Phenomenological Targets for String Model Building

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Please ask questions while I’m talking
Targets

- Higgs
- Supersymmetry
- $t\bar{t}$ asymmetry
- $b$ results
- 130 GeV dark matter line
- Neutrino masses/mixings
2011 Higgs Exclusion

![ATLAS Preliminary 2011 Data](image1.png)

![CMS Preliminary](image2.png)
2011 Higgs Signal

ATLAS

Data

MC $m_H=130$ GeV, 1xSM

Total background (Fit)

$H \rightarrow \gamma\gamma$

$\int Ldt = 4.9 \text{ fb}^{-1}$

Events / 1 GeV

$\gamma\gamma$
2011 Higgs Signal

**ATLAS:** $H \rightarrow \gamma\gamma$: 2.8\sigma
$H \rightarrow ZZ \rightarrow llll$: 2.1\sigma
$H \rightarrow WW^*$: 1.4\sigma.

**CMS:** $H \rightarrow \gamma\gamma$: 3.1\sigma
$H \rightarrow ZZ \rightarrow llll$: 2.4\sigma.

combined LEE: 2.2\sigma
combined LEE: 1.5\sigma
Branching ratios

![Graph showing branching ratios for Higgs boson decay modes: H → bb, H → ττ, H → γγ, H → WW, H → ZZ → 4l, with CMS data at √s = 7 TeV, L = 4.6 - 4.8 fb⁻¹.]
2012 Higgs

NNLO+NNLL QCD+2 loop EW predictions

$$\sigma_H(7 \text{ TeV}) = 15\pm3\pm1 \text{ pb}, \; \sigma_H(8 \text{ TeV}) = 20\pm3\pm1 \text{ pb}.$$ 

Backgrounds also go up, but overall an increase of 10-20% sensitivity is expected for the same luminosity.

If it goes away, you’ll need to build invisible higgs models, or models with suppressed cross-sections.

Implications for MSSM SUSY breaking:

<table>
<thead>
<tr>
<th>model</th>
<th>AMSB</th>
<th>GMSB</th>
<th>mSUGRA</th>
<th>no-scale</th>
<th>cNMSSM</th>
<th>VCMSSM</th>
<th>NUHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_h^{\max}$</td>
<td>121.0</td>
<td>121.5</td>
<td>128.0</td>
<td>123.0</td>
<td>123.5</td>
<td>124.5</td>
<td>128.5</td>
</tr>
</tbody>
</table>
$E_T = 984, \ p_T = 974, 276, 146, 61$
Natural SUSY

The particles coupling the most strongly to the higgs are the stops\( ^a \). Minimising the MSSM Higgs potential,

\[
-\frac{M_Z^2}{2} \approx |\mu|^2 + m_{H_2}^2,
\]

\[
\delta m_{H_2}^2 \approx \frac{-3h_t^2}{4\pi^2} \frac{m_t^2}{m_{\tilde{t}}} \ln \left( \frac{\Lambda_{\text{UV}}}{m_{\tilde{t}}} \right)
\]

\( ^a \) M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926;
Natural SUSY

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\[-\frac{M_Z^2}{2} \approx |\mu|^2 + m_{H_2}^2,\]

\[\delta m_{H_2}^2 \approx -\frac{3h_t^2}{4\pi^2}m_t^2 \ln \left( \frac{\Lambda_{UV}}{m_t} \right)\]

No cancellation⇒

\[m_t \sim 700 \text{ GeV}, \quad m_g \sim 1000 \text{ GeV}.\]

Experimental $E_T$ searches⇒

\[m_t > 500 \text{ GeV}, \quad m_g > 900 \text{ GeV}.\]

\(^a\) M. Papucci, J. T. Ruderman and A. Weiler, arXiv:1110.6926;
$\tilde{g}t: \quad E_T^* > 50/120 \text{ GeV}, \quad N_b \geq 2, \quad \#j \geq 2, \quad H_T > 320 \text{ GeV}$
Higgs and SUSY Implications

Getting a high enough $m_h$ may require heavy stops in the MSSM, which is usually *un-natural*. Solutions:

- High energy correlations between parameters in your string model
- Build in a singlet: the NMSSM, or other structure on top of the MSSM, raising the Higgs mass
Jets Plus $E_T$ Search

![Graph showing squark-gluino-neutralino model with $m(\tilde{\chi}_0) = 0$ GeV. The graph includes ATLAS Preliminary Combined limits, observed and expected limits, and various SUSY production cross sections. The graph demonstrates the search for SUSY particles through the analysis of $E_T$.](image-url)
Bottom Up Implications of 2011 Data

Naturalness is under pressure. Ways to get around it:

- First two generation squarks $> 1.8$ TeV, $m_{\tilde{t}} = 0.5 - 0.7$ TeV, $m_{\tilde{g}} = 0.9 - 1$ TeV, $m_{\chi_1^0} < 0.5$ TeV. Ruled out soon?

- Compressed spectra$^a$ bounds from current jets plus $E_T$ searches become less stringent

- RPV decreases/removes the $E_T$.$^b$
  - Explains why natural SUSY hasn’t been found yet
  - Like-sign dileptons is a generic signature, as we’ll see

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$^a$LeCompte, Martin arXiv:1111.6897

$^b$BCA, Gripaios arXiv:1202.6616
Baryon Number Violating Example

Can lead to natural SUSY with light stops and gluinos that hasn’t been excluded yet. A difficult case: \( W \supset \lambda''_{ijk} U_i D_j D_k \).

\[ \tilde{g} \rightarrow \tilde{t}^* \rightarrow t \]

\[ \tilde{g} \rightarrow \tilde{t}^* \rightarrow \bar{t} \]

\[ \tilde{g} \rightarrow d_j \to b \]

\[ \tilde{g} \rightarrow d_j \to b \]

\( \tilde{g}\tilde{g} \) production dominates. Here, you can look for like-sign di-leptons since gluinos decay into \( t \) and \( \bar{t} \) with equal branching ratios.
$A_{FB}$ in the Standard Model

1.96 TeV $p\bar{p}$ collisions at the Tevatron.

$$A_{FB} = \frac{N(c > 0) - N(c < 0)}{N(c > 0) + N(c < 0)}, \quad c = \cos \theta.$$  

SM Prediction: 0.066.
Measurements of $A_{FB}$

S Leone (CDF) talk at Electroweak session of Rencontres de Moriond 2012.
Other Constraints

\[ \sigma_{tt}^{LHC7} = 173.4 \pm 10.6 \text{ pb}, \quad \sigma_{tt}^{SM} = 163 \pm 10 \text{ pb} \]

\[ A_y^C = \frac{N(|y_t| > |\bar{y}_t|) - N(|\bar{y}_t| > |y_t|)}{N(|y_t| > |\bar{y}_t|) + N(|\bar{y}_t| > |y_t|)} = -0.015 \pm 0.04, \]

where \( y_i = \frac{1}{2} \ln \left( \frac{E_i - p_{iz}}{E_i + p_{iz}} \right) \) is the rapidity of particle \( i \). \( A_y^{SM} = 0.006 \pm 0.002 \).
Many models of random particles have been proposed, but most don’t fit all the data. However, this one does:

\[ W = \frac{\lambda''^*_{313}}{2} t_R d_R b_R \]

\[ \chi''_313 \]

\[ \tilde{b}_R \]

\[ t_R(q_1) \]

\[ t_R(q_2) \]

\[ d_R(p_1) \]

\[ d_R(p_2) \]

\[ \chi''_313 \]

Figure 1: SUSY contribution to \( \Delta A_{FB} \)

\[ \Delta A_{FB} \]

BCA, Sridhar arXiv:1205.5170
$B_s \rightarrow \mu^+\mu^- : \text{LHCb 1 fb}^{-1}$

$BR(B_s \rightarrow \mu^+\mu^-) = 0.8^{+1.8}_{-1.3} \times 10^{-9}$

$BR(B_s \rightarrow \mu^+\mu^-)^{SM} = 3.2 \pm 0.2 \times 10^{-9}$

Morata, Moriond 2012: better not have too large $\tan^6 \beta/M_A^4$ for light $\tilde{t}$!
130 GeV Fermi/LAT line

Fermi/LAT measures galactic $\gamma$s. Weniger$^{a}$ analysed their data with optimised regions of the sky and found $3.3\sigma$ evidence of a $\gamma$ ray line at 130 GeV. Rates $\chi_1$ predicted by eg $\chi_0 \rightarrow \gamma$ are too low: BR would need to be $5 - 8\%$. Models have been built where dark matter annihilates to heavy states which then decay to approximately mono-energetic photons, however.

$^{a}$Weniger, arXiv:1204.2797
Residual Map
Su, Finkbeiner arXiv:1206.1616
Energy Spectrum in Cusp

\[ 3.7\sigma \]
Daya Bay and Neutrino Oscillations

Previous oscillation results for 3 neutrino flavours imply:

\[ |\Delta m^2_{21}| = 7.6 \times 10^{-5} \text{eV}^2, \quad |\Delta m^2_{31}| = 2.3 \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 2\theta_{12} = 0.86 \]

Measure \( \bar{\nu}_e \) survival probability

\[
P = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.267 \Delta m^2_{31}}{E} \right) \]

\[- \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{1.267 \Delta m^2_{21} L}{E} \right) \]

by measuring total reactor flux from near/far detectors. Know everything expect for \( \theta_{13} \).
Neutrino mixing

Good prospects to measure CP violation.

Models: Strict Tri-bimaximal is \textit{out}\footnote{Daya Bay, MINOS, Chooz, Double Chooz, T2K.}

\begin{equation*}
\begin{bmatrix}
|U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\
|U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2 \\
|U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2 \\
\end{bmatrix} = \begin{bmatrix}
2 & 1 & 0 \\
\frac{3}{2} & \frac{1}{3} & \frac{1}{2} \\
\frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\
\end{bmatrix}
\end{equation*}
Summary

• All eyes on the Higgs boson this (apparently 4th) July

• MSSM is under naturalness pressure from Higgs results: opportunity for stringy model builders

• SUSY is natural only if one has: compressed spectra, $R$—parity violation, or a split spectrum with certain particles light (i.e. sub-TeV): gluino, stop, neutralino, chargino, first two generations of sleptons

• Tevatron $t\bar{t}$ forward backward asymmetry stands out

• As does a potential 130 GeV gamma ray line in Fermi-LAT data: keep an eye on it
Backup
Other Light States

How robust is the same-sign dilepton signature in the case that other states are also light?

**Figure 1.** Gluino decays without right-handed bottom squarks in the presence of $W \supset U_3 D_1 D_2$, via (a) right-handed top, (b) left-handed top, and (c) left-handed bottom. Same sign leptons are obtained in (c) only if the charged Higgs subsequently decays to $t\bar{b}$ or to leptons.

**Figure 2.** Gluino decays with right-handed bottom squarks in the presence of $W \supset U_3 D_1 D_2$, via (a) left-handed top squark, (b) left-handed bottom squark, and (c) right-handed bottom squark.
Can we avoid SS dileptons?

- For $m_{H^\pm} > m_t + m_b$, $H^+ \rightarrow t\bar{b}$ dominates, which again will yield same-sign dileptons.

- $H^+ \rightarrow \tau^+\nu_\tau$ is also OK, since we’ll get like-sign di-taus.

- Only fly in the ointment comes from Fig. 1c: when $H^+ \rightarrow c\bar{b}$ (but only happens when $\tan \beta \ll m_t V_{cb}/m_\tau \sim 3$, which seems unlikely).
Same-sign $\not{E}_T$ Limits

CMSSll1a: $H_T > 400$ GeV, $|\not{E}_T| > 120$ GeV

CMS-PAS-SUS-010; ATLAS-CONF-2012-004
Many models of random particles have been proposed, but most don’t fit all the data. However, this one does:

\[ W = \frac{\lambda_{313}''}{2} t_R d_R b_R \]

\[ \chi''^{*} \]

\[ d_R(p_1) \rightarrow t_R(q_1) \]

\[ \tilde{b}_R \]

\[ \chi'' \]

\[ d_R(p_2) \rightarrow t_R(q_2) \]

\[ \lambda_{313} \]

Figure 2: SUSY contribution to $A_{FB}^a$
\[
\frac{d\Delta \sigma}{dc} = \frac{|\lambda''_{313}|^4}{384\pi} \beta \hat{s} \left[ \frac{(\beta c - 1)}{\hat{s}(\beta c - 1) + 2m_t^2 - 2m_{b_R}^2} \right]^2 + \frac{\alpha_s |\lambda''_{313}|^2 \beta}{72\hat{s}} \frac{4m_t^2 + \hat{s}(\beta c - 1)^2}{\hat{s}(\beta c - 1) + 2m_t^2 - 2m_{b_R}^2}.
\]

where \( \beta = \sqrt{1 - 4m_t^2/\hat{s}} \), \( \hat{s} = (p_1 + p_2)^2 \), \( \alpha_s \) is the strong coupling constant and \( m_t \) is the top quark mass.
Calculate observables with MadGraph arXiv:1205.5170

Allanach and Sridhar, 2012

ΔA_{FB}

Allanach and Sridhar, 2012

ΔA_{C}^{y}

DAMTP HEP/GR colloquium 2012

B.C. Allanach – p. 32
## Constraints and Predictions

| 0.037 < $\Delta A_{FB}$ < 0.205 | −0.079 < $\Delta A_{yC}^y$ < 0.061 |
|−0.65 < $\Delta \sigma_{tt}^{TEV}$/pb < 1.51 | 4 < $\Delta \sigma_{tt}^{TEV}$ (bin)/fb < 156 |
|−0.38 < $\Delta A_{FB}^l$ < 0.23 | 0.062 < $\Delta A_{FB}^h$ < 0.33 |
|−19.2 < $\Delta \sigma_{tt}^{LHC7}$/pb < 39.2 |

**Table 1: 95% CL constraints**

| 0.037 < $\Delta A_{FB}$ < 0.09 | 0.02 < $\Delta A_{yC}^y$ < 0.06 |
| 0 < $\Delta \sigma_{tt}^{TEV}$/pb < 1.8 | 110 < $\Delta \sigma_{tt}^{TEV}$ (bin)/fb < 156 |
| 0.005 < $\Delta A_{FB}^l$ < 0.04 | 0.062 < $\Delta A_{FB}^h$ < 0.14 |
| 8 < $\Delta \sigma_{tt}^{LHC7}$/pb < 25 | 13 < $\Delta \sigma_{tt}^{LHC8}$/pb < 33 |

**Table 2: Predicted values in good fit region**
RPV and Dark Matter

If one gives up $R$–parity, $\chi_1^0$ is no longer a good dark matter candidate, since it decays. One then has to have something else, eg:

- *Gravitino* - still decays, but lifetime may be much longer than the age of the universe
- *Hidden sector matter*
- *Axion/axino*

The implications of each of these is that direct dark matter search shouldn’t find anything.
Upper Bounds on $\lambda''_{ijk}$

<table>
<thead>
<tr>
<th>$\lambda''_{11k}$</th>
<th>$(10^{-8} - 10^{-7})(10^8 s/\tau_{osc})\tilde{m}^{5/2} [n\tilde{n}]$ (6.128)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda''_{112}$</td>
<td>$10^{-6} \ [NN] \ (\tilde{m} = 300 \text{ GeV})$ (6.131)</td>
</tr>
<tr>
<td></td>
<td>$6 \times 10^{-17} \tilde{f}<em>{R}^2 (m</em>{3/2}/1 \text{ eV})$</td>
</tr>
<tr>
<td></td>
<td>$[p \rightarrow K^+ \tilde{G}]$ (6.121)</td>
</tr>
<tr>
<td></td>
<td>$8 \times 10^{-17} C_q^{-1} \tilde{f}_{R}^2 (F_a/10^{10} \text{ GeV})$</td>
</tr>
<tr>
<td></td>
<td>$[p \rightarrow K^+ \tilde{a}]$ (6.122)</td>
</tr>
<tr>
<td>$\lambda''_{113}$</td>
<td>$10^{-3} \ [NN] \ (\tilde{m} = 300 \text{ GeV})$ (6.131)</td>
</tr>
<tr>
<td>$\lambda''_{123}$</td>
<td>1.25 $[RG]$</td>
</tr>
<tr>
<td>$\lambda''_{212}$</td>
<td>1.25 $[RG]$</td>
</tr>
<tr>
<td>$\lambda''_{213}$</td>
<td>1.25 $[RG]$</td>
</tr>
<tr>
<td>$\lambda''_{223}$</td>
<td>1.25 $[RG]$</td>
</tr>
<tr>
<td>$\lambda''_{312}$</td>
<td>1.45 $[R_l]$ (6.41)</td>
</tr>
<tr>
<td></td>
<td>$(\tilde{m} = 100 \text{ GeV})$</td>
</tr>
<tr>
<td></td>
<td>4.28 $[RG]$</td>
</tr>
<tr>
<td></td>
<td>$2.1 \times 10^{-3} [n\tilde{n}]$ (6.129)</td>
</tr>
<tr>
<td>$\lambda''_{313}$</td>
<td>1.46 $[R_l]$ (6.41)</td>
</tr>
<tr>
<td></td>
<td>$(\tilde{m} = 100 \text{ GeV})$</td>
</tr>
<tr>
<td></td>
<td>1.12 $[RG]$</td>
</tr>
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<td></td>
<td>$2.6 \times 10^{-3} [n\tilde{n}]$ (6.129)</td>
</tr>
<tr>
<td>$\lambda''_{323}$</td>
<td>1.46 $[R_l]$ (6.41)</td>
</tr>
<tr>
<td></td>
<td>$(\tilde{m} = 100 \text{ GeV})$</td>
</tr>
<tr>
<td></td>
<td>1.12 $[RG]$</td>
</tr>
<tr>
<td>$\lambda''_{ijk}$</td>
<td>$(10^{-11} \tilde{m}^3 - 10^{-8} \tilde{m}^2)$</td>
</tr>
<tr>
<td></td>
<td>$\times (m_{3/2}/1 \text{ eV}) \ [p \rightarrow K^+ \tilde{G}]$ (6.123)</td>
</tr>
<tr>
<td></td>
<td>$\times (F_a/10^{10} \text{ GeV}) \ [p \rightarrow K^+ \tilde{a}]$ (6.124)</td>
</tr>
</tbody>
</table>
Gluino/stop production at LHC7

The graph shows the NLO production cross-section $\sigma_{\text{prod}}$ (in pb) as a function of mass (in GeV) for gluinos and stops. The cross-section decreases rapidly as the mass increases, with gluinos having a slightly higher cross-section than stops at lower masses. The plot is used to illustrate the expected production rates of supersymmetric particles at the LHC7.
Gluinos With $R_p$ Violation

- We assume lightish $\tilde{g}, \tilde{t}_R$. If one has lepton number violating $LLE$ or $LH_1$ operators, the gluinos decay producing various leptons. These cases ought to be easy to find, and are good candidates for searches. Get same-sign leptons.

- With $LQD$ operators, the stops will again decay into leptons, easy to see. Flavour constraints imply that $L_3QD$ operators are likely to be the largest. Get same-sign leptons in $\sim \frac{7}{9}$ of $\tilde{g}\tilde{g}$ events.

- With $UDD$ operators, the (right-handed) top decays directly into jets.
### Sets of Cuts

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>( m_{\mu\mu}/\text{GeV} )</th>
<th>( \sigma_{SS\mu\mu}^{\text{test}}/\text{fb} )</th>
<th>( A/10^{-3} )</th>
<th>( \sigma_{SS\mu\mu}^{95}/\text{fb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS_{\mu\mu1}</td>
<td>&gt;15</td>
<td>12</td>
<td>1.3</td>
<td>58</td>
</tr>
<tr>
<td>ATLAS_{\mu\mu2}</td>
<td>&gt;100</td>
<td>7.5</td>
<td>0.86</td>
<td>16</td>
</tr>
<tr>
<td>ATLAS_{\mu\mu3}</td>
<td>&gt;200</td>
<td>2.1</td>
<td>0.29</td>
<td>8.4</td>
</tr>
<tr>
<td>ATLAS_{\mu\mu4}</td>
<td>&gt;300</td>
<td>0.41</td>
<td>0.077</td>
<td>5.3</td>
</tr>
</tbody>
</table>

**Table 3:** The ATLAS same-sign di-muon analysis search regions.
## Sets of Cuts

| Signal Region | $|p_T^{\text{miss}}|$/GeV | $m_T(l_1)$/GeV | $A/10^{-3}$ | $\sigma_{95}^{SSll}$/fb |
|---------------|--------------------------|----------------|-------------|-------------------|
| ATLAS$ll_1$   | $> 150$                  | $> 0$          | 1.0         | 1.6              |
| ATLAS$ll_2$   | $> 150$                  | $> 100$        | 0.6         | 1.5              |

Table 4: ATLAS same sign-di lepton analysis search regions.
Sets of Cuts

| Signal Region | $H_T$/GeV | $|p_T^{\text{miss}}|$/GeV | $N_{ll}$/fb | $A \times \epsilon / 10^{-3}$ | $N_{ll}^{95}$ |
|---------------|-----------|-----------------|-----------|-----------------|-------------|
| CMS$ll1$      | $>400$    | $>120$          | 2.4       | 3.5             | $<3.7$      |
| CMS$ll2$      | $>400$    | $>50$           | 4.6       | 6.8             | $<8.9$      |
| CMS$ll3$      | $>200$    | $>120$          | 2.5       | 3.7             | $<7.3$      |

Table 5: Number of events past cuts for the CMS same sign-di lepton analysis $N_{ll}$ predicted by our test point over SM backgrounds, and acceptance $A$ times efficiency $\epsilon$ of the signal selection, for the test point.
Test Point

\[ m_{\tilde{g}} = 588 \text{ GeV}, \quad m_{\tilde{t}} = 581 \text{ GeV}. \]

LH panel: \( \not{p}_T/\text{GeV} \), RH panel: \( H_T/\text{GeV} \)
Test Point

\[ m_{\tilde{g}} = 588 \text{ GeV}, \quad m_{\tilde{t}} = 581 \text{ GeV}. \]

LH panel: \( p_T(j_1)/GeV \), RH panel: \( p_T(l_1)/GeV \)
Test Point

\[ m_{\tilde{g}} = 588 \text{ GeV}, \ m_{\tilde{t}} = 581 \text{ GeV}. \]

LH panel: \( N_J \), RH panel: \( N_{\text{isol } e,\mu} \)
Efficiencies of CMSll$E_T$

$$\epsilon = \frac{\text{SUSY events past cuts}}{\text{SUSY events}}$$

You pay for the di-leptonic $tt$ branching ratio.

Allanach and Gripaios, 2012