Naturalness and Dark Matter in the BLSSM

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Outline

1 Motivations and Explanation of BLSSM
2 Solving Problems in the SM
3 Results - Fine-Tuning & Dark Matter
4 Conclusions

In collaboration with L. Delle Rose, S. Khalil, C. Marzo, S. Moretti, C.S. Ün [arXiv: 1702.01808]
Motivations

- Hierarchy Problem

\[ H \]

\[ f \]
Motivations

- Hierarchy Problem

\[ f \]
\[ H \]

- Dark Matter

Figure: Chandra X-ray Observatory
Motivations

- Hierarchy Problem

- Dark Matter

- Non-vanishing Neutrino Masses

Figure: Chandra X-ray Observatory // KamLAND experiment, 0801.4589
Explaining the BLSSM – “B-L”

- SM has *exact* B-L conservation
- Promote accidental, global symmetry to local. SM gauge group now extended to: $G_{B-L} = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- anomaly cancellation - require SM singlet fermion (right-handed neutrinos)
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Explaining the BLSSM – “SSM”

<table>
<thead>
<tr>
<th>Chiral Superfield</th>
<th>Spin 0</th>
<th>Spin 1/2</th>
<th>$G_{B-L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quarks/Squarks, (x3 generations)</strong></td>
<td>$\hat{Q}$</td>
<td>$(\bar{u}_L \tilde{d}_L) \equiv \tilde{Q}_L$</td>
<td>$(u_L d_L)$</td>
</tr>
<tr>
<td></td>
<td>$\hat{U}$</td>
<td>$\tilde{u}_R^*$</td>
<td>$u_R^*$</td>
</tr>
<tr>
<td></td>
<td>$\hat{D}$</td>
<td>$\tilde{d}_R^*$</td>
<td>$d_R^*$</td>
</tr>
<tr>
<td><strong>Leptons/Sleptons, (x3 generations)</strong></td>
<td>$\hat{L}$</td>
<td>$(\bar{\nu}_L \tilde{e}_L) \equiv \tilde{L}_L$</td>
<td>$(\nu_L e_L)$</td>
</tr>
<tr>
<td></td>
<td>$\hat{E}$</td>
<td>$\tilde{e}_R^*$</td>
<td>$e_R^*$</td>
</tr>
<tr>
<td><strong>Higgs/Higgsinos</strong></td>
<td>$\hat{H}_u$</td>
<td>$(H_u^+ H_u^0)$</td>
<td>$(\tilde{H}_u^+ \tilde{H}_u^0) \equiv \tilde{H}_u$</td>
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<tr>
<td></td>
<td>$\hat{H}_d$</td>
<td>$(H_d^0 H_d^-)$</td>
<td>$(\tilde{H}_d^0 \tilde{H}_d^-) \equiv \tilde{H}_d$</td>
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<tr>
<th><strong>Vector Superfields</strong></th>
<th>Spin 1/2</th>
<th>Spin 1</th>
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<tbody>
<tr>
<td><strong>Gluino, gluon</strong></td>
<td>$\tilde{g}$</td>
<td>$g$</td>
<td>$(8, 1, 0, 0)$</td>
</tr>
<tr>
<td><strong>Wino/W bosons</strong></td>
<td>$\tilde{W}^\pm \tilde{W}^0$</td>
<td>$W^\pm W^0$</td>
<td>$(1, 3, 0, 0)$</td>
</tr>
<tr>
<td><strong>Bino / B boson</strong></td>
<td>$\tilde{B}^0$</td>
<td>$B^0$</td>
<td>$(1, 1, 0, 0)$</td>
</tr>
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Explaining the BLSSM – “SSM”

Content in addition to MSSM:

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<th>$G_{B-L}$</th>
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<tbody>
<tr>
<td>RH Sneutrinos / Neutrinos (x3)</td>
<td>$\hat{\nu}$</td>
<td>$\bar{\nu}^*$</td>
<td>$\nu_R$</td>
</tr>
<tr>
<td>Bileptons/Bileptinos</td>
<td>$\hat{\eta}$</td>
<td>$\eta$</td>
<td>$\bar{\eta}$</td>
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<tr>
<td></td>
<td>$\bar{\eta}$</td>
<td>$\bar{\eta}$</td>
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<tr>
<td>BLino / B’ boson</td>
<td>$\tilde{B}^0$</td>
<td>$B^0$</td>
<td>(1, 1, 0, 0)</td>
</tr>
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</table>

- Three extra RH neutrinos + SUSY partner (from anomaly cancellation condition)
- Two extra Higgs (for breaking gauged $U(1)_{B-L}$)
- One B’ + SUSY partners (from broken $U(1)_{B-L}$)
Hierarchy Problem

\[ H \quad \quad \quad \quad \quad \quad \quad f \]

\[ = - \frac{|\lambda_f|^2}{8\pi^2} \Lambda_{NP}^2 + \ldots \]

- Self energy correction to bare Higgs mass. Treating \( \Lambda_{NP} \) at GUT scale (\( 10^{16} \) GeV) means the bare Higgs mass is fine-tuned to \( \frac{m_H^2}{\Lambda_{UV}^2} \sim 1 \) in \( 10^{30} \)!
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- **Supersymmetry** - for every fermion, there is a scalar partner providing the opposite sign contribution
Non-vanishing Neutrino Masses I

- $\nu_L$ have mass!
- Introducing RH neutrinos can explain mass for $\nu_L$

The seesaw mass insertion diagram responsible for the light effective LH Majorana neutrino mass

$$m_\nu = -m_D M_R^{-1}$$

Collecting together Eqs. 34, 35 (assuming Eq. 33 terms to be absent) we have the seesaw mass matrix,

$$\begin{pmatrix} \nu_L \nu_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}.$$

Since the RH neutrinos are electroweak singlets the Majorana masses of the RH neutrinos $M_R$ may be orders of magnitude larger than the electroweak scale. In the approximation that $M_R \approx m_D$ the matrix in Eq. 37 may be diagonalised to yield effective Majorana masses of the type in Eq. 33,

$$m_\nu = -m_D M_R^{-1}.$$

The seesaw mechanism formula is represented by the mass insertion diagram in Fig. 4. This formula is valid below the EW scale. Above the EW scale, but below the scale $M_R$, the seesaw mechanism is represented by the Weinberg operator in Eq. 2, whose coefficient has the same structure as the seesaw formula in Eq. 38.

The light effective LH neutrino Majorana mass is naturally suppressed by the heavy scale $M_R$, but its precise value depends on the Dirac neutrino mass $m_D$. Suppose we fix the desired physical neutrino mass to be $m_\nu = 0.1 \text{ eV}$, then the seesaw formula in Eq. 38 relates the possible values of $m_D$ to $M_R$ as shown in Fig. 5. This illustrates the huge range of allowed values of $m_D$ and $M_R$ consistent with an observed neutrino mass of 0.1 eV, with $M_R$ ranging from 1 eV up to the GUT scale, leading to many different types of seesaw models and phenomenology, including eV mass LSND sterile neutrinos, keV mass sterile neutrinos suitable for warm dark matter (WDM), GeV mass sterile neutrinos suitable for resonant leptogenesis and TeV mass sterile neutrinos possibly observable at the LHC (for a review see e.g. [61] and references therein). In this review we shall focus on the case of Dirac neutrino masses identified with charged quark and lepton masses, leading to a wide range of RH neutrino (or sterile neutrino) masses from the TeV scale to the GUT scale, which we refer to as the classic seesaw model.

For example, if we take $m_D$ to be 1 GeV (roughly equal to the charm quark mass) then a neutrino mass of 0.1 eV requires a RH (sterile) neutrino mass of $10^{10}$ GeV.
Non-vanishing Neutrino Masses I

- $\nu_L$ have mass!
- Introducing RH neutrinos can explain mass for $\nu_L$
- Large RH mass can explain small LH mass in a see-saw mechanism

$$\langle H_u \rangle$$

$$\langle H_u \rangle$$

$\nu_L$ $\nu_R$ $M_R$ $\nu_R$ $\nu_L$

$Y^\nu$ $Y^\nu$

Figure: 1701.04413
...However, this leads to $B - L$ violation, as in $0\nu 2\beta$-decay.

In BLSSM, gauge symmetry is broken with a Higgs mechanism.
Numerical work?

- Mathematica package SARAH makes a spectrum generator based on SPheno
- SPheno then calculates the full spectrum, for 60,000 data points, over a range of the GUT parameters ($m_0$, $m_{1/2}$, $A_0$, $\mu$, $B\mu$, $\mu'$, $B\mu'$)
- Current Higgs constraints are applied in HiggsBounds / HiggsSignals
- Finally, MicroOMEGAs finds the relic density.
Introduction to Fine-Tuning

- We use the Ellis-Enqvist-Nanopoulos-Zwirner / Barbieri-Giudice definition of fine-tuning
  \[ \Delta = \text{Max} \left\{ \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2(a_i, m_t)}{\partial a_i} \right| \right\} \]

- Definition applied for two scales:
  - GUT-scale parameters \((m_0, m_{1/2}, A_0, \mu, B\mu, \mu', B\mu')\)
  - SUSY-scale parameters \((m_{H_u}, m_{H_d}, m_{Z'}, \mu, \Sigma_u, \Sigma_d)\)

- Recent work\(^1\) has shown that loop contributions to tadpole equations may be important to GUT fine-tuning

- Both CMSSM and the BLSSM with universality have GUT-FT reduced by factor \(\sim 2\)

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\(^1\)Ross, Schmidt-Hoberg, Staub, 1701.03480
Fine-Tuning Results GUT scale

- Fine-tuning plotted in $m_0, m_{1/2}$ frame. Points are blue for $FT < 500$, orange $500 < FT < 1000$, green $1000 < FT < 5000$, red $FT > 5000$.
Fine-Tuning Results SUSY scale

- Fine-tuning plotted in $m_0$, $m_{1/2}$ frame. Points are blue for FT < 500, orange 500 < FT < 1000, green 1000 < FT < 5000, red FT > 5000
Dark Matter

- In SUSY models, the lightest super-partner is *stable* from R-parity conservation
- CMSSM only candidate Bino ($\tilde{B}^0$). BLSSM (with universality) also has Sneutrino ($\tilde{\nu}_R^*$), Bileptino ($\tilde{\eta}$, $\tilde{\eta}$), BLino ($\tilde{B}'^0$)

![CMSSM vs BLSSM](1702.01808)

**Figure:** 1702.01808 - This work
Conclusions

- The BLSSM . . .
  - Solves the hierarchy problem
  - predicts light, non-vanishing left-handed neutrino masses
  - offers multiple dark matter candidates
- Fine-tuning in BLSSM is comparable to CMSSM
- ...But with *much* larger parameter space available

For more details, see: arXiv: 1702.01808