Long Lived BLSSM particles

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The Model: BLSSM

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \]
Extra gauge group requires:

- One extra vector boson $Z'$

To cancel the gauge anomalies, three right-handed neutrinos and their superpartners are required.

Breaking $U(1)_{B-L}$, two scalar singlets are needed: $\eta$ and $\bar{\eta}$. 
Super potential extended to be

\[ W = Y_{ij}^{u} \hat{u}_i^c \hat{Q}_j \hat{H}_u - Y_{ij}^{d} \hat{d}_i^c \hat{Q}_j \hat{H}_d - Y_{ij}^{e} \hat{e}_i^c \hat{L}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d \\
+ Y_{ij}^{\nu} \hat{\nu}_i^c \hat{L}_j \hat{H}_u - \mu' \hat{\eta} \hat{\eta} + Y_{ij}^{x} \hat{\nu}_i^c \hat{\eta} \hat{\nu}_j^c \]
Super potential extended to be

\[ W = Y_{ij}^u \hat{u}_i^c \hat{Q}_j \hat{H}_u - Y_{ij}^d \hat{d}_i^c \hat{Q}_j \hat{H}_d - Y_{ij}^e \hat{e}_i^c \hat{L}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d \]

Original MSSM potential
Super potential extended to be

\[ W = Y_u^{ij} \hat{u}^c_i \hat{Q}_j \hat{H}_u - Y_d^{ij} \hat{d}^c_i \hat{Q}_j \hat{H}_d - Y_e^{ij} \hat{e}^c_i \hat{L}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d \]
+ \[ Y_{\nu}^{ij} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c - \mu' \hat{\eta} \hat{\eta} + Y_{x}^{ij} \hat{\nu}_i \hat{\eta} \hat{\nu}_j \]

Original MSSM potential

Soft breaking terms extended by

\[-\mathcal{L}_{soft} = m^2 |\eta|^2 + m^2 |\bar{\eta}|^2 + m^2 (\tilde{\nu}^c)^* \tilde{\nu}^c + T \eta \tilde{\nu}^c \tilde{\nu}^c + T H \tilde{\nu}^c \tilde{\nu}^c + B \mu' \eta \bar{\eta} \]
+ \[ 1/2 M_{B-L} \tilde{Z}_{B-L} \tilde{Z}_{B-L} + M'_{BB} \tilde{Z}_{B-L} \tilde{Z} \]
After symmetry breaking Higgs fields doublet and singlets acquire vacuum expectation value

\[
H_d^0 = \frac{1}{\sqrt{2}} (\sigma_d + \nu_d + i\phi_d), \quad H_u^0 = \frac{1}{\sqrt{2}} (\sigma_u + \nu_u + i\phi_u),
\]
\[
\eta = \frac{1}{\sqrt{2}} (\sigma_\eta + \nu_\eta + i\phi_\eta), \quad \bar{\eta} = \frac{1}{\sqrt{2}} (\sigma_{\bar{\eta}} + \nu_{\bar{\eta}} + i\phi_{\bar{\eta}}).
\]

In analogy to MSSM \( \tan \beta' = \nu_\eta / \nu_{\bar{\eta}} \)
AT tree level the mass matrix squared in the basis \((h_d, h_u, h_\eta, h_{\bar{\eta}})\):

\[
\begin{pmatrix}
    m_{A_0}^2 s_\beta^2 + g_\Sigma^2 v_u^2 & -m_{A_0}^2 c_\beta s_\beta - g_\Sigma^2 v_d v_u & \frac{g g_{BL}}{2} v_d v_\eta & -\frac{g g_{BL}}{2} v_d v_{\bar{\eta}} \\
-m_{A_0}^2 c_\beta s_\beta - g_\Sigma^2 v_d v_u & m_{A_0}^2 c_\beta^2 + g_\Sigma^2 v_d^2 & -\frac{g g_{BL}}{2} v_u v_\eta & \frac{g g_{BL}}{2} v_u v_{\bar{\eta}} \\
\frac{g g_{BL}}{2} v_d v_\eta & -\frac{g g_{BL}}{2} v_u v_\eta & m_{A_\eta}^2 c_\beta^2 + g_{BL}^2 v_\eta^2 & -m_{A_\eta}^2 c_\beta s_\beta - g_{BL}^2 v_\eta v_{\bar{\eta}} \\
-\frac{g g_{BL}}{2} v_d v_{\bar{\eta}} & \frac{g g_{BL}}{2} v_u v_{\bar{\eta}} & -m_{A_\eta}^2 c_\beta s_\beta - g_{BL}^2 v_\eta v_{\bar{\eta}} & m_{A_\eta}^2 c_\beta^2 + g_{BL}^2 v_{\bar{\eta}}^2
\end{pmatrix}
\]
AT tree level the mass matrix squared in the basis \((h_d, h_u, h_\eta, h_{\bar{\eta}})\)

\[
\begin{pmatrix}
    m_{A_0}^2 s^2_\beta + g_\Sigma^2 v_u^2 & -m_{A_0} c_\beta s_\beta - g_\Sigma^2 v_d v_u \\
    -m_{A_0} c_\beta s_\beta - g_\Sigma^2 v_d v_u & m_{A_0}^2 c_\beta^2 + g_\Sigma^2 v_d^2 \\
    \frac{g g_{BL}}{2} v_d v_\eta & -\frac{g g_{BL}}{2} v_u v_\eta \\
    -\frac{g g_{BL}}{2} v_d v_{\bar{\eta}} & \frac{g g_{BL}}{2} v_u v_{\bar{\eta}}
\end{pmatrix}
\]

With gauge kinetic mixing vanishes the MSSM higgs sector decouples

\(\text{NH} \quad \nu_\eta, \nu_{\bar{\eta}} \geq \nu_u, \nu_d \quad \Rightarrow \quad h_d(SM) < h_u < h_\eta < h_{\bar{\eta}}\)

\(\text{IH} \quad \nu_\eta, \nu_{\bar{\eta}} < \nu_u, \nu_d \quad \Rightarrow \quad h_\eta < h_{\bar{\eta}} < h_d(SM) < h_u\)
Neutrino Masses

With TeV scale B-L breaking neutrino mass matrix

\[ M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^\dagger & M_N \end{pmatrix} \]
Neutrino Masses

With TeV scale B-L breaking neutrino mass matrix

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M_\nu = \begin{pmatrix}
0 & m_D \\
m_D^\dagger & M_N
\end{pmatrix}
\]

Dirac neutrino mass \(\sim 10^{-5}\text{GeV}\)  \hspace{1cm} Majorana neutrino mass \(\sim \mathcal{O}(\text{TeV})\)
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\[
m_L \sim m_D M_N^{-1} m_D^\dagger \\
m_H \sim M_N
\]
S-Neutrino Masses

\[ M^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ (M_{LR}^2)^\dagger & M_{RR}^2 \end{pmatrix} \]

\[ M_{LL}^2 = \begin{pmatrix} m_L^2 + m_D^2 + \frac{1}{2} M_Z^2 \cos 2\beta - \frac{1}{2} M_Z^2 \cos 2\beta' \\
0 \\
0 \\
0 \\
0 \end{pmatrix} \]

\[ M_{RR}^2 = \begin{pmatrix} M_N^2 + m_N^2 + m_D^2 + \frac{1}{2} M_Z^2 \cos 2\beta' \\
M_N (A_N - \mu' \cot \beta') \\
M_N (A_N - \mu' \cot \beta') \\
M_N^2 + m_N^2 + m_D^2 + \frac{1}{2} M_Z^2 \cos 2\beta' \end{pmatrix} \]

\[ M_{LR}^2 = \begin{pmatrix} m_D (A_\nu - \mu \cot \beta + M_N) \\
0 \\
0 \\
0 \\
0 \end{pmatrix} \]
S-Neutrino Masses

Naturally suppressed causing the mixing between left and right handed S-neutrino very small

IN case for very high suppression the masses of left handed S-neutrino and S-leptons are almost degenerate

\[ M^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ (M_{LR}^2)^\dagger & M_{RR}^2 \end{pmatrix} \]
Even for large mass difference we still can have a small decay width
Can we get a similar results in MSSM if we replace the S-neutrinos with neutralino??
In MSSM Such scenario requires a large fine tuning for masses of NLSP and LSP.


Long lived Analysis

Charged Long lived S-tau  Neutral Long lived S-neutrino
Neutral long lived

Long lived neutral signature probed by its displaced distance in X-Y plane $L_{xy}$ and the impact parameter $d_0$

$$d_0 = L_{xy} \times \sin \theta$$
Charged long lived

Unlike the neutral case the charged long lived candidate make tracks in the inner tracker

*For displaced vertex search we rely on momentum associated to DV track as well TOF
Monte Carlo “truth”
Monte Carlo "truth"

MadGraph generate the displaced distance by applying a exponential distribution function
Event display by Delphes for S-neurino long lived candidate
Event display by Delphes for S-neurino long lived candidate
Analysis

**Charged**

Signature: Charged Tracks
reconstructed as a slow moving muon
search variables: track $p_T$ and time of flight
study case: $c\tau_0 = 85$ cm, 6.9 m
$Xsec$: 1.7, 9.6 fb

**Neutral**

Signature: displaced di-leptons
SM Z boson decays to OSSF lepton pair
search variables: $L_{xy}$ and $d_0$
study case: $c\tau_0 = 90$ cm, 6.5 m
$Xsec$: 4.9, 7.6 fb
Analysis

HSCP 8, 13 TeV
arXiv:1305.0491, CMS-PAS-EXO-16-036

Final state targeted | 7 TeV | 8 TeV
--- | --- | ---
1. displaced SF dilepton pairs | 1211.2472 | 1411.6977
2. displaced μ-μ pairs in muon system | 2005761 |  
3. displaced e-μ pairs | 1409.4789 |  
4. displaced μ-μ pairs (dark photons) | 1506.00424 |  
5. displaced photons using ECAL timing | 1212.1838 | 2063495
6. displaced photons using conversions | 1207.0627 | 2019862
7. displaced vertices | to appear |  
8. displaced dijets | 1411.6530 |  
9. short, highly ionizing disappearing tracks | thesis |  
10. disappearing tracks | 1411.6006 |  
11. kinked tracks | thesis |  
12. fractionally charged particles | 1210.2311 | 1305.0491
13. heavy stable charged particles (HSCP) | 1205.0272 | 1305.0491
14. stopped particles | 1207.0106 | 1501.05603
15. out of time muons | thesis |  

direct searches | 13 TeV HSCP: 2114818
indirect searches
Set of cuts:

1. Lepton momentum > 25 GeV
2. Isolation cone radius < 0.1

- Reduces the charge mis-identification of leptons and jet mis-identification

1. $L_{xy} > 20$ mm
2. $d0 > 4$ mm

- Reduces Non prompt SM candidate and soft leptons from heavy object decay

C.O.M.E = 13 TeV
Integrated Lumi = 100 fb

Analysis S-Neutrino
Results S-Neutrino
Results S-tau

\begin{align*}
\beta & \quad \text{Event/0.1 (Lumi = 100 fb}^{-1}\text{)} \\
\text{ct}_0 = 6.9 \text{ m} & \quad \text{ct}_0 = 85 \text{ cm}
\end{align*}
Summary

* B-L Extension of MSSM can provide wide spectrum for neutral and charged long lived particles
* Unlike MSSM, the life time is independent of the mass difference between NLSP and LSP
* Fast detector simulation has been done, while with full simulation more info will provided
  * For the neutral LLP we rely on L_xy and d0 parameter as discriminator
* For the charged LLP we rely on the track + TOF info