Light Higgs bosons in SUSY cascades

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Implications of LHC results for TeV-scale physics

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Motivation

- Most studies of BSM Higgs concern changes to rates – nothing fundamentally different from SM

- Obvious benefits, but restricting Higgs searches to ‘SM-like’ scenarios may be too limited in the sense that
  - Lighter, non-SM like, Higgs bosons could exist
  - Heavy Higgs bosons may decay to new physics (or H)
  - Higgs bosons may be produced from new particle decays
  - New physics production may be background to Higgs
  - Higgs production may be background to new physics

- Treat Higgs physics and new physics in conjunction
  😊 Tackle some of these issues   😞 Increased model dependence
Outline

1. Scenarios with light Higgs bosons
   a) CP-violating MSSM
   b) NMSSM

2. Higgs production in SUSY cascades

3. Phenomenological LHC analysis
Light Higgs bosons I: MSSM

- LEP -> Lower limit on Higgs mass
- SM-like Higgs: $M_H \gtrsim 114$ GeV
- SUSY -> two Higgs doublets -> 3 neutral Higgs states $H_i$
- CP-conserving MSSM: $H_i, A^0$
  \[
  \frac{C(H_iVV)}{C(H_iVV)_{SM}} \propto g_i \sum_{i=1}^{2} g_i^2 = 1
  \]
- Lightest Higgs mass
  \[
  90 \text{ GeV} \lesssim M_h \lesssim 130 \text{ GeV}
  \]
Light Higgs bosons II: CP-violating MSSM

- Relaxing CP conservation, all 3 neutral Higgs bosons mix

\[ \sum_{i=1}^{3} g_i^2 = 1 \]

- Benchmark scenario “CPX” shows hole in excluded region

\[ M_{H_1} \sim 35–45 \text{ GeV} \]

- Such light \( H_1 \) also opens for

\[ H_2 \rightarrow H_1 H_1 \]

- Complicated 4f final states from SM-like Higgs

Williams, Rzehak, Weiglein, [1103.1335]
Light Higgs bosons III: The NMSSM

- The NMSSM extends the MSSM, solves $\mu$-problem

$$W_{\text{MSSM}}^{(2)} \sim \mu \hat{H}_2 \cdot \hat{H}_1 \rightarrow \lambda \hat{S} \hat{H}_2 \cdot \hat{H}_1 + \frac{1}{3} \kappa \hat{S}^3$$

- Additional singlet $\rightarrow$ 3 CP-even, 2 CP-odd Higgs states

$$\sum_{i=1}^{3} g_i^2 = 1$$

- If lightest Higgs is singlet dominated $\rightarrow$ Avoid LEP bound

- Another interesting possibility is very light $A_1$: $M_{A_1} < 2m_b$

  $H_1$ explains largest LEP excess: “Ideal” Higgs scenarios

  (Dermisek, Gunion)

- Difficult to discover light $A_1/H_1$ at LHC, and also “$H_{\text{SM}}$” since

  $$H_{\text{SM}} \rightarrow \phi \phi \rightarrow 4b, 4\tau, 2b2\tau$$

  $\phi = A_1, H_1$
MSSM -> NMSSM – Light CP-even Higgs bosons

- The lightest NMSSM Higgs may be much lighter than for the corresponding MSSM scenario...

... provided the $H_1$ coupling to Z bosons is suppressed by a large singlet component

- This also means reduced production in standard channels at LHC
Searching for Higgs bosons in SUSY cascades

\[ \tilde{q} \rightarrow q\tilde{\chi}_i^0 \rightarrow q\tilde{\chi}_j^0 H_k \rightarrow \ldots \]

- Alternative to standard production (\( gg \rightarrow H, \) VBF, etc.)
  - Strong cross sections
  - Hard scale for \( H \rightarrow b\bar{b} \)
  - Trigger on hard jet(s) + high MET

- CMS MC analysis of “LM5”
  \[ M_{H_1} \sim 116 \text{ GeV} \]
  \[ 5\sigma \text{ with } 1.5 \text{ fb}^{-1} (14 \text{ TeV}) \]

- Boosting the bb analysis

Kribs, Roy, Martin, Spannowsky,, [0912.4731], [1006.1656]
Gori, Schwaller, Wagner [1103.4138]
Cascades for light Higgs scenarios

- Higgs modes can be dominant when kinematically accessible Full 1-loop corrections to $\tilde{\chi}^0_i \rightarrow \tilde{\chi}^0_j H_k$ decays in CPV MSSM.

Also in the NMSSM the relevant decays have been studied at the level of BR:

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 H_i$

$M_{H_1} = 40$ GeV
$tan \beta = 5.5$

Fowler, Weiglein, [0909.5165]

Bandyopadhyay, [1008.3339]

Kraml, Porod, [hep-ph/0507055]

Choi, Miller, Zerwas, [hep-ph/0407209]

Cheung, Hou, [0809.1122]
**Phenomenological LHC analysis**

OS, G. Weiglein, [1108.0595]

- Starting point: NMSSM “P4” benchmark (light singlet $H_1$)...

  A. Djouadi et al, [0801.4321]

... slightly modified to allow for varying lightest Higgs mass

<table>
<thead>
<tr>
<th>Higgs sector parameters</th>
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<tbody>
<tr>
<td>$\lambda$</td>
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<tr>
<td>$\tan \beta$</td>
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<tr>
<td>$A_\lambda$</td>
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<tr>
<td>$\kappa$</td>
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<tr>
<td>$\mu_{\text{eff}}$</td>
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<tr>
<td>$A_\kappa$</td>
<td>$0 - 300$</td>
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Gaugino masses

| $M_1$               | 300 GeV |
| $M_3$               | 1000 GeV |

Trilinear couplings

$A_t = A_b = A_\tau = 0$ GeV

Soft scalar mass

$M_{\text{SUSY}} = 750$ GeV, 1 TeV
**Modified P4 Higgs spectrum**

NMSSMTools 2.3.5

- Example working point

\[
M_{H_1} = 40 \text{ GeV} \\
M_{H_2} = 116 \text{ GeV} \\
M_{A_1} = 184 \text{ GeV} \\
M_{H^\pm} \simeq 570 \text{ GeV} (\simeq M_{H_3} \simeq M_{A_2})
\]
Neutralino sector

\begin{align*}
\tilde{\chi}_1^0 & \quad 97.6 \text{ GeV} \quad \tilde{S}, \tilde{H} \\
\tilde{\chi}_2^0 & \quad 227 \text{ GeV} \quad \tilde{H} \\
\tilde{\chi}_3^0 & \quad 228 \text{ GeV} \quad \tilde{H} \\
\tilde{\chi}_4^0 & \quad 304 \text{ GeV} \quad \tilde{B} \\
\tilde{\chi}_5^0 & \quad 616 \text{ GeV} \quad \tilde{W} \\
\tilde{\chi}_2^0 & \quad \tilde{\chi}_3^0 & \quad \tilde{\chi}_4^0
\end{align*}

\begin{align*}
\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{W}^\pm \\
\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 \tilde{Z} \\
\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 \tilde{H}_1 \\
\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_1^0 \tilde{A}
\end{align*}
LHC analysis: MC simulation strategy

- **SUSY-QCD matrix elements**: 
  
  \[ pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \]

- **NMSSM resonance decays (external BR)**
  
  \[ \tilde{q} \to q\chi^0_i \to q\chi^0_1 H_k \to q\chi^0_1 b\bar{b}, \quad n_j \geq 1, \quad n_b \geq 2, \]
  
  \[ \tilde{g} \to g\tilde{q} \to gq\chi^0_i \to gq\chi^0_1 H_k \to gq\chi^0_1 b\bar{b}, \quad n_j \geq 2, \quad n_b \geq 2 \]

  Cascades may include charginos, W, Z, ...

- **ISR, FSR, Fragmentation, MPI**

- **Energy Smearing, fast ‘ATLAS’ detector simulation**
  
  \[ P(b\text{tag}|b) = 60\% \quad P(b\text{tag}|c) = 10\% \quad P(b\text{tag}|q) = 1\% \]
**Squark/Gluino production**

- Production of colored sparticles unchanged wrt MSSM
  \[ pp \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \]

- (S)QCD corrections **sizable** -> NLO

T. Plehn, Prospino

<table>
<thead>
<tr>
<th>Masses (GeV)</th>
<th>$\sigma_{LO}$ (pb)</th>
<th>$\sigma_{NLO}$ (pb)</th>
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<tr>
<td></td>
<td>$\tilde{g}\tilde{g}$</td>
<td>$\tilde{g}\tilde{q}$</td>
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<td>$\sqrt{s} = 7$ TeV</td>
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<td>0.07 0.27 0.39 0.08 0.82</td>
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<tr>
<td>1000 750</td>
<td>0.002 0.19 0.06 0.05 0.31</td>
<td>0.006 0.21 0.10 0.07 0.39</td>
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<tr>
<td>1000 1000</td>
<td>0.001 0.03 0.02 0.004 0.06</td>
<td>0.005 0.04 0.04 0.006 0.08</td>
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<tr>
<td>$\sqrt{s} = 14$ TeV</td>
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<tr>
<td>750 750</td>
<td>1.18 1.67 5.20 1.06 9.11</td>
<td>2.21 2.06 6.78 1.53 12.6</td>
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<tr>
<td>1000 750</td>
<td>0.15 1.41 1.86 0.96 4.38</td>
<td>0.32 1.59 2.44 1.34 5.69</td>
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<tr>
<td>1000 1000</td>
<td>0.14 0.42 0.87 0.18 1.61</td>
<td>0.31 0.51 1.19 0.26 2.27</td>
</tr>
<tr>
<td>1500 1500</td>
<td>0.01 0.04 0.05 0.01 0.10</td>
<td>0.01 0.05 0.07 0.02 0.15</td>
</tr>
</tbody>
</table>
Kinematic distributions

All histograms normalized to unity

$M_{\text{SUSY}} = 750 \text{ GeV}$
Results for LHC@7 TeV

- Cuts-based analysis to suppress SM tt background
- $\Delta R$ cut selects b-jet pairs from $H_1$ SUSY BG suppressed by $N_b$

\[ N_{jets} \geq 4 \quad N_b \geq 2 \]
\[ p_T(jet1) > 250 \text{ GeV} \]
\[ p_T(jet2) > 100 \text{ GeV} \]
\[ E_T^{miss} > 150 \text{ GeV} \]
\[ \min \Delta R(b\bar{b}) < 1.5 \]
Outlook: LHC@14 TeV

- Statistics greatly improved
- Clear signal also for 1 TeV case

\[ N_{\text{jets}} \geq 4 \quad N_b \geq 2 \]
\[ p_T(\text{jet1}) > 250 \text{ GeV} \]
\[ p_T(\text{jet2}) > 100 \text{ GeV} \]
\[ E_T^{\text{miss}} > 200 \text{ GeV} \]
\[ \min \Delta R(b\bar{b}) < 1.2 \]
Conclusions

- Light Higgs bosons ($M_H < M_Z$) compatible with constraints can exist in CP-violating MSSM and the NMSSM

- One method to search for light Higgses at the LHC could be through their production in SUSY cascades

- Several studies have shown that SUSY cascades have potential to aid Higgs searches in otherwise difficult channels

- We have worked out one NMSSM example in some detail
  -> Still meaningful to do Higgs searches in SUSY cascades at 7 TeV with squarks and/or gluinos close to present bounds
  -> Prospects at 14 TeV promising for even higher masses