Dark Matter and the Higgs in Natural SUSY

Sebastian Macaluso
NHETC, Rutgers University

Phenomenology 2016 Symposium
9-11 May, 2016

Aria Basirnia, SM & David Shih 1605.xxxxxx
Outline

1. The model
2. Higgs mass and fine tuning
3. Direct detection
4. Thermal relic density
5. Putting it all together
The model

\begin{tabular}{|c|c|c|c|c|}
\hline
 & $SU(3)_c$ & $SU(2)_L$ & $U(1)_Y$ & $Z^{DM}_2$ & $Z^{M}_2$ \\
\hline
$L$ & 1 & 2 & $-\frac{1}{2}$ & -1 & 1 \\
$L$ & 1 & 2 & $\frac{1}{2}$ & -1 & 1 \\
$S$ & 1 & 1 & 0 & -1 & 1 \\
\hline
\end{tabular}

$Z_2$ symmetry keeps lightest state stable -- WIMP DM candidate!

Majorana mass term for $S$, otherwise immediately killed by $Z$-mediated SI DD. (Key diff with previous works on vector-like MSSM extensions!)

$$W = \frac{1}{2} M_S S^2 + M_L \bar{L}L + k_u H_u \bar{L}S - k_d H_d LS$$

$$\delta L_{\text{soft}} = -m^2(\bar{\ell} \ell + \bar{s} s)$$

Take $m^2 > 0$ to lift the Higgs mass $\Rightarrow$ DM is fermionic

Fermion mass matrix:

$$\mathcal{M} = \begin{pmatrix}
M_S & k_u v \sin \beta & k_d v \cos \beta \\
k_u v \sin \beta & 0 & M_L \\
k_d v \cos \beta & M_L & 0
\end{pmatrix}$$
The Model

After diagonalizing, get couplings of mass eigenstates to $h$ and $Z$ (and $W$):

$$\delta \mathcal{L} = c_h h \bar{\psi}_\chi \psi_\chi + c_Z Z_\mu \bar{\psi}_\chi \gamma^\mu \gamma^5 \psi_\chi$$

Focus on mostly singlet DM: $m_\chi \sim M_S < M_L$ and $v \ll M_L, M_L-M_S$

$$c_h = -\frac{m_\chi}{\sqrt{2}v} + \frac{2k_d M_L}{k_u \tan \beta} \frac{k_u^2 v^2}{M_L^2} + \ldots$$

$$c_Z = \frac{g}{4c_W} \frac{k_u^2 v^2}{M_L^2} + \ldots$$

Part of a broader framework of Higgs and $Z$-portal dark matter
(cf e.g. Giudice, de Simone and Strumia ’14, Cheung & Sanford ’13; Calibbi et al ’15)
Higgs mass and fine-tuning

One-loop Higgs mass in the mostly singlet DM regime: \( \tan \beta \to \infty \)

\[
\delta m_h^2 = \frac{k_u^4 v^2}{4\pi^2} \log \left( 1 + \frac{m^2}{M_L^2} \right) + \mathcal{O}(M_S^2/M_L^2)
\]

Assume MSSM stops get you to \( m_h \sim 110 \text{ GeV} \) (~10% FT).
Need \( \delta m_h^2 \sim 3500 \text{ GeV}^2 \).

Fine tuning measure:

\[
\Delta = \frac{2\delta m_{H_u}^2}{m_h^2} = \frac{k_u^2 m^2 \log 10}{4\pi^2} \left( \frac{125 \text{ GeV}}{4\pi^2} \right) \sim k_u^2 e^{\frac{4\pi^2 \delta m_h^2}{k_u^4 v^2}}
\]

FT exponentially worse as \( k_u \) decreases. This requires \( k_u \gtrsim 1.2 \) (Different from Bino-Higgsino system where \( k_u = g'/\sqrt{2} \))
Direct Detection

DM direct detection experiments are probing couplings of DM to nucleons

\[
\xi_{q}^{SI} (\bar{\chi} \chi)(\bar{q}q) + \xi_{q}^{SD} (\bar{\chi} \gamma^{\mu} \chi)(\bar{q} \gamma^{\gamma \mu} q)
\]

SI controlled by \( c_h \) and SD controlled by \( c_Z \).
Thermal relic density

\[ \Omega_{DM} h^2 \approx 9.2 \times 10^{-12} \text{ GeV}^{-2} \times \left( \int_{x_f}^{\infty} dx \frac{\langle \sigma v \rangle}{x^2} \right)^{-1} \]

\[ \sigma_{xy} v_\chi = r_{xy} (a_{xy} + b_{xy} v_\chi^2 + \mathcal{O}(v_\chi^4)) \quad r_{xy} \equiv \sqrt{1 - (m_x + m_y)^2/4m_\chi^2} \]

DM slowly moving at freeze out \((v^2 \sim 0.1)\), so all else being equal, annihilation rate dominated by s-wave.

Initial state (pair of identical Majorana fermions) is CP odd, so no s-wave through s-channel Higgs. This leaves s-channel \(Z\) and t-channel.

Additional simplifications in large \(M_L\) limit...
Thermal relic density

\[ a_{f \bar{f}} = \frac{3k_u^4}{32\pi M_L^2} \frac{m_f^2}{M_L^2(1 - (M_S/M_L)^2)^2} \]

\[ a_{\psi_H \psi_H} = \frac{(k_d^2 + k_u^2)^2}{16\pi M_L^2} \frac{\mu^2}{M_L^2(1 + (M_S/M_L)^2 + (m/M_L)^2)^2} \]

Comments:

- s-wave annihilation is to \( t\bar{t} \) and Higgsinos to leading order in \( v^2/M_L^2 \).
- Annihilation to dibosons is always subdominant for the parameter space that we study.
- \( c_Z \) controls both the SD DD cross section and the annihilation to \( t\bar{t} \).
Putting it all together

• Confirms analytics of DD bounds.
• Confirms estimates of FT via one-loop Higgs mass.

Numerical pipeline: SARAH-SPheno-Micromegas. Confirmed using analytics.
Thermal relic contour plots

We can move toward the blind spot by varying $k_d$.

Within a factor of a few of being ruled out by SD DD!

Confirms the direct relation between $\Omega_{\text{DM}}$ and $c_Z$!
Conclusions

We studied an economic extension of the MSSM that gives a 125 GeV Higgs mass with a fine-tuning as low as 10% and provides a natural thermal WIMP DM candidate.

The main annihilation channels in our model are s-wave annihilation to tt and Higgsinos.

Imposing the relic density constraint immediately implies a particular value for the SD cross-section. This value is not ruled out yet, but the next generation of DM experiments (e.g. \Xenon1T, LZ) should completely rule out or discover this model.

Thanks for your attention!
LHC prospects

Mono(H,Z,W) through $\chi_1 + (\chi_{2,3}, \chi^\pm)$ production:

$k_u=1.6$, $k_d=-1.5$, $\mu=300$ GeV
Outlook

Xenon1T should probe the entire parameter space of our model in a few years. More generally true for Higgs and Z-portal DM!

Other models for Higgs and DM beyond the MSSM:

- Other SU(2) representations?
- NMSSM?
- Non-decoupling D-terms?
- ...

Extra particles expected for unification...explore their phenomenology?

Further explorations of the more general effective operator story...

Landau pole problem...
To satisfy LUX SI bounds, need a mild blind spot cancellation (factor of \( \lesssim 2 \)).
Landau Pole Problem

Generally there is a Landau pole well before the GUT scale. Theory needs to be UV completed -- or extended with gauge interactions to deflect the Yukawas...
Electroweak Precision Tests

Model is totally safe from EWPT -- in mostly singlet regime, thermal relic constraint requires doublet mass $\gtrsim 1$ TeV...

Calculated using formulas in Abe, Kitano & Sato '14.

Agrees qualitatively with results there and in Martin '09.
Direct detection: SI

LUX currently sets strongest SI constraints.
Direct Detection: SD

LUX 1602.03489

![Graph showing SD WIMP-neutron cross-section](image)

![Graph showing SD WIMP-proton cross-section](image)

Official ttbar limit is new; previously had to be recasted (see e.g. Cheung, Hall & Ruderman ’12).

Factor of a few weaker ttbar vs WW makes a big difference for our model!

LUX neutron (IceCube proton) strongest below (above) ~250 GeV.
Indirect detection

![Graphs showing constraints on DM annihilation cross section for the \(bb\) (left) and \(\tau^+\tau^-\) (right) channels derived from a combined analysis of 15 dSphs. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles.](image)

No official \(ttbar\) limits, but probably ineffective above 100 GeV...
Conclusions

We studied an economic extension of the MSSM that gives a 125 GeV Higgs mass with a fine-tuning as low as 10% and provides a natural thermal WIMP DM candidate. The constraints on the parameter space are:

$\Delta \simeq 10$ requires $k_u \gtrsim 1.2$

Also $k_u \lesssim 2$ from UV considerations

$\Omega_{DM}$ and SD DD are determined by $k_u^2/M_L^2 \propto c_Z$ for each $\mu$

Once $M_L$ is given, then the contribution to $\delta m_h^2 \simeq 3500 GeV^2$ fixes $m \sim M_L$

To satisfy SI DD we need $|k_d| \gtrsim 1$

Thanks for your attention!
**Conclusions**

We studied an economic extension of the MSSM that gives a 125 GeV Higgs mass with a fine-tuning as low as 10% and provides a natural thermal WIMP DM candidate. The constraints on the parameter space are:

\[ \Delta \simeq 10 \text{ requires } k_u \gtrsim 1.2 \]

Also \[ k_u \lesssim 2 \text{ from UV considerations} \]

\[ \Omega_{DM} \text{ and SD DD are determined by } \frac{k_u^2}{M_L^2} \propto c_Z \text{ for each } \mu \]

Once \( M_L \) is given, then the contribution to \( \delta m_h^2 \simeq 3500 GeV^2 \) fixes \( m \sim M_L \)

To satisfy SI DD we need \( |k_d| \gtrsim 1 \)

For each \( \mu \) only \( M_S \) is free.

Thanks for your attention!
Introduction: two questions

Why is the Higgs at 125 GeV?
Is it compatible with naturalness?

What is the dark matter?
Does it have anything to do with the theory of the weak scale?

In minimal SUSY, the answer to both questions is basically NO.

- Higgs at 125 GeV in the MSSM requires multi-TeV A-terms or 10 TeV stops. Either way it is fine tuned at the sub-percent level or worse.

- WIMP dark matter in the MSSM requires either a heavy SUSY scale or contrived numerical coincidences (blind spots, funnels, co-annihilation).

So if SUSY solves the hierarchy problem, the source of both DM and the Higgs mass likely lies beyond the MSSM.
Introduction

|      | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $Z^DM_2$ |
|------|-----------|-----------|----------|----------|
| $L$  | 1         | 2         | $-\frac{1}{2}$ | $-1$     |
| $\tilde{L}$ | 1 | 2 | $\frac{1}{2}$ | $-1$ |
| $S$  | 1         | 1         | 0        | $-1$     |

In this talk, we will study a simple, economical extension of the MSSM that includes both DM and the source of the Higgs mass.

We will see that it is possible to achieve $\sim 10\%$ fine-tuning, a 125 GeV Higgs, and thermal relic DM consistent with all experimental constraints, by just adding a singlet and pair of vector-like doublets to the MSSM.
Introduction

Previous work:

- Singlet-doublet DM extension of SM [Mahbubani & Senatore '05, Cohen et al '11, Cheung & Sanford '13, Calibbi et al '15]

- Lifting the Higgs mass with vector-like extensions of the MSSM [Moroi & Okada '92...Martin '09 '10, Graham et al '09...Evans et al '11, Li et al '11, Moroi et al '11, Martin & Wells '12, Endo et al '11 '12, Ishikawa et al '12,...]

But as far as I know, nobody has combined the two ideas before.
Perhaps it didn’t look promising, because direct-detection bounds on the Higgs portal are quite stringent?

Key points:

- Blind spot: since it’s a 2HDM, effective DM-DM-Higgs coupling $c_h$ can be tuned to zero by balancing up-type and down-type couplings against each other in a particular way.

- DM is lightest mass eigenstate out of a singlet+doublet+anti-doublet, so there is more than one $c_h$ coupling. DD only probes about $c_h$ for DM, while Higgs mass is sensitive to all of them.
The Model

|      | SU(3)_c | SU(2)_L | U(1)_Y | Z^DM
|------|---------|---------|--------|------
| L    | 1       | 2       | -1/2   | -1   
| \tilde{L} | 1       | 2       | 1/2    | -1   
| S    | 1       | 1       | 0      | -1   

Z_2 symmetry keeps lightest state stable -- WIMP DM candidate!

Majorana mass term for S, otherwise immediately killed by Z-mediated SI DD. (Key diff with previous works on vector-like MSSM extensions!)

Take k_u > 1 to help lift the Higgs mass and improve fine tuning.

\[ \delta W = k_u \tilde{L} H_u S + k_d L H_d S + \frac{1}{2} M_S S^2 + M_L L \tilde{L} \]

\[ \delta \mathcal{L}_{soft} = m^2_S |S|^2 + m^2_L |L|^2 + m^2_L |\tilde{L}|^2 + (A - terms) + (B - terms) \]

Assume \[ m^2_S = m^2_L = m^2_{\tilde{L}} = m^2, \quad A = B = 0 \quad \text{for simplicity} \]

Take m^2 > 0 to lift the Higgs mass \( \Rightarrow \) DM is fermionic
The Model

Fermion mass matrix: 
\[ \mathcal{M} = \begin{pmatrix} M_S & k_u v s_\beta & k_d v c_\beta \\ k_u v s_\beta & 0 & M_L \\ k_d v c_\beta & M_L & 0 \end{pmatrix} = U^\dagger \mathcal{M}_{diag} U^* \]

After diagonalizing, get couplings of mass eigenstates to h and Z (and W):
\[ \delta \mathcal{L} \supset m_i \bar{\chi}_i \chi_i + c_{hij} h \bar{\chi}_i \chi_j + c_{Zij} Z_\mu \bar{\chi}_i \gamma^\mu \gamma^5 \chi_j \]

The DM talks to the SM through these couplings.

Focus on mostly singlet DM: \( m_\chi \sim M_S \ll M_L \).

- Mostly doublet regime is not promising for fine-tuning (cf pure Higgsino DM), direct detection
- Well-tempered regime ruled out by DD

Assume large tan\( \beta \) otherwise MSSM contribution to Higgs mass too small
The Model

\[ \delta \mathcal{L} \supset m_\chi \bar{\chi} \chi + c_h h \bar{\chi} \chi + c_Z Z_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi \]

Then much of the physics (thermal relic density, direct detection, LHC signatures, ...) controlled by DM-DM-Higgs and DM-DM-Z couplings.
(Cheung & Sanford '13; Calibbi et al '15)

In our model, these are given by:

\[ c_h = \frac{1}{\sqrt{2}} (k_u s_\beta U^*_{11} U^*_{12} + k_d c_\beta U^*_{11} U^*_{13}) = \left( \frac{M_S - \frac{2k_d M_L}{k_u \tan \beta}}{\sqrt{2} v} \right) \frac{k_u^2 v^2}{M_L^2} + \ldots \]

\[ c_Z = \frac{g_2}{4 c_W} (|U_{12}|^2 - |U_{13}|^2) = \frac{g_2 k_u^2 v^2}{4 c_W M_L^2} + \ldots \]

Part of a broader framework of Higgs and Z-portal dark matter
(cf e.g. Giudice, de Simone and Strumia '14)
Higgs mass and fine-tuning

Need $k_u > 1$ to avoid same fate as MSSM stops. For $k_u \sim 1.5$, can achieve $\Delta \sim 10$. 

$(M_l = 1200 \text{ GeV}, M_S = 300 \text{ GeV})$
Thermal relic density determined by $2 \rightarrow 2$ annihilation of DM to SM particles.

DM slowly moving at freeze out ($v^2 \sim 0.2$), so all else being equal, annihilation rate dominated by s-wave.

Initial state (pair of identical Majorana fermions) is CP odd, so no s-wave through s-channel Higgs. This leaves s-channel $Z$ and t-channel.

Additional simplifications in large $M_L$ limit...
Thermal relic density

no s-wave due to CP and angular momentum conservation

s-wave helicity suppressed

s-wave cancels at leading order in $1/M_L$

extra $1/M_L$ suppressed

At leading order in $1/ML$, only s-wave annihilation is to ttbar, and it's controlled by $cz$!
Thermal relic density

\begin{equation}
\langle \sigma v \rangle_{tt} = \frac{3}{8\pi} \frac{\hat{g}^2 m_t^2}{m_Z^4} c_Z^2 = \frac{3k_u^4 m_t^2}{32\pi M_L^4}
\end{equation}

\begin{equation}
\Omega_{DM} \approx \frac{3 \times 10^{-27}}{\langle \sigma v \rangle} \text{cm}^3/\text{s} \approx 0.12 \left( \frac{0.008}{c_Z} \right)^2 \approx 0.12 \left( \frac{M_L/k_u}{800 \text{ GeV}} \right)^4
\end{equation}

Comments:

- To leading order, \( c_Z \) is fixed to 0.008 by the relic density constraint! Compatible with DD? No escape!

- In our model, \( M_L/k_u \) is fixed to 800 GeV. For \( k_u \sim 1.5 \) this is \( M_L \sim 1200-1300 \text{ GeV} \).

- Dependence on DM mass drops out at leading order -- WIMP miracle in terms of mediator scale!

- Higgsinos should be light for naturalness. So if DM heavier than Higgsino, should include DM annihilation to Higgsinos as well. Parametrically similar to ttbar.
Direct Detection

DM direct detection experiments are probing couplings of DM to nucleons

\[ \xi_q^{SI} (\bar{\chi}\chi)(\bar{q}q) + \xi_q^{SD} (\bar{\chi}\gamma^5\gamma^\mu\chi)(\bar{q}\gamma^5\gamma^\mu q) \]

SI controlled by \( c_h \) and SD controlled by \( c_Z \).
Direct detection: SI

LUX currently sets strongest SI constraints.
Direct Detection: SD

LUX 1602.03489

![Graph showing LUX upper limits on the WIMP-neutron (top) and WIMP-proton cross-sections.](Image)

**Graph Description:**
- The graph illustrates limits on the WIMP-neutron (top) and WIMP-proton cross-sections for a range of dark matter masses.
- The limits are shown for various experiments and theoretical models, such as DAMA, CDMS, KIMS, PICASSO, XENON10, and XENON100.
- The LZ Projected limits are also shown for future projections.
- The allowed region is indicated by the green shaded area for the 90% CL.

**Legend:**
- Green line: LUX 90% C.L.
- Other colored lines represent different experimental limits.

**Text:**
- Official ttbar limit is new; previously had to be recasted (see e.g. Cheung, Hall & Ruderman '12).
- Factor of a few weaker ttbar vs WW makes a big difference for our model!

**Note:**
- LUX neutron (IceCube proton) strongest below (above) ~250 GeV.
Indirect detection

No official ttbar limits, but probably ineffective above 100 GeV...
Direct Detection

Reinterpretation in terms of $c_h$ and $c_Z$

Note: although SD bounds are 5 orders of magnitude weaker than SI bounds in terms of cross section, SD is slightly stronger than SI in terms of $c_Z$ and $c_h$!
To satisfy LUX SI bounds, need a mild blind spot cancellation (factor of $\sim 2$)
Conclusions

We studied an economic extension of the MSSM that gives a 125 GeV Higgs mass with a fine-tuning as low as 10% and provides a natural thermal WIMP DM candidate.

We interpret the latest constraints from LUX and IceCube on dark matter couplings to Higgs and Z in the Standard Model.

The main annihilation channels in our model are s-wave annihilation to tt and Higgsinos.

Imposing the relic density constraint immediately implies a particular value for the SD cross-section. This value is not ruled out yet, but the next generation of DM experiments (e.g. Xenon1T, LZ) should completely rule out or discover this model.

Thanks for your attention!