Natural and Unnatural supersymmetry

Thomas Grégoire
Carleton University

CAP congress 2015
### Status of Supersymmetry

**ATLAS SUSY Searches** - 95% CL Lower Limits

**Status:** Feb 2015

**ATLAS Preliminary**

\[ \sqrt{s} = 7, 8 \text{ TeV} \]

- **Models**
  - MSUGRA/CMSSM
  - \( \tilde{b}, \tilde{g}, \tilde{\tau}, \tilde{\mu}, \tilde{\tau} \)
  - \( \tilde{t}, \tilde{\tau}, \tilde{\mu}, \tilde{\tau} \)
  - \( \tilde{g}, \tilde{\tau}, \tilde{\mu}, \tilde{\tau} \)

<table>
<thead>
<tr>
<th>Model</th>
<th>( E_{JET} )</th>
<th>( \log_{10}(\text{BR}) )</th>
<th>( \text{Mass limit} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tilde{b}, \tilde{g}, \tilde{\tau}, \tilde{\mu}, \tilde{\tau} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tilde{t}, \tilde{\tau}, \tilde{\mu}, \tilde{\tau} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tilde{g}, \tilde{\tau}, \tilde{\mu}, \tilde{\tau} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
stop searches

$m_{\tilde{t}} \gtrsim 700\text{GeV}$

 gluino searches

$m_{\tilde{g}} \gtrsim 1.4\text{TeV}$
What does it mean for naturalness?

‘natural SUSY’ (stop, gluino, higgsino)  

\[ \delta m_h^2 = -\frac{3}{8\pi^2} y_t^2 \left( m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2 \right) \log \left( \frac{\Lambda}{\text{TeV}} \right) \]

\[ \sqrt{m_t^{21} + m_t^{22}} \lesssim 600 \text{GeV} \left( \frac{\Delta^{-1}}{20\%} \right)^{-1/2} \]

Papucci, Ruderman, Weiler ’11

stop

\[ \delta m_h^2 = -\frac{2}{\pi^2} y_t^2 \left( \frac{\alpha_s}{\pi} \right) M_3^2 \log^2 \left( \frac{\Lambda}{\text{TeV}} \right) \]

\[ M_3 \lesssim 900 \text{ GeV} \sin \beta \left( \frac{\Delta^{-1}}{20\%} \right)^{-1/2} \]
125 Gev Higgs: prefers heavy stops

\[ \delta m^2_h = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \log \left( \frac{m^2_{\tilde{t}}}{m_t^2} \right) \]

~ 1-10 TeV stop depending on A-term

More complete models generally yield %-level fine-tuning

CMSSM

Strumia '11
NMSSM, split generation, low-scale mediation and even R-parity breaking are generically tuned.

More clever model building might save the day

Scherk-Schwartz SUSY breaking

Compressed spectrum

Stealth supersymmetry

Twin Higgs

Arvanitaki, Baryakhtar, Huang, Tiburg, Villadoro '13

Dimopoulos, March-Russell ‘14
LeComte, Martin ‘11
Dimopoulos, March-Russell, Scoville ‘14

Fan, Reece, Ruderman ‘11

Chacko, Goh, Harnik ‘05
Craig, Howe ‘13
Dirac gauginos

In the MSSM gauginos are Majorana

\[ M \lambda \lambda \]

Can be Dirac if new superfields are added

\[ W^1_\alpha, W^2_\alpha, W^3_\alpha, S, T, G \]

N=2 supersymmetry

extra-dimension
Supersoft SUSY breaking

Fox, Nelson, Weiner ’02

\[ D' \theta_\alpha \]

D-term breaking

\[ \int d^2 \theta W'_\alpha W_i^\alpha \Phi_i \]

Dirac gauginos do not feed into scalar masses through renormalization

\[ m^2 = \frac{C_i(r) \alpha_i m_i^2}{\pi} \log \left( \frac{\delta^2}{m_i^2} \right) \]
They can be naturally **heavier than scalars**
LHC will have a harder time seeing the gluino...

...and squarks

M. Heikinheimo, M. Kellerstein, V. Sanz '12
Kribs, Martin '12
Squark production

\[ \sigma(\tilde{q}\tilde{q}^*) \]

\[ M_{\tilde{g}} = 2 \text{ TeV} \]

Frugiuele, T.G., Kumar, Ponton
R-symmetry

With Dirac gaugino: possible to impose an U(1) R-symmetry

\[ M_D \lambda \Psi \]

Kribs, Poppitz, Weiner ’02

- Bounds from FCNC are weaker: off diagonal \( m_{ij} \)

\[
R[Q, U^c, D^c, L, E^c] = 1 \quad R[H_u, H_d] = 0
\]

\[ \mu H_u H_d \]
Higgs mass

Tree-level:

Reduced quartic, usual of Dirac gauginos

\[ \int d^2 \theta W'_\alpha W_i^\alpha \Phi_i \rightarrow D_2 = M_2 T^a + H^+_u \sigma^a H_u + ... \]

When the scalar \( T \) is integrated out:

\[ \lambda \rightarrow 0 \]

Higgs quartic

If the mass of \( T \) is set by \( M_2 \) and \( \lambda_T = 0 \)
No help (at tree-level) from

\[ \lambda_T H_u T R_d + \lambda_S H_u S R_d \]

don’t get a vev (In the limit of exact R-symmetry)

But do help in models without an R-symmetry

Benakli, Goodsell, Staub 1211.0552
Loop-level

Usual stop correction (but A-terms are 0)

Similar loop from the triplet
\[ V_{CW} \sim \frac{1}{16\pi^2} \left( 5\lambda_T^4 \log \frac{m_T^2}{M_2^2} + 3\lambda_t^4 \log \frac{m_t^2}{m_t^2} \right) \]

\[ \Downarrow \]

Very sensitive to \( \lambda_T \)

….but so are electroweak precision measurements
\[ B_T = B_S = \frac{1}{3} \left( -m_{\tilde{t}}^2 - M_D^2 \right) \text{GeV}^2, \mu = 300 \text{ GeV} \]

\[ m_{\tilde{t}} = 300 \text{ GeV} \]

\[ m_{\tilde{t}} = m_{\tilde{\text{adj}}} \]

Bertuzzo, Frugiuele, T.G., Ponton

allowed by EWPT
Split Supersymmetry

Naturalness might not be a good guide

SUSY might still be relevant

• Dark matter
• Gauge coupling unification
• ‘UV’ reasons

Gauginos and scalars might not be at the same mass scale

natural in for example anomaly mediation
Prediction for the Higgs mass

Split–SUSY

$M_1 = M_2 = M_3 = \mu = 1$ TeV

Observed $M_{h}$

Bagnaschi, Giudice, Slavich, Strumia ‘14
Mini-split in anomaly mediation

Gaugino masses (AMSB):

\[ M_i = \frac{b_i}{16\pi^2} g_i^2 m_{3/2} \]

Scalar masses (gravity mediation):

\[ m^2 = m_{3/2}^2 \]

Higgsino (mu term): chosen to be at \( m_{3/2} \)

Similar possibility in gauge mediation
Gaugino masses $M_{\tilde{B}, \tilde{W}, \tilde{G}}$, [GeV]

$C_\mu = \frac{\mu}{m_{3/2}} \frac{m_A^2 \sin^2 \beta}{m_A^2 - \mu^2} \ln \frac{m_A^2}{\mu^2}$

Parametrize deflection from AMSB spectrum
Gluino decay (through 3rd generation)

\[ \tilde{g} \rightarrow \chi_1^0 t \bar{t} \]

\[ \tilde{g} \rightarrow \chi_2^0 t \bar{t} \]

\[ \tilde{g} \rightarrow \chi_1^0 b \bar{b} \]

\[ \tilde{g} \rightarrow \chi_2^0 b \bar{b} \]

\[ \tilde{g} \rightarrow \chi_1^+ b \bar{t} + \text{h.c.} \]

\[ M_{\tilde{W}} \text{ [GeV]} \]

\[ 0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \]

\[ 0. \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1. \]

\[ m_{\tilde{G}} = 1.5 \text{ TeV} \quad m_{\tilde{B}} = 0 \text{ GeV} \]
LHC limits

Gaugino spectrum and branching ratios are obtained as a function of $m_{3/2}$ and $C_\mu$. The correct Higgs mass is obtained by fixing $\tan \beta$.

Recast LHC searches

Beauchesne, Earl, T.G. ‘15

ATLAS multi-leptons+b-jets
ATLAS 0-1 lepton+b-jets
CMS high jets multiplicity
CMS 2 OS leptons+jets
Gauge mediation

\[ \Lambda \text{ [TeV]} \]

\[ M_{\tilde{G}} \text{ [GeV]} \]

\[ C'_{\mu} \]
Prospect for a 100 TeV collider

0-lepton + jets +MET analysis

2 SS lepton analysis

Jung, Wells ’13

Cohen et al. ‘14

AMSB