The Day After:
Strategies for Characterizing New Physis
Introduction to the session/discussion

Missing Energy Signals at LHC
<table>
<thead>
<tr>
<th>Year</th>
<th>Idea</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>’67</td>
<td>The Standard Model</td>
<td>a classic! aged to perfection</td>
</tr>
<tr>
<td>’77</td>
<td>Vin de Technicolor</td>
<td>better drink now</td>
</tr>
<tr>
<td>’70’s</td>
<td>Supersymmetry: MSSM</td>
<td>mature, balanced, well developed – the Wino’s choice</td>
</tr>
<tr>
<td>’90’s</td>
<td>SUSY Beyond MSSM</td>
<td>svinters blend</td>
</tr>
<tr>
<td>’90’s</td>
<td>CP Violating Higgs</td>
<td>all upfront, no finish lacks symmetry</td>
</tr>
<tr>
<td>’98</td>
<td>Extra Dimensions</td>
<td>bold, peppery, spicy uncertain terrior</td>
</tr>
<tr>
<td>’02</td>
<td>Little Higgs</td>
<td>complex structure</td>
</tr>
<tr>
<td>’03</td>
<td>Fat Higgs</td>
<td>young, still tannic needs to develop</td>
</tr>
<tr>
<td>’03</td>
<td>Higgsless</td>
<td>sleeper of the vintage what a surprise!</td>
</tr>
<tr>
<td>’04</td>
<td>Split Supersymmetry</td>
<td>finely-tuned</td>
</tr>
<tr>
<td>’05</td>
<td>Twin Higgs</td>
<td>double the taste</td>
</tr>
</tbody>
</table>

We have a lot of signatures to look for...
It is high time we get the data!

**Last Minute Model Building**

**Anything Goes!**

- Non–Communtative Geometries
- Return of the 4th Generation
- Hidden Valleys
- Quirks – Macroscopic Strings
- Lee–Wick Field Theories
- Unparticle Physics

...
Historical Perspective

J. Incandela

SPS turn-on led to quick major discoveries at the start

Tevatron discoveries came as luminosity increased
The Day After...

We just observed a signal at the LHC!!

• How well can we determine what it is? Does a specific experimental signature map back into a ~unique theory with a fixed set of parameters? If LHC “just” a discovery machine or can we learn much more from the data?

• Even within a very specific context, e.g., the MSSM, can one uniquely determine the values of, e.g., the weak scale Lagrangian parameters from LHC data alone?

We know that we will have to expect “degeneracies” but we do have many handles at the LHC, which are starting to get explored.
The Day After…

• Discovery of an excess!!
• Get detailed information from the data
  - Determine masses or mass related quantities
  - Spin or spin sensitive information
  - Event rates/cross sections
  - Decay patterns
  - Importance of the third generation
  - Look for special -- unusual -- characteristics (eg displaced vertices)
  - Look for (predicted?) other signatures
E.g. Di-lepton Resonance

If we are lucky: a signal could be seen very early on

\[ \text{pp} \rightarrow \mu^+ \mu^- + X \]

First months of operation

More information wanted
- Other partners? (W'..)
- Other messengers (eg radions/higgs)
- Decay modes and BRs
- Detailed mass & width
- Couplings (T. Rizzo/LHC2FC)
- Spin! high lumi...

Example: The Di-lepton channel

- \( Z' \) (New gauge bosons)
- \( A_H, Z_H \) (Little Higgs)
- \( G(1) \) (Randall-Sundrum)
- \( G^{(KK)} \) (ADD)
- \( \gamma^{(1)}/Z^{(1)} \) (TeV\(^{-1}\) Extra Dimensions)
Spin of the Resonances

100 fb\(^{-1}\)

Electron study (mass resolution ~ 0.6% at 2 TeV)

Muon study based on \(\cos\theta^*\) analysis

Lumi needed to distinguish spin 1 from 2

CMS PTDR

<table>
<thead>
<tr>
<th>(\sqrt{s}), TeV</th>
<th>(c)</th>
<th>([L_{\text{int}}, \text{fb}^{-1}])</th>
<th>(N_{\text{obs}})</th>
<th>(N_{0})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.01</td>
<td>50</td>
<td>200</td>
<td>87</td>
</tr>
<tr>
<td>1.0</td>
<td>0.02</td>
<td>10</td>
<td>146</td>
<td>16</td>
</tr>
<tr>
<td>1.5</td>
<td>0.02</td>
<td>90</td>
<td>174</td>
<td>41</td>
</tr>
<tr>
<td>3.0</td>
<td>0.05</td>
<td>1200</td>
<td>154</td>
<td>22</td>
</tr>
<tr>
<td>3.0</td>
<td>0.10</td>
<td>290</td>
<td>148</td>
<td>6</td>
</tr>
</tbody>
</table>
Mass precision for a favorable benchmark point at the LHC LCC1~ SPS1a~ point B' (this is a favorable scenario)

\[ m_0=100 \text{ GeV} \]
\[ m_{1/2}=250 \text{ GeV} \]
\[ A_0=-100 \]
\[ \tan\beta=10 \]
\[ \text{sign}(\mu)=+ \]

hep-ph/0508198

More this afternoon from
K Matchev et al.
Is it SUSY?

Example: Universal Extra Dimensions
Phenomenology: a Kaluza Klein tower pattern like a SUSY mass spectrum:
Can the LHC distinguish?

Look for variables sensitive to the particle spin eg. lepton charge asymmetries in squark/KKquark decay chains

Barr hep-ph/0405052; Smillie & Webber hep-ph/0507170

e.g. Cheng, Matchev, Schmaltz hep-ph/0205314

\[ A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)} \]

KK like spectrum (small mass splitting)

SPS1a benchmark type spectrum

Method works better or worse depending on (s)particles spectrum

More discriminating variables needed!!
Spin measurements

Last few years: lot of new ideas being proposed
Most still need the detailed test of the ‘experimental reality’

Kilic-Wang-Yavin:
Spin measurements in cascade decays
Angular correlations in decays...

Alves-Eboli
Sbottom spin

Alves-Eboli-Plehn
Spins in Gluino Decays

Athanasiou-Lester-Smillie-Webber
Distinguishing spins in decay chains at the LHC

Choi-Hagiwara-Kim-Mawatari-Zerwas
Tau polarization in SUSY cascade decays

Further: Wang & Yavin, S. Thomas et al, Kane et al, Kong et al

Most of these proposals still need an “experimental” check
New Variables: eg $M_{T2}$

\[ m_{T2}^2 = \min \left[ \max \left[ m_T^2(m_{dm}; p_T^{(1)}), m_T^2(m_{dm}; p_T^{(2)}) \right] \right] \]

\[ p_T^{(1)} + p_T^{(2)} = p_T^{\text{miss}} \]

so \[ m_{T2} \leq m_P \]

Get information on an ensemble of events when particles go undetected

Can be extended
Still much to gain @LHC by exploring kinematics
Find SUSY models that give a similar ET signature

Only limited number of observable used.

Situation probably “not so bad”

Note Spins statistics ⇔ Cross sections
Little Higgs, UED >> SUSY for same mass
(ADR, Matchev JHEP ’05)
Reverse: use cross sections for spin determination Kane, wang et al arXiv:0805.1397


- many improvements of mT2

- the mT2 upper endpoint as a function of m_dm has a “kink” at the true value of m_dm


- can generalize mT2 to intermediate particles in sub-decay chains

  M. Burns, KC Kong, K. Matchev, M. Park, arXiv:0810.5576

- can find new mT2-like observables, e.g. shat_min


Most of these proposals still need an “experimental” check

First Application of $M_{T2}$ to Real Data

CDF (Feb. 2009)

Using Only $M_{T2}$ for the CDF Dilepton $\mu\mu$ Data

(3 fb$^{-1}$)

$$m_t = 167.9^{+4.8}_{-4.1} \text{ (stat)} \pm 2.9 \text{ (sys)} \text{ GeV}$$
**Missing E_T RPV SUSY**

- High $p_T$ muons arise from the direct decays: $\tilde{d}_R \rightarrow \mu^- t$, $\tilde{t}_1 \rightarrow \mu^+ d$.

Plot

- Neutrino $p_T$ (GeV)
- $p_T(\mu)$ (GeV) from $\tilde{\chi}^0_1 \rightarrow \mu \mu$
- $p_T(\mu)$ (GeV) from $\tilde{d}_R \rightarrow \mu t$
- $p_T$(top) (GeV) from $\tilde{d}_R \rightarrow \mu t$

H. Dreiner
LHC2FC

Missing ET can be large in these events too
Special Signatures

• Recent developments: unusual signatures in the detectors
  - Large displaced vertices (Hidden Valleys,...)
  - Heavy ionizing particles & heavy stable charged particles (GMSB, Spilt SUSY, Gravitino DM SUSY. Monopoles...)
  - Stable particles that get stopped and decay with time delay in the detector (Split SUSY...)
  - Boomerang particles (ie get stuck outside the detector and return in detector after decay...)
  - Non-pointing photons (GMSB)
  - Special showers in the calorimeters (Split SUSY...)
  - Unexpected jet structures (Hidden Valley, Unparticles...)
  - Very short tracks (stubs)... (AMSB G2-SUSY models)

Experiment/analyses need to be prepared (trigger...)
New Signatures

Heavy stable particles

Quirks

\[ \Lambda_{IC} \lesssim \text{keV}: \text{Anomalous curvature} \]

Long Lived Gluinos

\[ \tau_{\tilde{g}} > 100 \text{ ns} \]

looking for stopped gluinos that later decay

100s GeV Unbalanced = \( E_T \)

Hidden Valleys

Markus Luty/Aspen 07
New Physics Search Challenges...

4th LHC Workshop

Princeton, 22 March, 2007

Blind SUSY Analysis Lyon Workshop

(last week)

- Project details: http://www-clued0.fnal.gov/~muanza/Blind_SUSY_Analysis.html
Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space...

→ model degeneracy but not too large (~ 10–100)

Follow up by Berger, Hewett, Gainer, Lillie & Rizzo for the ILC  

arXiv:0711.1374
The Inverse Problem

Attempts to Map Measurements to the Parameter Space

Inclusive+Exclusive
Inclusive [counting/cross section] and exclusive [end-point type] of measurements → a-posteriori probabilities of mapping back to the parameter space (cf references last slide and “Olympics” series)

Example

[3] a-posteriori probability distribution of mSUGRA parameters using cross-section + end-point measurements in a Markov Chain Monte Carlo sampling of the parameter space. The two regions reflect the lack of knowledge of which slepton is involved in the decay chain.

⇒ Studies of different variables/separating power

Other

Lester et al., hep-ph/0508143

Kane et al., arXiv:0709.4259
2→2 Folk Theorem

\[
\frac{d\sigma}{dp_T} = \int L \times \int \times |M|^2
\]

Has been exercised in CMS
⇒
• Quick turn around cycle
• Understand basic pattern of the data
• Predictions to check in data

# Model Characterization

## Dictionary of LHC signatures

A. Belyaev, I.A. Christidi, A. De Roeck, R.M. Godbole, B. Mellado, A. Nyffeler, C. Petridou, D.P. Roy

Table 1. Discriminating signatures between SUSY (MSSM), LHT and UED. See description in the text. "YES" or "NO" mean presence or absence of the particular signature respectively, "SS" stands for "like-sign leptons".

<table>
<thead>
<tr>
<th>Variables</th>
<th>SUSY (MSSM)</th>
<th>LHT (littlest)</th>
<th>UED(MUED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin</td>
<td>heavy partners are spin 1/2 different</td>
<td>heavy partners have the same spin, no heavy gluon</td>
<td>heavy partners have the same spin</td>
</tr>
<tr>
<td>Higher level modes</td>
<td>NO heavy partners</td>
<td>NO heavy partners</td>
<td>YES heavy partners</td>
</tr>
<tr>
<td>(N_{t+}/N_{t-})</td>
<td>(&lt; 4:1)</td>
<td>(4:1)</td>
<td>(4:1)</td>
</tr>
<tr>
<td>SS leptons rates</td>
<td>from several channels: SS heavy fermions, Majorana fermions</td>
<td>only from SS heavy fermions</td>
<td>only from SS heavy fermions</td>
</tr>
<tr>
<td>(R = \frac{N(E_T + \text{jets})}{N(E_T + \text{jets})} )</td>
<td>(R_{\text{SUSY}})</td>
<td>(R_{LHT} &lt; R_{\text{SUSY}})</td>
<td>(R_{\text{UED}}) to be studied</td>
</tr>
<tr>
<td>b-jet multiplicity</td>
<td>enhanced (FP)</td>
<td>not enhanced</td>
<td>not enhanced</td>
</tr>
<tr>
<td>Single heavy (t)</td>
<td>NO</td>
<td>YES</td>
<td>YES via KK2 decay</td>
</tr>
<tr>
<td>polarization effects</td>
<td>(tt + E_T) to be studied</td>
<td>to be studied</td>
<td>to be studied</td>
</tr>
<tr>
<td>Direct DM</td>
<td>high (FP)</td>
<td>low (Bino-like LTP)</td>
<td>typically low for (\gamma_1(5D)) DM [20]</td>
</tr>
<tr>
<td>detection rate</td>
<td>low (coann)</td>
<td>low (Bino-like LTP)</td>
<td>typically high for (\gamma_H(6D)) DM [20]</td>
</tr>
</tbody>
</table>
We are not alone!

- LHC: LHCb has a complementary sensitivity to CMS/ATLAS for new physics.
  - Not yet explored in a systematic way
- Heavy flavor variables (precision measurements)
- $g-2$ new measurements (factor 5-10 improvement in O(5) years? )
- Dark matter hints from outer space (PAMELA/ATIC GLAST-Fermi..)
  - Wait until the dust settles...!
- New Collider?... not any time soon
The most interesting observables in the MSSM with MFV:

\[ B(B_s \rightarrow \mu\mu)_{SM} \approx 3.5 \times 10^{-9} \]
\[ B(B_d \rightarrow \mu\mu)_{SM} \approx 1.3 \times 10^{-10} \]

\[ e \] channels suppressed by \((m_e/m_\mu)^2\)
\[ \tau \] channels enhanced by \((m_\tau/m_\mu)^2\)

Most interesting bound set by:

\[ B(B_s \rightarrow \mu\mu) < 5.8 \times 10^{-8} \text{ (95\%CL)} \]

CDF+D0 '07

Significant constraint, but a good fraction of the parameter space is still allowed

N.B.: the \( B(B_d \rightarrow \mu\mu)/B(B_s \rightarrow \mu\mu) \) ratio is a key observable to proof or falsify MFV

Unfortunately no systematic comparison between the LHCb and ATLAS/CMS New Physics reach yet...
O. Buchmuller et al
arXiv:0808.4128

Where do we expect SUSY?

“LHC Weather Forecast”

Reversely: once we have first signals for New Physics at the LHC: use synergy to extract/learn as much as possible on the New Physics
Data presentation/storage discussion

- Often released data are presented under model assumptions, thus making it difficult to interpret in a different context
- How to communicate/catalogue an excess best
- Time overlaps between running of big facilities (Eg LHC/SLC and the LC) could be small. How to bridge that gap so that (S)LHC data is still fully alive when the next machine comes online?

Lively discussion! To be continued
Since we do not know what we will find...

...we will look at it from all angles....

Close interaction between Experiment and Theory will be important