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Precision study of the minimal $B - L$ model using the SUSY-Toolbox

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We discuss a CMSSM variant of the minimal, supersymmetric $B-L$ extension of the minimal supersymmetric standard model. This model provides many new, phenomenological aspects because it extends not only the gauge, but also the Higgs, the neutralino, the neutrino and the sneutrino sector. We demonstrate how the SUSY-Toolbox can be used to perform a comprehensive study of this model with a precision needed for a linear collider. This includes a calculation of the mass spectrum based on two-loop RGEs and a complete one-loop renormalization using SPheno and the possibility performing exhaustive collider studies due to a full-fledged implementation in well-tested Monte-Carlo tools like WHIZARD or CalcHep. In addition, checks of Higgs and dark matter constraints can be applied using HiggsBounds and MicrOmegas. This tool-chain is based on the easy implementation of new models in the SARAH.

1 Introduction

Models with an additional $U(1)_{B-L}$ gauge symmetry at the TeV scale have recently received considerable attention: they can explain neutrino data, they might help to understand the origin of R-parity and its possible spontaneous violation in supersymmetric models [1, 2, 3] as well as the mechanism of leptogenesis [4, 5] and they provide a rich phenomenology by introducing new states in the Higgs, the neutralino and the neutrino/sneutrino sector. This has already observable consequences at the LHC [6, 7, 8, 9], which will be most likely much more pronounced at a linear collider (LC).
An extended gauge sector containing $U(1)_Y \times U(1)_{B-L}$ can be embedded in an $E_8 \times E_8$ heterotic string theory [10]. We include in our study [11] a detailed analysis of impact of kinetic mixing what has been neglected so far in literature [3, 12]. It is well known that in models with several $U(1)$ gauge groups, kinetic mixing terms

$$-\chi_{ab} \hat{F}^{a,\mu\nu} \hat{F}^{b}_{\mu\nu}, \quad a \neq b \tag{1}$$

between the field strength tensors are allowed by gauge and Lorentz invariance [13], see *e.g.* [14]. Even if these terms are absent at tree level at a particular scale, they might be generated by RGE effects [15, 16]. To perform our studies we have used the environment provided by the SUSY-Toolbox [17]. The SUSY-Toolbox includes scripts to download, to configure and to install the public codes CalcHep [18, 19], HiggsBounds [20, 21], MicrOmegas [22], SARAH [23, 24, 25], SPheno [26, 27], SSP and WHIZARD [28, 29]. In addition, it gives the possibility for a one-step implementation of new SUSY models in all packages based on the implementation in SARAH.We discuss the implementation of the model presented in [1, 3] in SARAH and present results of our detailed analysis concerning the mass spectrum using SPheno [11]. In particular we will demonstrate that gauge kinetic mixing effects are particularly important in the Higgs and neutralino sectors. These effects do not only change the masses of these particles but have quite some impact of their nature, *e.g.* they induce tree-level mixing which would be absent if these effects were to be neglected. Therefore, it should be no longer neglected in the analysis of this and similar models, especially with regard to the precision necessary

Superfield	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)_Y \otimes SU(2)_L \otimes SU(3)_C \otimes U(1)_{B-L})$
$\hat{Q}$	$\tilde{Q}$	Q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, \frac{1}{6})$
$\hat{D}$	$\tilde{d}^c$	d^c	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{U}$	$\tilde{u}^c$	u^c	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{L}$	$\tilde{L}$	L	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})$
$\hat{E}$	$\tilde{e}^c$	e^c	3	$(1, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{\nu}$	$\tilde{\nu}^c$	ν^c	3	$(0, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{\eta}$	η	$\tilde{\eta}$	1	$(0, \mathbf{1}, \mathbf{1}, -1)$
$\hat{\bar{\eta}}$	$\bar{\eta}$	$\tilde{\bar{\eta}}$	1	$(0, \mathbf{1}, \mathbf{1}, 1)$

Table 1: Chiral superfields and their quantum numbers.

for a LC.
We will show that new light Higgs states are possible without being in conflict with current data while having at the same time a SM-like Higgs in the range close to 120 GeV. In addition, we give a short outlook of dark matter aspects using `MicrOmegas`: we show that in our model the nature of lightest supersymmetric particle (LSP) can be quite different in comparison to the minimal supersymmetric standard model (MSSM). We identify regions where it is either mainly a $SU(2)_L$-doublet Higgsino, a $U(1)_{B-L}$-gaugino which we dub the BLino, or a fermionic partner of the $U(1)_{B-L}$-breaking scalar which we dub the bileptino. It turns out that the BLino and the bileptino can have the correct abundance for being valid dark matter candidates [30].

2 The Model

2.1 Particle content and superpotential

The model under consideration, called $B-L$SSM in the following, extends the MSSM matter content by three generations of right-handed neutrino superfields. Moreover, below the GUT scale the usual MSSM Higgs doublets are present as well as two fields η and $\bar{\eta}$ responsible for the breaking of the $U(1)_{B-L}$. Furthermore, η is responsible for generating a Majorana mass term for the right-handed neutrinos and thus we call this field a bilepton. 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

$$W = Y_u^{ij}\,\hat{U}_i\,\hat{Q}_j\,\hat{H}_u\,-Y_d^{ij}\,\hat{D}_i\,\hat{Q}_j\,\hat{H}_d\,-Y_e^{ij}\,\hat{E}_i\,\hat{L}_j\,\hat{H}_d\,+\mu\,\hat{H}_u\,\hat{H}_d\,+Y_\nu^{ij}\,\hat{L}_i\,\hat{H}_u\,\hat{\nu}_j\,-\mu'\,\hat{\eta}\,\hat{\bar{\eta}}\,+Y_x^{ij}\,\hat{\nu}_i\,\hat{\eta}\,\hat{\nu}_j \tag{2}$$

and we have the additional soft SUSY-breaking terms:

$$\begin{aligned} L_{SB} =& L_{MSSM} - \lambda_{\tilde{B}}\lambda_{\tilde{B}'}M_{BB'} - \frac{1}{2}\lambda_{\tilde{B}'}\lambda_{\tilde{B}'}M_{B'} - m_\eta^2|\eta|^2 - m_{\bar{\eta}}^2|\bar{\eta}|^2 - m_{\nu,ij}^2(\tilde{\nu}_i^c)^*\tilde{\nu}_j^c \\ & - \eta\bar{\eta}B_{\mu'} + T_\nu^{ij}H_u\tilde{\nu}_i^c\tilde{L}_j + T_x^{ij}\eta\tilde{\nu}_i^c\tilde{\nu}_j^c \end{aligned} \tag{3}$$

i, j are generation indices. The extended gauge group breaks to $SU(3)_C \otimes U(1)_{em}$ as the Higgs fields and bileptons receive vacuum expectation values (VEVs):

$$H_d^0 = \frac{1}{\sqrt{2}}\left(\sigma_d + v_d + i\phi_d\right), \qquad H_u^0 = \frac{1}{\sqrt{2}}\left(\sigma_u + v_u + i\phi_u\right) \tag{4}$$

$$\eta = \frac{1}{\sqrt{2}}\left(\sigma_\eta + v_\eta + i\phi_\eta\right), \qquad \bar{\eta} = \frac{1}{\sqrt{2}}\left(\sigma_{\bar{\eta}} + v_{\bar{\eta}} + i\phi_{\bar{\eta}}\right) \tag{5}$$

We define $\tan\beta' = \frac{v_\eta}{v_{\bar{\eta}}}$ in analogy to the ratio of the MSSM VEVs ($\tan\beta = \frac{v_u}{v_d}$).

2.2 Gauge kinetic mixing

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: the gauge kinetic mixing. This can be seen most easily by inspecting the matrix of the anomalous dimension, which at one loop is given by $\gamma_{ab} = \frac{1}{16\pi^2}\text{Tr}Q_a Q_b$, where the indices a and b run over all $U(1)$ groups and the trace runs over all fields charged under the corresponding $U(1)$ group. For our model we obtain

$$\gamma = \frac{1}{16\pi^2} N \begin{pmatrix} 11 & 4 \\ 4 & 6 \end{pmatrix} N. \tag{6}$$

and we see that there are sizable off-diagonal elements. N contains the GUT normalization of the two Abelian gauge groups. We will take as in ref. [3] $\sqrt{\frac{3}{5}}$ for $U(1)_Y$ and $\sqrt{\frac{3}{2}}$ for $U(1)_{B-L}$, i.e. $N = \text{diag}(\sqrt{\frac{3}{5}}, \sqrt{\frac{3}{2}})$. In practice it turns out that it is easier to work with non-canonical covariant derivatives instead of off-diagonal field-strength tensors such as in Eq. (1). However, both approaches are equivalent [31]. Hence in the following, we consider covariant derivatives of the form

$$D_\mu = \partial_\mu - i Q_\phi^T G A \tag{7}$$

where Q_ϕ is a vector containing the charges of the field ϕ with respect to the two Abelian gauge groups, G is the gauge coupling matrix

$$G = \begin{pmatrix} g_{YY} & g_{YB} \\ g_{BY} & g_{BB} \end{pmatrix} \tag{8}$$

and A contains the gauge bosons $A = (A_\mu^Y, A_\mu^B)^T$.

As long as the two Abelian gauge groups are unbroken, we have still the freedom to perform a change of basis. This freedom can be used to choose a basis such that electroweak precision data can be accommodated in an easy way. A convenient choice is the basis where $g_{BY} = 0$. Therefore we choose the following basis at the electroweak scale [32]:

$$g'_{YY} = \frac{g_{YY} g_{BB} - g_{YB} g_{BY}}{\sqrt{g_{BB}^2 + g_{BY}^2}} = g_1 \,, \qquad g'_{BB} = \sqrt{g_{BB}^2 + g_{BY}^2} = g_{BL} \tag{9}$$

$$g'_{YB} = \frac{g_{YB} g_{BB} + g_{BY} g_{YY}}{\sqrt{g_{BB}^2 + g_{BY}^2}} = \tilde{g} \,, \qquad g'_{BY} = 0 \tag{10}$$

Immediate consequences of this kinetic mixing are: (i) it induces mixing at tree level between the H_u, H_d and η, $\bar{\eta}$; (ii) additional D-terms contribute to the mass matrices of the squarks and sleptons; (iii) off-diagonal soft-SUSY breaking terms for the gauginos are induced via RGE evolution [31, 33] with important consequences for the neutralino sector, even if at some fixed scale $M_{ab} = 0$ for $a \neq b$.

2.3 Tadpole equations

We solve the minimum conditions at tree-level with respect to μ, B_μ, μ' and $B_{\mu'}$ as these parameters do not enter any of the RGEs of the other parameters. Using $x^2 = v_\eta^2 + v_{\bar{\eta}}^2$ and $v^2 = v_d^2 + v_u^2$ we find an approximate relation between M'_Z and μ'

$$M_{Z'}^2 \simeq -2|\mu'|^2 + \frac{4(m_{\bar{\eta}}^2 - m_\eta^2 \tan^2\beta') - v^2 \tilde{g} g_{BL} \cos\beta (1 + \tan\beta')}{2(\tan^2\beta' - 1)} \tag{11}$$

A closer inspection of the system shows that either $m_{\bar{\eta}}^2$ or m_η^2 has to become negative to break $U(1)_{B-L}$. Because of the structure of the RGEs [11], $m_{\bar{\eta}}$ will always be positive whereas m_η^2 can become negative for sufficient large Y_x and T_x. In addition, we expect that large values of m_0 and A_0 will be preferred, implying heavy sfermions. Moreover, $\tan\beta'$ has to be small and of $O(1)$ in order to get a small denominator in the second term of Eq. 11.

For the numerical results we include one-loop corrections to the tadpole equations as well as for all masses. This is done by using the $\overline{\text{DR}}$ scheme and extending the MSSM results given in ref. [34] in a similar manner to the NMSSM case discussed in ref. [35].

2.4 Gauge boson mixing

Due to the presence of the kinetic mixing terms, the B' boson mixes at tree level with the B and W^3 bosons. Requiring the conditions of Eqs. (9)-(10) means that the corresponding mass matrix reads, in the basis (B, W^3, B'),

$$\begin{pmatrix} \frac{1}{4}g_1^2 v^2 & -\frac{1}{4}g_1 g_2 v^2 & \frac{1}{4}g_1 \tilde{g} v^2 \\ -\frac{1}{4}g_1 g_2 v^2 & \frac{1}{4}g_2^2 v^2 & -\frac{1}{4}\tilde{g} g_2 v^2 \\ \frac{1}{4}g_1 \tilde{g} v^2 & -\frac{1}{4}\tilde{g} g_2 v^2 & (g_{BL}^2 x^2 + \frac{1}{4}\tilde{g}^2 v^2) \end{pmatrix} \tag{12}$$

In the limit $\tilde{g} \to 0$ both sectors decouple and the upper 2×2 block is just the standard mass matrix of the neutral gauge bosons in EWSB. This mass matrix can be diagonalized by a unitary mixing matrix to get the physical mass eigenstates γ, Z and Z'. Expanding the eigenvalues in powers of v^2/x^2, we find up to first order:

$$M_Z = \frac{1}{4}\left(g_1^2 + g_2^2\right) v^2 \,, \qquad M_{Z'} = g_{BL}^2 x^2 + \frac{1}{4}\tilde{g}^2 v^2 \tag{13}$$

All parameters so far as well as in the following mass matrices are understood as running parameters at a given renormalization scale Q.

2.5 The Higgs sector

In this section we present the tree-level formulas for the Higgs sector and we briefly discuss the main steps to include the one-loop corrections. The one-loop formulas and further details will be presented elsewhere [36].

2.5.1 Pseudo scalar Higgs bosons

It turns out that in this sector there is no mixing between the $SU(2)$ doublets and the bileptons at tree level and we obtain in the basis $(\phi_d, \phi_u, \phi_\eta, \phi_{\bar{\eta}})$:

$$m^2_{A,T} = \begin{pmatrix} B_\mu \tan\beta & B_\mu & 0 & 0 \\ B_\mu & B_\mu \cot\beta & 0 & 0 \\ 0 & 0 & B_{\mu'} \tan\beta' & B_{\mu'} \\ 0 & 0 & B_{\mu'} & B_{\mu'} \cot\beta' \end{pmatrix} . \tag{14}$$

Obviously, both sectors decouple at tree level. One obtains two physical states A^0 and A^0_η with masses

$$m^2_{A^0} = \frac{2B_\mu}{\sin 2\beta} \,, \qquad m^2_{A^0_\eta} = \frac{2B_{\mu'}}{\sin 2\beta'} \,. \tag{15}$$

2.5.2 Scalar Higgs bosons

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

$$m^2_{h,T} = \begin{pmatrix} m^2_{A^0} s^2_\beta + \bar{g}^2 v_u^2 & -m^2_{A^0} c_\beta s_\beta - \bar{g}^2 v_d v_u & \frac{\tilde{g} g_{BL}}{2} v_d v_\eta & -\frac{\tilde{g} g_{BL}}{2} v_d v_{\bar{\eta}} \\ -m^2_{A^0} c_\beta s_\beta - \bar{g}^2 v_d v_u & m^2_{A^0} c^2_\beta + \bar{g}^2 v_d^2 & -\frac{\tilde{g} g_{BL}}{2} v_u v_\eta & \frac{\tilde{g} g_{BL}}{2} v_u v_{\bar{\eta}} \\ \frac{\tilde{g} g_{BL}}{2} v_d v_\eta & -\frac{\tilde{g} g_{BL}}{2} v_u v_\eta & m^2_{A^0_\eta} c^2_{\beta'} + g^2_{BL} v^2_\eta & -m^2_{A^0_\eta} c_{\beta'} s_{\beta'} - g^2_{BL} v_\eta v_{\bar{\eta}} \\ -\frac{\tilde{g} g_{BL}}{2} v_d v_{\bar{\eta}} & \frac{\tilde{g} g_{BL}}{2} v_u v_{\bar{\eta}} & -m^2_{A^0_\eta} c_{\beta'} s_{\beta'} - g^2_{BL} v_\eta v_{\bar{\eta}} & m^2_{A^0_\eta} s^2_{\beta'} + g^2_{BL} v^2_{\bar{\eta}} \end{pmatrix} \tag{16}$$

where we have defined $\bar{g}^2 = \frac{1}{4}(g_1^2 + g_2^2 + \tilde{g}^2)$, $c_x = \cos(x)$ and $s_x = \sin(x)$ $(x = \beta, \beta')$. The one-loop corrections are included by calculating the real part of the poles of the corresponding propagator matrices [34, 36]

$$\text{Det}\left[p_i^2 \mathbf{1} - m^2_{h,1L}(p^2)\right] = 0, \tag{17}$$

where

$$m_{h,1L}^2(p^2) = m_T^{2,h} - \Pi_{hh}(p^2). \tag{18}$$

Equation (17) has to be solved for each eigenvalue $p^2 = m_i^2$ which can be achieved in an iterative procedure, see [35].

2.6 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. The mass matrix reads in the basis $\left(\lambda_{\tilde{B}}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \lambda_{\tilde{B}'}, \tilde{\eta}, \tilde{\bar{\eta}}\right)$

$$m_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & \frac{1}{2}M_{BB'} & 0 & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 & 0 & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu & -\frac{1}{2}\tilde{g} v_d & 0 & 0 \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 & \frac{1}{2}\tilde{g} v_u & 0 & 0 \\ \frac{1}{2}M_{BB'} & 0 & -\frac{1}{2}\tilde{g} v_d & \frac{1}{2}\tilde{g} v_u & M_B & -g_{BL} v_\eta & g_{BL} v_{\bar{\eta}} \\ 0 & 0 & 0 & 0 & -g_{BL} v_\eta & 0 & -\mu' \\ 0 & 0 & 0 & 0 & g_{BL} v_{\bar{\eta}} & -\mu' & 0 \end{pmatrix} \tag{19}$$

In this model, for the chosen boundary conditions, the lightest supersymmetric particle (LSP), and therefore the dark matter candidate, is in general the lightest neutralino. The reason is that m_0 must be very heavy in order to solve the tadpole equations, and therefore all sfermions are heavier than the lightest neutralino. However, under special conditions also a CP even or odd sneutrinos can be the lightest SUSY particle. A neutralino LSP is in general a mixture of all seven gauge eigenstates. However, normally the character is dominated by only one or two constituents. In that context, we can distinguish the following extreme cases: (i) $M_1 \ll M_2, \mu, M_B, \mu'$: Bino-like LSP, (ii) $M_2 \ll M_1, \mu, M_B, \mu'$: Wino-like LSP, (iii) $\mu \ll M_1, M_2, M_B, \mu'$: Higgsino-like LSP, (iv) $M_B \ll M_1, M_2, \mu, \mu'$: BLino-like LSP, (v) $\mu' \ll M_1, M_2, \mu, M_B$: Bileptino-like LSP. Although the gauge kinetic effects do lead to sizable effects in the spectrum, they are not large enough to lead to a large mixing between the usual MSSM-like states and the new ones. Therefore, we find that the LSP is either mainly a MSSM-like state or mainly an admixture between the BLino and the bileptinos.

2.7 Sfermions and charginos

We don't consider here the the chargino and sfermion sector. Interested readers are referred to [11].

2.8 Boundary conditions at the GUT scale

We will study in the following a scenario motivated by minimal supergravity (mSUGRA). This means that we assume a GUT unification of all soft-breaking scalar masses as well as a unification of all gaugino mass parameters

$$m_0^2 = m_{H_d}^2 = m_{H_u}^2 = m_\eta^2 = m_{\bar{\eta}}^2 \tag{20}$$

$$m_0^2 \delta_{ij} = m_D^2 \delta_{ij} = m_U^2 \delta_{ij} = m_Q^2 \delta_{ij} = m_E^2 \delta_{ij} = m_L^2 \delta_{ij} = m_\nu^2 \delta_{ij} \tag{21}$$

$$M_{1/2} = M_1 = M_2 = M_3 = M_{\tilde{B}'} \tag{22}$$

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

$$T_i = A_0 Y_i, \qquad i = e, d, u, x, \nu\ . \tag{23}$$

We do not fix the parameters μ, B_μ, μ' and $B_{\mu'}$ at the GUT scale but determine them from the tadpole equations. In addition, we consider the mass of the Z' and $\tan\beta'$ as inputs and use the following set of free parameters

$$m_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \tan\beta',\ \text{sign}(\mu),\ \text{sign}(\mu'),\ M_{Z'},\ Y_x \text{ and } Y_\nu. \tag{24}$$

Y_ν is constrained by neutrino data and must therefore be very small in comparison to the other couplings. Y_x can always be taken diagonal and thus effectively we have 9 free parameters and two signs. If not mentioned otherwise, we will always take positive signs for μ and μ'. Finally, we assume that there are no off-diagonal gauge couplings or gaugino mass parameters present at the GUT scale

$$g_{BY} = g_{YB} = 0 \qquad M_{BB'} = 0 \tag{25}$$

3 Results obtained using the SUSY toolbox

In this section we discuss the implementation of the $B-L$SSM in the `SUSY-Toolbox` presented in [17]. The `SUSY-Toolbox` scripts can be downloaded from

`http://projects.hepforge.org/sarah/Toolbox.html`

After the installation of all packages via `configure` and `make`, each model implemented in `SARAH` can be added to the other tools due to

```
> ./butler MODEL
```

3.1 Implementation of the $B-L$SSM in SARAH

`SARAH` is a package for `Mathematica` version 5.2 or higher and has been designed to handle every $N = 1$ SUSY theory with an arbitrary direct product of $SU(n)$ and/or $U(1)$ factors as gauge group. The chiral superfields can transform under arbitrary, irreducible representations with regard to this gauge group, and all possible renormalizable superpotential terms are supported. There are no restrictions on either the number of gauge group factors, the number of chiral superfields or the number of superpotential terms. Furthermore, any number of symmetry breakings or field rotations is allowed.
The implementation of new models in `SARAH` is straightforward. The fastest and easiest way is usually to start with the model files for the MSSM and apply the changes necessary for the new mode. For instance, to create a new gauge group according to $U(1)_{B-L}$, only one line has to be added to the array `Gauge`

```
Gauge[[1]]={B,   U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left,        g2,True};
Gauge[[3]]={G,  SU[3], color,       g3,False};
Gauge[[4]]={Bp,  U[1], BminusL,     g1p, False};
```

and afterwards the corresponding quantum numbers for all MSSM fields and the new $B-L$ fields are defined:

```
Fields[[1]] = {{uL,  dL},  3, q,   1/6, 2, 3, 1/6};
...
Fields[[9]]  = {et, 1, eta, 0, 1, 1, -1};
Fields[[10]] = {etb, 1, etabar,  0, 1, 1, 1};
```

First, the root of the names is given, at second position the number of generations is defined and the third entry is the name of the entire superfield. The remaining entries are the transformation properties with respect to the different gauge groups. Using these definitions, the superpotential Eq. 2 can be defined as

```
SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}}, {{-1,Ye},{e,l,Hd}},
  {{1,\[Mu]},{Hu,Hd}}, {{1,Yv},{l,Hu,vR}}, {{-1,MuP},{eta,etabar}}, {{1,Yn},{vR,eta,vR}}  };
```

In addition, the definition of gauge symmetry breaking, the gauge fixing terms, the mixing in the gauge and matter sector have to be adjusted. Also, these changes are intuitive to understand and the entire model file is given in the appendix of [11]. Furthermore, the model files are already part of the public version of `SARAH` and can be used out of the box.
Using this model file `SARAH` calculates analytically all mass matrices, vertices as well as the two-loop Renormalization Group Equations (RGEs) and one-loop corrections to self-energies and tadpoles. The calculation of the loop corrections is performed in $\overline{\text{DR}}$ scheme and 't Hooft gauge. This information can afterwards be used to write model files for `CalcHep/CompHep`, `FeynArts/FormCalc` [37, 38], `MadGraph` [39] and

OMEGA/WHIZARD, or to create modules for SPheno or just to write a LaTeX file containing all information in a readable form.

3.2 Spectrum calculation with SPheno

We start the calculation of the mass spectrum using SPheno. SPheno [26, 27] is a F95 program designed for the precise calculation of the masses of supersymmetric particles. SPheno provides fast numerically routines for the evaluation of the RGEs, calculating the phase space of 2- and 3-body decays as well as Passarino Veltman integrals and much more. Since these routines are model independent, they can be used for all SUSY models implemented in SARAH. As mentioned above SARAH calculates all analytical expressions needed for a complete analysis of the model. This information is exported to Fortran code in a way suitable for inclusion in SPheno. This generates a fully functional version of SPheno for the new model without any need to change the source code by hand. The SPheno version generated by SARAH calculates the complete mass spectrum using 2-loop RGEs and 1-loop corrections to the masses, including the full momentum dependence of all loop integrals. In addition, for MSSM-like Higgs sectors, the known two loop corrections to the Higgs masses and tadpoles can be included. All calculations are performed with the most general flavor structure and allow for the inclusion of CP phases and fully support kinetic mixing. To show the importance of the

Figure 1: Mass of the lightest Higgs. The other parameters have been $\tan(\beta) = 10$, $A_0 = -1000$ GeV, $\tan(\beta') = 1.07$, $M_{Z'} = 3000$ GeV, $Y_x^{ii} = 0.41$. Left: with kinetic mixing, right: without kinetic mixing.

kinetic mixing we give in Fig. 1 a comparison between the mass and bilepton fraction of the lightest with and without kinetic mixing. It can be seen that the masses are only slightly shifted while, of course, there is a huge difference of several orders in the bilepton fraction between both cases. While the bilepton contribution for MSSM-like scalars in the case without kinetic mixing is solely based on the mixing at one-loop level, the off-diagonal gauge couplings introduce already a tree-level mixing. Close to the border of the allowed regions in the $(m_0, M_{1/2})$-plane shown in Fig. 1, the lightest Higgs particles become bilepton-like. This can not only be observed for a variation of m_0 and $M_{1/2}$ but also by adjusting $\tan\beta'$, as shown in Fig. 2 where we have fixed $m_0 = 1000$ GeV and $M_{1/2} = 500$ GeV. As can be seen in Fig. 2, the mass of the MSSM-like Higgs boson gets pushed to larger values for very light bilepton scalars. Such a behavior has already been observed in the literature when considering models with extended gauge symmetries [40, 41, 42, 43, 44, 45]. If the very light bileptons are consistent with all experimental data will be discussed in sec. 3.3. We turn now to the neutralino sector. Similarly to the CMSSM, the lightest neutralino is often bino-like and the main difference is, in this case, that the relation between the parameters at different scales gets changed due to the gauge kinetic mixing. Note that this holds even though the soft-breaking gaugino mass term $M_{B'}$ is

Figure 2: a) masses of two lightest scalars. b) doublet (green) and bilepton (blue) fraction of lightest Higgs as function of $\tan\beta'$. The other input parameters are $m_0 = 1$ TeV, $M_{1/2} = 500$ GeV, $\tan(\beta) = 20$, $A_0 = -1$ TeV, $M_{Z'} = 2750$ GeV, $Y_x^{ii} = 0.43$.

Figure 3: a) μ' as function of m_0. b) masses of all neutralinos. c) content of the lightest neutralino: gaugino fraction (red), Higgsino fraction (green), BLino fraction (blue) and bileptino fraction (black). The input parameters were $M_{1/2} = 1000$ GeV, $\tan\beta = 40, A_0 = 1500$ GeV, $\tan\beta' = 1.20, M_{Z'} = 2$ TeV.

always smaller than M_1, because, at one-loop level and without kinetic mixing, the relation

$$\frac{M_{1/2}}{g_{GUT}^2} = \frac{M_1}{g_Y^2} = \frac{M_{B'}}{g_{BL}^2} \tag{26}$$

would hold and g_{BL} is always smaller than g_Y if unification at the GUT scale is assumed, as can be seen in Eq. (6). However, usually there is a large mixing between the BLino with the bileptinos, leading to heavy states. However, there are regions where this mixing is small and the BLino becomes the LSP. In particular this happens if $\mu' \gg g_{BL}x \simeq M_{Z'}$ which happens either for large $|Y_x|$ or large m_0, as this increases the difference $m_{\bar{\eta}}^2 - m_{\eta}^2$. As an example we show in Fig. 3 that μ' grows with increasing m_0 leading to a larger mass splitting between the bileptino-like neutralinos and the others. For very large values of μ', the bilepton fields are nearly decoupled and the nature of the LSP becomes BLino-like. Finally, we note that also a bileptino-like LSP can be obtained in this model. The necessary condition, $|\mu'|$ being smaller than $|\mu|$ and all gaugino mass parameters, can be obtained if the difference between m_η^2 and $m_{\bar{\eta}}^2$ becomes small. This can be accommodated by adjusting the entries of Y_x. As an example, we show in Fig. 4 the masses of all neutralinos as well as the composition of the lightest neutralino as function of $Y_{x,11}$ while keeping all other values fixed. Already a 10 per-cent decrease leads to a nearly a pure bileptino LSP and its mass depends strongly on $Y_{x,11}$. For larger values a level crossing takes place and the LSP becomes bino-like.

Figure 4: LSP with large bileptino fraction: a) mass of neutralinos, b) neutralino content. The color code on the right hand side is as follows: gaugino fraction (red), Higgsino fraction (green), BLino fraction (blue), bileptino fraction (black). The other parameters have been $m_0 = 1$ TeV, $M_{1/2} = 1.5$ TeV $\tan(\beta) = 20$, $A_0 = -1.5$ TeV, $\tan(\beta') = 1.15$, $M_{Z'} = 2.5$ TeV, $Y_x^{22} = Y_x^{33} = 0.40$

Figure 5: Mass of the two lightest Higgs fields (first row) as well as the logarithm of the bilepton fraction (left plot in second row) in the $(m_0, M_{1/2})$-plane. The right plot in the second row shows the saturation of the tightest bound (which is all cases $e^+e^- \to Zh_1, h_1 \to b\bar{b}$) as calculated by `HiggsBounds`: the blue area is allowed, the red one excluded by Higgs searches: The most sensitive channels are $e^+e^- \to Zh_2, h_2 \to b\bar{b}$, $pp \to A^0 \to \tau\bar{\tau}$ and $pp \to h_2 \to W^+W^-$. The other parameters are those of Fig. 2 and we used $\tan(\beta') = 1.075$.

3.3 Checking Higgs constraints with `HiggsBounds`

As show in Fig. 2 very light bilepton states can be present. Hence, existing constraints on Higgs masses coming from collider experiments have to be checked carefully. This can be done with `HiggsBounds`. `HiggsBounds` [20, 21] is a tool to test the neutral and charged Higgs sectors against the current exclusion bounds from the Higgs searches at the LEP, Tevatron and LHC experiments. The required input consists of the masses, width and branching ratios of the Higgs fields. In addition, it is either possible to provide full information about production cross sections in e^+e^- and pp collisions, or to work with a set of effective couplings. Although `HiggsBounds` supports the LesHouches interface, this functionality is restricted so far to at most 5 neutral Higgs fields, and therefore, we don't use it. Instead, `SPheno` modules generated by `SARAH` can create all necessary input files needed for a run of `HiggsBounds` with effective couplings (option `whichinput=effC`). We checked that very light bilepton-like Higgs scalars are not ruled out by experimental data using `HiggsBounds 3.6.1beta`. However, the mixing between the bilepton and the MSSM-like Higgs is rather small and thus the branching ratio $h_2 \to h_1h_1$ is at most a few per-cent. Therefore, the main decay channels of the doublet Higgs are still SM final states and the well-known bounds do hold. In Fig. 5 we fix ed

Figure 6: Left: $\log(\Omega h^2)$ as a function of $\tan(\beta')$. Right: mass difference between the LSP and twice the light bilepton scalar. The other parameters have been $m_0 \sim 2.8$ TeV, $M_{1/2} \sim 650$ GeV, $\tan\beta \sim 7$, $A_0 \sim -2.8$ TeV, $M_{Z'} \sim 3.2$ TeV, $Y_x^{ii} \sim 0.42$.

$\tan(\beta') = 1.075$ and vary m_0 and $M_{1/2}$. We see that there is a sizable region where the lightest Higgs, being essentially a bilepton, has a mass of less than half of the second lightest, which is mainly like the MSSM h^0. Even though the bilepton has only a small admixture of the doublet Higgs bosons, it is large enough to determine its main decay properties, which are mainly SM-like with respect to its decay into SM fermions.

3.4 Calculating dark matter relic density with `MicrOmegas`

It has been shown in sec. 3.2 that there are new possibilities for LSP coming from the $B-L$-sector. The question arises if a BLino- or a Bileptino-like neutralino can have the correct relic density for being the dark matter in the universe. To test this, we have used `MicrOmegas` . `MicrOmegas` [22] is a well known tool for the calculation of the relic density of a dark matter candidate. As `MicrOmegas` uses `CalcHep` for the calculation of (co-)annihilation cross sections, the `CalcHep` output of `SARAH` is sufficient to calculate the relic density for new models. As the SLHA+ import functionality of `CalcHep` [46] can also be used with `MicrOmegas`, it is sufficient to simply copy the spectrum file written by `SPheno` to the directory of `MicrOmegas` and start the calculation. It turns out that it is indeed possible to have valid BLino and Bileptino dark matter candidate [30]. For instance, we give in Fig. 6 the relic density as function of $\tan(\beta')$. Since the main annihilation comes from a resonance with the lightest bilepton scalar, there is a strong dependence on $\tan(\beta')$: not only the mass of the bilepton is sensitive to $\tan(\beta')$, but also the BLino-Bileptino mixing depends on it. For sufficient annihilation, not only $m_{\tilde{\chi}^0_1} = \frac{1}{2} m_{h_2}$ is needed but also some admixture of the bileptino to the BLino. Similarly, also the bileptino can annihilate via a bilepton resonance.

3.5 Collider studies with `WHIZARD`

Finally, it is of course very interesting to study the impact on the new states and the kinetic mixing effects on the phenomenology on a linear collider. Therefore, the next step in our study of the $B-L$MSSM will be to perform collider studies using `WHIZARD`. `WHIZARD` [29] is a fast tree-level Monte Carlo generator for parton level events. A particular strength of the code is the efficient generation of unweighted events for high multiplicity final states (simulations with 8 final state particles have been performed successfully) using exact matrix elements. This makes it particularly useful for the study of supersymmetric models which generically feature complicated multiparticle final states arising from long decay chains. The interface between `SARAH` and `WHIZARD` shares significant parts of its code with the interface between `FeynRules` [47], with a thin layer on top to interface with `SARAH`. In order to communicate the numerical values of the parameters calculated by `SPheno` to `WHIZARD`, each `SPheno` version generated by `SARAH` is capable of writing out a separate file which can be directly included from the `WHIZARD` input script.

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