Supersymmetry at the LHC

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★ SUSY at LHC
  • SUSY signatures
  • SM backgrounds
  • cuts: optimizing signal/BG
  • LHC reach for SUSY
  • beyond discovery:
    ★ precision measurements
SUSY signatures at LHC

- \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} production dominant for \( m \lesssim 1 \) TeV
- lengthy cascade decays of \( \tilde{g} \tilde{q} \) are likely
- events characterized by multiple hard jets, isolated and non-isolated leptons \( e, \mu \), and \( E_T \) from \( \tilde{Z}_1 \) or \( \tilde{G} \) or \( \nu \)s escaping
- many jets are \( b \) (displaced vertices due to long \( B \) lifetime) and \( \tau \) (1 or 3 charged prongs) jets
- one way to classify signatures is according to number of isolated leptons
Classify event topologies according to isolated leptons

- $E_T + \text{jets}$
- $1\ell + E_T + \text{jets}$
- \textit{opposite − sign (OS)} $2\ell + E_T + \text{jets}$
- \textit{same − sign (SS)}$2\ell + E_T + \text{jets}$
- $3\ell + E_T + \text{jets}$
- $4\ell + E_T + \text{jets}$
- $5\ell + E_T + \text{jets}$
Backgrounds to SUSY events at LHC

Star: numerous SM processes give same signature as SUSY!

Star: SM BGs include:

- QCD: multi-jet $qq, q\bar{q}, qg, gg$ production where $E_T$ comes from mis-measurement, cracks, etc.
  - $t\bar{t}$, $b\bar{b}$, $c\bar{c}$

- $W$ or $Z$+ multi-jet production

- $WW$, $WZ$, $ZZ$ production, where $Z \rightarrow \nu\bar{\nu}$ or $\tau\bar{\tau}$
  * all of above embedded in Isajet, Pythia, Herwig

- four particle processes: e.g. $t\bar{t}t\bar{t}$, $ttbb$, etc.

- $WWW$, etc.
  * the $2 \rightarrow n$ for $n > 2$ processes usually need CalcHEP/Madgraph

- overlapping events; fake $b$-jets; fake leptons, etc
Background issues

★ The BGs must be estimated using full event simulation
  – jet broadening, interaction of particles with detectors

★ Must also simulate detector: GEANT or toy or...

★ If possible, use complete $2 \rightarrow n$-body matrix elements

★ matching of PS and HO-ME results? avoid double counting
  – VECBOS, AlpGEN, MCNLO, etc.

★ NLO QCD corrections?

★ matching the data: how well do we know SM BG rates?

★ first order of business at LHC: re-discover the SM!
  – calibrate detectors using $Z$+jets, $W$+jets, $t\bar{t}$ production
Example: calculate SUSY reach of LHC for 10, 100 fb$^{-1}$

★ Cuts and pre-cuts:

★ $E_T > 200$ GeV

★ $N_j \geq 2$ (where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$

★ Grid of cuts for optimized S/B:
  - $N_j \geq 2 - 10$
  - $E_T > 200 - 1400$ GeV
  - $E_T(j1) > 40 - 1000$ GeV
  - $E_T(j2) > 40 - 500$ GeV
  - $S_T > 0 - 0.2$
  - muon isolation

★ $S > 10$ events for 100 fb$^{-1}$

★ $S > 5\sqrt{B}$ for optimal set of cuts
Sparticle reach of LHC for $100^{-1}$ fb

$m_{\text{Sugra with } \tan\beta = 10, A_0 = 0, \mu > 0}$

$m_{\text{Sugra with } \tan\beta = 30, A_0 = 0, \mu > 0}$

HB, Balazs, Belyaev, Krupovnickas, Tata: JHEP 0306, 054 (2003)
Old sparticle reach of LHC for $10^{-1}$ fb incl. $2\ell$ and $3\ell$

Sparticle reach of LHC for $10^{-1} \text{ fb}$; RPV with $\tilde{Z}_1 \rightarrow c\bar{d}s$

HB, Chen, Paige, Tata: PRD55, 1466 (1997)
mSUGRA reach in $E_T^{\text{miss}} + \text{jets}$ final state

$A_0 = 0$, $\tan\beta = 35$, $\mu > 0$

- Charged LSP
- Chargino Searches at LEP
- No symmetry breaking

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Sparticle reach in AMSB model

\[ \tan \beta = 35, \; \mu > 0 \]

\[ m_\tilde{g} \approx m_\tilde{e}_R \]

\[ m_\tilde{\nu} = 2 \text{ TeV} \]

\[ m_\tilde{u}_R = 2 \text{ TeV} \]

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### Sparticle reach in GMSB model: various model lines

<table>
<thead>
<tr>
<th>Model</th>
<th>NLSP</th>
<th>Tevatron ((25 , fb^{-1}))</th>
<th>LHC ((10 , fb^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(\tilde{Z}_1 \sim \tilde{B}) (\tilde{Z}_1 \rightarrow \gamma \tilde{G})</td>
<td>(\Lambda \approx 115 , \text{TeV}, ) (m_{\tilde{g}/\tilde{q}} \sim 0.87 , \text{TeV}, ) (ll\gamma\gamma + E_T^{\text{miss}})</td>
<td>(\Lambda \approx 400 , \text{TeV}, ) (m_{\tilde{g}/\tilde{q}} \sim 2.8 , \text{TeV}, ) (\gamma\gamma + E_T^{\text{miss}})</td>
</tr>
<tr>
<td>B</td>
<td>(\tilde{\tau}_1)</td>
<td>(\Lambda \approx 53 , \text{TeV}, ) (m_{\tilde{g}/\tilde{q}} \sim 0.82 , \text{TeV}, ) (\text{Clean channels}) (3l + 1\tau 2l + 1\tau 3l) (+2\tau 1l + 3\tau 2l)</td>
<td>(\Lambda \approx 150 , \text{TeV}, ) (m_{\tilde{g}/\tilde{q}} \sim 2.0 , \text{TeV}, ) (3l + E_T^{\text{miss}})</td>
</tr>
</tbody>
</table>
Sparticle reach of all colliders and relic density

$m_{Sugra}$ with $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

$m_{Sugra}$ with $\tan\beta = 45$, $A_0 = 0$, $\mu < 0$

HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)
Sparticle reach of colliders plus DM DD/IDD

HB, Belyaev, O’Farrill, Krupovnickas: JHEP 0408, 005 (2004)
Reach of Atlas for SUSY Higgs: 300 fb$^{-1}$

- $t \rightarrow bH^+, H^+ \rightarrow \tau\nu$
- $h \rightarrow \gamma\gamma$ and $Wh/ttH, h \rightarrow \gamma\gamma$
- $tth, h \rightarrow bb$
- $H/A \rightarrow \mu\mu$
- $H/A \rightarrow \tau\tau$
- $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons
- $H \rightarrow hh \rightarrow bb\gamma\gamma$
- $A \rightarrow Zh \rightarrow llbb$
- $H/A \rightarrow tt$

ATLAS $\int L dt = 300$ fb$^{-1}$
Maximal mixing

LEP2
$\sqrt{s} = 200$ GeV
$\int L dt = 200$ pb$^{-1}$

$\sqrt{s} = 189$ GeV
$\int L dt = 175$ pb$^{-1}$

$m_A$ (GeV)
Precision measurements at LHC

- \( M_{eff} = \cancel{E_T} + E_T(j1) + \cdots + E_T(j4) \) sets overall \( m_{\tilde{g}}, m_{\tilde{q}} \) scale
- \( m(\ell\ell) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \) mass edge
- \( m(\ell\ell) \) distribution shape
- combine \( m(\ell\ell) \) with jets to gain \( m(\ell\ell j) \) mass edge: info on \( m_{\tilde{q}} \)
- further mass edges possible \( e.g. \) \( m(\ell\ell jj) \)
- Higgs mass bump \( h \to b\bar{b} \) likely visible in \( \cancel{E_T} + jets \) events
- in favorable cases, may overconstrain system for a given model
  - methodology very p-space dependent
  - some regions are very difficult \( e.g. \) HB/FP
Paige, Hinchliffe et al. case studies:

- examined many model case studies in mSUGRA, GMSB, high $\tan \beta$...
- $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu) = (100, 300, 0, 2, 1)$ in GeV
- dominant $\tilde{g}\tilde{g}$ production with $\tilde{g} \rightarrow q\tilde{q}_L \rightarrow qq\tilde{Z}_2 \rightarrow q_1q_2\ell_1\ell \rightarrow q_1q_2\ell_1\ell_2\tilde{Z}_1$ (string of 2-body decays)
- can reconstruct 4 mass edges; allows one to fit four masses: $m_{\tilde{q}_L}$, $m_{\tilde{Z}_2}$, $m_{\ell}$, $m_{\tilde{Z}_1}$ to $3 - 12\%$
- can also find Higgs $h$ in the SUSY cascade decay events
- if enough sparticle masses measured, can fit to MSSM/SUGRA parameters
$M_{\text{eff}} = E_T(j1) + E_T(j2) + E_T(j3) + E_T(j4) + E_T$

- rough estimate of $m_{\tilde{g}}, m_{\tilde{q}}$ can be gained from max of $M_{\text{eff}}$

Atlas TDR (F. Paige)
\( m(\ell^+\ell^-) \) mass edge from \( \tilde{Z}_2 \rightarrow \ell^+\ell^-\tilde{Z}_1 \)

- kinematically, \( m(\ell^+\ell^-) < m\tilde{Z}_2 - m\tilde{Z}_1 \)
- for \( \tilde{Z}_2 \rightarrow \tilde{\ell}^+\ell^- \rightarrow (\ell^+\tilde{Z}_1)\ell^- \), have

\[
m(\ell^+\ell^-) < m\tilde{Z}_2 \sqrt{1 - \frac{m_{\ell}^2}{m_{\tilde{Z}_2}^2}} \sqrt{1 - \frac{m_{\tilde{Z}_1}^2}{m_{\ell}^2}} < m\tilde{Z}_2 - m\tilde{Z}_1
\]
$m(\ell^+ \ell^- q)$ **mass edge from** $\tilde{q} \rightarrow q\tilde{Z}_2$

- $\tilde{q}_L \rightarrow q\tilde{Z}_2 \rightarrow q\ell^\pm \ell^\mp \rightarrow q\ell^\pm \ell^\mp \tilde{Z}_1$

![Graph showing event distribution](image)

Atlas TDR (F. Paige)
$m(\ell q)$ mass edge from $\tilde{q} \rightarrow q\tilde{Z}_2$
$m(\ell q)$ mass edge from $\tilde{q} \rightarrow q \tilde{Z}_2$
\( m(\bar{b}b) \) Higgs mass bump in SUSY jets + \( \not{E}_T \) events

Atlas TDR (F. Paige)
Case study of SUSY in the focus point region of mSUGRA

- $m_0 \sim 3$ TeV so squarks/sleptons decouple
- $m_{\tilde{g}} \sim 1$ TeV and $\mu \sim 226$ GeV so $\tilde{W}_1$, $\tilde{Z}_2$ light
- SUSY production: soft ($\tilde{W}_1^+ \tilde{W}^-, \tilde{W}^\pm \tilde{Z}_2$) and hard ($\tilde{g}\tilde{g}$) component

**Diagram:** HB/FP Sparticle Masses

**Graph:**
- HB, Barger, Shaughnessy, Summy and Wang

*Howie Baer, SUSY at LHC, lecture 3: Karlsruhe, July 25, 2007*
FP case study: cross sections

HB/FP Cross Sections

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Apply cuts set C1

- $\bar{E}_T > \max(100 \text{ GeV}, 0.2M_{\text{eff}})$
- $n_j \geq 4; \ S_T > 0.2$
- $E_T(j_1, j_2, j_3, j_4) > 100, 50, 50, 50 \text{ GeV}$
$n(jets)$ distribution

No. of Jets
Cuts C1

$\sigma$ (fb)

$\#$ of Jets

- FP(3050,4000,0,30,1,175)
- QCD Jets
- $t\bar{t}$
- W+jets
- Z+jets
- WW, WZ, ZZ
- Sum of Backgrounds

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$n(b-jets)$ distribution

No. of $b$-jets (60% eff.)

Cuts C1

FP(3050,400,0,30,1,175)
QCD Jets
$t\bar{t}$
W+jets
Z+jets
WW, WZ, ZZ
Sum of Backgrounds

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$n(\text{leptons})$ (isolated) distribution

No. of Isolated Leptons

Cuts C1

- FP(3050,400,0,30,1,175)
- QCD Jets
- $t\bar{t}$
- W+jets
- Z+jets
- WW, WZ, ZZ
- Sum of Backgrounds

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The distribution of isolated leptons is shown in the plot. The x-axis represents the number of leptons, while the y-axis represents the cross-section (σ) in fb. Different cuts (C1) are applied to separate the signal from background. The distributions of different processes, such as QCD Jets, ttbar, W+jets, Z+jets, WW, WZ, ZZ, and the sum of backgrounds, are plotted separately. The plot illustrates how the number of leptons varies with the cross-section for different cuts and processes.
Augmented effective mass $A_T$

- $n(jets) \geq 7$
- $n(b-jets) \geq 2$

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Augmented effective mass $A_T$

- $n(jets) \geq 7; n(b - jets) \geq 2; A_T > 1400$ GeV

- signal way above BG; purely from $\tilde{g}\tilde{g}$ production

- extract $m_{\tilde{g}}$ from total rate to $\sim 8\%$
• cuts C1; $n(\text{leps}) \geq 2$; $n(\text{jets}) \geq 4$; $n(\text{b-jets}) \geq 2$; $A_T > 1200$ GeV

• two mass edges stand out
Conclusions

★ SUSY at LHC
  • event signatures
  • backgrounds
  • cuts
  • reach
  • precision measurements

★ We now have a good idea of what SUSY will look like at the LHC for many SUSY models

★ in 2008, the road to discovery begins at the LHC: time to either discover or rule out supersymmetry at the weak scale, and resolve the physics behind electroweak symmetry breaking!