Simplified Models of Heavy Higgs Bosons Decaying to Supersymmetric Particles

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*Master thesis
(work in progress)

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August 24, 2017
The Current Situation

Where are we?
- Well-motivated New Physics searches without success
  → Constraints on the MSSM parameter space\(^1\)
- Current searches of heavy Higgs bosons assume only SM decay channels\(^2\)

Where to go?
- Are there supersymmetric decays of Higgs bosons which offer additional search channels?\(^3\)

\(^1\) Belanger, Ghosh, Godbole, and Kulkarni, “Light stop in the MSSM after LHC Run 1”.
\(^2\) Arbey, Battaglia, and Mahmoudi, “Supersymmetric Heavy Higgs Bosons at the LHC”.
\(^3\) Barman, Bhattacherjee, Chakraborty, and Choudhury, “Study of MSSM heavy Higgs bosons decaying into charginos and neutralinos”.
Content

1. Minimal Supersymmetric Standard Model
2. ATLAS pMSSM Dataset
3. SModelS framework
4. Results
5. Conclusion
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Supersymmetry

- Bosonic superpartners of fermions: squarks, sleptons
- Fermionic superpartners of bosons: gluinos, neutralinos, charginos
- Five Higgs bosons
Minimal Supersymmetric Standard Model

- Constrain the number of MSSM parameters with simple assumptions
  - R-Parity conservation with neutral LSP as DM candidate
  - Electroweak/Soft Symmetry Breaking
  - No new CP-violation, no FCNC at tree-level
  - ...
  \[ \rightarrow \text{only 19 additional free parameters in pMSSM} \]

- \( \tan \beta, M_{1,2,3}, \mu, M_A, M_{\tilde{q}, \tilde{l}}, M_{\tilde{Q}, \tilde{L}}, M_{\tilde{u}, \tilde{d}, \tilde{e}} \) \( M_{\tilde{t}, \tilde{b}, \tilde{\tau}} \)

- Higgs Masses Determined by \( M_A \) and \( \tan \beta \) at Tree Level

\[
M_{H,h}^2 = \frac{1}{2} \left[ M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2M_Z^2\cos^2(2\beta)} \right]
\]

\[ \frac{M_A \gg M_Z}{(\text{decoupling limit})} \Rightarrow M_H \approx M_A \]
Heavy Higgs Production and Couplings

- **Main Heavy Higgs Production Mechanisms @ LHC**

- **Normalized Higgs Couplings and the Decoupling Limit** $M_A \gg M_Z$

<table>
<thead>
<tr>
<th>$\Phi$</th>
<th>$g_{\Phi u\bar{u}} / g_{\Phi u\bar{u}}^{SM}$</th>
<th>$g_{\Phi d\bar{d}} / g_{\Phi d\bar{d}}^{SM}$</th>
<th>$g_{\Phi VV} / g_{\Phi VV}^{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>$\cos \alpha / \sin \beta \rightarrow 1$</td>
<td>$- \sin \alpha / \cos \beta \rightarrow 1$</td>
<td>$\sin(\beta - \alpha) \rightarrow 1$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\sin \alpha / \sin \beta \rightarrow \cot \beta$</td>
<td>$\cos \alpha / \cos \beta \rightarrow \tan \beta$</td>
<td>$\cos(\beta - \alpha) \rightarrow 0$</td>
</tr>
</tbody>
</table>
Heavy Higgs Decay Width to Electroweakinos

- Heavy Higgs Decay Width

\[
\Gamma(H \rightarrow \tilde{\chi}_i \tilde{\chi}_j) \sim M_H \left[ \left( (g_{Hij}^L)^2 + (g_{Hij}^R)^2 \right) \left( 1 - \frac{M_{\tilde{\chi}_i}^2}{M_H^2} - \frac{M_{\tilde{\chi}_j}^2}{M_H^2} \right) - 4\epsilon_i \epsilon_j g_{Hij}^L g_{Hij}^R \frac{M_{\tilde{\chi}_i} M_{\tilde{\chi}_j}}{M_H^2} \right]
\]

\(\epsilon_i\) ... sign of \(i^{th}\) EWino mass EV

High \(\mathcal{B}(H \rightarrow \tilde{\chi} \tilde{\chi})\) for

- \(\epsilon_i \neq \epsilon_j\)
- \(\text{sign}(g_{Hij}^L) \neq \text{sign}(g_{Hij}^R)\)

→ Preferred asymmetric decay \((i \neq j)\)
EWino Mass Eigenvalues

- **Elektroweakino Masses**: Diagonalizing the
  - Neutralino Mass Matrix

\[
M_{\tilde{N}} = \begin{pmatrix}
M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\
0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\
-M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\
M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0
\end{pmatrix}
\]

- Chargino Mass Matrix

\[
M_C = \begin{pmatrix}
M_2 & \sqrt{2}M_W s_\beta \\
\sqrt{2}M_W c_\beta & \mu
\end{pmatrix}
\]

- **Elektroweakino Characterization**

- Bino-like LSP: $M_1 \ll M_2, \mu$
- Higgsino-like LSP: $\mu \ll M_1, M_2$
- Wino-like LSP: $M_2 \ll M_1, \mu$
Content

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pMSSM Point Selection

**Sample Size:**

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample Size (ATLAS)</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bino-like LSP</td>
<td>103.410</td>
<td>32.566</td>
</tr>
<tr>
<td>Higgsino-like LSP</td>
<td>126.684</td>
<td>65.083</td>
</tr>
<tr>
<td>Wino-like LSP</td>
<td>80.233</td>
<td>(43.680)</td>
</tr>
</tbody>
</table>

**Experimental Constraints**

- Dark Matter Relic Density
- LEP constraints on SUSY
- ATLAS constraints on SUSY

- SuperISO - 3.6
- HiggsSignals - 1.4.0
- HiggsBounds - 4.3.1
- SModelS - 1.1.1

← Flavor Sector
← Light Higgs Mass & Signal Rate
← Cross Section Limit for Heavy Higgs
← Possible Decay of H to Sparticles
← Lifetime of Sparticles

Lukas Lechner*, Ursula Laa, Suchita Kulkarni
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Decomposition of given Spectra

\[ \tilde{\chi}_1^+, \tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\mu}_R, \tilde{\tau}_R, \tilde{\nu}, \tilde{\tau}, \tilde{\mu}, \tilde{\tau} \]
SMoDeLS

- Constraining using LHC Results

- Identifying Missing Topologies

- Workaround for Resonant Searches
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Missing Topologies

- Higgsino (Bino) dataset
- Mono-$X$ are most dominant and frequent missing topologies
- Additional signatures due to off-shell $X$

![Graph showing missing topologies]
Mono-X Results @ $\sqrt{s} = 14$ TeV

- Large cross sections up to $\mathcal{O}(10 \text{ fb})$ if kinematically allowed
- Heavy Higgs searches @ HL-LHC?
- Re-interpretation of current mono-X searches for resonant heavy Higgs?
Wino Results @ $\sqrt{s} = 14$ TeV

- Large cross sections up to $\mathcal{O}(10 \text{ fb})$
- Displaced vertices due to long-lived light charginos $\tilde{\chi}_1^\pm$ ($\sim 95\%$ of Wino-Set)

$\rightarrow$ can’t be handled by SModelS yet $\rightarrow$ stay tuned!
Conclusion

Search for heavy Higgses is an important avenue for BSM searches

We use SModelS to classify supersymmetric decays of heavy Higgses

Complicated dependencies of Higgs decays reduce to simple detector signatures
We find potentially large cross sections mono-\(X\) signatures
Promising results for HL-LHC with 3 ab\(^{-1}\) integrated luminosity

We propose a reinterpretation of current DM mono-\(X\) analyses
Displaced vertex analyses also promising for heavy Higgs searches
Characterising simplified models for heavy Higgs decays to supersymmetric particles

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\textsuperscript{2} Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften, Nikolsdorfer Gasse 18, 1050 Wien, Austria

The search for heavy Higgs bosons is an important step to probe the parameter space of the Minimal Supersymmetric Standard Model. We define simplified models for heavy Higgs bosons decaying to supersymmetric particles by using the SModelS framework. We use the allowed points from ATLAS pMSSM dataset for this purpose. Furthermore, we characterize the parameter space resulting in maximal signal in a given decay mode at the LHC 14 TeV. Systematically studying the possible decay modes, we propose a reinterpretation of current mono-X analyses (mono-Higgs, -W, -Z).
Thank you for your attention!
Any questions?
Backup
Backup - pMSSM Parameter Assumptions

- R-Parity conservation
- Neutral Lightest Supersymmetric Particle (LSP)
- Electroweak Symmetry Breaking
- Real soft parameters (no new CP-violation)
- No FCNC at tree-level
- Negligible trilinear couplings $A_{q,l}$ at low energy for 1st- and 2nd-gen sparticles
- Degenerate 1st- and 2nd-gen sparticle states with negligible Yukawa couplings

→ 19 free parameters:
  $\tan \beta$, $M_{1,2,3}$, $\mu$, $M_A$, $M_{\tilde{q},\tilde{l}}$, $M_{\tilde{Q},\tilde{L}}$, $M_{\tilde{u},\tilde{d},\tilde{e}}$, $M_{\tilde{t},\tilde{b},\tilde{\tau}}$, $A_t, A_b, A_{\tau}$
Strong Influences of 3rd-gen (S)Quarks in Loop-Corrections

\[ \rightarrow M_{\tilde{Q}}, M_{\tilde{t}_R, \tilde{b}_R}, A_t, b \text{ parameter dependence} \]
Two Higgs doublets are required in SUSY models

\[ H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = \left( \begin{pmatrix} \nu_d + \phi_d^0 + i\chi_d^0 \\ \phi_d^- \end{pmatrix} / \sqrt{2} \right) \]  \[ \langle H_d \rangle = \frac{\nu_d}{\sqrt{2}} \]

\[ H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} = \left( \begin{pmatrix} \nu_u + \phi_u^0 + i\chi_u^0 \\ \phi_u^+ \end{pmatrix} / \sqrt{2} \right) \]  \[ \langle H_u \rangle = \frac{\nu_u}{\sqrt{2}} \]

\[ \nu^2 = \nu_d^2 + \nu_u^2 = \nu_{SM}^2 = (246 \text{ GeV})^2 \]

\[ \tan \beta = \frac{\nu_u}{\nu_d} \]
Backup - Higgs Bosons in MSSM

- CP-even Higgs bosons $h, H$
- CP-odd Higgs boson $A$
- charged Higgs bosons $H^+, H^-$
- neutral Goldstone boson $G^0$
- charged Goldstone bosons $G^+, G^-$

\[
\begin{align*}
(H) &= \begin{pmatrix} c_\alpha \\ -s_\alpha \end{pmatrix} \begin{pmatrix} \phi_d^0 \\ \phi_u \end{pmatrix} \\
(h) &= \begin{pmatrix} s_\alpha \\ c_\alpha \end{pmatrix} \\
(G^0) &= \begin{pmatrix} c_\beta \\ -s_\beta \end{pmatrix} \begin{pmatrix} \chi_d^0 \\ \chi_u \end{pmatrix} \\
(A) &= \begin{pmatrix} s_\beta \\ c_\beta \end{pmatrix} \\
(G^\pm) &= \begin{pmatrix} c_\beta \\ -s_\beta \end{pmatrix} \begin{pmatrix} \phi_d^\pm \\ \phi_u \end{pmatrix} \\
(H^\pm) &= \begin{pmatrix} s_\beta \\ c_\beta \end{pmatrix}
\end{align*}
\]
Pre-Defined Experimental Constraints
- Flavor Sector
- Dark Matter Relic Density
- Lower Limit on Lightest Chargino Mass
- Lower Limit on Lightest Charged Sparticle Mass
- Lower Limit on Lightest Squark Mass
- Mass Window for Light Higgs

Additional Experimental Constraints
- SuperISO - 3.6
- HiggsSignals - 1.4.0
- HiggsBounds - 4.3.1
- SModelS - 1.1.1

← Flavor Sector
← Light Higgs Mass & Signal Rate
← Cross Section Limit for Heavy Higgs
← Possible Decay of H to Sparticles
← Lifetime of Sparticles
### Backup - pMSSM Parameter Range

<table>
<thead>
<tr>
<th>Lower Limit</th>
<th>Parameter</th>
<th>Upper Limit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 GeV</td>
<td>$M_{\tilde{\tau}<em>1} = M</em>{\tilde{\tau}_2}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Left-handed 1st- and 2nd-gen slepton</td>
</tr>
<tr>
<td>90 GeV</td>
<td>$M_{\tilde{\ell}<em>{R}} = M</em>{\tilde{\mu}_{R}}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Right-handed 1st- and 2nd-gen slepton</td>
</tr>
<tr>
<td>90 GeV</td>
<td>$M_{\tilde{\ell}_3}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Left-handed 3rd-gen slepton</td>
</tr>
<tr>
<td>90 GeV</td>
<td>$M_{\tilde{\tau}_{R}}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Right-handed 3rd-gen slepton</td>
</tr>
<tr>
<td>200 GeV</td>
<td>$M_{\tilde{q}<em>1} = M</em>{\tilde{q}_2}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Left-handed 1st- and 2nd-gen squark</td>
</tr>
<tr>
<td>200 GeV</td>
<td>$M_{\tilde{\mu}<em>{R}} = M</em>{\tilde{\tau}_{R}}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Right-handed 1st- and 2nd-gen up-type squark</td>
</tr>
<tr>
<td>200 GeV</td>
<td>$M_{\tilde{\tau}<em>{R}} = M</em>{\tilde{\mu}_{R}}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Right-handed 1st- and 2nd-gen down-type squark</td>
</tr>
<tr>
<td>100 GeV</td>
<td>$M_{\tilde{\tau}_3}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Left-handed 3rd-gen squark</td>
</tr>
<tr>
<td>100 GeV</td>
<td>$M_{\tilde{\tau}_{R}}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Right-handed 3rd-gen up-type squark</td>
</tr>
<tr>
<td>100 GeV</td>
<td>$M_{\tilde{\tau}_{R}}$</td>
<td>$\leq$ 4000 GeV</td>
<td>Right-handed 3rd-gen down-type squark</td>
</tr>
<tr>
<td>0 GeV</td>
<td>$</td>
<td>M_1</td>
<td>$</td>
</tr>
<tr>
<td>70 GeV</td>
<td>$</td>
<td>M_2</td>
<td>$</td>
</tr>
<tr>
<td>80 GeV</td>
<td>$</td>
<td>\mu</td>
<td>$</td>
</tr>
<tr>
<td>200 GeV</td>
<td>$M_3$</td>
<td>$\leq$ 4000 GeV</td>
<td>Gluino mass parameter</td>
</tr>
<tr>
<td>0 GeV</td>
<td>$</td>
<td>A_t</td>
<td>$</td>
</tr>
<tr>
<td>0 GeV</td>
<td>$</td>
<td>A_b</td>
<td>$</td>
</tr>
<tr>
<td>0 GeV</td>
<td>$</td>
<td>A_\tau</td>
<td>$</td>
</tr>
<tr>
<td>100 GeV</td>
<td>$</td>
<td>M_A</td>
<td>$</td>
</tr>
<tr>
<td>1</td>
<td>$\tan\beta$</td>
<td>$\leq$ 60</td>
<td>Ratio of the Higgs vev</td>
</tr>
</tbody>
</table>
### Pre-defined Constraints

<table>
<thead>
<tr>
<th>Lower Limit</th>
<th>Parameter</th>
<th>Upper Limit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-0.0005)</td>
<td>(\Delta \rho)</td>
<td>(0.0017)</td>
<td>Electroweak parameter</td>
</tr>
<tr>
<td>(-17.7 \times 10^{-10})</td>
<td>(\Delta (g - 2)_{\mu})</td>
<td>(43.8 \times 10^{-10})</td>
<td>Anomalous magnetic moment of the muon</td>
</tr>
<tr>
<td>(2.69 \times 10^{-4})</td>
<td>(B(b \to s \gamma))</td>
<td>(3.87 \times 10^{-4})</td>
<td>Branching ratio FCNC</td>
</tr>
<tr>
<td>(1.6 \times 10^{-9})</td>
<td>(B(B_s \to \mu \mu))</td>
<td>(4.2 \times 10^{-9})</td>
<td>Branching ratio (B_s \to \mu \mu)</td>
</tr>
<tr>
<td>(66 \times 10^{-6})</td>
<td>(B(B^+ \to \tau^+ \nu_\tau))</td>
<td>(161 \times 10^{-6})</td>
<td>Branching ratio (B^+ \to \tau^+ \nu_\tau)</td>
</tr>
<tr>
<td>(\Omega_{\tilde{\chi}_1^0} h^2)</td>
<td>(0.1208)</td>
<td>Cold dark matter energy density</td>
<td></td>
</tr>
<tr>
<td>(\Gamma_{\text{inv} (\text{SUSY})}(Z))</td>
<td>(2\ MeV)</td>
<td>Z-boson decay width to invisible</td>
<td></td>
</tr>
<tr>
<td>100 GeV</td>
<td>(M_{\tilde{X}_1^\pm})</td>
<td>Lightest charged sparticle mass</td>
<td></td>
</tr>
<tr>
<td>103 GeV</td>
<td>(M_{\tilde{\chi}_1^\pm})</td>
<td>Lightest chargino mass</td>
<td></td>
</tr>
<tr>
<td>200 GeV</td>
<td>(M_{\tilde{q}})</td>
<td>Lightest squark mass</td>
<td></td>
</tr>
<tr>
<td>124 GeV</td>
<td>(M_h)</td>
<td>(128\ GeV)</td>
<td>Light Higgs boson mass</td>
</tr>
</tbody>
</table>
## Backup - pMSSM Point Selection

<table>
<thead>
<tr>
<th>Losses</th>
<th>Bino-like</th>
<th>Higgsino-like</th>
<th>Wino-like</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Size (ATLAS)</td>
<td>103.410</td>
<td>126.684</td>
<td>80.233</td>
</tr>
<tr>
<td>Valid Sample Size (ATLAS)</td>
<td>61.370</td>
<td>77.981</td>
<td>43.680</td>
</tr>
<tr>
<td>SuperISO (2σ)</td>
<td>-1.504</td>
<td>-1.988</td>
<td></td>
</tr>
<tr>
<td>HiggsBounds (2σ)</td>
<td>-109</td>
<td>-160</td>
<td></td>
</tr>
<tr>
<td>HiggsSignals (2σ)</td>
<td>-9.765</td>
<td>-1.199</td>
<td></td>
</tr>
<tr>
<td>SModelS Direct Search (σ_{th} &gt; σ_{UL})</td>
<td>-517</td>
<td>-2.440</td>
<td></td>
</tr>
<tr>
<td>SModelS Res. Higgs Search</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Long-Lived Sparticles ((c\tau &gt; 1) mm)</td>
<td>-4.571</td>
<td>-1.792</td>
<td>(-39.243)</td>
</tr>
<tr>
<td>No Decay Mode to SUSY</td>
<td>-12.338</td>
<td>-5.319</td>
<td></td>
</tr>
<tr>
<td>Valid Sample Size (total)</td>
<td>32.566</td>
<td>65.083</td>
<td>(43.680)</td>
</tr>
</tbody>
</table>
Backup - SModelS

- Database of ATLAS and CMS SUSY results
- Decomposing parameter set to Simplified Model Spectrum (SMS) topologies
- Identifying new signatures/missing topologies
- MET in the final state

\[ \rightarrow \text{Constrains parameter sets with existing LHC limits (}\sigma_{\text{th}} > \sigma_{\text{UL}}^{\text{exp}}?\) \]

- Use a workaround to use SModelS for resonant searches:

\[
\sigma(pp \rightarrow H) \times \text{BR}(H \rightarrow \tilde{\chi}_i \tilde{\chi}_j)
\]
Backup - SModelS

- **SModelS Bracket Notation**

  ![Diagram showing Bracket Notation]

- **SModelS Mass Compression** ($\Delta M < 5$ GeV)

  ![Diagram showing Mass Compression]
Detailed studies of heavy Higgs production channel
Almost entirely due to bottom-quark annihilation
→ up to two additional b-jets!
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Higgsino-like LSP

![Graph showing Higgsino-like LSP](image-url)
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Higgsino-like LSP

![Diagram showing Higgsino-like LSP distributions](image)
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Higgsino-like LSP

![Graph showing simplified models of heavy Higgs bosons](image)
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Higgsino-like LSP

![Graph showing Higgsino-like LSP with axes $M_{\chi_1^0}$ vs $M_{\chi_3^0}$ and $\tan\beta$ vs $M_A$ with color scale representing $\sigma_{pp\rightarrow H}/\sigma_{pp\rightarrow H}$]
Most frequent missing topologies

Bino-like LSP

Higgsino-like LSP
Most dominating missing topologies
(highest missing topology cross section of the parameter-set)
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Bino-like LSP

![Graph showing Bino-like LSP with $(M_{\tilde{\chi}_1^0}, M_{\tilde{\chi}_3^0})$ and $(\tan\beta, M_A)$ plots.](image-url)
Bino-like LSP

Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Bino-like LSP

![Graph showing Bino-like LSP distributions]
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Bino-like LSP

![Graph](image-url)
Backup - Wino Results @ $\sqrt{s} = 14$ TeV

- Wino-like LSP