The Upside of Seesaw in Anomaly Mediated Supersymmetry Breaking

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Outline

1. Motivation: SUSY, Neutrinos, and AMSB
2. The Model: Predicting Seesaw and AMSB
3. Conclusion

Motivation

- Supersymmetry (SUSY)
  - Solves Planck-weak Hierarchy Problem
  - Permits dark matter candidate if LSP is stable
- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - R-parity potential remnant symmetry: $P_R = (-1)^{3(B-L)+2s}$
  - More physical charge relation, $Q_{\rm EM} = I_{3L} + I_{3R} + \frac{1}{2}(B-L)$
  - Seesaw mechanism arises naturally

    [Mohapatra and Senjanovic **Phys.Rev.Lett.44:912**,1980]
- Deflected Anomaly Mediated SUSY Breaking
  - AMSB above M_R, the right-handed breaking scale
  - At M_R get GMSB and YMSB contributions
  - Still introduce only one new parameter, $F_\phi \gtrsim 20$ TeV
  - Flavor violation in SUSY breaking proportional to FV of Yukawas

SUSYLR Particle Content

Fields	$SU(3)^c$	$\times$	$SU(2)_L$	$\times$	$SU(2)_R$	$\times$	$U(1)_{B-L}$
Q	3		2		1		$+\frac{1}{3}$
Q^c	$\bar{3}$		1		2		$-\frac{1}{3}$
L	1		2		1		-1
L^c	1		1		2		$+1$
Φ	1		2		2		0
Δ^c	1		1		3		-2
$\bar{\Delta}^c$	1		1		3		$+2$

Superpotential

$$\mathcal{W}_Y = \mathbb{i} y_Q Q^T \tau_2 \Phi Q^c + \mathbb{i} y_L L^T \tau_2 \Phi L^c + \mathbb{i} f_c L^{cT} \tau_2 \Delta^c L^c$$

$$\mathcal{W}_M = M_{\Delta^c} \phi \, \mathrm{Tr}\left(\Delta^c \bar{\Delta}^c\right) + M_\Phi \phi \, \mathrm{Tr}\left(\Phi^T \tau_2 \Phi \tau_2\right)$$

$$\begin{aligned}\mathcal{W}_{\mathrm{NR}} = & -\frac{\lambda_A}{M_P \phi}\left(\mathrm{Tr}\left(\Delta^c \bar{\Delta}^c\right)\right)^2 + \frac{\lambda_B}{M_P \phi} \mathrm{Tr}(\Delta^c \Delta^c) \, \mathrm{Tr}\left(\bar{\Delta}^c \bar{\Delta}^c\right) \\ & + \frac{\lambda_\alpha}{M_P \phi} \mathrm{Tr}\left(\Delta^c \bar{\Delta}^c\right) \mathrm{Tr}\left(\Phi^T \tau_2 \Phi \tau_2\right)\end{aligned}$$

Superpotential

$$\mathcal{W}_Y = \mathbb{i} y_Q Q^T \tau_2 \Phi Q^c + \mathbb{i} y_L L^T \tau_2 \Phi L^c + \mathbb{i} f_c L^{cT} \tau_2 \Delta^c L^c$$

$$\mathcal{W}_M = \cancel{M_{\Delta^c} \phi \,\mathrm{Tr}\left(\Delta^c \bar{\Delta}^c\right) + M_{\Phi} \phi \,\mathrm{Tr}\left(\Phi^T \tau_2 \Phi \tau_2\right)}$$

$$\mathcal{W}_{\mathrm{NR}} = -\frac{\lambda_A}{M_P \phi}\left(\mathrm{Tr}\left(\Delta^c \bar{\Delta}^c\right)\right)^2 + \frac{\lambda_B}{M_P \phi}\mathrm{Tr}\left(\Delta^c \Delta^c\right)\mathrm{Tr}\left(\bar{\Delta}^c \bar{\Delta}^c\right) + \frac{\lambda_\alpha}{M_P \phi}\mathrm{Tr}\left(\Delta^c \bar{\Delta}^c\right)\mathrm{Tr}\left(\Phi^T \tau_2 \Phi \tau_2\right)$$

$$(\bar{\Delta}^c, \Delta^c, \Phi) \to e^{\mathbb{i}\pi/2}(\bar{\Delta}^c, \Delta^c, \Phi)$$
$$(L, L^c, Q, Q^c) \to e^{-\mathbb{i}\pi/4}(L, L^c, Q, Q^c)$$
$$\mathcal{W} = \mathcal{W}_Y + \mathcal{W}_{\mathrm{NR}}$$

Features

- Seesaw achieved through right-handed $B - L = -2$ triplet Δ^c

$$\mathcal{W} \supset \mathbb{i} f_c L^{cT} \tau_2 \Delta^c L^c \to f_c \left\langle \Delta^{c\,0} \right\rangle \nu^c \nu^c \leftrightarrow M_R \nu^c \nu^c$$

- R-Parity is a remnant symmetry after $SU(2)_R \times U(1)_{B-L}$ breaks

$$P_R = (-1)^{3(B-L)+2s} \;\leftrightarrow\; P_M = (-1)^{3(B-L)}$$

- Seesaw scale (VEV of Δ's) predicted:

$$\left\langle \Delta^{c\,0} \right\rangle = \left\langle \bar{\Delta}^{c\,0} \right\rangle = v_R = \sqrt{\frac{|F_\phi|\, M_P}{6|\lambda_A|}} \simeq 10^{11}\ \text{GeV}$$

- Light Particles...

Extended Symmetries of Vacuum

- Triplets then have extended symmetry: $GL(3,\mathbb{C}) \times GL(1,\mathbb{C})$

  [Chacko and Mohapatra **Phys.Rev.D58:015003**,1998]
- Spontaneous symmetry breaking and Super Higgs Mechanism imply 6 massless modes: Δ^{c--}, $\bar{\Delta}^{c++}$, and 2 Neutral Particles
- Get Mass from non-renormalizable terms that break $GL(3,\mathbb{C})$:

$$\mathcal{W}_{\mathrm{NR}} \supset \frac{\lambda_A}{M_P}\,\mathrm{Tr}(\Delta^c\Delta^c)\,\mathrm{Tr}\left(\bar{\Delta}^c\bar{\Delta}^c\right) \to \frac{v_R^2}{M_P}\Delta^{c--}\bar{\Delta}^{c++}$$

- For $v_R \sim 10^{11}$ GeV, effective mass term, $\mu_{DC} \sim 10^4$ GeV
- The doubly-charged Higgs fields are naturally light (exist below v_R)

A New Yukawa Coupling

- Below right-handed scale the seesaw couplings survives through the doubly-charged fields:

$$\mathcal{W}_{seesaw} = f_c L^{cT} \tau_2 \Delta^c L^c \to f_c e^c \Delta^{c--} e^c$$

  yielding a new Yukawa coupling to the leptonic sector
- Assume $f_c^{ij} = f\delta^{ij}$ and $\alpha_R = \alpha_{B-L} = 2\alpha_1 \sim 0.044$ then

$$\begin{aligned} m^2_{\tilde{e}^c} &= m^2_{AMSB} + m^2_{mixed} + m^2_{GMSB} \\ m^2_{AMSB} &\sim f^4 - \alpha_1 f^2 - \alpha_1^2 \\ m^2_{mixed} &\sim f^4 - \alpha_1 f^2 + \alpha_1^2 \\ m^2_{GMSB} &\sim f^4 + \alpha_1 f^2 - \alpha_1^2 \end{aligned}$$

Right-handed sleptons at v_R

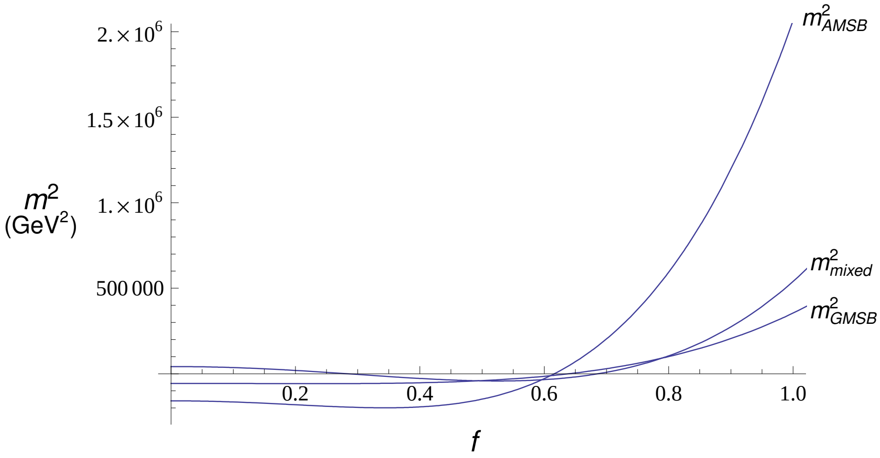


Figure: $F_\phi = 36$ TeV and $\alpha_1 = 0.02$. The AMSB dominates and is positive for $f > 0.6$.

Left-handed sleptons

- Left-handed sleptons have no such Yukawa coupling
- But have a *D*-terms contribution, and $\langle D \rangle \neq 0$
- Sign of *D*-term contribution depends on charge:

$$\delta m_{\tilde{L}}^2 = \frac{3}{512\pi^4}\left(-\frac{2}{3}\right)^2 |F_\phi|^2 \left(9f^4 - 40\pi\alpha_1 f^2\right)$$

- Amazingly enough this is of the right sign for the large *f* needed by right-handed sleptons

Left-handed sleptons at v_R

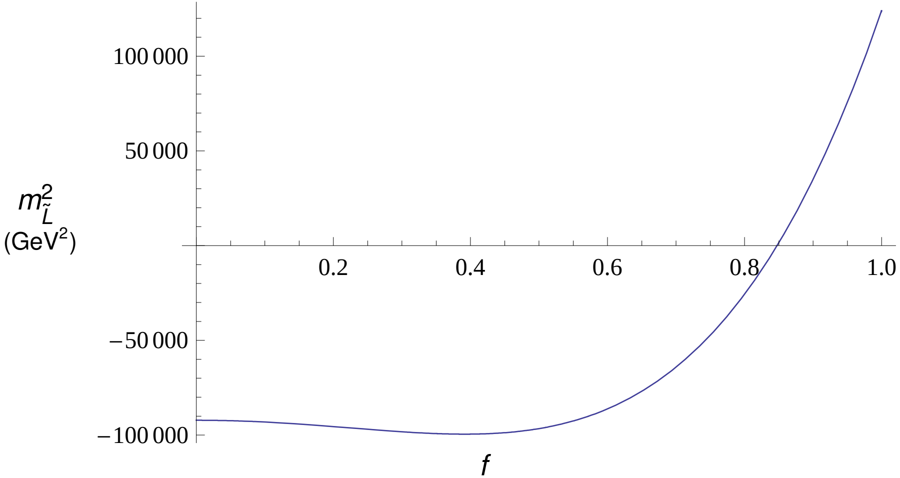


Figure: At $f > 0.85$, the D-terms cause the square mass to be positive.

D-terms

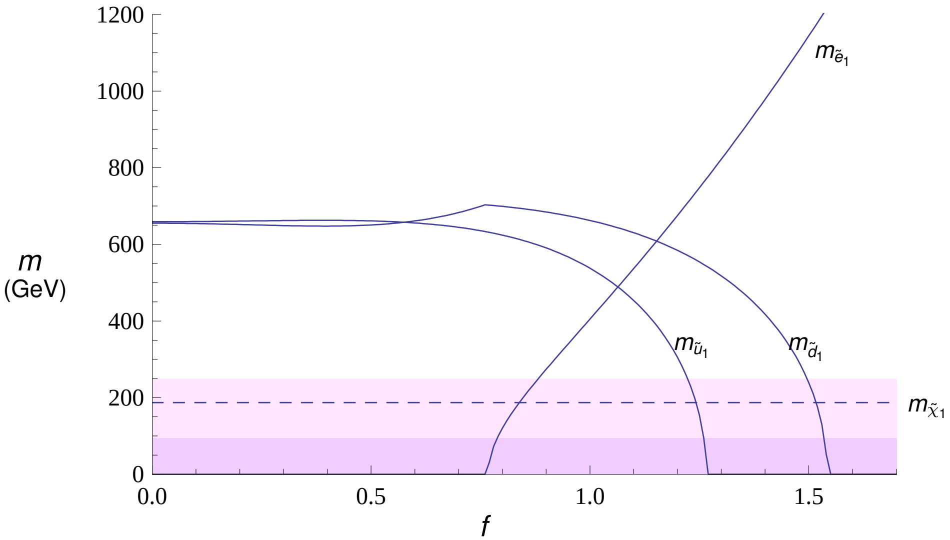
- Of course, other sparticles can also get negative D-term contributions

	$U(1)_{B-L}$	$SU(2)_R$
Q	$-\frac{\pi}{3}\alpha_{BL}D$	0
u^c	$+\frac{\pi}{3}\alpha_{BL}D$	$-\pi\alpha_R D$
d^c	$+\frac{\pi}{3}\alpha_{BL}D$	$+\pi\alpha_R D$
L	$+\pi\alpha_{BL}D$	0
e^c	$-\pi\alpha_{BL}D$	$+\pi\alpha_R D$
H_u	0	$+\pi\alpha_R D$
H_d	0	$-\pi\alpha_R D$

Table: The D-term contributions to the scalar masses at v_R. The quantity D is defined as $D \equiv \frac{1}{4\pi}\frac{m^2_{\Delta^c} - m^2_{\bar{\Delta}^c}}{\alpha_{BL}+\alpha_R}$

- Need to examine the lightest eigenvalues for up and down squarks as well as the selectron

Lightest Mass Eigenstates verses f



Gauginos

- LSP is important for phenomenology since heavier particles cascade decay to it
- Best prospects for LSP (as dark matter) from neutralino
- Neutralino is mixture of: $\tilde{H}_u$, $\tilde{H}_d$, $\tilde{W}$, and $\tilde{B}$
- Gaugino contribution easy to see for AMSB:

$$M_3 : M_2 : M_1 \sim \frac{\alpha_3 b_3}{\alpha_2 b_2} : 1 : \frac{\alpha_1 b_1}{\alpha_2 b_2}$$

- In this model $M_3 : M_2 : M_1 \sim 4 : 1 : 3$, implying wino LSP (just like mAMSB)

Some Wino LSP Signatures

- Wino charginos and neutralinos form a highly degenerate isospin triplet
- In large M_2 limit, $\Delta_\chi \sim \alpha M_W \sim 165$ MeV
- Therefore, $\tilde{\chi}_1^+ \rightarrow \pi^+ \chi_1^0$
- Pion very soft, can't trigger
- Trigger on hard radiated photons or jets, look for chargino track.

[Chen, Drees, and Gunion arXiv:hep-ph/9512230]

[Feng, Moroi, Randall, Strassler and Su arXiv:hep-ph/9904250]

Dark Matter

- Remember R-parity is automatic, but wino LSP annihilate too fast—not enough relic abundance to explain dark matter
- In AMSB, gravitino is heavy $m_{3/2} \sim F_\phi$ and decays after LSP freeze out but before big bang nucleosynthesis
- Decay is to LSP: $\tilde{G} \to SM + LSP$
- Such decay lead to out of equilibrium freeze out, and a proper relic abundance [Moroi and Randal **Nucl.Phys.B570:455-472**,2000]

Conclusion

- Gauge hierarchy solved; neutrinos have non-zero light masses
- New “exotic” light particles: the doubly-charged Higgses
- All sparticle mass squares are positive
- Dark matter candidate
- All of this is natural from this minimal left-right seesaw model

Decoupling: Toy Model

	X	$\overline{X}$	Ψ	$\overline{\Psi}$	S
$U(1)$	-2	$+2$	$+1$	-1	0

$$\mathcal{W}_{\text{DCPL}} = fX\Psi\Psi + yS\left(X\overline{X} - M_{\text{int}}^2\phi^2\right)$$

$$\langle \underline{X} \rangle = \langle \underline{\overline{X}} \rangle = M_{\text{int}}$$

$$\langle F_X \rangle = \langle X \rangle \, F_\phi$$

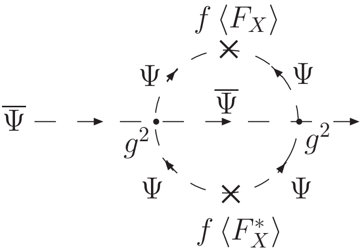
$$\langle D \rangle = \frac{1}{2g}\left(m_{\overline{X}}^2 - m_X^2\right) = -\frac{|F_\phi|^2}{4g}\frac{\partial \gamma_X^+}{\partial f}\beta_f$$

Decoupling: Toy Model

Above M_{int}		Below M_{int}	
$(m^2_{\overline{\Psi}})^+ = -\frac{5}{4} g^4 \left\lvert \frac{F_\phi}{16\pi^2} \right\rvert^2$ $(m^2_X)^+ \neq (m^2_{\overline{X}})^+$	$\langle D \rangle \neq 0$	$(m^2_{\overline{\Psi}})^- = 0$ $(m^2_X)^- = (m^2_{\overline{X}})^- = 0$	$\langle D \rangle = 0$

Ψ's act as messengers giving a GMSB contribution at M_{int}:

$$\mathcal{L} \supset f \langle F_X \rangle \underline{\Psi\Psi} = f M_{\text{int}} F_\phi \underline{\Psi\Psi} = M_\Psi F_\phi \underline{\Psi\Psi}$$



$$\sim \frac{g^4 f^2 |F_X|^2}{(16\pi^2)^2 M^2_\Psi} = g^4 \left\lvert \frac{F_\phi}{16\pi^2} \right\rvert^2$$

Deflection: The PR Model

Consider now the Pomarol and Rattazzi (PR) Model with $U(1)$

$$\mathcal{W}_{PR} = fX\Psi\Psi - \frac{\lambda}{\Lambda\phi}\left(\overline{X}X\right)^2$$

$$|\langle \underline{X}\rangle| = \left|\langle \overline{\underline{X}}\rangle\right| = \sqrt{\frac{|F_\phi|\,|\Lambda|}{6|\lambda|}} \equiv M$$

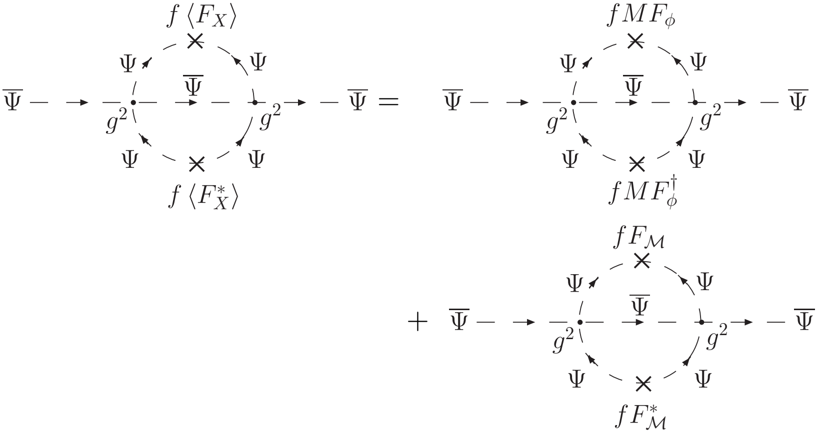
$$-\langle F_X\rangle^* = \frac{2\lambda}{\Lambda}\langle \underline{X}\rangle\left\langle \overline{\underline{X}}\right\rangle^2 = -\frac{1}{3}\langle \underline{X}\rangle^* F_\phi^\dagger$$

$$\langle F_X\rangle = \frac{1}{3}\langle \underline{X}\rangle F_\phi$$

PR Model F-term

Use knowledge of threshold decoupling to re-write F-term

$$\langle F_X\rangle = \frac{1}{3}\langle \underline{X}\rangle\, F_\phi = \langle \underline{X}\rangle\, F_\phi + \underbrace{\boxed{-\frac{2}{3}\langle \underline{X}\rangle\, F_\phi}}_{\boxed{F_{\mathcal{M}}}}$$



PR D-Terms

- **Analysis for $m^2_{\overline{\Psi}}$ also true for m^2_X and $m^2_{\overline{X}}$**
- Important because affects D-term VEV

$$\langle D \rangle = \frac{1}{2g}\left[m^2_{\overline{X}}\Big|_M - m^2_X\Big|_M \right] \sim \frac{1}{4g}\left|\frac{F_{\mathcal{M}}}{M}\right|^2 f^4 \neq 0$$

- Thus, scalar mass $\overline{\Psi}$ below M has two contributions:

$$m^2_{\overline{\Psi}} = \left(m^2_{\overline{\Psi}}\right)_{F_{\mathcal{M}}} + \left(m^2_{\overline{\Psi}}\right)_D$$

Return