IMPLICATIONS OF A STOP SECTOR SIGNAL AT THE HL-LHC

BASED ON:
HEP-PH 1611.00771 W/ AARON PIERCE

BIBHUSHAN SHAKYA

UNIVERSITY OF CINCINNATI

LEINWEBER CENTER FOR THEORETICAL PHYSICS
UNIVERSITY OF MICHIGAN
THE SEARCH FOR STOPS AT THE LHC

- strong constraints, but plenty of space left
- fine tuned, but not disastrous
- discovery of stops at HL/HE LHC with high significance still possible
THIS TALK

• IMPLICATIONS OF DISCOVERING A STOP SECTOR SIGNAL:

  • Not only a discovery of BSM physics, but an opportunity at the HL-LHC to
  • test the Higgs mass relation and the underlying theory
  • predict masses and properties of other supersymmetric particles
**HOW HEAVY ARE STOPS?**

\[ m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3 \sin^2 \beta y_t^2}{4\pi^2} \left[ m_t^2 \ln \left( \frac{m_{t_1} m_{t_2}}{m_t^2} \right) + c_t^2 s_t^2 (m_{t_2}^2 - m_{t_1}^2) \ln \left( \frac{m_{t_2}^2}{m_{t_1}^2} \right) \right] \\
+ c_t^4 s_t^4 \left\{ (m_{t_2}^2 - m_{t_1}^2)^2 - \frac{1}{2} (m_{t_2}^4 - m_{t_1}^4) \ln \left( \frac{m_{t_2}^2}{m_{t_1}^2} \right) \right\} / m_t^2, \]

Supersymmetry Primer

Higgs mass at one loop in the MSSM

- Determined by four parameters: two stop masses, mixing angle, tan beta (mild dependence)
- at higher order, depends on other parameters (e.g. gluino mass)
- 1 loop formula within 5 GeV of the correct mass
HOW HEAVY ARE STOPS?

\[ m^2_h = m_Z^2 \cos^2(2\beta) + \frac{3 \sin^2 \beta y_t^2}{4\pi^2} \left[ m_t^2 \ln \left( \frac{m_{t_1} m_{t_2}}{m_t^2} \right) + c_t^2 s_t^2 (m_{t_2}^2 - m_{t_1}^2) \ln \left( \frac{m_{t_2}^2}{m_{t_1}^2} \right) \right] \]

\[ + c_t^4 s_t^4 \left\{ (m_{t_2}^2 - m_{t_1}^2)^2 - \frac{1}{2} (m_{t_2}^4 - m_{t_1}^4) \ln \left( \frac{m_{t_2}^2}{m_{t_1}^2} \right) \right\} / m_t^2 \]

Knowing the Higgs mass does not constrain the stop mass scale:
Arbitrarily high stop masses compatible with the observed Higgs mass

- Giudice, Strumia;1108.6077
HOW HEAVY ARE STOPS?

\[ m_h^2 = m_Z^2 \]

\[ + c_t^4 s_t^4 \]

Knowing the Higgs mass does not constrain the stop mass scale: Arbitrarily high stop masses compatible with the observed Higgs mass...
HOW HEAVY ARE STOPS?

\[
m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3 \sin^2 \beta y_t^2}{4\pi^2} \left[ m_t^2 \ln \left( \frac{m_{t_1} m_{t_2}}{m_t^2} \right) + c_t^2 s_t^2 (m_{t_2}^2 - m_{t_1}^2) \ln \left( \frac{m_{t_2}^2}{m_{t_1}^2} \right) \right]
\]

\[
+ c_t^4 s_t^4 \left\{ (m_{t_2}^2 - m_{t_1}^2)^2 - \frac{1}{2} (m_{t_2}^4 - m_{t_1}^4) \ln \left( \frac{m_{t_2}^4}{m_{t_1}^4} \right) \right\} m_t^2 ,
\]

This outlook COMPLETELY changes if a stop discovered!

- Can no longer push the second stop mass arbitrarily high! (for nonzero mixing) - negative corrections to the Higgs mass!

- Stop discovery \(\rightarrow\) an upper bound on the heavier stop mass [in the MSSM]
**BASIC IDEA**

- Three parameters (two stop masses and the stop mixing angle) determine the Higgs mass at 1 loop in the MSSM
- **ONE** measurement allows strong constraints on the two remaining parameters
- **TWO** measurements allow prediction of the third parameter. Falsifying this prediction rules out the MSSM
- **THREE** measurements allow a consistency check of the Higgs mass, MSSM
EXAMPLE 1

$\tilde{b}_1$

A SBOTTOM SIGNAL IN MULTILEPTONS
[LET HANDED] SBOTTOM: PART OF THE STOP SECTOR

\[ m_{\tilde{b}_1}^2 = m_{\tilde{t}_2}^2 \sin^2 \theta_{\tilde{t}} + m_{\tilde{t}_1}^2 \cos^2 \theta_{\tilde{t}} - m_t^2 + m_W^2 \]

red, black, green, blue: \( m_{\tilde{b}_1} > 1000, 750 < m_{\tilde{b}_1} < 1000, 500 < m_{\tilde{b}_1} < 750, \) and \( m_{\tilde{b}_1} < 500 \) GeV respectively. Scan points consistent with \( 120 < m_h < 130 \) GeV and \( m_{\tilde{t}_1} < 1 \) TeV.
red, black, green, blue : \( m_{\tilde{b}_1} > 1000, 750 < m_{\tilde{b}_1} < 1000, 500 < m_{\tilde{b}_1} < 750, \) and \( m_{\tilde{b}_1} < 500 \) GeV respectively.

Scan points consistent with \( 120 < m_h < 130 \) GeV and \( m_{\tilde{t}_1} < 1 \) TeV
BENCHMARK SCENARIO

\[ \tilde{t}_2 : \quad m_{\tilde{t}_2} = 1022.2 \text{ GeV}, \quad \text{BR: } \tilde{t}_1 Z 79\%, \tilde{b}_1 W 15\%, \tilde{t}_1 h 2\%, \quad \sin \theta_t = 0.75 \]
\[ \tilde{b}_1 : \quad m_{\tilde{b}_1} = 885.4 \text{ GeV}, \quad \text{BR: } \tilde{t}_1 W 99.5\% \]
\[ \tilde{t}_1 : \quad m_{\tilde{t}_1} = 646.1 \text{ GeV}, \quad \text{BR: } t\chi_0 100\% \]
\[ \chi_0 : \quad m_{\chi} = 445.7 \text{ GeV}, \quad \text{LSP} \]
\[ h : \quad m_h = 123.2 \text{ GeV} \]

- sbottom decays give a multilepton signal
ANALYSIS

• Implement existing CMS search strategies


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<thead>
<tr>
<th>Search</th>
<th>$\sigma_{\text{prod/fb}}$</th>
<th>$\epsilon$</th>
<th>no. of signal events (S)</th>
<th>background events (B)</th>
<th>$S_{\sigma_{bg} = 0}$</th>
<th>$S_{\sigma_{bg} = 0.1}$</th>
<th>$S_{\sigma_{bg} = 0.3}$</th>
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<tr>
<td>$\tilde{t}_2$ contribution</td>
<td>5</td>
<td>8</td>
<td>11</td>
<td>-</td>
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<th>Search</th>
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<td>$\tilde{t}_2$ contribution</td>
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<td>21</td>
<td>-</td>
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</table>
HEAVIER STOP SEARCH

- knowing mass range and dominant decay channel for stop2, can optimize search strategy

Search for SUSY with multileptons in 13 TeV data, Tech. Rep. CMS-PAS-SUS-16-003

+ Z requirement instead of Z veto

<table>
<thead>
<tr>
<th>Search</th>
<th>$\sigma_{\text{prod}}$/fb</th>
<th>efficiency($\epsilon$) ($\times 10^{-4}$)</th>
<th>no. of signal events (S)</th>
<th>background events (B)</th>
<th>$S$</th>
<th>$S$</th>
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<td>$&gt;3l\text{onZ}$</td>
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<td>-</td>
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<td>1.7</td>
<td>0.7</td>
<td>0.3</td>
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</tbody>
</table>
• EXAMPLE 2

A HEAVIER STOP SIGNAL IN BOOSTED DIBOSONS
HEAVIER STOP IN MULTIPLE CHANNELS

- High lumi LHC can detect heavier stops in multiple decay channels

- Relative abundance of various channels contains information about the underlying parameters!

\[
R_{hZ} \equiv \frac{\Gamma(\tilde{t}_2 \to \tilde{t}_1 h)}{\Gamma(\tilde{t}_2 \to \tilde{t}_1 Z)} = \left[ \left( 1 - \frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}} \right) \cos 2\theta_{t} + \frac{m^2_W}{m^2_{\tilde{t}_2}} \left( 1 - \frac{5}{3} \tan^2 \theta_W \right) \right]^2 \approx \left( 1 - \frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}} \right)^2 \cos^2 2\theta_{t}
\]

- Experimentally: measure the ratio as

\[
R_{hZ} \sim \frac{2 n_{hh}}{n_{Zh}}
\]
### BENCHMARK SCENARIO

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
<th>Branching Ratios</th>
<th>Other Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{t}_2$</td>
<td>$m_{\tilde{t}_2} = 994.2$ GeV</td>
<td>$\tilde{t}_1 Z$ 52%, $\tilde{t}_1 h$ 28%, $\sin^2 \theta_t = 0.988$</td>
<td></td>
</tr>
<tr>
<td>$\tilde{b}_1$</td>
<td>$m_{\tilde{b}_1} = 977.5$ GeV</td>
<td>decays dominantly to $\tilde{t}_1 W$</td>
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</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td>$m_{\tilde{t}_1} = 486.0$ GeV</td>
<td>decays dominantly to $c\chi_0$</td>
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<tr>
<td>$\chi_0$</td>
<td>$m_\chi = 406.0$ GeV</td>
<td>LSP</td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>$m_h = 109.2$ GeV</td>
<td></td>
<td></td>
</tr>
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</table>
• Implemented search strategy for boosted dibosons from

• We end up with $n_{hh} = 47$, $n_{Zh} = 176$
We conclude this section with a few miscellaneous comments. With approximate knowledge of the stop masses (darker red band) or with an improved analysis with better signal event tagging, while assume that the stop mixing angle is known to fall in the 994 GeV. The blue dot denotes the benchmark point in our analysis. The golden band of data.

Next, we discuss how this measurement can shed light on the Higgs boson mass relation. Like-wise, if the sbottom has not already been discovered, the above measurements can also be used to predict the mass and decay channels of the sbottom, aiding in its discovery. For our benchmark point (with the narrower stop mass windows discussed above), we find that the stop mixing angle. For our benchmark point.

Light red: $440 \leq m_{\tilde{t}_1} \leq 520$ GeV and $930 \leq m_{\tilde{t}_2} \leq 1030$ GeV

Dark red: $450 \leq m_{\tilde{t}_1} \leq 510$ GeV $945 \leq m_{\tilde{t}_2} \leq 1015$ GeV

The trend in Fig. 8 is consistent with these observations. Thus, an inferred value of $\sin \beta$ is known to fall in the 994 GeV. The blue dot denotes the benchmark point in our analysis. The golden band of data.

For our benchmark point. Under our assumptions, exclusion of the MSSM region $(\tilde{t}_1\tilde{t}_2)$ is incompatible with the MSSM Higgs mass relation. Such an inferred value of $\sin \beta$ is known to fall in the 994 GeV. The blue dot denotes the benchmark point in our analysis. The golden band of data.

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SUMMARY

- Stop sector intricately tied to the Higgs mass. Stop sector discovery is an opportunity to test the Higgs mass relation.

- Can predict masses and properties of other supersymmetric particles, aiding in their discovery (example: sbottom signal in multileptons).

- Can perform consistency checks to identify the underlying theory / rule out the MSSM (example: heavier stop decays in boosted dibosons).