (s)particle mass bounds). Green points also satisfy the $(g-2)_\mu$ constraint.
Figure 4: Plots in the $m_{\tilde{\chi}_1^0}$ (bino) - $m_{\tilde{\chi}_2^0}$ (wino), $m_{\tilde{\chi}_1^0}$ (not bino) - $m_{\tilde{\chi}_2^0}$ (not wino), $m_{\tilde{\chi}_1^0} - m_{\tilde{g}}$, $2m_{\tilde{\chi}_1^0} - m_A$, $m_{\tilde{\chi}_1^0} - m_t$ and $m_{\tilde{\chi}_1^0} - m_{\tilde{\tau}}$ planes. Also shown is the unit slope line in each case. Color coding same as in Figure 3.
Figure 5: $M_3/M_2$ versus $m_{\chi_2^0}/m_{\tilde{\chi}_1^0}$, $m_h/2m_{\tilde{\chi}_1^0}$, $m_\phi/m_{\tilde{\chi}_1^0}$, $m_A/2m_{\tilde{\chi}_1^0}$, $m_t/m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}/m_{\tilde{\chi}_1^0}$. Color coding same as in Figure 3.
|                | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 |
|----------------|---------|---------|---------|---------|---------|
| $m_0$          | 244.10  | 1193.7  | 4778.5  | 3064.6  | 464.83  |
| $M_2$          | 206.02  | 914.41  | 126.07  | 304.23  | 407.81  |
| $M_3$          | 563.02  | 93.34   | 66.51   | 927.12  | 492.05  |
| $\tan\beta$   | 13.45   | 49.20   | 7.79    | 52.42   | 12.85   |
| $A_0$          | -26.02  | -1161.5 | -4716.2 | -4928.0 | -299.34 |
| $m_{H_u}$      | 156.95  | 381.52  | 4983.6  | 2339.3  | 898.58  |
| $m_{H_d}$      | 134.74  | 534.6   | 4376.1  | 5660.1  | 467.12  |
| $\text{sgn} \mu$ | +       | +       | +       | +       | +       |
| $m_h$          | 114.7   | 114.7   | 117.9   | 122.8   | 114.9   |
| $m_H$          | 746     | 438     | 4394    | 4783    | 575     |
| $m_A$          | 741     | 435     | 4365    | 4752    | 571     |
| $m_{H^\pm}$    | 751     | 447     | 4395    | 4784    | 580     |
| $m_{\tilde{\chi}^\pm_{1,2}}$ | 156,742 | 746,946 | 110,402 | 262,2451| 221,358 |
| $m_{\tilde{\chi}^0_{1,2}}$   | 140,155 | 255,745 | 46,109  | 244,262 | 166,230 |
| $m_{\tilde{\chi}^0_{3,4}}$   | 736,741 | 928,945 | 390,403 | 2449,2449| 252,362 |
| $m_{\tilde{\nu}}$ | 1293    | 295     | 274     | 2207    | 1151    |
| $m_{\tilde{\chi}_{L,R}}$     | 1157,1159 | 1331,1205 | 4731,4775 | 3540,3392 | 1122,1114 |
| $m_{\tilde{\chi}_{1,2}}$     | 944,1120 | 707,1028 | 2489,3777 | 1855,2385 | 752,1011 |
| $m_{\tilde{\chi}_{L,R}}$     | 1160,1158 | 1334,1203 | 4732,4748 | 3541,3584 | 1125,1098 |
| $m_{\tilde{\chi}_{1,2}}$     | 1073,1149 | 870,1032 | 3774,4717 | 2360,2562 | 975,1083 |
| $m_{\tilde{\nu}}$           | 271     | 1334    | 4787    | 2955    | 548     |
| $m_{\tilde{\nu}}$           | 269     | 1181    | 4772    | 1861    | 543     |
| $m_{\tilde{\nu}_{L,R}}$      | 286,277 | 1336,1216 | 4785,4744 | 2956,3277 | 555,462 |
| $m_{\tilde{\nu}_{1,2}}$      | 246,308 | 830,1186 | 4714,4769 | 492,1881 | 453,551 |
| $\mu$                      | 730     | 934     | 376     | 2456    | 243     |
| $\Omega_{CDM}h^2$           | 0.111   | 0.105   | 0.113   | 0.111   | 0.105   |

Table 1: Sparticle and Higgs masses (in GeV units), with $m_t = 172.6$ GeV and $\mu > 0$. Points 1, 2 and 3 respectively correspond to the bino-wino coannihilation, gluino coannihilation and $m_Z$ resonance channels. Point 4 lists the spectrum for a solution for which the left-handed selectron is lighter than the right-handed selectron. Point 5 is an example of a scenario in which the little-hierarchy problem is ameliorated. Points 1, 2 and 5 satisfy all the constraints listed at the end of Section 2, while points 3 and 4 satisfy all constraints except $(g - 2)\mu$. 