BSM THEORY

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HCP Symposium
University of Toronto
August 26, 2010
This talk is being given

• by a theorist/phenomenologist/experimentalist
This talk is being given

- by a theorist/phenomenologist/experimentalist

The experimentalist asks:  

The theorist answers:
This talk is being given

- by a theorist/phenomenologist/experimentalist

The experimentalist asks:

Is it possible to have a theory model which gives signature X?

The theorist answers:

Yes.
This talk is being given

- by a theorist/phenomenologist/experimentalist

The experimentalist asks:

- Is it possible to have a theory model which gives signature X?
- Are there any well motivated such models?

The theorist answers:

- Yes.
- No.
- You bet. Let me tell you about those. Actually I have a paper…
This talk is being given

- by a theorist/phenomenologist/experimentalist

The experimentalist asks:

- Is it possible to have a theory model which gives signature X?
  - Yes.

- Are there any well motivated such models?
  - No.
  - You bet. Let me tell you about those. Actually I have a paper…

- Is there any Monte Carlo which can simulate those models?
  - I’m the wrong person to ask. Ask a phenomenologist.

MC4BSM workshops: http://theory.fnal.gov.mc4bsm/
MC4BSM workshops

• Held every year since 2006:
  – Fermilab, 2006
  – Princeton, 2007
  – CERN, 2008
  – UC Davis, 2009 (jointly with “Missing Energy” workshop)
  – Copenhagen, 2010

• Goal: “to gather together theorists and experimentalists interested in developing and using Monte Carlo tools for Beyond the Standard Model Physics in an attempt to be prepared for the analysis of data focusing on the LHC”

• BSM tool repositories:
  – http://www.phys.ufl.edu/~matchev/MC4BSM/writers.html
  – http://www.ippp.dur.ac.uk/montecarlo/BSM/

• Organizing committee(s):
Outline of the talk

• The latest fashionable models? No.
  – Any given model is surely wrong

• Supersymmetry (SUSY) in general.
  – theoretical motivations
    • gauge unification
    • hierarchy problem
  – experimental motivations
    • not ruled out
    • dark matter candidate
  – sociological motivations
    • popular, must learn for final exam, competition is doing it...
      • looks like many other models anyway  Cheng,KM, Schmaltz 2002

• This talk: a fresh new look at SUSY phenomenology
SUSY under the lamppost

• The first LHC discovery may not be in the TDR

• It will be easier to make a discovery if
  – there are many new particles to be discovered
  – the new particles are colored (produced with QCD-type cross-sections)
  – the signal involves (lots of) isolated, high $P_T$ leptons

• Look for new physics under the lamppost

How many?
The vicious circle

• Problem: even the minimal SUSY model (MSSM) has too many parameters
  – solution: take benchmark points within some good theory models with much fewer parameters (MSUGRA, GMSB)

• Problem: what is a good theory model?
  – solution(?): we don’t know. Popular doesn’t mean “good”.

• Problem: then by focusing on these benchmark points we might be missing something important.
  – solution: look at benchmark points in non-minimal models

• Problem: but the non-minimal models have a lot of parameters again...
  – solution: then go back to the minimal models.
SUSY signatures determined by

• **Quantitative factors: require parameter space scans.**
  – value of SUSY masses themselves
    • size of the cross-section
    • relative contribution of strong vs. electroweak production
  – SUSY mass splittings
    • phase space suppression factors in the BR’s
    • hardness of the SM particles, efficiency of cuts

• **Qualitative factors: requires considering permutations**
  – the hierarchical ordering of the SUSY particles

• The parameter space is infinite, the number of permutations is finite! Let’s study all permutations first!
Particle content of the MSSM

- Standard Model
  - Fermions
  - Bosons
  - Quarks: $u, c, t, d, s, b$
  - Leptons: $\nu_e, \nu_\mu, \nu_\tau, e, \mu, \tau$
  - Higgs Boson: $H$
  - Gauge Bosons: $\gamma, g, W, Z$

- Supersymmetry
  - Bosons
  - Fermions
  - Squarks: $\tilde{u}, \tilde{c}, \tilde{t}$
  - Sleptons: $\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau, \tilde{e}, \tilde{\mu}, \tilde{\tau}$
  - Higgsinos: $H$
  - Gauginos: $\tilde{\gamma}, \tilde{g}, \tilde{W}, \tilde{Z}$

- The spins are determined by SUSY
SUSY decay modes

- Couplings also determined by SUSY
  - mixing angles are small
  - branching ratios uniquely predicted
The SUSY parameter space

- The relevant parameters are the physical masses
  - taken directly at the weak scale, no need to run any RGE’s

<table>
<thead>
<tr>
<th>$\tilde{u}_L, \tilde{d}_L$</th>
<th>$\tilde{u}_R$</th>
<th>$\tilde{d}_R$</th>
<th>$\tilde{e}_L, \tilde{\nu}_L$</th>
<th>$\tilde{e}_R$</th>
<th>$\tilde{h}^\pm, \tilde{h}_u^0, \tilde{h}_d^0$</th>
<th>$\tilde{b}^0$</th>
<th>$\tilde{w}^\pm, \tilde{\nu}^0$</th>
<th>$\tilde{g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>$U$</td>
<td>$D$</td>
<td>$L$</td>
<td>$E$</td>
<td>$H$</td>
<td>$B$</td>
<td>$W$</td>
<td>$G$</td>
</tr>
<tr>
<td>$M_Q$</td>
<td>$M_U$</td>
<td>$M_D$</td>
<td>$M_L$</td>
<td>$M_E$</td>
<td>$M_H$</td>
<td>$M_B$</td>
<td>$M_W$</td>
<td>$M_G$</td>
</tr>
</tbody>
</table>

TABLE I: The set of SUSY particles considered in this analysis, shorthand notation for each multiplet, and the corresponding soft SUSY breaking mass parameter.
SUSY collider signatures

• There are $9! = 362,880$ possible permutations

• First: who is the LSP (lightest superpartner)
  – CHAMP ($8! = 40,320$) if LSP=E
  – R-hadron ($4 \times 8! = 161,280$) if LSP=G, Q, U or D
  – Missing energy ($4 \times 8! = 161,280$) if LSP=L, H, W or B

• Second: who is the LCP (lightest colored particle)
  – most abundantly produced at hadron colliders

• Third factor: what is the dominant decay of the LCP
  – count suppressions by multibody phase space
  – count suppressions from neutralino mixing angles

$\boxed{x \ldots x C \ y \ldots y \ L}$
LCP decays: an example

• A variation of the travelling salesman problem
• Several possible paths:
  – QBH, QWH: give jet plus V
  – QBLH, QWLH, give jet plus 2L
• Count all signatures for each permutation
Counting signatures

- Counting all possible dominant LCP decays

**TABLE II:** Number of hierarchies for the various dominant decay modes of the LCP $C$.

<table>
<thead>
<tr>
<th>$n_\nu = 0$</th>
<th>$n_\nu = 1$</th>
<th>$n_\nu = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_\ell$</td>
<td>$n_j = 1$</td>
<td>$n_j = 2$</td>
</tr>
<tr>
<td>0</td>
<td>79296</td>
<td>26880</td>
</tr>
<tr>
<td>1</td>
<td>30240</td>
<td>10080</td>
</tr>
<tr>
<td>2</td>
<td>19770</td>
<td>6030</td>
</tr>
<tr>
<td>3</td>
<td>4656</td>
<td>1296</td>
</tr>
<tr>
<td>4</td>
<td>1656</td>
<td>396</td>
</tr>
</tbody>
</table>

$x \times 2$

8 lepton events!

- Only the maximally leptonic dominant LCP decays

**TABLE III:** Number of hierarchies for the *maximally leptonic* decay modes of the LCP $C$.

<table>
<thead>
<tr>
<th>$n_\nu = 0$</th>
<th>$n_\nu = 1$</th>
<th>$n_\nu = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_\ell$</td>
<td>$n_j = 1$</td>
<td>$n_j = 2$</td>
</tr>
<tr>
<td>0</td>
<td>61488</td>
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<td>24150</td>
<td>8310</td>
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<td>2</td>
<td>17190</td>
<td>5550</td>
</tr>
<tr>
<td>3</td>
<td>4362</td>
<td>1242</td>
</tr>
<tr>
<td>4</td>
<td>1656</td>
<td>396</td>
</tr>
</tbody>
</table>

$x \times 2$

8 lepton events!
MSUGRA result

- Only 47 out of the 161,280 possible hierarchies
- Only 4 out of the 26 possible decay channels.
Study one 8-lepton hierarchy

\[ \tilde{\chi}^\pm_2 \tilde{\chi}^0_3 \tilde{\chi}^0_4 \tilde{\chi}^0_1 \tilde{\ell}^\pm_R \tilde{\nu}_L \tilde{\ell}^\pm_L \]

\[ \begin{align*}
\sigma(pp \rightarrow QQ+X) &\quad \text{14 TeV} \\
\sigma(pp \rightarrow 8\text{leptons+jets}+E_T) &\quad \text{7 TeV} \\
\text{BR}(QQ \rightarrow 8\text{lep}) &\quad \text{14 TeV} \\
\end{align*} \]

Mass

\[ \begin{align*}
\tilde{\chi}^0_1 &\quad \tilde{\chi}^+_2 \\
\tilde{\chi}^0_2 &\quad \tilde{\ell}^+_L \\
\tilde{\chi}^0_3 &\quad \tilde{\ell}^+_R \\
\tilde{\chi}^+_1 &\quad \tilde{\ell}^-_L \\
\tilde{\chi}^-_2 &\quad \tilde{\ell}^-_R \\
\tilde{\chi}^0_0 &\quad \tilde{\nu}_L \\
\end{align*} \]
Multi-lepton yields

- The study points are chosen to maximize the rate
- Simulation: PYTHIA+PGS
  - count isolated leptons with default $P_T$ cuts.
- Can be easily discovered, perhaps with 10 inv. pb

TABLE IV: Input soft SUSY mass parameters (in GeV) for the $xxGQWLBEH$ study points used for Figs. 3 and 4.

<table>
<thead>
<tr>
<th>$M_G$</th>
<th>$M_Q$</th>
<th>$M_W$</th>
<th>$M_L$</th>
<th>$M_B$</th>
<th>$M_E$</th>
<th>$M_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>300</td>
<td>220</td>
<td>190</td>
<td>130</td>
<td>130</td>
<td>130</td>
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<tr>
<td>450</td>
<td>350</td>
<td>280</td>
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<tr>
<td>500</td>
<td>400</td>
<td>280</td>
<td>190</td>
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</tr>
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<td>550</td>
<td>450</td>
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<td>600</td>
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<td>350</td>
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<td>130</td>
<td>120</td>
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<td>230</td>
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<td>130</td>
<td>120</td>
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<td>700</td>
<td>480</td>
<td>250</td>
<td>160</td>
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<td>120</td>
</tr>
<tr>
<td>900</td>
<td>800</td>
<td>500</td>
<td>250</td>
<td>170</td>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>1000</td>
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And so, my fellow Americans:

ask not what your country can do for you -

ask what you can do for your country.

Theorists

The LHC

The LHC
BACKUPS
How do 8 lepton events come about?

• Clean multilepton + MET events in SUSY
  – 3 leptons: gold plated mode
  – 4 leptons: platinum plated?
  – 8 leptons: ???

• What is the max number of leptons?

\[ - - - - - q_L \]
\[ \text{hino} \]
\[ - - - - - l_L \]
\[ \text{wino} \]
\[ - - - - - l_R \]
\[ \text{bino} \]
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- $I_L$
- $bino$
- $I_R$
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All 4 leptons come from the same side!