Displaced Supersymmetry
(and other stories)

SavasFest, May 2012
Happy Birthday Savas!
Supersymmetry

- Naturalness (a la Wilson)
- Unification (LEP circa 1990)
- Dark Matter (LSP)
The LHC

• 2012 - announce the Higgs discovery (?)

• 2012 data - Is the electroweak scale “natural”? 
Menu

• Appetizer: Finding stops

• Entree: Displaced SUSY

• Dessert: Mixing stops and the Higgs mass
Whine List

• “Oh my god, another crappy model.”

• “Can we stop talking about supersymmetry for god’s sake?”

• “Holy christ, three talks!?!?”
Appetizer: Stops

- For a weakly coupled Higgs, what cancels the top loop? Stop - but not too heavy

\[
\delta m^2_{h_u} \simeq -\frac{3y_t^2}{8\pi^2} (m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + A_t^2) \log \frac{M}{m_{\tilde{t}}}
\]
Searches: t t\bar{t} + met

Semi-leptonic tops have a small cross section - about 1/6 of Dirac Fermions.
Searches: t \bar{t} + met

Semi-leptonic tops

Neutrino in signal and background affects efficiency of cuts
Suggest: loose ‘top tags’

- Look for fully hadronic tops: large BR and no neutrino
- “Top tag”s kill combinatoric background for a very mild cost in signal
### Cuts

- Veto isolated leptons, hadronic taus
- Require MET is isolated
- MET > 175 GeV
- Cluster with R=1.2, require 2 fat jets, one passes HEPTopTagger, other b-tagged.

**dominant background:**

\[
tt + nj \rightarrow (bjj)(b\tau_h\nu_\tau) + nj
\]
Transverse mass cuts

- $m_{T2}$ cut on two fat jets and MET (>200 GeV)
- $m_T$ cut on each of the two fat jets (>200 GeV) (helps kill the tau neutrino)

![Histogram](image)

$\tilde{t}$ + jets
$t\bar{t} +$ jets
Single top + jets
$V+$jets
$V+b\bar{b}+$jets

$m_{\tilde{t}} = 340$
$m_\chi = 100$
Transverse mass cuts

- $m_{T2}$ cut on two fat jets and MET (>200 GeV)
- $m_T$ cut on each of the two fat jets (>200 GeV) (helps kill the tau neutrino)

Can be done now!
Transverse mass cuts

- $m_{T2}$ cut on two fat jets and MET (>200 GeV)
- $m_T$ cut on each of the two fat jets (>200 GeV) (helps kill the tau neutrino)
Entree: Displaced Vertices
State of SUSY

With maximized missing $E_T$

Only 1st/2nd generation squarks
Allow LSP to Decay

- Lost LSP dark matter (could be plenty of other stable particles)
- Preserve Unification! (and naturalness)
- R-parity violation
Bilinear RPV

• Simplest GUT embedding:

\[ W \supset \epsilon \mu L H_u + \epsilon \mu H_T u D^c \]  \[ (\epsilon \mu \bar{55}_H) \]

• Doublet-triplet splitting required anyway, thus baryon number violation suppressed (p-decay).

• Bilinear terms naturally dominate if RPV is spontaneous in another sector:

\[ \langle O \rangle \neq 0 \]

\[ \frac{O}{\Lambda n^{-1}} L H_u \sim \epsilon \mu L H_u \]

\[ \frac{O}{\Lambda n} U^c D^c D^c \sim \epsilon \frac{\mu}{\Lambda} U^c D^c D^c \]
Bilinear RPV

\[ W \supset \epsilon \mu LH_u + \mu H_u H_d \]

Rotate L and Hₜ:

\[ W \supset \epsilon y_b LQ_3 D^c_3 + \epsilon y_\tau LL_3 E^c_3 \]

Predictive - mostly 3rd generation

(Higgs triplet rotation gives baryon number violating coupling:

\[ \epsilon \frac{\mu y}{M_T} U^c D^c D^c \]

which is safe for GUT-scale triplet and small enough epsilon)
Bounds: nu masses

\[ \Delta m_\nu \sim \frac{\epsilon^2 y_b^4}{16\pi^2} m_{\text{weak}} \]

Requires roughly: \( \epsilon < 10^{-3} \)

(Satisfies p-decay bounds too)
LSP decays

<table>
<thead>
<tr>
<th>LSP</th>
<th>( \tilde{\chi} )</th>
<th>( \tilde{\nu} )</th>
<th>( \tilde{\tau} )</th>
<th>( \tilde{u}_L )</th>
<th>( \tilde{b} )</th>
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<tbody>
<tr>
<td>Dominant Decays</td>
<td>( \nu \bar{b} \bar{b}, \nu \tau l )</td>
<td>( \bar{b} \bar{b} )</td>
<td>( l^\pm \nu )</td>
<td>( l^\pm \bar{q} )</td>
<td>( b \nu )</td>
</tr>
</tbody>
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- Suppressed missing energy
- Additional jets, b’s
- possibly leptons
Displaced Vertices!
Displaced Vertices!

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<th>Collider Search</th>
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<td>Searches in leptons and $b$-jets</td>
<td>Displaced tracks prevent reconstruction</td>
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<tr>
<td>Searches in jets + MET</td>
<td>Highly suppressed missing energy, CMS jets require good tracks</td>
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<td>Searches for displaced vertices</td>
<td>Specific decay topologies not yet searched for</td>
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Neutralino LSP

\[ \epsilon = 10^{-3} \]
\[ m_{\tilde{q}} = m_{\tilde{\ell}} \]
\[ \tan \beta = 5 \]
Neutralino LSP

Gluino: 2 TeV
Constraints on squarks and gluinos

ATLAS: stable, 3rd generation decoupled

\[ m_\chi = 0, \]
\[ \chi \rightarrow b\bar{b}\nu \]
(3 gen.s)
perfect eff.
degraded 30%

\[ m_\chi = 50 \text{ GeV}, \]

Constraints, Searches

- All squarks as low as 450 GeV
- Displaced vertex searches only significantly constrain $\chi \rightarrow \nu\mu\tau$
- Discovery: displaced vertex triggers (LHCb only?) and continued jets + MET
Dessert: Higgs mass

- MSSM looks challenged if you don’t like tuning:

![Graph showing Higgs mass vs. supersymmetry breaking scale](Image)

(Giudice and Strumia, 2011)
Higgs mass corrections

Top Yukawa coupling has a significant impact on the effective potential of the Higgs:

$\sim y_t^4$

Let’s increase it!
Top Yukawa vs. Top Mass

- The top Yukawa can be increased relative to $m_t$ by mixing the top with extra vector-like fermions:

$$W \supset y_{ij} H_u Q_i U_j^c + M (\bar{Q}_4 Q_4 + \bar{U}_4^c U_4^c)$$

$(i, j = 3, 4)$

$$\rightarrow y_h q_3 u_3^c (1 + \tilde{y}^2 (h^2 / M^2))$$

$$y_t \neq m_t / v$$
Higgs mass: Data point

\[ m_t = 173 \]

\[ y_{33} = 1.05, \ y_{43} = 1.0, \ y_{34} = 0, \ y_{44} = 0.5 \]

\[ m_{soft} = 500 \text{ GeV}, \ A = 350 \text{ GeV}, \ M = 550 \text{ GeV} \]

\[ m_h = 125.2 \text{ GeV} \]

But - like most deserts, it isn’t exactly healthy:
Landau pole at \( 2 \times 10^6 \) GeV
Coffee?: Questions?