B – L neutralino dark matter

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\textbf{Abstract.} We focus on the supersymmetric extension of the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ in which we have included the right handed neutrino superfield gauged only under $B - L$. In this context, it is possible to address the problem of neutrino masses and the DM problem can be tackled via the $B - L$ fermion sector instead of the MSSM one.

1. Introduction
Strong evidences propose the existence of a Dark Matter (DM) component in the Universe. Experiments such as Wilkinson Microwave Anisotropy Probe (WMAP) and Sloan Digital Sky Survey have determined that the dark matter density is \[ \Omega_{CDM} h^2 = 0.1126^{+0.0161}_{-0.0181} \] at 95\% C.L. Such an accurate measurement imposes strong constraints to any theory which would attempt to bring a solution to the DM problem. In general, a Weakly Interactive Massive Particle (WIMP) would explain satisfactory this problem under certain conditions. WIMPs appear in several kind of models.

However, there is an incompatibility between DM problem and the Standard Model (SM) of particle physics; the discrepancy is simple: in the SM framework there is no candidate which could be the DM particle. Nevertheless, an sterile neutrino with mass around 1 keV could be added in the SM in order to contribute to the DM content and also in order to generate neutrino masses via the usual Dirac and Majorana mass terms \[ \delta \mathcal{L} = i \bar{\nu}_R \gamma^\mu \nu_R - h \bar{\nu}_R \nu_R - h' \bar{L} \tilde{H} \nu_R. \] But, the addition by hand of these terms breaks the beauty of gauge symmetries that underly in the SM. Therefore, if Eq. (2) is considered as a consistent gauge extension of the SM, one might have a candidate for the DM problem and to neutrino masses at the same time; the issue would be the determination of which gauge symmetry would allow those additional terms in the SM Lagrangian without spoiling its own amazing predictions.

If supersymmetry is discovered, it would be a great advantage on the knowledge of the unification of the SM gauge groups, the spontaneous symmetry breaking of the electroweak sector and the solution of the hierarchy problem, among other features.
In addition, the lightest supersymmetric particle (LSP) fits perfectly for being a DM candidate. A caveat for the Minimal Supersymmetric Standard Model (MSSM) extension is that one has to impose $R$–Parity by hand in order to avoid baryon and lepton number violating operators in the superpotential. Amazingly, imposing the discrete symmetry $U(1)_{B-L}$, operators such as,

$$W \supset \lambda^{ijk} L_i L_j \bar{e}_k + \lambda^\nu_{ijk} L_i Q_j \bar{d}_k + \mu' L_i H_u + \lambda^\nu_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

are no longer allowed, which is phenomenologically expected because they provoke a very fast proton decay, so far unobserved. Therefore, the supersymmetric extension of the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ leads naturally to a dark matter candidate, it also address the problem of neutrino masses due to the Dirac and Majorana Yukawas in the superpotential, finally, it is also attractive for collider phenomenology due to it contains inherently a $Z'$–type gauge boson and extra fermion fields.

2. The model
We studied a model based in the supersymmetric extension of the gauge group $\mathcal{G} = SU(3)_c \times SU(2)_L \times U(1)_{Y} \times U(1)_{B-L}$, where the matter superfields considered in the model are those of the MSSM, plus the right handed neutrino superfield, $\tilde{N}$, and two Higgses, $\tilde{\sigma}_1$ and $\tilde{\sigma}_2$, assigned to the following representations of $\mathcal{G}$,

$$\tilde{N} \sim (1,1,0,1), \quad \tilde{\sigma}_1 \sim (1,1,0,-2), \quad \tilde{\sigma}_2 \sim (1,1,0,2).$$

With this quantum numbers, we allow to construct the supersymmetric version of Eq. (2), and immediately $R$–parity is no longer needed. Without imposing $R$–parity the only contribution to the MSSM superpotential that can be constructed with the extra superfields is given by

$$\Delta W = \tilde{N} Y^R_N \bar{L} \tilde{H}_u + \tilde{N} Y^M_N \tilde{H}_u \tilde{N} \tilde{\sigma}_1 + \mu' \tilde{\sigma}_1 \tilde{\sigma}_2,$$

where $Y^M_N$ and $Y^R_N$ are the Yukawa matrices. One can easily realize that Eq. (5) is the supersymmetric realization of Eq. (2) which now contains the Dirac and Majorana terms plus the corresponding $\mu'$–term.

Applying the general prescription for the soft supersymmetric breaking terms, we add the following terms to the MSSM Lagrangian,

$$-\Delta \mathcal{L}_{SB} = \tilde{N} h^R_N \bar{L} H_u + \tilde{N}^c h^M_N \tilde{N} \sigma_1 + \tilde{N} \tilde{\mu}_N \tilde{N} + m^2_{\sigma_1} \sigma_1^2 + m^2_{\sigma_2} \sigma_2^2 + B' \sigma_1 \sigma_2 + \frac{1}{2} M_{B-L} \tilde{Z}_{B-L} \tilde{Z}_{B-L}$$

where the tilde fields are the scalar fields involved in the superpotential, and $\tilde{Z}_{B-L}$ is corresponding the $B - L$ gaugino field of the theory.

3. Neutralino sector
In the neutralino sector, one can easily check that there is no mixing between the $SU(3)_c \times SU(2)_L \times U(1)_Y$ and the $U(1)_{B-L}$ sector, due to the assignation of the $B - L$ quantum numbers. Then, we can write down the neutralino mass matrix in the basis, $\psi^0 = (\tilde{B}^0 \tilde{W}^0 \tilde{\psi}_d^0 \tilde{\psi}_u^0 \tilde{Z}^0_{B-L} \psi^0_{\tilde{\sigma}_1} \psi^0_{\tilde{\sigma}_2})$ as,

$$M_\chi^0 = \begin{pmatrix} M_\chi^0_{\tilde{\chi}^0_{\tilde{\chi}^0}} & 0 \\ 0 & M_\chi^0_{\tilde{\chi}^0_{B-L}} \end{pmatrix}$$

(7)
where $M_{\nu}^{\chi}$ is the usual neutralino mass matrix from the MSSM, and the $U(1)_{B-L}$ sector is,

$$
M_{B-L}^{\chi} = \begin{pmatrix}
M_{B-L} & 2\sqrt{2}g_{B-L}v's_0 & -2\sqrt{2}g_{B-L}v'c_0 \\
2\sqrt{2}g_{B-L}v's_0 & 0 & -\mu' \\
-2\sqrt{2}g_{B-L}v'c_0 & -\mu' & 0
\end{pmatrix}
$$

where we have defined, after $U(1)_{B-L}$ breaking,

$$
\langle \sigma_i \rangle = v'_i, \quad \tan \theta = \frac{v_1'}{v_2'}, \quad \text{and} \quad v'^2 = v_1'^2 + v_2'^2.
$$

It is straightforward to realize that the wave functions of the physical particles are,

$$
\tilde{X}_i^0 = N_{ij}v_j^0, \quad i, j = 1, 2, 3, 4
$$

$$
\tilde{\chi}^{0\beta}_{B-L} = N_{ij}v_j^0, \quad i, j = 5, 6, 7
$$

where $N_{ij}$ is now the unitary matrix that diagonalize Eq. (7). $B - L$ sector is relevant because low energy mass associated to this gauge group, $M_{B-L}$, turns to be very close to $M_1$ (under the renormalization group equations) and it would mean that the LSP is related to the $B - L$ sector, depending on the other parameters of the model. In the most general case neutralinos and neutrinos must be in the same mass matrix and masses will be defined for superposition states of neutralinos and neutrinos. Nevertheless, neutrinos are expected to be much lighter than neutralinos and therefore, we can apply a double $\text{see saw}$ [3] in order to generate neutrino masses while neutralino mass matrix remains the same.

4. Neutrino sector

The mass mixing between neutrinos and neutralinos has the following structure,

$$
M_{\nu} = \begin{pmatrix}
0 & M_D^T & \Lambda \\
(M_D)^T & M_M^T & \Omega \\
\Lambda^T & \Omega^T & M_{\chi}^{\nu}
\end{pmatrix}
$$

where we have taken the basis $(\nu_L, \nu_R, \tilde{\nu}^0)$, and the elements in Eq. (12) are

$$
M_D^T = \frac{u s_\beta y_D}{\sqrt{2}}, \quad M_M^T = v's_\beta y_M,
$$

$$
\Lambda = \begin{pmatrix}
0 & 0 & \frac{v y_D}{\sqrt{2}} & 0 & 0
\end{pmatrix},
$$

$$
\Omega = \begin{pmatrix}
0 & -\sqrt{2}g_{B-L}v_R & \frac{y_M v_R}{\sqrt{2}} & 0
\end{pmatrix},
$$

and $M_{\chi}^{\nu}$ is the corresponding mass matrix for neutralinos [4], the parameters are defined as, $c_\beta = \cos \beta$, $s_\beta = \sin \beta$, $\tan \beta$ corresponds to the ratio between the vacuum expectation values of the MSSM Higgses, $\tan \beta = v_u/v_d$, and $v^2 = v_1'^2 + v_2'^2 \approx (276 \text{ GeV})^2$. Following the result of Ref. [5], we have considered that sneutrino can also acquire a vacuum expectation value labeled as $\langle \tilde{N} \rangle \equiv v_R/\sqrt{2}$. As a first approximation, we have taken the Yukawa matrices as $Y_D^\nu \sim \text{diag}(0, 0, y_D)$ and $Y_M^\nu \sim \text{diag}(0, 0, y_M)$.

Now, we are able to introduce a $\text{see saw}$ mechanism between neutrinos and neutralinos and, in the basis $(\nu_L, \nu_R)$, we find that the elements of the neutrino mass matrix are found to be,

$$
[M_{\nu}]_{11} = \frac{v_R^2 y_D^2}{4 \mu \left( t_\beta - \frac{M_1 M_2 v^2}{m_\nu^2 (M_1 + M_2) v^2 c_\beta^2} \right)},
$$
Figure 1. Left panel: Right handed neutrino mass in terms of unified $B-L$ gaugino mass for $M_1 = \frac{1}{2}M_2 = 100$ GeV, $\tan \beta = \tan \theta = 10$, $\mu = \mu' = 200$ GeV and $v_R = v' = 500$ GeV. Right panel: In the upper panels we plot the contributions to the Light and Heavy Higgs masses of the MSSM in terms of the pseudo-scalar mass for different values of $a_D$, where we have set the parameters to those of the left panel. In the lower panels we can observe that for $a_D = 100$ GeV, the Light Higgs mass receive contributions that makes it three times heavier than the MSSM Light Higgs for large $m_{A_0}$.

Thus, masses of right and left handed neutrinos can be computed by the standard diagonalization.

With the previous expressions, we can implement an scanning over all our parameter space. In order to find the allowed masses for the right handed neutrino, we have imposed the cosmological contraint [6], $\sum_{\nu} m_\nu < 2$ eV, and we have found that the allowed range for the right handed neutrino is, $m_{\nu_R} < 80$ GeV, depending on the unified $B-L$ gaugino mass parameter. A sample of the scanning can be seen on the left panel in Figure 1.

5. Higgs Sector

In general, we can write the Higgs mass lagrangian as,

$$\mathcal{L} = \frac{1}{2} \Phi^T M_\Phi^2 \Phi,$$

such as,

$$M_\Phi^2 = \begin{pmatrix} M_0^2_{B-L} & M_{mix}^2 \\ (M_{mix}^2)^T & M_{MSSM}^2 \end{pmatrix},$$

(19)

in the basis, $(\Phi)^T = (\nu_L, \nu_L^\dagger, \Sigma_1, \Sigma_2, h_u^0, h_d^0)$. Then, we have implemented the diagonalization of the mass matrix numerically. We are interested in constraining the parameters of the model, therefore, we computed the contribution to the MSSM Higgses due to the extra parameters.
Figure 2. Relic density for the $\tilde{Z}_{B-L}$-like neutralino in terms of the mass parameter $m_{\tilde{Z}_{B-L}}$, where we have included the cosmological and the Higgs mass constraint.

Light and Heavy Higgs masses are shown in the right panel in Figure 1 in terms of the pseudoscalar mass for different values of $a_D$.

We consider a random scanning over the parameter space, and we have observed that the physical masses do not receive relevant contributions from the Yukawa parameters, the left-handed sneutrino mass nor $\tan \theta$. However, large values of $a_D$ can avoid the limits of Higgs searches and we can see it on the left panel of Figure 1. In the lower panels we can observe that we can give large contributions to the Higgs masses by tuning the $a_D$ parameter. Therefore, $a_D$ will be restricted to satisfy Higgs searches in the following analysis. So, within this approximation and by considering all the constraints reviewed, we are now able to compute the corresponding relic density of the model.

6. Relic Density

In order to compute the total relic density we followed the general procedure shown in Ref. [7], thus, we needed to know which neutralino is the lightest. The solution of the renormalization group equations has shown that the $B - L$ sector could contain the lightest gaugino, $\tilde{Z}_{B-L}$; depending on the value of $\mu'$, $v'$, and $\tan \theta$ we can make it heavier than lightest MSSM neutralino. On the other hand, we can consider in general that, the total relic density is a contribution of the MSSM and the $B - L$ sector,

$$\Omega h^2_{\text{Tot}} = (\Omega h^2_{\chi_i^0}) + (\Omega h^2_{\chi_{B-L}^0}).$$

In the following, we are going to consider that the LSP is mainly $B - L$ and $(\Omega h^2_{\chi_i^0}$ is a small contribution to it. In this sense, we have three different scenarios. The LSP is mainly: a) $\tilde{Z}_{B-L}$-like, b) $\tilde{\sigma}_1$-like, and c) $\tilde{\sigma}_2$-like. In here, we will only show the solution for the $\tilde{Z}_{B-L}$ scenario, and the other two cases will be published soon.

In this case, the Feynman diagrams involved are the t-channel and u-channel of the $\tilde{Z}_{B-L}\tilde{Z}_{B-L} \rightarrow f \bar{f}(\sigma_{1(2)}\bar{\sigma}_{1(2)})$ via exchange of an $\tilde{f}$ ($\tilde{\sigma}_{1(2)}$). We made a random scanning over
the parameter space; and we set the values to be in the regions,

\begin{align}
100 \text{ GeV} &< m_N < 500 \text{ GeV}, \\
100 \text{ GeV} &< m_{\sigma_1} < 500 \text{ GeV}, \\
m_{\sigma_2} &= m_{\sigma_1} + 30 \text{ GeV}.
\end{align}

The solution of the relic density is shown in Figure. 2. As we can distinguish from the scanning, \( \tilde{Z}_{B-L} \) masses greater than 950 GeV would overclose the universe. The correct amount of relic density can be reproduced for masses of the \( \tilde{Z}_{B-L} \) around

\[ 200 \text{ GeV} < m_{\tilde{Z}_{B-L}} < 950 \text{ GeV}. \]

Nevertheless, there is still possible to overclose the universe in this range depending on the other parameters.

7. Conclusions

We have studied the phenomenological implications of the gauge group \( SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \). By gauging an extra superfield, the right handed neutrino, only under \( B-L \), we can provide a non zero mass to neutrinos which could explain the neutrino oscillation phenomena. We have applied the double seesaw mechanism induced by the mixing between neutrinos and neutralinos. We found that neutrino masses which are in agreement with cosmological constraints pushes the value of right handed neutrinos to be of the order of 1 GeV or higher. Extra neutralinos have been added to the spectra; this extra particles might help to explain the DM content of the universe and, in particular, we focused on the relic density problem. For instance, if the LSP is given by the superpartner of the extra \( B-L \) gauge boson, \( \tilde{Z}_{B-L} \), we can generate the correct amount of relic density if its mass resides in the range of \( 200 < m_{\tilde{Z}_{B-L}} < 950 \) GeV.

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