Naturalness and Dark Matter in the BLSSM

Simon J. D. King

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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

\[ f \]

\[ H \]
Motivations

- Hierarchy Problem

\[ f \]
\[ H \]

- Dark Matter

**Figure:** Chandra X-ray Observatory
Motivations

- Hierarchy Problem

\[ f \]

- 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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\[
U(1)_{B-L}
\]

\[
\nu_R \quad \nu_R \quad \nu_R
\]

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

- Content in addition to MSSM:

<table>
<thead>
<tr>
<th>Chiral Superfield</th>
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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>$\tilde{\nu}_R^*$</td>
<td>$\tilde{\nu}_R$</td>
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<td>Bileptons/Bileptinos</td>
<td>$\hat{\eta}$</td>
<td>$\eta$</td>
<td>$\tilde{\eta}$</td>
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<tr>
<td></td>
<td>$\hat{\tilde{\eta}}$</td>
<td>$\tilde{\eta}$</td>
<td>$\tilde{\tilde{\eta}}$</td>
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</tbody>
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<table>
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<th>Vector Superfields</th>
<th>Spin 1/2</th>
<th>Spin 1</th>
<th>$G_{B-L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLino / B’ boson</td>
<td>$\tilde{B}^0$</td>
<td>$B^0$</td>
<td>(1, 1, 0, 0)</td>
</tr>
</tbody>
</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

$$H \quad \quad \quad f \quad \quad \quad = - \frac{|\lambda_f|^2}{8\pi^2} \Lambda_{NP}^2 + \ldots$$

- 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 $m_H^2/\Lambda_{UV}^2 \sim \textbf{1 in } 10^{30}$!
Hierarchy Problem

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

- Self energy correction to bare Higgs mass. Treating \( \Lambda_{NP} \) at GUT scale (\( 10^{16} \text{GeV} \)) means the bare Higgs mass is fine-tuned to \( m_H^2/\Lambda_{UV}^2 \approx 1 \text{ in } 10^{30}! \)

- 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 $\nu_L$

Large RH mass can explain small LH mass in a see-saw mechanism

\[
\left( \bar{\nu}_L \nu_R^c \right) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}
\]

\[
\langle H_u \rangle
\]

Figure: 1701.04413

The light effective LH Majorana neutrino mass

\[
m_\nu = -m_D M_R^{-1} \]

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 $m_\nu = 0.1$ 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.
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

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

Figure 4: 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,

$$\begin{pmatrix} \nu_L \nu_L^c \end{pmatrix}$$

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,

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

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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.

\[17\]
Non-vanishing Neutrino Masses II

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

In BLSSM, gauge symmetry is broken with a Higgs mechanism
Superpotential:

\[ W = \mu H_u H_d + Y_u^{ij} Q_i H_u u_j^c + Y_d^{ij} Q_i H_d d_j^c + Y_e^{ij} L_i H_d e_j^c + Y_\nu^{ij} L_i H_u N_i^c + Y_N^{ij} N_i^c N_j^c \eta_1 + \mu' \eta_1 \eta_2 \]

Type-I see-saw mechanism, RH neutrinos have \( \lesssim \) TeV mass

**Natural** R-parity: \( R = (-1)^{3(B-L)+2S} \). If \( B - L \) broken by Higgs with even \( B - L \) charge, then \( Z_2 \) remains unbroken

\( M_{Z'} \) fixed at 4 TeV, from LEP-II EWPOs and LHC di-lepton searches

Complete universality at GUT scale, \( g_{bl} = g_1 = g_2 = g_3, \tilde{g} = 0 \). From RGE evolution, at EW scale, \( \tilde{g} \approx -0.1 \) and \( g_{bl} \approx 0.5 \)
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, MicroMEGAs finds the relic density.
Introduction to Fine-Tuning

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

- Definition applied for two scales:
  - GUT-scale parameters \((m_0, m_{1/2}, A_0, \mu, B\mu, \mu', B\mu')\)
  - SUSY-scale parameters \((m_{H_u}, m_{H_d}, m_{Z'}, \mu, \Sigma_u, \Sigma_d)\), where
    \[ \Sigma_{u,d} = \frac{\partial \Delta V}{\partial v^2_{u,d}} \]

- 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
GUT Scale Fine-Tuning

- Simply input GUT parameters into fine-tuning measure: \( a_i = (m_0, m_{1/2}, A_0, \mu, B\mu, \mu', B\mu') \rightarrow \Delta = Max \left\{ \left| \frac{a_i}{M_Z^2} \frac{\partial M^2_Z(a_i,m_t)}{\partial a_i} \right| \right\} \), tadpole loop effects absorbed into parameters
- Histogram: Counts for each parameter determining fine-tuning

**Figure:** 1702.01808 - This work
SUSY Scale Fine-Tuning - CMSSM

- Fine-tuning measure may also be applied to MSSM SUSY-Scale parameters:
  \[
  \frac{1}{2} M_Z^2 = \left( \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \right) \rightarrow \Delta = \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2(a_i, m_t)}{\partial a_i} \right|
  \]

- \[\Delta_{\text{SUSY}} \equiv \text{Max}(C_i)/(M_Z^2/2),\]

- \[C_{H_d} = \left| m_{H_d}^2 \frac{1}{(\tan^2 \beta - 1)} \right|,\]

- \[C_{\Sigma_d} = \left| \Sigma_d \frac{1}{(\tan^2 \beta - 1)} \right|,\]

- \[C_\mu = \left| \mu^2 \right|, \ldots\]

**Figure:** 1702.01808 - This work
SUSY Scale Fine-Tuning - BLSSM

- Fine-tuning measure may also be applied to BLSSM SUSY-Scale parameters:

\[
\frac{1}{2} M_Z^2 = \frac{1}{X} \left( \frac{m_{H_d}^2 + \Sigma_d}{\tan^2(\beta) - 1} - \frac{m_{H_u}^2 + \Sigma_u \tan^2(\beta)}{(\tan^2(\beta) - 1)} + \frac{\tilde{g} M_Z^2 Y}{4g_{BL}} - \mu^2 \right)
\]

\[
X = 1 + \frac{\tilde{g}^2}{(g_1^2 + g_2^2)} + \frac{\tilde{g}^3 Y}{2g_{BL}(g_1^2 + g_2^2)}
\]

\[
Y = \frac{\cos(2\beta')}{\cos(2\beta)}
\]

\[
\Delta_{\text{SUSY}} \equiv \text{Max}(C_i)/(M_Z^2/2),
\]

\[
C_{Z'} = \left| M_{Z'} \frac{\tilde{g} Y}{4g_{BL} X} \right|
\]

\[
C_{\Sigma_d} = \left| \Sigma_d \frac{1}{X (\tan^2 \beta - 1)} \right|
\]

\[
C_{\mu} = \left| \frac{\mu^2}{X} \right|, \ldots
\]

Figure: 1702.01808 - This work
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 $FT > 5000$

**Figure:** 1702.01808 - This work
Fine-Tuning Results SUSY scale

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Figure: 1702.01808 - This work
Dark Matter

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

Figure: BLSSM DM candidates - 1702.01808 - This work
Dark Matter

- CMSSM severely constrained by relic-density limits
- Bino ($\tilde{B}^0$), Sneutrino ($\tilde{\nu}_R^*$), Bileptino ($\tilde{\eta}$, $\tilde{\bar{\eta}}$), BLino ($\tilde{B}'^0$)

\[ \text{CMSSM} \quad \text{BLSSM} \]

**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
Back-up slides
Scan range:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>range</th>
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<tbody>
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<td>$m_0$</td>
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<tr>
<td>$m_{1/2}$</td>
<td>[0, 5] TeV</td>
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<tr>
<td>$\tan(\beta)$</td>
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<tr>
<td>$\tan(\beta')$</td>
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<td>$A_0$</td>
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<td>$Y^{(1,1)}$</td>
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<td>$Y^{(3,3)}$</td>
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<td>$M_{Z'} = $</td>
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