Natural Susy Endures

Andreas Weiler
(DESY)

Implications of LHC results for TeV-scale physics: WG2 meeting
11/1/11

In collaboration w/
Michele Papucci & Josh Ruderman (Berkeley)
arXiv:1110.6926
The next 16 minutes

- Reminder about bottom-up naturalness: Which super-partners need to be light?
- Current status of SUSY searches
- Our Limits
  - Method & Caveats
  - Stop limits
  - +Gluino limits

→ Nima’s talk
The next 16 minutes

- Reminder about bottom-up naturalness: Which super-partners need to be light?
- Current status of SUSY searches
- Our Limits
  - Method & Caveats
  - Stop limits
  - +Gluino limits

Which current searches work best?

→ Nima's talk
Natural EWSB & SUSY*  
* valid beyond MSSM

Do not want tuning in \((\text{Higgs mass})^2\)

\[
\frac{m_{Higgs}^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2
\]
Natural EWSB & SUSY*

*valid beyond MSSM

Do not want tuning in \((\text{Higgs mass})^2\)

\[
\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H
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Higgsinos
Natural EWSB & SUSY

Do not want tuning in \((\text{Higgs mass})^2\)

\[
\frac{m^2_{\text{Higgs}}}{2} = -|\mu|^2 + \ldots + \delta m^2_H
\]

\(\text{Higgsinos}\)

1 loop

\[
\delta m^2_H|_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left( m^2_{U_3} + m^2_{Q_3} + |A_t|^2 \right) \log \left( \frac{\Lambda}{\text{TeV}} \right)
\]

2 loop

\[
\delta m^2_H|_{\text{gluino}} = -\frac{2}{\pi^2} y_t^2 \left( \frac{\alpha_s}{\pi} \right) |M_3|^2 \log^2 \left( \frac{\Lambda}{\text{TeV}} \right)
\]
Natural EWSB & SUSY

Do not want tuning in $(\text{Higgs mass})^2$

\[
\frac{m_{Higgs}^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2
\]

Higgsinos

1 loop \( \delta m_H^2 \mid_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left( m_{U3}^2 + m_{Q3}^2 + |A_t|^2 \right) \log \left( \frac{\Lambda}{\text{TeV}} \right) \)

stops, sbottom

2 loop \( \delta m_H^2 \mid_{\text{gluino}} = -\frac{2}{\pi^2} y_t^2 \left( \frac{\alpha_s}{\pi} \right) |M_3|^2 \log^2 \left( \frac{\Lambda}{\text{TeV}} \right) \)

gluino
Bottom-up natural spectrum

The “Nuclear Family” of the Higgs

500 GeV

1 TeV

μ

Closeness to Higgs

Fig. from L.Hall’s recent talk @ LBL
Bottom-up natural spectrum

The “Nuclear Family” of the Higgs

The “Nuclear Family” of the Higgs

Can be light, but don’t have to

“Distant Cousins”

Fig. from L.Hall’s recent talk @ LBL
Current status

Gluino $\gtrsim 0.7-0.9$ TeV

Squarks$_{1,2} \gtrsim 0.8 - 1$ TeV
Current status

Gluino $\gtrsim 0.7-0.9$ TeV

Squarks$_{1,2} \gtrsim 0.8 - 1$ TeV
Current status

Gluino $\gtrsim 0.7-0.9$ TeV

Squarks $1,2 \gtrsim 0.8 - 1$ TeV

For natural spectrum need to split 1,2 vs. 3rd generation squarks
Existing limits on Stops and sbottoms

- Tevatron:
  - **Stops** can still be **light** (even 120-180 GeV)
  - **Sbottoms** should be > 250 GeV
Existing limits on Stops and sbottoms

- **Tevatron:**
  - Stops can still be light (even 120-180 GeV)
  - Sbottoms should be > 250 GeV

- **LHC on 3rd generation:**
  - exclusion driven by gluinos

\[ \tilde{g} \rightarrow \tilde{b}_1 \]

\[ pp \rightarrow 4b + 2\tilde{N}_1 \]

\[ \tilde{B} \]

\[ \tilde{t}_1, \tilde{b}_1 \]

---

**Note:**

The diagram shows the exclusion limits on the \( m(\tilde{g}) \) vs. \( m(\tilde{b}_1) \) plane for different scenarios. The HS model is discussed, where larger branching ratios are found for gluino masses above 200 GeV. The results can be generalised in terms of 95% C.L. upper cross sections. The expected limits are shown for the ATLAS experiment. The long-dashed line indicates the expected limit. The figure includes a reference point and a table with specific values.
Direct stop prod. with 1/fb?

\[ \sigma_{\text{tot}}[\text{pb}]: pp \rightarrow \text{SUSY} \]

\[ m_{\text{average}}[\text{GeV}] \]

Prospino2.1

Covered by exp

\[ \tilde{q}\tilde{g} \]
\[ \tilde{g}\tilde{g} \]
\[ \tilde{q}\tilde{q}^* \]
\[ \tilde{\chi}^0_{2}\tilde{\chi}^0_{LO} \]
\[ \tilde{\chi}^0_{1}\tilde{\chi}^0_{1}^* \]
\[ \tilde{\chi}_{2}\tilde{\chi}_{1}^{+} \]
\[ \tilde{\nu}_{e}^* \]

Direct stop production with 1/fb?
Direct stop prod. with 1/fb ?

\[ \sigma_{\text{tot}} \text{[pb]} : pp \rightarrow \text{SUSY} \]

Covered by exp

\[ q\tilde{g}, \tilde{q}\tilde{g}, \tilde{q}\tilde{q}^* \]

\[ \tilde{g}\tilde{g} \]

Direct stop prod. with 1/fb ?

Prospino2.1

Average \[ \sqrt{s} = 7 \text{ TeV} \]
“The experiments haven’t covered my favorite model”

Relax & Wait?

Michele* vs.

* not his real attitude.
“The experiments haven’t covered my favorite model”

Relax & Wait?

Michele* vs. Josh

Check yourself!

* not his real attitude.
Our Limits

today: arXiv:1110.6926
M. Papucci, J. Ruderman, AW
our pipelines

**ATOM**

- public code soon
- pythia / herwig / etc
- fastjet
- truth leptons / photons / b’s
  - l/gamma iso
  - parameterized efficiencies

**PGS**

- pythia
- crude detector sim
- cone jets
- truth muons/b’s
  - parameterized efficiencies
- crude simulated e/gamma

checks sensitivity of cut & leakage in control region
Calibration

“theorist limits”

To calibrate compare:
1) key kinematical distributions
2) limits
Check:

- kinematic distortions (shape)
- signal $\epsilon \times A$ (normalization)

+ compare to all available limit plots…

~ 50 GeV accuracy (usually better)
# Large signature space

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets + $E_T$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-8 jets</td>
<td>$L = 1.34$ [fb$^{-1}$] ref. [2]</td>
<td></td>
</tr>
<tr>
<td>B-jets (+ l’s + $E_T$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1$b$, 2$b$</td>
<td>$L = 0.83$ [fb$^{-1}$] ref. [3]</td>
<td>$m_{T2}$ (+ $b$) $L = 1.1$ [fb$^{-1}$] ref. [13]</td>
</tr>
<tr>
<td>$b + 1l$</td>
<td>$L = 1.03$ [fb$^{-1}$] ref. [4]</td>
<td>$1b$, 2$b$ $L = 1.1$ [fb$^{-1}$] ref. [14]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$b'b' \rightarrow b + l^\pm l^\pm, 3l$ $L = 1.14$ [fb$^{-1}$] ref. [15]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$t't' \rightarrow 2b + l^+l^-$ $L = 1.14$ [fb$^{-1}$] ref. [16]</td>
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<tr>
<td>Multilepton (+ $E_T$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^\pm \mu^\pm$</td>
<td>$L = 1.6$ [fb$^{-1}$] ref. [6]</td>
<td>SS dilepton $L = 0.98$ [fb$^{-1}$] ref. [18]</td>
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<tr>
<td>$t\bar{t} \rightarrow 2l$</td>
<td>$L = 1.04$ [fb$^{-1}$] ref. [7]</td>
<td>OS dilepton $L = 0.98$ [fb$^{-1}$] ref. [19]</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow 1l$</td>
<td>$L = 1.04$ [fb$^{-1}$] ref. [8]</td>
<td>$Z \rightarrow l^+l^-$ $L = 0.98$ [fb$^{-1}$] ref. [20]</td>
</tr>
<tr>
<td>4$l$</td>
<td>$L = 1.02$ [fb$^{-1}$] ref. [9]</td>
<td>$3l, 4l + E_T$ $L = 2.1$ [fb$^{-1}$] ref. [21]</td>
</tr>
<tr>
<td>2$l$</td>
<td>$L = 1.04$ [fb$^{-1}$] ref. [10]</td>
<td>$3l, 4l$ $L = 2.1$ [fb$^{-1}$] ref. [22]</td>
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</tr>
<tr>
<td>jets + $E_T$</td>
<td></td>
<td></td>
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<tr>
<td>2-4 jets</td>
<td>1.04</td>
<td>1.14</td>
</tr>
<tr>
<td>6-8 jets</td>
<td>1.34</td>
<td>1.1</td>
</tr>
<tr>
<td>$b$-jets (+ $l$’s + $E_T$)</td>
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<td>0.98</td>
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<td>$t\bar{t} \rightarrow 2l$</td>
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<td>1.02</td>
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<td>1.04</td>
<td>2.1</td>
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**TABLE I:** Searches by ATLAS and CMS, with about 1 fb$^{-1}$, for signatures that are produced by models of natural supersymmetry. We have categorized the searches into three categories, (1) fully hadronic, (2) heavy flavor, with or without leptons, and (3) multileptons without heavy flavor. The searches with blue labels have not been used by experimentalists to set limits on supersymmetry, but we have included them because they overlap with SUSY signature space. We have simulated all of the above searches and included them in our analysis, with the exception of the searches with red labels, which were released while we were finalizing this study. We explored the possibility of using the CMS search for $t\bar{t}$ in the lepton plus jets channel, however this search uses a kinematic fit on signal plus background and does not report enough information for us to extrapolate this fit to other signals.
Stops (sbottom) + Higgsinos

Stops can act as “sbottom” (bjet+χ)!
Chargino-neutralino splitting irrelevant for present searches
For comparison with the LHC limits, we have also shown in Fig. 3, the strongest limit from the Tevatron, which comes from the D_{0} s bottom with \text{5.2 fb}^{-1}. This search sets limits on sbottom pair production, with the decay \tilde{b} \rightarrow \tilde{b} N_{1}. For the left-handed spectrum, this limit applies directly to the sbottom, which decays \tilde{b}_{L} \rightarrow \tilde{b} H_{0} for the mass range of interest (the decay to top and chargino is squeezed out). For the right-handed stop, the dominant decay is \tilde{t}_{R} \rightarrow \tilde{b} H^{\pm}, which means that the stop acts like a sbottom, from the point of view of the Tevatron search. We note that the Tevatron limit only applies for higgsinos just above the LEP-2 limit, \text{m}_{\tilde{H}_{1}} < \sim 110 \text{ GeV}, and we see that the Tevatron has been surpassed by the LHC in this parameter space.

LHC surpasses Tevatron:
Strongest bounds from jets + MET
• RH stop → Bino: top-like final state. Weak bound around 200 GeV, but we don’t trust it too much. Further (exp’) study needed...
Un-Splitting the spectrum

\[ m_{Q_3} - m_{u_3} > 0 \]
\[ \tilde{X}_t = 0 \]

\[ m_{Q_3} - m_{u_3} < 0 \]
\[ \tilde{X}_t = 0 \]

\[ |\tilde{X}_t| > 0 \]
Un-Splitting the spectrum

stronger bound on the left due to light sbottom

TeVatron bounds not shown b/c they have no sensitivity for \( m_{\text{LSP}} > 110 \text{GeV} \)
Adding gluinos

- \tilde{g}
- \tilde{t}_{L,R}
- \tilde{b}_L
- \tilde{H}
- higgsino LSP
- split stops
- \tilde{t}_R
- \tilde{b}_L
- \tilde{H}
- \tilde{B}

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- \tilde{H}
- higgsino LSP
- split stops
- \tilde{t}_R
- \tilde{b}_L
- \tilde{H}
- \tilde{B}

quasi-degenerate 3-rd gen’
Adding the gluinos

Higgsino LSP

Gluino bounded (again) by jets+MET, and 1lep searches

Bino LSP

Gluino mostly bounded by Same Sign searches
Adding the squarks, too

- Bounds similar to the ATLAS/CMS plots (800 GeV - 1 TeV)
- Decoupling not effective until 1.2-1.4 TeV

Un-decoupling the other squarks

- $m_{\tilde{g}}$ = 520 GeV
- $\mu$ = 200 GeV
- $M_1$ = 100 GeV
Squashed spectrum

Somewhat Squashed Spectrum

CMS $H_T$/MET, 1.1 fb$^{-1}$
CMS $M_{T2}$, 1.1 fb$^{-1}$
CMS $\alpha_T$, 1.14 fb$^{-1}$
ATLAS b, 0.83 fb$^{-1}$

CMS $H_T$/MET, 1.1 fb$^{-1}$
CMS $M_{T2}$, 1.1 fb$^{-1}$
CMS $\alpha_T$, 1.14 fb$^{-1}$
ATLAS b, 1.14 fb$^{-1}$

Split Stops

CMS SS, 0.98 fb$^{-1}$
CMS $M_{T2}$, 1.1 fb$^{-1}$
CMS $\alpha_T$, 1.1 fb$^{-1}$
ATLAS b, 1.14 fb$^{-1}$

$M_3 - M_1 = 300$ GeV
$M_3 - \mu = 150$ GeV

$\tilde{g}$

$\tilde{t}_L, \tilde{t}_R$

$\tilde{b}_L$

$\tilde{H}^0, \pm$

$\tilde{B}$

$\tilde{g}$

$\tilde{t}_R$

$\tilde{t}_L, \tilde{b}_L$

$\tilde{H}^0, \pm$

$\tilde{B}$
MSSM little hierarchy problem

• Higgs mass lifted by large A-terms $\rightarrow$ split stop spectrum, 1 stop may be light and constrained by searches

• Compare to constraints from the Higgs mass bound?

• CAVEAT: only for higgsinos (higgsinos+binos) lighter than stops...
MSSM higgs: LEP2 tuning vs. direct stop

\[
\sqrt{m_{Q_3}^2 + m_{U_3}^2} = \delta m_H^{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left( m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2 \right) \log \left( \frac{\Lambda}{\text{TeV}} \right)
\]
MSSM higgs: LEP2 tuning vs. direct stop

Maximal mixing (for light Higgsino case) probed by the LHC… interesting interplay with Higgs searches.
Summary

<table>
<thead>
<tr>
<th>production</th>
<th>LSP</th>
<th>$\tilde{t}$ limit [GeV]</th>
<th>figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{t}_L + \tilde{b}_L$</td>
<td>$\tilde{H}$</td>
<td>$\sim 250$</td>
<td>3</td>
</tr>
<tr>
<td>$\tilde{t}_R$</td>
<td>$\tilde{H}$</td>
<td>$\sim 180$</td>
<td>3</td>
</tr>
<tr>
<td>$\tilde{t}_L + \tilde{b}_L$</td>
<td>$\tilde{B}$</td>
<td>$\sim 250 - 350$</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>scenario</th>
<th>$\tilde{g}$ limit [GeV]</th>
<th>$\tilde{t}$ limit [GeV]</th>
<th>figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{H}$ - LSP</td>
<td>$\sim 650 - 700$</td>
<td>$\sim 280$</td>
<td>10</td>
</tr>
<tr>
<td>$\tilde{B}$ - LSP</td>
<td>$\sim 700$</td>
<td>$\sim 270$</td>
<td>10</td>
</tr>
<tr>
<td>somewhat squashed</td>
<td>$\sim 600 - 700$</td>
<td>–</td>
<td>11</td>
</tr>
<tr>
<td>split $\tilde{t}$</td>
<td>$\sim 550 - 650$</td>
<td>–</td>
<td>11</td>
</tr>
<tr>
<td>flavor degen.</td>
<td>$1200$ (fixed)</td>
<td>$600 - 900$</td>
<td>16</td>
</tr>
<tr>
<td>gaugino unify</td>
<td>$\sim 750 - 800$</td>
<td>$\sim 260$</td>
<td>16</td>
</tr>
</tbody>
</table>

arXiv:1110.6926
Outlook

- Next frontier: **Heavy flavor themed naturalness** (Eder’s & Andrey’s talks), **EW-inos** (Shufang’s talk)

- Natural SUSY not in trouble yet (and won’t be before shutdown). Trouble only for high-scale, flavor universal models

- LHC will cover very exciting ground in the coming years
Backup
Projections?

Higgsino LSP w/ 10 fb\(^{-1}\)

- **dashed** - perfect bgd's
- **solid** - statistics improves, systematics same fraction

* Large uncertainty
* Targeted searches do likely better.
natural SUSY

\[ g \]
\[ \tilde{b}_L \quad \tilde{t}_L \quad \tilde{b}_R \quad \tilde{t}_R \]
\[ \tilde{H} \]

decoupled SUSY

\[ \tilde{B} \quad \tilde{W} \]
\[ \tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2} \]
\[ \tilde{L}_i, \tilde{e}_i \]
\[ \tilde{b}_R \]
this part of the spectrum does not matter much for naturalness & can be heavier
parameters: \( \mu, \tan \beta \)
\( m_{Q_3}, m_{u_3}, A_t \)
\( M_3 \)

\[ \begin{align*}
\tilde{g} \\
\tilde{t}_L & \quad \tilde{t}_R \\
\tilde{b}_L \\
\tilde{H} \\
\end{align*} \]

\[ \begin{align*}
\tilde{B} \\
\tilde{W} \\
\tilde{L}_i, \tilde{e}_i \\
\tilde{Q}_{1,2}, \tilde{u}_{1,2}, \tilde{d}_{1,2} \\
\tilde{b}_R \\
\end{align*} \]

natural SUSY

decoupled SUSY

This part of the spectrum does not matter much for naturalness and can be heavier.
Calibrate w/ limit plots

- broad range of kinematical configurations
- even with 50% accuracy of $\epsilon \times A$ (mostly better)
  limits are very similar (thanks to pdf’s!)

Caveat: if efficiency very sensitive to cut: wouldn’t trust it (ATOM flags that).
Back to the flavor degenerate case

Hard to investigate more squashed spectra
(+ additional tuning due to squashing...)

Flavor Degenerate Squarks

ATLAS 2–4 j, 1.04 fb$^{-1}$
CMS $H_T$/ MET, 1.1 fb$^{-1}$
CMS $\alpha_T$, 1.14 fb$^{-1}$
CMS $M_{T2}$, 1.1 fb$^{-1}$

$m_g = 1.2$ TeV
Tuning in the MSSM

\[ m_{h^0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\text{stop}}^2}{m_t^2} \]
Tuning in the MSSM

\[ m^2_{h_0} \approx m^2_Z \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m^2_{\text{stop}}}{m_t^2} \]

Negative search at LEP: \( m_H > 114 \text{ GeV} \)

Therefore need \( m_{\text{stop}} \sim O(1 \text{ TeV}) \).

But at minimum,
Tuning in the MSSM

\[ m_{h_0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{\text{stop}}^2}{m_t^2} \]

Negative search at LEP: \( m_H > 114 \) GeV
Therefore need \( m_{\text{stop}} \sim O(1 \text{ TeV}) \).

But at minimum,

\[ \frac{m_Z^2}{2} = -|\mu|^2 - \frac{m_{H_u}^2 \tan^2 \beta - m_{H_d}^2}{\tan^2 \beta - 1} \approx -m_{H_u}^2 \]
Tuning in the MSSM

\[ m_{h_0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln \frac{m_{stop}^2}{m_t^2} \]

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\[ \delta m_{H_u}^2 (\text{loop}) = -\frac{3y_t^2}{8\pi^2} m_{stop}^2 \ln \frac{\Lambda^2}{m_{stop}^2} \approx 600 \cdot \frac{m_Z^2}{2} \]
Tuning in the MSSM

\[ m_{h_0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2v^2} \ln \frac{m_{stop}^2}{m_t^2} \]

Negative search at LEP: \( m_H > 114 \) GeV

Therefore need \( m_{stop} \sim O(1 \text{ TeV}) \).

But at minimum,

\[ \frac{m_Z^2}{2} = -|\mu|^2 \approx \frac{m_{H_u}^2}{\tan^2 \beta - \tan^2 \beta - 1} \tan^2 \beta - 1 \approx -m_{H_u}^2 \]

\[ \delta m_{H_u}^2 (\text{loop}) = -\frac{3y_t^2}{8\pi^2} m_{stop}^2 \ln \frac{m_{stop}^2}{m_{stop}^2} \approx 600 \cdot \frac{m_Z^2}{2} \]
Raise tree-level Higgs mass? $m_{\text{stop}}$ reduced!

a) F-Term (NMSSM)
b) D-term (extended gauge structure)
\[ \delta m_{Hu}^2 \text{(loop)} = - \frac{3y_t^2}{8\pi^2} m_{stop}^2 \ln \frac{\Lambda^2}{m_{stop}^2} \]

- Raise tree-level Higgs mass? \( m_{stop} \) reduced!
  
  a) F-Term (NMSSM)
  
  b) D-term (extended gauge structure)

- Lower the cut-off?
  
  c) NMSSM (large \( S H_u H_d \) coupling \( \Rightarrow \Lambda_{\text{Landau}} \ll M_{\text{Gut}} \))

  d) Find rationale why \( \Lambda = \text{(protection scale} \ f) \sim \mathcal{O}(\text{TeV}) \)
      (i.e. little Higgs like protection)