Dark matter scenarios in the minimal SUSY $B − L$ model

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Abstract: We perform a study of the dark matter candidates of a constrained version of the minimal $R$-parity-conserving supersymmetric model with a gauged $U(1)_{B − L}$. It turns out that there are four additional candidates for dark matter in comparison to the MSSM: two kinds of neutralino, which either correspond to the gaugino of the $U(1)_{B − L}$ or to a fermionic bilepton, as well as “right-handed” CP-even and -odd sneutrinos. The correct dark matter relic density of the neutralinos can be obtained due to different mechanisms including new co-annihilation regions and resonances. The large additional Yukawa couplings required to break the $U(1)_{B − L}$ radiatively often lead to large annihilation cross sections for the sneutrinos. The correct treatment of gauge kinetic mixing is crucial to the success of some scenarios. All candidates are consistent with the exclusion limits of XENON100.
1. Introduction

The LHC has been running now for more than 2 years and the ATLAS [1] and CMS [2] experiments at the LHC have collected about 5 fb$^{-1}$ of data. While so far there has been no hint of the presence of supersymmetry (SUSY) [3, 4, 5, 6, 7, 8], there is an indication for a Higgs boson in the mass range of 124–127 GeV [9, 10]. Both observations can be explained within the minimal supersymmetric standard model (MSSM) and even within its constrained, $R$-parity-conserving version (CMSSM); however, masses in the multi-TeV range are needed. In addition, the CMSSM provides a candidate particle – the lightest neutralino – to explain the observation that roughly 23% of the energy density of the universe consists of non-baryonic matter [11, 12]. However, the observation of massive neutrinos [13, 14, 15, 16] is not covered by the MSSM and requires an extension, e.g. a kind of seesaw mechanism [17, 18, 19, 20, 21] or $R$-parity violation [22, 23, 24]. Furthermore, also
the explanation of the origin of $R$-parity or the baryon asymmetry of the universe might demand an extension of the MSSM, see [25, 26] and references therein.

All-in-all, there has been a growing interest in non-minimal SUSY scenarios. For instance, it has been shown that in the next-to-minimal supersymmetric standard model (NMSSM) and in the generalized NMSSM (GNMSSM) it is easier and more natural to obtain Higgs masses in the preferred mass range without the need to make the superpartners extremely heavy [27, 28, 29]. Also in this context, there have been studies of extended gauge groups, since they can offer heavier Higgs masses more easily [30, 31, 32, 33, 34, 35] as well as new collider phenomenology [36, 37, 38, 39, 40, 41, 42, 43, 44]. One of the simplest possibilities to extend the MSSM gauge sector is to add an additional Abelian gauge group. We will focus here on the presence of an $U(1)_{B-L}$ group which can be a result of an $E_8 \times E_8$ heterotic string theory (and hence M-theory) [45, 46, 47]. This model, the minimal $R$-parity-conserving $B-L$ supersymmetric standard model (BLSSM), was proposed in [48, 49] and neutrino masses are obtained via a type I seesaw mechanism. Furthermore, it could help to understand the origin of $R$-parity and its possible spontaneous violation in supersymmetric models [48, 50, 49] as well as the mechanism of leptogenesis [51, 52]. While the mass spectrum of the constrained version of this model has been studied in detail in ref. [53], we will focus in this work on the dark matter aspects of the model.

The model here considered contains an enhanced variety of candidates for the particle responsible for the relic density compared to the MSSM: an extended neutralino sector and an extended sneutrino sector as the model contains right-handed neutrinos. If one introduces an additional $Z_2$ symmetry to the model the right-handed neutrino can also be a valid dark matter candidate [54]. The “right-handed” sneutrinos (R-sneutrinos for short) have been considered in various models [55, 56, 57, 58] including $U(1)$ extensions of the MSSM [59, 60, 61]. However, in $U(1)_{B-L}$-extended supersymmetric models, sneutrinos have mostly been studied in the context of the inverse seesaw mechanism [62]. In this inverse-seesaw $B-L$ model, the large Yukawa couplings $Y_{\nu}$ lead to an annihilation cross section that is large enough to get the correct relic density. It might even be possible that R-sneutrinos in R-sneutrino-extended models are connected to inflation [63]. The $B-L$ gaugino has also already been considered as dark matter [64]. However, we will restrict ourselves to the most predictive setup: a constrained version of the BLSSM, the CBLSSM. Here a large Majorana mass term for the right-handed neutrinos implies a splitting of the sneutrinos into their scalar and pseudoscalar components with important consequences for their properties as dark matter candidates. As already shown in Ref. [53], there are new possibilities for the lightest supersymmetric particle (LSP): the lightest neutralino can be the gaugino of the $B-L$ gauge group, the BLino, or a fermionic partner of the bilepton scalars needed to break the $U(1)_{B-L}$, i.e. a bileptino, in addition to the normal MSSM neutralino LSP possibilities.
Much like a neutralino LSP in the CMSSM, the lightest neutralino in the CBLSSM has in general so great an abundance that it would overclose the universe. This is solved in the CMSSM in four distinct regions of the parameter space: the bulk region, the focus point region, the co-annihilation region and the Higgs funnel. Similarly, we also find regions in the BLSSM with sufficient co-annihilation not only with stops and staus but also with CP-even and -odd sneutrinos. There are also new resonances with scalar Higgs fields, which can be either MSSM-like or correspond to the extended Higgs sector, as well as with the $Z'$ boson. The low abundance of R-sneutrinos is related to the breaking of $U(1)_{B-L}$ which requires certain Yukawa couplings to be large. These also induce a Majorana mass term for the right-handed neutrinos and thus also a splitting of the sneutrinos into CP-even and CP-odd mass eigenstates.

Furthermore, it has been pointed out that the presence of two Abelian gauge groups in this model gives rise to kinetic mixing terms of the form

$$-\chi_{ab} \hat{F}^{a,\mu\nu} \hat{F}_b^{\mu\nu}, \quad a \neq b$$  \hspace{1cm} (1.1)$$

that are allowed by gauge and Lorentz invariance [65], as $\hat{F}^{a,\mu\nu}$ and $\hat{F}_b^{\mu\nu}$ are gauge-invariant quantities by themselves, see e.g. [66]. Even if these terms are absent at tree level at a particular scale, they will in general be generated by RGE effects [67, 68]. These terms can have a sizable effect on the mass spectrum of this model [53]. As we will see, gauge kinetic mixing in the context of supersymmetric dark matter is even more important and several scenarios do not work if it is neglected. This agrees with previous observations concerning kinetic mixing in the context of non-SUSY dark matter [69, 70, 71].

We start in section 2 with an introduction to the CBLSSM, including a discussion of the relevant masses and the physics of gauge kinetic mixing. In section 3 we present in detail our results on the properties of the dark matter candidates. Finally, we conclude in section 4.

2. The Model

In this section we discuss briefly the particle content and the superpotential of the model under consideration. Furthermore, the tree-level masses and mixings of the particles important for our dark matter studies are given. For a detailed discussion of the masses of all particles as well as of the corresponding one-loop corrections, we refer to [53]. In addition, we show the main aspects of $U(1)$ kinetic mixing since it can have important consequences for the abundance of the dark matter candidate.

2.1 Particle content and superpotential

The model consists of three generations of matter particles including right-handed neutrinos which can, for example, be embedded in $SO(10)$ 16-plets. Moreover, below
the GUT scale the usual MSSM Higgs doublets are present as well as two fields $\eta$ and $\bar{\eta}$ responsible for the breaking of the $U(1)_{B-L}$. Furthermore, $\eta$ is responsible for generating a Majorana mass term for the right-handed neutrinos and thus we interpret the $B-L$ charge of this field as its lepton number, and likewise for $\bar{\eta}$, and call these fields bileptons since they carry twice the lepton number of (anti-)neutrinos.

We summarize the quantum numbers of the chiral superfields with respect to $U(1)_Y \times SU(2)_L \times SU(3)_C \times U(1)_{B-L}$ in Table 1.

The superpotential is given by

$$W = Y^{ij}_{u} \tilde{u}^c_i \tilde{Q}_j \hat{H}_u - Y^{ij}_{d} \tilde{d}^c_i \tilde{Q}_j \hat{H}_d - Y^{i\nu}_{e} \tilde{e}^c_i \tilde{L}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$

and we have the additional soft SUSY-breaking terms:

$$\mathcal{L}_{SB} = \mathcal{L}_{MSSM} - \lambda_B \lambda_{B'} M_{BB'} - \frac{1}{2} \lambda_{B'eff} M_{B'eff} - m_\eta^2 |\eta|^2 - m_{\tilde{u}_{ij}}^2 (\tilde{\nu}_j^c)^* \tilde{\nu}_j^c$$

$$- \bar{\eta} B_{\mu'} + T_{\nu}^{ij} H_u \tilde{\nu}_j^c \tilde{L}^c_i + T_{\nu}^{ij} \eta \tilde{\nu}_j^c \bar{\nu}_j^c$$

$i, j$ are generation indices. Without loss of generality one can take $B_u$ and $B_{\mu'}$ to be real. The extended gauge group breaks to $SU(3)_C \otimes U(1)_{em}$ as the Higgs fields and bileptons receive vacuum expectation values (vevs):

$$H^0_d = \frac{1}{\sqrt{2}} (\sigma_d + v_d + i\phi_d), \quad H^0_u = \frac{1}{\sqrt{2}} (\sigma_u + v_u + i\phi_u)$$

$$\eta = \frac{1}{\sqrt{2}} (\sigma_\eta + v_\eta + i\phi_\eta), \quad \bar{\eta} = \frac{1}{\sqrt{2}} (\sigma_\bar{\eta} + v_\bar{\eta} + i\phi_\bar{\eta})$$

We define $\tan \beta' = v_\eta/v_\bar{\eta}$ in analogy to the ratio of the MSSM vevs ($\tan \beta = v_u/v_d$).
2.2 The Z′ sector

As already mentioned in the introduction, the presence of two Abelian gauge groups in combination with the given particle content gives rise to a new effect absent in the MSSM or other SUSY models with just one Abelian gauge group: gauge kinetic mixing.

The details of this mechanism and how it affects the mass spectrum are elaborated in Ref. [53]. We merely note here that the off-diagonal coupling constant $\bar{g}$, which plays an important role in the mass matrices of the neutralinos and of the scalar bosons, is not negligible (typically about a third the size of the diagonal $U(1)$ couplings).

We also note that $M_{Z'}^2 \approx g_{BL} x$ and thus we find an approximate relation between $M_{Z'}$ and $\mu'$

$$M_{Z'}^2 \simeq -2|\mu'|^2 + \frac{4(m_\eta^2 - m_\eta^2 \tan^2 \beta') - v^2 \bar{g} g_{BL} \cos \beta (1 + \tan \beta')}{2(\tan^2 \beta' - 1)}$$  \hspace{1cm} (2.5)

2.3 The scalar Higgs sector

In the scalar sector the gauge kinetic terms induce a mixing between the $SU(2)$ doublet Higgs fields and the bileptons. The mass matrix reads at tree level in the basis ($\sigma_d, \sigma_u, \sigma_\eta, \bar{\sigma}_\eta$):

$$m^2_{h,T} = \begin{pmatrix}
    m^2_{A^0} s_\beta^2 + g_2^2 v_u^2 & -m^2_{A^0} c_\beta s_\beta - g_2^2 v_d v_u & \frac{\bar{g} g_{BL}}{2} v_d v_\eta & -\frac{\bar{g} g_{BL}}{2} v_u v_\eta \\
    -m^2_{A^0} c_\beta s_\beta - g_2^2 v_d v_u & m^2_{A^0} c_\beta^2 + g_2^2 v_d^2 & -\frac{\bar{g} g_{BL}}{2} v_u v_\eta & \frac{\bar{g} g_{BL}}{2} v_u v_\eta \\
    \frac{\bar{g} g_{BL}}{2} v_d v_\eta & -\frac{\bar{g} g_{BL}}{2} v_u v_\eta & m^2_{A^0} c_\beta^2 + g_2^2 v_\eta^2 & -m^2_{A^0} c_\beta' s_\beta' - g_2^2 v_\eta v_\bar{\eta} \\
    -\frac{\bar{g} g_{BL}}{2} v_d v_\bar{\eta} & \frac{\bar{g} g_{BL}}{2} v_u v_\bar{\eta} & -m^2_{A^0} c_\beta s_\beta' - g_2^2 v_\eta v_\bar{\eta} & m^2_{A^0} c_\beta' s_\beta' - g_2^2 v_\eta v_\bar{\eta}
\end{pmatrix}$$  \hspace{1cm} (2.6)

where we have defined $g_2^2 = \frac{1}{4}(g_1^2 + g_2^2 + \bar{g}^2)$, $c_x = \cos(x)$, and $s_x = \sin(x)$ ($x = \beta, \beta'$), and used the masses of the physical pseudoscalars $A^0$ and $A^0_\eta$ given by

$$m^2_{A^0} = \frac{2B_\mu}{\sin 2\beta}, \quad m^2_{A^0_\eta} = \frac{2B_{\mu'}}{\sin 2\beta'}.$$  \hspace{1cm} (2.7)

For completeness we note that the mass of charged Higgs boson reads, as in the MSSM, as

$$m^2_{H^+} = B_\mu (\tan \beta + \cot \beta) + m^2_w.$$  \hspace{1cm} (2.8)

2.4 Neutralinos

In the neutralino sector we find that the gauge kinetic effects lead to a mixing between the usual MSSM neutralinos with the additional states, similar to the mixing in the
CP-even Higgs sector. In other words, were these to be neglected, both sectors would decouple. The mass matrix reads in the basis \((\lambda_B, \tilde{W}_0^0, \tilde{H}_d^0, \tilde{H}_u^0, \lambda_{B'}, \tilde{\eta}, \tilde{\bar{\eta}})\)

\[
m_{\tilde{\chi}^0} = \begin{pmatrix}
M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & \frac{1}{2}M_{BB'} & 0 & 0 \\
0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 & 0 & 0 \\
-\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu & -\frac{1}{2}g v_d & 0 & 0 \\
\frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 & \frac{1}{2}g v_u & 0 & 0 \\
\frac{1}{2}M_{BB'} & 0 & -\frac{1}{2}g v_d & \frac{1}{2}g v_u & M_B & -g_{BL} v_\eta & g_{BL} v_{\bar{\eta}} \\
0 & 0 & 0 & 0 & -g_{BL} v_\eta & 0 & -\mu' \\
0 & 0 & 0 & 0 & g_{BL} v_{\bar{\eta}} & -\mu' & 0
\end{pmatrix} \tag{2.9}
\]

It is well known that for real parameters such a matrix can be diagonalized by an orthogonal mixing matrix \(N\) such that \(N^* M_{\tilde{\chi}^0} N^\dagger\) is diagonal. For complex parameters one has to diagonalize \(M_{\tilde{\chi}^0}^\dagger (M_{\tilde{\chi}^0}^\dagger)^\dagger\).

In addition, we will refer to the bino- and wino-like states, i.e. the states built by the gauginos of the MSSM, often in the following as ‘gaugino-like’. Note that this does not include the BLino, the gaugino of the \(B - L\) sector.

In this model, for the chosen boundary conditions, the lightest supersymmetric particle (LSP), i.e. the dark matter candidate, is always either the lightest neutralino or the lightest sneutrino. The reason is that \(m_0\) must be very large in order to solve the tadpole equations, and therefore all sfermions are heavier than the lightest neutralino, with the possible exception of the sneutrinos. A neutralino LSP is in general a mixture of all seven gauge eigenstates. However, its properties are typically dominated by only one or two constituents. In this context, we can distinguish the following extreme cases:

1. \(M_1 \ll M_2, \mu, M_{B'}, \mu'\): bino-like LSP

2. \(M_2 \ll M_1, \mu, M_{B'}, \mu'\): wino-like LSP

3. \(\mu \ll M_1, M_2, M_{B'}, \mu'\): Higgsino-like LSP

4. \(M_{B'} \ll M_1, M_2, \mu, \mu'\): BLino-like LSP

5. \(\mu' \ll M_1, M_2, \mu, M_{B'}\): bileptino-like LSP

If we neglect the kinetic mixing for a moment, the MSSM and \(B - L\) sectors decouple and we can study the \(3 \times 3\) sub-matrix to get some feeling of the basic properties of the latter system. The matrix can be re-written as

\[
\begin{pmatrix}
M_{B'} & -M_{Z'} \sin \beta' & M_{Z'} \cos \beta' \\
-M_{Z'} \sin \beta' & 0 & -\mu' \\
M_{Z'} \cos \beta' & -\mu' & 0
\end{pmatrix} \tag{2.10}
\]
Figure 1: Properties of the $3 \times 3 B - L$ neutralino sub-mass matrix. The left column shows the value of the lightest eigenvalues, the right column shows the BLino (black) and bileptino (blue) fraction of the lightest eigenstates for a variation of $M_{B'}$, $M_{Z'}$, $\mu'$ and $\tan \beta'$. The solid lines correspond to a starting point with $M_{B'} = \mu' = \frac{1}{2} M_{Z'} = 1$ TeV and $\tan \beta' = 1.1$, for the dashed lines $M_{B'} = 1$ TeV, $\mu' = 1.5$ TeV, $M_{Z'} = 3$ TeV and $\tan \beta' = 1.4$ has been chosen.

While $M_{B'}$, $M_{Z'}$ and $\beta'$ are nearly independent, $\mu'$ is not a fundamental parameter of this model but it is connected through the tadpole equations to the other three
parameters. Nevertheless, it is possible to change $\mu'$ by changing $m_0$ and $A_0$ and therefore we will consider it here as independent. The dependence of the smallest eigenvalue, as well as its BLino and bileptino fractions, on these four parameters is depicted in Figure 1. We can observe some interesting features of that mass matrix, in particular in the phenomenologically interesting range of $\tan \beta'$ close to 1. Therefore we study the matrix in the limit $\tan \beta' = 1$ where one gets the following eigenvalues

$$m_1 = -\mu'$$

$$m_{2,3} = \frac{1}{2} \left( M_{B'} + \mu' \mp \sqrt{(M_{B'} - \mu')^2 + 4M_{Z'}^2} \right)$$

which is sufficient to understand the numerical results. Note that the ordering of the eigenvalues at this stage is arbitrary. From these equations one can easily derive two cases where one eigenvalue is rather small

1. small $\mu'$

2. small $M_{Z'}$ combined with small $M_{B'}$ 

3. $M_{B'} \mu' \simeq M_{Z'}^2$

This explains the features of the plots in Fig. 1: in the plot where $M_{B'}$ is varied, the lightest eigenvalue corresponds to $m_2$ of eq. (2.12) for $M_{B'} \gtrsim 1$ TeV. This is also the case when $M_{Z'}$ is varied. The plots showing the $\mu'$ dependence show the lightest eigenvalue switching from being given by $m_1$ to $m_2$ at around $\mu' = 1$ TeV. Increasing $\tan \beta'$ leads in general to a decrease of the lightest mass eigenvalue. For completeness we note that with these considerations one gets a rough understanding of the extended neutralino sector. However, for masses in the order of $\max(|\tilde{g}_u|, |M_{BB'}|)$, the thus-far neglected mixing with the MSSM neutralinos becomes important.

2.5 Sneutrinos

We focus here on the sneutrino sector as it shows two distinct features compared to the MSSM. Firstly, it gets enlarged by the superpartners of the right-handed neutrinos. Secondly, even more drastically, a splitting between the real and imaginary parts of each sneutrino occurs resulting in twelve states: six scalar sneutrinos and six pseudoscalar ones [74, 75]. The origin of this splitting is the $Y_{\nu}^{ij} \tilde{\nu}_i^c \hat{\eta} \tilde{\nu}_j^c$ term in the superpotential, eq. (2.1), which is a $\Delta L = 2$ operator after the breaking of $U(1)_{B-L}$. Therefore, we define

$$\tilde{\nu}_L^i = \frac{1}{\sqrt{2}} (\sigma_L^i + i\phi_L^i) \quad \tilde{\nu}_R^i = \frac{1}{\sqrt{2}} (\sigma_R^i + i\phi_R^i)$$

In the following we will denote the partners of the left-handed and right-handed neutrinos by L-sneutrinos and R-sneutrinos, respectively. The $6 \times 6$ mass matrices of
In addition, we treat the parameters $A$, and $\mu$-terms, and we have assumed CP conservation. In the case of complex trilinear terms, a mixing between the scalar and pseudoscalar particles occurs, resulting in 12 mass matrices and consequently in a 12×12 mass matrix. It particular the term $v_2 \mu' T_r$ is potentially large and induces a large mass splitting between scalar and pseudoscalar states. Also the corresponding soft SUSY-breaking term $v_2 T_x$ can lead to a sizable mass splitting in the case of large $|T_x|$, e.g. for large $|A_0|$ at the GUT-scale where $T_x = A_0 Y_x$ holds.

To gain also some feeling for the behavior of the sneutrino masses we can consider a simplified setup: neglecting kinetic mixing as well as left-right mixing, the masses of the R-sneutrinos can be expressed as

$$m^2_{\tilde{\nu}^s} \simeq m^2_{\tilde{\nu}^c} + M^2_{\tilde{Z}^c} \left( \frac{1}{4} \cos(2\beta') + \sqrt{2} \frac{y_x}{g_{BL}} \sin \beta' \right) + M_Z \sqrt{2} \frac{y_x}{g_{BL}} (A_0 \sin \beta' - \mu' \cos \beta') ,$$

(2.18)

$$m^2_{\tilde{\nu}^p} \simeq m^2_{\tilde{\nu}^c} + M^2_{\tilde{Z}^c} \left( \frac{1}{4} \cos(2\beta') + \sqrt{2} \frac{y_x}{g_{BL}} \sin \beta' \right) - M_Z \sqrt{2} \frac{y_x}{g_{BL}} (A_0 \sin \beta' - \mu' \cos \beta') .$$

(2.19)

In addition, we treat the parameters $A_x$, $m^2_{\tilde{\nu}^c}$, $M^2_{\tilde{Z}^c}$, $\mu'$, $Y_x$ and $\tan \beta'$ as independent. The different effects on the sneutrino masses are shown in Figure 2 and can easily be understood by inspecting eqs. (2.18) and (2.19). The first two terms give always a

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1 We have neglected the splitting induced by the left-handed neutrinos as this is suppressed by powers of the light neutrino mass over the sneutrino mass.
positive contribution whereas the third one gives either a positive or a negative one depending on the sign of $A_x \sin \beta' - \mu' \cos \beta'$. For example choosing $Y_x$ and $\mu'$ positive, one finds that the CP-odd (CP-even) sneutrino is the lighter one for $A_x < 0$ ($A_x > 0$). For completeness we note that for $A_x \sin \beta' \simeq \mu' \cos \beta'$, the mass splitting is rather small compared to the masses and thus one has effectively a complex sneutrino.

2.6 Constrained model

We will consider in the following a scenario motivated by minimal supergravity assuming a GUT unification of all soft SUSY-breaking scalar mass parameters as well
as a unification of all gaugino mass parameters

\[ m_0^2 = m_{Hd}^2 = m_{Hu}^2 = m_{\eta}^2 = m_{\bar{\eta}}^2 \]  
\[ m_0^1 = m_D^2 = m_U^2 = m_Q^2 = m_E^2 = m_L^2 = m_{\nu c}^2 \]  
\[ M_{1/2} = M_1 = M_2 = M_3 = M_{\tilde{B}} \]  

(2.20)  
(2.21)  
(2.22)

Also, for the trilinear soft SUSY-breaking coupling, the ordinary mSUGRA-inspired conditions are assumed

\[ T_i = A_0 Y_i, \quad i = e, d, u, x, \nu . \]  

(2.23)

Furthermore, we assume that there are no off-diagonal gauge couplings or gaugino mass parameters present at the GUT scale

\[ g_{BY} = g_{YB} = 0 \]  
\[ M_{BB'} = 0 \]  

(2.24)  
(2.25)

This choice is motivated by the possibility that the two Abelian groups are a remnant of a larger product group which gets broken at the GUT scale as stated in the introduction. In that case \( g_{BY} \) and \( g_{BB} \) correspond to the physical couplings \( g_1 \) and \( g_{BL} \), which we assume to unify with \( g_2 \):

\[ g_1^{GUT} = g_2^{GUT} = g_{BL}^{GUT} . \]  

(2.26)

where we have already taken into account the correct GUT normalization as discussed in section 2.2.

In addition, we consider the mass of the \( Z' \) and \( \tan \beta' \) as inputs and use the following set of free parameters

\[ m_0, M_{1/2}, A_0, \tan \beta, \tan \beta', \text{sign}(\mu), \text{sign}(\mu'), M_{Z'}, Y_x \text{ and } Y_\nu. \]  

(2.27)

\( Y_\nu \) is constrained by neutrino data and must therefore be very small in comparison to the other couplings in this model, as required by the embedded TeV-scale type-I seesaw mechanism. Therefore we neglect it in the following. \( Y_x \) can always be taken diagonal and thus effectively we have 9 free parameters and 2 signs.

3. \( B - L \) Dark Matter

Astrophysical observations and the data from WMAP [76] put the existence of non-baryonic dark matter in the Universe on solid grounds. The best-fit value from a combined analysis of the cosmic microwave background (CMB), supernovae observations and baryonic acoustic oscillations (BOA) predicts a dark matter density of [77]

\[ \Omega h^2 = 0.1123 \pm 0.0035 \]  

(3.1)
at the 1σ level. As already mentioned, there are four distinct regions in the parameter space of the CMSSM which lead to a neutralino density consistent with this observation: (i) the bulk region with light sfermions enabling a sufficient t-channel annihilation, (ii) the co-annihilation region with a second, particle close in mass to the LSP with stronger interactions [78, 79, 80, 81], (iii) the Higgs funnel characterised by a resonance of the LSP with the pseudoscalar Higgs bosons [82] and (iv) the focus point region where the large Higgsino fraction of the LSP increases the coupling to the SM gauge bosons and third generation quarks [83, 84].

As stated above, the extended neutralino and sneutrino sectors yield additional possibilities for explaining the relic density. Here we discuss the details of how the correct value can be obtained. As in the usual CMSSM, this requires some special mechanisms, either resonances or co-annihilation. The CBLSSM requires in general large values of m_0 to get a consistent solution for the tadpole equations. Therefore it does not seem to be possible to find a bulk-like region, despite the presence of new D-term contributions to the masses of the sfermions. However, it turns out that there are different manifestations of the other mechanisms to reduce the relic density for a neutralino LSP which is either mainly BLino or bileptino.

Another dark matter candidate in the CMSSM is the lightest sneutrino. However, due to its coupling to the Z boson, a pure “left-handed” sneutrino LSP is already ruled out by direct dark matter searches [85]. In contrast, as shown in sec. 2.5, the LSP in the BLSSM can be a CP-even or -odd R-sneutrino with a very suppressed coupling to the Z boson. We will start our discussion with the sneutrino LSPs in section 3.1 and we will present the results for the BLino and bileptino LSPs in sec. 3.2. Finally, we will discuss the impact of direct detection experiments on the different dark matter candidates in sec. 3.3 and comment briefly on the impact of the BLSSM on MSSM-like dark matter candidates in sec. 3.4. Before we start, some remarks about the numerical calculation are in order.

Numerical setup To check the properties of the new dark matter candidates arising in the BLSSM, we have used the implementation of the model in SPheno [86, 87] based on the corresponding output of SARAH [88, 89, 90]. This implementation provides a precise mass calculation using two-loop RGEs and one-loop corrections to all masses. Also, all effects of kinetic mixing are taken into account during the RGE running by using the results presented in Ref. [72]. For more details about the calculation of the mass spectrum, we refer the interested reader to Ref. [53]. The calculation of the relic density of the LSP is done with MicrOmegas [91] version 2.4.5 based on the CalcHep output of SARAH. The data transfer between SPheno and MicrOmegas happens via the SLHA+ functionality of CalcHep [92] which enables CalcHep to read the SLHA spectrum file written by SPheno. To perform the scans we have used the Mathematica package SSP [93]. In particular, all presented benchmark scenarios in the following include scalar Higgs bosons in the preferred mass range of
122-128 GeV. All scalar masses are calculated using the full one-loop corrections as well as the dominant two-loop corrections known from the MSSM.

3.1 Sneutrino dark matter

Since there is a large mass splitting only for R-sneutrinos, the LSP can be either a CP-even or -odd R-sneutrino. Neglecting the tiny $Y_\nu$ neutrino Yukawa couplings, the only tree-level interactions are with the Higgs particles and the corresponding superpartners. However, the $Z'$ boson cannot contribute to the dark matter annihilation because it just couples to one CP-even and one CP-odd sneutrino at a time, but it is only possible to get one of them lighter than the neutralinos at the same time. Furthermore, in the CBLSSM, the typically large value of $m_\eta$ leads to very heavy Higgs pseudoscalars and therefore the main annihilation properties are fixed by the interaction with the scalar Higgs fields. We can write the corresponding three- and four-point interactions in the limit of vanishing $Y_\nu$ neutrino Yukawa couplings and diagonal $Y_x$ as

$$\Gamma_{\tilde{\nu}_i^{S,P},\tilde{\nu}_j^{S,P}, h_{L,R}} \simeq \frac{i}{4} \left(-16 \sum_{c=1}^{3} |Y_{x,cc}|^2 Z_{i3}^X Z_{j3}^X Z_{k3}^H Z_{l3}^H \right. $$

\[ \left. + g_B \sum_{a=1}^{3} Z_{i3+a}^X Z_{j3+a}^X \left(2g_B(Z_{k4}^H Z_{l4}^H - Z_{k3}^H Z_{l3}^H) + g(Z_{k1}^H Z_{l1}^H - Z_{k2}^H Z_{l2}^H) \right) \right. $$

\[ \left. + \sum_{a=1}^{3} Z_{ia}^X Z_{ja}^X \left(2g_B (\tilde{g} + g_{BL}) \right) \left(Z_{k4}^H Z_{l4}^H - Z_{k3}^H Z_{l3}^H \right) \right. $$

\[ \left. - (\tilde{g} (\tilde{g} + g_{BL}) + g_1^2 + g_2^2) (Z_{k1}^H Z_{l1}^H - Z_{k2}^H Z_{l2}^H) \right) \] (3.2)

$$\Gamma_{\tilde{\nu}_i^{S,P},\tilde{\nu}_j^{S,P}, h_{L,R}} \simeq \frac{i}{4} \left( \pm g_{BL} \sum_{a=1}^{3} Z_{i3+a}^X Z_{j3+a}^X \left(2g_B(v_\eta Z_{k4}^H - v_\eta Z_{k3}^H) - \tilde{g}(v_d Z_{k1}^H - v_u Z_{k2}^H) \right) \right. $$

\[ \left. + 2 \left( \pm 8v_\eta \sum_{c=1}^{3} |Y_{x,cc}|^2 Z_{i3+c}^X Z_{j3+c}^X + 2\sqrt{2} \sum_{b=1}^{3} Z_{i3+b}^X Z_{j3+b}^X T_{x,bb} \right) Z_{k3}^H \right. $$

\[ \left. - \sqrt{2} \left( \mu_\eta \sum_{b=1}^{3} \bar{v}_x^* Z_{i3+b}^X Z_{j3+b}^X + \mu_\eta \sum_{b=1}^{3} Z_{i3+b}^X Z_{j3+b}^X \right) \right. $$

\[ \left. + \sum_{a=1}^{3} Z_{i3+a}^X Z_{ja}^X \left(2g_B (\tilde{g} + g_{BL}) \right) \left(v_\eta Z_{k4}^H - v_\eta Z_{k3}^H \right) \right. $$

\[ \left. \pm (\tilde{g} (\tilde{g} + g_{BL}) + g_1^2 + g_2^2) (v_d Z_{k1}^H - v_u Z_{k2}^H) \right) \] (3.3)

with $X = S, P$ for the rotation matrices in case of CP-even ($Z^S$) and CP-odd ($Z^P$) sneutrinos, respectively. In eqs. (3.2) and (3.3) the upper (lower) signs are for CP-even (CP-odd) sneutrinos. The bilepton or the sneutrino LSP masses because of the large $Z'$ mass. Thus we can
Figure 3: CP-even sneutrino dark matter. The left plot shows the dependence of the relic density $\log(\Omega h^2)$ on the mass of the LSP $m_{\tilde{\nu}_S}$. The right hand side gives $\log(\Omega h^2)$ as function of $10^{14} \left( \frac{Y_{33}^x}{(M_{Z'} m_{\nu_{\tilde{S}}}^1)} \right)^2$. The chosen parameter ranges are $m_0 = [1.7, 1.9]$ TeV, $M_{1/2} = [1.5, 1.8]$ TeV, $\tan \beta = [6, 11]$, $A_0 = -1.4$ TeV, $\tan \beta' = [1.16, 1.20]$, $M_{Z'} = [2.5, 3.0]$ TeV, $Y_{33}^x = [0.10, 0.42]$, $Y_{11}^x = Y_{22}^x = 0.42$.

expect that diagrams involving two three-point interactions dominate over those with one four-point interaction. Furthermore, there is also the possibility of a resonance between the sneutrino and a Higgs particle. Since there are qualitative differences between the behaviour of CP-even and -odd sneutrinos, we discuss them separately in the following, starting with the CP-even case.

3.1.1 CP-even sneutrino LSP

In Fig. 3 (left-hand side) the relic density is shown as a function of the CP-even sneutrino mass. As seen in sec. 2.5, scalar sneutrinos can be the LSP for large negative values of the combination $T_x \sin \beta' - Y_x \mu' \cos \beta'$. This can be obtained for large positive values of $Y_x$ and large negative values of $A_0$. Therefore, the sneutrino interactions coming from F-terms dominate and for a fixed value of the $Z'$ mass their annihilation cross section is determined mostly by $Y_x$, increasing with larger $Y_x$. However, the sneutrino mass depends strongly on $Y_x$ due to the RGE evolution and it gets smaller with increasing $Y_x$. All-in-all, the relic density drops for smaller sneutrino masses. To make the dependence of the annihilation cross section on $Y_x$ more visible, on the right-hand side of Fig. 3 we plot the relic density as a function of $\left( \frac{Y_{33}^x}{(M_{Z'} m_{\nu_{\tilde{S}}}^1)} \right)^2$, i.e. we have divided out the dependence on the sneutrino mass and on the $Z'$ mass, finding a clear correlation.

The most important annihilation channel is the one with a bilepton pair ($h_2 h_2$) in the final state which can reach up to 98 per-cent. As can be seen, the sneutrino usually has a mass of several hundred GeV. The reason is that there is an upper bound on the entries of $Y_x$ from the requirement that there should be no Landau pole up to the GUT scale. It is still possible to get lower masses by tuning $|A_0|$ and/or $\tan \beta'$ and one can even find sneutrino masses below 200 GeV. However, in
Figure 4: Rather light CP-even sneutrinos: $\log(\Omega h^2)$ vs. $m_{\tilde{\nu}}^S$ (left) and $\log(\Omega h^2)$ vs. $2 \cdot m_{\tilde{\nu}}^S - m_h^2$ (right). The chosen parameter ranges were $m_0 = [1.55, 1.65] \text{ TeV}$, $M_{1/2} = [500, 550] \text{ GeV}$, $\tan \beta = [13, 15]$, $A_0 = [-2.65, -2.5] \text{ TeV}$, $\tan \beta' = [1.33, 1.36]$, $M_{Z'} = [2.0, 2.4] \text{ TeV}$, $Y_{33}^x = [0.33, 0.35]$, $Y_{11}^x = Y_{22}^x = 0.42$.

This region of parameter space the relic density is usually too small, as shown in Fig. 4, because of the large annihilation cross section in two bileptons. Even if this final state is kinematically forbidden and the mass of the sneutrino is well below the resonance point, the annihilation cross section for final states containing SM vector bosons and Higgs bosons is still too large. Typically we find the following ratios for the three dominant final states, provided there is no kinematical suppression: $W^+W^- : ZZ : h_1h_1 \simeq 2 : 1 : 1$. We want to stress that this is a consequence of gauge kinetic mixing, as otherwise these final states would be strongly suppressed and the calculated relic density would be several orders of magnitude too large, and much larger than the measured value. For completeness we note that these parameter points with a very small sneutrino abundance are not ruled out, because the dark matter can still be formed by another particle like the axino or the axion [94, 95], or even by primordial black holes [96].

3.1.2 CP-odd sneutrino LSP

For CP-odd sneutrinos to be the LSP, a necessary requirement is $T_x \sin \beta' - Y_x\mu' \cos \beta' > 0$. It turns out that this can be achieved for $A_0 > 0$ and if one of the entries in $Y_x$ is smaller compared to the others which avoids also the problem of a Landau pole. We easily find sneutrino LSPs with a mass of 50 GeV and below\(^2\) as can be seen from Fig. 5. Note the clear correlation between the relic density and the mass of the sneutrino between 100 and 700 GeV. The reason is that the mass of the sneutrino decreases with decreasing $Y_x$ while the annihilation cross section increases: the D-terms in eq. (3.3) are positive while the F-terms and the trilinear soft SUSY-breaking terms are negative. The smaller $Y_x$ is the more the gauge interactions dominate increasing the cross section. In general the final states from the annihilation of CP-odd

\(^2\)We note that such light sneutrinos are not constrained by LEP data as they are mainly SM singlets.
sneutrinos are similar to those from CP-even sneutrinos: if kinematically allowed, the final state with two bilepton dominates followed by those with SM vector bosons and MSSM Higgs bosons. However, for sneutrino masses below about $m_Z/2$, only SM fermions show up as final states with the following branching ratios: $\bar{b}b$ ($\simeq 78\%$), $\bar{\tau}\tau$ ($\simeq 16\%$) and $\bar{c}c$ ($\simeq 5\%$) for the dominant channels. However, there is one important difference: around 60 GeV there is a pronounced dip because of the resonance with the light MSSM-like Higgs. For completeness, we mention that a resonance is possible with not only the MSSM-like Higgs, as shown in Fig. 5, but also with the bileptons. However, since the preferred final states are either SM gauge bosons or the light MSSM Higgs, the bilepton has to have a non-vanishing doublet fraction. Therefore, kinetic mixing is crucial for this case as well. A bilepton resonance in general suppresses the relic density even more than a doublet resonance and the abundance of sneutrinos would be even smaller.

3.2 BLino and bileptino dark matter

We turn now to the new fermionic dark matter candidates arising in the BLSSM: the BLino and bileptino. Much like a neutralino LSP in the CMSSM, the relic density of a neutralino LSP in the BLSSM is in general too large. Therefore, special mass configurations are needed to reduce the abundance to the correct amount. We found as possible scenarios: (i) Higgs resonances, (ii) $Z'$ resonance, (iii) sneutrino co-annihilation (iv) stop and stau co-annihilation and (v) annihilation by a t-channel neutralino similar to the focus point in the CMSSM. As we will see during our discussion of the different mechanisms, kinetic mixing turns out to be of large importance.

3.2.1 Higgs resonances

A resonant annihilation of neutralino LSP with a Higgs particle is already well-known from the Higgs funnel region in the CMSSM, which is characterised by $2 \cdot m_{\tilde{\chi}_1^0} = m_A$.
Figure 6: First row (left): \(\log(\Omega h^2)\) vs. the mass of the lightest CP-odd sneutrino. The jump around 300 GeV is an caused by the mass of the bilepton as shown on the right side. The second row contains the same information, but kinetic mixing has been neglected.

Parameters:

\[ m_0 = [0.8, 1.2] \text{ TeV}, \quad M_{1/2} = [1.7, 1.9] \text{ TeV}, \quad \tan \beta = [10, 15], \quad A_0 = [4.5, 5] \text{ TeV}, \]
\[ \tan \beta' = [1.3, 1.35], \quad M_{Z'} = [2.7, 3.0] \text{ TeV}, \quad Y_{33}^{x} = [0.36, 0.40], \quad Y_{11}^{x} = 0.42, \quad Y_{22}^{x} = 0.33. \]

\((m_A\) the mass of the pseudoscalar)\(^3\). However, the extended Higgs sector offers the possibility of additional resonances. We find that in the bilepton sector the resonance is usually via the lightest scalar which is relatively light as \(\tan \beta'\) is close to 1 [53, 35]. However, the pseudoscalar as well as the heavier scalar bilepton are usually heavier than the \(Z'\) and thus can only be effective for very heavy LSPs. Therefore, we concentrate here on the resonances with scalars. The interaction between a neutralino and the scalar Higgs can be parametrised by

\[
\Gamma^L \frac{1 - \gamma_5}{2} + \Gamma^R \frac{1 + \gamma_5}{2} \tag{3.4}
\]

\(^3\)In some parts of the parameter space resonances via the scalar Higgs bosons \(h^0\) and \(H^0\) are also open in models with non-universal Higgs masses, see e.g. [97].
Figure 7: BLino resonance with bilepton. The plots show \( \log(\Omega h^2) \) as a function of \( 2 \cdot m_{\tilde{\chi}_1^0} - m_{h_2} \) in case of kinetic mixing (left) and without kinetic mixing (right). The parameter ranges were chosen to be \( m_0 = [3.5, 4.0] \) TeV, \( M_{1/2} = [1.5, 2.0] \) TeV, \( \tan \beta = [30, 40] \), \( A_0 = [-5.5, -4] \) TeV, \( \tan \beta' = [1.5, 1.7] \), \( M_{Z'} = [2.0, 2.5] \) TeV, \( Y_x^{33} = [0.40, 0.45] \), \( Y_x^{11} = 0.42 \), \( Y_x^{22} = 0.377 \).

with the coefficients

\[
\Gamma^R_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 h_k} = \frac{i}{2} \left( Z_k^H \left( g_1 N_{i1} - g_2 N_{i2} + \bar{g} N_{i5} \right) N_{j3} + N_{i3} \left( g_1 N_{j1} - g_2 N_{j2} + \bar{g} N_{j5} \right) \right)
- Z_k^{H*} \left( g_1 N_{i1} - g_2 N_{i2} + \bar{g} N_{i5} \right) N_{j4} + N_{i4} \left( g_1 N_{j1} - g_2 N_{j2} + \bar{g} N_{j5} \right)
+ 2 \left( Z_k^{H*} \left( g_{BL} N_{i5} + N_{i6} g_{BL} N_{j5} \right) - Z_k^H \left( g_{BL} N_{i5} N_{j7} + N_{i7} g_{BL} N_{j5} \right) \right)
\]

\[
\Gamma^L_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 h_k} = - \left( \Gamma^R_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 h_k} \right)^* 
\]

Here, \( Z^N \) is the \( 7 \times 7 \) neutralino mixing matrix and \( Z^H \) the \( 4 \times 4 \) rotation matrix of the scalars. To have a non-vanishing coupling between a \( B - L \) neutralino and the bilepton component of the Higgs, the neutralino must always be an admixture of BLino and bileptino. As can be seen from Fig. 1, a BLino LSP has a sizeable bileptino fraction whereas the BLino contribution to a bileptino LSP is rather small. Therefore, one expects the Higgs resonance to be more effective in the case of a BLino LSP.

**BLino** We first take a look at the more obvious resonance of a BLino with a bilepton Higgs. Because of the sizeable bileptino fraction, the coupling between the LSP and the bilepton is large enough to cause a pronounced resonance. This is shown in the left-hand plot of Fig. 7. If we pick a point with a relic density of \( \Omega h^2 = 0.116 \), with LSP mass of \( m_{\tilde{\chi}_1^0} = 377.5 \) GeV and bilepton mass \( m_{h_2} = 844.5 \) GeV, the main annihilation channels are
**Figure 8:** BLino resonance with bilepton due to a variation of $M_{Z'}$. The left figure shows $\log(\Omega h^2)$ as a function of $M_{Z'}$, the right figure show the dependence of the mass of the light bilepton Higgs ($m_{h_2}$) (solid, blue line) and twice the mass of the LSP (dashed, black line).

\[
\begin{align*}
\tilde{\chi}_1^0 \tilde{\chi}_1^0 & \rightarrow W^+W^- \quad (48.5\%) \\
\tilde{\chi}_1^0 \tilde{\chi}_1^0 & \rightarrow h_1 h_1 \quad (24.7\%) \\
\tilde{\chi}_1^0 \tilde{\chi}_1^0 & \rightarrow ZZ \quad (24.0\%) \\
\tilde{\chi}_1^0 \tilde{\chi}_1^0 & \rightarrow \bar{t}t \quad (2.7\%)
\end{align*}
\]

For this point the MSSM-like Higgs mass is also in the preferred range, as $m_{h_1} = 126.8$. Obviously, only SM/MSSM final states appear and the $B-L$-specific states like right-handed neutrinos are not important because their masses are too large. However, the particles in the final states couple to the bilepton at tree level only through kinetic mixing. Therefore, if we switch off the kinetic mixing, the resonance also disappears, as shown on the right side of Fig. 7.

In general, it is often rather easy to find a resonance with a bilepton Higgs and the BLino. The two masses scale differently with a variation of $M_{Z'}$ or $\tan(\beta')$ and they can be easily tuned. This is shown in Fig. 8. While the bilepton mass has only a mild dependence on $M_{Z'}$, the BLino mass scales much more with a variation of the $Z'$ mass. This strong dependence is mostly given by the change of the bilepton fraction because $\mu'$ is very sensitive to $M_{Z'}$, see eq. (2.5).

However, resonances of a BLino with a bilepton Higgs are not the only possibility. Resonances with the light MSSM Higgs can appear too, especially for a light LSP, with a mass of 50–70 GeV. As already pointed out in [53], one feature of this $B-L$ model is that we can have a rather light gaugino LSP with gaugino unification at the GUT scale without being in conflict with the mass limits of the chargino. The reason is that the mass of a BLino LSP is not as strongly correlated to the mass of the wino-like chargino as the bino, because of the rather strong BLino-bilepton mixing. This mixing can cause a smaller mass than naively expected from the running value of the gaugino mass term $M_B$. Therefore, scanning over a broader parameter range one finds both Higgs resonances in the dark matter abundance, as depicted in Fig. 9. Here the resonance with the bilepton Higgs is broader than the one with the...
Figure 9: BLino relic density $\log(\Omega h^2)$ vs. the mass of the LSP. The narrow dip around 60 GeV corresponds to resonance with the MSSM-like Higgs, the broader dip between 120 and 150 GeV is due to resonance with the light bilepton Higgs. The chosen parameter ranges were $m_0 = [4.0, 5.0]$ TeV, $M_{1/2} = [1.8, 2.0]$ TeV, $\tan \beta = [35, 40]$, $A_0 = [4, 5]$ TeV, $\tan \beta' = [1.19, 1.21]$, $M_{Z'} = [2.2, 2.4]$ TeV, $Y_{x}^{33} = [0.40, 0.45]$, $Y_{x}^{11} = 0.42$, $Y_{x}^{22} = 0.377$.

Left: with kinetic mixing, right without kinetic mixing.

MSSM-like Higgs because the bilepton mass has, of course, a larger dependence on the variation of the $B - L$-specific parameters $\tan(\beta')$ and $M_{Z'}$, and varies in the shown parameter range between 240 and 330 GeV, while the MSSM-like Higgs mass lies between 122 and 125 GeV. The importance of the final states is similar to the branching ratios of the SM-like Higgs: $b\bar{b}$ (75.7%), $\tau\bar{\tau}$ (18.3%) and $c\bar{c}$ (5.9%), but MicrOmegas doesn’t take loop-induced decays into two gluons or two photons into account, leading to some theoretical uncertainty.

The right plot in Fig. 9 shows that both Higgs resonances can be visible even without kinetic mixing, but the reduction of the neutralino abundance is not large enough to explain dark matter.

Bileptino A bileptino LSP can also have a resonance with a bilepton Higgs. However, there are some qualitative and quantitative differences: the main difference is that often the relic density is not as strongly reduced as for a BLino LSP. One has to be very close to the resonance point to get $\Omega h^2$ below 0.12, see Fig. 10. The reason is that the coupling of the bileptino to the bilepton is actually through its BLino component, which is typically below 1%. Another difficulty is that the masses of the bileptino and the bilepton are sensitive to the same parameters. Therefore, it is much more difficult to tune the parameters to get a resonance than for the BLino case: the parameter ranges chosen for Fig. 10 had to be much smaller than those for instance used in Fig. 7. On the other hand, the final states are very similar to those of a BLino-bileptino resonance and include SM gauge bosons and the light doublet Higgs.

Given that the bilepton resonance is generally unable to allow sufficient bileptino annihilation, one would expect that there would be even less scope for a suffi-
Figure 10: Bileptino resonance with a bilepton. The chosen parameter ranges were $m_0 = [1.45, 1.5]$ TeV, $M_{1/2} = [1.08, 1.1]$ TeV, $\tan \beta = [18, 20]$, $A_0 = [-3.52, -3.5]$ TeV, $\tan \beta' = [1.52, 1.53]$, $M_{Z'} = [2.48, 2.52]$ TeV, $Y_{x}^{33} = [0.41, 0.42]$, $Y_{x}^{11} = Y_{x}^{22} = 0.42$.

Figure 11: Indirect bileptino resonance with third Higgs which is MSSM-like: the $\tilde{\chi}_0^2$ annihilates resonantly with the doublet Higgs and due to the small mass splitting between $\tilde{\chi}_0^0$ and $\tilde{\chi}_0^2$ there is a co-annihilation of the LSP with the second neutralino. Left: $\log(\Omega h^2)$ vs. $m_{\tilde{\chi}_1^0}$, right: $\log(\Omega h^2)$ as function of $m_{h_3} - 2m_{\tilde{\chi}_1^0}$ (black) and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ (red). The parameter ranges were $m_0 = [850, 900]$ GeV, $M_{1/2} = [1.0, 1.2]$ TeV, $\tan \beta = [38, 41]$, $A_0 = [1.5, 1.6]$ TeV, $\tan \beta' = [1.10, 1.11]$, $M_{Z'} = [2.7, 2.8]$ TeV, $Y_{x}^{33} = [0.42, 0.43]$, $Y_{x}^{11} = 0.38$, $Y_{x}^{22} = 0.42$.

sufficiently strong doublet Higgs resonance. The coupling between a doublet Higgs and a bilepton is highly suppressed: firstly, by the small BLino fraction of the bileptino; secondly, by the small bilepton fraction of the doublet Higgs. Nevertheless, an ‘indirect’ doublet resonance can be important. If the second-lightest neutralino is MSSM-like and very close in mass to the LSP, and the mass of the Higgs fulfils $2m_{\chi_1^0} \simeq m_h \simeq 2m_{\chi_2^0}$ there is, of course, also a resonance between $\tilde{\chi}_2^0$ and the doublet Higgs. Because of this resonance, the second neutralino annihilates very efficiently and the small mass difference with the lightest neutralino leads to a co-annihilation between the neutralinos. In Figs. 11 we show an example where this mass configuration appears and leads to the correct relic density. As can be seen, the mass difference between the first and second neutralinos as well as the distance to the res-
Anomalous point have to be very small to obtain a relic density of $\Omega h^2 = 0.1$. Because of the large value of $\tan \beta$ for the shown parameter range, the dominant final channels are (for $m_{\tilde{\chi}^0_1} = 563.9$ GeV, $m_{\tilde{\chi}^0_2} = 564.8$ GeV, $m_{h_3} = 1148.5$ GeV)
\[
\begin{align*}
\tilde{\chi}^0_2 \tilde{\chi}^0_2 & \rightarrow b\bar{b} \quad (78.8\%) \\
\tilde{\chi}^0_2 \tilde{\chi}^0_2 & \rightarrow \tau\bar{\tau} \quad (20.8\%)
\end{align*}
\]
and involve only the second neutralino. The first channel involving the LSP is $\tilde{\chi}^0_1 \tilde{\chi}^0_2 \rightarrow \tau\bar{\tau}$ and contributes only 0.008%.

3.2.2 $Z'$ resonance

The other possibility for a resonance is a neutral, massive gauge boson, i.e. either the $Z$ or $Z'$. However, it turns out that a resonance with the $Z$ boson is usually not important because the coupling of the $Z$ boson to the neutralino is proportional to the Higgsino fraction, which is usually negligible for a $B - L$ neutralino. Also the $B'$ contribution to the $Z$ boson due to kinetic mixing is too constrained to cause a significant resonance effect. Therefore we can concentrate here on the heavy $Z'$ boson. One general drawback of this mechanism is that the LSP has to be very heavy because of bounds on the $Z'$ mass. There is a lower limit of roughly 1.6 TeV for the mass of the $Z'$ in this model and our chosen setup [43].

The coupling between the $Z'$ boson and two neutralinos is given by
\[
\gamma_\mu \left( \Gamma^L \frac{1 - \gamma_5}{2} + \Gamma^R \frac{1 + \gamma_5}{2} \right)
\]
with
\[
\Gamma^L_{\tilde{\chi}^0_i \tilde{\chi}^0_j Z'} = \frac{i}{2} \left( \left( N^*_{j3} \left( (g_1 \sin \Theta_W + g_2 \cos \Theta_W) \sin \Theta'_{W'} + \bar{g} \cos \Theta'_{W'} \right) N_{i3} \\
- N^*_{j4} \left( g_1 \sin \Theta_W \sin \Theta'_{W'} + g_2 \cos \Theta_W \sin \Theta'_{W'} + \bar{g} \cos \Theta'_{W'} \right) N_{i4} \\
+ 2g_{BL} \cos \Theta'_{W} \left( N^*_{j6} N_{i6} - N^*_{j7} N_{i7} \right) \right)
\]
\[
\Gamma^R_{\tilde{\chi}^0_i \tilde{\chi}^0_j Z'} = \left( \left( \Gamma^L_{\tilde{\chi}^0_i \tilde{\chi}^0_j Z'} \right)^* \right)
\]

Analogously to the MSSM where a non-vanishing Higgsino fraction is needed for a coupling to the $Z$ boson, we need here a non-zero bileptino fraction. Since the gauge couplings are fixed by the GUT condition, the only free parameters for the $Z'$ resonance are $M_{Z'}$ and the bileptino fraction, i.e. a decreasing bileptino fraction has to be compensated by a lower $Z'$ mass. Our result is that to satisfy the bounds on the $M_{Z'}$, the LSP has to be at least 45% bileptino-like. Thus, a BLino LSP has to be strongly mixed with the bileptino, and if we demand a $M_{Z'}$ of at least 2 TeV it is not possible to find a LSP with the correct relic density which is more BLino than bileptino, see Fig. 12.
Figure 12: Bileptino resonance with $Z'$. Top Left: $\log(\Omega h^2)$ vs. $m_{\tilde{\chi}_1^0}$. Top right: $\log(\Omega h^2)$ vs. $2 \cdot m_{\tilde{\chi}_1^0} - M_{Z'}$. The second row shows the dependence of the relic density on the BLino fraction (left) and the bileptino fraction (right). The parameter ranges were $m_0 = [0.8, 1.3]$ TeV, $M_{1/2} = [1.9, 2.4]$ TeV, $\tan\beta = [10, 25]$, $A_0 = [1.3, 1.7]$ TeV, $\tan\beta' = [1.06, 1.13]$, $M_{Z'} = [1.7, 2.5]$ TeV, $Y^3_3 = [0.2, 0.3]$, $Y^{11}_x = Y^{22}_x = 0.42$.

We see that over a large range of values of the bileptino fraction, the relic density is consistent with the limits on dark matter. Only if the bileptino fraction drops below 50% or gets larger than 95% does the relic density grow rapidly. The reason for the high neutralino abundance in the case of a very small BLino admixture is that the mass of the LSP drops quickly with the increasing bileptino fraction for the given parameter range: the upper mass limit for the LSP is roughly 1.0 TeV (98% bileptino), 0.8 TeV (99% bileptino) and 0.5 TeV (100% bileptino). Hence, the distance to the resonant point gets too large.

In case of a dominant $Z'$ resonance, the annihilation channels are just the same as the branching ratios of the $Z'$ boson and given by

\[
\begin{align*}
\tilde{\chi}_1^0 \tilde{\chi}_1^0 &\rightarrow \sum_i \ell_i \bar{\ell}_i \quad (36.1\%) \\
\tilde{\chi}_1^0 \tilde{\chi}_1^0 &\rightarrow \sum_i \nu_i \bar{\nu}_i \quad (23.0\%) \\
\tilde{\chi}_1^0 \tilde{\chi}_1^0 &\rightarrow h_1 h_1 \quad (1.5\%) \\
\tilde{\chi}_1^0 \tilde{\chi}_1^0 &\rightarrow \sum_i d_i \bar{d}_i \quad (29.6\%) \\
\tilde{\chi}_1^0 \tilde{\chi}_1^0 &\rightarrow \sum_i u_i \bar{u}_i \quad (8.4\%)
\end{align*}
\]

where we have summed over the different generations of charged leptons ($\ell_i$), down-type quarks ($d_i$), up-type quarks ($u_i$) and light neutrinos ($\nu_i$), $i = 1, 2, 3$. This scenario is very appealing because it is very predictive due to the small number of
important parameters. However, due to the sizable couplings to quarks, this mechanism is also under some pressure from direct detection experiments, as discussed in sec. 3.3.

### 3.2.3 Sneutrino co-annihilation

As we have seen in sec. 3.1.1 - 3.1.2, the R-sneutrinos annihilate very efficiently due to the large F- and D-term couplings with the bileptinos. Not only does this allow a low abundance for a sneutrino LSP, but it also allows a sneutrino NLSP to have an important effect on the dark matter relic density: if the neutralino LSP is close in mass to the sneutrino NLSP, a new co-annihilation comes into play.

The important ingredients to understand the behavior of sneutrino co-annihilation are the couplings between the sneutrinos and the Higgs fields given in eqs. (3.2) - (3.3) as well as the interaction of the neutralino with a neutrino/sneutrino pair. Ignoring the contributions of the tiny neutrino Yukawa couplings, we can write this chiral coupling using eq. (3.4) as

\[
\Gamma_{\tilde{\chi}_0^i \nu^j \tilde{\nu}^{S,P}_k}^{L} = -\frac{\alpha}{2} \left( (g_1 N_{11}^* - g_2 N_{12}^*) N_{i5}^* \sum_{a=1}^3 U_{ja}^{V^*} Z^X_k a \right)
\]

\[
\Gamma_{\tilde{\chi}_0^i \nu^j \tilde{\nu}^{S,P}_k}^{R} = -\frac{\alpha}{2} \left( -g_{BL} N_{i5}^* \sum_{a=1}^3 U_{ja}^{V^*} Z^X_k a - 2\sqrt{2} N_{i6}^* \sum_{b=1}^3 U_{ja}^{V^*} Z^X_k a Y_{x,bb} b \right)
\]

with \(X = S, P\) for the rotation matrices of the CP-even or -odd sneutrinos and the upper signs correspond to the CP-even and the lower ones to the CP-odd interactions.

**BLino** Co-annihilation of a BLino LSP with both CP-even and CP-odd sneutrinos is possible. However, the co-annihilation with a CP-even sneutrino is more likely because the larger values of \(Y_x\) usually required to obtain a BLino LSP also prefer a light CP-even sneutrino. An example of co-annihilation between the lightest scalar sneutrino and a BLino LSP is given in Fig. 13. Since both the BLino and the sneutrino masses are very sensitive to \(\tan \beta'\), small changes in that parameter can be sufficient to obtain an efficient co-annihilation: for the shown range of \(\tan \beta' = [1.285, 1.300]\) in the right-hand plot of Fig. 13, the BLino mass covers the range [670, 780] GeV and the sneutrino mass lies between [680, 950] GeV. In general, the mass difference between LSP and NLSP has to be around 3 GeV or smaller. This difference is smaller than the one known from the MSSM where stau or stop co-annihilation works even with mass differences of more than 15 GeV. The reason
Figure 13: BLino LSP and co-annihilation with a scalar sneutrino. The left plot shows the dependence of the relic density $\log(\Omega h^2)$ on the mass splitting between the lightest neutralino and the lightest scalar sneutrino, the right plot gives $\log(\Omega h^2)$ as function $\tan \beta'$. The mass of the LSP is between 670 and 780 GeV, while the co-annihilation can happen in the range between 670 and 720 GeV. The other parameters were $m_0 = [2.75, 2.8] \text{ TeV}$, $M_{1/2} = [1.7, 1.75] \text{ TeV}$, $\tan \beta = 29$, $A_0 = -1.45 \text{ TeV}$, $\tan \beta' = [1.26, 1.30]$, $M_{Z'} = [2.25, 2.3] \text{ TeV}$, $Y_{x}^{33} = [0.37, 0.38]$, $Y_{x}^{11} = 0.42$, $Y_{x}^{22} = 0.45$

is that the equivalent channels to the main co-annihilation channels in the MSSM, like $\tilde{\chi}_1^0 \tilde{e}_1 \rightarrow Z\tau$, are $\tilde{\nu}_1^S \tilde{\nu}_S \rightarrow Z'\nu_4$. However, these are all kinematically forbidden, and this has to be compensated by a smaller mass difference. For a chosen point with $m_{\tilde{\chi}_1^0} = 726.9 \text{ GeV}$, $m_{\tilde{\nu}_S^0} = 727.9 \text{ GeV}$ and $\Omega h^2 = 0.107$, the most important (co-)annihilation channels are

\[
\tilde{\nu}_1^S \tilde{\nu}_1^S \rightarrow h_2 h_2 \quad (96.7\%)
\]
\[
\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h_2 h_2 \quad (3.0\%)
\]

To get the CP-odd sneutrino sufficiently light, at least one diagonal entry of $Y_x$ has to be small. This has to be compensated by large values of $A_0$ to keep the BLino character of the LSP. For instance, one point for which the CP-odd co-annihilation is important is given by

\[
m_0 = 1890 \text{ GeV}, \quad M_{1/2} = 1736 \text{ GeV}, \quad \tan \beta = 25, \quad \mu > 0, \quad A_0 = 6345 \text{ GeV},
\]
\[
\tan \beta' = 1.277, \quad \mu' > 0, \quad M_{Z'} = 1695 \text{ GeV},
\]
\[
Y_{x}^{11} = 0.42, \quad Y_{x}^{22} = 0.40, \quad Y_{x}^{33} = 0.02.
\]

The mass of the BLino LSP is $m_{\tilde{\chi}_1^0} = 239.5 \text{ GeV}$, the light CP-even sneutrino has a mass of $m_{\tilde{\nu}_S^0} = 247.5 \text{ GeV}$ and the relic density of this point is calculated to be $\Omega h^2 = 0.108$. In contrast to the examples of scalar sneutrino co-annihilation, the neutralino itself already has a sizable cross section into two bileptons due to its light mass. This effect is discussed in more detail in sec. 3.2.5. Therefore, the co-annihilation channels contribute only a bit more than one third of the total annihilation:
\[ \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h_2 h_2 \ (58.0\%) \]
\[ \tilde{\nu}_1^P \tilde{\nu}_1^P \rightarrow h_2 h_2 \ (35.1\%) \]
\[ \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h_1 h_2 \ (3.5\%) \]
\[ \tilde{\nu}_1^P \tilde{\nu}_1^P \rightarrow h_1 h_2 \ (1.4\%) \]

In addition, the lightest right-handed neutrino is also lighter than the LSP because of the small \( Y_{x}^{33} \). Therefore, the mass splitting between the LSP and NLSP can be larger than in the case of a CP-even sneutrino NLSP.

**Bilepton**  In contrast to the BLino, the bilepton prefers a co-annihilation with the CP-odd sneutrino to with a CP-even sneutrino: both states are lighter if the entries of \( Y_{x} \) are not too large and the mass degeneracy is easier to obtain. In addition, the example given in Fig. 14 shows that the co-annihilation is possible over a wide range of the bilepton mass.

For the chosen parameters, the lightest scalar is a bilepton and the most important annihilation channel is \( \tilde{\nu}_1^P \tilde{\nu}_1^P \rightarrow h_1 h_1 \). In addition, the small value of \( Y_{x}^{33} \) leads also to a right-handed neutrino which is lighter than the LSP. Therefore, also co-annihilations of the form \( \tilde{\nu}_1^P \tilde{\chi}_1^0 \rightarrow h_1 \nu_4 \) are sizable and the mass splitting between LSP and NLSP can be of order \( \mathcal{O}(10 \text{ GeV}) \). For a chosen point with the correct \( \Omega h^2 \) of 0.115, the channels which contribute more than 1% to the total annihilation read

\[ \tilde{\nu}_1^P \tilde{\nu}_1^P \rightarrow h_1 h_1 \ (57.0\%) \]
\[ \tilde{\nu}_1^P \chi_1^0 \rightarrow h_1 \nu_4 \ (22.1\%) \]
\[ \tilde{\nu}_1^P \tilde{\nu}_1^P \rightarrow h_1 h_2 \ (14.1\%) \]
\[ \tilde{\nu}_1^P \chi_1^0 \rightarrow h_2 \nu_4 \ (3.3\%) \]
\[ \tilde{\nu}_1^P \tilde{\nu}_1^P \rightarrow h_2 h_2 \ (2.5\%) \]

To find parameter points where a co-annihilation between the bilepton and the CP-even sneutrino is realised it was necessary to choose small, negative values for
and a positive $A_0$ of a few TeV. This scenario is depicted in Fig. 15. We can see again that in a small parameter region the LSP mass can vary between 100 and 450 GeV, but it is always possible to get the correct relic density due to a CP-even sneutrino which is nearly degenerate in mass.

Despite the fact that the co-annihilation with scalar sneutrinos seems to be less generic than with pseudoscalar sneutrinos, the efficiency is even better than for the example shown in Fig. 13: a mass splitting between the LSP and NLSP of only 10 GeV is needed to get the correct abundance. The final states are comparable with the ones for the pseudoscalar sneutrino since a light right-handed neutrino is present. For a chosen point, the light bilepton is the second scalar Higgs and the channels read:

$$\tilde{\nu}_1^S \tilde{\nu}_1^S \rightarrow h_2 h_2 \quad (66.4\%)$$
$$\tilde{\nu}_1^S \tilde{\nu}_1^S \rightarrow h_1 h_2 \quad (20.1\%)$$
$$\tilde{\chi}^0_1 \rightarrow h_2 \nu_4 \quad (7.1\%)$$
$$\tilde{\nu}_1^S \tilde{\nu}_1^S \rightarrow h_1 h_1 \quad (3.8\%)$$
$$\tilde{\nu}_1^S \tilde{\chi}^0_1 \rightarrow h_1 \nu_4 \quad (1.2\%)$$

### 3.2.4 Stop and stau co-annihilation

Co-annihilation scenarios for $B-L$ dark matter is not restricted only to other $B-L$ states like the sneutrinos but may also occur with MSSM states. For the BLino and for the bileptino the relic density can be strongly reduced if a charged or colored sfermion like a light stau or stop is close enough in mass. The interaction of a neutralino LSP with a light stau is given by

$$\Gamma^{L}_{\tilde{\chi}_1^0 \tilde{\tau}_1} = \frac{i}{2} \left( -2 N_{13}^{*} Y_{e,33} Z_{16}^{E} + \sqrt{2} \left( g_1 N_{11}^{*} + g_2 N_{12}^{*} + \left( \bar{g} + g_{BL} \right) N_{13}^{*} \right) Z_{13}^{E} \right)$$

$$\Gamma^{R}_{\tilde{\chi}_1^0 \tilde{\tau}_1} = -\frac{i}{2} \left( 2 Y_{e,33} Z_{13}^{E} N_{13} + \sqrt{2} Z_{16}^{E} \left( 2 g_1 N_{11} + \left( \bar{g} + g_{BL} \right) N_{15} \right) \right)$$
where $Z^E$ is the $6 \times 6$ mixing matrix of the charged sleptons, while the coupling to a squark/quark pair reads

$$
\Gamma_{\tilde{\chi}^0_1 \tilde{t} \tilde{u}^*_1}^L = - \frac{i}{6} \left( 6 N_{14}^* \sum_{b=1}^{3} U_{L,3b}^{u,*} \sum_{a=1}^{3} Y_{u,ab} Z_{13+a}^U \right. \\
+ \sqrt{2} \left( 3 g_2 N_{12}^* + g_1 N_{11}^* + \left( \bar{g} + g_{BL} \right) N_{15}^* \right) \sum_{a=1}^{3} U_{L,3a}^{u,*} Z_{14}^U \right) \tag{3.14}
$$

$$
\Gamma_{\tilde{\chi}^0_1 \tilde{t} \tilde{u}^*_1}^R = \frac{i}{6} \left( - 6 \sum_{b=1}^{3} \sum_{a=1}^{3} Y_{u,ab}^* U_{R,3a}^u Z_{14}^U N_{14} \right. \\
+ \sqrt{2} \sum_{a=1}^{3} Z_{13+a}^U U_{R,3a}^u \left( 4 g_1 N_{11} + \left( 4 \bar{g} + g_{BL} \right) N_{15} \right) \right) \tag{3.15}
$$

In both cases there is no tree-level coupling between a pure bileptino and the MSSM particle, while the BLino couples proportionally to the $B - L$ charge. This may lead one to think that co-annihilation scenarios with a MSSM particle work better for a BLino than for a bileptino. However, this is not necessarily the case, as we will discuss now. A general drawback of stop co-annihilation is that at least one stop has to be rather light and the loop correction to the light MSSM Higgs gets reduced. Since we did not find a parameter point with stop co-annihilation and a Higgs mass above 115 GeV for either a BLino or bileptino LSP, we concentrate in the following on stau co-annihilation. For the shown examples, the mass of the light doublet Higgs lies in the preferred range of 123-127 GeV.

**BLino** To get a very light stau for values of $m_0$ in the TeV range, large values of $A_0$ and of $\tan \beta$ are needed as in the MSSM. An example for stau co-annihilation with a BLino LSP is shown in Fig. 16

---

**Figure 16:** BLino co-annihilation with stau. Left: $\log(\Omega h^2)$ vs. $m_{\tilde{\chi}^0_1}$. Right: $\log(\Omega h^2)$ vs. $m_{\tilde{\chi}^0_1} - m_{\tilde{\chi}^0_1}$. Parameter ranges: $m_0 = [2150, 2200]$ GeV, $M_{1/2} = [1700, 1750]$ GeV, $\tan \beta = [50, 52]$, $A_0 = [5550, 5650]$ GeV, $\tan \beta' = [1.31, 1.33]$, $M_Z' = [2.0, 2.1]$ TeV, $Y_{33} = [0.42, 0.43]$, $Y_{11} = Y_{22} = 0.42$. 
Obviously, the mass difference between the LSP and NLSP has to be very small and much smaller than normally necessary in the CMSSM. This is even more surprising when we take into account that there are new D-term contributions to the stau vertices for the interaction with scalar Higgs particles of the form

\[ \Gamma_{\tilde{t}_1\tilde{t}_1 h_k}^D = \frac{i}{4} \left( \sum_{a=1}^{3} Z_{13+a}^E Z_{13+a}^E \left( (2g_1^2 + \bar{g}(2\bar{g} + g_{BL})) (v_d Z_{k1}^H - v_u Z_{k2}^H) + 2g_{BL} (2\bar{g} + g_{BL}) (v_\eta Z_{k3}^H - v_\eta Z_{k3}^H) \right) \right. + \left. \sum_{a=1}^{3} Z_{1a}^E Z_{1a}^E \left( 2g_{BL} (\bar{g} + g_{BL}) (v_\eta Z_{k4}^H - v_\eta Z_{k3}^H) \right) - (\bar{g}(\bar{g} + g_{BL}) + g_1^2 - g_2^2) (v_d Z_{k1}^H - v_u Z_{k2}^H) \right) \]

(3.16)

Similar contributions also exist for the four point interactions \( \tilde{e}_1^* \tilde{e}_1^* h_k h_l \). Because of these new contributions, the most important final state for stau co-annihilation can be the one with two bilepton fields. For instance, the annihilation channels for one point with \( \Omega h^2 = 0.116 \), \( m_{\tilde{\chi}^0_1} = 426.0 \text{ GeV} \), \( m_{\tilde{e}_1} = 426.4 \text{ GeV} \) are given by

- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow h_2 h_2 \) (17.7%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow W^+ W^- \) (12.0%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow e^+ e^- \) (9.9%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow \tau^+ \tau^- \) (8.6%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow h_1 h_1 \) (8.1%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow h_1 \tau \) (7.7%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow Z \gamma \) (6.8%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow \gamma Z \) (5.2%)
- \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow h_2 h_2 \) (4.6%)
- \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow \gamma \tau \) (3.7%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow h_1 h_2 \) (3.5%)
- \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow t \bar{t} \) (3.5%)
- \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow Z \tau \) (1.9%)
- \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow W^- \nu_2 \) (1.9%)
- \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow h_1 \tau \) (1.7%)
- \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow b \bar{b} \) (1.1%)

The reason that the mass difference between LSP and NLSP has to be so small is that the mass spectrum is in general very heavy: the second stau as well as the lightest L-sneutrino have masses of 1.95 TeV for the shown point, as consequence of the huge values of \( |A_0| \) and \( m_0 \). These heavy masses suppress the t-channel diagrams \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow h_i h_i \) and \( \tilde{e}_1^* \tilde{e}_1^* \rightarrow W^+ W^- \). Were the mass of the second stau of order 1 TeV, the relic density of exactly the same point would be \( \Omega h^2 = 0.04 \). However, those values are necessary to obtain a sufficiently large \( \mu' \) and the BLino character of the LSP.

**Bilepton** In case of a bilepton LSP, stau co-annihilation works as efficiently as in the MSSM, as can be seen in Figs. 17: a mass splitting of 10 GeV is still sufficient to reduce \( \Omega h^2 \) to roughly 0.1. The main difference compared to a BLino LSP is that the second stau as well as the L-sneutrinos have a mass below 1.5 TeV. The dip around 120 GeV is due to a resonance with the second scalar Higgs which is a bilepton. However, since the LSP has only a very small BLino fraction, the coupling to the
bilepton is not large enough for a sufficient annihilation even at the resonance, see also sec. 3.2.1. Hence, for the shown parameter range only stau co-annihilation leads to the correct relic density.

Figure 17: Bileptino co-annihilation with stau. Top left: \( \log(\Omega h^2) \) vs. \( m_{\tilde{e}_1} \). Top right: \( \log(\Omega h^2) \) vs. \( m_{\tilde{e}_1} - m_{\tilde{\chi}_1^0} \). Bottom left: \( \log(\Omega h^2) \) vs. \( 2 \cdot m_{\tilde{\chi}_1^0} - m_h \). Bottom right: bileptino fraction. Parameter ranges: \( m_0 = [1500, 1550] \) GeV, \( M_{1/2} = [960, 990] \) GeV, \( \tan \beta = [39, 41] \), \( A_0 = [-3650, -3600] \) GeV, \( \tan \beta' = [1.21, 1.23] \), \( M_{Z'} = [3.8, 3.9] \) TeV, \( Y_{x}^{33} = [0.40, 0.41] \), \( Y_{x}^{11} = 0.42 \), \( Y_{x}^{22} = 0.373 \).

For the shown example, the pure bilepton final state is even more important than in the example with a BLino LSP since the t-channel diagrams are less suppressed. We get, for instance, for a \( m_{\tilde{e}_1} = 438.5 \) GeV and \( m_{\tilde{\chi}_1^0} = 433.3 \) GeV, a relic density of \( \Omega h^2 = 0.095 \) due to

\[
\begin{align*}
\tilde{e}_1 \tilde{e}_1^{*} &\rightarrow h_2 h_2 \quad (52.5\%) \\
\tilde{e}_1 \tilde{e}_1^{*} &\rightarrow W^+ W^- \quad (9.5\%) \\
\tilde{e}_1 \tilde{e}_1^{*} &\rightarrow Z Z \quad (5.0\%) \\
\tilde{e}_1 \tilde{e}_1^{*} &\rightarrow \gamma Z \quad (1.8\%) \\
\tilde{e}_1 \tilde{e}_1^{*} &\rightarrow h_2 \bar{\tau} \quad (1.3\%) \\
\tilde{e}_1 \tilde{e}_1^{*} &\rightarrow h_2 \gamma \quad (1.2\%)
\end{align*}
\]

All-in-all, stau co-annihilation seems to work better with a BLino LSP than with a bileptino LSP despite the fact that there is no tree-level coupling between bileptino and the stau. However, this is compensated by the lighter sfermion spectrum. The same statement also holds in the case of stop co-annihilation. However, in that case
the mass difference between the LSP and NLSP can be in general larger than for the stau since the gluons also contribute to the annihilation.

3.2.5 Neutralino t-channel annihilation

The last mechanism we found to get the correct abundance of a BLino LSP is similar to the focus point region in the MSSM and is based on a sizable bileptino fraction of the BLino LSP. For a rather light LSP with bilepton masses even lighter than the LSP mass, the BLino/bileptino mixing leads to a strong annihilation $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow h Bh_B$ due to a light neutralino in the t-channel.

As can be seen in Fig. 18, there is a clear correlation between the neutralino mass and the relic density. For a LSP mass around 200 GeV, $\Omega h^2 = 0.1$ is reached. The greatest coupling between a bilepton and the neutralino is for a maximally mixed BLino/bileptino state. However, it can be seen on the second plot of Fig. 18 that this mixing becomes smaller with decreasing mass and the BLino clearly dominates. Therefore, the relic density shows the counter-intuitive dependence on the BLino and bileptino fractions depicted in the second row of Fig. 18.
The most important final states appearing in the annihilation for a chosen point with $\Omega h^2 = 0.110$ are two bilepton Higgs ($h_2$), with a contribution of $\sim 90\%$, as well as $h_1h_2$, $W^+W^-$ and $h_1h_1$ as long as the bilepton mass is lower than the LSP mass. If the bileptons are so heavy that their presence in the final state is kinematically forbidden, the same mechanisms work if the neutralino masses are even lighter. In that case the cross section induced by kinetic mixing can be large enough. For instance, $\Omega h^2 = 0.103$ for a BLino mass of 158.3 GeV is obtained by

$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^- \quad (52.4\%)$$
$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ \quad (24.9\%)$$
$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_1h_1 \quad (22.7\%)$$

Hence, especially for light neutralinos, it is very important to include the effects of kinetic mixing. However, as soon as the LSP mass is also below 125 GeV, i.e. the mass of the light doublet Higgs, the mechanism fails and the relic density starts to grow rapidly until the Higgs resonance appears around 60 GeV, see also Fig. 9.

### 3.2.6 Summary of BLino and bileptino dark matter

**Failed attempts** Before we summarise the different mechanisms that work for fermionic $B – L$ dark matter, we want to add some remarks about scenarios which do not seem to work. Firstly, chargino co-annihilation turns out to be rather difficult to achieve. The chargino mass is always correlated to the mass of a MSSM neutralino and because of the larger loop corrections the charginos are in general heavier. Hence, before the chargino mass is close enough to the mass of a BLino or bileptino LSP, a mass crossing between the lightest $B – L$ neutralino and the lightest MSSM-like neutralino takes place. Secondly, the bulk region of the CMSSM is known to be ruled out by the bounds on squark masses coming from LHC. However, in this model there are new D-term contributions to the sfermions which are larger for the sleptons than for the squarks because of their larger $B – L$ charges. Nevertheless it was not possible to find regions with sufficiently large annihilation of two neutralinos into two standard model fermions through sleptons in the t-channel. The reason for this is that only the BLino has a tree-level coupling to the charged sleptons but obtaining a BLino LSP demands in general even larger values of $m_0$ than needed for a bileptino LSP.

**Working annihilation mechanisms** A summary of possible mechanisms to get the correct amount of dark matter for BLino and bileptino LSPs is given in Table 2. Some scenarios are viable for both dark matter candidates, such as sufficient annihilation through a bilepton resonance. Others mechanisms like stau co-annihilation seem to work much better for a bileptino LSP than for a BLino LSP, while a sufficient t-channel annihilation does not seem to be possible at all for a bileptino LSP.

Of course, the picture changes significantly if we allow deviations from the strict universal boundary conditions at the GUT scale. In this framework, it should be
Table 2: Dark matter scenarios for a $B - L$ neutralino LSP. The scenarios marked with a ‘✓’ work very well and are possible in several regions in parameter space. Scenarios with a ‘∼’ work in principle but it is much more difficult to tune the relic density to the correct amount or there are other drawbacks like the light Higgs mass in the case of stop co-annihilation. Mechanisms marked by a ‘×’ could not be found at all.

### 3.3 Direct detection

We have presented in the previous two subsections four new potential dark matter candidates. However, to be a valid candidate not only does the relic density have to be correct but the particle must also be in agreement with all experimental limits. Therefore, here we check against the limits on the interaction cross section with nuclei derived by direct detection experiments. The strongest bounds come from the XENON100 experiment [98]. The best sensitivity on the spin-independent cross section between the LSP and a proton or neutron is roughly $10^{-44}$ cm$^2$ for a LSP mass of around 50 GeV.

**BLino and bileptino** $B - L$ neutralino LSPs interact with nucleons through diagrams with s-channel squarks or t-channel neutral vector or scalar bosons. As we have already seen in eqs. (3.14) and (3.15) only the BLino component of the LSP can couple to a quark/squark pair. Therefore, especially for BLino, the s-channel contributions are important. In addition, exchange of Higgs bosons can be important, as can also be seen from the corresponding couplings in eqs. (3.5) and (3.6). In contrast, the $Z'$ has only an axial coupling to the Majorana LSPs as given in eqs. (3.8) and (3.9). Hence, it cannot contribute much to the spin-independent cross section. Furthermore, the coupling to the $Z$ boson is too small to be of any relevance. Therefore, both $B - L$ neutralino dark matter candidates interact with the same strength with the proton as with the neutron and we don’t have to distinguish them in the following

| Mechanism                          | BLino | bileptino |
|------------------------------------|-------|-----------|
| Bilepton Higgs resonance           | ✓     | ✓         |
| Doublet Higgs resonance            | ✓     | ∼         |
| CP-even sneutrino co-annihilation  | ∼     | ∼         |
| CP-odd sneutrino co-annihilation   | ∼     | ✓         |
| Stau co-annihilation               | ∼     | ✓         |
| Stop co-annihilation               | ∼     | ∼         |
| Neutralino t-channel annihilation  | ✓     | ×         |
| $Z'$ resonance                     | ∼     | ✓         |
Figure 19: BLino direct detection. First row: direct detection cross section vs. LSP mass (left) and direct detection cross section vs. dark matter abundance (right). Second row: direct detection cross section as function of gaugino (left) and Higgsino (right) fraction. Third row: direct detection cross section as function of BLino (left) and bileptino fraction (right). The red line shows the exclusion limit of XENON100. Parameters are the same as in Fig. 18.

discussion. The calculations of the cross section were performed with MicrOmegas, with the bounds coming from XENONP rovided by DMTools [99].

The coupling of a pure BLino LSP to squark/quark is comparable to that of a pure bino up to a factor $c(g_{BL}/g_1)^2 \sim 2c$ with a numerical coefficient of order 1 fixed by the quantum numbers. On the other hand, a BLino LSP has some bileptino fraction which doesn’t couple at all to the (s)quarks, with the negative $\bar{g}$ that also reduces the coupling. Thus we expect the BLino interaction with a proton or neutron to be of the same size as the bino interaction in the MSSM. This agrees with the
outcome of the numerical calculations shown in Fig. 19. The large majority of the tested points are well below the current experimental limits. Also the dependence on the BLino and bileptino fractions is as expected: the cross section increases with increasing BLino fraction and becomes very small for an LSP with a large bileptino component. The contributions of the small admixture of MSSM states is very sub-dominant simply because of their smallness. The ostensible correlation between the bino fraction and the cross section is based on the correlation between the BLino and bino fraction due to kinetic mixing.

The general picture doesn’t change if we check regions in parameter space in which resonances with doublet or bilepton Higgs states are present: the coupling of both kinds of scalars to the quarks of the first two generations is too small to increase the cross section visibly. This is depicted in Fig. 20. As mentioned above, the $Z'$ couples only axially to the bileptino LSP and the resulting contribution to the spin-independent cross section is therefore always very small. All-in-all, the BLino is consistent with all direct detection bounds but might be tested with the next generation experiments, if a sensitivity of $10^{-45}$ cm$^2$ - $10^{-46}$ cm$^2$ is reached.

Since the spin-independent direct detection cross section of a bileptino is in general even smaller than that of a BLino in the absence of any resonance, we can immediately move on to the most interesting scenario involving the $Z'$ resonance. The results of the numerical calculation are given in Fig. 21. A non-vanishing fraction of the points in the high mass regime which are close to the resonance are already in conflict with XENON100 results. The reason for the increased cross section is that the coupling to the bilepton becomes large for a maximally mixed BLino-bileptino state. For the given parameters, the mass of the light bilepton is about 100 GeV for a LSP mass close to 1 TeV. Together with the large mixing, this allows for an enhanced t-channel interaction with the quarks. However, there are still valid points with the correct dark matter relic density and a cross section below $10^{-44}$ cm$^2$. With the expected sensitivity of $10^{-46}$ cm$^2$ of Xenon1t [100], all of these points could
Figure 21: Bileptino direct detection cross section near $Z'$ resonance. First row: $m_{\tilde{\chi}_0^1}$ vs. $\sigma_{SI}^N$ (left) and $\Omega h^2$ vs. $\sigma_{SI}^N$ (right). Second row $\sigma_{SI}^N$ as function of BLino (left) and bileptino (right) fraction. The red line shows the exclusion limit of XENON100. Parameters are the same as in Fig. 12.

be tested. The surprising dependence of the cross section on the BLino fraction is caused by the dependence of the LSP mass on the BLino fraction: while the $Z'$ boson couples to the bileptino component, it is only possible to have an LSP which is mainly bileptino if it is also relatively light and thus far from the resonance.

**Sneutrinos** Sneutrino dark matter in the MSSM is already ruled out because of the $t$-channel contributions of the $Z$ boson. However, $B-L$ sneutrinos as dark matter candidates are CP eigenstates with different masses, hence neither the $Z$ nor the $Z'$ boson can contribute. In addition, there is no tree-level coupling between the sneutrinos and squarks. The only possible contributions are due to $t$-channel diagrams involving Higgs bosons which couple only weakly to the quarks. All-in-all, the cross section is very small and always more than one order of magnitude below the current experimental limits as shown in Fig. 22.

### 3.4 Impact on MSSM dark matter candidates

In addition to the new candidates for dark matter, the BLSSM also retains the candidates of the MSSM. There are, however, some differences in the properties of these shared candidates in how their relic densities are in the context of the BLSSM.
Figure 22: First row: direct detection cross section for CP-even sneutrinos: $\sigma_{SI}^{S}$ as function of the mass of the lightest scalar sneutrino. The parameters were those of Fig. 3 (left) and Fig. 4 (right). Second row: direct detection cross section for CP-odd sneutrinos using the parameters of Fig. 6. The red line shows the exclusion limit of Xenon100.

We give here a short list of possible effects, since a detailed study of these cases goes beyond the scope of this paper:

- **Stau/squark co-annihilation**: the masses of the sfermions receive new contributions from the D-terms involving bileptons. The bino mass is also slightly altered due to the effect of kinetic mixing. Therefore it can be expected that the co-annihilation regions of the MSSM get shifted.

- **Focus point**: it has already be pointed out in Ref. [53] that a change in $M_{Z'}$ or $\tan \beta'$ can also alter the Higgsino fraction of an MSSM neutralino LSP. Hence the new parameter will have an impact on the focus point region.

- **Higgs resonances**: the MSSM and the $B - L$ sector are already coupled at tree level due to kinetic mixing. Therefore resonances between a MSSM neutralino and a bilepton are also possible. In contrast to the Higgs funnel in the CMSSM, these resonances don’t demand a very large value of $\tan \beta$, but are rather easy to find because the mass of a bino LSP and the light bilepton are sensitive to different parameters.
• Z’ resonances: the coupling of a MSSM neutralino to the Z’ boson is very weak and the corresponding resonance won’t reduce the abundance to an acceptable amount. Nevertheless, there exists the possibility of indirect resonances similar to the one discussed in sec. 3.2.1 for the bilepton with the MSSM Higgs. If the second neutralino is a bilepton and also very close in mass to the LSP and to the resonant point with the Z’ boson, it annihilates very efficiently and can also co-annihilate with the LSP to reduce its relic density.

4. Conclusion

We have discussed here the additional possibilities for dark matter candidates arising in a constrained version of the minimal R-parity-conserving supersymmetric model with a gauged $U(1)_{B-L}$. In addition to the candidates known from the MSSM, the LSP can be either a BLino or bileptino neutralino, or a CP-even or -odd bosonic partner of a right-handed neutrino. In the case of a sneutrino LSP, the dark matter relic density is often of the correct order of magnitude or even well below the measured value because of the strong interaction between the sneutrinos and the light bilepton. However, kinetic mixing is crucial for many annihilation channels and light sneutrinos below the bilepton mass threshold would be ruled out without kinetic mixing. Since the sneutrino LSP is a CP eigenstate with a sizable mass difference to the eigenstate with opposite CP quantum number, there is no tree-level coupling to the Z boson and the spin-independent cross section to nuclei is much smaller than that of the scalar partner of the left-handed neutrino in the MSSM. Therefore, the sneutrinos clearly fulfill all bounds coming from direct detection experiments like XENON100.

In contrast, for a BLino or bileptino LSP, specific mass configurations are needed to reduce the abundance to a level consistent with the measured dark matter abundance in the Universe. Possible mechanisms that we have discussed are resonances with Higgs fields and co-annihilations with $SU(2)_L$-singlet sneutrinos, which work very well for both the BLino and the bilepton. A co-annihilation with staus is also possible but easier to realize for a bilepton. Stop co-annihilation would also work but leads in general to a mass of the light doublet Higgs which is in conflict with recent indications coming from the LHC. In the case of a rather light BLino LSP with a non-negligible bileptino fraction, the t-channel annihilation into two bileptons can also be sufficient to get the correct relic density. None of these scenarios are in conflict with the bounds coming from XENON100. However, the Z’ resonance, which is only relevant for a bileptino LSP, can increase the spin-independent cross section of the LSP with nuclei to a level excluded by XENON100 for smaller values of $M_{Z'}$.

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