

Naturalness and Dark Matter in the BLSSM

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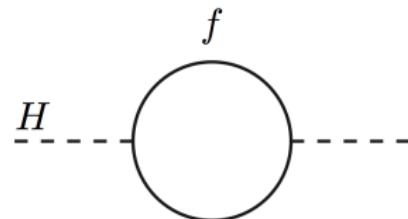
Outline

- 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]

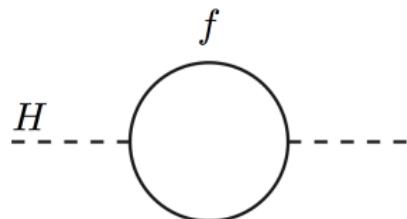
Motivations

- Hierarchy Problem



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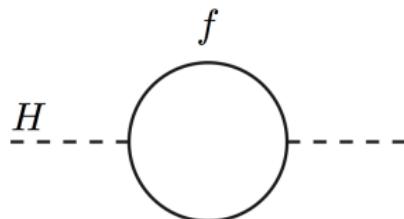
- Dark Matter



Figure: Chandra X-ray Observatory

Motivations

- Hierarchy Problem



- Dark Matter



- Non-vanishing Neutrino Masses

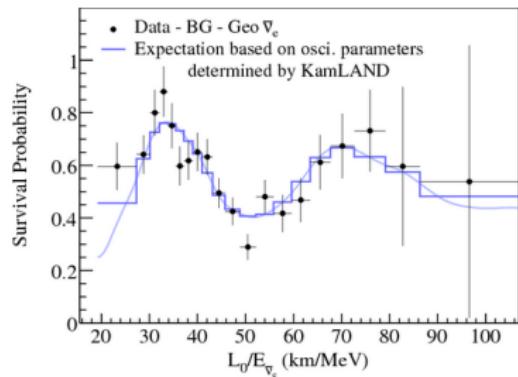
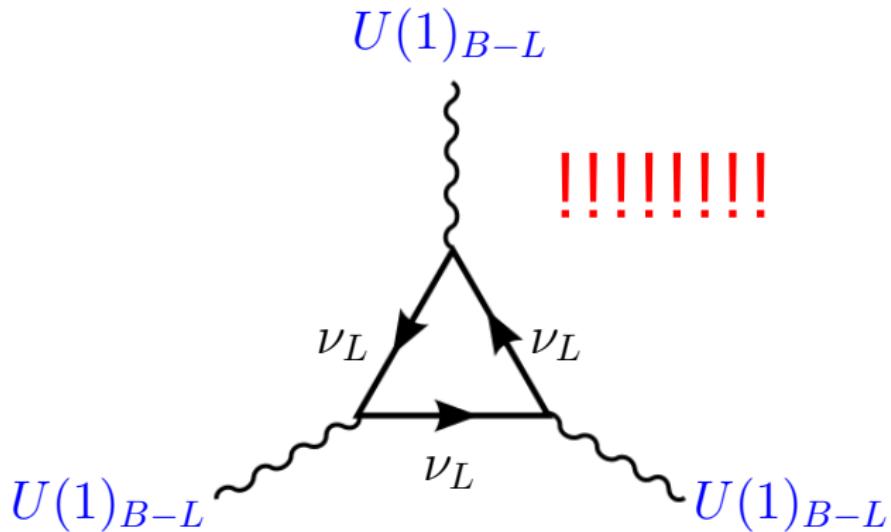


Figure: Chandra X-ray Observatory // KamLAND experiment, 0801.4589

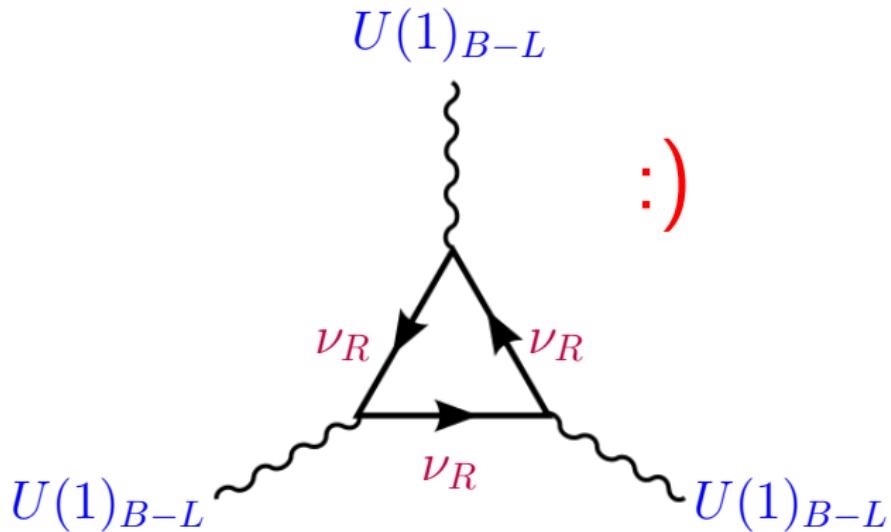
Explaining the BLSSM – “B-L”

- 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”

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^*	u_R^-	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, -\frac{1}{6})$
	\hat{D}	\tilde{d}_R^*	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^*	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)	$\hat{\nu}$	$\tilde{\nu}_R^*$	$\bar{\nu}_R$	(1, 1, 0, $\frac{1}{2}$)
Bileptons/Bileptinos	$\hat{\eta}$ $\hat{\bar{\eta}}$	η $\bar{\eta}$	$\tilde{\eta}$ $\tilde{\bar{\eta}}$	(1, 1, 0, -1) (1, 1, 0, 1)
Vector Superfields		Spin 1/2	Spin 1	G_{B-L}
BLino / B' boson		\tilde{B}'^0	B'^0	(1 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

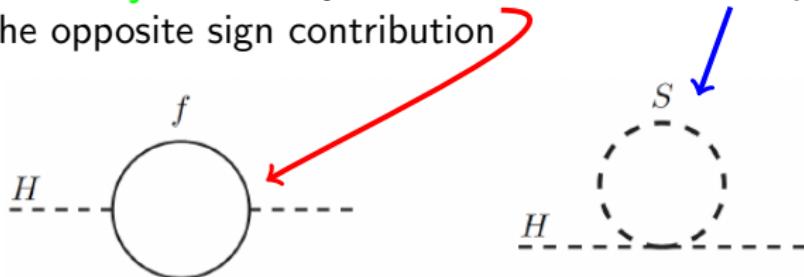
A Feynman diagram illustrating the hierarchy problem. It consists of a central circle labeled f . Two dashed lines extend from the left side of the circle. The top line is labeled H and the bottom line is unlabeled. To the right of the circle, an equals sign follows by a mathematical expression: $= -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{NP}^2 + \dots$.

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

Hierarchy Problem

A Feynman diagram showing a bare Higgs boson H (dashed line) entering a loop containing a fermion f (solid circle). The loop is closed by a dashed line. To the right of the loop is the equation $= -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{NP}^2 + \dots$.

- 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 $m_H^2/\Lambda_{UV}^2 \approx 1 \text{ in } 10^{30}!$
- **Supersymmetry** - for every **fermion**, there is a **scalar** partner providing the opposite sign contribution



Non-vanishing Neutrino Masses I

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

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

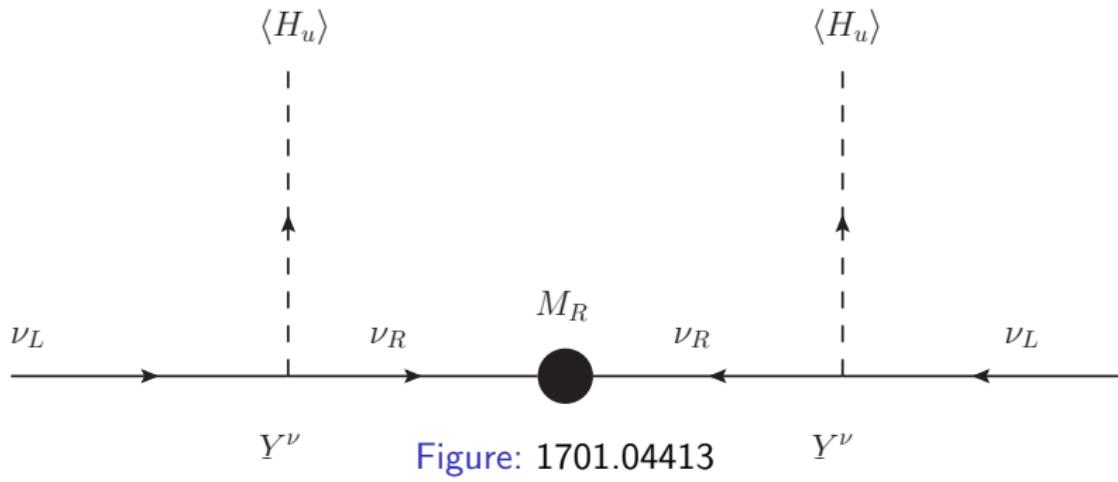
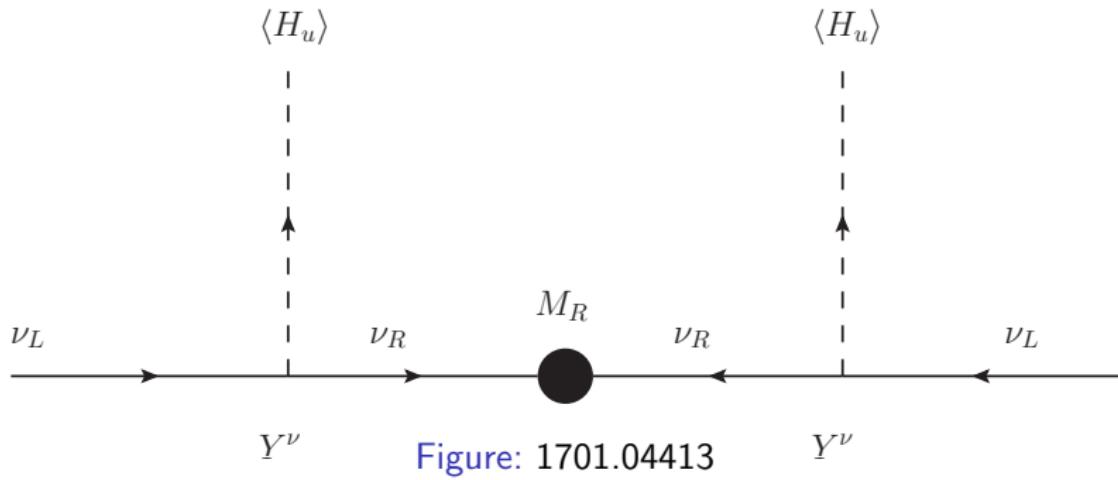


Figure: 1701.04413

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

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

Non-vanishing Neutrino Masses II

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

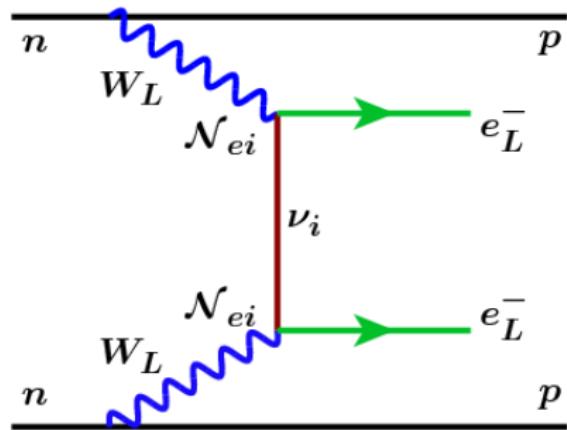


Figure: 1301.4784

- In BLSSM, gauge symmetry is broken with a Higgs mechanism

BLSSM Review

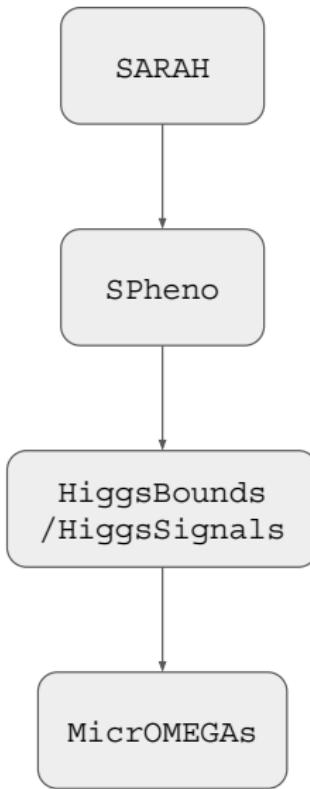
- Superpotential:

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

- 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, $\tilde{g} \simeq -0.1$ and $g_{bl} \simeq 0.5$

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



Introduction to Fine-Tuning

- We use the Ellis / 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 ($m_{H_u}, m_{H_d}, m_{Z'}, \mu, \Sigma_u, \Sigma_d$), where

$$\Sigma_{u,d} = \frac{\partial \Delta V}{\partial v_{u,d}^2}$$

- Recent work¹ 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

¹Ross, Schmidt-Hoberg, Staub, 1701.03480

GUT Scale Fine-Tuning

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

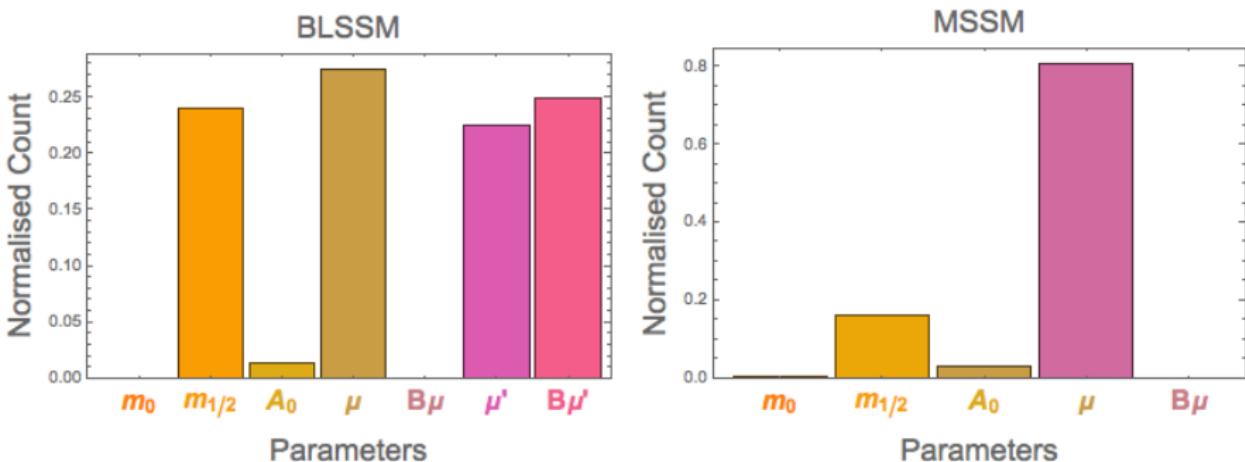


Figure: 1702.01808 - This work

SUSY Scale Fine-Tuning - CMSSM

- Fine-tuning measure may also be applied to MSSM SUSY-Scale parameters:
- $\frac{1}{2}M_Z^2 = \left(\frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \right) \rightarrow \Delta = \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2(a_i, m_t)}{\partial a_i} \right|$
- $\Delta_{\text{SUSY}} \equiv \text{Max}(C_i)/(M_Z^2/2),$
- $C_{H_d} = \left| m_{H_d}^2 \frac{1}{(\tan^2 \beta - 1)} \right|,$
- $C_{\Sigma_d} = \left| \Sigma_d \frac{1}{(\tan^2 \beta - 1)} \right|,$
- $C_\mu = |\mu^2|, \dots$

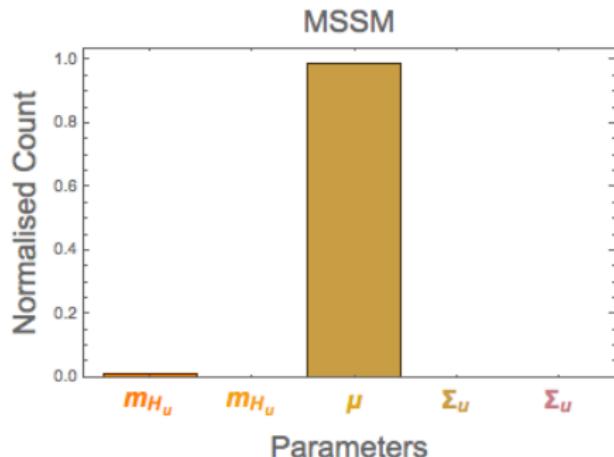


Figure: 1702.01808 - This work

SUSY Scale Fine-Tuning - BLSSM

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

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

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

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

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

$$\bullet C_{Z'} = \left| M_{Z'}^2 \frac{\tilde{g} Y}{4g_{BL} X} \right|$$

$$\bullet C_{\Sigma_d} = \left| \Sigma_d \frac{1}{X(\tan^2 \beta - 1)} \right|,$$

$$\bullet C_\mu = \left| \frac{\mu^2}{X} \right|, \dots$$

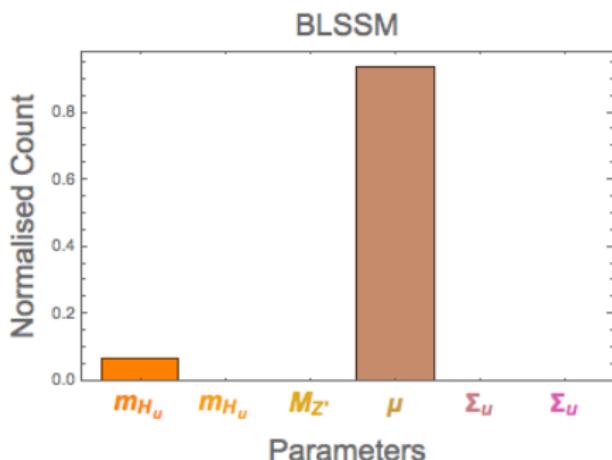


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Fine-Tuning Results GUT scale

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

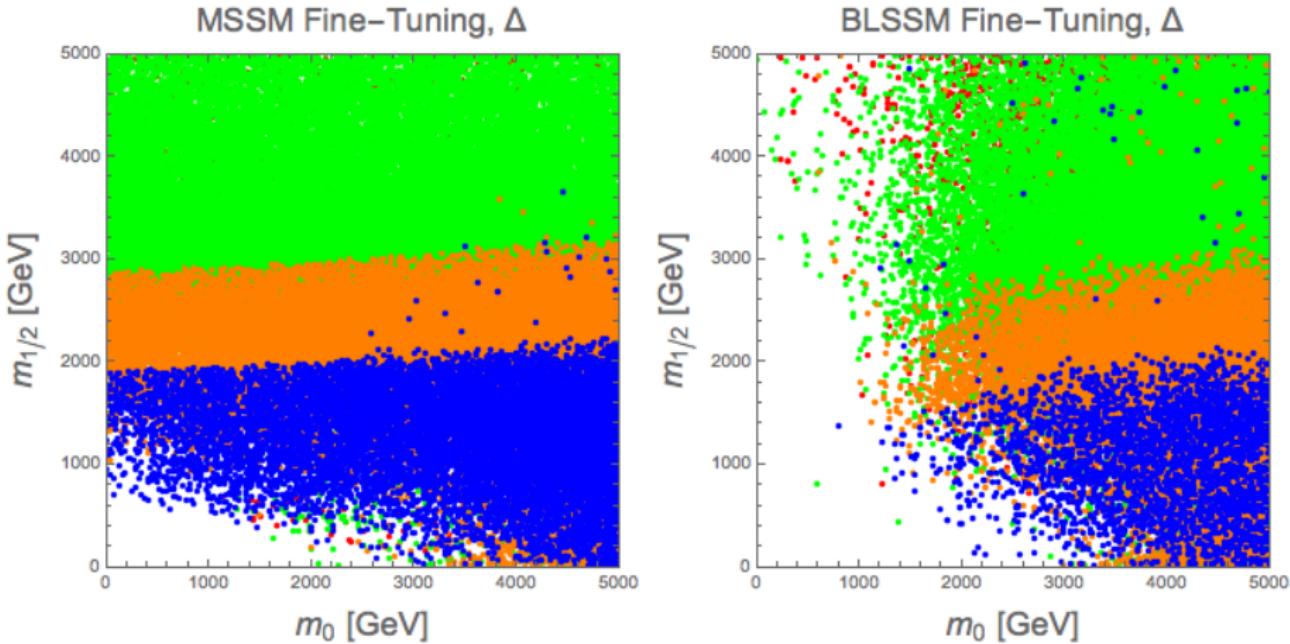


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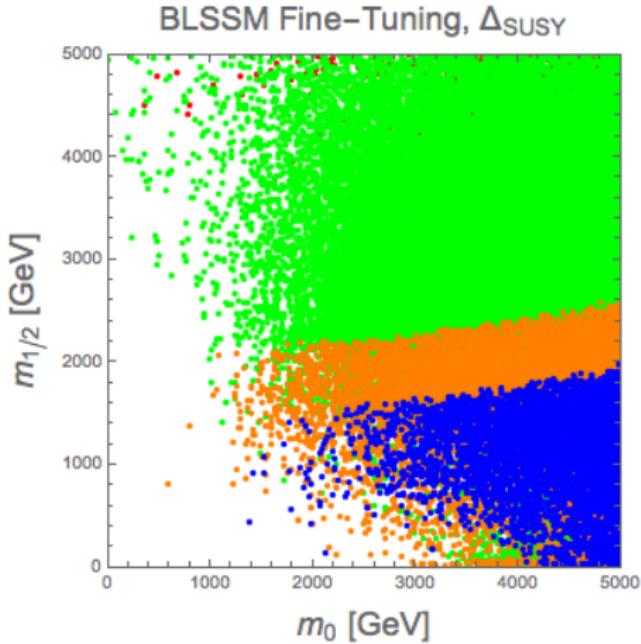
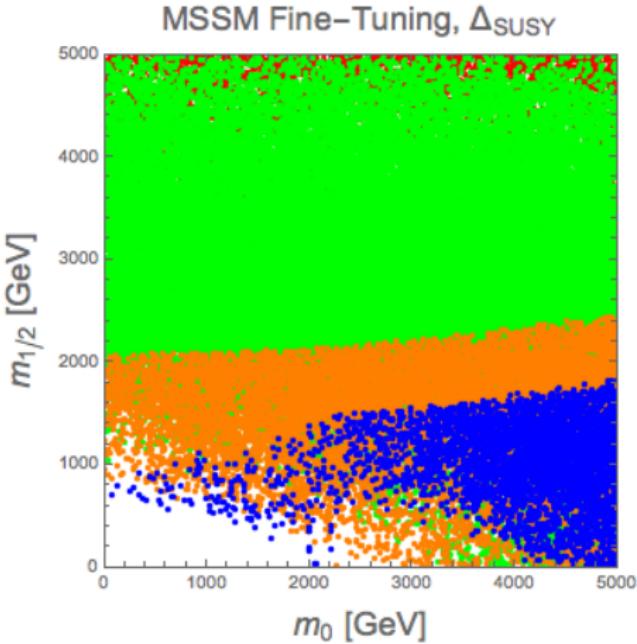


Figure: 1702.01808 - This work

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)

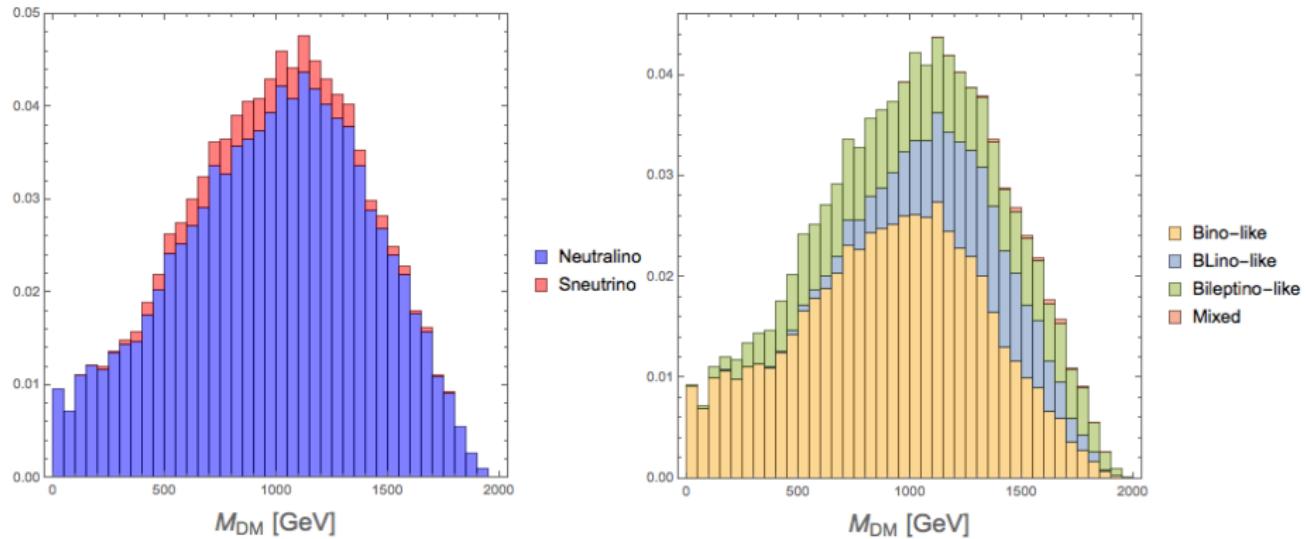
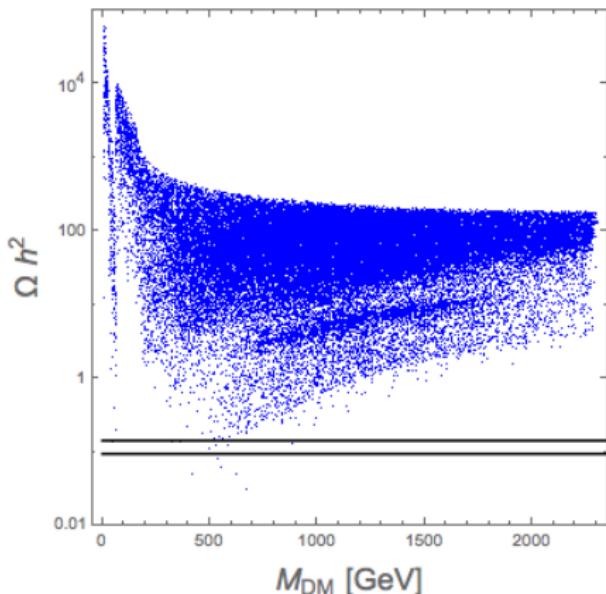


Figure: BLSSM DM candidates - 1702.01808 - This work

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)

CMSSM



BLSSM

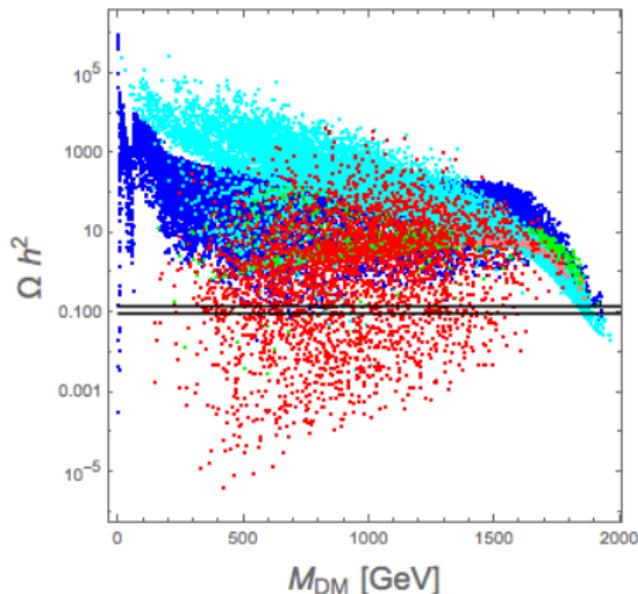


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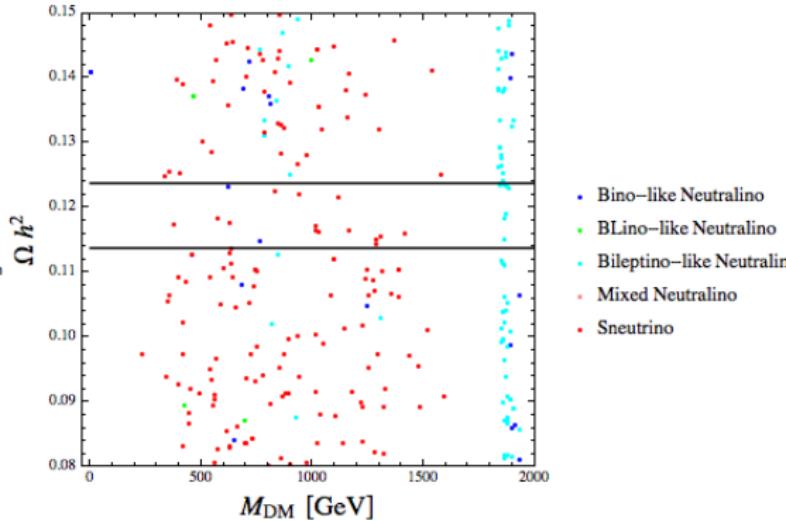
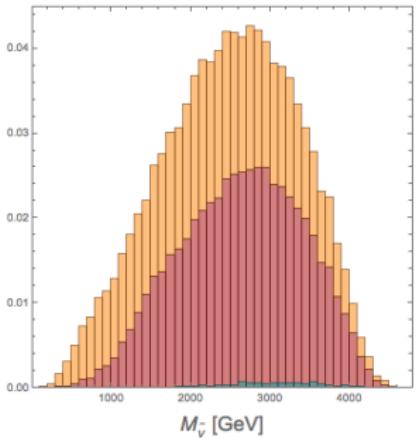
Conclusions

- 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

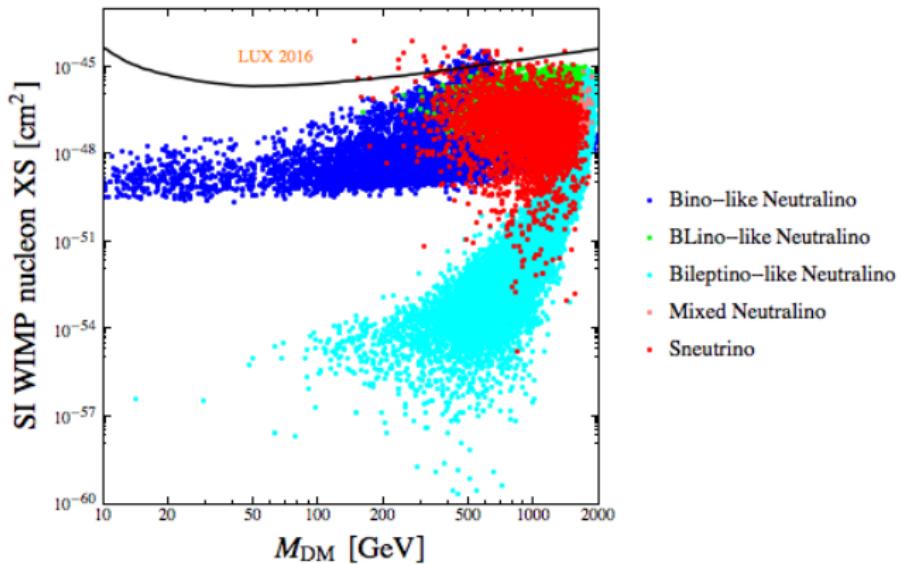
For more details, see:

arXiv: 1702.01808

Back-up slides



Back-up slides



Scan range:

Parameter	range
m_0	[0, 5] TeV
$m_{1/2}$	[0, 5] TeV
$\tan(\beta)$	[0, 60]
$\tan(\beta')$	[0, 2]
A_0	[-15, 15] TeV
$Y^{(1,1)}$	[0,1]
$Y^{(3,3)}$	[0,1]
$M_{Z'} =$	4.0TeV