SUSY at LHC

Thoughts about short term discovery, mid-term measurements, and long term cooperations

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well .... I did this talk in SUSY04
LHC is far more important than any experiment in the past

• Expand experimental reach significantly

• Cutting into TeV scale first time. **Last chance** to solve naturalness problem.

• We have solid observational evidence of DM in our Universe. New particle!

• All future experimental projects are now tied up with “LHC discovery”, ILC, Super B factory, DM searches....**Huge responsibility to provide correct scientific result quickly.**
Basic objects at LHC

- jet and lepton momentum
  \[ p_{j1}, p_{j2}, \ldots, p_{l1}, p_{l2}, \ldots \]
- Jet and lepton transverse momentum (to the beam)
  \[ p_{T1}, p_{T2}, p_{T3}, \ldots \]
- \( E_{T\text{miss}} \): Sum of the transverse momentum of all particles.
- \( M_{\text{eff}} \): Sum of the transverse energy of first 4 jets + \( E_{T\text{miss}} \)

\[
M_{\text{eff}} \equiv \sum_{i=1,\ldots,4} p_{Ti} + \sum_{\text{leptons}} p_{Tl} + E_{T\text{miss}}
\]
DM and collider signature

- **“SUSY signature”**
  “Models with new colored particles decaying into a stable neutral particle--LSP”

- **“New physics”** are migrated into SUSY category.
  - Universal extra dimension lightest of first level KK is stable.
  - Little Higgs model with T parity. T parity in the model, T odd sector has stable particle (AH)

- **Signal:**
  - High $P_T$ jets ($p_{T_1} > 100$ GeV, $p_{T_2,3,4} > 50$ GeV)
  - $p_{T_1} > 20$ GeV, $S_T > 0.2$
  - $E_{T\text{miss}} > \max(100$ GeV, $0.2M_{\text{eff}})$
• SUSY models get more and more peculiar
  
  • Gauge mediation (NLSP → gravitino)
  
  • Anomaly mediation (Wino like LSP)
  
  • Mixed modulars anomaly mediation (MMAM) model (KKLT setup) allows gaugino/sfermion mass unification at SUSY scale
  
  • Split supersymmetry (only gauginos)
  
  • Experimentalists are asked to study missing ET signatures in more “Model independent” context. (boson or fermion, branching ratios, mass splitting, cross sections)
Background and discovery

• Typical SUSY events are $10^5$ events for 10 fb$^{-1}$, while BG rate is $10^{9-8}$ for W, Z, ttbar production. $10^{-4}$ rejection of SM process is required.

• Can we reject/discover “SUSY” by “counting experiments” or need more “kinematical evidence”?

*Summarizing situation in next slide......
How to find them quickly and reliably?
Discovery and Recent BG issues

• Bg process $pp \rightarrow W(Z)+X$, ttbar ....

• Lowest order process $gq \rightarrow W q$ etc, small number of high PT jets, small $E_{T\text{miss}}$ relative to $M_{\text{eff}}$, $M_{\text{eff}}$ reduces rather quickly.

• BG had been estimated by PS approximation. Now including “multiple parton final states” such as $gq \rightarrow W + n$ jet...(ME collections, Mangano, Rainwater, Asai...)

• Some generators(ALPGEN, MADevent..) allows us to simulate BG of multi-parton final state. Matching between PS and ME is an issue(not expert).

• up to ttbar + 3 jet, W(Z) +6 jet (!) have been included in BG estimation. Also more detailed detector simulations are getting ready.
• High $P_T$ jets increase drastically when taking into ME.

• $K$ factor is 2~4 for large $M_{\text{eff}}$.

• Scale uncertainty still remains (order of $\alpha^n(\mu)$), easily gets factor 2.

• One lepton channel: BG is smaller and dominated by ttbar. Experimental calibration of the ttbar background is studied in ATLAS. Tune $E_{\text{Tmiss}}$ cut.
From Kanay’s Slide fo this meeting.

**Discovery Potential**

5-sigma discovery potential on $m_0$-$m_{1/2}$ plane

![Graph 100pb$^{-1}$](image1.png)

- $100\text{pb}^{-1}$
- $m(\tilde{g}) \sim 1\text{TeV}$
- $m(\tilde{q}) \sim 1\text{TeV}$

![Graph 1fb$^{-1}$](image2.png)

- 1fb$^{-1}$
- $m(\tilde{g}) \sim 1.6\text{TeV}$
- $m(\tilde{q}) \sim 1.5\text{TeV}$

- Fast simulation result
- Signal : Isawig/Jimmy
- Background : Alpgen

- **Only statistical error is included.**
- **Background is estimated by Alpgen.**
- **0-lepton mode : More statistics is available.**
- **1-lepton mode : Relatively smaller background uncertainty.**
- Major background is tt(+njets) is comparatively predictable.
For some region of MSUGRA parameter space Higgs will be produced from sparticle decays.
Reach in mSUGRA

\[ \text{SUSY} \rightarrow \text{Higgs} \rightarrow bb \]
Getting off from MSUGRA

- In KKLT model, both volume modulas $T$ and compensator $C$ contribute to the SUSY breaking.
  \[ M_a = \left( \frac{l_a}{R} + \frac{b_a g_{\text{GUT}}^2}{16\pi^2} \right) m_{3/2} \]

- mass spectrum can be quite degenerated. The $F_T/F_C$ gives one dim parametrization from MSUGRA → UED like → AM

- The minimum mass difference is determined by $\mu$ parameter. matter sector

- $K=Z_i Q_i^* Q_i$ and

  \[ Z_i = \frac{1}{(T + T^*)^{n_i}} \quad n=0 \text{ for D7, } n=1 \text{ for D3} \]
SUSY at LHC in degenerated limit

- degenerate SUSY = lower $P_T$ jets, small $M_{\text{eff}}$. Discovery gets difficult (no chance if all masses are same)

- "Benchmark" of degenerate scenario

- Need to take into account the background unlike MSUGRA.

- $S/N<1$, discovery is in ?? because of the background uncertainty

Kawagoe and Nojiri
DM signature in degenerate mass spectrum: $E_{\text{miss}}$ vs $M_{\text{eff}}$

Msq~1.5TeV

$E_{\text{miss}}$ takes large fraction of $M_{\text{eff}}$ 2/3 of Max in general

Discovery may be secure in $E_{\text{miss}}$ and $M_{\text{eff}}$ plane? (2dim fit of BG and signal)

Kawagoe and MN (June, 2006)
Dark matter in $M_{\text{eff}}-E_{T\text{miss}}$ plane

- Dominant production occurs at threshold. Two slow particles decay into DM.
- Dark matter signature at LHC
  - 2 uncorrelated particles with same energy $|p_{\text{CM}}|$.
  - $E_{T\text{miss}}=M_{\text{eff}}-2p_{\text{CM}}$ for DM while $E_{\text{tmiss}}<0.2M_{\text{eff}}$ for SM.
- Need more investigations in 2 dim plane.
Measurements
Mass reconstruction in SUSY

• “SUSY distributions” are not correction of the 1 dim distributions. It lives in multi-dimentional space— momentum space of jets and leptons.

• Invariant mass distribution

  • Tag particles from a SUSY particle decay chains (jet selections are essential)

  • end point of distributions

  • distributions at the end point (momentums are aligned)

• Exact Kinematical relation (long decay chains)

• $P_T$ of the jets (Peaks at typical scale) $\Rightarrow M_{T2}$
determination of the boundary of phase space for mass determination.

Here is the trick!

**LSP**

m(jll) with mll > 0.5 mll(max)

ee+μ-μ subtraction is effective to select single channel

m(jll)
Exact treatments

- example: bbl1 channel
  \[ \tilde{g} \rightarrow \tilde{b} \rightarrow \tilde{\chi}^0_2 \rightarrow \tilde{l} \rightarrow \tilde{\chi}^0_1 \]
- 5 mass involved. Each event define a 4 dim hypersurface in the 5 dim mass space.

- 5 events → solutions of masses. Likelihood analysis from a few SUSY events might work. Demonstrated for two unknown masses. Kawagoe, Polesello, MN 2004

- If sparticle masses are all known, LSP momentum is reconstructed up to two fold ambiguity. full reconstruction?
  talk along this: D. Miller in this meeting

\[
\begin{align*}
    m^2_{\tilde{\chi}} &= p^2_{\chi} \\
    m^2_{\tilde{l}} &= (p_{\chi} + p_{l_1})^2 \\
    m^2_{\tilde{\chi}_2} &= (p_{\chi} + p_{l_1} + p_{l_2})^2 \\
    m^2_{\tilde{b}_1} &= (p_{\chi} + p_{l_1} + p_{l_2} + p_{j_1})^2 \\
    m^2_{\tilde{g}} &= (p_{\chi} + p_{l_1} + p_{l_2} + p_{j_1} + p_{j_2})^2
\end{align*}
\]
from SUSY04

One event $\Rightarrow$ probability density for true masses (logL) from expected b jet smearing

\[
\log L(1) + \log L(2) + \log L(3) + \log L(4) + \ldots
\]

useful only when distribution agree with MC.
from SUSY04

One event \( \Rightarrow \) probability density for true masses (\( \log L \)) from expected b jet smearing

\[ \log L(1) + \log L(2) + \log L(3) + \log L(4) + \ldots = \sum \log L(\sim \Delta \chi^2) \]

Gluino mass

Gluino-sbottom

useful only when distribution agree with MC.
event without leptons

❤ squark(R) pair production

2 high pT jets with missing momentum

$$M_{T2}^2 = \min_{\nu_1+\nu_2=\nu_T} \left[ \max \left\{ m_T^2(p_T^{\ell_1}, \not{p}_T), m_T^2(p_T^{\ell_2}, \not{p}_T) \right\} \right]$$

❤ top reconstruction
discovery for $M_{1/2}$~500 GeV

Moortgat (CMS) in SUSY06

Little higgs with T parity predicts light top partner(fermion) decaying into t+DM

SUSY→t +X 3.5 pb

Hubisz and Meade hep-ph 0411264
top from SUSY(II): measurement

Hisano, Kawagoe, Nojiri (2003)

- $t \rightarrow bW \rightarrow bjj$
- $N(\text{jet}) > 7$ typically.
  Many jet pairs with $m(jj) \sim M_w$
- Background to $t \rightarrow bW \rightarrow bjj$ is estimated from events in the sideband $m_{jj} < M_w - 15 \text{ GeV}$ $m_{jj} > M_w + 15 \text{ GeV}$.
- Reconstructed top quarks are used to study $tb$ distribution
- Warning about jet background (more high $p_T$ jet) We may have to require leptons.
gluino→stop reconstruction

\[ \tilde{g} \rightarrow (t\tilde{t} \text{ or } b\tilde{b}) \rightarrow tb\tilde{\chi}_1^{\pm} \]

depends on stop mass and mixing angles→edge hightes and end point* gives constraints to 3rd generation SUSY breaking, B physics....

\[ M_{tb}^w = \frac{Br(\tilde{t})M_{tb}(\tilde{t}) + Br(\tilde{b})M_{tb}(\tilde{b})}{Br(\tilde{t}) + Br(\tilde{b})} \]

Uncertainty(QCD): fragmentation (Herwig : Phythia =1.3:1) jet finding algorithm.... How to tune MC?
Summary in SPS1a (most lucky case) from LHC/LC study

<table>
<thead>
<tr>
<th>particle</th>
<th>mass</th>
<th>error(low)</th>
<th>error(high)</th>
<th>bbll</th>
<th>M_{T2} 10GeV sys</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino</td>
<td>595</td>
<td>16.3</td>
<td>8.0</td>
<td></td>
<td></td>
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<tr>
<td>squark(L)</td>
<td>540</td>
<td>21.2</td>
<td>8.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>squark(R)</td>
<td>520</td>
<td>17.7</td>
<td>11.8</td>
<td></td>
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</tr>
<tr>
<td>\tilde{\chi}_0^0</td>
<td>378</td>
<td>14.6</td>
<td>5.1</td>
<td></td>
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</tr>
<tr>
<td>\tilde{\chi}_4^0</td>
<td>177</td>
<td>13.4</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>\tilde{\chi}_2^0</td>
<td>96</td>
<td>13.2</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Most of mass error is LSP mass error. Mass differences are known rather precisely.
- Access to 3 neutralino mass, information on 3 of (M1,M2,\mu, \tan\beta).
- selectron and smuon mass error is about same to that of N02.
- stau mass also can be measured from tau tau end point. many fake tau background. Need more study, but don’t be nervous.
Trying to ping down
Dark matter nature

- DM density: for SPS1a
  - slepton exchange (\wedge\wedge)\nu
  - stau co-annihilation (\wedge\wedge; not enough in co-annihilation region because dependence is so large. (Discussed in Baltz et al)
  - higgs s-channel exchange (; ;) Heavy higgs is not accessible in many cases.
  - higgsino component (\wedge\wedge)

fermion/boson? Left/Right?

• charge asymmetry in $j\ell(+ \text{ or } -)$ distributions (Barr, Goto et al) in SUSY

• Need following to have this asymmetry
  • pp collider (squark> anti-squark)
  • squark/sleptons are dominantly left or right.
  • neutralino is spin $1/2$
  • SUSY is the chiral theory, gaugino-$sL-L$ vertex

• Distribution would be different for UED cases (Smillie and Webber, hep-ph 0406317, Alves et al hep-ph/0605067)

• general discussion (by Athanasious et al hep-ph 0605286) for general decays involving 4 new particles
Thoughts

- First discovery/non-discovery data is not enough to discriminate “SUSY like scenarios”. How about other parameter such as “production cross section”.

- Need model independent output (not only for MSUGRA), but how?

- Models are increasing. (and disappear quickly after LHC starts...) **How to feed back the theoretical ideas to experimentalists?**, especially when we start to see deviation from SM/SUSY.

- **How to feedback reality to the theorists?**: Need quick publication from experimental side in accessible format. Learning from astrophysicists?