Dark Matter &
Higgs bosons in MSSM

Higgs Signal Workshop
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Tao Han

arXiv:1303.3040,
TH, Zhen Liu,
Aravind Natarajan
SUSY Dark Matter:

One of the most appealing features for SUSY

Good News: Higgs boson discovered!

\[ M_h = 125.7 \pm 0.3 \pm 0.3 \text{ GeV (CMS, Korytov)} \]
\[ = 125.5 \pm 0.2 \pm 0.6 \text{ GeV (ATLAS, Hays)} \]

Weakly coupled theory, like SUSY:

\[ M_h \rightarrow \lambda \sim 1/8 \sim \frac{(g_1^2 + g_2^2)}{8} \]

Its existence argues for new physics (naturalness)

Bad News: No clear sign for DM.

Direct searches: Xenon10,100 ... (DAMA, CoGeNT, CRESST? CDMS2?)

Indirect searches: Pamela? Fermi/LAT, IceCube, AMS2

Collider searches: Tevatron, LHC (ILC?)
Assume MSSM

Scan over Parameters:

\[ 5 \text{ GeV} < |M_1| < 2000 \text{ GeV}, \quad 100 \text{ GeV} < |M_2, \mu| < 2000 \text{ GeV}, \]
\[ 3 < \tan \beta < 55, \quad 80 \text{ GeV} < M_A < 1000 \text{ GeV}, \]
\[ -4000 \text{ GeV} < A_t < 4000 \text{ GeV}, \quad 100 \text{ GeV} < M_{Q3, U3} < 3000 \text{ GeV}, \]
\[ -4000 \text{ GeV} < A_b < 4000 \text{ GeV}, \quad 100 \text{ GeV} < M_{D3} < 3000 \text{ GeV}, \]
\[ -4000 \text{ GeV} < A_\tau < 4000 \text{ GeV}, \quad 100 \text{ GeV} < M_{L3, E3} < 3000 \text{ GeV}. \]

Lower bounds are typically from the collider searches.

Upper bounds are from “naturalness” argument
\[ \mu \sim 2 \text{ TeV} \Rightarrow 0.04\% \text{ fine tune}. \]

* Higher values \( M_2 \sim \mu \) change results: “well-tempered” OK

* Signs of \( M_1, M_2, \mu \) important – fine-tuned: “blind spots”
**Constraints:**

\[ 123 \text{ GeV} < m_h < 128 \text{ GeV}, \quad \sigma_{\gamma\gamma} > 0.8 \sigma_{\gamma\gamma}(SM), \]

plus Higgs search bounds from LEP, Tevatron, LHC, plus LEP bounds on the chargino mass (\( \geq 100 \text{ GeV} \)) and the slepton mass (\( \geq 80 \text{ GeV} \)).

**Belle/BaBar:**

\[ 2.31 \times 10^{-4} < \quad \text{BR}(b \rightarrow s\gamma) \quad < 4.51 \times 10^{-4}, \]

**LHCb:**

\[ \text{BR}(B_s \rightarrow \mu^+\mu^-) < 5.1 \times 10^{-9}. \]

**WMAP9/ACT/SPT/Planck...**

+ 10\% Theo. Uncertainty, 2\( \sigma \) window:

\[ 0.0947 < \Omega_{\chi_1^0} h^2 < 0.1427 \]
Grey: Collider Higgs + not over-close the Universe
Red: + $b$-flavor constraints
Blue: + correct relic density
Green: + XENON 100 bound

TH, Su, Christensen, arXiv:1203.3207
More, versus $M_A$:
Blue: + correct relic density
Green: + XENON 100 bound

H/A-funnel & around:
**B-flavor constraints:**

\( b \rightarrow s\gamma \) and \( B_s \rightarrow \mu^+\mu^- \) complementary.

\[
\tan^6\beta / M_A^4
\]
SUSY PARAMETERS:

Wino mass parameter

Higgsino mass parameter

Features: Z, h \rightarrow 2 \text{ “binos”}
m_1-m_2 co-annihilations seen
\mu-m_2 co-annihilation limited by Xenon100
Neutralinos/charginos:

Features:
Z, h \rightarrow 2 \text{ LSPs}
Bino-wino co-annihilation common;
Bino-Higgsino co-annihilation limited
Features:
LSP-stau co-annihilation seen
LSP-stop co-annihilation seen
Light-stop removed by b-flavor bounds
Summary plot: Direct searches

Features:

- $Z, h, H/A \rightarrow 2$ LSPs: green; Fully covered by Xenon1T
- Co-annihilations: w/ NLSP yellow; w/ stau: magenta
- Lower bound $10^{-46}$ cm$^2$ ($M1, M2, \mu > 0$)
- Except for the “blind spots” …
The blind spots:

<table>
<thead>
<tr>
<th>$m_\chi$</th>
<th>condition</th>
<th>signs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$</td>
<td>$M_1 + \mu \sin 2\beta = 0$</td>
<td>$\text{sign}(M_1/\mu) = -1$</td>
</tr>
<tr>
<td>$M_2$</td>
<td>$M_2 + \mu \sin 2\beta = 0$</td>
<td>$\text{sign}(M_2/\mu) = -1$</td>
</tr>
<tr>
<td>$-\mu$</td>
<td>$\tan \beta = 1$</td>
<td>$\text{sign}(M_{1,2}/\mu) = -1$</td>
</tr>
<tr>
<td>$M_2$</td>
<td>$M_1 = M_2$</td>
<td>$\text{sign}(M_{1,2}/\mu) = -1$</td>
</tr>
</tbody>
</table>
Indirect Searches:
**Nature of the LSP:**

**After Xenon 100:**

**Features:**
- Largely Bino, but with Wino/Higgsino
- Before Xenon: well-tempered scenario still valid
- After Xenon 100: Wino/Higgsino less than 20%
  (depending on M2, mu ~ 1 TeV)
## Summary Table:

<table>
<thead>
<tr>
<th>Type labels</th>
<th>DM mass $m_{\chi_1^0}$</th>
<th>Annihilation channels</th>
<th>Partial waves</th>
<th>$\langle \sigma v \rangle (v \rightarrow 0)$</th>
<th>Collider searches</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-A</td>
<td>$\sim m_Z/2$</td>
<td>$\rightarrow Z$</td>
<td>p</td>
<td>low</td>
<td>$Z, h, H, A \rightarrow \chi_1^0\chi_1^0$</td>
</tr>
<tr>
<td>I-B</td>
<td>$\sim m_h/2$</td>
<td>$\rightarrow h$</td>
<td>p</td>
<td>low</td>
<td>$h, H, A \rightarrow \chi_1^0\chi_1^0$</td>
</tr>
<tr>
<td>I-C</td>
<td>$\sim m_A/2$</td>
<td>$\rightarrow A$</td>
<td>s</td>
<td>high</td>
<td>$H, A \rightarrow \chi_1^0\chi_1^0$</td>
</tr>
<tr>
<td>II-A</td>
<td>$m_{\chi_1^0} \sim m_{\chi_1^\pm}$</td>
<td>$\chi_1^0\chi_2^0, \chi_1^0\chi_1^\pm$</td>
<td>s+p</td>
<td>medium</td>
<td>$H, A \rightarrow \chi_1^0\chi_2^0$</td>
</tr>
<tr>
<td></td>
<td>$\sim m_{\chi_2^0}$</td>
<td>$\chi_2^0\chi_2^0, \chi_1^+\chi_1^-$</td>
<td></td>
<td></td>
<td>$H, A \rightarrow \chi_2^0\chi_2^0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\rightarrow SM$</td>
<td></td>
<td></td>
<td>$H^\pm \rightarrow \chi_1^0\chi_1^\pm$</td>
</tr>
<tr>
<td>II-B</td>
<td>$m_{\chi_1^0} \sim m_{\tilde{\tau}_1}$</td>
<td>$\tilde{\tau}<em>1^+\tilde{\tau}<em>1^-, \tilde{\nu}</em>\tau\tilde{\nu}</em>\tau$, $\chi_0^1\tilde{\tau}_1^\pm$</td>
<td>s+p</td>
<td>medium</td>
<td>$H, A \rightarrow \tilde{\tau}_1^+\tilde{\tau}_1^-$</td>
</tr>
<tr>
<td></td>
<td>$\sim m_{\tilde{\nu}_\tau}$</td>
<td>$\rightarrow SM$</td>
<td></td>
<td></td>
<td>$H^\pm \rightarrow \tilde{\tau}<em>1^\pm\tilde{\nu}</em>\tau$</td>
</tr>
</tbody>
</table>
Complementarity:
S-wave enhancement via A-funnel:
Velocity-independent s wave
Invisible Decays:

Features:

\[ h \rightarrow 2 \text{ LSP invisible as high as 10\% at Z-funnel!} \]

but, \[5\% \text{ at h-funnel, due to threshold suppression.} \]

\[ H,A \rightarrow 2 \text{ LSP invisible 3-4\%} \]

LHC insufficient.

ILC?
More Invisible Decays:

Features:
H, A, H$^\pm$ → 2 LSP or NLSP could be all invisible! as high as 20%!
Correlations among observables:
Summary:

- The Higgs boson(s) could be the pivot: $\chi\chi \rightarrow h, H, A (Z)$ funnels for correct $\Omega h^2$

- Direct search fully cover the funnels!

- Indirect detections complementary.

- LHC/ILC search for invisible modes crucial for confirmation.

An exciting journey ahead of us!
A Natural Higgs Sector at LHC

Supersymmetry:

Current bounds on the “most wanted” are still loose.

LHC will push stop to the extreme.

LHC may be limited to cover gauginos and Higgsinos.

<table>
<thead>
<tr>
<th>CMS preliminary</th>
<th>m(mother)−m(LSP) = 200 GeV</th>
<th>m(LSP)=0 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: $\tilde{g} \rightarrow q\tilde{q}^0$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T1bbbb: $\tilde{g} \rightarrow bb\tilde{\chi}^0$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T1tttt: $\tilde{g} \rightarrow tt\tilde{\chi}^0$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T2: $\tilde{q} \rightarrow q\tilde{\chi}^0$</td>
<td>squark</td>
<td></td>
</tr>
<tr>
<td>T2bb: $\tilde{t} \rightarrow b\tilde{\chi}^0$</td>
<td>sbottom</td>
<td></td>
</tr>
<tr>
<td>T2tt: $\tilde{t} \rightarrow t\tilde{\chi}^0$</td>
<td>stop</td>
<td></td>
</tr>
<tr>
<td>T3lh: $\tilde{g} \rightarrow q\tilde{q}(\tilde{\chi}^0 \rightarrow l^+ l^- \tilde{\chi}^0)$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T3w: $\tilde{g} \rightarrow q\tilde{q}(\tilde{\chi}^0 \rightarrow W^+ \nu \tilde{\chi}^0)$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T5lnu: $\tilde{\chi}^\pm \rightarrow t^\pm \nu \tilde{\chi}^0$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>T5zz: $\tilde{g} \rightarrow q\tilde{q}(\tilde{\chi}^0 \rightarrow 2\tilde{\chi}^0)$</td>
<td>gluino</td>
<td></td>
</tr>
<tr>
<td>TChiSlep: $\tilde{\chi}^0 \tilde{\chi}^\pm \rightarrow t\bar{t}b\tilde{\chi}^0 \tilde{\chi}^0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TChSlep: $\tilde{\chi}^\pm \tilde{\chi}_2^0 \rightarrow WZ\tilde{\chi}^0 \tilde{\chi}^0$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7 TeV, $\leq 4.98$ fb$^{-1}$
MSSM: Two Higgs-Doublet Model

3 Goldstone bosons, 5 Higgs bosons:

\[ h^0, \ H^0, \ A^0, \ H^\pm \]

Tree-level masses given by \( M_A, \tan \beta \)

Current LHC bounds:

\[ \text{TH, Su, Christensen, arXiv:1203.3207} \]