Searches for Supersymmetry at ATLAS

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On behalf of the ATLAS Collaboration

- $pp \rightarrow \tilde{b}_1 \tilde{b}_1 + X$ candidate
- 2 b-tagged jets $p_T \sim 152$ GeV and 96 GeV
- $E_T^{miss} \sim 205$ GeV, $M_{CT}(bb) \sim 201$ GeV
Supersymmetry

- **New symmetry between fermions and bosons**
  - A superpartner for every SM particle differing by half unit of spin
  - At least 2 Higgs doublets

- Physics motivations:
  - TeV scale supersymmetry motivated by gauge hierarchy problem
    - Stabilize the Higgs mass
  - Other pros:
    - Good dark matter candidate
    - Gauge unification

- No protection against baryon or lepton number violation by default
  => Postulate a new quantum number R:
    - SM $R=+1$, SUSY $R=-1$

For R-parity conserving models:
- SUSY particles produced by pairs
- Lightest susy particle (LSP) is stable
  ⇒ Large impact on phenomenology
Supersymmetry is a theory => plethora of models

Simplest extension of SM the MSSM has 105 new parameters

How to test that at LHC?

1. Top/down approaches:
   - Supersymmetry is broken, different models: Gravity mediated (SUGRA), Gauge mediated (GSMB), ...
   - GUT scale unification => few free parameters

   - Benchmark model: CMSSM / mSUGRA
     - $m_0$ common scalar mass (GUT)
     - $m_{1/2}$ common gaugino mass (GUT)
     - $\tan\beta$ ratio of Higgs vacuum expectation values
     - $A_0$ common trilinear coupling
     - $\text{Sign}(\mu)$ Higgs mass term

2. Bottom/up approaches:
   a. Pheno. models:
      - Assume masses and hierarchy
      - Scan remaining parameters
   b. Simplified models:
      - Specific decay chain

   ✓ Kinematic and rate determined by very few mass parameters
A typical analysis

- **Simple « cut & count » analysis**
  - Many jets + large $E_T^{\text{miss}}$ + eventually leptons (inc. taus)/photons/bjets
  - Cut sufficiently hard to reduce largely unknown background processes (fake MET, fake-leptons from QCD)
  - Apply discriminating cuts to enhance signal/background ratio

\[ m_{\text{eff}} = \sum_{\text{jets}} p_T + \sum_{\text{lept.}} p_T + E_T^{\text{miss}} \]

- **Remaining backgrounds estimated via**
  - Fully data-driven methods for difficult bkgs (QCD, fake-leptons)
  - Semi-data-driven methods for main processes

\[ N_{\text{SR\,est.}} = \frac{N_{\text{SR\,MC}}}{N_{\text{CR\,MC}}} \times (N_{\text{CR\,obs}} - N_{\text{CR\,bkg}}) \]
ATLAS SUSY Searches

1. **Strong production channels:**

   \[ pp \rightarrow \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{g}\tilde{g} + X \]

   - Copious production at hadron colliders
   - Etmiss based generic search channels
   - Plus more exotic channels
     - Long-Lived (LL) particles
     - Resonances

2. **Third generation sparticles searches:**

   - Expected from naturalness to be O(< TeV)
   - Expected lighter than other squarks due to mixing
   - Can search for more specific final states

3. **Leptons/photons searches:**

   \[ pp \rightarrow \tilde{\chi}_i^{\pm} \tilde{\chi}_j^{\pm}, \tilde{\chi}_i^{\pm} \tilde{\chi}_j^{0}, \tilde{\chi}_i^{0} \tilde{\chi}_j^{0} + X \]

   Relevant when:
   - colored spartners are too heavy => direct gaugino production
   - RPV decays
   - Gauge-Mediated models
Strong production – R-parity conserving models

- SUSY particles mainly produced via strong interaction (gluino, squarks) at hadron colliders

If R-parity is conserved:
- sparticles produced by pair
- decay to invisible LSP

\[ \Rightarrow \text{Search for jets} + E_T^{\text{miss}} + 0,1,2\text{-leptons} \]

Benchmark, interpretation in CMSSM:
- Exclude \( m \sim 1075 \) GeV for \( m(\tilde{q})=m(\tilde{g}) \)
- 3 very different analysis confirm exclusion limit at high \( m_0 \)
- Update with 5 fb\(^{-1}\) foreseen in coming weeks
Strong production, bottom-up interpretations

Pheno MSSM model:
- Only gluino, squark, LSP
- LSP is light

✓ Limits independent of LSP mass for m(LSP) up to ~ 200 GeV

- See Robin’s talk for further results!
- Small mass splittings (compressed spectra) will require specific channels
- Results (+ acceptance & efficiency) available in HEPDATA format
...even more exotic channels

... still strong production, but with long-lived supersymmetric particles (RPV, GMSB, AMSB models)

RPV decays of LSP:

\[
\tilde{\chi}^0 \rightarrow q_i \tilde{\mu} \tilde{\mu}
\]

Search for displaced vertex:
- many tracks
- large vertex mass

Limits depend on lifetime:

![Graph showing cross section vs. c_t (mm)]
...even more exotic channels

... still strong production, but with long-lived supersymmetric particles (RPV, GMSB, AMSB models)

Exclude chargino lifetime between 0.5 and 2 ns for $m(\text{chargino}) = 90.2$ GeV

**AMSB model:** neutralino and chargino are nearly mass degenerate $\Rightarrow$ LL track

Search for disappearing track:
- small number of TRT hits

**ATLAS specific study thanks to the Transition Radiation Tracker (TRT)**
…even more exotic channels

… still strong production, but with long-lived supersymmetric particles (RPV, GMSB, AMSB models)

- Long-lived sleptons or R-hadrons (gluino or squarks binding with other quarks)

- Depending on nature/interaction/lifetime could produce:
  - large ionization loss in trackers
  - long time-of-flight in calorimeters
  - heavy-like muons (staus) seen in muon spectrometers
  - large calorimeter deposit in empty bunch crossings

ATLAS
Leading Jet Energy $>100$ GeV
$N_{jet} = 1$

Exclude R-hadron $m < 340$ GeV if $10^{-5} < \tau < 10^3$ s
Possible search strategies:

- If gluino is light enough => dominant process
  - Gluino pair production
    - \( \tilde{g} \rightarrow b\bar{b}_1, \tilde{g} \rightarrow t\bar{t}_1 \)
  - Search for b-jets + MET + jets

- If not and only 3\textsuperscript{rd} gen. squarks are light
  - Sbottom pair production => 2 b-jets + MET
  - Stop pair production => several decay chains depending on mass hierarchy
Gluino mediated sbottom production

✓ **Signature:** 0-lepton + several b-jets + $E_T^{\text{miss}}$ => make use of flavor tagging

✓ **Interpretations:** pheno. MSSM model
  o Only gluino, sbottom, LSP
  o Mass spectrum: $m(\tilde{g}) > m(\tilde{b}_1) > m(\tilde{\chi}_1^0)$

✓ **Exclude** $m(\text{gluino}) < 900$ GeV for $m(\text{sbottom})$ up to ~ 800 GeV
Gluino mediated stop production

✓ Signatures:
  a. 1-lepton + several b-jets + $E_t^{miss}$
  b. 2 same sign leptons + several jets + $E_t^{miss}$

✓ Interpretations: Pheno MSSM model:
  o Only gluino, stop, chargino, LSP
  o Mass spectrum: $m(\tilde{g}) > m(\tilde{t}_1) > m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$
    $$\text{Br}(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}) = 1$$

✓ Exclude $m(\text{gluino}) < 650$ GeV for $m(\text{stop})$ up to $\sim 450$ GeV
Direct sbottom pair production

✓ Signature: exactly 2 b-jets + $E_T^{\text{miss}}$ => make use of flavor tagging

✓ Interpretations: pheno. model with $Br(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 1$

✓ Excluding sbottom mass < 380 GeV for neutralino masses up to ~ 100 GeV

✓ What about stop pair production?
  ▪ Effort ongoing but harder because numerous decay chains
  ▪ Cross-section is small (scalar), difficult to distinguish from top pairs
SUSY signatures with tau leptons

✓ For each SM fermion, two scalar sfermion (\(\tilde{f}_L, \tilde{f}_R\))
✓ Gauge eigenstates mix to form mass eigenstates \(m(\tilde{f}_1) < m(\tilde{f}_2)\)
✓ Mixing \(\propto\) yukawa coupling => 3\(^{rd}\) gen. sfermions are often lightest

Consequence: \(\tilde{\tau}_1\) is lightest slepton, very often NLSP in GMSB models

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Tau decays
• hadrons (65%)
• leptons (35%)

\[ \Rightarrow \text{signatures:} \]
✓ 2 opposite sign electron(s)/muon(s)
✓ 1 hadronic tau + jets + \(E_t^{\text{miss}}\)
✓ 2 hadronic taus + jets + \(E_t^{\text{miss}}\)
1 hadronic tau + 1 muon + jets + \(E_t^{\text{miss}}\) (on-going)

Independently of \(\tan(\beta)\), \(\Lambda < 31\) TeV is excluded
Lepton(s)/photon(s) based signatures

4-leptons search:
- RPV decays
- Direct gaugino production

- No specific excess found

$e\mu$ resonance:
- RPV decay of sneutrino

+ Large ongoing effort to extend ATLAS searches to direct gaugino production
**ATLAS SUSY searches limits**

We are approaching limits on TeV-scale new physics

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### ATLAS SUSY Searches - 95% CL Lower Limits (Status: BSM-LHC 2011)

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM: 0-lep + j/s + E_{T,mass}</td>
<td>990 GeV</td>
</tr>
<tr>
<td>MSUGRA/CMSSM: 1-lep + j/s + E_{T,mass}</td>
<td>875 GeV</td>
</tr>
<tr>
<td>MSUGRA/CMSSM: multijets + E_{T,mass}</td>
<td>860 GeV</td>
</tr>
<tr>
<td>Simpl. mod. (light $\tilde{\chi}<em>1^0$): 0-lep + j/s + E</em>{T,mass}</td>
<td>860 GeV</td>
</tr>
<tr>
<td>Simpl. mod. (light $\tilde{\chi}<em>1^0$): 0-lep + j/s + E</em>{T,mass}</td>
<td>800 GeV</td>
</tr>
<tr>
<td>Simpl. mod. (light $\tilde{\chi}<em>1^0$): 0-lep + j/s + E</em>{T,mass}</td>
<td>720 GeV</td>
</tr>
<tr>
<td>Simpl. mod. (light $\tilde{\chi}<em>1^0$): 0-lep + b-jets + j/s + E</em>{T,mass}</td>
<td>560 GeV</td>
</tr>
<tr>
<td>Pheno-MSSM (light $\tilde{\chi}<em>1^0$): 2-lep SS + E</em>{T,mass}</td>
<td>600 GeV</td>
</tr>
<tr>
<td>Pheno-MSSM (light $\tilde{\chi}<em>2^0$): 2-lep OS + E</em>{T,mass}</td>
<td>550 GeV</td>
</tr>
<tr>
<td>Simpl. mod. ($\tilde{g} \rightarrow 2\tilde{\chi}<em>1^0$): 1-lep + j/s + E</em>{T,mass}</td>
<td>260 GeV</td>
</tr>
<tr>
<td>GMSB (GGM) + Simpl. model: $\gamma + E_{T,mass}$</td>
<td>770 GeV</td>
</tr>
<tr>
<td>Stable massive particles: R-hadrons</td>
<td>562 GeV</td>
</tr>
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<td>Stable massive particles: R-hadrons</td>
<td>264 GeV</td>
</tr>
<tr>
<td>Stable massive particles: R-hadrons</td>
<td>368 GeV</td>
</tr>
<tr>
<td>Hypercolour scalar gluons: 4 jets, $m_0 = m_{\tilde{g}}$</td>
<td>180 GeV</td>
</tr>
<tr>
<td>RPV ($\lambda_{311}, 0.10, \lambda_{312}, 0.05$): high-mass $\tilde{\chi}_1^0$</td>
<td>5.5 GeV</td>
</tr>
<tr>
<td>Bilinear RPV (ct^2 &gt; 15 mm): 1-lep + j/s + E_{T,mass}</td>
<td>760 GeV</td>
</tr>
</tbody>
</table>

*Only a selection of the available results leading to mass limits shown*
Summary

• **Generic SUSY searches:**
  – Simplest SUSY models have been excluded up to TeV scale
  – But there is still a long way till light SUSY is excluded:
    • Compressed spectra
    • Long decay chains
    • Long-lived particles
    • R-parity violation models

• **Naturalness problem:**
  – Extensive search of third generation sparticles started and is ongoing
  – Many new results expected in coming weeks

• **Keep informed / read more (~ 20 papers in 1 year) by looking at:**
  [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublic Results](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublic Results)
Backup
A typical analysis

- simple « cut & count » analysis
  - Many jets + large $E_T^{miss}$ + eventually leptons (inc. taus)/photons/bjets

- Cut sufficiently hard to reduce largely unknown background processes (fake MET, fake-leptons from QCD)

- Apply discriminating cuts to enhance signal/background ratio

Multijets analysis

- $2-\tau + E_T^{miss}$ analysis

\[ m_{\text{eff}} = \sum_{\text{jets}} p_T + \sum_{\text{lept.}} p_T + E_T^{\text{miss}} \]
A typical analysis

✓ simple « cut & count » analysis
✓ Cut sufficiently hard to reduce largely unknown background processes (fake MET, fake-leptons from QCD)
✓ Apply discriminating cuts to enhance signal/background ratio

✓ Remaining backgrounds are estimated via
  ✓ Fully data-driven methods for difficult but small processes

1. Determine the jet response function $R$ from dijet balance and 3-jets mercedes events
2. Take a control sample of multijets events with small MET.
3. Smear each jet by its response $R$
4. Normalize the shape obtained in a QCD enhanced region with low $\Delta\phi(\text{jet, } E_T^{\text{miss}}) < 0.4$
5. Propagate to signal region
**A typical analysis**

- simple « cut & count » analysis
- Cut sufficiently hard
- Apply discriminating cuts to enhance signal/background ratio

**Remaining backgrounds are estimated via**

- Fully data-driven methods for difficult but small bkgs
- Semi-data-driven methods for main processes

\[
N_{SR}^{\text{est.}} = \frac{N_{SR}^{\text{MC}}}{N_{SR}^{\text{MC}}} \times (N_{CR}^{\text{obs.-bkg}})
\]

**Top CR: 1lep+bjet+MET+3jets**

\[
\int L \, dt \sim 1.04 \, fb^{-1}
\]

**W CR: 1lep+nojet+MET+3jets**

**Z CR: γ+3jets**

\[
\int L \, dt \sim 1.04 \, fb^{-1}
\]

**Signal Region**

\[
\int L \, dt \sim 1.04 \, fb^{-1}
\]
Reconstructing b-jets, tau hadrons

B-jets are identified via IP3D+JetFitter tagger based on:

- IP3D: transverse and longitudinal impact parameters of the tracks in the jets
- JetFitter: vertices of b- and c-Hadrons decays are inside the jet

Working point selected with:

- 60% efficiency for b-jets produced in top pairs process
- Mis-tag rate < 1%

Tau hadrons, contrary to hadronic jets:

- Are well collimated
- Have large electromagnetic fraction

ATL-CONF-2011-102
• Only gluino, LSP are accessible
• 1 step decay involving a $W \rightarrow 0$- or 1-lepton + jets +MET signatures

\[ \begin{array}{c}
\text{✓ Exclude } m(\text{gluino}) < 600 \text{ GeV for } m(\text{LSP}) \text{ up to } \sim 200 \text{ GeV} \\
\end{array} \]

• Highlight complementarity of channels without/with leptons
• Small mass splittings (compressed spectra) will require specific channels
Gluino mediated sbottom production (simplified model)

✓ Signature: 0-lepton + several b-jets + $E_t^{\text{miss}}$ => make use of flavor tagging
✓ Interpretations:

Simplified model:

• Only gluino, sbottom, LSP
• Mass spectrum: $m(\tilde{b}_1) > m(\tilde{g}) > m(\tilde{\chi}_1^0)$

✓ Exclude $m(\text{gluino}) < 900$ GeV for $m(\text{LSP})$ up to ~ 300 GeV
Gluino mediated stop production

✓ Signatures:
  a. 1-lepton + several b-jets + $E_t^{\text{miss}}$
  b. 2 same sign leptons + several jets + $E_t^{\text{miss}}$

✓ Interpretations:

Simplified model:

- Only gluino, stop, LSP
- Mass spectrum: $m(\tilde{t}_1) > m(\tilde{g}) > m(\tilde{\chi}_1^0)$
  $Br(\tilde{g} \rightarrow t\tilde{\chi}_1^0) = 1$

✓ Exclude $m(\text{gluino}) < 650$ GeV for $m(\text{LSP})$ up to ~ 215 GeV
Lepton(s)/photon(s) based signatures

Gauge mediation:

- Bino NLSP: $\chi_1^0 \rightarrow \gamma G$
- Search for $2\gamma + E_T^{miss}$

✓ Exclude gluino masses ~ 800 GeV independently of neutralino mass