DARK LIGHT HIGGS

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`` Dark Light Higgs ''

A Supersymmetric Scenario Characterized by Novel Dark Matter and Higgs Physics

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In collaboration with

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`` Dark Light Higgs ''

A Supersymmetric Scenario Characterized by Novel Dark Matter and Higgs Physics

☑ What is the ``Dark Light Higgs'' Scenario
☑ Supersymmetric Light Dark Matter
☑ Non-standard Higgs Physics
☑ Conclusions
- What is the "Dark Light Higgs" Scenario
- Supersymmetric Light Dark Matter
- Non-standard Higgs Physics
- Conclusions
Two Approximate Global Symmetries in the NMSSM

\[ W_{NMSSM} = Y_U Q H_u U^c - Y_D Q H_d D^c - Y_E L H_d E^c + \lambda N H_u H_d + \frac{1}{3} \kappa N^3 \]

\[ V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_N^2 |N|^2 - (\lambda A \lambda H_u H_d N + \text{h.c.}) + \left( \frac{\kappa}{3} A \kappa N^3 + \text{h.c.} \right) \]

- **R-symmetry**

  \[ H_u \rightarrow H_u \exp(i\phi_R), \quad H_d \rightarrow H_d \exp(i\phi_R), \quad N \rightarrow N \exp(i\phi_R) \]

- Explicitly broken by trilinear soft terms in the Higgs sector.

- **Pecci-Quinn (PQ) symmetry**

  \[ H_u \rightarrow H_u \exp(i\phi_{PQ}), \quad H_d \rightarrow H_d \exp(i\phi_{PQ}), \quad N \rightarrow N \exp(-2i\phi_{PQ}) \]

- Explicitly broken by cubic term and its correspondent soft SUSY-breaking term in the Higgs sector.

- Three CP-even mass eigenstates \((h_1, h_2, h_3)\) and two CP-odd ones \((a_1, a_2)\)

- In the symmetry limits, \(m_{a_1} \ll \text{EW scale} \) (pseudo - Goldstone boson)

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Old Story

- Almost all old studies were focused on the R-symmetry limit (B. A. Dobrescu et al., Phys. Rev. D 63 (2001); R. Dermisek et al., Phys. Rev. Lett. 95 (2005))

- $a_1$ is light $\ll$ EW scale (pseudo-Goldstone boson);

- $h_1$ is the SM-like Higgs boson;

- $h_1 \rightarrow a_1 a_1 \rightarrow 4$ fermions is typically dominant, allowing $h_1$ to be as light as below 100 GeV and hence relaxing the little hierarchy tension

- Dark matter candidate (chi1) is typically of EW scale
What is the "Dark Light Higgs" Scenario?

Nearly PQ limit: \( \kappa/\lambda \to 0 \),
\[ A_\kappa \to 0 \]
+ Moderate or small \( \lambda \): \( \lambda < \) or \( \sim 0.1 \)

Mass of the Lightest Higgs Scalar

» Tree-level contribution

\[ m_{h_1}^2 \approx -4\varepsilon^2 v^2 + \frac{4\lambda^2 v^2}{\tan^2 \beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2 \mu^2}{\lambda^2} \tan^2 \beta + \kappa A_\kappa \mu \]

with \( \varepsilon = \frac{\lambda \mu}{m_Z} \left( \frac{A_\lambda}{\mu \tan \beta} - 1 \right) \) being a measure of the deviation of the soft parameter \( A_\lambda \) from \( \mu \tan \beta \)

» Loop correction

\[ \Delta m_{h_1}^2 \approx \frac{\lambda^2 \mu^2}{2\pi^2} \log \frac{\mu^2 \tan^3 \beta}{m_Z^2} \]

» Vacuum stability sets a small upper bound

\[ \varepsilon_{\text{max}}^2 \approx \frac{1}{4v^2} \left( \frac{4\lambda^2 v^2}{\tan^2 \beta} + \frac{\kappa A_\kappa \mu}{\lambda} + \frac{4\kappa^2 \mu^2}{\lambda^2} + \frac{\lambda^2 \mu^2}{2\pi^2} \log \frac{\mu^2 \tan^3 \beta}{m_Z^3} \right) \]

» \( m_{h_1}^2 \) is generically small
Mass of the Lightest Higgs Scalar (cd.)

\[(\text{NMSSMTools 2.3.1 + MicrOMEGAS})\]

\[5 \leq \tan \beta \leq 50, \ 0.05 \leq \lambda \leq 0.5, \ 0.0005 \leq \kappa \leq 0.05, \ -0.8 \leq \varepsilon' \leq 0.8, \ -40 \text{GeV} \leq A_\kappa \leq 0, \ 0.1 \text{TeV} \leq \mu \leq 1 \text{TeV}\]

\[\lambda < 0.30, \ \kappa/\lambda < 0.05, \ \mu < 400 \text{GeV}\]

\[\lambda < 0.15, \ \kappa/\lambda < 0.03, \ \mu < 250 \text{GeV}\]

\[\nabla \text{ No point for an epsilon far away from 0 -- vacua are not stable!}\]

\[\nabla \text{ Blue and red points have a mass range 0.1 ~ 10 GeV -- the ``DLH'' scenario.}\]
Mass of the Lightest Higgs Pseudoscalar and Neutralino

- A light CP-odd Higgs $a_1$
  \[ m_{a_1}^2 \approx -\frac{3\kappa A \kappa \mu}{\lambda} \]

- A light lightest neutralino $\chi_1$
  \[ m_{\chi_1} \approx \frac{\lambda^2 v^2}{\mu} \sin 2\beta + \frac{2\kappa \mu}{\lambda} \]

- Lambda is not large, $\Rightarrow h_1, a_1$ and $\chi_1$ are singlet-like or singlino-like

- $h_2$ is SM-like
  \[ h_2 \sim h_u + h_d \cot \beta - \frac{2 \varepsilon v m_Z}{m_Z^2 + \mu^2} h_n \]

- Comparison: in the R-symmetry limit, $h_1$ and $\chi_1$ are typically not so light and $h_1$ is SM-like
What is the ``Dark Light Higgs'' Scenario

Supersymmetric Light Dark Matter

Non-standard Higgs Physics

Conclusions
A Novel Supersymmetric Light DM Scenario!

\[ \sigma_{SI} \approx \left[ \left( \frac{\varepsilon}{0.04} \right) + 0.46 \left( \frac{\lambda}{0.1} \right) \left( \frac{v}{\mu} \right) \right]^2 \left( \frac{y_{h_1} x_1 x_1}{0.003} \right)^2 \times \left( \frac{m_{h_1}}{1 \text{GeV}} \right)^4 \times 10^{-40} \text{cm}^2 \]

A t-channel process is dominant in spin-independent direct-detection \( \Rightarrow \) xection be strongly enhanced by a small \( m_{h_1} \)

\( m_{h_1} (\text{GeV}) \)

\( \tan\beta \)

\( \mu (\text{GeV}) \)

\( \sigma_{SI} (\text{cm}^2) \)
Breit-Wigner Effect => Right Relic Density

\[
\sigma_{\tilde{N}\tilde{f}} \approx \frac{3|y_{a_1\chi_1\chi_1} y_{a_1sf}|^2(1 - m_f^2/m_{\chi_1}^2)^{1/2}}{32\pi m_{\chi_1}^2 \left(\delta^2 + \left|\frac{\Gamma_{a_1m_{\chi_1}}}{4m_{\chi_1}^2}\right|^2\right)}
\]

\[
\delta \equiv |(1 - v_{\chi_1}^2/4)^{-1} - m_{a_1}^2/(4m_{\chi_1}^2)|
\]

Thermal average of the LSP annihilation section

\[
\Omega h^2 \approx 0.1 \left(\frac{m_{a_1}}{15\text{GeV}}\right) \left(\frac{\Gamma_{a_1}}{10^{-6}\text{GeV}}\right) \left(\frac{\mu}{\kappa}\right)^2 \left(\frac{0.003}{\lambda}\right)^2 \left(\frac{0.1}{\lambda}\right)^2 \frac{\text{erfc}\left(\frac{2m_{\chi_1}}{m_{a_1}}\sqrt{x_f\delta_{v_{\chi_1}\to 0}}\right)}{\text{erfc}(2.2)}
\]

Relic density
No Strong Constraints from Cosmic Ray Exps.


\[ \langle \sigma v \rangle_{\text{today}} \ll \langle \sigma v \rangle_{\text{freezing out}} \]

Resonance region (red solid line): dark matter particles in this region has a delta ~ 0, maximizing their annihilation
Numerical Results

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\kappa (10^{-3})$</th>
<th>$A_\lambda (10^3)$</th>
<th>$A_\kappa$</th>
<th>$\mu$</th>
<th>$\tan \beta$</th>
<th>$m_{h_1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1205</td>
<td>2.720</td>
<td>2.661</td>
<td>-24.03</td>
<td>168.0</td>
<td>13.77</td>
<td>0.811</td>
</tr>
<tr>
<td>$m_{a_1}$</td>
<td>$m_{\chi_1}$</td>
<td>$m_{h_2}$</td>
<td>Brhh</td>
<td>Braa</td>
<td>$\Omega h^2$</td>
<td>$\sigma_{SI} (10^{-40})$</td>
</tr>
<tr>
<td>16.7</td>
<td>7.20</td>
<td>116</td>
<td>0.158%</td>
<td>0.310%</td>
<td>0.112</td>
<td>2.34</td>
</tr>
</tbody>
</table>

$0.09 \leq \Omega h^2 \leq 0.13$

$0.05 \leq \lambda \leq 0.15$, $0.001 \leq \kappa \leq 0.005$, $|\varepsilon'| \leq 0.25$, $-30 \text{GeV} \leq A_\kappa \leq -15 \text{GeV}$, $5 \leq \tan \beta \leq 50$, $100 \text{GeV} \leq \mu \leq 250 \text{GeV}$

* All points have passed the current exp. bounds of flavor physics, meson decays, and collider exp.

* The blue points fall in a 3 sigma range of the observed relic density.

* Their Sigma_SI can be as large as above $10^{-40} \text{ cm}^2$
``One thing we know for sure: such large cross sections can not be realized within the MSSM'', Kathryn Zurek, PCTS Workshop, ``Dark Matter: Direct Detection and Theoretical Developments'', Princeton, Nov. 2010

``If COGENT excess were caused by Dark Matter, we would know only one thing: Within the NMSSM, we would know that the Dark Matter is not singlino-like. The cross section is simply too small'', Ulrich Ellwanger, Plenary Talk, SUSY 2010

``After imposing LEP and B-physics constraints the lightest neutralino is always bino-like and elastic cross sections as large as required by CoGeNT and DAMA/LIBRA are not possible in the NMSSM.'', J. F. Gunion et. al., arXiv:1009.2555 [hep-ph]
The War in Dark Matter World

(1) Changes the idea that supersymmetry is incompatible with a light (~ O(1) GeV) DM scenario characterized by a large xection of spin-independent direct-detection (10^{-40} cm^2), without violating current exp. bounds

(2) Provides a supersymmetric light DM scenario accessible to the current direct detections or the ones in the near future
What is the ``Dark Light Higgs'' Scenario

Supersymmetric Light Dark Matter

Non-standard Higgs Physics

Conclusions
Searching for Light Higgs Pair Decays of a SM-like Higgs Boson

- Motivated by the studies in the R-symmetry limit

- Tevatron searches: h_SM -> a1a1, h1h1 -> 4 mu, 2 mu 2 tau (V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 103 (2009))
Story in the DLH Scenario

- Such decays are kinematically allowed in the DLH scenario.
- Leading-order couplings between $h_2$ and $h_1 h_1$, $a_1 a_1$ are generically suppressed.

\[ |y_{h_2 h_1 h_1}| = |y_{h_2 a_1 a_1}| = \frac{\lambda v m_Z \varepsilon}{\sqrt{2} \mu} \]
Story in the DLH Scenario

- Such decays are kinematically allowed in the DLH scenario.
- Leading-order couplings between $h_2$ and $h_1h_1, a_1a_1$ are generically suppressed.

\[ |y_{h_2} h_1 h_1| = |y_{h_2} a_1 a_1| = \frac{\lambda v m_Z \epsilon}{\sqrt{2} \mu} \]

We convert the $2\mu 2\tau$ constraints to $4\mu$ constraints, using the relation

\[ BR(h_1 \rightarrow 2\tau) = BR(h_1 \rightarrow 2\mu) \times \left( \frac{m_{\tau}}{m_\mu} \right)^2 \left( \frac{1 - 4m_\tau^2/m_{h_1}^2}{1 - 4m_\mu^2/m_{h_1}^2} \right)^{3/2} \]
Q1: How Does the SM-like Higgs Decay?

- b bar mode becomes dominant sometimes, but not generic.
- As long as kinematically allowed, h2 -> chi_1 chi_2 becomes dominant (chi2 is bino-like)
- Not very hard because chi1 is light
- h2 with a mass ~100 GeV is allowed; stop quark mass can be below 300 GeV

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Decay Topology of a SM-like Higgs Boson

On-shell resonance
Q2: How to Search for the SM-like and the light Higgs Bosons?

- The non-standard decays will necessarily change the searching strategies of both the SM-like (h2) and the light Higgs bosons (a1, h1)

- For the searches of a SM-like Higgs boson

  \[ h_2 \rightarrow \chi_1 + \chi_2, \text{ with } \chi_2 \rightarrow \chi_1 + h_1, a_1. \]

- Multiple possibilities - how h2 is produced? + how h1, a1 are decayed? (In progress, T.L., J.R. Huang, S.F. Su, L.T. Wang, C. Wagner and F. Yu)

- A complementary way - searching for light Higgs bosons directly, in supersymmetric cascaded decays (In progress, S.F. Su, T.L., Wang and C. Wagner)
Some Preliminary Results at the 7 TeV LHC

- One example: pp → w h2, w → μμ and h2 → 2χ1 + h1, h1 → μμ μμ
- Dominant background: w + photon*
- Two useful cuts: (1) missing energy cut, (2) mass window cut

L = 2 fb⁻¹
What is the ``Dark Light Higgs'' Scenario
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Conclusions
Conclusions

- A benchmark scenario (DLH) in the NMSSM possessing novel Higgs and DM properties

- The lightest Higgs scalar and pseudoscalar and the lightest neutralino are light, all of order 10 GeV or below

- Provides a supersymmetric light DM scenario characterized by large spin-independent direct detection xection

- $h_2$ is SM-like, whose light Higgs pair decays are generically suppressed. However, Supersymmetric non-standard decays become dominant more often.

- Searching strategies of both the SM-like and the light Higgs bosons need to be dramatically changed.

- Interesting implications for electroweak phase transition in the early Universe (see Nasheen R. Shah’s talk after me)
Thank you!
Collider (LEP + Tevatron)
(1) Direct searches for new particles at LEP;
(2) Direct searches for new particles at the Tevatron;
(3) Electroweak precision observables;
(4) muon anomalous magnetic moment

Flavor physics and meson decay:
(1) Constraints from B-system;
(2) Constraints from K-system;
(3) Constraints from charm system;
(4) Upsilon decays

Cosmology:
(1) Dark matter relic density;
(2) Dark matter direct detection;
(3) Dark matter indirect detection, cosmic rays;
(4) Big bang nucleosynthesis, Cosmic Microwave Background Radiation
Cut Flow

- $|\eta_\mu| \leq 2.4$, $PT_\mu \geq 5\text{GeV}$;
- $|\eta_\mu| \leq 2.4$, $PT_\mu \geq 5\text{GeV}$;
- $MET \geq 30\text{GeV}$;
- $0.9\text{GeV} \leq M(\mu^+,\mu^-) \leq 1.1\text{GeV}$.

<table>
<thead>
<tr>
<th>$N_{PreSel}$</th>
<th>4215</th>
<th>$\epsilon_{PreSel}$</th>
<th>42.15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_\eta$</td>
<td>4215</td>
<td>$\epsilon_\eta$</td>
<td>42.15%</td>
</tr>
<tr>
<td>$N_{PT}$</td>
<td>3897</td>
<td>$\epsilon_{PT}$</td>
<td>38.97%</td>
</tr>
<tr>
<td>$N_{MET}$</td>
<td>3137</td>
<td>$\epsilon_{MET}$</td>
<td>31.37%</td>
</tr>
<tr>
<td>$N_{m\mu\mu}$</td>
<td>3079</td>
<td>$\epsilon_{m\mu\mu}$</td>
<td>30.79%</td>
</tr>
</tbody>
</table>
Quantitatively Description

\[ F = \max_a F_a \equiv \max_a \left| \left. \frac{d \log m_Z}{d \log a} \right| \]

``a'' denotes soft parameters and \( \mu \) parameter at GUT scale

\((G. \ Kane \ and \ S. \ King, \ Phys.\ Lett.\ B451 \ (1999))\)

Preliminary figure. T.L., C. Wagner and Z. Hao. In progress