SUSY Searches with $E_T$ T

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Outline

- Introduction
  Why supersymmetry

- Inclusive searches
  Squark/gluino production

- Natural SUSY searches
  3rd generation squarks
  *(Light gauginos – Richard's talk)*

- Outlook
Supersymmetry

Supersymmetry common in many SM extensions

Strong motivation for TeV-scale SUSY:
- Stabilize a light Higgs mass
- Dark-matter candidate
- Gauge coupling unification

SUSY is not just one model
Many possible variations
- SUSY breaking mechanism: gravity-, gauge-, anomaly-mediated, …
- Beyond MSSM
- R-parity = (-1)^2S(-1)^3B+L conserved?
  If not, lifetime of lightest sparticle

Wide range of possible signatures
for SUSY to be searched for
(and many ways to hide)
SUSY – Under Pressure

No signs of SUSY yet
Allowed phase space is getting squeezed
- Flavor physics remains in good agreement with SM
- Light Higgs-like boson discovered, but at high end of (MSSM) preference

- Either large stop mixing
- Very heavy squarks
- Or beyond MSSM

Strong constraints from direct searches
SUSY Searches at the LHC

Many past searches at LEP & Tevatron
Now largely superseded by large collection of LHC results

Focus on new 2011 results and first 8 TeV results

Analysis details can be found in parallel session talks and posters
Inclusive Searches
Inclusive Searches

Most generic searches: strongly produced squarks/gluons

- High production cross-section
- Select on jets+$\not{E}_T$ signature
- Can reduce backgrounds by requiring additional leptons/photons/(b)-jets) from intermediate sparticles in cascade decay
Example Inclusive Searches

**ATLAS example: jets+$\not{E}_T$**
- 5 signal regions (2-6 jets) each with 1-3 $m_{\text{eff}}$ selections to probe multiple SUSY masses
- 4 control regions per SR to estimate backgrounds

**CMS example: $\alpha_T$+0-4 b-jets**
- Suppress QCD by requiring $\alpha_T$ > 0.55
- Z,W and top backgrounds measured in (2)$\mu$+jets and $\gamma$+jet control regions
- Fit in b-jet multiplicity and $H_T$ (scalar sum of jet $p_T$)
Interpretation in CMSSM

Many inclusive searches from both ATLAS and CMS
No excess observed anywhere
CMSSM used as benchmark

- Common models for (almost) all searches
- \( \tan \beta = 10, A_0 = 0, \mu > 0, \) scan \( m_0, m_{1/2} \)
- Only weak dependence on \( \tan \beta \) up to \( \sim 40 \)
CMSSM Limits on Sparticles

Limits in terms of squark and gluino masses

\[ m_q \gtrsim 1400 \text{ GeV}, \]
\[ m_g \gtrsim 900 \text{ GeV} \quad \text{OR} \]
\[ m_q \sim m_g \gtrsim 1400 \text{ GeV} \]
Simplified Models

- Consider only 2-4 new particles in final state with BF=100%
- $\sigma$ limit on decay topology vs masses
- Mass limits assuming SUSY $\sigma$ prod.

Useful for
- Signal selection optimization
- Illustrate sensitivity independently of SUSY-breaking model

Note that limits collapse for heavy $\chi^0_1$ (degenerate scenarios)
Searches with Leptons

Several searches with ≥1 leptons in ATLAS & CMS

- Sensitive to gauginos and sleptons in cascade

**ATLAS:** 1-2 $\ell$+jets+$E_T$

- 5 signal regions to maximize sensitivity
- Special soft-lepton signal region for degenerate signals

**CMS:** $e/\mu+\tau_{had}+$Razor

$g \rightarrow qq\chi^+_1, \chi^+_1, \rightarrow \ell\nu\chi^0_1$

**CMS:** 2 OS $\ell$+jets+$E_T$+ANN

$g \rightarrow qq\chi^0_2, \chi^0_2, \rightarrow \ell\ell\chi^0_1$

*New*
Gauge-mediated SUSY Breaking

SUSY breaking mediated from hidden sector by gauge interactions
The LSP will be a light gravitino
Next to lightest SUSY particle (NLSP) determines phenomenology

- $\tilde{\tau}$ NLSP will increase $\#\tau$'s in final state
- More leptons if $\tilde{e}$ or $\tilde{\mu}$ is NLSP

CMS: jets+$E_T$ + 2x$\tau_{\text{had}}$

ATLAS: jets+$E_T$ + 2 OS leptons($e$, $\mu$, $\tau_{\text{had}}$)
Gauge-mediated SUSY Breaking

If NLSP is neutralino, decay will depend on bino/wino/higgsino mixture

- **Wino-like:** \( \tilde{\chi}_0^0 \rightarrow \gamma/Z+G, \tilde{\chi}_+^+ \rightarrow W+G \)
- **Higgsino-like:** \( \tilde{\chi}_0^0 \rightarrow h/Z +G \)
- **Bino-like:** \( \tilde{\chi}_0^0 \rightarrow \gamma+G \)

**CMS:** \( 2\gamma+\text{jet}+\not{E}_T \)

**ATLAS:** \( \ell+\gamma+\not{E}_T \)

**ATLAS:** \( b\text{-jet}+\gamma+\not{E}_T \)

**ATLAS:** \( Z+\not{E}_T +\text{jets} \)

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Limit on Gravitino Mass

Mono-jet analysis
Limit on direct gravitino-squark/gluino production

Limit on m_{\tilde{G}} using
\[ \sigma \sim 1/m_{\tilde{G}}^2 \]

Limits assume
BF(\tilde{q} \rightarrow q\tilde{G})=100%
Natural SUSY
Natural SUSY

Inclusive searches constrain 1\textsuperscript{st}/2\textsuperscript{nd} generation squarks and gluinos to be \(\gtrsim\) TeV, unless \(\chi_0^1\) is heavy.

Only light stop needed to regularize light Higgs boson

The gluino should not be too heavy either

New search frontier

- Search for stop and sbottom
- Direct production or through gluino pairs

Light as \(\mu \sim m_Z\) at tree level
Stop and sbottom Production

Gluino-mediated production
Dominates if gluino light enough
– final state rich in b-jets and top

On-shell: \( m(\tilde{t}_1) < m(\tilde{g}) \)

Off-shell: \( m(\tilde{t}_1) > m(\tilde{g}) \)

Small x-section for direct production
– final state is typically top-like
Gluino-Mediated sbottom

Hadronic searches in multi-bjet channel most sensitive

ATLAS: 3 b-jets+$E_T$ (4 jets)

CMS: 2-4 b-jets+$\alpha_T$

8 TeV
Gluino-Mediated stop - ATLAS

4 top quarks in decay
Many searches sensitive
- Multi-jets (6-9 jets)
- 3 b-jets
- Same-charge dileptons
- 3 leptons

ATLAS: 3 b-jets+$E_T$ (6 jets)

ATLAS: 3 leptons + 4 jets+$E_T$
Gluino-Mediated stop - CMS

CMS: 2-4 b-jets + α_T

CMS Preliminary, 11.7 fb⁻¹, \( \sqrt{s} = 8 \text{ TeV} 

Data (hadronic sample, \( n_b \geq 3 \); \( n_j \geq 4 \))

Standard Model ± Expected Unc.

SM + pp → \( \bar{g}g, g \bar{g} \rightarrow b \bar{b} \chi_1^- \)

(\( m_{\tilde{g}} = 1100 \text{ GeV}, m_{\chi_1^-} = 500 \text{ GeV} \))

Events / bin

8 TeV

CMS: SS dileptons + bjets

CMS Preliminary, \( \sqrt{s} = 8 \text{ TeV}, L_{int} = 10.5 \text{ fb}^{-1} \)

8 TeV

CMS-PAS-SUS-12-028

CMS-SUS-12-029

CMS-PAS-SUS-12-028

CMS-PAS-SUS-12-028

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CMS-PAS-SUS-12-028
Direct sbottom Production

Exploit 2-body decay kinematics for $\tilde{b}_1 \rightarrow b\tilde{\chi}^0_1$

Use leptonic decay for $\tilde{b}_1 \rightarrow t\tilde{\chi}^\pm_1$

All limits assume 100% BF for $\tilde{b}_1$
Direct Stop – CMS

Dedicated $\ell+b$-jet+$E_T$ search
- Use 7 signal regions in $E_T$ and $m_T$
- Mass limits in two decay models

CMS Preliminary

$\sqrt{s} = 8$ TeV, $\int dt = 9.7$ fb$^{-1}$

CMS-SUS-12-023
Direct Stop – CMS

New all hadronic search

- Large $E_T$ and #jets (5-7)
- No top-tagging to maintain sensitivity to $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$
- Dominant background from $t \rightarrow b\tau_{\text{had}}$ (estimate with $\tau$-embedding)

$$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$$

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$$
Direct Stop – ATLAS

Multiple dedicated searches
Target different stop mass & decay

- High stop mass, $\tilde{t}_1 \rightarrow t\chi_1^0$
- $m(\tilde{t}_1) \sim m(t)$
- Light stop, $\tilde{t}_1 \rightarrow b\chi_1^{\pm}$

Soft di-leptons+$\mathbb{E}_T$ significance

1 lepton + b-jets+$\mathbb{E}_T$

ArXiv:1208.4305

ArXiv:1208.2590
Light Stop - Tevatron

Still some areas not yet explored by ATLAS/CMS

Light $\tilde{t}_1 \rightarrow c\tilde{\chi}^0_1$

CDF: jets+$E_T$

ANN-based charm tagger

Higgsino-like chargino enhancing $\tau$ coupling

D0: $\mu+\tau+2$-jets+$E_T$

CDF Run II Preliminary

D0, $L = 7.3$ fb$^{-1}$

Phys. Lett. B 710, 578
Summary and Outlook

Large set of inclusive searches
Many different signatures and methods
No evidence of signal in any search

Squark (1\textsuperscript{st}/2\textsuperscript{nd} gen.) and gluino masses above \(~1\) TeV except for very heavy neutralinos

New focus: 3rd generation squarks
First results already available
Sensitive up to \(~0.5\) TeV
(but read the fine-print)

Most searches now done with \(~5\) fb\(^{-1}\) 7 TeV data
Expect many \(~20\) fb\(^{-1}\), 8 TeV updates this winter
Ultimately, will likely need 14 TeV data to discover TeV-scale SUSY
Backup
### ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)

<table>
<thead>
<tr>
<th>ATLAS SUSY Searches</th>
<th>95% CL Lower Limits</th>
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<tbody>
<tr>
<td>ATLAS Preliminary</td>
<td></td>
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</table>

\[ \int L dt = (2.1 - 13.0) \text{ fb}^{-1} \]

\[ \sqrt{s} = 7, 8 \text{ TeV} \]

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*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
CMS Results – Simplified Models

**Best limits:**

<table>
<thead>
<tr>
<th>CMS preliminary</th>
<th>Leptonic</th>
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<tr>
<td>m(µ)−m(LSP) = 330 GeV</td>
<td>m(µ)−m(LSP) = 0 GeV</td>
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| T1: \(\tilde{t}_1 \rightarrow q \tilde{q} \tilde{b}\) | \(\tilde{t}_1 \rightarrow t \tilde{q} \tilde{b}\) |
| T1: \(\tilde{b}_1 \rightarrow b \tilde{q}_1\) | \(\tilde{b}_1 \rightarrow b \tilde{q}_1\) |
| T3: \(\tilde{b}_1 \rightarrow b \tilde{q}_1\) |
| T5: \(\tilde{t}_1 \rightarrow t \tilde{q} \tilde{b}\) |
| T2: \(\tilde{t}_1 \rightarrow t \tilde{q} \tilde{b}\) |
| T2b: \(\tilde{b}_1 \rightarrow b \tilde{q}_1\) |
| T2b: \(\tilde{b}_1 \rightarrow b \tilde{q}_1\) |

Does not include latest HCP results