

$B - L$ Supersymmetric Extension of the Standard Model (BLSSM)

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Supersymmetry and the MSSM

- ▶ SUSY remains a well-motivated framework beyond the SM, although direct experimental evidence is still lacking.
- ▶ It extends the spacetime symmetries of quantum field theory, relating bosonic and fermionic degrees of freedom.
- ▶ SUSY cancels quadratic Higgs-mass divergences. With soft SUSY breaking, naturalness depends on the superpartner spectrum.
- ▶ The MSSM is the minimal supersymmetric extension of the SM, with superpartners and two Higgs doublets.

R-parity-conserving superpotential

$$W = h_U Q_L U_L^c H_2 + h_D Q_L D_L^c H_1 + h_L L_L E_L^c H_1 + \mu H_1 H_2.$$

Soft SUSY-breaking boundary conditions at the GUT scale

- ▶ **Universal:** common scalar mass m_0 , gaugino mass $m_{1/2}$, and trilinear coefficient A_0 .
- ▶ **Non-universal:** independent soft parameters and a larger parameter space.

Why Go Beyond the MSSM?

- ▶ Conserved R -parity allows a stable LSP, potentially providing a dark matter candidate.
- ▶ The observed Higgs mass, $m_h \simeq 125 \text{ GeV}$, typically requires heavy stops and/or substantial stop mixing.
- ▶ Collider and dark matter constraints restrict constrained MSSM scenarios and sharpen the tension with naturalness.
- ▶ Extended SUSY models can ease these tensions and offer new experimental signatures:
 - **NMSSM**: an additional Higgs singlet.
 - **BLSSM**: an additional $U(1)_{B-L}$ gauge symmetry.

The Supersymmetric $B - L$ Extension

- Neutrino oscillations establish nonzero neutrino masses, motivating physics beyond the minimal SM.
- The BLSSM extends the MSSM by gauging baryon minus lepton number:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}.$$

- The additional chiral superfields are:
 - Three $\hat{N}_i^c$, one per generation, to cancel gauge and mixed gravitational anomalies.
 - Two SM-singlet Higgs superfields $\hat{\chi}_{1,2}$ with $B - L$ charges -2 and $+2$, whose scalar vacuum expectation values break $U(1)_{B-L}$.

	$\hat{Q}_i$	$\hat{U}_i^c$	$\hat{D}_i^c$	$\hat{L}_i$	$\hat{E}_i^c$	$\hat{N}_i^c$	$\hat{H}_1$	$\hat{H}_2$	$\hat{\chi}_1$	$\hat{\chi}_2$
$SU(3)_C$	3	$\bar{3}$	$\bar{3}$	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	2	1	1
Y	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$B - L$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-1	1	1	0	0	-2	2

The $B - L$ Higgs Sector

- The BLSSM superpotential extends that of the MSSM:

$$W_{\text{BLSSM}} = W_{\text{MSSM}} + Y_\nu L H_2 N^c + \frac{1}{2} Y_N N^c N^c \chi_1 + \mu' \chi_1 \chi_2.$$

- The coupling Y_N links the right-handed neutrino sector to $B - L$ symmetry breaking.
- Neglecting gauge kinetic mixing and taking $\langle \tilde{N}^c \rangle = 0$, the tree-level Higgs potential separates:

$$V_{\text{Higgs}} = V_{\text{MSSM}}(H_1, H_2) + V_{B-L}(\chi_1, \chi_2).$$

$$V_{B-L} = \frac{g_\chi^2}{2} (|\chi_2|^2 - |\chi_1|^2)^2 + \mu_1^2 |\chi_1|^2 + \mu_2^2 |\chi_2|^2 - (b' \chi_1 \chi_2 + \text{h.c.}),$$

where

$$\mu_i^2(Q) = m_{\chi_i}^2(Q) + |\mu'(Q)|^2, \quad b' = B' \mu'.$$

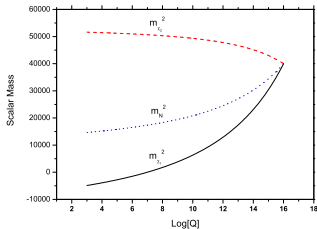
Here g_χ is the magnitude of the gauge coupling to $\chi_{1,2}$.

Radiative $B - L$ Symmetry Breaking

- A stable symmetry-breaking minimum in the singlet Higgs sector requires

$$\underbrace{\mu_1^2 + \mu_2^2 > 2|b'|}_{\text{stability along the } D\text{-flat direction}}, \quad \underbrace{\mu_1^2 \mu_2^2 < |b'|^2}_{\text{instability of the origin}}.$$

- These conditions cannot both hold for $\mu_1^2 = \mu_2^2 > 0$, as implied by universal scalar masses at the GUT scale.
- RG evolution splits the singlet soft masses: Y_N drives $m_{\chi_1}^2$ downward, while χ_2 has no analogous Yukawa coupling.
- For suitable parameters, $m_{\chi_1}^2$ becomes negative and the vacuum conditions can be satisfied, inducing $B - L$ breaking near the SUSY scale.



Illustrative running of the $B - L$ scalar masses.

- The neutrino superpotential generates a **type-I seesaw**:

$$W_\nu = Y_\nu L H_2 N^c + \frac{1}{2} Y_N N^c N^c \chi_1.$$

- Symmetry breaking generates Dirac and Majorana masses:

$$m_D = Y_\nu \langle H_2^0 \rangle, \quad M_R = Y_N \langle \chi_1 \rangle.$$

- In the basis (ν_L, ν_R^c) ,

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}, \quad m_\nu \simeq -m_D M_R^{-1} m_D^T,$$

where $\|m_D\| \ll \|M_R\|$.

- For $M_R \sim 1$ TeV, light-neutrino masses of order 0.05 eV require $Y_\nu \sim 10^{-6}$, comparable in order of magnitude to the electron Yukawa coupling.

Additional states beyond the MSSM

- **Neutral gauge boson**

$Z_{B-L} \equiv Z'$, associated with $U(1)_{B-L}$.

- **Neutrinos and sneutrinos**

Three right-handed neutrinos ν_{R_i} and their scalar partners $\tilde{\nu}_{R_i}$.

- **Extended Higgs sector**

Two additional CP-even states, h' and H' , and one CP-odd state, A' .

- **Extended neutralino sector**

A $B-L$ gaugino $\tilde{Z}'$ and two singlet higgsinos $\tilde{\chi}_{1,2}$, giving seven neutralino mass eigenstates after mixing.

Phenomenology: new collider signatures and dark matter candidates.

The Z' Boson and Heavy Neutrinos

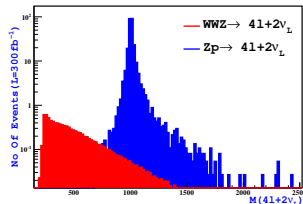
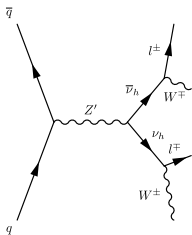
- Gauge kinetic mixing between $U(1)_Y$ and $U(1)_{B-L}$ can be encoded in the covariant derivative through the coupling $\tilde{g}$. For small Z - Z' mixing,

$$M_Z^2 \simeq \frac{1}{4}(g_1^2 + g_2^2)v^2, \quad M_{Z'}^2 \simeq g_{BL}^2 v'^2 + \frac{1}{4}\tilde{g}^2 v^2.$$

- If $M_{Z'} > 2M_N$, the Z' can decay into a pair of heavy Majorana neutrinos:

$$q\bar{q} \rightarrow Z' \rightarrow NN \rightarrow (\ell W)(\ell W) \rightarrow 4\ell + 2\nu.$$

- The observable signature is **four isolated charged leptons plus missing transverse momentum**, offering sensitivity to both Z' and heavy neutrinos.



- Kinematic selections can suppress SM backgrounds, including WWZ , and improve the signal sensitivity.

The BLSSM Higgs Spectrum

- ▶ Two Higgs doublets and two complex singlets contain **12 real scalar degrees of freedom**. Four Goldstone modes are absorbed by $W^\pm$, Z and Z' .
- ▶ In the CP-conserving limit, the physical spectrum contains:
 - Four CP-even neutral states: h, H, h', H' .
 - Two CP-odd neutral states: A, A' .
 - One charged pair: $H^\pm$.
- ▶ The doublet and singlet CP-odd sectors do not mix at tree level:

$$\mathcal{M}_P^2 = \begin{pmatrix} \mathcal{M}_{P,D}^2 & 0 \\ 0 & \mathcal{M}_{P,S}^2 \end{pmatrix}.$$

Each block contains one Goldstone mode and one physical pseudoscalar:

$$m_A^2 = \frac{2B_\mu}{\sin 2\beta}, \quad m_{A'}^2 = \frac{2B_{\mu'}}{\sin 2\beta'}.$$

- ▶ Both pseudoscalars can have TeV-scale masses, depending on the soft-breaking parameters.

A Light Singlet-Like Higgs Boson

- In the basis $(\sigma_1, \sigma_2, \sigma'_1, \sigma'_2)$, the tree-level CP-even mass matrix has the form

$$\mathcal{M}_S^2 = \begin{pmatrix} M_D^2 & X \\ X^T & M_S^2 \end{pmatrix}.$$

Here M_D^2 and M_S^2 describe the doublet and singlet sectors, while X mixes them.

- For negligible singlet–doublet mixing, the singlet-sector eigenvalues are

$$m_{h',H'}^2 = \frac{1}{2} \left[S \mp \sqrt{S^2 - 4m_{A'}^2 M_{BL}^2 \cos^2 2\beta'} \right],$$

where

$$S = m_{A'}^2 + M_{BL}^2, \quad M_{BL}^2 = g_{BL}^2 v'^2.$$

- For $\tan \beta' \simeq 1$,

$$m_{h'}^2 \simeq \frac{m_{A'}^2 M_{BL}^2}{m_{A'}^2 + M_{BL}^2} \cos^2 2\beta'.$$

Thus, h' can remain light even when $m_{A'}$ and M_{BL} are at the TeV scale.

Radiative corrections and mixing must be included when comparing the Higgs spectrum with experiment.

Higgs Mixing and Observable Couplings

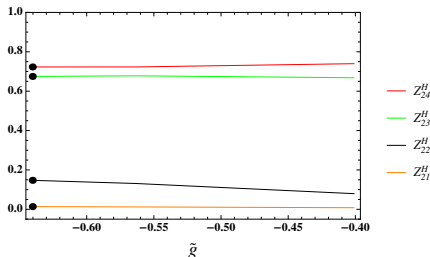
- Gauge kinetic mixing generates the tree-level doublet–singlet mixing block:

$$X = \frac{1}{2} \tilde{g} g_{BL} \begin{pmatrix} v_1 v'_1 & -v_1 v'_2 \\ -v_2 v'_1 & v_2 v'_2 \end{pmatrix}.$$

- For benchmarks where h' is the second-lightest CP-even state,

$$h' = Z_{21}^H \sigma_1 + Z_{22}^H \sigma_2 + Z_{23}^H \sigma'_1 + Z_{24}^H \sigma'_2.$$

Its doublet components provide couplings to SM fermions and electroweak gauge bosons.



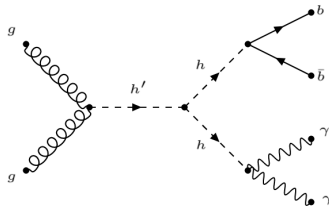
Components Z_{2i}^H of h' versus the kinetic-mixing coupling $\tilde{g}$ for the illustrated benchmark.

Heavy Higgs Searches in the $b\bar{b}\gamma\gamma$ Channel

- For the benchmarks considered, gluon fusion is the dominant production mechanism for h' .
- For $m_{h'} > 2m_h$, we study resonant Higgs-pair production:

$$pp \rightarrow h' \rightarrow hh \rightarrow b\bar{b}\gamma\gamma.$$

- The $b\bar{b}\gamma\gamma$ final state has a lower branching fraction than $b\bar{b}b\bar{b}$.
- Photon identification and excellent diphoton mass resolution help suppress backgrounds.



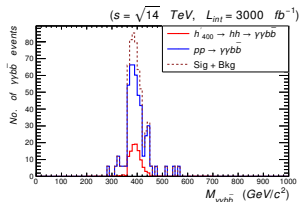
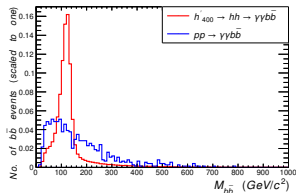
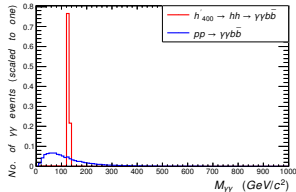
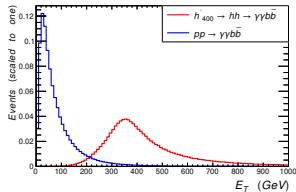
In the narrow-width approximation:

$$\begin{aligned}\sigma_{b\bar{b}\gamma\gamma} &\simeq \sigma(pp \rightarrow h') \text{BR}(h' \rightarrow hh) \\ &\quad \times 2 \text{BR}(h \rightarrow b\bar{b}) \text{BR}(h \rightarrow \gamma\gamma).\end{aligned}$$

HL-LHC projection: $\mathcal{L}_{\text{int}} = 3000 \text{ fb}^{-1}$.

Signal and Background Distributions

Distributions after acceptance cuts, used to guide the event selection.



$m_{\gamma\gamma}$ and $m_{b\bar{b}}$ identify the daughter Higgs candidates; $m_{b\bar{b}\gamma\gamma}$ probes the heavy resonance.

Lightest Neutralino in the BLSSM

The BLSSM contains seven neutralinos. In the gauge-eigenstate basis

$$\psi^0 = \left(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{B}', \tilde{\chi}_1, \tilde{\chi}_2 \right),$$

the neutralino mass matrix is

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & M_{BB'} & -g_{BY} v_\eta & g_{BY} v_{\tilde{\eta}} \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 & 0 & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu & -\frac{1}{2}g_{YB} v_d & 0 & 0 \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 & \frac{1}{2}g_{YB} v_u & 0 & 0 \\ M_{BB'} & 0 & -\frac{1}{2}g_{YB} v_d & \frac{1}{2}g_{YB} v_u & M_{BL} & -g_B v_\eta & g_B v_{\tilde{\eta}} \\ -g_{BY} v_\eta & 0 & 0 & 0 & -g_B v_\eta & 0 & -\mu_\eta \\ g_{BY} v_{\tilde{\eta}} & 0 & 0 & 0 & g_B v_{\tilde{\eta}} & -\mu_\eta & 0 \end{pmatrix}.$$

Here

$$v_\eta = \langle \chi_1 \rangle, \quad v_{\tilde{\eta}} = \langle \chi_2 \rangle,$$

and the mass eigenstates are obtained through

$$V \mathcal{M}_{\tilde{\chi}^0} V^T = \text{diag} \left(m_{\tilde{\chi}_1^0}, \dots, m_{\tilde{\chi}_7^0} \right).$$

Lightest neutralino

$$\tilde{\chi}_1^0 = V_{11} \tilde{B} + V_{12} \tilde{W}^0 + V_{13} \tilde{H}_d^0 + V_{14} \tilde{H}_u^0 + V_{15} \tilde{B}' + V_{16} \tilde{\chi}_1 + V_{17} \tilde{\chi}_2.$$

Right-Handed Sneutrinos in the BLSSM

After $B - L$ symmetry breaking, the complex right-handed sneutrino $\tilde{\nu}_R$ mixes with its conjugate $\tilde{\nu}_R^*$. Neglecting the small left-right sneutrino mixing, the relevant mass-squared matrix in the basis $(\tilde{\nu}_R, \tilde{\nu}_R^*)$ is

$$M_{RR}^2 = \begin{pmatrix} m_0^2 & X_N \\ X_N & m_0^2 \end{pmatrix},$$

where

$$m_0^2 = M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2} M_{Z'}^2 \cos 2\beta',$$

and

$$X_N = M_N (A_N - \mu' \cot \beta').$$

The complex RH sneutrino can be decomposed into CP-even and CP-odd states,

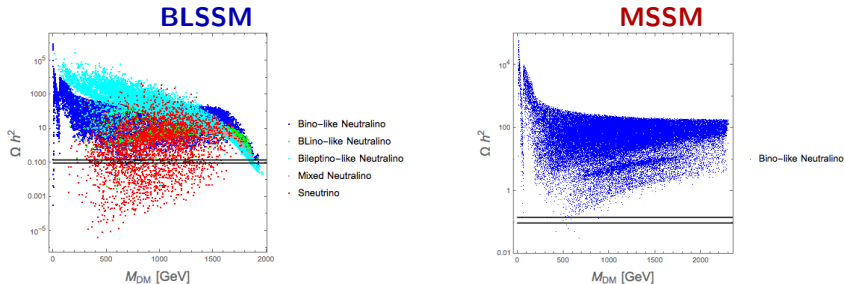
$$\tilde{\nu}_R = \frac{1}{\sqrt{2}} (\tilde{\nu}_R^R + i \tilde{\nu}_R^I).$$

Key feature

The off-diagonal term X_N lifts the degeneracy between the CP-even and CP-odd RH sneutrinos. Consequently, either state can become the lightest supersymmetric particle and provide a viable dark-matter candidate.

Dark Matter in the MSSM versus BLSSM

The relic density as a function of the LSP mass illustrates the much richer dark-matter phenomenology of the BLSSM.



1. Viable DM in the BLSSM

The BLSSM admits several possible LSP compositions:

$$\tilde{B}, \quad \tilde{B}', \quad \tilde{\chi}_{1,2}, \quad \tilde{\nu}_R,$$

as well as mixed neutralino states.

Viable solutions extend over a **wide range of LSP masses**, reaching the TeV scale.

2. MSSM is more constrained

For the MSSM parameter scan shown here, viable solutions are concentrated at

lower LSP masses,

and are predominantly associated with the conventional **Bino-like neutralino**.

The allowed DM configurations are therefore more restricted than in the BLSSM.

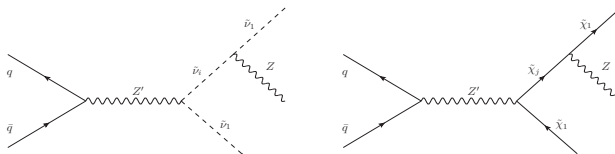
3. BLSSM advantages

The additional $B - L$ states provide

- ▶ a richer LSP spectrum,
- ▶ new annihilation channels,
- ▶ additional coannihilation mechanisms.

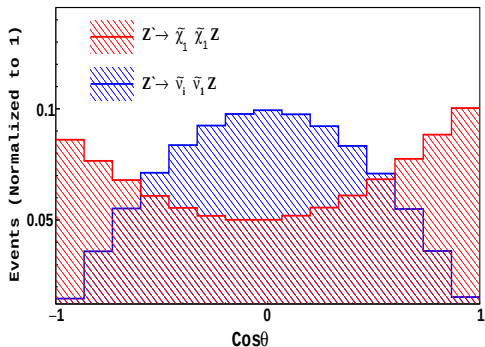
These features substantially enlarge the parameter space compatible with the observed relic abundance.

- ▶ In BLSSM, one can extract mono-Z signatures leading to the identification of the DM properties of its spin.
- ▶ **Spin determination methods rely on the final state spins and the chiral structure of the couplings.**
- ▶ Thus, we focus on the following FSR Mono-Z signals of $\tilde{\nu}_1$ and $\tilde{\chi}_1$ DM:



- ▶ The decays of heavier neutralinos, $\tilde{\chi}_i$, to a massive Z boson and $\tilde{\chi}_1$ DM, $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 Z (\rightarrow \ell^+ \ell^-)$, produce a Z boson in three helicity states: ± 1 (transverse) and 0 (longitudinal).
- ▶ The decays of heavier sneutrinos, $\tilde{\nu}_i$, to a massive Z boson and $\tilde{\nu}_1$ DM, $\tilde{\nu}_i \rightarrow \tilde{\nu}_1 Z (\rightarrow \ell^+ \ell^-)$, produce a Z boson in a zero-helicity (longitudinal) state only.
- ▶ Determining DM spin state through angular distributions in rest frame analysis of Z Boson leptonic decays

- The transverse states follow an angular distribution proportional to $(1 \pm \cos^2 \theta)$, while the longitudinal state follows an angular distribution proportional to $\sin^2 \theta$.
- θ is the angle between the momentum direction of the lepton and the Z boson in the rest frame Z boson.



- Angular Distribution of Final State Leptons in the Rest Frame of the Z Boson: Neutralino and Sneutrino Mediators

Conclusions

- ▶ We have introduced the minimal SUSY version of the well established $B - L$ model.
- ▶ The BLSSM nicely combines the theoretically appealing features of SUSY with key experimental evidence of BSM physics in the form of neutrino masses.
- ▶ We constructed the BLSSM Lagrangian and demonstrated how dynamical EWSB occurs through RGE evolution.
- ▶ We outlined the particle spectrum of the BLSSM, focusing on the dynamics of the four sectors: Z' , Higgs, neutralino, and (s)neutrino.
- ▶ We discussed how Z' can be produced and decay into various leptonic and hadronic signatures through heavy neutrinos, resulting in detectable signals at the LHC.
- ▶ We emphasized the notable aspect of the BLSSM in the Higgs sector, which includes a potential light Higgs resonance that leads to significant di-Higgs signal.
- ▶ Our study reveals that the mono- Z channel at the LHC can differentiate between a fermionic or (pseudo)scalar dark matter particle in the BLSSM.
- ▶ The BLSSM is a viable SUSY model that complies with current data and provides unique signatures at the LHC, allowing it to be distinguished from other BSM scenarios.