Naturalness and Dark Matter in the BLSSM

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EPS-HEP 2017,
Venice, Italy

6th July 2017

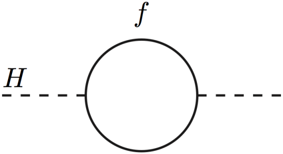
Outline

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



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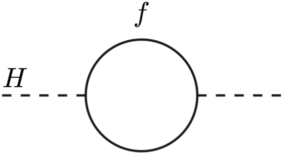

- Dark Matter

Figure: Chandra X-ray Observatory

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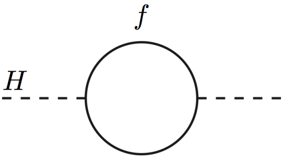


- Dark Matter

- Non-vanishing Neutrino Masses

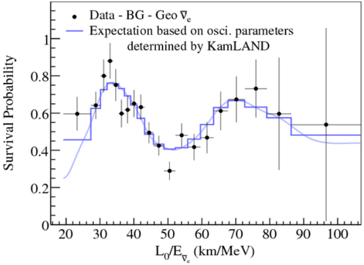
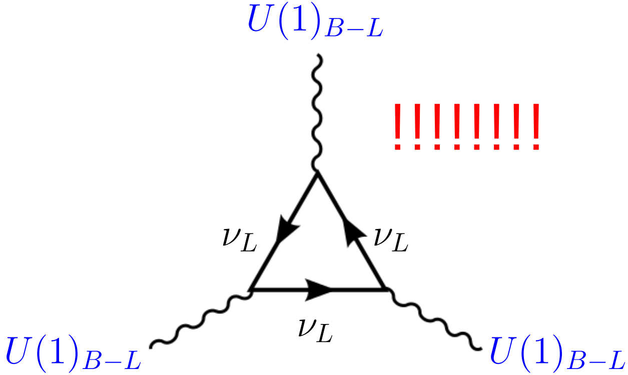


Figure: Chandra X-ray Observatory // KamLAND experiment, 0801.4589

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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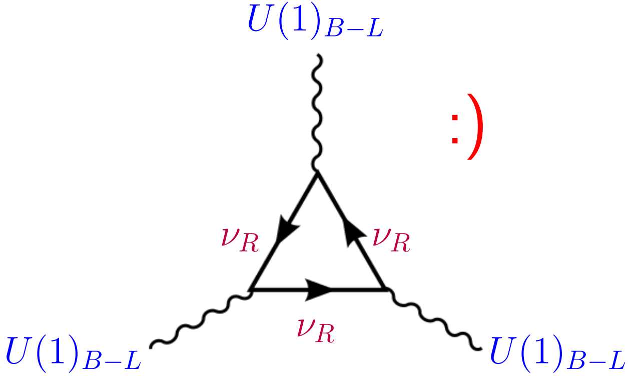


Explaining the BLSSM – “SSM”

Chiral Superfield		Spin 0	Spin 1/2	G_{B-L}
Quarks/Squarks, (x3 generations)	$\hat{Q}$	$(\tilde{u}_L \tilde{d}_L) \equiv \tilde{Q}_L$	$(u_L d_L)$	$(\mathbf{3},\ \mathbf{2},\ \frac{1}{6},\ \frac{1}{6})$
	$\hat{U}$	$\tilde{u}_R^*$	$\bar{u_R}$	$(\bar{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3},\ -\frac{1}{6})$
	$\hat{D}$	$\tilde{d}_R^*$	$\bar{d_R}$	$(\bar{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3},\ -\frac{1}{6})$
Leptons/Sleptons, (x3 generations)	$\hat{L}$	$(\tilde{\nu}_L \tilde{e}_L) \equiv \tilde{L}_L$	$(\nu_L e_L)$	$(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2},\ -\frac{1}{2})$
	$\hat{E}$	$\tilde{e}_R^*$	$\bar{e_R}$	$(\mathbf{1},\ \mathbf{1},\ 1,\ \frac{1}{2})$
Higgs/Higgsinos	$\hat{H}_u$	$(H_u^+ H_u^0)$	$(\tilde{H}_u^+ \tilde{H}_u^0) \equiv \tilde{H}_u$	$(\mathbf{1},\ \mathbf{2},\ \frac{1}{2},\ 0)$
	$\hat{H}_d$	$(H_d^0 H_d^-)$	$(\tilde{H}_d^0 \tilde{H}_d^-) \equiv \tilde{H}_d$	$(\mathbf{1},\ \mathbf{2},\ -\frac{1}{2},\ 0)$
Vector Superfields		Spin 1/2	Spin 1	G_{B-L}
Gluino, gluon		$\tilde{g}$	g	($\mathbf{8}$, $\mathbf{1}$, 0,0)
Wino/W bosons		$\tilde{W}^{\pm}\ \tilde{W}^0$	$W^{\pm} W^0$	($\mathbf{1}$, $\mathbf{3}$, 0, 0)
Bino / B boson		$\tilde{B}^0$	B^0	($\mathbf{1}$ $\mathbf{1}$, 0, 0)

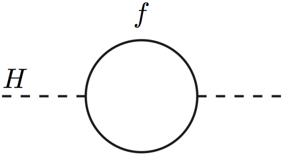
Explaining the BLSSM – "SSM"

- Content in addition to MSSM:

Chiral Superfield		Spin 0	Spin 1/2	G_{B-L}
RH Sneutrinos / Neutrinos (x3)	$\hat{\nu}$	$\tilde{\nu}_R^*$	$\bar{\nu}_R$	$(\mathbf{1}, \mathbf{1}, 0, \frac{1}{2})$
Bileptons/Bileptinos	$\hat{\eta}$	η	$\tilde{\eta}$	$(\mathbf{1}, \mathbf{1}, 0, -1)$
	$\hat{\bar{\eta}}$	$\bar{\eta}$	$\tilde{\bar{\eta}}$	$(\mathbf{1}, \mathbf{1}, 0, 1)$
Vector Superfields		Spin 1/2	Spin 1	G_{B-L}
BLino / B' boson		$\tilde{B}'^0$	B'^0	$(\mathbf{1}\ \mathbf{1}, 0, 0)$

- 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



$$= -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{NP}^2 + \dots$$

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

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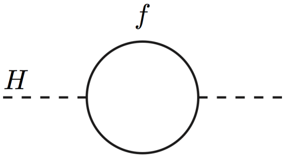

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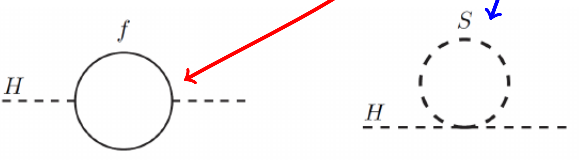
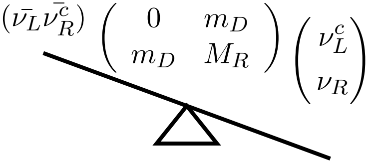
- Supersymmetry - for every fermion, there is a scalar partner providing the opposite sign contribution



Non-vanishing Neutrino Masses I

- ν_L have mass!
- Introducing RH neutrinos can explain mass for ν_L



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

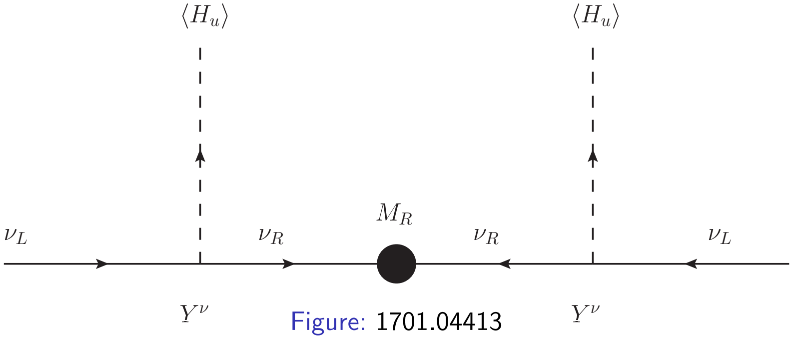
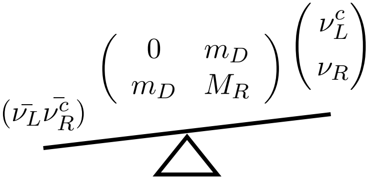


Figure: 1701.04413

Non-vanishing Neutrino Masses I

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



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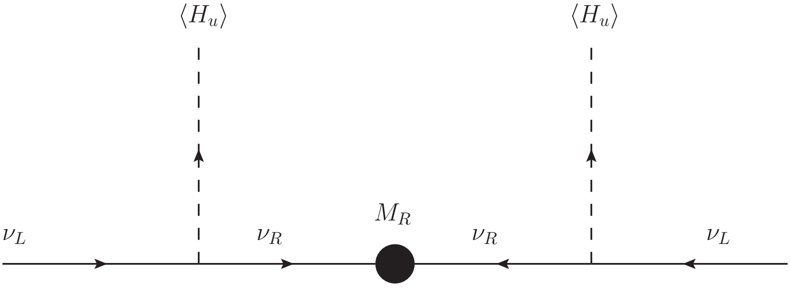


Figure: 1701.04413

Non-vanishing Neutrino Masses II

- ...However, this leads to $B-L$ violation, as in $0\nu2\beta$-decay

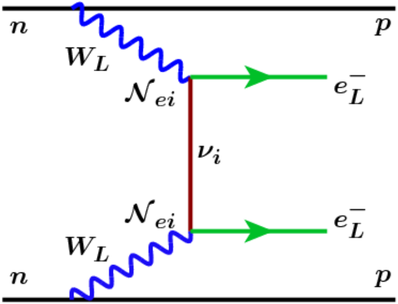
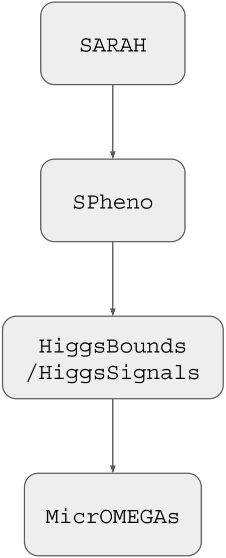


Figure: 1301.4784

- 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, μ, $B\mu$, μ', $B\mu'$)
- Current Higgs constraints are applied in `HiggsBounds` / `HiggsSignals`
- Finally, `MicroOMEGAs` finds the relic density.



SARAH

SPheno

HiggsBounds
/HiggsSignals

MicrOMEGAs

Introduction to Fine-Tuning

- We use the Ellis-Enqvist-Nanopoulos-Zwirner / Barbieri-Giudice definition of fine-tuning

$$\Delta = Max\left\{ \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2(a_i, m_t)}{\partial a_i} \right| \right\}$$

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

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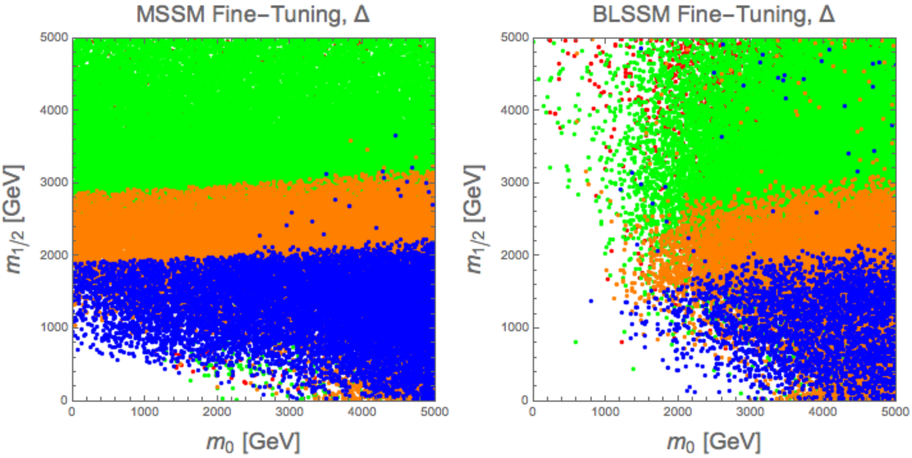
[1] Ross, Schmidt-Hoberg, Staub, 1701.03480

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



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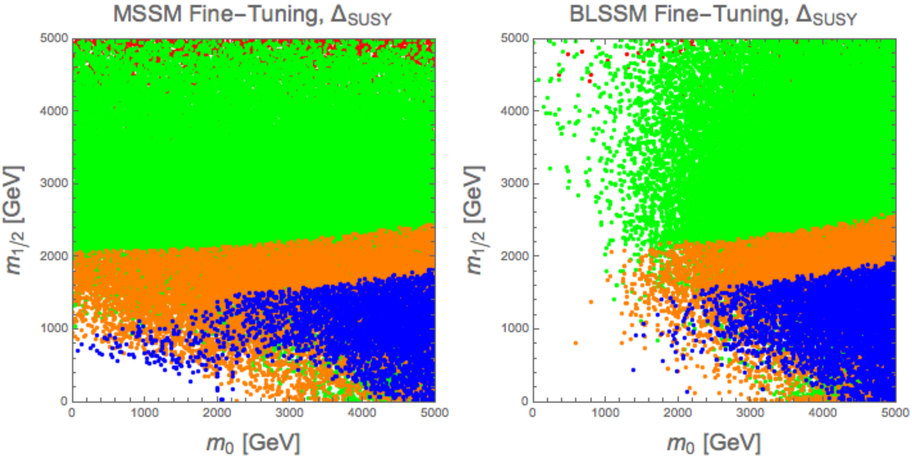

Dark Matter

- 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 ($\tilde{\eta}$, $\tilde{\bar{\eta}}$) , BLino ($\tilde{B}'^0$)

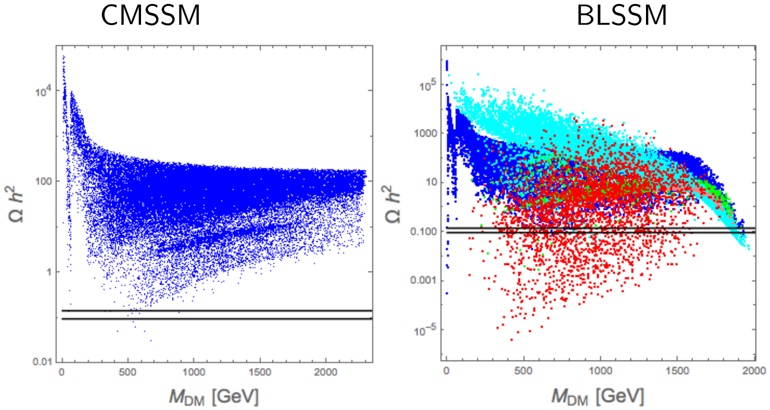

Figure: 1702.01808 - This work

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