Heavy Dark Matter Through The Higgs Portal

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J. March-Russell, SMW, D. Cumberbatch, D. Hooper:
arXiv:0801.3440 [hep-ph] and more to come...
Outline

Introduction
Hidden Sectors, Hidden Valleys and Higgs Portals.
DM in Higgs Portal Models

Heavy DM from SUSY Higgs Portals
The Model
The Sommerfeld Enhancement

DM Phenomenology
Relic Density Calculation
Direct and Indirect Detection

Summary

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Hidden Sectors.

- Hidden sectors common in many extensions of SM, e.g. SUSY, string theory, hidden/secluded RS warped throats etc...

We consider,

- Extra states not charged under the SM gauge group, possibly charged under exotic gauge symmetry.
- SM or MSSM communicates with hidden sector via $Z'$ or Higgs interactions.
- Nice feature: interactions between hidden sector and SM involve $d \leq 4$ operators.
- Also consider mass scale of hidden sector close to or just above weak scale.
- Attractive alternative to usual desert above weak scale.
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SM-hidden sector communication via $Z'$ interactions.

- $Z'$ interactions occur either by:
  - SM states charged under $U(1)'$ or
  - Indirectly due to kinetic mixing term $\varepsilon F^\mu_Y F'_{\mu\nu}$
    
    (e.g. Babu, Kolda, March-Ruessl.)

- Example Hidden Valley Model:
  - SM gauge group, $G_{sm}$, extended by non-abelian group $G_v$.
  - SM states only charged under $U(1)'$ subgroup of $G_v$.
  - Extra “valley" particles not charged under $G_{sm}$.
  - Example $G_v = U(1)' \times SU(n_v)$.
  - Interesting collider phenomenology and DM possibilities.

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SM-hidden sector communication via “Higgs Portals”.

- Extra states, not charged under $G_{sm}$ but can be charged under exotic gauge symmetry.
- Communication via interactions involving SM (or MSSM) Higgs
  \[ \lambda |H|^2 |\phi|^2 \]
  (Schabinger, Wells; Patt, Wilczek...)
  $\phi$ is a singlet under $G_{sm}$ but charged under $G_{hidden}$.
  - $\phi$ could have many more interactions with hidden sector states.
  - Changes Higgs phenomenology.
  - Provides opportunities for DM in the hidden sector.
SM-hidden sector communication via “Higgs Portals”.

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Can also have couplings involving fermions:

$$\psi \psi_L H$$

just neutrino Dirac term or in SUSY

$$W \supset \lambda S H_u H_d$$

just the usual term found in models like the NMSSM.

Point is $\psi$ or $S$ could have further interactions with other states from the Hidden sector.
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DM in Higgs Portal Models.

- Assume dominant form of DM comes from hidden sector,
  - Efficient coannihilation channels for neutralino LSP or
  - Light gravitino LSP in gauge mediated models or
  - $R_p$ violation

- Example 1: Direct coupling between hidden and visible sector
  \[ \lambda |H|^2 |\phi|^2 \]
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- DM with large masses (multi TeV) for large $\lambda$ interesting parameter range.
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  \[
  \begin{array}{c}
  \phi \\
  \lambda \\
  \phi \\
  \end{array}
  \quad\quad
  \begin{array}{c}
  H \\
  \lambda \\
  H \\
  \end{array}
  \]
  (McDonald...)
  (Cirelli, Fornengo, Strumia...)
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\end{array} \quad \begin{array}{c}
H \\
\lambda \\
H
\end{array}$$

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Example 2: Indirect coupling between hidden and visible sector

\[ \lambda' \psi \psi \phi + \lambda \phi \psi_{vis} \psi'_{vis} \]

- For SUSY model
  \[ \psi_{vis} \psi'_{vis} \Rightarrow \text{Higgsino pair, Higgsino Lepton pair.} \]
- Coannihilation diagram:

  \[ \psi \quad \phi \quad \psi'_{vis} \]

  \[ \lambda' \quad \lambda \]

  \[ \psi \quad \psi_{vis} \]

- \( \psi \) DM could be heavy requiring large couplings to be viable thermal relic.

- For DM above \( \sim 1 \ TeV \) extra non-perturbative Sommerfeld effect important, more later...
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Heavy DM in SUSY Higgs Portal Models

- The model defined by the superpotential

\[ W = W_{MSSM}(\mu=0) + \lambda N H_u H_d + t_2 N + \frac{\lambda'}{2} NS^2 + \frac{m_\tilde{S}}{2} S^2 \]

- S has a non-R \( Z_2 \) symmetry leads to a stable relic.
- DM particle will be \( \tilde{S} \) (fermionic cpt of S).
- Model is simple extension of MNSSM

(Panagiotakopoulos, Pilaftsis; Dedes et al.)

- MNSSM coupling, \( \lambda \), taken perturbative up to \( M_\rho \).
- Our variant, added another singlet, \( S \), with large (multi TeV) mass.
- We need large \( \lambda \) and \( \lambda' \) to get correct relic abundance.

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Large coupling and UV completion

- Taking cut off for theory $\Lambda_0 \geq M_{GUT}$
  - Couplings, $\lambda, \lambda'$, blow up well before $\Lambda_0$.
  - $S$ mass term implies large tadpole terms spoiling the stability of the weak scale. (Panagiotakopoulos, Pilaftsis; Dedes...)

- Can take $S$ to be elementary and simultaneously choose large values for $\lambda, \lambda'$ if theory is an effective theory with cutoff $\Lambda_0 < 100\,\text{TeV}$.

- No problem in having a mass for $S$ in this case. But no UV completion

- Treat model as effective theory of the “Fat Higgs” model
  - $S \Rightarrow$ composite meson field of new susy-preserving strong-interaction dynamics.
  - No large tadpole terms.
  - Natural to expect large couplings $\lambda$ and $\lambda'$.  

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\begin{align*}
\text{Appendix} & \\
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DM Interactions

- Lagrangian determining relevant interactions and masses, \( \mathcal{L} = \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{scalar}} \), where

\[
\mathcal{L}_{\text{fermion}} = \left( -\lambda n \tilde{h}_u \tilde{h}_d - \lambda \tilde{n} \tilde{h}_u h_d - \lambda \tilde{n} h_u \tilde{h}_d - \frac{\lambda'}{2} n \tilde{s} \tilde{s} - \lambda' \tilde{n} \tilde{s} - \frac{m_\tilde{s}}{2} \tilde{s} \tilde{s} + \text{h.c.} \right)
\]

\[
\mathcal{L}_{\text{scalar}} = |\lambda' ns + m_\tilde{s} s|^2 + |\lambda h_u h_d + t_2 + (\lambda'/2)s^2|^2 + |\lambda n h_d|^2 + |\lambda n h_u|^2
\]

\[
+ \left(A_\lambda \lambda n h_u h_d + \frac{A\lambda'}{2} \lambda' ns^2 + \frac{B}{2} m_\tilde{s} s^2 + C t_2 n + \text{h.c.} \right) + M_{h_u}^2 |h_u|^2 + M_{h_d}^2 |h_d|^2
\]

\[
+ M_s^2 |s|^2 + M_n^2 |n|^2 ,
\]

- In the limit \( m_\tilde{s} \gg m_{\text{susy}} \), mass difference

\[
m_s - m_\tilde{s} \simeq m_{\text{susy}}^2 / m_\tilde{s} < T_f \simeq m_\tilde{s} / 25 .
\]

\( \Rightarrow \) s and \( \tilde{s} \) will freeze out at similar \( T \)

\( \Rightarrow \) must include s annihilations in relic density calculation

- Relevant scalar interactions:

\[
\lambda' m_\tilde{s} |s|^2 n + \text{h.c.,}
\]

\[
\lambda' \lambda h_u h_d s^*^2 + \text{h.c.}
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  \]

  \[
  \mathcal{L}_{\text{scalar}} = |\lambda' ns + m_{\tilde{s}} s|^{2} + |\lambda h_{u} h_{d} + t_{2} + (\lambda'/2)s^{2}|^{2} + |\lambda nh_{d}|^{2} + |\lambda nh_{u}|^{2}
  \]

- In the limit $m_{\tilde{s}} \gg m_{\text{susy}}$, mass difference $m_{s} - m_{\tilde{s}} \approx m^{2}_{\text{susy}}/m_{\tilde{s}} < T_{f} \approx m_{\tilde{s}}/25$.
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  $\Rightarrow$ must include $s$ annihilations in relic density calculation

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The Sommerfeld Enhancement

- Heavy DM moving at small (relative) velocities, due to exchange of scalar states
  \[ \Rightarrow \text{Enhancement} \propto \frac{1}{v}. \]
  (Sommerfeld, Hisano et al; Strumia et al...)

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- Only significant for s-wave, (AM barrier suppresses effect)
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Sommerfeld Enhancement

- Calculation formulated as non-relativistic two-body QM problem with a potential.
- Equivalent to the distorted Born-wave approximation common in nuclear physics.
- Can be an enhancement or suppression for vector states.
- Including the effect (to a good approximation)

\[ \sigma = R\sigma^{\ell=0}_{\text{tree}} \]

- Full calculation of \( R \) can be involved.
- For Yukawa potential, cannot be solved analytically.
Calculation of the Sommerfeld Enhancement

- Our model, only scalar \( n \) states are “rungs on the ladder”

- The Schrödinger equation for the two dark matter particle state, \( \psi \),

\[-\frac{1}{m_{\tilde{s}}} \frac{d^2 \psi}{dr^2} + V \cdot \psi = K \psi, \quad V = -\frac{\lambda' r^2}{8\pi r} e^{-m_{n}r}, \quad K = m_{\tilde{s}} v^2\]

- Enhancement factor is

\[R = |\psi(0)/\psi(\infty)|^2.\]

- Outgoing b.c., \( \psi'(\infty)/\psi(\infty) = im_{\tilde{s}} v \)
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Coulomb limit of Sommerfeld Enhancement

- Recall approximation $m_{\tilde{S}} \gg m_{\text{susy}}$

- Analytic form for $R$ in limit $\varepsilon \equiv m_n/m_{\tilde{S}} = 0$,

$$R = \frac{y}{1 - e^{-y}}, \quad y = \frac{\lambda'^2}{8v} = \frac{\lambda'^2}{4v_r}$$

- Small $v_r$ limit

$$R \approx \frac{\lambda'^2}{4v_r}$$

- Next paper, more detailed analysis for Sommerfeld effect, e.g. non-zero $\varepsilon$. 

- For the Fat Higgs Appendix, consult the next paper for a more detailed analysis of the Sommerfeld effect, especially for non-zero $\varepsilon$. 

- For the Coulomb limit of Sommerfeld Enhancement, see the following equations:
Coulomb limit of Sommerfeld Enhancement

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- Analytic form for $R$ in limit $\varepsilon \equiv m_n/m_{\tilde{S}} = 0$,
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- Small $v_r$ limit
  $$R \approx \frac{\lambda'^2}{4v_r}$$
- Next paper, more detailed analysis for Sommerfeld effect, e.g. non-zero $\varepsilon$. 
Relic Density Calculation

- Important points and assumptions:
  - Take DM masses greater than $\sim 3\,\text{TeV}$
    $\Rightarrow T_f \sim \frac{m_\tilde{s}}{25} > T_c \Rightarrow$ EW still good symmetry,
    $\Rightarrow$ Apart from DM all fermions massless.
  - Set soft params to zero, $A_\lambda = A_\lambda'$.
  - Soft masses negligible compared to $m_\tilde{s}$.

- Recall scalar $s$ ($m_s \sim m_\tilde{s} + m^2_{\text{susy}}/m_\tilde{s}$)
  $\Rightarrow s$ freezes out at similar $T$ as $\tilde{s}$
  $\Rightarrow$ must include $s$ annihilation rates in relic calc.
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Scalar $s$ annihilations.

- Interactions: $\lambda n \tilde{h}_u \tilde{h}_d + \lambda' m_\tilde{s} |s|^2 n + \lambda' \lambda h_u h_d s^* s^2 + h.c.$

Scalar states split into CP eigenstates, $A = \frac{1}{\sqrt{2}} (\phi + i a)$

\[
\sigma (ss \rightarrow XX') = \frac{(\lambda' \lambda)^2 y}{256 \pi v_r m_\tilde{s}^2 (1 - e^{-y})}, \quad y = \frac{\lambda^2}{4v_r}
\]
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\( \tilde{s}s \) annihilations.

- Interactions: \( \lambda \tilde{n}\tilde{h}_uh_d + \lambda \tilde{n}\tilde{h}_u\tilde{h}_d + \lambda' \tilde{n}\tilde{s}s + h.c \)

\[
\sigma (s\tilde{s} \rightarrow XX') = \frac{(\lambda'\lambda)^2}{2\pi v_r m_{\tilde{s}}^2} \frac{y}{1 - e^{-y}}, \quad y = \frac{\lambda'^2}{4v_r}
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$	ilde{s}\tilde{s}$ annihilations.

- Interactions: $\frac{\lambda'}{2} n\tilde{s}\tilde{s} + \lambda n\tilde{h}_u\tilde{h}_d + h.c$

\[
\sigma(\tilde{s}\tilde{s} \rightarrow XX') = \frac{(\lambda'\lambda)^2}{128\pi v_r m_s^2} \frac{y}{1 - e^{-y}}, \quad y = \frac{\lambda'^2}{4v_r}
\]
Relic Density Numerics.

1. Re-label \((\tilde{s}, s)\) as \((s_1, s_2)\)

2. Define

\[
\begin{align*}
    r_i &\equiv \frac{g_i (1+\Delta_i)^{3/2} \exp[-x\Delta_i]}{g_{\text{eff}}}, \\
    \Delta_i &\equiv \frac{(m_i-m_1)}{m_1}, \\
    \end{align*}
\]

where

\[
\begin{align*}
    g_{\text{eff}} &\equiv \sum_i g_i (1+\Delta_i)^{3/2} \exp[-x\Delta_i], \\
    x &\equiv m_{\tilde{s}}/T
\end{align*}
\]

For our two species

\[
\begin{align*}
    g_1 = g_2 = 2, \\
    \Delta_1 = 0, \\
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\end{align*}
\]
Relic Density Numerics.

- Re-label \((\tilde{s}, s)\) as \((s_1, s_2)\)
- Define

\[
\begin{align*}
 r_i & = \frac{g_i (1+\Delta_i)^{3/2} \exp[-x \Delta_i]}{g_{\text{eff}}}, \\
\Delta_i & = \frac{(m_i - m_1)}{m_1},
\end{align*}
\]

where

\[
g_{\text{eff}} = \sum_i g_i (1+\Delta_i)^{3/2} \exp[-x \Delta_i], \quad x = \frac{m_\tilde{s}}{T}
\]

For our two species

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For our two species

\[ g_1 = g_2 = 2, \quad \Delta_1 = 0, \quad \Delta_2 = m_s - m_{\tilde{s}} \approx \frac{m_{\text{susy}}^2}{m_{\tilde{s}}}. \]
 Freeze-out temperature, \( T_f = m_{\tilde{s}} / x_f \), found by iteratively solving

\[
x_f = \ln \left[ \frac{0.038 g_{\text{eff}} M_{\text{pl}} m_{\tilde{s}} \langle \sigma_{ij} v_r \rangle}{\sqrt{g_x x_f}} \right],
\]

with

\[
\sigma_{\text{eff}} = \sum_{i,j} \sigma_{ij} r_i r_j = \sum_{i,j} \sigma_{ij} \frac{g_i g_j}{g_{\text{eff}}^2} (1 + \Delta_i)^{3/2} (1 + \Delta_j)^{3/2} \exp(-x(\Delta_i + \Delta_j)).
\]

 Final relic density

\[
\Omega h^2 = \frac{1.07 \times 10^9 x_f}{\sqrt{g_x M_{\text{pl}} (\text{GeV})}} J, \quad J = \int_{x_f}^{\infty} x^{-2} a_{\text{eff}} dx
\]

(Griest, Seckel; Gondolo, Gelmini)
Comparing with and without Sommerfeld.

- Plotted for $\lambda = \lambda' = 1.5, 2, 2.5$, with $m_{\text{susy}} = 100$ GeV
Heavy Dark Matter Through The Higgs Portal

Introduction
Hidden Sectors, Hidden Valleys and Higgs Portals.
DM in Higgs Portal Models

Heavy DM from SUSY Higgs Portals
The Model
The Sommerfeld Enhancement

Phenomenology
Direct and Indirect Detection

Summary
Fat Higgs
Appendix

$\lambda \lambda'$ parameter space.

- Plotted for $m_{\text{susy}} = 100 \text{ GeV}$. 

![Graph showing the $\lambda \lambda'$ parameter space with curves for different $m_s$ values.](attachment:graph.png)
Direct Detection.

- Main analyses next paper...
  - Quick look:
  - Direct detection phenomenology: No restrictive limits BUT sizeable fraction of future parameter space covered by next generation detectors.
  - Our DM interacts with quarks in nuclei via effective scalar interaction

\[
\mathcal{L} = \sum_{U=u,c,t} C_U \bar{\tilde{s}} \tilde{s} U + \sum_{D=d,s,b} C_D \bar{\tilde{s}} \tilde{s} D,
\]

where

\[
C_U = \sum_i \frac{\lambda_U V_{1i} V_{2i} \lambda'}{2m_{h_i}^2}, \quad C_D = \sum_i \frac{\lambda_D V_{1i} V_{3i} \lambda'}{2m_{h_i}^2},
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- \( V_{ij} \) is Higgs mixing matrix.

(Griest; Bertone, Hooper, Silk...)
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\]

- \(V_{ij}\) is Higgs mixing matrix. (Griest; Bertone, Hooper, Silk...)
Direct Detection Cont...

- Estimate elastic scattering cross section per nucleon

\[
\sigma_{\tilde{s}N} \sim 2 \times 10^{-7} \text{pb} \left( \frac{V_{ij}}{0.5} \right)^4 \left( \frac{\lambda'}{3} \right)^2 \left( \frac{120 \text{GeV}}{m_{h_1}} \right)^4.
\]

- For \( m_{\tilde{s}} \geq 3 \text{ TeV} \), cross section below current constraints from experiments such as XENON and CDMS.

- Future measurements could probe parameter region.

- For smaller values of \( \lambda' \), \( V_{ij} \) gets harder...
Indirect Detection.

- Indirect signals are modified by potentially large Sommerfeld enhancements.
- Depends on astrophysical environment, specifically velocity distribution.
- Annihilation rates can be enhanced by $10^3$ to $10^5$ or more.
- Could favour objects with low velocity dispersion e.g. dwarf satellite galaxies of the Milky Way.
- Full calculation needed:
  - Need to understand resonance structure of the Sommerfeld enhancement in the non-coulombic and low $v_r$ regime
  - Need full details of low energy model.
- Potential for significant signals in future observations.
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- Models with very heavy (∼3 – 30 TeV) dark matter.
- Motivated by Higgs Portal (and Hidden Valley) models
  → DM interacts with visible sector only through Higgs interactions (and Z’).
- Such models have UV completion using a composite “Fat Higgs” model.
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- DM up to ∼30 TeV can be thermal relic with correct relic abundance.
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  → Greatly improving detection possibilities.
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The Fat Higgs Model.

- The Fat Higgs model is an $N=1$ supersymmetric $SU(2)$ gauge theory with six doublets.
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Particle content of the Fat Higgs Model:

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<th>$SU(2)_R$</th>
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</tbody>
</table>
More Fat Higgs...

- Tree Level Superpotential, $W_{FH\text{tot}} = W_1 + W_2$, where

\[
W_1 = y_1 S_a T_1 T_2 + y_2 S_b T_3 T_4 + y_3 S_a T_3 T_4 + y_4 S_b T_1 T_2 W_2 - m T_5 T_6
\]

\[
W_2 = y_5 \begin{pmatrix} T_1 & T_2 \end{pmatrix} P \begin{pmatrix} T_5 \\ T_6 \end{pmatrix} + y_6 \begin{pmatrix} T_3 & T_4 \end{pmatrix} Q \begin{pmatrix} T_5 \\ T_6 \end{pmatrix}.
\]

- After $SU(2)_H$ becomes strong, effective superpotential becomes (after canon. norm.)

\[
W_{\text{dyn}} = \lambda \left( Pf M - v_0^2 M_{56} \right) + m_1 S_a M_{12} + m_2 S_b M_{34} + m_3 S_a M_{34} + m_4 S_b M_{12} + m_5 (M_{15} P_{11} + M_{16} P_{12} + M_{25} P_{21} + M_{26} P_{22}) + m_6 (M_{35} Q_{11} + M_{36} Q_{12} + M_{45} Q_{21} + M_{36} Q_{22}),
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Using NDA, we have (Luty)

\[
v_0^2 \sim \frac{m^\Lambda_H}{(4\pi)^2},
\]

\[
m_i \sim y_i \frac{^\Lambda_H}{4\pi},
\]

\[
\lambda(^\Lambda_H) \sim 4\pi.
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Yet More Fat Higgs...

- Make assumption \((m_5, m_6) \gg (m_1, m_2, m_3, m_4)\), integrate out heavy states

\[
W'_{dyn} = \lambda M_{56} \left( M_{14} M_{23} - M_{24} M_{13} - v_0^2 + M_{12} M_{34} \right) + m_1 S_a M_{12} + m_2 S_b M_{34} + m_3 S_a M_{34} + m_4 S_b M_{12}.
\]

- With \(m_1 \sim m_2 \sim m_3 \sim m_4 \sim m'\), fermionic components of \(S_a, S_b, M_{12}\) and \(M_{34}\) mix lightest eigenvalue \(\sim m'\).

- Diagonalization, integrate out all but the lightest eigenvalue, \(S_1\),

\[
W = \lambda N \left( H_u H_d - v_0^2 \right) + \frac{\lambda'}{2} N S_1^2 + \frac{m_{s1}}{2} S_1^2,
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- Final assumption: \(m_{s1} \gg\) electroweak scale and soft supersymmetry breaking masses.
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