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

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# Introduction

- Despite the absence of direct experimental verification, SUSY is still the most promising candidate for a unified theory beyond the SM.

- SUSY is a generalization of the space-time symmetries of the QFT that relates bosons to fermions .

- SUSY solves the problem of the quadratic divergence in the Higgs sector of the SM in a very elegant natural way.

- The most simple supersymmetric extension of the SM is know as the MSSM.

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

- Soft SUSY breaking terms at GUT scale:
  - Universal: $m_0$, $m_{1/2}$, $A_0$
  - Non-Universal: Large number of free paramters

- Due to $R$-parity conservation, SUSY particles are produced or destroyed only in pairs.The LSP is absolutely stable, candidate for DM.
- MSSM predicts an upper bound for the Higgs mass: $m_h \lesssim 130$ GeV, which was consistent with the measured value of Higgs mass (of order 125 GeV) at the LHC.
- This mass of lightest Higgs boson implies that the SUSY particles are quite heavy. This may justify the negative searches for SUSY at the LHC-run I & II.
- Combining the collider and astrophysics constraints almost rule out the MSSM (with universal soft SUSY breaking).
- Non-minimal supersymmetric extensions of the SM with a larger particle content or a higher symmetry can evade the problems of the MSSM.
- Such models may be well-motivated by Grand Unified Theories (GUTs) and can provide a rich new phenomenology.
- Simple examples of Non-minimal SUSY models:

  ($i$) Extended Higgs sector, *eg.* NMSSM
  ($ii$) Extended Gauge sector, *eg.* BLSSSM

# SUSY $B-L$ Extension of the SM

- The solid experimental evidence for neutrino oscillations, pointing towards non-vanishing neutrino masses, is one of the few firm hints for physics beyond the SM.
- BLSSM is the minimal extension of MSSM, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$.

**S.K (2008)**

- This type of extension implies the existence of extra 3 superfields, one per generation, with $B-L$ charge equal $-1$, in order to cancel the associate $B-L$ triangle anomaly.
- These superfields are identified with the right-handed neutrinos and will be denoted $N_i$.
- In addition, in order to break the $B-L$ symmetry at TeV scale, two Higgs superfields $\hat{\chi}_{1,2}$ with $\mp 2$ $B-L$ charges are required.

| | $\hat{Q}_i$ | $\hat{U}_i^c$ | $\hat{D}_i^c$ | $\hat{\ell}_i$ | $\hat{E}_i^c$ | $\hat{N}_i^c$ | $\hat{H}_1$ | $\hat{H}_2$ | $\hat{\chi}_1$ | $\hat{\chi}_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_c$ | 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 |
| $U(1)_Y$ | $\frac{1}{6}$ | $-\frac{2}{3}$ | $\frac{1}{3}$ | $-\frac{1}{2}$ | 1 | 0 | $-\frac{1}{2}$ | $\frac{1}{2}$ | 0 | 0 |
| $U(1)_{B-L}$ | $\frac{1}{3}$ | $\frac{1}{3}$ | $\frac{1}{3}$ | $-1$ | $-1$ | $-1$ | 0 | 0 | $-2$ | 2 |

## Radiative $B-L$ symmetry breaking in the BLSSM

- The superpotential of BLSSM is given by $W_{\rm BLSSM} = W_{\rm MSSM} + W_{\rm BL}$:

$$W_{\rm BLSSM} = Y_U Q H_2 U^c + Y_D Q H_1 D^c + Y_E L H_1 E^c + Y_\nu L H_2 N^c + \frac{1}{2} Y_N N^c N^c \chi_1 + \mu H_1 H_2 + \mu' \chi_1 \chi_2$$

- The soft breaking terms

$$\begin{aligned} V_{\rm soft} &= V_{\rm soft}^{\rm MSSM} + m^2_{\tilde N}|\tilde N|^2 + m^2_{\chi_1}|\chi_1|^2 + m^2_{\chi_2}|\chi_2|^2 + \Big[\Big(\frac{1}{2} M_{1/2} \tilde Z' \tilde Z' + Y_\nu A_\nu \tilde L H_2 \tilde N^c + \\ &+ \frac{1}{2} Y_N A_N \tilde N^c \chi_1 \tilde N^c + B\mu' \chi_1 \chi_2\Big) + h.c.\Big] \end{aligned}$$

- The Higgs Potential

$$\begin{aligned} V(H_1, H_2, \chi_1, \chi_2) &= \frac{g^2 + g'^2}{8}(|H_2|^2 - |H_1|^2)^2 + \frac{1}{2} g''^2 \left(|\chi_2|^2 - |\chi_1|^2\right)^2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 \\ &- m_3^2 (H_1 H_2 + h.c.) + \mu_1^2 |\chi_1|^2 + \mu_2^2 |\chi_2|^2 - \mu_3^2 (\chi_1 \chi_2 + h.c.) \end{aligned}$$

where $m_i^2 = m_0^2 + \mu^2, \quad i = 1,2 \quad m_3^2 = B\mu,$

$\mu_i^2 = m_0^2 + \mu'^2, \quad i = 1,2 \quad \mu_3^2 = B\mu'.$

- The full scalar potential is splitted into two separated terms:

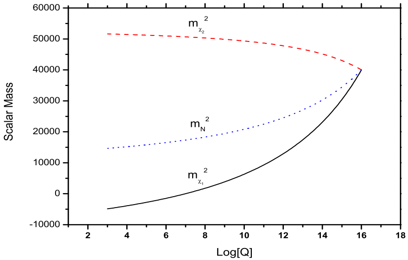
$$V(H_1, H_2, \chi_1, \chi_2) = V_1(H_1, H_2) + V_2(\chi_1, \chi_2)$$

The condition of stability of $V_2(\chi_1, \chi_2)$: $2\mu_3^2 \; < \; \mu_1^2 + \mu_2^2$.

Also, to get a non-zero vev, we must impose the condition: $\mu_1^2 \mu_2^2 < \mu_3^4$

And, as before, these two conditions can not be satisfied simultaneously for positive values of $\mu_1^2, \mu_2^2$.

- Running from GUT down to $B-L$ breaking scale shows that Higgs singlets $\chi_1$ and $\chi_2$ have different mass running. At $B-L$ scale, $m^2_{\chi_1}$ becomes negative and $m^2_{\chi_2}$ remains positive.




$$\frac{dm^2_{\chi_1}}{dt} = 9\tilde{\alpha}_{B-L}\, M^2_{B-L} - 2\tilde{Y}_N\,(m^2_{\chi_1} + 2m^2_{\tilde{N}} + A^2_N)$$

S.K.,Masiero (2008)

# Neutrino Masses in BLSSM

- A type I seesaw can be obtained from the BLSSM super potential:

$$\mathcal{L}_{B-L} \in Y_\nu \bar{l} H_2 \nu_R + \frac{1}{2} Y_N \bar{\nu}_R^c \chi_1 \nu_R^c + h.c.$$

  Majorana mass, after B-L symmetry breaking is generated: $M_R = Y_N \langle \chi_1 \rangle = Y_N v'$. Thus

$$v' \sim \mathcal{O}(1)\mathrm{TeV}, \ \ Y_N \sim \mathcal{O}(1) \Rightarrow M_R \sim \mathcal{O}(1)\mathrm{TeV}$$

  Dirac mass ( after Electroweak symmetry breaking): $m_D = Y_\nu \langle H_2 \rangle = Y_\nu v$

- Thus, the follow neutrino mass matrix is obtained:

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- Light neutrino mass: $m_\nu = -m_D M_R^{-1} m_D^T$.

  Thus $m_\nu \sim \mathcal{O}(1)$ eV if $m_D \sim 10^{-4}$ GeV $\Rightarrow Y_\nu \sim 10^{-6} \sim Y_E$

# BLSSM Spectrum

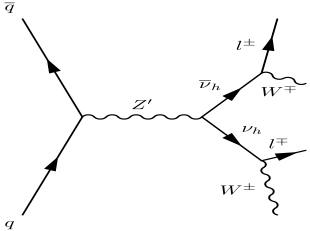
- BLSSM New Particle Contents:
  1. Extra Neutral Gauge Boson: $Z_{B-L} \equiv Z'$
  2. Right-Handed Neutrinos and Sneutrinos: $\nu_{R_i}$ and $\tilde{\nu}_{R_i}$
  3. Extra Higgs Bosons: $h'$, $A'$, and $H'$
  4. Extra Neutralinos: $\tilde{Z}'$, $\tilde{\chi}_i$
- **Signatures and Implications**

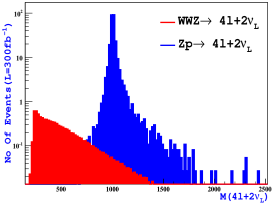
# Neutral Gauge Bosnon $Z'$

- The $U(1)_Y$ and $U(1)_{B-L}$ gauge kinetic mixing can be absorbed in the covariant derivative redefinition. In this basis, one finds $M_Z^2 = \frac{1}{4}(g_1^2 + g_2^2)v^2, \quad M_{Z'}^2 = g_{BL}^2 v'^2 + \frac{1}{4}\tilde{g}^2 v^2$.

- The decay of a $Z'$ boson to heavy neutrinos, which subsequently decay into four leptons and two neutrinos, is a promising channel for probing $Z'$ at the LHC.

- This channel, $q\bar{q} \to Z' \to \nu_h \bar{\nu}_h \to WW\ell\ell$, offers a distinct signature and has a tiny SM background




- Invariant mass of 4-leptons plus 2 light neutrinos from $Z'$ with $WWZ$ background.

- The decay channel $4\ l + 2\ \nu$ is the quite clean channel and quite promising for probing both $Z'$ and $\nu_h$ using only few cuts to extract signals from background.

# Higgs Bosons in BLSSM

- In BLSSM, we have 2 Higgs doublet and 2 Higgs singlet superfields, i.e. 12 degrees of freedom:
  - ⋆ 4 have been eaten by $W^{\pm}$, $Z$, and $Z'$.
  - ⋆ 2 neutral pseudoscalar Higgs bosons $A$.
  - ⋆ 2 charged Higgs bosons $H^{\pm}$.
  - ⋆ 4 neutral scalar Higgs bosons $h$, $H$.
- The squared-mass matrix of the BLSSM CP-odd neutral Higgs fields at tree level is given by

$$m^2_{A,A'} = \begin{pmatrix} B_\mu \tan\beta & B_\mu & 0 & 0 \\ B_\mu & B_\mu \cot\beta & 0 & 0 \\ 0 & 0 & B_{\mu'} \tan\beta' & B_{\mu'} \\ 0 & 0 & B_{\mu'} & B_{\mu'} \cot\beta' \end{pmatrix}.$$

- It is clear that the MSSM-like CP-odd Higgs $A$ is decoupled from the BLSSM-like one $A'$ (at tree level).
- Due to the dependence of $B_\mu$ on $v'$, $m_A^2 = \frac{2B_\mu}{\sin 2\beta} \sim m^2_{A'} = \frac{2B_{\mu'}}{\sin 2\beta'} \sim \mathcal{O}(1\ \text{TeV})$.

- The mass matrix of BLSSM CP-even neutral Higgs at tree level is given by

$$M^2 = \left( \begin{array}{cc} M^2_{hH} & M^2_{hh'} \\ \\ {M^2_{hh'}}^T & M^2_{h'H'} \end{array} \right)$$

- $M^2_{hH}$ is MSSM neutral CP-even Higgs mass matrix $\Rightarrow m_h \sim 125$ GeV $\& m_H \sim m_A \sim \mathcal{O}(1 \text{ TeV})$.

- $$M^2_{h'H'} = \left( \begin{array}{cc} m^2_{A'} c^2_{\beta'} + g^2_{BL} v'^2_1 & -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 \\ \\ -\frac{1}{2} m^2_{A'} s_{2\beta'} - g^2_{BL} v'_1 v'_2 & m^2_{A'} s^2_{\beta'} + g^2_{BL} v'^2_2 \end{array} \right)$$

$$\Rightarrow m^2_{h',H'} = \frac{1}{2} \left[ (m^2_{A'} + M^2_{Z'}) \mp \sqrt{(m^2_{A'} + M^2_{Z'})^2 - 4 m^2_{A'} M^2_{Z'} \cos^2 2\beta'} \right]$$

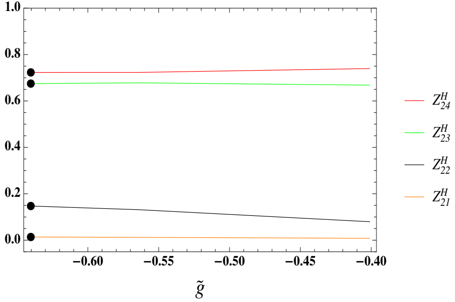
$$\Rightarrow m_{h'} \simeq \left( \frac{m^2_{A'} M^2_{Z'} \cos^2 2\beta'}{m^2_{A'} + M^2_{Z'}} \right)^{\frac{1}{2}} \simeq \mathcal{O}(100 \text{ GeV})$$

- Finally, $$M^2_{hh'} = \frac{1}{2}\tilde{g} g_{BL} \begin{pmatrix} v_1 v_1' & -v_1 v_2' \\ -v_2 v_1' & v_2 v_2' \end{pmatrix}$$

- This mixing is crucial for generating mixing between BLSSM Higgs bosons and MSSM-like Higgs states.

- A numerical scan confirms that, while $\tan' \beta \leq 1.2$, the $h'$ state can be the second Higgs boson mass whereas the other two CP-even states $H, H'$ are heavy, i.e.,

$$h' = \Gamma_{21}\ \sigma_1 + \Gamma_{22}\ \sigma_2 + \Gamma_{23}\ \sigma_1' + \Gamma_{24}\ \sigma_2'.$$



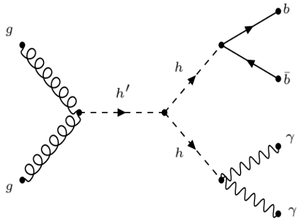

The Higgs mixing $Z^H_{2i}$ $(i = 1, \ldots, 4)$ versus the gauge kinetic mixing coupling $\tilde{g}$

# Search for a heavy BLSSM Higgs boson at the LHC

- Heavy BLSSM Higgs boson, $h'$, is mainly produced at the LHC from gluon-gluon fusion process.

- We focus on the on-shell SM Higgs pair production from $h'$, followed by their decays: $h' \to hh \to bb\gamma\gamma$.

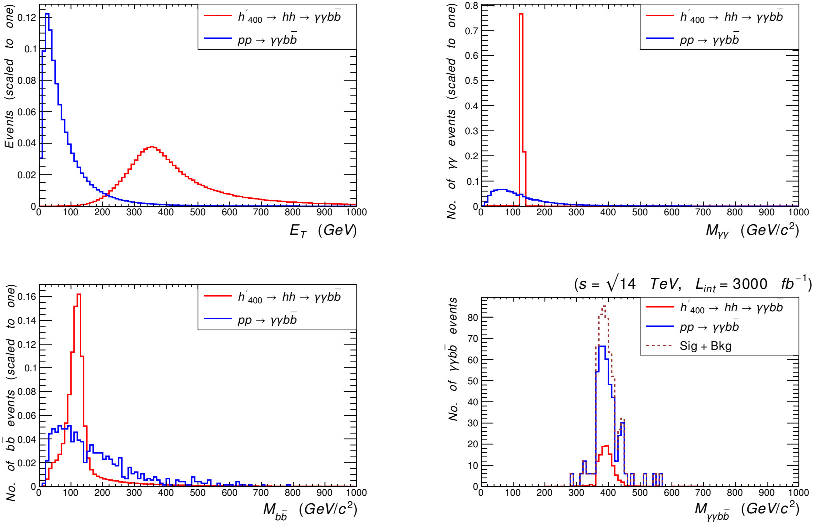
- This process has smaller cross section than $\sigma(pp \to h' \to hh \to 4b)$ but is more promising due to the clean di-photons trigger with excellent mass resolution and low background contamination.




$$\sigma(pp \to h' \to hh \to b\bar{b}\gamma\gamma) \approx \sigma(pp \to h') \times \mathrm{BR}(h' \to hh \to b\bar{b}\gamma\gamma).$$

We use HL-LHC luminosity, $L_{\text{int}} = 3000\ \text{fb}^{-1}$, as this channel is not accessible during Run 3.

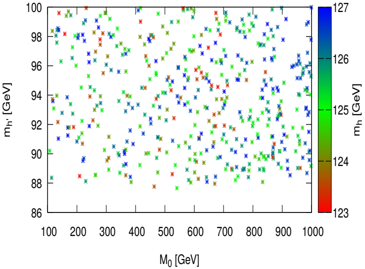
- $S$ and $B$ distributions in $E_T$, $M_{\gamma\gamma}$, $M_{b\bar{b}}$,and $M_{\gamma\gamma b\bar{b}}$ ,




- Notice that event rates are computed after implementing the acceptance cuts.

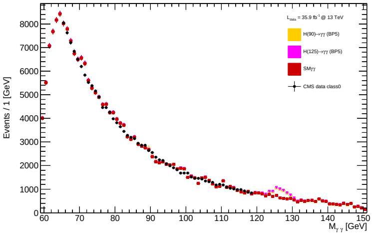
# Di-photon decay of a light Higgs state

- In the BLSSM, we investigate the consistency of a light Higgs boson, with mass around $90-97$ GeV, with the results of a search performed by the CMS collaboration in the di-photon channel.

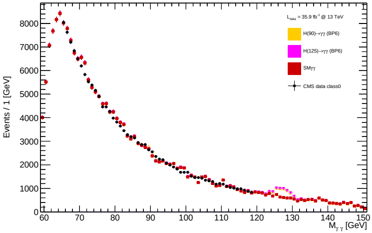



| BP | $M_0$ | $M_{\frac{1}{2}}$ | $\tan\beta$ | $A_0$ | $\mu$ | $\mu'$ |
|---|---|---|---|---|---|---|
| 1 | 998 | 2141 | 29.9 | 3837 | 1849 | 2020 |
| 2 | 359 | 3103 | 31.2 | 3705 | 2561 | 1247 |
| 3 | 146 | 3351 | 44.7 | 3736 | 2739 | 1162 |
| 4 | 874 | 2450 | 11.4 | 3709 | 2092 | 1770 |
| 5 | 870 | 4014 | 57.4 | 3477 | 3222 | 1522 |
| 6 | 363 | 4234 | 40.2 | 3744 | 3386 | 1237 |

| $m_{h'}$ | $m_h$ | $\sigma(pp \to h' \to \gamma\gamma)$ | $\sigma(pp \to h \to \gamma\gamma)$ |
|---|---|---|---|
| 95.3 | 125.9 | 13.1 | 43.5 |
| 94.2 | 125.3 | 8.6 | 49.3 |
| 96.3 | 125.4 | 10.0 | 49.0 |
| 96.6 | 125.3 | 13.0 | 44.7 |
| 89.7 | 125.7 | 9.7 | 49.3 |
| 90.0 | 126.2 | 8.7 | 47.6 |




BP5 versus CMS data at 13 TeV. Yellow points represent $h' \to \gamma\gamma$, pink points represent $h \to \gamma\gamma$ while red points show the SM background.




BP6 versus CMS data at 13 TeV. Yellow points represent $h' \to \gamma\gamma$, pink points represent $h \to \gamma\gamma$ while red points show the SM background.

# Lightest Neutralino in the BLSSM

- In BLSSM the neutralino mass matrix, in the basis: $\left(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{B}', \tilde{\chi_1}, \tilde{\chi_2}\right)$, is given by

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

where $v_\eta = \langle \chi_1 \rangle$ and $v_{\bar\eta} = \langle \chi_2 \rangle$

$$V \mathcal{M}_7 V^T = \mathrm{diag}(m_{\tilde{\chi}_k^0}), \quad k = 1, \dots, 7.$$

$$\tilde{\chi}_1^0 = V_{11}\tilde{B} + V_{12}\tilde{W}^3 + V_{13}\tilde{H}_d^0 + V_{14}\tilde{H}_u^0 + V_{15}\tilde{B}' + V_{16}\tilde{\chi}_1 + V_{17}\tilde{\chi}_2.$$

# Right-handed Sneutrinos in the BLSSM

- In the BLSSM model, the sneutrino mass matrix is a $2 \times 2$ block diagonal matrix in the basis $(\tilde{\nu}_L, \tilde{\nu}_L^*, \tilde{\nu}_R, \tilde{\nu}_R^*)$. The element 11 corresponds to the diagonal left-handed sneutrino mass matrix, and the element 22 represents the right-handed sneutrino mass matrix, denoted as $M_{RR}$.

$$M_{RR}^2 = \begin{pmatrix} M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2} M_{Z'}^2 \cos 2\beta' & M_N(A_N - \mu' \cot \beta') \\ M_N(A_N - \mu' \cot \beta') & M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2} M_{Z'}^2 \cos 2\beta' \end{pmatrix}.$$

- The mass eigenvalues of right-handed sneutrinos are given by

$$m_{\tilde{\nu}_{\mp}}^2 \equiv m_{\tilde{\nu}_{I,R}}^2 = M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2} M_{Z'}^2 \cos 2\beta' \mp \Delta m_{\tilde{\nu}_R}^2$$

where

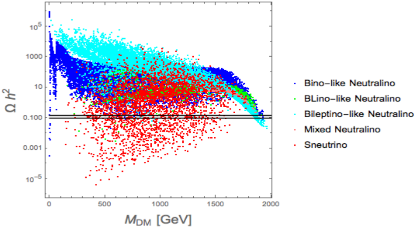
$$\Delta m_{\tilde{\nu}_R}^2 = \left| M_N(A_N - \mu' \cot \beta') \right|$$

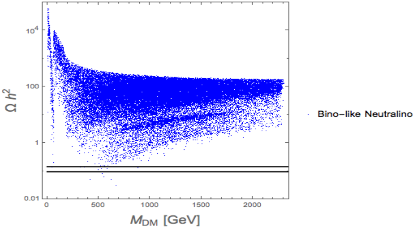
- When the mass difference is positive, the $\tilde{\nu}_1^{\mathrm{I}}$ has the lightest mass of $m_{\tilde{\nu}_-}$. In the case of a negative mass difference, $\tilde{\nu}_1^{\mathrm{R}}$-LSP, with mass $m_{\tilde{\nu}_-}$.

- In general, one finds that $M_N(A_N - \mu' \cot \beta')$ tends to be positive and so there are many more CP-odd sneutrino LSPs than CP-even.

# DM in MSSM versus BLSSM

- Here we present the relic density as function of the LSP mass for both the BLSSM and MSSM.




- Different DM types (Bino-, BLino-, Bileptino-like and mixed neutralino, alongside the sneutrino) can comply with experimental evidence over a $M_{\rm DM}$ interval which extends up to 2 TeV.

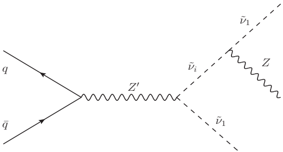
- In the MSSM case solutions can only be found for much lighter LSP masses and limitedly to one nature (the usual Bino-like neutralino).

- BLSSM yields a more varied nature of the LSP, with more numerous combinations of DM annihilation diagrams, and can play a significant role in dramatically changing the response of the model to the cosmological data, in comparison to the much constrained MSSM.

# DM Spin Characterization

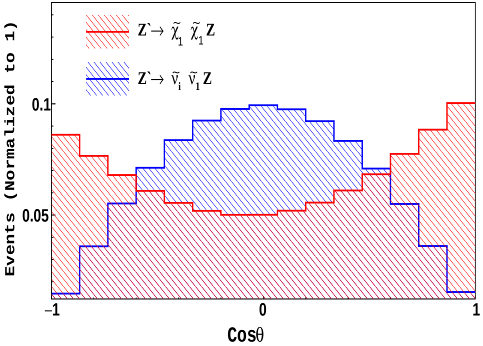
**Abdallah, Hammad, S.K, Moretti (2019)**

- 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 , $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 Z(\to \ell^+\ell^-)$), produce a $Z$ boson in three helicity states: $\pm 1$ (transverse) and 0 (longitudinal).
- The decays of heavier sneutrinos, $\tilde{\nu}_i$, to a massive $Z$ boson and $\tilde{\nu}_1$ DM, $\tilde{\nu}_i \to \tilde{\nu}_1 Z(\to \ell^+\ell^-)$, 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 $\sin^2\theta$.
- $\theta$ 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 $Z\gamma$ production.
- 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.